United States Coast Guard

Report of the Marine Board of Investigation into the Steam Ship EL FARO (O.N. 561732) Sinking and Loss of the Vessel With 33 Persons Missing and Presumed Deceased Northeast of Acklins and Crooked Island, Bahamas On October 1, 2015

MISLE Activity Number: 5735749

U.S. Department of Homeland Security
United States Coast Guard

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STEAM SHIP EL FARO (O.N. 561732) SINKING AND LOSS OF THE VESSEL WITH 33 PERSONS MISSING AND PRESUMED DECEASED NORTHEAST OF ACKLINS AND CROOKED ISLAND, BAHAMAS ON OCTOBER 1, 2015

MARINE BOARD'S REPORT

1. Executive Summary

The loss of the U.S. flagged cargo vessel EL FARO, along with its 33 member crew, ranks as one of the worst maritime disasters in U.S. history, and resulted in the highest death toll from a U.S. commercial vessel sinking in almost 40 years. At the time of the sinking, EL FARO was on a U.S. domestic voyage with a full load of containers and roll-on roll-off cargo bound from Jacksonville, Florida to San Juan, Puerto Rico. As EL FARO departed port on September 29, 2015, a tropical weather system that had formed east of the Bahamas Islands was rapidly intensifying in strength. The storm system evolved into Hurricane Joaquin and defied weather forecasts and standard Atlantic Basin hurricane tracking by traveling southwest. As various weather updates were received onboard EL FARO, the Master directed the ship southward of the direct course to San Juan, which was the normal route.

The Master's southern deviation ultimately steered EL FARO almost directly towards the strengthening hurricane. As EL FARO began to encounter heavy seas and winds associated with the outer bands of Hurricane Joaquin, the vessel sustained a prolonged starboard list and began intermittently taking water into the interior of the ship. Shortly after 5:30 AM on the morning of October 1, 2015, flooding was identified in one of the vessel's large cargo holds. At the same time, EL FARO engineers were struggling to maintain propulsion as the list and motion of the vessel increased. After making a turn to shift the vessel's list to port, in order to close an open scuttle, EL FARO lost propulsion and began drifting beam to the hurricane force winds and seas. At approximately 7:00 AM, without propulsion and with uncontrolled flooding, the Master notified his company and signaled distress using EL FARO's satellite distress communication system. Shortly after signaling distress, the Master ordered abandon ship. The vessel, at the time, was near the eye of Hurricane Joaquin, which had strengthened to a Category 3 storm. Rescue assets began search operations, and included a U.S. Air National Guard hurricane tracking aircraft overflight of the vessel's last known position. After hurricane conditions subsided, the Coast Guard commenced additional search operations, with assistance from commercial assets contracted by the vessel's owner. The search located EL FARO debris and one deceased crewmember. No survivors were located during these search and rescue operations.

On October 31, 2015, a U.S. Navy surface asset contracted by the NTSB, using side-scan sonar, located the main wreckage of EL FARO at a depth of over 15,000 feet. EL FARO's voyage data recorder was successfully recovered from EL FARO's debris field on August 15, 2016, and it contained 26-hours of bridge audio recordings as well as other critical navigation data that were used by the MBI to help determine the circumstances leading up to this tragic incident.

Over the course of the investigation the MBI relied on visits to EL FARO's sister vessel, EL YUNQUE, to help understand the internal configuration of the PONCE class vessels and also identify operational and maintenance issues that could have impacted both vessels.

The scope of the MBI was expanded to include the entire Coast Guard Alternate Compliance Program after Authorized Class Society performance and regulatory oversight concerns were noted for EL FARO, EL YUNQUE, and several additional U.S. flagged vessels in the program.

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2. Preliminary Statement

This marine casualty investigation was conducted and this report was submitted in accordance with 46 Code of Federal Regulations (CFR) § 4.09, and under the authority of 46 United States Code (U.S.C.) Chapter 63. Under 46 U.S.C. § 6308, no part of a report of a marine casualty investigation, including findings of fact, opinions, recommendations, deliberations, or conclusions, shall be admissible as evidence or subject to discovery in any civil or administrative proceedings, other than an administrative proceeding initiated by the United States.

The Chairman of the Marine Board of Investigation (MBI) was Captain Jason D. Neubauer, United States Coast Guard (Coast Guard) Office of Investigations and Analysis. The MBI's legal advisor was Mr. Jeff Bray, Coast Guard Office of Maritime and International Law. Members of the MBI were: CDR Matthew J. Denning and Mr. G. Keith Fawcett, Coast Guard Investigations National Center of Expertise. Technical Advisors to the MBI were: CDR Michael Odom and CDR Michael Venturella, Coast Guard Traveling Inspection Staff; Dr. Jeffrey Stettler and LT Michael Comerford, Coast Guard Marine Safety Center; and Mr. Paul Webb, Coast Guard District Seventeen Search and Rescue Specialist. The MBI's Recorder was LCDR Damian Yemma, Coast Guard Investigations National Center of Expertise, and the Media Liaison was Mrs. Alana Miller, Coast Guard Office of Public Affairs.

The following organizations and person were designated as Parties-in-Interest (PII) in this investigation: TOTE Incorporated, as the parent corporation of the vessel's owner and operator; ABS, as the authorized classification society of EL FARO; Herbert Engineering Corporation, as the naval architecture firm for the owner and operator; and Ms. Teresa Davidson, as next of kin for Captain Michael Davidson, Master, EL FARO.

The MBI held three public hearing sessions in Jacksonville, Florida, in February and May 2016, and February 2017; 76 witnesses testified during 30 days of hearings. All witnesses appeared as requested, and PII representatives participated throughout the hearings. PIIs and witnesses cooperated with all investigation requests.

The National Transportation Safety Board (NTSB) was the lead federal agency for initial evidence collection activities, and led all efforts to recover and transcribe the vessel's voyage data recorder (VDR). The NTSB participated in all hearing sessions, and the MBI and NTSB shared all evidence and factual material gathered throughout the course of their investigations. However, the MBI and NSTB worked separately during the analysis phase of their respective investigations in order to prepare independent conclusions and recommendations.

Unless otherwise noted, references to time in this report are in Eastern Daylight Time, Coordinated Universal Time (UTC) offset minus 4 hours.

TOTE Maritime Puerto Rico (TMPR) was EL FARO's owner responsible for managing the movement of cargo between Jacksonville, Florida, and San Juan, Puerto Rico. TOTE Services Inc. (TSI) operated and crewed EL FARO. Both TSI and TMPR are subsidiary companies of TOTE Inc. Throughout the report, these two companies will be collectively referred to as TOTE, unless otherwise specified.

In addition to the Safety Recommendations in Section 10 of this report, the MBI will also prepare lessons learned, which are advisories for vessel owners, operators, crew members, and other interested parties. The Coast Guard will release these lessons learned in a separate report.

Throughout the investigation, recommendations, information and unique insight into the loss of EL FARO were provided to the MBI through the ELFARO@uscg.mil email address. These emails provided great assistance to the MBI, and selected correspondence will be included in the Coast Guard's MISLE database for this activity.

3. List of Acronyms

1A/E	1st Assistant Engineer
2A/E	2nd Assistant Engineer
2/M	2nd Mate
3A/E	3rd Assistant Engineer
3/M	3rd Mate
AB	Able Seaman
ABS	American Bureau of Shipping
ACP	Alternate Compliance Program
ACS	Authorized Classification Society
BVS	Bon Voyage System
CDO	Command Duty Officer
C/E	Chief Engineer
CEO	Chief Executive Officer
CFR	Code of Federal Regulations
C/M	Chief Mate
CPA	Closest Point of Approach
CSM	Cargo Securing Manual
COI	Certificate of Inspection
DPA	Designated Person Ashore
EPIRB	Emergency Position Indicating Radio Beacon
EPMV	Emergency Preparedness Manual - Vessel
GEO	Geostationary Earth Orbiting
GM	Metacentric Height
GMDSS	Global Maritime Distress and Safety System
HEC	Herbert Engineering Corporation
IACS	International Association of Classification Societies
ICCL	International Convention on Load Lines
ILLC	International Load Line Certificate
ISM	International Safety Management
KW	Kilowatt
LEO	Low Earth Orbiting
LES	Land Earth Station
LO/LO	Lift-On/Lift-Off
LRIT	Long Range Identification and Tracking
LUT	Local User Terminal
MBI	Marine Board of Investigation
MSM	Marine Safety Manual
MEO	Mid Earth Orbiting
MISLE	Marine Information for Safety and Law Enforcement
MSC	Marine Safety Center
NAIS	National Automated Identification System
NCS	Network Coordination Station
NHC	National Hurricane Center
NOAA	National Oceanographic and Atmospheric Administration

NTSB	National Transportation Safety Board
NVIC	Navigation and Vessel Inspection Circular
OCMI	Officer In Charge, Marine Inspection
OMV	Operations Manual -Vessel
OPBAT	Operations Bahamas and Turks and Caicos
OUC	Operations Unit Controller
PII	Party in Interest
P/E	Port Engineer
P/M	Port Mate
PSI	Pounds Per Square Inch
QMED	Qualified Member of the Engine Department
RCC	Rescue Coordination Center
RO/RO	Roll on/Roll off
RPM	Revolutions Per Minute
S.S.	Steam Ship
SAR	Search and Rescue
SART	Search and Rescue Transponder
SLDMB	Self Locating Datum Marker Buoy
SMC	Search and Rescue Mission Coordinator
SMS	Safety Management System
SOLAS	International Convention for the Safety of Life at Sea
SRR	Search and Rescue Region
SSAS	Ship Security Alert System
SSL	Sea Star Lines
STCW	Standards of Training, Certification, and Watchkeeping
SUC	Situation Unit Controller
S-VDR	Simplified Voyage Data Recorder
T&S	Trim and Stability
TMPR	TOTE Maritime Puerto Rico
TS	Tropical Storm
TSI	TOTE Services Inc.
USMCC	United States Mission Control Center
U.S.C.	United States Code
USCG	United States Coast Guard
UTC	Coordinated Universal Time
VDR	Voyage Data Recorder
VHF	Very High Frequency
VP	Vice President

4. List of Figures

5. <u>Vessel Involved in the Incident</u>

Figure 1. S.S. EL FARO. (Source: TOTE)

Official Name	EL FARO
Official Number	561732
Flag	United States
Service	Freight Ship
Type	RO/RO and Container
Build Year	1975
Gross Registered Tons	17,527
Length overall	790 feet
Beam	92 feet

Molded Draft	42 feet
Propulsion	Steam Turbine
Ahead Horsepower	30,000 BHP
Maximum Speed	24 knots
Boilers	2 Babcock & Wilcox Co.
General Boiler Type	Water Tube with Natural Circulation
Owner	TOTE Maritime Puerto Rico (formerly Sea Star Line, LLC) Jacksonville, Florida
Operator	TOTE Services, Inc. Jacksonville, Florida
Classification Society	ABS
Date of Enrollment in ACP	February 27, 2006
Inspection Subchapter	I – Cargo and Miscellaneous Vessels
Certification Date	February 22, 2011
Expiration Date	February 22, 2016
Hailing Port	San Juan, Puerto Rico
Route	Between San Juan, Puerto Rico and Jacksonville, Florida
Builder	Sun Shipbuilding and Drydock
Construction	Welded Steel
Furnace	Pressure Firing with Oil Two Divided
Design Pressure	1,070 PSI
Generator Prime Mover	Two Terry Steam Turbines
Rated Horsepower	2,000 KW
Operating Speed	7,024 RPM
Marine A.C. Generator	Two General Electric
Volts	450 V
Emergency Power Generation	350 KW Delco A.C. Generator
Emergency Power Prime Mover	Detroit Diesel V-71
Steering Gear	Electro-hydraulic
Manning During Accident Voyage	27 Crew and 6 Supernumeraries
Cargo Aboard During Accident Voyage	Electric Reefers with Logs – 238 Dry – 3 Trailer – 118 Autos – 149 Not in Containers – 15 Containers – 391 Other – 4 Fructose – 600.9 Long tons Total Tonnage – 11,045.9 Long Tons

6. Persons Missing and Presumed Deceased

All persons on board EL FARO at the time of the casualty, listed below in alphabetical order, are missing and presumed deceased, as determined by the Coast Guard Sector Commander and Officer In Charge, Marine Inspection (OCMI), Jacksonville, Florida on October 14, 2015.

Name	**Sex**	**Age**	**Position**
Louis M. Champa	M	51	Qualified Member of the Engine Department
Roosevelt L. Clark	M	38	Utility Person
Sylvester C. Crawford Jr.	M	40	Qualified Member of the Engine Department
Michael C. Davidson	M	53	Master
Brookie L. Davis	M	63	Able Seaman
Keith W. Griffin	M	33	1st Assistant Engineer
Frank J. Hamm III	M	49	Able Seaman
Joe E. Hargrove	M	65	Oiler
Carey J. Hatch	M	49	Able Seaman
Michael L. Holland	M	25	3rd Assistant Engineer
Jack E. Jackson	M	60	Able Seaman
Jackie R. Jones, Jr.	M	38	Able Seaman
Lonnie S. Jordan	M	35	Messman
Piotr M. Krause	M	27	Supernumerary/Riding Crew
Mitchell T. Kuflik	M	26	3 rd Assistant Engineer
Roan R. Lightfoot	M	54	Bosun
Jeffrey A. Mathias	M	42	Supernumerary/Riding Crew Supervisor
Dylan O. Meklin	M	23	3 rd Assistant Engineer
Marcin P. Nita	M	34	Supernumerary/Riding Crew
Jan P. Podgórski	M	43	Supernumerary/Riding Crew
James P. Porter	M	40	Utility Person
Richard J. Pusatere	M	34	Chief Engineer
Theodore E. Quammie	M	67	Steward
Danielle L. Randolph	F	34	2nd Mate
Jeremie H. Riehm	M	46	3rd Mate
LaShawn L. Rivera	M	32	Chief Cook
Howard J. Schoenly	M	51	2nd Assistant Engineer
Steven W. Schultz	M	54	Chief Mate
German A. Solar-Cortes	M	51	Oiler
Anthony S. Thomas	M	47	Oiler
Andrzej R. Truszkowski	M	51	Supernumerary/Riding Crew
Mariette Wright	F	51	Utility Person
Rafal A. Zdobych	M	42	Supernumerary/Riding Crew

7. Findings of Fact

7.1. The Incident

Monday, September 28, 2015

EL FARO arrived at the Jacksonville Sea Buoy at 10:36 AM on a voyage from San Juan, Puerto Rico, and docked at the Blount Island terminal at 12:42 PM, starboard side to the pier. The terminal was operated by PORTUS stevedoring.

Upon docking, the stevedores and longshoremen began unloading the ship. The cargo consisted of both load on/load off (LO/LO) containerized cargo and roll on/roll off (RO/RO) wheeled cargo on trailers or chassis. After the unloading was complete, stevedores and longshoremen began loading cargo for the voyage back to San Juan. They loaded containers on the upper deck and drove RO/RO cargo into the holds below deck via cargo ramps. Once the RO/RO cargo was placed in a stowed position, lashing gangs secured the cargo with chains and other lashing gear, pursuant to the vessel's cargo securing procedures. PORTUS personnel lashed the cargo with supervisors overseeing the cargo operations on the vessel's decks.

PORTUS personnel developed the stow plan using the Spinnaker® software, and TOTE personnel in the terminal operations branch input cargo weight and other information into the CargoMax® stability software. During the September 28, 2015 loading of EL FARO, the TMPR Marine Operations Manager was on vacation and his duties were assumed by the TMPR Terminal Manager.

The mates aboard EL FARO were responsible for ensuring the cargo was properly loaded and secured, and the Chief Mate (C/M) had the overall responsibility for the safe loading of cargo. TOTE had previously hired Port Mates (P/M) in San Juan and Jacksonville to assist the ship's mates with in-port duties. However, after September 1, 2015, TOTE did not provide P/Ms in Jacksonville. The crew of EL FARO had difficulty keeping up with the pace of cargo loading, which continued until shortly before EL FARO departed Jacksonville.

On September 28, service technicians from Harding Safety Inc. boarded EL FARO to replace the clutches on the port and starboard life boat davit system. The technicians completed this work on September 29, shortly before EL FARO departed. Neither the Coast Guard nor ABS was notified of the life boat davit repairs prior to EL FARO departing Jacksonville.

The southbound voyage to San Juan, Puerto Rico was designated voyage *185S*; *185* indicated the sequential number of the voyage, and *S* indicated the direction - southbound.

A well-defined surface low that had been strengthening in the Western Atlantic since 2:00 PM on September 26, 2015, was upgraded to Tropical Depression 11 at 8:00 PM on September 27, 2015. Tropical Depression 11 intermittently intensified during EL FARO's port call in Jacksonville and it was upgraded to Tropical Storm (TS) Joaquin in a public advisory issued by the National Hurricane Center (NHC) at 10:36 PM on September 28, 2015. At the time, TS

Joaquin was approximately 295 nautical miles northeast of San Salvador and heading in a southwesterly direction at a speed of about 4 knots.

Tuesday, September 29, 2015

The Master monitored the developing storm system as he considered route options for the trip to San Juan. In general, onboard EL FARO, the Second Mate (2/M) was responsible for developing the voyage plan, which the Master reviewed and approved. EL FARO's normal southerly route, which it sailed weekly, took the ship from the sea buoy at Jacksonville, Florida directly to San Juan, Puerto Rico; a distance of approximately 1,100 nautical miles. In late August 2015, with tropical systems Erika and Danny in the vicinity of the eastern Bahamas, the same Master took EL FARO on a diverted path through the Old Bahama Channel to San Juan. Although the Old Bahama Channel added about 160 nautical miles to the length of the voyage, the route provided better protection from storm generated waves in the open waters of the Atlantic Ocean.

At 10:03 AM, the Master received a text message advising him of the storm from an off-duty EL FARO 2/M who had recently sailed on the vessel. The Master sent a response text acknowledging he was aware of the storm. At 6:31 PM, the off-duty 2/M sent a follow-up text to the Master specifically inquiring about the intended route plan to avoid TS Joaquin. The Master responded that he intended to take the normal, direct route to San Juan. The off-duty 2/M sent a final text reminding the Master about available alternate routes, including mid-transit voyage alternatives to the Old Bahama Channel, if that became necessary.

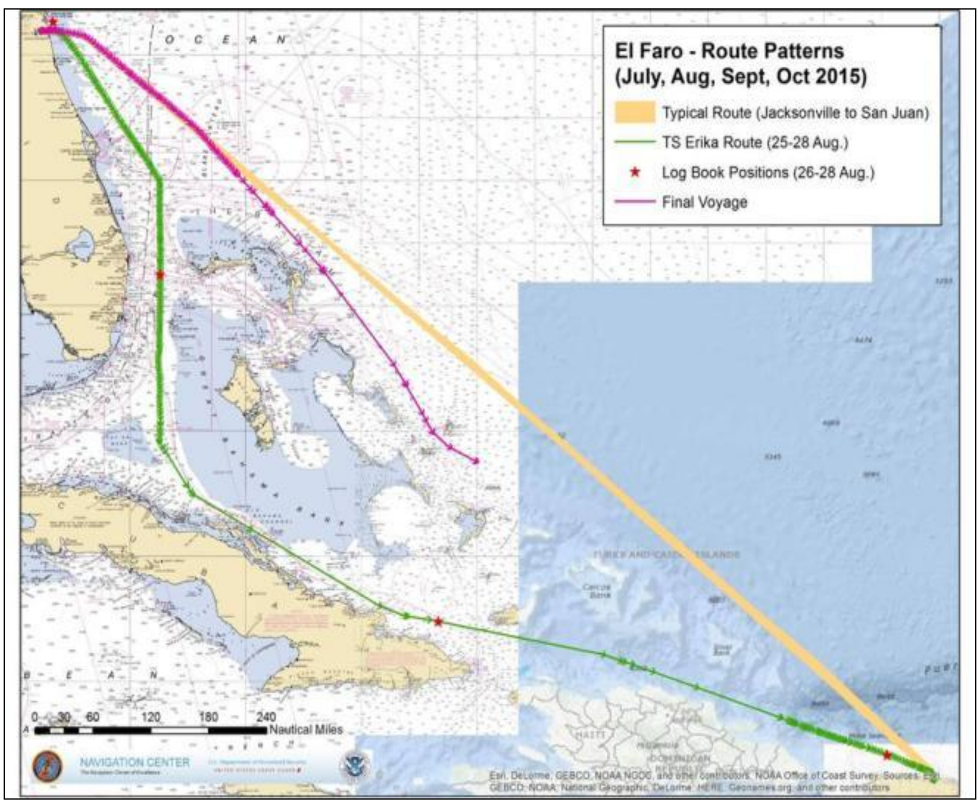

Figure 2. EL FARO's typical southerly route, deviation route during TS Erika, and final voyage route.

The C/M's standing orders for loading and unloading operations required that the mates pay attention to any developing list during cargo loading, and to contact the C/M if the list exceeded 2.5 degrees. On the afternoon of September 29, the TMPR Terminal Manager noted a starboard list greater than he had ever observed during loading. As a result, the TMPR Terminal Manager took a photograph of the list and alerted the stevedores to immediately load containers onto the ship's port side to correct the list. Later analysis of the photograph by a Coast Guard engineer determined the list was approximately four degrees. Based on the Terminal Manager's alert, the stevedores loaded cargo on the port side and corrected the list before EL FARO sailed.

Figure 3. Photograph taken by TMPR Terminal Manager on September 29, 2015, showing starboard list of approximately 4 degrees during loading operations prior to the final voyage.

A TSI Port Engineer (P/E) had dinner with the Master onboard EL FARO; he was the last TOTE shore side management employee to visit EL FARO prior to the casualty. The P/E testified that he and the Master discussed the tropical storm that was developing, but that the Master had no specific concerns about weather; the P/E could not recall any discussions about the planned route. The P/E also testified that he was stressed by the amount of work he needed to get accomplished during EL FARO's final voyage, in preparation for the vessel's scheduled dry docking in Tacoma, WA. He specifically referenced the installation of new winches, power cables, and a glycol heating system for ramp deicing.

At the time of the accident voyage, EL FARO was in the process of converting its cargo carrying arrangements in preparation for a move back to the Alaskan RO/RO trade. A TOTE labor supervisor onboard EL FARO managed a team of five Polish workers, who were onboard to conduct the conversion work. TOTE planned to complete the conversion at EL FARO's next scheduled yard period in December 2015. Four of the Polish workers spoke and understood very limited English, and relied on the fifth Polish member to serve as a translator between themselves and the Riding Crew Supervisor and EL FARO crew members. The Polish workers were not provided a safety indoctrination or Basic Safety Training (BST) before sailing on EL FARO.

At 6:37 PM, the Master downloaded a Bon Voyage System (BVS) weather package from the Inmarsat email system. BVS is an Applied Weather Technologies (AWT) product that uses weather data from the National Hurricane Center (NHC), and other sources, to graphically display anticipated weather conditions along the vessel's intended or planned route. BVS emails were regularly sent to the Master's shipboard email account; the Master then had to manually forward them to the bridge for use by the navigational watchstanders.

AWT had a subscription-based routing service to help vessels avoid heavy weather. TOTE did not subscribe to that service at the time of the accident voyage. BVS also had a tropical update feature which would automatically email tropical updates to a ship, generally within one hour of the NHC issuing a new Tropical Cyclone Forecast/Advisory. EL FARO did not have this feature activated during the final voyage.

Loading operations ended at 6:54 PM, and the vessel was fully loaded as indicated in the vessel details section of this report. Prior to departure, the TMPR Terminal Manager provided the EL FARO C/M with the CargoMax® load case file on a portable flash memory storage device.[1]

Figure 4. EL FARO computer rendering showing the vessel in the departure condition, with mean draft 30.1 feet, 0 degree list, and the stern trimmed down 5.0 feet. Illustration produced by the USCG Marine Safety Center.

As the ship was readied to sail, the Docking Master and the Jacksonville Pilot boarded and conducted a standard Pilot/Master exchange, with no discrepancies noted or discussed. At 8:06 PM, EL FARO pulled away from the pier. EL FARO's typical scheduled departure time from Jacksonville was 7:00 PM. As the ship made the 70-minute transit to the sea buoy, the Pilot and Master engaged in casual conversation, including a brief discussion about TS Joaquin. At 9:48

[1] On October 1, after EL FARO was reported missing, the TMPR Terminal Manager noted an error in the CargoMax® stability calculations for the departure loading condition, and created a revised report that lowered the vessel's stability margin by 0.16 feet.

PM, the Pilot disembarked and the ship cleared the sea buoy en route to San Juan. EL FARO sent a departure report to shore side TOTE personnel, which did not include any indication of the Master's intended route to San Juan.

When EL FARO departed Jacksonville, the lube oil level in the sump that served the steam turbines and the main reduction gear was 24.6". The recommended operating level in the Machinery Operating Manual was 27", and the approved lube oil sump plan indicated that the operating range was 18"-33". TOTE had no guidance or policy that required maintaining the recommended 27" operating level.

Former TOTE crew members testified that fire dampers for the cargo hold ventilation system on EL FARO were only closed in the event of a cargo hold fire, and were otherwise left open, even in heavy weather conditions. Leaving the fire dampers open for cargo holds that carry vehicles with fuel was done to prevent flammable vapors from accumulating in accordance with SOLAS II-2 Regulation 20 and 46 CFR § 92.15-10.

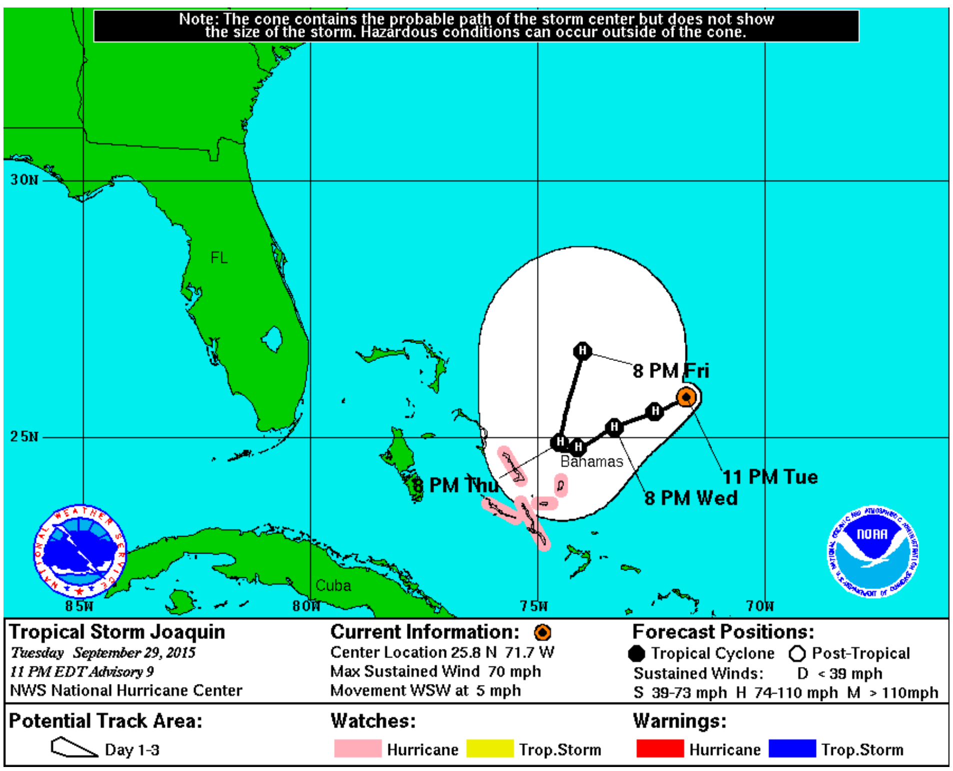

Figure 5. NHC Tropical Storm Joaquin Advisory 9, 11 PM EDT September 29, 2015, 3 day cone.

As EL FARO headed to sea, TS Joaquin was located about 365 nautical miles east of the Northwestern Bahamas and was moving west-southwest at 4 knots. Starting at 4:51 PM on September 29, the NHC advisories began to indicate that TS Joaquin could impact the Bahamas as a hurricane. All prior NHC advisories had predicted that TS Joaquin would change to a northerly heading and not impact the Bahamas. The NHC's 11:00 PM advisory confirmed that TS Joaquin would continue to strengthen and remain on a southwesterly track for the next couple days. As a result, Joaquin's first hurricane watch was established for the central Bahamas.

At 11:29 PM, the Master downloaded a BVS weather package from the Inmarsat email system.

During the accident voyage, EL FARO sent a departure report and noon position reports, as required by TOTE's Operations Manual – Vessel (OMV). These messages were not required to indicate the route that EL FARO would take, and the subject was not indicated in the Master's remarks sections.

Wednesday, September 30, 2015

At 2:00 AM, the NHC upgraded TS Joaquin to a Category 1 Hurricane.

EL FARO's Voyage Data Recorder (VDR) provided audio and parametric data beginning at 5:36 AM.[2] The VDR recorded audio from the bridge of EL FARO and voyage data such as the ship's position, speed, heading, course-over-ground, and radar images.[3]

Figure 6. Photograph of EL FARO's bridge. (Photograph provided by TOTE)

At 6:08 AM, the Master downloaded a BVS weather package from the Inmarsat email system. This package contained a duplicate NHC trackline for Hurricane Joaquin from the

[2] EL FARO's VDR was designed to record data on a continuous loop that was required to capture at least 12-hours of data prior to an accident that cuts power to the device. When EL FARO sank its VDR contained 26-hours of data starting at 5:36 AM on September 30, 2015.
[3] For the remainder of this section of the report, all quotes and references to discussions onboard EL FARO were taken from the NTSB transcript of the VDR audio recording, unless otherwise noted.

previously issued data package that was downloaded at 11:29 PM on September 29. However, the BVS weather package did contain the most current wind and wave data.[4]

At 06:13 AM, the Master and C/M observed that they would be southwest of the hurricane the following day, based on the forecast information they were reviewing. They decided to alter course further to the south to open up the closest point of approach (CPA) to the hurricane.

At 10:17 AM, the Master received a satellite email message from the Master of EL YUNQUE, who was northbound en route to Jacksonville from San Juan. EL YUNQUE's Master asked about EL FARO's plans and intentions for the storm. EL FARO's Master responded at 11:10 AM that he was watching the storm and had altered course slightly to the south.

At 11:21 AM, EL YUNQUE's Master responded to the Master of EL FARO, "[t]hat's good to hear. Hopefully, it will turn to the North soon. As we passed to the west of it we recorded a 100 knot relative wind gust. Luckily, it was coming from directly ahead."

At 11:24 AM, the Master downloaded a BVS weather package from the Inmarsat email system.

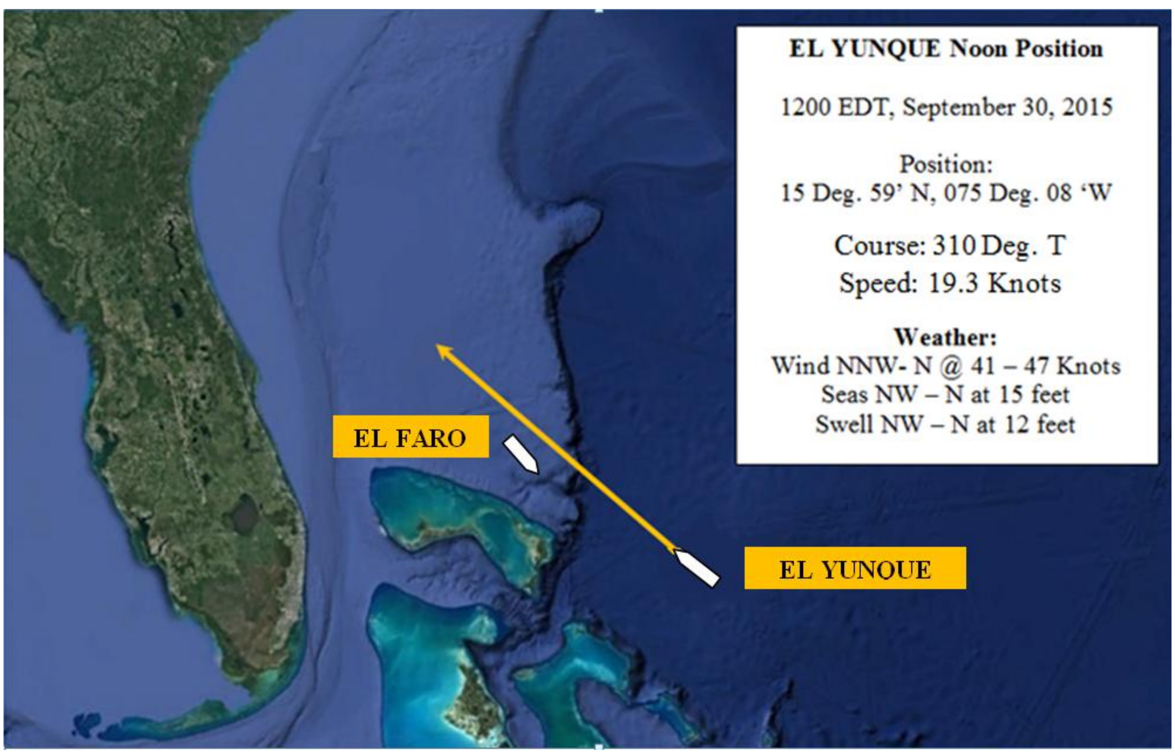

Figure 7. Noon positions of EL YUNQUE and EL FARO on September 30, 2015; information from noon report of EL YUNQUE

At 1:22 PM, EL FARO's Master transmitted a noon report email to shore. This report noted "precautions observed regarding Hurricane Joaquin." Around the same time, the Master also

[4] Refer to Weather background section for forecast graphics and additional detail.

sent a more detailed email to TOTE management personnel indicating he had monitored the storm, adjusted the route, and intended to pass south of the storm at a distance of +/- 65 nautical miles. He anticipated being on the backside of the storm by 8:00 AM on October 1.

In this email, the Master also stated he would like to take the Old Bahama Channel on the return trip from San Juan, and that he would await a reply from the company before making a final decision on the return voyage. EL FARO received a reply from the TSI Director of Ship Management at 4:09 PM stating, "[d]iversion request through Ol' Bahamas Channel understood and authorized. Thank you for the heads up." At this time, the TSI Director of Ship Management was in California attending to construction issues regarding TOTE's new MARLIN class ships.

At 1:55 PM, the 2/M discussed preparing a voluntary weather observation report due to their anticipated proximity to the storm.[5] The 2/M sent this observation message at 2:21 PM, but erroneously transcribed EL FARO's position, placing the ship over mainland Cuba.

At 2:14 PM, the Master and 2/M heard a VHF sécurité broadcast from a Coast Guard aircraft, relaying an NHC hurricane warning for the Bahamas, which requested that mariners use extreme caution.[6]

Around 3:50 PM, EL YUNQUE and EL FARO passed each other at a distance of approximately 33 nautical miles. The two bridge watches contacted one another and carried on a short conversation on VHF radio, including a brief discussion of Hurricane Joaquin.

At 5:47 PM, the Master downloaded the most current BVS weather package via satellite email. The Master sent this weather package to the bridge computer at 6:51 PM, and then went to the bridge to discuss the storm and voyage plan with the C/M. The Master and C/M decided on a new track for the ship that would take it further to the south, passing between the islands of San Salvador and Rum Cay. The C/M proposed extending the course to sail south of Samana Cay; however, the Master decided that would not be necessary and instead directed the route between San Salvador and Rum Cay but north of Samana Cay. The Master stated this route was simpler for the watch because it involved one course change, as opposed to two.

The 3/M arrived on the bridge to relieve the C/M at 7:43 PM.

At 7:52 PM, the Master discussed the storm with the oncoming AB, who asked if the storm was going to intensify. The Master responded that they had picked a new route to get away from "the low." At 8:00 PM, Joaquin was a category 3 Hurricane with winds estimated at 100 knots.

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[5] Ships may send at-sea weather observations to a national meteorological service, such as NOAA's National Weather Service. Scientists can then use this information for forecasting and climate study. For more information on the Voluntary Observing Ship Program, see http://www.vos.noaa.gov/.
[6] A sécurité broadcast is safety message that reports important navigational and meteorological warnings or other unusual events that might impact maritime activities.

The Master left the bridge around 8:00 PM. Before leaving, he told the 3/M that he would be awake for the better part of the 3/M's watch. The Master's voice was not detected on the bridge again until 4:09 AM the next morning.

At 11:04 PM, there was a new BVS weather package available for download on EL FARO. However, satellite email transmission records show that this email was not downloaded to EL FARO until 4:45 AM on the morning of October 1.

At 11:05 PM the 3/M called the Master on the house phone[7] after reviewing the SAT-C weather report, which arrived at 10:53 PM. He advised the Master that the hurricane's maximum winds were 100 miles per hour[8] and that the storm was advancing toward their trackline. During this call the 3/M twice told the Master that he thought the Master might want to look at the weather report. The Master did not come to the bridge. The 3/M told the Master he would get more specific information, and called the Master again at 11:13 PM. He advised the Master that EL FARO would be 22 miles from the hurricane's center at 4:00 AM the next morning, and that winds were "one hundred with gusts to one-twenty and strengthening." The 3/M suggested altering course to the south at 2:00 AM to increase the distance between EL FARO and the hurricane.

After his phone conversation with the Master ended, the 3/M told the Able Seaman (AB) on watch that the Master thought they would be south of the storm "by then" and the wind would not be an issue because EL FARO would be in the southwest quadrant of the hurricane. The 3/M stated that he trusted the Master, but still expressed concern regarding EL FARO's closest point of approach to the hurricane. For the remainder of his watch, the 3/M continued to sail EL FARO along the Master's planned course.

Between 11:45 PM and shortly after midnight, the 3/M and 2/M conducted watch relief and discussed the hurricane, current route, and other route options.

Thursday, October 1, 2015

At 12:26 AM the 2/M received a SAT-C weather update and began planning an alternate route to the south through Crooked Island Passage, then joining the easterly Old Bahama Channel route to the ship's destination in San Juan. The 2/M plotted the course change to begin at 2:00 AM.

At 1:15 AM, the 2/M heard on the commercial satellite radio that Joaquin was upgraded to a Category 3 hurricane. At 1:18 AM, as EL FARO transited out of the lee of San Salvador Island, the AB stated "biggest one since I've been up here" when discussing the ship's rolling. The 2/M questioned why they are rolling if they were between the islands.

[7] The "house phone," or electric telephone, is an internal ship's phone. It is referred to as "ET" in the NTSB VDR transcript.
[8] The SAT-C weather report indicated that the wind speed was actually 100 *knots*, or approximately 115 miles per hour.

At 1:20 AM, the 2/M called the Master and advised him of the upgraded hurricane category. The 2/M also proposed altering course directly south, starting at 2:00 AM. The 2/M stated that the proposed course would take them through "all these * shallow areas." After speaking to the Master, the 2/M told the AB on watch that "he said to run it." The 2/M also later told the AB that it sounded like the Master was sound asleep. There is no indication the 2/M made any further calls to the Master during the watch.

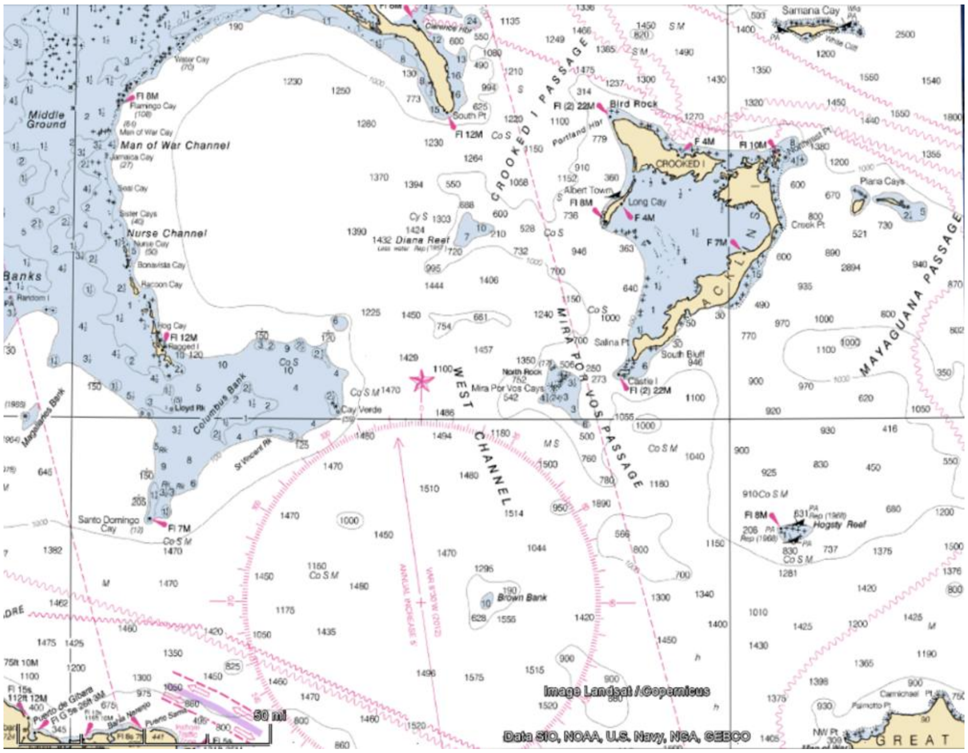

Figure 8. Google Earth NOAA raster nautical chart image of Crooked Island Passage.

At 1:24 AM, as EL FARO passed between San Salvador and Rum Cay, the 2/M told the AB to begin the course change to 116 degrees as the Master previously planned. Shortly after making the turn, the AB made a comment about wind heel.

At 1:29 AM, the 2/M remarked "startin' to hear the wind now." U.S. Navy weather analysis indicated that, around this time at EL FARO's position, seas were 14', swells were 10', and wind speed was 55 knots at 320 degrees.[9] The 2/M also noted that EL FARO had lost a little speed.

At 1:40 AM, the 2/M and the AB discussed drills, and the 2/M commented that "nobody ever takes these-the drills-seriously," and that no one actually checks to make sure their survival suits fit.

At 2:11 AM, the 2/M noted "green water on the bow," and the AB commented that he could hear "clanking going on."

[9] Per U.S. Navy Hindcast information provided by Senior Meteorologist, Fleet Weather Center Norfolk.

As EL FARO's heading changed and the weather conditions worsened, EL FARO's speed began to drop. At 2:15 AM, the AB noted that the speed was down to 16 knots, from about 20 knots.

At 2:47 AM, the 2/M and the AB on watch discussed that the Master was not on the bridge, the 2/M stated: "He said he was gonna come up. When I asked him that – he said that yesterday. He said that today he said he would probably be up here."

At 2:50 AM, the AB described hearing an internal thump. The AB and the 2/M then discussed that things were likely breaking free inside the superstructure.

At around 2:54 AM, a sound consistent with the steering stand alarm was heard on the bridge. The 2/M questioned whether the vessel was off course and the AB responded that it was. The 2/M then noted that the steering alarm was set to sound when the vessel was three degrees off course. This alarm was heard a few more times during the 2/M's watch. The 2/M made minor course corrections to keep EL FARO on course.

The C/M came to the bridge to relieve the 2/M at 3:44 AM. The watch relief was complete and the 2/M departed the bridge at about 3:48 AM. A portion of the watch relief was unintelligible on the VDR audio, and the exact watch relief procedures conducted could not be determined by the MBI. The 2/M did tell the C/M that the Second Assistant Engineer (2A/E) was blowing tubes, that she called the Master, and that the ship was holding her heading good, but may lose heading a little when the ship took good slams and pitches.

Immediately after getting off watch, the 2/M typed three short emails to family and friends stating that the ship was heading into Hurricane Joaquin.

Shortly after relieving the watch, the C/M began to make incremental heading changes to port, in an attempt to reacquire the planned 116 degree trackline. The steering alarm sounded persistently for several minutes and the AB commented on the difficulty of keeping the heading steady. The vessel was in auto pilot at this time.

At 3:47 AM, the C/M made a comment to the AB that "it's hard to tell which way the wind's blowing' huh?" followed by "I assume that we're heelin' to starboard (must be blowin') port to starboard."

At 3:50 AM, the AB watch relief takes place and the 4:00 to 8:00 AB remains on watch for the remainder of the voyage.

At 3:55 AM, a Third Assistant Engineer (3A/E) who stood the midnight to 4:00 AM engine room watch came to the bridge through 2nd deck, and told the C/M that some cords on the reefer containers on 2nd deck were "cut."

At 4:05, the C/M stated that they were steering "up like thirty degrees into the wind."

At 4:09 AM, the Master arrived on the bridge. The Master remarked that "there is nothing bad about this ride," and that he was "sleepin' like a baby." The Master and C/M agreed that the conditions were similar to "every day in Alaska." The Master also observed that the ship was not rolling, pitching, or pounding. The C/M told the Master that he turned off the off-course alarm because it was sounding repeatedly.

At 4:12 AM, the C/M told the Master he was trying to make good on the previously planned 116 degree course. The Master and C/M also discussed the wind on the port bow, and the Master stated that "the only way to do a counter on this is to fill the port side ramp tank up."[10]

At 4:15 AM, the Master questioned whether the ship was starting to slow down. He contacted the engine room on the house phone and after hanging up, commented "blowin' tubes."

At 4:24 AM, the C/M reported a barometer reading of 970 millibars to the Master and then followed-up by stating "think it's gunna go down (before it goes up)." The Master responded to the C/M that "we won't be goin' through the eye."

At 4:27 AM, the C/M noted 100 RPMs and the Master commented that they need the RPMs. A few minutes later the C/M responded "this might be as high as it's gunna go."

At 4:34 AM, the C/M called the engine room to remind them that the weather decks were secured, and that he did not want anyone coming up from 2nd deck like the 3A/E had earlier. The Master departed the bridge and went to the galley.

At 4:36 AM the C/M received a call on the house phone from the Chief Engineer (C/E), reporting that a container was leaning over on the 2nd deck. A few minutes later at 4:40 AM, the C/E called the C/M again and reported an issue with "the list and oil levels." The C/M called the Master in the galley, and the Master returned to the bridge. After calling the engine room and speaking with the 2A/E, the Master stated, "He wants to take the list off, so let's put it in hand steering."

At 4:44 AM, the Master commented "* * just the list. The sumps are actin' up *. To be expected." The C/M replied "yeah the oil sumps I understand." Between approximately 4:45 AM and 5:05 AM, the Master and C/M make a series of heading adjustments to orient the vessel's bow nearly directly into the wind in order to reduce the wind heel effects on the vessel so that the engineers could troubleshoot the problems the starboard list was having on the lube oil system.

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[10] The ramp tanks are used to correct list during cargo loading in port, and are effective to correct a list of less than 2 degrees.

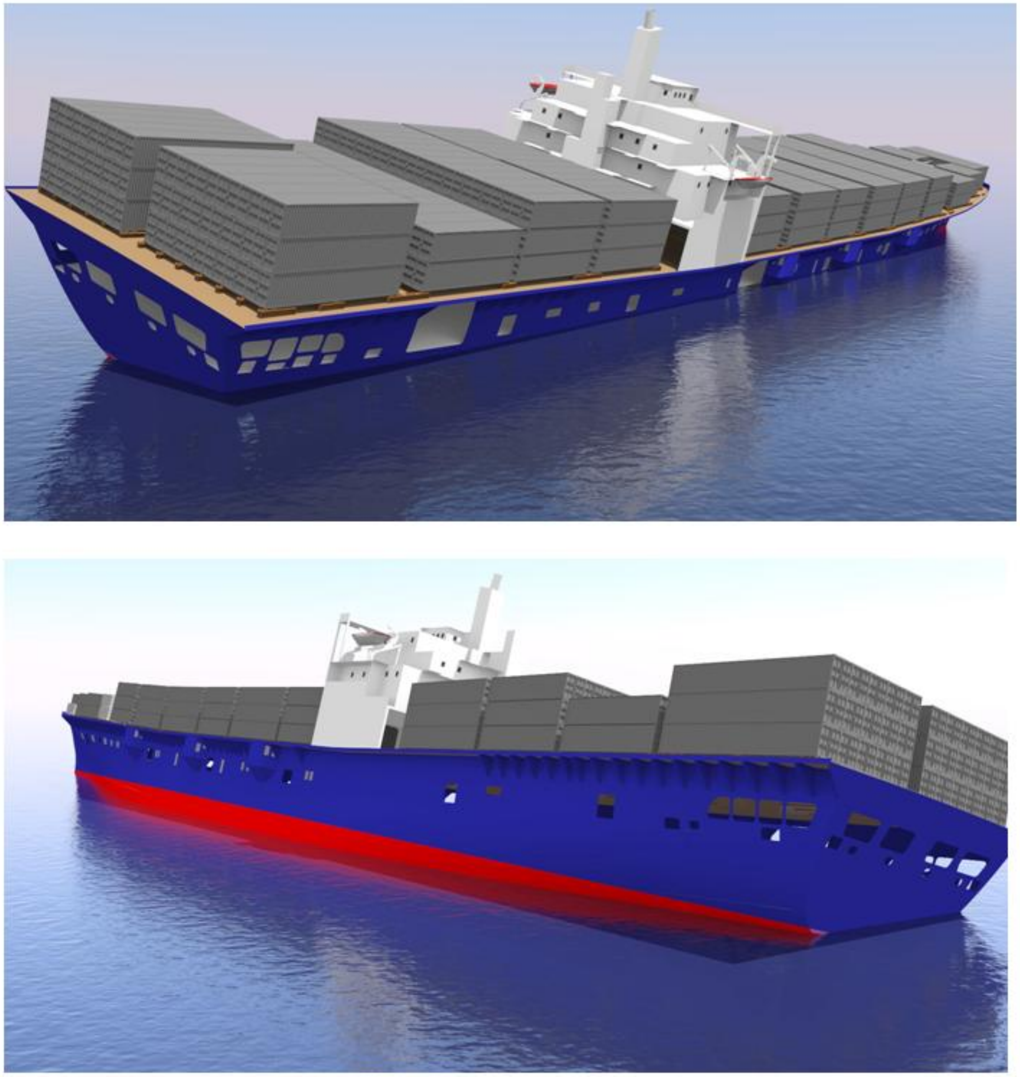

Figure 9. EL FARO computer rendering with 15 degree starboard list and trimmed down by the stern 5.8 feet, due to flooding of Hold 3 estimated at 20% and wind heel. Illustration produced by the USCG Marine Safety Center.

At 4:45 AM, the Inmarsat email system showed that the 11:00 PM BVS weather package was downloaded to the Master's email address.

Also at 4:45 AM, the C/M noted that the barometric pressure was "down to 960 millibars." SAT-C and NHC weather information indicated that the barometric pressure in the eye of Joaquin was estimated to be 950 millibars.

At 4:46 AM, the Master took the conn and issued helm commands to the AB. Shortly after that, EL FARO received a SAT-C weather update. This update indicated that the barometric pressure in the eye of Joaquin was estimated to be 948 millibars and max sustained winds of 105 knots.

At 4:57 AM, the Master went below to check the satellite email system. Before leaving the bridge, he told the C/M to steer in the general direction of 050 degrees.

At 5:01 AM, the C/M stated that he was expecting the wind to come around to the bow and then to the starboard side. He also noted that the ship was still heeling.

By 5:02 AM, the Master had returned to the bridge, and stated he sent the BVS weather package to the bridge. He stated there were conflicting reports about the center of the storm and questioned whether the barometer was coming up. The C/M replied that the pressure was still 960.

At 5:04 AM, the Master ordered the rudder hard right and then eased to right twenty. He then commented "Our biggest enemy here right now is we can't see. That's our biggest enemy."

At 5:06 AM, the Master commented that they were trying to get back on their original course and remarked that they were on the back side of the storm.

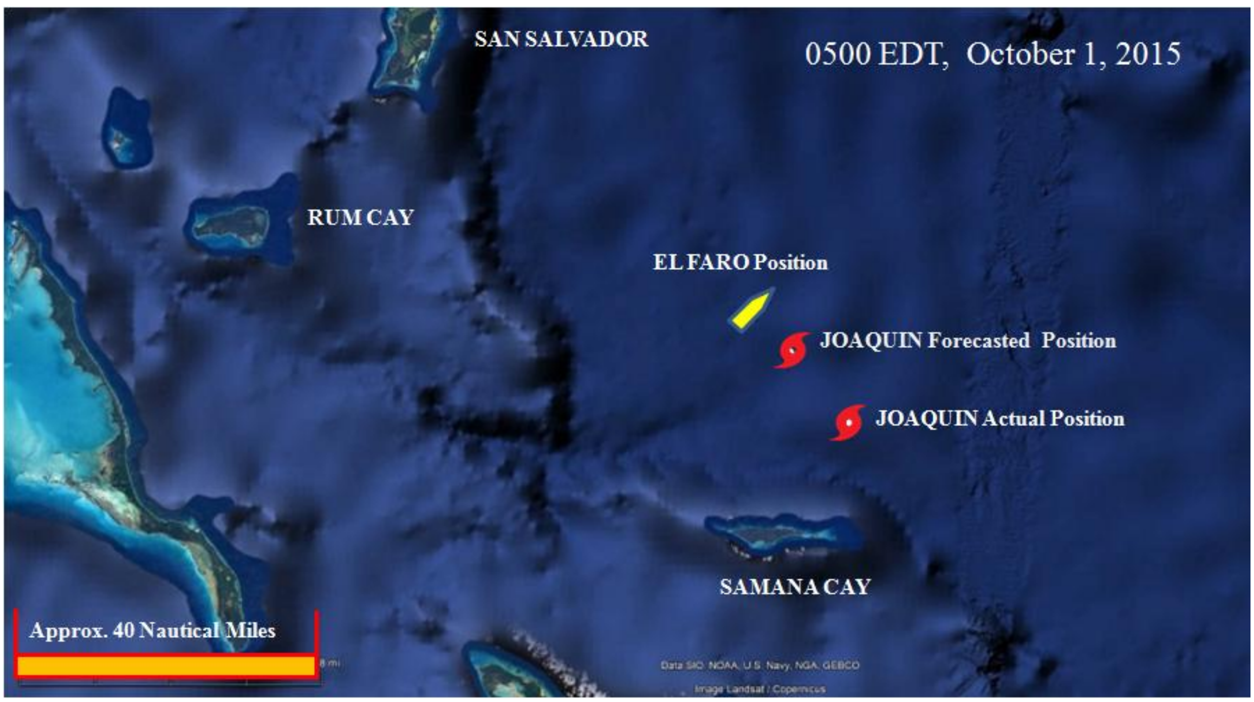

Figure 10. Google Earth image showing the 5:00 AM positions of EL FARO, the center of Hurricane Joaquin as detailed in NHC Advisory 14, and the center of Hurricane Joaquin determined during a NHC post-storm 'best track' analysis.

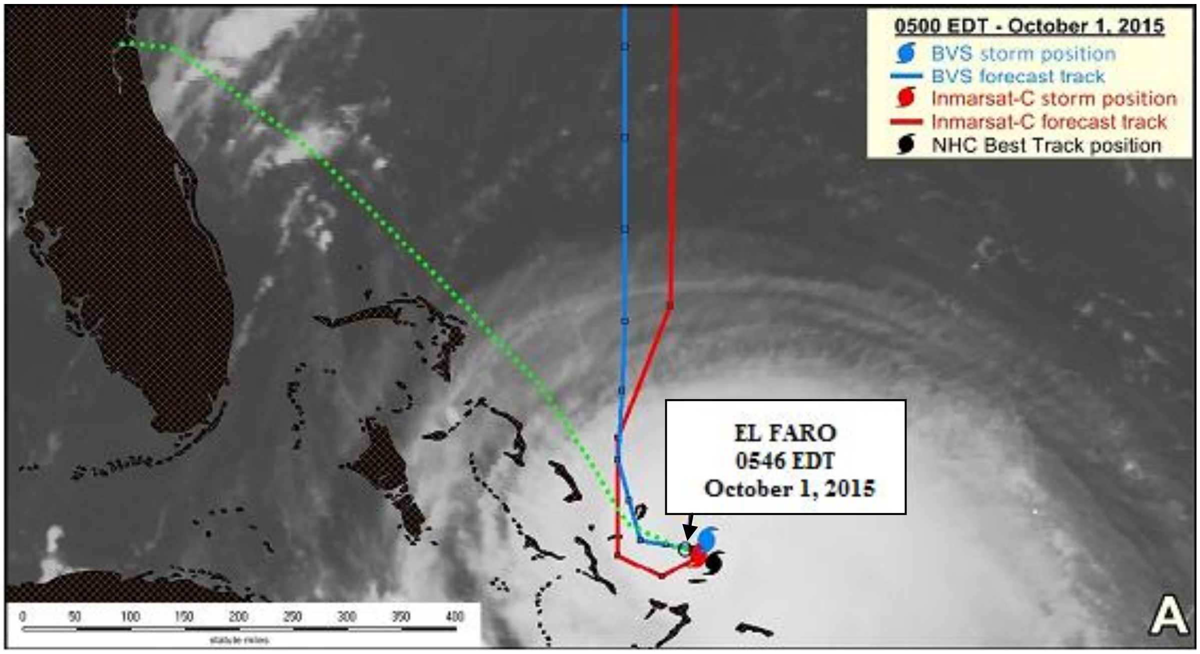

Figure 11. 5:00 AM October 1, 2015 image showing the approximate relationship between EL FARO and forecasted storm positions. The extent of the weather system is also visible. (Source: NTSB Weather Factual Report)

Shortly after this comment the Riding Crew Supervisor arrived on the bridge. He stated that the ship's list was unusual and he had never seen the ship "hang" like it was. He and the Master discussed the effect of the list on the lube oil levels. A few minutes later, the C/E called the Master and discussed the effects of the list.

At 5:22 AM, the C/M reported that the barometer was reading 950 millibars.[11] This barometer reading was the lowest level recorded by the VDR during the accident voyage. This pressure reading placed EL FARO close to the eye of Hurricane Joaquin, which at that time had a minimum estimated pressure of 948 millibars.

At 5:30 AM, the C/M noted a change in the relative wind direction as the spray was hitting them directly instead of going across the beam. He also remarked about taking water on the stern.

At 5:43 AM, the Master received a call on the house phone reporting water in Hold 3. He directed the C/M to go below to assess the situation. Before leaving the bridge, the C/M answered a call on the house phone and discussed the source and amount of flooding, and use of the bilge pumps. The Master took the phone from the C/M and acknowledged that the bilge pump was running and water was still rising.

A minute later the Master made the comment, "We got cars loose. Yeah." According to the cargo manifest documents for voyage 185S there were 50[12] automobiles in the lowest level of that hold. The vehicles were strapped to chains that ran across the width of the ship. The average

[11] The VDR Transcription Team was undecided on whether the reading was passed as 950 or 951 MB. Regardless, the reading was the lowest pressure recorded on the VDR during the accident voyage.
[12] MBI Exhibit 069, p. 30.

weight used for each automobile in the cargo documentation was 1.5 long tons[13] (3,360-LBS). The C/M then left the bridge to get the off-duty 3A/E and investigate the flooding.

At 5:48 AM, the Master called the C/E and directed him to begin transferring from the starboard ramp tank to port.

At 5:52 AM, the Master received a call on the house phone informing him that the source of the flooding was an open scuttle. He then turned the ship to port to put the wind on the starboard side and induce a port list. The Master ordered this maneuver to enable the crew to access the partially flooded 2nd deck in order to secure the cargo Hold 3 scuttle on the starboard side. A post-casualty analysis noted that the configuration of the lube oil sump suction valve, which was offset 22" to starboard of centerline, was susceptible to losing suction during a port list.

At 5:55 AM, the C/M called the Master on a UHF radio and reported a flooded hold on the starboard side with knee deep water.

By 5:56 AM the ship was on a new heading of 350 degrees with the wind on the starboard side and the ship listing to port. The Master then called the engine room and told them to stop transferring ballast from starboard to port ramp tanks.

At 5:59 AM, the 2/M returned to the bridge and the Master told the 2/M that "a scuttle popped open and there's a little bit of water on in three hold, they're pumping it out right now."

Based on radar and VDR parametric data, EL FARO's propulsion was reduced just prior to 6:00 AM. Around this time, EL FARO's heading was approximately due north, but the vessel started to be set in a westerly direction.

[13] MBI Transcript February 20, 2016, p. 176.

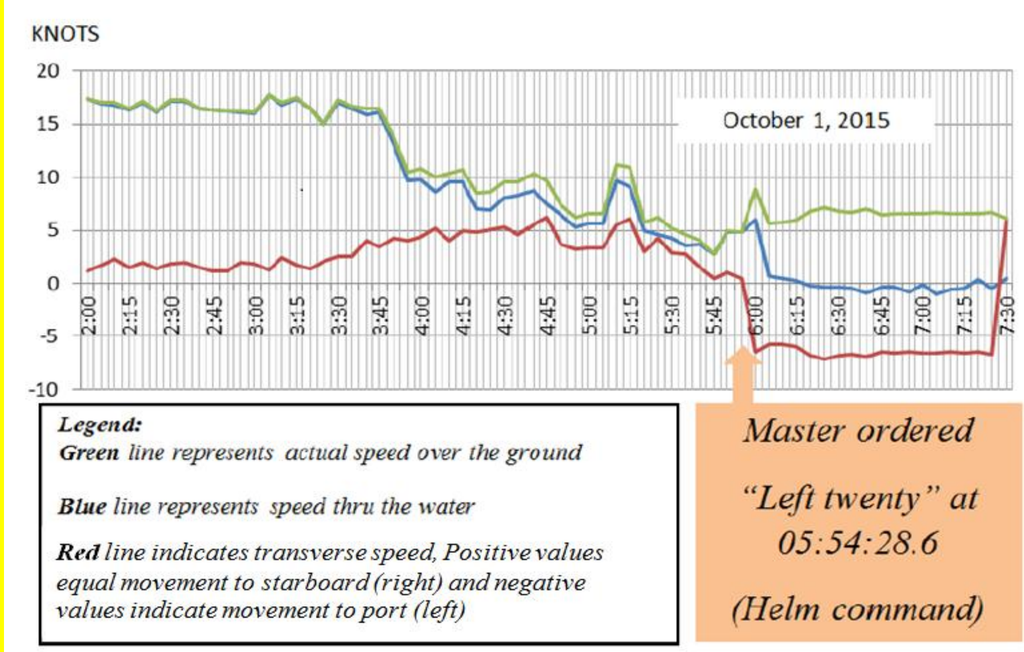

Figure 12. Graph of EL FARO's speed over ground and speed through the water on October 1, 2015.

Shortly after, at 6:00 AM, the Master received simultaneous calls on the house phone and UHF radio. The Master responded to the engine room with a question, "(all through) the ventilation?" He then stated to the engine room, "Want me to bring it back over to starboard?" and "bring it back roll back over to starboard." The C/M was heard on the UHF radio reporting to the Master that the scuttle was secured.

The first discussion on the VDR audio regarding the actual loss of propulsion was at approximately 6:04 AM when the 2/M noted a reduction in RPMs and questioned whether the bridge or engine room initiated the reduction.

The C/M returned to the bridge at 6:04 AM and explained to the Master that when he was on the 3rd deck, he had seen water coming down through the scuttle, but he could not see whether cars had broken free on fourth deck. The Master told him to return to the 3rd deck to look into the 4th deck of Hold 3. The Master also continued to issue helm commands to the AB.

At 6:09 AM, satellite email transmission records show that the most recent BVS weather package was downloaded on EL FARO. This was the 5:00 AM BVS weather package.

At 6:12 AM, the Master remarked that he did not like the list, followed by "I think we just lost the plant."

At 6:16 AM, the engine room called the Master on the house phone, and the Master asked if there was "any chance of gettin' it back online?"

At 6:19 AM, the Master called the engine room and ordered shifting ballast from port to starboard ramp tanks. This was the first of several requests from the Master to transfer ramp tank ballast to the starboard side.

At 6:21 AM, the Master received a call on the house phone from a 3A/E. The Master questioned whether there was any way to tell if he had suction and was pumping a hold.

At 6:24 AM, the Master called back to the engine room and spoke with a 3A/E to get an update and to confirm they were pumping ballast from port to starboard ramp tanks. During the call the Master confirmed that a 3A/E was pumping on the hold.

At approximately 6:30 AM, the 3/M and 2/M were on the bridge and the 2/M began to draft a Global Maritime Distress and Safety System (GMDSS) message to alert the rescue agencies of the ship's situation.

At 6:34 AM, after calling the C/E, the Master stated, "They're gettin' that boiler back up. They're gettin' lube oil pressure up."

At 6:40 AM, the Master sent the C/M below to check the condition of Hold 3.

At 6:44 AM, the Master and the engine room communicated, and the Master remarked to the AB that "you got some turns now." However, at 6:48 AM, the Master told the AB at the helm that there were not any RPMs. VDR parametric and radar data during this time does not show any changes in heading, course over ground, or speed over ground that would indicate a restoration of propulsion.

At 6:52 AM, the Master went below. After he left, someone called the bridge looking for the Master and the caller was told to try contacting him in his office.

The Master returned to the bridge at around 6:54 AM. He called the C/E on the house phone for a status check. After the call, he stated to the 2/M that the engineers were having a hard time getting "it" back online because of the list.

At 6:59 AM, the Master attempted to contact the TSI Designated Person Ashore (DPA), and left a voice mail. At that time the DPA had been out of the office for a few days and was not aware of EL FARO's position in relation to Hurricane Joaquin. No other shore side TOTE personnel were actively monitoring EL FARO's position in relation to the hurricane.

The Master then called the Emergency Call Center. After speaking with the call center operators for approximately seven minutes, the Master was connected to the TSI DPA at 7:07 AM. The Master briefed the DPA with the details of the situation on EL FARO, including that that the engineers could not get lube oil pressure on the plant, they had no main engine, they had a 10-15 degree port list, they were not gaining ground pumping out the hold, and that they were in survival mode but were not planning to abandon the ship. The Master also briefed the DPA on the weather conditions, including that the barometric pressure was 958.8 millibars.

Figure 13. EL FARO computer rendering showing list to port of 18 degrees with departure trim 5.8 feet by the stern due to flooding of Hold 3 estimated at 20% and wind heel. Illustration produced by the USCG Marine Safety Center.

The Master ended the call with the DPA at 7:12 AM and immediately instructed the 2/M to send the GMDSS message to communicate the distress to the shore side rescue agencies. The Ships Security Alert System (SSAS) was also activated.[14]

At 7:14 AM, the C/M told the Master that the water level was rising. The C/M told the Master that the C/E mentioned the fire main as a potential source of flooding. The C/M tightly dogged the door on 3rd deck and the Master told him not to open it again.

At 7:15 AM, the Coast Guard Atlantic Area Command Center in Portsmouth, Virginia, received EL FARO's GMDSS and SSAS alert messages.

At 7:16 AM, the C/M talked to the C/E on the house phone. After this call, the C/M stated there was a bilge alarm going off in Hold 2A, but that he would not go on 2nd deck to check that. The Master then called the C/E and agreed that the list was getting worse.

At 7:18 AM, the Master and C/M discussed cars floating or bobbing in Hold 3. The Master asked whether there was anything near the fire main. The C/M responded that the water level was too high, and the fire main was right below dark black water. The Master and C/M then discussed isolating the fire main in the engine room as an option for controlling the flooding. The Master spoke with the First Assistant Engineer (1A/E) on the house phone and asked if the 1A/E could isolate the fire main.

At 7:23 AM, the Master talked to a crew member on the house phone, and was not able to answer a question about EL FARO's downflooding angle. The Master also stated they still had reserve buoyancy and stability. He next stated that he was going to ring the general alarm to wake or get everybody up.

[14] The SSAS is an alert system primarily intended for use in cases of piracy, terrorism, or other security-related issues.

Figure 14. EL FARO modeling with 20 degree port list and departure trim down by the stern at 5.8 feet due to flooding of Hold 3 estimated at 20% and wind heel. Illustration produced by the USCG Marine Safety Center.

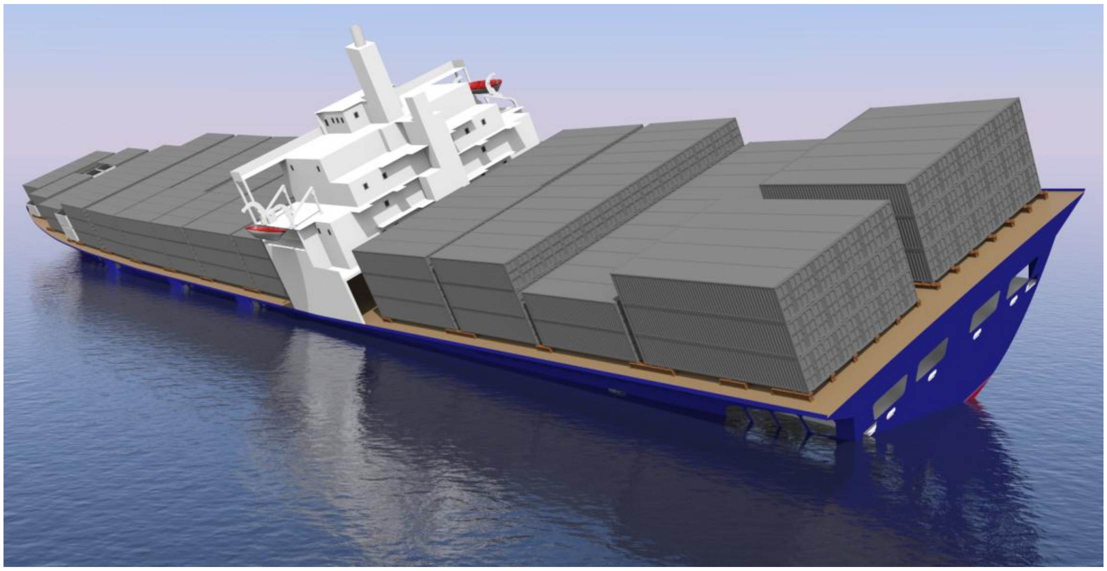

Figure 15. EL FARO computer rendering with 25 degrees port list and departure trim of down by the stern at 5.8 feet due to flooding of Hold 3 estimated at 20% and wind heel. Illustration produced by the USCG Marine Safety Center.

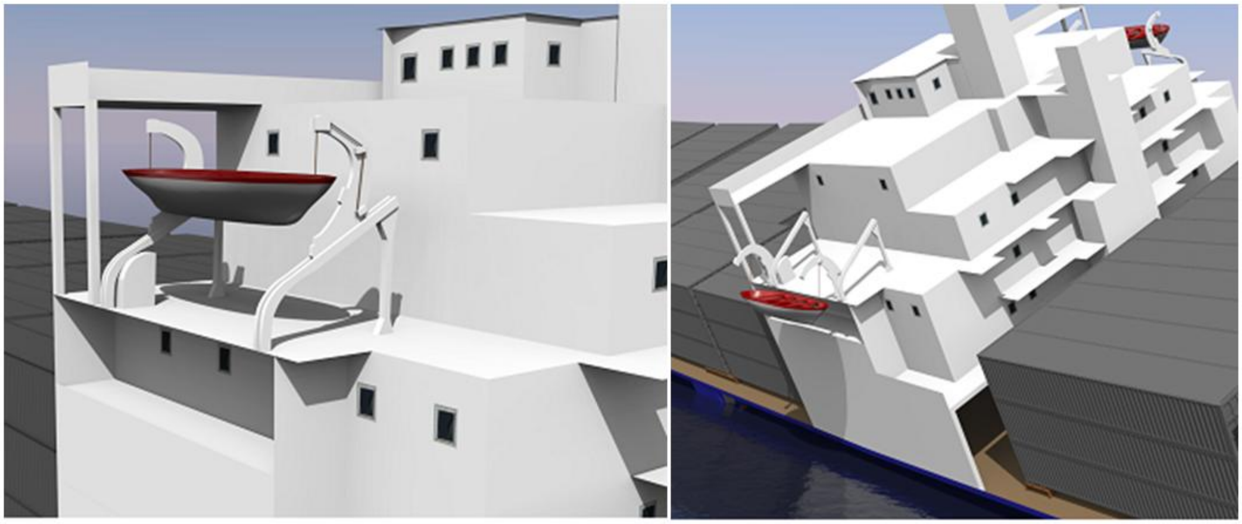

Figure 16. EL FARO computer rendering. On the left, the port lifeboat is shown in the davit in its normally stowed position with EL FARO on an even keel. On the right, the lifeboat is shown lowered to the embarkation deck with EL FARO listing 25 degrees to port. There is no evidence that the use of the lifeboats was discussed by the crew. Large life rafts were stored in close proximity to the lifeboats. Illustration produced by the USCG Marine Safety Center.

At 7:24 AM, the DPA contacted the Coast Guard Atlantic Area Command Center by phone to report EL FARO's situation. The Coast Guard Atlantic Area Command Center collected his contact information and passed it, via email at 7:33 AM, to the Coast Guard District Seven Command Center in Miami, Florida.

At 7:25 AM, the Master asked the C/M to make a round on the 2nd deck. The C/M responded that he would open a door and look, but would not go out on 2nd deck.

At 7:26 AM, the Master called the C/M on the radio and told him that he was going to ring the general alarm, and to get muster while he was down there. The Master then called the engine room on the house phone and told them he was going to ring the general alarm, but they did not have to-or were not going to-abandon ship yet. The general alarm was then heard on the VDR audio at 7:27 AM.

At 7:28 AM, the Master communicated with the C/M on the radio, and made an unintelligible remark about the starboard side. The C/M asked the Master if he was getting ready to abandon ship and the Master responded, "Yeah what I'd like to make sure everybody has is their immersion suits and uh-stand by. Get a good head count. Good head count."

At 7:29 AM, the 2/M on the bridge yelled about containers in the water, and the Master directed the ringing of the abandon ship alarm. The 2/M departed the bridge to get a life vest, and the Master and the AB requested that the 2/M return with vests for them.

At 7:30 AM, the Master twice stated, "Bow is down."

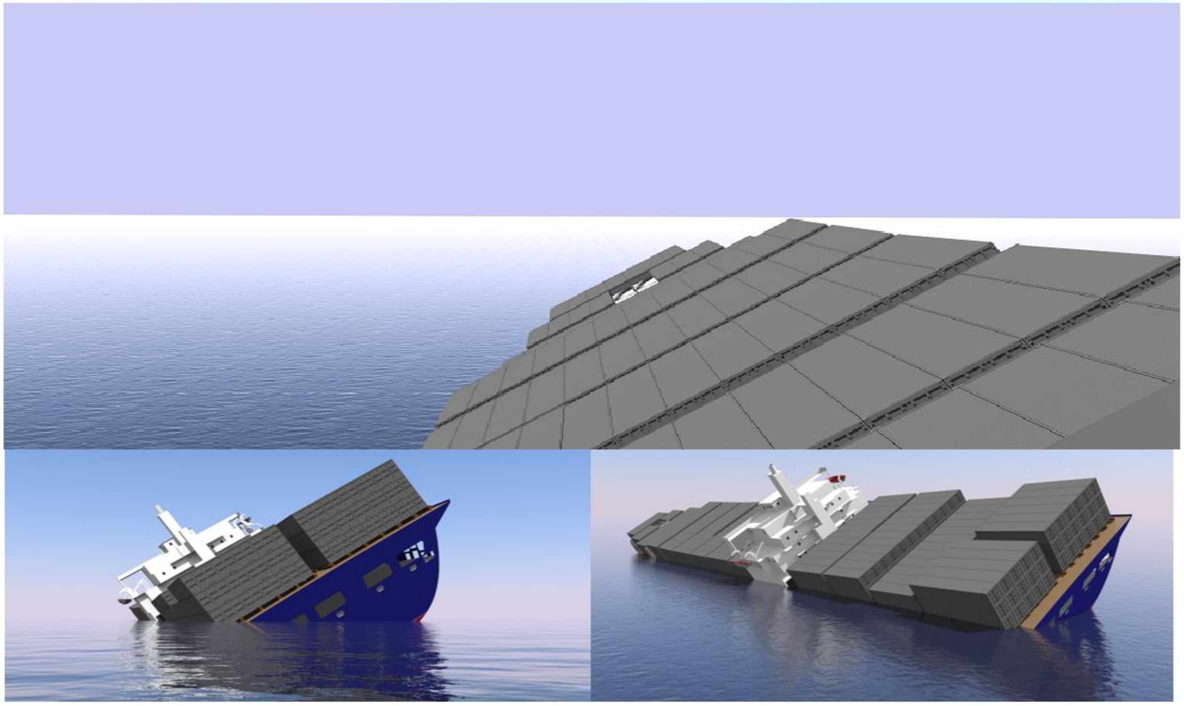

Figure 17. EL FARO computer renderings showing the vessel with progressive flooding and wind heel, listing to port at 35 degrees with 5.0 feet aft trim and 37.0 foot draft amidships. The upper illustration simulates a view forward from the starboard side of the navigation bridge which was the assumed location of the vessel Master when the Master makes the "bow is down" statement at 7:30 AM on the VDR audio transcript. Illustration produced by the USCG Marine Safety Center.

At 7:31 AM, the Master communicated with the C/M over the radio to have personnel get into their rafts, throw the rafts into the water, get off the ship and stay together. There was no discussion of the lifeboats or preparation of the lifeboats for abandoning ship heard on the VDR.

At 7:33 AM, the Coast Guard District Seven (D7) Command Center contacted the TSI DPA by phone. The D7 Operations Unit Controller (OUC) reviewed the information the TSI DPA had previously provided to the Coast Guard Atlantic Area Command Center—that EL FARO was disabled, the source of flooding was secured, and the crew was attempting to dewater. The D7 OUC told the TSI DPA that based on this information; they were not in a distress phase because the ship was not at risk of sinking. The D7 OUC also told the TSI DPA that in this type of situation—non-distress, in foreign territorial waters—it is generally up to the company to provide tug assistance. The TSI DPA stated he would contact their salvage service. The D7 OUC stated he would try to contact the ship for an update, and would call the TSI DPA back with more information. The Coast Guard was never able to establish contact directly with EL FARO.

For the remainder of the VDR Audio, the Master is heard repeatedly trying to encourage the AB who had been manning the helm to "get to safety." At 7:36 AM, the Master told the AB to "work your way up here." At 7:37, the Master twice yelled out for the location of lifejackets on the bridge. At 7:38 AM, the AB yelled to the Master that his feet were slipping and he needed a ladder; the Master responded that they did not have a ladder or line.

The audio recording ends at 7:39:41 AM on October 1, 2015. At that time the Master is still heard on the bridge attempting to encourage the AB to "come this way."

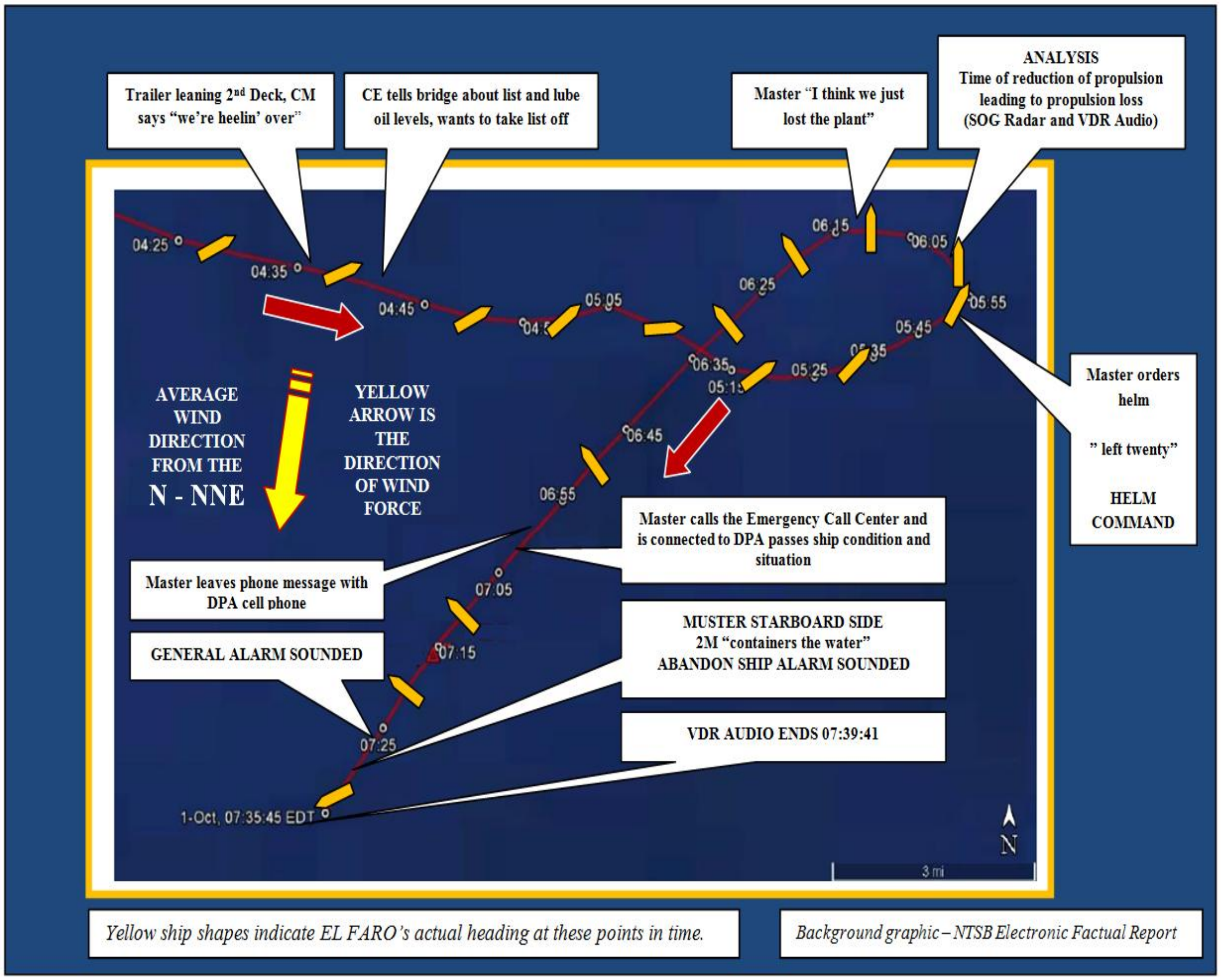

Figure 18. Illustration of significant events between 4:20 AM on October 1 and the sinking, showing ship heading and course over ground.

EL FARO's last recorded position on the VDR parametric data, at 7:35 AM, was 23-23.4N, 073-54.0W. The main wreckage of EL FARO was located on October 31, 2015, approximately one nautical mile away, in position 23-22.9N, 073-54.9W, and at a depth of approximately 15,400 feet.

The post analysis conducted by the National Hurricane Center found that at 8:00 AM on October 1, Joaquin was a Category 4 Hurricane with an estimated sustained wind speed of 115 knots.

Two flights conducted by Air National Guard Hurricane Hunters, which were flying observation missions, conducted VHF radio call outs and radar searches for the EL FARO, with negative results. However, because of the weather conditions in the last reported position of EL FARO, no aircraft or surface assets were able to get a visual assessment of the area until October 3, 2015.

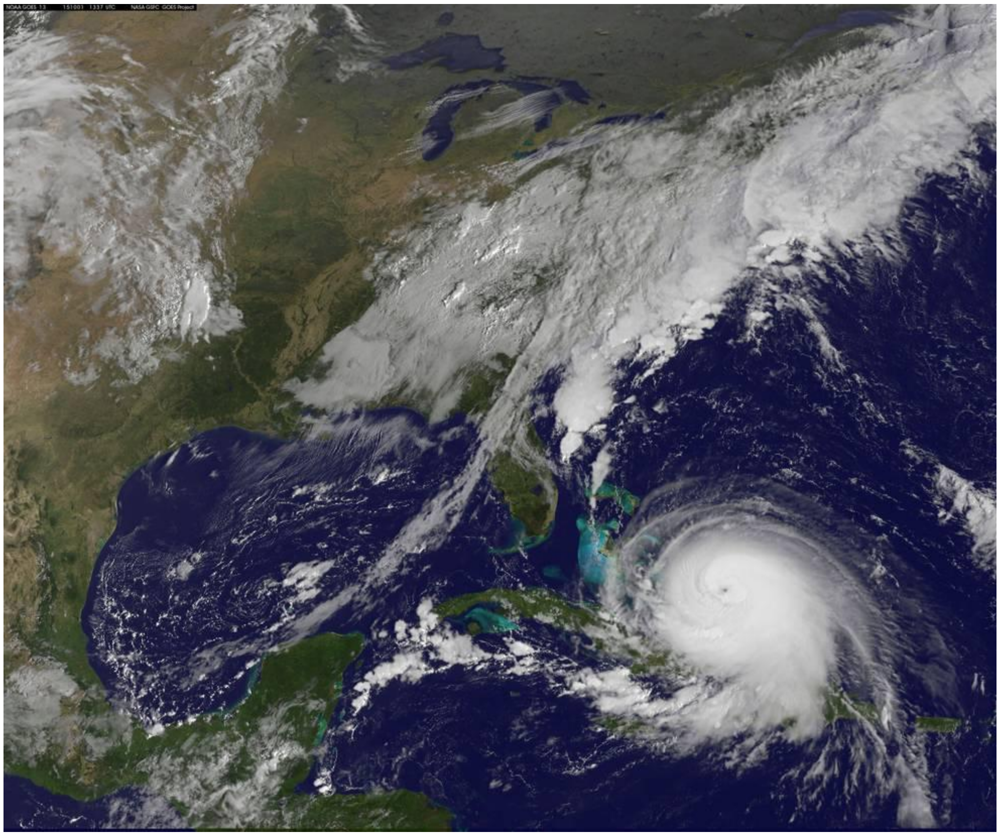

Figure 19. Image of Joaquin affecting the Bahamas on October 1 at 8:55 AM. (Source: https://www.nasa.gov/feature/goddard/joaquin-atlantic-ocean)

The first aircraft on scene on October 3, a U.S. Air National Guard Hurricane Hunter, noted the presence of an oil sheen and debris field. On October 4, a Coast Guard helicopter located an individual in a survival suit. A Coast Guard rescue swimmer entered the water and determined that the individual was deceased, but he was unable to identify or recover the body. On October 5th, the Coast Guard declared that EL FARO was sunk and transitioned to searching for survivors in the water. At sunset on Wednesday, October 7, 2015, the Coast Guard suspended active searching for the survivors of EL FARO. The search activities covered 195,602 square nautical miles using surface and aviation assets. TOTE-contracted surface and aviation assets continued to conduct searches for survivors and the recovery of surface debris. No survivors or other bodies were located. More detailed information on the search and rescue activities involved in this case are included in the Search and Rescue section of this report.

On October 14, 2015, the Sector Commander, Coast Guard Sector Jacksonville, declared that all persons onboard EL FARO were missing and presumed deceased.

7.2. Additional/Supporting Information

7.2.1. TOTE Corporate and Operational Framework

TSI and TMPR offices are located in Jacksonville, Florida. TOTE, Inc., the parent company to TSI, TMPR, TOTE Shipholding, and TOTE Maritime Alaska, is headquartered in New Jersey.

TOTE, Inc. is a subsidiary of Saltchuk, which owns a diverse range of companies.[15] At the time of the accident, EL FARO was engaged in domestic trade between Jacksonville, Florida and San Juan, Puerto Rico. Leading up to the accident TOTE operated two vessels in the Puerto Rican trade and two in the Alaskan trade.

In 1985, Sea Star Line formed to provide a trade connection from the United States mainland to Puerto Rico. At one time the company operated three PONCE class ships, which were engaged primarily in Jones Act trade. The three steamships were EL MORRO, EL FARO and EL YUNQUE; EL MORRO was taken out of service by TOTE and scrapped prior to the accident voyage. Through 2013, Sea Star maintained nautical operations support personnel ashore to support PONCE class operations. A number of these personnel had backgrounds in nautical operations and related training from maritime academies. These shore side support personnel provided technical and marine operations support to vessel crews, and also conducted internal audits. During adverse weather, the nautical operations shore side support personnel would interact with and assist ship's Masters with voyage planning, assessment of risk, development of vessel specific heavy weather plans and monitoring of anticipated heavy weather in relation to the intended voyage plan.[16]

TOTE Inc. began reorganizing in mid-2013, which resulted in fewer personnel assigned to provide shore side nautical operations support. A team of managers with deck officer experience was replaced by a single position with the title of TSI Marine Operations Manager, which was located in the Jacksonville office. The person in this position at the time of the accident voyage never held a Merchant Mariner Credential (MMC). He had filled the position since 2008.[17]

During the reorganization, the remaining PONCE class shore side management support was focused on the marine engineering side. MBI testimony indicated that the TSI President could be called upon to provide advice and guidance to Masters as needed, but that rarely if ever occurred. The TSI Vice President (VP) of Commercial Operations operated out of the Tacoma, Washington TOTE Maritime Alaska office.

Sea Star Line changed its name to TOTE Maritime Puerto Rico (TMPR) in September 2015. At the time of the accident TMPR owned EL FARO and EL YUNQUE. TOTE Inc. formed TOTE Shipholding in December 2012, and contracted to build two new liquefied natural gas (LNG) dual-fuel powered vessels, designed to replace the PONCE class vessels on the Puerto Rico trade route. These two new MARLIN class ships were slated to be ISLA BELLA and PERLA DEL CARIBE. In order to bring the new vessels into service, TOTE Inc. and TSI personnel were delegated additional duties beyond their day-to-day management of the PONCE fleet. As an example, the Director of Safety and Services[18] was tasked with oversight of the LNG fuel issues as the new ships were outfitted. The oversight included fuel tanks, shore side fueling, and permit approvals for the new fueling systems. In MBI testimony the Director of Safety and Services stated that the percentage of time he worked on the MARLIN class ships varied and that it was cyclical, but could represent up to 85% of his total workload at times.

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[15] https://www.saltchuk.com/sc-directory.
[16] NTSB Interview transcript, Former Manager of Safety and Operations, DPA, March 27, 2017.
[17] MBI Transcript February 20, 2016, p. 171.
[18] MBI Transcript February 17, 2016, p. 87.

During 2015, through to the accident voyage, TOTE was using a number of tugs and barges to move cargo to and from Puerto Rico, in addition to the PONCE class vessels. The TOTE Inc. Director of Ship Management was responsible for managing both the PONCE vessels and the tug and barge cargo operation.[19] Additionally, in late August and throughout September 2015, he was managing issues related to stern bearing problems encountered during sea trials of ISLA BELLA. The issue necessitated a trip to San Francisco drydock for diagnosis and repair of the problem.

TSI's safety department was comprised of the Manager of Safety and Operations/DPA and an Assistant Manager of Safety and Operations/Property Manager. These two personnel were responsible for overseeing a fleet of 25 vessels that operated globally. A position described as Safety and Ops Coordinator was listed on the TSI March 31, 2015, organization chart.[20] This position was annotated as "TBD" (to be determined) on the organization chart and remained unfilled at the time of the accident. A candidate had been interviewed for the position and MBI testimony[21] from the Manager of Safety and Operations indicated that in August 2015 a decision was made to not fill that position. As a result, the duties that were intended for that position were distributed among existing personnel within TSI.

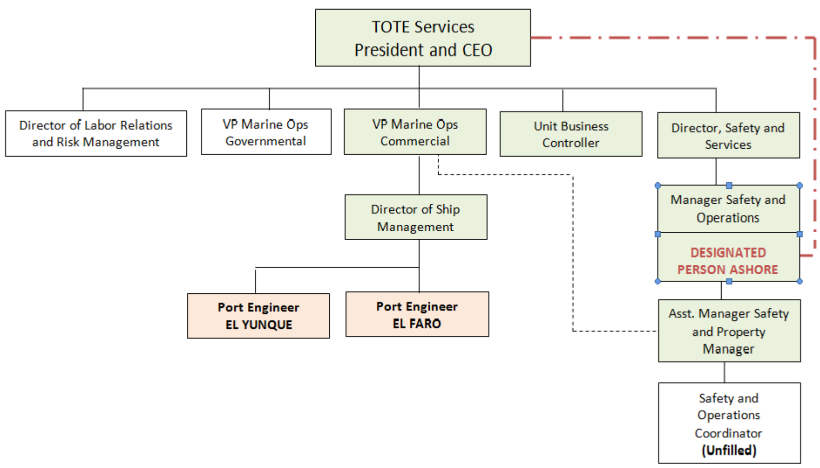

Figure 20. TSI simplified organization chart at the time of casualty.

Both TSI and TMPR experienced an increased workload as a result of the new MARLIN class LNG ships. This workload included obtaining the necessary permits and approvals for the fueling, procedures, and terminal operations. TSI personnel were also engaged in the final preparations for delivery and acceptance of the two new vessels, including working on issues related to loading and stowage plans for the fully containerized cargo as the new ships were not designed to handle RO/RO cargo. In 2014 TOTE began examining crewing options for the new vessels. After the launching of the MARLIN class ships the company needed to expand its marine labor force. As the MARLIN class ships were being placed into service, TOTE planned to shift EL FARO to the West Coast of the United Stated to act as a relief ship on the Alaskan

[19] MBI Exhibit 004, p. 63.
[20] MBI Exhibit 047, p. 9.
[21] MBI Transcript February 20, 2016, p. 24.

run while the two ORCA class ships assigned to that run entered the shipyard. Once in the shipyard, these ORCA class ships were scheduled to have their main propulsion engines replaced with engines that could run on LNG fuel or traditional marine fuel.

In late spring of 2015, TSI began formal efforts to crew the two new MARLIN class ships; this had to occur while simultaneously continuing to crew EL FARO and EL YUNQUE, as well as the other vessels in the fleet. Crew members selected for the new ships had to undergo special training on LNG fuel safety.

7.2.1.1. Operational Framework for EL FARO

The TSI Operations Manual – Vessel (OMV), Rev. 21, which was in effect at the time of the accident, described the operational framework onboard EL FARO, as well as the interface between shipboard and shore side operations. The chart below displays the vessel to shore reporting relationship.

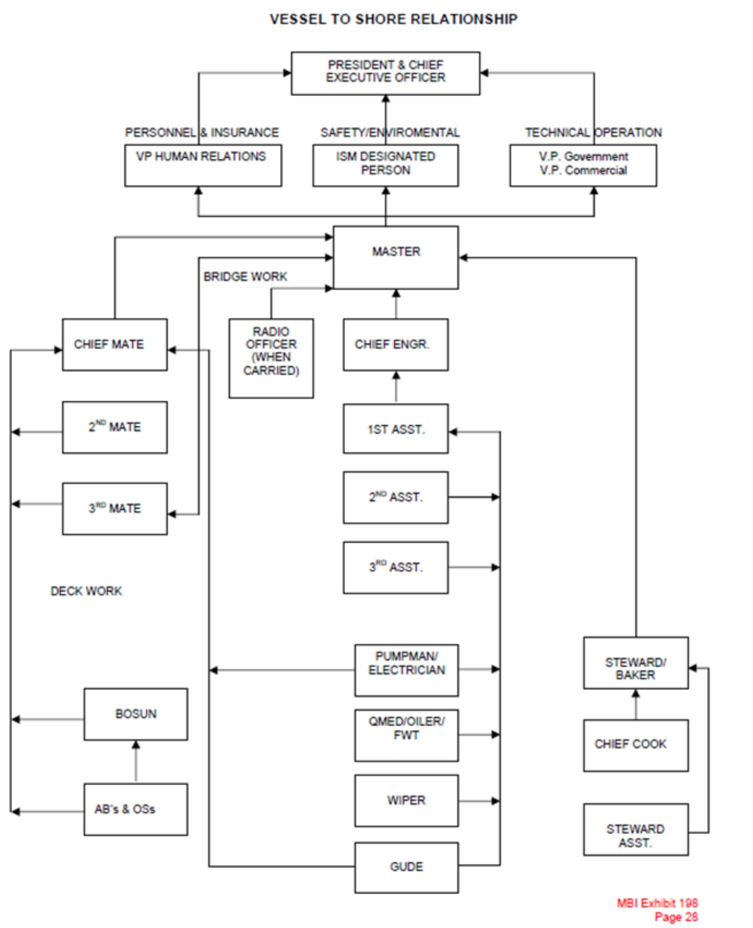

Figure 21. Vessel to shore relationship, from OMV. (Source: MBI Exhibit 198)

Onboard the ship unlicensed crew reported to junior officers based on the department in which they worked. Engineering crew reported to the C/E while deck crew reported to the C/M. During the accident voyage, a Polish riding crew was onboard working on the Alaskan conversion project. This conversion was being performed to return EL FARO to a configuration where it would only carry RO/RO cargo. The work included installing fittings and winches for loading ramps, a heating system to provide deicing for vehicle ramps, as well as electrical wiring for the new equipment. The Polish workers were supervised by a supernumerary EL FARO C/E who was onboard solely for that purpose. The Riding Crew Supervisor ensured that the conversion work remained on schedule and that the quality of the work conformed to TSI's expectations.

EL FARO's C/E and C/M reported to the Master. The OMV (Fig. 11) indicated a direct reporting relationship between the Master and various corporate officers, as well as between the Master and the International safety Management (ISM) designated person for safety and environmental matters. The OMV did not, however, indicate a reporting relationship between the Master and the TSI P/E, despite that being the person the Master interacted with on day-to-day operational matters while EL FARO was in Jacksonville. The P/Es working at the time of the accident voyage primarily had a marine engineering background, with minimal nautical operations expertise. P/Es were responsible for conducting annual evaluations of the Masters and the C/Es. The annual evaluation[22] was designed to assess the Master's competency in voyage planning, navigation, cargo loading and stability assessment, oversight of the safety of vessel operations, and several other performance dimensions.

The P/Es reported to the Director of Ship Management – Commercial, who was also a marine engineer. Finally, the Director of Ship Management – Commercial reported to the VP of Commercial Operations who is located in the TSI Tacoma Washington office. The VP of Commercial Operations did not have a marine operations background or Merchant Mariner Credential. In MBI testimony the TSI witnesses stated that they expected EL FARO to operate autonomously without oversight from TOTE. The Director of Ship Management – Commercial testified in the MBI:[23]

> *The Master operates autonomously. There's multiple lines of responsibility. There's multiple lines of people he can address issues to, but the Master is the Master of the ship.*

Multiple witnesses testified that Masters were primarily responsible for the safety of the vessel, and operated autonomously in regard to ship routing, speed, and other voyage decisions. Shore side management was not required to approve these decisions.[24] The TOTE OMV states the following:

> *Master is responsible for managing and protecting the Company's interests in all phases of the vessel's operation. TSI staff personnel are available for consultation and/or assistance and can be contacted at any time, including nights, weekends and holidays.*[25]

[22] MBI Exhibit 424.
[23] MBI Transcript February 19, 2016, p. 13.
[24] MBI Transcript February 14, 2016, p. 51, 62, and February 13, 2017, p. 1060.
[25] MBI Exhibit 198, p. 107.

Whenever a tropical weather system directly or indirectly impacted the port of Jacksonville or San Juan, TOTE implemented a Port Hurricane Plan in order to safeguard its shore side assets. This included measures to ensure the protection of personnel, critical equipment (e.g., gantry cranes), cargo and other company assets. However, there was no similar hurricane plan in place to protect underway TOTE vessels that could potentially encounter adverse weather conditions. There was also no vessel-specific heavy weather plan produced for EL FARO.

In late August 2015, two tropical weather systems in the Atlantic Ocean impacted the Puerto Rican trade operations. During that same time period, a West Coast sea trial in the Port of San Diego for TOTE's first LNG fueled vessel, ISLA BELLA, identified a problem with the vessel's shaft bearings. ISLA BELLA was drydocked in San Francisco in September 2015 to resolve the shaft alignment and bearing issues. Upon completion of repairs, ISLA BELLA departed drydock for further sea trials on September 29, 2015, the same day EL FARO departed Jacksonville on the accident voyage. Delivery of the MARLIN class ships required considerable attention from TOTE management in the months leading up to and also during the accident voyage. ISLA BELLA's delayed delivery created cascading effects that impacted the ORCA class ship conversion[26] and TOTE operations on the Puerto Rico run.

While underway EL FARO communicated with shore side personnel by means of a satellite communication system called Inmarsat. In MBI testimony, TSI stated that they did not maintain a list of people who would monitor EL FARO's departure, arrival and noon report email messages. The TOTE VP Ops – Commercial stated that "he was not aware of particular shore side person who had the specific duty to monitor EL FARO email reports."[27] As a result, EL FARO's Inmarsat emails were sent to a number of individuals at TSI and TMPR who would collectively monitor the vessel's status and individually reply as needed.

7.2.2. Regulatory Framework

7.2.2.1. Coastwise Transportation of Merchandise

EL FARO carried cargo between the United States ports of Jacksonville, Florida and San Juan, Puerto Rico, and was therefore required to comply with U.S. laws regarding coastwise transportation of merchandise, commonly known as the Jones Act.[28]

Under the Jones Act, all cargo shipped to Puerto Rico from a port in the United States must be carried onboard a vessel that is owned by citizens of the United States and that has a Coast Guard issued Certificate of Documentation with a coastwise endorsement. Other than some limited exceptions, only vessels built in the United States qualify for a coastwise endorsement.[29]

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[26] The ORCA ships were the ships in trade between Washington and Alaska. The plan was for these ships to be converted to a dual fuel LNG power plant. EL FARO was to be the relief ship that would fill in for each of the ORCA ships as they were converted to the LNG fuel. Once the first of the new MARLIN ships arrived in Jacksonville this would free up EL FARO to head to a planned yard period in the Tacoma area for reconversion back to the Alaska configuration. Then EL FARO would enter service on the Washington to Alaska run relieving one of the ORCAs at a time to begin their repowering to LNG.

[27] MBI Transcript, February 16, 2016, p. 50.

[28] 46 U.S.C. §§ 55101, 55102, 19 CFR § 4.80.

[29] 46 U.S.C. § 12112 and 46 U.S.C. § 12103.

7.2.2.2. Coast Guard Inspection of Domestic Commercial Vessels

46 U.S.C. Chapter 33 requires that certain vessels possess a Coast Guard issued Certificate of Inspection (COI). A COI is issued to a vessel once it satisfactorily completes an inspection for certification. A vessel must be maintained in a safe operating condition in order to retain a COI. An OCMI may issue a Temporary COI, valid for up to one year, pending issuance of the permanent COI, which is valid for five years from the original issue date of the Temporary COI.[30] COIs are only issued when the OCMI determines that a vessel complies with all applicable statutes and regulations and that it can be operated safely without endangering life, property or the environment.

7.2.2.3. Alternate Compliance Program (ACP)

The ACP is a voluntary system that allows owners of U.S. vessels to obtain a COI based on inspections conducted by an Authorized Classification Society (ACS). Under this program, an ACS is authorized to conduct certain functions and certifications on U.S. flagged vessels on behalf of the Coast Guard.[31]

The Coast Guard began implementing the ACP in 1995, following requests from the U.S. maritime industry to reduce the duplication of effort between Coast Guard inspections and classification society surveys, which caused extra costs to U.S. vessel owners.[32] A task force of Coast Guard and American Bureau of Shipping (ABS) representatives determined that compliance with ABS classification rules, SOLAS, and MARPOL 73/78 would satisfy the majority of U.S. regulatory requirements. The Coast Guard and ABS developed a U.S. Supplement to the ABS rules to address any identified gaps between SOLAS, ABS Rules, and Coast Guard regulations. The Coast Guard concluded that compliance with the ABS rules, international conventions, and the U.S. Supplement to the ABS rules would provide a level of safety equivalent to federal requirements. Under ACP policy, the U.S. Supplement is required to be updated annually and the ACS and Coast Guard were jointly responsible for making the updates. The updates were necessary to cover any new domestic regulations and compliance gaps identified by ACS surveyors or Coast Guard Marine Inspectors in the field. At the time of EL FARO's sinking, the U.S. Supplement for ABS had last been updated in April 2011. The Coast Guard also has U.S. Supplements for other ACSs authorized to participate in the ACP. When asked during MBI testimony whether the U.S. Supplements were being updated according to Coast Guard policy, the Chief of the Coast Guard's Office of Design and Engineering Standards responded:

> *The simple fact of the matter is that we are strained by resources to keep up with those reviews. So we have Supplements that are pending review we just haven't gained a lot of ground on that. But when we do, that is the process that we go through.*

All U.S. vessels enrolled in ACP are required to comply with international SOLAS requirements for international voyages. EL FARO was enrolled in the ACP at the time of the

[30] MSM Volume II, Section B1.B.1.
[31] NVIC 2-95 Ch. 2.
[32] 61 Federal Register 68510, December 27, 1996.

accident voyage and ABS was the vessel's Classification Society, responsible for performing the certification functions delegated to it by the Coast Guard under the program.

EL FARO was enrolled into the ACP on February 27, 2006.[33] Based on its enrollment date, EL FARO was required to comply with applicable SOLAS conventions, ABS Steel Vessel Rules, and the June 2003 U.S. Supplement to ABS Rules for Steel Vessels Certificated for International Voyages.

7.2.2.3.1. ACP Roles and Responsibilities

The owner of a vessel is responsible for ensuring its vessels are maintained and continually operated in compliance with all applicable statutes and regulations; this remains the case with the ACP. As a result of a vessel being accepted and enrolled in the ACP, the ACS assumes responsibility from the Coast Guard for verifying that a vessel maintains substantial compliance with applicable standards. The ACS also issues international certificates and documentation attesting to the vessel's compliance. Additionally, the International Safety Management Code, 2014 (ISM Code), is applicable to all vessels enrolled in the ACP. Per the ISM Code, the Recognized Organization (RO) is responsible for issuing the Safety Management Certificate (SMC) and conducting annual external audits that verify compliance with the company Safety Management System (SMS). ABS was the RO for TOTE. The Coast Guard retains authority and primary responsibility for certain activities for vessels enrolled in the ACP, including approval of security plans, major conversion determinations, ballast water management compliance, marine casualty investigations, and enforcement actions.[34]

The Coast Guard conducts an annual examination onboard each vessel enrolled in the ACP. This examination, which is more limited in scope than a traditional Coast Guard inspection of a non-ACP vessel, includes a general walk-though of the vessel, an examination of the vessel's certificates and crew documents, an evaluation of crew member proficiency during emergency drills, and a verification of the vessel's security plan. The primary objective of the Coast Guard annual examination is to ensure the ACS is meeting its obligations under the ACP. The Coast Guard ACP Freight Vessel Examination Booklet[35] contains an extensive list of items Coast Guard Marine Inspectors may check during an annual examination of an ACP vessel.

In addition to the annual examination, the Coast Guard can also conduct oversight activities at the discretion of the local OCMI where an ACP vessel is operating. For non-passenger ACP vessels, the Coast Guard Headquarters Office of Commercial Vessel Compliance (CG-CVC) can also mandate additional oversight examinations based on an annual risk assessment that is conducted on every vessel enrolled in the ACP.

In accordance with Coast Guard policy, deficiencies found during a Coast Guard inspection of a non-ACP U.S. vessel are documented through the use of a Record of Merchant Marine Inspection Requirements (Coast Guard form CG-835), which is issued to a vessel's owner or representative. All CG-835s are logged into the Coast Guard's MISLE database, which creates a

[33] MBI Exhibit 020.
[34] For a complete list of inspection activities retained by the Coast Guard, see section B9.F of MSM Volume II.
[35] MBI Exhibit 226.

permanent record of the discrepancy detected while also tracking the corrective actions performed to rectify the discrepancy. If the Coast Guard discovers deficiencies during an examination of an ACP vessel, the Marine Inspector notifies the ACS. Coast Guard policy dictates that the issuance of a CG-835 to an ACP vessel owner is a "last resort after all other corrective measures have proven impractical or if a classification society surveyor is not immediately available to attend the vessel."[36] Thus, CG-835s are generally not issued to ACP vessel operators. As a result, deficiencies are not recorded in the Coast Guard's MISLE database for the majority of Coast Guard detected deficiencies on ACP vessels, and corrective actions are not tracked.

Although an ACS is delegated the authority to conduct ACP inspections, only the Coast Guard can deny issuance or revoke vessel certificates for non-compliance.

Prior to the loss of EL FARO in October 2015, the Coast Guard Headquarters Traveling Inspection Staff began a review and evaluation of the ACP by attending annual examinations of vessels determined by CG-CVC to be in the high risk category. The Traveling Inspection Staff accelerated their evaluation of ACP vessels after the sinking of EL FARO, and their findings are discussed in a September 6, 2016, report from the Chief Traveling Inspector to the Assistant Commandant for Prevention Policy.[37] The report discussed several ACP concerns including communication problems between Coast Guard Marine Inspectors and ACS surveyors, a lack of training for Coast Guard Marine Inspectors regarding ACS rules and survey procedures, an absence of standardized training or qualification requirements for ACS surveyors, and confusion regarding the various ACS Supplements. The report also made several recommendations including the development of more specific guidance on the ACP for Coast Guard field units, ACSs, owners, and operators of U.S. vessels enrolled in the ACP.

After the sinking of EL FARO, the Traveling Inspection Staff continued their review and evaluation of ACP vessels. Vessels were selected based on age, compliance history, and propulsion type, and additional ACP vessels were visited at the request of local Coast Guard OCMIs. Several of the ACP vessels inspected during this review were found to be in substantially substandard condition. The substandard vessels frequently lacked ACS or Coast Guard issued deficiency records that would have been expected to accurately reflect the material conditions found on the vessels. Prior to Coast Guard Traveler Inspector visits, it was concluded by data/record review that the vessels were in full compliance. Three vessels visited were subsequently scrapped by the owner as a result of Coast Guard issued deficiencies and two others were issued no-sail deficiencies temporarily removing them from service until serious safety issues were resolved. Significant safety and structural deficiencies were found on other vessels visited by the Traveling Inspection Staff during 2016. During MBI testimony the Chief of the Coast Guard's Traveling Inspection Staff confirmed that his inspectors found safety deficiencies on approximately15 deep draft vessels[38] they visited during this review.

[36] NVIC 2-95 Change 2, p. 10.
[37] MBI Exhibit 329.
[38] A records check conducted by the Traveling Inspection Staff in September 2017 located 14 visit records for the timeframe referenced in the testimony including visits to 10 ACP vessels, 4 Military Security Program (MSP) vessels, and one Coast Guard inspected vessel.

In Calendar Year 2016, the Coast Guard Office of Investigations and Analysis determined that there were 110 active U.S. flagged general dry cargo and RO/RO vessels enrolled in the ACP. During that year, Coast Guard OCMIs were required to intervene and issue a no-sail order to a vessel within that fleet on 13 occasions.

The Coast Guard does not publish a Domestic Vessel annual report and the domestic no-sail rate for vessels enrolled in ACP is not tracked or published. The Coast Guard also does not have a process in place to track or hold accountable an ACS performing ACP inspections on its behalf when the Coast Guard issues a no-sail order for safety violations detected during a follow-on Coast Guard ACP oversight exam.

In contrast, when foreign vessels are detained in a U.S. port after a Coast Guard Port State Control examination, the overall detention rates for each flag administration are tracked and published by the Coast Guard Office of Commercial Vessel Compliance in an annual Port State Control Report.[39] In addition, after a foreign vessel is detained for a safety issue, the Office of Commercial Vessel Compliance conducts an analysis to determine if the vessel's Recognized Organization[40] should be associated with the detention for not detecting a safety issue. Foreign vessels that use Recognized Organizations with a high rate of associated detentions receive points on a targeting matrix that can lead to additional Coast Guard Port State Control exams.

7.2.2.3.2. <u>Inspections of EL FARO's Safety Equipment and Crew Proficiency Under ACP</u>

EL FARO did not conduct required underway operational tests of its lifeboats during the last inspection for certification prior to the accident voyage. At the time of the last inspection, ACP policy dictated that the Coast Guard was responsible for observing the operational lifeboat tests in the water and assessing the crew's performance during those tests, which were supposed to be conducted during the ACP oversight examination.

In MBI testimony a Coast Guard Marine Inspector[41] who examined EL FARO provided the following background on the testing of the lifeboats:

> ***Question:*** *Page 66 is part of a checklist on ACP statutory surveys to be done in conjunction with initial MAS[42] and renewal safety equipment surveys. It's listed as not Coast Guard approved in the front of the supplement, but as we heard from ABS surveyors in previous testimony it is included as part of their exams. On page 66 under life boat operational test Part 3, specifically number 1 under Part 3 it indicates in A that Coast Guard inspectors will have a crew proficiency test to conduct during their boarding. At that time the crew must operate each boat in the water and the following test will be carried out. Can you comment on whether that is something that Sector San Juan does during alternate compliance program exams? And is that in any inspection guidance the Coast Guard publishes?*

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39 MBI Exhibit 436.
40 Recognized Organization is a term used to describe a Classification Society which is issuing statutory certificates on a flag administration's behalf.
41 MBI Transcript May 25, 2016, pp. 18 - 19.
42 MAS = Mandatory Annual Survey (source www.eagle.org).

> ***WITNESS:*** *It's in the 840*[43] *book for us to do the drills. And usually on the life boat we've actually – there was some guidance that came out for internationally about doing the lifeboat test. They're kind of dangerous. So usually what we do is just lower the life boat to the water and have them bring it back up. We don't do the dock side boat. Because it wouldn't be safe to do so. If something happened to the davit or something you would damage the life boat or hit the dock.*
>
> ***Question:*** *So you would say it's not part of the Coast Guard ACP oversight exam to conduct a crew proficiency test with the boat in the water?*
>
> ***WITNESS:*** *We currently don't do that. Like I said we stopped doing that because of the guidance that we got on the port state side of not putting the crew into the boat into the water because of the dangers.*

And:[44]

> ***WITNESS:*** *I know that ABS as part of their exam is supposed to lower the vessel, uh lower the boats. So since we're doing the oversight I don't see – didn't see any real need to take them all the way to the water just to – prove proficiency to make sure that they can lower the boats. And the crew's also required every three months to actually lower the boat to the water and operate it, so.*

Coast Guard procedures[45] to determine the effectiveness of shipboard safety equipment on U.S. commercial vessels require that the lifeboats be lowered to the rail, boarded by crew, lowered to the water, released and then operated in the water. There is a provision for modifying the procedure due to weather; however, deviations from the requirement for a full abandon ship drill are required to be documented and the drill performed at a later date. The Coast Guard procedures for testing lifeboats on foreign vessels under the Port State Control program allow the scope of the lifeboat tests to be reduced.

The 2011 U.S. Supplement to the ABS rules for steel vessels[46] on international voyage contains a check sheet for ABS statutory surveys. The note states,

> *III. Lifeboat Operational Tests*
>
> *1. Proper operation of the propelling gear and/or motors was demonstrated. (IMO allows this testing to be carried out while the boat is secured in the falls.)*
>
> > *a. The CG inspectors will have a crew proficiency test to conduct during their boarding. At that time, the crew must operate each boat in the water, and the following tests will be carried out:*

[43] "840 book" is a job aid for Coast Guard Marine Inspectors.
[44] MBI Transcript May 25, 2016, p. 67.
[45] MSM Volume II Section B Chapter 1 section v. pp. B1-131.
[46] MBI Exhibit 113, p. 66.

Note: The CG inspectors will have a crew proficiency test to conduct during their boarding. At that time, the crew must operate each boat in the water, and the following tests will be carried out:
Note: The USCG will accept load tests done by ABS.

4.	Each motor lifeboat and hand-propelled boat was operated at full speed both ahead and astern.	☐	☐	
5.	Each installed system, such as any powered bilge pump or water spray system, was successfully operated.	☐	☐	
6.	Compass readings were compared with several known bearings.	☐	☐	
7.	Each air tank buoyancy unit was visually inspected and appears fit for service.	☐	☐	☐
	Note: In case of doubt, air tanks may be tested for air-tightness per Marine Safety Manual, Chapter 6, Section R.			
8.	Water tanks were inspected and confirmed watertight.	☐	☐	
	Note: This should be demonstrated by either an airtight test or filling with water and watching for leaks. Refer to Marine Safety Manual, Chapter 6, Section R.			
9.	Batteries for engine starting and searchlights have a means for recharging, which are in satisfactory condition.	☐	☐	
10.	The condition and quantity of survival equipment was checked as per the standard ABS check sheets.	☐	☐	

7.2.3. Safety Management System (SMS)

As a result of being enrolled in the ACP, EL FARO was required to be in compliance with the ISM Code. TOTE had an SMS in effect at the time of the accident, which was designed to ensure the company provided procedures for the safety of operations onboard EL FARO. The SMS consisted of the Operations Manual – Vessel (OMV, rev. 21, Aug 2015), and the Emergency Preparedness Manual – Vessel (EPMV, rev. 13, Apr 2014). There were no specific SMS manuals that provided guidance to management for shore-based operations of the company.

The ISM Code, Part A section 1.2.2.2 requires that each maritime "Company" assess all identified risk to its ships, personnel, and the environment and establish safeguards. In TOTE's EPMV there were sections that provided guidance for the loss of propulsion, flooding, and abandoning ship. At the time of the accident TOTE had not formally identified weather as a risk to its ships as part of its SMS. In the General Section of the document, Section 5 EMERGENCY PROCEDURES, 5.1 GENERAL there was the following explanation:

> *The object of this section is to assist the Master in making decisions when confronted with a perilous situation. It is reasonable to assume that few people will reach for this manual in the time of an emergency, therefore, excerpts from this section should be used as drill scenarios to promulgate policy and procedures before an incident is at hand.*

There are sections in the SMS (OMV)[47] that discuss various operations related to weather conditions such as:

> *10.8.1 General...Rev. 13 1/08*

[47] MBI Exhibit 025.

10.8.2 Adverse Weather..Rev. 0 3/96
10.8.3 Additional Ballast in Heavy Weather ....Rev. 0 3/96
10.8.4 Weather Routing ....Rev. 15 9/09
10.8.5 Adverse Conditions While at Anchor or Moored ....Rev. 8 7/02

The only section directly related to the navigation of the vessel to reduce the risks associated with severe weather is in the EPMV.[48] Specifically, Section 5.12 [49]SEVERE WEATHER contained the following information:

5.12 SEVERE WEATHER

5.12.1 IN PORT

Masters are advised to always berth their vessels with the most severe conditions in mind. Special attention should be paid to the time of the year and the locale of the vessel. The deck officers should be familiar with prevailing winds and storm track probabilities.

In the event the vessel is in port during a severe storm, the Master is to assess the situation and confer with the HQ Office who will clear the vessels' actions (when necessary) with the local MSC (Military Sealift Command) representative or charterer, before moving the vessel.

(In most cases the MSC representative will have access to USN weather information and the USN weather routing service.) Masters must take advantage of all information available and act in accordance with the owner's representative's /MSC's directions. If, in the opinion of the Master, an unwise course of action is advised, he/she shall alert TSI Headquarters and the Manager of Marine Safety & Compliance will liaison with MSC Headquarters and work for a quick resolution of the matter.

5.12.2 AT SEA

Severe weather is to be avoided where possible by altering the track of the vessel. Instruction for maneuvering in extreme weather can be found in "The American Practical Navigator" HO Pub. #9.

Section 8.1 and 8.3 of the ISM Code state that companies should identify potential emergency shipboard situations and establish procedure to respond to them. Additionally, the SMS should provide for measures ensuring that the company's organization can respond at any time to hazards, accidents, and emergency situations involving its ships. The code refers to International Maritime Organization (IMO) resolution A.852(20), which has been superseded by IMO resolution A.1072(28) as guidance for the development of an "Integrated System of Contingency Plans." The Coast Guard has provided no guidance to either companies or ROs

[48] MBI Exhibit 026.
[49] MBI Exhibit 026.

representing the Coast Guard that addresses the development of integrated contingency plans for responding to shipboard emergencies.

If a company does identify potential shipboard emergencies, such as weather or near miss incidents, the company should establish programs for drills and exercises to prepare for those emergency actions. At the time of the accident voyage the Coast Guard did not require, and ABS provided no guidance on, which shipboard emergencies should be considered in the SMS. As a result, TOTE only conducted drills and exercises in accordance with basic SOLAS requirements.

MBI testimony from TOTE's Director of Safety and Services indicated that one of the purposes of TOTE's internal audits[50] was to verify that all regulatory drills and exercises were properly completed and logged. There is no record that TOTE shore side management completed evaluations or internal audits, as required by the ISM Code, to ensure that emergency drills and exercises involving shore side response were effective and that the crew members were competent in their knowledge of assigned watch, quarter, and station bill duties, or that TOTE management was prepared for responding to emergency situations involving its fleet.

The MBI examined EL FARO's training, drills, and logs related to shipboard training. Unsigned electronic logs covering the latter half of 2015 were substituted for hardcopy logs that were lost during the sinking of EL FARO. The actual paper records provided were signed and the duration of the training and drills was noted. In addition, some of the electronic records contained the duration of the drills.

The following findings were noted from EL FARO's logs:

- There was no record for 2015 of a lifeboat being lowered to the water, released, and operated in the water.
- The 2nd Quarter 2015 Non-Crew Indoctrination log does not list the signatures for two shipriders who were on a voyage of EL FARO from April 17 - 20, 2015. There was no record that they were provided their non-crew indoctrination.
- The electronic Safety Drills/Training forms (TSI-V-ADM-024 Rev. 2/13) for August 20, 2015; August 27, 2015; August 27, 2015; September 3, 2015; and September 10, 2015 did not contain the names of the Polish Riding Crew in the list of names in attendance for the safety drills listed. Records for the following safety drills were obtained and reviewed: fire, abandon ship with boat lowering to embarkation desk, container fire, and a medical emergency.
- A drill on June 4, 2015, which included a fire drill with rigging of hoses, conducting whistleblower /respirator training/MSDS review/HAZMAT and HAZWOPER training and abandon ship and lowering of the boat to the embarkation deck, was listed as 30 minutes in duration.

[50] MBI Transcript February 17, 2016, p. 89.

The VDR[51] transcript contains comments from the crew relating to the performance and efficiency of drills. The following conversation occurred on watch between the 2/M and AB at 1:40 AM on October 1, 2015:

2/M : *[sound of quick laugh] Usually people don't take the whole umm– uh– survival suit– safety meeting thing very seriously. Then it's "yeah– whatever. it fits" but nobody actually sees to see if their survival suit fits. I think today would be a good day [sound of laugh] for– for– for the fire and boat drill– just be like– "so we just wanna make sure everyone's survival suit fits" and then with the storm people are gunna (go/be like) "holy* [expletive]. *I really need to see if my survival suit fits– for reaaal." [laughter throughout]*

***2/M**:* *Nobody ever takes these– the drills– seriously.*

***AB**:* *No. Still have to do'em.*

Guidance for International Association of Class Societies[52] (IACS) Auditors to the ISM Code No. 41 section 8 (2005), provides examples of emergency situations auditors should sample. These include the use of an integrated vessel and shore side plans for damage from heavy weather, flooding, abandoning ship, or loss of propulsion. ABS, as the RO for TOTE vessels, is a member of IACS, and should follow the procedures established in IACS guidance. ABS, as RO, issued the Safety Management Certificate to EL FARO and the Document of Compliance to TOTE on behalf of the Coast Guard. As the RO, ABS completed external audits to ensure the Safety Management System was implemented and effective.[53] These audits were completed by taking a sampling of each section of the ISM code and verifying compliance through objective evidence. The specific samples that were chosen for review were determined by the ABS Lead Auditor. ABS external auditors did not engage with TOTE management regarding the development of integrated contingency plans and drills and exercises for emergency situations that EL FARO encountered during the accident voyage, including loss of propulsion, flooding, and heavy weather.

IACS Recommendation 41, (Rev. 4, Dec 2005) Guidance for IACS Audits to the ISM Code,[54] states the following:

8 EMERGENCY PREPAREDNESS

8.1 The Company should establish procedures to identify, describe, and respond to potential emergency shipboard situations.

8.2 The Company should establish programs for drills and exercises to prepare for emergency actions.

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[51] MBI Exhibit 266.
[52] http://www.iacs.org.uk/.
[53] 33 CFR § 96.320.
[54] http://www.iacs.org.uk/publications/recommendations/rec-41-rev4-corr1-cln/.

8.3 The safety management system should provide for measures ensuring that the Company's organization can respond at any time to hazards, accidents and emergency situations involving its ships.

Usually the following scenarios should be addressed by emergency plans as required by the specific ship types:
- structural failure / heavy weather damage
- failure of main propulsion
- steering gear failure
- electrical power failure
- collision
- grounding / stranding
- shifting of cargo
*- cargo / oil spillage / jettison **
- flooding
- fire / explosion
- abandoning ship
- man over board
- search and rescue operations
- serious injury
*- piracy / terrorism **
- helicopter rescue operations

Coast Guard Marine Inspectors did not issues any deficiencies or pass any safety related concerns to ABS after conducting EL FARO safety drills with the crew during the last annual ACP examination prior to the accident. The Coast Guard examiners did not require EL FARO's lifeboats to be operated in the water during the final ACP examination. ABS did not identify any concerns related to lifesaving gear or drills after conducting the last compliance survey on EL FARO nor did they require launching or witness the lifeboats operating in the water.

TOTE maintained an Emergency Response Manual (ERM) [55] that included emergency contacts for two types of vessel operational emergencies:

Section 8: Oil Spill Response Procedures and Contacts
Section 10: Security Emergency Procedures and Contacts

TOTE's ERM did not contain information related to any operational safety related emergencies including adverse weather, flooding, loss of stability, cargo shifting, or abandon ship.

On February 1, 2016, Coast Guard Traveling Inspectors and ABS surveyors conducted a Document of Compliance (DOC) Audit of TOTE Services Inc. to check SMS compliance. The audit resulted in the issuance of five non-conformities including the following items:

[55] MBI Exhibit 385.

- TSI did not document incident and investigation records as required by company procedure EPMV -10 (Rev 14 8/15) for three incidents including the sinking of the EL FARO.
- TSI representatives did not complete an annual "Vessel Inspection" or the "Ship Visit Report" for eight vessels.
- Cargo hold fire detection system maintenance records for the RO/RO COURAGE were found past due prior to a fire incident in June 2015.[56]

At the conclusion of the audit, TSI's full term DOC was suspended and ABS issued a short term (90-day) DOC due to the identified non-conformities and observations. The DOC audit included a walkthrough of EL YUNQUE. Additional details on issues identified by the attending Coast Guard Traveling Inspector during the EL YUNQUE visit are included in Section 7.2.9 of this Report of Investigation.

7.2.4. Construction, Modification, and Conversion

Sun Shipbuilding in Chester, Pennsylvania built a series of ten RO/RO "trailerships" between 1967 and 1977. While the ships were built for several different owners with minor differences in configurations to accommodate different trade routes, these ships were designated as the PONCE DE LEON class[57] of ships. All of these ships were arranged as "shelter deck" vessels with a semi-enclosed cargo deck intended to facilitate loading and stowage of vehicular cargo. EL FARO was originally named PUERTO RICO and also operated as the NORTHERN LIGHTS from 1991-2006 in the Alaska Trade. It was the seventh ship in the PONCE class. EL FARO's keel was laid in 1974 and construction completed in 1975, with an original length of 700 feet.

In 1992, EL FARO underwent a conversion at the Atlantic Marine Shipyard in Mobile, Alabama. This conversion included the addition of a 90-foot mid-body section between frames 134 and 135 that added a cargo hold (designated Hold 2A), a new spar deck to carry additional trailered containers, and 1,830 long tons of iron ore fixed ballast in one pair of double bottom tanks. Due to the lengthening and increase in cargo carrying capacity, the Coast Guard determined the mid-body insert to be a major conversion, which required the vessel to be brought up to current standards to the extent considered reasonable and practicable by the local Coast Guard OCMI. As part of the major conversion determination, the Coast Guard approved a request to have ABS conduct plan review and inspection on behalf of the Coast Guard.[58] Additionally, since the vessel was issued international certificates for foreign voyages and was required to comply with SOLAS requirements, it was also directed that all modifications to the vessel comply with the most recent SOLAS amendments (SOLAS 1974, as amended). This included meeting new IMO probabilistic damage stability standards, among other SOLAS amendments.

EL FARO completed another conversion in 2006 to carry lift-on/lift-off (LO/LO) container stacks on the main deck to facilitate service between East Coast ports and Puerto Rico. The

[56] The June 2, 2015 fire occurred in the RO/RO COURAGE's main cargo hold while the vessel was transiting the English Channel. The fire caused $100M in damage and led to the vessel being sold for scrap in March 2016.
[57] Referred to as 'PONCE Class' throughout this Report of Investigation.
[58] MBI Exhibit 422.

conversion, which also took place at Atlantic Marine Shipyard, included removal of the spar deck, structural reinforcement of the main deck, addition of container support foundations and structures, and an additional 4,875 long tons of iron ore fixed ballast in the remaining two additional pairs of double bottom ballast tanks.

The Coast Guard Marine Safety Center (MSC) did not designate the 2005-2006 conversion as a major conversion. According to available documentation regarding the determination, the Coast Guard originally designated the proposed project as a major conversion in 2002.[59] The Vice President for Marine Operations at TOTEM Ocean Trailer Express subsequently sent a series of requests for reconsideration to the MSC explaining that the NORTHERN LIGHTS (EL FARO) intended only to increase its container cargo volume, referred to as forty-foot equivalent units (FEU) and twenty-foot equivalent units (TEU). In a reconsideration request letter dated March 22, 2004, VP for Marine Operations stated:

> *A vessel's cargo carrying capacity is defined by its load line and stability characteristics, not by an FEU or TEU number count. Further, I know of no international or U.S. safety or environmental protection requirements that are based on TEU/FEU count…Only the load line is the measure of capacity.*

The MSC overturned its original determination in a November 8, 2004 letter that confirmed EL FARO's proposed conversion to a LO/LO configuration would not be treated as a major conversion. Although earlier MSC letters had voiced concerns about the potential for an increase to EL FARO's cargo carrying capacity, the Coast Guard's final non-major conversion determination letter did not include any restrictions related to increasing cargo capacity during the conversion. After the 2006 conversion, EL FARO's total cargo loading capacity changed and the vessel's maximum allowable draft was increased by over 2-feet. The change also reduced the vessel's freeboard which lowered hull openings by the same distance. The MSC's decision to not classify the conversion as a major modification meant EL FARO was not required to conform to applicable 2006 U.S. and international standards (e.g., CFR, ABS SVR, and SOLAS) in conjunction with the conversion work.

During MBI testimony a former EL FARO Master with 25 year of total service as Master on PONCE class vessels in the Alaskan and Puerto Rican trade provided the following description of the PONCE class vessel handling characteristics:

> *The Sea Star ships when you talk about structure they were RO/CONs. So the containers were on the upper decks. And with a heavy load of cargo they would be a tender ship as opposed to a stiffer ship in the Alaska service. They had a higher GM. So and a tender ship if a little bit more of a different animal to handle especially in rough weather and other conditions.*

The former EL FARO Master provided the following MBI testimony when asked about conditions he experienced in calm weather and seas near the end of his voyages to Puerto Rico:

[59] MBI Exhibit 013.

> *What I observed with the ship was a very slow return, it was a – the ship was becoming even more tender on arrival then it was when it left. You could even feel the ship list, I shouldn't say list, but lean over as she rolled from a rudder command alone, let alone rolling with a heavy swell. And because it was slow to right itself you could feel the ship respond more difficulty. And there's always a concern that she's not going to right herself adequately for other conditions. So we felt it important to build in a safety margin in case any other conditions changed during the voyage. That you needed that safety margin to preserve the stability of the ship. And for the routine voyage we had decided that decimal 5, 0.5 foot above the minimum safe GM would be adequate.*

Between April 23, 2014 and May 9, 2014, an ABS Surveyor attended a modification survey in Jacksonville, Florida for the installation of fructose tanks aboard EL FARO. These modifications, which were carried out in Hold 1 and Hold 2 at the inner bottom tank tops between frames 64 and 127, included six 53-ft, 18,000 gallon horizontal ISO shipping container tanks carrying fructose. Coast Guard inspectors from Sector Jacksonville did not attend the vessel during the modification, nor did they note any modifications to EL FARO during the next annual ACP examination. The tanks were permanently installed with piping, pumps, and support structure in accordance with ABS-approved drawings.[60] According to the drawings, two tanks were placed in Hold 1 and four tanks were placed in Hold 2. Despite the weight added to the vessel, no changes were made to the ABS-approved Trim and Stability Booklet or the ABS-approved CargoMax software. ABS's Chief Engineer for Statutes stated during MBI testimony that the weight change should have been submitted to ABS for evaluation and the Trim and Stability Booklet and CargoMax software should have been updated.[61] Under the guidelines of the Coast Guard MSC Marine Technical Note (MTN) 04-95, a detailed weight change can be accepted in lieu of a deadweight survey or inclining experiment when the aggregate weight change does not exceed 2% of a vessel's lightship. ABS's Chief Engineer for Statutes stated that the empty weight of the fructose tanks was approximately 100 tons, or approximately 0.5% of the light ship weight.[62] The additional estimated weight of the fructose tanks on EL FARO was accounted for in CargoMax by inserting RO/RO cargo items at the relevant locations. Specifically, the fructose tanks were accounted for with six approximately 100 long ton trailers in Holds 4A and 4B in EL FARO's departure condition.[63]

As EL FARO's Puerto Rico operations continued in 2015, TOTE made a decision to prepare EL FARO for Alaskan Trade operations as a relief vessel to support TOTE's planned ORCA vessel conversions. Prior to reentering service on the West Coast, EL FARO needed to convert its configuration back to carrying only RO/RO cargo. A plan was drafted for the conversion which included the installation of additional ramps, winches, wiring and a heating system to prevent ramp icing. In August 2015, a foreign riding crew comprised of Polish nationals was brought aboard EL FARO to start the conversion work while the vessel was operating. The five Polish workers included laborers, welders, and electricians, who worked under the supervision of a TOTE Riding Crew Supervisor. On September 13, 2015, the Riding Crew Supervisor sent an email to TOTE Services personnel ashore detailing progress already made on the conversion of

[60] MBI Exhibit 104.
[61] MBI Transcript May 20, 2016, pp. 32-33.
[62] MBI Transcript May 20, 2016, p. 47.
[63] MBI Exhibit 059, p. 8.

EL FARO back to the Alaska RO/RO only service.[64] TOTE P/Es directed the Riding Crew Supervisor to complete as much conversion work as possible ahead of an EL FARO dry dock period scheduled for October 2015. As a result, the riding crew continued working while underway on EL FARO through September, including during part of the accident voyage while transiting southbound toward Puerto Rico.

During MBI testimony, ABS's Chief Engineer for Statutes stated that ABS was not aware of the weight changes associated with the conversion work and he clarified that his office should have been made aware.[65]

7.2.5. Load Line, Stability, and Structures

7.2.5.1. Load Line

Load line is the formal term given to the mark located amidships on both sides of a ship to clearly display the limiting draft to which a vessel may be loaded. The limiting draft is obtained from the required minimum freeboard, which is the vertical distance from the uppermost continuous weathertight deck (normally the freeboard deck) to the load line mark amidships.[66]

The International Convention on Load Lines 1966 (ICCL), as modified by the protocol of 1988, requires the load line mark for all ships with keel laid after July 21, 1968. Coast Guard implementing regulations are contained in 46 CFR Part 42. Under these regulations, and 46 U.S.C. § 5107, ABS is designated as the assigning authority for load lines. As the assigning authority, ABS is empowered to assign load lines and issue certificates, perform surveys required for load line assignments, and determine that the position and manner of marking vessels is in accordance with applicable requirements. The Coast Guard has no direct role in load line assignment other than providing oversight. The MSC has responsibility for carrying out oversight of the load line assignments made on the behalf of the Coast Guard.[67] [68]

At the time of the accident voyage, EL FARO had a valid International Load Line Certificate (ILLC) issued by ABS on January 29, 2011, which assigned a summer load line molded draft of 30'-1-5/16" (30'-2-3/8" keel draft) corresponding to a 1966 Type "B" vessel freeboard of 12'-0-15/16" from the 2nd deck.[69] Prior to EL FARO's 2005-2006 conversion to LO/LO service, the assigned summer load line molded draft was 28'-0" (28'-1-1/8" keel draft) corresponding to a freeboard of 14'-1-3/8" from the deck.

EL FARO was provided with an original ABS Form LL-11-D, Survey for Load Lines, on November 10, 1974. At that time, EL FARO had not yet been extended through insertion of a mid-body plug and it was operating as a RO/RO ship only. The LL-11-D was based on

64 MBI Exhibit 054.
65 MBI Transcript May 20, 2016, p. 33.
66 Cleary, W.A., and Ritola, A.P., Ship Design and Construction (Chapter IV: Load Line Assignment), Society of Naval Architects and Marine Engineers (SNAME), New York, 1980.
67 MBI Exhibit 421.
68 NVIC No. 10-85, Oversight of Technical and Administrative Aspects of Load Line Assignment, dated October 24, 1985.
69 MBI Exhibit 260.

application of the International Convention on Load Lines (ICLL), 1966, which was adopted on April 5, 1966, and entered into force on July 21, 1968. At the time of the document's issuance, EL FARO had the following ICLL Regulation 19 ventilators identified in exposed positions on the freeboard or 2nd deck:

- 18-8'3" x 3'6"
- 2-8'3" x 3'7"
- 2-6'0" x 4'8"

Eight ventilators were provided with 3/8" steel "weathertight" fire dampers with double locking handles. Those eight ventilators were provided with 8-foot coamings which were "specially supported" as they exceeded 35-1/2 inches in height. The other fourteen ventilators were provided with hinged watertight covers with drop bolts.[70] Weathertight closing appliances were required for these exposed "position 1" ventilator openings because the coamings did not exceed 14.8 feet above EL FARO's exposed freeboard deck. The 8-foot coamings exceeded the minimum required height of 35-1/2 inches for "position 1" openings. As such, the exposed ventilators, including their coamings and closing appliances, did exceed the requirements of ICCL 1966 Regulation 19.

As discussed in Section 7.2.4., EL FARO completed a major conversion at the Atlantic Marine Shipyard in Mobile, Alabama in 1993. As part of this conversion, a 90-foot mid-body section was added, which included an additional cargo hold (designated as Hold 2A). Two new exhaust ventilators and two new supply ventilators were added as part of Hold 2A. The exhaust ventilators were provided with weathertight fire dampers with double locking handles and the supply ventilators were provided with watertight fire dampers with double locking handles. The watertight supply dampers had gaskets around the openings that provided a complete watertight closure.[71]

The ABS New York Office provided a Circular of Instruction "Survey for Load Lines, Form LL-11-D Record of Conditions of Assignment,"[72] to all exclusive and non-exclusive surveyors on November 22, 1982. The document provided the following direction:

> *When completing this form the freeboard deck…must be maintained weathertight. Weathertight means that in any sea condition water will not enter into the ship. A practical test for weathertightness is hose testing.*

The circular also included the following statement on what can constitute a weathertight appliance:

> *It should be noted that a fire damper alone generally does not suffice as a weathertight closing appliance.*

[70] Form LL 11-C EL FARO.
[71] H.T. McVey and Associates Drawing No. 027-100-1 Rev 1 "General Arrangement" and Sun Shipbuilding & Dry Dock Company "Ventil'n Arrang't Holds 2A and 3."
[72] MBI Exhibit 342.

In 1990, the Coast Guard commissioned ABS to prepare a report that integrated U.S. load line regulations and policies, ABS and IACS interpretations, IMO circulars, and the International Convention on Load Lines (ICLL) into a single reference document. The *Load Line Technical Manual* was created as a result of that effort. It sets forth the technical procedures for evaluating, calculating, and assigning ICLL load lines using Coast Guard and ABS policies where the Convention leaves certain requirements "to the satisfaction of the Administration," or is open to interpretation. The Load Line Technical Manual states the following, with regard to ventilator closures for positions 1 and 2:

> *Fire dampers of the normal type are not considered as meeting the minimum requirement unless they are strongly constructed, gasketed, and capable of being secured weathertight.*[73]

ABS was unable to find an updated form LL-11-D applicable to EL FARO's 1992-1993 major conversion, which would have included additional ventilators for Hold 2A. However, ABS checklists from past surveys on EL FARO indicate that the form was updated following the conversion.[74]

The "weathertight" fire dampers in EL FARO's exhaust ventilators were not gasketed, but were still considered by ABS and the Coast Guard to be weathertight and acceptable as dual use closures.[75] The weathertight designation remained in place for EL FARO's ungasketed fire dampers after the vessel's 1993 major conversion. The major conversion occurred after the 1982 surveyor guidance and 1990 Load Line Technical Manual both stated that fire dampers should not be considered as weathertight closures.

The Coast Guard Traveling Inspection staff and Sector Puget Sound conducted targeted inspections of EL FARO's sister ship EL YUNQUE's ventilators and closures, after the sinking of EL FARO. The examination of the exhaust and supply ventilators revealed gaskets missing from supply dampers, gasket flanges wasted, holes in ventilators including coamings, holes in the side shell in way of ventilator openings, and weathertight and watertight dampers that would not fully close. The resulting work list associated with the exhaust and supply ventilation ducts contributed to TOTE's decision to scrap EL YUNQUE.[76]

7.2.5.2. Intact and Damage Stability

EL FARO met applicable intact and damage stability requirements for the accident voyage that departed Jacksonville on September 29, 2015. However the vessel was operated very close to the maximum load line draft, with minimal stability margin beyond its required metacentric height (GM).[77] EL FARO's past conversions reduced its ballasting options, leaving little flexibility for improving stability at sea if necessary due to heavy weather or flooding.

[73] Load Line Technical Manual Chapter 3 p. 147.
[74] MBI Transcript February 10, 2017, p. 921.
[75] Sun Shipbuilding & Dry Dock Company "Ventil'n Arrang't Holds 2A and 3."
[76] MBI Exhibit 295.
[77] MSC Report.

At the time of the casualty, EL FARO was subject to intact stability requirements of 46 CFR § 170.170 (the GM "weather" criteria); and EL FARO met those requirements on the accident voyage. EL FARO departed Jacksonville on the accident voyage with a GM approximately 0.64 feet greater than the minimum required GM.[78] The difference between the minimum required GM and the calculated GM for a vessel is referred to as the vessel's GM margin. EL FARO's GM margin was reduced to approximately 0.3 feet at the time the vessel lost propulsion on the morning of October 1, 2015.[79]

As operated and loaded for the accident voyage, EL FARO's stability would not have met the stability criteria for a new cargo ship, as the vessel did not meet the righting arm criteria for new cargo ships based on limited available area (righting energy) above 30 degrees of heel and an insufficient angle of maximum righting arm (see Figure A from Figure Sheet).[80] In order to fully meet the intact stability criteria of Part A of the 2008 IS Code at the full load draft, the minimum required GM would be approximately 6.8 feet, which is 2.5 feet greater than the GM of the actual departure loading condition of the accident voyage. However, paragraph 2.2.3 of Part A of the 2008 IS Code provides that "alternate criteria based on an equivalent level of safety may be applied subject to the approval of the administration" if obtaining the required 25 degree angle for maximum righting arm is "not practicable." Thus, the Coast Guard can permit a relaxation of the limiting criteria for minimum angle of maximum righting arm (25 degrees) on a case-by-case basis for new cargo ships.

When EL FARO underwent its major conversion in 1992-1993, it was required to meet the probabilistic damage stability standard of SOLAS 1990. During the 1992-1993 conversion, ABS completed, reviewed, and approved a SOLAS probabilistic damage stability analyses,[81] and it was confirmed that the limiting stability criteria for EL FARO was the intact GM criteria (46 CFR § 170.170) for all loading conditions. Based on MBI testimony, Herbert Engineering Corporation (HEC), did not complete a new damage stability analysis to confirm that the limiting criteria would remain the intact stability criteria for all loading conditions[82] after the 2005-2006 conversion, and ABS had no records of a damage stability analysis being completed.[83] A damage stability analysis should have been conducted because the 2005-2006 LO/LO conversion increased EL FARO's load line draft by more than 2 feet. The increased load line draft invalidated the previous damage stability analysis completed in 1993.

During MBI testimony,[84] the ABS Chief Engineer for Statutes submitted results of an ABS SOLAS probabilistic damage stability analysis performed on EL FARO in May 2016,[85] where he applied the damage stability standards of SOLAS 1990, which would have been applicable in 2005-2006. This analysis determined that GM values of approximately 2.9 feet at both the load line and partial load line drafts (30.11 and 26.02 feet), would attain the required subdivision index of 0.60. MSC completed a similar analysis and obtained similar results, but with a slightly

[78] MSC Report.
[79] MSC Report.
[80] MSC Report.
[81] MBI Exhibit 265.
[82] MBI Transcript May 23, 2016, p. 39.
[83] MBI Transcript May 19, 2016, p. 152.
[84] Id, at p. 151.
[85] MBI Exhibit 166.

higher minimum GM value of 3.3 feet.[86] This suggests that for most EL FARO load conditions with two or more tiers of containers loaded, the limiting stability criteria would be the intact stability criteria (46 CFR § 170.170), but for some load conditions with less than two tiers of containers loaded, the limiting stability criteria could be the damage stability criteria. The potential for damage stability to be the limiting criteria was not reflected on the minimum required GM curves in EL FARO's T&S Booklet.[87] However, for the full load departure condition of the accident voyage, since the majority of container stacks were three tiers high, the limiting stability criteria was the intact stability criteria (46 CFR § 170.170), which was properly reflected in EL FARO's T&S Booklet and incorporated in its CargoMax stability software.

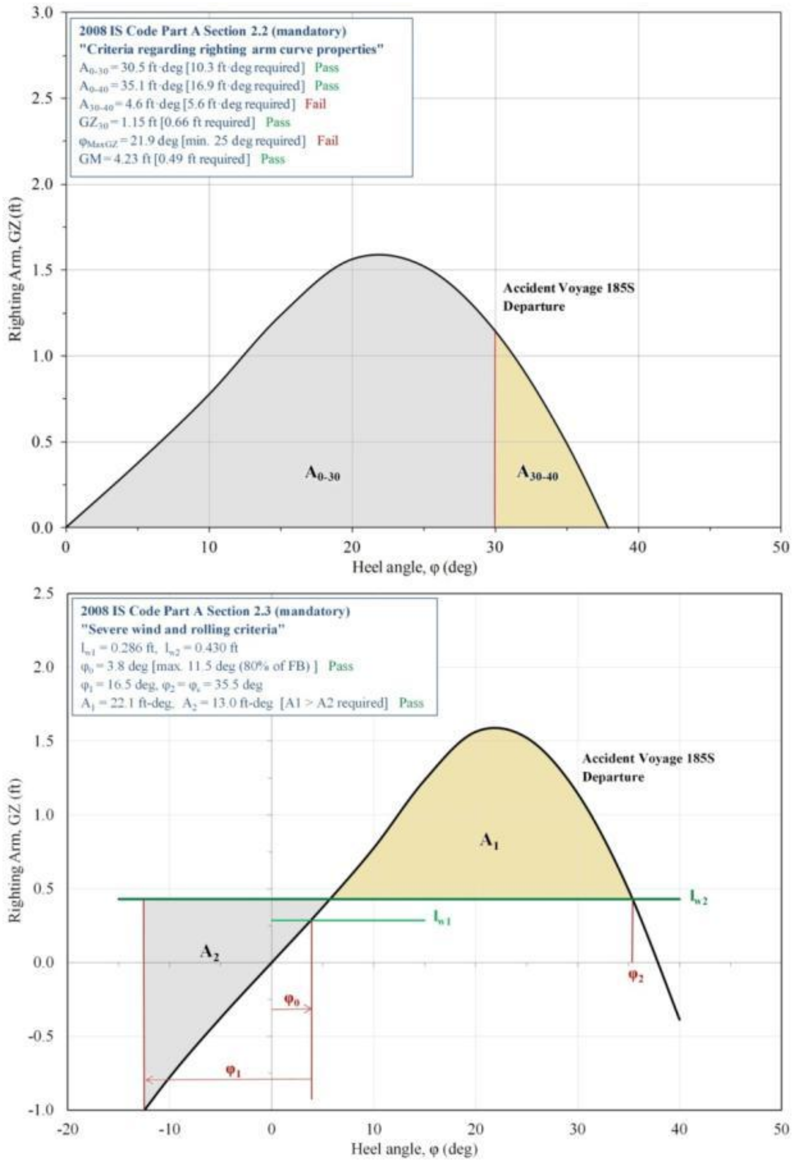

Figure 22. Application of 2008 IS Code righting arm criteria to the accident voyage departure loading condition. (Source: Figure 5-8 of the MSC report)

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[86] MSC Report.
[87] MBI Exhibit 008.

7.2.5.3. Onboard Software for Vessel Loading, Stability, Strength, and Cargo Securing

U.S. flagged vessels require a stability booklet (also referred to as a trim and stability booklet, or T&S booklet) in accordance with 46 CFR Subchapter S and the 2008 IS Code,[88] as applicable. In either case, the stability booklet must contain sufficient information to enable the master to operate the vessel in compliance with the applicable intact and damage stability requirements. For EL FARO, the most recent T&S Booklet, Rev E dated February 14, 2007,[89] was approved by ABS, on behalf of the Coast Guard.[90]

Onboard stability software, also referred to as a "stability instrument," was used on EL FARO. The software was used to calculate the loading condition and stability of the vessel to ensure that stability requirements specified for the ship in the stability booklet were met in an operational loading condition. Under both 46 CFR Subchapter S and the 2008 IS Code, stability software may be used only as a supplement (or adjunct) to the stability booklet. The stability and loading software CargoMax was approved by ABS, on behalf of the Coast Guard, for use on EL FARO.[91]

Recent amendments to several IMO instruments applicable to oil, chemical, and gas carriers make the use of approved stability software mandatory onboard those types of ships, when constructed after July 1, 2016. Flag Administrations (the Coast Guard for U.S. vessels), are required to approve such software.[92] There is no requirement for the use of stability software by other types of vessels; however, if vessels subject to the 2008 IS Code use stability software as a supplement to the stability booklet, then the software would be subject to the approval of the Administration.[93] Specific technical guidelines for review and approval of stability software are provided in IMO MSC.1/Circ.1229,[94] and in classification society rules, which are based on IACS Unified Requirement L5.[95]

A loading manual is a document containing sufficient information to enable the master of a vessel to arrange for the loading and ballasting of the vessel in a manner that avoids the creation of any unacceptable stresses to the vessel's structure.[96] Loading manuals are a requirement of vessel classification and became a requirement for all classed sea-going ships of 65-meters in length and above contracted for construction on or after July 1, 1998.[97] Since EL FARO was

[88] Annex 2 of Resolution MSC.267(85) (MSC 85/26/Add.1), "Adoption of the International Code on Intact Stability, 2008 (2008 IS Code)", Adopted December 4, 2008, International Maritime Organization (IMO).
[89] MBI Exhibit 008.
[90] MBI Exhibit 253.
[91] MBI Exhibit 254.
[92] IMO MSC.370(93), Amendments to the International Code for the Construction and Equipment of Ships Carrying Liquefied Gasses in Bulk (IGC Code), adopted May 22, 2014.
[93] Annex 2 of Resolution MSC.267(85) (MSC 85/26/Add.1), "Adoption of the International Code on Intact Stability, 2008 (2008 IS Code)", Adopted December 4, 2008, International Maritime Organization (IMO), at paragraph 2.1.6.
[94] IMO MSC.1/Circ.1229, Guidelines for Approval of Stability Instruments, adopted January 11, 2007.
[95] International Association of Class Societies (IACS) Unified Requirement L5: Onboard Computers for Stability Calculations, Corr. 1, dated 2006.
[96] ABS Rules for Building and Classing Steel Vessels (2013), American Bureau of Shipping.
[97] IACS Unified Requirement (UR) S, Requirements Concerning Strength of Ships, International Association of Classification Societies, 2016.

constructed in 1974-1975, there was no requirement for a loading manual and no loading manual existed for the vessel.[98]

A "loading instrument" is computer software which can be used to ascertain that still-water bending moments, shear forces and, where applicable, still-water torsional moments and lateral loads at specified points along the length of the vessel will not exceed the specified values in any load or ballast condition.[99] In addition to an approved loading manual, an approved loading instrument is required for classed "Category I" ships of 100-meters in length and above.[100] While not required by classification, the CargoMax software for EL FARO contained features for loading and hull strength for the associated bending moments and shear forces.[101] However, since there was no requirement for EL FARO to have a loading manual, and no loading manual existed, the loading and hull strength assessment features in CargoMax for EL FARO were not specifically reviewed and approved by ABS.[102]

Under Chapter VI of SOLAS and Coast Guard Navigation and Vessel Inspection Circular (NVIC) 10-97,[103] effective December 31, 1997, all U.S. flagged cargo vessels of 500 gross tons or more engaged in international trade, except those engaged solely in the transport of bulk solid or liquid cargoes, which are equipped with cargo securing systems or individual securing arrangements, must have onboard a Cargo Securing Manual (CSM) that has been approved by the vessel's flag state administration. The Coast Guard has delegated this approval authority to ACSs including ABS, and the National Cargo Bureau (NCB).[104]

EL FARO had an ABS-approved CSM.[105] Specific minimum requirements and guidelines for preparation of CSMs are provided in the IMO Code of Safe Practice for Cargo Stowage and Securing (CSS Code), as amended,[106] and specific approval procedures for U.S. flagged vessels are provided in NVIC 10-97. In addition to the minimum requirements and guidelines provided in the CSS Code, class societies may issue class-specific guidance and requirements for container loading and securing. For example, ABS issued voluntary certification requirements for classed vessels seeking special notation in the ABS Guide for Certification of Container Securing Systems.[107] [108] This guide, originally written in 1988 and updated in 2010, includes detailed requirements for container securing systems, loading and lashing calculation procedures, and effective April 1, 2014, includes specific requirements for ABS "certification" of onboard computer software for container loading and lashing calculations for vessels desiring the special

[98] MBI Transcript May 20, 2016, p. 156.
[99] ABS Rules for Building and Classing Steel Vessels (2013), American Bureau of Shipping.
[100] IACS Unified Requirement (UR) S, Requirements Concerning Strength of Ships, International Association of Classification Societies, 2016.
[101] MBI Exhibit 261.
[102] MBI Transcript May 20, 2016, p.116.
[103] NVIC 10-97, Guidelines for Cargo Securing Manual Approval, dated November 7, 1997.
[104] *Id*.
[105] MBI Exhibit 040.
[106] Resolution A.714(17), Code for Safe Practice for Cargo Stowage and Securing (CSS Code), Adopted November 6, 1991 (IMO).
[107] MBI Exhibit 173.
[108] MBI Exhibit 175.

class notation. See the Nautical Operations section of this report for additional discussion about cargo loading and securing requirements and practices.

Other than class-specific guides that provide for some voluntary review and "certification" of onboard computers for container loading and lashing calculations for vessels desiring the special class notation, there is no U.S. or international requirement for review, verification, validation, or approval of computer software for cargo loading and lashing calculations. Nor has the Coast Guard published policy or guidance on the subject. It was noted during MBI testimony that the CargoMax software used onboard EL FARO had not been reviewed and approved by ABS or the Coast Guard for loading and container securing calculations,[109] yet the crew and shore side operations personnel relied on the CargoMax software to complete those calculations.[110] [111] [112] [113] [114]

7.2.5.4. Structures

EL FARO's primary ship structures met all applicable regulatory and classification society (ABS) structural requirements.[115]

7.2.6. Engineering

Details of the complete EL FARO engineering system can be found in the NTSB Engineering Factual Report DCA16MM001, which is at the NTSB Docket.[116] Relevant components of EL FARO engineering systems related to the accident voyage are discussed in this section.

The MBI examined EL FARO's sister vessel EL YUNQUE to provide familiarization with the general layout of EL FARO's engine room. EL YUNQUE was a PONCE class vessel similar to EL FARO in design, although EL YUNQUE's hull did not undergo a major modification to add a ninety foot mid-body section as EL FARO did. EL YUNQUE was operated in the same service and on the same run from Jacksonville to San Juan. Examination of EL YUNQUE provided insight into the condition and operation of EL FARO engineering systems. EL YUNQUE was enrolled in the ACP and was surveyed and examined by the same ABS surveyors and Coast Guard Marine Inspectors as EL FARO.

7.2.6.1. Boiler System and Associated Components

The MBI found no indication that a failure of EL FARO's boiler system or its related components contributed to the loss of propulsion on the accident voyage. There was, however, MBI testimony about repairs done to EL FARO's boiler system components such as drain lines

[109] MBI Transcript May 23, 2016, p. 149.
[110] MBI Transcript February 18, 2016, p. 10.
[111] MBI Transcript February 20, 2016, p. 115.
[112] MBI Transcript February 24, 2016, p. 137.
[113] MBI Transcript February 25, 2016, p. 8.
[114] MBI Transcript May 16, 2016, p. 61.
[115] MSC Report.
[116] *https://dms.ntsb.gov/pubdms/search/hitlist.cfm?docketID=58116.*

in the superheated steam piping and boiler economizer tubes. These late August 2015 repairs to the economizer tubes were conducted by a certified welder from Jacksonville Machine Repair and the post repair pressure test was witnessed by an ABS surveyor to verify the integrity of the repairs. The surveyor required a test pressure below the operating pressure of the boiler piping, which while authorized under ABS Rules for Surveys of Vessels, is below the pressure that would be required by Coast Guard regulations for repairs to boiler piping, which is a minimum of 1.25[117] times the maximum allowable operating pressure. ABS rules do not require any pressure during a test; it is at the discretion of the Surveyor. The ABS Surveyor testified:

> *So based on no specific requirements in the rules for the hydro it's my opinion that it would be unsafe to test it above the operating. Keep in mind that new equipment that hasn't been in service for over 40 years, a test pressure in excess of operating would be satisfactory. But for a vessel that's been operating – for a boiler that's been operating over 40 years, in my opinion it could lead to an unsafe situation.*[118]

Additional repairs made to an EL FARO superheated steam piping drain line on August 24, 2015 were not reported to ABS or the Coast Guard. There was also MBI testimony and email traffic from crew members and a third-party vendor that identified boiler repair items to be completed at EL FARO's shipyard period scheduled for late 2015.

Automated Identification System (AIS), VDR audio transcript, and VDR parametric data[119] indicate EL FARO was steaming, as ordered by the Master, at maximum sea speed for the majority of the accident voyage. EL FARO maintained an average speed of more than 20 knots until approximately 1:30 AM on the morning of the accident. EL FARO steamed at nearly maximum available rpm from departure in Jacksonville until the main propulsion system shutdown approximately one hour and thirty minutes before the VDR audio stopped recording. There is no indication from the VDR audio transcript that a reduction in speed was ordered by the bridge at any time. The only time that the ship's speed was intentionally reduced was to accomplish the routine engineering procedure of "blowing tubes."

The 2A/E was responsible for blowing the tubes during underway watches which were daily from 4:00 to 8:00 AM and PM. To blow tubes, steam from the boiler is routed to soot blowers mounted on the boilers in order to blow accumulated soot off the boiler tubes. This is necessary to maintain the boilers' heat transfer efficiency and reduce the potential for a soot fire within the boiler. Soot blowers utilize steam; therefore there is less steam available for main propulsion during the procedure which results in a reduction of shaft RPM. This operation results in a reduction of speed of about 2 to 3 knots for a short period of time.

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[117] 46 CFR § T 61.15-5.
[118] MBI Transcript May 19, 2016, p. 130.
[119] Parametric data is the sensor data from EL FARO's VDR. This data includes the course, speed, position and other information that was contained in EL FARO's VDR capsule.

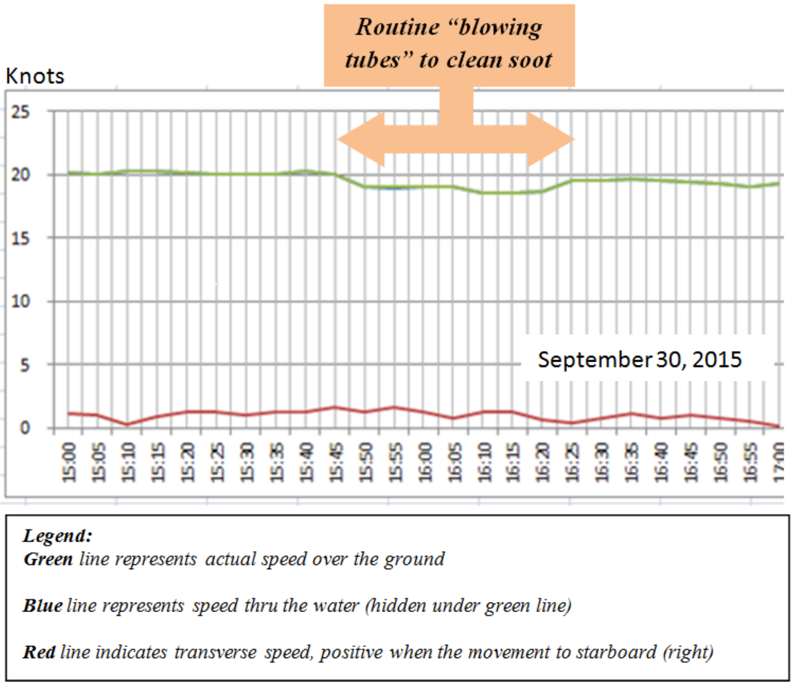

Figure 23. Speed graph from EL FARO showing the typical reduction in speed that resulted from "blowing tubes."

On the morning of the accident at 3:46 AM, the 2/M made the following remark to the C/M while discussing shaft speed reductions:

Bout max they can give us with the Second Assistant Engineer blowin soot right now.

At 4:16 AM the Master called the engine room and at the end of the conversation the Master remarked to the bridge:

Blowin tubes.

The typical operation for blowing tubes on EL FARO appeared to last approximately 30 minutes. At 4:33 AM there is a conversation between C/M and Master related to the RPMs, the C/M made the following comment:

This (the RPMs) might be as high as it's gunna go.

The Master responded:

Yeah. That might possibly be it.

The VDR audio contains the first reference relating to engineering difficulties at 4:40 AM:

> *The chief engineer just called and (then/they) called back again (yeah) something about the list and oil levels * * *.*

The VDR parametric data and the VDR radar images indicate that propulsion in terms of effective force of the propeller stopped at approximately 6:00 AM. In later sections of the audio transcript the Master made comments relating to the "boiler," including the following statement to the C/M at 6:34 AM:

> *(They're just uh)– they're gettin' that boiler back up. They('re) gettin' lube oil pressure up.*[120]

The MBI could not find any evidence corroborating the first part of the Master's statement, which infers that a boiler was down. Nor is there evidence to suggest that the boiler or boiler system components were compromised or failed. The comment from the master that the boiler will be coming back online is not supported by any other evidence or engineering conversations throughout the VDR. However, there is evidence corroborating problems created by the list of the ship and the associated problems with the lube oil system due that list. In a 7:07 AM satellite phone conversation with the TOTE DPA, the Master stated:

> *The engineers cannot get lube oil pressure on the plant therefore we've got no main engine.*

The Master did not mention a boiler failure while briefing the situation to TOTE's answering service and the TOTE DPA.

7.2.6.2. <u>Bilge and Ballast System</u>

EL FARO's bilge system linked each cargo hold to the engine room with independent piping to facilitate the removal of water from each cargo hold. The system took suction from a "rose box" or sump, which was recessed below the plane of the bottom of the hold and covered with a perforated plate that helped to prevent clogging while dewatering the hold. These rose boxes were located approximately 8 to 10-feet inboard from both the port and starboard sides in each cargo hold. The control panel for the bilge system was located in the engine room near the control station. This system was supplied with power from the ship service switchboard and could also be supplied by the emergency switchboard. The cargo holds were fitted with bilge high level alarms, which were not required by Coast Guard regulations. The bilge level alarm sensors were located in each cargo hold just above each rose box. There was no bilge high level alarm panel on the navigation bridge of EL FARO, the engine room's watch procedure was to acknowledge the bilge high level alarm and immediately notify the bridge watch. The bilge high level alarms in the cargo holds were installed on EL FARO in 2012 prior to an extended layup period in Baltimore, MD.

The bilge high level alarms were routinely tested by ABS surveyors, Coast Guard Marine Inspectors, and vessel crew, by manually raising the bilge high level alarm float switch and

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[120] MBI Exhibit 266.

waiting for acknowledgement from the engineer. The MBI heard testimony that no deficiencies were ever discovered during these tests and that the bilge high level alarm system was maintained in satisfactory condition. Additionally, prior crew and the service technician who installed the system testified that there was no easy way to disable the system and it remained on at all times while underway and in port.

At 5:43 AM the Master made the following statements while talking on the house phone:

> *We (got) a prrroooblem.*
>
> *Three hold? Ok.*
>
> *I'll send the mate down. Yeah.*

Immediately after discussing Hold 3 on the house phone the Master directed the C/M to address flooding in Hold 3 with the following statement:

> *Watch your step– go down to three hold– go down to three hold. * down there * start the pumping right now * (probably just) water * * *.*

The Master made the following comments on the VDR audio transcript starting at 5:44 AM:[121]

> *We got cars loose. Yeah.*
>
> *I'll go knock on his door. It's unsafe to go down in the cargo hold with gear adrift like that (it's just not safe/ it's a disaster) * * *. (Not gunna let them bang themselves up) * **.*

The bilge pump system provided a maximum dewatering capacity of 950 GPM at 28.5 PSI. The arrangement of the pumps and piping allowed for the pumping of more than one hold at a time.

EL FARO had fixed ballast consisting of heavy slurry in its ballast tanks. The only ballast tanks available to change heel were ramp tanks. These two small tanks were used to make minor adjustments to the list of the vessel to facilitate the angle of the loading ramp during cargo operations while in port. Shifting all of the water ballast from one ramp take to the other (e.g., starboard to port) would only make a relatively minor change of less than two degrees in the vessel's heel. The volume of each ramp tank was 150 long tons of water.

The Master first mentioned ramp tanks as a means to correct for list during the following conversation with the C/M starting at 4:12 AM on October 1, 2015:

> ***Master:*** *Port side yeah.*
> ***C/M:*** *(Yeah/wind).*
> ***Master:*** *The only way to do a counter on this is to fill the port side*

[121] Included in Attachment 1 to Addendum, VDR – Audio Transcript dated August 8, 2017.

ramp tank up.

C/M: ** * * (Starboard to port) * * * (no places for any others).*

Master: *Yeah.*

C/M: *Heel is not bad.*

At 5:47 AM, the Master asked about the possibility of reducing the list by shifting ballast between the port and starboard ramp tanks:

> *Bilge pump running water rising. Okay. Can we pump from the starboard ramp tanks to port?*

At 5:48 AM, the Master gave the following order to the C/E on the house phone:

> *Hey chief– [@Master] here just want to make sure you're down– you're in the engine room * * alright. Now go ahead transfer * starboard ramp tank to port.*

The shift of ballast to the port side ramp tank was an attempt to correct the starboard list condition that the crew attributed to wind heel. The effect of the wind blowing on the exposed side of the vessel is called "induced wind heel." At 5:52 AM, the Master began to change EL FARO's heading to port in order to bring the bow across the prevailing direction of the wind and put the wind on the starboard side to shift the wind heel from starboard to port. This was done to enable the crew to access the partially flooded 2nd deck in order to secure the cargo Hold 3 scuttle on the starboard side.

At 5:56 AM, the Master reported the following via portable radio:

> *Alright mate chief mate we got it listing over to port…….*

When the Master induced EL FARO into a port list, the available ramp tank ballast was being pumped into the port ramp tank. The ballasted port ramp tank added to the heeling effects of the hurricane force winds acting on EL FARO's starboard side. At 5:57:33 AM, the Master told the engine room to stop transferring ballast from starboard to port and then repeated the order 16 seconds later.

At 6:03 AM, the 2/M asked the following question on the bridge regarding the main propulsion:

> *Did we come down on the RPM or did they do that*?

At 6:10 AM, the following exchange between the Master and C/M occurred on portable radios:

Master-UHF: *Alright. That's good. * and transfer over to the starboard ramp tank * * starboard.*

C/M-UHF: ** * port to starboard ramp tank.*

At 6:12 AM, the Master made the following statement on the bridge:

I'm not liking this list.

Less than a minute later he made the following statement:

I think we just lost the plant.

The VDR radar screen images indicated that EL FARO experienced a significant reduction of forward speed at about 6:00 AM. The radar screen images provided the first indication of a total loss of propulsion.

7.2.6.3. Emergency Fire Pump System

EL FARO was equipped with a fire pump system that included an emergency fire pump. The electric emergency fire pump and its associated piping were located in the aft most area on the starboard side of cargo Hold 3. The sea chest where seawater entered the system was located below the loaded waterline in the starboard side of the hull in Hold 3. From this single suction point, the 6 – 8 inch pipe went to a skin valve[122] that could be remotely operated manually by a long reach rod, which allowed for manipulation from EL FARO's 2nd deck. There were no other remote means to close or open the valve. The emergency fire pump piping extended from the skin valve to the suction side of the pump and then discharged into the fire main system. There were vertical pipes or guards in place to prevent cargo from striking the pump, valve, and piping.

At 7:14 AM on October 1, 2015, the Master and the C/M discussed the emergency fire pump as a possible source of the rising water level in Hold 3. The C/M relayed to the Master a conversation he had with the C/E:

** (at) first the chief said something hit the fire main. Got it ruptured. Hard.*

After the Master asked if there was a way to secure the fire main the C/M responded:

We don't know if they've (seen/still have) any pressure on the fire main or not. Don't know where s'sea- between the sea suction and the hull or what uh but anything I say is a guess.

The Master and C/M continued discussing the emergency fire main and the fact that cars were floating in the vicinity of the piping. At 7:18 AM the C/M made the following statement when asked by the Master if he could see anything near the fire main:

(When/I mean) I saw the water level's too high (the) fire main's right below the water dark black water.

[122] The first valve inboard from the through hull fitting.

The Master and C/M then had a discussion that the engine room should isolate the fire main from the engine room. At 7:19 AM, the Master made the following statement to the 1 A/E on the house phone:

> *Yea can you…isolate the fire main from down in the uh engine room? The fire pump? Isolate it? 'Cause that may be the root cause of the water comin' in.*

There is no indication that EL FARO's crew was ever able to determine if the Hold 3 flooding was caused by damage to the emergency fire main.

7.2.7. Lube Oil System

EL FARO's lube oil system lubricated the bearings for the main propulsion high and low pressure steam turbines and the main reduction gear. The uninterrupted flow of oil to the bearings was critical to reducing friction and to cooling the bearings. Without the flow of oil the bearings would quickly fail and the ship would suffer an irreparable propulsion casualty. The loss of lube oil pressure would cause the propulsion main turbine to automatically shut down through the loss of pressure that was required to hold the main steam throttle valve open.

A detailed explanation of EL FARO's Lube Oil System is included in the Coast Guard's MSC LUBE OIL MODELING AND ANALYSES OF THE S.S. EL FARO.[123]

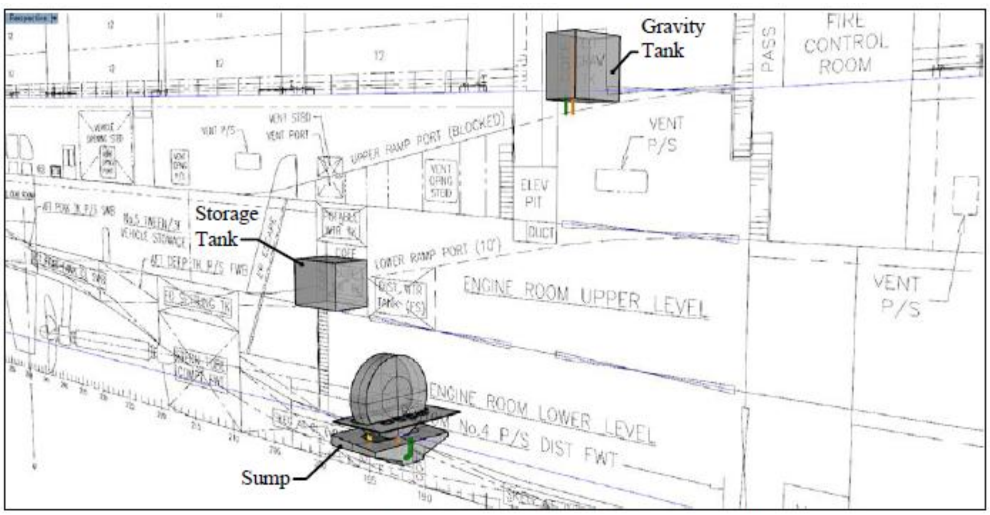

Figure 24. Inboard profile taken from a general arrangement drawing for EL FARO (MBI Exhibit 007).[124]

[123] MBI Exhibit 412.

[124] The MSC concluded that the drawing contains vertical scaling errors (see Section 2.2 of MSC Technical Report "SS EL FARO Stability and Structures" dated March 22, 2017. Accordingly, while useful for visualization purposes, this drawing was not used for the lube oil modeling and analysis work. This figure shows the modeled components in their correct locations relative to the vessel's baseline as depicted in the drawing.

7.2.7.1. Lube Oil System Design

At the time of EL FARO's construction, the 1973 ABS Rules for Building and Classing Steel Vessels were applicable. Those rules[125] required lubricating-oil systems "to be so arranged that they will function satisfactorily when the vessel is permanently inclined to an angle of 15 degrees athwartship and 5 degrees fore and aft."

EL FARO's original pre-build lubricating oil system sump, illustrated in Sun Drawing Number 663-904-100,[126] was altered during construction of the vessel. The sump level was changed to a High Level Capacity of 2,020 gallons, the Operating Level Capacity was changed from 900 to 1,426 gallons and the Low Level Capacity was changed from 750 to724 gallons. This mid-build change also lowered the overall Sump Design Capacity from 4,250 to 2,870 gallons. The drawing indicates these alterations received approval from the Coast Guard on October 19, 1972, then approval by ABS on October 24, 1972. The modifications applied to Sun Shipbuilding Hulls 662-664, but were extended to include EL FARO, Hull 670.

The lube oil sump levels corresponded to soundings[127] of 33" (High Level Capacity), 27" (Operating Level Capacity), 18" (Low Level Capacity), and 40" (Sump Design Capacity). The operating range for the lube oil sump was 18" to 33".[128] The lubricating oil system had 8" steel suction piping, which took suction from the lube oil sump though an 8" pipe with a flared end called a "bellmouth." The bellmouth faced down and took suction 10" above the bottom of the lube oil sump. The center of the bellmouth was approximately 22" to starboard of centerline, and approximately 24" from the after bulkhead of the lube oil sump. Both lube oil service pumps took suction through this bellmouth.

Sun Drawing Number 663-904-100 alteration five, item one, indicates there was a five and eight inch connection added for a future emergency Lube Oil pump. However, the MBI found no indication that EL FARO was equipped with an emergency lube oil pump.

ABS and the Coast Guard approved Sun Drawing Number 663-904-100. In the PII's Joint Response to MSC's Technical Reports,[129] ABS stated that the lube oil system was compliant with the 1973 Steel Vessel Rules, and that due to the location of the lube oil sump suction, the worst case scenario for maintaining suction to the bellmouth was a port list with forward trim. The ABS review examined the maximum angle of inclination requirement at the sump's normal (nominal) fill level, of 27" Operating Level Capacity, as indicated on the drawing. ABS stated that the Steel Vessel Rules do not require the lube oil system to function with both the worst case angle of inclination of 15 degrees athwartship and 5 degrees fore and aft and the sump oil level at the Low Level Capacity. ABS stated that the Steel Vessel Rules do not require the application of "additive faults."

[125] MBI Exhibit 276.
[126] MBI Exhibit 352.
[127] Physical measurements of the level of liquid in a tank measured in inches.
[128] MBI Exhibit 350.
[129] MBI Exhibit 418.

The Coast Guard MSC Lube Oil Modeling and Analysis[130] demonstrated that the 18" Low Level Capacity shown on the drawing, when combined with a 15 degree port list, would result in the main lube oil sump suction bellmouth coming out of the oil. It also demonstrated that lube oil pocketing would occur in the lube oil gravity tank based on a port list condition, due to a 33" offset of the supply and overflow piping to starboard inside the lube oil gravity tank.

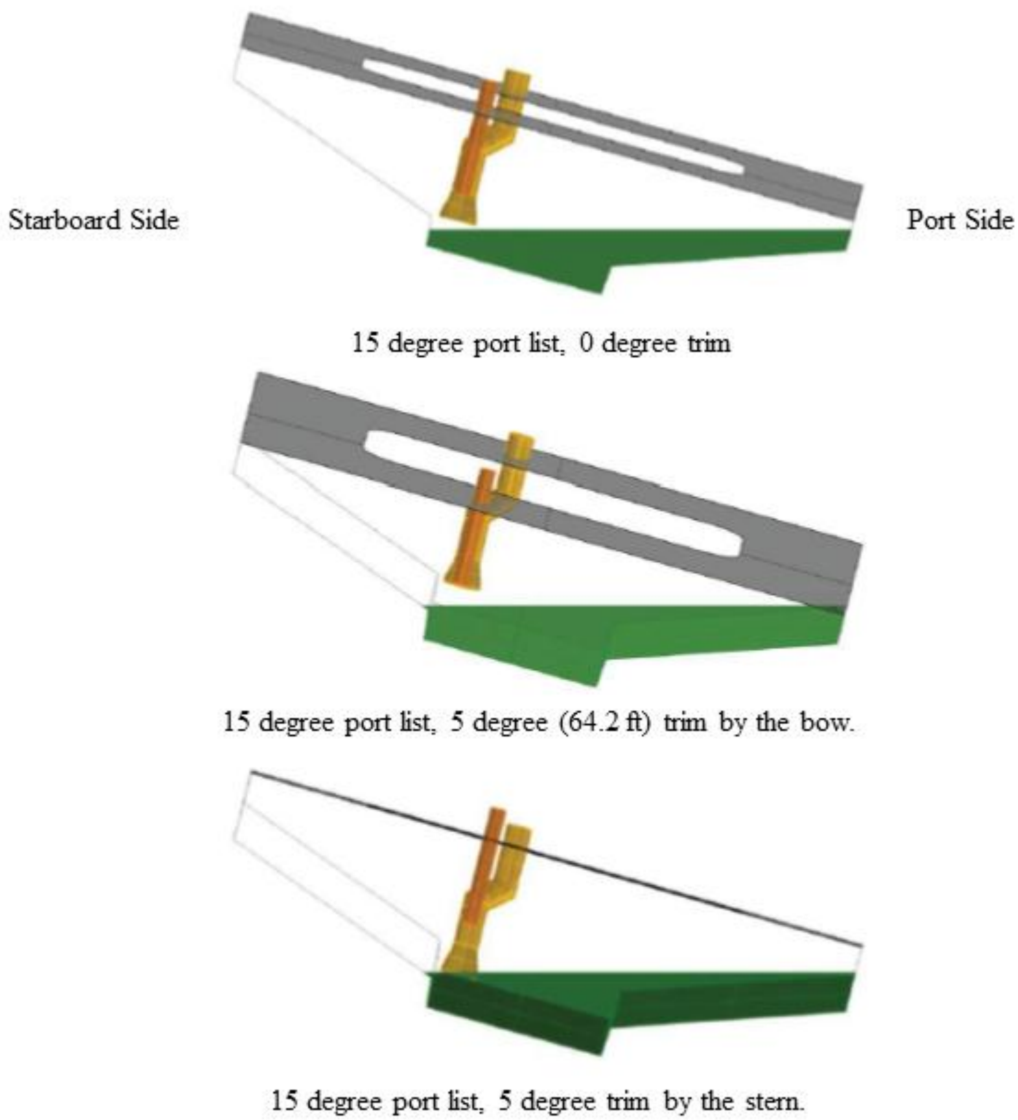

Figure 25. End views of the lube oil sump for the design low level capacity at 15 degree port list and differing trims.

[130] MBI Exhibit 412.

7.2.7.2. Lube Oil Volumes

A former EL FARO C/E testified at the MBI that during his tenure with Sea Star Lines (1998-2013), standard operating procedures were to operate with a lubricating oil sump level between 28 to 32 inches.[131] He testified that he normally kept the sump level higher to prevent the loss of lube oil suction. He further testified that during his time on EL FARO, the level was sometimes increased, at the direction of a C/E, to a higher level of 30"-32" for voyages where heavy weather was anticipated. The former C/E recalled needing to add an inch or two of oil to the sump once a quarter to compensate for normal oil consumption.

EL YUNQUE's Machine Operating Manual[132] states, "[w]hen necessary, add lube oil from the storage/settling tank to the sump, via purifier, to maintain the normal level at 27 inches. Record the amount added in the logbook." EL YUNQUE's Machine Operating Manual was used as a reference by the MBI because EL FARO's manual was not available and likely lost at sea. Between April 25, 2015, and September 1, 2015, the lube oil sump level on EL FARO gradually declined to a level of about 25". [133] There was a loss of lube oil[134] from the sump on July 20, 2015, due to an unknown cause, which resulted in the sounding dropping from 25" to 22". The sump was filled via the lube oil purifier on July 21, 2015; 289 gallons were added to bring the sounding back to 25".

At the time of EL FARO's departure on the accident voyage, the lube oil sump level was recorded in CargoMax[135] as 4.2 LT, 33.8%, or 163.8 FT^3. The CargoMax[136] departure condition indicated 1,225 gallons in the lube oil sump, which equated to a sounding of 24.6".

7.2.7.3. Lube Oil Pumps

EL FARO's lube oil service system was equipped with two positive displacement screw-type lube oil service pumps. The lube oil service pumps drew oil from the main reduction gear sump to provide the system with the appropriate supply pressure needed to lubricate the main propulsion turbine and reduction gear bearings. The lube oil service pumps had mechanical type seals. The forward main lube oil service pump was to have its mechanical seal replaced during a scheduled shipyard period[137] in October 2015. The aft main lube oil service pump was scheduled to be rebuilt or replaced because the pressure was running at 3 PSI[138] lower than the forward pump. A former EL FARO C/E[139] provided the following MBI testimony:

> *If a seal fails, you will usually get oil out the top of the pump on these particular pumps, and it would start collecting. Also you would start losing efficiency of that pump."*

[131] MBI Transcript February 08, 2017, pp. 45, 61-64.
[132] MBI Exhibit 384.
[133] MBI Exhibit 341.
[134] MBI Exhibit 387.
[135] MBI Exhibit 059.
[136] MBI Exhibit 323.
[137] MBI Exhibit 414.
[138] psi = pounds per square inch (a unit of pressure)
[139] MBI Transcript February 08, 2017, p. 47.

The TOTE Director of Safety and Marine Operations,[140] a former P/E, provided the following testimony:

> *If you lose oil on your seals, you're going to lose that— you're more likely to start pulling air in through your seals, also.*

He also stated that a pump could pull enough air in through the lost seal to cause the pump to lose prime completely.

7.2.7.4. Lube Oil Loss of Suction and Related Issues on the Accident Voyage

The following bridge conversations related to EL FARO's main propulsion unit are from the VDR audio transcript on the morning of October 1, 2015.[141]

At 4:39 AM, the C/E called the bridge and informed the C/M that the sumps were acting up due to the starboard list condition of EL FARO. Shortly after, the Master and the C/E spoke on the house phone and the C/E requested the bridge take action to remove the list.

One minute later the C/M called the Master and stated:

> *The C/E just called and (then/they) called back again (yeah) something about the list and oil levels * * *. Can't even see the (level/bubble).*

At 4:43 AM, the C/M directed the AB on the helm to put the ship in hand steering.

At 4:44 AM, the Master stated the following to an unidentified crew member on the house phone:

> *Alright. Shut her down.*

Shortly thereafter, the Master stated the following to the C/M on the bridge:

> *Just the list. The sumps are actin' up *. To be expected.*

A former EL FARO C/E testified:

> *There was the lube oil discharge low pressure alarm, and there's a low level alarm in the gravity tank and the main sump. There would also be alarms on the main unit themselves, the turbine bearings themselves if there was an issue there. Plus temperature alarms in case the temperature started getting too high, you would have a high temperature alarm.*[142]

[140] MBI Transcript February 13, 2017, p. 35.
[141] MBI Exhibit 266.
[142] MBI Transcript February 08, 2017, p. 477.

At 5:11 AM, the Master had a discussion with the Riding Crew Supervisor regarding the list and its impacts on lube oil system. The Riding Crew Supervisor stated that the vessel list could result in "the low pressure alarm on the lube oil."

At 5:14 AM, the Master directed the AB on helm watch to steer a course of 050 degrees.

At 5:15 AM, the Master continued his discussion with the Riding Crew Supervisor, and mentioned his earlier conversation with the C/E, stating "he's got a problem, like you said, a low level."

At 5:18 AM, the C/M mentions "(eighteen) degree list on."[143]

The Coast Guard MSC Lube Oil Modeling and Analyses of EL FARO[144] demonstrated that the lube oil system suction pipe bell mouth opening in the lube oil sump tank, using the 24.6" departure sounding obtained from the CargoMax entry, would have broken above the lube oil surface, resulting in a potential loss of suction at an 18° static list to port (see figures 9 and 10 below).

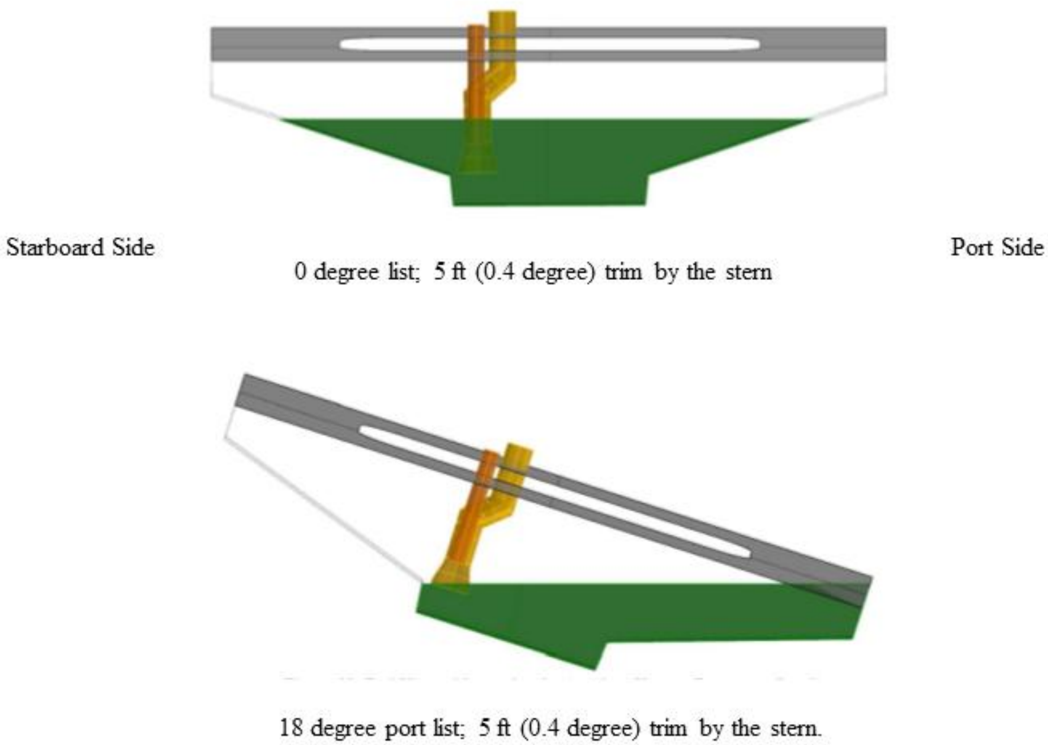

Figure 26. End views of sump for the accident voyage departure loading condition at 0 degree and 18 degree port list.

[143] From the NTSB VDR Audio Transcript forward, "( ) = Questionable insertion – the group either could not agree or was uncertain of a spoken word or phrase."
[144] MBI Exhibit 412.

At 5:47 AM, the Master was talking on the house phone and he made the following statement "Bilge pump running water rising. Okay. Can we pump from the starboard ramp tanks to port?" This would be an attempt to shift the limited amount of ballast from the starboard side ballast tank to the port side ballast tank in an attempt to overcome the list.

At 5:52 AM, the Master decided to turn the ship to port to get the wind on the starboard side, to induce a port list and enable the crew to access the partially flooded 2nd deck in order to secure the cargo Hold 3 scuttle on the starboard side.

At 5:57 AM, the Master told the engine room on the house phone, "[a]lright we got a nice port list can you stop transferring? From starboard to port segregated ballast (from/the) ramp tanks."

At 6:03 AM, the 2/M noted a loss of RPMs.

At 6:13 AM, the Master stated, "I think we just lost the plant."

At 6:57 AM, the Master mentioned to the 2/M that the engineers were having trouble getting the engines back online "because of the list."

At 7:07 AM, the Master spoke to the DPA and stated, "[w]e have a very– very– healthy port list. The engineers cannot get lube oil pressure on the plant therefore we've got no main engine." During the course of the conversation with the DPA the Master estimated the list at 15 degrees.

At 7:10 AM, the 2/M answered a house phone call from the C/E while the Master was talking with the DPA on the satellite phone. When the Master finished the call with the DPA, the 2/M relayed that the C/E said he could not regain propulsion due to the current listing condition.

At 7:17 AM, the C/E and the Master agreed that the list was getting worse.

The VDR transcript indicated a static list of 15 to possibly 18 degrees. The list described by various crew members is relatively permanent based on wind heel and free surface effect of water in Hold 3. There was additional motion of the ship caused by sea swell and lateral resistance to the waves, which combined to increase the angle of the ship in relation to an even keel.

7.2.8. EL FARO Compliance History

EL FARO was enrolled in the Coast Guard's ACP on February 27, 2006, with ABS as the ACS.

The complete record of the Coast Guard EL FARO MISLE inspection history, beginning in 2005, is included in Coast Guard MBI Exhibit 127. The following is a listing of pertinent items from EL FARO's compliance history:

Coast Guard Marine Inspectors from Sector San Juan conducted the last ACP Annual Oversight examination of EL FARO on March 6, 2015. The Coast Guard Marine Inspectors endorsed the COI as well as the International Ship Security Certificate after finding one deficiency that was converted to an ABS Condition of Class and later cleared by ABS.

On March 14, 2015, EL FARO reported a loss of propulsion to Coast Guard Sector San Juan. The incident occurred immediately following the San Juan pilot disembarking the vessel, which was outbound en route for Jacksonville, Florida. An investigation determined that an Oiler[145] mistakenly closed the lube oil outlet valve instead of the salt water cooling valve. The error caused the flow of lube oil to the main turbine and gravity tank to stop. EL FARO's crew responded by securing the main turbine and locking the shaft to prevent bearing damage.

On May 9, 2014, an ABS Surveyor attended EL FARO in Jacksonville, Florida to survey modifications carried out in way of Holds 1 and 2 inner bottom tank tops between frames 64 and 127. The modifications were made to accommodate the installation of six, 53-foot, 18,000 gallon horizontal fructose shipping container tanks, including associated piping and support structures.

On September 8, 2015, an ABS Surveyor attended EL FARO in Jacksonville, Florida for the purpose of verifying repairs made to the port boiler economizer tubes after the vessel experienced leaks in seven tubes. The surveyor determined the repairs were satisfactory after examining them and pressure testing them to 800 PSI. No other findings were noted and the vessel was cleared to sail.

During MBI testimony the ABS surveyor who conducted the repair survey on the EL FARO's port boiler economizer stated that she had not previously conducted any new construction or in service boiler tests. When asked what qualifications ABS required to conduct a boiler repair survey, the surveyor stated that ABS required that a surveyor complete two "repair tasks." The surveyor provided the following clarification regarding what constituted a repair task:

> *So the task is just repair. Repair surveys from piping to machinery to structure it's the same survey task.*

EL FARO was scheduled to be added to the 2016 ACP Targeted Vessel List. This is a Coast Guard list of approximately 10% of vessels enrolled in the ACP that show the most potential for being at risk of marine casualties due to factors such as age, ship type, and marine casualty history. The 2016 ACP Targeted Vessel List was intended to cover fiscal year 2016, but it was still undergoing internal routing at Coast Guard Headquarters when EL FARO sank on October 1, 2015. Vessels on the targeted list are subject to additional oversight at the 6-month mark of the ACP examination cycle. The scope of examination can be increased if Coast Guard inspectors find safety issues on board targeted vessels. In addition, both the Coast Guard and the classification society are required to attend drydock examinations for targeted vessels. The

[145] Junior level engine room watch stander.

classification society can conduct the required 3-year drydock examinations on behalf of the Coast Guard if a vessel is not on the targeted list.

The MBI noted that the majority of EL FARO's inspections, surveys, and examinations were conducted by either ABS Surveyors or Coast Marine Inspectors; they were rarely conducted by both ABS and the Coast Guard at the same time. The Chief of the Coast Guard's Office of Commercial Vessel Compliance testified during the MBI that ACP policy did not require a minimum level of Coast Guard oversight exams to be conducted in conjunction with an ACS inspection.

When asked by the MBI if the Coast Guard and ABS attended EL FARO together for field inspections, the Assistant Chief Surveyor of the Americas Division stated that he was aware of several instances where the compliance inspections were done separately.

When asked if it was valuable for the Coast Guard and ABS to align their inspections and Coast Guard oversight examinations during MBI testimony, the ABS Assistant Chief Surveyor of the Americas Division answered:

> *Yes for training I think it can help both sides and also for two sets of eyes is always better than one.*

7.2.9. EL YUNQUE Compliance History

EL YUNQUE was enrolled in the Coast Guard's ACP on May 4, 1999, with ABS serving as the ACS. EL YUNQUE was identified in the Coast Guard ACP Risk Assessment and Targeting Message for Fiscal Years 2014, 2015, and 2016, due to multiple reportable marine casualties. EL YUNQUE was considered a similar vessel to EL FARO, as it was configured to carry the same cargo and operated by the same company to conduct Puerto Rico trade.

A detailed compliance history for EL YUNQUE can be found in MBI Exhibits 363 and 369. The following is a listing of pertinent events from EL YUNQUE's compliance history:

On March 17 and 18, 2014, Coast Guard Sector Miami Marine Inspectors attended EL YUNQUE in dry dock at the Grand Bahamas Shipyard in Freeport Bahamas. They witnessed water tight door testing with high pressure water on cargo doors number 4, 5, 6, and 7 that separated the cargo holds on the vessel's 3rd deck. All of the cargo doors failed initial testing due to severe leakage at the top of the doors and around the dogs.

On December 15, 2015, the Coast Guard conducted an ACP oversight exam on EL YUNQUE. The oversight exam was conducted on a six-month cycle because EL YUNQUE was on the Coast Guard ACP Targeted Vessel List. During the exam the Coast Guard identified several missing or severely corroded piping areas throughout the lower cargo deck's sprinkler system, and several missing or damaged piping, horns, and nozzles on the CO2 fixed firefighting system serving RO/RO cargo spaces. The Coast Guard issued a no-sail order as a result of the firefighting deficiencies and requested that ABS issue conditions of class for nine other unrelated discrepancies.

On December 16, 2015, ABS cleared the no-sail order after witnessing repairs to the fixed firefighting systems. The surveyor also issued a condition of class to allow additional repairs to be completed on an extended timetable.

On December 22, 2015, Coast Guard Sector Jacksonville Marine Inspectors attended EL YUNQUE and noted the following sprinkler system discrepancies: three pin hole leaks in main line, several sections of cargo deck were dry after an operational test of the system, numerous sprinkler heads were clogged or not spraying correctly, and two sprinkler branches were completely fractured. Coast Guard Marine Inspectors subsequently witnessed failing sprinkler tests on EL YUNQUE on December 24, 2015; January 4, 2016; January 12, 2016; and January 18, 2016. On January 26, 2016, the Coast Guard determined that the sprinkler system was sufficiently repaired; however, the attending Sector Jacksonville Marine Inspector issued EL YUNQUE the following vessel inspection requirement (CG-835) due to the ongoing maintenance concerns on the vessel:

> *Several break downs have been observed with fundamental systems that enhance shipboard safety on board the vessel to include damaged and unrepaired CO2 fire fighting system in cargo spaces, clogged and completely wasted second deck sprinkler system piping, major rudder post seal leaks, and inoperative steering room ventilation. These shortfalls are an indication that a properly implemented preventative and corrective maintenance system, to include adequate documentation, does not exist on board the vessel. An internal SMS audit was performed on board the vessel on December 22, 2015 which did not properly address the lack of effective and systematic implementation of the vessel's SMS in this regard. Therefore, it is recommended that the Recognized Organization conduct an external audit to rectify deficits in the suitability to achieve the objectives of the company's SMS.*

On February, 1, 2016, three Coast Guard Traveling Inspectors attended EL YUNQUE as part of an ISM DOC Annual Audit of TOTE, which took place in Jacksonville, Florida. ABS led the DOC audit and provided three auditors, including the District Principal Surveyor. A Sector Jacksonville Coast Guard Marine Inspector also attended the audit as an observer. The Coast Guard does not normally participate in DOC audits; however, the Coast Guard Traveling Inspectors requested to be added to the team for TOTE's audit due to the previously identified maintenance concerns and the sinking of EL FARO four months earlier.

Part of the DOC audit included a general walk-through of EL YUNQUE, and the Traveling Inspectors requested that TOTE open up a starboard exhaust ventilation trunk serving cargo Hold 3 for inspection. The Traveling Inspectors noted severe corrosion within the ventilation trunk and they subsequently conducted testing of the soundness of the internal structure of the trunk. This test, which was performed in a typical manner using a hammer, resulted in a hole through baffle plating that was required to be watertight (see Figure 27). As the Traveling Inspectors were discussing expansion of their inspection to additional ventilation trunks, the senior Traveling Inspector received a cell phone call from the Sector Jacksonville Commanding Officer. The Sector Commander, as the OCMI for the Port of Jacksonville, ordered the Traveling Inspectors to stop further inspection and hammer testing of EL YUNQUE's ventilation trunks because it exceeded the scope of the DOC audit; the Traveling Inspectors complied with that order. However, the Senior Traveling Inspector suspected that the potential for long-standing corrosion existed for the other ventilation trunks and voiced a concern that the wastage could present a down flooding risk if the vessel experienced severe rolls. As a result, the Traveling Inspectors requested that Sector Jacksonville conduct a follow-up inspection to check additional trunks for conditions similar to that of Hold 3's starboard exhaust vent trunk.

Figure 27. Examples of wastage found within an EL YUNQUE ventilation trunk that were found by Coast Guard Traveling Marine Inspectors during a February 1, 2016, DOC audit of TOTE.

Under ACP protocols, Sector Jacksonville's Marine Inspector conferred with ABS and requested they oversee repairs to the ventilations trunks for Hold 3, check the condition of the other ventilation trunks, and issue conditions of class as necessary. ABS concurred with the Marine Inspector's concerns and required de-scaling and temporary repairs to the ventilation trunk casings that were identified as corroded during the DOC audit. On February 2, 2016, ABS surveyed temporary repairs to the holed and wasted areas in way of the port and starboard exhaust ventilation trunks for Hold 3[146] including the following items:

- The lower 24" of the louver chamber's inboard bulkhead was cropped and renewed.
- An opening around the side shell longitudinal angle in the transverse baffle plate was closed.
- Drainage holes on both port and starboard trunks (smaller and larger) were satisfactorily closed up.

The ABS surveyor gave TOTE 30 days, until March 2, 2016, to make permanent repairs to the Hold 3 ventilation ducts and EL YUNQUE continued to operate between Jacksonville and San Juan. On February 9, 2016, ABS advised Sector Jacksonville that the temporary repairs had been completed to EL YUNQUE's port and starboard ventilation trunks that were identified as corroded on February 1, 2016. In March 2016, TOTE relocated EL YUNQUE to Seattle, Washington and started the process of converting the vessel back to its original RO/RO configuration for Alaskan service.

[146] MBI Exhibit 363, pp. 24-26, is the ABS Class Survey report for the temporary repairs to the No. 3 Cargo Hold ventilation trunks. The report erroneously describes that the repairs were done to ducts serving No. 4 Cargo Hold.

During MBI testimony on May 19, 2016, the ABS surveyor who conducted the February 2016, repair survey on EL YUNQUE stated the following when asked if problems were detected in other ventilation trunks:

> *So after this was discovered we looked at the port side as well and then we sampled other trunks to verify that they were in good condition. This one that you have pictures of is the only one that was found in this condition with regards to the corrosion*.

From March 18 to August 14, 2016, Coast Guard Sector Puget Sound Marine Inspectors made several visits to EL YUNQUE and, despite the February 2016, ABS survey and testimony from the ABS surveyor, recorded the following pertinent findings:

- April 6-12, 2016: Directed extensive third party gauging for multiple suspect locations on the main deck. Found evidence of long-standing and uncorrected wastage.
- May 20, 2016: Examined supply vents for the Holds 1-3 port and starboard (6 total). Observed gaskets missing; holes in vent ducts; gasket flanges wasted; and holes in the side shell in way of vent inlets (see figure 28). Required all items to be added to the work list.
- August 14, 2016: TOTE halted work and requested to place the vessel in a lay-up vessel to be scrapped.
- December 23, 2016: Received notification that the vessel arrived at Brownsville, TX. Changed vessel status to "scrapped" in the Coast Guard's MISLE database.

Figure 28. Photographs taken by Coast Guard Traveling Inspectors during an October 2016 visit to EL YUNQUE in Tacoma, WA showing examples of corrosion within the vessel's exhaust ventilation trunks. (U.S. Coast Guard photographs)

7.2.10. Nautical Operations

7.2.10.1. Cargo Operations in Jacksonville – General Process and Responsibilities

Typical container cargo for EL FARO included 20-foot, 40-foot, and 53-foot intermodal containers. Refrigerated containers, commonly referred to as "reefer" containers or "reefers," were powered by connecting to the ship's electrical supply or separate generator packs. Typical RO/RO cargo for EL FARO included wheeled vehicles such as trailers on chassis and automobiles, as well as nonstandard rolling cargo such as boat trailers and large construction equipment. EL FARO was also fitted with six 53-foot ISO tank containers on the lower deck in the two forward cargo holds. These "tanktainers" were used to carry a viscous liquid product called fructose from Jacksonville to San Juan, each tank had the capacity to carry 18,000 gallons.[147]

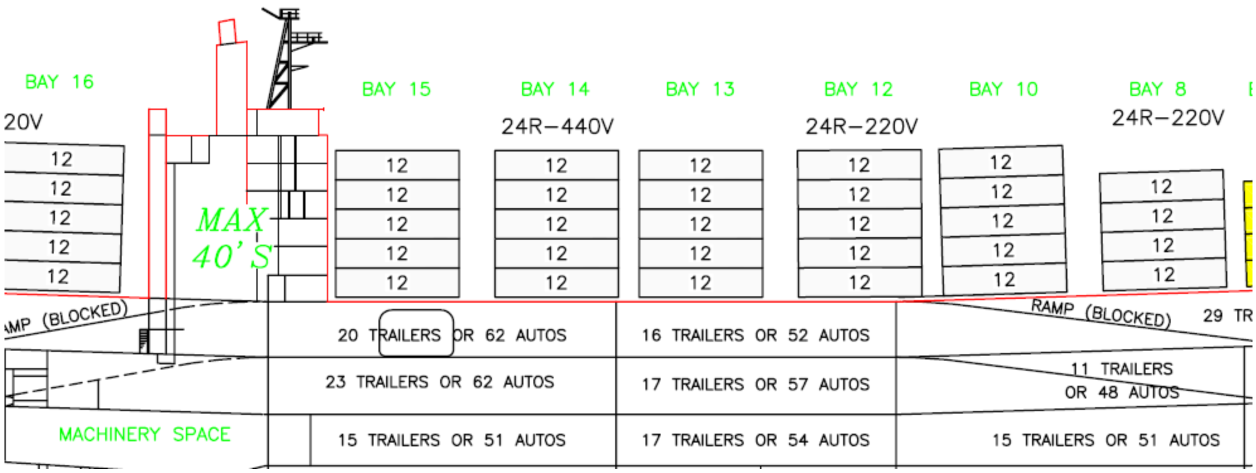

Figure 29. Partial vessel cross-section showing vertical location of container and RO/RO cargo.

When EL FARO arrived in Jacksonville a RO/RO ramp was attached to the side of the ship and trucks came aboard the ship to begin to hook up to and drive the cargo ashore. At the same time, gantry cranes on the pier would lower a special hoisting apparatus to latch on to the top of containers to lift them off the ship and move them to shore.

After cargo originating from San Juan was removed from the ship, the loading of cargo bound for San Juan would commence. Trailers and other vehicles were driven aboard the vessel using the ramps and would be placed into the position specified in the stow plan. Simultaneously, pier side gantry cranes would load containers onboard the ship. The process of securing the cargo is described later in this section.

As these simultaneous cargo loading operations took place, hoses would pump fructose to the tanks in the forward part of the ship.

Cargo discharging and loading operations in Jacksonville were managed by TOTE Maritime Puerto Rico (TMPR). TMPR's Marine Operations Manager was typically responsible for overseeing the proper execution of the following activities:[148]

- stowage, loading, and discharging of vessels;
- stability calculations;
- inspections of lashing gear and cargo securing fittings;
- monitoring vessel stability, stress, and trim calculations prior to, during, and at completion of cargo operations;

[147] MBI Exhibit 014.
[148] MBI Exhibit 372. Job description includes other duties and responsibilities not listed here.

- developing, maintaining, and modifying vessel stowage documents;
- coordinating vessel and terminal activities with port operations and vessel crew members to ensure vessels adhered as closely as possible to voyage schedules.

TMPR personnel worked with PORTUS Stevedoring personnel to conduct the cargo discharging and loading operations. PORTUS personnel utilized the computer program called Spinnaker to determine where each cargo unit would be placed based on volume and weight, they then created a stow plan which was updated throughout the operation.[149] TMPR used this information to manually enter weights of the cargo into the CargoMax computer program, which was used for stability calculations.[150]

The C/M on a merchant vessel is typically responsible for monitoring cargo and stability matters. The C/M on EL FARO was responsible for providing a final cargo and stability report to the Master.[151] While cargo was being discharged and loaded, the Mate on watch was responsible for supervising the lashing performed by stevedores.[152] The Mates on EL FARO stood the following watch schedule while in-port: [153]

- 2/M: 0000-0600 / 1200-1800;
- 3/M: 0600-1800 / 1800-2400;
- C/M: 0600-1800.

Port Mates (P/Ms) often provided assistance to Mates with their in-port duties, including but not limited to supervising the stevedores and ensuring that cargo was secured in accordance with the CSM. While P/Ms were provided for most port calls through August 2015, there were no P/Ms provided for EL FARO in Jacksonville after September 1, 2015. P/Ms continued to be provided in the Port of San Juan.

While standing the bridge watch on September 29, 2015, the 3/M made the following statements to his AB regarding Jacksonville cargo loading operations:[154]

> *(He) showed up after the fact. You know these you know wha– what's changed is. I mean granted obviously I missed something but man I could not (expletive) keep up I had (EL FARO General Utility, Deck, and Engineer worker) helping me. He couldn't keep up. I was helping him plug in and I didn't have time to get all the temps down and the ramp came off everything just happened in quick succession for a couple of reasons– I guess five hold didn't get finished up and until the last minute so all of the reefers that would have been already in and plugged in there weren't there they all just came on at the end. Yeah we just we had this perfect storm of shii– of (expletive) problems. We– we used to have a Port Mate and now we don't. We have a guy from PORTUS– a longshoreman– now we don't.*

[149] MBI Transcript February 20, 2016, p. 115.
[150] MBI Transcript February 20, 2016, p. 115.
[151] MBI Transcript February 20, 2016, p. 127.
[152] MBI Transcript February 19, 2016, p. 99.
[153] MBI Exhibit 283, p. 5.
[154] MBI Exhibit 266, p. 67.

*Then we lost our electrician and this guy wants to basically wash his hands of second deck and just have it all handed to him. * * (Alternate EL FARO Electrician) would always be that system of check where he would come down and make sure that every reefer was good and then he would call up— you'd hear him on the radio— "okay this— I got this many reefers and they're all good." That doesn't happen anymore.*

Yeah he's slow so he doesn't have time to (expletive) work— well— to do anything down there so he doesn't think it's his responsibility and no one has told him otherwise. So. He'll sit up there under— sit down up there and say they're too busy to come down you know like most of the (expletive)— I go up there— I make the rounds on main deck and most of the time they ain't doin' (expletive).

*It's (expletive) insane down there. The other thing is (Ex EL FARO 2/M) when we were northbound he would go set all the plugs up. Well that's not happening anymore either there's just (expletive) extension cords everywhere— it's a mess down there. It— it's— everything is falling apart. And yeah I'm (expletive) up, but I'm doin' the best I can and— I'm not the part of the equation that's changed. I'm doin' what I've always done, but it's just not enough anymore. ** The Mate said, "Oh well next time call for help."*

The AB standing watch with the 3/M made the following response:

All the extra people that are supposed to be doin' it are all gone ashore.

7.2.10.1.1. Cargo Securing, also Known as "Lashing"

The IMO issued Guidelines for the preparation of the CSM in MSC/Circ. 745 dated June 13, 1996. This Circular was subsequently superseded by MSC.1/Circ.1353, but was in effect at the time that EL FARO's CSM was approved. The Circular was included in its entirety in the 2003 Edition of the IMO Code of Safe Practice for Cargo Stowage and Securing (CSS Code).[155]

The CSM for EL FARO[156] was prepared by HEC and approved by ABS on behalf of the Coast Guard. EL FARO's CSM included the following:

- The Master shall ensure that cargo carried in the vessel is stowed and secured in a manner that takes into account the prevailing conditions and the general principles of safe stowage.
- This Cargo Securing Manual specifies the arrangements and cargo securing devices provided on board the ship for the correct application to, and the securing of, cargo units, containers, vehicles and other entities, based on transverse, longitudinal and vertical forces which may arise during adverse weather and sea conditions.
- The safe stowage and securing of cargoes depends on proper planning, execution, and supervision.

[155] MBI Exhibit 290.
[156] MBI Exhibit 040.

- Personnel planning and supervising the stowage and securing of cargo shall have a sound practical knowledge of the application and content of this Cargo Securing Manual.
- Decisions for the stowage and securing of cargo shall be based on the most severe weather conditions that may be reasonably expected by experience for the intended voyage.
- Ship-handling decisions made by the Master, especially in heavy weather conditions, shall take into account the type and stowage position of the cargo and the securing arrangements.
- Fixed cargo securing devices shall be visibly inspected routinely (at least once every other voyage) for damage such as cracking or deformation. In way of fixed cargo securing devices, the ship's structure that is visible shall be inspected at least once every six months for damage such as cracking or deformation.
- The principal means of preventing the improper stowage and securing of cargoes is through proper supervision of the loading operation and inspection of the stowage. Care shall be taken in planning and supervising the stowage and securing of cargoes in order to prevent cargo sliding, tipping, racking, collapsing, etc.
- It is important that all lashings be carefully examined and tightened at the beginning of the voyage as the vibration and working of the ship causes the cargo to settle and compress. They shall be further examined daily during the voyage and tightened as necessary.
- If cargo shifts or lashings become slack during the voyage, appropriate remedial action shall be taken. However, cargo shift is likely to occur in adverse weather conditions. Sending crew members to release or tighten lashings on a moving or shifting cargo in these conditions may represent a greater hazard than retaining a shifted load.

Representatives of the National Cargo Bureau (NCB) testified during the MBI that EL FARO's CSM had errors and inconsistencies. The NCB witnesses also stated that the CSM was confusing to them. However, the NCB witnesses did testify that if EL FARO cargo was secured in accordance with the CSM, the NCB would consider the cargo properly secured.[157]

Although longshoremen conduct the work of loading and securing cargo, it is ultimately the Master's responsibility to ensure that the cargo carried aboard the vessel is stowed and secured in accordance with the vessel's CSM.[158]

Containers on the main deck were attached to fixed base sockets using either conventional or semi-automatic twistlocks at all four corners of the container. Any container stacked above the bottom-most container was then attached to that container using twistlocks at all four corners. Some container stacks were also secured using lashing rods and tensioners, which were attached to the bottom casting on the 2nd tier container and to a padeye on the vessel's deck. There were a variety of factors that went into a determination whether to use lashing rods, including weights of container stacks and the forces and accelerations they would be subject to due to wind and the motions of the vessel. Generally, for standard enclosed containers, one-high and two-high deck container stacks needed only twistlocks, and no lashing rods were required. Three, four, and

[157] MBI Transcript February 8-9, 2017, p. 575.
[158] MBI Exhibit 040, p. 4, para 3.0 "Responsibility."

five-high deck container stacks may have required lashing rods if the container weights exceeded the limits of the "no lash" system. CargoMax software performed calculations and indicated which lashings were necessary to ensure compliance with the CSM.

The following illustrations show the typical "single lash" and "no lash" arrangements described above:

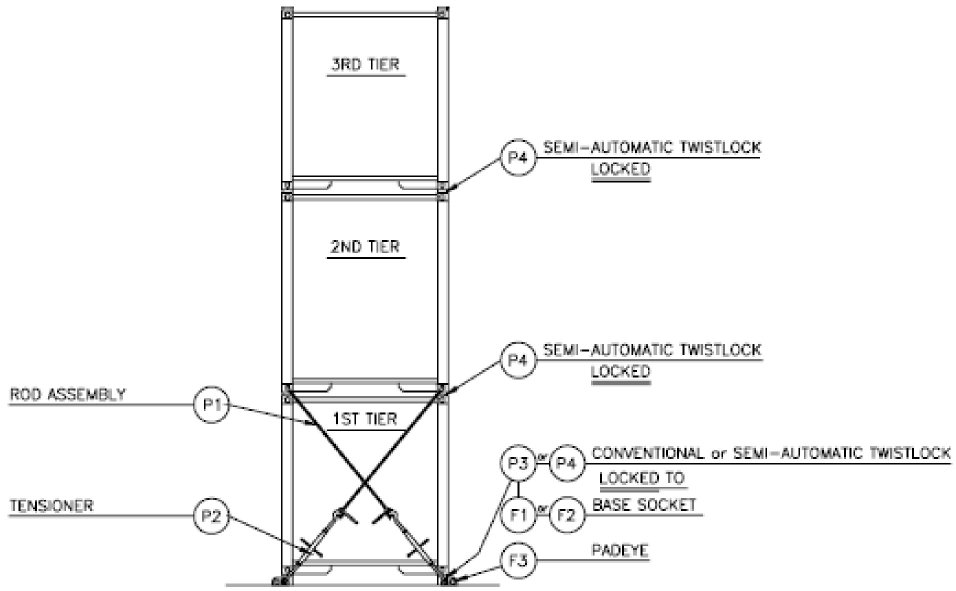

Figure 30. Typical single lash arrangement for container cargo on the main deck. (MBI Exhibit 040, Cargo Securing Manual)

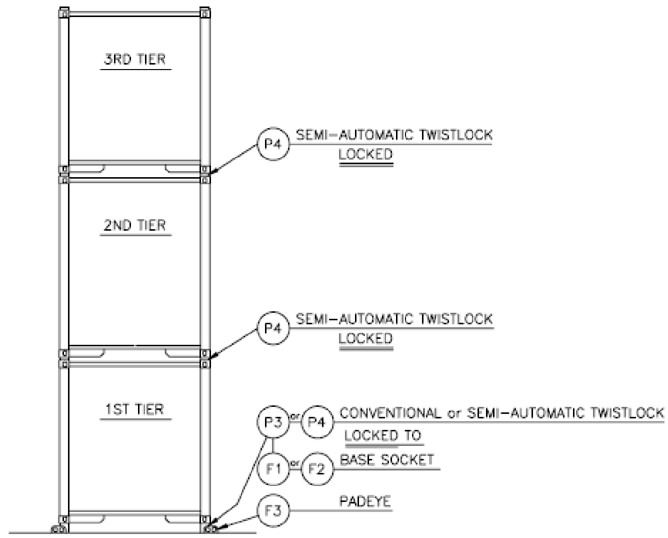

Figure 31. Typical no lash arrangement for container cargo on the main deck. (MBI Exhibit 040, Cargo Securing Manual)

Several MBI witnesses[159] testified about a "Lashing Manual," which was apparently an unofficial guide prepared by an unknown person. This unofficial lashing manual contained copies of many of the pages from the approved CSM, but contained additional diagrams and images which do not appear in the CSM. One such reference is called the "SSL EL Class Minimum Lashing Requirements – LoLo," which is a one-page diagram illustrating which containers should be lashed.[160] MBI testimony from PORTUS employees indicated they were unaware of the "lashing manual." However, TOTE's reply to the NCB report indicated the company did use the principles contained in "lashing manual" as guidelines for securing containers.

EL FARO's CSM stated that automobiles stored below decks should have their emergency brakes set and that four auto lashings were to be used, one at each corner.

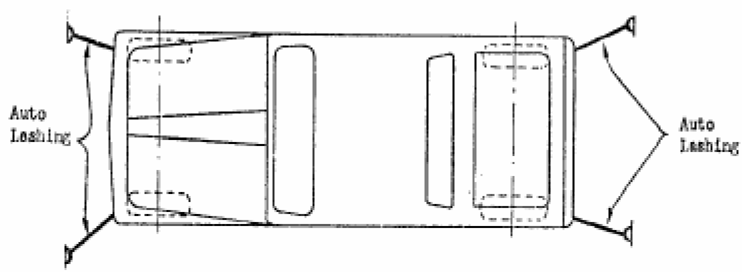

Figure 32. Image from Cargo Securing Manual for vehicles stored below the main deck. (MBI Exhibit 040)

The above image from the CSM shows auto lashings attached directly to D-rings secured to the deck. On EL FARO, a long chain running athwartships was secured to D-rings at each side. Auto lashings were secured to these chains instead of to individual D-rings.

[159] MBI Transcript February 19, 2016, p. 166 and February 20, 2016, p. 155.
[160] MBI Exhibit 042, p. 9.

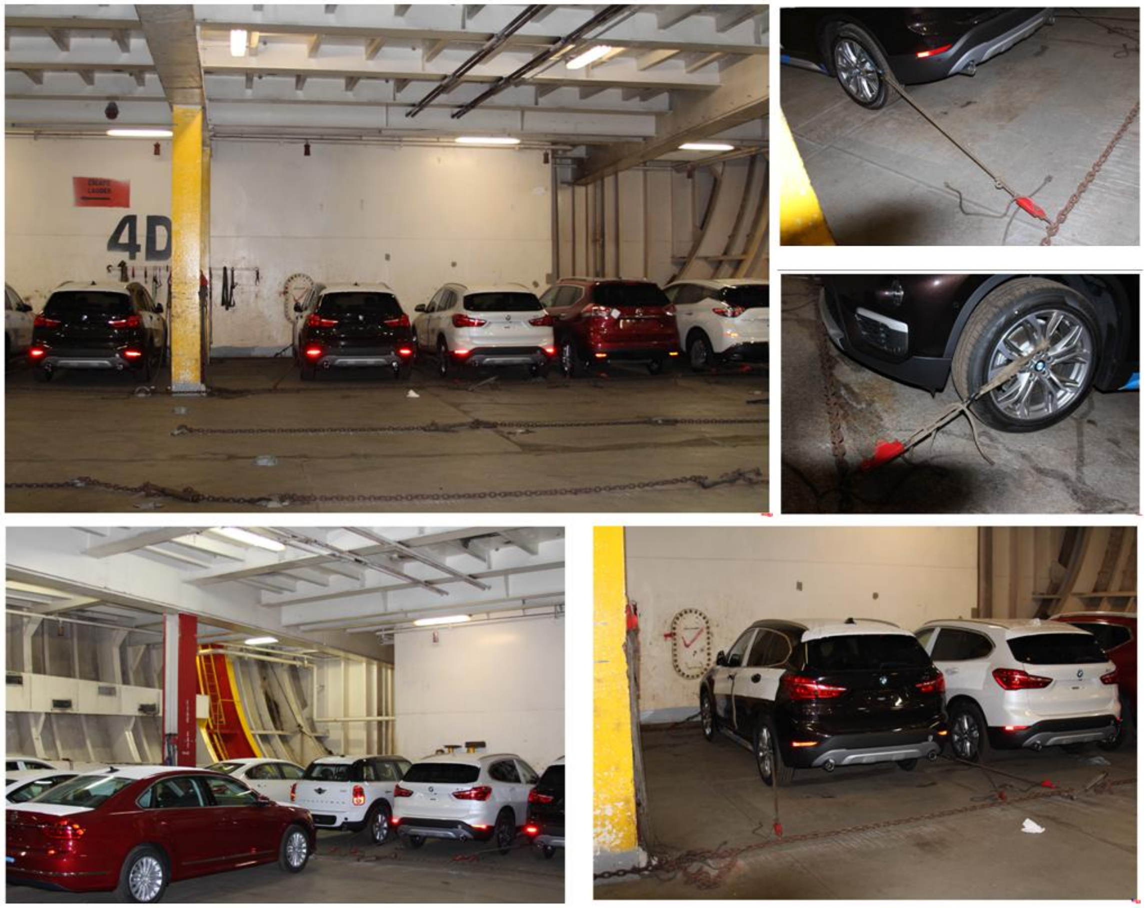

Figure 33. Select Coast Guard photographs from MBI Exhibit 109 that show examples of vehicle lashing methods aboard EL YUNQUE on December 1, 2015.

According to the CSM, wheeled vehicles such as trailer vans, flatbed trailers, and containers on chassis were driven aboard, parked, and secured to fittings installed on deck. Trailers were required to be secured to the deck using ROLOC boxes and lashings. ROLOC boxes were secured to the deck at dedicated sockets, which are commonly referred to as "buttons." The locking spud on the ROLOC box was inserted into the hole in the deck socket and rotated to lock it in place. A wing nut could be adjusted to tighten the ROLOC box to the deck.[161]

[161] MBI Exhibit 040.

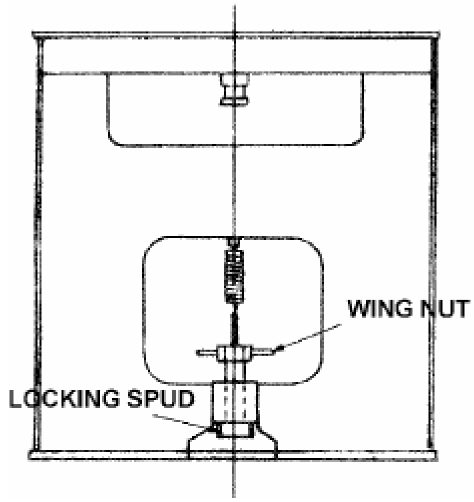

Figure 34. Cross section through ROLOC box (MBI Exhibit 040).

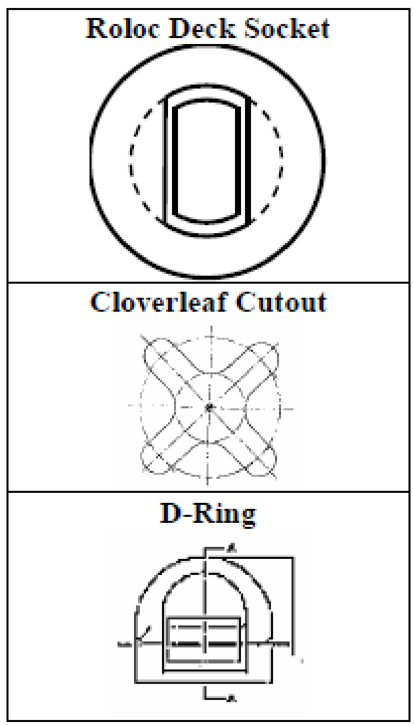

Figure 35. Fixed securing devices for RO/RO cargo (MBI Exhibit 040). ROLOC Deck Sockets are commonly referred to as "buttons."

The number of lashings required for trailers depended upon whether the trailer was oriented in a fore and aft direction (i.e., parallel to a line running between the ship's bow and stern) or in an athwartship direction (i.e., perpendicular to the ship).

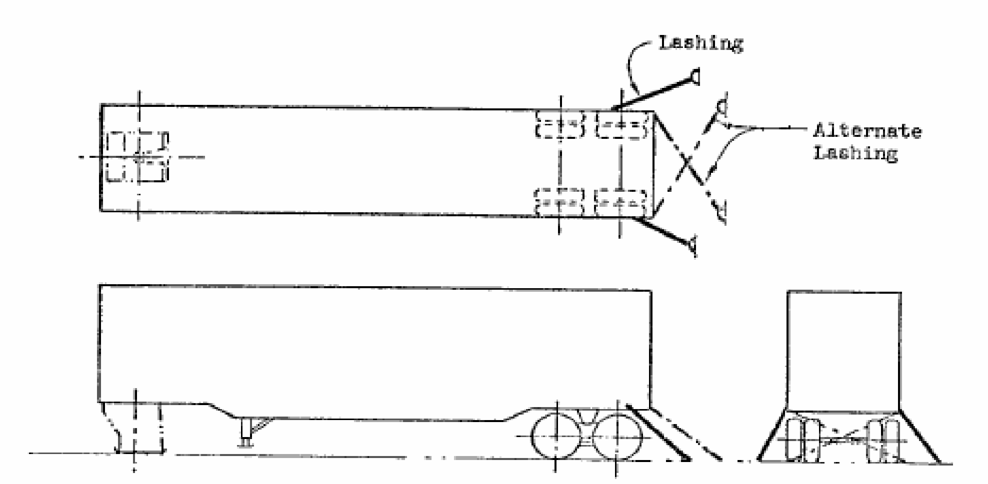

Figure 36. Fore/Aft stowage with a ROLOC Box, oriented normally. (MBI Exhibit 040)

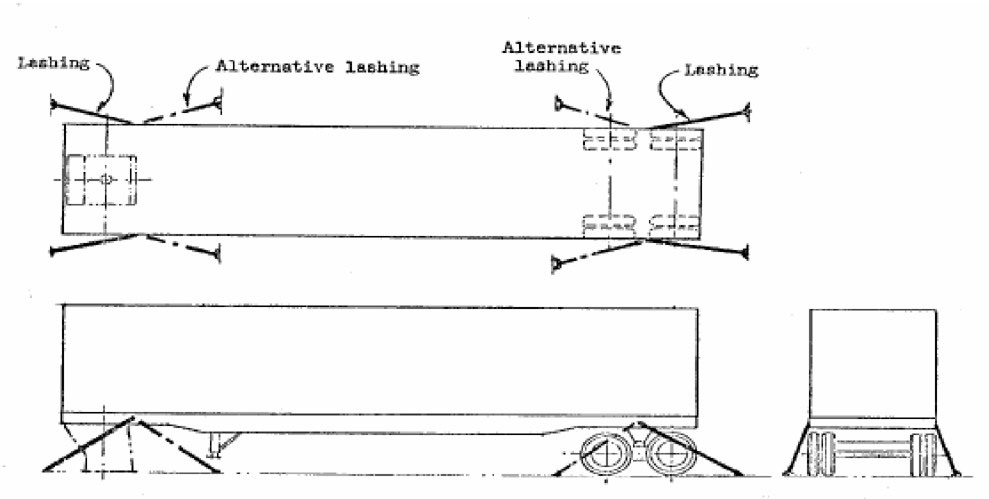

Figure 37. Athwartship stowage with a ROLOC box, oriented normally. (MBI Exhibit 040)

The PORTUS head lasher provided MBI testimony on how RO/RO cargo was secured for EL FARO's final voyage, and he supplemented his testimony by providing a diagram[162] illustrating how each cargo unit would have been lashed.

The head lasher indicated that it was not always possible to land the ROLOC boxes on a button and he indicated that this was particularly true on EL FARO's 2nd deck, which had fewer buttons as compared to EL YUNQUE.[163] The MBI was unable to determine precisely how many trailers stowed on EL FARO were off button during the final voyage due to conflicting testimony on the issue. However, it was determined that at least three trailers on 2nd deck were not attached to a button and that as many as 40 trailers may not have been attached to a button.

[162] MBI Exhibit 289.
[163] MBI Transcript May 23, 2016, p. 203.

When a trailer had to be secured off-button, the CSM stated that the instructions for non-standardized cargo (including the Advanced Calculation Method described in the *Code of Safe Practice for Cargo Stowage and Securing* (CSS Code)[164] and Appendix 17 of the CSM) should be followed in order to determine the appropriate lashing arrangements.[165] Multiple former EL FARO crew members, TMPR personnel, and PORTUS personnel, testified that they had never performed the calculations described in the Advanced Calculation Method. Instead, the standard cargo securing practice was to apply two additional chains (six lashings total) to the forward end of a trailer in the vicinity of the ROLOC box in lieu of it being attached to the button.[166]

According to NCB testimony,[167] the use of six lashings in lieu of attaching a ROLOC box to a button would likely be considered satisfactory for many trailers. However, the weight of heavier trailers stowed off button could exceed this type of securing arrangement. This was particularly true if lashings were applied as shown in TOTE Lashing Manual photos.[168] These photos show lashings which were not consistent with the requirements in the CSM, including attaching hooks to cargo in an improper manner and running lashings at excessive angles. A report prepared by the NCB concluded that EL FARO's rolling action in heavy weather would have likely caused some trailer lashings to fail, which could also have led to a domino effect of progressive lashing failures as shifting trailers fell against adjacent trailers.

EL FARO's VDR audio transcript indicated that at least one trailer was "leaning" as early as 4:37 AM on October 1, 2015. As EL FARO proceeded eastward, the weather became more severe, increasing the likelihood of additional lashing failures. At 5:54 AM, after the vessel had already experienced green water on the 2nd deck and intermittent flooding into one or more cargo holds, the Master altered course to port in order to intentionally put the wind on the vessel's starboard side and shift the vessel from a starboard list to a port list. This sudden shift, combined with free surface conditions due to flood waters and loose debris, would have put a shock load and additional stress on the lashings.[169]

During MBI testimony, the PORTUS Services foreman who supervised EL FARO's lashing gangs during cargo loading prior to the accident voyage stated that he had never seen a copy of EL FARO's current lashing manual or approved CSM.

7.2.10.1.2. Stability calculations during loading operations

Shore side personnel used computer software called Terminal Operating System (TOS) to manage vessel cargoes as they arrived at the terminal gate and were moved through the terminal on their way to the ship. There were three scales at the gates to weigh the incoming cargo so that

[164] MBI Exhibit 189.
[165] MBI Exhibit 40, Section 6.1.
[166] MBI Exhibit 354.
[167] MBI Transcript February 08-09, 2017, p. 589.
[168] MBI Exhibit 042.
[169] Navigation and Vessel Inspection Circular (NVIC) 4-77 discusses the danger of shifting weights or counter flooding when a vessel experiences a permanent heel due to a combination of shifting cargo and flooding water; https://www.uscg.mil/hq/cg5/nvic/pdf/1970s/n4-77.pdf

the weights could be entered into the CargoMax software in order to calculate allowable stack weights and vessel trim and stability. This software is described in more detail in the Load Line, Stability, and Structures section of this report. According to MBI testimony,[170] trucks bringing the cargo to the facility were weighed the first time they came to the facility in order to remove the weight of the truck and trailer from the combined calculated weight of the truck and cargo. The terminal maintained a record of that initial weight and applied the same weight to subsequent calculations rather than weighing the truck each time it came to the facility. Potential differences in the fuel level of the truck were not considered for each arrival. According to testimony,[171] containers and NIC cargo would have their weights rounded to the nearest thousand pounds and automobiles were always estimated to weigh 1.5-long tons, or 3,300-pounds each.

Stability calculations were conducted by TMPR shore side personnel throughout the loading operation using CargoMax software.[172] These duties were normally the responsibility of the Marine Operations Manager, who had regular interaction and communication with vessel crew members throughout cargo operations. However, during EL FARO's final port call these duties were carried out by the Terminal Manager because the Marine Operations Manager was on vacation.[173] Neither the Marine Operations Manager nor the Terminal Manager had received any formal training on vessel stability or the CargoMax software and they each learned to use the software via on-the-job training from prior Sea Star employees.[174]

TOTE had not established any written policies or checklists to ensure that the tasks performed by the TMPR personnel were completed in the same manner for each vessel port call. The Terminal Manager testified that he had filled in for the Marine Operations Manager less than ten times per year. The Terminal Manager's testimony also indicated that he did not clearly understand the lashing margin and strength margin fields in CargoMax.[175] Additionally, as TOTE worked with ABS Rapid Response Damage Assessment team during the response to the loss of EL FARO, it was discovered that the CargoMax load case for the departure condition that was printed at 5:56 PM on September 29, 2015, and delivered to EL FARO's crew, contained an error in lube oil and fuel oil quantities.[176] After EL FARO was reported missing on October 1, 2015, the TMPR Terminal Manager generated a revised CargoMax departure condition load case for EL FARO that corrected the lube oil and fuel oil quantities. The corrected CargoMax report printed at 11:48 AM on October 1, 2015, calculated a GM margin of 0.64 feet, which was 0.16 feet less than the GM margin on the CargoMax load report that was delivered to EL FARO's crew prior to their departure on the accident voyage.

The typical practice for EL FARO and EL YUNQUE was to calculate stability and have a minimum GM margin for safety at sea. This was an informal arrangement and there was no written policy for terminal operators or vessel crews to reference. This GM margin for routine voyages was described as 0.5 feet, which accounted for a GM decrease of approximately 0.25

[170] MBI Transcript February 20, 2016, p. 138.
[171] MBI Transcript February 20, 2016, p. 176.
[172] MBI Transcript February 18, 2016, p. 16.
[173] MBI Transcript February 20, 2016, p. 1713.
[174] MBI Transcript February 18, 2016, p. 121.
[175] MBI Transcript February 20, 2016, p. 67.
[176] MBI Transcript February 20, 2016, p. 152.

feet due to fuel burn during a typical voyage to San Juan. The GM margin helped to ensure that the vessels did not fall below their required GM while underway.

TOTE's SMS manuals state that the vessel's stability is to be verified and found safe for sea "prior to the departure from the loading port."[177] The final printed stow plans, dangerous cargo manifest, and electronic CargoMax load case file, which was calculated ashore, were typically provided to the C/M approximately 30 to 45 minutes prior to vessel departure. This common practice for TOTE vessels in the port of Jacksonville left little time for the C/M and Master to verify the loading information and stability calculations prior to departing the dock, and MBI witnesses indicated that the CargoMax report verifications would sometimes occur after the vessel was underway.

The TMPR Terminal Manager testified that while EL FARO was being loaded during its final port call, he did not have discussions with the crew regarding heavy weather. The Terminal Manager also testified that there were no discussions related to potentially reducing EL FARO's cargo load or increasing the GM margin in preparation for the heavy weather.[178]

EL FARO's crew was required to take the forward, aft, and midship drafts of the ship on both sides prior to departure. This procedure would validate that the Cargo Max calculations being performed by TMPR shore side personnel matched actual observed conditions. Drafts for the dockside of the ship were typically recorded by the C/M and the Terminal Manager. A bucket was used to take a water sample from the St. Johns River. The water sample would then be analyzed by a hydrometer to determine the salinity of the water around the ship. This salinity would then be used to calculate the expected ocean draft for the vessel. MBI testimony indicated that it was difficult to observe EL FARO's offshore midship draft due to the location of the draft marks and there was no standard practice in place to obtain the offshore midship draft. When the Terminal Manager met with the C/M immediately prior to EL FARO's final departure, the C/M had already taken the drafts. EL FARO's departure message indicated that the last Ro-Ro cargo came aboard at 6:30 PM on September 29, 2015, and the last of the Lo-Lo cargo came aboard at 6:54 PM.

7.2.10.2. Voyage Planning

On August 20, 2015, the TSI Manager of Safety and Operations sent out a Safety Alert,[179] 15-008 entitled "Hurricane Danny." This alert contained information about Danny and also included a storm forecast for the 2015 hurricane season. The alert ended with the following statement:

> *This is a reminder that ALL our vessels, in all oceans, should review their general and vessel specific heavy weather procedures and be prepared for the unexpected occurrence.*

[177] MBI Exhibit 025, pp. 129-130.
[178] MBI Transcript February 20, 2016, p. 125.
[179] MBI Exhibit 045.

EL FARO did not have any vessel specific heavy weather procedures, whereas the Ready Reserve Fleet (Military Sealift Command) vessels operated by TSI did have specific heavy weather procedures. The President of TSI provided the following MBI testimony:

> *I would expect that our Masters based on this would go back to the – refer to the operating manual for vessels and then refer to their own professional references that guide them in acumen of being the enormously competent mariners that they are and we hold them to be based on their credentials.*[180]

On August 26, 2015, EL FARO transited the Old Bahama Channel while en route to San Juan, Puerto Rico, in an attempt to avoid Tropical Storm Erika. During that voyage the TSI Manager of Safety and Operations sent an email to the Master of EL FARO[181] which included the following statement:

> *…to ensure we are all on same page and nothing is missed in the risk assessments and action area, please send me a detailed email with your preparedness / avoidance plans and update daily until all clear.*[182]

The TSI Manager of Safety Operations testified that he did not remember why he asked for daily updates and avoidance plans other than because he wanted to be kept informed.[183] The Manager of Safety and Operations was out of the office when EL FARO was departing Jacksonville on September 29, 2015, and he did not pass on his DPA duties to another TOTE manager while he was traveling.

EL FARO's P/E had dinner with the Master onboard EL FARO prior to the vessel's departure from Jacksonville on September 29, 2015. The P/E testified that during their dinner the Master indicated that he was aware that a tropical storm was brewing, but that he was not concerned about "major weather." In an email to TOTE executives on the afternoon of October 1, 2015, the same P/E stated that weather was not a topic of conversation while he was interacting with the Master. The MBI could not find evidence indicating that any other members of TOTE management had discussions or inquired with the Master regarding potential safety precautions for heavy weather ahead of the EL FARO's final voyage. In his September 30, 2015 noon position report email, the Master noted "[p]recautions observed regarding Hurricane Joaquin," but he did not go into specifics as to what precautions were being taken.[184]

EL FARO and EL YUNQUE usually took the most direct and economical route from Jacksonville to San Juan, which was a course of 131 degrees.[185] Additional routes available to the vessels included:

- Straits of Florida to Old Bahama Channel;

[180] MBI Transcript February 16, 2016, p. 28.
[181] The Master of EL FARO during TS ERIKA voyage was the same Master onboard for the accident voyage.
[182] MBI Exhibit 004, p. 30.
[183] MBI Transcript February 20, 2016, p. 94.
[184] MBI Exhibit 004.
[185] MBI Transcript February 16, 2016, p. 49.

- Straits of Florida to Northwest Providence Channel to Northeast Providence Channel;
- Normal route of 131 then Northeast Providence Channel, Northwest Providence Channel, Straits of Florida, and Old Bahama Channel (this route involves significant back-tracking, but is an option);
- Normal route of 131 then Crooked Island Passage.

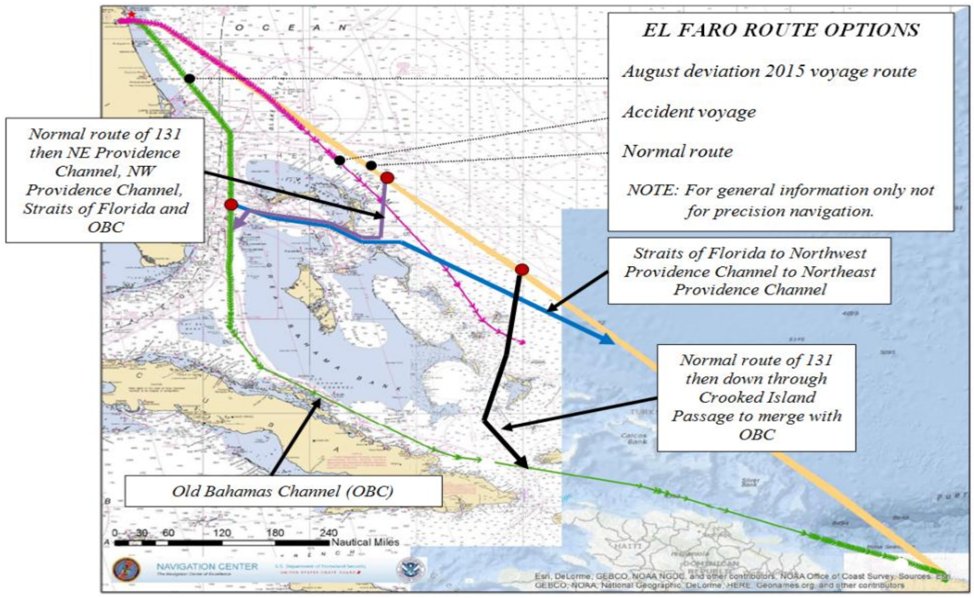

Figure 38. EL FARO route options for the accident voyage (Source Coast Guard)

According to MBI testimony from TOTE company officials their vessel Masters: [186]

- have total responsibility for all voyage planning and routing decisions.
- operate autonomously, and are free to choose whichever route they feel is safe.
- are the experts in the safe operation of the vessel which includes voyage planning elements that would be associated with evaluating environmental conditions.
- are the "nautical experts" within TSI.
- do not need permission to change the vessel's route.

The Master of EL FARO was not required to consult with TSI on the route the vessel would take. The Manager of Safety and Operations testified that no one at TOTE except for vessel crew had the specific task of monitoring weather and making weather assessments.[187] As EL FARO departed Jacksonville on the accident voyage, no one at TSI monitored EL FARO's position until the first noon report was received onshore about 16 hours after departure.

According to testimony from a prior TOTE Master, EL FARO used to have a document referred to as a "hurricane plan," which discussed additional routes that could be used to avoid a

[186] MBI Transcript February 16, 2016, pp. 48-50.
[187] MBI Transcript February 20, 2016, p. 13.

storm.[188] No evidence or testimony was provided to indicate that this hurricane plan was incorporated into TOTE's SMS or any other procedures.

There were no general or vessel specific heavy weather procedures for EL FARO or EL YUNQUE, with the exception of the general guidance contained in the SMS manuals.

The Operations Manual – Vessel stated:

- The Master is responsible for the monitoring and analysis of the weather along the vessel's intended track. Current weather conditions, outlooks, and predications must be considered in the planning and undertaking of a voyage. The Master should use all available means to determine the weather that the vessel may encounter on a given voyage.[189]

- The Master shall be very careful that the vessel is properly handled during periods of adverse weather. Before encountering heavy weather, the Master should take proper precautions to safely stow and secure all the vessel's equipment to prevent any damage to the equipment or vessel. The Master shall take whatever action is necessary to prevent excessive damage to the vessel from heavy weather. The Master shall advise the HQ Office of speed reductions and/or course changes due to adverse weather.[190]

MBI testimony from TOTE employees indicated that the notification of a course deviation to avoid a storm was solely for the purpose of informing shore side management regarding an updated arrival time so that they could in turn advise customers, tugs, pilots, and stevedores at the destination port.[191] An EL YUNQUE Master testified that his understanding was that this notice is advisory in nature and that Masters didn't need company permission to transit an alternate route.[192]

Guidance provided in EL FARO's OMV contained a section titled "Weather Routing,"[193] but it refers to the Bon Voyage System provided by Applied Weather Technology, which was not a routing service and only provided graphical weather information.[194]

Guidance provided in EL FARO's EMPV contained the following information: [195]

5.12.2 AT SEA
Severe weather is to be avoided where possible by altering the track of the vessel. Instruction for maneuvering in extreme weather can be found in "The American Practical Navigator" HO Pub. #9.[196]

[188] MBI Transcript February 06, 2017, p. 1599.
[189] MBI Exhibit 025, OMV Section 10.8.1, p. 217.
[190] MBI Exhibit 025, OMV Section 10.8.2, p. 218.
[191] MBI Transcript February 16, 2016, p. 60.
[192] MBI Transcript February 16, 2016, p. 51.
[193] MBI Exhibit 025, p. 218.
[194] MBI Transcript February 16, 2016, p. 108.
[195] MBI Exhibit 026, p. 107.
[196] MBI Exhibit 026, p. 107.

This widely used publication describes the principles and factors of navigation including piloting, electronic navigation, celestial navigation, mathematics, safety, oceanography, and meteorology.[197]

The American Practical Navigator has been continuously updated since its publication in 1802 and the version in place during the accident voyage included the following passages:

> ***3509. Locating the Center of a Tropical Cyclone***
> *If intelligent action is to be taken to avoid the full fury of a tropical cyclone, early determination of its location and direction of travel relative to the vessel is essential. The bulletins and forecasts are an excellent general guide, but they are not infallible, and may be sufficiently in error to induce a mariner in a critical position to alter course so as to unwittingly increase the danger to his vessel. Often it is possible, using only those observations made aboard ship, to obtain a sufficiently close approximation to enable the vessel to maneuver to the best advantage.*
>
> *The winds are probably the best guide to the direction of the center of a tropical cyclone. The circulation is cyclonic, but because of the steep pressure gradient near the center, the winds there blow with greater violence and are more nearly circular than in extratropical cyclones. According to **Buys Ballot's law**, an observer whose back is to the wind has the low pressure on his left in the Northern Hemisphere, and on his right in the Southern Hemisphere.*
>
> ***3511. Maneuvering to Avoid the Storm Center***
> *A plot of successive positions of the storm center should indicate the semicircle in which a vessel is located. However, if this is based upon weather bulletins, it may not be a reliable guide because of the lag between the observations upon which the bulletin is based and the time of reception of the bulletin, with the ever-present possibility of a change in the direction of the storm. The use of radar eliminates this lag at short range, but the return may not be a true indication of the center. **Perhaps the most reliable guide is the wind.** Within the cyclonic circulation, a wind shifting to the right in the northern hemisphere and to the left in the southern hemisphere indicates the vessel is probably in the dangerous semicircle. A steady wind shift opposite to this indicates the vessel is probably in the less dangerous semicircle.*

Comments recorded on EL FARO's VDR during the early morning hours of October 1, 2015, indicated that the bridge crew was not able to accurately determine the direction or speed of the winds they were encountering because visibility was poor and they did not have a working anemometer.

[197] Full document available at https://msi.nga.mil/NGAPortal/.

7.2.11. Weather

The MBI was unable to accurately determine the weather conditions encountered by the crew on EL FARO at the time the VDR ended at approximately 7:40 AM on October 1, 2015.

The last estimated wind speed was made by the C/M[198] at 6:09 PM on September 30, 2015, when he stated:

> *I'm gonna log it as force six[199] here.*

Throughout the morning of October 1, 2015, crew members on the bridge of EL FARO, including the Master, made statements indicating that they were having trouble assessing weather conditions due to limited visibility. The last known description of sea conditions and a barometer reading were discussed on the bridge as the Master called TOTE's DPA. At 7:10 AM the Master made the following statement while talking on the bridge satellite phone:

> *(The) swell is out the northeast. A solid— solid ten to twelve feet (over) spray high winds very poor visibility that's the best I can give ya right now— I'll give ya barometric pressure.*

The Master then asked the 2/M to provide the barometric pressure and she responded that it was 958.8 millibars (MB). The barometer had been dropping throughout the morning of the accident voyage. At 4:24 AM the C/M reported to the Master that the barometric pressure was at 970 MB. At 4:45 AM, the C/M informed the Master that the pressure had dropped to 960 MB. A short while later at 5:03 AM, the C/M appeared to tell the Master that the level was still at 960 MB when the Master inquired if the barometer was coming back up. At 5:22 AM, the C/M reported to the Master that the barometer was at 950 or 951 MB. That reading, which was the lowest recorded on EL FARO's VDR, placed EL FARO close to the eye of Hurricane Joaquin which had a minimum estimated pressure of 948 MB at the time.

An Air National Guard Hurricane Hunter aircraft extrapolated that minimum central pressure of Hurricane Joaquin was 942 MB at 8:00 AM on October 1, 2015, with maximum sustained winds of 120 MPH and higher gusts. Hurricane force winds were estimated to extend out approximately 35 NM from the center of storm.[200]

7.2.11.1. Development of Hurricane Joaquin

A tropical cyclone was first forecasted as a tropical depression on September 28, and reached maximum intensity on October 3, 2015. A major hurricane is defined as a Category 3 Hurricane or greater, which means 96 knots of wind or greater. The NHC stated that Joaquin was rare in that it achieved major hurricane status after forming in a non-tropical region.[201] The Branch

[198] MBI Exhibit 266, p. 182.
[199] Beaufort Storm Force number defined as a strong breeze which starts to create large waves. White foam crests becoming more extensive and some spray is probable.
[200] NHC Hurricane Joaquin Intermediate Advisory Number 14A.
[201] NHC Tropical Cyclone Report Hurricane Joaquin, Ronnie Berg, January 12, 2016.

Chief of the Hurricane Specialist Unit testified that Joaquin was particularly difficult to predict for several reasons. One of the greatest challenges in accurately predicting Joaquin was a significant divergence in the early model guidance. The NHC Annual Summary[202] for the 2015 Hurricane Seasons describes Hurricane Joaquin in this manner:

> *Joaquin's formation is notable in that the cyclone did not have tropical origins, which is rare for a major hurricane. The incipient disturbance can be traced back to 8 September when a weak mid- to upper-level low developed over the eastern Atlantic Ocean west-southwest of the Canary Islands. A piece of this system moved westward across the Atlantic for over a week, and amplified into a more significant mid- to upper-level low over the central Atlantic northeast of the Leeward Islands on 19 September. This feature continued to move westward for several more days and gradually acquired more vertical depth, with a small but well-defined surface low developing on 26 September about 350 n mi east-northeast of San Salvador Island in the central Bahamas. A tropical depression formed two days later on 28 September.*

A moderate northerly shear at higher elevations made it difficult to reconcile the environmental conditions. As the storm developed, the forecasting models slowly converged and the model guidance began to indicate the initial southwesterly direction of the storm.[203] In MBI testimony the NHC Branch Chief Hurricane Specialist stated: [204]

> *It's rare for storms to take a southward component of motion. It's particularly rare in sort of the heart of hurricane season. That sort of behavior is more common as you get towards the tail end of the season in particular as the genesis areas tend to show up further north. But having that southward motion is unusual. Having a storm strengthen when it's moving southward is even more unusual. Southward moving storms rarely strengthen in the way that we saw with Joaquin.*

EL FARO departed Jacksonville, Florida on the evening of September 29, 2015. The NHC published 42 public forecasts and advisories for tropical cyclone Joaquin, from September 28, through October 8, 2015. The first forecast and advisory, which predicted that Joaquin would develop into a Category 1 hurricane (winds 64 knots or greater), was released to the public at 4:41 PM on September 29, 2015. This forecast predicted that the storm would achieve Category 1 level winds by 2:00 PM on September 30, 2015, and the maximum forecasted 80-knot winds would be observed by 2:00 PM on October 2, 2015.[205] The first forecast and advisory to predict that Joaquin would become a major hurricane was released by the NHC on September 30, 2015, at 10:53 AM. This message predicted that a maximum wind of 100 knots would be observed by 8:00 AM on October 3, 2015. The NHC Branch Chief testified that on September 30 and into October 1, 2015, Hurricane Joaquin underwent a rapid intensification.[206] No more than 12 hours later, the NHC published Public Forecast and Advisory #13, which predicted that the storm

[202] MBI Exhibit 197.
[203] MBI Transcript May 17, 2016, p. 172.
[204] MBI Transcript May 17, 2016, p. 137.
[205] http://www.nhc.noaa.gov/archive/2015/JOAQUIN.shtml.
[206] MBI Transcript May 17, 2016, p. 169.

would rapidly intensify and that it would have winds as great as 110 knots by 8:00 AM on October 1, 2015.[207]

7.2.11.2. National Hurricane Center –Tropical Cyclone Intensity Forecasting

The Branch Chief for the NHC's Hurricane Specialist Unit testified at the MBI that predicting the intensity of Hurricane Joaquin was very difficult due to wind shear. He stated:

> *Wind shear refers to the difference in wind flow in the lower part of the atmosphere relative to the upper part of the atmosphere. So if the winds are blowing in roughly the same direction at roughly the same speed as you go from the bottom of the hurricane to the top, then we say that's a low wind shear environment. If there's high wind shear, then either the wind speed is very different or more commonly the wind direction at the top is blowing very differently than wind direction at the bottom. We know that when there's a lot of wind shear that it's pretty easy to predict the behavior of a tropical cyclone. The thunderstorms get ripped off, the storm becomes shallow, it tends to weaken, it tends to move with the lower layer of flow. We also have a pretty good handle on things when the wind shear is very low. When the wind shear is very low there's an opportunity for the storm to hold together vertically if the moisture is right and the underlying sea surface is right, then you know we can get lots of intensification. The – one of our biggest challenges is trying to sort out what's going to happen at intermediate levels of shear. When you have the thunderstorm activity and the tropical cyclone is trying to keep the storm vertically coherent, wind shear is trying to tear it apart and the forecaster has to decide based on the guidance that he has which of those two competing factors is going to win. And in those situations the – getting the intensity forecast right and getting the track forecast right really go hand-and- hand. If you don't get the intensity right you're probably not going to get the track right because the storm is now going to be steered by a flow at a different layer of the atmosphere. So that was certainly the problem in the first few forecasts for Joaquin where we were expecting very high levels of shear. We expected that the storm was not going to handle that shear very well and basically become very shallow and move off to the West and Northwest in the shallow flow. Joaquin didn't cooperate with that particular line of thinking. It, for whatever reason, and to this day can't really tell you why it did so, but that storm was particularly resistant to the wind shear. Now maybe, we – maybe there was less shear out there than we thought. Or perhaps there was something about the dynamics of that particular storm that allowed it to resist. But that was the basic challenge in trying to figure out how that storm was going to respond to the shear that was being imposed on it. And that affected both the intensity forecast and the track forecast.*

Tropical Cyclone Joaquin developed into a Category 4 Hurricane on the Saffir-Simpson Hurricane Wind Scale on October 3, 2015. The Saffir-Simpson Hurricane Wind Scale uses a description to help people understand the catastrophic damage that will occur; it does not consider damage to vessels or maritime infrastructure.

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[207] MBI Exhibit 153.

4 (major)	130-156 mph 113-136 knots 209-251 km/hr	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

7.2.11.3. Prediction Errors with Hurricane Joaquin

In MBI testimony[208] the NHC Branch Chief for the Hurricane Specialist Unit stated:

The initial forecast for Joaquin had errors that were much larger than normal. So for example the 3 day forecast that would have verified the morning of October 1st had a track error…it was 536 miles. So the 3 day forecast verifying it at 8:00 AM October 1st. That's an extraordinarily large area. That's really about 1 in 100 type of track error. The 48-hour track forecast that verified at the same time had an error of 180 miles and that's something like a 90 or 95th percentile of error. So it's certainly a very large error. By the time one day it was a 62 mile error, the 1 day forecast was verified at 8:00 AM and that's more in line, at least close to what the average was. So the earlier forecast, track forecast had errors that were much larger than normal for us. The same was true with the intensity errors. The 3 day intensity error that verified at that time was 80 knots too low. The 2 day forecast that verified at that time was 60 knots too low. And the 1 day was 30 knots too low. So the forecast called for a relatively weak system, the initial forecast called for a relatively weak system to head off to the west and northwest and this instead it moved west southward and southward and strengthened.

[208] MBI Transcript May 17, 2016, p. 178.

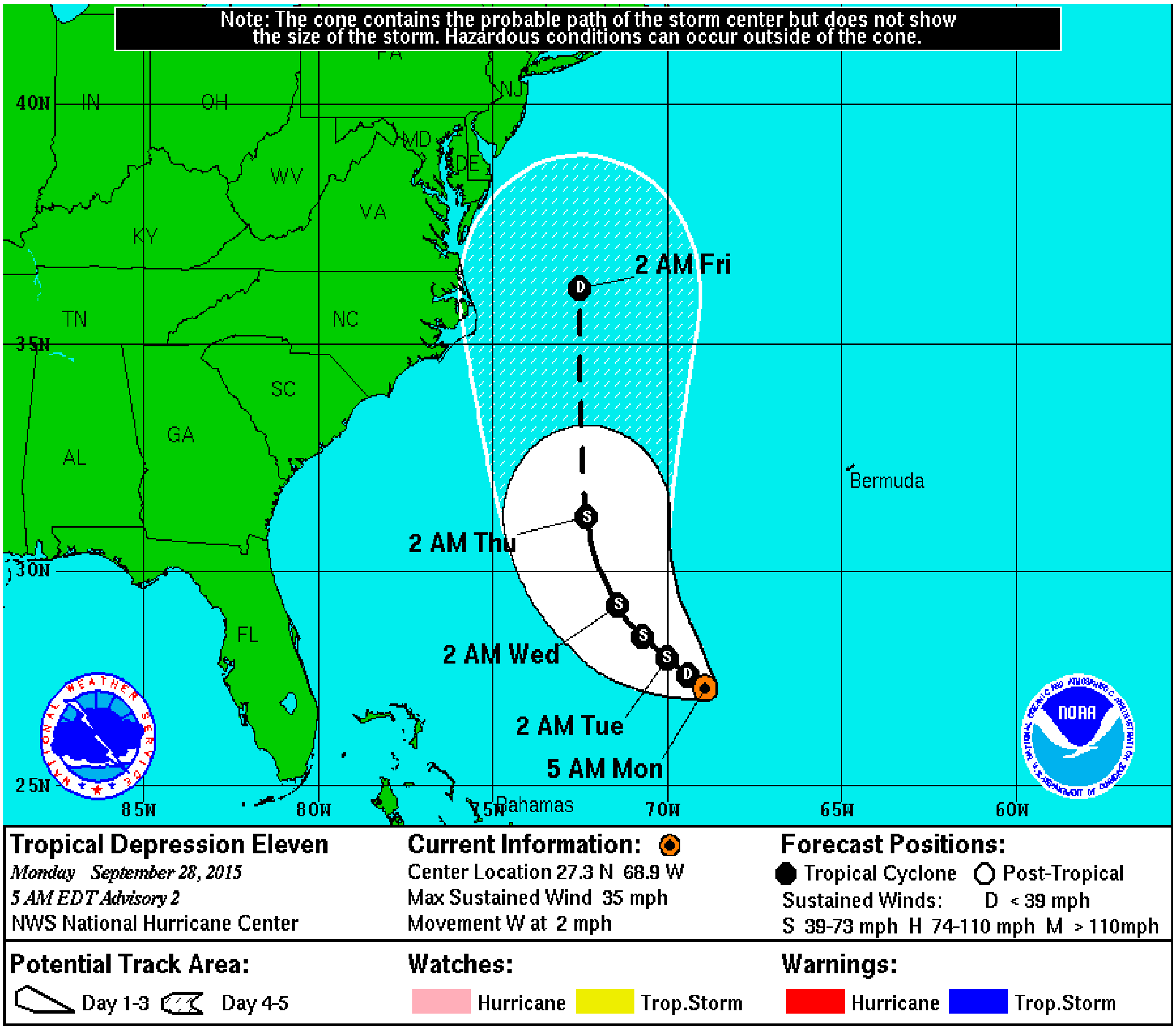

Figure 39. NHC Tropical Depression Eleven 5 AM EDT Advisory 2 with 5-day Cone and Warnings dated September 28, 2015. Early forecasts for the storm that would become Hurricane Joaquin indicated the system would head in a Northwesterly direction. The 2 AM Thu projection of a Tropical Storm off the coast of South Carolina correlates to the morning of the accident voyage (October 1, 2015).

7.2.11.4. Unique Characteristics of Hurricane Joaquin (Storm Quadrants)

Tropical cyclone forecasts are accompanied by quadrants, which indicate the largest expected radii for wind and seas. The quadrants are listed by cardinal[209] or primary intercardinal directions[210] and are meant to cover the graphical areas 45 degrees to either side of the listed direction. For a normal, fully developed hurricane moving in a northerly direction, the quadrants to the right side of the direction of storm movement tend to be larger in range than the left side of the storm. However, for Hurricane Joaquin it was noted that the larger quadrants were depicted on the east side of the storm despite the southwesterly track of the storm. The NHC Hurricane

[209] Cardinal directions include North, East, South and West.
[210] Primary intercardinal directions include Northeast, Southeast, Southwest and Northwest.

Specialist Unit was asked about this in a follow up interview and they stated that Hurricane Joaquin had an unusual asymmetry that resulted in displacement of the wind fields from the southwest. As a result, as the storm progressed on its southwesterly course, the wind fields were forced tighter to the storm on the leading edge, and expanded further out on the trailing edge. Examples of the resulting quadrants are shown below in the graphical overlay of the 11:00 EDT September 30, 2015, forecast and advisory.

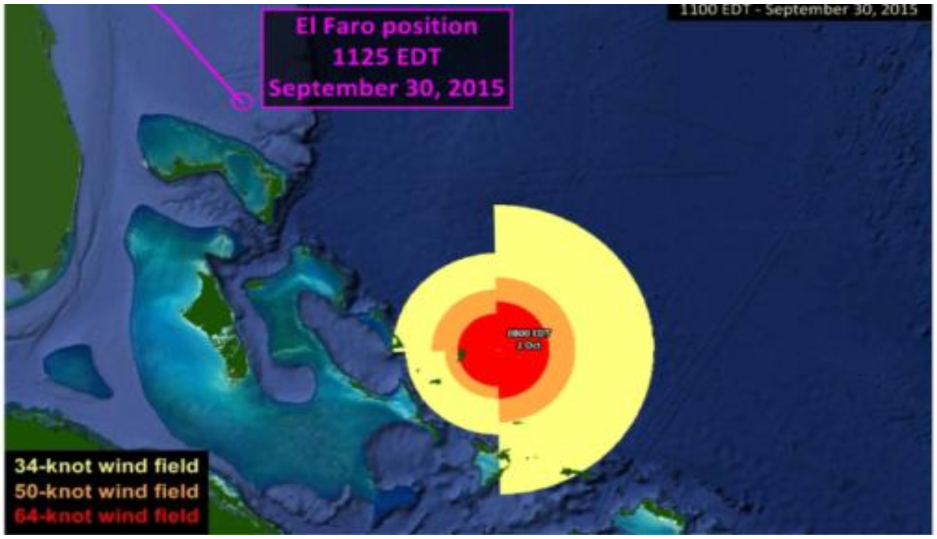

Figure 40. EL FARO position at 1125 EDT September 30, 2015 showing relationship with Hurricane Joaquin wind fields. (Source: NTSB Weather Factual Report)

7.2.11.5. NOAA Weather –Tropical Cyclone Related Products

The NHC, which is a division of the National Weather Service under NOAA, develops several messages specifically for tropical cyclone events. These messages include the Tropical Weather Outlook, Tropical Weather Discussion, Tropical Cyclone Public Advisory, Tropical Cyclone Forecast and Advisory, and Tropical Cyclone Updates. The Tropical Weather Outlook (AWIPS header TWOAT[1-5] for Atlantic systems) is both a textual[211] and graphical product. The textual product provides all the active tropical cyclones and disturbances, along with the probability of formation for the next five days. This product is published at the nominal times of 0000Z, 0600Z, 1200Z and 1800Z.[212]

The Tropical Cyclone Discussion (AWIPS header TCDAT[1-5] for Atlantic systems) provides a free script textual product where the forecaster discusses the reasoning for the forecast and analysis. The Tropical Cyclone Discussion is issued at nominal times of 0300Z, 0900Z, 1500Z, and 2100Z.[213]

[211] A textual product conveys the weather information on the printed page relying on the reader to assess the information.
[212] EDT, which was in effect on October 1, 2015, can be obtained by subtracting 4-hours from the zulu times (e.g., 1200Z converts to 8:00 AM EDT).
[213] MBI Exhibit 152 contains copies of the TCDAT messages released before the sinking of EL FARO.

The Tropical Weather Discussion (TWDAT for the Atlantic systems) describes all the major synoptic weather features and significant areas of disturbance in the tropics. This message provides insight regarding the current state of the atmosphere, expected trends for decision making, significant weather, the meteorologist's reasoning for the forecast, model performance, and, in some cases, degree of confidence. This message is released at nominal times of 0005Z, 0605Z, 1205Z, and 1805Z.[214]

The Tropical Cyclone Public Advisory (AWIPS header TCPAT[1-5] for Atlantic systems) lists all current watches and warnings for a tropical or subtropical cyclone with its position (latitude and longitude), course, speed, max sustained winds, estimated central pressure at the center of the storm, and distance from a selected land point. This message may also include information such as storm tides, rainfall, or tornadoes associated with the cyclone, as well as other pertinent information. The Tropical Weather Discussion is published on a nominal schedule of 0300Z, 0900Z, 1500Z, and 2100Z.[215]

The Tropical Cyclone Forecast and Advisory (AWIPS header TCMAT[1-5] for Atlantic systems) is a text product that contains a list of the watches and warnings for a tropical and sub-tropical cyclone. It contains the storm's current center position (latitude and longitude), course, speed, maximum winds, barometric pressure, and, in some cases, the current diameter of the storm's eye wall. It also provides projected tropical cyclone geographical positions, the maximum wind speed and wind speed probability cones for 34 knot, 50 knot, and 64 knot wind speeds. The NHC publishes a minimum of four Tropical Cyclone Forecast and Advisories each day for tropical cyclones. The nominal release times for those forecast and advisories are 0300Z, 0900Z, 1500Z, and 2100Z.[216]

The NHC also issues intermediate advisories to update a storm's position, course, and speed. Intermediate advisories do not update the complete forecast, so the forecasted track and cone of probability remain unchanged from the previous forecast and advisory. The intermediate advisories are issued at nominal times three hours after the regular forecast and advisory, and they are normally issued when there is a coastal watch or warning in effect.

When there is a change in a Tropical Cyclone, the NHC can issue a corrected forecast and advisory. If the forecaster deems it necessary, they can also issue a Special Forecast and advisory when there is an unexpected significant change in the cyclone. The special forecast and advisory is distinct from the intermediate advisory in that it develops a full suite of forecasts resulting in an updated trackline for a forecasted storm.

The High Seas Forecast (AWIPS header HSFAT[1-2] for the North Atlantic) provides sea state analysis for various regions of the ocean. The High Seas Forecast message that is broadcasted to mariners includes the information presented in both HSFAT1 for the West Atlantic and HSFAT2 for the Tropical Atlantic, so this forecast contained information about Tropical Cyclone Joaquin. For the area east of the Bahamas during this event, a portion of the important information from the High Seas Forecast included current position, course, and speed

[214] MBI Exhibit 155.
[215] MBI Exhibit 162.
[216] NOAA Marine Text Forecasts and Products Listing webpage; http://www.nws.noaa.gov/om/marine/forecast.htm.

of Joaquin; seas; swell direction; and a 24 and 48-hour forecast. The High Seas Forecast, which is made available to mariners, is issued at nominal times of 0430Z, 1030Z, 1630Z, and 2230Z.[217]

The Marine Offshore Waters Forecast (AWIPS header OFFNT3 for the Southwest and Tropical North Atlantic and Caribbean Sea) is a text product describing the winds, seas, and predominant weather events in predefined areas. It also provides a synopsis of significant weather, trends, or expectations. The Marine Offshore Forecast for the Southwest and Tropical North Atlantic and Caribbean Sea is issued at nominal times of 0330Z, 0930Z, 1530Z, and 2130Z.[218] The applicable zones for the area east of Florida are shown below.[219] A condensed version of this weather message is broadcasted as a digital voice recording via High Frequency by Coast Guard.[220]

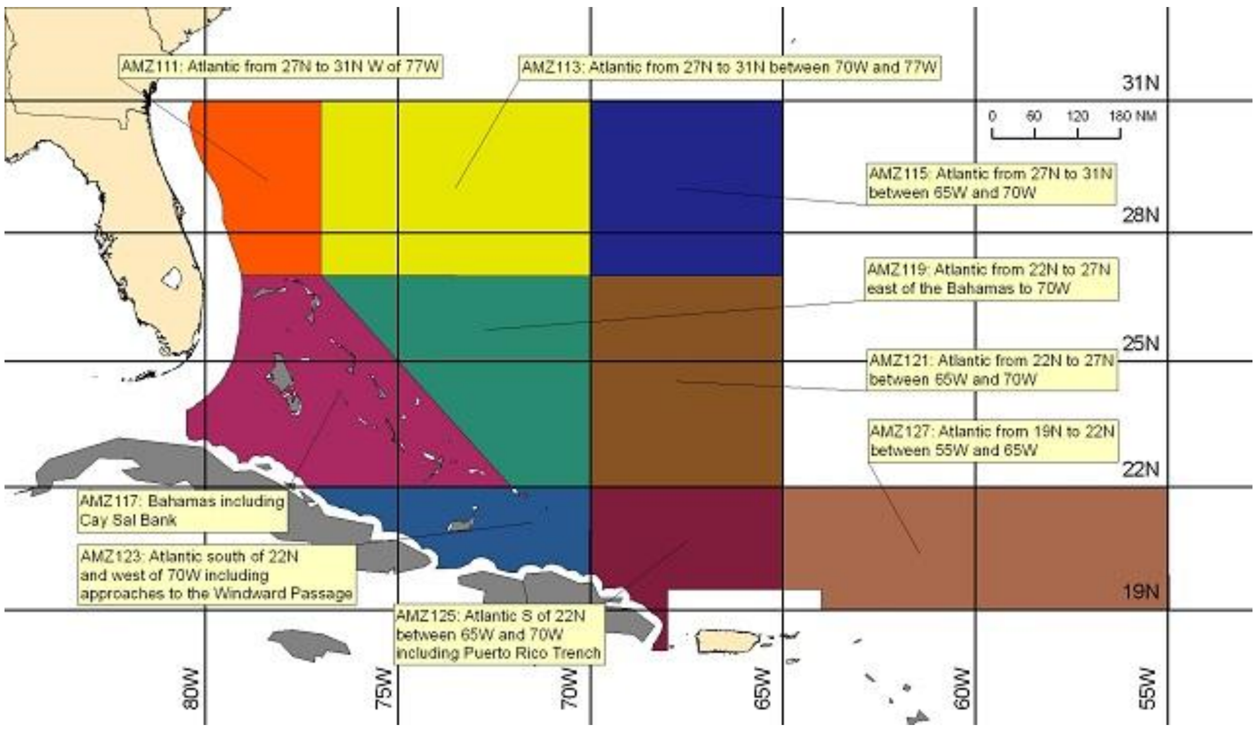

Figure 41. The gridded zones pertaining to each Offshore Waters Forecast area (AWIPS header PWSAT[1-5] for the Atlantic).

The Marine Weather Discussion (AWIPS header MIMATS for the Atlantic and Gulf of Mexico) provides the forecaster a venue to discuss general trends and information on the performance of the models. This message is published online twice daily with nominal release times of 0600Z and 1800Z.[221]

217 MBI Exhibit 151.
218 NOAA Marine Text Forecasts and Products Listing webpage; http://www.nws.noaa.gov/om/marine/forecast.htm.
219 http://www.nws.noaa.gov/om/marine/zone/off/offnt3amz.htm.
220 MBI Exhibit 299.
221 MBI Exhibit 160.

7.2.11.6. Transmittal of Marine Weather Forecasts to Ships

NOAA is the primary federal agency that publishes marine weather forecasts; it uses several means to distribute weather products to mariners. These methods include online weather graphical and textual resources, NOAA near shore very high frequency (VHF) radio, NAVTEX, high frequency voice broadcasts (HF-VOBRA), weather fax, and Inmarsat SafetyNet (also known as Sat-C) messages.

Ships underway can receive NOAA marine weather forecasts, as well as forecasts from a variety of commercially available sources. Some of these sources include satellite television (TV) packages, satellite radio packages, commercial forecasting services, marine weather routing services, and several other services. EL FARO was equipped to receive weather information from Inmarsat Sat-C communications, NAVTEX, HF-VOBRA, weather fax, satellite TV services, satellite radio services, and Inmarsat-C on-demand weather forecasting services.[222] During the ship's port calls, and while transiting close to shore, the ship could use the full range of broadcast media as well as wireless or cellular access to all of the available weather forecasting technology such as the Weather Channel © and Weather Underground©. During EL FARO's accident voyage the Coast Guard had aircraft on patrol over the eastern Bahamas broadcasting information about the developing tropical system and the associated watches and warnings on Ch. 16 VHF- FM. (156.8 MHZ). The Coast Guard aircraft VHF radio broadcast was heard by watch standers on EL FARO's bridge.

The crew of EL FARO utilized Sat-C weather messages, a commercial satellite TV provider, and a commercial weather forecasting service[223] provided by Applied Weather Technology (AWT).[224] AWT provided EL FARO with the Bon Voyage System (BVS).[225] There were also indications that the crew on EL FARO listened to Sirius-XM satellite radio to get updates on the status of Hurricane Joaquin.[226]

7.2.11.6.1. Maritime Safety Information – Inmarsat SafetyNet (Sat-C) Weather Messages

SOLAS approved vessels on international voyages are required to be outfitted with a Global Maritime Distress and Safety System (GMDSS), capable of receiving Maritime Safety Information (MSI). MSI includes priority weather messages related to tropical cyclones. The National Weather Service (NWS), a NOAA Office, has a contract with Satcom Direct Government, Inc. to broadcast certain weather messages to GMDSS Inmarsat capable marine operators. NWS makes some weather messages available to Satcom Direct Government, Inc. which then releases them via a land-earth station.

EL FARO was outfitted with a Furuno type Sat-C terminal to receive GMDSS MSI. This terminal was configured with an audible alarm for priority messages and configured to print priority weather messages automatically on a manufacturer supplied printer. EL FARO is

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222 MBI Exhibit 043, p. 1 and MBI Exhibit 266.
223 MBI Exhibit 266.
224 AWT is now called "StormGeo."
225 MBI Exhibit 268.
226 MBI Exhibit 266.

believed to have been outfitted with the same GMDSS suite as EL YUNQUE, which was outfitted with a FELCOM 15 GMDSS[227] console and Furuno PP-510 heat printer.[228] On EL FARO's VDR the GMDSS alarm and printer could be heard at various times that correlated with the broadcast times of three distinct weather messages. These messages were the Tropical Weather Outlook, Tropical Cyclone Forecast and Advisory, and the High Seas Forecast.[229]

7.2.11.6.2. Weather Messages Not Broadcasted via GMDSS (Available only over the internet)

Several messages that contain information pertinent to tropical cyclones are not released to mariners via Inmarsat. If mariners do not have internet access, they are incapable of receiving all of the messages. Of the messages mentioned in this report, the TCPAT, TCDAT, TWDAT, and the TCUAT are not released via GMDSS alert systems. Intermediate advisories and special forecast and advisories are also not released via GMDSS alert systems. Bandwidth limitations preclude some commercial marine operations from full access to the internet, which limits their ability to receive these additional products in a timely manner. One limited option available is to use NOAA's on-demand, free FTPmail. However, FTPmail requires the user to develop a command script to be sent to a NOAA server which queries the server for the requested message and returns it to the sender. EL FARO did not have full internet service onboard and there was no indication that the crew accessed the additional products available from the NOAA FTP site.

7.2.11.6.3. Commercial Weather Service – Bon Voyage System

EL FARO used the commercially available weather and sea state forecasting provided by AWT. AWT produced BVS, a proprietary graphical interface software system. BVS is designed to provide crews with useful tools to help plan voyage routes, taking into account the predicted oceanographic and atmospheric conditions. This system is graphical and the user can control the number of layers, and thereby the amount of information viewed at one time in the forecast package. Some of these layers include seas, swell, rogue waves, winds, current, barometric pressure, and even piracy warnings. The user can also perform route optimization analysis by configuring BVS with their vessel type, speed, fuel consumption rates, and intended tracklines in order to view potential effects on the ship due to weather.

Former EL FARO crew members testified that they had the BVS system properly installed on the bridge and on the Master's stateroom computer.[230] The system was designed to send weather packages via email on a routine basis. The weather packages were developed by AWT using proprietary forecasting models, WaveWatchIII,[231] and the Global Forecast System (GFS) model. The inputs to their overarching model begin six times a day and it takes approximately nine hours before a completed product is emailed to a customer. If a tropical cyclone forecast and advisory is issued during the run time window, the data taken directly from the NHC will be incorporated into AWT's model while blending the data taken from the NHC tropical cyclone

[227] MBI Exhibit 043, p. 1.
[228] MBI Exhibit 301, p. 1.
[229] MBI Exhibits 266 and 268.
[230] MBI Transcript February 19, 2016, p. 106.
[231] WaveWatchIII is a wave prediction model developed and maintained by National Centers for Environmental Prediction office of NOAA.

forecast and advisory. The end product in that instance would be the atmospheric and oceanographic forecasts generated from AWT's model, with the information from the NHC forecast and advisory overlaid so the mariner has a graphical means to interpret the current conditions.

AWT recommended that their users, at a minimum, request weather packages at nominal release times of 0300Z, 0900Z, 1500Z, and 2100Z. Due to the processing time, the recommended delivery schedule caused users to receive their weather product with the overlay of the NHC forecast and advisory from the previous nominal release time six hours prior. For example, if a mariner used the recommended delivery time and received a weather package at 0900Z, they would actually be viewing the 0300Z NHC forecast and advisory even though NHC was set to release its next forecast and advisory at 0900Z. If a mariner wanted to get the updated track, the BVS program had a set up option available to receive "Tropical Updates." If that option was selected at set up, AWT sent a follow up weather package normally within an hour of the NHC's newest forecast and advisory to update the mariner's graphical overlay. This updated weather package does not change the oceanographic or atmospheric model data provided in the previous weather package, but it does update the tropical cyclone overlay data. MBI testimony from several TOTE officials and crew members revealed that EL FARO did not have the Tropical Updates active on its BVS.

AWT provided the Coast Guard with copies of the data files that were transmitted to EL FARO for the days leading up to the incident, including copies of the Tropical Updates that could have been made available to EL FARO if they had selected that option during the system's initial setup. The AIS trackline for EL FARO was replicated into the BVS software and used to examine the forecasted weather as EL FARO transited along its accident voyage trackline.[232] Below are several screenshots from BVS. For each, the approximate location of the ship around the time of product dissemination is noted with a ship's symbol, the AIS trackline of EL FARO is shown, and the forecasted trackline of Joaquin is shown.

[232] MBI Exhibit 172.

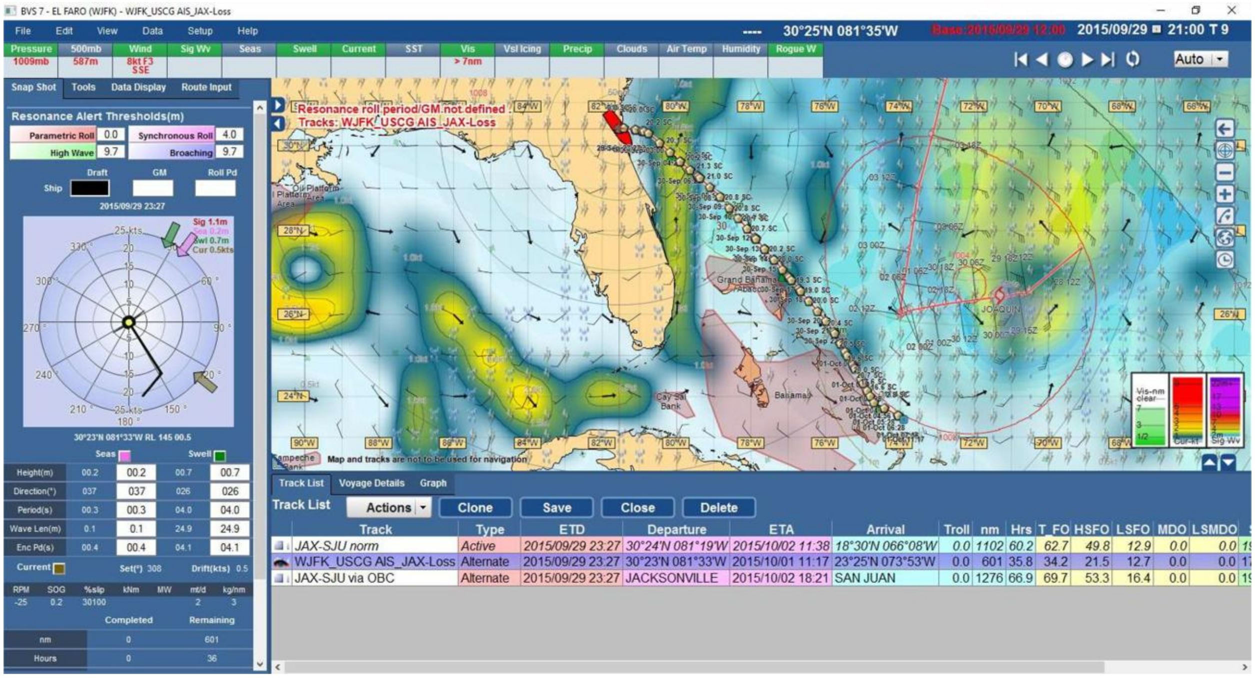

Figure 42. BVS weather package transmitted to EL FARO at 5:04 PM and downloaded at 6:37 PM on September 29, 2015.

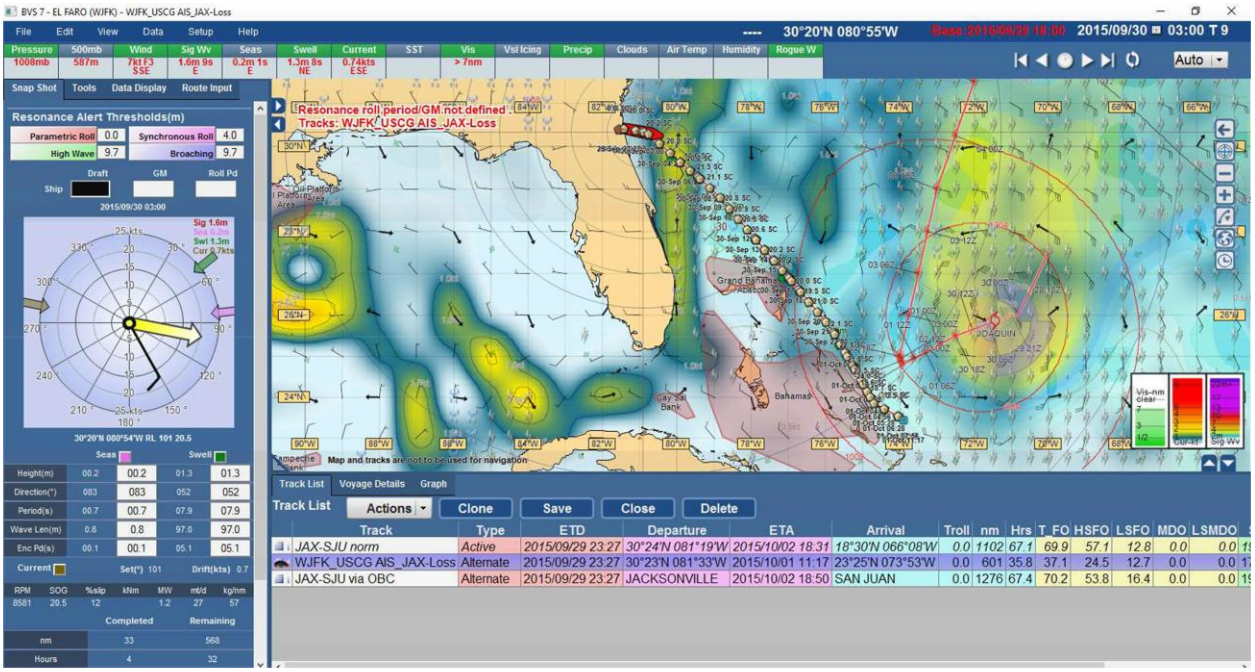

Figure 43. BVS weather package transmitted to EL FARO at 11:04 PM and downloaded at 11:29 PM on September 29, 2015.

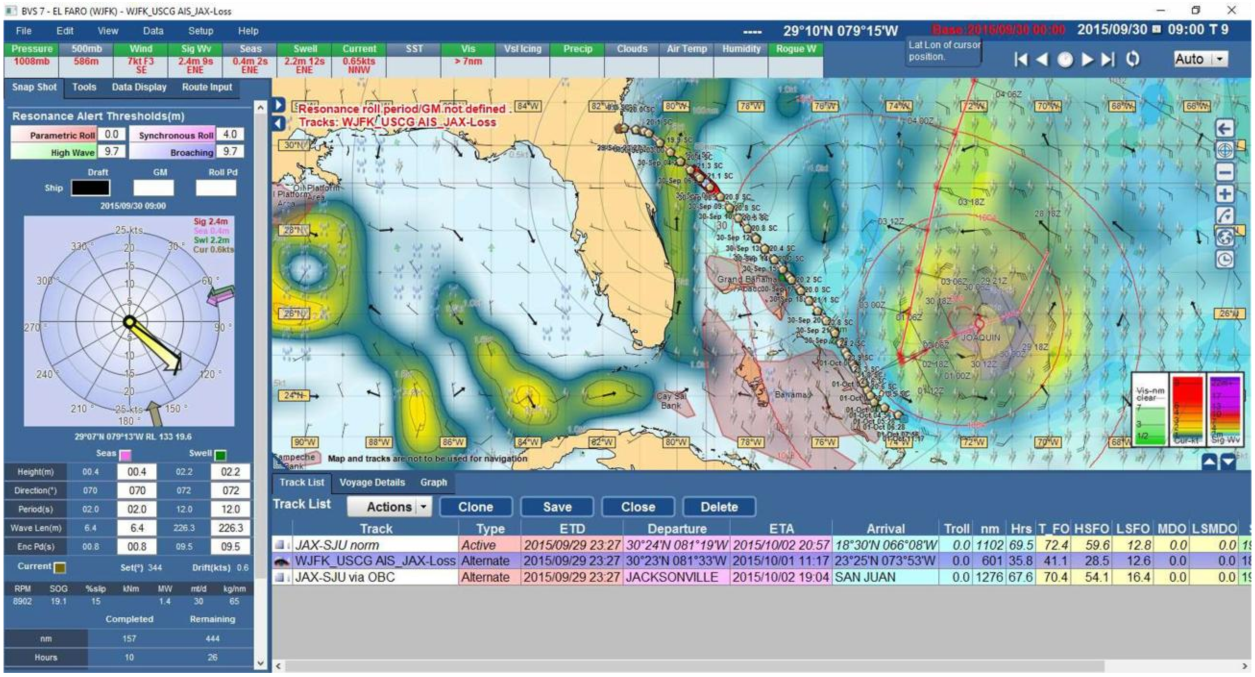

Figure 44. BVS weather package transmitted to EL FARO at 5:04 AM and downloaded at 6:08 AM on September 30, 2015.

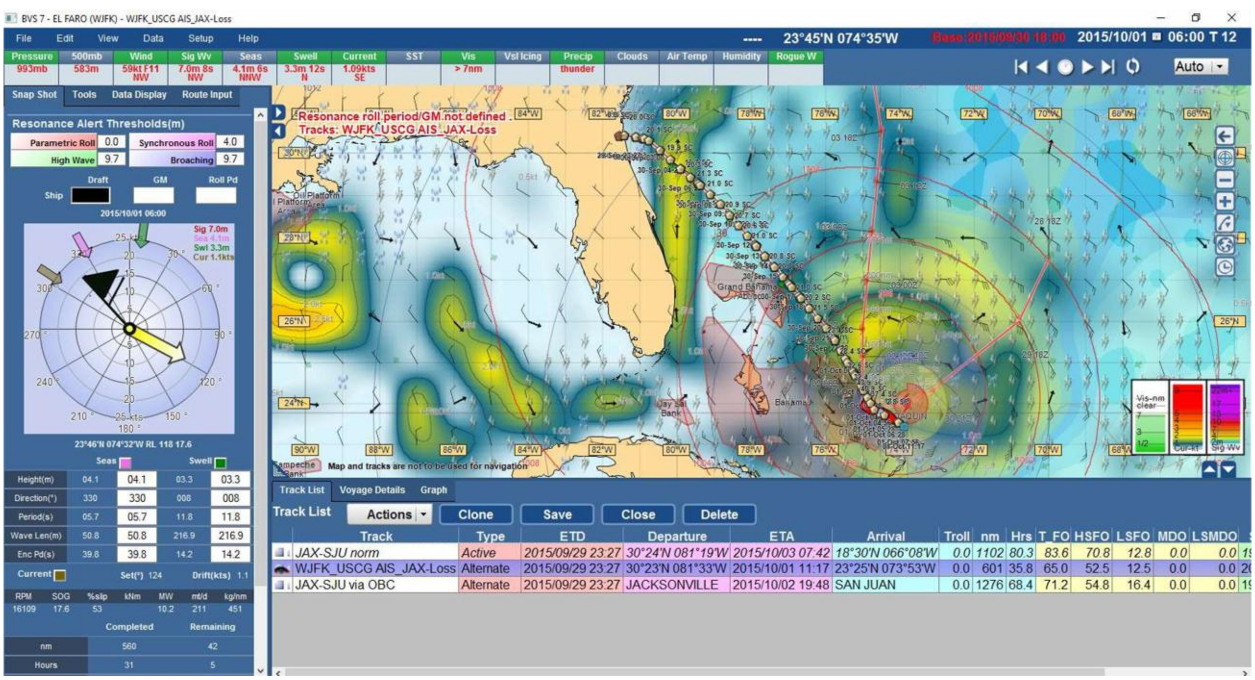

Figure 45. BVS weather package transmitted to EL FARO at 11:04 PM on September 30, 2015, and downloaded at 4:45 AM on October 1, 2015.

During the testimony from AWT, it was discovered that there was an error in one weather package sent on September 30, 2015. The message sent at about 0900Z (5:00 AM EDT) contained the same NHC forecast and advisory overlaid from the previous weather package sent at 0300Z (11:00 PM EDT) on September 29, 2015. The 0300Z weather package contained the

NHC forecast and advisory information published at the nominal time of 2100Z on September 29, 2015. This error meant that the 0900Z BVS weather package that was sent to EL FARO on September 30, 2015, still contained the NHC forecast and advisory from 12 hours prior. However, the 0900Z weather forecast with the duplicate NHC forecast did include properly updated oceanographic and atmospheric model data generated by AWT.[233] The repeated hurricane forecast that was replicated in the error can be seen in the graphics above.

Beginning at about 6:14 AM on September 30, 2015, the C/M and Master discussed the weather and potentially altering EL FARO's trackline.[234] The route chosen provided two waypoints, waypoints "Alpha" and "Bravo." The resulting trackline was then entered into BVS. The BVS screenshot below shows the new route with the weather forecast that was downloaded at 6:08 AM on September 30, 2015. This was the BVS forecast data package that was available to the Master and C/M at the time they were choosing waypoints "Alpha" and "Bravo." The Tropical Cyclone forecasted track depicted in this package delivered to EL FARO is the duplicate report showing the NHC's forecast from 5:00 PM on September 29, 2015.

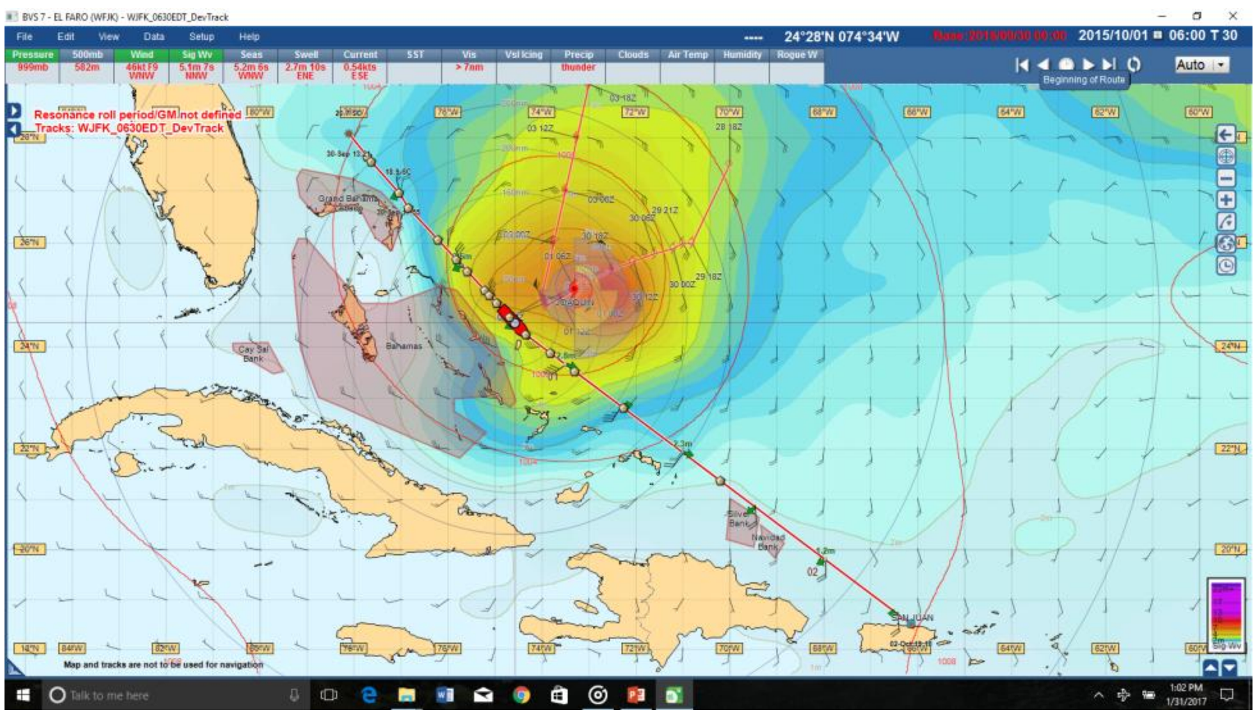

Figure 46. BVS screenshot of EL FARO's adjusted route along with the weather forecast downloaded at 6:08 AM on September 30, 2015.

7.2.11.6.4. <u>Marine Weather Radio Broadcasts: Coast Guard Fixed Wing Aircraft</u>

At 2:14 PM[235] on September 30, 2015, the bridge crew heard this message from a Coast Guard patrol aircraft, tail number CG-2310:

233 MBI Transcript May 19, 2016, p. 10.
234 MBI Exhibit 266, pp. 19-30.
235 MBI Exhibit 266, p. 129.

> *Sécurité. Sécurité. Sécurité. * * * The National Hurricane Center has issued a hurricane warning for the central Bahamas including Cat Island– Exuma– Long Island– Rum Cay– San Salvador. The National Hurricane Center has issued a hurricane watch for northwestern Bahamas including the Abaco– the (Canary) Islands– Bimini– (Elliotbrook)– Grand Bahama Island and New Providence. The Coast Guard requests all * mariners use extreme caution for * *. The United States Coast Guard aircraft standing by on channel sixteen.*

At 2:38 PM, there was another broadcast picked up on the VHF radio on EL FARO's bridge that was similar to the previous broadcast. Due to the nature of the storm, a decision was made by the Coast Guard to have its fixed wing patrol aircraft make broadcasts regarding Joaquin on its flight track. During the flight, five vessels responded to the aircraft sécurité asking for additional information regarding the call outs about Joaquin. EL FARO was not one of the five vessels.

7.2.11.6.5. Marine Weather Message Radio Broadcasts: Coast Guard Communications Command

The Coast Guard has a Memorandum of Understanding (MOU) with NOAA to disseminate certain weather messages via various Coast Guard radio broadcast systems. The MOU is managed by a joint-agency working group which is referred to as UNCLOG.[236] NOAA and the Coast Guard have UNCLOG meetings quarterly where they discuss improvements or changes in weather dissemination. The Coast Guard unit responsible for releasing these messages for the Atlantic Area and Gulf of Mexico (except for Puerto Rico), is Coast Guard Communications Command (COMMCOM). These communications include NAVTEX, high-frequency voice broadcast (HF-VOBRA), high-frequency simplex teletype over radio (HF-SITOR), and weather fax. On behalf of NOAA, the Coast Guard broadcasts the offshore forecast and advisory, high seas forecast, tropical cyclone forecast and advisory, the tropical weather outlook, and weather faxes.

Prior to the summer of 2015, NOAA sent their weather messages directly to the Coast Guard. In the summer of 2015, NOAA could no longer access the Coast Guard's messaging system because the Coast Guard shifted to Command and Control Official Information Exchange (C2OIX) messages to align with the Department of Defense (DOD) policies. As a result, NOAA lost the ability to send their weather messages directly to the Coast Guard for transmission. To remedy this, the Coast Guard established an agreement with the Navy Fleet Weather Center (FWC-N) in which the Navy would access NOAA PORTS,[237] download the NOAA weather messages, and forward them to the Coast Guard for dissemination. This agreement was in effect during EL FARO's accident voyage.

When the Coast Guard receives the forwarded weather messages from the Navy, they are input into an automated distribution system. Any messages that will be voice broadcast are automatically converted into a digitized voice product. The messages are then queued for

[236] USCG-NOAA/NWS Coordination Liaison Group.
[237] Physical Oceanographic Real-Time System (PORTS) is a system managed by National Ocean Service office of NOAA designed to promote navigation safety by providing real-time tide, current and forecast data.

broadcast from a pre-designated antenna on shore. In the Atlantic, the Coast Guard has antennae in Boston, MA; Chesapeake, VA; Charleston, SC; Miami, FL; New Orleans, LA; and San Juan, PR. The high seas forecast, tropical cyclone forecast and advisory messages, and the tropical weather outlook are only scheduled to be broadcasted as HF-VOBRA messages from Chesapeake, VA and New Orleans, LA. The Offshore Forecast for sea area 20 (OFFN20) was broadcast as a NAVTEX message from Miami, FL and it also contained some limited information about tropical cyclone Joaquin. The OFFN20 is a condensed radio broadcast version of OFFNT3 (Marine Offshore Waters Forecast) with the same coverage zone as shown previously.

Coast Guard COMMCOM electronic logs of message release times are only required, per Coast Guard policy, to be maintained for 30 days, the logs are then deleted. The MBI contacted COMMCOM after the 30-day window, and therefore, many of the weather message logs were no longer available. COMMCOM did find an archived image[238] of their log client server record for September 30, and October 1; 19 weather messages could not be verified as sent and 2 weather messages were logged as having been missed. Of these messages, 11 messages contained information about tropical cyclone Joaquin. During MBI testimony, COMMCOM's Commanding Officer stated that the unit was running a Continuity of Operations (COOP) exercise[239] during the dates being reviewed. During this COOP exercise, they transferred control of their antenna to a server located in Pt. Reyes, CA. As a result, there was no way to determine if these messages were actually missed transmissions. Other messages that were grouped in these missing messages were sent and recorded during these periods when the COOP exercise occurred.[240]

COMMCOM does not maintain an exact schedule of when a particular weather broadcast will be delivered. COMMCOM did have a schedule showing which time windows each message was intended to be sent; however, the schedule was not made widely available to the public. According to testimony, mariners may access some information about when these messages are scheduled for broadcast from NOAA websites,[241] through Coast Guard NAVCEN's website,[242] or Nautical Pub No. 117.[243] However, the two-page compressed COMMCOM schedule that shows the entire broadcast schedule along with frequencies and windows of broadcasts was not available for public download.

There was no evidence on the VDR that the crew of EL FARO made attempts to receive COMMCOM's high frequency radio messages.[244] During MBI testimony, a former EL FARO Master stated that he did not use EL FARO's high frequency radio to receive COMMCOM broadcasts during his time on the vessel.

[238] MBI Exhibit 300.
[239] A COOP exercise tests the readiness of Coast Guard units to withstand the interruption of normal operations due to natural disaster or similar threat.
[240] MBI Transcript February 07, 2017, p. 314. CDR Crider was not the Commanding Officer assigned to COMMCOM on the date of the accident.
[241] http://www.nws.noaa.gov/om/marine/hfvoice.htm.
[242] https://www.navcen.uscg.gov/?pageName=mtMsi.
[243] NGA Publication No. 117, Radio Navigational Aids, 2014 Edition.
[244] MBI Exhibit 266.

7.2.11.6.6. EL FARO Shipboard Weather Measurement Devices

EL FARO was fitted with weather measurement instruments, including a digital and an analog recording barometer. Crew members mentioned barometric readings in millibars several times on the VDR. There was also an anemometer to measure wind speed and direction, but it was not properly functioning in the time period leading up to and including the accident voyage.[245]

The Master gave the following response to the C/M on September 30, 2015, after being asked if the anemometer wind velocity reading could be used:

I wouldn't trust it.

After being questioned about the wind speed at 5:10 AM on October 1, 2015, the Master responded with the following statement:

We don't know. We don't have (any) anemometer.[246]

During MBI testimony, a former EL FARO 2/M who served on EL FARO during the summer of 2015 stated that the vessel's only anemometer was not working when he was onboard. When asked for how long, he replied:

I want to say 2 to 3 months, maybe longer because I was on vacation for a while. But at least 2 to 3 months.

EL FARO's radars could be used to monitor sea and swell conditions as well as cloud and rain patterns. However, the only evidence the MBI could find indicating that the crew may have used the radar to monitor the storm was a brief exchange on the bridge of EL FARO at 3:27 AM on October 1, 2015, when the AB made the following statements:

Think there's something (ahead/out there).

Look at that radar.

It's just getting' bigger— our path is going right through it.

7.2.11.6.7. NOAA Voluntary Observing Ship (VOS) Program

The mission of the VOS program[247] is to collect and disseminate critical real-time maritime weather observations through the recruitment and support of ships. This fulfills national needs and international agreements supporting commerce, forecasts and warning programs, and the

[245] MBI Exhibit 301 lists under bridge equipment lists a "Wind Tracker" (anemometer) identified as manufactured by Young. R.M. Young. Young manufactures various models of "wind monitors" which measure the speed and direction of the wind.
[246] MBI Exhibit 266, p. 398.
[247] NOAA Voluntary Observing Ship (VOS) Program Internet Site.

safety of life at sea worldwide. Further, it is designed to help define the global climate and help measure extreme weather events, climate variability, and long-term climate changes.

VOS operates at no cost to participating vessels; NWS pays communication charges, observing equipment, and reporting supplies.

During a tropical cyclone, NOAA asks ships that transit within 300 miles of the movement of the storm's eye to make 3 hourly reports under the VOS Program. While it is not encouraged to be within 300 miles, the in situ data points are highly valuable in validating the forecast products. Ships in close proximity to tropical cyclones are able to provide validation for the NHC products being developed as the ships are able to make timely weather observations and then transmit them to NOAA.

EL FARO participated in the VOS program. Onboard EL FARO, as well as most participating vessels, the process required a bridge officer to draft a special formatted message for release to NOAA using the vessel's email server. In order to facilitate the process, NOAA Port Meteorological Officers provide training to crews upon request, and provide a computer program[248] that facilitates the formatting of the message. Once in the program, the officer filing the observation would follow the step-by-step instructions by making weather observations and looking at the computer program to come up with the appropriate answers. The observer would look at wind speed and direction, swell height, sea state, barometric tendency, cloud cover and other information. Although EL FARO was outfitted with an anemometer, the observations filed by EL FARO's crew during 2015 voyages generally noted that wind direction and speed were given as estimates instead of recorded measurements. The NTSB Factual Weather Report makes the following statement:

> *The NWS provided metadata on anemometer installations and wind reporting practices for all ships (active and inactive) in the US VOS Program database (current as of October 12, 2016). With regard to wind observing practice, approximately 99 percent of the vessels in the database (who did not have a "NULL" indicator for wind observing practice) were identified as using anemometers rather than visual estimation techniques for assessing the wind information they provide in ship reports.*

In July, August and September of 2015, there was a decrease in EL FARO's participation in the VOS program, only one report was filed for the month of September. On the accident voyage, the 2/M made the observation and prepared a VOS report on her watch. At 2:16 PM[249] on September 30, 2015, the 2/M made the following statement about her VOS report:

> *I sent a weather report I hope it works 'cause I've never had to do it before. Oh but it's for fourteen hundred and eighteen hundred weather report. Uh (send as) an email (I guess) * *.*

The Master then responded to the 2/M that she should email it out.

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[248] TurboWin/AMVER software, publically accessible at http://www.vos.noaa.gov/turbowin_amver.shtml.
[249] MBI Exhibit 266, p. 130.

Upon receipt of EL FARO's weather observation report on the afternoon of September 30, 2015, the NWS forecasters discounted it because the ship's geographic coordinates contained in the message placed EL FARO over the mainland of Cuba.[250] This error in EL FARO's latitude and longitude made the observations unusable.

During MBI testimony the NHC's Hurricane Specialist Unit Branch Chief provided the following statement when asked if he could monitor vessels on the high seas:[251]

> *We see ship observations plotted on our display. So if a ship is reporting an observation we will see that. If a ship is not reporting weather observations then I think it's extremely unlikely that any of the hurricane forecasters would know about it.*

When asked about seeing vessels on the NHC display in close proximity to Hurricane Joaquin, he stated:

> *I have no recollection of seeing any. The forecasters who worked on shift might, but I don't.*

7.2.12. Safety Culture

7.2.12.1. TSI Quarterly Safety Meetings

TSI held corporate safety meetings on a quarterly basis; this practice was in place in 2015.[252] Each quarter a safety newsletter was produced and the corporate meeting required that a sign-in sheet be filled out by the attendees. A review of these sign-in sheets found that while P/Es and senior officers from other TOTE vessels participated in the quarterly meetings, none of the P/Es or crew members from EL FARO or EL YUNQUE called into or participated.

The TOTE Newsletter lists the following examples under the category of "incidents" for the period that was reviewed: anchor brake, flooding, oil spill and loss of containments.

7.2.12.2. The Designated Person Ashore

The Manager of Safety and Operations served as the TSI DPA, and in that capacity he had a direct line of communication to the TSI President. The DPA was responsible for an overall fleet of approximately 25 vessels. This included 14 active vessels and 10 vessels in a ready status which were not active. Although the Director of Safety and Services was designated the alternate DPA, TOTE expected the DPA to be responsible and on duty at all times. There was no evidence presented to indicate that the alternate DPA had been utilized to fill in for the DPA when the DPA was not in the office. The DPA's emergency telephone contact number was clearly identified onboard EL FARO and the 24-hour phone numbers and the backup phone number to the Emergency Call Center were posted in numerous locations onboard the vessel.

[250] MBI Exhibit 277.
[251] MBI Transcript May 17, 2016, p. 193.
[252] MBI Exhibit 061.

In February 2014, TOTE brought in a new Manager of Safety and Operations and DPA to work out of the Jacksonville TSI offices. The previous Manager of Safety and Operations/DPA left TOTE in May 2014. As part of the transition, the departing DPA prepared detailed turnover notes. These notes[253] contained job aids, best practices, and procedures, some of which were in the form of decision matrices. One of these decision matrices detailed the procedures for *Routine Daily Duties.*[254] That matrix or flow chart showed the processes related to vessel operations and the tracking of vessel movements.

The DPA job description is contained in the OMV:[255]

> *2.2.2 DESIGNATED PERSON*
>
> *The concept of a "designated person" is intended to provide the shipboard crew an additional option to express a safety concern if he/she is of the opinion that an unsafe condition or practice is not being satisfactorily addressed within the shipboard chain of command in a timely manner.*
>
> *In order to implement and monitor the ISM program, to ensure the safe operation of TSI's fleet and to provide a link between the company and the vessel, TSI has designated the Manager, Safety & Operations as the ISM Designated Person. His/her responsibilities and authority include monitoring of the safe operation and environmental protection aspects of the operation of TSI's fleet and that adequate resources and shore side support are applied.*
>
> *He/she has direct access to the President who represents the Executive Group. When performing as ISM Designated person, he/she shall act independently from other assigned responsibilities. The name and telephone number of the ISM Designated Person shall be posted in a relevant location selected by the Master. The post up should include the statement found in this section.*
>
> *Home and emergency contact numbers are located in OMV Section 11.6.*
>
> ***SHOULD A CONFLICT OF INTEREST OCCUR WITH THE DESIGNATED PERSON'S RESPONSIBILITIES WITHIN THE COMPANY, OR THE MASTER DEEMS THE ISM DESIGNATED PERSON TO BE NON-RESPONSIVE, THE MASTER HAS THE AUTHORITY TO CONTACT THE TSI VICE PRESIDENT/GEN. MGR., WHO UPON BEING CONTACTED WILL ASSUME ISM DESIGNATED PERSON RESPONSIBILITIES.***

MBI testimony from a former EL FARO crew member indicated that there was reluctance on the part of the TOTE vessel crew members to contact the DPA because of a general perception that raising issues could result in retaliatory action by TOTE. [256] While at sea, EL FARO crew

[253] MBI Exhibit 471.
[254] MBI Exhibit 417.
[255] MBI Exhibit 025, pp. 27-28.
[256] MBI Transcript February 14, 2017, p. 176.

members did not have the ability to anonymously communicate with the DPA. Confidential communications could only take place in proximity to shore using a crew member's personal cell phone or other communication device. When a vessel was at sea out of cell tower range, crew members would have to use satellite email or the vessel's satellite phone which was located on the bridge. In order to use the satellite phone, the crew would have to ask the Master for permission. Communications made on the ship's email equipment were not private and an Inmarsat email sent to the DPA from the ship could be reviewed by the Master in the ship's email server prior to release. The Master released the Inmarsat emails to shore in a batch, which could delay the delivery of an email that was drafted by a crew member voicing an urgent safety concern.

7.2.12.3. <u>Safety and Operations Department</u>

A partial list of the duties for the Manager of the Safety and Operations is listed below:

> *Coordinates with Marine Personnel Department to insure the assignment of properly licensed and capable individuals to man the vessels. Evaluates deck officers assigned to TSI fleet.*
>
> *Conduct shipboard security and safety assessments as necessary to meet SMS and regulatory obligations. Identifies risks to personnel, the environment and the ships and recommends corrective actions to sr. mgt.*
>
> *Participate in the investigation of accidents and injurers* [sic] *and cooperates in the preparation of material and evidence for organization use in hearings, lawsuits, and insurance investigations.*
>
> *SUPERVISORY RESPONSIBILITIES:*
>
> *Manage officers on managed fleet who supervise a total of 250 or more seagoing personnel on the active vessels. Is responsible for the overall direction, coordination, and evaluation of this unit.*[257]

The Manager of Safety and Operations did not evaluate EL FARO's Master or deck officers who were on board for the accident voyage. Neither he, nor TOTE, identified adverse weather as a potential risk to TSI vessels.

The Manager of the Safety and Operations, who was also the DPA at the time of the accident, had previously held a Merchant Mariner Credential as a Master of Steam or Motor Vessels of Any Gross Tons Upon Oceans, and was issued a Continuity Credential in July 2015.

The Safety Department sent out periodic Safety Alerts and Operations Memos to the fleet. The Operations Memos were described as interim notifications of important content that would eventually be incorporated as updates to the SMS.[258] Once the content of the Operations Memo

[257] MBI Exhibit 006, pp. 18-20.
[258] MBI Transcript February 17, 2016, p. 27.

was incorporated into either the OMV or the EPMV, the Operations Memo would be cancelled. The Safety Department also created Safety Alerts to disseminate critical information to TOTE vessels and crew.

An example of this alert is Safety Alert 15-008 (Hurricane Danny), which advised TOTE vessels about the formation of Hurricane Danny. The Alert also advised *ships in all oceans to review their vessel specific heavy weather procedures.* [259]

EL FARO had no vessel specific heavy weather procedure, plan, or checklist.

7.2.12.4. Internal Audits

Internal safety audits were a component of the TOTE SMS and an internal audit was performed on EL FARO on an annual basis. Audits were announced in advance and a list of items to be audited was also provided in advance. The audits normally occurred during cargo operations, there were no recent audits performed while the vessel was underway. There was no TOTE requirement to conduct audits to assess crew's proficiency while a ship was at sea conducting operations. The last internal audit for EL FARO took place on March 4, 2015.[260] A significant focus of the audit involved reviewing paperwork. A security audit was also performed at the same time. The Safety Manager signed the internal audit report for the last audit on June 4, 2015. There were no significant findings noted in relation to the actual operation of the vessel. The audit report did not indicate whether STCW rest records, medical logs, officer or crew evaluations, or other logs and records were examined and validated to determine the effectiveness of operations. For example, there was no record to show that an examination of the STCW rest records was completed in conjunction with a comparison to ship's logs, overtime, and payroll records to determine the accuracy of the crew's documentation of their required rest periods.

7.2.12.5. Determination and Notification of Safety Issues by TOTE

The TOTE OMV[261] states:

> *NEAR MISS REPORTING*
>
> *A "Near Miss" is defined by the IMO as "a sequence of events and/or conditions that could have resulted in loss. This loss was prevented by a fortuitous break in the causal chain of events and/or conditions."*
>
> *The ultimate objective of near miss reporting and investigating is to identify areas of concern and implement appropriate corrective actions to avoid future losses. To do so, requires that reports are generated, shared, read and acted upon.*

[259] MBI Exhibit 045.
[260] MBI Exhibit 311.
[261] MBI Exhibit 025, pp. 187-188.

The reporting of a "Near Miss" may result, depending on potential severity of the incident or the materials involved, in the issuance of a Corrective Action Response. TSI is trying to learn from those incidents where a safety or mechanical issue is discovered and an incident averted. Near misses are not viewed by TSI as poor performance. Rather they are viewed as a necessary part of a functional and working QMS.

The sharing of the experience gained from "near misses" is critical. The on board safety committee shall review "near-misses" as they occur using the TSI form [TSI-V-SAF-027]. The Master (or person in charge of the vessel), shall forward the report to TSI Safety & Operations Dept by e-mail. TSI will review and disseminate to all appropriate vessels and related parties.

The OMV also contained the following direction:

The scope of near miss reporting is unlimited. All phases of vessel operation will be part of the near miss reporting concept. Some areas of special concern would include the following:

- *Mooring operations* • *Bunkering operations*
- *Cargo operations* • *Shipyard periods*
- *Navigation of the vessel* • *Heavy weather precautions*
- *Critical operations* • *Port arrivals/departures*
- *Maneuvering* • *Storing operations*
- *Underway repairs* • *Confined Space entry*

An ergonomic fix should also be reported as a near miss. If your vessel has discovered an actual or potential hazard and a way to eliminate this hazard through an adaptation or minor modification, the 'fix' should be shared with the other vessels in the fleet.

During the MBI, senior TOTE officials testified that the Master of EL FARO had the overall responsibility for the safe loading and securing of cargo on the ship. There was no evidence presented to indicate that anyone else provided safety oversight of the actual terminal-to-ship operations. In mid-September 2015, there was as incident where the Master of EL FARO stopped the loading of the ship due to an excessive list that developed while loading. The C/M onboard at the time sent an email containing the following observation:

Over the past few weeks the Captain and I have routinely needed to advise the SJU ops team of the vessels list and insist that steps be taken to remedy the problem….. An excessive list creates many large risks for the vessel and her equipment.

During this incident the Master stopped cargo and performed a root cause analysis investigation to identify the causes of the problem. Both terminals were notified as well as management executives in TMPR. The Manager of Safety and Operations and TSI management were not notified of this safety related issue that involved the interaction between EL FARO and the San Juan terminal. Another excessive list incident due to improper cargo loading operations occurred in Jacksonville on September 29, 2015, as EL FARO was loading for the accident voyage. In this second incident, there was no record of the Master stopping cargo. While the TOTE OMV discusses "excessive list," there are no specific procedures or checklists offering guidance on evaluating the safety impacts the excessive list might have on the vessel, dock side equipment (e.g., mooring appliances, loading ramps), or cargo.

During the summer of 2015, EL FARO was provided with Port Mates (P/Ms) to assist the ships' officers with cargo operations and other duties while in port. After September 1, 2015, TOTE stopped providing P/Ms to EL FARO in Jacksonville. TSI's Manager of Safety and Operations testified at the MBI that he was not aware of discussions about the absence of the P/Ms or what TOTE was doing, if anything, to get P/Ms back aboard EL FARO. Safety personnel were not involved in any discussions related to the absence of P/Ms for EL FARO.[262]

The assessment of an incident, near miss, or accident, was a duty of the Manager of Safety and Operations, as outlined in the SMS for TSI. This responsibility was shared with the Master of a TOTE ship. The EPMV made the following statement in Section 10.1:

> *GENERAL*
> *It is the responsibility of the vessel senior officers to ensure that accidents and incidents are thoroughly investigated and documented. This section is provided to assist the on board investigator with the process.*
>
> *It must also be noted that investigation of accidents and incidents involving non-crew members must be pursued with equal vigor. This includes passengers, contractors, guests, and longshoremen.*

During late 2014, an EL FARO C/M (not present on the accident voyage) was found sleeping on watch at sea on multiple occasions. Two different EL FARO Masters caught the individual sleeping on watch. However, the Masters did not make notifications to shore side labor relations or safety department personnel when the problem was detected. In mid-July 2015 almost nine months after the issue was initially identified, a notification was made to the DPA via an anonymous text message,[263] which included crew member commentary and photos. The person who contacted the DPA indicated that the issue was serious and that they intended to notify the Coast Guard. The DPA notified the TSI's VP of Operations. After a preliminary discussion, TOTE management decided that the matter would be handled by the human resources department,[264] and the issue was classed as a human resource problem. The DPA stated in MBI testimony that he believed that Labor Relations conducted an investigation.

The EMPV[265] contained a section that addressed investigation of incidents or accidents. The following distinction was made regarding an "incident":

> *For TSI's purposes, an incident is separated from an accident in that it involves damage to the vessel, cargo / machinery, or could cause significant harm to the environment.*

[262] MBI Transcript February 13-14, 2017, p. 1149.
[263] MBI Exhibit 282.
[264] MBI Transcript February 14, 2017, p. 1173.
[265] MBI Exhibit 026, pp. 168-171.

*10.7 USE OF FORM **TSI-V-SAF-012A***

The primary use of this guide is as a day-to-day safety management tool for each ship. The intent is not to scrutinize the ship's performance as this could inhibit the development of honest reporting and the all important "no blame" culture.

*Nevertheless, lessons learned on one ship may prevent accidents on another. The on-board Safety Committee shall summarize important findings on the last page of **TSI-V-SAF-012** and forward the report to the HQ Office in the Accident or Incident Package for inclusion in the total pool of safety wisdom. The TSI Manager of Marine Safety & Compliance will review all recommendations and make any appropriate comments or recommendations, returning a copy of the findings to the vessel.*

This guide should not be used only for investigating serious accidents. Valuable lessons are to be learned from studying minor accidents and near misses, which often could have had more serious consequences, but for sheer good luck.

The DPA, in his email correspondence with the VP of Commercial Ops, indicated that the central issue regarding the crew member allegedly caught sleeping was whether the anonymous report was viable and that there were *"a few different issues."* The DPA's email did not address potential impacts to the safety of the vessel and crew from the sleeping officer. In an email to the VP of Commercial Ops, the DPA wrote that he did not feel a full investigation was needed due to a lack of specific details.

An assessment of the human factors aspect of the sleeping incidents is discussed in the Human Factors section of this report. The MBI could find no record of the incidents in EL FARO logs, mariner evaluation forms and personnel files, or any other documentation produced by TOTE for the involved C/M or Masters. At the final MBI hearing in February 2017, TOTE produced a letter of warning[266] that was issued to the C/M for sleeping on watch. It was determined during subsequent MBI testimony that the C/M admitted to sleeping on watch and signed a letter of warning proffered by the Director of Labor Relations when he was confronted with the allegations.

7.2.12.6. Safety Culture Considerations Affecting EL FARO's Accident Voyage

7.2.12.6.1. Bridge Team Management

MBI testimony from several former EL FARO crew members indicated that the accident voyage Master's management style was primarily one-on-one interaction with his deck officers. A new TOTE Master who trained under EL FARO's Master stated the following when asked whether he gathered the navigation officers together as a group to talk about voyage plans, weather, and duties to protect the ship:

[266] MBI Exhibit 401.

I wouldn't say all at once as a formal meeting. I believe, you know when we got underway and preparing to get underway, he communicated those topics to each one of individually. Any night orders that he may have had. I found that he spent a lot of time on the bridge, at least with me.[267]

Former EL FARO crew members testified that they did not personally participate in Bridge Team Management processes under the Master.

While standing watch during the accident voyage on September 30, 2015, the 3/M called the Master at 11:05 PM and again at 11:38 PM, to discuss a text-based SAT-C weather report that was received on the bridge at 10:56 PM. The 3/M stated that EL FARO was projected to be 22 miles from Joaquin's center at around 4:00 AM the next morning. During the calls the 3/M suggests three times that the Master might want to review or verify the new weather information. However, the Master did not come to the bridge and there is no indication in the VDR audio that the Master reviewed the SAT-C weather report.

7.2.12.6.2. Navigation Equipment

At the time of the accident voyage EL FARO was operating with an anemometer that had not been working[268] properly for an extended period of time. An anemometer is an instrument that allows for the accurate determination of relative wind direction and speed. Simple conversion of the relative wind speed and direction yields the true wind speed and direction, which are essential factors in determining the position of a tropical system in low visibility conditions. During MBI testimony EL FARO's P/E testified that either the Master or an EL FARO Mate, he could not recall which, told him the anemometer was not working around June of 2015. When asked if actions were taken to correct the issue, the P/E answered:

No, sir. If the Captain wanted it fixed he would have put in a work order for it and it would have got fixed.

The MBI found no evidence indicating that the crew of EL FARO submitted a work order request to repair the anemometer after the verbal notification in June 2015.

7.2.12.6.3. Shore Side Support

EL FARO relied on TMPR for the following:

- safe loading of cargo, including dangerous or hazardous cargo,
- securing of unique loads,
- the weighing of cargo, and
- many other issues related to vessel loading and unloading operations.

[267] MBI Transcript May 24, 2016, p. 42.
[268] MBI Transcript February 18, 2016, p. 57.

There was no "safety department" within the TMPR corporate organization.[269] There was a "risk management" component in the TMPR organization, but that component did not examine or address the safety of terminal operations as they related to the vessels. The TMPR VP of Cargo Service[270] testified that she could not recall if there were specific Saltchuk University[271] training, safety meetings, or other guidance specifically related to the safety of cargo operations.

7.2.12.6.4. Riding Crew

On EL FARO's accident voyage, four of the five Polish riding crew members did not speak English, and none of them received the required training on muster location for abandon ship, alarms, emergency procedures, and lifesaving equipment familiarization. The Polish riding crew also did not receive the indoctrination for non-crew and contractors, which was required by TOTE policy. The NTSB collected information from the spouses and families of the deceased riding crew as part of its investigation. The spouse of one Polish riding crew member provided the following response in an NTSB questionnaire:[272]

> *After he boarded the boat, my husband was in despair about the conditions there. He told me it was dirty and hot because the air conditioning was not working. He was happy that he had managed to get a cabin with a fan. He also said he had never seen or worked on a hulk like this. While he was working, rust was falling into his eyes. He didn't go through any training about boat safety, such as an evacuation drill.*
>
> *My husband wasn't telling me about weather conditions because he knew I was worrying a lot. During my husband's voyage on the El Faro there were two tropical storms that I found out about only after they were over. My husband was trying to calm me down and he was telling me not to worry because their Captain was prudent and he in such situations would always steer in between islands, which was safer.*[273]

7.2.12.6.5. Lifesaving Equipment

EL FARO's Station Bill[274] states:

> *1) Each person, upon boarding the vessel, shall familiarize himself with his assigned location, in the event of an emergency.*
> *2) All crew members shall be thoroughly familiar with the duties they are assigned to perform in the event of an emergency.*
> *3) Each person on board shall participate in emergency drills and shall be properly dressed, including a properly donned life preserver.*

[269] MBI Exhibit 047.
[270] MBI Transcript May 27, 2016, p. 20.
[271] Saltchuk University – a corporate in house training program that is requires specific personnel in the office setting to complete 12 training class per year on a wide variety of topics.
[272] NTSB Human Factor Factual report July 26, 2017.
[273] The questionnaire response was translated to English by the U. S. State Department.
[274] MBI Exhibit 326.

On the VDR transcript, both the 2/M and Master are heard making statements questioning whether there were lifejackets on the bridge and where they were stowed. The 2/M first commented on this around 1:46 AM on October 1, 2015, and the Master's comments were made around 7:30 AM just prior to the sinking. Under 46 CFR § 199.70(b)(2)(iv), additional lifejackets for watch personnel must be stowed on the bridge because it is a manned watch location. A former C/M and Master of EL FARO testified during the MBI that he believed there were lifejackets stowed on the bridge while he was onboard.

7.2.13. Human Factors

7.2.13.1. TOTE –Marine Personnel

7.2.13.1.1. TOTE Drug and Alcohol Policy

The TSI OMV states:

> *TSI's company policy prohibits the use of alcohol, narcotics or drugs on company vessels or reporting for work under the influence of these substances. It is, and has been, TSI's expressed intent to actively discourage all forms of illegal drug activities. This includes the use, sale, traffic and possession of drugs. Persons should also note that use of prescription drugs by anyone other than the person listed on the prescription or in the Medical Logbook is prohibited by law and TSI policy. (Crew members shall advise the Master at sign-on of all current Prescriptions).*[275]

The OMV does not address the use of over-the-counter medication by crew members.

The TSI Crewing Manager stated in testimony that TSI maintained a "[z]ero tolerance drug and alcohol policy."[276]

TSI marine personnel participated in a random testing program for illegal drugs. The TSI OMV states:

> *When a vessel is selected for random drug testing, the following procedures must be observed in order to comply with AMS's, Coast Guard reviewed, compliance plan. The TSI Manager, Safety & Operations will contact the Captain (or person in charge of the vessel) 24 hours prior to the scheduled collection to inform him/her of the pending collection.*[277]

The TSI coordinator for the random testing program notified EL FARO of an upcoming random drug test via email at 10:15 AM on September 25, 2015.[278] The email except below shows that the notification exceeded TSI's 24 hour limit described in company policy:

[275] MBI Exhibit 025, p. 103.
[276] MBI Transcript February 16, 2017, p. 1583.
[277] MBI Exhibit 025, p. 101.
[278] MBI Exhibit 301, p. 10.

Sent: Friday, September 25, 2015 10:15 AM
To: capt@vessel.com
Cc: Manager, Safety and Operations/ DPA; Sea Star Port Engineer, EL YUNQUE; Sea Star Port Engineer, EL FARO
Subject: Random Drug TEST - El Faro
Good Morning,
The El Faro has been selected for a random Drug Test. It is scheduled for arrival in Jacksonville on Monday Morning Sept 28, 2015 The collector will be in touch with you P/E for port access requirements and to confirm the arrival schedule.

Ultimately the testing scheduled for September 28, 2015, did not take place because the collection company was not able to meet the vessel and conduct testing.

7.2.13.1.2. TOTE Medical Screenings for Crew Reporting Aboard

The TSI OMV addresses medical reporting procedures for oncoming crew members:

> *The Master is responsible for having each crew member complete a statement of physical condition form when joining or being reassigned to the vessel. This form is to be completed by each crew member who joins your vessel in a sailing capacity. (It does not have to be completed for port standbys or reliefs.) Any and all returning crew members are to complete this form each and every time they return - the fact that they completed it once is not sufficient.*[279]

In MBI Testimony, a previous TOTE Master described a system whereby mariners would receive a physical before reporting to the vessel. In that testimony he stated:

> *The new required physical for all crew members administered by Anderson Kelley seems to be working good, this should weed out the personnel that aren't physically able to do their jobs or have preexisting conditions that they don't write on their sign-on forms.*[280]

There is no evidence that the requirement for crew to obtain physical exams was still in effect for EL FARO crew members on the accident voyage.

The unlicensed crew members on EL FARO were provided a "Fitness for Duty Certification" as part of the Seafarer's Health and Benefit Plan for their union, the Seaman's International Union (SIU). This certification remained valid for one year from date of issuance.

The officers of EL FARO were required to complete a physical for their Coast Guard credential renewal at five year intervals.

[279] MBI Exhibit 025, p. 281.
[280] MBI Transcript February 16, 2017, p. 1663.

7.2.13.1.3. EL FARO's Accident Voyage Master

EL FARO's Master was properly credentialed by the Coast Guard. His MMC allowed for service as Master on vessels of unlimited tonnage upon ocean routes. He held his Master's unlimited credential since July 2001 and was on the fourth issuance of this officer level credential. His credentials also included an endorsement for pilotage of Prince William Sound in Alaska. His previous experience was in the tanker trade in the Pacific Northwest and the RO/RO trade on the Atlantic Ocean.

An examination of the records for EL FARO officers, including the Master, revealed that personnel evaluations, disciplinary records, and other required forms were missing from the personnel files.[281] A former EL FARO Master who resigned in August 2015 testified during the MBI that he was not aware of a process for conducting his evaluations.[282]

Prior to rejoining TOTE in 2013, EL FARO's Master worked as a Master for another company starting in 2010. In a NTSB Interview of the Master's spouse focusing on why the Master left his previous employer she stated:

> *So he ordered two tugs to move the ship and when he came back from vacation they weren't too happy with the bill and told him he was no longer employed*.[283]

When the Master approached TSI for employment in 2013, he was asked why he left his previous employer. TSI's Crewing Manager testified during the MBI that the Master told her he had "resigned."[284]

The interview of the TSI Crewing Manager and a review of TOTE's personnel records indicated the Master left the previous employer as a Master and came to work at TSI as a 3/M in May 2013. He was initially assigned to a vessel in Hawaii, the cargo vessel PACIFIC TRACKER as the 3/M.

The TSI Crewing Manager indicated that she did not check references or conduct a background check on the Master from his tenure at his previous employer. The Crewing Manager also testified that work histories were not typically checked for marine employees being hired.[285]

The sudden termination of senior officers on EL MORRO in mid-summer 2013 ultimately provided the Master an opportunity to move up and fill the position as EL MORRO's Master. The Master took command of EL MORRO in July 2013. At the end of the rating year in October

[281] Evaluations were required by TOTE to be conducted for unlicensed to C/M positions at the completion of service period. In the case of the Master and C/Es the evaluations were to be conducted annually with a two step review process, Port Engineer and then Director of Ship Management. In the case of the Master's evaluation this would be conducted by marine engineers.
[282] MBI Transcript May 16, 2016, p. 34.
[283] NTSB Testimony – 4 – Transcript of Interview of Wife of EL FARO Captain, January 05, 2016.
[284] MBI Transcript February 16, 2017, p. 22.
[285] MBI Transcript February 16, 2017, pp. 1561-1562.

2013, he was evaluated as Master for one rotation period on the vessel. During his employment at TOTE, the Master received a total of two incomplete evaluations. In October 2013, he was rated as Master on EL MORRO including a rating of "exceptional" in the categories "safety awareness" and "vessel safety record" and in "cooperation with technical manager." In the performance dimensions of "cargo familiarity or eng. plant familiarity" he was rated as "good." In the remaining categories he was given numerical ratings from 4 to 4.5 which were defined as "very good."[286] Although TOTE's evaluation system required a second level reviewer, the Master's July 2013 evaluation had no input from, and was not signed by the second level reviewer.

The Master took command of EL FARO in May 2014. His 2014 evaluation was completed by EL FARO's P/E and the Master was rated "exceptional" in all of the completed areas for the evaluation.[287] The "5" ratings were the highest numerical rating. As with the 2013 evaluation, the Master's May 2014 evaluation form was not forwarded to the Director of Ship Management for input or final approval. As a result, the performance dimension labeled "cooperation with technical manager" was not graded. Neither the 2013 nor the 2014 evaluations were completed in accordance with TSI policy, and neither were discussed with the Master as the evaluated employee.

In the DPA turnover notes dated January 20, 2014, one of the duties of the Safety Manager was to perform evaluations for senior officers every fall.[288] The Director of Labor Relations testified as to why the Master's final evaluation was incomplete:

> *Not 100 percent certain, but I think it was– knowing about it, it was somewhere lost on the hand off between the Port Engineer and the Director of Ship Management. Because it had been executed at least by the Port Engineer.*[289]

In the middle of 2014, construction of the MARLIN class ships was progressing, and TSI began considering crewing options. In May 2015 EL FARO's Master was being considered for a position as Master on one of the new MARLIN class ships. A team of senior TOTE officials was formed to select crews for the vessels and the team gathered comments on the various candidates. The team did not select the Master, based on negative comments that were received, including comments related to his suitability for command. The TSI Crewing Manager, in a May 26, 2015 email to the Director of Labor of Relations, who was also on the interview team, gave examples of comments[290] considered by the interview team:

> *Regarding* [the Master]:
>
> *There was a report several months ago that he had not been making rounds on deck/ cargo spaces. He was on vacation at the time this was brought to our attention. The situation was monitored upon his return to the vessel and it was noted he had been*

[286] MBI Exhibit 424.
[287] MBI Exhibit 052.
[288] MBI Exhibit 006.
[289] MBI Transcript February 17, 2016, p. 155.
[290] MBI Exhibit 005.

making rounds to check on any work in progress and overall condition of the vessel. I still do not feel as though this is being done consistently, but the only true way to monitor this situation is to enlist spies onboard the vessel to "rat him out" so to speak if he is wearing a path between the bridge, his office and the galley. This becomes something that is very hard to prove when the vessel is at sea, but is a concern.
Dwindling confidence in his abilities as a leader overall.

This situation is being monitored at this time. Any failure to handle future issues properly will result in a verbal or written warning and progressive discipline to ensure the EL FARO is being properly managed, but I would not recommend him for a position on the Marlins.

The Crewing Manager testified that the email quoted above represented the consensus of the TOTE interview team that conducted the interview for the Master[291] rather than her personal assessment of the Master's attributes.

When the Master was not selected to a position on a MARLIN class ship, he sent an email in July 2015 to the TMPR President, asking to use the President as a reference for other possible jobs. As the MARLIN master selection process was still ongoing at the time, the TMPR President interacted with TSI, the result of which was the Master being given another interview for the MARLIN class ships. The TSI President communicated that the Master should be considered for a position as Master of one of the new ships. In advance of this interview there was an email exchange[292] between the Director of Ship Management and the VP Marine Ops. The Director of Ship Management email included the following statement about the Master:

Subject: Re: Confidential Master Candidate

He's a stateroom Captain. I'm not sure he knows what the deck looks like. Least engaged of all four Captains in the deck operation.

The VP Marine Ops provided the following response in a reply email:

Needless to say I'm not happy about this message; but we just have to work through it. Can you provide me with some simple talking points why we didn't select him? Not active, not on deck, all talk no action, so on and so forth. Keep this confidential.

Despite the concerns voiced in the emails, a decision was made, after the second interview, to give the Master an assignment as Master of the second new MARLIN class ship, PERLA DEL CARIBE.

In August 2015, the TSI President sent the following email to the TMPR President:

After a thorough assessment of [the Master], *I am pleased to inform you that* [the Master], *will be offered the position of Master in Marlin 496.* [the Master], *will be*

[291] MBI Transcript February 16, 2017, p. 27.
[292] MBI Exhibit 005, p. 14.

assuming Master of EF on Tues, so it affords to meet with [the Master], *F2F to convey our desire for him to sail Master in 496. Would you be available on Tuesday to kindly join me so we can deliver the positive news together?*

Following delivery of the positive news, [*VP of Marine Operations Commercial] and I intend to stay behind in order to provide* [the Master], *feedback garnered from the operational team during the interview process. I think it will serve as constructive insight for* [the Master], *to further enhance his operational effectiveness as he moves forward with our TOTE Maritime team.*

The plan was for TSI Management to deliver the positive news, in person, at EL FARO's Jacksonville port call on August 11, 2015. Prior to this occurring, however, the Director of Labor Relations and the Crewing Manager sought out the TSI President and expressed unknown concerns relating to the Master's selection. During MBI testimony the Crewing Manager stated: [293]

The general points that were raised were different points that had been discussed with several people in the selection committee and they were raised again at that time with [*TSI President*]. *And then a discussion took place after that I was not – that I didn't participate in*.

It is unclear through evidence or testimony if the Master was ever told of the fact that he was not selected for any position on a MARLIN class ship. On September 24, 2015, the Master sent an email to one of his immediate family members stating:

I have no idea if I am even going on the Marlin Class vessels yet.[294]

In 2015 there were recommendations made that the Master should receive two verbal warnings related to performance of duties as Master of EL FARO. In both cases these warnings were intended to be formal written warnings. In one instance, the Master was notified that minor steel repairs were supposed to be undertaken. These repairs were not completed in a timely manner; this incident resulted in a January 2015 proposal for a written warning to be issued to the Master and C/E. The MBI found no written warning despite the fact that the VP Ops later stated the following in an email:

They need to be written up. This is unacceptable.[295]

The second incident where a written warning was discussed for the Master related to the case of an EL FARO C/M (not the C/M on the accident voyage) repeatedly sleeping on watch. The incidents occurred on EL FARO while the ship was underway. Both the accident voyage Master and a Master who resigned in August 2015 were aware that the C/M was sleeping on watch.

[293] MBI Transcript February 15, 2017, p. 38.
[294] MBI Exhibit 302, p. 9.
[295] MBI Exhibit 005, p. 5.

During the EL FARO's accident voyage on September 30, 2015, at 8:50 PM the 3/M made the following statements on the bridge to his AB in regard to the past incidents involving the sleeping C/M:[296]

> *Like [ex EL FARO C/M]— the first time he fell asleep on watch— he must have been "huh that was kind of nice and refreshing."*
>
> *Then he got caught and nothing happened. Then he caught again and nothing happened.*
>
> *[Expletive] kept on doing it.*

Despite being caught by both two EL FARO Masters, there is no evidence to indicate that the Masters informed TSI management or the DPA about the incidents.

7.2.13.1.4. Evaluation of Other EL FARO and EL YUNQUE Officers

The junior deck officers on the accident voyage were not evaluated in accordance with company policy in terms of the required frequency. In late August 2015, a crewing assistant notified[297] the crewing manager that she had not received evaluations for the company ships as required. The crewing manager asked for a list of the vessels that were not in compliance with the TOTE evaluation policy. The assistant subsequently provided a list of vessels and neither EL FARO nor EL YUNQUE was included on the list despite having mariners on board who were overdue.

The evaluation record for officers on EL FARO was as follows:

Accident Voyage Officers EL FARO	
Position	Last Evaluation Produced
Chief Mate	June 2015[298]
Second Mate	November 2011
Third Mate	February 2014
Chief Engineer	October 2014
First Assistant Engineer	June 2015
Second Assistant Engineer	May 2015
Third Assistant Engineer (1)	January 2015
Third Assistant Engineer (2)	November 2015
Third Assistant Engineer (3)	N/A

Overall the average rating for these officers was very good to excellent with some exceptions.

On October 2, 2014, EL YUNQUE's P/E, who would later become the TOTE's Director of Ship Management – Commercial, sent an email that included in the following statement along with his completed evaluations for EL YUNQUE's senior officers:

[296] MBI Exhibit 266, p. 253.
[297] MBI Exhibit 178.
[298] Evaluated on EL YUNQUE for the positions of 2/M and 3/M.

My honest evaluations will kill motivation for the following individuals. I know we have to word them very carefully. These are draft comments. I don't want to finalize these comments until we're all in agreement that you have no plans to take them to the Marlins. Feel free to add to the below.[299]

7.2.13.1.5. Attrition in the Senior Officer Positions aboard EL FARO and EL YUNQUE

In late summer of 2015, two TOTE masters resigned; one from EL YUNQUE and one from EL FARO.[300] One of the permanent Masters of EL FARO resigned and departed EL FARO on August 4, 2015. On August 3, 2015, the Crewing Manager sent an email[301] to the Director of Labor Relations and stated that one of the reasons he resigned was:

….and all of the Drama (sic) *that is going on aboard the EL FARO he decided to resign.*

The attrition, coupled with the demotion of an EL FARO C/M for sleeping on watch, caused a shuffling of officers to fill positions on EL FARO. To backfill crewing needs, a 2/M (with an unlimited Master credential) was brought over to EL FARO to sail as C/M. In the months of August and September 2015, EL FARO had four people sail as C/M, the last being the C/M who moved over from EL YUNQUE from his former position as 2/M.[302] That C/M sailed on the accident voyage.

7.2.13.1.6. Training and Certification of other EL FARO Officers

An examination of the Coast Guard records for EL FARO officers indicated that there were no deficits in the required Coast Guard training for the officers on the accident voyage.

The training for EL FARO 3A/Es was conducted at the maritime academies. Their particular training focused on marine engineering. The engineers graduated with 3A/E marine engineer licenses for motor and steam propulsion. Some engineers also received an endorsement for gas turbine propulsion systems.

The MMC endorsements for EL FARO engineers on the accident voyage were:

- One 3A/E had: 3A/E of steam, motor, or gas turbine vessels of any horsepower.
- Two other 3A/Es had: 3A/E of motor or steam vessels of any horsepower.

All 3A/Es attended Maine Maritime Academy. The training ship for that school is the "State of Maine," which is a diesel powered ship. Only one of these 3A/Es sailed on a steam powered ship during the course of their sea cruise training. The 3A/E that joined the vessel on the accident departure day did not have practical maritime experience on a steam powered vessel prior to signing on EL FARO. Once aboard EL FARO, the intent was to pair the newly reporting

[299] MBI Exhibit 423.
[300] MBI Exhibit 005, p. 42.
[301] MBI Exhibit 305, p. 1.
[302] MBI Exhibit 005, p. 42.

3A/E with another experienced steam 3A/E to provide onboard orientation and familiarization with the steam plant and the engineering systems on EL FARO. The newly reporting 3 A/E was an extra engineer not required by the EL FARO's Certificate of Inspection.

7.2.13.1.7. TOTE – Cargo Operations, Port Mates, and Fatigue

Each time EL FARO arrived in Jacksonville, the ship's crew would unload cargo and then begin the process of loading and securing cargo. The efficiency of the vessel's arrivals and departures was noted on a TOTE management spreadsheet. These statistics indicated 100% attainment of the goal if the ship departed or arrived within a scheduled two hour window.

To assist in the cargo loading and unloading, an additional P/M was routinely brought aboard while EL FARO was in both Jacksonville and San Juan. The P/Ms served two functions. First, they directly assisted with the oversight of cargo securing and lashing, second, they provided the full time Mates with in port rest periods to mitigate the effects of fatigue. Typically the 2/M and 3/M would stand 6-hours on and 6-hours off watch rotation while in port, and the C/M would stand a 6:00 AM to 6:00 PM watch in port. During MBI testimony, a former EL FARO C/M described the need for a P/M as "essential," and there were multiple[303] internal TOTE emails related to the need for the P/Ms on EL FARO.

At one point, the Marine Operations Manager emailed that he thought about getting the appropriate Merchant Mariner Credential so he could fulfill the duties of the P/M. The P/M that served on September 1, 2015 would be the last P/M employed on EL FARO in Jacksonville. TOTE had difficulty locating qualified P/Ms, however, the issue was not raised above the level of the Marine Operations Manager at the Jacksonville Terminal. There is no evidence that the absence of the P/Ms and the potential impacts to the safety of EL FARO were communicated to TSI management beyond the terminal during the pre-accident timeframe starting on September 1, 2015.

While standing watch on the bridge of EL FARO on September 30, 2015, the 3/M made several statements to the AB regarding lack of P/Ms and the resulting effect on cargo operations. Section 7.2.10.1. of this report includes those statements.

7.2.13.1.8. TOTE – Training for Marine Personnel

TOTE required training for its marine personnel under the supervision of the Safety and Operations Department and the Master of EL FARO. This training was accomplished through shipboard drills, safety, and ISM Code safety committee meetings, and through TOTE's tracked training. Evidence shows that this training adhered to the frequency and schedule published by the company. Tracked training could cover a wide variety of relevant subjects and sign up and tracking sheets were provided.[304]

In addition to shipboard training, marine personnel were required to attend professional training for the maintenance of their Coast Guard issued MMCs. TOTE did not provide

[303] MBI Exhibit 303.
[304] MBI Exhibit 355.

additional enhanced training, with the exception of LNG Safety Awareness Training for personnel designated for assignment on the new LNG fueled MARLIN class ships. This specialized training was a requirement for crew on the new LNG fueled ships.

In March 2015, EL FARO's Master attended two classes during his time ashore. This training was comprised of Radar Refresher Training which is required at five year intervals, as well as Leadership and Management Training, which is an STCW training requirement. The Leadership and Management Course at the STAR Center in Dania Beach, Florida covered the following subjects:

Leadership and Management:

- Decision Making
- Strategic Planning, Task and Workload Management
- Effective Resource Management Onboard
- Effective Communications
- Assertiveness, Leadership and Motivation
- Obtaining and Maintaining Situational Leadership

Leadership in the Maritime Environment:

- Personnel Management and Administration
- Operations, Drills and Training
- Maintenance and Dry-docking
- International Maritime Conventions and Recommendations and National Legislation
- Safety and Environmental Leadership in the Maritime Industry
- Development, implementation and oversight of standard operating procedures

TOTE did not provide enhanced training for EL FARO officers such as emergency ship handling, heavy weather ship handling, damage control, weather training or other optional training courses designed to enhance expertise for handling the variety of special situations that may be encountered at sea. There was no specialized training provided to EL FARO officers covering stability or cargo securing.

7.2.13.1.9. EL FARO – Functioning of Bridge Team (Resource) Management (BTM)

In numerous instances on EL FARO's VDR transcript[305] the Master used the words "low" and "storm" when discussing Hurricane Joaquin with other crew members. The Master was never heard using the words "hurricane" or "tropical storm" on the VDR audio or in recorded calls to shore.

At 1:20 AM on October 1, 2015, the 2/M made the following statement to the AB on watch after hearing on the satellite radio that Hurricane Joaquin had been upgraded to a Category 3 storm:

[305] MBI Exhibit 266.

*I'm gunna give the captain a call and see if he wants to come up and (look at it) *.*

The 2/M passed the following update to the Master on the house phone a minute later:

*Right now my uh– trackline I have zero-two hundred– alter course straight south and then (we'll) * go through all these * shallow areas. Umm (and the next) course change (will/gunna) be (through the Bahamas) and then (just gunna) turn * * *.*

The total conversation lasted 2 minutes and 7 seconds and the Master did not come to the bridge following the call.[306] Immediately after the call, the 2/M informed the AB that they were going to run the course that had been planned out the night before. At 1:24 AM the 2/M directed the AB to start easing EL FARO to port in order to slowly obtain a course of 116 degrees true directly toward their planned destination of San Juan, Puerto Rico. The Master did not come to the bridge until 4:09 AM.

At 1:43 AM[307] the AB on watch reported seeing unidentified flashes of light on the ship and discussed the possible causes of the flashes with the 2/M. The Master was not notified of the unidentified flashes of light.

At 2:11 AM the AB reported that there was clanking going on during a period of time when there were also comments about green (seawater as opposed to spray) water on the bow. The Master was not notified of the clanking sounds or the green water on the bow.

At 2:53 AM the first steering alarm [308]was heard on the bridge. This alarm indicated that the ship was more than three degrees off course.[309] At 3:20 AM, the steering alarm began to be sound more frequently. At 3:21 AM the 2/M made the following statement to the AB:

Yeah– she's goin'– she's goin' left– she's got right rudder.

When the 2/M turned over the watch to the C/M at approximately 3:47 AM, there was no evidence on the VDR that she briefed him on the thumps and clanking noises heard and the unidentified flashes observed occurring on the forward portion of the ship. The 2/M did not notify the Master of the steering alarms she experienced during her watch or the difficulties she encountered while trying to maintain course in worsening wind and sea conditions.

7.2.13.1.10. INTEC Polish Riding Crew

The TSI OMV[310] stated the following:

[306] EL FARO's VDR indicated that the Master came to the bridge at 4:09 AM on October 01, 2015.
[307] MBI Exhibit 266, p. 318.
[308] MBI Exhibit 266, p. 336.
[309] MBI Exhibit 266, p. 337.
[310] MBI Exhibit 025, p. 86.

> *All persons covered by the 'underway' section, shall be included in the "new crew member indoctrination procedures" described in OMV 3.2.1 and shall sign the "Non- Crew Indoctrination" log stating that they have been given appropriate emergency instruction. In addition all persons covered by this section shall complete "Seaman's Statement of Physical Condition," [TSI-PER-005].*

Beginning on August 18, 2015, there was a Polish "riding crew" onboard EL FARO to conduct the Alaska service conversion work. This crew worked under the direction of an off duty EL FARO C/E, who was working on a contracted basis. Only one member of the Polish riding was fully fluent in English and that individual served as the interpreter for the other four members of the riding crew. No other provisions were made by TOTE officials or EL FARO crew members to mitigate the language barriers faced by the riding crew members and there were no safety or work instructions provided in Polish.

On the departure day of the accident voyage, two members of the riding crew that had been on EL FARO during previous voyages were relieved and returned to Poland. They had been onboard EL FARO since the start of the conversion work in mid-August. During the MBI hearings, a riding crew witness testified that when he arrived on EL FARO he was not aware it was Atlantic Hurricane season. He also testified that he received a general orientation of the vessel and completed a medical questionnaire, but did not receive a safety briefing, don a life jacket or immersion suit, or receive information about his muster station and lifeboat assignment.

When asked by the MBI if he attended safety drills the former Polish riding crew member stated:[311]

> *We did not participate in those— we did not participate in those drills because they did not apply to us.*

A spouse of one of the deceased Polish riding crew members also provided the following response to an NTSB questionnaire:

> *He didn't go through any training about boat safety, such as an evacuation drill.*

A former EL FARO Bosun also testified during the MBI that he did not see the Polish ship riders at any drills, including boat drills.[312]

Safety familiarization and basic safety training requirements of the International Convention of Training, Certification, and Watchkeeping for Seafarers (STCW), 1978, are mandated by law.[313] There was no evidence presented that Coast Guard approved basic safety training was completed by the riding crew, in accordance with STCW Regulation VI/1 and 46 CFR § 15.1105.

[311] MBI Transcript February 15, 2017, p. 22.
[312] MBI Transcript February 23, 2017, p. 135.
[313] 46 U.S.C. § 8106(a)(4).

7.2.13.1.11. Fatigue and STCW Rest Requirements

TOTE employed a medical firm, Andersen-Kelly, to certify mariners as fit for duty before signing onboard a ship.[314] The Master was responsible for evaluating the medical information that was provided by mariners as they checked in aboard the vessel, to determine if there were any current medical issues or medication issues that would render the seafarer unfit for duty.

Merchant mariners are required to take a physical every five years as part of the process to renew their MMC. Mariners must document that they have seen a medical practitioner and obtained a physical. In the Application for Merchant Mariner Medical Certificate (CG-719K (01/09), OMB. 1625-0040) questionnaire portion of the document on page 4 of 9 there is a section on Medications, Section III. The 2015 version of the form included these instructions:

> *Credential applicants who are required to complete a general medical exam are required to report all prescription medications prescribed, filled or refilled and/or taken within 30 days prior to the date that the applicant signs the CG· 719K. In addition all prescription medications, and all non-prescription (over-the-counter) medications including dietary supplements and vitamins that were used for a period of 30 or more days within the last 90 days prior to the date that the applicant signs the CG· 719K or approved equivalent form must also be reported.*
>
> *The information reported by the applicant must be verified by the verifying medical practitioner or other qualified medical practitioner to the satisfaction of the verifying medical practitioner to include the following two items.*
>
> *1. Report all medications (prescription and non-prescription), dietary supplements, and vitamins.*
>
> *2. Include dosages of every substance reported on this form. as well as the condition for which each substance is taken.*
>
> *Additional sheets may be added by the applicant and/or qualified medical practitioner if needed to complete this section (include applicant name and date of birth on each additional sheet).*

On the morning of October 1, 2015, at 1:05 AM the 2/M made the following statement to the AB about how she avoided hearing all the noise created by the riding crew:[315]

> *Well I wasn't awake for that.– Nope. Ear plugs– Zzzquil. That Zzzquil knocks me out. I love it– It's just when it wears out– I wake up*.

The February 25, 2015, CG-719K submitted by EL FARO's 2/M listed "none*"* in the "Medications or over the counter (OTC)" section.[316]

[314] MBI Transcript February 16, 2017, p. 1663.
[315] MBI Exhibit 266, p. 301.
[316] Coast Guard National Maritime Center; Mariner files.

Coast Guard NVIC 04-08 Change 2, which came into effect in 2016, after the loss of EL FARO, states the following:

> *25 APR 2016*
> *COMMANDANT CHANGE NOTICE 16700.4*
> *Subj: CH-2 TO MEDICAL AND PHYSICAL EVALUATION GUIDELINES FOR MERCHANT MARINER CREDENTIALS, NVIC 04-08, COMDTPUB 16700.4*
> *Ref: (a) Marine Safety Manual, Volume III, Marine Industry Personnel, COMDTINST.*
>
> *Important Safety Warning.*
>
> *Certain medications, whether prescription or over-the-counter, have known impairing effects and their labels warn about risk of drowsiness and caution against use while driving or operating hazardous machinery.*
>
> *The nature of shipboard life and shipboard operations is such that mariners may be subject to unexpected or emergency response duties associated with vessel, crew, or passenger safety, prevention of pollution and maritime security at any time while aboard a vessel.*
>
> *In the interest of safety of life and property at sea, the Coast Guard views shipboard life and the attendant shipboard duties that can arise without warning, as safety sensitive duties that are analogous to operating hazardous machinery. As such:*
>
> 1. *Mariners are advised to discuss all medication use with their treating providers and to inform them of the safety sensitive nature of their credential; and 2. Mariners are cautioned against acting under the authority of their credential while under the influence of medications that:*
>
> a. *can cause drowsiness, or*
>
> b. *can impair cognitive ability, judgment or reaction time, or c. carry warnings that caution against driving or operating heavy machinery.*
>
> *3. Mariners are advised that they are considered to be acting under the authority of the credential, for the purposes of this Enclosure, anytime they are aboard a vessel in a situation to which 46 CFR § 5.57(a) applies, even when off-watch or while asleep, or any time they are subject to recall for duty or emergency response.*

In an NTSB interview[317] a friend of the 2/M stated the following:

[317] NTSB Interview Testimony, 4 – Transcript of Witness Interviews, Friends of 2/M, November 04, 2015.

NTSB: With the captain that was on board the ship during the accident, [the Master], *did you ever get any indication that she either enjoyed -- or how she felt working with him or for him?*

Witness: She couldn't stand it. She was exhausted. There were a lot of weird rules put in place that they had to be on the 12 hours, and it couldn't be the 8 to 12. It was strict 12. She was always exhausted and tired.

On September 28, 2015, the 2/M sent the friend quoted above the following text message:

I'm getting a headache now. Time to sleep for the little bit I have. Then midnight to 06 watch. Then back up to make all my phone calls for moving. Grrrrr.

On the VDR transcript[318] the 2/M made the following statement while standing the bridge watch at 3:30 PM on September 30, 2015:

(Alright) so I called 'em up yesterday. I didn't get much sleep yesterday because I was on the phone with everyone. The fuel company canceled my account fuel up that thing– I'm not payin' for somebody else's fuel.

On the VDR transcript[319] the 2/M came onto the bridge at 4:46 PM on September 30, 2015, and relieved the C/M so he could eat dinner. The relief watch lasted approximately 30 minutes.

The 2/M's at sea schedule indicated on STCW records for a August 25, 2015, EL FARO voyage was as follows:[320]

Watch at sea 0000-0400/1200-1600
Deck Maintenance schedule at sea is 0800-1130
Rest Period at sea is 0400-0800 and 1600-2400[321]

The IMO [322] makes the following statements about fatigue:

GUIDELINES ON FATIGUE INTRODUCTION

Fatigue can be defined in many ways. However, it is generally described as a state of feeling tired, weary, or sleepy that results from prolonged mental or physical work, extended periods of anxiety, exposure to harsh environments, or loss of sleep. The result of fatigue is impaired performance and diminished alertness.

However, recent accident data and research point to fatigue as a cause of and/or contributor to human error precisely because of its impact on performance. Human

[318] MBI Exhibit 266, p. 136.
[319] MBI Exhibit 266, p. 169.
[320] MBI Exhibit 283.
[321] MBI Exhibit 283, p. 5.
[322] IMO MSC/ Circ. 1014, Ref T2/4.2, dated June 12, 2001.

error resulting from fatigue is now widely perceived as the cause of numerous marine casualties, including one of the worst maritime environmental disasters in the last century, the Exxon Valdez.

The negative effects of fatigue present a disastrous risk to the safety of human life, damage to the environment, and property. Because shipping is a very technical and specialized industry, these negative effects are exponentially increased, thereby requiring seafarers' constant alertness and intense concentration.

2. DEFINING FATIGUE: There is no universally accepted technical definition for fatigue. However, common to all the definitions is degradation of human performance. The following definition is found in IMO's MSC/Circ.813/MEPC/Circ.330, List of Human Element Common terms:

A reduction in physical and/or mental capability as the result of physical, mental or emotional exertion which may impair nearly all physical abilities including: strength; speed; reaction time; coordination; decision making; or balance.

Furthermore MSC/Circ.1014 ANNEX on page 10 states:

Fatigue is known to detrimentally affect a person's performance and may reduce individual and crew effectiveness and efficiency; decrease productivity; lower standards of work and may lead to errors being made. Unless steps are taken to alleviate the fatigue, it will remain long after the period of sustained attention, posing a hazard to ship safety.

During the MBI proceedings several witnesses[323] could not explain who within the TOTE organization was responsible for providing oversight of evaluations, medical forms, disciplinary records, and other records, including STCW records pertaining to the required work rest history for mariners.[324]

Specific rules apply to mariners who serve as deck watch officers, they are required to get six hours of rest in the twelve hours immediately before getting underway.[325] [326]

A former 2/M and 3/M on EL FARO stated during MBI testimony that he was not aware of the legal requirement for a rest prior to taking the deck watch immediately before going to sea.[327] This requirement was not captured in any TSI produced form.[328] The requirement was also not factored into EL FARO's automatic STCW required work/rest calculation formulas.

[323] MBI Transcript February 16, 2016, p. 14.
[324] The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) 1978 sets qualification standards for masters, officer and watch personnel on seagoing ships.
[325] MBI Exhibit 304.
[326] 46 U.S.C. § 8104.
[327] MBI Transcript February 9-10, 2017, p. 812.
[328] MBI Exhibit 283.

The purpose of the STCW rest requirement is to combat the effects of fatigue that can have an adverse impact on the cognitive thinking and the performance of watchstanders.

The MBI examined a sampling of STCW work rest histories to determine if the 46 U.S.C. § 8104 requirements were met during past voyages for EL FARO bridge officers. The MBI detected three potential violations of the rest provisions in the twelve hours immediately prior to departing port. STCW samples for the accident voyage 3/M were examined from July 7, July 14, and September 1, 2015, and the rest periods varied between 5.5 hours and 4 hours[329] for the 12 hour period immediately prior to getting underway.

A review of the STCW records also detected violations for the rest requirements mandating six hours of continuous rest in a 24 hour period that are contained in 46 CFR § 15.1111. These violations occurred in the months of August and September 2015.

During the MBI,[330] a former EL FARO AB provided the following statement about STCW recordkeeping:

> *You're not going to hear, because just like I said, they make good money, and there's ways around everything. Even the STCW just being honest. There's ways around it because they got a program on the ship where once you put your hours in and it don't line up, get red, it turns red. So the only thing you have to do is just go around and fixing numbers and you're back.*

STCW compliance was managed by shipboard personnel with minimal oversight by TOTE management. The Safety Manager[331] indicated during MBI testimony that TOTE would review STCW records if something was brought to the Safety Department's attention. In a TOTE internal audit report of EL FARO conducted in early 2015, there was no mention of a review of STCW work rest logs. The MBI was unable to obtain records for the STCW work rest logs for the weeks prior to the accident voyage as they were only maintained onboard EL FARO.

7.2.13.1.12. EL FARO – Distractions Caused By the Crewing of the MARLIN Class Ships

Distractions arose during TOTE's selection process for the MARLIN class crews and each person that was selected for a position was asked to sign a non-disclosure agreement. The bridge officers and C/E on the accident voyage had not been selected to go to the new ships. The Master of EL FARO was also unsure whether he would receive his desired position on the MARLIN class ships. On the accident voyage VDR transcript the Master and the C/M discussed concerns about their future with TOTE around 7:00 PM on September 30, 2015:

> ***C/M:*** *I hear what you're saying Captain. I'm in line for the choppin' block...*
>
> ***Master:*** *Yeah. Same here.*

[329] MBI Exhibit 283.
[330] MBI Transcript February 14, 2017, p. 1360.
[331] MBI Transcript February 14, 2017, p. 1189.

C/M: *... I'm waitin' to get screwed.*

Master: *Same here.*

C/M: *I don't know what's gunna happen to me.*

7.2.13.1.13. EL FARO – Bridge Officer Human Factor Issues

Since 2014, including at the time of the accident voyage, there were no expectations at TOTE that the Master of EL FARO share or discuss the intended route for a particular voyage with shore side TOTE mangers, even during hurricane season. A former DPA and Marine Operations Manager testified that prior to 2014 it was standard practice for TOTE to be apprised of the route and plans for a vessel ahead of a voyage with expected heavy weather. When asked if there was ever pushback from a Master to inform the company of his voyage plans the former marine manager said that he had previously told a master that if he did not tell him his plans and intentions he would have another master relieve that master in two hours. [332]

Along with the lack of shore side oversight, there were also internal shipboard communication issues. During the last nighttime watches on EL FARO prior to the accident, the VDR recorded several critical communications from the bridge watch officers to the Master.

At 11:05 PM on September 30, 2015, the 3/M called the Master and made the following statements:

Hey captain sorry to wake ya.

Naw– nothin' and uh the latest weather just came in.– And umm– thought you might wanna take a look at it.

So– (yeah) if you have a chance.
Just lookin' at the forecast and lookin' at our trackline. Which way it's goin' and uhhh– thought you might wanna take a look at it.

Uhh well it's– the– the– the current forecast has it uhh– max winds um a hundred miles– an hour. At the center.– Umm and if I'm lookin' at this right– um– and it's moving at– at two-three-zero at uh five knots. So I assume it stays on that same– moves that same direction for say the next five hours. And uh so it's advancing toward our trackline– and uhh– puts us real close to it. Umm you know like– I could be more specific– I could um– plot that out. But it's gunna be like real close (and). And uh– don't know. Uh– uh I can give ya a better number and call ya back. We're lookin' a meet it at say like four o'clock in the morning. (You know).

As the 3/M was conversing with the Master, the inbound email with the BVS weather attachment arrived in the Master's email inbox. The 3/M and 2/M were expecting the BVS

[332] NTSB Interview of Captain Harry Rogers.

weather update to be forwarded to the bridge computer for their review and potential action. The Master did not forward the 11 PM BVS package to the bridge until the next morning at 4:45 AM.

Just before watch relief at 11:13 PM the 3/M called the Master again and made the following statements while discussing Hurricane Joaquin:

> *(Okay) it's (3/M) again.*
>
> *So– at oh–four hundred we'll be twenty-two miles from the center. With uh max one hundred with gusts to one-twenty and strengthening so– the option that we do have– umm from what I can see– is at oh-two hundred we could head south. And that would open it up some– so I mean of course I'd want you to verify what I'm seeing. I do understand you expect us not get into the quadrant dead ahead and (expose) us. Just so you know that– that's how that's how close we'll be.– You're welcome.*

The Master did not come to the bridge after the call and the 3/M and AB had the following conversation on the bridge regarding the call:

> ***3/M:*** *It'll be at that strength according to the forecast– twenty miles from the center.*
>
> ***AB:*** [Expletive].
>
> ***3/M**:* *What he's saying is "well– we'll be in the southwest quadrant. Wind will be comin' from the north."— So.*
>
> ***AB:*** *Nantucket sleigh ride.* [A term used in the whaling era that described the wild ride incurred by sailors immediately after harpooning a whale.]
>
> ***3/M:*** *I trust what he's saying– It's just being twenty miles away from hundred knot winds– this doesn't even sound right.*

The 2/M also called the Master at 1:20 AM on October 1, 2015, during her bridge watch to discuss Hurricane Joaquin after learning that the storm had been upgraded to Category 3. During the call the Master instructed the 2/M to take the voyage route that had been planned the night before. Specific details from the call are included in Section 7.2.13.3.1. of this report.

The 2/M and the AB on the 0000 – 0400 watch were closely monitoring the clock as the weather worsened and the time until their watch relief approached. At 2:54 AM, the AB on watch stated:

> *Just hold out baby– We ain't got but an hour to go.*[333]

[333] MBI Exhibit 266, p. 338.

At 3:28 AM, after the AB stated that EL FARO's path would be going right through a large storm signature on the radar, the 2/M responded:

> *It's good (just keep bein' like) fifteen more minutes. (Keep it)* [AB] *and then we're off.*[334]

When the C/M relieved the 2/M's watch at 3:44 AM on October 1, 2015, the relief process lasted less than three minutes. During the relief the 2/M did not mention problems that had been encountered with the autopilot system or unidentified flashes that the AB had seen forward on the ship. The 2/M did not mention her 1:20 AM conversation with the Master concerning the intensification of the storm or the Master's response to run the 116 degrees course. The relief process also did not include a discussion about the errors between predicted wind direction and actual observed direction of the hurricane winds, which were discussed at 03:24 AM when the 2/M made the following statement to the AB on the bridge:

> *I think it's shifting. Cause that weather report say tha– uhh– west-southwest wind which we were not getting but I think it's starting to shift west and now it's coming back around. We're gunna start getting it on the starboard side*.[335]

Shortly after coming on the bridge at 4:09 AM on the morning of October 1, 2015, the Master stated to the C/M that he had been "sleepin' like a baby."[336] The VDR transcript contains several references by the Master whereby he notes the difference in perception of the noise and fury of the storm between his cabin and the bridge. At 05:16 AM the Master made the following statements on the bridge:

> *It sounds so much worse up here.*
>
> *When you get down (below) (it's just a lullaby) * * *.*[337]

7.2.13.1.14. <u>TSI – Operational Span of Control</u>

TSI, which operated EL FARO, was a relatively small company that required many of its office personnel to cover multiple duties at the same time. In the months leading up to EL FARO's accident voyage there were corporate discussions about potentially downsizing the office staff further.[338]

The multi-tasking of the TSI staff became more demanding as the new MARLIN class ships were being constructed. Many members of the TSI management and operations teams were tasked with additional duties to bring the new ships into service. As an example, the Director of Safety and Services was involved in MARLIN LNG fueling related issues. During the accident voyage the Crewing Manager was looking for crew for the MARLIN ships and the Director of Ship Management was in California attending to one of the MARLIN class ships in the shipyard.

[334] MBI Exhibit 266, p. 347.
[335] MBI Exhibit 266, p. 347.
[336] MBI Exhibit 266, p. 367.
[337] MBI Exhibit 266, p. 405.
[338] MBI Transcript February 13, 2017, p. 187.

The time-line to complete conversion work on EL FARO also created additional duties for TOTE shore side staff. During MBI testimony EL FARO's P/E stated:

> *Well there's day-to-day operation and then we had a dry docking and also the conversion work. So I had to— basically three jobs going, or two and a half. The dry docking is part of the normal Port Engineer's job, but it's every two to three years. Where this was all happening at once.*

EL FARO's DPA was responsible for a fleet of approximately 25 vessels. These vessels were in active and standby status around the world.

7.2.13.1.15. TOTE Operations –Regular Route, Schedule and Commercial Pressure

EL FARO sailed on what was described as a "liner service." This service included regularly scheduled weekly transits between Jacksonville and San Juan. The route to and from San Juan was called the "Atlantic Route." Deck officers did not receive a direct incentive or bonus for meeting the cargo delivery schedules, but those statistics were advertised to TOTE's customers. TOTE incurred costs from delayed ship arrivals or departures in the form of labor costs for terminal personnel. Per company policy, TOTE's PONCE class vessels were considered to be on schedule if they arrived or departed port within a specified two hour window.

Several former EL FARO and EL YUNQUE crew members testified during the MBI that they had encountered fair weather conditions for the vast majority of voyages for the two year period prior to the accident voyage.

The Master made the following statement on the bridge of EL FARO at 9:23 AM on September 30, 2015:

> *I mean when we went through Erika* [Reference to Tropical Storm Erika] *this last * that's the first real– real storm I've been on with this ship.*[339]

7.2.14. Lifesaving

EL FARO was equipped with the required lifesaving equipment as specified in the vessel's Coast Guard issued COI. This equipment included lifeboats, life rafts, life preservers, survival suits, emergency position indicating radio beacon (EPIRB), search and rescue transponders (SART). EL FARO was also equipped with a Global Maritime Distress and Safety System (GMDSS) radio system, the Ship Security Alert System (SSAS), and a Long Range Identification and Tracking (LRIT) radio system.

[339] MBI Exhibit 266, p. 73.

7.2.14.1. Lifesaving Equipment Training

The operation of lifesaving equipment is required to be incorporated into training,[340] in order that the crew is proficient in its use. Lifesaving equipment can be tested and exercised during the required drills such as an abandon ship drill; it can also be tested during equipment maintenance periods.

The Marine Safety Manual (MSM) Volume II states that it is the Coast Guard's responsibility to determine if the crew can effectively use equipment such as the lifeboats. Coast Guard Marine Inspectors are required to observe the launch of the lifeboats to test the crew's proficiency in the operation of the boats. This includes the lowering of the boat to the water and then the actual operation of the boat in the water. This also includes the operational testing of the diesel powered lifeboat and the manually propelled lifeboat that EL FARO carried. There is a provision to amend the procedures due the adverse weather. In those instances, upon conclusion of the inspection, the attending Coast Guard Marine Inspector is required by policy to document that a full abandon ship drill was not carried out with a notation of what tests remain to be completed at a later date.

An MBI review of emergency drill records for EL FARO indicated that the lifeboats were only lowered to the rail during drills. There was no record the lifeboats being lowered to the water and operated as part of an emergency drill.

A former EL FARO Bosun[341] provided the following MBI testimony about the inspection and testing of one of EL FARO's lifeboats:

> *Okay, again, I did the COIs, and we also lowered our boat, the starboard boat, went down in Puerto Rico into a cradle, a wooden cradle, and we flipped the lever. The davits were operable and I was on the lever. I lowered that boat to second mate, dropped the man ropes. Chief mate and cadet were on the deck, I believe at the time. We lowered down in the cradle, flipped the lever and we brought her back home, and when I say home, I mean it's secured.*

A former EL FARO 2/M testified[342] during the MBI that launching lifeboats in scenarios where EL FARO was heeling over was not discussed during abandon ship drills. The 2/M provided the following description of a typical EL FARO abandon ship drill:

> *In a typical abandoned ship drill we would lower the boats to the deck, embarkation deck which is at feet level, easily can just walk on the boat. We would lower it to the embarkation deck and then restow it.*

ABS was responsible for ensuring EL FARO conducted the operational test of lowering the boat to the water and operating the boat in the water during the Safety Equipment statutory survey. During EL FARO's most recent inspections prior to the accident voyage, the Coast

[340] MSM Volume II, Section B, Chapter 1, section v, pp. B1-B31.
[341] MBI Transcript February 14, 2017, p. 1290.
[342] MBI Transcript February 18, 2016, p. 65.

Guard Marine Inspector witnessed the boat being lowered to the rail. The Marine Inspector did not require that the lifeboats be lowered to the water, released from the davits, or operated underway, because he mistakenly assumed that ABS had witnessed those actions as part of the Safety Equipment statutory survey. The miscommunication between the Coast Guard and ABS extended for several inspection cycles since the ABS surveys and Coast Guard examinations were generally conducted separately on EL FARO.

7.2.14.2. Lifeboats and Launching Systems

EL FARO had two open, gravity davit launched fiberglass lifeboats fitted on the port and starboard sides. Because EL FARO was delivered in 1975, the vessel was required to comply with SOLAS 1960 requirements for lifesaving appliances, including lifeboats. SOLAS 1974 updated the requirements for cargo vessel lifeboats, requiring motorized and enclosed lifeboats for vessels with keel laying dates after July 1, 1986. SOLAS 1974 was not retroactive to older vessels such as EL FARO, and the enclosed lifeboats were not required to be installed on these older vessels as long as the existing gravity davit launching systems could be maintained.

EL FARO's starboard lifeboat, Boat 1, had a capacity of 43 persons and was propelled by the manual movement of levers which in turn operated a propeller. This propulsion system is known as Fleming gear.

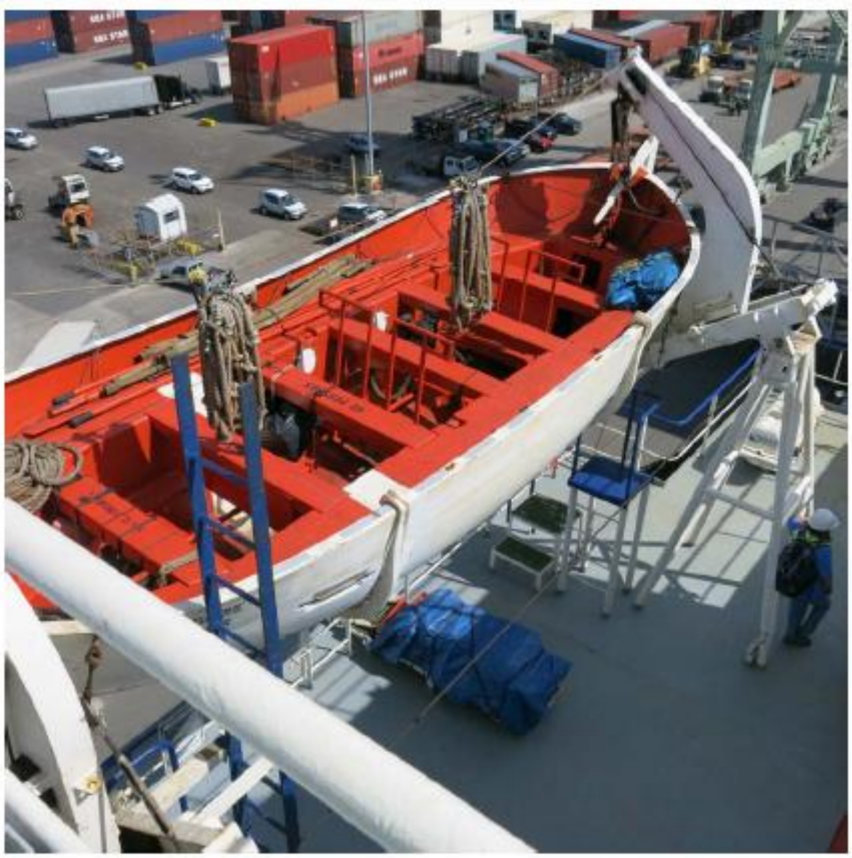

Figure 47. EL YUNQUE starboard lifeboat. NTSB photo.

The port lifeboat, Boat 2, had a capacity of 48 persons, was powered by a diesel engine, and was classified as EL FARO's rescue boat. Under standard operating conditions, these lifeboats could be launched by removing the securing devices and lowering them to the embarkation point where assigned personnel could board. Each lifeboat had a deck officer designated to be in command. In actual abandon ship scenarios, one crew member was required to operate the launching appliance controls to lower the boat to the water. That person would then have to use a rope ladder to descend down the side of EL FARO and board the boat in the water. The boat crew would then release the boat hooks and steer the lifeboat away from the side of the ship.

The main limitation for the gravity launching of the boat was the design of the launching system with respect to trim and list.[343] The system was designed to operate with a list up to 15 degrees with a fully loaded boat. The VDR audio recording did not contain any discussion regarding the readying, manning, or use of EL FARO's lifeboats.

After the accident, Boat 1 was discovered floating in EL FARO's debris field, partially submerged with severe damage. It was eventually recovered and transported to shore. Boat 2 was located on the ocean floor, severely damaged, with one end severed and the engine missing. During the MBI, an expert in the field of lifesaving appliances testified that the damage to the two lifeboats was consistent with damage that occurs during sinking, including environmental forces from wind and seas.[344] He stated that, based on their condition, there was no evidence indicating that the crew attempted to launch either lifeboat. Subsea video and still images taken of EL FARO by a remotely operated underwater vehicle showed extensive damage to both boat lifeboat launching systems including twisted davit arms. Some of the images of the sunken port lifeboat showed that a sheering force was applied diagonally to one end of the sunken boat.[345]

On September 28, 2015, the day before the accident voyage departure, two repair technicians boarded EL FARO to replace two free wheel clutches on the lifeboat davits.[346] The technicians completed and tested the repairs on September 29, just prior to EL FARO's departure on the accident voyage. TOTE did not provide ABS or the Coast Guard with notification of these repairs. TOTE's repair plan for the davits was to complete the repairs in port. However, the servicing technician who completed the repairs testified during the MBI that he was asked by TOTE if he could get underway with EL FARO if the repairs were not completed prior to departure from port. The servicing technician testified at the MBI that an EL FARO officer had asked him if he was willing to get underway with the vessel because, "the work was progressing kind of slow just due to age and it was hard to get a part."[347] The davit repairs were subsequently completed prior to departure and the outboard lifeboat was lowered and raised to test the clutch repairs. The starboard lifeboat, which was over the dock, was not lowered. The repair was completed without lowering the boat with the understanding that EL FARO's crew would lower the starboard lifeboat at a later time.

[343] MBI Transcript February 15, 2017, p. 91.
[344] MBI Transcript February 17, 2017, pp. 110-113.
[345] NTSB Survival Factors Factual Report.
[346] MBI Exhibit 074.
[347] MBI Transcript May 26, 2016, p. 20.

There are commercially available alternatives to the gravity style open top lifeboats that were on EL FARO. One system incorporates a stern mounted lifeboat that slides down a ramp into the water. The boat is closed and fitted with seats that include a restraint system. Once the boat is loaded with passengers properly harnessed in place, the boat operator activates the launching system from inside the lifeboat; no one needs to stay behind on the ship to activate the launching of a stern launched boat. The boat slides down the rail and momentum propels it clear of the ship. The rolling and other motions of the ship have less effect on the ability of the boat to safely launch. Once clear of the ship the lifeboat can motor clear of the accident scene. The following figure illustrates the operation of a stern launched enclosed lifeboat.

Figure 48. The launching sequence for a gravity launch, free-fall lifeboat arrangement. Upper left, crew enters boat and straps in. Boat is released and enters the water where the kinetic energy propels the boat clear of the ship. The engine is running when the boat enters the water. (Source: Karishma Marine Solutions Pvt Ltd (KARCO), India)

During MBI testimony the Coast Guard Seventh District Chief of Incident Response Management stated the following when asked if a modern enclosed lifeboat would have changed his assessment of the survivability of EL FARO's crew in hurricane conditions:

Yes. If— I – in my initial interview if there was one thing that I was wishing that this crew had from the onset of this case was an enclosed lifeboat, self-launching on the rails. But, there is a caveat to that. In that the decision to abandon ship would have had to been made in a timely enough manner for them to clear the vessel. If the ship started to capsize and that was the moment they decided to go, I don't know that it would have made a difference. But if they had the option, in my professional opinion the safest place for that crew to be in those conditions was on the ship. Once that was compromised, in my opinion they did not have any other options. That lifeboat would have given them an option that they could have used earlier.

7.2.14.3. Life Rafts

Figure 49. Viking 25 person life raft of the type carried on EL FARO.

EL FARO was equipped with one 6-man raft forward and two 25-person rafts that were located on the embarkation deck near the after end of the lifeboats. These three rafts were stored in cradles with hydrostatic releasing mechanisms that would enable the rafts to automatically release and inflate should the ship sink. The rafts were equipped with a self-inflating canopy, under hull stability bags, boarding ladder, sea anchor, and survival equipment. The stability bags below the hull of the raft were designed to help stabilize the raft when deployed. These rafts could be automatically released when the vessel sank or could be manually deployed by holding onto the attached painter, throwing the raft into the water, and pulling on the painter. The painter would secure the raft to the boarding location until the raft was boarded. In a calm and stable environment, the embarkation rope ladder would be used by the crew to climb down from the embarkation point to the raft location where the crew would enter the raft. When boarding was complete the painter would be cut or released and the raft would drift free or in ideal conditions be towed away from the ship by the diesel powered lifeboat.

In addition to the required rafts, EL FARO had two additional 25-person rafts in cradles or lashed to the railings near the boat deck.[348] The additional rafts were placed on EL FARO after issues with the davit deck foundations were discovered on EL YUNQUE in mid-summer 2015. These extra rafts were still onboard EL FARO when the ship departed Jacksonville on September 29.

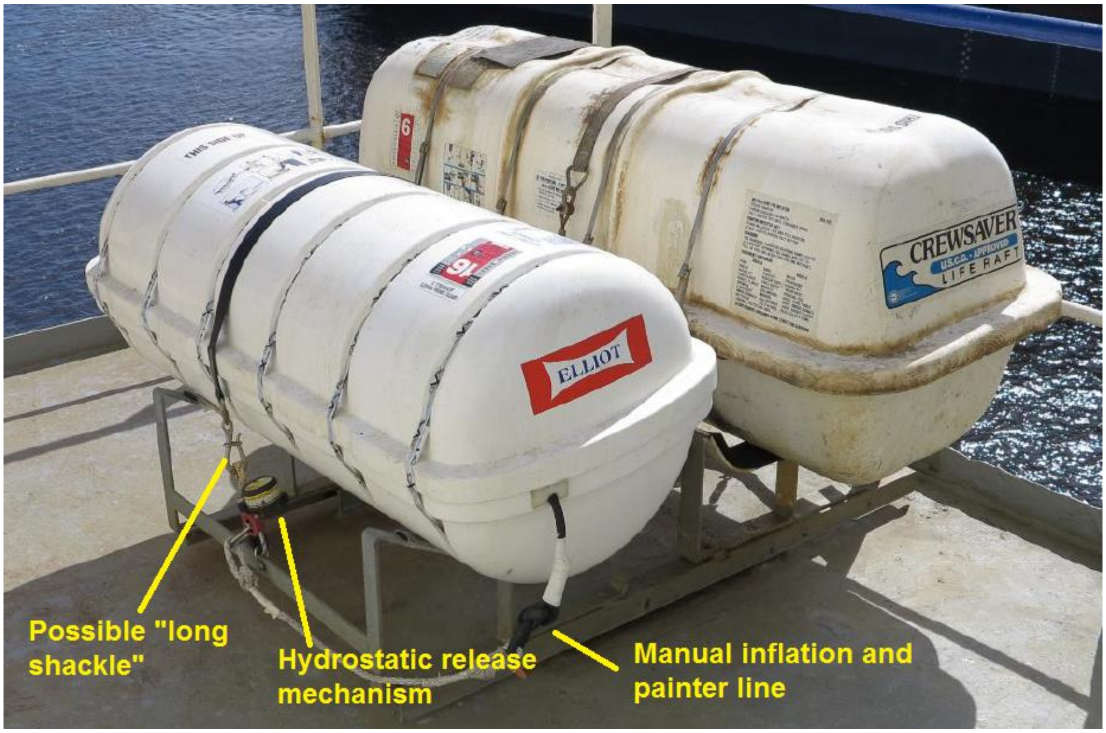

Figure 50. Required 25 person life raft with extra raft on the port side of EL YUNQUE showing the stowage of the rafts and the hydrostatic release mechanism.

The Master of EL FARO ordered the bridge watch to sound the abandon ship alarm at 7:29 AM on October 1, 2015. At 7:31 AM, the Master directed the C/M by UHF radio to throw the rafts into the water and for everyone to get off the ship and stay together.

As the crew was attempting to embark the life rafts, EL FARO was listing to port at angles in excess of fifteen degrees. At 5:18 AM the C/M[349] seemed to mention a list of eighteen[350] degrees, although the VDR audio recording could not be deciphered with complete consensus by the NTSB transcription team. The Master also described EL FARO's list as "healthy" while talking to TOTE's DPA on the satellite phone at 7:07 AM. During EL FARO's final moments, the starboard side was the weather side and the wind and seas would have affected the launching of the rafts. The port list of the ship would have brought the portside rafts very close to or possibly immersed in the sea.

[348] MBI Transcript February 19, 2016, pp. 92 and 118.
[349] MBI Exhibit 266, p. 407.
[350] MBI Exhibit 266.

During MBI testimony the Coast Guard Seventh District Chief of Incident Response Management, who also served as the SAR Mission Controller for the EL FARO incident stated the following when describing the challenges of trying to abandon a vessel into a life raft:

> *Similarly the ability to abandon ship into a life raft under good conditions is difficult because you have to get down the freeboard of the ship to the raft if the – if conditions aren't such that you can inflate the raft on deck and have the ship sink out from underneath it, it it's tied off to the ship and the ship's rolling in 30 to 40-foot seas, that's just going to be yanked back and forth. How you get down the side of ship and into a life raft in a survival suit is difficult to imagine. And if the raft isn't tied off to the ship it's just going to blow away, you're not going – you're not going to be able to get to it in those kinds of seas.*

During the Coast Guard's search and rescue phase there were two EL FARO rafts sighted. One was examined by a Coast Guard swimmer for remains and then intentionally sunk to prevent confusing later search and rescue efforts. A second life raft, which was sighted but not investigated, was not able to be relocated. No life rafts were observed in the storage locations on EL FARO during a survey of the wreckage.

7.2.14.4. Life Preservers (Lifejackets)

EL FARO carried Coast Guard approved, Type-1 life preservers, or Personal Floatation Devices (PFDs) that were designed for offshore, commercial service. Each crew member had a PFD located in their stateroom and additional PFDs were required to be located in watch stations such as the navigation bridge, the bow, and the engine room.[351] On the morning of October 1, 2015, the 2/M made a comment to the AB on watch that she did not know if there were life preservers on the bridge.[352] At 7:30 AM, after the abandon ship alarm was sounded, the 2/M asked the Master on the bridge if she could retrieve her vest. The Master made the following response:

> *Yup. Bring mine up too and bring one for [AB].*

The 2/M was not heard again on the VDR after departing to retrieve her vest. At 7:37 AM, just four minutes before EL FARO submerged, the Master yelled the following questions on the bridge:

> *Where are the life preservers (up/on) here?*
>
> *Where are the life preservers on the bridge?*

During emergency drills all crew members, including supernumeraries such as the Polish riding crew, were required to don their life preservers.

[351] MBI Transcript February 26, 2016, p. 138.
[352] MBI Exhibit 266, p. 323.

On September 29, 2015, two Polish riding crew members were relieved onboard EL FARO, they had been on the ship since August 2015. During MBI testimony one of the former riding crew members stated that he did not don a life preserver or an immersion suit during his service on EL FARO. He also stated that he did not participate in drills and that he did not know his muster station or assigned lifeboat.

7.2.14.5. Immersion Suits (Survival Suits)

Survival suits are designed to provide thermal protection to combat the effects of hypothermia, to provide floatation, and to be easily donned. Once they are donned, the wearer's physical performance of routine tasks like walking and manual dexterity for hand and finger functions would be limited.

Each EL FARO immersion suit was stored in a bag. To properly don the suit, the wearer had to lay out the suit in a relatively clear area of the deck. The wearer then put on the suit in the same manner a person would put on a pair of coveralls. Once in the suit, the wearer must zip it up and fasten the face flap over the face. During drills, the crew was expected to don the suit to the satisfaction of a deck officer.

Each crew member on EL FARO had an immersion suit stowed in their berthing area and there were also spare suits located in the engine room, at the bow, and in an internal storeroom.[353] The suits were inspected and pressure tested in August 2015. There were no discernible statements on the VDR that discussed the storage and location of the suits. There was also no VDR evidence indicating that the crew attempted to locate immersion suits on EL FARO's bridge.

At 7:28 AM, just ten minutes prior to the sinking of EL FARO, the Master instructed the C/M via UHF radio to "make sure that everyone has their immersion suits." At the time, the C/M was mustering the crew and preparing to launch the life rafts.

Three EL FARO immersion suits were located during search and rescue activities. One of the suits found floating at sea contained a deceased crew member's remains, which were not able to be identified or recovered. Further details regarding that suit are discussed in the Search and Rescue section of this report. Two other empty immersion suits, found floating on the surface, were recovered and brought ashore. One of the recovered suits was undamaged. The other recovered suit had a large tear at the waist on the front right side extending from the zipper to the side of the suit. The two recovered immersion suits were manufactured in June of 1985.

[353] MBI Transcript February 19, 2016, p. 95.

Figure 51. One of the two immersion suits that were recovered during the EL FARO search.

International Organization for Standardization (ISO) 15027 is intended to serve as a minimum performance requirement for manufacturers, purchasers, and users of safety equipment such as immersions suits. The ISO standard seeks to ensure that the equipment provides effective performance in use. It describes the immersion suit as an "abandonment" suit and includes the following guidance:

> *The abandonment suit shall have no features which will be likely to have any detrimental effect on the operation of other life-saving equipment that may be used. In particular, any part of the suit which might pose a snagging hazard shall be suitably covered, protected or restrained.*
>
> *The primary aims in wearing an abandonment suit are:*
> *a) to reduce the risk of cold shock and delay the onset of hypothermia;*
> *b) to enable the user to propel himself in the water and extricate himself from the water without it becoming an encumbrance;*
> *c) to make the user sufficiently conspicuous in the water so as to aid his recovery.*
>
> *Many circumstances may alter the performance of the suit, such as wave action or the wearing of additional equipment. Users, owners, and employers should ensure that equipment is correctly maintained according to the manufacturer's instructions.*

An abandonment suit may often be worn with a lifejacket as it will provide extra flotation and may help to bring a user to a face-up position.

Testing protocols for buoyancy and personal dexterity are detailed in 46 CFR § 160.171-17.

7.2.14.6. Other Lifesaving Equipment

EL FARO was equipped with lifesaving equipment including life rings, water lights, buoyant smoke floats, lifeboat VHF radios, [354] pyrotechnic signaling devices, line throwing appliances and small search and rescue transponder (SARTs). Based on the evidence reviewed by the MBI all the equipment listed in this section was available and in serviceable condition at the time of the accident; none of this equipment was discussed on EL FARO's VDR during the accident voyage.

7.2.15. Emergency Communications

7.2.15.1. Initial Emergency Communications

During the initial distress communications phase of the emergency, EL FARO broadcast three distinct distress alerts: Inmarsat C Distress Alert, Ship Security Alert System (SSAS), and SARSAT 406 EPIRB first Alert. The Coast Guard received all three alerts. TOTE's DPA and P/E[355] received the SSAS Inmarsat C message**.**

7.2.15.1.1. Distress Communications by Inmarsat C GMDSS Alert

The initial Inmarsat C "Distress Alert Received" email was sent to the Coast Guard Atlantic Area Command Center (LANT) at approximately 11:13 UTC[356] (7:13 AM EDT) on October 1, 2015, from the Inmarsat C, Land Earth Station (LES)/Network Coordination Station (NCS) in Eik, Norway.[357]

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[354] VHF Radios – line of sight handheld battery powered radios.
[355] TOTE Emergency Response Manual (NAU-v1CCI_ERT Manual).
[356] Time estimated, time of receipt of the email was not recorded by the LANTWatch CDO or D7 Initial Notification in MISLE.
[357] Operated by Marlink, formally Astrium Services.

```
Subject:                Message from Inmarsat-C Mobile

Categories:             SAR

Telenor INM-C LES 436820812=FARO X  1-OCT-2015 11:13:20
Ref nr.: 910348      Ocean : AORW


------------- Distress Alert Received -------------
Mobile Terminal No    : 436820812
To CES                : 001
Position              : 23.28'N 73.48'W
Position updated      : 10:30 UTC
Nature of distress    : Flooding
Course                : 235          Speed : 8
Activation            : Distress Alert
Position activated    : Yes
Course/Speed updated  : Yes
---------------------------------------------------
```

Figure 52. Eik NCS/LES - Inmarsat C Distress Alert - EL FARO.

```
Subject:                Distress info

http://10.107.5.32/tss/images/web/ADS_Logo_small.png

 DISTRESS INFORMATION SHEET

FROM:

ASTRIUM,
EIK EARTH STATION

EIK TELEPHONE: +47 5140 8000, FAX: +47 5140 2240 EMAIL: EIKVAKT@MARLINK.COM

TO:

NORFOLK

FAX: +1 757 398 6775

PHONE: +1 757 398 6700


ALERT DATE: 2015-10-01

ALERT TIME: 11:13:21

TYPE OF ALERT:

INMARSAT

OCEAN REGION:

AORW

ALERT MODE: DISTRESS

POSITION: 23.28N 73.48W

INMARSAT NUMBER:

436820812

ANSWERBACK:

FARO

VESSEL NAME:

EL FARO

CALL SIGN:
                                        1
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Figure 53. Eik NCS/LES - Inmarsat C Distress Vessel Information Sheet - EL FARO.

Following the initial report of distress a "Distress Information Sheet" was transmitted to LANTWatch at 07:15 AM. Both the Distress Alert and Information Sheet contained position information on the location of EL FARO; 23 Degrees 28 Minutes North, 73 Degrees 48 Minutes West. The positions were displayed in the messages as 23.28'N 73.48'W and 23.28N 73.48W. This format is: Degrees, period used as separation, Minutes. The Distress Alert also contained course, speed, and nature of distress information.

By policy, the Coast Guard Rescue Coordination Center (RCC) that receives a distress alert is responsible for taking initial action on that emergency.[358] An Inmarsat C Distress Alert received by either Atlantic or Pacific Area Command Centers[359] through the NCS/LES associated with the ocean region the MES distress alert was sent[360] becomes the responsible RCC. The situation is then evaluated to determine which Search and Rescue Region (SRR)[361] has responsibility, and the situation is forwarded on to the responsible SAR Coordinator and RCC.

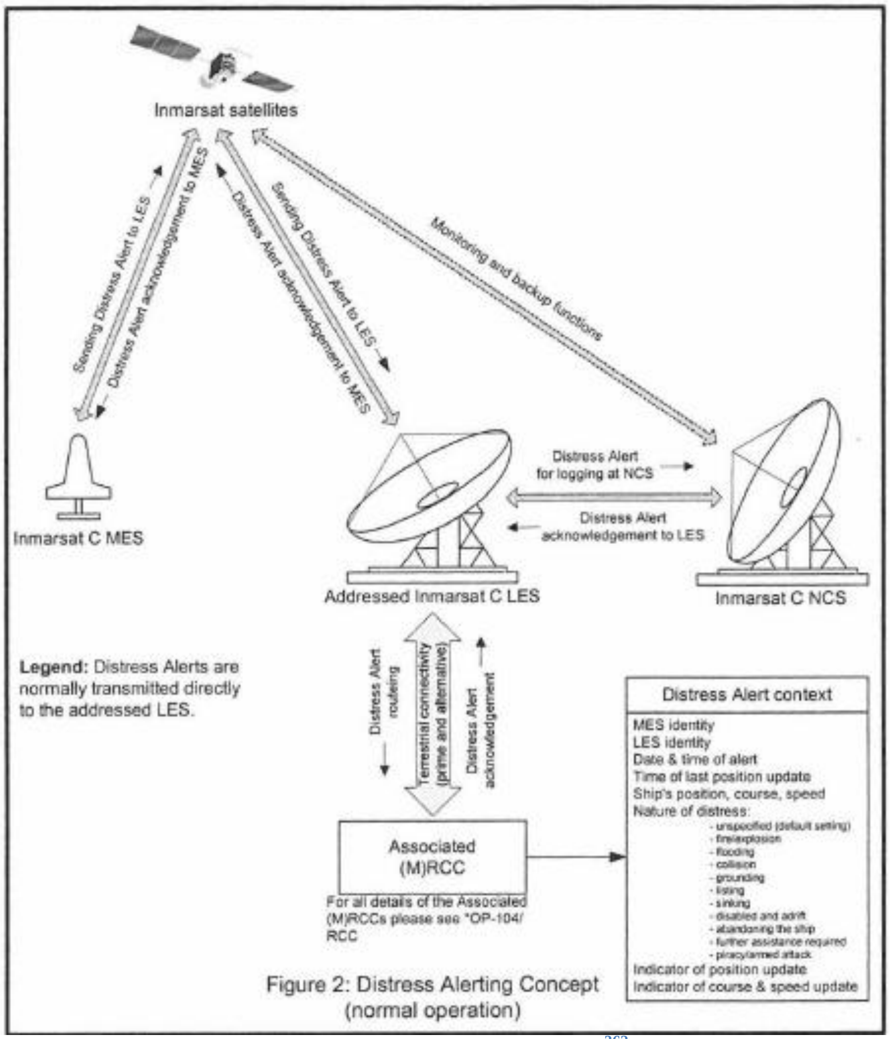

Figure 54. Inmarsat C - OP-104 Distress Alerting Concept.[362]

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[358] U.S. Coast Guard Addendum to the National SAR Supplement COMDTINST M16130.2 (series) – Section 1.2. SAR Coordination.

[359] *Id*. pp. 2-6, Para 2.1.5.3.

[360] Inmarsat C OP-104 Processing of Ship to Shore Distress Alerts and Handling the Follow-Up Distress Communications.

[361] Search and Rescue Region – U.S. National SAR Supplement to IAMSAR.

[362] Inmarsat C OP-104 Processing of Ship to Shore Distress Alerts and Handling the Follow-Up Distress Communications.

At 7:32 AM, a LANT watch stander sent an email to the Coast Guard Seventh District Command Center (D7CC) with the Distress Information Sheet attached.[363] [364] This email also contained the vessel's position as passed during an earlier phone conversation with TOTE's DPA which was 23^{o}-26.3'N, 073^{o}-51.6'W.

7.2.15.1.2. Inmarsat C Position Discrepancy

In the Distress Alert, the time of the position update was 10:30 UTC (6:30 AM EDT), approximately 43 minutes prior to the actual transmission time of the alert. The distress alert position was 4.88 nautical miles to the northeast of the SSAS position that was transmitted at 11:13:49 UTC (7:13:49 AM EDT).

The FELCOM 15 GMDSS used aboard EL FARO was capable of generating an automatic or manual position depending on the option the operator selected. During the 2/M's preparations to abandon ship, while entering the information on EL FARO's course, speed and nature of distress, she also entered the position. Manually entering the position switched the system's position input from automated to manual. After a manual input is made the system will stop doing automatic positional updates until the unit is cycled through (rebooted).[365]

7.2.15.2. Ships Security Alert System (SSAS) – By Inmarsat C

The SSAS is a covert distress signaling system that can be activated either by SARSAT/COSPAS system or Inmarsat C. This system is designed to be used when a ship is under attack by pirates. Reports are transmitted to receiving authorities that will then determine a proper course of action. For the United States, the receiving authority is the Coast Guard Pacific Area Command Center (RCC Alameda). [366] Distribution of all reports is through RCC Alameda. The Atlantic Area Command Center is also copied on the email reports, through the email group rule set up by RCC Alameda.

When EL FARO's crew prepared to abandon ship, the master informed the DPA that he was going to activate all forms of distress communications, specifically that he was activating the Inmarsat C GMDSS and SSAS units. [367] At 11:13:49 UTC (7:13:49 AM EDT) the SSAS unit was activated, sending one of three reports to the Coast Guard. Following the Coast Guard report, the DPA received a report at 11:15:57 UTC (7:15:57 AM EDT) followed by a secondary emergency response contact identified through the TOTE Emergency Response Manual as the P/E in Tacoma, WA at 11:18:39 UTC[368] (7:18:39 AM EDT).

[363] LANTWATCH Email - Inmarsat C distress: Distress info EL FARO, 48NM East of San Salvador.
[364] D7CC Email to LANTWATCH - Read: Inmarsat C distress: Distress info EL FARO, 48NM East of San Salvador.
[365] NTSB/FURUNO FELCOM 15 Demonstration March 09, 2017.
[366] COMDINSTR M3120.3 Guidance for the Ships Security Alert System (SSAS).
[367] MBI Transcript February 20, 2016, p. 78.
[368] Inm-C 436820812 Log 0000 Sept 28 to 1800 Oct 1, 2015 (160307).

```
--- SSAS ALERT MESSAGE ---
Vessel Name: EL FARO
MMSI:     368208000
IMN:      436820812
LAT:      23:25.39N
LON:      073:52.51W
Time:     10/01/2015 11:13:49(UTC)
COURSE:   214 deg
SPEED:    04 kt
Time:     10/01/2015 11:13:49(UTC)
```

Figure 55. SSAS report transmitted to U.S. Coast Guard.

```
--- SSAS ALERT MESSAGE ---
Vessel Name: EL FARO
MMSI:     368208000
IMN:      436820812
LAT:      23:25.22N
LON:      073:52.68W
Time:     10/01/2015 11:15:57(UTC)
COURSE:   227 deg
SPEED:    10 kt
Time:     10/01/2015 11:15:57(UTC)
```

Figure 56. SSAS report transmitted to TOTE services.

The SSAS positions are generated automatically using the ship's GPS and they cannot be manually overwritten. Formatting of the position is in Degrees, Minutes/Decimal Minutes and is displayed as DD:MM.mmN, DDD:MM.mmW. There are no degrees or minutes symbols displayed in a SSAS message.

7.2.15.3. <u>SARSAT/COSPAS 406Mhz Distress Alert</u>

EL FARO's 406Mhz Emergency Position Indicating Radio Beacon (EPIRB)[369] was activated at 11:36 UTC (7:36 AM EDT). The D7CC received a 406 Beacon Unlocated First Alert report at 11:39 UTC (7:39 AM EDT).[370] This report was "unlocated" because it did not contain position information; however, it still acted as an alert of EL FARO's distress.

```
********************* 406 BEACON UNLOCATED FIRST ALERT ********************

BEACON ID: ADCD0 28F4A 40C01      SITE ID: 38753

**************** DETECTION TIME AND POSITIONS FOR THE BEACON *************

PROB  SOL  LATITUDE  LONGITUDE  DETECT TIME  SAT  SOURCE SRR   /BUFFER
N/A   N/A  N/A                  01 1136 OCT  G13  MD1    CGD07

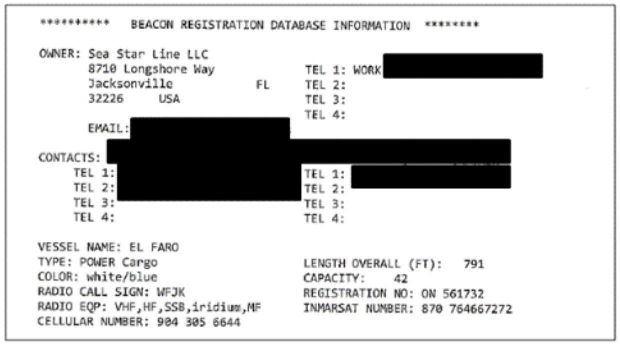
DETECTION FREQUENCY: 406.0369 MHZ
```

Figure 57. SARSAT - 406 Beacon unlocated First Alert - EL FARO.

[369] Model: Jotron Tron 40S MkII Frequency: 406.037 MHz Serial nos.: 09170 (on 1/27/22015 safety survey by Imtech Marine/Radio Holland); ADCDO 28F4A 40C01 (ID FCC registration); 49989 (on ABS certificate) Antenna: omni-directional, 5 watts GPS: none Operating life: minimum 48 hr Battery exp.: 2/1/2019 Release: manual or hydrostatic Bracket: Type FB-6; Serial 03101 Hydrostatic release expires: 2/1/2016 Date Registered: 2/1/2012 Last Update: 12/3/2013 Decal Expires: 12/3/2015 In service: 2/16/2007, Jacksonville FL.

[370] 406 Beacon Unlocated First Alert – USMCC Report to the Coast Guard D7 Command Center.

At the time of EL FARO's accident voyage, NOAA SARSAT[371] system relied on two satellite systems to detect and track active 406Mhz beacons throughout the U.S. and worldwide.[372] These two satellite systems are the geostationary satellites (GOES) and low earth orbiting (LEO) satellites. Geostationary satellites do not normally provide geographic locations, but they provide initial notification of an active beacon and responsible party contact information. If GPS had been embedded in EL FARO's EPIRB, the vessel's position could have been determined in a single satellite pass. However, EL FARO's 406Mhz beacon did not contain embedded GPS.



********** BEACON REGISTRATION DATABASE INFORMATION ********

OWNER: Sea Star Line LLC
8710 Longshore Way
Jacksonville FL
32226 USA

TEL 1: WORK [redacted]
TEL 2:
TEL 3:
TEL 4:

EMAIL: [redacted]

CONTACTS: [redacted]
TEL 1: [redacted]
TEL 2:
TEL 3:
TEL 4:

TEL 1: [redacted]
TEL 2:
TEL 3:
TEL 4:

VESSEL NAME: EL FARO
TYPE: POWER Cargo
COLOR: white/blue
RADIO CALL SIGN: WFJK
RADIO EQP: VHF,HF,SSB,iridium,MF
CELLULAR NUMBER: 904 305 6644

LENGTH OVERALL (FT): 791
CAPACITY: 42
REGISTRATION NO: ON 561732
INMARSAT NUMBER: 870 764667272

Figure 58. Beacon registration database information.

No position was available from the GOES-E Satellite (G13) Geostationary satellite (GEOSAR) that detected the signal from EL FARO's Emergency Position Locating Radio Beacon (EPIRB)[373].

No Low Earth Orbiting Satellites (LEOSAR) were in range of EL FARO during the period of time the beacon was active[374] and therefore no Doppler position could be determined.[375]

[371] Summary of EL FARO final with coverage of satellites final with correction on AIS inputs March 16, 2016.
[372] United States Mission Control Center (USMCC), National Rescue Coordination Center (RCC) and Search and Rescue Point of Contact (SPOC) 406 MHz Alert and Support Messages for the LEOSAR/GEOSAR/MEOSAR (LGM) System.
[373] http://www.sarsat.noaa.gov/sys-diag.html NOAA Search and Rescue Satellite Aided Tracking System Overview.
[374] Summary of EL FARO final with coverage of satellites final with correction on AIS inputs March 16, 2016.
[375] MBI Transcript February 15, 2017, p. 1468.

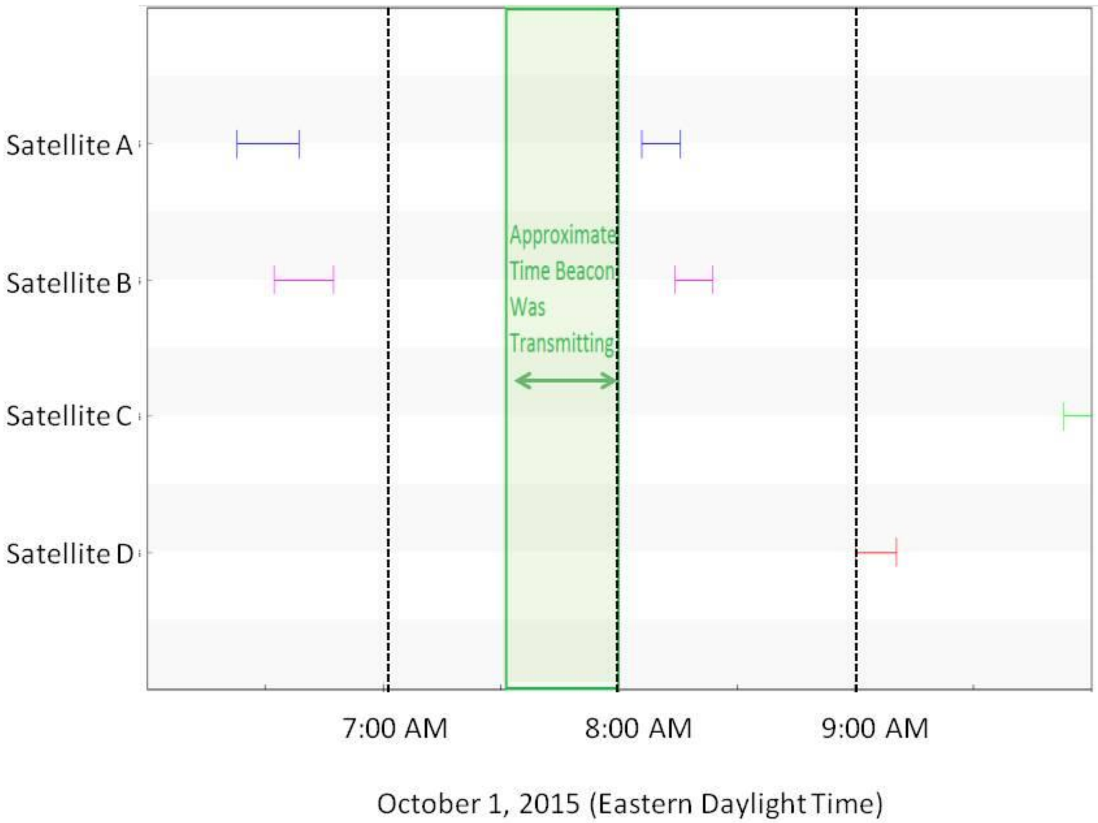


Figure 59. LEO satellite in view periods.[376]

The Coast Guard received no other SARSAT alerts, which was by design. The United States Mission Control Center (USMCC)[377] reporting rules are only to send each report type one time, unless there is a change in the information.[378] When the unlocated information for EL FARO was solely received by the GEO Local User Terminal (LUT), they only transmitted the initial report to the Coast Guard.[379] When the EPIRB signal ceases, the report of closure of the site does not occur for 18 hours. The next report expected after an Unlocated SARSAT report is a LEOSAR report (if the signal is within visibility of the LEOSATs) of Ambiguity Unresolved with two potential positions listed.

[376] Summary of EL FARO final with coverage of satellites final with correction on AIS inputs March 16, 2016.
[377] See NOAA Search and Rescue Satellite Aided Tracking webpage: http://www.sarsat.noaa.gov/usmcc.html.
[378] 406 beacon located first alert - ambiguity unresolved: This message is sent when a 406 MHz beacon is first detected with encoded or Doppler position information available, but ambiguity is not resolved.
[379] CG-NTSB Transcript and Errata – Survival – SARSAT Senior Space System Engineer – NOAA, March 04, 2016, pp. 46-47.

SIT	Message Name / Comments
160	**406 BEACON UNLOCATED FIRST ALERT** This message is sent when a 406 MHz beacon (with registration information or craft identification) is first detected but no encoded or Doppler position information is available. This message is usually sent when a beacon signal is detected first by a Geostationary satellite. Section 3.2.3.8.1 describes distribution procedures for unlocated alerts.
161	**406 BEACON LOCATED FIRST ALERT (AMBIGUITY UNRESOLVED)** This message is sent when a 406 MHz beacon is first detected with encoded or Doppler position information available, but ambiguity is not resolved.
162	**406 BEACON LOCATED FIRST ALERT UPDATE (AMBIGUITY UNRESOLVED)** This message is sent prior to ambiguity resolution when an alert with Doppler location (SIT 161) was previously sent and updated information regarding the A/B probability is available for the same satellite pass. It is only sent if the "A" side probability in the new solution is at least 30% higher than the "A" side probability in the old solution.

Figure 60. Alert message types for 406 EPIRBs.[380]

Two LEOSAR satellites (S7 and S10) [381] did not detect EL FARO's beacon while in view of the area where it sank because they crossed before and after the signal was active. During the time period the EPIRB was active neither satellite was in view. As a result, EL FARO's position could not be determined using the SARSAT system.[382]

7.2.15.4. SARSAT Modernization GEO/MEO/LEO

Prior to the accident, NOAA/SARSAT[383] in Suitland, Maryland was in the process of adding capability to the SARSAT system used by the United States as part of the SARSAT/COSPAS System.[384] The network of satellites and ground stations provides mariners with the ability to send automated distress alerts that are monitored and processed by USMCC and transmitted to the Coast Guard for response. Prior to the implementation of MEOSAR, NOAA relied on two types of satellites to receive signals from 406Mhz distress beacons including EPIRBs, ELTs and PLBs. These satellite systems are geostationary (GEO) and low earth polar orbiting (LEO). Because the system relies on the Doppler Effect to calculate vessel positions, only the LEO satellites can provide position information, unless the EPIRB contains GPS capability. When an EPIRB is registered, its Beacon ID hexadecimal serial code is registered to the USMCC database and cross referenced with the owner and point of contact information.[385] Because GEO satellites are in a geostationary orbit with the planet and at a high altitude over the earth, they can receive

380 USMCC National Rescue Coordination Center (RCC) and Search and Rescue Point of Contact (SPOC) 406MHz Alert and Support Messages 1 May 2013 Version 2.00 Paragraph 2.1.1 Alert Message Types.
381 CG-NTSB Transcript and Errata – Survival – SARSAT Senior Space System Engineer – NOAA, March 04, 2016, pp. 47-48.
382 Summary of EL FARO final with coverage of satellites final with correction on AIS inputs March 16, 2016.
383 http://www.sarsat.noaa.gov/sys-diag.htm NOAA Search and Rescue Satellite Aided Tracking – SARSAT System Overview.
384 Transcripts and Errata – Survival – SARSAT Senior Space Systems Engineer – NOAA- March 04, 2016.
385 The BEACON ID is a 15 character hexadecimal code that identifies the 406 MHz beacon. The BEACON ID corresponds to bits 26 to 85 of the 406 MHz message transmitted by the beacon as described in document C/S T.001. For location protocol beacons (which use GPS/navigation input to determine beacon position), the bits of the BEACON ID that contain location are defaulted, so that the same BEACON ID is referenced regardless of its encoded position. The BEACON ID is used to reference USMCC registration data for the beacon. The BEACON ID is useful in discussing a SAR case with other SAR agencies, especially when the other SAR agency does not receive alert messages from the USMCC, since the SITE ID (described below) is specific to the USMCC.

the hexadecimal code, but they have no capability to determine a Doppler location due to their synchronous orbit with the rotation of the earth. GPS capable EPIRBs are the only method for GEOSAR Satellites to receive a position.

There are five LEOSAR satellites operating today. The system is old by satellite standards and within a short span of time many will become inoperable without replacement systems. Because of this, USMCC was testing a Mid-Earth Orbiting (MEOSAR) system[386] when the accident occurred. The MEOSAR system uses the GPS constellation of satellites to determine position of an EPIRB's hexadecimal signal by measuring the time difference of when the signal is received by the satellites.

During the timeframe of EL FARO's casualty the MEOSAR system was not fully operational or monitored in real time by USMCC. The system was under an evaluation process and therefore USMCC had the ability to receive and store data from EL FARO's EPIRB. NOAA/USMCC engineers completed a post-accident review for EL FARO,[387] which provided detailed information on the length of time the beacon was activated, the number of data bursts received, and the relative position of satellites before, during, and after the beacon was active.[388]

Burst #	Time (UTC)	MD1	MD2
1	10/01/15 11:35:05.000	1	
2	10/01/15 11:35:55.000		
3	10/01/15 11:36:45.000	1	1
4	10/01/15 11:37:35.000	1	
5	10/01/15 11:38:25.000	1	
6	10/01/15 11:39:15.000	1	
7	10/01/15 11:40:05.000	1	1
8	10/01/15 11:40:55.000		1
9	10/01/15 11:41:45.000	1	
10	10/01/15 11:42:35.000		1
11	10/01/15 11:43:25.000		1
12	10/01/15 11:44:15.000		
13	10/01/15 11:45:05.000	1	
14	10/01/15 11:45:55.000	1	1
15	10/01/15 11:46:45.000		
16	10/01/15 11:47:35.000		1
17	10/01/15 11:48:25.000		
18	10/01/15 11:49:15.000		
19	10/01/15 11:50:05.000		1
20	10/01/15 11:50:55.000		
21	10/01/15 11:51:45.000	1	1
22	10/01/15 11:52:35.000		1
23	10/01/15 11:53:25.000		1
24	10/01/15 11:54:15.000		
25	10/01/15 11:55:05.000		
26	10/01/15 11:55:55.000		
27	10/01/15 11:56:45.000		
28	10/01/15 11:57:35.000	1	
29	10/01/15 11:58:25.000	1	1
30	10/01/15 11:59:15.000	1	1

Table 1 – MD1 / GOES-E Data – 13 Bursts MD2 / GOES-W Data – 13 Bursts

Figure 61. USMCC GOES satellite reception of data transmitted by the EL FARO's EPIRB

386 Transcripts and Errata – Survival – SARSAT Senior Space Systems Engineer – NOAA- March 04, 2016, p. 9.
387 Summary of EL FARO final with coverage of satellites final with correction on AIS inputs March 16, 2016.
388 *Id.*

USMCC was able to confirm that the beacon was active for 24 minutes and that two LEOSAR satellites passed over the area prior to beacon activation and after the beacon signal ceased. An analysis of the MEOSAR system showed that EL FARO's beacon provided adequate data to create position reports seven times over the 24 minutes the signal was active. These positions were processed by MEOLUTs in Hawaii and Florida, which calculated EL FARO's position within five minutes of beacon transmission.[389] As of December 16, 2016, MEOSAR began operating an Early Operational Capability (EOC) period. As a result, MEOSAR beacon detections are now actively monitored.

7.2.16. Voyage Data Recorder (VDR).

The VDR carriage requirements for EL FARO are contained in Chapter V of the International Convention for the Safety of Life at Sea (SOLAS), Regulation 20. Under that regulation, cargo ships larger than 3,000 gross tons must be equipped with a VDR. Ships larger than 3,000 GT built before July 2002, such as EL FARO, may carry a Simplified VDR (S-VDR).

In 2009, EL FARO was fitted with a Sperry Marine VoyageMaster II VDR, Serial no.: A06032-000937. EL FARO's S-VDR system was in compliance with the existing carriage requirement at the date of installation and at the time of the accident voyage.

A VDR is intended to provide marine casualty investigators with a tool to hear recorded conversations, and to see video as well as critical navigational information that is contained in the VDR memory.

The VDR system collects data from several different feeds. Ships' navigational instruments, such as the global position system (GPS), send data to the VDR control cabinet. From there, the input is recorded and the same data is sent to the VDR capsule. The VDR control cabinet gets its power from the ship's electrical system and if that fails, internal batteries continue to power the VDR system. If a vessel sinks, one of two things happen; either the VDR capsule goes down with the ship with the data stored on a memory card in the VDR capsule, or the VDR capsule detaches from the storage cradle and the VDR capsule floats free. In either case, the VDR capsule is a watertight enclosure that can withstand the environment and the water pressure at the bottom of the ocean. The capsule is fitted with a locator beacon, and in the case of a float-free capsule, also contains a marker light and EPIRB. Both types of VDR capsules are encircled with reflective tape and painted a bright color to facilitate location of the devices. The float-free VDR capsule is a combination unit that combines a GPS equipped EPIRB with the capability of storing at least 48 hours of VDR information.

The S-VDR capsule equipped on EL FARO was designed to stay with the ship for retrieval by a remotely operated underwater vehicle (ROV). It contained the following types of sensor information:[390] geographical position in latitude and longitude, speed, course, rate of turn, and other navigation related data. In addition to this information, the S-VDR also recorded audio

[389] Summary of EL FARO final with coverage of satellites final with correction on AIS inputs March 16, 2016 – Table 3 MEOLUT Input to MEOMCC DB.

[390] For a complete list of the sensor data contained on EL FARO S-VDR see the NTSB Group Electronics Factual Report in the NTSB Docket, DCA16MM001.

from microphones on the navigation bridge and on the exterior bridge wings. There was also an input that captured radar screen still images from one of EL FARO's radars every 15 seconds.

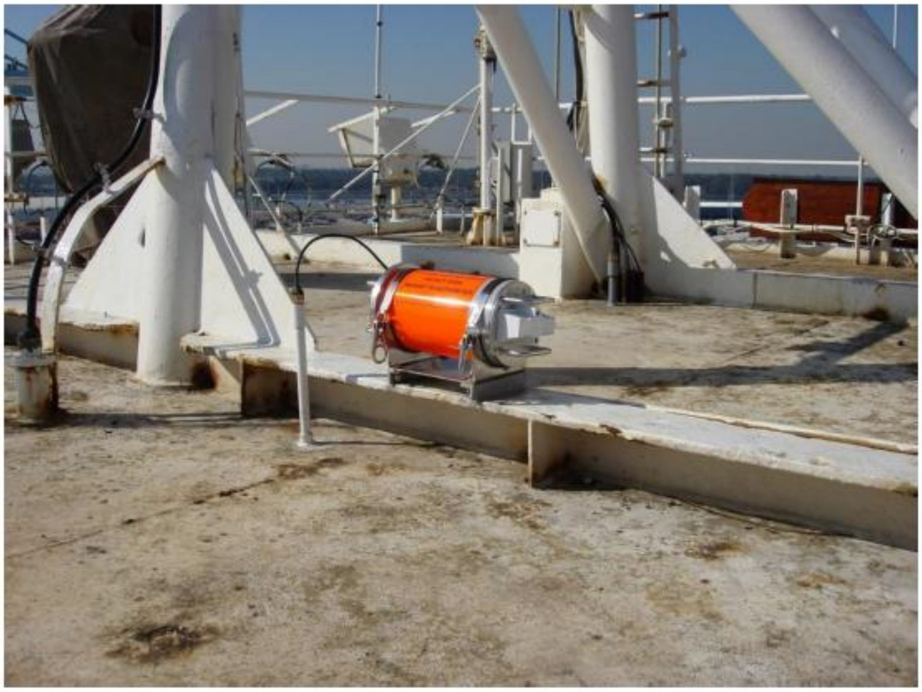


Figure 62. Archive photo of the EL FARO S-VDR capsule mounted on a beam on the flying bridge, port side. (Source: Radio Holland)

To aid in the recovery of EL FARO's S-VDR capsule, the recorder contained a water-activated, battery-powered, acoustic beacon. When submerged, the beacon was designed to transmit a signal to aid location and recovery of the unit for at least 30 days. However, the first search for EL FARO's VDR, which was conducted within 30 days of the accident using a towed underwater listening device, could not detect the S-VDR beacon. EL FARO wreckage was discovered using side scan sonar on November 1, 2015.

EL FARO's capsule was mounted on a beam on the deck of the flying bridge, which supported the large mast on the vessel. The capsule was held in the bracket by the required straps fitted with latches and large rings. The system was designed so that in the event recovery was necessary after an accident, an ROV could use its manipulator arms to open the latches by grasping the rings on the latches. After opening the latches the ROV could remove the capsule from the bracket and then bring the capsule to the surface. The capsule also had a single wire bundle which penetrated the deck of the ship and led to the VDR equipment cabinet.

The VDR system for EL FARO was required to be examined during an annual performance test (APT) that was to be carried out by a certified technician. The last APT for EL FARO's S-VDR was completed in December 2014. During the APT, the technician inspected and tested the unit and found the operation of the system satisfactory. The servicing technician did not make a notation regarding potential issues with the VDR input from the anemometer(s). The battery for the acoustic pinger was due to expire in May 2015, which was well before expiration of the APT certificate that was issued after the APT. It was Sperry's policy that the acoustic pinger battery expiration date must be after the expiration of the APT certificate. The IMO,[391] on the other hand, only required that the battery not be expired at the time of the APT. The acoustic beacon itself was set to expire in May 2015 and the typical service protocol[392] was to change out the beacon itself to ensure reliability. The checklist that the APT technician used to verify proper operation included the notation that the battery should have been replaced as part of the inspection and issuance of the Compliance Certificate.[393]

EL FARO's recorded audio came from six microphones in and around the bridge. The S-VDR's recorded audio from EL FARO's capsule was examined[394] and transcribed by a team led by the NTSB. In general, the recordings from all the microphones contained only poor quality audio recordings. The recorded VHF marine radio channel had a flat signal indicating that the VHF radio set up to be recorded was not activated. NTSB VDR technical experts concluded that Channel M3, covering the port and starboard bridge wings, was not useable.

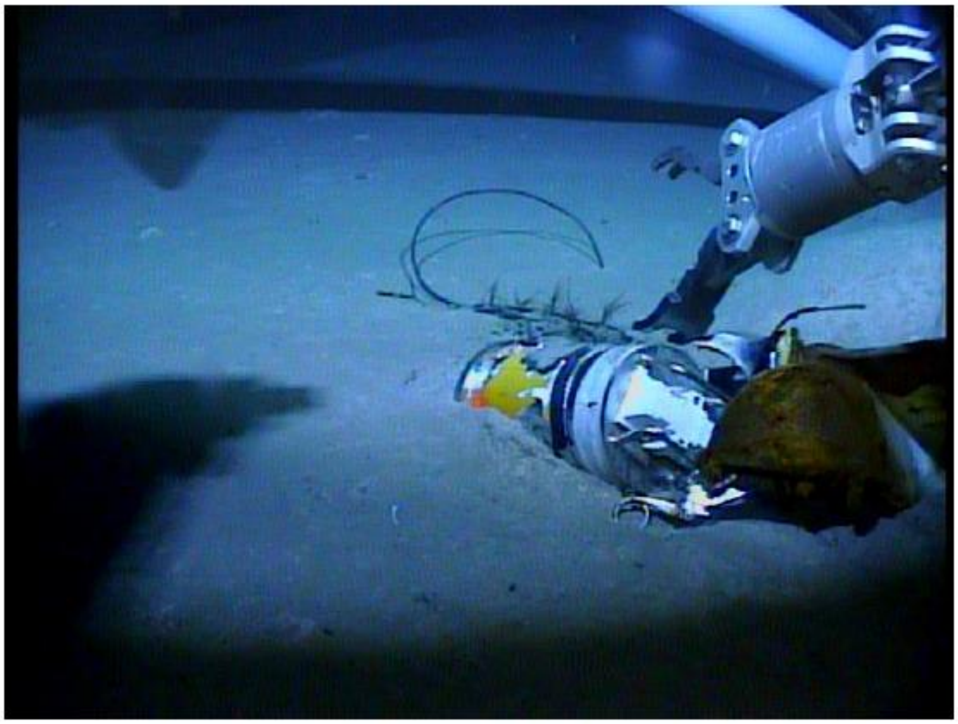


Figure 63. Remote operating vehicle (ROV) manipulator arm positioned above the EL FARO S-VDR capsule on the sea floor prior to the capsule recovery (Source: U.S. Navy Supervisor of Salvage).

Following the loss of EL FARO, the NTSB immediately commenced efforts to recover the S-VDR. Three voyages were conducted to the accident site to locate and recover the S-VDR. The first voyage located and documented EL FARO's wreck site, which was located in over 15,000 of water near the last known location of the ship prior to sinking. The second voyage to the

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[391] MBI Transcript February 24, 2016, p. 86.
[392] MBI Transcript February 14, 2016, p. 124.
[393] For complete details see Attachment 7, NTSB Group Electronics Factual Report in the NTSB Docket, DCA16MM001.
[394] NTSB Voyage Data Recorder Group Chairman Factual Report.

accident site located the S-VDR capsule near EL FARO's mast, which had broken away from the main wreckage. The capsule's reflective tape aided in locating the capsule on the sandy bottom, as the tape was illuminated by the ROV's camera strobe light system.

Although the VDR was located during the second search mission, the vessel did not have an ROV capable of retrieving the capsule. A final recovery mission was able to secure the capsule on August 8, 2016, and it was preserved and transported to the NTSB laboratory for data recovery and analysis.

7.2.17. <u>EL FARO Wreckage Observations</u>

The wreckage of EL FARO sits at a depth of approximately 15,400 feet, in position 23-22.9N, 073-54.9W.

The primary objective of NTSB's search for EL FARO's wreckage was to recover the S-VDR. However, while doing so, the NTSB was also able to collect imagery of the wreckage on the sea floor. The equipment used for the S-VDR search was too large to enter the interior of EL FARO, and the risk of entangling the ROV's tether was too great to attempt entry into one of EL FARO's large 2nd deck cargo bay openings.

EL FARO's mast was located 1,476 feet from the bow of the vessel, with the radar still affixed and the VDR located near the base of the mast. The S-VDR capsule was recovered intact, and the data it contained provided critical information to the MBI and NTSB investigations.

NTSB Accident Docket DCA16MM001 contains detailed information regarding the VDR search efforts and underwater wreckage observations.

The general configuration of the wreckage on the bottom was mapped on a bathymetric composite image (see Figure 64).

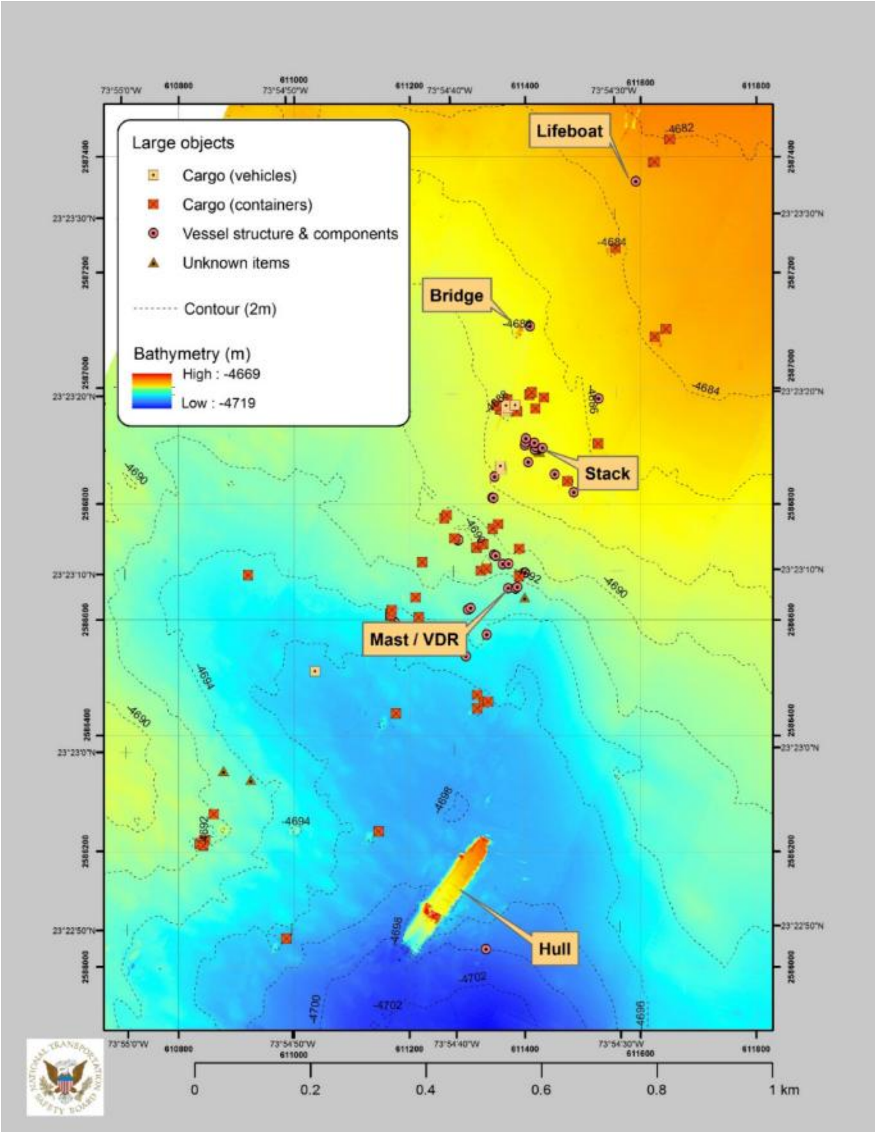

Figure 64. Composite EL FARO debris field chart (reproduced from NSTB Naval Architecture Group factual report).

The ship's accommodations space, called the "house," is partially intact, and the majority of that structure remains affixed to the hull. The navigation bridge was separated from the rest of the vessel and was located north of the vessel, as indicated in figure #64. The navigation bridge structure was damaged, but landed upright and structurally intact on the sea floor, about half a mile from the hull. The deck that housed the staterooms and offices for senior officers immediately below the bridge is missing, and the bulkheads for that portion of the superstructure are scattered around the wreck. The rest of the superstructure decks were still affixed to the hull along with ship fixtures, including the lifeboat davits, ladders, and lockers. There were large, arch-shaped scratches noticeable on the vertical surface of the exterior accommodation space on the port side of the vessel, in the vicinity of where the port lifeboat was cradled. The exterior starboard side vertical surface of the accommodation area does not have this same damage, and the starboard lifeboat davits were not as severely damaged as the portside davits.

The hull of EL FARO is sitting on the seafloor in an upright position with the bottom portion buried in the silt of the seabed. The upper portion of the ship's stem and bulbous bow were left exposed with the forward draft marks indicating that about 14 feet of the bow section is buried in the seabed. The remainder of the hull gradually slopes to the stern where the bottom of the stern transom is partially visible. The containers that were located on the upper deck of the vessel are missing and there are a large number of containers located on the seafloor in EL FARO's debris field. The transverse beams and the deck sockets for the container securing mechanisms are intact in some areas and missing and damaged in others. The portion of the hull that is buried in the silt, including the propeller, shaft, and rudder, could not be examined. There was visible damage to the bottom of the transom just above the rudder.

There are several fractures in the hull plating, most notably near bay 16 at frame 200. This crack, which has a maximum width of three feet, extends from the sediment line up to the main deck, and then continues athwartship across the vessel's main deck.

EL FARO's port diesel-powered lifeboat was located on the seafloor in a severely damaged condition, the buoyancy tanks along the interior side of the hull, running fore and aft, are gone, but the hull shape remains mostly intact. The aft end of the port lifeboat was severed off at an oblique angle, in a position where the gripes would have secured the lifeboat in its cradle. The damaged starboard lifeboat was found floating on the surface in EL FARO's debris field during search and rescue efforts, it was recovered and brought to shore for a full survey. The equipment that was used to secure the lifeboats in the launching appliances appears to be lying in close proximity to the hull wreckage. The davit systems for both lifeboats were twisted and heavily damaged by either the hurricane conditions, the forces incurred as the vessel sank to the bottom, or both. The launching rails for the starboard life boat are relatively intact, while the equipment for the port life boat appears more heavily damaged and is hanging off the decks where they were mounted.

Figure 65. EL FARO Starboard Lifeboat. Heavy damage to the starboard side of the lifeboat is visible. Photo taken at Coast Guard Air Station Miami.

Figure 66. EL FARO Starboard Lifeboat. Damage to the port bow of the lifeboat is visible. Photo taken at Coast Guard Air Station Miami.

7.2.18. Search and Rescue

7.2.18.1. Summary of Search and Rescue Efforts

The Coast Guard became aware of EL FARO being in distress at approximately 07:15 AM on October 1, 2015, through an Inmarsat C message and a telephone call with the TSI DPA. The Coast Guard Atlantic Area Command Center (LANTCC)[395] Command Duty Officer (CDO)[396] passed initial information to the Coast Guard Seventh District Command Center (D7CC)[397] Operations Unit Controller (OU)[398] verbally, and followed up their phone conversation with an email that included the Inmarsat C Distress Alert Information Sheet. Following receipt of that email, the D7CC OU contacted the DPA to gather additional information about EL FARO's situation. During this conversation, a satellite distress 406MHz alert was received by D7CC from United States Mission Control Center (USMCC).[399] This report, categorized as; 406 Beacon Unlocated First Alert, did not include position information,[400] the EPIRB on EL FARO did not contain an integral GPS, which would have relayed the ship's position to the overhead satellite in a single pass. After receiving the notification from LANTCC, D7 designated the SAR Mission Coordinator (SMC)[401] for the case.

[395] LANTCC, Coast Guard Atlantic Area Command Center Watch.
[396] Atlantic Area Command Duty Officer for the Atlantic Area Commander located in Portsmouth, Va.
[397] District Seven Headquarters, Command Center, located in Miami, Fl.
[398] Command Center Manual M3120.20: Operations Unit; The Operations Unit is responsible for the planning and execution of incident response missions conducted within the AOR. At the different levels of CCs, these responsibilities may translate into different positions.
[399] United States Mission Control Center (USMCC) in Suitland, MD. USMCC is operated by the National Oceanic and Atmospheric Administration.
[400] Coast Guard SARSAT 406MHz Beacon Unlocated First Alert, SS EL FARO Site ID 38753.
[401] Chief of Incident Management Branch (DRM), CGD7.

Over the next six days, until suspension of search activities, the Coast Guard conducted 55 sorties that searched over 709,000 square nautical miles of ocean. The search assets included units from the Coast Guard, Department of Defense, Air National Guard, and commercial crafts. The search efforts located EL FARO debris fields and one deceased crew member in a survival suit. The Coast Guard's rescue coordinator for the case testified at the MBI that the Coast Guard helicopter that located the deceased crew member had to temporarily depart the location, after confirming that the crew member was deceased, to check on a report of another immersion suit floating in the water. Before departing to continue the search for survivors, the Coast Guard rescue swimmer marked the crew member's remains with a SLDMB; however, the datum buoy failed to operate and the deceased crew member was not able to be relocated. Upon concluding that the ship had sunk, and after finding no signs of life, the search was suspended at sunset on October 8, 2015.[402]

7.2.18.2. Initial Notification

EL FARO activated its Inmarsat C distress and Ship Security Alert System (SSAS) at 7:13 AM on October 1, 2015,[403] which alerted the LANTCC of the distress situation. LANTCC also received an SSAS report[404] from the Pacific Area Command Center[405] via email at 7:15 AM, which was two minutes after EL FARO activated the system. The position on the SSAS message was 23° 25.39'N and 073° 52.51'W. Upon receiving the alert, the LANTCC CDO notified[406] the D7CC watchstander. LANTCC provided minimal details during the initial call, but stated that EL FARO's position information would be sent by email after the call. At 7:24 AM, as the LANTCC watchstander was in the process of drafting the follow-up email, he received a call from the TSI DPA,[407] who provided further details on EL FARO's situation.

The D7 watch called back the LANTCC duty officer in Portsmouth, Virginia,[408] inquiring about the status of the follow-up email they were expecting. The duty officer stated that more information would follow shortly, including details from the conversation with the TSI DPA, the Inmarsat C Alert, and the SSAS Alert. The LANTCC email was subsequently sent to the D7CC at 7:32 AM,[409] and included an Inmarsat C position of 23°28′N and 073°48′W, the TSI DPA's contact information, and the last position passed from the Master of EL FARO (23° 26.3′N, 073° 51.6′W),[410] which was described as 48 nautical miles east of San Salvador. The Portsmouth based duty officer also notified D7CC of the SSAS alert received from EL FARO, but he failed to include the position from the SSAS message in his email. The LANTCC email notification also contained a MARLINK/ASTRIUM Inmarsat C Distress Vessel Information Sheet that listed a position of 23.28N and 73.48W.

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402 CGD7 Next of Kin Briefing, October 06, 2015.
403 SSAS Alert Email INMC.eik.com to the Coast Guard.
404 SSAS Alert Email INMC.eik.com to the Coast Guard.
405 COMDTINST 3120.3 Guidance For The Ship Security Alert System (SSAS).
406 MBI Exhibit 033.
407 MBI Exhibit 032.
408 D7CC DVL Recording SAR_844084470 (D7CC to LANTWatch).
409 MBI Exhibit 034.
410 MBI Exhibit 032.

Following receipt of the LANTCC email report, at approximately 7:38 AM,[411] the D7CC watch contacted the TSI DPA. During this conversation, recorded background audio from the command center picked up a computer generated voice alert stating "Attention Emergency" that is consistent with a Coast Guard SARSAT notification alarm going off within the command center.[412] This alarm was the first notification of the SARSAT activation at 7:36 AM.[413] This 406MHz SARSAT Unlocated First Alert from EL FARO's EPIRB was the only SARSAT alert received by the Coast Guard and it was processed at 7:39 AM. From 7:35 AM to 7:59 AM (a period of 24 minutes) 30 bursts were received by USMCC; however the satellite system that captured those bursts was not being actively monitored at the time of EL FARO's sinking.[414]

7.2.18.3. D7 Miami Initial Actions

The D7 Miami command center watchstander determined the last known position (LKP) of EL FARO by taking the position information received from the Inmarsat C[415] Data Information Sheet and entering it into the Coast Guard Search and Rescue Optimal Planning System (SAROPS).[416] The position was entered into SAROPS as degrees and tenths of degrees, rather than degrees and minutes. Entering the information in degrees and tenths of degrees introduced an error for the initial position that was never corrected during the course of D7CC's case.

The MARLINK[417] Inmarsat C displayed position coordinates formatted as degrees and minutes as DD.MM, with a decimal point used as a separator between the degree and minute value. The Coast Guard Atlantic Area Command Center received two types of reports from MARLINK. One was "Distress Alert"[418] and the other was a "Distress Information Sheet." The LANTCC duty officer only sent the "Distress Information Sheet" to the D7CC and the original "Distress Alert" was not sent. The Distress Alert had a "minute" symbol after the minute digits (DD.MM'N DD.MM'W), while the Distress Information Sheet did not contain the minute symbol. The Distress Alert also contained the following additional data that was not included on the Distress Information Sheet: position update time, nature of distress, course and speed.

The error was introduced into the Inmarsat C LKP because the Distress Information Sheet position of 23.28N, 73.48W was entered directly into the SAROPS. SAROPS automatically converted that format and changed it to degrees, minutes, and decimal minutes (DD-MM.mmN DDD-MM.mmW). As a result, SAROPS plotted EL FARO position as 23-16.8N, 079-28.9W because it was programmed to recognize positions being entered as degrees and tenths of degrees

[411] MBI Exhibit 032.
[412] SAROPS .wav file selections when configuring SARSAT Alerts on the Coast Guard Standard Workstation. CGD7 configures SAROPS/SARSAT for new alert uses AttentionEmergency.wav. Source D7 SAR Specialist.
[413] MBI Exhibit 072.
[414] Summary of EL FARO final with coverage of satellites final with correction on AIS inputs March 16, 2016.
[415] Figure 1 - Marlink - Inmarsat C Distress Vessel Information Sheet – EL FARO.
[416] Search and Rescue Optimal Planning System (SAROPS) is designed to assist with search and rescue planning. SAROPS is built upon the Environmental Systems Research Institute (ESRI) Geographic Information System (ArcGIS).
[417] Marlink - Inmarsat C Distress Vessel Information Sheet – EL FARO – EIK Operation to LANTWATCH October 01, 2015 03:15 PST.
[418] EL FARO Distress Alert Message from 436820812@inmc.eik.com to LANTWATCH Dated October 01, 2015, 7:13AM.

DD.dd. SAROPS did not distinguish the difference between tenths of degrees or minutes in this format.[419] The United States recognizes the format as degrees, decimal degrees[420] and it is the watchstanders responsibility to convert coordinates into that format before entering them into SAROPS.

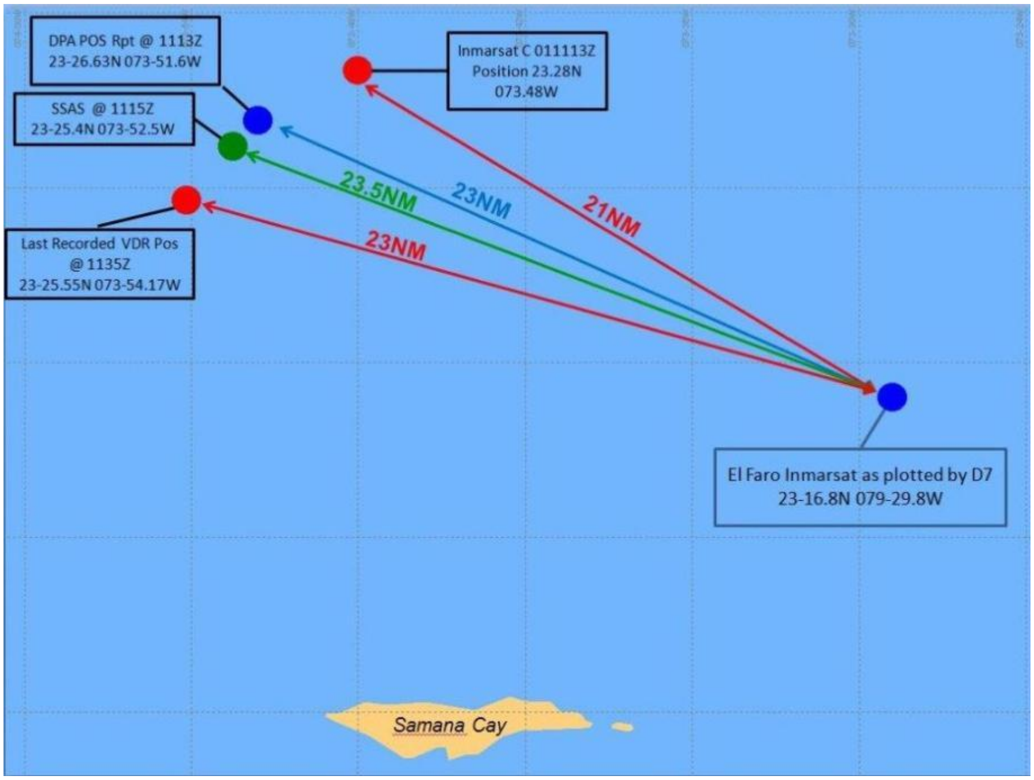

Figure 67. D7CC electronic alert plot SAROPS. The position entered into SAROPS (displayed on the right) was more than 20 nautical miles away from the actual last known position of EL FARO.

The SMC has overall responsibility for the response to a search and rescue case, including the final decisions on how to respond effectively to a distress event. The SMC[421] assigned to the EL FARO case was the District Incident Management Branch Chief. According to the timeline entered into the Coast Guard's MISLE database, the SMC was initially briefed on EL FARO's situation at 7:59 AM on October 1, 2015. D7CC watchstanders contacted the nearest aviation facility, located at Great Inagua (GI) in the Bahamas, to determine if a Coast Guard MH-60T medium range helicopter could respond. It was determined that due to the location of the eye of the storm, no aviation assets could respond near EL FARO's LKP on the first day[422] of the emergency. The D7CC watch continued to reach out to other assets, including commercial vessels, in the area to determine if any were available to assist EL FARO. The M/V EMERALD

[419] Coast Guard SAROPS LKP Icon Plotter – EL FARO – Initial Position Explanation PPT – Source Paul Webb, D17 SAR Specialist.
[420] Catastrophic Incident SAR Addendum 3.0 & NSARC - NTSB Hearing Input (030909).
[421] COMDTINST 161302 (series) CG Addendum to the National SAR Supplement 1.2.2 SAR Mission Coordinator (SMC).
[422] MISLE Activity 5733198 1305 (UTC).

EXPRESS,[423] a 180-foot Panamanian flagged RO/RO, was identified using D7CC's AIS as one of the closest possible search assets. However, the EMERALD EXPRESS, which was transiting south of Crooked Island en route to Fort Lauderdale, Florida, responded to the D7CC that they were unable to assist due to the severe hurricane conditions to their east. The D7 watch then requested that the EMERALD EXPRESS make VHF[424] radio callouts to EL FARO.[425] D7CC watchstanders also reached out to Air National Guard (ANG) HC-130J Hurricane Hunters[426] that were flying observation missions over Hurricane Joaquin for NOAA NWS. The two flights covered the area of EL FARO's LKP, and each aircraft conducted VHF radio call outs and radar searches. Due to the 10,000-foot altitude of the callouts, the range of the radio transmissions was much greater than the callouts made by the EMERALD EXPRESS. An ANG HC-130 aircraft, call sign TEAL 75, was the initial aircraft on scene and it reported hearing the EMERALD EXPRESS call out to EL FARO on the radio; however, no voice radio communications with EL FARO were ever established by the EMERALD EXPRESS[427] or TEAL 75. During a debriefing, the TEAL 75 pilot stated that he used surface search radar during his search, but that no surface targets were located.[428]

7.2.18.4. First Coast Guard Search Assets on Scene - October 2, 2015

The Coast Guard was first able to arrive on scene of EL FARO's LKP at first light on October 2, 2015. A Coast Guard Air Station Clearwater, Florida HC-130H aircraft, tail sign CGR1503, arrived on scene and was able to obtain a visual of the ocean's surface. CGR1503 conducted its assigned search in hurricane conditions at altitudes ranging between 2,500 to 3,000-feet. The aircraft sustained damage during the search due to the meteorological conditions it encountered near the LKP, and was forced to return to Coast Guard Air Station Miami. Another Coast Guard aircraft, tail sign CGR6027, also conducted a search on the afternoon of October 2, with no sightings of EL FARO. Because of the extreme weather and risk to the air crews, no further searches were assigned on October 2. However, the ANG Hurricane Hunter C-130[429] continued to conduct communications and radar searches for EL FARO through October 2,[430] while conducting hurricane hunting duties.[431] On the morning of October 3, it was deemed safe enough for aircraft and Coast Guard cutters to commence a coordinated search effort. Seven aircraft from the Coast Guard, Navy and ANG participated in the effort.

[423] D7 DVL Recording SAR_844096302 -M/V EMERALD EXPRESS voice conversation with D7 18-20ft seas, winds 65-70kts.
[424] VHF radio is a ship to ship line of sight radio for short range communications.
[425] MISLE Activity 5733198 1536 (UTC).
[426] 53rd Air Reconnaissance Division, Kessler AFB.
[427] The EMERALD EXPRESS was overcome by Hurricane Joaquin's heavy seas and winds on the afternoon of October 1, 2015. After drifting for two days, storm surge propelled the vessel over Crooked Island and it grounded in a mangrove swamp 21-miles from shore.
[428] Conversation with Major Steven Burton, 53rd Air Reconnaissance Division, Kessler AFB and DVL Conversation SAR_844096982 – 1434 (UTC) ANG C-130 TEAL 75 and D7CC.
[429] TEAL 75.
[430] MBI Transcript 23 February 2016, p. 188.
[431] MISLE Timeline Entry 020853Z October 15, OS1 Overton.

Figure 68. Air Station Clearwater CGR-1503 - EL FARO search area visual conditions on October 2, 2015.

7.2.18.5. SAR Planning

Over the first three days of the SAR case, D7CC watchstanders created drift models using SAROPS. The SAROPS is supposed to take into account all of the environmental information available, and to use that data to calculate the drift or projected movement of various search objects. However, the SAROPS was not programmed to accept wind values and other environmental conditions into the drift model that matched the extreme hurricane conditions that were observed on scene by search assets. The D7CC was also hampered because the SAROPS program continuously crashed while the watch was attempting to establish search runs and drift models. Because of these issues, the SMC and the D7 Search and Rescue Specialist[432] had to rely on manual solution methods for drifting search objects, a technique taught in Maritime Search Planning prior to the introduction of computer based modeling.[433] D7 SMC used the manual solution techniques to provide a predicted drift to determine initial search areas for the fixed wing aircraft flying on October 3, 2015.[434] After October 3, as Hurricane Joaquin moved to the north, SAROPS was able to provide search plans until the case was suspended.

7.2.18.6. Search and Rescue Operations

On October 3 and 4, as the weather conditions near the Bahamas improved, SAROPS was able to provide drift information and search patterns for the assets engaged in the search. Additional assets arrived in the search area, including three Coast Guard cutters and several commercial vessels. Search efforts discovered two debris fields during the Bravo Search EPOCH.[435] The Bravo Search Area was located 38 NM southeast of San Salvador and Rum Cay near EL FARO's actual LKP and the second field was centered 78 NM northeast of the LKP. Various types of debris, gear, and cargo were located.

[432] D7 SAR Specialist.
[433] COMDTINST 161302 (series) CG Addendum to the National SAR Supplement H.2 Manual Solution Model.
[434] 1021NTSB-A-Coggeshall October 14, 2015 p. 38.
[435] EPOCH searches are SAROPS "runs". There is one SAROPS run per EPOCH. COMDTINST M161302 (series) CG Addendum to the National SAR Supplement H.4.2.3.

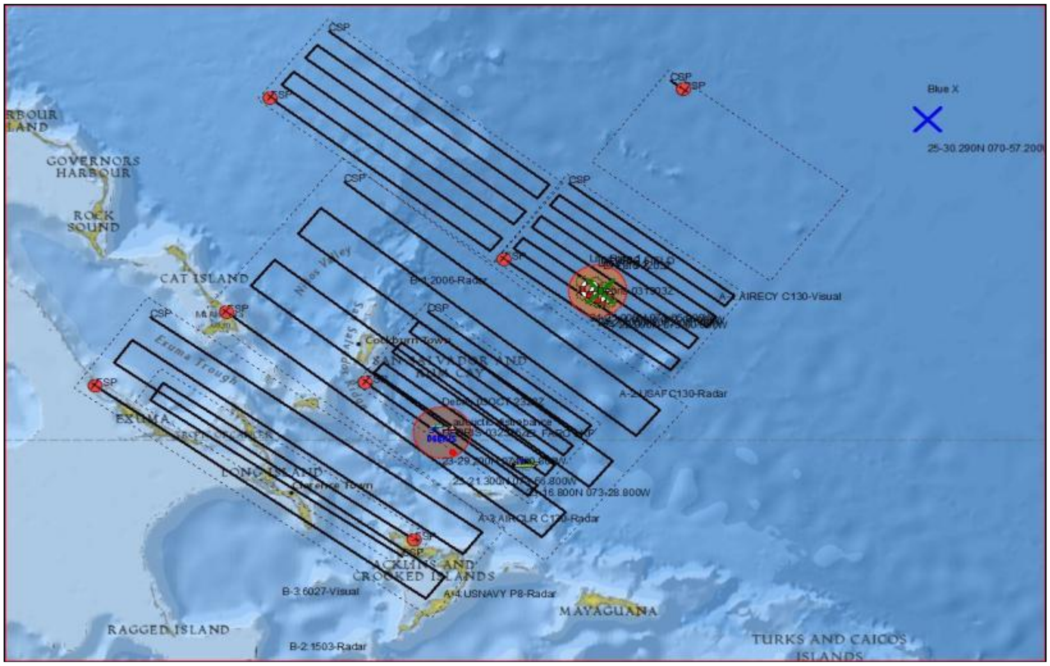

Figure 69. EL FARO ALPHA and BRAVO search areas.

On October 4, 2015, search conditions continued to improve. At 4:35 PM a Coast Guard MH-60T helicopter, tail sign CGR6009, was en route to its assigned search area and overflew a floating object identified as an immersion suit, 22 NM east of EL FARO's LKP. CGR6009 lowered a rescue swimmer, who confirmed that there were remains of a deceased EL FARO crew member in the suit. The rescue swimmer was unable determine if the deceased person was male or female due to advanced decomposition. Before any action could be taken to recover the body, the On Scene Commander (OSC) on the Coast Guard Cutter NORTHLAND reported that a Navy P8 aircraft had identified a possible person in the water (PIW) about 20 minutes from the location of the body in the immersion suit. The CGR6009 pilot asked the On Scene Commander (OSC) if they wanted his helicopter to investigate. The OSC concurred and the CGR6009 deployed a SLDMB[436] to mark the location of the deceased victim in the immersion suit. Upon arriving on scene of the reported area of the PIW sighting, the CGR6009 was directed to the location to the possible location by the Navy P8 aircraft. CGR6009 was only able to locate a piece of orange plastic, which was mistaken as a person moving in the water due to wave action. The CGR6009 then returned to the area where the deceased victim was discovered; however, they were unable to relocate the victim, as the SLDMB dropped near the immersion suit failed to activate. After conducting a search of the area CGR6009 had to return to base.[437] The immersion suit and the crew member's remains were never recovered.

If the SLDMB dropped by CGR6009 had activated its data would have been automatically displayed in SAROPS, showing the total drift (actual position of) the SLDMB. The data could have been used by the D7CC to develop a more localized drift for the search object.

[436] ARCOS 43396, ALMIS Mission Record Review, Air Station Clearwater 6009 October 04, 2015.
[437] NTSB Transcripts and Errata – Survival – CG-6009 Pilot in Command, USCG February 11, 2016.

During MBI testimony the Coast Guard SMC for EL FARO stated the following when asked about the reliability of the SLDMB that was used to mark the deceased crew member's location:

The – generation 2 self-locating datum marker beacons have a 40 to 50 percent failure rate. We're in the process of fielding 3rd generation datum marker beacons.

Figure 70. An example of a sample self locating datum marker buoy (SLDMB) plot in SAROPS (Not EL FARO case related).

From October 4 to October 7 another 42 sorties were conducted. Debris confirmed to be from EL FARO confirmed that the ship had sunk. No survivors or additional bodies were discovered during the search.

7.2.18.7. Case Conclusion

At 7:15 EST on October 7, 2015, the SAR Coordinator granted suspension of search efforts (ACTSUS) based on the diminished chance of crew member survival after six days in the maritime environment and the high coverage of the planned search area.

8. Analysis

The analysis section addresses issues that the MBI was unable to definitively classify as facts in Section 7 of this Report of Investigation, due to a lack of sufficient evidence or to conflicting evidence obtained over the course of the investigation.

8.1. Forensic Sinking Analyses

The MSC report includes documentation of the MSC hydrostatic analyses of the sinking of EL FARO. The analyses used the MSC's computer model and focused on assessment of righting arms, including righting energy and range of stability considerations, in order to gain insight into the characteristics of vessel dynamics and motions due to wind, waves, and flooding. The effects of wind are discussed, along with considerations associated with floodwater, including effects of free surface, compartment permeability, and pocketing. The potential sources of flooding of Hold 3 are discussed, including photographs and drawings for reference of the vulnerability to flooding through the cargo hold ventilation openings and potentially through damaged emergency fire pump piping. Potential progressive flooding paths into Hold 2A and other cargo holds are discussed, including downflooding through the cargo hold ventilation system openings and possibly through leakage of the watertight door seals. Analyses of various wind heel and flooding conditions were used to assess likely scenarios leading to the capsizing and sinking of the vessel given the environmental conditions.

The results were highly sensitive to variation in permeability values, and a range of permeability values was used to assess impacts of the variability. The evaluation of flooding required careful consideration of compartment permeability and pocketing effects. For permeability, this includes significant variability in both overall permeability fraction and uniformity throughout the cargo holds. This is especially important when considering containers, where permeability varies significantly depending on the assumed watertight integrity and specific locations of the containers.

The results were also highly sensitive to variations in wind speed, especially in combination with floodwater free surface. Even single compartment flooding of Hold 3, when combined with a wind heel from 70-90 knot beam winds, would result in very small residual righting arms and little residual righting energy (please see Figure 71). This would suggest that it would be highly unlikely that EL FARO could have survived even single compartment uncontrolled flooding of Hold 3, given the wind and sea conditions generated by Hurricane Joaquin.

The report analyzed several potential sources of flooding of Hold 3 and the other cargo holds, including vulnerabilities associated with the cargo hold ventilation system. The MSC report notes that, for the accident voyage loading condition, flooding through the open cargo hold ventilation system would occur at angles of heel or roll as low as 27 degrees. This would likely result in at least intermittent flooding into the cargo holds, as the vessel was subject to a variable wave height on the side shell due to 25-30 foot seas, and also heaved and rolled about the mean heel angle of approximately 15 degrees. If there were vulnerabilities in the cargo hold ventilation trunks due to wastage or unauthorized modifications to bulkheads and baffles plates, the flooding into the cargo hold ventilation trunks could have occurred at an angle less than 27 degrees. The MBI determined that wastage and modifications to EL YUNQUE's cargo ventilation trunks would have led to downflooding on that vessel at angles of heel below the design criteria. The wastage in EL YUNQUE's was considered by the MBI to be longstanding through multiple inspection and dry dock cycles. An MBI review of EL FARO's survey and inspection records could not find evidence detailing that the vessel's ventilation trunks received an internal inspection by TOTE personnel, ABS or the Coast Guard. After the sinking of EL FARO, the Coast Guard Traveling Inspectors discovered a pattern of severely corroded and unserviceable watertight fittings, ducts, and dampers on multiple targeted ACP vessels that they visited during their focused ACP reveiw. As a result, hundreds of fittings were replaced or repaired and several ACP vessels received no-sail orders from the Coast Guard. Based on all the evidence available, there is a high likelihood that EL FARO's ventilation trunks, dampers, cargo bay doors, and deck scuttles were in a material condition that increased EL FARO's susceptibility to flooding.

Regardless of the initial source or sources of flooding on EL FARO during the accident voyage, the free surface associated with the floodwater in the cargo holds combined with hurricane force winds and seas would have inevitably resulted in the capsizing of the vessel. The capsizing may have been slowed or temporarily arrested as containers on deck began to wash overboard, but as the vessel slowly rolled onto its port side, a large volume of floodwater would have been entering through the ventilation openings into all of the cargo holds and the engine room, resulting in the sinking.

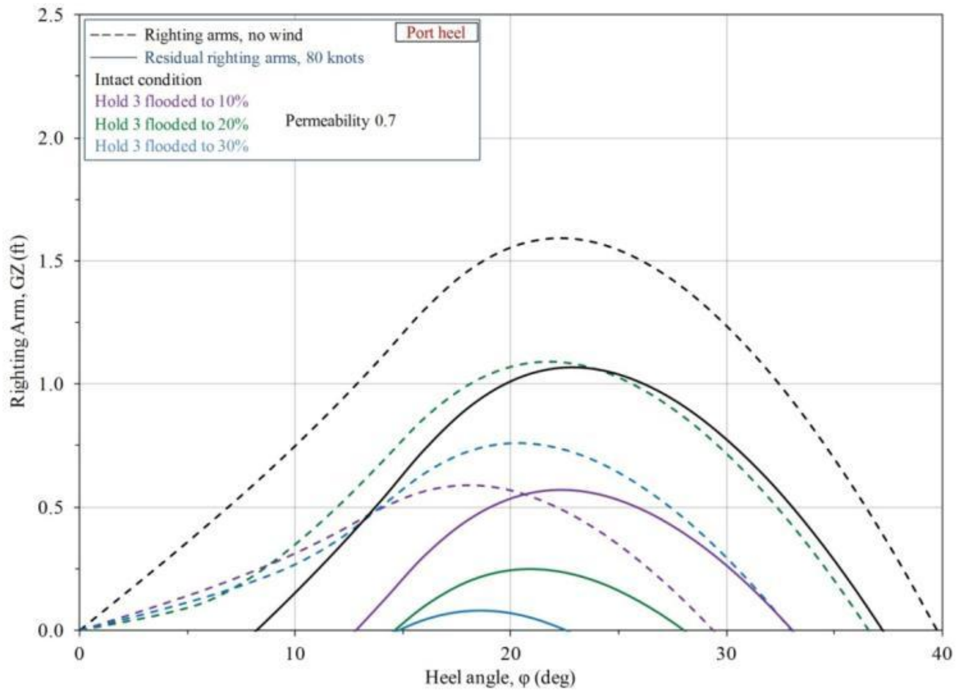

Figure 71. Righting arms (dashed curves) and residual righting arms (solid curves) with 80 knot beam winds with Hold 3 flooded to 10%, 20%, and 30%. Permeability is 0.7 (Figure 6-24 of the MSC report).

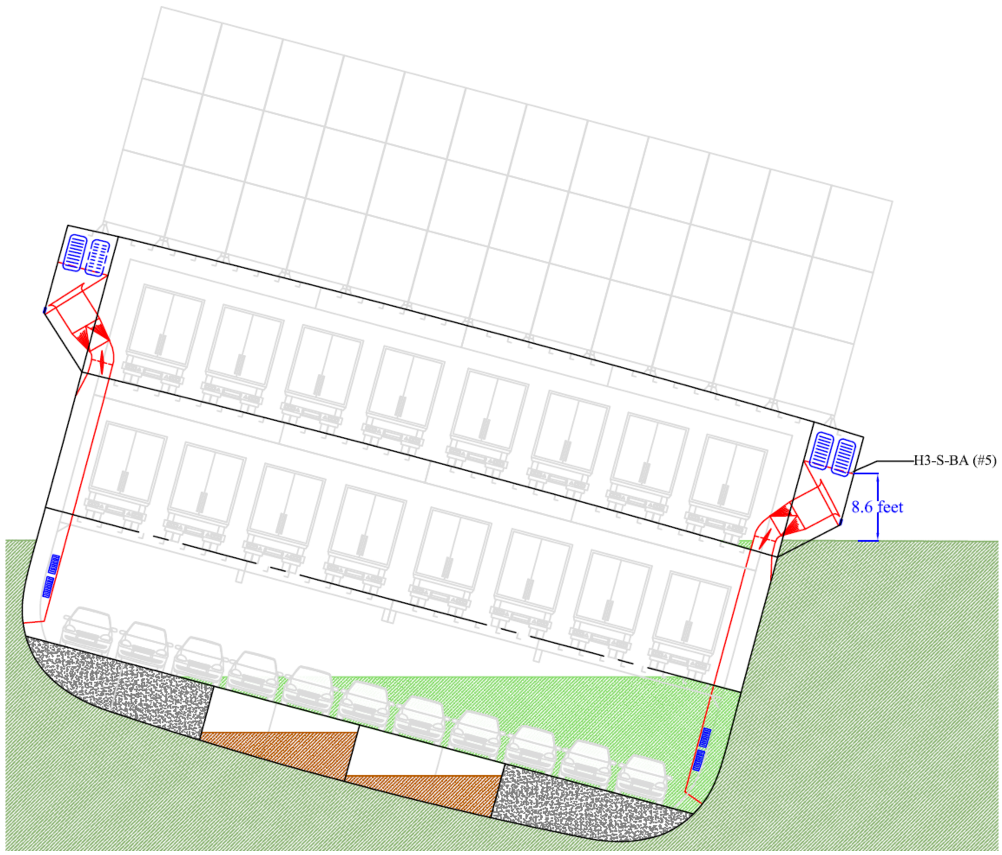

Figure 72. Section at frame 143 (Hold 3 ventilation supply trunk) with flooding of Hold 3 to 20% with heel angle 15 degrees. Downflooding point at the top of the vertical baffle plate is shown (Figure 6-18 of the MSC report).

8.2. Bilge Pump System Alarms and Associated Components

The flooding of Hold 3 was reported by a house phone call to the bridge at 5:43 AM on the October 1, 2015. The MBI could not determine whether the first report of flooding in Hold 3 came from a bilge high level alarm; or from visual observation of the water in the hold by a crew member. There was a watertight door fitted in the forward bulkhead of the engine room that gave direct access to Hold 3. If the forward engine room watertight door had been open for increased engine room ventilation, which former EL FARO engineers testified was common practice under normal operating conditions, it could have been the means of discovery. If the flooding in Hold 3 activated the bilge high level alarm, the engineers would have received an audible and visual alarm at the bilge high level alarm control panel near the watch station. This alarm could only be silenced by the engineer acknowledging the alarm on the bilge high level alarm control panel. The high level indicator light was designed to remain illuminated until the water level dropped below the float alarm set point.

The exact position and layout of EL FARO's bilge alarm sensors could not be determined because no drawings or plans were produced, and testimony from former EL FARO crew members and a TOTE P/E was not consistent. The bilge high level sensors were estimated to be 2 to 3 inches above the rose box in each cargo hold. The MBI estimates that it would take approximately 1,800 gallons of water to activate the high level bilge alarm with EL FARO in static and even keel condition. The MBI was unable to determine how EL FARO's persistent starboard list during the early morning hours of October 1, 2015, may have impacted the sounding of the bilge alarms in Hold 3 or other cargo holds.

8.3. Container Conversion (2005-2006), Non-Major Conversion Determination

The MSC's final decision to consider EL FARO's conversion to a combination container and RO/RO vessel as not a major conversion was ultimately based on the "Precedence Principle." Specifically, TOTE argued that the Coast Guard had not previously designated similar conversions of EL FARO's sister vessels EL YUNQUE and EL MORRO, as well as two other Matson steam ships, as major conversions. In addition to the economic cost-benefit that such a conversion would provide, with an increased cargo-carrying capacity, there was also an indication in the correspondence that EL FARO's maximum design or load line draft would be substantially increased. Neither of these facts was used by the Coast Guard to stay with the initial major conversion determination. In their requests for reconsideration, TOTE argued that the vessel's load line (maximum design draft) would be the appropriate measure of cargo capacity, rather than container TEU or FEU, which the Coast Guard had used as the basis for the original major conversion determination. What appears to have been confused in the correspondence and discussion was that the required additional fixed ballast necessary to meet stability criteria with the additional containers on the main deck would necessarily result in a significant increase in the maximum design or load line draft, which is considered by most naval architects to be a principal vessel dimension. It should have been clear to the MSC that the intent of the conversion was to enable the vessel to carry substantially more containerized cargo (otherwise the conversion would not have been economically viable), and this would also require a significant increase of the maximum design or load line draft. Under the definition of "major conversion" in 46 USC § 2101(14a), both the substantial increase in the maximum draft (a principal vessel dimension) and the intent to increase cargo carrying capacity (for economic viability) should have been sufficient justification for a major conversion determination.

Even if the 2005-2006 conversion had been deemed a major conversion, Coast Guard policy dictated that particular requirements to meet current standards were made by the cognizant OCMI on a case-by-case basis, if deemed reasonable and practicable to do so. The Coast Guard policy stated:

> *With the passage of time, existing vessels will be retired and only those built to newer standards will continue in service. For this reason, it is costly and impractical to require existing vessels to be modified each time a safety standard is updated. However, when a major conversion or modification of an existing vessel is planned, there is a definite intent to extend the service life of the vessel. When this is the case, it is appropriate to bring the entire vessel into compliance with the latest safety standards where reasonable and practicable…The entire vessel must meet all current standards, as far as is reasonable and practicable, in effect at the contract date of a major conversion.*

The Coast Guard has minimal guidance available to OCMIs on what should be considered as "reasonable and practicable," after a major conversion is completed. As a result, OCMI imposed requirements after a major conversion are made on a case-by-case basis, which leads to inconsistencies across the Coast Guard.

Nevertheless, even if it had been deemed reasonable and practicable to require meeting current stability standards in 2006, there would likely have been no change in applicability of the stability standards since the previous major conversion in 1992-1993 (see the MSC report, Appendix 1). For intact stability, the GM criteria of 46 CFR § 170.170 would still have been applicable in 2006, since the 2008 IS Code requiring assessment of righting arms and righting energy implemented with 46 CFR § 170.165 was not applicable until 2011. For damage stability, 1990 SOLAS damage stability standards would still have been applicable in 2006, since the 2009 SOLAS damage stability standards requiring a higher level of safety were not applicable until 2011. However, requiring EL FARO to comply with all of the latest safety standards could have resulted in upgrades in other areas including modern lifesaving appliances.

8.4. Flooding of EL FARO

It is not possible to determine exactly when downflooding of EL FARO started, as there were multiple paths for seawater to enter the ship other than the first specific source of flooding that was identified on the VDR as the 2nd Deck starboard scuttle for Hold 3. Other possible sources include hull breaches, watertight openings left open or failing to function properly, or internal failures of the ventilation trunk structures.

8.4.1. Seawater Ingress Other than the 2nd Deck Scuttle for Hold 3

It is not possible to determine if there was flooding within the internal watertight envelope before the discovery of the open scuttle in Hold 3 at 5:43 AM on October 1, 2015. However, there were statements made on the VDR prior to 5:43 AM that indicate EL FARO was likely experiencing free surface effects prior that time. Shortly after taking over the bridge watch at 3:51 AM on the morning of the accident, the C/M stated "don't like this" and then commenced making a series of course changes to improve EL FARO's ride. At 5:11 AM, the C/E who was assigned to supervise the riding crew made the following statement to the Master and C/M on the bridge:

> *I've never seen it list like this— you gotta be takin' more than a container stack *. I've never seen it hang like this.*

The Riding Crew Supervisor appeared to be concerned about the list and handling of EL FARO. He seemed to be speculating that a leaning container stack could be the cause, but it would have been impossible for the crew to visually confirm the conditions of the containers considering the prevailing storm conditions and darkness at that time of the morning. It's likely EL FARO's list and hanging conditions were due to free surface from flooding already occurring within Hold 3, across the 2nd Deck, and possibly other cargo holds.

A ship flooding with seawater, coupled with the sloshing of the free water in the holds, behaves differently than a ship with a typical load and no internal flooding. The rolling of the ship, the speed of the ship, and other changes in ship's motion characteristics change as the volume of water inside the hull increases.

8.4.2. Downflooding from the Starboard Scuttle into Hold 3

EL FARO's scuttles on the 2nd Deck were secured by closing the scuttle and spinning a hand wheel. Once the hand wheel was spun the hatch was designed to be dogged or secured. There was no way for a crew member to visually determine that the closure was properly secured from a 2nd Deck vantage point. A crew member would have needed to spin the wheel to see if it had been rotated in the proper direction or lift on the heavy scuttle hatch to see if it was secured. While standing watch on at 6:48 PM on September 30, 2015, the C/M made the following comments related to the proper securing of EL FARO's scuttles on the 2nd Deck:

> *I've got to send these guys. I've seen the water chest deep down there on (the) second deck.*
>
> *Yeah it's no joke.*
>
> *Yeah when I said you know those scuttles need to be dogged– not just flipped down. You know– they need to be spun and sealed.*

These comments indicate that there was a need to remind the crew to properly secure the scuttles. The implication from this exchange was that the scuttles were not consistently secured. This situation would also be compounded by having a riding crew aboard who were not given a complete safety briefing detailing the need to secure watertight fittings after use.

There is no way to determine how long the scuttle on the starboard side of Hold 3 was open and allowing seawater to enter the hold. Each cargo hold had a scuttle on the port and starboard side of the hold that led to the 2nd deck. It is possible that the starboard scuttle for Hold 3 was in the down and unsecured position prior to the morning of October 1, 2015, but evaded detection by crew members making rounds on the 2nd deck on the evening of September 30, because it appeared to be closed. At some point the force of water on the 2nd deck, coupled with the movement of debris, likely forced the scuttle into the open position.

The MBI could also not determine how that breach of the watertight envelope was detected by the crew. Based on the large volume initially reported in Hold 3, it is likely that the EL FARO was flooding for an extended period of time, probably in several holds, prior to detection. Detection of the flooding was hindered because the crew lacked the ability to remotely monitor the cargo holds and crew member rounds of the 2nd deck and cargo holds were severely restricted during the heavy weather conditions encountered on the accident voyage due to safety concerns.

8.4.3. Downflooding or Progressive Flooding into Hold 2A

As EL FARO's list steadily increased on the morning of October 1, and the ship settled in to worsening seas, the vessel likely began to take water into Hold 2A through the exhaust and supply ventilation ducts. The interior material condition of the ventilations trunks, which the MBI determined was likely heavily corroded, could have exacerbated the flooding by an undetermined amount. Flood water could have also passed from hold-to-hold through damaged or worn seals around the large watertight vehicle cargo doors.

8.4.4. Potential Flooding into Hold 3 from Ruptured Emergency Fire Main Piping

At 5:44 AM on October 1, 2015, the Master made the following statement to the C/M after receiving a report about flooding in Hold 3:

We got cars loose. Yeah.

The loose cargo shifting in the hold combined with flood water could have resulted in cascading cargo breakaways in the hold.

At 7:17 AM, the Master made the following statement to the C/M just prior to discussing the possibility of damage to the emergency fire main:

The cars that are floating in 3 Hold…

The vehicles in Hold 3 were likely adrift and moving around in Hold 3 for at least 90 minutes while EL FARO was transiting through heavy seas with a starboard list. There is a possibility that loose vehicles could have damaged the ship's structure including the emergency fire main piping. The emergency fire pump, which was situated near the aft end of Hold 3 on the starboard side, was comprised of a sea chest, piping, a sea chest valve, strainers, and the emergency fire pump. That system was partially protected by various structures, but it was still vulnerable to damage. Damage to the suction piping would have resulted in flooding considering the sea chest intake was located well below EL FARO's waterline, which would have resulted in water entering Hold 3 at a substantial pressure and volume. The volume would have far exceeded what the bilge system was designed to accommodate. The MBI was unable to accurately determine if damage occurred to this system as comments made by EL FARO's crew regarding the emergency fire main were inclusive. However, after reviewing all of the available evidence, the MBI determined that it is unlikely that a rupture to the emergency fire contributed to the flooding in Hold 3.

8.4.5. Gradual Flooding and Final Flooding of EL FARO

As greater volumes of flood water entered the ship from Hold 3 and Hold 2A, the ship began to settle in the water and the list continued to increase. This was coupled with the angle of the ship's hull in relation to the seas. At some undetermined point shortly after the vessel induced the port list, all of the ventilation trunks were being periodically submerged and water would have begun entering all of the unprotected openings into the watertight spaces of the ship. The fact that EL FARO always operated with its ventilation trunk fire dampers in the open position would have allowed the flooding via the trunks to occur unchecked. There is no mention of attempting to secure the fire dampers on the VDR. The manual closures for the dampers were located on the 2nd Deck of EL FARO along the port and starboard sides of the vessel. When considering that the 2nd Deck was reportedly flooded with waist deep water, securing the dampers would not have been a viable option for the crew.

8.5. Damage Control Knowledge and Effectiveness

EL FARO's side shell openings for the ventilation trunks posed a risk to the vessel when the ship was listing. This risk existed despite the internal baffles and other protective design features within the ventilation trunks. The ventilation trunks were especially vulnerable to a sustained heel because flood water would not drain out of the trunks as effectively and the height of the internal baffle plates would be partially degraded due to the heel. Seawater would enter the openings at greater volumes as the ship was settling into the water due to the weight of the flood water and green water on deck. After losing main propulsion around 6:00 AM on October 1, 2015, the available VDR data indicated that EL FARO was lying in the trough of the seas aligned with the trough, which is an extremely vulnerable position for a ship in high seas. As EL FARO's crew attempted to combat the flooding and discussed the survivability of the ship, the Master and C/M appeared to be uncertain about the ship's downflooding points, bilge system, reserve buoyancy, and stability. At 7:22 AM the Master made the following statements while talking to the engine room on the house phone:

> *It's lookin' pretty nasty. (Uh/on) the downflooding angle? Um that I don't have an answer for (ya).*
>
> *What's it called again?*
>
> *Okay we'll check that. (It's/that's) in the chief's office?*
>
> *Um no. I mean we still got reserve buoyancy and stability.*

Four minutes later the Master ordered the general alarm to be rung to alert the crew to the emergency situation.

8.6. Basic Wreckage Analysis

The material condition of EL FARO related to possible damage incurred during the course of the voyage through Hurricane Joaquin was difficult to determine due to the fact that the vessel was subjected to severe forces as it sank to a depth of nearly three miles below the surface of the ocean. In the case of another vessel which sank to a similar depth, the TITANIC, it was estimated that the main sections of the ship sank to the bottom at a speed of approximately 35 – 50 miles per hour.[438] EL FARO's impact with the seafloor and the dynamic motion of the ship as it travelled to the bottom would have imparted significant force to the vessel and the vessel's structures. The bottom of the crumpled transom plating at the stern, where the vessel's name and hailing port are displayed, showed damage that was likely due to the stern, rudder, and propeller shaft striking the bottom first and exerting an upward force on the transom structure at the stern. After contacting the bottom the rest of EL FARO's hull settled into the sea floor, partially burying the hull into the silt on the bottom.

[438] Source: www.titanicfacts.net

One of the aspects of a ship propelled by a steam system was the extreme heat generated by the boiler structures. In the case of EL FARO, the boiler system and components being immersed in seawater could have produced a thermal event where the superheated boiler equipment catastrophically failed as it reacted with the colder seawater flooding into the engine room. The result would have caused a significant thermal pressure wave that that radiated upwards from the engineering spaces. The resulting forces likely caused EL FARO's upper superstructure and the ship's smokestack to detach from the vessel. The ship's bridge and smokestack were located partially damaged but primarily intact on the seafloor near the wreck. Photographs taken by a ROV during the survey of EL FARO's wreckage indicate signs of damage above the boiler casings that are consistent with a catastrophic steam boiler failure.

8.7. ACP Effectiveness

After encountering ACP related concerns during the EL FARO investigation, the MBI expanded the scope of its investigation to examine ACP effectiveness for EL YUNQUE and several other U.S. flagged vessels enrolled in the program. After the sinking of EL FARO, the Coast Guard Traveling Inspectors began a focused effort to ascertain the material condition of the ACP vessels targeted by Office of Commercial Vessel Compliance. In addition, several Coast Guard field units reached out to the Traveling Inspectors for assistance with ACP vessels that were known to be operating in a substandard safety condition starting in early 2015 and accelerating after the loss of EL FARO. In October 2016, the Commanding Officer of Coast Guard Activities Europe sent an internal memorandum to the Office of Commercial Vessel Compliance that detailed ACP concerns his inspectors had observed while conducting oversight exams in Western Africa on offshore supply vessels.

In general, the ACP is not currently functioning as envisioned when the Program was created in 1996. The primary shortfalls observed over the course of the MBI include the following:

- An ACP training course for ACS surveyors and Coast Guard inspectors to interact and become familiar with the Program was never implemented.
- ACS surveyors and Coast Guard inspectors are often unfamiliar with the program requirements and the U.S. Supplement.
- The U.S. Supplement for ABS is not being updated on an annual basis and marine inspector identified gaps (e.g., the lack of hydrostatic testing requirements for propulsion boiler repairs) are not being incorporated into the Supplement updates.
- ACS surveyors and Coast Guard inspectors rarely interact in the field during ACP activities and there is no required minimum level of Coast Guard oversight required.
- There is no minimum qualification level required for Coast Guard personnel to conduct ACP oversight exams.
- The Coast Guard does not require marine inspectors to be trained as auditors.
- ABS training requirements for certain inspections activities (e.g., overseeing repairs to a propulsion steam boiler) are far less than the Coast Guard would require for a marine inspector conducting a similar inspection activity.
- ACS surveyors performing ACP inspections are reluctant to hold up a commercial vessel especially for observations that are outside the scope of the survey being performed.

- Coast Guard OCMIs often lack the Prevention experience necessary to make time sensitive decisions to hold up substandard ACP vessels that have been cleared to operate by the ACS – a problem that is exacerbated by the limited number of Jones Act vessels available to perform certain trade routes.
- The Coast Guard Traveling Inspectors are encountering numerous long-standing safety deficiencies when they attend inspections on targeted ACP vessels which have frequently led to those vessels receiving no-sail orders.
- ACS surveyors are not held accountable for performing substandard ACP inspections that miss glaring safety deficiencies and the Coast Guard Office of Commercial Vessel Compliance does not have a system in place to associate an ACS with a substandard inspection they conduct on behalf of the Coast Guard.
- The Coast Guard does not publish an annual report on ACP vessel compliance or ACS performance. The lack of transparency has enabled vessel compliance and surveyor performance issues to continue unabated.
- The Coast Guard MISLE database is not available to ABS surveyors and they are often unaware of outstanding requirements and special notes on the vessels they are surveying.
- The Coast Guard MISLE database is not designed to record and track the results of CG auditing activities.
- A formal Coast Guard course for advanced and specialized marine inspections (e.g., steam propulsion plants) is not available and the Coast Guard Center of Expertise that previously covered Vintage Vessels like the EL FARO was disbanded around 2012.
- The Liaison Officer for the Recognized and Authorized Class Societies (LORACS) billet at Coast Guard Headquarters that previously provided ACSs with a single point of contact for ACP related issues was eliminated in 2012.
- The ACP does not have a designated lead office or individual at Coast Guard Headquarters. As a result, multiple offices share responsibility for overseeing different aspects of the ACP which leads to confusion.

Based on the results of the Coast Guard Traveling Inspector ACP oversight exams that were conducted in 2015 and 2016, it is clear that multiple U.S. cargo vessels were operating for prolonged periods in a substandard material condition. Although the Coast Guard's focused oversight on the ACP targeted vessels corrected the most egregious cases of non-compliance, a seminal change in the overall management and execution of the Program is urgently needed to ensure safe conditions are sustained on the enrolled U.S. commercial vessels.

9. Conclusions

9.1. Events and Contributing Factors

The Marine Board of Investigation identified the following series of events and associated contributing factors.

9.1.1. Event #1: EL FARO Sailed Within Close Proximity to Hurricane Joaquin

9.1.1.1. TOTE did not ensure the safety of marine operations and failed to provide shore side nautical operations supports to its vessels.

9.1.1.2. TOTE did not identify heavy weather as a risk in the Safety Management System (SMS) and the Coast Guard had not exercised its flag state authority to require identification of specific risks.

9.1.1.3. TOTE and the Master did not adequately identify the risk of heavy weather when preparing, evaluating, and approving the voyage plan prior to departure on the accident voyage.

9.1.1.4. TOTE and the Master and ship's officers were not aware of vessel vulnerabilities and operating limitations in heavy weather conditions.

9.1.1.5. TOTE did not provide the tools and protocols for accurate weather observations. The Master and navigation crew did not adequately or accurately assess and report observed weather conditions.

9.1.1.6. TOTE did not provide adequate support and oversight to the crew of EL FARO during the accident voyage.

9.1.1.7. The National Hurricane Center (NHC) created and distributed tropical weather forecasts for Tropical Storm and Hurricane Joaquin, which in later analysis proved to be inaccurate. Applied Weather Technologies used these inaccurate forecasts to create the Bon Voyage System (BVS) weather packages.

9.1.1.8. The Master and deck officers were not aware of the inherent latency in the BVS data when compared to the NHC forecasts. Additionally, the Master and deck officers were not aware that they received one BVS data package with a redundant hurricane trackline.

9.1.1.9. The Master and deck officers relied primarily on graphical BVS weather forecasts rather than the most current NHC data received via SAT-C. EL FARO crew did not take advantage of BVS's tropical update feature and the ability to send BVS weather information directly to the bridge.

9.1.1.10. The Master did not effectively integrate the use of Bridge Resource Management techniques during the accident voyage. Furthermore, the Master of EL FARO did not order a reduction in the speed or consider the limitations of the engineering plant as EL FARO converged on a rapidly intensifying hurricane. This resulted in loss of propulsion, cargo shifting and flooding.

9.1.1.11. The Master of EL FARO failed to carry out his responsibilities and duties as Captain of the vessel between 8:00 PM on September 30 and 4:00 AM on October 1, 2015. Notably, the Master failed to download the 11:00 PM BVS data package, and failed to act on reports from the 3/M and 2/M regarding the increased severity and narrowing of the closest point of approach to Hurricane Joaquin, and the suggested course changes to the south to increase their distance from the hurricane.

9.1.1.12. The cumulative effects of anxiety, fatigue, and vessel motion from heavy weather degraded the crew's decision making and physical performance of duties during the accident voyage.

9.1.2 Event #2: EL FARO Experienced an Initial Starboard List and Intermittent Flooding

9.1.2.1. EL FARO developed a sustained wind heel to starboard as a result of the course change from 155 degrees to 116 degrees after passing south of San Salvador at approximately 1:30 AM on October 1. The wind heel brought the 2nd deck closer to the water line.

9.1.2.2. Intermittent flooding into one or more cargo holds on EL FARO began at this time. Water was able to enter Hold 3 through the open scuttle, and likely through deteriorated internal structures and open cargo hold ventilation fire dampers, which compromised watertight integrity.

9.1.2.3. The increasing of EL FARO's load line drafts following the 2005-2006 conversion, combined with loading to near full capacity with minimal stability margin, increased the vessel's vulnerability to flooding in heavy weather.

9.1.2.4. Despite the apparent increase in cargo carrying capacity and increase load line draft which would result, the 2005-2006 conversion was not designated as a major conversion by the Coast Guard. Based on the available documentation, the final decision was based on the "Precedence Principle," in that the Coast Guard had previously not designated similar conversions of sister vessels EL YUNQUE and EL MORRO as major conversions.

9.1.2.5. The crew's complacency, lack of training and procedures, and EL FARO's design contributed to the crew's failure to assess whether the vessel's watertight integrity was compromised.

9.1.2.6. EL FARO's conversion in 2005-2006, which converted outboard ballast tanks to fixed ballast, severely limited the vessel's ability to improve stability at sea in the event of heavy weather or flooding.

9.1.2.7. The Master, C/M, and crew did not ensure that stevedores and longshoremen secured cargo in accordance with the Cargo Securing Manual, which contributed to RO/RO cargo breaking free.

9.1.2.8. The practice of sailing with open cargo hold ventilation system fire dampers in accordance with SOLAS II-2, Regulation 20 and U.S. regulations created a downflooding vulnerability which is not adequately considered for the purposes of intact and damage stability, nor for the definitions of weathertight and watertight closures for the purpose of the applicable Load Line Convention.

9.1.2.9. The Coast Guard practice of verbally passing deficiency information to the ACS surveyor without written documentation of the deficient condition resulted in an unknown or incomplete compliance and material condition history of EL FARO.

9.1.3 Event #3: EL FARO experienced a reduction in propulsion

9.1.3.1. EL FARO's reduction in speed, from approximately 16 knots to 9 knots that occurred between 3:45 AM to 4:15 AM on October 1 was the result of the routine blowing of tubes and the C/M making course changes. EL FARO never reached a speed through the water above 10 knots for the remainder of the voyage.

9.1.3.2. EL FARO's departure with a main lube oil sump level of 24.6", which was below the Machinery Operating Manual recommended operating level of 27", reduced the crew's ability to maintain lube oil suction for the main propulsion plant.

9.1.3.3. Prior to 4:36 AM, EL FARO's main propulsion unit developed intermittent lube oil problems due to the starboard list.

9.1.4. <u>Event #4: EL FARO Incurred a Severe Port List and Lost Propulsion</u>

9.1.4.1. At 5:54 AM on October 1, the Master altered course to intentionally put the wind on the vessel's starboard side to induce a port list and enable the C/M to access and close the Hold 3 starboard scuttle. This port list was exacerbated by his previous order to transfer ramp tank ballast to port, and resulted in a port list that was greater than the previous starboard list and a dynamic shifting of cargo and flood water.

9.1.4.2. The port list, combined with the offset of the lube oil suction bellmouth 22" to starboard of centerline, resulted in the loss of lube oil suction and subsequent loss of propulsion at around 6:00 AM.

9.1.4.3. Coast Guard and ABS plan review for EL FARO's lube oil system did not consider the worst case angle of inclination in combination with the full range of lube oil sump operating levels specified in the machinery operating manual. This led the crew to operate with a lube oil sump level within the operating range specified on the Coast Guard and ABS approved drawing, but below the 27" operating level, which was the only level reviewed by ABS.

9.1.4.4. The Master and C/E did not have a complete understanding of the vulnerabilities of the lube oil system design, specifically the offset suction. This lack of understanding hampered their ability to properly operate the ship in the prevailing conditions.

9.1.4.5. TOTE's lack of procedures for storm avoidance and vessel specific heavy weather plans containing engineering operating procedures for heavy weather contributed to the loss of propulsion.

9.1.5. <u>Event #5: EL FARO sank</u>

9.1.5.1. The loss of propulsion resulted in the vessel drifting and aligning with the trough of the sea, exposing the beam of the vessel to the full force of the sea and wind.

9.1.5.2. Even after securing the scuttle to Hold 3, water continued to flood into cargo holds through ventilation openings, and also likely between cargo holds through leaking gaskets on large watertight cargo hold doors.

9.1.5.3. The EL FARO crew did not have adequate knowledge of the ship or ship's systems to identify the sources of the flooding, nor did they have equipment or training to properly respond to the flooding.

9.1.5.4. Even though EL FARO met applicable intact and damage stability standards as loaded for the accident voyage, the vessel could not have survived uncontrolled flooding of even a single cargo hold given the extreme wind and sea conditions encountered in Hurricane Joaquin.

9.1.6. Event #6: All 33 Persons Aboard EL FARO Are Missing and Presumed Deceased

9.1.6.1. A lack of effective training and drills by crew members, and inadequate oversight by TOTE, Coast Guard and ABS, resulted in the crew and riding crew members being unprepared to undertake the proper actions required for surviving in an abandon ship scenario.

9.1.6.2. After 5:43 AM on October 1, the Master failed to recognize the magnitude of the threat presented by the flooding into the hold combined with the heavy weather conditions. The Master did not take appropriate action commensurate with the emergent nature of the situation onboard EL FARO, including alerting the crew and making preparations for abandoning ship.

9.1.6.3. When the Master made the decision to abandon ship, approximately 10 minutes before the vessel sank, he did not make a final distress notification to shore to update his earlier report to TOTE's Designated Person Ashore that they were not abandoning ship. This delayed the Coast Guard's awareness that EL FARO was sinking and the crew was abandoning ship, and impacted the Coast Guard's search and rescue operation.

9.1.6.4. Although EL FARO's open lifeboats met applicable standards (SOLAS 60), they were completely inadequate to be considered as an option for the crew to abandon ship in the prevailing conditions.

9.1.6.5. The Coast Guard's existing Search and Rescue equipment and procedures were unable to effectively mark and track a deceased EL FARO crew member for eventual recovery. As a result the crew member remains missing and unidentified.

9.2. Unsafe Actions or Conditions that Were Not Causal Factors in this Casualty

9.2.1. Other than class specific guides that provide for voluntary review (and certification) of software for container loading and securing calculations for vessels desiring the special class notation, there is no specific U.S. or international requirement for review and approval of software for cargo loading and securing calculations. The Coast Guard also has not published any policy or guidance regarding such software or calculations.

9.2.2. There are no domestic regulations or policy for Coast Guard approval of stability software, and the Coast Guard has not delegated any such approval authority to an ACS.

9.2.3. As a result of TOTE's failure to notify ABS and the Coast Guard about the lifeboat davit repair work on September 28 and 29, 2015, the full materiel condition of the lifeboat davit repairs before EL FARO departed could not be assessed.

9.3. Evidence of Acts subject to Civil Penalty

9.3.1. STCW rest violations – on numerous occasions there were violations for the rest hours prescribed in STCW for deck officers serving onboard EL FARO, these violations were systemic and not addressed by TOTE.

- In particular there were three violations for the requirement contained in 46 U.S.C. § 8104 for a Third Mate on July 7, 2015 and July 14, 2015 and for a different Third Mate on September 1, 2015. This rest requirement is for deck officers to get a minimum of six hours rest in the twelve hours immediately before the vessel goes to sea.

- Furthermore there is evidence that the 3/M did not meet the 6 hours of uninterrupted rest (per 46 CFR § 15.1111) on the following dates: August 5, 8, 22, and September 5 based on the records that were provided by TOTE. The complete STCW work records for the accident voyage are not available due to the loss of the EL FARO.

9.3.2. Potential violation of 46 U.S.C. § 8106(a)(4) – no safety orientation or Coast Guard approved Basic Safety Training (BST) for the Polish riding crew.

9.3.3. Failure to notify the Coast Guard or ABS of repairs to primary lifesaving appliances that were conducted on September 28 and 29, 2015, just prior to EL FARO's departure from Jacksonville on the accident voyage.

9.3.4. Failure to notify the Coast Guard or ABS of repairs to EL FARO's main propulsion boiler superheating piping on August 24, 2015.

10. Safety Recommendations

Recommendation #1 – High Water Alarms. It is recommended that Commandant direct a regulatory initiative to require high water audio and visual alarms, capable of providing audible and visual alarms on the navigation bridge, in cargo holds of dry cargo vessels. Furthermore, it is recommended that Commandant work with the International Maritime Organization (IMO) to amend the applicability of SOLAS Chapter II-1/25 (2015 consolidated) to include all new and existing multi-hold cargo ships.

Recommendation #2 – Ventilators and Other Hull Openings for Cargo Ships. It is recommended that Commandant direct a review of U.S. regulations, international conventions, and technical policy to initiate revisions to ensure that all ventilators or other hull openings, which cannot be closed watertight or are required to remain normally open due to operational reasons such as continuous positive pressure ventilation, should be considered as down-flooding points for intact and damage stability. Additionally, fire dampers or other closures protecting openings required to remain normally open due to operational reasons such as continuous positive pressure ventilation should not be considered weathertight closures for the purpose of the applicable Load Line Convention. These changes should apply to new and existing vessels.

Recommendation #3 – Addressing Safety Concerns Related to Open Lifeboats. It is recommended that Commandant initiate a Legislative Change Proposal and direct a regulatory initiative to eliminate open top gravity launched lifeboats for all oceangoing ships in the U.S. commercial fleet. As an immediate interim safety measure, it is recommended Commandant direct all Officers in Charge of Marine Inspection (OCMIs) to conduct a concentrated inspection campaign on all existing vessels outfitted with gravity launched open lifeboats, including a Coast Guard supervised launching and underway operational test of every lifeboat in service. This concentrated inspection campaign should also ensure that companies have adequately identified and addressed the hazards related to operating with open top gravity launched lifeboats in their identified Safety Management System (SMS) risks.

Recommendation #4 – Indicators for Watertight Closures on Bridge Alarm Panels. It is recommended that Commandant direct a regulatory initiative to require open/close indicators on the bridge of all existing cargo ships, for all watertight closures that are identified as watertight on the conditions of assignment for assignment of load line form for unmanned and cargo spaces. Furthermore, it is recommended that Commandant work with the IMO to amend the applicability of paragraph 3 of SOLAS II-1/13-1 (2015 consolidated) to include all existing cargo ships. This change would require open/close indicators on the bridge of all existing cargo ships, for all watertight closures (e.g., doors, scuttles, fire dampers) that are identified as watertight on the conditions of assignment for assignment of load line form for unmanned compartments and cargo spaces.

Recommendation #5 – Requirement for Closed Circuit Television (CCTV) Camera Installation in Stowage Areas. It is recommended that Commandant direct a regulatory initiative to require the installation of CCTV cameras to monitor unmanned spaces from the bridge cargo vessels, such as cargo holds and steering compartments. Furthermore, it is recommended that Commandant work with the IMO to create a new requirement to install and utilize CCTV cameras, or other similar technology, in cargo stowage areas on cargo ships.

Recommendation #6 – Vessel Weight Change Tracking. It is recommended that Commandant direct a regulatory initiative to require that a company maintain an onboard and shore side record of all incremental vessel weight changes, to track weight changes over time so that the aggregate total may be readily determined.

Recommendation #7 – Approval of Software for Cargo Loading and Securing. It is recommended that Commandant direct a regulatory initiative to require review and approval of software that is used to perform cargo loading and securing calculations. Furthermore, it is recommended that Commandant work with the IMO to implement international requirements for review and approval of such software.

Recommendation #8 - Review and Approval of Stability Software. It is recommended that Commandant update policy to address Coast Guard review and approval of stability software, and delegate review and approval authority to ACSs, where appropriate. This should include establishing specific policy and assigning technical requirements for review and approval of stability software by the Coast Guard, which may be required to review and approve such software for vessels that do not fall under the Alternate Compliance Program (ACP) or Navigation and Vessel Inspection Circular (NVIC) 3-97 authorities.

Recommendation #9 – Float-free Voyage Data Recorder (VDR) Equipped with an Emergency Position Indicating Radio Beacon (EPIRB). It is recommended that Commandant direct a regulatory initiative to require that all VDR capsules be installed in a float-free arrangement, and contain an integrated EPIRB for all domestic vessels currently required to be equipped with a VDR. Furthermore, it is recommended that Commandant work with the IMO to amend SOLAS V/20 (2015 consolidated) to require this VDR configuration for existing vessels.

Recommendation #10 – Locating and Marking Objects in the Water. It is recommended that Commandant direct an examination of the reliability rate of SLDMBs and other similar technology used during Coast Guard Search and Rescue operations. Additionally, the Coast Guard should develop pre-deployment protocols to conduct circuit testing on beacons prior to deploying them on-scene.

Recommendation #11 – Attachable Beacon for Assisting in Relocating Search Objects that are Initially Unrecoverable. It is recommended that Commandant identify and procure equipment that will provide search and rescue units the ability to attach a radio or Automated Identification System/strobe beacon to a found search object that is not immediately retrievable. This beacon should be able to be quickly activated and attached to the object, and have a lanyard of sufficient length to keep the beacon on the surface of the water if the object sinks below the surface.

Recommendation #12 – Personal Locator Beacon Requirement. It is recommended that Commandant direct a regulatory initiative to require that all Personal Flotation Devices on oceangoing commercial vessels be outfitted with a Personal Locator Beacon.

Recommendation #13 – Anonymous Safety Reporting to Shore for Ships at Sea. It is recommended that Commandant direct the development of a shipboard emergency alert system that would provide an anonymous reporting mechanism for crew members to communicate directly with the Designated Person Ashore or the Coast Guard while the ship is at sea. The system would be in place to report urgent and dire safety concerns that are not being adequately addressed onboard the ship or by shore based company resources in a timely manner.

Recommendation #14 – National Oceanographic and Atmospheric Administration (NOAA) Evaluation of Forecast Staffing and Products for Maritime Interests. It is recommended that Commandant request that NOAA evaluate the effectiveness and responsiveness of current National Weather Service (NWS) tropical cyclone forecast products, specifically in relation to storms that may not make landfall but that may impact maritime interests. To improve service to marine stakeholders the evaluation should consider the inclusion of past track waypoints for the tropical system for a period of 48 hours and a graphical depiction of the forecast model track of the best performing prediction models.

Recommendation #15 – Clarification of Flag State Expectations for SMS Implementation. It is recommended that Commandant direct the development and implementation of policy to make it clear that the Coast Guard has a shared responsibility to assess the adequacy of a company's SMS. This responsibility includes, but is not limited to, assessing identified risks and contingency plans (as described in IMO Resolution A.1072(28)), and ensuring that the duties, authorities, and qualifications of the Designated Person Ashore and other shore side management who support vessel operations while underway are specifically described.

Recommendation #16 – Damage Control Information for Existing Cargo Vessels. It is recommended that Commandant direct a regulatory initiative to require that all cargo ships have a plan and booklets outlining damage control information. Furthermore, it is recommended that Commandant work with the IMO to amend the applicability of SOLAS Chapter II-1/19 (2015 consolidated), to apply to all existing cargo ships, ensuring these ships have the damage control information.

Recommendation #17 – Ship Specific Damage Control Competency. It is recommended that Commandant direct a regulatory initiative to update 46 CFR to establish damage control training and drill requirements for commercial, inspected vessels. Furthermore, it is recommended that Commandant work with the IMO to amend SOLAS to establish similar requirements.

Recommendation #18 – Evaluation of Mariner Training Institutions and Coast Guard Merchant Mariner Credentialing Process. It is recommended that Commandant direct a review of the EL FARO VDR transcript and this Report of Investigation, specifically focusing on the effectiveness of the Coast Guard credentialing exams and third party provided training including navigation simulators, heavy weather avoidance, cargo lashing/securing, stability, damage control, and bridge resource management. The Coast Guard should use the review to identify potential areas and competencies needing improvement and expeditiously develop a plan to implement those findings into the mariner credentialing process.

Recommendation #19 – Electronic Records and Remote Monitoring of Vessels at Sea. It is recommended that Commandant direct a regulatory initiative to require electronic records and periodic electronic transmission of records and data to shore from oceangoing commercial ships. This requirement would include records such as bridge and engine room logs, Standards of Training Certification and Watchkeeping (STCW) records, significant route changes, critical alarms, and fuel/oil records. The regulation should ensure Coast Guard access to these records regardless of their location. Furthermore, it is recommended that Commandant work with the IMO to amend SOLAS to require this same electronic transmission of records from all oceangoing commercial ships.

Recommendation #20 – Prevention Training Course for Prospective Coast Guard Sector Commanders and Deputies. It is recommended that Commandant explore adding an OCMI segment to Training Center Yorktown's Sector Commander Indoctrination Course for prospective officers who do not have the Prevention Ashore Officer Specialty Code, OAP-10. The recommended OCMI training segment would be similar to the additional Search and Rescue (SAR) Mission Coordinator Course that is currently required for prospective Sector Commanders and Deputies who lack previous SAR experience.

Recommendation #21 – Coast Guard Oversight of ACSs that Conduct ACP Activities. It is recommended that Commandant update NVIC 2-95 and Marine Safety Manual Volume II to require increased frequency of ACS and Third Party Organizations (TPOs) direct oversight by attendance of Coast Guard during Safety Management Certificate and Document of Compliance audits. Additionally, the Coast Guard shall perform a quality audit specific to the ACS representation and performance on U.S. flag vessels. The Coast Guard personnel conducting the oversight should be fully trained and certified to conduct audits, and given clear authority to issue non-conformities to a vessel, company, or ACS.

Recommendation #22 – ACP Efficiency and Manageability. It is recommended that Commandant direct a regulatory initiative to revise 46 CFR § 8.430 in order to eliminate the use of U.S. Supplements that currently exist for each ACS authorized to conduct all delegated activities. The regulatory revision should clarify that ACS personnel shall default to 46 CFR requirements in circumstances identified in the Critical Ship Safety Systems Table in the Federal Register on February 13, 1998 (63 FR 7495).[439]

Recommendation #23 – ACS Accountability and Transparency. It is recommended that Commandant establish and publish an annual report of domestic vessel compliance. This report shall include domestic vessel no-sail rates for each type of inspected subchapter, and a methodology for associating a Coast Guard-issued no-sail control action with an ACS, for vessels found to have deficiencies or major non-conformities that were misclassified, or not previously identified during an ACS-led inspection or survey.

Recommendation #24 – ACS Surveyor Performance and Interactions with OCMIs. It is recommended that Commandant direct the implementation of a policy requiring that individual ACS surveyors complete an assessment process, approved by the cognizant OCMI, for each type of delegated activity being conducted on behalf of the Coast Guard. The assessment shall ensure vessel surveys and audits meet the Coast Guard marine inspection standard. If an OCMI determines that an ACS surveyor's performance is substandard, that OCMI should be given the authority to revoke the Surveyor's authority to conduct surveys on their behalf.

Recommendation #25 – Competency for Steamship Inspections. It is recommended that Commandant direct a study to explore adding a Steam Plant Inspection course to the Training Center Yorktown curriculum. The course should be required for Coast Guard Marine Inspectors and made available to ACS surveyors who conduct inspections on behalf of the Coast Guard. The steam inspection course could serve as an interim measure until an Advanced Journeyman Course covering steam vessel inspections is implemented (please see Recommendation #26).

Recommendation #26 – Competency for Marine Inspections and ACS Surveyors Conducting Inspections on Behalf of the Coast Guard. It is recommended that Commandant direct the addition of an Advanced Journeyman Inspector course to the Training Center Yorktown curriculum. The course should cover ACS oversight, auditing responsibilities, and the inspection of unique vessel types. The course should be required for senior Coast Guard Marine Inspectors and made available to ACS surveyors who conduct inspections on behalf of the Coast Guard.

Recommendation #27 – Coast Guard Major Conversion Determinations for Vessels. It is recommended that Commandant direct the review of policies and procedures for making and documenting major conversion determinations, including use of the Precedence Principle.

[439] Available at https://www.gpo.gov/fdsys/pkg/FR-1998-02-13/pdf/98-3628.pdf.

Recommendation #28 – Intact and Damage Stability Standards Review. It is recommended that Commandant direct a review of current intact and damage stability standards to improve vessel survivability in extreme wind and sea conditions.

Recommendation #29 – Applying Intact and Damage Stability Standards to Existing Cargo Vessels. It is recommended that Commandant direct a regulatory initiative to require that all existing cargo vessels meet the most current intact and damage stability standards.

Recommendation #30 – Third Party Oversight National Center of Expertise. It is recommended that Commandant consider creation of a Third Party Oversight National Center of Expertise to conduct comprehensive and targeted oversight activities on all third party organizations and ACSs that perform work on behalf of the Coast Guard. The Center of Expertise should be staffed with Subject Matter Experts that are highly trained inspectors, investigators, and auditors with the capability and authority to audit all aspects of third party organizations. As an alternative, the Coast Guard could add a new Third Party Oversight Office at Coast Guard Headquarters with a similar staffing model as the proposed Center of Expertise. The new Third Party Oversight Office could function similar to the Traveling Inspector Office and report directly to the Assistant Commandant for Prevention Policy.

Recommendation #31 – Technical Review of Critical Propulsion System Components. It is recommended that Commandant immediately review a representative sample of existing engineering system plans and implement a policy to ensure future Coast Guard or ACS reviews of such plans consider the full designed operating range when reviewing design elements for critical propulsion system components (e.g., the operating range for lube oil systems should ensure satisfactory function for the full range of allowable oil sump levels and vessel lists.)

11. Administrative Recommendations

Administrative Recommendation #1 – Acquiring DNA Sample for Identification of Human Remains. It is recommended that Commandant direct the development and implementation of Coast Guard policy for the collection of DNA samples by Coast Guard personnel when deceased individuals are unable to be recovered during Search and Rescue cases or post-incident marine casualty investigations. These DNA samples could be used to provide identification of human remains

Administrative Recommendation #2 - VDR Performance Standards. It is recommended that Commandant direct a regulatory initiative to require that all VDRs capture all communications on ship's internal telephone systems. Furthermore, it is recommended that Commandant work with the IMO to amend SOLAS and update performance standards to ensure that all VDRs capture these two-way internal ship communications.

Administrative Recommendation #3 – VDR Data and Audio Access. It is recommended that Commandant initiate a Legislative Change Proposal to amend 46 U.S.C. Chapter 63, to ensure that, notwithstanding NTSB statutory authority, the Coast Guard has full access and ability to use VDR data and audio in marine casualty investigations, regardless of which agency is the investigative lead.

Administrative Recommendation #4 – MISLE Documentation of Deficiencies that the OCMI Refers to an ACS. It is recommended that Commandant require the addition of specific MISLE data fields for documenting deficiencies that the OCMI refers to an ACS for correction. The deficiency should remain open in MISLE until the ACS provides the OCMI who issued the deficiency with a written report documenting corrective action has been completed or the condition has been appropriately recorded in the Class database. This will ensure that vessel compliance history is documented and accessible to Coast Guard Marine Inspectors and investigators.

12. Enforcement Recommendations

Recommendation #1 – TOTE Services Violations. It is recommended that Sector Jacksonville initiate civil penalty action against TOTE Services for the following offenses:

- Failure to comply with the work-rest requirements detailed in 46 U.S.C. § 8104 and 46 CFR § 15.1111 for EL FARO crew members on multiple dates prior to the accident voyage.
- Failure to comply with emergency procedures for special personnel detailed in 46 CFR § 199.180. Specifically, Polish ship rider Mr. Marek Pupp testified that he continued to conduct work on EL FARO during the emergency muster and abandon ship drills.
- Failure to notify the Coast Guard or ABS of repairs to primary lifesaving appliances that were conducted on September 28, 2015 just prior to EL FARO's departure from Jacksonville on the accident voyage.
- Failure to notify the Coast Guard or ABS of repairs to EL FARO's main propulsion boiler superheating piping on August 24, 2015.

Based on the findings of this investigation, the MBI does not recommend any administrative or punitive action against any Coast Guard personnel. The MBI does not recommend any suspension or revocation action against any credentialed mariner. Additionally, the MBI does not recommend criminal prosecution against any person or entity.

JASON D. NEUBAUER
Captain, U.S. Coast Guard
Chairman, Marine Board of Investigation

Enclosures: (1) Marine Board of Investigation Convening Order
(2) Marine Board of Investigation Hearing Witness list
(3) Marine Board of Investigation Exhibit list

Appendices (A) Coast Guard MSC Technical Review and Analysis of the SS EL FARO
(B) Coast Guard MSC Lube Oil Modeling and Analysis

U.S. Department of Homeland Security
United States Coast Guard

Commandant
United States Coast Guard

2703 Martin Luther King Ave SE
Stop 758, Washington, DC 20593-7581
Staff Symbol: CG-INV
Phone: (202) 372-1030

16732
OCT - 8 2015

MEMORANDUM

From: Mark E. Butt, RADM
Acting DCO

To: J. D. Neubauer, CAPT

Subject: MARINE BOARD OF INVESTIGATION CONCERNING THE SINKING OF THE S. S. EL FARO (O.N. 561732) APPROXIMATELY 36NM NORTHEAST OF ACKLINS & CROOKED ISLANDS, BAHAMAS, WITH MULTIPLE LOSS OF LIFE

1. Pursuant to the authority contained in Title 46, United States Code (U.S.C.), Section 6301 and the regulations promulgated thereunder, you are to convene a Formal Marine Board of Investigation consisting of the following membership. The Board will convene as soon as practicable to inquire into all aspects of the subject casualty at such times and places as directed by you:

- CAPT Jason Neubauer, USCG, Chariman
- CDR Jeff Bray, USCG, Legal Counsel
- CDR Matthew Denning, USCG, Member
- Mr. Keith Fawcett, Member
- LCDR Damian Yemma, USCG, Recorder

2. The Board will thoroughly investigate the sinking and loss of life of the S. S. EL FARO (O.N. 561732) in accordance with the all applicable statutory and regulatory mandates. Upon completion of the investigation, the Board will issue a report to the Commandant with the collected evidence, the established facts, and its conclusions and recommendations. Conclusions or recommendations concerning commendatory actions or misconduct that would warrant further inquiry shall be referred by separate correspondence to the cognizant District Commander for consideration and action. A daily summary of significant events shall be transmitted to Commandant (CG-5PC) while the Board is in formal session.

3. You will complete and submit your investigative report to Commandant (CG-5PC) within 12 months of the convening date. If this deadline cannot be met, a written explanation for the delay and the expected completion date shall be submitted. You are highly encouraged to submit any interim recommendations intended to prevent similar casualties, if appropriate, at any point during your investigation.

4. The National Transportation Safety Board (NTSB) is also charged with the responsibility of determining the cause or probable cause of this casualty by the Independent Safety Board Act of 1974 (49 U.S.C. 1901, et. seq.) and may designate a representative to participate in this

investigation. The NTSB representative may make recommendations regarding the scope of the inquiry, may identify and examine witnesses, and/or submit or request additional evidence.

5. The Commandant (CG-INV) will furnish such funding and/or technical assistance as may be required by the Marine Board when deemed appropriate and within the requirements for the scope of this investigation. Commander, Seventh Coast Guard District, will provide such administrative, logistical, and/or legal support as may be required.

#

Copy: CG-LMI
LANTAREA(p)
CCGD7(p)
Sector Jacksonville

Marine Board of Investigaiton Witness List

Hearing transcripts are available at [Homeport link]

Witness #	Testimony Date	Name	Position and/or Association
1	16 Feb 2016	Mr. Phillip Morrell	TSI VP of Marine Operations
2	17 Feb 2016	Mr. Philip Greene	TSI President & CEO
3	17 Feb 2016	Mr. Lee Peterson	TSI Director of Safety & Services
4	17 Feb 2016	Mr. Mick Kondracki	TSI Director of Labor Relations & Risk Management
5	18 Feb 2016	Capt. Earl Loftfield	Master S.S. EL YUNQUE
6	18 Feb 2016	Mr. Charlie Baird	Former 2nd Mate, S.S. EL FARO
7	18 Feb 2016	Mr. Tim Nolan	TMPR President
8	19 Feb 2016	Mr. Jim Fisker-Anderson	TSI Director of Ship Management
9	19 Feb 2016	Mr. Alejandro Berrios	Former 2nd and 3rd Mate, S.S. EL FARO
10	19 Feb 2016	Mr. Tony Callaway	PORTUS Vessel Supervisor
11	20 Feb 2016	Mr. John Lawrence	TSI Manager of Safety and Operations, DPA
12	20 Feb 2016	Mr. Ron Rodriguez	TMPR Terminal Manager
13	20 Feb 2016	Mr. Don Matthews	TMPR Marine Operations Manager
14	22 Feb 2016	CAPT John Mauger	USCG Commanding Officer, Marine Safety Center
15	22 Feb 2016	CAPT Kyle McAvoy	USCG HQ Office of Commercial Vessel Compliance (CG-CVC)
16	23 Feb 2016	Mr. James Robinson	Former Chief Engineer, S.S. EL FARO
17	23 Feb 2016	Mr. J. Kenny Walker	Former Bosun S.S. EL FARO
18	23 Feb 2016	CAPT Todd Coggeshall	USCG District 7 Chief, Incident Management Branch
19	24 Feb 2016	OS2 Matthew Chancery	USCG District 7 Command Center SAR Controller
20	24 Feb 2016	Mr. John Fletcher	Sperry Marine, Global Services Manager
21	24 Feb 2016	Mr. Jerry Michel	Northup Grumman Lead Marine Service Engineer
22	24 Feb 2016	Mr. Bryan Vagts	Former Chief Mate S.S. EL FARO

Marine Board of Investigaiton Witness List

Hearing transcripts are available at [Homeport link]

Witness #	Testimony Date	Name	Position and/or Association
23	25 Feb 2016	Mr. Jamie Torres	Former Chief Mate S.S. EL FARO
24	25 Feb 2016	LT Kim Beisner	Former USCG Shiprider on S.S. EL FARO
25	25 Feb 2016	Mr. Luke Laakso	Walashek Boiler Inspectors Superintendant
26	26 Feb 2016	Mr. Louis O'Donnell	ABS Assistant Chief Surveyor, Americas Division
27	26 Feb 2016	Mr. Tim Neeson	TSI Port Engineer
28	16 May 2016	Capt. James Frudaker	Docking Pilot
29	16 May 2016	Capt. Eric Bryson	Bar Pilot
30	16 May 2016	Capt. Eric Axelsson	Former Master S.S. EL FARO
31	17 May 2016	Capt. Jack Hearn	Former Master S.S. EL FARO
32	17 May 2016	Mr. James Franklin	Branch Chief, Hurricane Specialist Unit, National Hurricane Center
33 34	18 May 2016	Mr. Rich Brown Mr. Jerry Hale	VP Applied Weather Technology Support Manager for Bon Voyage System, Applied Weather Technology
35	18 May 2016	Mr. Jim Wagstaff	VP of Operations TMPR
36	19 May 2016	Mr. Mark Larose	ABS Surveyor
37	19 May 2016	Ms. Jamie D'Addieco	ABS Surveyor
38	19 and 20 May 2016	Mr. Thomas Gruber	ABS Chief Engineer - Statutes
39	20 May 2016	Capt. Raymond Thompson	Former Chief Mate S.S. EL FARO
40 41	20 May 2016	Mr. Suresh Pisini Mr. Dan Cronin	ABS Structures Group Head ABS VP of Engineering (former)
42 43	23 May 2016	Mr. Spencer Schilling Mr. Michael Newton	President Herbert Engineering Corp. VP Herbert-ABS Software Solutions (HASS) and Cargo Max Product Manager

Marine Board of Investigaiton Witness List

Hearing transcripts are available at [Homeport link]

Witness #	Testimony Date	Name	Position and/or Association
44	23 May 2016	Mr. Randall Kidd	PORTUS Stevedore Securing Team
45	24 May 2016	Capt. Kevin Stith	Former Chief Mate S.S. EL FARO; Master S.S. EL YUNQUE
46	24 May 2016	Mr. Stephen Hohenshelt	ABS ISM Audit Coordinator and Surveyor
47	25 May 2016	Mr. Jerry McMillan	USCG Sector San Juan Marine Inspection Training Officer (MITO)
48	25 May 2016	Mr. John Hannon	USCG HQ Office of Commercial Vessel Activities (CG-CVC-1)
49	25 May 2016	CWO4 Andrew Schock	USCG Marine Inspector
50	26 May 2016	Mr. Bruce Wagner	Harding Safety Field Service Engineer Level 2
51	26 May 2016	Mr. Peter Keller	Executive VP TOTE Inc.
52	26 May 2016	Mr. William Weinbecker	Port Engineer TMPR
53	27 May 2016	Ms. Alyse Lisk	VP of Cargo Services TMPR
54	27 May 2016	CAPT Benjamin Hawkins	USCG HQ Office of Design and Engineering Standards (CG-ENG)
55	6 Feb 2017	Capt. Raymond Thompson	Former Chief Mate S.S. EL FARO
56	6 Feb 2017	Dr. Jeff Stettler	USCG Marine Safety Center
57	7 Feb 2017	Mr. Jaideep Sirkar	USCG HQ Office of Design and Engineering Standards, Naval Architecture Division (CG-ENG-2)
58	7 Feb 2017	CDR Michael Crider	Commanding Officer, USCG Communications Command (COMMCOM)
59	7-8 Feb 2017	CAPT David Flaherty	USCG HQ, Chief, Traveling Inspectors (CG-5P-TI)
60	8 Feb 2017	Mr. Mark Gay	Former Chief Engineer S.S. EL FARO
61 62	8-9 Feb 2017	Capt. Phil Anderson Capt. Edward Walker	NCB, Chief, Technical Department NCB, Assistant Deputy, Technical Department
63	9 Feb 2017	Mr. Tom Gruber	ABS Chief Engineer - Statutes

Marine Board of Investigaiton Witness List

Hearing transcripts are available at [Homeport link]

Witness #	Testimony Date	Name	Position and/or Association
64	9-10 Feb 2017	Mr. Alejandro Berrios	Former 3rd Mate S.S. EL FARO
65	10 Feb 2017	Mr. Lou O'Donnell	ABS Assistant Chief Surveyor, Americas Division
66	13 Feb 2017	Mr. Lee Peterson	TMPR Director of Operations (Prior TSI Director of Safety and Marine Operations)
67	13 Feb 2017	Mr. Tim Neeson	TSI Port Engineer
68	13-14 Feb 2017	Capt. John Lawrence	TSI Manger of Safety and Operations
69	14 Feb 2017	Mr. Evan Bradley	Former Bosun S.S. EL FARO
70	14 Feb 2017	Mr. Marvin Hearman III	Former A/B S.S. EL FARO
71	15 Feb 2017	Mr. Marek Pupp	Intec (via Skype and telephone from Poland)
72	15 Feb 2017	Mr. Mickey Fitzmaurice	NOAA Search and Rescue Satellite Aided Tracking (SARSAT) Program (via telephone from Suitland, MD)
73	15 Feb 2017	Mr. Tio Devaney	Palfinger Marine, Operations Director for the Americas
74	16 Feb 2017	Ms. Melissa Clark	Former TSI Crewing Manager
75	16 Feb 2017	Capt. Peter Villacampa	Former Master S.S. EL MORRO
76	17 Feb 2017	Mr. Don Matthews	TMPR Marine Operations Manager

S.S. EL FARO MARINE BOARD OF INVESTIGATION EXHIBIT LIST			
Exhibit #	**Name**	**Type**	**# of Pages**
001	EL FARO Overview	Powerpoint	
002	Voyage and Storm Tracklines - Erica and Joaquin	Powerpoint	
003	Timeline (To be developed)	Powerpoint	
004 (Updated)	Emails - Weather and Operations	PDF	118
005	Emails - Personnel Matters	PDF	54
006	Tote Corporate Position Descriptions	PDF	45
007	General Arrangement Drawing	PDF	4
008	Trim and Stability Booklet Herbert Engineering (Feb 2007)	PDF	59
009	RoRo Plan EF185S 9-29-2015	PDF	16
010	Space Availability Pinksheet Worksheets EF185S 9-29-2015	Excel File	
011	Email - Boiler Condition Chief Engineer to Port Engineer	PDF	1
012	Walashek 2015 Boiler Survey	PDF	7
013	Major Conversion Letter 8Nov2004	PDF	19
014	Fructose Tank Drawing	PDF	1
015	Evaluation of Buckling for LURLINE 03 July08	PDF	7
016	Cargomax Review Letter	PDF	2
017 (Updated)	Scantling Reassessment-2007-2008	PDF	14
018	EL FARO ABS Statutory Requirement	PDF	1
019	Torres to Matthews Lashing Gear email	PDF	1
020	Certificate of Inspection	PDF	2
021	Rodriguez Email Re: Need Cargo Port Side Immediately	PDF	3
022	Boiler Repairs 8_23 Departing Jax Schedule	PDF	1
023	Hold3-Scuttle-Port_2005_HerbertEngineering	PDF	1
024	MARINE ELECTRIC ROI - Excerpts	PDF	26
025	Operations Manual - Vessel Rev. 21	PDF	357
026	Emergency Preparedness Manual - Vessel Rev. 13	PDF	185
027	Hydrostatic Release Email (INMARSAT) 29 Sep 2015	PDF	3
028	Message from EL FARO to John Lawrence	Audio File	
029	Capt. Davidson phone call to emergency service 1 of 2	Audio File	
030	Capt. Davidson phone call to emergency service 2 of 2	Audio File	
031	D7 Command Center Call to Lawrence	Audio File	
032	Lawrence Notes for CG Notification	PDF	4
033	LANTCC Call To D7	Audio File	
034	LANTCC Email to D7	PDF	3
035	D7CC Call to OPBAT	Audio File	
036	Deck Log Books Deviation Voyage (TS Erika)	PDF	7
037	Draft mark photos - EL YUNQUE	PDF	1
038	VDR - 2013 and 2014 APT and Certificate of Compliance	PDF	22
039	EL FARO LO LO Bay Plans 2014	PDF	14
040	Approved - EL FARO Cargo Securing Manual REV 0, dated 1.20.2006	PDF	159
041	CCI_Lashing_ELFARO-CSM-Addendum13A	PDF	9
042	CCI_Tote Lashing Manual	PDF	139
043	Bridge Equip List - EL Yunque	PDF	3
044	Cargo Max User Manual - Excerpt (page 13)	PDF	1
045	Hurricane Danny Safety Alert	PDF	1
046	El Faro - 222744 - radio survey	PDF	27
047	Organization Charts - TOTE Maritime PR and TSI	PDF	9
048	Loftfield Standing Orders August 2012	PDF	4
049	Master's Turnover 08-11-15_CCI	PDF	6
050	Capt. Stith Standing Orders 04 Sept 2015	PDF	10
051	Departure Message and Noon Position Graphic	PDF	2
052	Evaluation Forms	PDF	2
053	El Faro Survey Report CCI	PDF	33
054	Conversion Progress Email	PDF	2
055	EL FARO Repairs Email (Economizer)	PDF	1
056	Cargomax Printout EF178JX 11 Aug 15	PDF	9
057	Cargomax Printouts EF185JX - LC File 29 Sep 15	PDF	9
058	Cargomax Printouts EF185JX 29 Sep 15	PDF	11
059	Cargomax Printouts EF185JX - 01 Oct 15	PDF	9
060	EL FARO Shipyard Worklist Items for Oct 2015	PDF	1
061	TOTE Newsletters	PDF	23
062	ABS Economizer Report	PDF	4
063	Email - Chief Engineer re Urgent Repairs ,20 August 2015	PDF	1
064	Email - Requesting Surveyor re: EL FARO Economizer	PDF	1
065	EL YUNQUE Machine Operating Manual Excerpt - Superheated Steam Drawing	PDF	1
066	Bunker Email Aug 2015	PDF	4
067	Preliminary Report TOTE SERVICE AUDIT	PDF	9

S.S. EL FARO MARINE BOARD OF INVESTIGATION EXHIBIT LIST			
Exhibit #	Name	Type	# of Pages
068	Cargomax Load Case File EF178JX.LC	PDF	1
069	Final Stow Plan EF185S	PDF	30
070	REVISED GUIDELINES FOR A STRUCTURE OF AN INTEGRATED SYSTEM OF CONTINGENCY PLANNING FOR SHIPBOARD EMERGENCIES	PDF	22
071	ABS Cargo Ship Safety Equipment Record	PDF	30
072	EL FARO SARSAT EPIRB Alert	PDF	3
073	Pre-Arrival and Departure Checklist	PDF	1
074	Harding Services Report (Lifeboat Winches)	PDF	5
075	EL FARO AIS Trackline 14 Mar 2015 (Depart San Juan)	PDF	1
076	Revision of SOLAS Chapter V, 18 Feb 2000	PDF	3
077	DOC Audit Status Report	PDF	14
078	ABS Statutory Survey Report, 5 July 2014	PDF	10
079	CGD7 EL FARO SAR Next of Kin Brief	PDF	28
080	Marine Safety Analysis Report (VADM Card Report)	PDF	35
081	Arrangement of Machinery Material List Plan for 3rd Deck Level, sheet 3 of 3	PDF	1
082	NVIC 2-95, Ch 2 - Alternate Compliance Program	PDF	33
083	Pages from International Safety Management Code 2014 ed.	PDF	4
084	Alternative Compliance Federal Register	PDF	13
085	Search and Rescue SITREP	PDF	24
086	SOLAS V Reg 34	PDF	1
087	IMO Guidelines for Voyage Planning	PDF	5
088	DeckLog_11Aug2015_EF178JX	PDF	2
089	USCG.LTR.NOV.92	PDF	2
090	AY15-16 Sector Command Position Breakdown	PDF	1
091	Tote Maritime Puerto Rico SOP-Monitor Stowage-Trim-Stability	PDF	2
092	ACS.Oversight.2014.Review.C2-1500740	PDF	15
093	2015 Sperry Marine Org Chart	PDF	6
094	EL FARO Engine Room Photos	PDF	6
095 (Updated)	Soft Patch Emails	PDF	4
096	Email - El Faro - AMOS Requisition 26 May 2016	PDF	4
097	15 APRIL 2011 EL FARO Lost Power	PDF	2
098	PA2136822-A Lay up survey 19 April 2012	PDF	10
099	2013-054-001 Rev 0_T1133593	PDF	10
100	2013-054-003 Rev 1_T1167927	PDF	1
101	PA2451530-D Annual Safety Construction Survey 2	PDF	6
102	Review Letter_T1133593	PDF	2
103	Review Letter_T1167927	PDF	1
104	Fructose Tank Installation Survey	PDF	4
105	Journal Bearing Turbine, Special Continuous Survey Machinery 8	PDF	7
106	ENG_v1_Walachek Boiler Repair Estimate_El Faro	PDF	1
107	7500285_02K REPORTS_SJ_2816446	PDF	6
108	ABS Report Cracks in Double Bottom 27 Jan 2015	PDF	2
109 (Updated)	EL YUNQUE Cargo Lashing Photos 01 Dec 2015	PDF	40
110	NVIC 8-01 Enclosures 4 and 5	PDF	16
111	USCG ABS MOU	PDF	11
112	El Faro Survey Status Report	PDF	47
113	ABS ACP Supplement	PDF	115
114	Boilers Propulsion BW Hydro Specs	PDF	1
115	ABS Survey Report	PDF	6
116	ABS Report Cracks in double bottom REPORTS_JS_2906321	PDF	2
117	2014 MSC Plan Review Oversight Findings by Activity Type	PDF	1
118	Butterworth Install Photo	PDF	1
119	Electronic Asset Logbook	PDF	2
120	Witness Statement - Lynch	PDF	2
121	Witness Statement - Lloyd	PDF	1
122	Witness Statement - McDowell	PDF	1
123	Witness Statement - Zylinski	PDF	1
124	Witness Statement - Atwater	PDF	1
125	Witness Statement - Heard	PDF	1
126	Sperry Marine VDR APT Email	PDR	1
127	SS EL FARO MISLE Inspection Records	PDF	480
128	Marine Safety Center Docs 1	PDF	40
129	Marine Safety Center Docs2	PDF	14
130	EL FARO Turnover Notes (Master, CE, CM)	PDF	99
131	Grand Bahamas Inspection Application Emails	PDF	4
132	Cargo Lashing Gear Maintenance Records	PDF	9
133	Capacity Plan Rev C Mar 2006	PDF	3

S.S. EL FARO MARINE BOARD OF INVESTIGATION EXHIBIT LIST			
Exhibit #	**Name**	**Type**	**# of Pages**
134	Fire Control & Safety Plan Rev A Jan 2006	PDF	2
135	Final Offsets 1967	PDF	77
136	Cargo Max Users Manual 9th Ed Sep 2011	PDF	86
137	Cargo Max El Faro Vessel Information Booklet Ver 1.21 Rev 2 Mar 2007	PDF	34
138	Cargo Max El Faro Wind Heel Report Apr 2006	PDF	59
139	Stability Test Report 2006	PDF	31
140	Container Support Structure June 2005	PDF	4
141	Mods to Main Deck Structure Jul 2005	PDF	3
142	Spar Deck Removal	PDF	4
143	SS Great Land - Innerbottom Scantling Reassessment - Design Memo Oct 2006	PDF	32
144	Deck Structure Analysis - Norther Lights Jul 2005	PDF	16
145	Updated TOTE Organization Chart	PDF	1
146	2015 Hurricane Tracking Chart	PDF	1
147	National Hurricane Center Hurricane Joaquin Report	PDF	36
148	National Hurricane Center Monthly Tropical Weather Summary	PDF	2
149	National Hurricane Center Model Summaries	PDF	18
150	National Hurricane Center Archive - Hurricane Sandy	PDF	2
151	High Seas Forecast for Tropical Atlantic (HSFAT)	PDF	24
152	Hurricane Joaquin Discussions (TCDAT)	PDF	34
153	Hurricane Joaquin Forecasts and Advisories (TCMAT)	PDF	26
154	Offshore Forecast for SW and Tropical North Atlantic and Caribbean (OFFNT)	PDF	165
155	Tropical Weather Discussions (TWDAT)	PDF	45
156	BVS Data Sources and Quick Reference Guides	PDF	5
157	BVS User's Manual	PDF	188
158	NOAA RUC Archive of Joaquin Model Tracks	PDF	14
159	Joaquin - Online Graphical Tropical Cylclone Forecast Products	PDF	22
160	Marine Weather Discussions (MIMATS)	PDF	37
161	Joaquin Wind Speed Probabilities (PWSAT)	PDF	48
162	Joaquin Advisories (TCPAT1)	PDF	50
163	ABS Org Charts	PDF	3
164	ABS Assistant Chief Surveyor Job Description	PDF	16
165	ABS General Instructions SWZ-102-99-P02 Rev	PDF	12
166	ABS EL FARO SOLAS Damage Summary and Associated Files	PDF	30
167	EL FARO Hull Girder Section Modulus Analysis	PDF	4
168	Loading Conditions - Fructose Tanks	PDF	16
169	Lifeboat and Davit Plans	PDF	4
170	Turnover Notes Part 2	PDF	66
171	NOAA Marine Text Forecasts	PDF	7
172	Bon Voyage System Screenshots	PDF	35
173	ABS Guide to Certification of Container Securing Systems (1988)	PDF	44
174	ABS Guide to Certification of Container Securing Systems (1988) - Notices 1-4	PDF	16
175	ABS Guide to Certification of Container Securing Systems (2014)	PDF	116
176	Deck Logs August 1-5, 2015	PDF	7
177	Combined Survey Reports	PDF	41
178 (Updated)	Combined Emails	PDF	116
179	Evaluations - 3rd Mate	PDF	47
180	EL FARO Repositioning Decision Memo	PDF	2
181	Tropical Depression Grace Map	PDF	1
182	EL FARO FAQ with Edits	PDF	2
183	Consolidated Scorecard Results	PDF	1
184	ABS Survey Manager Comments	PDF	1
185	PR-17 Reporting by Surveyors of Deficiencies relating to Possible SMS Failures	PDF	4
186	US SARSAT Engineering report on MV El Faro Incident, Oct. 1, 2015	PDF	18
187	NAVCEN AIS Position Data for EL FARO 30 Sep - 1 Oct 2015	PDF	2
188	Logs Aug21-31, 2015	PDF	19
189	Code of Safe Practice for Cargo Stowage and Securing	PDF	110
190	Inclining ABS Suveyor's Report 2006	PDF	26
191	EL FARO ABS Vessel Survey History	PDF	2
192	Navigation And Vessel Inspection Circular 10-97	PDF	22
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259	SS EL FARO Inclining Experiment Record Sheet, dated February 12, 2006, Herbert Engineering Corporation	PDF	1
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U.S. Department of Transportation
United States Coast Guard

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United State Coast Guard

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16732
22 Jul 2016

MEMORANDUM

NEUBAUER.JASON.D.1170236480 Digitally signed by NEUBAUER.JASON.D.1170236480 DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USCG, cn=NEUBAUER.JASON.D.1170236480 Reason: I am the author of this document Date: 2016.07.22 12:40:50 -04'00'

From: J. D. Neubauer, CAPT
COMDT (CG-INV)

To: CG MSC

Subj: MSC TECHNICAL REVIEW AND ANALYSES OF THE SS EL FARO, O. N. 561732

Ref: (a) COMDT (DCO) memo 16732 of 08 Oct 2015

1. In accordance with reference (a), the Marine Board of Investigation (MBI) is investigating the sinking of the SS EL FARO and loss of her 33 crew members on October 1, 2015. I request Marine Safety Center (MSC) technical assistance in support of the investigation.

2. Specifically, I request that the MSC complete the following reviews and analyses to support the MBI:

   a. Conduct stability review and analysis of the EL FARO including the following primary elements:

      (1) Summary of stability criteria, including criteria applicable to the EL FARO at the time of the casualty, and criteria which would apply if the vessel were constructed or underwent a major modification in 2016.

      (2) Review of the EL FARO inclining experiment and Stability Test Report, including calculation of an engineering estimate of the uncertainty in the vessel's KG for the lightship condition and for the accident voyage departure condition.

      (3) Review of the EL FARO Trim and Stability Book.

      (4) Review of the EL FARO CargoMax stability and loading software application and vessel operator usage as a supplement to the Trim and Stability Book for load planning and stability evaluation.

      (5) Review and assessment of the intact and damage stability for the accident voyage, based on the documented departure loading condition (to be provided).

   b. Conduct a structures review of the EL FARO including the following primary elements:

(1) Summary of applicable structures criteria, whether based on class or other requirements.

(2) Review of the documented structural assessments completed on behalf of the vessel owners and approved by ABS, including assessments for the 1992-1993 vessel lengthening, 2005-2006 deck container (LO/LO) conversion, 2007-2009 scantling and allowable bending moment reassessments, and the post-accident hull girder section modulus and buckling analysis completed by ABS in 2015.

(3) Review of the EL FARO CargoMax stability and loading software application and vessel operator usage for hull girder strength assessment.

c. Conduct hydrostatic sinking analyses for the accident voyage of the EL FARO, incorporating the following considerations:

(1) The vessel in a "dead-ship" condition (i.e., after loss of propulsion).

(2) An estimated fuel burn-off at the time of sinking (to be provided).

(3) Wind heel resulting from estimated category 3 hurricane wind speeds and gusts (modeled meteorological wind spectra to be provided).

(4) Down-flooding through multiple feasible paths, including ventilation intake and exhaust openings, and cargo hold access scuttle openings (specific scenarios to be provided).

(5) Individual compartment and combined/progressive flooding through down-flooding points considering a range of estimated cargo hold permeability values (specific scenarios to be provided).

(6) Additional heeling moments due to potential cargo shifts of trailer (RO/RO) and above deck container (LO/LO) cargo, and entrapped water on the 2nd deck (specific scenarios to be provided).

(7) Feasibility of the installed bilge pumping system keeping up with flooding through ventilation openings or other down-flooding points.

3. MSC will have access to all information available to the MBI, including all materials provided by the parties in interest (PII), other MBI exhibits, and public hearing witness transcripts.

4. Please provide the results of your technical reviews and analyses in the form of a stand-alone MSC report suitable for inclusion as an Appendix to the MBI's Report of Investigation (ROI). It is important to note that MSC's report will be provided to the National Transportation Safety Board (NTSB) and that it may be included in the NTSB's report of investigation and posted on their public docket.

#

U.S. Department of Homeland Security
United States Coast Guard

Commanding Officer
United States Coast Guard
Marine Safety Center

US Coast Guard Stop 7430
2703 Martin Luther King Jr. Ave
Washington, DC 20593-7430
Staff Symbol: MSC-1
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16732/P019910
Serial: A0-1700861
22 Mar 2017

MEMORANDUM

From: J.W. Mauger, CAPT
CG MSC

Reply to Attn of: Dr. Jeffrey Stettler
(202) 795-6783

To: J.D. Neubauer, CAPT
COMDT (CG-INV)

Subj: MSC TECHNICAL REVIEW AND ANALYSIS OF THE SS EL FARO, O.N. 561732

Ref: (a) Your memo 16732 of July 22, 2016

1. As requested in reference (a), the Marine Safety Center (MSC) completed technical reviews and analyses in support of the Marine Board of Investigation (MBI) investigating the sinking of the SS EL FARO and loss of her 33 crew members on October 1, 2015.

2. The MSC has completed the following technical reviews and analyses:

   a. Stability: including review of intact and damage stability criteria, and assessment of the EL FARO against applicable criteria and criteria which would apply if the vessel were constructed in 2016.

   b. Structures: including review of structures criteria, and review of documented structural assessments.

   c. Hydrostatic sinking analyses of the accident voyage: including review of wind heel and flooding effects, potential downflooding through multiple feasible paths, and combined effects of wind, seas, and flooding on hydrostatics and stability.

3. The results of the requested reviews and analyses are provided in a stand-alone MSC technical report, which is included as the enclosure to this memorandum.

4. If you have any questions or need additional information, please contact Dr. Jeffrey Stettler.

#

Enclosure: MSC Technical Report: SS EL FARO Stability and Structures

U.S. Coast Guard
Marine Safety Center

Technical Report

SS EL FARO
Stability and Structures

March 22, 2017

Table of Contents

Executive Summary

This report documents technical reviews of the stability and structures of the SS EL FARO completed by the Marine Safety Center (MSC), as requested by the Marine Board of Investigation (MBI) in support of the investigation into the sinking of the EL FARO and loss of her 33 crew members on October 1, 2015. The report also documents forensic hydrostatic sinking analyses conducted to assess likely contributing factors to the sinking. To aid in the accomplishment of the reviews and analyses, the MSC independently generated a detailed computer model, and used this model for analyses of vessel hydrostatics, stability and strength.

Based on review of the available technical documents and independent analyses, the MSC determined that the vessel met applicable intact and damage stability and structural strength requirements, as loaded for the accident voyage which departed Jacksonville on September 29, 2015. However, it is noted that the vessel was operated very close to the maximum load line drafts, with minimal stability margin compared to the required metacentric height (GM), and with limited available freeboard and ballast capacity, leaving little flexibility for improving stability at sea if necessary due to heavy weather or flooding.

The hydrostatic sinking analyses were based on first-principles, focusing on the righting arms, including righting energy and range of stability considerations, with effects of wind heel and free surface due to the floodwater in the cargo holds included. The results were highly sensitive to estimated cargo hold permeability. The results were also highly sensitive to variation in wind speed, especially in combination with floodwater free surface and permeability. Single-compartment flooding of Hold 3 with combined wind heel due to 70-90 knot beam winds resulted in very small residual righting arms and little residual righting energy (area under the righting arm curve). This would suggest that it would be highly unlikely that the EL FARO could have survived even single compartment flooding of Hold 3, given the sea conditions with estimated 70-90 knot winds and 25-30 foot seas. Potential sources of flooding of Hold 3 and the other cargo holds were also investigated, including vulnerabilities associated with the cargo hold ventilation system openings and the emergency fire pump piping in Hold 3. Given the sea conditions and reported initial flooding through the Hold 3 scuttle, the ventilation openings would have allowed at least intermittent flooding into the cargo holds, as the vessel was subject to variable wave height on the side shell and rolled about an estimated mean heel angle of approximately 15 degrees.

As requested by the MBI, the MSC also compared the stability of the EL FARO against criteria which would apply if the vessel were constructed in 2016. In this case, the EL FARO would be required to meet minimum righting arm criteria of Part A of the International Code on Intact Stability (2008 IS Code). Based on the MSC analyses, the EL FARO, as operated and loaded for the accident voyage, would not meet the righting arm criteria of Part A of the 2008 IS Code. Additionally, the EL FARO would have been required to meet probabilistic damage stability standards of SOLAS 2009. Based on the MSC analyses, the EL FARO, as operated and loaded for the accident voyage, would not meet the SOLAS 2009 damage stability standards. In order for the EL FARO to meet the current intact and damage stability standards at the full load draft, the minimum required GM would be in the range of 5.8-6.8 feet, which is 1.5-2.5 feet greater than the GM of the actual departure loading condition of the accident voyage.

1. Introduction

1.1. Background

Reference [1] is the memorandum from the President of the Marine Board of Investigation (MBI) to the Commanding Officer of the Marine Safety Center (MSC), requesting technical assistance in support of the investigation of the sinking of the SS EL FARO (EL FARO) and loss of her 33 crew members. The memorandum requested that the MSC complete the following reviews and analyses to support the MBI:

(1) Stability review and analysis of the EL FARO including the following primary elements:

   a. Summary of stability criteria, including criteria applicable to the EL FARO at the time of the casualty, and criteria which would apply if the vessel were constructed or underwent a major conversion in 2016.

   b. Review of the EL FARO inclining experiment and Stability Test Report, including calculation of an engineering estimate of the uncertainty in the vessel's KG for the lightship condition and for the accident voyage departure condition.

   c. Review of the EL FARO Trim and Stability Booklet (T&S Booklet).

   d. Review of the EL FARO CargoMax stability and loading software application, and the vessel operator usage as a supplement to the T&S Booklet for load planning and stability evaluation.

   e. Review and assessment of the intact and damage stability for the accident voyage, based on the documented departure loading condition.

(2) Structures review of the EL FARO including the following primary elements:

   a. Summary of applicable structures criteria, whether based on class or other requirements.

   b. Review of the documented structural assessments completed on behalf of the vessel owners and approved by the American Bureau of Shipping (ABS), including assessments for the 1992-1993 vessel lengthening, 2005-2006 deck container (LO/LO) conversion, 2007-2009 scantling and allowable bending moment reassessments, and the post-accident hull girder section modulus and buckling analysis completed by ABS in 2015.

   c. Review of the EL FARO CargoMax stability and loading software application and vessel operator usage for hull girder strength assessment.

(3) Hydrostatic sinking analyses for the accident voyage of the EL FARO, incorporating the following considerations:

a. The vessel in a "dead-ship" condition (i.e. after loss of propulsion).

b. An estimated fuel burn-off at the time of the loss of propulsion.

c. Wind heel resulting from estimated category 3 hurricane wind speeds and gusts (modeled meteorological wind spectra provided).

d. Down-flooding through multiple feasible paths, including ventilation intake and exhaust openings, and cargo hold access scuttle openings.

e. Individual compartment and combined/progressive flooding through down-flooding points, considering a range of estimated cargo hold permeability values.

f. Additional heeling moments due to potential cargo shifts of roll-on/roll-off (RO/RO) and above deck container lift-on/lift-off (LO/LO) cargo, and entrapped water on the 2nd deck.

g. Feasibility of the installed bilge pumping system keeping up with flooding through ventilation openings or other down-flooding points.

It was also requested that the MSC reviews and analyses be documented in a stand-alone MSC report suitable for inclusion as an appendix of the formal Report of Investigation (ROI).

1.2. Approach

To provide the desired reviews and analyses, MSC has reviewed hundreds of technical documents including drawings, calculations, procedures, etc. provided by the MBI. MSC has also reviewed MBI hearing transcripts and exhibits, as well as the voyage data recorder (VDR) audio transcript. Based on the available documentation, MSC has completed the requested independent reviews and a series of independent technical analyses where appropriate, and as requested. To aid in the accomplishment of the reviews and analyses, MSC independently generated a detailed computer model for analysis of vessel hydrostatics, stability and strength.

Section 2 provides an overview of the development of the MSC computer model. Additionally comparisons of hydrostatics properties and tank properties are made between the MSC computer model and the T&S Booklet and the CargoMax loading software application.

Section 3 documents the MSC review of the 2006 stability test (inclining experiment), and provides a summary of the requested uncertainty analysis of the lightship KG (height of the center of gravity) and the GM (metacentric height) for the accident voyage departure condition derived from the stability test. The uncertainty analysis is documented in detail in Appendix A.

Section 4 documents the MSC review of the T&S Booklet and of the CargoMax stability and loading software used onboard the EL FARO and by shore-side personnel for cargo load planning and stability assessment.

Section 5 provides a primer on basic ship stability and provides a detailed summary of the intact and damage stability criteria applicable to the EL FARO at the time of the casualty, and criteria which would apply if the vessel were constructed in 2016. The MSC computer model was used to conduct an intact stability assessment of eight "benchmark" loading conditions, including departure and arrival conditions from the 1993 and 2007 T&S Booklets, a representative departure and arrival condition from August 2015, and the accident voyage departure condition and estimated condition at the time of loss of propulsion on October 1, 2015. Damage stability criteria and application are discussed and the EL FARO is assessed in comparison to applicable damage stability criteria, with detailed results provided in Appendix B.

Section 6 documents the MSC hydrostatic analyses of the sinking of the EL FARO. The hydrostatic analyses use the MSC computer model, focusing on assessment of righting arms including righting energy and range of stability considerations, in order to gain insight into the characteristics of vessel dynamics and motions due to wind heel and flooding. The effects of wind heel are addressed in detail, along with general and nuanced considerations associated with floodwater, including effects of free surface, compartment permeability, and pocketing. The potential sources of flooding of Hold 3 are discussed, using annotated photographs and drawings for reference. Analyses of an array of wind heel and flooding conditions are used to assess likely conditions leading to the capsizing and sinking of the vessel given the estimated environmental conditions, and based on insight gained through review of the VDR audio transcript.

Section 7 documents the MSC review of the ship structures, and includes a summary of the applicable structures criteria and review of documented structural assessments completed and approved by ABS. This section also provides a summary of the CargoMax usage for hull girder strength assessment.

Section 8 provides conclusions based on the reviews and analyses.

Section 9 is a listing of references, including publicly available documents as well as MBI hearing exhibits.

Appendix A provides the detailed procedure and results for the requested uncertainty analysis of the vessel's lightship KG and GM for the accident voyage departure condition. A separate listing of references for the uncertainty analysis is provided, including publicly available documents and MBI hearing exhibits.

Appendix B provides detailed documentation of the SOLAS damage stability analysis of the EL FARO completed using the MSC GHS computer model.

1.3. Nomenclature

A listing of nomenclature used throughout the report, including abbreviations, symbols and acronyms, is provided in Table 1-1. The listing is presented alphabetically, with special symbols given at the end. For nomenclature with multiple uses or meanings, commas separate different uses.

A	Area (wind heel), area under righting arm curve	LCF	Longitudinal position of center of flotation
A	Attained index	LCG	Longitudinal position of center of gravity
a	Distance moved	LO	Lube oil (tank)
ABS	American Burea of Shipping	LO/LO	Lift-On/Lift-Off (containers)
AP	Aft perpendicular (plane)	LT	Long ton (2,240 pounds)
ASTM	American Society for Testing and Materials	LWL	Length on the waterline
b	Intercept (linear fit)	m	Slope (linear fit)
B	Beam, center of buoyancy	M	Metacenter, bending moment
BL	Baseline (plane)	MARAD	Maritime Administration
BM	Metacentric radius	MS	Midship section (plane)
B_m	Breadth (beam at half draft)	MSC	Marine Safety Center
C	Form factor (stability), drag coefficient (wind heel)	MT1"	Moment to trim one inch
CAD	Computer Aided Design (software)	N	Number of measurement data points
C_B	Block coefficient	P	Wind pressure, port side
C_D	Coefficient of discharge (flooding)	p_i	Probability of flooding compartment i
CFR	Code of Federal Regulations	Q	Flow rate
CL	Centerline (plane)	R	Required index
CON/RO	Container / Roll On / Roll Off	ROI	Report of Investigation
Cons	Consumables (fuel, lube, fresh water)	RO/RO	Roll-On/Roll-Off (trailers, automobiles)
C_W	Waterplane coefficient	S	Starboard side, standard error
D	Depth	s_i	Probability of sinking with flooding compartment i
d	Draft (mean)	SM	Section modulus
D'	Molded depth (corrected)	SOLAS	Safety of Life at Sea (conventions)
DB	Double bottom (tank)	SVR	Steel Vessel Rules (ABS)
DT	Deep tank	T	Limiting angle (stability), roll period
F_B	Force of buoyancy	T&S	Trim and Stability (Booklet)
FO	Fuel oil (tank)	TCG	Transverse position of center of gravity
FP	Forward perpendicular (plane)	TPI	Tons per inch immersion
g	Acceleration due to gravity	U	Uncertainty
G, g	Center of gravity (ship, component)	Û	Relative (%) uncertainty
GHS	General Hydrostatics (software)	V	Volume, wind velocity
GM	Metacentric height	VCB	Vertical (height) position of center of buoyancy
GZ	Righting arm	VCG	Vertical (height) position of center of gravity (KG)
H	Arm (wind heel), hydrostatic head (height)	VDR	Voyage Data Recorder
HA	Heeling arm	W, w	Weight (ship, component)
HM	Heeling moment	WL	Waterline
IACS	International Association of Classification Societies	x,y	Independent, dependent variable
IMO	International Maritime Organization	φ	Angle of heel (same as θ)
KG	Vertical (height) position of center of gravity (VCG)	θ	Angle of heel (same as φ)
KMt	Height of the metacenter	Δ	Displacement (weight of ship)
l	Wind heeling arm (lever)	∇	Displacement volume
LBP	Length between perpendiculars	ρ	Density of water, density of air
LCB	Longitudinal position of center of buoyancy	γ	Specific weight ($\gamma = \rho g$)

Table 1-1: Nomenclature.

2. MSC Computer Model

2.1. Introduction

In order to assess the hydrostatics and stability of the EL FARO, a detailed 3-dimensional computer model of the vessel was created for use with the MSC's analysis software GHS (General HydroStatics by Creative Systems, Inc.). All modeling and analyses were completed using GHS Version 15.00. No attempt was made to thoroughly investigate how the results of analyses using Version 15.00 would compare to analyses using prior versions of GHS (other than as documented in Section 5.3.3). This section describes the development of the MSC GHS computer model for use in subsequent stability analyses and hydrostatic sinking analyses.

2.2. Development of the MSC Computer Model

An original computer model was provided by Herbert-ABS Software Solutions, LLC, created using their software HECSALV, file "Faro-10.shp" [2]. The HECSALV model file was provided along with the Final Offsets document [3] and General Arrangement Drawing [4]. Initially the HECSALV model was converted into a format compatible with the GHS software, and MSC verified that the hull stations and offsets (lines) contained in the HECSALV model accurately reflected the table of offsets in the Final Offsets document. MSC found that the HECSALV model accurately reflected the table of offsets at the stations contained in the model (see Figure 2-1), but some detail was not reflected due to the selected station spacing (particularly in the bow, stern and skeg areas), which might affect the accuracy of the calculated areas and volumes in those areas. Additionally, the HECSALV model only extended to the 2nd (bulkhead) deck, which was the freeboard or watertight deck. The MSC GHS computer model extends to the main deck to include modeling of the semi-enclosed spaces above the 2nd deck. Finally, it was noted that the hull model, when imported into Rhinoceros CAD (Rhino) software and converted to a surface model, showed that with the given lines, the hull was not fair in a number of areas when rendered. This was manifested by a number of obvious visual "dents" in the rendered hull surface when viewed in Rhino. Upon further investigation, it was determined that the table of offsets in the Final Offsets document contained a number of apparent errors (perhaps due to manual errors in measuring dimensions from the original drafted lines or writing the offset numbers into the ledger, which we might now call "typographical errors"). These apparent errors in the table of offsets manifested themselves as irregularities in the surface of the hull model, and only became apparent when the model was converted and viewed in the Rhino program viewer. Rhino was used to view the model in three different ways: (1) as a series of stations, (2) as a mesh connecting stations and offset points, and (3) as a series of NURBS (Non-Uniform Rational B-Spline) surfaces created from the existing mesh nodes. In the mesh and NURBS views the irregularities in the hull surface were most apparent. It should be noted that overall these irregularities are relatively small and result in only small differences in calculated results, as will be demonstrated subsequently.

For the MSC GHS computer model, it was decided to develop a faired hull model in the Rhino software that was consistent with the Final Offsets document including the table of offsets, but also contained necessary fairing to correct for the discovered errors in the table of offsets. It was decided that this would likely better represent the "as-built" hull surface, since during the lofting and construction process, some fairing would have taken place to provide a smooth hull surface. To begin, the original HECSALV model consisting of 28 stations (Figure 2-1) was converted to a standard CAD Drawing Exchange Format (DXF), which was imported into Rhino for further refinement. The imported 28 stations were supplemented with details from the Final Offsets document including centerline deck heights with sheer, deck camber, midship section geometry, stem profile and radii, transom profile, house deck heights, and frame locations. With these details as reference, the series of NURBS surfaces was created, and then faired.

Once the fairing was completed in Rhino (Figure 2-2), the hull model was converted into a GHS format with a larger number of stations for higher definition such that internal tanks and compartments to be added would be created with desired accuracy. To ensure accurate numerical integration with the trapezoidal integration method used in the GHS software, MSC defined both hull and compartment stations at relatively close spacing of 2-3 feet. Figure 2-3 shows the final hull lines. Note that a separate set of lines was created for the semi-enclosed 2nd Deck so that a separate compartment external to the main watertight hull could be created to allow free flood or partial flooding as desired in the hydrostatic sinking analyses, and the wind profile area could be calculated directly by the GHS software in the analyses (see Figure 2-5 and Figure 5-5). Additional hull components were added with separate sets of lines to provide accurate definition and volumes for the keel skeg, rudder, and shafting as shown, and external components were appended to the upper hull to incorporate the external volumes of the forward and aft cargo ramps and boiler casing, as shown in Figure 2-4. A shell plating thickness of 0.8 inches was added to account for an average hull plating thickness taken from the Midship Construction Drawing [5] and Shell Expansion Plans [6, 7, 8].

Once the hull model was complete, the internal tanks and compartments were modeled including definition of decks and bulkheads making up tank and compartment boundaries. Transverse bulkheads and boundaries were based on frame locations provided in the Final Offsets document. Deck heights were defined based on the Final Offsets document, including the required deck sheer (note that the Main Deck and 2nd Deck included sheer and camber and both were included in the hull model). Longitudinal bulkheads and boundaries were defined based on a number of references including the Final Offsets document, General Arrangement Drawing, Midships Construction Drawing, and Combined Bulkhead drawing [9]. For simplicity and since it is only required for wind heel area calculations, a simple deckhouse was added external to the main hull with boundaries based on the Final Offsets document and General Arrangement Drawing. Similarly, containers were added for wind heel area calculations as "sail" components in GHS, with boundaries based on the Final Offsets document, Capacity Plan [10] and the CargoMax loading computer printout for the accident voyage [11]. Figure 2-5 shows inboard profile and plan views of the MSC GHS computer model showing decks, bulkheads, compartments, tanks, deck house, and the container profile for the accident voyage.

It was noticed in the course of creating the decks and compartment boundaries that the deck heights measured from the General Arrangement Drawing [4] were significantly different compared to the Final Offsets document [3], Midship Construction Plan [5], and other structural drawings. This led MSC to conclude that there were vertical scaling errors on the General Arrangement Drawing. It appears that the errors may be associated with typographical errors instead of a constant vertical scaling factor error, as the midships deck heights fall precisely on whole or half feet, as shown in Table 2-1. This is considered notable since the General Arrangement Drawing is an engineering drawing and as such should be correctly scaled, and in fact the drawing states a 1/16" = 1'-0" scale in the title block. Due to the noted errors, vertical dimensions were not taken from the General Arrangement Drawing for the MSC GHS computer model development. The errors in deck heights on the General Arrangement Drawing may provide an explanation for the freeboard reference discrepancies noted by the test engineers in the 2006 Stability Test Report (see Section 3 of this report).

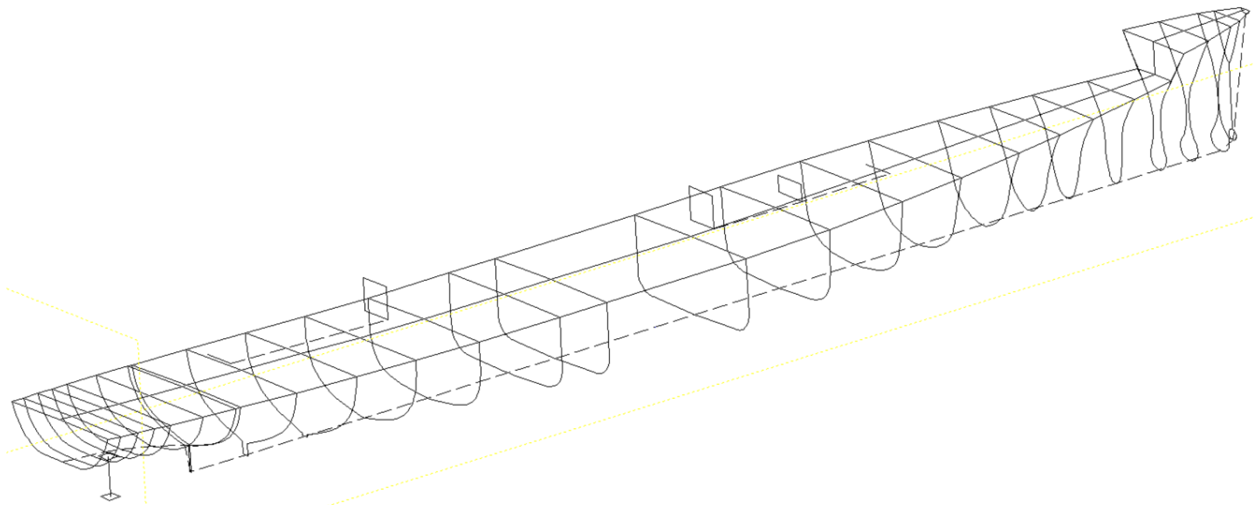

Figure 2-1: Original HECSALV computer model hull stations.

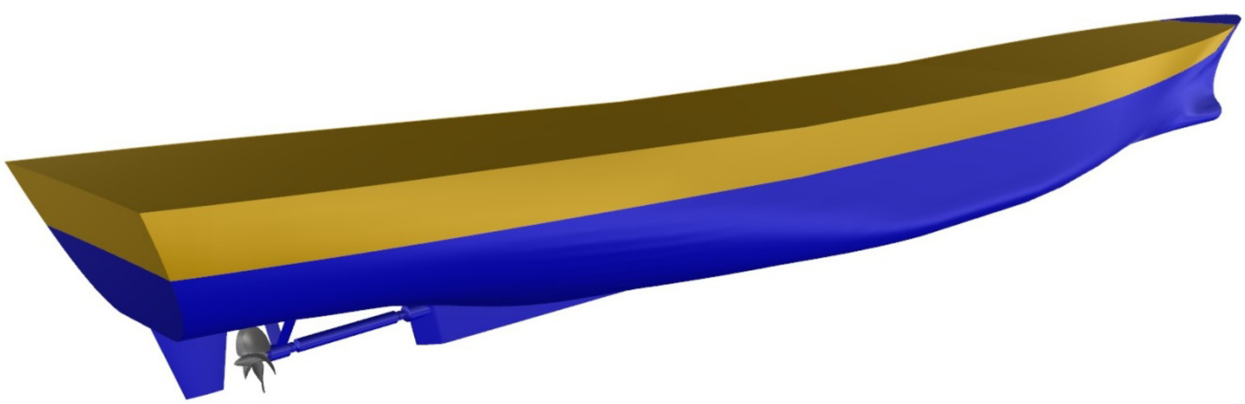

Figure 2-2: The MSC Rhino CAD surface hull model, including semi-enclosed 2nd deck.

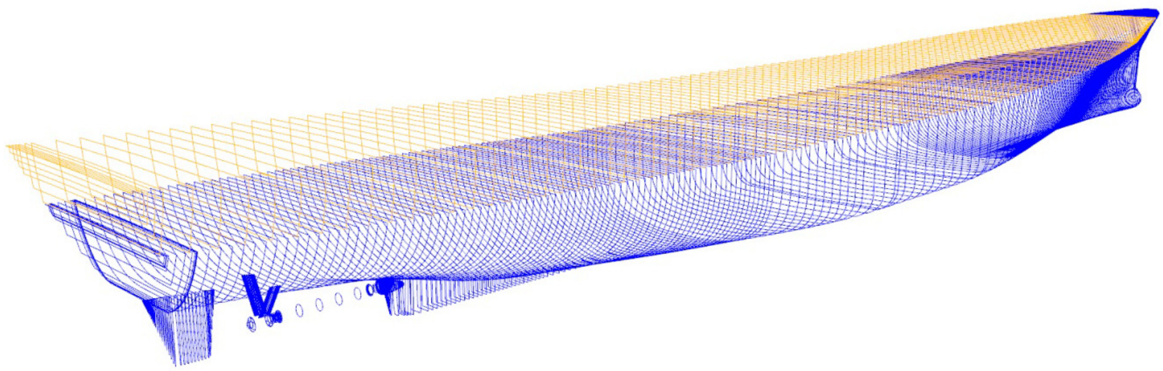

Figure 2-3: Hull stations and lines generated from the Rhino CAD surface hull model, with included lines for keel skeg, rudder and shafting, also including the semi-enclosed 2nd deck.

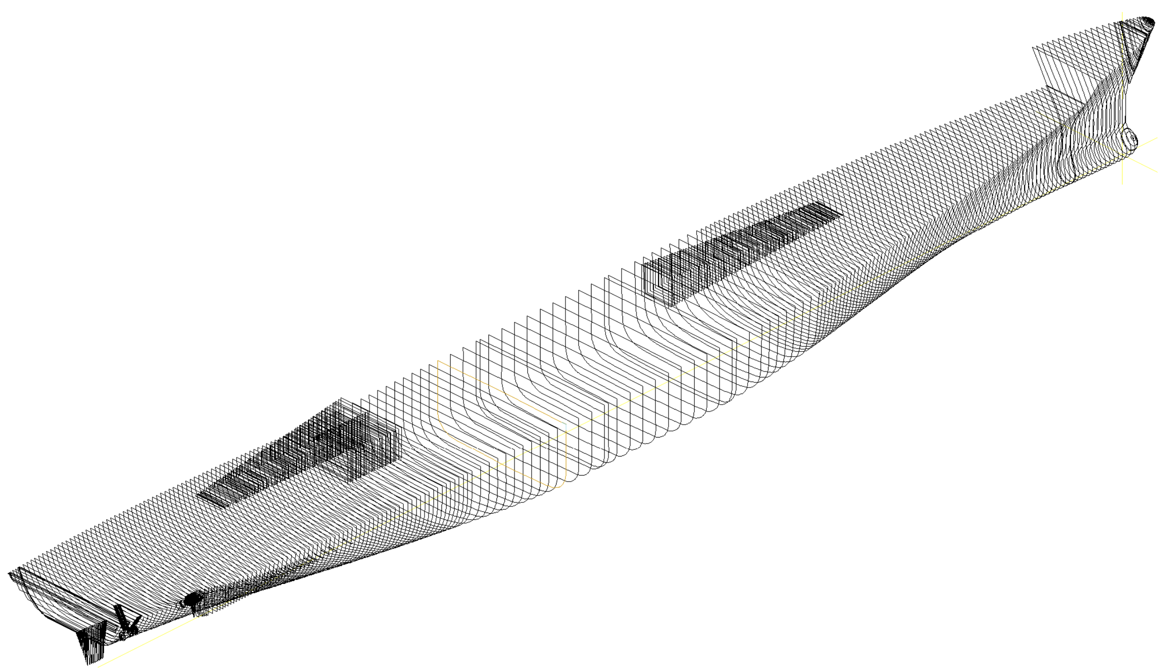

Figure 2-4: Hull stations and lines of the MSC GHS computer model, including appended forward and aft cargo ramps and boiler casing, not including the semi-enclosed 2nd deck.

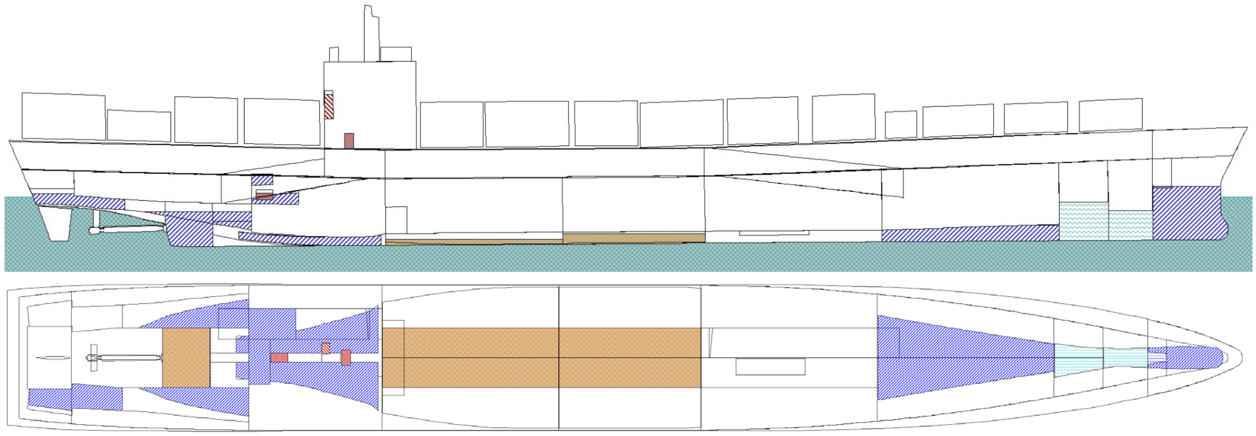

Figure 2-5: Inboard profile and plan views of the MSC GHS computer model showing decks, bulkheads, compartments, tanks, deck house, and the container profile for the accident voyage. Tanks are shown as loaded for the accident voyage.

	Final Offsets (Lines Drawing), Structural Drawings	General Arrangement Drawing
	feet above baseline	
Midships 4th Deck (Inner Bottom)	7.50	8.00
Midships 3rd Deck	24.14	24.50
Midships 2nd Deck @ CL	42.64	43.50
Midships Main Deck @ CL	60.64	62.00
Transom Main Deck @ CL	67.98	70.50
Transom 2nd Deck @ CL	49.75	50.85
Stem Main Deck @ CL	71.32	72.63
Length Between Perpendiculars (feet)	733.75	733.50
Beam, Molded (feet)	92.00	92.00
Beam, Maximum at Main Deck (feet)	105.00	105.00

Table 2-1: Comparison of deck heights and principal dimensions provided on different reference drawings.

2.3. Comparison with the T&S Booklet and CargoMax Stability Software

Table 2-2 provides key hydrostatic parameters at a nominal full load departure draft of 30.0 feet in salt water without trim or hull deflection, calculated using the MSC GHS computer model. For comparison, the values in the T&S Booklet [12] are also provided. Note that the hydrostatic tables used in the CargoMax stability software are the same as those in the T&S Booklet. Also included in the table are the calculated difference and percent difference for each parameter, using the MSC GHS computer model as the basis. To compare each to an objective quality standard, the last column provides the acceptance tolerance based on IMO MSC.1/Circ.1229, Guidelines for the Approval of Stability Instruments [13], which are identical to those in the IACS Unified Requirement L5 applied by class societies [14].

As mentioned previously, the MSC GHS computer model includes refined hull shape in the bow, stern and skeg areas. Because of the increased definition, the integrated section areas and calculated volumes are slightly greater in these areas compared to the hydrostatic table and tank tables provided in the T&S Booklet. The largest impact of this is on the moment to trim 1-inch (MT1"). For displacement the differences are relatively small, and only amount to a total difference of about 0.1% at the draft of 30.0 feet as shown in Table 2-2, but the difference increases to approximately 1% at the draft corresponding to the lightship displacement.

	MSC GHS Computer Model	T&S Booklet and CargoMax	Difference	Difference %	IMO/IACS Tolerance
Displacement (LT)	34,334	34,380	46	0.1%	2%
LCB (ft-FP)	391.2	391.2	0.0	0.0%	1% or 1.64 ft
VCB (ft-BL)	16.72	NA	NA	NA	1% or 0.164 ft
LCF (ft-FP)	427	426.6	0.4	0.1%	1% or 1.64 ft
MT1" (ft·LT/in)	5,346	5,259	87.0	1.6%	2%
KMt (ft-BL)	41.40	41.51	0.11	0.3%	1% or 0.164 ft
TPI (LT/in)	124.6	124.5	0.1	0.1%	NA

Table 2-2: Comparison of key hydrostatic properties at a nominal full load keel draft of 30.0 feet in salt water, without trim or hull deflection. Note that values for VCB are not provided in the hydrostatic table in the T&S Booklet or in CargoMax. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

Table 2-3 provides comparison between calculated tank properties, including 100% volume and center of gravity, and maximum (slack) free surface inertia. Also included in the table are the calculated differences and tolerances based on the IMO and IACS guidelines.

The following specific comments are provided:

(1) Tank volume and center of gravity calculations are based on an assumed "permeability" factor, which mathematically accounts for the fraction of the tank volume that can be filled with liquid, accounting for such things as internal structure, piping, and other internal components. The precise permeability factors assumed in the original calculation of the tank volumes and centers are not available in the documentation. However, for comparison, by reviewing the original HECSALV model, the permeability factors provided in the table were incorporated. The MSC GHS computer model used the same permeability factors where appropriate; however it was noted that the HECSALV model inconsistently applied permeability factors of 0.95 and 0.98 for the double bottom tanks. Based on MSC review of EL FARO structural drawings associated with the double bottom tanks [15, 16], double bottom tanks have internal transverse floor structure which would reduce the volume available for liquid. Based on this review, the MSC GHS computer model includes the consistent 0.95 permeability factor for all double bottom tanks between frames 46 and 169, as reflected in the table.

(2) A comparison of tank volumes of the MSC GHS computer model with the T&S Booklet and CargoMax (Table 2-3) shows a large number of tanks with differences in excess of the 2% tolerance of MSC Circ. 1229 and IACS UR L5. A total of 19 tanks are in excess of the 2% tolerance. Of these 19 tanks, 8 are either small tanks (less than 2,000 ft^3), are very close to the 2% tolerance, or have different assumed permeabilities. The set of tanks which stand out most is DT Aft P/S, with the T&S Booklet and CargoMax values being 20% higher than the MSC GHS computer model. These tanks are relatively simple geometrically and the difference in calculated volumes does not appear to be explainable based on difference in the station spacing and location or differences in integration techniques used. Further review of previous T&S Booklets including the 1993 T&S Booklet [17] and older T&S Booklets for sister vessels dating back to the 1970s reveals that the higher volume value of 11,286 ft^3 came from the original integration of the tank volumes, probably done by hand back in the 1960s or 1970s. Based on calculation with both the MSC GHS computer model and the HECSALV model "Faro-10.shp" [2], it appears that the original volume calculation was in error. While the differences with DT Aft P/S are the most significant, similar differences are also noted with tanks DB 4 P/S and Aft Peak P/S, which are not explainable based on differences in station location and spacing, integration methods, or assumed permeability.

(3) Transverse locations of centers of gravity (TCG) are not included in the T&S Booklet. As was common with stability booklets until recent years, the calculations contained in the sample load cases and calculation forms in the T&S Booklet account for vertical and longitudinal locations of the centers of gravity but do not account for transverse locations. This means that calculations performed in accordance with the T&S Booklet do not include static heeling effects and do not calculate static list angle. The CargoMax stability software does include transverse locations of centers of gravity of all cargo and tank weights, and does calculate vessel static list, although tank TCG values do not vary with tank level (i.e. they are given as constant). It should be noted however, that the CargoMax software applies an incorrect lightship TCG of 0.00 ft-CL, and therefore the calculation of the static list angle in CargoMax is inaccurate (see Section 3.2 of this report). The magnitude of this inaccuracy depends on the vessel loading condition and the actual metacentric height (GM). Based on MBI hearing testimony [18, 19, 20], the ship's list calculated by CargoMax was inaccurate compared to the observed list between 2 and 3 degrees for typical full load departure conditions. For example, for the accident voyage departure condition, CargoMax calculated a list of 2.3 degrees to starboard with the assumed lightship TCG of 0.00 ft [11]; however, a simple moment calculation confirms that a lightship TCG of approximately 0.3 feet port of CL would result in the list of 0.0 degrees, as observed at departure [18]. This will be discussed in greater detail in Sections 5 and 6 of this report, as results of hydrostatic calculations using the MSC GHS computer model are provided.

(4) The transverse locations of a number of smaller tanks (less than 5,000 ft^3) are not identified correctly in the EL FARO CargoMax application. It appears that the transverse locations of these tanks were based on the original HECSALV model [2], where they were modeled as rectangular volumes placed on the centerline (i.e. TCG set

to 0.0) rather than their actual transverse locations. The largest of these tanks were the potable water and distilled water tanks. These differences introduce additional list angle error in the CargoMax calculations. For example, the 22 foot error in TCG of the distilled water tank (see Table 2-3) would introduce an error in the calculated angle of list of approximately 0.85 degrees for the accident voyage departure condition, with displacement 34,624.5 LT, GM 4.284 ft, and the distilled water tank nearly full with 100 LT of weight [11].

(5) Longitudinal locations of centers of gravity (LCG) in the T&S Booklet and in CargoMax are constant values and do not vary with tank level. The MSC GHS computer model does include full variable tank calculation, so variable LCG and TCG are included in the MSC calculations. However, the effects of these differences on predicted drafts and trim are minimal, considering the much larger effects of the large quantity of RO/RO cargo, which was not accounted for precisely in the load plan, but placed at the centers of the holds (see Section 5 of this report).

(6) Similar to the differences noted with tank volume calculations, review of Table 2-3 also highlights differences with calculated free surface inertias, which are used in calculation of the free surface correction to GM for stability calculations. All but one of the tanks had differences in excess of the 2% tolerance. There is no obvious reason for these differences. However, it is noted that because the moment of inertia of liquid free surface is roughly proportional to the cube of the breadth multiplied by the length of the tank, errors in transverse and length dimensions propagate to larger errors in moments of inertia (see Appendix A for a discussion of propagation of errors and uncertainty).

The IMO Circ. 1229 and IACS UR L5 tolerance comparisons included in Table 2-2 and Table 2-3 are meant to illustrate the variability of the calculated results in comparing the detailed MSC GHS computer model to the previously approved T&S Booklet and CargoMax values, and to apply an objective quality standard to the differences. However, at the time of approval of the CargoMax software application for the EL FARO by ABS [21], it was apparently determined that the tank values for the CargoMax application met the tolerance requirements since they were based on "pre-programmed data" (i.e. the previously approved T&S Booklet), and therefore met the tolerance requirements by definition.

	100% Volume (ft^3)		100% VCG (ft abv BL)		100% LCG (ft aft FP)		100% TCG (ft stbd CL)		Slack (Max) Free Surface (ft4)		Permeability Factor		Volume Difference (%)	VCG Difference (%)	LCG Difference (%)	TCG Difference (ft)	FS Inertia Difference (%)	
	MSC GHS	T&S & CargoMax	MSC GHS	T&S & CargoMax	MSC GHS	T&S & CargoMax	MSC GHS	CargoMax	MSC GHS	T&S & CargoMax	MSC GHS	T&S & CargoMax	Tolerance 2%	Tolerance 1% or 0.164 ft	Tolerance 1% or 1.64 ft	Tolerance 0.5% of B (0.46 ft) or 0.164 ft	Tolerance 2%	Comments/Notes
Fuel Oil																		
DB No 2A IP	12,130	12,617	3.84	3.90	370.5	370.6	-9.50	-9.62	51,265	56,290	0.95	0.98	4.0%	1.6%	0.0%	0.12	9.8%	Outer bound 19.25 ft. Double bottom permeability 0.95.
DB No 2A IS	12,130	12,617	3.84	3.90	370.5	370.6	9.50	9.62	51,265	56,290	0.95	0.98	4.0%	1.6%	0.0%	0.12	9.8%	Outer bound 19.25 ft. Double bottom permeability 0.95.
DB No 3 IP	15,047	15,312	3.85	3.90	472.0	471.6	-9.47	-9.56	63,679	69,936	0.95	0.95	1.8%	1.3%	0.1%	0.09	9.8%	Outer bound 19.25 ft.
DB No 3 IS	15,047	15,312	3.85	3.90	472.0	471.6	9.47	9.56	63,679	69,936	0.95	0.95	1.8%	1.3%	0.1%	0.09	9.8%	Outer bound 19.25 ft.
FO Sett	10,299	10,152	23.50	23.50	653.5	654.1	0.00	0.00	140,968	143,856	0.98	0.98	1.4%	0.0%	0.1%	0.00	2.0%	
Fresh Water																		
Fore Pk Tk	15,431	15,029	23.53	23.68	16.8	16.7	0.00	0.00	13,922	12,934	0.98	0.98	2.6%	0.6%	0.5%	0.00	7.1%	
DT No 1B S	16,973	16,996	31.22	31.40	85.1	85.2	6.73	6.74	28,167	29,121	0.98	0.98	0.1%	0.6%	0.1%	0.01	3.4%	
DB No 1 P	11,262	11,504	5.22	5.30	163.2	163.3	-7.12	-7.05	66,918	60,296	0.95	0.98	2.1%	1.5%	0.1%	0.07	9.9%	Double bottom permeability 0.95
DB No 1 S	11,262	11,504	5.22	5.30	163.2	163.3	7.12	7.05	66,918	60,296	0.95	0.98	2.1%	1.5%	0.1%	0.07	9.9%	Double bottom permeability 0.95
DB No 2 IP	14,785	15,090	3.90	4.10	269.8	269.9	-9.38	-9.48	63,617	69,936	0.95	0.95	2.1%	5.1%	0.0%	0.10	9.9%	Outer bound 19.25 ft.
DB No 2 IS	13,628	13,668	3.71	3.90	268.9	266.4	9.68	9.48	63,617	69,936	0.95	0.95	0.3%	5.1%	0.9%	0.20	9.9%	Outer bound 19.25 ft. Deduction for elevator pit.
DB No 4 P	3,932	4,291	3.94	4.50	561.6	565.1	-10.45	-10.44	50,735	62,148	0.98	0.98	9.1%	14.2%	0.6%	0.01	22.5%	
DB No 4 S	3,932	4,291	3.94	4.50	561.6	565.1	10.45	10.44	50,735	62,148	0.98	0.98	9.1%	14.2%	0.6%	0.01	22.5%	
Pot Water	2,735	2,504	42.25	41.30	607.0	606.9	2.50	0.00	27,377	26,532	0.98	NA	8.4%	2.2%	0.0%	2.50	3.1%	No variable tank data T&S Book
Dist Water	3,225	3,691	29.75	29.20	596.0	596.2	-21.63	0.00	17,617	17,280	0.98	NA	14.4%	1.8%	0.0%	21.63	1.9%	No variable tank data T&S Book
Stern T Comp	6,777	7,073	13.72	14.50	651.8	651.9	0.00	0.00	113,599	121,811	0.90	0.90	4.4%	5.7%	0.0%	0.00	7.2%	
DT Aft P	9,394	11,286	23.42	23.36	645.0	647.1	-26.06	-26.05	35,092	32,776	0.98	0.98	20.1%	0.3%	0.3%	0.01	6.6%	
DT Aft S	9,394	11,286	23.42	23.36	645.0	647.1	26.06	26.05	35,092	32,776	0.98	0.98	20.1%	0.3%	0.3%	0.01	6.6%	
Salt Water																		
DT No 1A	20,211	20,091	31.13	31.40	55.2	55.1	0.00	0.00	82,110	72,148	0.98	0.98	0.6%	0.9%	0.2%	0.00	12.1%	
Aft Peak CL	28,781	29,257	28.24	28.40	711.9	710.6	0.00	0.00	362,635	353,455	0.95	0.95	1.7%	0.6%	0.2%	0.00	2.5%	
Aft Peak P	4,150	4,299	31.72	31.60	726.9	726.1	-24.52	-24.47	7,210	8,462	0.95	0.95	3.6%	0.4%	0.1%	0.05	17.4%	
Aft Peak S	4,150	4,299	31.72	31.60	726.9	726.1	24.52	24.47	7,210	8,462	0.95	0.95	3.6%	0.4%	0.1%	0.05	17.4%	
Miscellaneous																	.	
DT No 1B P Slop	16,973	16,996	31.22	31.40	85.1	85.2	-6.73	-6.74	28,167	29,121	0.98	0.98	0.1%	0.6%	0.1%	0.01	3.4%	
Diesel Oil	679	688	89.50	87.50	564.3	564.5	-6.00	0.00	165	3,192	0.98	NA	1.3%	2.2%	0.0%	6.00	1834.5%	No variable tank data T&S Book.
LO Storage	491	616	32.50	32.00	605.7	605.7	3.50	0.00	311	NA	0.98	NA	25.6%	1.5%	0.0%	3.50	NA	No variable tank data T&S Book
LO Sump	552	484	5.54	6.00	594.8	596.1	0.00	0.00	3,689	NA	0.98	NA	12.3%	8.3%	0.2%	0.00	NA	No variable tank data T&S Book
LO Settling	631	695	32.50	32.00	605.7	605.7	-4.50	0.00	660	NA	0.98	NA	10.2%	1.5%	0.0%	4.50	NA	No variable tank data T&S Book
LO Gravity	539	450	66.00	65.00	551.5	554.8	0.00	0.00	466	NA	0.98	NA	16.5%	1.5%	0.6%	0.00	NA	No variable tank data T&S Book

Table 2-3: 100% tank volumes, centers and maximum (slack) free surface comparisons between the MSC GHS model and the T&S Book and CargoMax. Also included in the table are the calculated differences and tolerances based on the IMO and IACS guidelines.

2.4. Lightship Weight, Center of Gravity, and Distribution

In order to perform hydrostatic and stability analyses, the ship's lightship weight (displacement) and location of the center of gravity must also be known. The lightship weight and center of gravity was taken from the most recent Stability Test Report [22] which is based on the inclining experiment completed on February 12, 2006. Table 2-4 provides a summary of the lightship condition from the Stability Test Report. Note that the lightship weight of 19,943 LT includes 6,705 LT of fixed ballast in the outboard double bottom tanks. Additional discussion about the lightship weight and center of gravity, including review of the stability test and an uncertainty analysis of the lightship weight and center of gravity, are provided in Section 3 of this report. Note that the TCG of the lightship condition was incorrectly calculated in the Stability Test Report, as explained in Section 3.2.

	Lightship Condition
Displacement (LT)	19,943
KG/VCG (ft-BL)	27.82
LCG (ft-FP)	412.01
TCG (ft-CL)	0.12 port (incorrect)
Draft Aft Perp (ft)	26.65
Draft Fwd Perp (ft)	10.81
Trim (ft)	15.84 aft

Table 2-4: Lightship weight (displacement), center of gravity, drafts and trim, based on the Stability Test Report [22 (page 17)].

Based on the date of construction of the EL FARO, there was no requirement for a Loading Manual and thus, no requirement for approval of a lightship weight distribution, and none was approved. However, a Preliminary Weight Estimate was issued by JJH, Inc. (Revision A2 dated November 11, 1992) [23] which included an engineering estimate of a lightship weight distribution for the 1992-1993 conversion. Additionally, although not reviewed and approved by ABS, a lightship weight distribution was included in the CargoMax application for calculation of longitudinal bending moments and shear forces for comparison with ABS allowables.

The lightship weight distribution for the MSC GHS computer model was developed using the Preliminary Weight Estimate issued by JJH, Inc. (Revision A2 dated November 11, 1992) [23], along with estimated changes. Distributed weight for the 6,705 LT of fixed ballast was added, based on the approved Fixed Ballast Installation Drawing [24], as three trapezoidal weight distributions from 212.42 ft-FP to 528.67 ft-FP. An additional estimated 200 LT of distributed weight was added to account for the container foundations and main deck support structure which was added in the 2005-2006 conversion [25]. The estimated 713 LT spar deck structure which was removed as part of the 2005-2006 conversion [26] was accounted for in the application of the Preliminary Weight Estimate by JJH, Inc.
Figure 2-6 provides a plot of the lightship weight distribution used in the MSC GHS computer model.

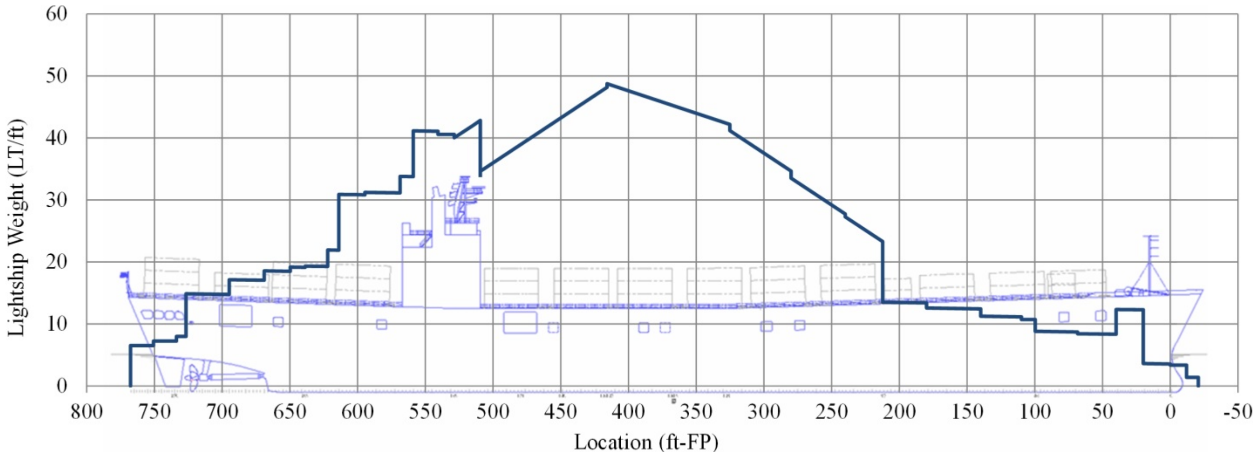

Figure 2-6: Lightship weight distribution used in the MSC GHS computer model.

2.5. Summary

This section provided an overview of the development of the MSC GHS computer model for hydrostatic and stability analyses. Additional comparisons of hydrostatics properties and tank volumes and centers of gravity between the MSC GHS computer model and the T&S Booklet and CargoMax loading software application were made, with a number of differences highlighted.

Hull hydrostatic properties compared closely, with approximately 0.1% difference in calculated displacement at the full load draft. All hydrostatic properties were within the tolerance of IMO MSC.1/Circ.1229, which has been used as an objective quality standard.

Comparison of tank volumes, centers and free surface inertia values identified discrepancies with T&S Booklet and CargoMax values. Using IMO MSC.1/Circ.1229 as an objective quality standard, 19 tanks were in excess of the 2% tolerance for volume, and 22 tanks were in excess of the 2% tolerance for maximum slack free surface inertia. Based on additional MSC review of EL FARO and sister vessel T&S Booklets going back to the 1970s, it appears that errors were made in the original tank geometry definition and/or in the original numerical integration. It also appears that these discrepancies in tank values would apply to all of the vessels of the PONCE DE LEON class.

3. Stability Test and Uncertainty Analysis

3.1. Introduction

In order to assess a vessel's hydrostatics and stability characteristics, a vessel's weight (displacement) and location of the center of gravity must be determined. For variable or deadweight loads such as cargo and onboard liquids, the weight and centers of gravity can be calculated or tabulated. However, the weight and centers of gravity of the ship's structure and other fixed weights must be experimentally determined. Upon new construction or after significant changes to the lightship are made, this is accomplished by performing a stability test, also called an inclining experiment.

For the EL FARO, a stability test was required by 46 CFR Part 170 Subpart F, Determination of Lightweight Displacement and Centers of Gravity. Standardized technical guidance for conducting a stability test is provided in ASTM F1321 (series) [27], Standard Guide for Conducting a Stability Test (Lightweight Survey and Inclining Experiment) to Determine the Light Ship Displacement and Centers of Gravity of a Vessel.

The most recent stability test for the EL FARO was completed at the Atlantic Marine Shipyard in Mobile, Alabama on February 12, 2006, following conversion for carrying LO/LO container cargo on the main deck. As required by 46 CFR 170.085, a Stability Test Procedure was submitted and approved by ABS on behalf of the USCG on February 2, 2006 [28]. After completion of the stability test, the Stability Test Report was submitted and reviewed by ABS and approved on March 22, 2006 [22], incorporating reviewing engineer's comments as well as the witnessing ABS surveyor's field notes and comments provided in the ABS Survey Report M662652 [29].

This section provides MSC review comments regarding the EL FARO Stability Test Report with ABS approval notes, along with the Stability Test Procedure and Inclining Experiment Record Sheet [30]. Additionally, as requested by the MBI, an uncertainty analysis of the stability test and departure condition of the accident voyage was completed by MSC, as documented in Appendix A of this report. Results of the uncertainty analysis are also summarized in this section.

3.2. Stability Test

As part of the reviews requested by the MBI, MSC reviewed the Stability Test Report with ABS approval notes, along with the Stability Test Procedure and Inclining Experiment Record Sheet, and provides the following comments:

(1) The ABS approved Stability Test Procedure required that, in accordance with ASTM F1321-92 (2004), five (5) sets of freeboard and draft readings per side be taken, but draft marks may be used in lieu of specific freeboard readings only if verified and certified to approved drawings by an ABS surveyor with the vessel in drydock. As noted in the Stability Test Report, only the midship draft marks were certified by the ABS surveyor, with the fore and aft marks only "checked" by an Atlantic Marine surveyor. It was also

noted in the Stability Test Report that the reliability of the freeboard readings was in question, due to identified discrepancies between ship's drawings regarding deck heights including sheer; therefore draft marks were considered superior and freeboards were not included in definition of the fit waterline and the hydrostatic calculations by the test engineers. This effectively limited the waterline measurement to one set of three drafts (forward, midship, aft), with the draft readings taken only once at the beginning of the experiment. Although not in accordance with the ASTM F1321 guidelines, given the questions regarding accuracy of the deck height freeboard reference datum from the drawings, the use of the draft readings alone is reasonable. Further, although ships are generally built to specified construction tolerances, freeboard reference datum (deck heights), are rarely surveyed and documented to be accurate compared to ship's drawings during a typical vessel's lifetime, and therefore the practice recommended in the ASTM F1321 of using freeboard measurements with draft marks may be questionable in any case.

(2) During the "deadweight survey" portion of the stability test, a survey of all weights to add, remove or relocate was completed to correct the "as-inclined" condition (Condition 0) to the "lightship" condition (Condition 1) by accounting for all liquids and dry items onboard [22 (pages 16-17)]. However, test engineers did not keep track of transverse center of gravity (TCG) locations for liquids and dry surveyed items and all were assigned a TCG of 0.00 feet from the centerline (ft-CL) in the Stability Test Report and the supporting calculations. Although there is no requirement in the ASTM F1321 guidelines for calculating TCG for the lightship condition, the effect of not keeping track of TCG values in the deadweight survey was that the lightship TCG calculated and presented in the summary table for the lightship (Condition 1) was incorrect.

(3) The documentation of weights throughout the Stability Test Report did not provide sufficient significant figures for MSC to verify the supporting calculations, with weights in the report displayed only to the nearest whole long ton (LT). This applied to all inclining weights, all deadweight survey items, and the calculated results. However, based on the weight logs provided in the ABS Survey Report for the Inclining M662652 [29], it appears that this is a display issue only and calculated moments from weights and distances appear correct (to the nearest whole long ton).

The as-inclined and lightship values of displacement, centers of gravity, drafts, trim and specific gravity are provided in Table 3-1 below, based on the Stability Test Report. As noted above, the TCG of the lightship condition was incorrectly calculated in the Stability Test Report, as noted in the table.

	As-inclined (Condition 0)	Lightship (Condition 1)
Displacement (LT)	23,512	19,943
KG/VCG (ft-BL)	26.02	27.82
LCG (ft-FP)	388.08	412.01
TCG (ft-CL)	0.10 port	0.12 port (incorrect)
GMt (ft)	18.26	20.82
Draft Aft Perp (ft)	24.82	26.65
Draft Midships (ft)	22.41	Not provided
Draft Fwd Perp (ft)	20.72	10.81
Trim (ft)	4.10 aft	15.84 aft
Hog/sag (ft)	0.36 hog	Not provided
Specific Gravity	1.002	1.025

Table 3-1: As-inclined and lightship displacements, centers of gravity, drafts, trim and specific gravity, based on the Stability Test Report [22 (pages 16-17)].

3.3. Uncertainty Analysis

The MSC was requested by the MBI to review the EL FARO inclining experiment and Stability Test Report and calculate the uncertainty in the vessel's KG for the lightship condition and for the accident voyage departure condition. Appendix A of this report provides the detailed procedure and results for the requested uncertainty analysis. A summary of the results is provided in this section.

It should be noted that there is no standard accepted procedure or guidance for completing an uncertainty analysis from the results of a stability test. The procedure undertaken by the MSC is based on an application of the principles of experimental uncertainty analysis, including assessment of potential sources of measurement errors, statistical analysis, and propagation of errors. The results of the analysis are fundamentally limited based on the size and type of vessel, the stability test procedure, the type of cargo and the specific loading condition. The results obtained for the uncertainty associated with the stability test and the lightship weight and center of gravity could be considered somewhat typical of similar large deep draft vessels. The additional uncertainty associated with the vessel loading condition can vary, depending on the particular type of cargo and loading procedures.

It is often the case that vessel operators consider the calculated GM, whether calculated by hand or by stability and loading software, to be fairly precise, and then operate the vessel fairly close to the minimum required GM. It is apparent from the MBI hearing testimony [18, 19, 31, 32] that this was the case for the operation of the EL FARO, including for the accident voyage. It is important to recognize that the actual GM may not be precisely known and uncertainty in the calculated GM can exist. However, calculated uncertainty in KG or GM for an operating condition should not be used to calculate a probability that the vessel would not meet the stability criteria for that operating condition. There is currently no consideration for uncertainty in assessing a vessel's stability in accordance with U.S. or international standards, as discussed in Section 5 of this report.

As discussed in detail in Appendix A of this report, the equation for calculating the metacentric height (GM) in the as-inclined condition from the inclining experiment is [27]

$$GM = \frac{w \cdot a}{\Delta \cdot tan\theta} = \left(\frac{w \cdot a}{tan\theta}\right) \cdot \left(\frac{1}{\Delta}\right) \quad (3\text{-}1)$$

where w is the weight of inclining weights (LT), a is the distance inclining weights are moved (ft), tanθ is the tangent of the angle of heel induced by the movement of inclining weights, and Δ is the vessel weight (displacement) in the as-inclined condition (LT). The first term is determined from the slope of the "best fit" line from the plot of the applied moment (w·a) and the measured angle tangent (tanθ) for a series of sequential weight movements. Therefore, for the inclining experiment

$$GM = \left(\frac{1}{slope}\right) \cdot \left(\frac{1}{\Delta}\right) \quad (3\text{-}2)$$

The second term is determined by calculation of the displacement using the measured drafts and the hull offsets. In order to calculate the uncertainty in as-inclined GM, the uncertainty in each term must be calculated based on the experimental method, and then combined.

As developed in Appendix A, the uncertainty in as-inclined GM can be calculated

$$\left(\frac{U_{GM}}{GM}\right) = \sqrt{\left(\frac{U_{slope}}{slope}\right)^2 + \left(\frac{U_{\Delta}}{\Delta}\right)^2} \quad (3\text{-}3)$$

where U_{GM} is the uncertainty in as-inclined GM, U_{slope} is the uncertainty in slope, and U_{Δ} is the uncertainty in displacement.

For the EL FARO inclining experiment completed in 2006, each of seven steps or "trials" involved moving two or three inclining weights in sequence from port to starboard or starboard to port (initially, five weights were placed port and five weights were placed starboard). For each trial, three independent pendulums were used to measure the tangent of the induced angle. Thus there were 21 measurements of tangent (three in each of the seven trials) which could be used in the determination of the slope. A "best fit" linear slope, standard error of the slope, and 95% confidence uncertainty of the slope (U_{slope}) and other fit statistics are calculated using a linear least-squares regression method in a spreadsheet calculation.

Assessment of the uncertainty in the calculated as-inclined displacement (U_{Δ}) requires consideration of a number of independent sources of error, since the displacement is a derived quantity based on measurement of drafts, calculation of the submerged volume from the ship's lines, and measurement of water density. This procedure is detailed in Appendix A.

Based on the Stability Test Report, the calculated value of the as-inclined GM was 18.26 ft. Based on the results of the uncertainty analysis detailed in Appendix A, the uncertainty in the as-inclined GM (U_{GM}) is 0.24 ft with a 95% confidence level. This means that there is a 95%

confidence that the true value lies within ±0.24 ft of the calculated value, or in equation form the as-inclined GM can be written (to one decimal place)

$$GM = 18.3 \pm 0.2\ ft\ (with\ 95\%\ confidence)$$

Appendix A also describes calculation of uncertainties associated with the lightship KG and the KG and GM of the accident voyage. First, the as-inclined KG is calculated from the as-inclined GM by subtracting the GM from the height of the metacenter (KM), and therefore the uncertainty in the as-inclined KG accounts for the additional uncertainty in KM, which is a hydrostatic property and based on the hull offsets. The lightship KG is calculated from the as-inclined KG by adding and subtracting all of the liquid and solid weights identified during the deadweight survey portion of the stability test, and the uncertainty in the lightship KG accounts for the additional uncertainties associated with these weights and their centers of gravity. The KG for the accident voyage departure condition is calculated from the lightship KG by adding all liquid and cargo loads based on the voyage loading plan, and the uncertainty in the departure KG accounts for the additional uncertainties associated with these weights and their centers of gravity. Finally, the GM for the accident voyage is calculated by subtracting the KG from the height of the metacenter (KM), and the uncertainty in the GM for the accident voyage accounts for the additional uncertainty in the value of KM. See Appendix A for a full description of the procedure.

Table 3-2 below provides a summary of all of the key calculated uncertainties from Appendix A. The table reflects key results from the uncertainty analysis of the February 12, 2006 stability test, plus results of the additional uncertainty analysis of the lightship condition and departure condition for the accident voyage (185S).

Using the final calculated uncertainty in Table 3-2 for GM for the accident voyage departure condition, this says that there is a 95% confidence that the calculated value of GM lies within ±0.69 ft of the true value of GM, or in equation form the departure GM can be written (to one decimal place)

$$GM = 4.3\ ft \pm 0.7\ ft\ (with\ 95\%\ confidence)$$

As discussed in Appendix A, the centers of gravity for LO/LO containers were calculated by default in CargoMax at the geometric center of the containers. It is recognized that most containers would likely contain cargo which would result in a center of gravity below the center of the container, and this would suggest addition of a KG-reducing (negative) bias error adjustment to the estimate of uncertainty based on the conservative calculation in CargoMax. This is estimated to be approximately a 0.2 feet reduction in KG or increase in GM for the accident voyage (see Appendix A).

With this estimated bias error adjustment applied for the accident voyage loading condition the departure GM can be written

$$GM = (4.3 + 0.2) \pm 0.7\ ft = 4.5 \pm 0.7\ ft\ \ (with\ 95\%\ confidence)$$

Parameter	Measured, calculated or nominal value with units	Uncertainty with units
Slope (tangent/moment)	2.3460×10^{-6} 1/ftLT	16.68×10^{-9} 1/ftLT
Molded vs. as-built volume (V)	849,229 ft^3	1,673 ft^3
Vessel drafts	22.45 ft	0.061 ft
Calculated molded volume (m)	849,229 ft^3	8,492 ft^3
Displacement volume (∇)	849,229 ft^3	9,126 ft^3
Specific weight, density	62.55 lb/ft^3	0.09 lb/ft^3
Vessel displacement (Δ)	23,512 LT	260 LT
As-inclined GM	18.26 ft	0.24 ft
As-inclined KG	26.02 ft	0.45 ft
Lightship KG	27.82 ft	0.72 ft
Accident voyage departure KG	37.25 ft *[-0.2 ft]	0.63 ft
Accident voyage departure GM	4.28 ft *[+0.2 ft]	0.69 ft

Table 3-2: Summary of results of the uncertainty analyses of the stability test and the loading condition for the accident voyage. All uncertainties are at the 95% confidence level. *Bracketed estimated values reflect potential bias correction, lowering KG and increasing GM due to default location of centers of gravity of LO/LO containers in CargoMax (see Appendix A).

3.4. Summary

This section documented the MSC review of the 2006 stability test (inclining experiment) and assessment of the calculations associated with determination of the lightship weight and center of gravity provided in the Stability Test Report. This section also provided a summary of the requested uncertainty analysis of the lightship KG and the GM for the accident voyage departure condition, which is documented in detail in Appendix A.

Based on the MSC uncertainty analysis of the stability test, the uncertainty in the as-inclined GM was calculated to be approximately 0.2 feet (with 95% confidence). This means that there is a 95% confidence that the true value of GM in the as-inclined condition is within ±0.2 feet of the value calculated in the Stability Test Report. The uncertainty in the lightship KG was calculated to be approximately 0.7 feet (with 95% confidence), and the uncertainty in the GM for the accident voyage departure condition was calculated to be approximately 0.7 feet (with 95% confidence). The last statement means that there is a 95% confidence that the true value of the accident voyage GM was within ±0.7 feet of the calculated value.

4. Trim and Stability Booklet (T&S Booklet) and Stability Software

4.1. Introduction

A stability booklet (also referred to as a trim and stability booklet) is required by 46 CFR Subchapter S, Subdivision and Stability, and must contain sufficient information to enable the master to operate the vessel in compliance with applicable regulations within the subchapter, most notably applicable intact and damage stability criteria. For the EL FARO the most recent T&S Booklet, Rev E dated February 14, 2007 [12] was approved on behalf of the U.S. Coast Guard by ABS on May 31, 2007 [33]. The stability review was completed in association with a summer load line molded draft of 30’-1-5/16” (30’-2-3/8” keel draft) corresponding to a 1966 Type “B” vessel freeboard of 12’-0-15/16” from the 2nd deck. At the time of the accident voyage, the vessel had a valid International Load Line Certificate issued by ABS on behalf of the U.S. Coast Guard on January 29, 2011 [34]. The approved load line and freeboard had not changed since the issuance of the T&S Booklet. It is noted that a stability booklet is not intended to address the assessment of vessel loading and hull strength (bending moments and hull stresses), or the assessment of cargo loading and securing. Vessel loading and hull strength assessment would be included in a vessel loading manual, if one is required; however, a loading manual was not required or provided for the EL FARO. Cargo loading and securing would be included in a vessel cargo securing manual, and the EL FARO had an ABS-approved Cargo Securing Manual [35].

Onboard stability software, also referred to as a “stability instrument”, is software used to calculate the loading condition and stability of a vessel to ascertain that stability requirements specified for the ship in the stability booklet are met in an operational loading condition. For the EL FARO, the stability and loading software CargoMax was approved for onboard use by ABS on February 8, 2008 [21], as it met the requirements of the applicable ABS Steel Vessel Rules [36], IACS Unified Requirement L5 [14], and MSC.1/Circ.1229 [13]. It should be noted from the ABS approval letter [21] that the CargoMax software was reviewed and approved by ABS for use onboard the EL FARO only as a supplement to facilitate stability calculation, and not as a substitute for the approved T&S Booklet. Based on the MBI hearing testimony [18, 19, 31, 32], CargoMax was routinely used by the Tote Services, Inc. operations personnel independently of the T&S Booklet. It should also be noted from the ABS approval letter that the CargoMax software was neither reviewed nor approved for assessment of loading and hull strength (bending shear forces and moments) or for assessment of cargo loading and securing (container stack weight, tier weight and lashing requirements). However, the EL FARO CargoMax software contained features used by the Tote Services, Inc. operations personnel for these purposes and, based on MBI hearing testimony [18, 19, 20, 31, 32], was relied on for these purposes.

With the exception of recent amendments to several IMO instruments applicable to oil, chemical and gas carriers, there are no requirements for the use of onboard software for vessel stability, strength or cargo loading and securing. Under Coast Guard policy [37], the master must be provided with the capability to manually calculate stability. However, he may use whatever tools he wishes to assist him in his responsibility to ensure satisfactory stability. The Coast Guard will, upon request, verify that the onboard stability software produces nearly identical results to the approved stability booklet in a number of representative loading conditions. After verification, the Coast Guard will recognize the software as an adjunct to the stability booklet; however, it remains incumbent upon the master to ensure the vessel is compliant with all aspects of the stability booklet.

4.2. T&S Booklet

The most recent EL FARO T&S Booklet, Rev E dated February 14, 2007 [12] was issued by Herbert Engineering Corporation and was based on the T&S Booklet, Rev 0 dated May 6, 1993, [17]. Rev 0 was applicable from the time the vessel was lengthened in 1992-1993 until the conversion in 2005-2006. Four revisions were written between 2005 and 2007, which included accounting for removal of the spar deck, addition of deck containers, container foundations and securing system, addition of permanent ballast, revision of lightship weight and center of gravity based on the 2006 stability test, and addition of variable tank data tables. Additional notes, new sample load cases, and new calculation forms were also added to reflect the conversion of the vessel to carry containers on deck (LO/LO cargo).

The most recent 2007 T&S Booklet was approved on behalf of the U.S. Coast Guard by ABS on May 31, 2007 [33], having met the requirements of 46 CFR 170.110. In addition to comments provided in Section 3 of this report applicable to the 2007 T&S Booklet, the following comments are provided:

(1) The instructions for computation of the vessel's stability and trim on page 7 of the T&S Booklet do not appear to provide correct instructions for computation of hydrostatic properties given vessel drafts. The instructions direct that the mean draft be used to read a corresponding displacement, instead of the draft at the LCF, which must be calculated by applying a trim correction. However, it is noted that the example calculation forms provided on pages 32-35 of the T&S Booklet do provide spaces for applying the required trim corrections, although the instructions for application by the user are not clear. There are also no instructions on the proper method to correct the height of the metacenter (KM_T) for trim using the table on page 12 of the T&S Booklet.

(2) The minimum required GM curves provided on page 16 of the T&S Booklet produced by Herbert Engineering Corporation (see Figure 4-1) were generated based upon the minimum GM required to meet the intact stability criteria of 46 CFR 170.170 (see Section 5 of this report for additional information about intact stability criteria). However, in MBI hearing testimony [38, 39, 40] it was noted that Herbert Engineering did not complete a damage stability analysis to confirm that, after the 2005-2006 conversion, the limiting criteria would remain the intact stability criteria for all loading conditions, and ABS had no records of a damage stability analysis being completed. This is important because the 2005-2006 conversion resulted in a 2-foot increase in the load line draft (28'-1-1/16" to 30'-2-3/8"), and therefore the previous damage stability analysis completed in 1993 no longer applied. In his MBI hearing testimony [38, 39], Mr. Thomas Gruber of ABS submitted results of his independent SOLAS probabilistic damage stability analysis performed in May 2016 [41], where he applied the damage stability standards which would have been applicable in 2005-2006. Mr. Gruber's analysis determined that for GM values of approximately 2.9 feet at both the load line

and partial load line drafts (30.11 and 26.02 feet), the required subdivision index of 0.60 would be attained (see Section 5.3 of this report for a more detailed discussion of damage stability assessment). This suggests that for most load conditions with 2 or more tiers of containers loaded, the limiting stability criteria would be the intact stability criteria as reflected in the T&S Booklet. However, this also means that for some load conditions with less than 2 tiers of containers loaded, the limiting stability criteria could be the damage stability criteria, and this was not reflected on the minimum required GM curves of the T&S Booklet. The MSC also performed an independent SOLAS probabilistic damage stability analysis using the MSC GHS computer model, and confirmed Mr. Gruber's basic result, with a slightly higher GM of 3.3 feet (see Section 5.3 of this report). However, it should be noted that, for the full load departure condition of the accident voyage, the limiting stability criteria would have been the intact stability criteria, which was properly reflected in the T&S Booklet and incorporated in the CargoMax stability software, since the majority of the container stacks included 3 tiers. Section 5 of this report provides additional detailed discussion of applicable intact and damage stability criteria.

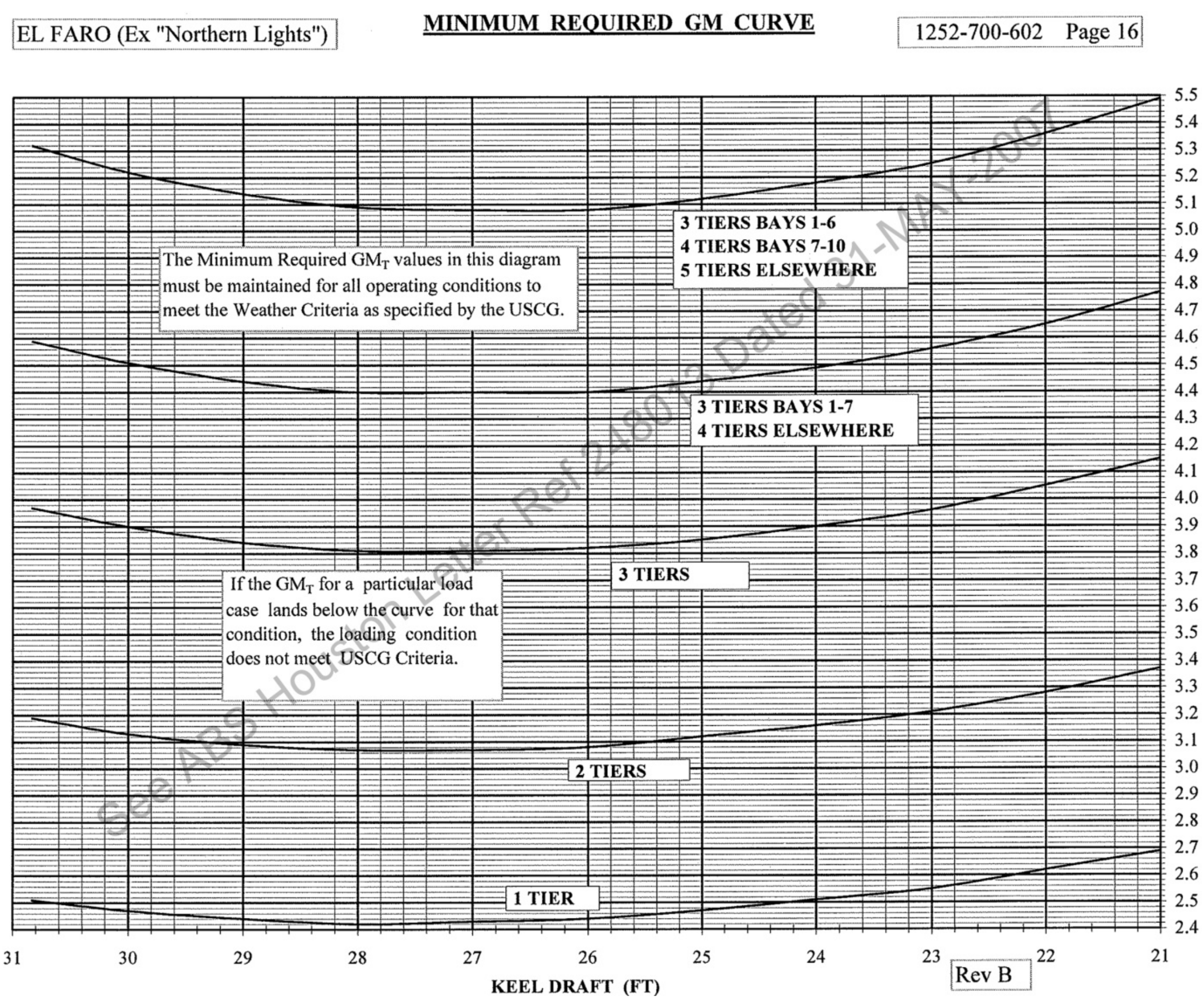

Figure 4-1: Minimum required GM curves from the 2007 T&S Booklet [12].

4.3. CargoMax Stability Software

The stability and loading software CargoMax (Herbert-ABS Software Solutions, LLC) was used onboard the EL FARO and by shore-side operations personnel for cargo load planning and stability assessment. CargoMax Version 1.21.162 dated August 31, 2007 with EL FARO ship model dated September 20, 2007 was approved for use onboard the EL FARO by ABS on February 8, 2008 [21]. However, at the time of the accident voyage, CargoMax Version 1.21.203 dated June 1, 2010 with EL FARO ship model dated June 17, 2010 was installed and being used onboard the EL FARO and by shore-side operations personnel. Based on MBI hearing testimony [38, 39] Version 1.21.203 was not specifically reviewed and approved by ABS.

In granting CargoMax approval in 2007, ABS reviewed and approved the CargoMax Vessel Information Book for the SS EL FARO, Rev 2 dated March 13, 2007 [42], and the supporting report Direct Calculation of Required GM for USCG Windheel Criteria within the CaroMax Loading Program: Implementation System and Supporting Calculations for the SS EL FARO, dated April 14, 2006 [43]. While the CargoMax for Windows User's Manual [44] is the standard reference for information about the software program, the CargoMax Vessel Information Book is the necessary companion to the User's Manual. The Vessel Information Book presents necessary ship-specific information incorporated into the EL FARO CargoMax vessel model, includes instructions for program options and custom features, and documents sample load cases comparable to those in the T&S Booklet and to be used for onboard in service verifications [42].

As stated previously, the CargoMax software was reviewed and approved by ABS for use onboard the EL FARO only as a supplement to facilitate stability calculation, and not as a substitute for the approved T&S Booklet. As such, the vessel operator was obligated to follow all operating instructions delineated in the T&S Booklet, regardless of whether or not the CargoMax software checked or warned for violations of the T&S Booklet instructions. The MSC review found that there are operating instructions in the T&S Booklet which were not followed by the operating personnel in loading the vessel using the CargoMax software for the accident voyage [11]. Specifically, it is stated in the T&S Booklet that not more than one pair of tanks assigned to each type of consumable liquid onboard the vessel shall be slack at one time. It is further stated that tanks required to be ballasted with salt water shall be immediately filled and carried pressed up at all times while such ballast is necessary, and otherwise kept pumped to minimum contents at all time. It is noted that for the accident voyage, all 5 fuel oil tanks were slack, 4 fresh water tanks were slack, and 4 of the larger salt water ballast tanks were slack. While there are checks and warnings within CargoMax to check the load line limit and the intact stability criteria, there are no warnings for T&S Booklet slack tank limitations. However, it is also noted that CargoMax does properly include all tank free surface corrections in the calculation of the vessel GM, so while this slack loading is not in accordance with the T&S Booklet and it does introduce some additional risk to the vessel, it is not an unassessed risk. In MBI hearing testimony [18, 19, 32] witnesses stated that fuel loading was normally limited to 8,200 barrels (1,825 LT) and tanks were not pressed up; the rationale given was that this would enable them to carry more cargo, but also provide enough fuel for a round trip voyage plus several days reserve.

During MSC review of the approved CargoMax Vessel Information Book for the SS EL FARO, Rev 2 dated March 13, 2007 [42] it was noted that necessary key data used to configure the CargoMax program for the EL FARO was not included; specifically documentation of the operating lightship weight and weight distribution, load line data, draft mark locations, minimum required GM tables, and allowable shear force and bending moments. Additional investigation by MSC found that the missing 15 pages were included with Rev 1 dated October 19, 2006 [45], but were apparently inadvertently omitted from the approved Rev 2 dated March 13, 2007. It is not clear if the missing pages were reviewed by ABS.

The report Direct Calculation of Required GM for USCG Windheel Criteria within the CaroMax Loading Program: Implementation System and Supporting Calculations for the SS EL FARO [43] documents required GM calculation features implemented in CargoMax which are not provided in the T&S Booklet. The calculation features in CargoMax replaced the more conservative calculation method used in the T&S Booklet in which the required GM curves were provided only for specific container stack height combinations (see Figure 4-1) without a method for interpolation or incorporation of actual container loading and wind profiles. The direct calculation method implemented in CargoMax provides a calculation of the required GM directly from the USCG criteria of 46 CFR 170.170 (see Section 5 of this report) using a calculated wind heel area based on the actual container loading profile. The report documents the calculation method and provides verification calculations and sample cases. As the calculation method provides a direct calculation of the minimum required GM based on the explicit formula provided in 46 CFR 170.170, with lateral wind area based on the actual loading condition, it meets the necessary requirements for calculation of minimum required GM.

The accuracy of the CargoMax calculations can be considered as good (or better) than the tabular form calculation performed by hand using the T&S Booklet. Fundamentally, the CargoMax model for the EL FARO consists of the same vessel data contained in the T&S Booklet, including principal dimensions, draft mark locations, hydrostatic tables, variable tank data tables including free surface, trim table, and required GM curves. The latter (required GM) may also be calculated using direct calculation of required GM as discussed previously. Otherwise, the calculations are carried out in basically the same manner. Of course, human errors may be reduced and computer precision may increase accuracy of results to some extent. For comparison, the sample load cases “full load departure” and “ballast arrival” provided in the CargoMax Vessel Information Book can be compared directly to the “homogenous full load departure” and “ballast arrival” conditions in the T&S Booklet, with the results being nearly identical, as expected.

Since the CargoMax and T&S Booklet calculations are based on the same hydrostatic tables, variable tank data tables including free surface, and other tabular vessel data, it is worthwhile comparing the results of the basic CargoMax calculation to that using the MSC GHS computer model. As discussed in Section 2 of this report, the GHS calculation implements direct calculation of all areas and volumes from the hull and tank stations and offsets using numerical integration, as opposed to the tabular data method used in CargoMax and the T&S Booklet. It would therefore be expected that the results would differ by some amount. Table 4-1 provides a summary of the results for the departure condition of the accident voyage (185S). The definition of weight for the loading condition summary was taken from the CargoMax printout [11]. The minimum required GM was calculated using the direct calculation method using the actual wind heel area per 46 CFR 170.170 (see Figure 2-5). The calculated results are nearly identical. See Section 5 of this report for a more detailed discussion of analysis methods and stability criteria.

As discussed in Section 2.3, the CargoMax software for EL FARO applies an incorrect lightship TCG of 0.0 ft-CL, and therefore the calculation of the static list angle in CargoMax is inaccurate. From a practical perspective, using a lightship TCG of 0.00 ft-CL in the CargoMax stability software calculations led to incorrect list prediction in development of load plans using the software. This is important in that the vessel operators would have to plan for the incorrect list prediction in developing the load plan. This would be especially challenging since the amount of calculated and/or induced list would vary depending on drafts and vertical location of the center of gravity (VCG or KG), and therefore would not be a constant correction. Based on the MBI hearing testimony [18], vessel operators who used the CargoMax loading and stability software tried to anticipate the induced angle of list based upon this recognized but unquantified discrepancy in TCG.

	CargoMax	MSC GHS Computer Model
Displacement (LT)	34,625	34,516
VCG (ft-BL)	37.25	37.32
LCG (ft-FP)	402.0	401.5
Draft @ LCF (ft-K)	30.1	30.0
Trim (ft-aft)	5.8	5.6
GM uncorrected (ft)	4.69	4.60
FS correction (ft)	0.40	0.37
GM corrected (ft)	4.28	4.23
GM required (ft)	3.64	3.78
GM margin (ft)	0.64	0.45

Table 4-1: Comparison of CargoMax and MSC GHS computer model calculation results for the departure condition of the accident voyage. Drafts are above the keel (K) and GM required is calculated directly using 46 CFR 170.170.

An important note about the hydrostatics calculations regarding hull deflection should be made. Based on the calculation of bending moments for the departure condition [11], the vessel would have experienced a “hogging” hull deflection (i.e. deflected with a concave-down curvature) leading to a difference in the mean draft (average of forward and aft drafts) as compared to the actual measured midship draft. Although the calculation of the deflection based on bending moment is possible in CargoMax, it would require tabulation of structural moments of inertia at a number of frame locations, and this data was not available with the EL FARO CargoMax vessel data. However, it may be estimated that several inches of “hogging” hull deflection could be expected in the full load condition, and this is supported by reviewing historical deck logs for EL FARO Jacksonville departures over the months leading up to the accident voyage, in which forward, midship and aft draft measurements at the full load departure are documented based on crew measurement [see reference 46 for example]. The review suggests typical “hogging” deflection on the order of 3-5 inches for full load Jacksonville departures. Based on an MSC calculation, for a midship draft near the load line of 30'-2-3/8" (the summer load line draft), the effect of 3-5 inch "hogging" hull deflection would be that the actual vessel displacement would exceed the calculated (without deflection) displacement by 300-500 LT.

4.4. Summary

This section documented the MSC review of the T&S Booklet and review of the CargoMax stability and loading software used onboard the EL FARO and by shore-side personnel for cargo load planning and stability assessment.

The CargoMax stability software used onboard the EL FARO and for load planning by shore-side personnel was neither reviewed nor approved for assessment of loading and hull strength since there was no loading manual required for the EL FARO. However, the EL FARO CargoMax software did contain features to assess hull strength, and the vessel operators relied on these features for assessment of hull girder bending moment in load planning.

The CargoMax software was neither reviewed nor approved for assessment of cargo loading and securing, including calculations required in the Cargo Securing Manual, which had been reviewed and approved by ABS. However, the EL FARO CargoMax software did contain features for assessment of cargo securing, and the vessel operators relied on these features for assessment of LO/LO container loading and securing.

With the exception of recent amendments to several IMO instruments applicable to oil, chemical and gas carriers, there are no requirements for the use of onboard software for vessel stability, strength or cargo loading and securing. Under Coast Guard policy, the master must be provided with the capability to manually calculate stability. However, he may use whatever tools he wishes to assist him in his responsibility to ensure satisfactory stability. The Coast Guard will, upon request, verify that the onboard stability software produces nearly identical results to the approved stability booklet in a number of representative loading conditions. After verification, the Coast Guard will recognize the software as an adjunct to the stability booklet; however, it remains incumbent upon the master to ensure the vessel is compliant with all aspects of the stability booklet.

5. Intact and Damage Stability

5.1. Introduction

Through proper design, loading and operation, a ship should possess enough reserve buoyancy and stability to ensure that with motion in heavy seas and even with some damage and limited flooding it will remain afloat and upright. A ship will remain afloat as long as sufficient buoyant volume exists to support the weight of the ship, its contents and limited floodwater. In order to remain upright the external forces and moments acting on a ship must be counteracted by internal forces and moments sufficient to ensure that the vessel will neither capsize nor heel to an excessive angle considering the conditions the vessel will likely encounter in service; this is ship stability. Assessment of a vessel's stability without damage is "intact stability." Assessment of a vessel's ability to withstand limited damage and flooding is "damage stability."

5.2. Intact Stability

5.2.1. Background

For a conventional ship in a seaway, external forces acting on the ship include primarily wind and wave forces exerted on the underwater and above-water surface area of the hull and any exposed structure including superstructure and above-deck cargo such as container stacks. Internal righting capacity arises from the ship's own weight and buoyant forces providing a righting moment (see Figure 5-1). As the ship is heeled by external forces, the change in the shape of the underwater volume results in a shift in the center of the underwater volume, called the center of buoyancy (B), through which the force of buoyancy (F_B) acts. As long as onboard weights do not shift, the center of gravity (G), through which the resultant weight (W) acts, remains fixed, and a righting moment is created due to the horizontal separation of the lines of action of the forces of weight and buoyancy. This horizontal separation (GZ) is referred to as a "righting arm" or a "righting lever." Depending on the location of the center of gravity and the shape of the underwater hull form, as heel angle is increased, GZ increases, achieves a maximum, and then decreases to zero as the lines of action of weight and buoyancy are again aligned. Heel beyond this point results in capsizing of the ship, and this point is often referred to as the angle of vanishing stability or simply the range of stability.

A plot of righting arms (GZ) as a function of heel angle (φ) is called a "righting arm curve" or "stability curve" (because this is based on a static analysis of forces and moments, it is sometimes called a "statical stability curve"). Figure 5-2 shows a righting arm curve for a notional vessel. A plot of righting moments can also be created by simple multiplication of the righting arms with the ship's weight or displacement (based on Archimedes' Principle and static equilibrium, for a floating vessel the weight and buoyant forces are equal and are referred to as the displacement). The area under a righting moment curve to a given angle is the righting energy available to restore the ship to the upright position, and the entire area under a righting moment curve is the righting energy available to resist capsizing (or conversely the energy required to capsize the vessel). For this reason the area under a righting arm curve may be used in evaluating the ability of a ship to resist capsizing. This is the case since the righting arm curve is simply a scaled version of the righting moment curve (scaled by the displacement or weight of the vessel).

This consideration of "statical stability" as the area under the righting arm curve and available righting energy is sometimes loosely referred to as "dynamic stability" of a vessel. It should be recognized however that this does not consider true dynamics of vessel motion in a seaway, including important mass and mass moments of inertia, and synchronous roll, pitch and heave motions due to alignment of vessel natural periods or frequencies of motion with ocean wave periods or frequencies. Nevertheless, the "statical stability" view of ship stability is comparatively simple and has been used as the primary means for assessing seaworthiness of commercial and military vessels alike. However, dynamic analyses and/or model testing programs to assess true dynamics of vessel motion are often required in vessel design for critical applications or for forensic analyses.

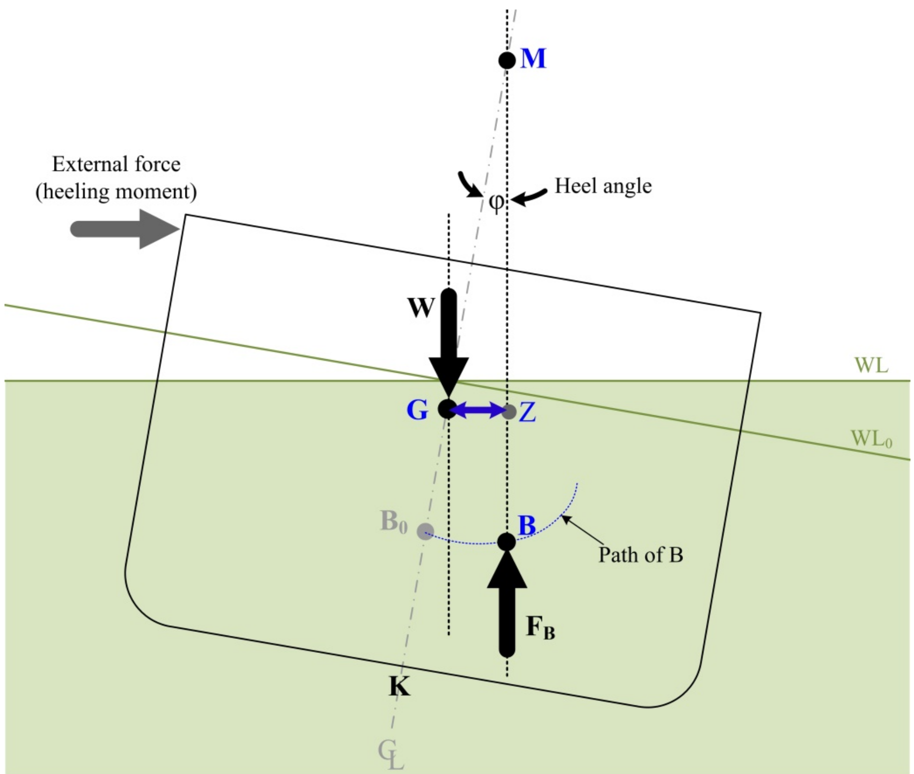

Figure 5-1: Development of righting arms (GZ) (righting moments) with vessel heel due to external forces.

Figure 5-1 includes annotation of an imaginary point through which the lines of action of the buoyant force act as the vessel is inclined through small angles of heel. This point, called the metacenter (M), is the center of the arc traveled by the path of the center of buoyancy (B) through small angles of heel (the distance from B to M is referred to as the "metacentric radius"). However, since the path of B is not a true circular arc for most vessels (other than those with circular cross sections), the metacenter is generally only applicable for small angles of heel where the path of B may be approximated by a circular arc as shown. It should be noted from Figure 5-1 that as long as the center of gravity (G) is below the metacenter (M), then the vessel would have positive righting arms for small angles of heel, and the vessel would return to an upright condition if disturbed by a small external force. The distance from G to M is called the "metacentric height" or simply "GM," and its magnitude is frequently used as an indicator of the initial (small angle) stability of a ship. From Figure 5-1:

$$GM = GZ/sin\varphi = GZ/\varphi \;\; for\ small\ \varphi \;\; (in\ radians) \quad (5\text{-}1)$$

GM is therefore the initial slope of the righting arm curve. Noting that 1 radian is equal to 57.3 degrees, GM is often annotated graphically on a righting arm curve as shown in Figure 5-2.

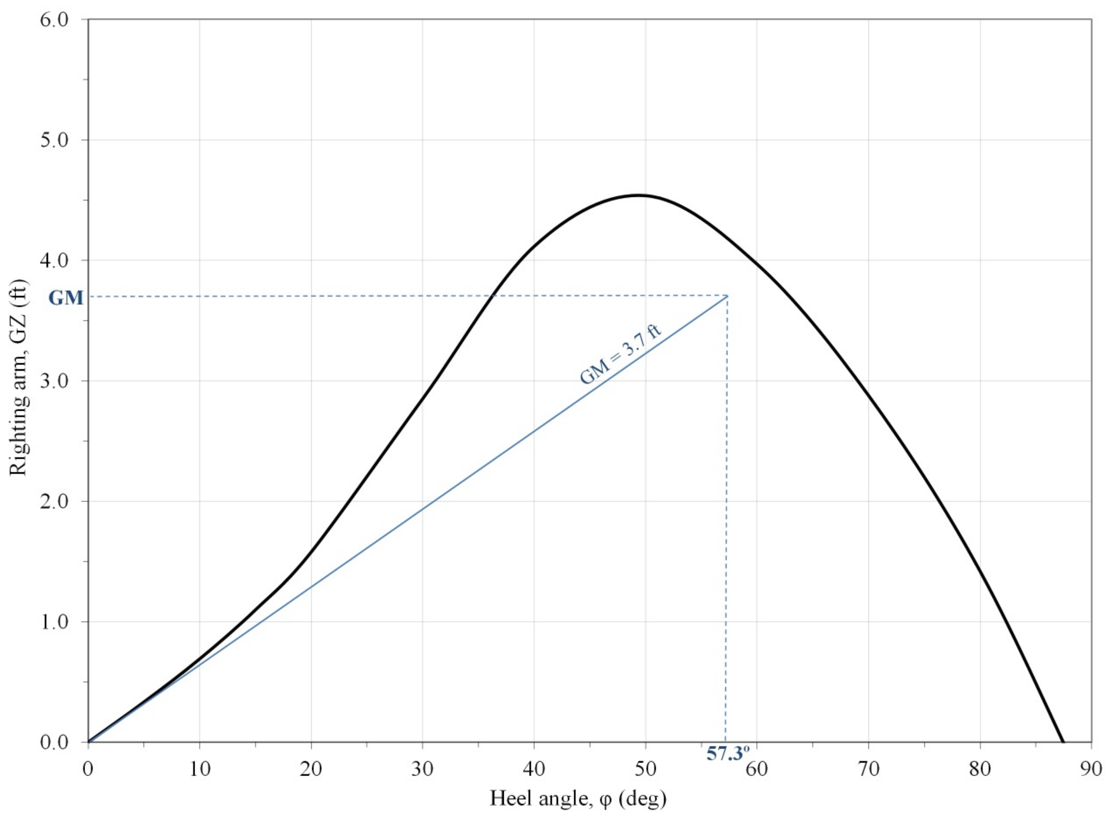

Figure 5-2: A righting arm curve for a notional vessel. GM is the initial slope of the righting arm curve.

Importantly, since GM is only the initial slope of the righting arm curve (and is only applicable for small angles), the magnitude of GM does not give an indication of the magnitude of the maximum righting arm, the angle at which the maximum occurs, the angle of vanishing stability (range of stability), or the area under the righting arm curve (righting energy). Therefore the use of GM as a stability indicator may be misleading if used by itself. However, since calculation of GM is relatively simple compared to calculation of righting arms, GM has been used extensively as a basis for evaluating stability of many types of ships, including general cargo vessels.

5.2.2. Intact Stability Criteria

A thorough discussion of intact stability, including theory and assessment criteria is provided by Moore [47]. A historical perspective of intact stability criteria applicable in the U.S., based on

GM, righting arms, righting moment and righting energy balances, including strengths and weaknesses of each method, is provided by Henrickson [48]. Additional general discussion of stability criteria applicable to U.S. flagged vessels under the U.S. Code of Federal Regulations (CFR) is provided in the U.S. Coast Guard Marine Safety Manual [37]. A historical perspective of the development of international intact stability standards through the International Maritime Organization (IMO) is provided in MSC.1/Circ. 1281 [49].

Intact stability criteria, both in the U.S. and internationally, have historically been developed based on statistical analysis of vessel casualty data. Rahola in his 1939 doctoral thesis [50] discussed the origins of the GM criteria going back to the 1920s. In the 1940s the U.S. Coast Guard refined the GM criteria based on a database using WWII "Liberty Ships" and "T2" tanker type vessels [37]. The developed GM criteria have remained mostly unchanged and are the basis for the current GM criteria specified in 46 CFR 170.170, also referred to as the "weather criteria", as they specify minimum required GM to limit static heel angle due to a steady wind. The 170.170 weather criteria limit induced static heel due to a prescribed steady wind pressure to the lesser of 14 degrees or the angle to submerge half of the available freeboard. The applied wind heel (moment) is calculated by multiplying a prescribed wind pressure (calculated as a function of vessel length) with the projected lateral area of the vessel above the waterline and the vertical distance from the center (centroid) of the lateral area above the waterline to the center of the underwater lateral area or approximately to the one-half draft point. In equation form the minimum required GM is calculated (46 CFR 170.170):

$$GM_{required} = \frac{P \cdot A \cdot H}{\Delta \cdot tanT} \tag{5-2}$$

where:

- P = $0.005 + (L/14{,}200)^2$ (LT/ft^2) for ocean service
- L = LBP (ft)
- A = projected lateral area of the vessel and deck cargo above the waterline (ft^2)
- H = vertical distance from the center of A to the center of the underwater lateral area or approximately half the draft (ft)
- Δ = displacement (LT)
- T = lesser of either 14 degrees or the angle of heel at which one-half of the freeboard to the deck edge is immersed.

The vessels used in development of the weather criteria had limited superstructure and generally carried their deadweight inside their hull envelope, typically providing a large range of stability and large righting energy, even with relatively small GM [37]. By the 1960s it was realized that some vessels could easily meet the GM weather criteria with little or no righting energy (area under the righting arm curve) and/or with very small range of stability. This became especially evident with the development of offshore supply vessels, which had larger beam-to-depth ratios producing higher GMs, but also lower freeboards causing deck edge immersion at lower angles of heel compared to conventional hulls, consequently resulting in lower range of stability and lower overall righting energy [48]. Figure 5-3 shows comparison of righting arm curves for a conventional cargo vessel and offshore supply vessel circa 1960s (reproduced from [51] with permission) illustrating the lower range of stability and righting energy of the offshore supply vessel. Following the loss of eight offshore supply vessels due to capsizing in the Gulf of

Mexico between 1956 and 1963, the Coast Guard began to apply more stringent criteria to offshore supply vessels based on Rahola's righting arm criteria [48, 51]. Rahola published his recommended righting arm criteria as part of his doctoral thesis in 1939 [50], basing the recommended criteria on statistical analysis of casualty data from a database using coastal freighters of length 100-300 feet. In the 1960s Rahola's recommended criteria also became the basis for newly developed international intact stability standards adopted by IMO with Resolution A.167(ES.IV) in 1968, which are the basis for the criteria specified in 46 CFR 170.173 applicable for ships under 100 meters (328 feet) in length (other than tugboats).

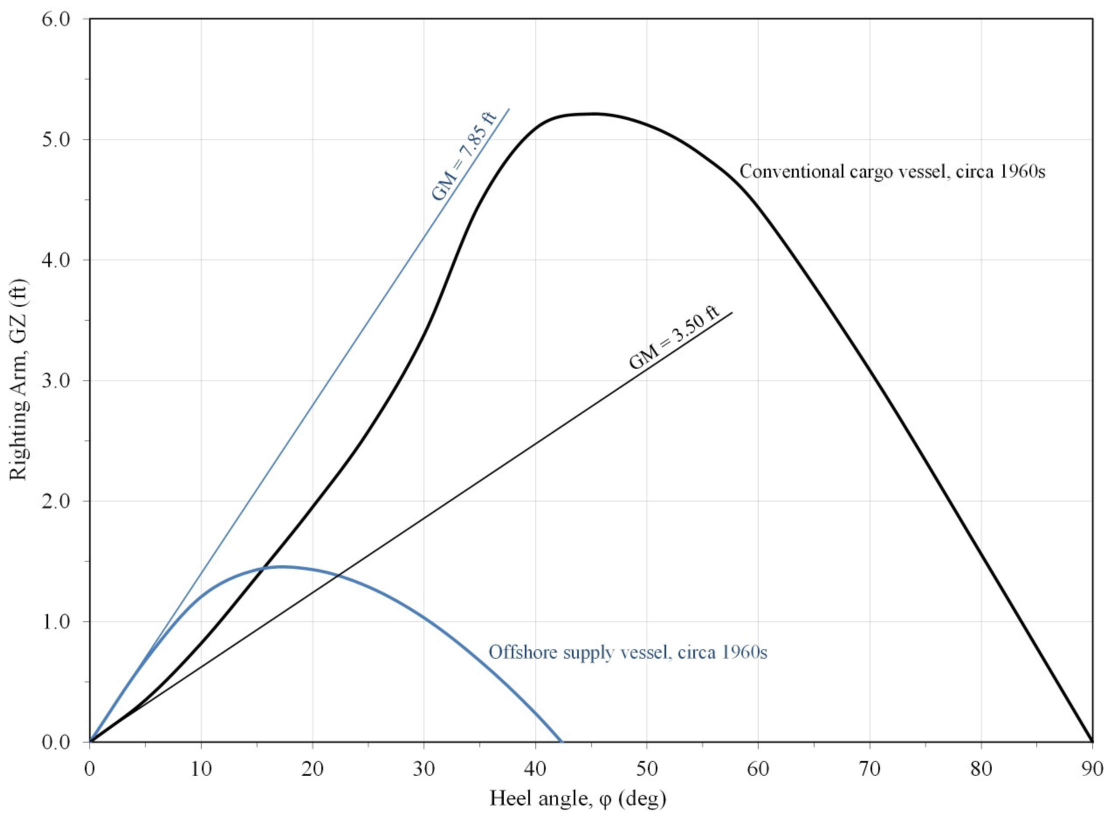

Figure 5-3: Comparison of righting arm curves for a conventional cargo vessel and offshore supply vessel circa 1960s (reproduced from [51] with permission).

Current international intact stability standards are provided in the International Code on Intact Stability, 2008 (2008 IS Code) [52]. Explanatory notes for development of the international standards are provided in the Explanatory Notes to the International Code on Intact Stability, 2008 [49]. The 2008 IS Code includes two parts: "Mandatory Criteria" (Part A) and "Recommendations for Certain Types of Ships and Additional Guidelines" (Part B).

46 CFR 170.165, which became effective in 2011, requires U.S. flagged vessels possessing certain types of international certificates (including International Load Line Certificates) to comply with the Introduction and Part A of the 2008 IS Code, unless permitted otherwise. For the special case of a vessel under the Alternate Compliance Program (ACP), the vessel must meet requirements of SOLAS and the classification society rules, with additional requirements contained in the ACP Supplement for the applicable classification society. The ACP Supplement for ABS [53] states that intact stability of cargo and passenger vessels is to comply with the

applicable parts of Subchapter S (including therefore 46 CFR 170.165, and by reference Part A of the 2008 IS Code, if applicable).

Part A of the 2008 IS Code presents minimum requirements to apply to cargo and passenger ships of 24 meters in length and over, and includes two types of intact stability criteria:

(1) Criteria regarding righting arm (lever) curve properties (Section 2.2). These were formerly the “general criteria” originally adopted by IMO with Resolution A.167(ES.IV) in 1968, based on Rahola’s righting arm criteria. These criteria are implemented in the U.S. in 46 CFR 170.173. The following righting arm criteria are specified [52]:

   a. The area under the righting arm curve shall not be less than 0.055 meter-radians (10.3 ft·deg) up to an angle of heel of 30 degrees, and not less than 0.09 meter-radians (16.9 ft·deg) up to an angle of heel of 40 degrees or the angle of downflooding if less than 40 degrees. Additionally the area under the righting arm curve between 30 and 40 degrees, or between 30 degrees and the angle of downflooding if less than 40 degrees, shall not be less than 0.03 meter-radians (5.6 ft·deg).

   b. The righting arm shall be at least 0.2 meters (0.66 ft) at an angle of heel equal to or greater than 30 degrees.

   c. The maximum righting arm shall occur at an angle of heel not less than 25 degrees.

   d. The initial metacentric height GM shall not be less than 0.15 meters (0.49 ft).

(2) Severe wind and rolling criteria (Section 2.3). These were formerly the “weather criteria” originally adopted by IMO with Resolution A.562(1) in 1985. The criteria were originally developed with the intent to “guarantee the safety against capsizing for a ship losing all propulsive and steering power in severe wind and waves, which is known as a dead ship” [49]. The criteria are based on an energy balance between beam wind heeling and righting moments, with roll motion also taken into account. The method is semi-empirical and based to a large extent on 1950s and 1960s Japanese data and mathematical models for steady wind, wind gusts and ship roll angle in waves. The following righting arm criteria are specified [49, 52], referring to Figure 5-4:

   a. The ship is subjected to a steady wind pressure acting perpendicular to the ship’s centerline which results in a steady wind heeling arm (lever) l_{wl}. The angle of heel under action of the steady wind φ_0 shall not exceed 16 degrees or 80% of the angle of deck edge immersion, whichever is less.

   b. From the resultant equilibrium angle of heel due to the steady wind φ_0, the ship is assumed to roll due to wave action to an angle of roll φ_1 to windward (upwind). The ship is then subjected to a gust wind of heeling arm l_{w2}. Based on energy balance, under these circumstances, the available or potential energy to resist capsizing to leeward, represented by area A_1, shall be equal to or greater than the stored energy or work done due to the roll angle to windward, represented by area A_2, as indicated in the figure. The upper boundary of area A_1 is the limit angle φ_2, which is the lesser of 50 degrees, the angle of downflooding, or the angle of second intercept φ_c.

The wind heeling arms (l_{w1} and l_{w2}) are assumed constant at all angles of heel and are calculated as follows:

$$l_{w1} = \frac{P \cdot A \cdot H}{1000 \cdot g \cdot \Delta} \; (meters) \;\; and \;\; l_{w2} = 1.5 \cdot l_{w1} \qquad (5\text{-}3)$$

The wind pressure P is specified as 504 Pa (0.074 psi or 0.0047 ton/ft^2), which is based on an assumed average wind speed of 26 m/s (50.5 knots) [49]. Area A is the projected lateral area of the ship including superstructure and deck cargo above the waterline. Vertical distance H is from the center of area A to the center of the underwater lateral area or approximately to a point one-half of the mean draft. The displacement Δ is in metric tons (1,000 kg) and the acceleration due to gravity g is 9.81 m/s^2. Note that this calculation is similar to the 46 CFR 170.170 "weather criteria" calculation but with different assumed wind velocity (pressure) and heel angle limits, so they do not provide for direct comparison.

The roll angle φ_1 is calculated as a function of several shape factors which are functions of vessel principal dimensions and coefficients of form, the height of the center of gravity (KG or VCG), and a calculated roll period based on the vessel's calculated GM.

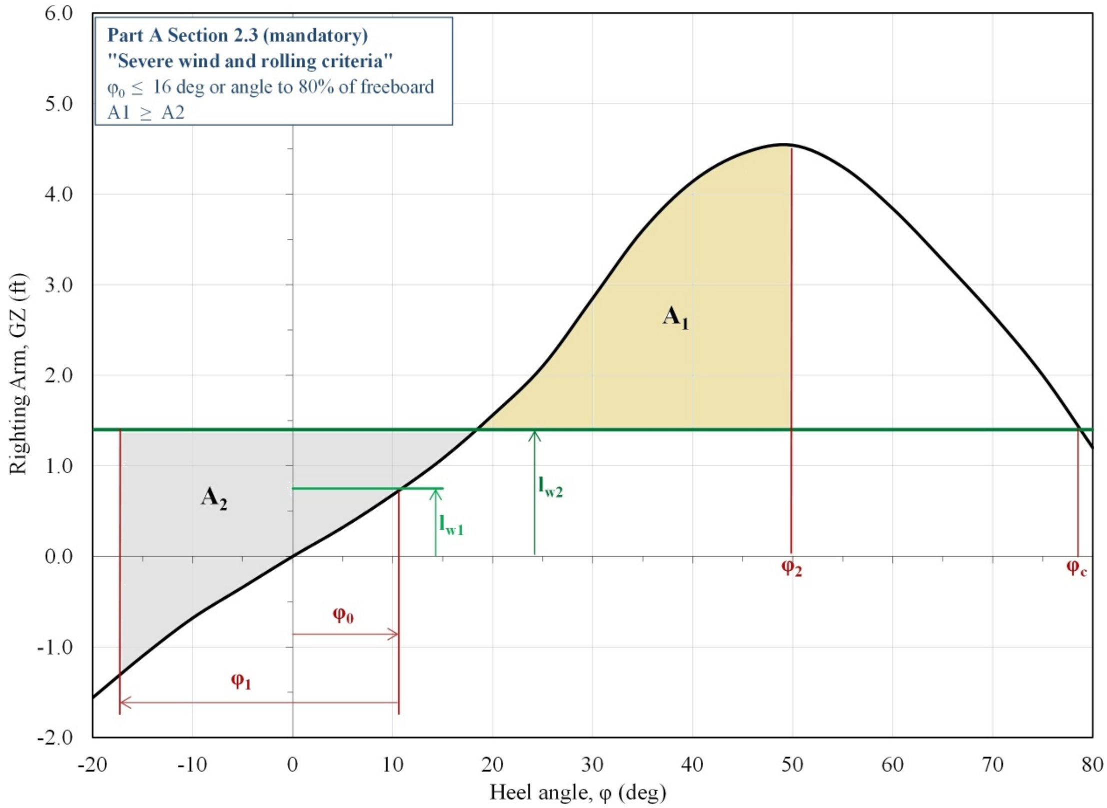

Figure 5-4: IMO severe wind and rolling criteria.

5.2.3. Intact Stability Assessment of EL FARO

5.2.3.1. GM Criteria

Based on date of construction in the 1970s and major conversion in 1992-1993, from a regulatory standpoint EL FARO was required to meet only the intact stability criteria of 46 CFR 170.170 for minimum GM. Since the GM criteria were the only applicable intact stability criteria, the operator of the EL FARO was only required to verify through calculation that the calculated GM, including a free surface effect calculated in accordance with the requirements of 46 CFR 170.285, would exceed the minimum required GM calculated in accordance with 170.170. As discussed in Section 4 of this report, the 170.170 intact stability criteria was the limiting criteria for normal full load operation of the EL FARO, since container stack heights were typically three or higher, in lieu of less restrictive damage stability criteria (although damage stability calculations were not carried out during the 2005-2006 conversion to verify this, see Section 4 of this report).

To provide an overall assessment of the intact stability of the EL FARO, eight “benchmark” loading conditions have been evaluated by the MSC using the MSC GHS computer model. These “benchmark” loading conditions are listed in Table 5-1, which provides a comparison of calculated drafts, trim, free surface correction, GM corrected, GM required, and GM margin for each of the loading conditions. The required GM is calculated using the 46 CFR 170.170 criteria, and the GM margin is the difference between GM corrected and GM required.

The following notes are applicable to all of the MSC calculations:

(1) The 1993 T&S Booklet [17] full load departure condition is as specified on pages 26-30 and the full load arrival (10% consumables) is as specified on pages 36-40 of the T&S Booklet. The 2007 T&S Booklet [12] full load departure condition is as specified on page 32 and the full load arrival (10% consumables) is as specified on page 33 of the T&S Booklet. The voyage 178S (departed Jacksonville August 11, 2015) full load departure and arrival conditions are as specified in the CargoMax printout for voyage 178S [54] which was printed from the CargoMax load case file "EF178JX.LC" provided by Tote, Inc. It is noted that the arrival condition varies from the departure condition only by a fuel burn-off of 164 LT from each of the DB NO 3 IP and DB NO 3 IS tanks (328 LT total). The accident voyage 185S (departed Jacksonville September 29, 2015) full load departure condition is as specified in the revised CargoMax printout for voyage 185S [11]. The accident voyage estimated condition at the time of the loss of propulsion was derived from the departure condition by subtracting an estimated 240 LT of fuel burn-off, with 55 LT taken from each of the DB NO 3 IP and DB NO 3 IS (110 LT total) and 130 LT taken from the FO SETT tank used as a service tank. This estimate was based on review of the noon reports, estimated burn rates and estimated time to loss of propulsion at approximately 0600 on October 1, 2015. This is discussed in greater detail in Section 6 of this report.

(2) For all tanks, loading in the MSC GHS computer model was specified based on the tank loading fraction (% full) provided in the reference document (T&S Booklets or CargoMax printouts). For all cargo and miscellaneous items, weights were entered with weights and centers of gravity based on the reference document. As a result of the small differences between the T&S Booklet and CargoMax and the MSC GHS computer model (see Section 2 of this report), small differences in calculated displacement, TCG and LCG are manifested. For tank free surface the GHS software was run to calculate actual free surface effect for each heel angle by direct calculation of the liquid free surface rather than using tabular look-up of free surface inertia or moment values as in the T&S Booklet and CargoMax calculations for each tank.

(3) A correction was applied to the lightship transverse center of gravity position (TCG) to account for initial vessel list at departure, which was assumed to be zero. This was accomplished in order to correct for the lightship TCG in CargoMax as discussed in Sections 2 and 4 of this report, since it was known through testimony before the MBI that loading was accomplished to achieve a list at departure as close to zero as possible [18, 19, 20]. Based on the assumed zero departure list for voyages 178S and 185S, it was calculated that the lightship TCG should have been approximately 0.3 ft-CL to port (not 0.00 as entered into the CargoMax loading program). For the 1993 and 2007 T&S Booklet calculations, no TCG data was included so it was assumed that the vessel would be at zero list for departure, and lightship TCG was corrected to achieve the zero list for each case. Note that these small lightship TCG corrections have no effect on calculation of vessel drafts and negligible effect on calculation of GM, but are essential for proper assessment of vessel righting arms.

(4) Wind heel areas were calculated by the GHS software based on entry of vessel profiles including specific deck cargo for each condition. For the 1993 T&S Booklet full load comparison, as the vessel did not have deck containers but included a spar deck for additional RO/RO cargo, the wind heel profile was generated assuming an average trailer height of 13’0” (including container and chassis) closely packed onto the main deck, spar deck and ramp in accordance with the cargo capacity drawings in the 1993 T&S Booklet [17]. For the 2007 T&S Booklet full load comparison, the specified uniform 3-tier profile was generated based on the Capacity Plan [10]. For the voyage 178S full load condition, a profile based on the deck container loading provided in the CargoMax printout for voyage 178S [54] was generated. For the voyage 185S (accident voyage) full load departure condition, the profile based on the deck container loading provided in the CargoMax printout for voyage 185S [11] was generated. Figure 5-5 below shows the resulting GHS model wind heel profiles for the 1993 T&S Booklet full load, 2007 T&S Booklet full load, and voyage 178S full load. The wind heel profile for the accident voyage departure condition is shown in Figure 2-5 in Section 2 of this report.

In general, the calculation results in Table 5-1 show good agreement between the original calculation source (T&S Booklet or CargoMax) and the MSC GHS computer model. Differences in free surface (FS) correction are partially due to differences in tank geometries and calculations as discussed in Section 2, but are also a manifestation of the different methods of free surface calculation. In the T&S Booklets and CargoMax program, free surface calculation is based upon tabulated tank data, while the MSC GHS computer model calculates free surface effect directly based on the actual weight shift of the liquid in the tank. For the 1993 T&S Booklet, free surface corrections are significantly higher due to the application of maximum “slack” values for all intermediate tank levels, noting variable tank data is not included in the 1993 T&S Booklet. For the 2007 T&S Booklet and CargoMax calculations, variable tank data is used, so free surface effect calculations are in closer agreement. It should also be noted that Table 5-1 provides a demonstration of some of the uncertainty in calculated GM discussed in Section 3. As can be seen by reviewing the “GM margin” column, calculated values for the MSC GHS computer model were 0.20-0.25 feet less than the CargoMax-calculated values.

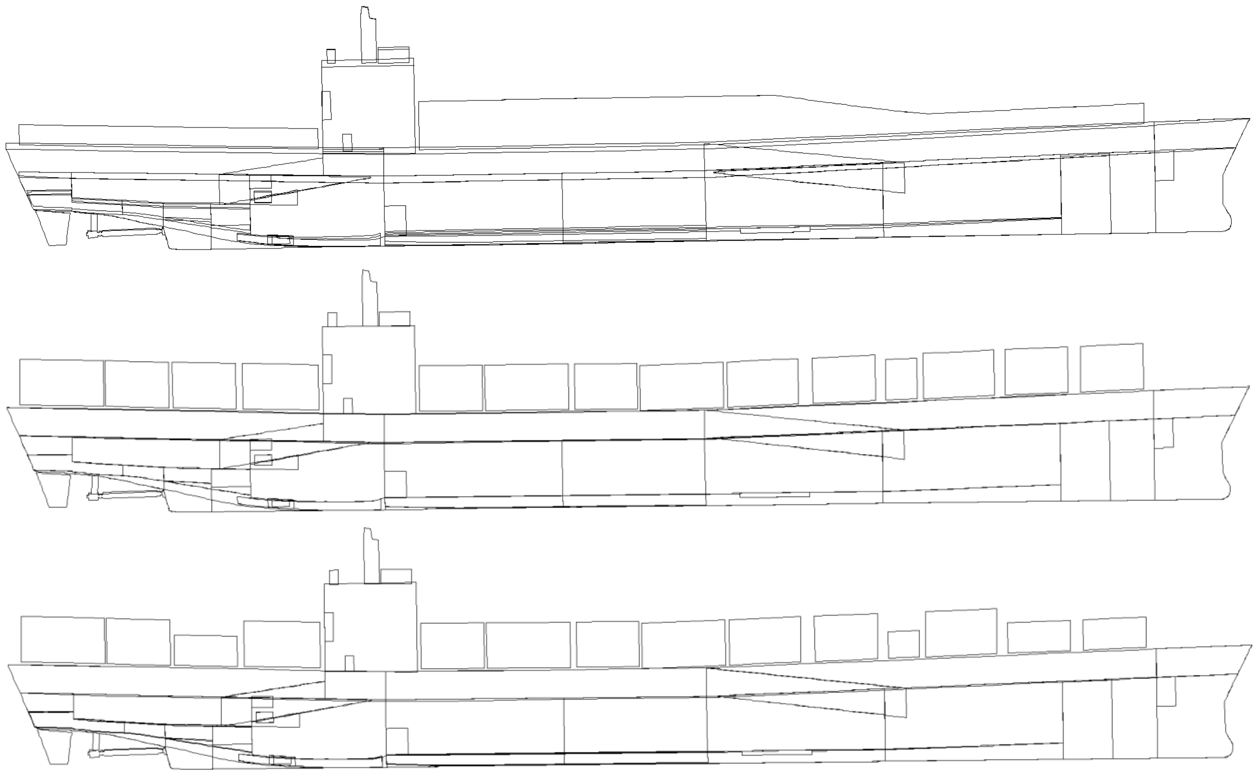

Figure 5-5: MSC GHS computer model wind heel profiles for the 1993 T&S Booklet full load, 2007 T&S Booklet full load, and voyage 178S full load.

		Calculation Source	Displacement (LT)	VCG (ft-BL)	LCG (ft-FP)	Draft at LCF (ft-BL)	Trim (ft-aft)	GM Solid (ft)	F.S. Correction (ft)	GM Corrected (ft)	GM Required (ft)	GM Margin (ft)
1993 T&S Book Full Load	Departure	1993 T&S Book	31,494	36.65	397.3	28.0	5.0	4.98	0.68	4.30	3.14	1.16
		MSC GHS Model	31,394	36.71	398.1	27.9	5.3	5.51	0.36	5.15	3.35	1.80
	Arrival (10% consumables)	1993 T&S Book	30,876	37.96	389.8	27.6	1.4	3.75	0.57	3.18	3.13	0.05
		MSC GHS Model	30,704	37.98	389.8	27.5	1.4	3.87	0.39	3.48	3.45	0.03
2007 T&S Book Full Load	Departure	2007 T&S Book	34,667	35.36	395.2	30.1	2.1	6.31	0.45	5.87	3.92	1.95
		MSC GHS Model	34,545	35.43	394.6	30.0	1.8	6.12	0.42	5.70	3.88	1.82
	Arrival (10% consumables)	2007 T&S Book	32,930	36.70	391.0	29.0	0.7	4.98	0.53	4.45	3.84	0.61
		MSC GHS Model	32,859	36.74	390.4	28.9	0.4	4.79	0.47	4.32	3.92	0.40
Voyage 178S Full Load Depart Jacksonville 8/11/2015	Departure (Jacksonville)	CargoMax	34,964	37.30	401.4	30.3	5.3	4.59	0.40	4.19	3.71	0.48
		MSC GHS Model	34,857	37.37	400.9	30.3	5.1	4.47	0.37	4.10	3.86	0.24
	Arrival (San Juan)	CargoMax	34,636	37.61	400.7	30.1	5.1	4.32	0.40	3.92	3.68	0.24
		MSC GHS Model	34,535	37.68	400.2	30.0	4.8	4.16	0.37	3.79	3.83	-0.04
Voyage 185S Full Load Accident Voyage Depart Jacksonville 9/29/2015	Departure (Jacksonville)	CargoMax	34,625	37.25	402.0	30.1	5.8	4.69	0.40	4.28	3.64	0.64
		MSC GHS Model	34,516	37.32	401.5	30.0	5.6	4.60	0.37	4.23	3.78	0.45
	Estimated at Loss of Propulsion (0600, 10/1/2015)	CargoMax	34,385	37.41	400.8	30.0	5.3	4.54	0.40	4.14	3.63	0.51
		MSC GHS Model	34,276	37.48	400.3	29.9	5.0	4.40	0.37	4.03	3.74	0.29

Table 5-1: Comparison of the calculated drafts, trim, free surface correction, GM corrected, GM required and GM margin for 8 benchmark loading conditions calculated manually from the T&S Books, using CargoMax, or using the MSC GHS analysis (as indicated). GM margin is the difference between GM corrected and GM required.

5.2.3.2. Righting Arm Criteria

As requested by the MBI, the intact stability of the EL FARO is also assessed in comparison to current criteria which would apply if she were constructed in 2016. If the EL FARO underwent a major conversion in 2016, she might also be required to comply with the current criteria, if it were deemed reasonable and practicable by the USCG.

Based on 46 CFR 170.165 and the ACP Supplement for ABS, since the EL FARO was issued an International Load Line Certificate, she would be required to comply with Part A of the 2008 IS Code. As discussed previously, Part A of the 2008 IS Code is the mandatory part which requires meeting two sets of criteria: (1) criteria regarding righting arm curve properties (Section 2.2 of Part A), and (2) severe wind and rolling criteria (Section 2.3 of Part A). The former is based on the Rahola criteria and is also incorporated in 46 CFR 170.173. The latter is a semi-empirical physics-based method applying an energy balance between beam wind heeling and righting moments, with roll motion also taken into account.

As discussed previously, GM is a good indicator of the initial stability for small angles of heel in response to small heeling forces and moments; however it is in general a poor indicator of overall stability, especially in response to large heeling forces and moments as might be experienced by a vessel in heavy weather where high winds and seas can be expected. The range of stability, maximum righting arm and angle, and area under the righting arm curve are the more important stability characteristics for heavy seas, and GM provides little or no insight into these characteristics. It is instructive to consider the general characteristics of the stability curve of the EL FARO prior to completing numerical assessment in comparison to the righting arm and energy criteria specified by the 2008 IS Code. Noting the previously discussed comparison of righting arm curves for a conventional cargo vessel and offshore supply vessel circa 1960s (Figure 5-3) provided by Mok and Hill [51], it is instructive to plot the righting arm curve for the EL FARO accident voyage departure condition along with these vessels, as shown in Figure 5-6. It is apparent that although the EL FARO had a GM larger than the conventional cargo vessel, the total righting energy available to resist capsizing (represented by the total area under the righting arm curve) is only a fraction of the conventional cargo vessel (16% in this illustration), and is even less than the offshore supply vessel. This is due to lower freeboards causing deck edge immersion at lower angles of heel compared to the conventional hull, resulting in lower range of stability and lower overall righting energy.

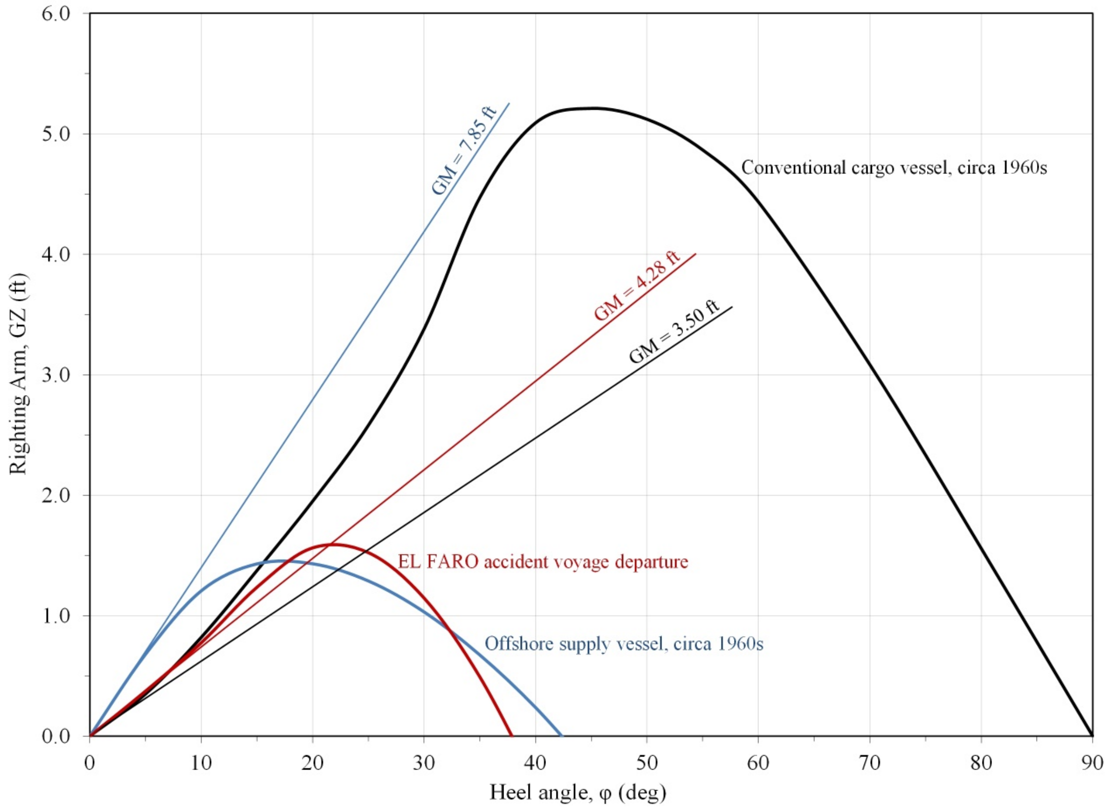

Figure 5-6: Comparison of righting arm curves for the EL FARO accident voyage departure condition with the conventional cargo vessel and offshore supply vessel from Figure 5-3.

The righting arm curves incorporated in Figure 5-3 and Figure 5-6 do not include consideration of the angles at which downflooding would occur for any of the vessels. Including downflooding angles would have the effect of truncating the righting arm curves for evaluation of the righting arm criteria. For the purposes of the evaluation of the intact stability criteria the term "downflooding" means (46 CFR 170.055) "the entry of seawater through any opening into the hull or superstructure of an undamaged vessel due to heel, trim or submergence of the vessel." The "downflooding angle" is "the static angle from the intersection of the vessel's centerline and the waterline in calm water to the first opening that cannot be closed weathertight and through which downflooding can occur." The last statement is of profound importance in the consideration and analysis of the sinking of the EL FARO, as the EL FARO had large open ventilation trunks leading to the cargo holds which would have submerged at angles of heel as low as 27 degrees in the accident voyage loading condition. However, from the definition, these ventilation openings, as they could potentially be closed by means of manually-closable fire dampers, would not have been considered as providing a means of "downflooding" and therefore would not need to be considered in evaluation of the stability criteria, even under the current criteria of the 2008 IS Code. This is in apparent conflict with 46 CFR 92.15-10 which requires that fire dampers remain open at all times in port and underway (except when combating a fire) to provide positive ventilation of the vehicles holds. This will be addressed in greater detail in discussion of the sinking of the EL FARO in Section 6 of this report.

To provide an assessment of the EL FARO intact stability against current standards (i.e. if she were to be built today), the eight benchmark conditions specified in Table 5-1 were evaluated against the mandatory criteria of Part A of the 2008 IS Code. For an initial comparison, Figure 5-7 provides the righting arm curves for the eight benchmark full load conditions, shown on one plot. Solid curves are the departure conditions and dashed curves are the arrival conditions (loss of propulsion for the accident voyage). One important observation is the reduced righting energy (area under the righting arm curve) and range of stability of the actual departure conditions 178S and 185S compared to the homogeneous full load departure conditions in the T&S Booklets. There are several reasons for this. T&S Booklet full load departure conditions were established to permit the full load arrival conditions (with 10% consumable tank loads) to meet minimum GM criteria with minimum GM margin. Consumable tank (fuel, lube and potable water) "burn-off" to the 10% level is significantly greater than what the EL FARO typically burned during the transit between Jacksonville and San Juan. Therefore, the differences between departure and arrival in the T&S Booklet cases are significantly greater than the differences for the actual voyages (here voyages 178S and 185S). As discussed previously and based upon MBI witness statements [18, 19, 31, 32], the EL FARO often departed Jacksonville loaded with cargo and consumables with GM margin around 0.5 feet in order to arrive in San Juan with GM margin around 0.25 feet. It may also be noted from Figure 5-7 that the range of stability (angle of vanishing stability) is significantly higher for both of the T&S Booklet values. This is due not only to the lower KG and increased GM at departure (reflected in the initial slope of the righting arm curves for the departure conditions) but also to the reduced drafts (increased freeboards) for the arrival condition with 10% consumables. The latter is illustrated by the reduction in draft at the LCF shown in Table 5-1 between the departure and arrival conditions for the T&S Booklet conditions.

For the righting arm curves shown in Figure 5-7, the 2008 IS Code righting arm criteria were applied, with results summarized in Table 5-2. Red (italics) indicates that the attained value does not meet the specific criteria and green indicates that the attained value meets the specific criteria. For the general righting arm criteria (Part A, Section 2.2), due to the relatively low range of stability, the actual operating conditions of voyage 178S and the accident voyage 185S do not meet criteria for minimum area between 30 and 40 degrees and minimum angle of maximum righting arm. All of the eight conditions meet the severe wind and rolling righting arm criteria (Part A, Section 2.3). This can be seen in greater detail in Figure 5-8, which illustrates the application of the criteria for the accident voyage (185S). In order for the EL FARO to have fully met the criteria of Part A of the 2008 IS Code at the full load draft, the minimum required GM would have been approximately 6.8 feet, which is 2.5 feet greater than the GM of the actual departure loading condition of the accident voyage.

It is noted that paragraph 2.2.3 of Part A of the 2008 IS Code provides that "alternate criteria based on an equivalent level of safety may be applied subject to the approval of the administration" if obtaining the required 25 degree angle for maximum righting arm is "not practicable." Thus there could be permitted a relaxation of the limiting criteria for minimum angle of maximum righting arm (25 degrees), if allowed by the USCG on a case-by-case basis. In such a case the minimum required GM could be less, and could also become limited by the damage stability criteria (see Section 5.3 of this report).

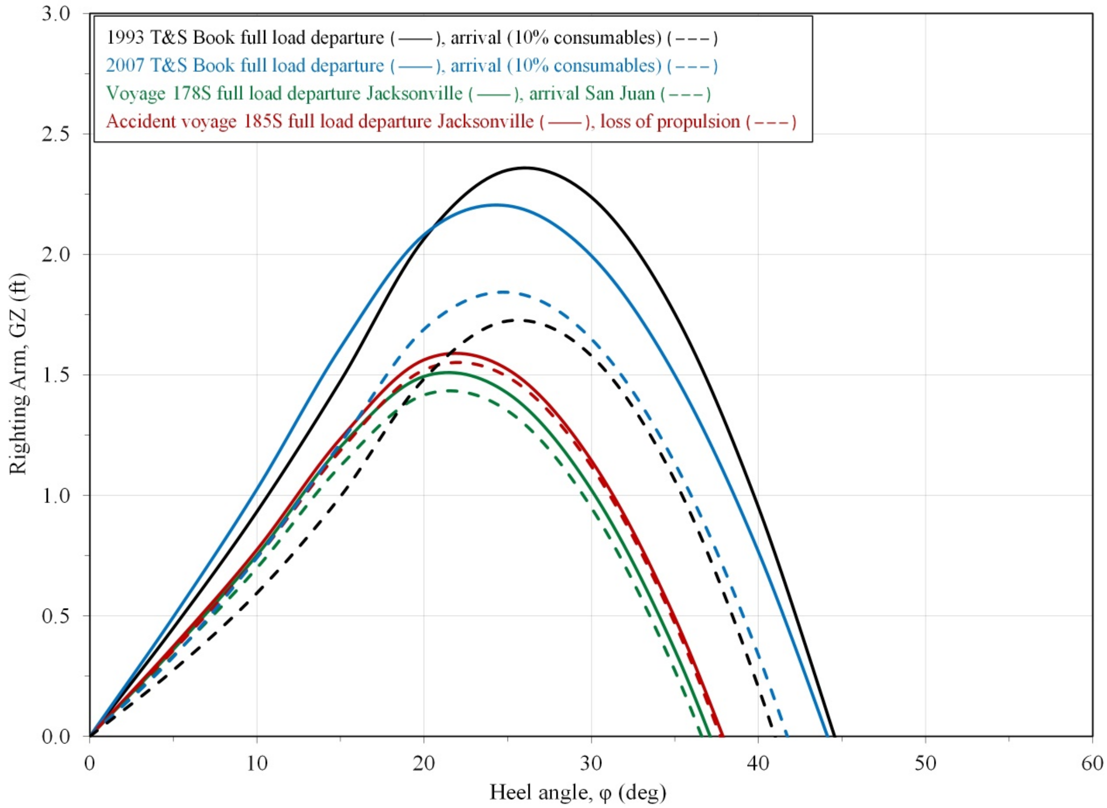

Figure 5-7: Righting arm curves for the eight benchmark full load conditions.

	Units	1993 T&S Book Full Load		2007 T&S Book Full Load		Voyage 178S Full Load Depart Jacksonville 8/11/2015		Voyage 185S Full Load Accident Voyage Depart Jacksonville 9/29/2015		Required Value
		Departure	Arrival (10% Cons.)	Departure	Arrival (10% Cons.)	Departure (Jacksonville)	Arrival (San Juan)	Departure (Jacksonville)	Estimated at Loss of Propulsion (0600, 10/1/2015)	
Part A Section 2.2 - Criteria regarding righting arm curve properties										
Area to 30 degrees	ft·deg	42.2	29.2	42.4	33.3	29.0	27.3	30.5	29.6	At least 10.3 ft·deg (0.055 m·rad)
Area to 40 degrees/downflooding	ft·deg	59.2	39.1	57.0	44.1	32.3	29.7	35.1	33.9	At least 16.9 ft·deg (0.09 m·rad)
Area between 30 and 40 degrees/downflooding	ft·deg	17.0	9.9	14.6	10.8	*3.2*	*2.4*	*4.6*	*4.3*	At least 5.6 ft·deg (0.03 m·rad)
Maximum righting arm at 30 degrees or greater	ft	2.24	1.58	1.99	1.65	1.00	0.95	1.15	1.12	At least 0.66 ft (0.2 m)
Angle of maximum righting arm	deg	26.1	25.5	*24.2*	*24.7*	*21.5*	*21.6*	*21.9*	*22.1*	At least 25 deg
Initial GM	ft	5.15	3.47	5.70	4.31	4.10	3.79	4.23	4.03	At least 0.49 ft (0.15 m)
Part A Section 2.3 - Severe wind and rolling criteria										
Steady wind heeling arm (l_{w1})	ft	0.300	0.308	0.305	0.326	0.288	0.292	0.286	0.289	NA
Angle of static heel (φ_0)	deg	3.3	5.9	3.1	4.9	4.0	4.4	3.8	4.1	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Roll angle to windward (φ_1)	deg	16.9	15.1	18.3	16.2	16.5	16.1	16.5	16.3	NA
Gust wind heeling arm (l_{w2})	ft	0.450	0.463	0.458	0.490	0.432	0.437	0.430	0.434	NA
Angle of 2nd intercept (φ_c)	deg	43.5	39.4	42.9	40.3	35.0	34.4	35.5	35.8	NA
Limit angle for area A_1 (φ_2)	deg	43.5	39.4	42.9	40.3	35.0	34.4	35.5	35.8	NA
Stored energy due to the roll angle to windward (Area A_2)	ft·deg	16.3	9.7	20.4	13.1	12.5	11.3	13.0	12.1	NA
Potential energy to resist capsizing to leeward (Area A_1)	ft·deg	47.3	25.2	44.2	29.8	19.6	17.4	22.1	21.0	NA
Area ratio (A_1/A_2)	ft·deg	2.9	2.6	2.2	2.3	1.6	1.5	1.7	1.7	Greater than 1

Table 5-2: Application of the 2008 IS Code criteria to the eight benchmark loading conditions. Red (italics) indicates that the attained value does not meet the specific criteria and green indicates that the attained value meets the specific criteria. The 2008 IS Code would be applicable if the EL FARO were constructed in 2016.

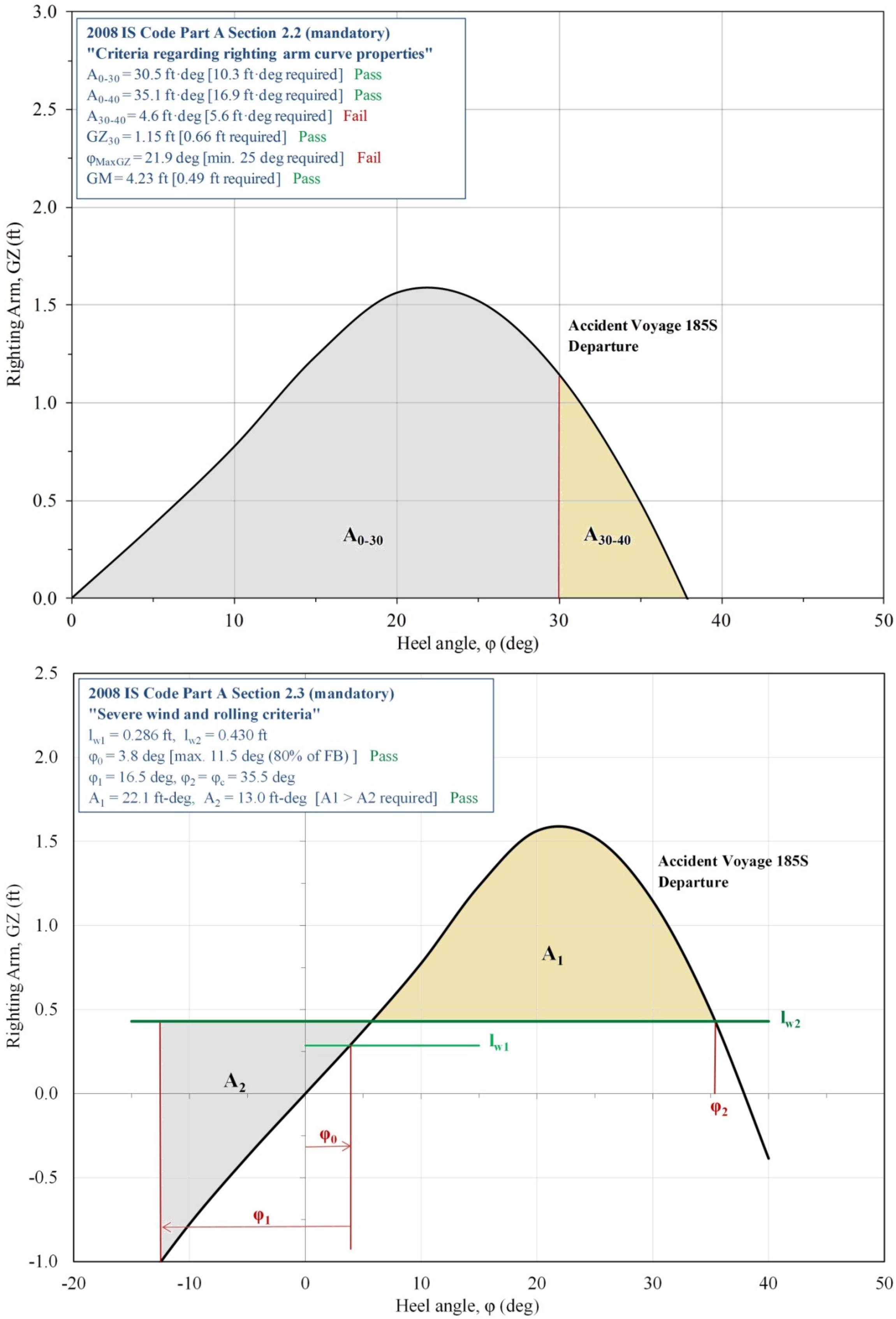

Figure 5-8: Application of 2008 IS Code righting arm criteria to the accident voyage (185S).

5.3. Damage Stability

5.3.1. Background

As stated previously, through proper design, loading and operation, a ship should possess enough reserve buoyancy and stability to ensure that with motion in heavy seas and even with some damage and limited flooding it will remain afloat and upright. Assessment of a vessel's ability to withstand limited damage and flooding is "damage stability." Requirements and regulations for ship subdivision and damage stability date back to the 1854 British Maritime Act, but recent subdivision and damage stability requirements have been primarily initiated through the International Convention for the Safety of Life at Sea (SOLAS) [55]. SOLAS conventions and amendments have been adopted internationally through IMO resolutions. Current SOLAS subdivision and stability standards applicable for dry cargo vessels including RO/RO vessels are implemented in the U.S. in 46 CFR Part 174 Subpart J.

5.3.2. Damage Stability Standards

Early damage stability standards generally consisted of single-compartment standards, which provided for maximum spacing of watertight transverse bulkheads in order to keep the ship sufficiently upright after breaching one of the main compartments [55]. One such standard was a requirement of vessels built under U.S. government subsidy or mortgage guarantee programs administered by the Maritime Administration (MARAD), the MARAD Damaged Stability Standard, also called MARAD Design Letter No. 3 [56]. Until 1992, there were no other damage stability standards applicable to dry cargo vessels such as RO/RO ships. The MARAD single-compartment standard is an example of a "deterministic" standard, in that it is based on specific damage scenarios, including specified extent and location of damage. In order to meet the standard, each damage case (single-compartment) was required to meet prescribed acceptable measures of survival, including limitations on equilibrium heel angle (15 degrees), margin line submergence, downflooding points, range of stability (20 degrees past equilibrium heel angle), GZ (4 inches), and GM (2 inches). Other "deterministic" standards were applicable to various types of vessels required surviving damage to 1, 2 or more compartments, with similar survivability measures [57].

In 1992 "probabilistic" damage stability standards became applicable to dry cargo ships over 100 meters, including RO/RO vessels, which were newly constructed or undergoing major conversions. These standards were incorporated into SOLAS 1990, Chapter II-1 Part B-1 (see [58]), with explanatory notes adopted by IMO Resolution A.684(17) [59]. These standards were subsequently modified and incorporated into SOLAS 2009 (see [60]), with explanatory notes adopted by IMO Resolution MSC.281(85) [61].

Damage survivability criteria based on probabilistic analysis are generally more complex from an application perspective, but are also generally considered to be superior for evaluating relative safety of ships exposed to damage [55]. The SOLAS probabilistic approach takes the probability of survival after a collision as a measure of a ship's safety in the damaged condition. Referring to [58], the measure of survivability is the "attained subdivision index" A. The "required subdivision index" R is a function of ship's length and determines the degree of subdivision to be provided, through the requirement that the attained index A must be no less than the required index R. The attained index A is calculated by the summation of the products of the probabilities that each compartment or group may be flooded and the probability of survival after flooding of each compartment or group. Written in equation form:

$$A = \sum p_i s_i \tag{5-5}$$

The subscript i represents each compartment or group of compartments, p_i accounts for the probability that only the i^{th} compartment or group of compartments may be flooded, and s_i accounts for the probability of survival after flooding the i^{th} compartment or group of compartments. Calculation of factors p_i is carried out based on formulae involving the vessel's geometry and extent of damage. Calculation of factors s_i is carried out based on formulae involving vessel loading and survivability criteria. It is noted that the s_i values must be weighted according to the draft considerations to average the contributions for the deepest subdivision load line draft and the partial load line draft (as defined by SOLAS 1990). This is equivalent to calculating a separate attained index A for each draft, and then taking the average (this is the way it is implemented in the GHS software as demonstrated in Appendix B). The formulae for p_i and s_i are based on damage statistics as described in the explanatory notes [59].

One important consideration is the specification of permeability values for each compartment. A significant change was implemented in SOLAS 2009 which prescribes permeability of RO/RO spaces differently than those in SOLAS 1990. For SOLAS 1990 (which was applicable in 2005-2006), the prescribed permeability for all dry cargo spaces (including RO/RO spaces) was 0.7. For SOLAS 2009, prescribed permeability values for RO/RO spaces are 0.9 for the deepest load line and partial load line drafts, and 0.95 for the light service draft. There are, however, additional differences in the calculations which make direct comparison between results of SOLAS 1990 and SOLAS 2009 more complicated. However, Tagg [62] discusses in some detail that, in general, for RO/RO cargo ships it has been accepted that the SOLAS 2009 regulations represent a higher standard, but notes that there seems no compelling need to address the safety level of existing ships considering the limited number of ships, the limited consequences, and the rate at which the older ships are being removed from the world fleet.

5.3.3. Damage Stability Assessment of the EL FARO

There is no evidence from the documentation available to the MBI if the EL FARO (originally named PUERTO RICO, then NORTHERN LIGHTS) was built under a MARAD government subsidy, or if the loan or mortgage obligation under the subsidy was still outstanding at the time of implementation of the MARAD Damaged Stability Standard (MARAD Design Letter No. 3) in 1983 [56]. If this were the case, then the EL FARO may have been required to meet the single-compartment damage standard specified in MARAD Design Letter No. 3. There is also no documentation available to the MBI indicating that the EL FARO or any of her sister vessels were evaluated against the MARAD Damaged Stability Standard. It is worth mentioning that, from initial construction until the 1992 lengthening, there were no regulatory damage stability requirements applicable to the EL FARO. It is also of interest to note that the sister vessel EL YUNQUE, which remained in service until 2016, was never subject to regulatory damage stability requirements.

Regardless of the requirements applicable prior to 1992, when the EL FARO underwent the major conversion in 1992-1993, she was required to meet the probabilistic damage stability standard of SOLAS 1990, Chapter II-1 Part B-1. During the lengthening conversion in 1992-1993, SOLAS probabilistic damage stability analyses were completed, reviewed and approved by ABS [63], which confirmed that the limiting stability criteria were the intact ("weather" criteria) for all loading conditions. Thus the minimum required GM curves reflected in the 1993 T&S Booklet [17] were based on the USCG intact stability requirement (46 CFR 170.170).

As discussed in Section 4.2 of this report, in MBI hearing testimony [38, 39, 40] it was noted that Herbert Engineering did not complete a damage stability analysis to confirm that after the 2005-2006 conversion the limiting criteria would remain the intact stability criteria for all loading conditions, and ABS had no records of a damage stability analysis being completed. This is important since the 2005-2006 conversion resulted in a 2-foot increase in the load line draft, and therefore the previous damage stability analysis completed in 1993 no longer applied. In his MBI hearing testimony, Mr. Thomas Gruber of ABS submitted results of his independent SOLAS probabilistic damage stability analysis performed in May 2016 [41], where he applied the damage stability standards of SOLAS 1990, Chapter II-1 Part B-1, which would have been applicable in 2005-2006. Mr. Gruber's analysis determined that for GM values of approximately 2.9 feet at both the load line and partial load line drafts (30.11 and 26.02 feet), the required subdivision index of 0.60 would be attained. This suggests that for most load conditions with 2 or more tiers of containers loaded, the limiting stability criteria would be the intact stability criteria as reflected in the T&S Booklet, but for some load conditions with less than 2 tiers of containers loaded, the limiting stability criteria could be the damage stability criteria, and this was not reflected on the minimum required GM curves of the T&S Booklet (see Figure 4-1).

As requested by the MBI, the MSC performed independent SOLAS probabilistic damage stability analyses using the MSC GHS computer model and GHS Version 15.00. Two analyses were completed:

(1) Applying the standards of SOLAS 1990, which would have been applicable following the 2005-2006 conversion

(2) Applying the standards of SOLAS 2009, which would be applicable if the EL FARO were constructed in 2016

Applying the SOLAS 1990 standards, analyses were run for both the deepest subdivision load line draft (30.11 feet) and the partial load line draft (26.02 feet), with the required subdivision index R calculated as 0.602. Attained indices for both drafts were averaged as discussed above, and KG was iterated until the averaged attained index A equaled the required subdivision index R. Both port and starboard damage cases were investigated, but the more limiting case was the port damage (due primarily to the port side ramps). Details of calculation results are provided in Appendix B of this report. The MSC analyses applying the SOLAS 1990 standards provided similar results to Mr. Gruber's analysis, but with a slightly higher minimum GM value of 3.3 feet necessary to achieve the required subdivision index of 0.602. This confirms that for most load conditions with more than 2 tiers of containers loaded, the limiting stability criteria would be the intact stability criteria as reflected in the T&S Booklet. However, for load conditions with 2 or fewer tiers of containers loaded, the limiting stability criteria could be the damage stability criteria, and this was not reflected on the minimum required GM curves of the T&S Booklet (see Figure 4-1). However, as pointed out in Section 4.2, for the full load departure condition of the accident voyage, the limiting stability criteria would have been the intact stability criteria, which was properly reflected in the T&S Booklet and incorporated in the CargoMax stability software, since the majority of the container stacks were 3 tiers.

It should be noted that the MSC calculations were performed using GHS Version 15.00 (released in January 2016), but Mr. Gruber's analysis was completed using GHS Version 8.30, which ABS would have used if they had conducted a review back in 2006 [41]. For comparison, MSC also ran the analysis using GHS Version 8.50, and calculated a minimum GM value of 3.1 feet, as compared to Mr. Gruber's calculated 2.9 feet. This small difference is considered reasonable given likely small differences in vessel models. Similarly, small differences were noted between the results obtained analyzing MSC's model using GHS Versions 15.00 and 8.50. These differences are likely indicative of small changes in the computational algorithms in the software between 2006 and 2016. See Table 5-3 for a complete comparison.

Applying the SOLAS 2009 standards, analyses were run for the deepest subdivision load line draft (30.11 feet), the partial load line draft (26.02 feet) and a light service draft (22.54 feet), with the required subdivision index R calculated as 0.674. The overall attained index was calculated as the weighted-average of the attained indices for the 3 drafts in accordance with the SOLAS 2009 standards (40% for the load line draft, 40% for the partial load draft, and 20% for the light load draft), and KG was iterated until the overall attained index A was equal to the required subdivision index R. In this case, applying the SOLAS 2009 standards, a minimum GM value of 5.8 feet would be necessary to achieve the required subdivision index of 0.674. Note that this minimum GM is greater than would be required for any loading condition based on the 46 CFR 170.170 intact stability criteria (see Figure 4-1).

The large increase in minimum (required) GM is due to the differences in the 1990 and 2009 SOLAS standards as discussed in Section 5.3.2. The most important difference is in the specified permeability for RO/RO cargo holds, increasing from 0.7 in the 1990 SOLAS standards to 0.9 and 0.95 in the 2009 SOLAS standards. This difference is an illustration of the increased level of safety provided by the 2009 SOLAS probabilistic standards discussed by Tagg [62].

A summary of the SOLAS probabilistic damage stability analyses results for the load line draft of 30.11 feet (applicable after the 2005-2006 conversion) are provided in Table 5-3 below. Note that the 2009 SOLAS standards would be applicable if the EL FARO were constructed in 2016.

Analysis	SOLAS Standard	GHS Version	Required index (R)	Required GM (feet)
ABS (Gruber) [41]	1990	8.30	0.600	2.9
MSC	1990	8.50	0.602	3.1
MSC	1990	15.00	0.602	3.3
MSC	2009	15.00	0.674	5.8

Table 5-3: SOLAS probabilistic damage stability analyses results for load line draft of 30.11 feet (applicable after the 2005-2006 conversion). Note that the SOLAS 2009 standard would be applicable if the EL FARO were constructed in 2016.

5.4. Summary

This section provided a primer on basic ship stability and comparison of the EL FARO's stability characteristics against the intact and damage stability criteria applicable to the EL FARO at the time of the casualty, and criteria which would apply if the vessel were constructed in 2016.

The MSC computer model was used to assess eight "benchmark" loading conditions defined by the MSC against intact stability criteria. The eight "benchmark" conditions included the full load departure and arrival conditions from the 1993 and 2007 T&S Booklets, a representative departure and arrival condition from August 2015 (voyage 178S), and the accident voyage (185S) departure condition and estimated condition at the time of loss of propulsion on October 1, 2015.

The eight "benchmark" loading conditions all met the applicable intact stability requirements of 46 CFR 170.170 (the GM "weather" criteria), which were applicable to the EL FARO at the time of the casualty. However, it is noted that the vessel was often operated very close to the maximum load line drafts, with minimal stability margin compared to the required GM, and little available freeboard and ballast capacity, leaving little flexibility for improving stability at sea if necessary due to heavy weather or flooding

If EL FARO were constructed in 2016, she would be required to meet the righting arm criteria of Sections 2.2 and 2.3 of Part A of the 2008 IS Code. Of the eight "benchmark" conditions, only the 1997 T&S Booklet loading conditions would meet the righting arm criteria of Section 2.2. The actual operating conditions of voyage 178S and the accident voyage 185S would not meet the criteria based on limited available area (righting energy) between 30 and 40 degrees and insufficient angle of maximum righting arm. All of the eight conditions would meet the severe wind and rolling righting arm criteria of Section 2.3. In order to fully meet the intact stability criteria of Part A of the 2008 IS Code at the full load draft, the minimum required GM would be approximately 6.8 feet, which is 2.5 feet greater than the GM of the actual departure loading condition of the accident voyage. It is noted that paragraph 2.2.3 of Part A of the 2008 IS Code provides that "alternate criteria based on an equivalent level of safety may be applied subject to the approval of the administration" if obtaining the required 25 degree angle for maximum righting arm is "not practicable." Thus there could be permitted a relaxation of the limiting criteria for minimum angle of maximum righting arm (25 degrees), if allowed by the USCG on a case-by-case basis. In such a case the minimum required GM could be less, and could also become limited by the damage stability criteria.

Despite the 2-foot increase in the load line draft resulting from the 2005-2006 conversion for carrying LO/LO containers, there was no damage stability assessment completed to verify that the EL FARO would remain limited by the intact stability criteria for all loading conditions. Damage stability assessments conducted using the applicable 1990 SOLAS probabilistic stability standards demonstrate that for load conditions with two or fewer tiers of containers, the limiting stability criteria could be the damage stability criteria instead of the intact stability criteria, and this was not reflected on the minimum required GM curves of the T&S Booklet. However, for the departure condition of the accident voyage, the limiting stability criteria was the intact stability criteria, which was properly reflected in the T&S Booklet and incorporated in the CargoMax stability software. If EL FARO were constructed in 2016, she would be required to meet the 2009 SOLAS probabilistic damage stability standards. In order to fully meet these 2009 SOLAS damage stability standards at the full load draft, the minimum required GM would be approximately 5.8 feet, which is 1.5 feet greater than the GM of the actual departure loading condition of the accident voyage.

The righting arm curves for the EL FARO are generally characterized by relatively small area (righting energy) and range of stability compared to conventional cargo vessels (see Figure 5-6). These characteristics are especially significant in consideration of limited residual righting arms and righting energy with the vessel subjected to heeling forces and moments as might be experienced in heavy weather where high winds and seas can be expected. These characteristics are significant in consideration of limited residual righting arms and righting energy when subjected to flooding.

6. Hydrostatic Sinking Analyses

6.1. Introduction

Hydrostatic sinking analyses are conducted using the MSC GHS computer model utilizing additional information provided by the MBI including estimated fuel burn-off at the time of the loss of propulsion, estimated sea state and wind conditions at the time of the loss of propulsion and sinking, details of potential downflooding and progressive flooding paths, and additional information gained through review of the VDR audio transcript [64].

The MSC analyses are based upon a first principles approach. The term "hydrostatics" is meant to limit the scope to consideration of quasi-static forces including effects of floodwater, wind, and waves. Through assessment of righting arms, including righting energy and range of stability considerations, the analyses are intended to provide some insight into characteristics of vessel dynamics and motions in a seaway. The analyses, however, do not consider true dynamics of vessel motion in a seaway, including important mass and mass moments of inertia, and synchronous roll, pitch and heave motions due to alignment of vessel natural periods or frequencies of motion with ocean wave periods or frequencies. In addition to consideration of transverse stability effects due to wind, waves and flood water, longitudinal stability effects are included accounting for vessel sinkage and trim.

6.2. Vessel Loading and Environmental Conditions

At the time of the loss of propulsion, at approximately 0610 on October 1, 2015 [64 (pp. 438-440)], approximately 240 LT of fuel would have been burned since departure from Jacksonville. This estimate is based upon review of the ship's noon reports and typical burn rates based on previous voyages. Also, based on records of previous voyages, the crew would have replenished the fuel oil (FO) settling (service) tank from tanks FO DB 3 IP and IS (port and starboard), most likely twice a day during the 0400-0800 and 1600-2000 watches. It is unknown if the engineers actually transferred fuel on the 0400-0800 watch on the morning of October 1st, but it is considered highly unlikely due to the events unfolding, including problems with lube oil and eventual loss of propulsion [64 (pg. 338)]. For this reason it has been assumed for these analyses, that of the estimated 240 LT of fuel burned, approximately 110 LT would have been transferred from DB 3 IP and IS (55 LT each), leaving 130 LT net burn-off from the FO settling tank. The loading condition at the time of the loss of propulsion was based on this estimate.

At the time and location of the loss of propulsion and sinking, the EL FARO was in close proximity to Hurricane Joaquin. The precise wind and sea-state conditions are not known, as the nearest weather data buoy was hundreds of miles away and the ship did not have a working anemometer [64 (pg. 397)]. However, Fidele et.al. [65] provide hindcast analyses and numerical simulations, from which wind and wave conditions at the time and location of the loss of propulsion and sinking can be estimated. Estimated wind and wave conditions are summarized in Table 6-1. These wind and wave estimates were averaged based on hourly statistics from the simulations. The "significant wave height" is defined as the statistical average of the highest 1/3 of the waves measured (simulated), with height being measured from peak to trough. The "dominant wave period" is the wave period corresponding to the maximum energy (peak of the wave spectrum), and is equal to either the swell period or wind-wave period.

Significant wave height (feet)	25-30
Dominant wave period (seconds)	10-11.5
Dominant wave direction	Northerly
Average wind speed (knots)	70-90
Dominant wind direction	Northerly

Table 6-1: Estimated wind and wave conditions based on hindcast analyses and numerical simulations by Fidele et.al. [65].

Wind and wave directions from the simulations are slightly different than those based on actual ship and storm track data provided in the NTSB Weather Group Factual Report [66], which suggests wind and waves were from the east or northeast during the final hours prior to sinking. This is illustrated in Figure 6-1 which shows the actual EL FARO track and Joaquin storm track over the morning hours on October 1, 2015 (as annotated). As can be seen on the graphic, prior to the loss of propulsion, the vessel was heading east-southeast, with winds generally off the port bow. Following the turn to port and loss of propulsion around 0600, until the sinking around 0740, the ship was drifting in a southwesterly direction. Based on hydrodynamic considerations, the ship would likely have been drifting during this time with beam to the wind and waves. Based on normal counter-clockwise storm rotation, it can be estimated that the winds were out of the northeast at 70-90 knots (sustained) between 0600 and 0740. This is consistent with the statement made by the Captain at 0710 on the VDR transcript [64 (pg. 477)].

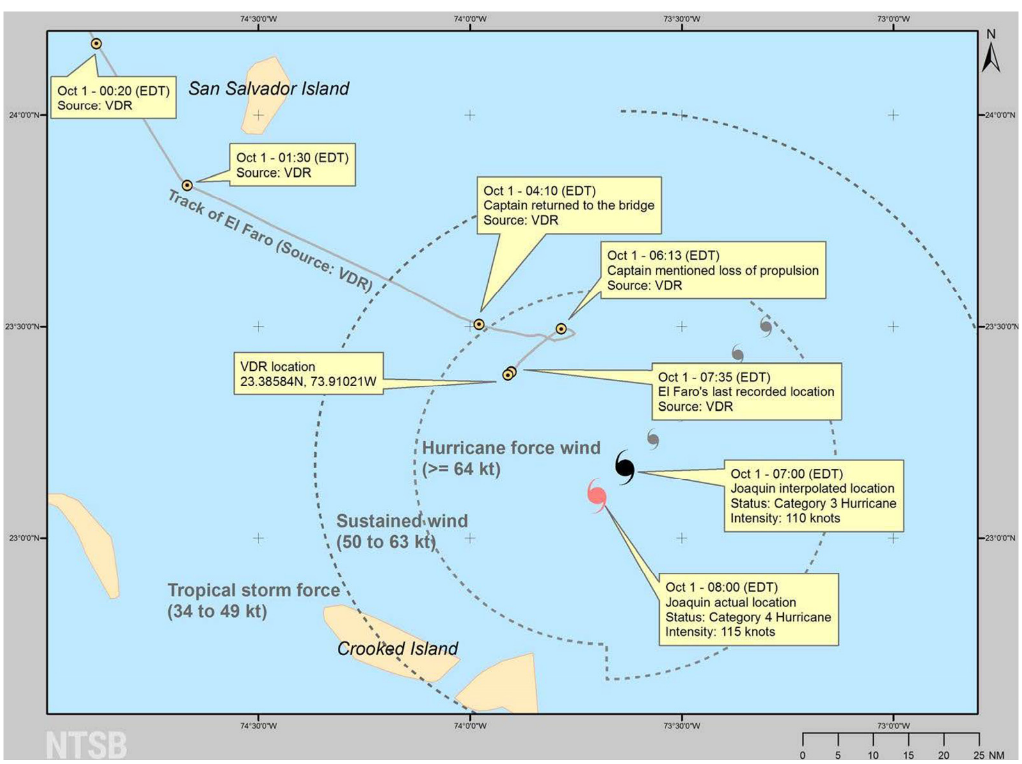

Figure 6-1: EL FARO track and Hurricane Joaquin storm track around the time of loss of propulsion and sinking. NTSB graphic.

6.3. Wind Heel

Early in the morning of October 1st the EL FARO crew discussed a noticeable list (heel angle) to starboard [64]. The crew initially believed the starboard heel to be wind-driven, being caused by the relative wind direction off the port beam as the ship headed southeast. After the turn to port and loss of propulsion around 0600, EL FARO maintained a heel to port, with wind off the starboard beam as she drifted to the southwest, as shown in Figure 6-1.

The exact magnitude of the heel during the early morning hours prior to 0518 [64 (pg. 406)] was not stated clearly in the audio transcript, but one statement which may have sounded like "eighteen degrees" was made (although the transcript notation makes this statement uncertain). It was not until the Captain prepared to call ashore that the first clear statement of a "fifteen degree list" (heel angle) was discussed at 0710 [64 (pg. 478)]. Unfortunately, nowhere in the audio transcript was the heel angle clarified further beyond this estimate and nowhere was any statement made as to the angles of dynamic roll the ship had been experiencing through the morning hours. It can only be interpreted by the Captain's statement that the ship was experiencing a mean heel angle of about 15 degrees but was also rolling about this mean heel angle due to wave action.

The force of wind acting on the above-water surface area of a hull and any exposed structure including superstructure and above-deck cargo produces a heeling moment tending to heel the vessel from its upright equilibrium. For a steady wind (or prolonged gust) in calm water, a ship will achieve an equilibrium heel angle when the wind heeling moment is balanced by the righting moment. As discussed in Section 5 of this report, the wind heeling moment is fundamentally calculated by multiplying the wind pressure (P) with the projected lateral area of the vessel (including deck cargo) above the waterline (A) and the vertical distance from the center of the lateral area above the waterline to the center of the underwater lateral area (H). For assessment of intact stability criteria the wind pressure is prescribed based on statistical analysis of vessel casualty data as discussed in Section 5 of this report. More generally however from fluid mechanics a wind pressure is calculated from wind velocity using

$$P = C\frac{1}{2}\rho V^2 \tag{6-1}$$

where C is a dimensionless drag coefficient, ρ is the density of air and V is the wind velocity. A common calculation of P in U.S. units is based on a combined coefficient using

$$P = 0.0035\,V^2 \tag{6-2}$$

with V in knots and P in lb/ft^2. A combined coefficient 0.004 has more commonly been used based on U.S. Navy criteria, but the slightly lower value of 0.0035 based on experimental model testing on different ship types and superstructure forms is also commonly used [47].

The desired expression for wind heeling moment (HM) as a function of heel angle φ is developed by considering that the effective area subject to the wind (A) and the vertical distance

(H) are both reduced approximately with the cosine of the heel angle (cos φ), and therefore the heeling moment is

$$HM(\varphi) = PAH\cos^2\varphi \tag{6-3}$$

Dividing the heeling moment by the displacement gives the desired expression for the heeling arm (HA). Combining, an expression in U.S. units is

$$HA(\varphi) = \frac{0.0035\, V^2 AH}{2240\,\Delta} cos^2\varphi \tag{6-4}$$

with V in knots, A in ft^2, H in ft, Δ in LT, and HA in ft.

For a steady wind (or prolonged gust) in calm water the ship would reach an equilibrium angle where the wind heeling moment (heeling arm) is balanced by the righting moment (righting arm). The residual righting arms are then calculated by simple subtraction of the heeling arms from the righting arms at each angle φ. The residual righting energy as the vessel is heeled by the wind (i.e. the reduced energy available to resist capsizing) is the area under the residual righting arm curve. This is shown graphically in Figure 6-2, which uses the EL FARO accident voyage condition at loss of propulsion, with 80 knot beam wind. Note that this condition does not consider the effects of flooding or cargo shifting, which will be addressed subsequently.

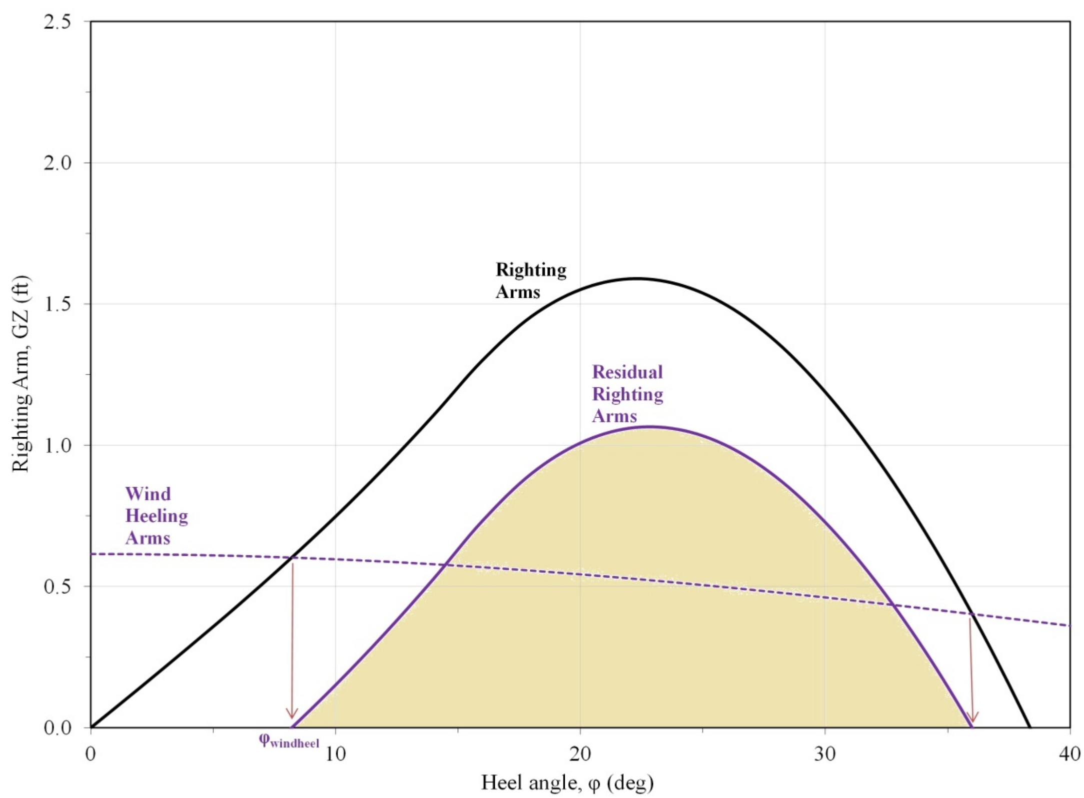

Figure 6-2: Effect of wind heeling arms on the righting arms, shown for the accident voyage condition at the time of loss of propulsion, with 80 knot beam wind (not including effects of flooding or cargo shifting). Starboard heel is shown.

Figure 6-3 provides a graphical illustration of the effects of various beam wind velocities (from 40 to 120 knots) on the righting arm curve for the accident voyage condition at the time of loss of propulsion (not including effects of flooding or cargo shifting). From the plots and based on the estimated wind conditions at the time of the loss of propulsion from 70-90 knots, it can be estimated that a wind heel angle of 7-11 degrees could be attributable to the steady beam wind alone. This does not include dynamic roll effects, as the ship would roll about the wind heel angle due to wave-driven roll motions. This also does not include the effects of flooding including the important free surface effects, as will be addressed subsequently.

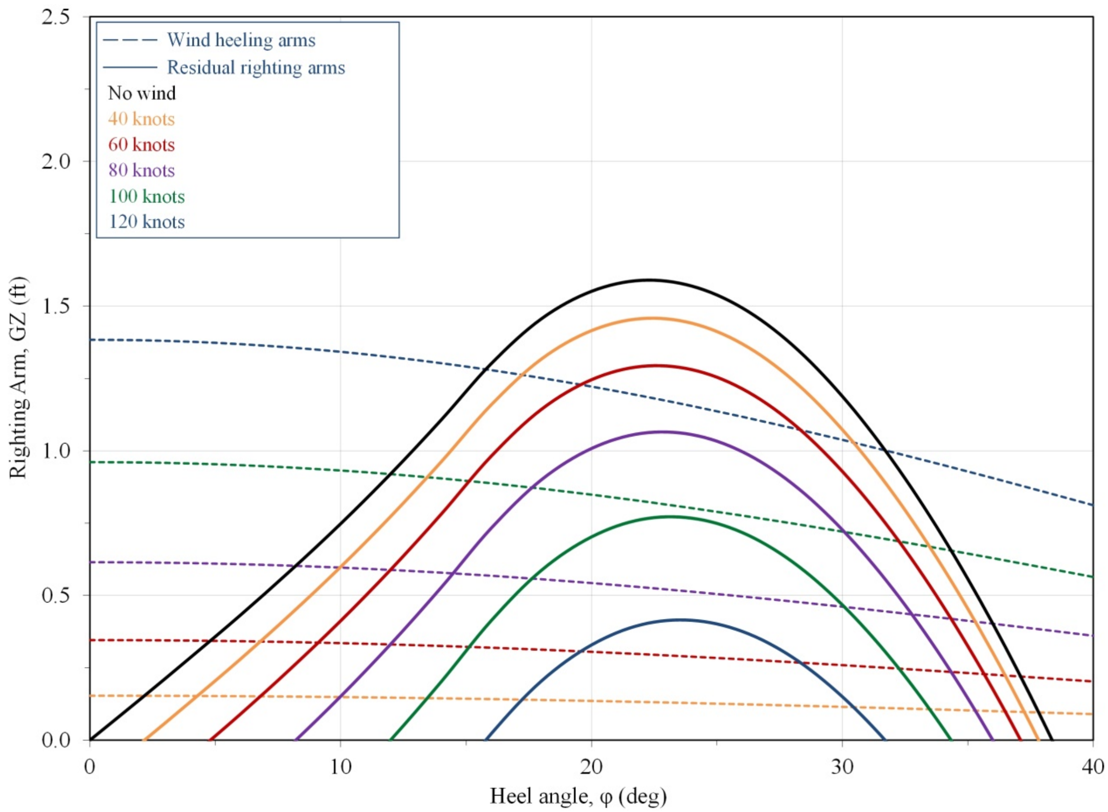

Figure 6-3: Heeling arms for beam winds from 40 to 120 knots (dashed curves) and residual righting arms (solid curves) for the accident voyage condition at the time of loss of propulsion (not including the effects of flooding or cargo shifting). Starboard heel is shown.

6.4. Flooding

6.4.1. General Effects of Flooding

From a hydrostatics, stability and trim perspective, flooding results in three primary effects. First, floodwater adds weight to the ship. The added weight increases the draft and may also cause the vessel to trim, depending on the location of the floodwater relative to the longitudinal center of flotation (LCF). If a flooded compartment is not symmetric about the centerline of the ship, the weight of the floodwater may also cause the vessel to heel. Of course, if sufficient floodwater is added to the ship to submerge additional openings in the hull, then the vessel can progressively flood and founder or sink. From a stability perspective, being below or at the external waterline (once equalized with the sea), the weight of floodwater is low and therefore generally lowers the center of gravity of the ship (VCG) and therefore increases GM and correspondingly increases righting arms (GZ). Thus one effect of flooding is a stabilizing effect.

Second, as floodwater in compartments usually involves free surface, which is free to move as the vessel rolls and pitches (heels and trims) unless water completely floods a compartment to the overhead, there is an additional horizontal and vertical shift in the ship's center of gravity, and this is detrimental to the stability of the vessel. Specifically, the effect of the free surface is a resulting horizontal and vertical shift of the center of gravity due to the shifting of the weight of the "wedge" of liquid on the free surface, as illustrated in Figure 6-4. This resulting shifting of the ship's center of gravity (G_0G) reduces the righting arms and has the equivalent effect on the righting arms (GZ) as a virtual rise in the center of gravity (G_0G_v). This virtual rise in the ship's center of gravity is the same as the "free surface correction" (FSC) applied to GM for intact stability analysis. Free surface is always detrimental to the stability of the vessel. The horizontal component of the weight shift also results in an increase in angle of heel or trim. For flooded compartments with large free surface areas, especially those with full-beam widths such as cargo holds, the free surface effect can be significant. The free surface effect is also important for tanks carrying liquids which are neither empty nor full, and is included in the "free surface correction" discussed in previous sections of this report. A more thorough discussion of free surface effects is provided by Moore [47]. Note that as the liquid level in a compartment or tank is raised toward the overhead, the free surface effect is significantly reduced (and eventually eliminated as the compartment or tank is completely filled). This reduction in the free surface effect as the liquid level approaches the compartment or tank overhead is known as "pocketing," and is important for many conditions of flooding.

A third effect of floodwater arises if a flooded compartment is not symmetric about the centerline plane of the ship and the compartment is open to the sea (for example through a side-shell or bottom hull breach), then water is able to freely communicate with the sea, and this exacerbates the free surface effect. In the case of the EL FARO, this "free communication effect" would not have existed for flooding of the cargo holds since the cargo holds were symmetric about the ship's centerline.

The rate of flooding through an opening of a given size and shape can be estimated through calculation using principles of fluid dynamics. Calculation can be carried out for flow through an "orifice", derived from the steady form of Bernoulli's equation (see for example [67]). The pressure or head driving the flow is due to the external water pressure above the opening, and the volumetric flow rate Q (ft^3/s) can be calculated from the standard equation for flow through a "sharp-edged orifice":

$$Q = C_D A_0 \sqrt{2gH_E} \qquad (6\text{-}5)$$

where A_0 is the area of the opening (ft^2), C_D is a dimensionless coefficient of discharge which depends primarily on the geometry of the opening (approximately 0.6 for flow through a sharp-edged opening), g is the acceleration due to gravity (32.2 ft/s^2), and H_E is the external hydrostatic water head (height) above the opening (ft). Figure 6-5 illustrates the geometry of the flow.

As a simple example, for a small opening of area 1 ft^2 located 1 ft below the external waterline, the calculated flow rate (Q) is approximately 4.8 ft^3/s, which is equivalent to 36 gal/s or 2,160 gal/min. Noting that the bilge pumping system on EL FARO had a capacity less than 1,000 gal/min, the bilge pumping system would be ineffective at keeping up with flooding through even a small opening just below the waterline.

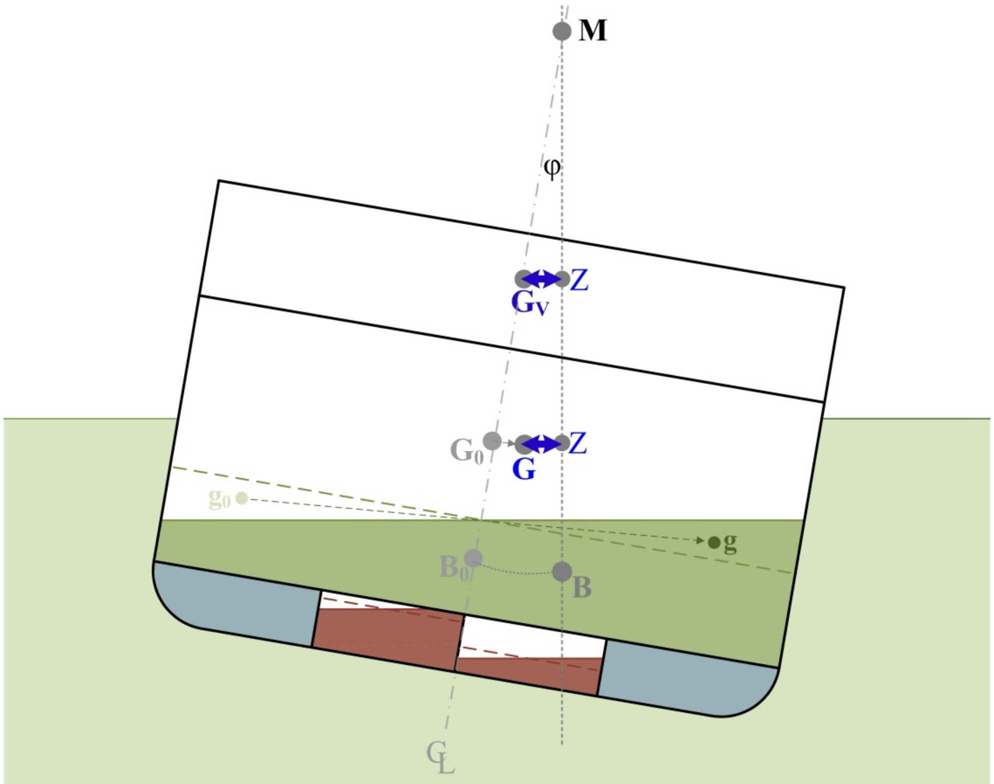

Figure 6-4: Flooding and free surface effect. Shifting of the ship's center of gravity (G_0G) has the equivalent effect on the righting arms (GZ) as a virtual rise in the center of gravity (G_0G_v).

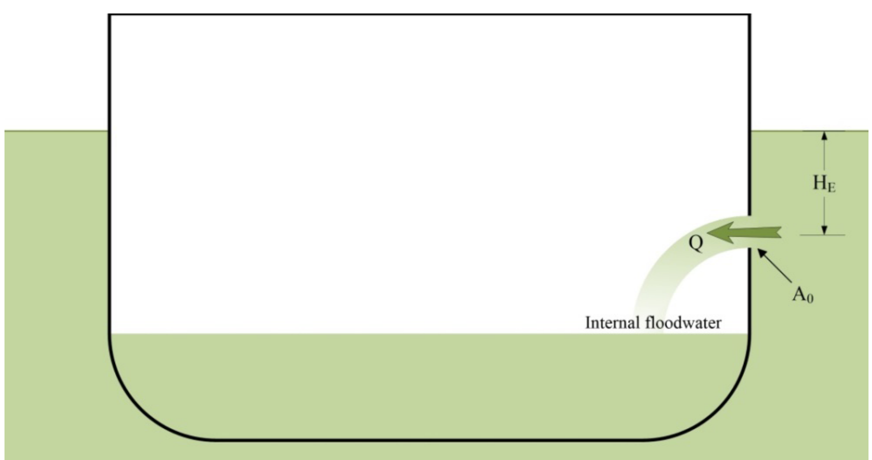

Figure 6-5: Geometry and nomenclature for the Bernoulli's equation for orifice fluid flow for calculation of flooding rate.

6.4.2. Potential Sources of Flooding

Based on the VDR audio transcript, it was not until 0543 [64 (pg. 414)] that first mention was made by the EL FARO crew that the ship might be taking on water into a cargo hold (Hold 3). Upon investigation by the Chief Mate, the initial assessment was that the source of flooding into Hold 3 was through the improperly secured personnel access scuttle on the starboard side of the 2nd deck, located at frame 163 (see Figure 6-6). This scuttle was subsequently secured, but the water level continued to rise in Hold 3 throughout the morning, indicating that there was another source or multiple sources of flooding.

During the final hour the crew attempted to identify potential sources of additional water ingress into cargo Hold 3. Based on a statement by the Chief Mate [64 (pg. 482)], the Chief Engineer identified the potential for flooding from the emergency fire pump piping, which was located on the 4th deck (tanktop, innerbottom) in the aft starboard corner of Hold 3 (see Figure 6-7). It was speculated that it may have been damaged by floating automobiles which had broken free in the lower hold. Although no visual identification of this potential source of flooding was made, the crew discussed potential methods of isolating the emergency fire pump piping from the engine room. There was no discussion on the audio transcript of closing the sea chest isolation valve with the hand-wheel remote operator from the 2nd deck starboard side (see Figure 6-6 and Figure 6-7).

Figure 6-6: Hold 3 (also called Hold D) starboard personnel access scuttle on the 2nd deck at frame 163. Note that the scuttle opening is 12 inches above the deck. The hand-wheel remote operator for the emergency fire pump sea-chest isolation valve is also shown. Screen capture from video taken aboard EL FARO September 2008 provided by Tote Inc.

Although there is no evidence suggesting a hull fracture or hull damage which may have caused additional flooding, there remains the unlikely possibility that some unspecified hull damage may have occurred and contributed to the continued flooding of Hold 3. There was no specific discussion of hull failure on the VDR audio transcript (other than an apparent misstatement by the Captain when trying to contact his shore-based support, where he referred to a "hull breach" but then quickly corrected by stating "…a scuttle blew open during a storm" [64 (pg. 474)]). Based on review of the underwater video from the Navy Remotely Operated Vehicle (ROV), the MSC noted that the bottom of the hull is immersed in the sediment and cannot be seen in entirety, but based on what can be seen, there appears to be no visual evidence of structural damage in the amidships region of the hull. Given that the vessel was loaded in a "hogging" condition (see Section 4.3 of this report), any significant hull girder structural failure would likely have resulted in compressive buckling of the bottom plating and/or tensile fracture of the upper decks. For significant bottom plate buckling of the hull, there would likely have been some visual evidence including buckling creasing of the lower side shell above the sediment. There was no evidence of buckling creasing of the side shell or tensile fracture of the upper decks on the underwater video.

Figure 6-7: Emergency fire pump station in Hold 3, aft starboard 4th deck (tanktop, innerbottom), showing the sea chest, isolation valve, and manual remote operator on sister vessel EL YUNQUE (EL FARO similar but not identical). Inset photo shows part of the arrangement onboard EL FARO. USCG photo with Tote, Inc. photo inset.

A potential source of continued and progressive flooding was through the cargo hold ventilation system. This potential source might have been mentioned by a crew member at 0600 [64 (Pg. 428)], but it is not clear from the audio transcript if the crew recognized the potential for flooding through the ventilation system or if they ever gave any consideration to trying to limit flooding by shutting the fire dampers.

The cargo hold ventilation system consists of ventilation supply trunks with integrated supply fans and fire dampers and ducting, and ventilation exhaust trunks with integrated fire dampers and ducting. The supply and exhaust trunks for Holds 2, 2A and 3 were all similar in configuration and differed primarily in internal details and height due to the sheer of the 2nd deck, with the Hold 3 openings being the lowest and closest to the waterline due to deck sheer and vessel trim aft. Figure 6-8 shows a photograph of the EL FARO port side, highlighting the ventilation supply and exhaust hull openings for Hold 3.

Scaled drawings of sections at frames 143 and 159 showing the supply and aft exhaust arrangements are provided in Figure 6-9. The section at frame 143 shows the Hold 3 ventilation supply arrangement. The supply arrangement includes an external hull blister with side shell louvered openings, baffle plates, bellmouth, supply fan, fire damper and supply plenum. The louvered openings are forward and aft of the bellmouth, separated by the vertical baffle plates. The section at frame 159 shows the Hold 3 aft exhaust arrangement. The exhaust arrangement includes an intake plenum, a fire damper, and an exhaust trunk with a 12-ft high baffle plate and side shell louvered opening. The louvered opening is forward of the fire damper trunk, separated by the vertical baffle plate. Based on the system design, the baffle plates were intended to provide a vertical boundary to limit water from entering the cargo hold through the fire dampers. For the accident voyage, the tops of the baffle plates were approximately 25 feet above the still waterline, and they would submerge at an angle of heel of approximately 27-29 degrees.

Figure 6-8: EL FARO port side showing ventilation supply and exhaust louvered hull openings. The openings for Hold 3 are highlighted. Photo copyright Will Van Dorp, used with permission.

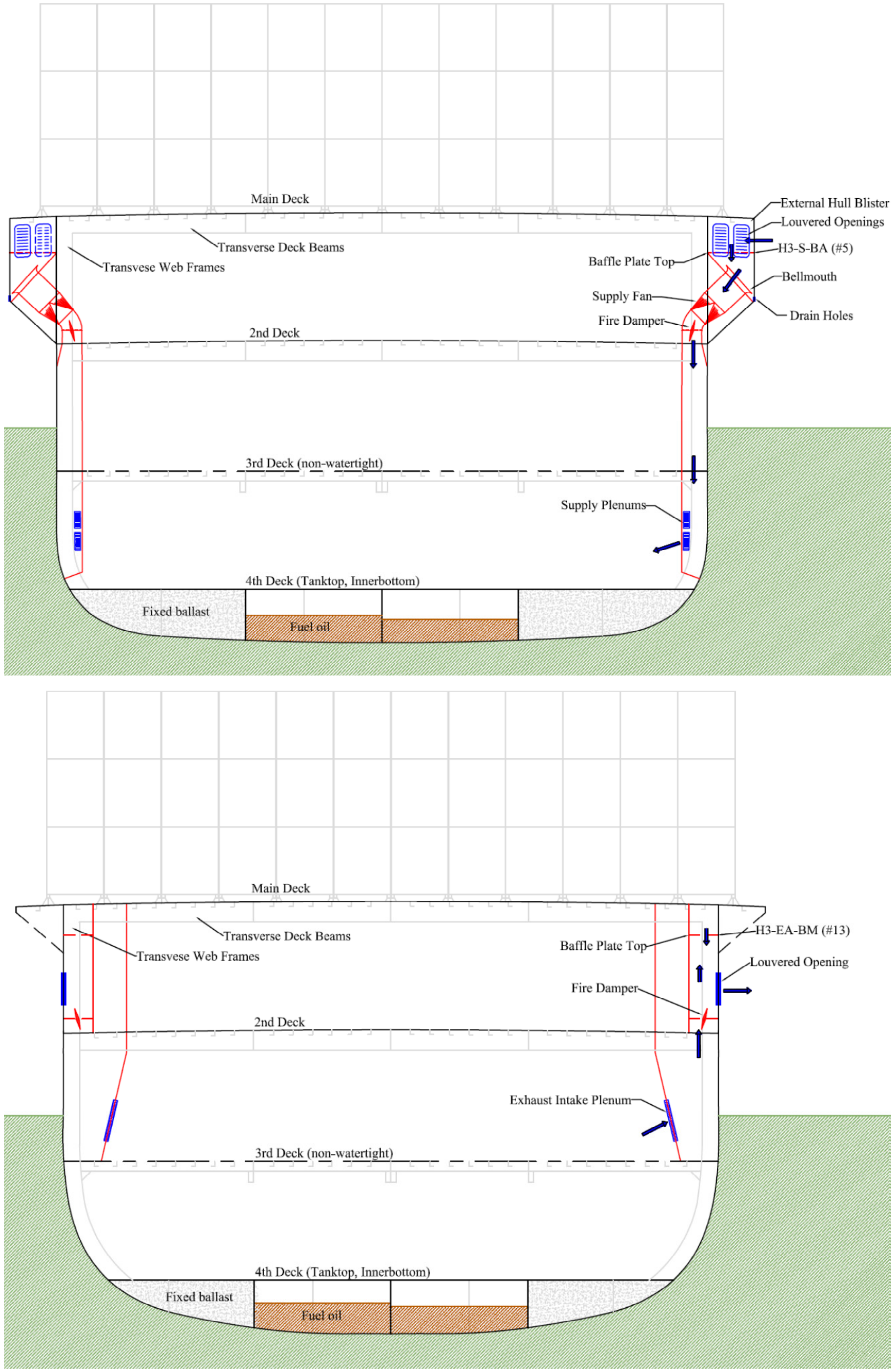

Figure 6-9: Sections at frames 143 (top) and 159 (bottom) showing Hold 3 ventilation supply and exhaust arrangements, respectively. Normal air supply and exhaust paths are shown.

Figure 6-10 through Figure 6-14 provide a series of photographs showing important components of the cargo hold ventilation system which illustrate the vulnerability of flooding through the ventilation supply and exhaust openings on the EL FARO. The ventilation system could be secured in the case of fire by manually closing the fire dampers. Otherwise the fire dampers were required to remain open at all times in port and at sea to provide positive ventilation of the vehicles holds, as required in 46 CFR 92.15-10. Based on MBI hearing testimony [19, 20, 32], crews did not close the fire dampers at sea for heavy weather. There was also no shipboard documentation in the form of a damage control plan or emergency plan which might recommend securing of the fire dampers in the case of extremely high seas to prevent flooding of the cargo holds.

Figure 6-10: Starboard ventilation louvered hull openings for Hold 3 ventilation supply and aft exhaust. Note that red paint delineates the load line (approximate full load waterline). Photo of sister vessel EL YUNQUE. USCG photo.

Figure 6-11: Hold 3 aft ventilation exhaust trunk with racking bulkhead, frames 159-162 starboard, 2nd deck. Screen capture from video taken September 2008 provided by Tote, Inc.

Figure 6-12: Hold 3 ventilation supply fan and fire damper enclosure, frames 141-144 starboard, 2nd deck. Screen capture from video taken September 2008 provided by Tote, Inc.

Figure 6-13: Ventilation supply plenums inside Hold 3, frames 141-144 port, 4th deck (tanktop, innerbottom). Photo of sister vessel EL YUNQUE. USCG photo.

Figure 6-14: Ventilation exhaust intake plenum inside Hold 3, frames 159-162 starboard, 3rd deck. Hold 3 starboard scuttle personnel access ladder and remote operator rod for the emergency fire pump suction valve (sea-chest isolation) are shown on the right. Photo of sister vessel EL YUNQUE. USCG photo.

The flooding vulnerability presented by the cargo hold ventilation system openings will be demonstrated in the subsequent analyses. To support this, various critical points (potential downflooding points) are added to the MSC GHS computer model in order to track the locations of the points relative to the still waterline, and also for annotation of righting arm curves. Table 6-2 provides specific critical points added to the MSC GHS computer model. Downflooding points were determined from the ventilation arrangement drawings [68, 69]. For the accident voyage, with the vessel at the draft and aft trim at the time of loss of propulsion, the top of the baffle plates for Hold 3 ventilation supply would submerge at an angle of heel approximately 27 degrees, and the top of the baffle plates for Hold 3 ventilation exhaust would submerge at an angle of heel of approximately 29 degrees. The significance of these downflooding points will be discussed in Section 6.6.

Critical Point Name	Short Name	Number	Longitudinal (ft-FP)	Transverse (ft-CL)	Vertical (ft-BL)
Hold 3 Access Scuttle Stbd (Coaming)	H3-SC-S	1	512.2	44.0	43.1
Downflooding Points					
Hold 1 Vent Supply (Bellmouth)	H1-S-BM	2	151.9	33.1	61.0
Hold 2 Vent Supply (Baffle)	H2-S-BA	3	274.3	47.7	55.9
Hold 2A Vent Supply (Baffle)	H2A-S-BA	4	373.3	49.0	55.2
Hold 3 Vent Supply (Baffle)	H3-S-BA	5	455.8	49.0	55.2
Hold 1 Vent Exhaust Fwd (Louver)	H1-EF-L	6	102.4	25.5	64.6
Hold 1 Vent Exhaust Aft (Louver)	H1-EA-L	7	193.2	35.5	61.5
Hold 2 Vent Exhaust Fwd (Baffle)	H2-EF-BA	8	228.9	45.2	58.6
Hold 2 Vent Exhaust Aft (Baffle)	H2-EA-BA	9	311.4	45.5	56.5
Hold 2A Vent Exhaust Fwd (Baffle)	H2A-EF-BA	10	341.7	45.7	55.9
Hold 2A Vent Exhaust Aft (Baffle)	H2A-EA-BA	11	402.2	45.8	55.9
Hold 3 Vent Exhaust Fwd (Baffle)	H3-EF-BA	12	435.2	46.0	55.9
Hold 3 Vent Exhaust Aft (Baffle)	H3-EA-BA	13	501.2	46.0	55.9

Table 6-2: Critical points (potential downflooding points) for the forward cargo holds added to the MSC GHS computer model.

6.4.3. Cargo Hold Permeability and Free Surface Pocketing Effects

An important consideration when assessing the effects of flooding is the effect of compartment permeability. This is the same effect which applies to tank volumes and free surface calculations discussed in Sections 2 and 4 of this report. Permeability is accounted for with a simple “permeability factor”, which mathematically accounts for the fraction of a compartment or tank that can be filled with liquid, accounting for such things as internal structure, piping, machinery, and any other internal components including cargo. The permeability factor therefore proportionally reduces the floodable volume (and floodwater weight) and also proportionally reduces the free surface effect. This is especially important in the case of cargo holds, where a large fraction of a compartment’s volume can be taken up with cargo. In the case of the trailered containers and automobiles carried below decks on EL FARO, permeability should be considered widely variable in both overall fraction and uniformity through the cargo hold volumes. This is especially important with containers, which depend on the assumed watertight integrity of the containers, and their specific locations in the cargo holds. Uncertainty in estimated permeability factors can lead to significant uncertainty in the calculated results. It is therefore appropriate to consider a range of estimated values of permeability in the calculations and assess the variability in the results.

In the case of EL FARO on the accident voyage, below-deck cargo holds separated by watertight bulkheads (Holds 1, 2, 2A and 3) were loaded with a combination of automobiles, trailered containers, miscellaneous trucks and other trailered cargo, and fructose tanks [70]. In Hold 3 (also called Hold D in some of the loading documents), the 4th deck (tanktop, innerbottom) was loaded with 50 automobiles, and the 3rd deck was loaded with 15 trailered containers of 40 and 45 foot lengths. With typical automobile sizes and the deck height of the lower hold (Hold 4D) of 16.5 feet, it can be estimated that the lower hold loaded with 50 automobiles would have an overall effective permeability factor of 0.8-0.9, with a much lower value in the range of 0.6-0.7 up to the top of the automobiles and a much higher value of approximately 0.95 from the top of the automobiles to the top of the lower hold (the 3rd deck). With typical trailered container heights with chassis and deck height of the upper hold (Hold 3D) of 18.5 feet, it can be estimated that the upper hold would have an overall effective permeability factor of 0.6-0.7 if the containers are initially considered watertight, with a higher value of approximately 0.7-0.8 as the containers flood if submerged over time. Hold 2A (also called Hold C) was loaded with a similar distribution of automobiles in the lower hold (Hold 4C) and trailered containers in the upper hold (Hold 3C). Hold 2 (also called Hold B) was loaded with a combination of automobiles, trailers and fructose tanks in the lower hold (Hold 4B) and a combination of automobiles and trailers in the upper hold (Hold 3B). Hold 1 (also called Hold A) contained only fructose tanks in the lower hold (Hold 4A) and trucks and trailers in the upper hold (Hold 3A).

For these flooding analyses and assessments, a range of permeability values of 0.7-0.9 are used for illustration of the variability of results. Where there are significant impacts of permeability factor variability, the effects are discussed in detail. This is especially important for initial flooding (10-20% in the cargo holds), as the lower holds 4C and 4D were filled with automobiles, reducing the initial effective permeability.

It should be noted that this type of flooding analysis is different than the damage stability analysis performed in accordance with SOLAS requirements (refer to Section 5 of this report), where permeability factors are specified based on vessel and cargo type. Based on current SOLAS regulations [60], summer load line (full load) draft permeability factors for RO/RO spaces with containers on wheels (trailers) are prescribed as 0.9; however in earlier versions of SOLAS regulations [58], a general permeability factor for dry cargo spaces was prescribed as 0.7. This analysis incorporates this range of values.

In addition to variability of results due to variability in compartment permeability, the free surface effect is also reduced due to the effective pocketing of the floodwater in the lower cargo holds. The term “pocketing” is used to describe the reduction in free surface effect due to interaction of the free surface with the overhead of the compartment or tank. This is important for the lower cargo holds because the 3rd deck, while essentially non-watertight (see Figure 6-9 and Figure 6-15 below), contains relatively small deck plate openings which would limit the rate of flow of water through the deck as the vessel rolls in the seaway. From a pure hydrostatics perspective the deck is considered non-watertight and the internal floodwater level would eventually equalize and rise above the deck for a given angle of heel, but due to the dynamic nature of the ship's roll motion, water would experience a partial dynamic "pocketing" effect, and therefore free surface effect would be significantly reduced in the lower cargo holds. This is illustrated in Figure 6-18 below.

Figure 6-15: Hold 3, 3rd deck, showing non-watertight openings. Photo of sister vessel EL YUNQUE. USCG photo.

6.4.4. Flooding of Hold 3

Flooding of Hold 3 would have several important effects. There would be an increase in drafts and a corresponding decrease in freeboard. Since the center of Hold 3 is aft of the LCF, aft trim would increase (i.e. aft draft would increase slightly more than forward draft). As a result of the overall reduction in freeboard and trim aft, the ventilation openings identified as potential downflooding points in Table 6-2 would move closer to the waterline. Concurrently, wind heel and roll motion due to encounter with the waves, especially after loss of propulsion when the ship would have drifted with beam to the wind and seas, would bring the ventilation openings to intermittent submergence, which would result in intermittent flooding. As Hold 3 continued to flood in this manner, eventually the ventilation openings for Hold 2A would likewise be brought to intermittent submergence as their freeboards would be reduced due to the flooding of Hold 3, the wind heel and the roll motion. This means of progressive flooding and consequences will be demonstrated subsequently.

To demonstrate the hydrostatics and stability effects of flooding Hold 3, flooding is calculated in 10% increments, from the intact condition to the level of equalization or equilibrium (i.e. until the internal level of the floodwater is equalized to the waterline external to the hull). Flooding is calculated for permeability factors 0.7, 0.8 and 0.9 to demonstrate the variability in results, as discussed previously. Figure 6-16 shows a centerline inboard profile graphic from the GHS software with Hold 3 flooded and equalized for permeability 0.8. Table 6-3 provides calculated values of displacement, floodwater weight, GM, drafts and trim, for each of the 10% flooding increments, for permeability 0.7 (the lower bound) and 0.9 (the upper bound). Figure 6-17 shows righting arm curves for each of the 10% flooding increments for permeability 0.7 (dashed curves) and 0.9 (solid curves).

One of the important conclusions that can be drawn from Table 6-3 and Figure 6-17 is the reduced righting arms and GM (slope of the righting arm curve) at the lower percentages (10% and 20%) for the higher permeability value (0.9) due to the initial free surface effect. However, as discussed previously, it is likely that due to the existence of the tightly packed automobiles in the lower holds, the effective initial permeability value would be closer to 0.6-0.7 and would only increase to an average value of approximately 0.8 as the floodwater levels increased toward the overhead of the lower hold. This is illustrated in Figure 6-18 which shows scaled drawings of the sections at frame 143 (location of the Hold 3 supply trunk) and frame 159 (location of the Hold 3 aft exhaust trunk). The loading of containers, trailers and automobiles are shown to scale and approximate position based on the Final Stow Plan [70]. The figure shows Hold 3 flooded to the 20% level, showing the effective reduction in permeability due to the automobiles, and also the impact of pocketing as the loose water hits the overhead (3rd Deck). In the figure, the flooding level at 20% and heel angle of 15 degrees are shown for example, as this was a condition which might have existed at early stages of flooding in Hold 3, based on the VDR audio transcript as previously discussed, and based on combined wind heel considerations as will be discussed. The scaled drawings in the figure also show how close the Hold 3 ventilation openings (tops of the baffle plates) would be to a still waterline with a 15 degree wind heel angle. The relative rise in water height due to waves and vessel roll motion would bring these ventilation openings to submergence, at least intermittently. This will be discussed in more detail subsequently.

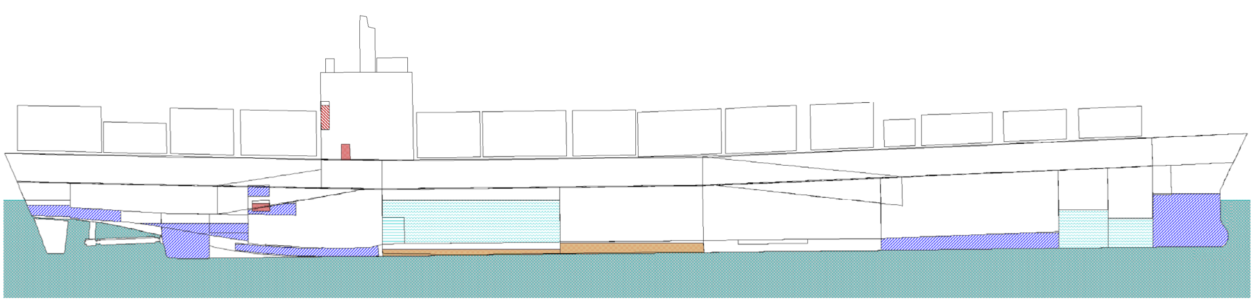

Figure 6-16: Centerline inboard profile from the GHS software showing the condition with Hold 3 flooded to equalization (i.e. flooded to the external waterline). Permeability is 0.8.

		Displacement (LT)	Total Floodwater (LT)	GM (ft)	Draft Fwd (ft-BL)	Draft Aft (ft-BL)	Trim (ft-aft)	Draft at LCF (ft-BL)
Intact Condition		34,277	0	4.03	26.9	31.9	5.0	29.9
Permeability 0.7	10%	34,970	693	0.92	27.2	32.6	5.4	30.3
	20%	35,662	1,385	1.22	27.4	33.2	5.8	30.8
	30%	36,355	2,078	1.55	27.6	33.8	6.2	31.3
	40%	37,047	2,770	1.85	27.8	34.4	6.6	31.7
	50%	37,740	3,463	2.04	28.1	35.0	6.9	32.2
	60%	38,433	4,156	2.26	28.3	35.6	7.3	32.6
	Equilibrium	39,394	5,117	2.84	28.6	36.5	7.9	33.2
Permeability 0.9	10%	35,167	890	0.05	27.2	32.8	5.6	30.5
	20%	36,058	1,781	0.46	27.5	33.5	6.0	31.1
	30%	36,948	2,671	0.89	27.8	34.3	6.5	31.7
	40%	37,839	3,562	1.29	28.1	35.1	7.0	32.2
	50%	38,730	4,453	1.56	28.4	35.9	7.5	32.8
	60%	39,620	5,343	1.84	28.7	36.6	7.9	33.4
	Equilibrium	41,173	6,896	2.61	29.2	38.0	8.8	34.3

Table 6-3: Comparison of calculated displacement, floodwater weight, GM, drafts and trim, for flooding of Hold 3 in 10% increments, for permeability 0.7 and 0.9.

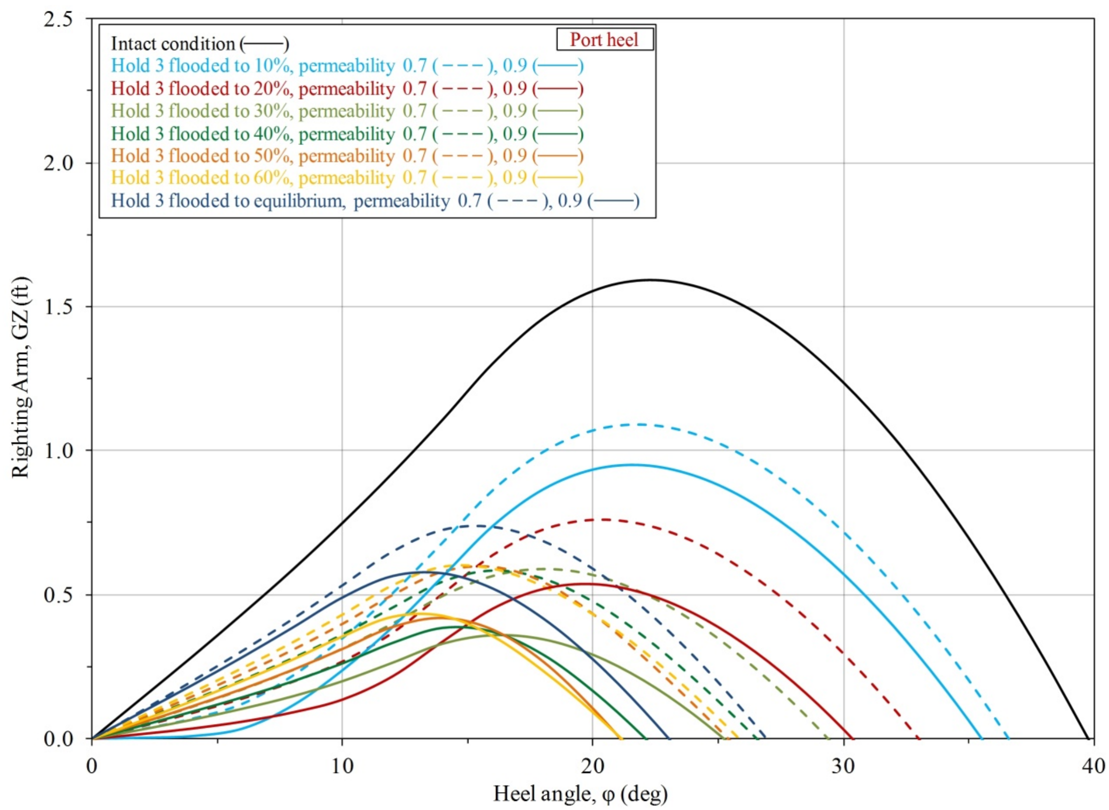

Figure 6-17: Comparison of righting arm curves for flooding of Hold 3 in 10% increments. Dashed curves are for permeability 0.7, solid curves are for permeability 0.9. Port heel is shown.

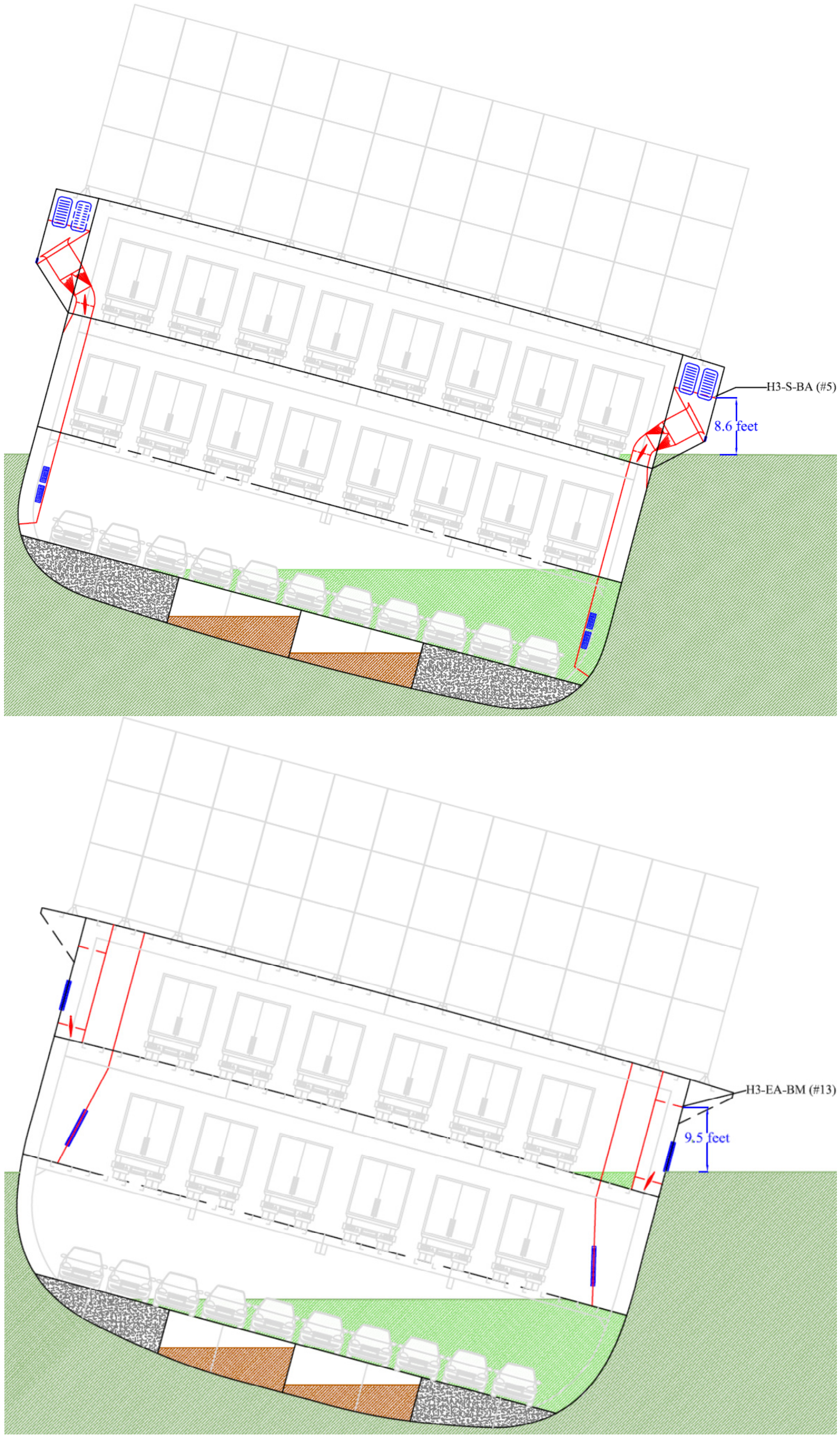

Figure 6-18: Scaled drawing of sections at frame 143 (Hold 3 ventilation supply trunk) and frame 159 (Hold 3 aft ventilation exhaust trunk), with flooding of Hold 3 to 20% with permeability 0.7 and heel angle of 15 degrees shown for example.

6.4.5. Progressive Flooding

As discussed previously, it is not clear from the VDR audio transcript when and where progressive flooding was occurring prior to the eventual capsizing of the vessel at approximately 0739 on October 1st [64 (pp. 507-508)]. However, as Hold 3 continued to flood, eventually the ventilation openings for Hold 2A would have been brought to intermittent submergence as their freeboards were reduced due to the flooding of Hold 3, in combination with the wind heel, waves and roll motion. This is illustrated in Figure 6-19, which shows a scaled drawing of the section at frame 134/22, the location of the aft ventilation exhaust trunk for Hold 2A. For a wind heel angle of 15 degrees, the waterline is shown incorporating the effect of flooding of Hold 3 to 20%. It should be noted that it is likely that Hold 2A (and perhaps also Hold 2) may have been taking on some water, at least intermittently, as the vessel rolled about a wind heel angle of 15 degrees and while Hold 3 was flooding.

In addition to the ventilation openings, it is possible that progressive flooding into Hold 2A could have also occurred through watertight door seal leakage or through leakage of the bilge pumping system check valves. Regardless of the source, at 0716 a report was made to the bridge that the Hold 2A bilge alarm had been sounding [64 (pg. 484)], suggesting that Hold 2A had been taking on some water. For illustrative purposes, the analysis is completed assuming that the progressive flooding would have occurred in sequence, once Hold 3 reached equilibrium.

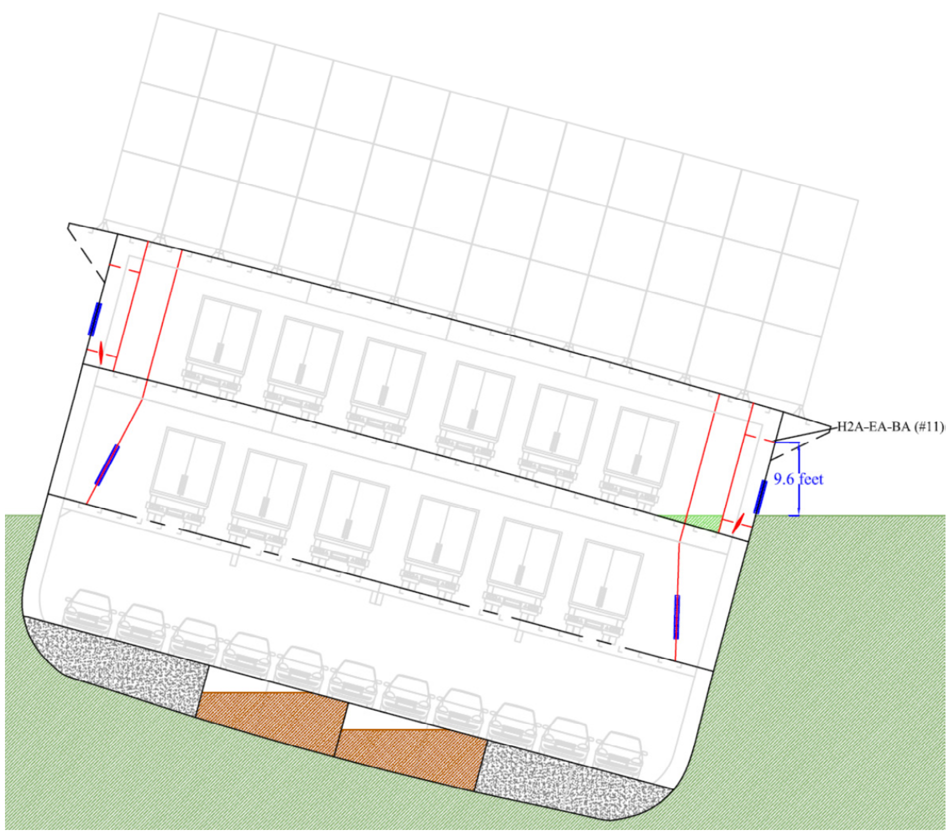

Figure 6-19: Scaled drawing of section at frame 134/22 (Hold 2A aft ventilation exhaust trunk) with still waterline resulting from flooding of Hold 3 to 20% with permeability 0.7 and heel angle of 15 degrees shown for example.

To demonstrate the hydrostatic effects of flooding Hold 2A after the flooding of Hold 3, flooding of Hold 2A is calculated in 10% increments for an average permeability value of 0.8. Figure 6-20 shows a centerline inboard profile graphic from the GHS software with Holds 3 and 2A flooded and equalized. Table 6-4 provides calculated values of displacement, floodwater weight, GM, drafts and trim, for each of the 10% flooding increments. Figure 6-21 shows righting arm curves for each of the 10% flooding increments.

As was the case with flooding of Hold 3 by itself, there is a significant reduction in GM and righting arms at lower levels of flooding (most notably 10% and 20%) due to the initial free surface effect. In fact, for the 10% level, GM and the initial righting arms are actually negative (see Figure 6-21), indicating a condition referred to as "lolling." In this lolling condition, even without the contribution of wind heel, the vessel would not be able to remain upright but would flop to either side to a "lolling angle" (approximately 7 degrees as shown in Figure 6-21 for the 10% level). With wind heel this type of condition may only be noticeable as an apparent increase in the wind heel angle. However, as was the case for flooding of Hold 3 by itself, in reality due to the existence of the tightly packed automobiles in the lower holds, the effective permeability value would be closer to 0.6-0.7 and would only increase to an average value of 0.8 as the floodwater levels increased toward the overhead of the lower hold, so this lolling effect would also be reduced.

Comparison of Figure 6-17 and Figure 6-21 indicates a significant reduction in righting arms with flooding of Hold 3 and additional flooding of Hold 2A. While theoretically there could be sufficient residual righting energy (area under the righting arm curve) to survive flooding of these 2 compartments in calm water, with almost any significant wind heel and additional wave effects including dynamic rolling, the vessel would likely have capsized. To confirm this limitation, MSC ran a number of additional analyses with different combinations of compartment flooding. It is evident that any additional free surface effect due to the flooding of a third cargo hold would be sufficient to capsize the vessel, even in calm water.

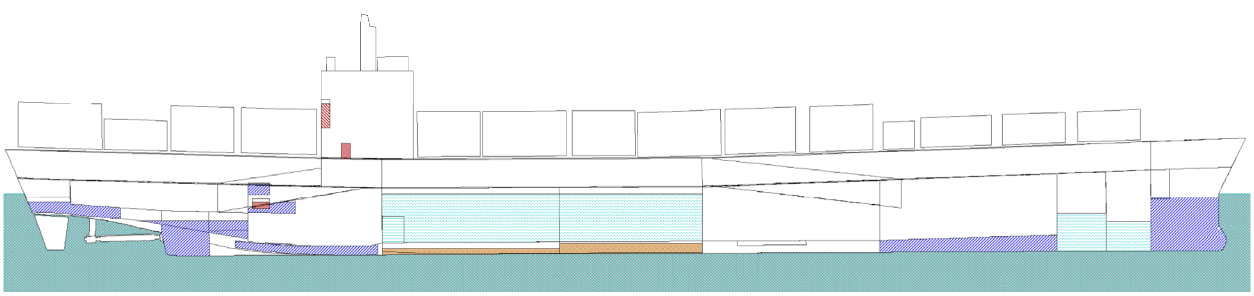

Figure 6-20: Centerline inboard profile from the GHS software showing the condition with Holds 3 and 2A flooded to equalization. Permeability is 0.8.

	Displacement (LT)	Total Floodwater (LT)	GM (ft)	Draft Fwd (ft-BL)	Draft Aft (ft-BL)	Trim (ft-aft)	Draft at LCF (ft-BL)
Hold 3 at Equilibrium	40,263	5,986	2.72	28.9	37.2	8.3	33.8
Hold 2A at 10%	41,022	6,745	-0.68	29.7	37.3	7.6	34.2
Hold 2A at 20%	41,803	7,526	-0.04	30.6	37.6	7.0	34.7
Hold 2A at 30%	42,589	8,312	0.38	31.4	38.0	6.6	35.3
Hold 2A at 40%	43,364	9,087	0.77	32.2	38.3	6.0	35.7
Hold 2A at 50%	44,138	9,861	1.09	33.0	38.5	5.5	36.2
Hold 2A at 60%	44,912	10,635	1.34	33.9	38.8	4.9	36.7
Hold 2A at 70%	45,686	11,409	1.53	34.7	39.1	4.4	37.2
Hold 2A at 80%	46,459	12,182	1.67	35.4	39.3	3.9	37.7
Hold 2A at Equilibrium	46,982	12,705	2.03	36.0	39.5	3.5	38.1

Table 6-4: Calculated displacement, floodwater weight, GM, drafts and trim, for progressive flooding of Hold 2A in 10% increments with Hold 3 flooded to equilibrium. Permeability is 0.8.

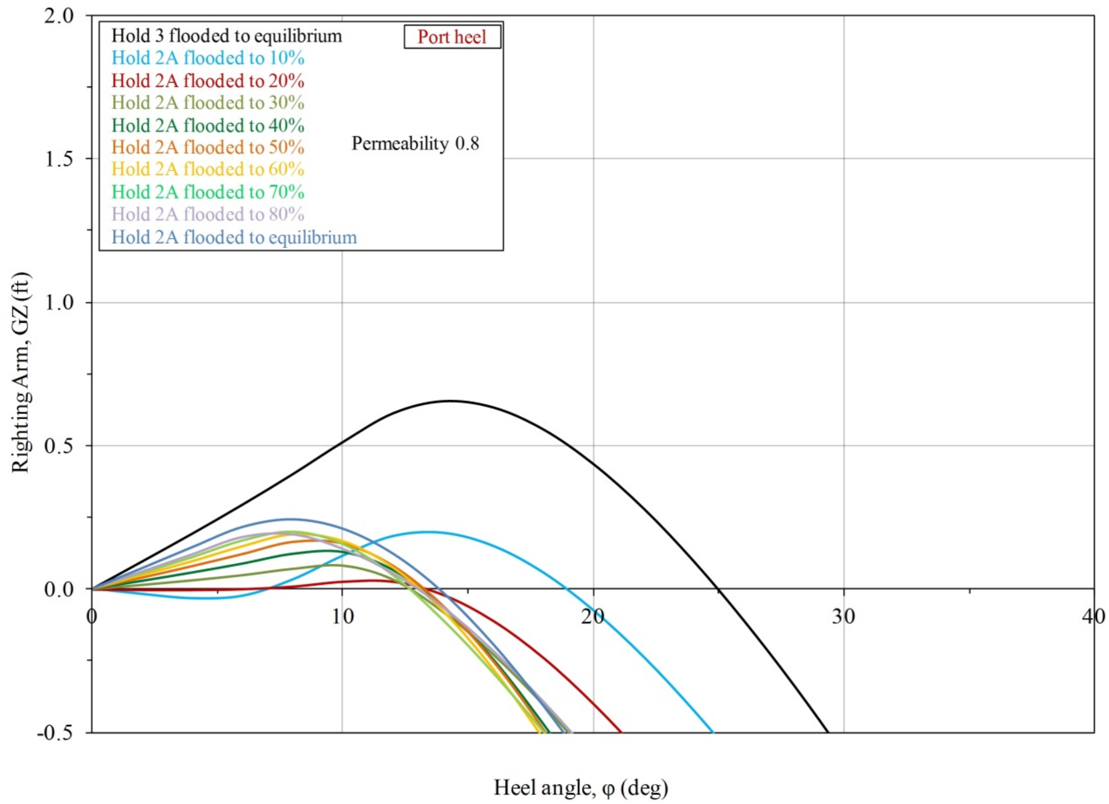

Figure 6-21: Righting arm curves for progressive flooding of Hold 2A in 10% increments with Hold 3 flooded to equilibrium. Permeability is 0.8. Port heel is shown.

6.5. Combined Effects of Wind Heel and Flooding

As illustrated in Figure 6-17 and Figure 6-21, flooding of Hold 3 and progressive flooding of Hold 2A would have left the ship with limited righting energy (area under the righting arm curve). The general effects of wind heel on the righting arm curve, including the calculation of residual righting arms and residual righting energy were discussed in Section 6.3. The combination of flooding and wind heel would have left the ship with little or no residual righting energy. Figure 6-22 shows the effects of wind heel on the righting arms with complete flooding of Hold 3 (top) and with complete flooding of Hold 3 and Hold 2A (bottom), both with average permeability of 0.8. Note that intermediate levels of flooding in either case would have reduced righting arms as shown in Figure 6-17 and Figure 6-21. One of the important conclusions that can be drawn from Figure 6-22 is that it is unlikely that the ship could survive uncontrolled flooding into even a single cargo hold with winds in excess of 70 or 80 knots, and it is unlikely that it could survive flooding of more than one cargo hold except in benign conditions with little wind and waves.

As discussed previously, for initial flooding of the lower cargo hold of Hold 3, the effective permeability factor would be closer to 0.7 up to the 20-30% flooding level. Combining these levels of flooding with permeability factor of 0.7 and wind heel in the range 70-90 knots, it can be demonstrated that a wind heel with initial flooding of Hold 3 could lead to a combined wind heel angle of approximately 15 degrees. This is illustrated in Figure 6-23, which shows wind heeling arms for 70, 80 and 90 knot winds and calculated residual righting arms, for flooding levels 10%, 20% and 30% in Hold 3, with permeability 0.7. It is clear that achieving a 15 degree heel angle as stated in the VDR transcript is possible with combined wind heel and initial flooding of Hold 3. Figure 6-24 shows the same calculation information, but shows righting arms with and without 80 knot wind for Hold 3 flooding levels 10%, 20% and 30%. It is important to recognize from these plots that the residual righting energy (area under the righting arm curves) is reduced significantly even for lower levels of flooding up to 30% when considered in combination with 80 knot beam wind. Thus, it is apparent that the vessel would have been in a vulnerable state and susceptible to capsizing even with flooding only of Hold 3, when considering the combined effects of partial flooding, wind heel and roll motion.

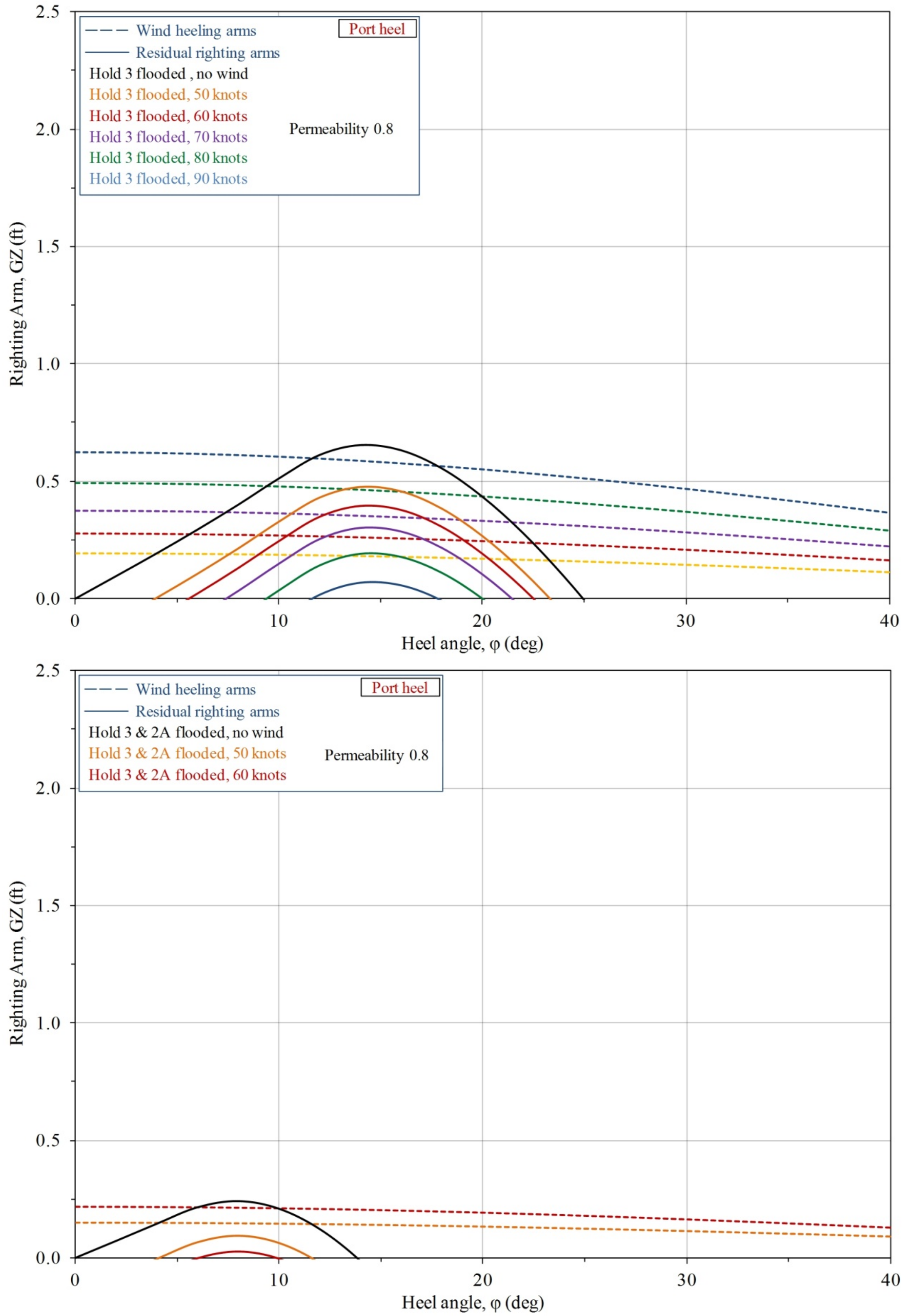

Figure 6-22: Wind heeling arms (dashed curves) and residual righting arms (solid curves) with Hold 3 flooded to equilibrium (top) and Hold 3 and Hold 2A flooded to equilibrium (bottom). Permeability is 0.8.

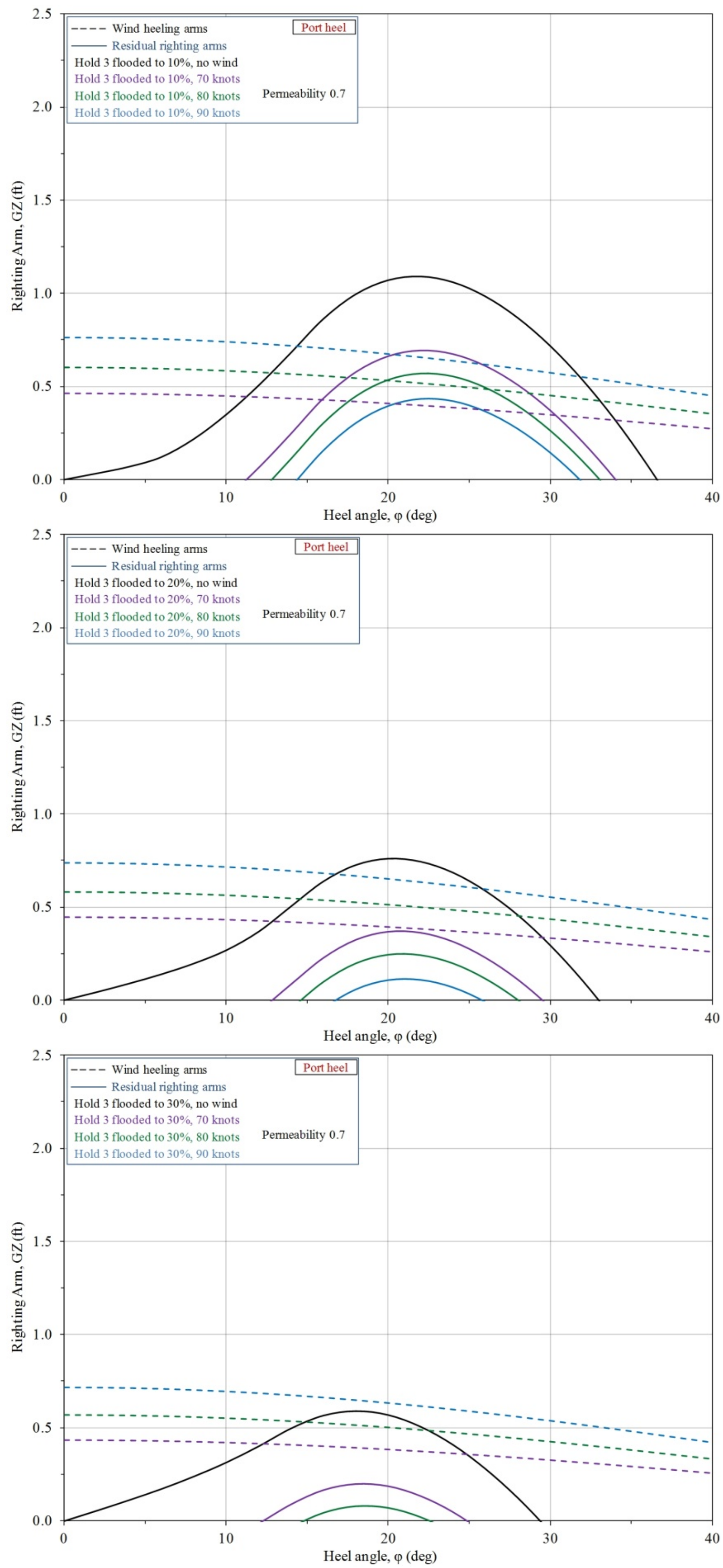

Figure 6-23: Beam wind heeling arms (dashed curves) and residual righting arms (solid curves) with Hold 3 flooded to 10% (top), 20% (middle) and 30% (bottom). Permeability is 0.7.

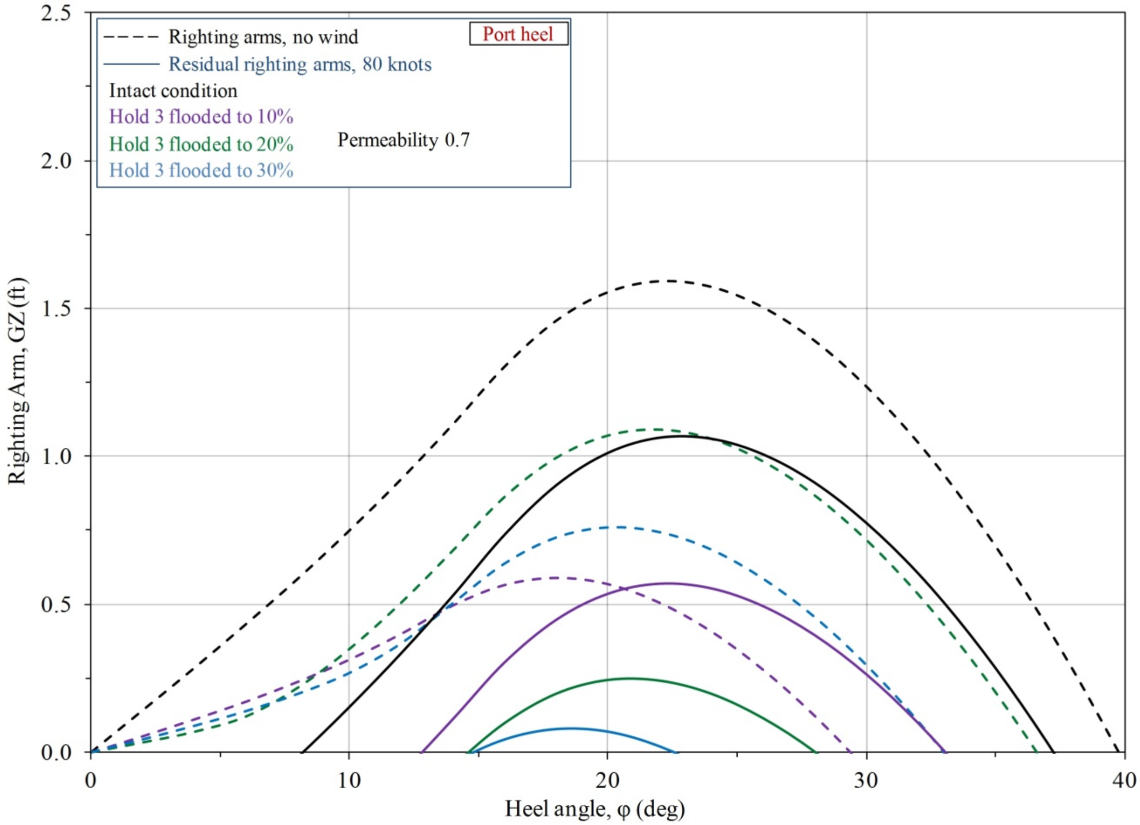

Figure 6-24: Righting arms (dashed curves) and residual righting arms (solid curves) for 80 knot beam winds with Hold 3 flooded to 10%, 20%, and 30%. Permeability is 0.7.

6.6. Downflooding

The flooding vulnerability presented by the cargo hold ventilation system was discussed in Section 6.4 and downflooding points were listed in Table 6-2. Downflooding angles for these points are tabulated and plotted on the righting arm curves for the intact condition at loss of propulsion (without flooding) and for the condition with Hold 3 flooded to 20%. Table 6-5 provides the downflooding angles for the listed points and Figure 6-25 plots downflooding points for each hold on the righting arm curves.

It was noted in Section 5.2.3.2 that including downflooding points and downflooding angles in the intact stability analysis would have the effect of truncating the righting arm curves for evaluation of the righting arm criteria. However, from the definitions based on 46 CFR 170.055, these ventilation openings, as they could potentially be closed by means of manually-closable fire dampers, would not have been considered as providing a means of “downflooding” and therefore would not need to be considered in evaluation of the stability criteria, even under the current criteria of the 2008 IS Code. This is in apparent conflict with 46 CFR 92.15-10 which requires that fire dampers remain open at all times in port and underway (except when combating a fire) to provide positive ventilation of the vehicles holds.

			Downflood Angle (deg)	
Critical Point Name	Short Name	Number	Intact Condition	Hold 3 Flooded to 20%
Hold 3 Access Scuttle Stbd (Coaming)	H3-SC-S	1	16.2	14.9
Downflooding Points				
Hold 1 Vent Supply (Bellmouth)	H1-S-BM	2	45.0	44.4
Hold 2 Vent Supply (Baffle)	H2-S-BA	3	29.6	28.9
Hold 2A Vent Supply (Baffle)	H2A-S-BA	4	27.7	26.9
Hold 3 Vent Supply (Baffle)	H3-S-BA	5	27.2	26.3
Hold 1 Vent Exhaust Fwd (Louver)	H1-EF-L	6	55.4	55.0
Hold 1 Vent Exhaust Aft (Louver)	H1-EA-L	7	43.2	42.5
Hold 2 Vent Exhaust Fwd (Baffle)	H2-EF-BA	8	33.7	33.0
Hold 2 Vent Exhaust Aft (Baffle)	H2-EA-BA	9	31.1	30.3
Hold 2A Vent Exhaust Fwd (Baffle)	H2A-EF-BA	10	30.3	29.4
Hold 2A Vent Exhaust Aft (Baffle)	H2A-EA-BA	11	29.8	28.9
Hold 3 Vent Exhaust Fwd (Baffle)	H3-EF-BA	12	29.5	28.6
Hold 3 Vent Exhaust Aft (Baffle)	H3-EA-BA	13	29.1	28.1

Table 6-5: Downflooding angles for forward cargo holds for intact condition (at loss of propulsion, without flooding) and with Hold 3 flooded to 20% with 0.7 permeability.

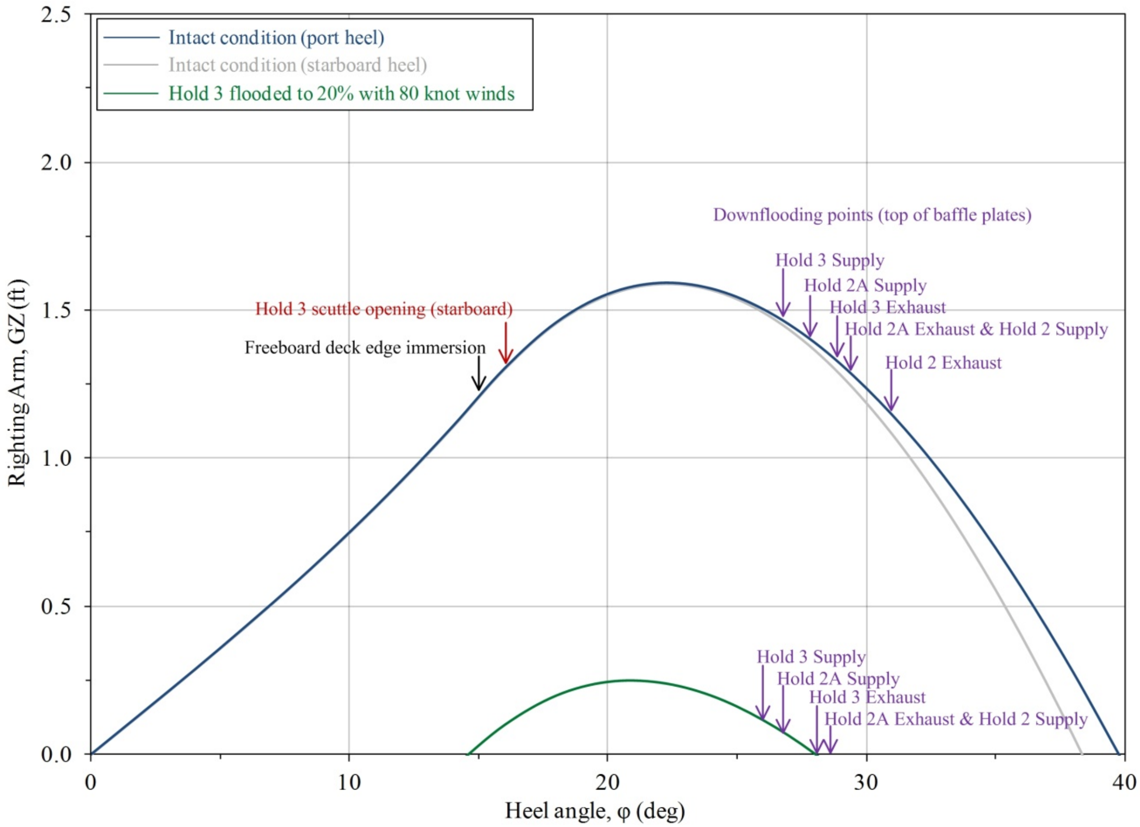

Figure 6-25: Righting arm curves with annotated downflooding angles from Table 6-5: intact condition (at loss of propulsion, without flooding) and Hold 3 flooded to 20% with 0.7 permeability and 80 knot winds.

6.7. Additional Considerations

In the foregoing analyses, no consideration was given to the impact of cargo shifting, or cargo loss. Although there was no mention specifically of large-scale cargo shift or loss until the very end of the VDR audio as the vessel slowly capsized, there was one mention of a single trailer cargo shift which was witnessed by the Chief Mate at 0436 [64 (pg. 380)] and there was some discussion of automobiles breaking free and floating in Hold 3 [64 (pg. 486)]. Cargo shifting can best be considered in this analysis as a transverse weight shift; specifically a given transverse moment which might be calculated based on shifting of a given number of trailers or containers by a given transverse distance. This is illustrated in Figure 6-26 below, which shows the effects of a transverse moment applied to the intact condition (at the loss of propulsion, not including floodwater and beam wind) and the condition with Hold 3 flooded to 20% with 80 knot beam winds. The 5,000 ft·LT transverse moment (weight multiplied by distance shifted) is shown as an example and is based on a notional shift of 20 containers of weight 25 LT each, shifting an average 10 feet. The net effect of any transverse weight shift is equivalent to a transverse shift in the ship's center of gravity, which results in a reduction in the righting arms and a list as shown. Note that in this case, even a 5,000 ft·LT transverse weight shift produces small reductions in righting arms and small induced heel angles, when compared to large reductions in righting arms and induced heel angles due to floodwater and hurricane force beam winds as discussed previously. However, it should be noted that even small transverse shifts in containers would exacerbate effects of floodwater and beam winds.

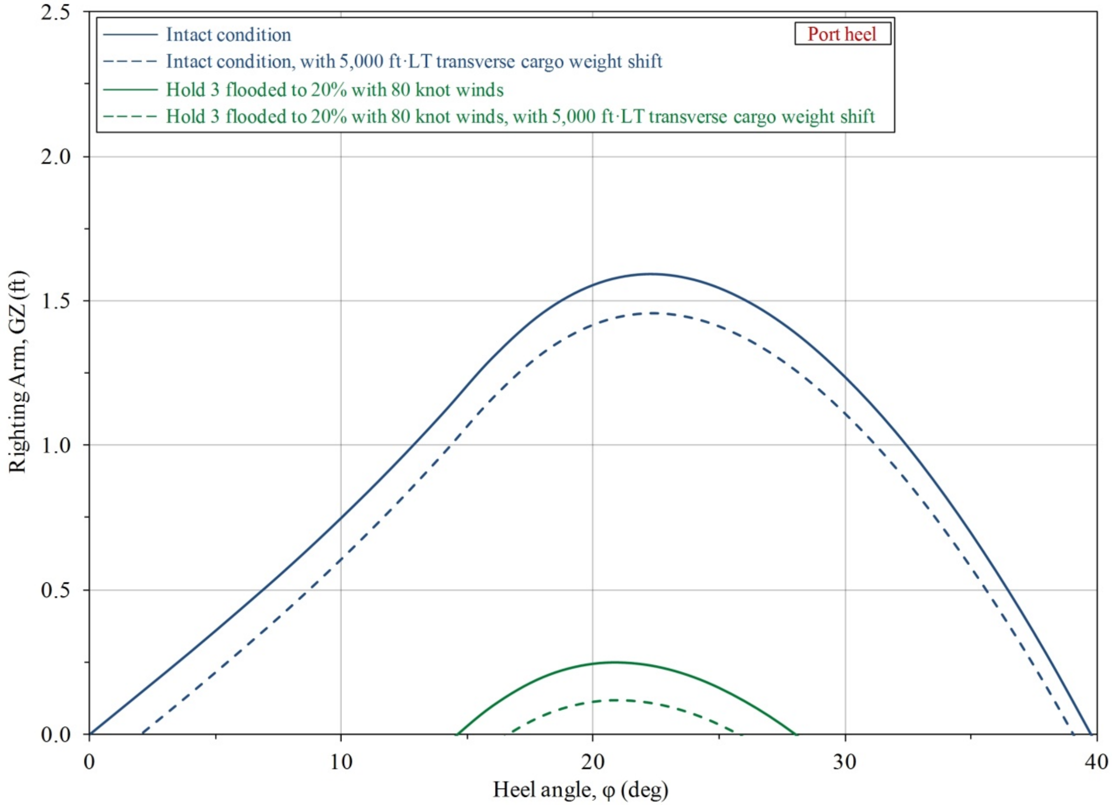

Figure 6-26: Comparison of righting arm curves with effects of transverse cargo weight shifts: intact condition (at loss of propulsion, without flooding) and Hold 3 flooded to 20% with 0.7 permeability and 80 knot winds.

The complete loss of topside containers as the vessel took heavy rolls in the seaway or while capsizing would actually lead to a temporary improvement in the stability condition of the vessel. This is the case because complete loss of topside containers would necessarily lower the ship's center of gravity and increase righting arms, providing temporary additional righting energy and stability margin. This is illustrated in Figure 6-27, which shows for an example the potential effects of a complete loss of all containers in Bay 13 (581 LT) applied to the intact condition (at the loss of propulsion, not including floodwater and beam wind) and the condition with Hold 3 flooded to 20% with 80 knot beam winds. However, it is also feasible that entire bays of containers or sections of bays could lose structural integrity and experience partial failure or deformation and lean to one side without actually washing overboard. This has occurred on container vessels in heavy seas in recent years, including as a consequence of so-called "parametric" roll motions. In this case, the results would be similar to those of container shifting shown in Figure 6-26 for example. There was, however, no statement made by the EL FARO crew on the VDR audio transcript regarding the loss or shifting of topside containers, until just prior to vessel capsizing at 0729 when it was noted that containers were in the water [64 (pg. 498)].

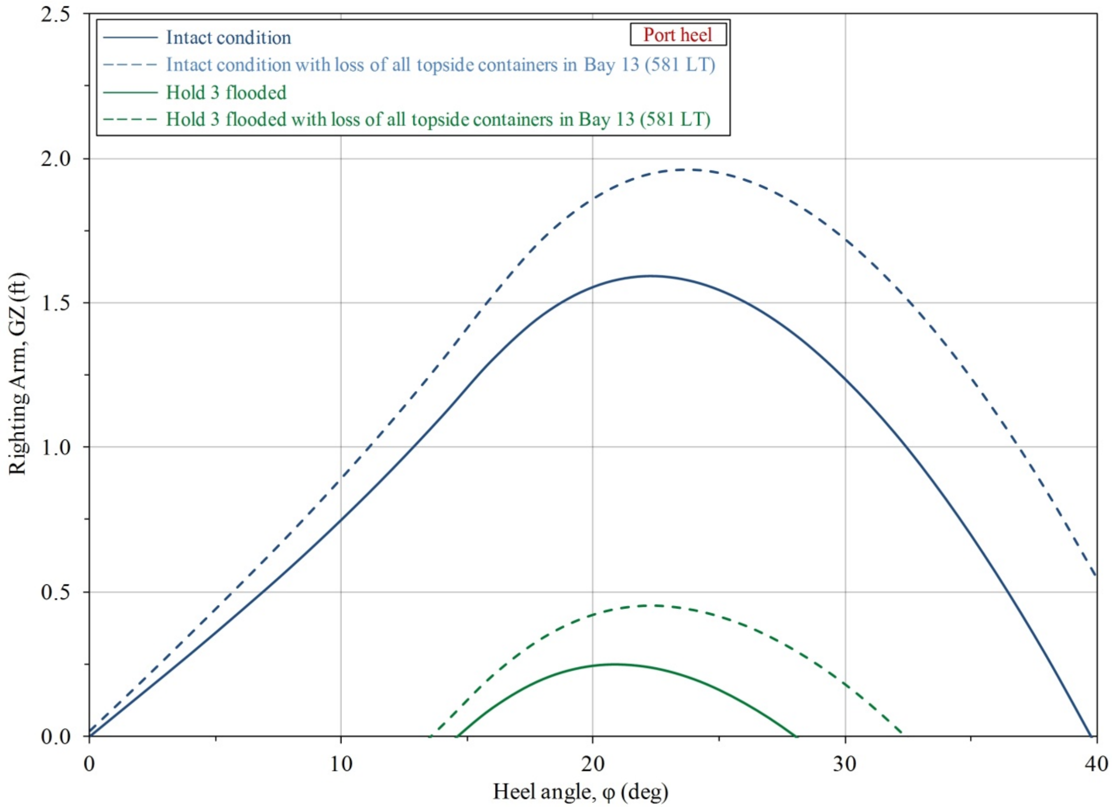

Figure 6-27: Comparison of righting arm curves with complete loss of all containers in Bay 13 for example: intact condition (at loss of propulsion, without flooding) and Hold 3 flooded to 20% with 0.7 permeability and 80 knot winds.

It was requested by the MBI to incorporate consideration of entrapped water on the 2nd Deck in the MSC analysis. This is a consideration since the 2nd Deck provides a semi-closed (semi-buoyant) free-flooding volume, allowing water to enter through limited deck openings along the side shell as the vessel rolls in the seaway. With this configuration the possibility exists for entrapment of water on the deck as the vessel rolls. Fundamentally, the hydrostatic effects of water on the 2nd Deck are included in the MSC GHS computer model and analyses, including their effects on attained static heel and the righting arm curve. For the MSC GHS computer model a separate set of lines was created for the semi-enclosed 2nd Deck, and this volume was allowed to free flood in the analysis (see Figure 2-3). However, it is noted that entrapment of water on the deck also has important dynamic effects which cannot be incorporated in a hydrostatic analysis. Specifically, entrapment of water to one side (port or starboard depending on the roll offset) would provide transverse force components on the side shell which would alter roll motions. Additionally, restriction of flow through the limited side shell openings would also provide a damping effect on the roll motion, limiting the amplitude of the roll motion. These dynamic effects could be parametrically incorporated and simulated in a dynamic analysis, but cannot be captured effectively in a hydrostatic analysis as provided.

To conclude this section, it should be noted that all of the hydrostatic sinking analyses are based on an assumption that the weight and center of gravity of the vessel and its cargo are fairly well defined based on the departure loading condition documentation. However, based on the propagation of uncertainty from the 2006 stability test (see Section 3 and Appendix A of this report), there exists a 95% confidence that uncertainty in the height of the center of gravity (KG) is on the order of 0.7 ft for the departure condition and for the lightship condition (see Table 3-2). These uncertainties could be considered in assessing the previous analyses, or should at least be used as a reminder of the uncertainty in any calculated results. To illustrate, Figure 6-28 provides a comparison of the righting arms for the accident voyage loading condition prior to the loss of propulsion (intact condition) and with Hold 3 flooded to 20% with 80 knot beam winds, with uncertainty in calculated lightship KG included. It should be noted that these righting arm curves include the uncertainty in the lightship KG, but do not include the additional uncertainty in the cargo and tank loading and weight and free surface associated with the floodwater. The primary point in illustrating this is to highlight the significant impact that uncertainty in the assumed lightship KG has on the righting arms. Note that for all of the previous righting arm plots, significant differences would exist in the calculated angle of wind heel and residual righting energy, depending on the desired level of confidence in the results.

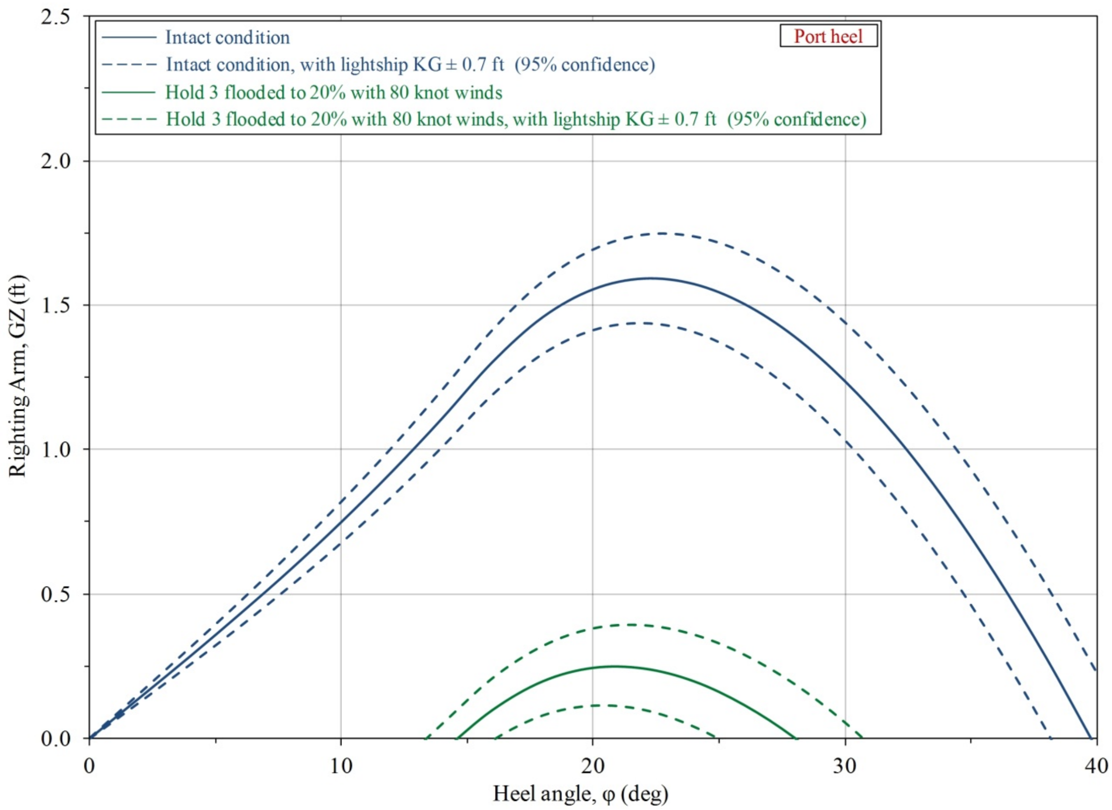

Figure 6-28: Comparison of righting arm curves with effects of uncertainty in lightship KG considered: intact condition (at loss of propulsion, without flooding) and Hold 3 flooded to 20% with 0.7 permeability and 80 knot winds.

6.8. Vessel Sinking

It can be concluded from the VDR audio transcript that the EL FARO experienced flooding of Hold 3 and was experiencing significant wind heel resulting in a mean heel angle of approximately 15 degrees. Following the loss of propulsion around 0600, the vessel would have been drifting with beam to the wind and waves, and it could be expected that the vessel would also have been rolling around the mean wind heel due to wave action. In this condition, eventually the Hold 2A ventilation supply and exhaust openings would have intermittently immersed allowing additional floodwater into Hold 2A. Additional progressive flooding could have occurred through watertight door seal leakage or leakage of the bilge pumping system check valves. Regardless of the source or sources, progressive flooding of Hold 2A was suggested by the bilge alarm as reported at 0716.

As demonstrated by the analyses, the free surface associated with the additional floodwater would likely have been sufficient to cause the vessel to capsize. However, the capsizing may have been slowed or temporarily arrested as containers on deck began to wash overboard, providing a stabilizing effect. As the vessel slowly rolled onto her port side, floodwater would have entered through the ventilation openings into all of the cargo holds and the engine room, resulting in the sinking. Due to the 6,700 tons of iron ore fixed ballast in the double bottom tanks, the vessel would have returned to an upright condition as the vessel sank.

There is one phrase in the VDR audio transcript, “bow is down” uttered by the Captain in the final minutes at 0730 [64 (pg. 499)], which might suggest that the ship was sinking by the bow. However, it may be considered that the utterance "bow is down" was likely referring to an observation through the bridge windows of the immersion of the forward main deck on the port side, which would have occurred at an angle of heel of only 20-30 degrees with Hold 3 flooded. Note that this statement was made only one minute after the 2nd Mate uttered "…containers in the water" [64 (pg. 498)], indicating that it was all happening rapidly. The interaction on the bridge between the Captain and AB-1 in the final minutes suggests that the AB-1 was stuck on the port side of the wheelhouse as the vessel was slowly capsizing to port, as the Captain yelled for him to “come up,” with the AB-1 requesting help, even requesting a ladder or a rope to assist his climb [64 (pp. 501-508)].

Based on the MSC analyses, it can be concluded that it would be highly unlikely that the vessel could have sunk by the bow, but highly likely that the vessel would have capsized. With the huge free surface effect due to the floodwater in the full-breadth cargo holds, the ship would have rolled over long before enough water entered the forward holds to put the bow down. This is illustrated by Figure 6-21 through Figure 6-24 and the text of Sections 6.4 and 6.5, as any combination of floodwater in 2 or more cargo holds would result in capsizing of the vessel. Note that the term “capsize” does not mean that the vessel completely inverted, and in fact that would be considered highly unlikely, since the deck containers would have broken free and washed overboard, and this would have temporarily improved stability (see Figure 6-27). It is considered most likely that in the final minutes, the vessel rolled on its port side due to the free surface of the floodwater and hurricane force winds, lost most or all of the deck containers (and probably most of the internal RO/RO cargo broke free and shifted), and then rapidly flooded through the cargo hold ventilation openings.

6.9. Summary

This section documented the MSC hydrostatic analyses of the sinking of the EL FARO. The hydrostatic analyses use the MSC GHS computer model, focusing on assessment of righting arms including righting energy and range of stability considerations, in order to gain insight into the characteristics of vessel dynamics and motions due to wind heel and flooding.

The effects of wind heel are addressed, along with general and nuanced considerations associated with floodwater, including effects of free surface, compartment permeability, and pocketing. The potential sources of flooding of Hold 3 are discussed, including photographs and drawings for reference of the vulnerability to flooding through the cargo hold ventilation openings, and potentially through damaged emergency fire pump piping. Potential progressive flooding paths into Hold 2A were discussed, including downflooding through the cargo hold ventilation system openings, and possibly through leakage of the watertight door seals or leakage of the bilge pumping system check valves. Analyses of an array of wind heel and flooding conditions are used to assess likely conditions leading to the capsizing and sinking of the vessel given the environmental conditions.

The analyses results were highly sensitive to variation in permeability values, and a range of permeability values was used to assess impacts of the variability on the hydrostatics and stability. The evaluation of flooding required careful consideration of compartment permeability and pocketing effects. For permeability, this included significant variability in both overall fraction and uniformity throughout the cargo holds. This is especially important when considering containers, where permeability varies significantly depending on the assumed watertight integrity and specific locations of the containers.

The analyses results were highly sensitive to variation in wind speed, especially in combination with floodwater free surface, with variability of permeability and pocketing effects considered. Single compartment flooding of Hold 3 with combined wind heel of 70-90 knot beam winds resulted in very small residual righting arms and little residual righting energy. This would suggest that it would be highly unlikely that the EL FARO could have survived even single compartment uncontrolled flooding of Hold 3, given the wind and sea conditions.

Potential sources of flooding of Hold 3 and the other cargo holds were investigated, including vulnerabilities associated with the cargo hold ventilation system. It was highlighted that the locations of the ventilation openings would likely result in at least intermittent flooding into the cargo holds, as the vessel was subject to a variable wave height on the side shell and rolled about the mean wind heel angle of around 15 degrees.

Based on the MSC analyses, regardless of the sources of flooding, the free surface associated with the floodwater in multiple cargo holds combined with hurricane force winds and seas would likely have resulted in the capsizing of the vessel. The capsizing may have been slowed or temporarily arrested as containers on deck began to wash overboard, but as the vessel slowly rolled onto her port side, floodwater would have entered through the ventilation openings into all of the cargo holds and the engine room, resulting in the sinking.

7. Ship Structures

7.1. Introduction

Sun Shipbuilding in Chester, Pennsylvania built a series of 10 RO/RO "trailerships" between 1967 and 1977. While built for several different owners, and with minor differences in configurations to accommodate different trade routes, these vessels, listed in Table 7-1, were generally known as the PONCE DE LEON class of ships. The first 7 of these ships were originally delivered as 700 foot vessels. The 8th ship, the GREAT LAND, was originally laid down as a 700 foot vessel but was lengthened to 790 feet prior to delivery. The last two ships were, from keel laying, 790 foot vessels. Four of the earlier vessels were subsequently lengthened to 790 feet with the last, EL FARO, being lengthened in 1992-1993.

Hull	Name(s)	Year Built	Length (ft)	Original Owner, Trade
647	PONCE DE LEON	1967	700/790	TTT/NPR, Puerto Rico
650	ERIC K. HOLZER	1970	700	TTT/NPR, Puerto Rico
662	LURLINE	1973	700/826	Matson, Hawaii
663	FORTALEZA	1972	700	TTT/NPR, Puerto Rico
664	MATSONIA	1973	700/713	Matson, Hawaii
666	EL TAINO (EL MORRO)	1974	700/790	PFEL, Persian Gulf
670	PUERTO RICO (NORTHERN LIGHTS, EL FARO)	1974	700/790	TTT/NPR, Puerto Rico
673	GREAT LAND	1975	790	TOTE, Alaska
674	ATLANTIC BEAR (EL YUNQUE)	1976	790	PFEL, Persian Gulf
675	WESTWARD VENTURE	1977	790	TOTE, Alaska

Table 7-1: Sun Shipbuilding PONCE DE LEON class "trailerships."

7.1.1. Original Construction

The EL FARO, Hull 670, was built in 1974, presumably in accordance with the 1974 American Bureau of Shipping (ABS) Rules for Building and Classing Steel Vessels (SVR 1974). Notes on the EL FARO's Midship Section Drawing [5], shown partially in Figure 7-1, indicate that the vessel's primary structure was derived from hulls 650, 662 and 663, and was identical to hulls 664, 666 and ultimately 673.

The ship's primary structure was arranged typically of a "shelter deck" vessel (with the semi-enclosed 2nd Deck), intended to load and stow vehicular cargo in open spaces, with minimal structural intrusions. The primary hull girder structure comprised 3 full decks (Main Deck, 2nd Deck and 3rd Deck), plus a solid floor double bottom tanktop deck (4th Deck) and shell plating.

Heavy web frames were fitted every 8 feet 3 inches, extending from the tanktop to the Main Deck, along the length of the vessel. Although not explicitly required to meet regulatory or class strength or damage stability requirements at the time of construction, watertight bulkheads, extending to the 2nd Deck, were fitted at frames 20, 46, 87, 128, 169, 200 and 246.

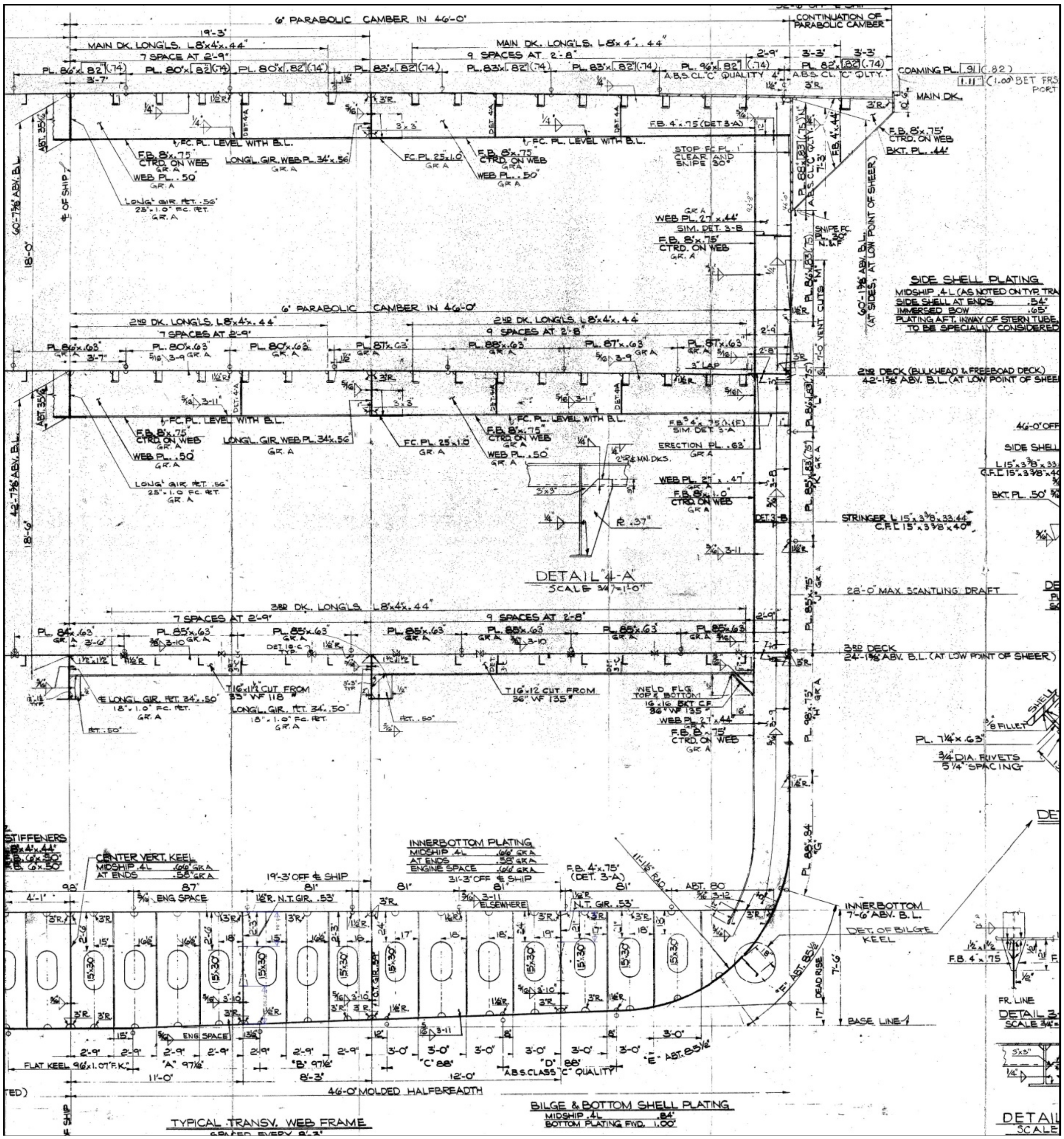

Figure 7-1: Midships Section. Taken from Sun Shipbuilding Midship Section Drawing 662-700-201, Alt E [5].

7.1.2. Significant Alterations

Although first assessed for lengthening in 1982, the EL FARO was the last of the PONCE DE LEON class of ships to be lengthened from 700 to 790 feet, and this occurred in 1992-1993. In addition to the fitting of the 90 foot mid-body section, the ship was also fit at this time with a Spar Deck above the Main Deck immediately forward of the superstructure extending from frames 128 to 162, and 1,830 LT of fixed ballast was added in double bottom tanks DB 2 P/S.

The second significant alteration to the vessel occurred in 2005-2006 with the conversion of the vessel from a pure RO/RO arrangement to a combined RO/RO and LO/LO arrangement (sometimes referred to as CON/RO). This was accomplished by removing the Spar Deck, adding container fittings to the Main Deck, adding reinforcing and supporting structure, and adding 4,875 LT of additional fixed ballast in double bottom tanks DB 2A P/S and DB 3 P/S. This would be the final significant configuration change made to the vessel.

7.2. Applicable Structural Criteria

7.2.1. Original Construction

As the continuation of a class of vessels which began construction in 1967, the EL FARO should have been built in accordance with the structural requirements of the 1974 American Bureau of Shipping (ABS) Steel Vessel Rules (1974 SVR). While there was no explicit documentation available to confirm this, a review of the information available on the Midship Section Drawing [5] does indicate that the vessel, as-built, did comply with the appropriate longitudinal strength (SVR 1974/6.3), shell plating (SVR 1974/15) and deck plating (SVR 1974/16) requirements of the 1974 SVR.

It should be noted that this class of vessels was originally designed to a maximum still water bending moment (SWBM) of 415,000 ft·LT and was constructed in accordance with the reduced plate scantling provisions of SVR 1974/15.7 and 174/16.5.10. These provisions permitted the shell plating above the deepest service draft, and exposed deck plating, to be reduced up to 10% from minimum required thickness, if they were provided with special protective coatings for corrosion control. In accordance with this allowance, and as indicated in Figure 7-2, side shell plating strakes K, L, M and N (extending from roughly 31.3 ft-BL (above baseline) up to the Main Deck), the coaming plate, and all of the vessel's Main Deck plating strakes, were all specified at 90% of the calculated scantling requirements of ABS SVR 1974/15.3 and 16.5.

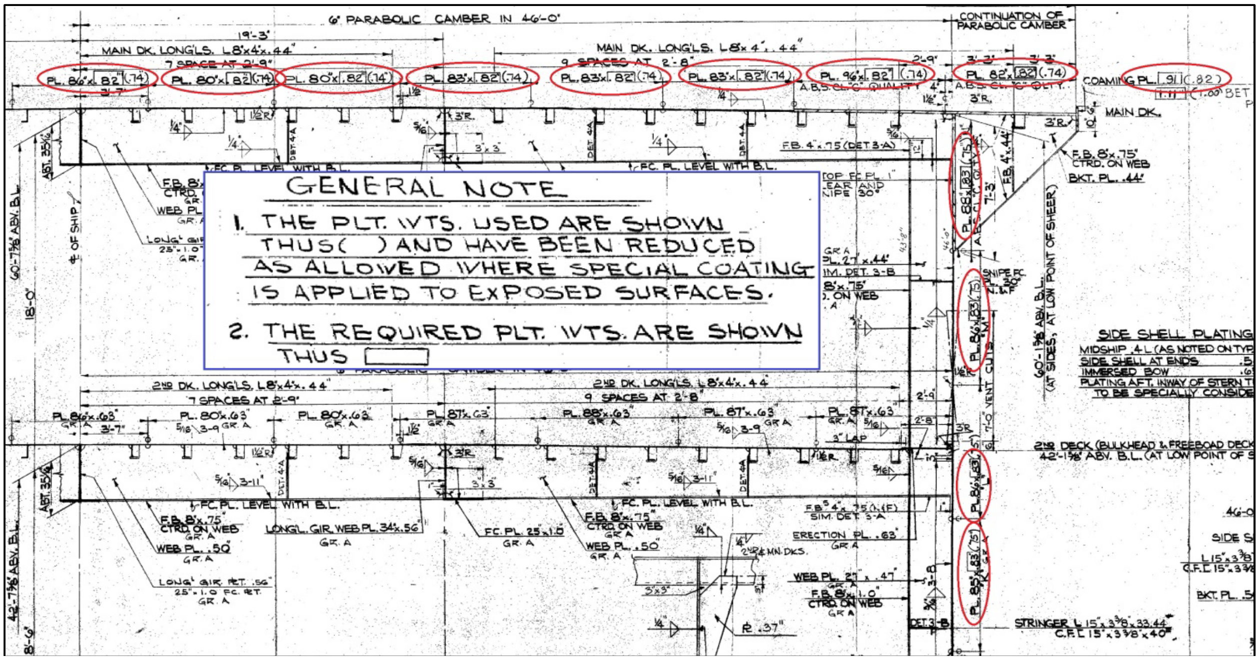

Figure 7-2: Reduced scantlings as permitted for strake plating with corrosion control coating (highlighted Midship Section Drawing [5]).

7.2.2. Lengthening Conversion (1992-1993)

As previously mentioned, the EL FARO was the fourth and final vessel of the class to be lengthened post-delivery. While several plans and structural calculations were approved by ABS for lengthening the vessel in 1982, the vessel was not actually lengthened until 10 years later in 1992-1993. Further, it is not clear what, if any, of the structural engineering performed in 1982 was used in the 1992-1993 lengthening, as the Scantling Plan [71] indicates that it was duplicated from Hull 675's construction plans for application to EL FARO's lengthening. As such, it is not clear what specific structural rule set was applied to the vessel for the 1992-1993 lengthening. There are, however, several aspects of the 1982 calculation package and structural plans which bear mentioning.

Of particular note, the calculation of section properties at all longitudinal locations ignored the 3rd Deck. As this deck is continuous throughout and beyond the midships 40% of the vessel's length (0.4L), is solidly connected to the shell structure, does not appear to be arranged with expansion joints, and meets the effectiveness criteria of SVR 1982/16.5.2, it is not clear why it was ignored in calculating the section properties. This might have been an effort to artificially balance the upper and lower section properties by artificially forcing the neutral axis higher in the vessel. In any case, independent calculations performed by the MSC confirm that the vessel's scantlings, as designed, were adequate when considering the 3rd Deck effective.

The 1982 structural calculations apply a longitudinal distribution factor to the minimum section modulus (SM) required by SVR 1982/6.3.1. It is not clear that this is appropriate, however, as SVR 1983/6.3.2c permits the Wave Induced Bending Moment (WIBM) to be modified by the distribution factor, whereas SVR 1982/6.3.2.a requires the SWBM to remain constant throughout the midships 0.4L. As applying the distribution factor to the minimum required SM value effectively reduces both the WIBM and SWBM, this application appears to be inappropriate.

Independent calculations performed by the MSC, however, show the new midbody scantlings meeting the minimum SM requirements of SVR 1982/6.3.1 for the full design bending moment (SWBM+WIBM) and the existing structure, within the midships 0.4L of the vessel, to be adequate when applying the distribution factor to the WIBM only per SVR/6.3.2c. It should be noted that, with the lengthening of the PONCE DE LEON class vessels, the design SWBM was increased to 500,000 ft·LT due to a combination of loading and structural changes.

There is no clear indication of when or why the PONCE DE LEON class vessels received deck and bottom strapping, other than listing of the weight of bottom strapping and Main Deck doubler plates in the Preliminary Weight Estimate for the 1992-1993 conversion [23]. Whereas the original midship structural section does not reflect any kind of strapping, both the 1982 structural calculations and the 1992 scantling plans clearly indicate that the lengthened vessels were outfitted with significant strapping, both on the Main Deck and on the bottom shell. While a large portion of the deck strapping appears to be compensatory for vehicle ramp deck cutouts, a reduced amount of strapping was carried continuous through the midships portion of the vessel. The purpose of the bottom strapping is not clear but it does appear to have been carried uniformly throughout the midships portion of the vessel.

As previously mentioned, the Spar Deck between frames 128 and 162 was also added to the vessel during the lengthening in 1992-1993, and, as it was wholly located within the midships 0.4L of the vessel, it was not considered effective relative to the vessel's longitudinal strength.

7.2.3. Container Conversion (2005-2006) and Scantling Reassessments

In 2005-2006 the vessel was modified to carry containers on the Main Deck by removing the Spar Deck, reinforcing and supporting structure and adding a significant amount of additional fixed ballast. As a result of this conversion, the vessel's maximum molded draft was increased from 28.0 ft (28' 0") to 30.11 ft (30' 1-5/16").

While calculations were prepared to assess the adequacy of the tank scantlings relative to the permanent ballast installations, no structural analysis was prepared for the structural alterations or for the increase in scantling draft. Instead, the structure was accepted based upon the scantlings of the EL MORRO (Hull 666) having been accepted for a maximum molded draft of 30.75 ft (30' 9"). This was confirmed by Mr. Suresh Pisini in his MBI hearing testimony [39].

Subsequent to these alterations, a significant portion of the vessel, including the Main Deck and 2nd Deck plating, the aft peak tank and the innerbottom structure, was reassessed by ABS. While insufficient information was available for MSC to independently verify these re-assessments, ABS re-evaluated these structural elements relative to the 2007 SVR requirements and re-established corrosion allowances and minimum member thicknesses for renewal.

7.2.4. Post-Casualty Strength Analysis

After the loss of EL FARO, ABS conducted an analysis [72] of the hull girder section modulus (SM) to both the 1975 and 2015 (current) ABS class rule requirements, and also a buckling verification of the bottom shell and deck plating to the 2015 class rule requirements.

SM was evaluated amidships using as-built scantlings, amidships using scantlings from a 2011 gauging report [73], and at Frame 120 (in way of ramp openings) using the same as-gauged scantlings. Results of all three of these evaluations indicated that the EL FARO was in compliance with both 1975 and 2015 SM requirements in this regard.

ABS also evaluated buckling of the vessel in way of critical areas in both the bottom and deck structure reflecting the 2011 as-gauged scantlings and reflecting the maximum design bending moment. ABS further examined buckling stress in the bottom structure, using the as-gauged scantlings and an assumed bending moment at the time of the casualty. Results of these analyses indicated that the maximum stresses in both the bottom shell and upper deck plating were within the critical buckling limits of the 2015 class rule requirements.

With minimal differences, independent calculations performed by the MSC of these SM and buckling analyses generally confirmed these findings.

7.3. CargoMax Hull Girder Strength Assessment

As discussed in Section 2 of this report, a lightship weight distribution was created for the MSC GHS computer model, and bending moment calculations were included in assessment of the accident voyage 185S departure condition. Figure 7-3 provides a plot of the calculated still water bending moments. For comparison, bending moments calculated by CargoMax are included, along with the allowable still water bending moment.

The bending moments calculated using the MSC GHS computer model are approximately 13% higher amidships compared to the CargoMax values, but are still within the ABS allowable bending moment limits. The differences in calculated bending moments can be attributed to differences in the estimated lightship weight distribution.

As noted in Section 2 of this report, vessel loading and hull strength assessment, including lightship weight distribution and bending moment calculations, would be included in a vessel loading manual, and this would be reviewed and approved by ABS. However, based on the original date of construction, a loading manual was not required by any Coast Guard or classification society standard for EL FARO. It should also be noted from the ABS approval letter of the CargoMax software [21] that the software was neither reviewed nor approved for assessment of loading and hull strength, but it was nevertheless relied on by the Tote operations personnel for loading and hull strength assessment, based on MBI hearing testimony [18, 19, 20, 31, 32].

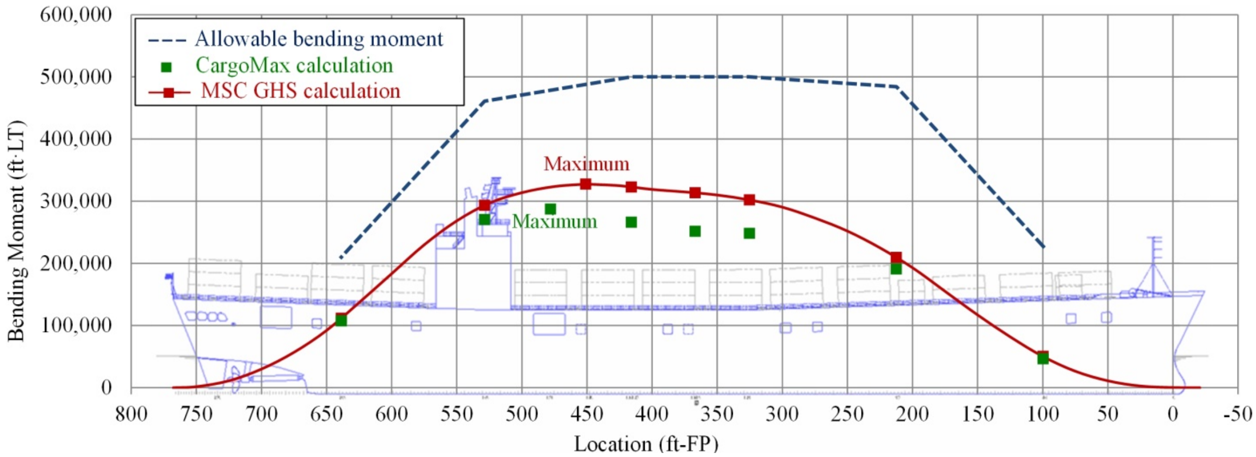

Figure 7-3: Calculated and allowable still water bending moments for the accident voyage 185S departure condition.

7.4. Summary

This section documented the MSC review of the ship structures, and provided a summary of the applicable structures criteria and review of documented structural assessments completed and approved by ABS. This section also provided a summary of the CargoMax application for hull girder strength assessment.

Based on the MSC review of the documentation available, it appears that the ship structures met all regulatory and classification society (ABS) structural requirements.

For the accident voyage, bending moments calculated using the MSC GHS computer model are approximately 13% higher amidships compared to the CargoMax values, but are still within the ABS allowable bending moment limits. The differences in calculated bending moments can be attributed to differences in the estimated lightship weight distribution.

8. Conclusions

The following provides a summary of key MSC observations and conclusions, listed by topic area:

(1) MSC computer model, and comparison with the T&S Booklet and CargoMax stability software:

a. Hull hydrostatic properties compared closely when comparing the T&S Booklet and CargoMax values to the MSC computer model, with approximately 0.1% difference in calculated displacement at the full load draft. All hydrostatic properties were within the tolerance of IMO MSC.1/Circ.1229, which has been used as an objective quality standard.

b. Comparison of tank volumes, centers and free surface inertia values identified discrepancies with T&S Booklet and CargoMax calculated values. Using IMO MSC.1/Circ.1229 as an objective quality standard, when comparing the T&S Booklet and CargoMax values to the MSC computer model, 19 tanks were in excess of the 2% tolerance for volume, and 22 tanks were in excess of the 2% tolerance for maximum slack free surface inertia. Based on additional MSC review of EL FARO and sister vessel T&S Booklets going back to the 1970s, it appears that errors were made in the original tank geometry definition and/or in the original numerical integration. It also appears that these discrepancies in tank values would apply to all of the vessels of the PONCE DE LEON class.

(2) Stability test, lightship calculations, and uncertainty analysis

a. Based on the MSC uncertainty analysis of the stability test, the uncertainty in the as-inclined GM was calculated to be approximately 0.2 feet (with 95% confidence). This means that there is a 95% confidence that the true value of GM in the as-inclined condition is within ±0.2 feet of the value calculated in the Stability Test Report. The uncertainty in the lightship KG was calculated to be approximately 0.7 feet (with 95% confidence), and the uncertainty in the GM for the accident voyage departure condition was calculated to be approximately 0.7 feet (with 95% confidence). The last statement means that there is a 95% confidence that the true value of the accident voyage GM was within ±0.7 feet of the calculated value.

(3) T&S Booklet and CargoMax stability software:

a. The CargoMax stability software used onboard the EL FARO and for load planning by shore-side personnel was neither reviewed nor approved for assessment of loading and hull strength since there was no loading manual required for the EL FARO. However, the EL FARO CargoMax software did contain features to assess hull strength, and the vessel operators relied on these features for assessment of hull girder bending moment in load planning.

b. The CargoMax software was neither reviewed nor approved for assessment of cargo loading and securing, including calculations required in the Cargo Securing Manual, which had been reviewed and approved by ABS. However, the EL FARO CargoMax software did contain features for assessment of cargo securing, and the vessel operators relied on these features for assessment of LO/LO container loading and securing.

c. With the exception of recent amendments to several IMO instruments applicable to oil, chemical and gas carriers, there are no requirements for the use of onboard software for vessel stability, strength or cargo loading and securing. Under Coast Guard policy, the master must be provided with the capability to manually calculate stability. However, he may use whatever tools he wishes to assist him in his responsibility to ensure satisfactory stability. The Coast Guard will, upon request, verify that the onboard stability software produces nearly identical results to the approved stability booklet in a number of representative loading conditions. After verification, the Coast Guard will recognize the software as an adjunct to the stability booklet; however, it remains incumbent upon the master to ensure the vessel is compliant with all aspects of the stability booklet.

(4) Intact and damage stability:

a. The MSC computer model was used to assess eight “benchmark” loading conditions defined by the MSC against intact stability criteria. The eight “benchmark” conditions included the full load departure and arrival conditions from the 1993 and 2007 T&S Booklets, a representative departure and arrival condition from August 2015 (voyage 178S), and the accident voyage (185S) departure condition and estimated condition at the time of loss of propulsion on October 1, 2015.

b. The eight “benchmark” loading conditions all met the applicable intact stability requirements of 46 CFR 170.170 (the GM “weather” criteria), which were applicable to the EL FARO at the time of the casualty. However, it is noted that the vessel was often operated very close to the maximum load line drafts, with minimal stability margin compared to the required GM, and little available freeboard and ballast capacity, leaving little flexibility for improving stability at sea if necessary due to heavy weather or flooding.

c. If EL FARO were constructed in 2016, she would be required to meet the righting arm criteria of Sections 2.2 and 2.3 of Part A of the 2008 IS Code. Of the eight “benchmark” conditions, only the 1997 T&S Booklet loading conditions would meet the righting arm criteria of Section 2.2. The actual operating conditions of voyage 178S and the accident voyage 185S would not meet the criteria based on limited available area (righting energy) between 30 and 40 degrees and insufficient angle of maximum righting arm. All of the eight conditions would meet the severe wind and rolling righting arm criteria of Section 2.3. In order to fully meet the intact stability criteria of Part A of the 2008 IS Code at the full load draft, the minimum required GM would be approximately 6.8 feet, which is 2.5 feet greater than the GM of the actual departure loading condition of the accident voyage. It is noted that paragraph 2.2.3 of Part A of the 2008 IS Code provides that "alternate criteria based on an equivalent level of safety may be applied subject to the approval of the administration" if obtaining the required 25 degree angle for maximum righting arm is "not practicable." Thus there could be permitted a relaxation of the limiting criteria for minimum angle of maximum righting arm (25 degrees), if allowed by the USCG on a case-by-case basis. In such a case the minimum required GM could be less, and could also become limited by the damage stability criteria.

d. Despite the 2-foot increase in the load line draft resulting from the 2005-2006 conversion for carrying LO/LO containers, there was no damage stability assessment completed to verify that the EL FARO would remain limited by the intact stability criteria for all loading conditions. Damage stability assessments conducted using the applicable 1990 SOLAS probabilistic stability standards demonstrate that for load conditions with two or fewer tiers of containers, the limiting stability criteria could be the damage stability criteria instead of the intact stability criteria, and this was not reflected on the minimum required GM curves of the T&S Booklet. However, for the departure condition of the accident voyage, the limiting stability criteria was the intact stability criteria, which was properly reflected in the T&S Booklet and incorporated in the CargoMax stability software. If EL FARO were constructed in 2016, she would be required to meet the 2009 SOLAS probabilistic damage stability standards. In order to fully meet these 2009 SOLAS damage stability standards at the full load draft, the minimum required GM would be approximately 5.8 feet, which is 1.5 feet greater than the GM of the actual departure loading condition of the accident voyage.

e. The righting arm curves for the EL FARO are generally characterized by relatively small area (righting energy) and range of stability compared to conventional cargo vessels (see Figure 5-6). These characteristics are especially significant in consideration of limited residual righting arms and righting energy with the vessel subjected to heeling forces and moments as might be experienced in heavy weather where high winds and seas can be expected. These characteristics are significant in consideration of limited residual righting arms and righting energy when subjected to flooding.

(5) Hydrostatic sinking analyses:

a. The MSC approach to the hydrostatic sinking analyses was fundamentally based on a first-principles assessment of flooding and wind heel, focusing on the righting arms, including righting energy and range of stability considerations. Effects of free surface effects due to the floodwater in the cargo holds were included.

b. The analyses results were highly sensitive to variation in permeability values, and a range of permeability values was used to assess impacts of the variability on the hydrostatics and stability. The evaluation of flooding required careful consideration of compartment permeability and "pocketing" effects. For permeability, this included significant variability in both overall fraction and uniformity throughout the cargo holds. This is especially important when considering containers, where permeability varies significantly depending on the assumed watertight integrity and specific locations of the containers.

c. The analyses results were highly sensitive to variation in wind speed, especially in combination with floodwater free surface, with variability of permeability and pocketing effects considered. Single compartment flooding of Hold 3 with combined wind heel of 70-90 knot beam winds resulted in very small residual righting arms and little residual righting energy. This would suggest that it would be highly unlikely that the EL FARO could have survived even single compartment uncontrolled flooding of Hold 3, given the sea conditions. This is illustrated in Figure 6-22 through Figure 6-24. To put this into perspective in terms of overall effects on righting arms and righting energy, Figure 8-1 adds several conditions with 80 knot beam winds and flooding of Hold 3 to the curves in Figure 5-6. It is clear from the minimal residual righting energy that with combined wind and flooding, the EL FARO would have had great difficulty surviving, when also considering the significant additional heeling energy imposed by the 25-30 foot seas she was encountering.

d. Potential sources of flooding of Hold 3 and the other cargo holds were investigated, including vulnerabilities associated with the cargo hold ventilation system. It was highlighted that the locations of the ventilation openings would likely result in at least intermittent flooding into the cargo holds, as the vessel was subject to a variable wave height on the side shell and rolled about the mean wind heel angle of around 15 degrees.

e. Based on the MSC analyses, regardless of the sources of flooding, the free surface associated with the floodwater in multiple cargo holds combined with hurricane force winds and seas would likely have resulted in the capsizing of the vessel. The capsizing may have been slowed or temporarily arrested as containers on deck began to wash overboard, but as the vessel slowly rolled onto her port side, floodwater would have entered through the ventilation openings into all of the cargo holds and the engine room, resulting in the sinking.

(6) Ship structures:

a. Based on the MSC review of the documentation available, the EL FARO ship structures met all regulatory and class structural requirements for strength.

b. For the accident voyage, bending moments calculated using the MSC GHS computer model are approximately 13% higher amidships compared to the

CargoMax values, but are still within the ABS allowable bending moment limits. The differences in calculated bending moments can be attributed to differences in the estimated lightship weight distribution.

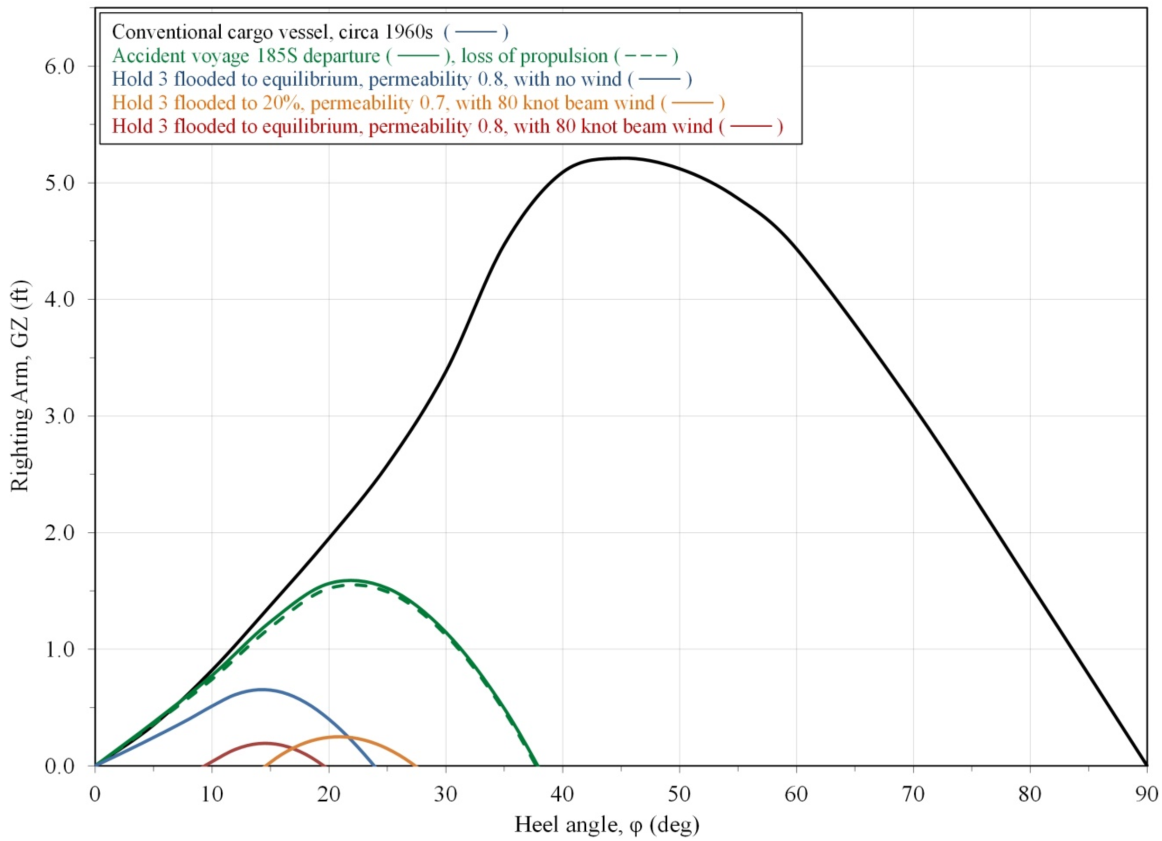

Figure 8-1: Righting arm curves for the accident voyage, with comparison to a conventional cargo vessel (conventional vessel curve reproduced from [51] with permission).

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Appendix A: Uncertainty Analysis of the Stability Test and Departure Condition

A.1. Introduction

The MSC was requested to review the EL FARO inclining experiment and Stability Test Report, and estimate the uncertainty in the vessel's lightship KG and in the GM for the accident voyage departure condition. This Appendix provides the detailed procedure and results for the requested uncertainty analysis. The analysis is based on the documentation available for the last stability test completed on the EL FARO on February 12, 2006 [A1 through A4], and the CargoMax accident voyage departure condition loading summary [A5].

It should be noted that there is no standard accepted procedure or guidance for completing an uncertainty analysis from the results of a stability test. The procedure undertaken by the MSC is based on an application of the principles of experimental uncertainty analysis, including assessment of potential sources of measurement errors, statistical analysis, and propagation of errors. The results of the analysis are fundamentally limited based on the size and type of vessel, the stability test procedure, the type of cargo and the specific loading condition. The results obtained for the uncertainty associated with the stability test and the lightship weight and center of gravity could be considered somewhat typical of similar large deep draft vessels. The additional uncertainty associated with the vessel loading condition can vary, depending on the particular type of cargo and loading procedures.

It is often the case that vessel operators consider the calculated GM, whether calculated by hand or by stability and loading software, to be fairly precise, and then operate the vessel fairly close to the minimum required GM. It is important to recognize that the actual GM may not be precisely known and uncertainty in the calculated GM can exist. However, calculated uncertainty in KG or GM for an operating condition should not be used to calculate a probability that the vessel would not meet the stability criteria for that operating condition. There is currently no consideration for uncertainty in assessing a vessel's stability in accordance with U.S. or international standards, as discussed in Section 5 of this report.

A.2. Background

A stability test (also called an inclining experiment) is conducted to experimentally determine a vessel's lightship weight (displacement) and location of the center of gravity, most importantly the vertical position or height of the center of gravity (KG or VCG). As with any experiment, errors in the measurements or measurement system create uncertainty in the results. The term "uncertainty" has been defined in this context as "a possible value that an error may have," and the term "uncertainty analysis" refers to the process of estimating how great an effect the uncertainties in the individual measurements have on the calculated result [A6, A7].

A thorough presentation of uncertainty analysis principles and techniques applied to a wide variety of experimental applications can be found in a variety of references. An excellent historical perspective on uncertainty analysis is provided by ITTC [A8]. One of the important aspects of this history is that despite the mathematical principles all being based on the same statistical principles, there is a wide variety of fundamental approaches and nomenclature that have been applied to uncertainty analyses over the years. Although there have been attempts to try to standardize around a single international standard with the International Standards Organization (ISO) "Guide to Expression of Uncertainty in Measurement" (ISO GUM), significant differences in techniques still exist, largely due to long-favored experimental approaches and unique experimental applications.

Most experimental uncertainty analysis techniques focus around statistical principles when an experimental measurement is repeated a large number of times, as is typically done in experimental hydrodynamics or other measurements where ensemble averaging can be used based on high sampling rates using electronic instrumentation and computer analysis. Basic statistical principles may be applied to uncertainty analysis whenever repeated measurements are made under fixed operating conditions. This is applicable to a portion of the ship inclining experiment, where a series of incremental transverse weight shifts are made and resulting angles measured. Uncertainty analysis is more difficult in engineering experiments which cannot be repeated enough times to provide useful statistical information, for reasons of cost or time [A7]. This is generally applicable to a portion of a ship inclining experiment, where only a single set of draft readings is taken to determine vessel hydrostatic properties including displacement. As will be shown in this case for the EL FARO, it is this portion of the stability test which introduces the most uncertainty in terms of the calculation of lightship KG and GM for the departure condition.

Historically for uncertainty analyses, sources of error have been considered as falling into one of two categories [A9, A10]. Systematic errors (also called bias or fixed errors) fundamentally remain constant in repeated measurements under fixed operating conditions, and may cause either a high or a low offset or bias in the estimate of the true value of the measured variable. Because the effect is constant, it is difficult to estimate or even recognize the contribution of a systematic error in an experimental measurement system, but it may be partially quantified through good modeling and calibration procedure, and in some sense by applying good engineering judgment to the experiment, in which systematic errors can be estimated from experience with similar experiments or measurement systems. Random errors (also called precision or variable errors) fundamentally are manifested as scatter of the measured data when repeated measurements are made under fixed operating conditions. Random errors arise due to measurement system resolution, environmental conditions causing random temporal and spatial variations, among other causes. Uncertainty associated with random errors may be quantified through repeated measurements under fixed operating conditions and statistical analysis.

For stability tests, there is an attempt in ASTM F1321 [A11] to specify precision of measurements taken in the inclining, but it does not address assessment of uncertainty for different error sources or quantities. Three papers were published in 1967, 1977, and 1985, which provide examples of uncertainty analyses of inclining experiments [A12, A13, A14]. The uncertainty analyses presented in those papers were based upon experience in construction and inclining operations at several large U.S. shipyards during the 1960s and 1970s, and can be considered good sources for baseline precision estimates associated with shipyard construction and inclining procedures, especially noting that the EL FARO was constructed in the mid-1970s at a large U.S. shipyard (Sun Shipbuilding). It is noted, however, that nomenclature and approach varied significantly. A modified nomenclature is adapted here for application to the EL FARO stability test.

As stated previously, uncertainty associated with random errors may be quantified through repeated measurements under fixed operating conditions and statistical analysis. A "single-sample" experiment is one in which each test point is run only once, or at most a few times [A7]. Normally it is desirable in single-sample experiments to run an auxiliary experiment in order to estimate the random component of uncertainty through statistical analysis of the auxiliary experiment. This usually takes the form of a set of independent measurements at a single representative test condition, with enough observations to establish a statistical basis which may be extended to other operating conditions. It should be noted that this is rarely done for draft measurement in an inclining experiment, so there is little statistical basis for quantifying uncertainty associated with random errors in draft readings and hydrostatic parameters. However, uncertainty in the reading of drafts may be assessed by making use of estimates of precision (for example per the guidance in ASTM F1321), and this may be applied to the results through an analysis of the propagation of the uncertainty in the measurements.

Propagation of error and uncertainty:

Consider a general functional equation of a result R which is a function of several variables [A9]

$$R = R(X_1, X_2, \dots, X_n) \tag{A-1}$$

The uncertainty in the result (U_R) is given by a root sum square (RSS) equation (derived from a Taylor Series expansion [A9, A10])

$$U_R = \sqrt{\left(\frac{\partial R}{\partial X_1} U_{X_1}\right)^2 + \left(\frac{\partial R}{\partial X_2} U_{X_2}\right)^2 + \dots + \left(\frac{\partial R}{\partial X_N} U_{X_N}\right)^2} \tag{A-2}$$

where U_{Xi} are the uncertainties in each of the measured variables X_i. The partial derivatives are often referred to as "sensitivity coefficients", since they reflect how the result changes with changes in each individual variable with other variables held constant. Therefore, each term represents the contribution made by each variable. Note that the uncertainty in the result U_R is the total uncertainty and has the same units as R.

Whenever the functional equation involves products, the uncertainty can be simplified and rewritten in terms of "relative uncertainties." For the general "product" form

$$R = X_1^a X_2^b X_3^c \dots X_N^n \tag{A-3}$$

the uncertainty can be simplified and written

$$\left(\frac{U_R}{R}\right) = \sqrt{\left(a\frac{U_{X_1}}{X_1}\right)^2 + \left(b\frac{U_{X_2}}{X_2}\right)^2 + \dots + \left(n\frac{U_{X_N}}{X_N}\right)^2} \tag{A-4}$$

This is in terms of relative uncertainties, which provides uncertainties as fractions (which can be converted to % by multiplying by 100). This is a convenient form as it shows clearly by each term the fraction (or %) of the total being contributed by each measured variable.

In this Appendix, for presentation clarity, the relative uncertainties will be written in a condensed or shorthand notation as

$$\widehat{U}_R \equiv \left(\frac{U_R}{R}\right) \quad \widehat{U}_{X_i} \equiv \left(\frac{U_{X_i}}{X_i}\right)$$

Depending on the relationship, either uncertainty result may be useful, as will be shown subsequently.

As stated previously, the term "uncertainty" has been defined as "a possible value that an error may have" [A6]. Therefore it is necessary to state to what confidence there is in any stated level of uncertainty. Indeed, the representation of any uncertainty must include the confidence level (sometimes referred to as "confidence interval" or "probability") of the uncertainty. These confidence levels should originate with the measurement statistics, but they are often based on experience from past experiments for certain measurement systems. The confidence level remains part of the uncertainty in the data reduction or propagation. In equation form, for a C% confidence that the true value of R lies within the interval $\pm U_R$ from the calculated (estimated) value of R:

$$R_{true} = R_{estimate} \pm U_R\ (C\%) \tag{A-5}$$

Historically, different confidence levels have been favored for documentation by different investigators or organizations. The ISO GUM suggest using a "standard error" ($1\sigma = 68.3\%$ confidence), but it is more common in the U.S. to see the 95% confidence level used (approximately $2\sigma = 95.5\%$), or in older literature 50% or even 99.7% (3σ) have been used. However the chosen confidence level does not change the final result since U_R can be converted from one confidence level to the other as desired.

A.3. Uncertainty in the As-Inclined GM

Basic relation:

In a stability test (inclining experiment), the equation for calculating the metacentric height (GM) in the as-inclined condition is [A11]

$$GM = \frac{w \cdot a}{\Delta \cdot tan\theta} = \left(\frac{w \cdot a}{tan\theta}\right) \cdot \left(\frac{1}{\Delta}\right) \tag{A-6}$$

where w is the weight of the inclining weights (LT), a is the distance inclining weights are moved (ft), $\tan\theta$ is the tangent of the angle of heel induced by the movement of the inclining weights, and Δ is the vessel displacement or total weight in the as-inclined condition (LT).

The first term is determined from the slope of the "best fit" line from the plot of the applied moment (w·a) and measured angle tangent (tanθ) for a series of sequential weight movements. The second term is determined by calculation of the displacement using the measured drafts and the hull offsets. In order to calculate the uncertainty in as-inclined GM, the uncertainty in each term must be calculated based on the experimental method, and then combined.

Equation A-6 can be rewritten in terms of the "best fit" slope and displacement:

$$GM = \left(\frac{1}{slope}\right) \cdot \left(\frac{1}{\Delta}\right) = (slope)^{-1} \cdot (\Delta)^{-1} \quad \text{(A-7)}$$

where the slope is that of the "best fit" line from the x-y plot of applied moment (independent variable, x) and measured tangent (dependent variable, y). The slope is typically calculated by computer by the method of least-squares (but was historically determined by hand from the plot by manual estimation).

Since this expression for GM in equation A-7 is a product, the uncertainty can be calculated (equation A-4)

$$\left(\frac{U_{GM}}{GM}\right) = \sqrt{\left(\frac{U_{slope}}{slope}\right)^2 + \left(\frac{U_{\Delta}}{\Delta}\right)^2} \quad \text{(A-8)}$$

where U_{GM} is the uncertainty in GM, U_{slope} is the uncertainty in slope, and U_{Δ} is the uncertainty in displacement. In shorthand notation:

$$\widehat{U}_{GM} = \sqrt{\widehat{U}_{slope}^2 + \widehat{U}_{\Delta}^2} \quad \text{(A-9)}$$

Uncertainty in the slope:

For the EL FARO inclining experiment completed in 2006 [A1 through A4], each of seven steps or "trials" involved moving two or three inclining weights in sequence from port to starboard or starboard to port (initially, five weights were placed port and five weights were placed starboard). For each trial, three independent pendulums were used to measure the tangent of the induced angle. Thus there were 21 measurements of tangent (three in each of the seven trials) which could be used in the determination of the slope. The measurement data from the Inclining Experiment Record Sheet [A3] with additional calculation of moments and tangents are provided in Table A-1.

A "best fit" slope is easily calculated using the ordinary linear least-squares regression method using a spreadsheet calculation. In Excel this is implemented through the basic TRENDLINE function, but additional statistics on the linear least-squares fit are provided using the LINEST function, which includes calculation of the least-squares slope and intercept, along with standard error of the slope, standard error of the intercept, and additional statistics of the fit.

The ordinary linear least-squares regression assumes a linear equation of the form

$$y = mx + b \tag{A-10}$$

where x is the independent variable and y is the dependent variable, m is the slope, and b is the y-intercept. For ordinary least-squares, all data points (i) are assumed to have the same error or uncertainty in y_i, and no error or uncertainty in x_i, and as a result each data point is given equal weight in the regression. Based on the ordinary least-squares regression, the slope m and intercept b are calculated [A9]

$$m = \frac{N\sum x_i y_i - \sum x_i \sum y_i}{N\sum x_i^2 - (\sum x_i)^2} \qquad b = \frac{\sum x_i^2 \sum y_i - \sum x_i \sum (x_i y_i)}{N\sum x_i^2 - (\sum x_i)^2} \tag{A-11}$$

where the summation is from 1 to N data points. The standard error of the estimate (predicted value of y) is

$$S_y = \sqrt{\frac{\sum\big(y_i - (mx_i + b)\big)}{N-2}} \tag{A-12}$$

And the standard error (68.3% confidence) of the slope is

$$S_{slope} = S_m = S_y\sqrt{\frac{N}{N\sum x_i^2 - (\sum x_i)^2}} \tag{A-13}$$

With N = 21 in the EL FARO inclining experiment, the 95% confidence uncertainty is approximately twice the standard error of the slope (actually 2.093 times the standard error, based on the t-distribution with N-2 = 19 degrees of freedom [A9]). Table A-2 lists the calculated slope, standard error of the slope, 95% confidence uncertainty, and 95% confidence relative uncertainty.

Trial #	Weight #	Weight (LT)	Distance Moved (ft)	Moment (ft·LT)	Trial Moment (ft·LT)	Pendulum #	Pendulum Length (in)	Pendulum Movement (in)	Tangent
1	1	18.571	88.0	1,634.3	3,286.3	1	199.38	1.52	0.00762
	3	18.772	88.0	1,652.0	3,286.3	2	203.13	1.62	0.00798
					3,286.3	3	331.50	2.56	0.00772
2	5	18.839	97.0	1,827.4	8,578.1	1	199.38	4.06	0.02036
	7	18.839	97.0	1,827.4	8,578.1	2	203.13	4.11	0.02023
	9	18.603	88.0	1,637.0	8,578.1	3	331.50	6.63	0.02000
3	3	18.772	-88.0	-1,652.0	5,098.7	1	199.38	2.53	0.01269
	5	18.839	-97.0	-1,827.4	5,098.7	2	203.13	2.44	0.01201
					5,098.7	3	331.50	4.01	0.01210
4	1	18.571	-88.0	-1,634.3	0.0	1	199.38	-0.04	-0.00020
	7	18.839	-97.0	-1,827.4	0.0	2	203.13	0.00	0.00000
	9	18.603	-88.0	-1,637.0	0.0	3	331.50	-0.04	-0.00012
5	2	18.683	-96.0	-1,793.6	-5,201.7	1	199.38	-2.40	-0.01204
	8	18.504	-88.0	-1,628.4	-5,201.7	2	203.13	-2.44	-0.01201
	10	18.348	-97.0	-1,779.8	-5,201.7	3	331.50	-3.99	-0.01204
6	4	18.884	-88.0	-1,661.8	-8,529.2	1	199.38	-3.97	-0.01991
	6	18.929	-88.0	-1,665.7	-8,529.2	2	203.13	-3.99	-0.01964
					-8,529.2	3	331.50	-6.62	-0.01997
7	2	18.683	96.0	1,793.6	-3,294.1	1	199.38	-1.55	-0.00777
	4	18.884	88.0	1,661.8	-3,294.1	2	203.13	-1.56	-0.00768
	10	18.348	97.0	1,779.8	-3,294.1	3	331.50	-2.54	-0.00766

Table A-1: Inclining measurement data with additional calculation of moments and tangents for slope calculation. Distances and moments are (+) for starboard and (–) for port.

It was stated that the ordinary least-squared regression assumes that all data points have the same error or uncertainty in y_i, and no error or uncertainty in x_i, and as a result each data point is given equal weight in the regression. However, in the more general case of unequal uncertainties in y_i (and perhaps also uncertainties in x_i), a weighted least-squares method can be applied. The foundation of this method applies a “best fit” by minimizing the sum of the weighted squared residuals (differences between the observed and calculated values) to each x_i and y_i value pair (see [A15, A16]). The weighting factors applied to each x_i and y_i are typically assigned as the inverse squares of the uncertainties in the data values of x_i and y_i. As a result, the general effect of the weighted linear least-squares method is that the fit favors the data points with smaller uncertainties at the expense of those with larger uncertainties. In general, this also reduces the standard error and uncertainty of the slope. A spreadsheet calculation implementing the method developed by Reed [A16] provides weighted least-squares results provided in Table A-2. Note that the standard error and uncertainty of the slope are significantly reduced with the weighted least-squares compared to the ordinary (unweighted) least-squares. Regardless, it will be shown that in this case the uncertainty in the slope is small compared to the uncertainty in displacement, so the resulting uncertainty in as-inclined GM is only minimally changed by the least-squares method chosen.

	Ordinary Least-Squares	Weighted Least-Squares
Slope (tangent/moment) (1/ft·LT)	2.3460×10^{-6}	2.3432×10^{-6}
Standard error of the slope, S_{slope} (1/ft·LT)	7.98×10^{-9}	1.61×10^{-9}
Uncertainty of the slope (95%), U_{slope} (1/ft·LT)	16.68×10^{-9}	3.37×10^{-9}
Relative uncertainty (95%), $\widehat{U}_{slope}$	0.0071 (0.71%)	0.0014 (0.14%)

Table A-2: Slope, standard error of the slope, 95% confidence uncertainty of the slope, and 95% confidence relative uncertainty.

To apply the weighted least-squares method, the weighting factors are chosen as the inverse of the uncertainties in the values of moment and tangent for each data point. These are calculated based on first-order estimates of uncertainties in the individual inclining weights, distance moved, and tangent of the induced angle, based on the EL FARO Stability Test Report and Inclining Experiment Record Sheet [A2, A3]. Results are provided in Table A-3, with the methodology summarized below. Figure A-1 shows the data points, the linear fit based on the ordinary least-squares method, and error bars showing the estimated 95% confidence level uncertainties for each data point.

The uncertainty in the weight of the inclining weights has several sources. The scale used to measure the weights has an uncertainty which arises from the resolution of the scale (i.e. how precisely the scale display can be read or discerned), but also uncertainties related to the linearity and hysteresis of the scale, and the procedure for weight measurement. The EL FARO Stability Test Report and Inclining Experiment Record Sheet [A2, A3] state a scale precision of ±750 lb or 1.5% of the full scale of 50,000 lb. It is noted however that the calibration certificate included in the ABS Surveyor's Report [A4] appears to show an error or precision of -0.5%. However it appears that there is a bias or systematic source of error since all readings vary precisely -0.5% compared to the calibration weights and there appears to be no random error in the calibration. Additionally, the calibration certificate also shows an accuracy of ±1% for the calibration source, and it is possible that it was on this basis that the test engineers cited ±1.5% as the uncertainty stated on the Inclining Experiment Record Sheet. It is also assumed that this overall uncertainty refers to the 95% confidence uncertainty. Since there is no detail given about the scale display, it is assumed that the display resolution uncertainty is small compared to the calibration uncertainty, although for an analog display scale this may not be the case. During the EL FARO inclining, each of the 7 trials or steps involved moving 2 or 3 of the 10 inclining weights in sequence from port to starboard or starboard to port (initially, 5 weights were placed port and 5 weights were placed starboard). Weights were provided in the Inclining Experiment Record Sheet [A3]. It was also stated in the notes of the Stability Test Report that there was up to 100 lb of rain water in the padeye recess for many of the weight blocks while they were weighed, and up to 15 lb remaining during the inclining. Because the process for subtraction of this water weight was not clear, additional uncertainty should be added on this basis, but this was not included in this analysis.

Although the placement and measurement of the distance moved for each weight block can be determined precisely if high-tech methods are used (for example, using laser measurement systems), in practice common hand-measurement methods for a carefully-conducted inclining provide an uncertainty on the order of 5/8 inch in 50 feet at 50% probability [A12]. Therefore the relative uncertainty in the distance shifted at the 95% confidence level is

$$\hat{U}_a = \left(\frac{U_a}{a}\right) = 3.0 \cdot \frac{(5/8\,in)(1ft/12in)}{50\,ft} = 0.003 = \ 0.3\% \ \ (95\%)$$

Note that the factor 3.0 converts uncertainty at the 50% confidence level [A12] to the 95% confidence level. Note also that the relative uncertainty of the distance moved is small compared to the relative uncertainty of the weight measurement.

The moment for each weight movement is calculated as the product of the weight and distance moved. Therefore the total uncertainty in the moment for each block move is (equation A-4)

$$\left(\frac{U_{moment}}{moment}\right) = \sqrt{\left(\frac{U_w}{w}\right)^2 + \left(\frac{U_a}{a}\right)^2}$$

As an example, for weight #1 in trial #1 (see Table A-3) the calculated moment and moment uncertainty are:

$$\hat{U}_{moment} = \left(\frac{U_{moment}}{moment}\right) = \sqrt{(0.015)^2 + (0.003)^2} = 0.0153$$
$$moment = w \cdot a = (18.571\,LT)(88.0\,ft) = 1{,}634.3\,ft \cdot LT$$
$$U_{moment} = 0.0153 \cdot 1{,}634.3\,ft \cdot LT = \ 25.0\,ft \cdot LT \ (95\%)$$

For each trial, the total moment is simply the sum of the moments for the weight blocks moved in that trial. Therefore the total moment uncertainty for each trial is simply the root sum square of the uncertainties of each weight moved (equation A-2).

The accuracy of measurement of the angle of induced heel is affected by a number of factors including wind, tides and currents, mooring arrangements, and movement of people and equipment (for small or tender vessels), in addition to equipment and procedural sources of error. ASTM F1321 provides guidance on test conditions and procedures for precision in measurement using pendulums, but does not provide specific guidance on assessing the uncertainty in the results of the inclining. While ASTM F1321 recommends that pendulum lengths and readings be precise to within 1/16 inch, in practice due to dynamic and procedural effects, common manual measurement methods provide uncertainty on the order of 1/8 inch [A12, A13]. The EL FARO Stability Test Report and Inclining Experiment Record Sheet [A2, A3] list pendulum lengths of 199.38 in, 203.13 in and 331.50 in. For this assessment, a practical measurement uncertainty value of 1/8 inch (at 95% confidence) is used, noting that the ASTM suggested precision of 1/16 inch, would likely only be achieved with a standard confidence (68.3%), which is equivalent to the 1/8 inch at the 95% confidence. As an example, for pendulum #1 in trial #1 (see Table A-3) the calculated tangent and uncertainty in the tangent are:

$$tan\theta = \frac{1.52\,in}{199.38\,in} = 0.00762 \qquad U_{tan\theta} = \frac{1/8\,in}{199.38\,in} = \ 0.00063\ (95\%)$$

The uncertainties in moment and tangent for each of the 21 measurements are plotted as error bars in Figure A-1. Note that the relative uncertainties of the moment values at only 1.5% are much smaller compared to the relative uncertainties of the tangent values, so the error bars for the moment values are difficult to see in the figure.

The use of the linear least-squares fit for calculation of the standard error and uncertainty of the slope assumes that errors associated with each data point measurement would be normally distributed if taken many times at each particular operating condition. Therefore the calculated standard error and uncertainty of the slope includes only a random component of uncertainty. If systematic or bias errors in the measurement or measurement system exist, they are not included in the error estimate. It has been assumed in this procedure that any systematic or bias errors of the measurements of weight, distance moved and angle tangent are small and can be neglected.

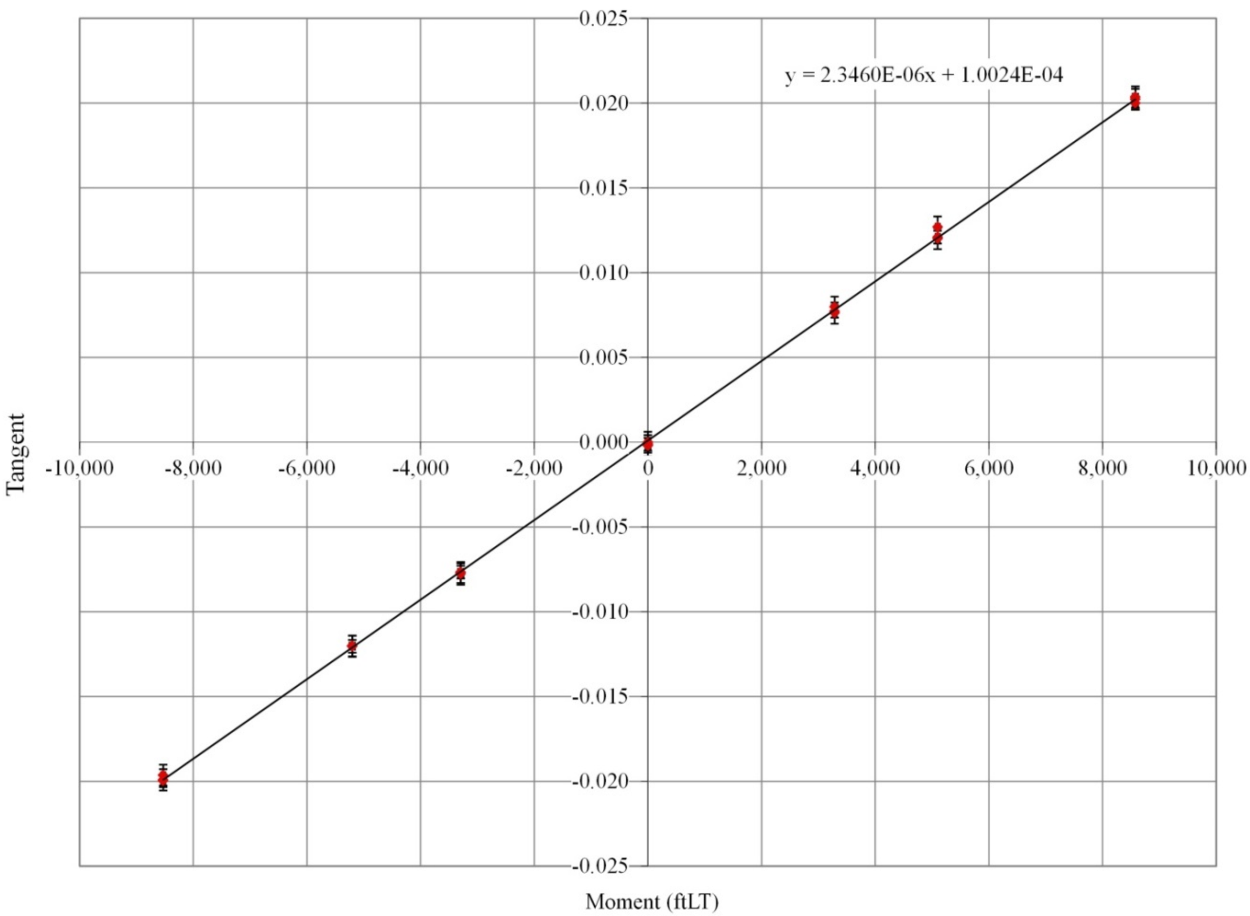

Figure A-1: Plot of moment vs. tangent data from the inclining with standard least-squares linear fit. Error bars show estimated 95% confidence level uncertainties for each data point based on separate error assessment.

Trial #	Weight #	Weight (LT)	Weight Rel Unc (1.5%)	Weight Unc (LT)	Distance Moved (ft)	Distance Rel Unc (0.3%)	Distance Unc (ft)	Moment (ft·LT)	Moment Rel Unc	Moment Unc (ft·LT)	Trial Moment (ft·LT)	Trial Moment Unc (ft·LT)	Pendulum #	Pendulum Length (in)	Pendulum Movement (in)	Pendulum Movement Unc (1/8 in)	Tangent	Tangent Unc
1	1	18.571	0.015	0.279	88.0	0.003	0.26	1,634.3	0.015	25.0	3,286.3	35.5	1	199.38	1.52	0.125	0.00762	0.00063
	3	18.772	0.015	0.282	88.0	0.003	0.26	1,652.0	0.015	25.3	3,286.3	35.5	2	203.13	1.62	0.125	0.00798	0.00062
											3,286.3	35.5	3	331.50	2.56	0.125	0.00772	0.00038
2	5	18.839	0.015	0.283	97.0	0.003	0.29	1,827.4	0.015	28.0	8,578.1	46.8	1	199.38	4.06	0.125	0.02036	0.00063
	7	18.839	0.015	0.283	97.0	0.003	0.29	1,827.4	0.015	28.0	8,578.1	46.8	2	203.13	4.11	0.125	0.02023	0.00062
	9	18.603	0.015	0.279	88.0	0.003	0.26	1,637.0	0.015	25.0	8,578.1	46.8	3	331.50	6.63	0.125	0.02000	0.00038
3	3	18.772	0.015	0.282	-88.0	0.003	-0.26	-1,652.0	0.015	-25.3	5,098.7	37.7	1	199.38	2.53	0.125	0.01269	0.00063
	5	18.839	0.015	0.283	-97.0	0.003	-0.29	-1,827.4	0.015	-28.0	5,098.7	37.7	2	203.13	2.44	0.125	0.01201	0.00062
											5,098.7	37.7	3	331.50	4.01	0.125	0.01210	0.00038
4	1	18.571	0.015	0.279	-88.0	0.003	-0.26	-1,634.3	0.015	-25.0	0.0	45.1	1	199.38	-0.04	0.125	-0.00020	0.00063
	7	18.839	0.015	0.283	-97.0	0.003	-0.29	-1,827.4	0.015	-28.0	0.0	45.1	2	203.13	0.00	0.125	0.00000	0.00062
	9	18.603	0.015	0.279	-88.0	0.003	-0.26	-1,637.0	0.015	-25.0	0.0	45.1	3	331.50	-0.04	0.125	-0.00012	0.00038
5	2	18.683	0.015	0.280	-96.0	0.003	-0.29	-1,793.6	0.015	-27.4	-5,201.7	46.0	1	199.38	-2.40	0.125	-0.01204	0.00063
	8	18.504	0.015	0.278	-88.0	0.003	-0.26	-1,628.4	0.015	-24.9	-5,201.7	46.0	2	203.13	-2.44	0.125	-0.01201	0.00062
	10	18.348	0.015	0.275	-97.0	0.003	-0.29	-1,779.8	0.015	-27.2	-5,201.7	46.0	3	331.50	-3.99	0.125	-0.01204	0.00038
6	4	18.884	0.015	0.283	-88.0	0.003	-0.26	-1,661.8	0.015	-25.4	-8,529.2	36.0	1	199.38	-3.97	0.125	-0.01991	0.00063
	6	18.929	0.015	0.284	-88.0	0.003	-0.26	-1,665.7	0.015	-25.5	-8,529.2	36.0	2	203.13	-3.99	0.125	-0.01964	0.00062
											-8,529.2	36.0	3	331.50	-6.62	0.125	-0.01997	0.00038
7	2	18.683	0.015	0.280	96.0	0.003	0.29	1,793.6	0.015	27.4	-3,294.1	46.3	1	199.38	-1.55	0.125	-0.00777	0.00063
	4	18.884	0.015	0.283	88.0	0.003	0.26	1,661.8	0.015	25.4	-3,294.1	46.3	2	203.13	-1.56	0.125	-0.00768	0.00062
	10	18.348	0.015	0.275	97.0	0.003	0.29	1,779.8	0.015	27.2	-3,294.1	46.3	3	331.50	-2.54	0.125	-0.00766	0.00038

Table A-3: Inclining measurement data with calculation of moments and tangents, and estimated 95% confidence level uncertainties for each data point based on error assessment. Distances and moments are (+) for starboard and (–) for port.

Uncertainty in the displacement:

Assessment of the uncertainty in the calculated as-inclined displacement (U_Δ) requires consideration of a number of independent sources of error, since the displacement is a derived quantity based on measurement of drafts, calculation of the submerged volume from the ship's lines, and measurement of water density

$$\Delta = \gamma \cdot \nabla \tag{A-14}$$

Note that this is just an expression of Archimedes' Principle. Since this is a simple product, the relative uncertainty in as-inclined displacement can be written

$$\hat{U}_\Delta = \sqrt{\hat{U}_\nabla^2 + \hat{U}_\gamma^2} \tag{A-15}$$

where $\hat{U}_\nabla$ is the relative uncertainty in displacement volume and $\hat{U}_\gamma$ is the relative uncertainty in water density (more precisely specific weight, $\gamma = \rho g$).

Displacement volume is calculated from integration of the lines, and is therefore a function of the longitudinal, transverse and vertical dimensions of the lines or offsets, as well as the actual vessel drafts. The uncertainty in displacement volume can therefore be written

$$U_\nabla = \sqrt{\left(\frac{\partial\nabla}{\partial V}U_V\right)^2 + \left(\frac{\partial\nabla}{\partial d}U_d\right)^2 + \left(\frac{\partial\nabla}{\partial m}U_m\right)^2}$$

where U_V is the uncertainty in volume between the molded lines and the as-built lines, U_d is the uncertainty in drafts, and U_m is the uncertainty in (calculated) volume from the molded lines.

Note that the partial derivatives $\partial\nabla/\partial V$ and $\partial\nabla/\partial m$ are both equal to 1, and $\partial\nabla/\partial d$ is the waterplane area (A_{wp}), therefore

$$U_\nabla = \sqrt{(U_V)^2 + \left(A_{wp} \cdot U_d\right)^2 + (U_m)^2} \tag{A-16}$$

The uncertainty in volume between the molded lines and the as-built dimensions can be separated into differences in longitudinal, transverse, and vertical dimensions, with the uncertainty in volume being the product of these. Therefore, the relative uncertainty can be written

$$\hat{U}_V = \sqrt{\hat{U}_L^2 + \hat{U}_B^2 + \hat{U}_D^2} \tag{A-17}$$

where $\hat{U}_L$ is the relative uncertainty in longitudinal dimension between molded and as-built lines, $\hat{U}_B$ is the relative uncertainty in transverse dimension between molded and as-built lines, and $\hat{U}_D$ is the relative uncertainty in vertical dimension between molded and as-built lines.

Each of these dimensions has uncertainty associated with construction tolerances plus deflection and distortion of the hull during construction. Construction tolerances may be specified but are fundamentally attributable to the construction processes, and therefore vary from shipyard to shipyard and even vessel to vessel. Typical construction tolerances given the shipyard construction processes in the 1960s and 1970s can be estimated [A12, A13] as

Length = ±1 inch per 100 ft length
Beam = ± 1 inch
Depth = ± ½ inch

In addition to these construction tolerances, the ship and the ways or drydock move continuously during construction due to a variety of causes including ambient temperature changes, including due to direct sunlight, progress of welding, settlement under load, tidal effects, etc. For example at Newport News in the 1960s and 1970s, the complex of ship and drydock could settle as much as ¾ in and the keel at the extreme ends could move up and down ¾ in with temperature changes and welding progress, and athwartships shifts of the vessel's centerline due to temperature and welding of 1 in, and length changes up to ¾ in [A12].

The relative uncertainties associated with construction tolerances plus deflection and distortion can be combined as

$$\hat{U}_L = \sqrt{\hat{U}_{L1}^2 + \hat{U}_{L2}^2} \quad \hat{U}_B = \sqrt{\hat{U}_{B1}^2 + \hat{U}_{B2}^2} \quad \hat{U}_D = \sqrt{\hat{U}_{D1}^2 + \hat{U}_{D2}^2} \qquad \text{(A-18)}$$

where subscript 1 refers to uncertainty due to construction tolerances and subscript 2 refers to uncertainty due to hull deflection and distortion during construction. Using the principal dimensions of the EL FARO (molded length overall, beam and depth), the associated uncertainties are

$$U_{L1} = \frac{1\,in}{100\,ft} \cdot 790.75\,ft = 7.91\,in = 0.659\,ft\ (95\%)$$
$$\hat{U}_{L1} = \frac{0.659\,ft}{790.75\,ft} = 0.083\%\ or\ 0.00083\ (95\%)$$
$$U_{L2} = 0.75\,in = 0.0625\,ft\ (95\%)$$
$$\hat{U}_{L2} = \frac{(3/4\,in)(1ft/12in)}{790.75\,ft} = 0.008\%\ or\ 0.00008\ (95\%)$$
$$U_{B1} = 1.0\,in = 0.0833\,ft\ (95\%)$$
$$\hat{U}_{B1} = \frac{0.0833\,ft}{92.0\,ft} = 0.091\%\ or\ 0.00091\ (95\%)$$
$$U_{B2} = 1.0\,in = 0.0833\,ft\ (95\%)$$
$$\hat{U}_{B2} = \frac{0.0833\,ft}{92.0\,ft} = 0.091\%\ or\ 0.00091\ (95\%)$$
$$U_{D1} = 0.5\,in = 0.0417\,ft\ (95\%)$$

$$\widehat{U}_{D1} = \frac{0.0417\,ft}{60.14\,ft} = 0.069\%\ or\ 0.00069\ (95\%)$$
$$U_{D2} = 0.75\,in = 0.0625\,ft\ (95\%)$$
$$\widehat{U}_{D2} = \frac{0.0625\,ft}{60.14\,ft} = 0.104\%\ or\ 0.00104\ (95\%)$$
$$\widehat{U}_{L} = 0.083\% = 0.00083\ (95\%)$$
$$\widehat{U}_{B} = 0.128\% = 0.00128\ (95\%)$$
$$\widehat{U}_{D} = 0.125\% = 0.00125\ (95\%)$$

and

$$\widehat{U}_{V} = \sqrt{\widehat{U}_{L}^{2} + \widehat{U}_{B}^{2} + \widehat{U}_{D}^{2}} = 0.00197 = 0.20\%\ (95\%)$$
$$U_{V} = \widehat{U}_{V} \cdot \nabla = (0.00197)(849{,}228\,ft^{3}) = 1{,}673\,ft^{3}$$

where the displacement volume has been calculated using the MSC GHS computer model for the measured drafts of the as-inclined condition.

Uncertainty in drafts comes from multiple sources, including uncertainty in measurement of the drafts during the inclining (i.e. how precisely the waterline on the draft markings can be read or discerned), uncertainty in the location of the marks relative to the baseline (i.e. vessel datum) due to layout and installation, uncertainty in the location of the marks relative to the baseline due to hull deflection or distortion during installation (due to temperature and welding and other sources), and uncertainty of the drafts due to hull deflection and trim during the inclining. These contributions are additive so the uncertainty can be written

$$U_{d} = \sqrt{U_{d1}^{2} + U_{d2}^{2} + +U_{d3}^{2} + U_{d4}^{2}} \qquad \text{(A-19)}$$

where U_{d1} is the uncertainty in drafts due to measurement during inclining, U_{d2} is the uncertainty in drafts due to layout and installation, U_{d3} is the uncertainty in drafts due to hull deflection and distortion during installation, and U_{d4} is the uncertainty in drafts due to hull deflection and trim during inclining.

The uncertainty in the drafts due to measurement includes a number of important factors, including the resolution of the draft markings themselves, how carefully the observer views, interpolates and averages the fluctuating waterline over the timeframe of the reading, the amplitude of local water level fluctuations due to wind, waves and currents, plus additional procedural effects such as viewing angle, proximity, etc. While ASTM F1321 suggests that draft "precision" should be to the nearest 1/8 in, Wood [A13] states an uncertainty in reading draft marks at Ingalls Shipbuilding of 0.5 in with 99% or 3σ confidence (3/8 in with 95% or 2σ confidence), and this is certainly more realistic given common practice. Shakshober and Montgomery [A12] cite uncertainty at Newport News of 1/2 in and 3/8 in for layout and installation, and hull deflection and distortion during installation, respectively. The uncertainty in drafts due to hull deflection and trim depends on how well the drafts measured and entered into the hydrostatic calculation program represent the trim and deflection of the hull in the as-inclined condition, and also whether or not the hydrostatic calculation program calculates the trimmed deflected waterline directly from the offsets or indirectly from Bonjean curves.

Methods for estimating equivalent drafts and estimating uncertainty of trimmed and deflected waterlines are provided by Shakshober and Montgomery [A12] and Hansen [A14]. However, since hull deflection and trim were accounted for in the EL FARO Stability Test Report based on direct integration of the waterlines using a parabolic curve fit, this contribution to uncertainty can be considered relatively small in this case, and is neglected. Therefore the uncertainty in drafts is

$$U_{d1} = 0.375\ in = 0.03125\ ft \text{ (95\%)}$$
$$U_{d2} = 0.5\ in = 0.0417\ ft \text{ (95\%)}$$
$$U_{d3} = 0.375\ in = 0.03125\ ft \text{ (95\%)}$$
$$U_{d4} = 0\ in$$

and

$$U_d = \sqrt{U_{d1}^2 + U_{d2}^2 + U_{d3}^2 + U_{d4}^2} = 0.73\ in = 0.0607\ ft \text{ (95\%)}$$

The waterplane area (A_{wp}) has been calculated using the MSC GHS computer model for measured drafts of the as-inclined condition as 47,879 ft^2.

It is noted in the Stability Test Report that only draft readings were used in the hydrostatic calculations, in lieu of combined draft and freeboard measurements or all freeboard measurements per the guidance in ASTM F1321. However, if freeboard measurements had also been used, additional uncertainty associated with location of the freeboard measurement references relative to the datum, and measurement of the freeboards themselves, would have been introduced, and would need to be added (by the root-sum-square). Based on discrepancies with freeboard references noted in the EL FARO documentation, test engineers decided not to use the freeboard measurements in the hydrostatic calculations, and therefore the freeboard uncertainties do not need to be included in this uncertainty analysis.

When computer calculations are used, the uncertainty in (calculated) volume from the molded lines (U_m) is associated with how precisely the lines are digitized, how closely the hull station spacing and placement represents the shape of the hull form, and the precision of the numerical integration technique itself (i.e. differences between Simpson's Rule and Trapezoidal Rule integrations). The International Association of Class Society (IACS) Unified Requirement L5 (Onboard Computers for Stability Calculations) [A17], sets limits on acceptable tolerances in comparing computer calculated hydrostatic parameters to approved hydrostatic values. For displacement, the acceptable tolerance is stated as 2% of the displacement. This is a likely upper bound on the variability of calculated displacement based on the molded lines, and might be used as a relative uncertainty in (calculated) volume from the molded lines at the 95% confidence level. However, a more "optimistic" estimate of 1% is used here. Using the MSC GHS computer model developed from the ship's lines, and comparing calculated displacement provided in the Stability Test Report for the as-inclined condition, the difference in displacement is 0.9% (23,715 LT from the MSC GHS computer model and 23,512 LT from the Stability Test Report). This suggests a 95% uncertainty in the calculated displacement from the lines to be at least 1%. Using this 1% value as a relative uncertainty in (calculated) volume from the molded lines

$$\widehat{U}_m = 1\% = 0.01 \text{ (95\%)}$$
$$U_m = \widehat{U}_m \cdot \nabla = \widehat{U}_m \cdot \Delta/\gamma = (0.01)(849{,}228\ ft^3) = 8{,}492 ft^3$$

where the displacement and specific weight are taken from the Stability Test Report.

Combining these uncertainties the uncertainty of the as-inclined displacement volume is

$$U_\nabla = \sqrt{(1{,}673\ ft^3)^2 + (47{,}879\ ft^2 \cdot 0.0607\ ft)^2 + (8{,}492\ ft^3)^2} = 9{,}130 ft^3$$
$$\widehat{U}_\nabla = U_\nabla/\nabla = 9{,}130\ ft^3/849{,}228\ ft^3 = 0.0107 = 1.07\%$$

It should be noted that the largest contributor in the uncertainty in volume is due to the uncertainty in the calculated volume from the molded lines, U_m.

The final uncertainty to consider is the uncertainty in water specific gravity, specifically density or specific weight (U_γ) (note $\gamma = \rho g$), which is a function primarily of water temperature and salinity (assuming water to be incompressible in this case). However, specific gravity can be measured experimentally during the inclining with good accuracy using a hydrometer. Hansen [A14] and Wood [A13] cite hydrometers used in inclining experiments having relative uncertainty of 0.1% and 0.25% respectively, including both precision of reading the hydrometer and actual specific gravity variations as a function of location along the length of a ship. It should be noted however, that in estuarial flows including many bays, salinity can vary significantly depending on tides and local rain runoff, and can lead to large fluctuations in specific gravity even during the course of an inclining experiment. In the case of the EL FARO inclining at the Atlantic Marine Shipyard in Mobile Alabama, the salinity in the northern portion of Mobile Bay tends to vary only slightly with tides, and it should be considered reasonable to use a small uncertainty in specific gravity, as long as the hydrometer was used properly. For simplicity, a relative uncertainty of density of 0.0015 = 0.15% is assumed here.

Therefore the relative uncertainty in the as-inclined displacement is

$$\widehat{U}_\Delta = \sqrt{\widehat{U}_\nabla^2 + \widehat{U}_\gamma^2} = \sqrt{(0.0107)^2 + (0.0015)^2} = 0.0109 = 1.09\%$$

Uncertainty in GM:

The relative uncertainties in slope and displacement are combined using equation A-9. With uncertainty in slope calculated using the ordinary least-squares method:

$$\widehat{U}_{GM} = \sqrt{\widehat{U}_{slope}^2 + \widehat{U}_\Delta^2} = \sqrt{(0.0071)^2 + (0.0109)^2} = 0.0130 = 1.3\%\ (95\%)$$

Using the calculated as-inclined GM of 18.26 ft based on the Stability Test Report, the total uncertainty in the as-inclined GM is

$$U_{GM} = 0.0130 \cdot 18.26\ ft = 0.24\ ft = 2.9\ in\ \ (95\%)$$

Using the weighted least-squares method $\widehat{U}_{slope} = 0.0014$ and the uncertainty in as-inclined GM would be 0.20 ft or 2.4 in (95%).

A.4. Uncertainty in the As-Inclined KG

The ultimate goal of the inclining experiment is to determine the lightship weight and center of gravity, most importantly the height of the center of gravity (VCG or KG). The lightship KG is calculated by first finding the as-inclined KG. The as-inclined KG is easily calculated by subtracting the metacentric height from the height of the metacenter

$$KG = KM - GM \tag{A-20}$$

where KM is the height of the metacenter, a hydrostatic property, which can be written

$$KM = KB + BM \tag{A-21}$$

KB is the height of the center of buoyancy (the center of the displacement volume,∇), and BM is the metacentric radius defined by

$$BM = I/\nabla \tag{A-22}$$

where I is the 2nd moment of area of the waterplane area about its longitudinal centroidal axis (sometimes referred to as the transverse moment of inertia of the waterplane).

Since KG is calculated from a summation, the uncertainty in the as-inclined KG is

$$U_{KG} = \sqrt{U_{KB}^2 + U_{BM}^2 + U_{GM}^2} \tag{A-23}$$

where, since BM is a product of I and ∇, the relative uncertainty in BM is calculated

$$\widehat{U}_{BM} = \sqrt{\widehat{U}_I^2 + \widehat{U}_\nabla^2} \tag{A-24}$$

Note that the uncertainty in the as-inclined GM and relative uncertainty in displacement volume ∇ are already known, so it is only a matter of determining the uncertainty in I and KB, and both are hydrostatic properties.

The 2nd moment of area of the waterplane is calculated by integration of the waterplane area offsets

$$I = \frac{2}{3}\int_0^L y^3 dx \tag{A-25}$$

where y is the transverse distance (offset) and x is the longitudinal distance. Since this is a product with an exponent (equation A-4), the relative uncertainty can be calculated

$$\widehat{U}_I = \sqrt{\widehat{U}_{\mathrm{L}}^2 + \left(3\widehat{U}_B\right)^2} \tag{A-26}$$

Relative uncertainties $\hat{U}_L$ and $\hat{U}_B$ have already been determined, therefore

$$\hat{U}_I = \sqrt{\hat{U}_L^2 + \left(3\hat{U}_B\right)^2} = \sqrt{(0.00083)^2 + (3 \cdot 0.00128)^2} = 0.0039 = 0.39\% \ (95\%)$$

and

$$\hat{U}_{BM} = \sqrt{\hat{U}_I^2 + \hat{U}_\nabla^2} = \sqrt{(0.0039)^2 + (0.0107)^2} = 0.0114 = 1.14\% \ (95\%)$$

The height of the center of buoyancy KB is the vertical centroid of the displacement volume and is calculated by integration of the underwater volume to the waterline

$$KB = \int_0^{wl} A(z)dz \,/\nabla \qquad \text{(A-27)}$$

where z is the vertical distance (height) and A(z) is the waterplane area. The area of the waterplane is calculated by integration of the waterplane area offsets

$$A = 2\int_0^L ydx \qquad \text{(A-28)}$$

Therefore

$$\hat{U}_A = \sqrt{\hat{U}_B^2 + \hat{U}_L^2}$$
$$\hat{U}_{KB} = \sqrt{\hat{U}_A^2 + \hat{U}_D^2 + \hat{U}_\nabla^2} \qquad \text{(A-28)}$$

and

$$\hat{U}_A = \sqrt{(0.00128)^2 + (0.00083)^2} = 0.00153 = 0.15\% \ (95\%)$$
$$\hat{U}_{KB} = \sqrt{(0.00153)^2 + (0.00125)^2 + (0.0107)^2} = 0.0109 = 1.09\% \ (95\%)$$

From the MSC GHS computer model, for the as-inclined condition with the measured drafts, KB is 12.6 ft and BM is 31.0 ft, therefore

$$U_{KB} = 0.0109 \cdot 12.6\,ft = 0.137\,ft \ \ (95\%)$$
$$U_{BM} = 0.0114 \cdot 31.0\,ft = 0.353\,ft \ \ (95\%)$$

Finally, the uncertainty in the as-inclined KG is

$$U_{KG} = \sqrt{U_{KB}^2 + U_{BM}^2 + U_{GM}^2} = \sqrt{(0.137\,ft)^2 + (0.353\,ft)^2 + (0.237\,ft)^2} = 0.45 \text{ ft} = 5.4 \text{ in } (95\%)$$
$$\hat{U}_{KG} = U_{KG}/KG = 0.45\,ft/26.02\,ft = 0.0172 = 1.7\% \ (\ 95\%)$$

A.5. Uncertainty in the Lightship KG

Note: Hereafter, values applicable to the "as-inclined" condition will be given a subscript "I" and values applicable to the lightship condition will be given a subscript "L".

The lightship weight is calculated from the as-inclined weight by adding or subtracting any changes identified in the deadweight survey using

$$\Delta_L = \Delta_I + \sum w_s + \sum w_l \tag{A-30}$$

The lightship KG_L is calculated from the as-inclined KG_I by adding or subtracting the moments of the weight changes identified in the deadweight survey using

$$KG_L = \frac{\Delta_I KG_I + \sum w_s kg_s + \sum w_l kg_l}{\Delta_L} \tag{A-31}$$

where subscript L refers to the lightship value, I refers to the as-inclined value, s refers to solid weights to be added or removed, and l refers to liquid (tank) weights to be added or removed.

Since the calculation of the lightship weight is a summation, the total uncertainty in the lightship weight can be calculated

$$U_{\Delta_L} = \sqrt{U_{\Delta_I}^2 + U_{w_s}^2 + U_{w_l}^2} \tag{A-32}$$

Since the calculation KG_L is a function including both products and sums, the total uncertainty in the lightship KG must be calculated by

$$U_{KG_L} = \sqrt{\left(\frac{\partial KG_L}{\partial \Delta_I} U_{\Delta_I}\right)^2 + \left(\frac{\partial KG_L}{\partial KG_I} U_{KG_I}\right)^2 + \left(\frac{\partial KG_L}{\partial w_s} U_{w_s}\right)^2 + \left(\frac{\partial KG_L}{\partial kg_s} U_{kg_s}\right)^2 + \left(\frac{\partial KG_L}{\partial w_l} U_{w_l}\right)^2 + \left(\frac{\partial KG_L}{\partial kg_l} U_{kg_l}\right)^2 + \left(\frac{\partial KG_L}{\partial \Delta_L} U_{\Delta_L}\right)^2}$$

Performing the required differentiations of KG_L, substituting and simplifying

$$U_{KG_L} = \sqrt{\left(\frac{KG_I}{\Delta_L} U_{\Delta_I}\right)^2 + \left(\frac{\Delta_I}{\Delta_L} U_{KG_I}\right)^2 + \left(\frac{kg_s}{\Delta_L} U_{w_s}\right)^2 + \left(\frac{w_s}{\Delta_L} U_{kg_s}\right)^2 + \left(\frac{kg_l}{\Delta_L} U_{w_l}\right)^2 + \left(\frac{w_l}{\Delta_L} U_{kg_l}\right)^2 + \left(\frac{KG_L}{\Delta_L} U_{\Delta_L}\right)^2}$$

Using this equation to perform a detailed uncertainty analysis in KG_L would be tedious in the post-analysis and require applying individual uncertainty for each weight and each vertical height for all solid weights and liquid (tank) weights in the summations. Wood [A13] takes this approach and suggests the following uncertainties be applied in the calculations

$$\widehat{U}_{w_s} = 4.0\%, \quad \widehat{U}_{w_l} = 2.0\%, \quad U_{kg_s} = 1.0\ ft, \quad U_{kg_l} = 0.4\ ft$$

Shakshober and Montgomery [A12] take a simplified approach and redefine the moment equation in terms of summation of individual calculated moments and then apply equivalent relative uncertainties, suggesting the following relative uncertainties be applied in the calculation

$\widehat{U}_{w_s} = 5\% \ (for\ solid\ weights\ to\ be\ added),$
$\widehat{U}_{kg_s} = 10\% \ (for\ solid\ weights\ to\ be\ added)$
$\widehat{U}_{w_s} = 10\% \ (for\ solid\ weights\ to\ be\ removed)$
$\widehat{U}_{kg_s} = 5\% \ (for\ solid\ weights\ to\ be\ removed)$
$\widehat{U}_{w_l} = \widehat{U}_{\nabla}$
$\widehat{U}_{kg_l} = \widehat{U}_{\mathrm{KB}}$
(all at the 50% confidence level)

The latter two assumptions are reasonable given that tank weights are based on integration of the hull offsets to obtain tank volumes, and vertical tank centers are the centroids of the tank volumes.

For simplicity and to provide a reasonable but "optimistic" engineering estimate of KG_L for this analysis, the approach taken here is to apply the approach by Shakshober and Montgomery for the liquids $\hat{U}_{wl}$ and $\hat{U}_{kgl}$, but a hybrid approach for the solid weights. Based on Wood's approach, a relative uncertainty $\hat{U}_{ws} = 4\%$ is applied for both added and removed solid weights, and for solid weights U_{kgs} is based on Wood's suggested 1.0 ft uncertainty, but normalized based on an assumed average vertical height of 54 ft based on the deadweight survey weight accounting provided in the Stability Test Report. Thus the following weight and vertical center of gravity uncertainties are assumed

$\widehat{U}_{w_s} = 0.04 = 4.0\%$
$\widehat{U}_{kg_s} = 1.0ft/54.0\ ft = 0.019 = 1.9\%$
$\widehat{U}_{w_l} = \widehat{U}_{\nabla} = 0.0107 = 1.1\% \ (from\ previous\ calculation)$
$\widehat{U}_{kg_l} = \widehat{U}_{\mathrm{KB}} = 0.0109 = 1.1\% \ (from\ previous\ calculation)$
(all are assumed at the 95% confidence level)

The moment equation for KG_L (equation A-26) can be rewritten as

$$KG_L\Delta_L = \Delta_I KG_I + \sum w_s kg_s + \sum w_l kg_l \quad \text{(A-33)}$$

or

$$M_L = M_I + M_{sa} - M_{sr} + M_{la} - M_{lr} \quad \text{(A-34)}$$

with the following definitions:

$M_L = KG_L \cdot \Delta_L$
$M_I = KG_I \cdot \Delta_I$
$M_{sa} = \sum w_{sa} kg_{sa} \ \ (for\ solid\ weights\ to\ be\ added)$
$M_{sr} = \sum w_{sr} kg_{sr} \ \ (for\ solid\ weights\ to\ be\ removed)$
$M_{la} = \sum w_{la} kg_{la} \ \ (for\ liquid\ weights\ to\ be\ added)$
$M_{lr} = \sum w_{lr} kg_{lr} \ \ (for\ liquid\ weights\ to\ be\ removed)$

Since the calculation involving the moments is now a simple summation, the total uncertainty in the lightship moment (M_L) can be calculated

$$U_{M_L} = \sqrt{{U_{M_I}}^2 + {U_{M_{sa}}}^2 + {U_{M_{sr}}}^2 + {U_{M_{la}}}^2 + {U_{M_{lr}}}^2} \tag{A-35}$$

and the relative uncertainty in KG_L can be calculated

$$\widehat{U}_{KG_L} = \sqrt{\widehat{U}_{\Delta_L}^2 + \widehat{U}_{M_L}^2} \tag{A-36}$$

For each of the weights to be added or removed the uncertainty in each moment can be calculated from the relative uncertainty for the moment and the tabulated summation of the moment of the weights added or removed (from the Stability Test Report)

$$U_{M_{sa}} = \widehat{U}_{M_{sa}} \cdot M_{sa} \qquad U_{M_{sr}} = \widehat{U}_{M_{sr}} \cdot M_{sr} \qquad U_{M_{la}} = \widehat{U}_{M_{la}} \cdot M_{ls} \qquad U_{M_{lr}} = \widehat{U}_{M_{lr}} \cdot M_{lr}$$

Since each moment is calculated from a product of weight and vertical position, the relative uncertainty for each moment is calculated using

$$\widehat{U}_{M_{sa}} = \widehat{U}_{M_{sr}} = \sqrt{\widehat{U}_{w_s}^2 + \widehat{U}_{\mathrm{kg}_s}^2} = \sqrt{(0.04)^2 + (0.019)^2} = 0.044\ (95\%)$$
$$\widehat{U}_{M_{la}} = \widehat{U}_{M_{lr}} = \sqrt{\widehat{U}_{w_l}^2 + \widehat{U}_{\mathrm{kg}_l}^2} = \sqrt{(0.0107)^2 + (0.0109)^2} = 0.015\ (95\%)$$

The weights, heights, and moments of solids (dry items) and liquids to add or remove are taken from the Stability Test Report

$$w_{sa} = 11\ LT,\ \ kg_{sa} = 51.47\ ft,\ \ M_{sa} = 465\ ftLT$$
$$w_{sr} = 286\ LT,\ \ \ kg_{sr} = 54.31\ ft,\ \ \ M_{sr} = 15{,}524\ ftLT$$
$$w_{la} = 0\ LT,\ \ kg_{la} = 0\ ft,\ \ M_{la} = 0 ftLT$$
$$w_{lr} = 3{,}292\ LT,\ \ kg_{lr} = 12.74\ ft,\ \ \ M_{lr} = 41{,}941\ ftLT$$

Therefore, the uncertainties are calculated

$$U_{M_{sa}} = \widehat{U}_{M_{sa}} \cdot M_{sa} = (0.044) \cdot (465\ ftLT) = 20.5\ ftLT\ (95\%)$$
$$U_{M_{sr}} = \widehat{U}_{M_{sr}} \cdot M_{sr} = (0.044) \cdot (15{,}524\ ftLT) = 683.0\ ftLT\ (95\%)$$
$$U_{M_{la}} = \widehat{U}_{M_{la}} \cdot M_{la} = (0.0153) \cdot (0\ ftLT) = 0\ ftLT\ (95\%)$$
$$U_{M_{lr}} = \widehat{U}_{M_{lr}} \cdot M_{lr} = (0.0153) \cdot (41{,}941\ ftLT) = 640.6\ ftLT\ (95\%)$$

and

$$M_I = KG_I \cdot \Delta_I = (26.02 ft) \cdot (23{,}512\ LT) = 611{,}782\ ftLT$$

$$U_{M_I} = \sqrt{\left(\frac{\partial M_I}{\partial KG_I} U_{KG_I}\right)^2 + \left(\frac{\partial M_I}{\partial \Delta_I} U_{\Delta_I}\right)^2} = \sqrt{\left(\Delta_I \cdot U_{KG_I}\right)^2 + \left(KG_I \cdot U_{\Delta_I}\right)^2}$$
$$= \sqrt{(23{,}512\ LT \cdot 0.447 ft)^2 + (26.02\ ft \cdot 256.3\ LT)^2}$$
$$= \sqrt{(10{,}486\ ftLT)^2 + (6{,}664\ ftLT)^2} = 12{,}425\ ftLT\ (95\%)$$

The uncertainty in the lightship moment is calculated

$$U_{M_L} = \sqrt{{U_{M_I}}^2 + {U_{M_{sa}}}^2 + {U_{M_{sr}}}^2 + {U_{M_{la}}}^2 + {U_{M_{lr}}}^2}$$
$$= \sqrt{(12{,}425\ ftLT)^2 + (20.5\ ftLT)^2 + (683\ ftLT)^2 + (0\ ftLT)^2 + (640.6\ ftLT)^2}$$
$$= 12{,}460\ ftLT\ (95\%)$$

and

$$M_L = KG_L \cdot \Delta_L = (27.82 ft) \cdot (19{,}943\ LT) = 554{,}814\ ftLT$$
$$KG_L = M_L / \Delta_L$$
$$U_{\Delta_L} = \sqrt{U_{\Delta_I}^2 + U_{w_s}^2 + U_{w_l}^2} = \sqrt{(256.3\ LT)^2 + (11.9\ LT)^2 + (36.5\ LT)^2}$$
$$= 259.2\ LT\ (95\%)$$
$$\widehat{U}_{\Delta_L} = U_{\Delta_L} / \Delta_L = 259.2\ LT / 19{,}943\ LT = 0.0130\ (95\%)$$
$$\widehat{U}_{M_L} = \frac{U_{M_L}}{M_L} = \frac{12{,}460\ ftLT}{554{,}814} ftLT = 0.0225\ (95\%)$$

Finally, the uncertainty in the lightship KG is

$$\widehat{U}_{KG_L} = \sqrt{\widehat{U}_{\Delta_L}^2 + \widehat{U}_{M_L}^2} = \sqrt{(0.0130)^2 + (0.0225)^2} = 0.0260 = 2.6\%\ (95\%)$$
$$U_{KG_L} = \widehat{U}_{KG_L} \cdot \mathrm{KG}_L = 0.0260 \cdot 27.82\ \mathrm{ft} = 0.72\ \mathrm{ft} = 8.6\ \mathrm{in}\ (95\%)$$

A.6. Uncertainty in KG and GM for the Accident Voyage

The uncertainty in the accident voyage KG and GM can be estimated by extending the above calculations, first for KG and then for GM. Note that in this case only solid and liquid weights to be added to the lightship need be considered. Table A-4 below provides the summary of the departure loading condition for the accident voyage, taken from the CargoMax loading computer printout [A5] along with calculated vertical moments and calculated relative uncertainties in weight and vertical centers. It is reasonable to reduce uncertainty in weight of the cargo from 4% to 2%, since based on the MBI hearing testimony [A18], the containers were routinely weighed as the containers were brought onto the terminal prior to being loaded onto trailers (for RO/RO cargo) or onto the container stows (for LO/LO cargo).

For an initial assessment, estimation of centers of gravity of containers and trailers is based on the CargoMax printout for the departure condition, and they are assumed to have an uncertainty in kg of 1.0 ft, but normalized separately for each dry weight category based on the respective vertical center from the CargoMax printout. This is summarized in Table A-4 below. This initial assessment will be revisited subsequently since the default kg value for LO/LO containers is set in CargoMax as the geometric center of the container, and this potentially adds a kg-reducing (negative) bias error to the estimate.

The relative uncertainty for each moment is calculated, for example for the LO/LO containers:

$$\widehat{U}_{M_{sa(LO/LO)}} = \sqrt{\widehat{U}_{w_s}^2 + \widehat{U}_{kg_s(LO/LO)}^2} = \sqrt{(0.01)^2 + (0.013)^2} = 0.0238\ (95\%)$$

Then the uncertainties for each moment can be calculated, for example for the LO/LO containers:

$$U_{M_{sa(LO/LO)}} = \widehat{U}_{M_{sa(LO/LO)}} \cdot M_{sa(LO/LO)} = (0.0238) \cdot (528{,}457\ ftLT) = 12{,}601\ ftLT\ (95\%)$$

All calculated values are shown in Table A-5.

Item	Weight (LT)	Vertical Center of Gravity (ft)	Vertical Moment (ft·LT)	$\hat{U}_w$	$\hat{U}_{kg}$
Lightship	19,943.0	27.82	554,814	0.013	0.0260
Constants	171.9	52.86	9,086	0.020	0.0189
LO/LO cargo	6,862.1	77.01	528,457	0.020	0.0130
RO/RO cargo	4,183.8	38.43	160,800	0.020	0.0260
Tanks (liquids)	3,463.7	10.55	36,545	0.011	0.0109
Total departure condition	34,624.5	37.25	1,289,704		

Table A-4: Departure loading condition summary for the accident voyage, with values and calculated uncertainties for weight (w), vertical center of gravity (kg). All uncertainties are given at the 95% confidence level.

The uncertainty in the departure condition moment is calculated

$$U_{M_D} = \sqrt{{U_{M_L}}^2 + \Sigma(U_M^2)} = 18{,}501\ ftLT\ (95\%)$$

and

$$M_D = KG_D \cdot \Delta_D = 1{,}289{,}704\ ftLT$$

$$U_{\Delta_D} = \sqrt{{U_{\Delta_L}}^2 + \Sigma(U_w^2)} = 307.4\ LT\ (95\%)$$

$$\widehat{U}_{\Delta_D} = U_{\Delta_D}/\Delta_D = 307.4\ LT/34{,}624.5\ LT = 0.0089\ (95\%)$$

$$\widehat{U}_{M_D} = \frac{U_{M_D}}{M_D} = \frac{18{,}501\ ftLT}{1{,}289{,}704\ ftLT} = 0.0143\ (95\%)$$

Finally, the uncertainty in the departure condition KG is

$$\hat{U}_{KG_D} = \sqrt{\hat{U}^2_{\Delta_D} + \hat{U}^2_{M_D}} = 0.0169 = 1.7\% \text{ (95\%)}$$
$$U_{KG_D} = \hat{U}_{KG_D} \cdot \mathrm{KG}_D = 0.0169 \cdot 37.25 \text{ ft} = 0.628 \text{ ft} = 7.5 \text{ in (95\%)}$$

The uncertainty in GM for the departure condition can be calculated in a similar manner to Section A.3 with

$$\begin{gathered} GM = KM - KG \\ KM = KB + BM \\ BM = I/\nabla \\ U_{GM} = \sqrt{U^2_{KB} + U^2_{BM} + U^2_{KG}} \\ \hat{U}_{BM} = \sqrt{\hat{U}^2_I + \hat{U}^2_\nabla} \\ I = \frac{2}{3}\int_0^L y^3 dx \\ \hat{U}_I = \sqrt{\hat{U}^2_\mathrm{L} + \left(3\hat{U}_B\right)^2} \end{gathered} \tag{A-37}$$

with $\hat{U}_I = 0.39\% = 0.0039$.

Item	Weight (LT)	Vertical Center of Gravity (ft)	Vertical Moment (ft·LT)	$\hat{U}_w$	U_w (LT)	$\hat{U}_{kg}$	U_{kg} (ft)	$\hat{U}_M$	U_M (ft·LT)
Lightship	19,943.0	27.820	554,814	0.013	259.2	0.0260	0.72	0.0225	12,460
Constants	171.9	52.859	9,086	0.020	3.4	0.0189	1.00	0.0275	250
LO/LO cargo	6,862.1	77.011	528,457	0.020	137.2	0.0130	1.00	0.0238	12,601
RO/RO cargo	4,183.8	38.434	160,800	0.020	83.7	0.0260	1.00	0.0328	5,277
Tanks (liquids)	3,463.7	10.551	36,545	0.011	38.1	0.0109	0.12	0.0155	566
Total departure condition	34,624.5	37.25	1,289,704	0.0089	307.4	0.0169	0.63	0.0143	18,501

Table A-5: Departure loading condition summary for the accident voyage, with values and calculated uncertainties for weight (w), vertical center of gravity (kg), and vertical moment (M). All uncertainties are given at the 95% confidence level.

From above, for the departure condition, $\hat{U}_{\Delta_D} = 0.0089$. For the departure on the accident voyage, the specific gravity is taken as 1.025 (salt water), but the relative uncertainty for the specific gravity depends primarily on the hydrometer precision as for the inclining, therefore

$$\hat{U}_{\nabla} = \sqrt{\hat{U}_{\Delta}^2 + \hat{U}_{\gamma}^2} = \sqrt{(0.0089)^2 + (0.0015)^2} = 0.0090 = 0.90\%$$

Therefore

$$\hat{U}_{BM} = \sqrt{\hat{U}_{I}^2 + \hat{U}_{\nabla}^2} = \sqrt{(0.0039)^2 + (0.0090)^2} = 0.0098 = 0.98\%\ (95\%)$$

and

$$\hat{U}_{KB} = \sqrt{\hat{U}_{L}^2 + \hat{U}_{B}^2 + \hat{U}_{D}^2 + \hat{U}_{\nabla}^2}$$
$$= \sqrt{(0.00083)^2 + (0.00128)^2 + (0.00125)^2 + (0.0090)^2} = 0.0092$$
$$= 0.92\%\ (95\%)$$

From the MSC GHS computer model, for departure drafts of 26.79 ft forward, 29.69 ft midship and 32.59 ft aft, KB is 16.9 ft and BM is 25.1 ft. Therefore

$$U_{KB} = 0.0092 \cdot 16.9\ ft = 0.155\ ft\ \ (95\%)$$
$$U_{BM} = 0.0098 \cdot 25.1\ ft = 0.246\ ft\ \ (95\%)$$

Finally, the uncertainty in GM for the departure condition is

$$U_{GM} = \sqrt{U_{KB}^2 + U_{BM}^2 + U_{KG}^2} = \sqrt{(0.155\ ft)^2 + (0.246\ ft)^2 + (0.628\ ft)^2} = 0.69\text{ ft}$$
$$= 8.3\text{ in } (95\%)$$

In words, this says that there is a 95% confidence that the calculated value of GM for the departure condition lies within ±0.69 feet of the true value of GM. In equation form this can be written (to one decimal place)

$$GM = 4.3 \pm 0.7\ ft\ (with\ 95\%\ confidence)$$

A.7. Additional Considerations

Use of results from prior stability tests:

This procedure calculates the uncertainty in GM and KG based solely on the results of the 2006 stability test, and the documented vessel loading for the departure condition. It is possible in theory to incorporate the results of prior stability tests to supplement the calculations and perhaps refine the uncertainty estimate. It might be possible to estimate the 2006 weight and KG based on the weight and KG from the 1993 stability test, accounting for all of the various weights which were added or removed over the 13 year period between stability tests. If these weight changes (and their centers of gravity) were known with quantifiable uncertainty, then this could add an additional calculation on which to base a refinement of the uncertainty estimate.

However, in the case of the EL FARO for the period between the 1993 and 2006 stability tests, a significant amount of weight was added and removed. The post-inclining 1993 displacement was 15,743 LT with KG 35.59 ft [A19] and the post-inclining 2006 displacement was 19,943 LT with KG 27.82 ft [A20]. The weight changes included removal of the spar deck (estimated at 713 LT) [A21], addition of container foundations and support structure (estimated at 200-300 LT), and addition of an estimated 4,875 LT of fixed ballast in the double bottom tanks [A22], plus numerous smaller changes. This total change amounts to more than 38% of the lightship weight, which is a significant change. Additionally, the center of gravity locations of these weights could only be estimated, and therefore uncertainty in moments of the weight changes could be significant. Nevertheless, it is acknowledged that this approach could potentially provide useful information which might be considered in assessment of the uncertainty, if sufficiently detailed weight data would be available.

Container centers of gravity:

As mentioned in Section A.6, the default centers of gravity (VCG or kg) for LO/LO containers were calculated by default in CargoMax at the geometric center of the containers. It is recognized that most containers would likely contain cargo which would result in a center of gravity below the center of the container, and this would potentially suggest addition of a KG-reducing (negative) bias error adjustment to the estimate of uncertainty provided in Section A.6.

Unfortunately, there is insufficient container weight data available on which to base a rigorous analysis to calculate the magnitude of this bias error. However, an estimate of the bias error can be made for the accident voyage. Page 10 of the Trim and Stability Booklet [A20] provides curves to estimate vertical center of gravity of 40-ft containers on trailers. Unfortunately, it is unknown how these curves were developed, what limitations might be required in their use, or how much uncertainty might be built into these curves. But these curves are used in this analysis as a tool to estimate the negative bias error for the accident voyage departure condition. Using the Final Stow Plan for the accident voyage [A23], and using the weight and height of the trailers and stands annotated, these curves can be used to provide a better estimate of the center of gravity of 40-ft containers in the various LO/LO container bays. Using this approach, the centers of gravity of the LO/LO containers onboard for the accident voyage are estimated to be on average approximately 1.0 ft below the center of the container. Using the CargoMax printout for the accident voyage and a simple moment calculation, the impact of this on the accident voyage departure condition would be approximately a 0.2 ft reduction in the departure KG (VCG) and a 0.2 ft increase in the GM. In equation form this can be written (to one decimal place)

$$GM = (4.3 + 0.2) \pm 0.7\ ft = 4.5 \pm 0.7\ ft \ \ (with\ 95\%\ confidence)$$

In the course of conducting this assessment, it was noticed that values of VCG of the trailered RO/RO cargo entered into CargoMax were all based on the default values from the Trim and Stability Book for 52,000 lb trailers, and were not appropriately adjusted (increased) for the heavier trailers being carried aboard on the accident voyage. However, KG-increasing (positive) bias errors introduced in this manner are only estimated to be on the order of 0.1-0.2 ft, and are therefore small compared to the larger 1.0 ft negative bias errors associated with the LO/LO containers.

A.8. Summary

Table A-6 below provides a summary of the calculated uncertainties. Included in the table are the key results from the uncertainty analysis of the February 12, 2006 stability test, plus results of the uncertainty analysis of the departure condition for the accident voyage.

Parameter	Measured, calculated or nominal value with units	Uncertainty with units	Relative uncertainty (%)
Slope (tangent/moment)	2.3460×10^{-6} 1/ftLT	16.68×10^{-9} 1/ftLT	0.007 (0.7%)
Molded vs. as-built volume (V)	849,229 ft^3	1,673 ft^3	0.002 (0.2%)
Vessel drafts	22.45 ft	0.061 ft	0.003 (0.3%)
Calculated molded volume (m)	849,229 ft^3	8,492 ft^3	0.01 (1%)
Displacement volume (∇)	849,229 ft^3	9,126 ft^3	0.011 (1.1%)
Specific weight, density	62.55 lb/ft^3	0.09 lb/ft^3	0.002 (0.2%)
Vessel displacement (Δ)	23,512 LT	260 LT	0.011 (1.1%)
As-inclined GM	18.26 ft	0.24 ft	0.013 (1.3%)
As-inclined KG	26.02 ft	0.45 ft	0.017 (1.7%)
Lightship KG	27.82 ft	0.72 ft	0.026 (2.6%)
Accident voyage departure KG	37.25 ft *[-0.2 ft]	0.63 ft	0.017 (1.7%)
Accident voyage departure GM	4.28 ft *[+0.2 ft]	0.69 ft	0.161 (16%)

Table A-6: Summary of results of the uncertainty analyses of the stability test and the departure condition for the accident voyage. All uncertainties are given at the 95% confidence level. *Bracketed estimated values reflect potential bias correction, lowering KG and increasing GM due to default location of centers of gravity of LO/LO containers in CargoMax.

A.9. Appendix References

A1 SS EL FARO Stability Test Procedure, Drawing SSL-670-100-10, dated December 23, 2005, ABS approved February 2, 2006, Herbert Engineering Corporation (MBI Exhibit 258).

A2 SS EL FARO Stability Test Report, date of inclining February 12, 2006, ABS approved March 22, 2006, Herbert Engineering Corporation (MBI Exhibit 139).

A3 SS EL FARO Inclining Experiment Record Sheet, dated February 12, 2006, Herbert Engineering Corporation (MBI Exhibit 259).

A4 ABS Statutory Survey Report M662652 – SS EL FARO Inclining Experiment, dated February 12, 2006 (MBI Exhibit 190).

A5 SS EL FARO CargoMax Printout, Voyage No. 185, printed 11:48 on 01 Oct 2015, Tote Inc (MBI Exhibit 059).

A6 Kline, S. J. and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments", ASME Mechanical Engineering, Vol. 75, No. 1, 1953, pp. 3-8.

A7 Moffat, R. J., "Describing the Uncertainties in Experimental Results", Experimental Thermal and Fluid Science, Vol. 1, No. 1, 1988, pp. 3-17.

A8 ITTC (International Towing Tank Conference), "The Specialist Committee on Uncertainty Analysis: Final Report and Recommendations to the 25th ITTC", Proceedings of the 25th ITTC, Fukuoka, Japan, 2008, pp. 433-471.

A9 Coleman, H.W. and Steele, W.G., Experimentation and Uncertainty Analysis for Engineers, John Wiley and Sons, New York, 1999.

A10 Figliola, R.S. and Beasley, D.E., Theory and Design for Mechanical Measurements, 5th Edition, John Wiley and Sons, Hoboken, NJ, 2011.

A11 ASTM F1321-92 (Reapproved 2004), Standard Guide for Conducting a Stability Test (Lightweight Survey and Inclining Experiment) to Determine the Light Ship Displacement and Centers of Gravity of a Vessel, ASTM International, 2004 (MBI Exhibit 194).

A12 Shakshober, M.C. and Montgomery, J.B., "Analysis of the Inclining Experiment," presented at the meeting of the Hampton Roads Section of the Society of Naval Architects and Marine Engineers, February 1967.

A13 Wood, N.L., "Inclining Experiment Uncertainty Analysis," Proceedings of the 36th Annual Conference of the Society of Allied Weight Engineers, San Diego, CA, May 1977.

A14 Hansen, E.O., "An Analytic Treatment of the Accuracy of the Results of the Inclining Experiment," Naval Engineer's Journal, American Society of Naval Engineers, May 1985, pp. 97-115.

A15 Reed, G.C., Linear Least-Squares Fits with Errors in Both Cordinates, American Journal of Physics, 57 (7), July 1989, pp. 642-646.

A16 Reed, G.C., A Spreadsheet for Linear Least-Squares Fitting with Errors in Both Coordinates, Physics Education, 45 (1), January 2010, pp. 93-96.

A17 International Association of Class Societies (IACS) Unified Requirement L5: Onboard Computers for Stability Calculations, Corr. 1, 2006.

A18 Transcript, U.S. Coast Guard Marine Board of Investigation ICO the Sinking of the SS El Faro Held in Jacksonville, Florida, February 20, 2016, Volume 5.

A19 SS NORTHERN LIGHTS Trim and Stability Booklet, Drawing 1252-700-602, Rev A1, dated May 6, 1993, Atlantic Marine Inc. (MBI Exhibit 251).

A20 SS EL FARO Trim and Stability Booklet, Drawing 1252-700-602, Rev E, dated February 14, 2007, Herbert Engineering Corporation (MBI Exhibit 008).
A21 SS NORTHERN LIGHTS (EL FARO) Spar Deck Removal, Drawing SSL-670-100-024, undated, Herbert Engineering Corporation (MBI Exhibit 406).
A22 SS NORTHERN LIGHTS (EL FARO) Fixed Ballast Installation, Drawing SSL-670-100-003, dated May 24, 2005, Herbert Engineering Corporation (MBI Exhibit 257).
A23 Final Stow Plan for EL FARO Voyage 185S, dated September 29, 2015, Tote Inc. (MBI Exhibit 069).

Appendix B: SOLAS Probabilistic Damage Stability Analysis

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GHS 15.00 **ELFARO321** RUN1

Damage Stability Analysis
GHS DAMSTAB2 Wizard version 13.38S

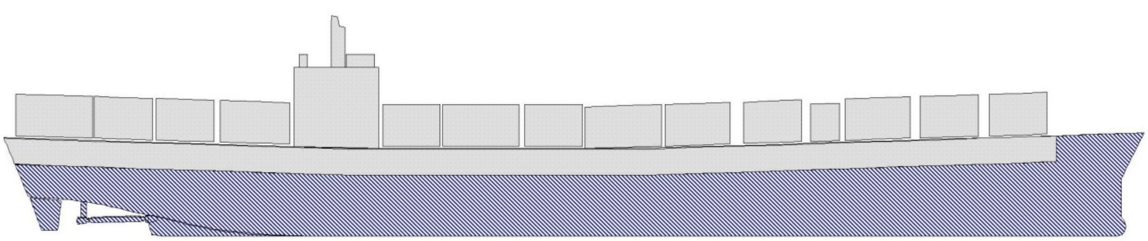
Probabilistic Damage

PORT-side Probabilistic Cargo old SOLAS Reg 25

Deepest draft (ds)

Condition Graphic

Outboard Profile View



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GHS 15.00 **ELFARO321** RUN1

DIVISION definitions

Division	Fwd End	Aft End	Wing	HBhd	Parts
1	20.59f	40.00a		51.43	BOSUNSTORES.C CHNLKRFP.C FOREPKTK.C
2	40.00a	68.42a			DTNO1A.C
3	68.42a	99.67a			DTNO1BP-SLOP.P
4	99.67a	212.42a			DBNO1P.P HOLDA.P
5	212.42a	325.17a	23.94 24.00		DBNO2IP.P DB2OP.P HOLDB.S HOLDA.P
6	325.17a	415.92a	26.75		DBNO2AIP.P DB2AOP.P HOLDC.C
7	415.92a	528.67a	26.73		DBNO3IP.P DB3OP.P HOLDD.C VOIDD.C
8	528.67a	613.92a	13.55 20.80		DBNO4P.P LO_SUMP.C ENGINEROOM.C DISTWTR.P HOLDF3RD.P
9	613.92a	638.67a	22.05		DBNO4P.P LO_SUMP.C ENGINEROOM.C DTAFTP.P HOLDF3RD.P
10	638.67a	668.92a	20.05		DTAFTP.P FOSETT.C HOLDF3RD.P STERNTCOMP.C
11	668.92a	694.75a	16.75		DTAFTP.P AFTPEAKCL.C HOLDF3RD.P
12	694.75a	726.75a	14.85		AFTPEAKCL.C AFTPEAKP.P HOLDF3RD.P
13	726.75a	758.75a	5.90	37.50	AFTPEAKCL.C AFTPEAKP.P STEERINGGEAR.C

Distances in FEET.

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GHS 15.00 **ELFARO321** RUN1

Downflooding Points

	Critical Points		**LCP**	**TCP**	**VCP**	**Tank**
(1)	H1-EF-L	FLOOD	102.40a	25.50	64.60	HOLDA.P
(2)	H1-EA-L	FLOOD	193.20a	35.50	61.50	HOLDA.P
(3)	H2-EF-BA	FLOOD	228.90a	45.20	58.60	HOLDB.S
(4)	H2-EA-BA	FLOOD	311.40a	45.50	56.50	HOLDB.S
(5)	H2A-EF-BA	FLOOD	341.70a	45.70	55.90	HOLDC.C
(6)	H2A-EA-BA	FLOOD	402.20a	45.80	55.90	HOLDC.C
(7)	H3-EF-BA	FLOOD	435.20a	46.00	55.90	HOLDD.C
(8)	H3-EA-BA	FLOOD	501.20a	46.00	55.90	HOLDD.C
(9)	H5-EF-BA	FLOOD	674.40a	44.70	61.30	HOLDF3RD.P

Distances in FEET.

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GHS 15.00 **ELFARO321** RUN1

WEIGHT STATUS

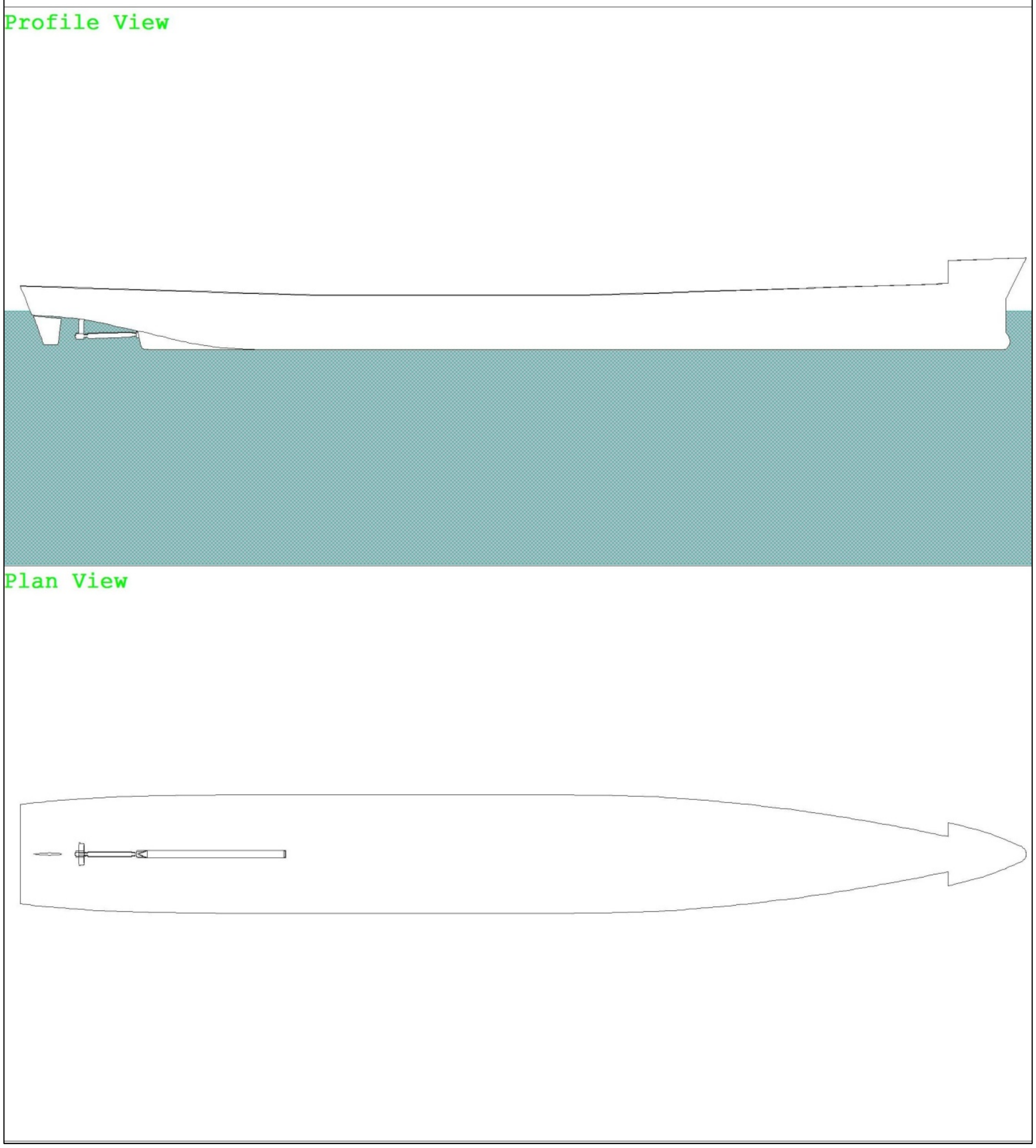
Trim: 0.00 deg., Heel: zero

Part	**Weight(LT)**	**LCG**	**TCG**	**VCG**
WEIGHT	34,646.44	391.49a	0.00	38.04

Distances in FEET.

Draft at LCF: 30.109
Draft at mid subdivision length: 30.109

Condition Graphic - Draft: 30.11 @ 0.00 Trim: 0.00 deg. Heel: zero



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GHS 15.00 **ELFARO321** RUN1

PERMEABILITY SETTINGS

Name	Description	Flooded	Normal	Cubic FEET
DBNO1P.P		0.9500	0.9500	11,262.4
DBNO1S.S		0.9500	0.9500	11,262.4
DBNO2IP.P		0.9500	0.9500	14,784.8
ELPITDB.S		0.9500	0.7500	913.3
DBNO2IS.S		0.9500	0.9500	13,628.0
DBNO2AIP.P		0.9500	0.9500	12,129.0
DBNO2AIS.S		0.9500	0.9500	12,129.0
DBNO3IP.P		0.9500	0.9500	15,047.0
DBNO3IS.S		0.9500	0.9500	15,047.0
LO_SETT.P		0.9500	0.9800	630.6
LO_STOR.S		0.9500	0.9800	490.5
POTWTR.S		0.9500	0.9800	2,735.4
DISTWTR.P		0.9500	0.9800	3,224.8
LO_SUMP.C		0.9500	0.9800	551.9
LO_GRAV.C		0.9500	0.9800	539.0
DO.P		0.9500	0.9800	679.1
FOSETT.C		0.9500	0.9800	10,299.4
FWDRAMP.P		0.7000	0.7000	14,972.2
AFTRAMP.P		0.7000	0.7000	11,686.0
HOLDA.P		0.7000	0.8000	193,548.9
FWDRAMPLOW.P		0.7000	1.0000	16,851.5
HOLDB.S		0.7000	0.8000	263,376.9
HOLDC.C		0.7000	0.8000	232,601.3
VOIDD.C		0.9500	1.0000	10,979.1
HOLDD.C		0.7000	0.8000	277,146.9
HOLDF3RD.P		0.7000	0.8000	140,035.7
ERRAMP.P		0.7000	1.0000	11,501.5
ENGINEROOM.C		0.8500	0.8500	212,361.0
DTNO1A.C		0.9500	0.9800	20,210.9
DTNO1BP-SLOP.P		0.9500	0.9800	16,973.2
DTNO1BS.S		0.9500	0.9800	16,973.2
DTAFTP.P		0.9500	0.9800	9,393.8
DTAFTS.S		0.9500	0.9800	9,393.8
CHNLKRFP.C		0.9500	1.0000	3,209.8
FOREPKTK.C		0.9500	0.9800	15,430.6
STEERINGGEAR.C		0.9500	0.9500	25,527.3
BOSUNSTORES.C		0.6000	0.9000	22,696.7
AFTPEAKCL.C		0.9500	0.9500	28,780.5
AFTPEAKP.P		0.9500	0.9500	4,150.2
AFTPEAKS.S		0.9500	0.9500	4,150.2
COFF.P		0.9500	1.0000	401.7
DBNO4P.P		0.9500	0.9800	3,932.2
DBNO4S.S		0.9500	0.9800	3,932.2
DB2OP.P		0.9500	0.9800	9,394.4
DB2OS.S		0.9500	0.9800	9,394.4
DB2AOP.P		0.9500	0.9800	13,461.6
DB2AOS.S		0.9500	0.9800	13,461.6
DB3OP.P		0.9500	0.9800	13,086.5
DB3OS.S		0.9500	0.9800	13,086.5
SECONDDECK.C		0.7000	0.9800	1,082,915.5
STERNTCOMP.C			0.9000	6,776.8

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GHS 15.00 **ELFARO321** RUN1

PROBABILISTIC DAMAGE STABILITY
Cargo Vessel Version
Subdivision length: 788.30 Terminals: 20.59f, 767.71a
Breadth: 96.00 Draft: 30.11 Hmax: 53.04

Divisions	P	Smin	P*S*V	A	Depth	Trim	Heel	Range	MaxRA
None	0.00000	1.000	0.000	0.000	30.11	0.00	0.00	29.22	1.28
1	0.06159	1.000	0.057	0.057	31.30	0.14f	0.00	28.83	1.28
1+u1	0.06159	1.000	0.004	0.062	31.30	0.14f	0.00	28.83	1.28
2	0.00734	1.000	0.007	0.069	31.10	0.11f	0.00	28.87	1.27
3	0.00882	1.000	0.009	0.078	30.89	0.09f	0.44p	28.43	1.25
4	0.09356	1.000	0.094	0.171	40.40	1.09f	1.64p	22.64	0.66
5	0.06620	0.955	0.063	0.235	41.13	1.01f	4.36p	18.25	0.36
5+i1	0.00005	0.000	0.000	0.235	37.94	6.32f	179.58p	0.00	
5+i1+i2	0.02731	0.000	0.000	0.235	43.49	6.84f	179.32p	0.00	
6	0.04815	0.912	0.044	0.278	35.37	0.33f	6.98p	16.63	0.37
6+i1	0.01545	0.883	0.014	0.292	35.76	0.36f	7.81p	15.61	0.35
7	0.05740	0.905	0.052	0.344	31.64	0.28a	5.76p	16.38	0.40
7+i1	0.02053	0.867	0.018	0.362	31.74	0.30a	6.77p	15.05	0.38
8	0.01965	0.185	0.004	0.365	23.98	1.42a	5.27s	5.57	0.04
8+i1	0.00723	0.185	0.001	0.367	23.98	1.42a	5.27s	5.57	0.04
8+i1+i2	0.01144	0.185	0.002	0.369	23.98	1.42a	5.27s	5.57	0.04
9	0.00300	0.000	0.000	0.369	-36.56	3.40a	179.73p	0.00	
9+i1	0.00022	0.000	0.000	0.369	-36.86	3.47a	179.68p	0.00	
10	0.00373	0.996	0.004	0.373	28.99	0.18a	6.35p	19.84	0.51
10+i1	0.00063	0.988	0.001	0.373	28.46	0.29a	6.21p	19.53	0.51
11	0.00228	0.996	0.002	0.376	28.99	0.18a	6.35p	19.84	0.51
11+i1	0.00064	0.946	0.001	0.376	27.18	0.51a	6.37p	17.91	0.44
12	0.00262	1.000	0.003	0.379	29.52	0.11a	1.51p	25.59	0.61
12+i1	0.00135	1.000	0.001	0.380	27.64	0.45a	2.36p	22.94	0.54
13	0.00112	1.000	0.000	0.380	30.02	0.02a	0.52p	28.67	1.22
13+i1	0.00235	1.000	0.001	0.381	28.74	0.25a	0.72p	28.26	1.24
13+u1	0.00112	1.000	0.001	0.382	30.02	0.02a	0.52p	28.63	1.20
13+u1+i1	0.00235	1.000	0.002	0.384	28.74	0.25a	0.72p	28.08	1.20
		1-division damage:		**0.384**		**Probability of damage:**		**0.463**	
1+2	0.02990	1.000	0.028	0.411	32.35	0.25f	0.00	28.45	1.28
1+2+u1	0.02990	1.000	0.002	0.413	32.35	0.25f	0.00	28.45	1.28
2+3	0.01392	1.000	0.014	0.427	31.94	0.21f	0.46p	28.02	1.23
3+4	0.03697	1.000	0.037	0.464	41.96	1.27f	2.64p	20.39	0.53
4+5	0.04187	0.000	0.000	0.464	43.58	6.87f	179.43p	0.00	
4+5+i1	0.00004	0.000	0.000	0.464	43.58	6.87f	179.43p	0.00	
4+5+i1+i2	0.03434	0.000	0.000	0.464	50.20	7.49f	179.16p	0.00	
5+6	0.04035	0.000	0.000	0.464	13.37	3.56f	179.95p	0.00	
5+6+i1	0.00004	0.000	0.000	0.464	642.07	90.00f	0.98p	0.00	0.00
5+6+i1+i2	0.03161	0.000	0.000	0.464	559.06	62.16f	176.96p	0.00	
6+7	0.03928	0.000	0.000	0.464	-8.46	0.93f	180.00s	0.00	
6+7+i1	0.02727	0.000	0.000	0.464	-8.46	0.93f	180.00s	0.00	
7+8	0.02045	0.000	0.000	0.464	-91.49	22.71a	179.04p	0.00	
7+8+i1	0.00722	0.000	0.000	0.464	-119.14	35.61a	178.31p	0.00	

continued next page

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GHS 15.00 **ELFARO321** RUN1

Divisions	P	Smin	P*S*V	A	Depth	Trim	Heel	Range	MaxRA
7+8+i1+i2	0.02462	0.000	0.000	0.464	-120.04	36.10a	178.31p	0.00	
8+9	0.00694	0.000	0.000	0.464	-36.80	3.45a	179.68p	0.00	
8+9+i1	0.00239	0.000	0.000	0.464	-37.23	3.55a	179.53p	0.00	
8+9+i1+i2	0.00699	0.000	0.000	0.464	-37.23	3.55a	179.53p	0.00	
9+10	0.00391	0.000	0.000	0.464	-36.56	3.40a	179.73p	0.00	
9+10+i1	0.00266	0.000	0.000	0.464	-39.51	4.02a	179.65p	0.00	
10+11	0.00334	0.996	0.003	0.468	28.99	0.18a	6.35p	19.84	0.51
10+11+i1	0.00290	0.941	0.003	0.470	26.55	0.64a	6.01p	17.70	0.44
11+12	0.00291	0.925	0.003	0.473	28.59	0.23a	8.07p	17.10	0.42
11+12+i1	0.00302	0.858	0.003	0.476	26.68	0.58a	8.41p	14.73	0.35
12+13	0.00160	1.000	0.001	0.476	29.52	0.11a	1.51p	25.59	0.61
12+13+i1	0.00475	1.000	0.002	0.478	27.64	0.45a	2.36p	22.94	0.54
12+13+u1	0.00160	1.000	0.001	0.479	29.52	0.11a	1.51p	24.06	0.57
12+13+u1+i1	0.00475	1.000	0.003	0.482	27.64	0.45a	2.36p	20.91	0.47
		2-division damage:		**0.098**	**Probability of damage:**			**0.389**	
1+2+3	0.02208	1.000	0.021	0.503	33.25	0.35f	0.48p	27.54	1.23
1+2+3+u1	0.02208	1.000	0.002	0.504	33.25	0.35f	0.48p	27.54	1.23
2+3+4	0.02196	0.936	0.021	0.525	44.11	1.52f	2.87p	17.54	0.44
3+4+5	0.00000	0.000	0.000	0.525	56.07	8.07f	179.20p	0.00	
3+4+5+i1	0.00000	0.000	0.000	0.525	56.07	8.07f	179.20p	0.00	
3+4+5+i1+i2	0.00189	0.000	0.000	0.525	66.78	9.09f	178.87p	0.00	
4+5+6	0.00000	0.000	0.000	0.525	532.75	58.66f	177.62p	0.00	
4+5+6+i1	0.00000	0.000	0.000	0.525	556.43	61.92f	177.17p	0.00	
4+5+6+i1+i2	0.00326	0.000	0.000	0.525	584.97	66.20f	176.61p	0.00	
5+6+7	0.00049	0.000	0.000	0.525	53.00	6.70f	177.48p	0.00	
5+6+7+i1	0.00000	0.000	0.000	0.525	SUNK				
5+6+7+i1+i2	0.00556	0.000	0.000	0.525	SUNK				
6+7+8	0.00000	0.000	0.000	0.525	-36.56	75.43a	177.46p	0.00	
6+7+8+i1	0.00000	0.000	0.000	0.525	SUNK				
6+7+8+i1+i2	0.00248	0.000	0.000	0.525	SUNK				
7+8+9	0.00100	0.000	0.000	0.525	-112.85	31.89a	178.26p	0.00	
7+8+9+i1	0.00032	0.000	0.000	0.525	-133.28	44.26a	177.50p	0.00	
7+8+9+i1+i2	0.00239	0.000	0.000	0.525	-133.28	44.26a	177.50p	0.00	
8+9+10	0.00550	0.000	0.000	0.525	-36.80	3.45a	179.68p	0.00	
8+9+10+i1	0.00204	0.000	0.000	0.525	-39.92	4.11a	179.50p	0.00	
8+9+10+i1+ i2	0.00646	0.000	0.000	0.525	-39.92	4.11a	179.50p	0.00	
9+10+11	0.00201	0.000	0.000	0.525	-36.56	3.40a	179.73p	0.00	
9+10+11+i1	0.00219	0.000	0.000	0.525	-45.80	5.35a	179.63p	0.00	
10+11+12	0.00249	0.925	0.002	0.527	28.59	0.23a	8.07p	17.10	0.42
10+11+12+i1	0.00322	0.854	0.003	0.530	26.07	0.70a	7.97p	14.58	0.35
11+12+13	0.00097	0.925	0.000	0.530	28.59	0.23a	8.07p	17.10	0.42
11+12+13+i1	0.00322	0.858	0.001	0.531	26.68	0.58a	8.41p	14.73	0.35
11+12+13+u1	0.00097	0.878	0.001	0.531	28.59	0.23a	8.07p	15.43	0.38
11+12+13+ u1+i1	0.00322	0.705	0.002	0.533	26.60	0.58a	8.72p	12.13	0.27
		3-division damage:		**0.051**	**Probability of damage:**			**0.090**	
1+2+3+4	0.01862	0.844	0.015	0.548	46.68	1.82f	3.10p	14.26	0.34

continued next page

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GHS 15.00 **ELFARO321** RUN1

Divisions	P	Smin	P*S*V	A	Depth	Trim	Heel	Range	MaxRA
1+2+3+4+u1	0.01862	0.843	0.001	0.549	46.68	1.82f	3.10p	14.22	0.34
2+3+4+5	0.00000	0.000	0.000	0.549	87.62	11.16f	179.07p	0.00	
2+3+4+5+i1	0.00000	0.000	0.000	0.549	87.62	11.16f	179.07p	0.00	
2+3+4+5+i1+ i2	0.00080	0.000	0.000	0.549	121.02	14.43f	178.62p	0.00	
7+8+9+10	0.00001	0.000	0.000	0.549	-112.85	31.89a	178.26p	0.00	
7+8+9+10+i1	0.00000	0.000	0.000	0.549	-144.21	55.62a	177.46p	0.00	
7+8+9+10+ i1+i2	0.00137	0.000	0.000	0.549	-144.21	55.62a	177.46p	0.00	
8+9+10+11	0.00261	0.000	0.000	0.549	-36.80	3.45a	179.68p	0.00	
8+9+10+11+ i1	0.00091	0.000	0.000	0.549	-46.33	5.48a	179.48p	0.00	
8+9+10+11+ i1+i2	0.00362	0.000	0.000	0.549	-46.33	5.48a	179.48p	0.00	
9+10+11+12	0.00149	0.000	0.000	0.549	-37.31	3.55a	179.52p	0.00	
9+10+11+12+ i1	0.00208	0.000	0.000	0.549	-46.86	5.59a	179.41p	0.00	
10+11+12+13	0.00082	0.925	0.000	0.549	28.59	0.23a	8.07p	17.10	0.42
10+11+12+ 13+i1	0.00285	0.854	0.001	0.550	26.07	0.70a	7.97p	14.58	0.35
10+11+12+ 13+u1	0.00082	0.878	0.000	0.550	28.59	0.23a	8.07p	15.43	0.38
10+11+12+ 13+u1+i1	0.00285	0.650	0.001	0.552	25.50	0.81a	8.16p	11.44	0.24
		4-division damage:		**0.018**	**Probability of damage:**			**0.035**	
7+8+9+10+11	0.00000	0.000	0.000	0.552	-112.85	31.89a	178.26p	0.00	
7+8+9+10+ 11+i1	0.00000	0.000	0.000	0.552	-142.25	67.52a	177.46p	0.00	
7+8+9+10+ 11+i1+i2	0.00052	0.000	0.000	0.552	-142.25	67.52a	177.46p	0.00	
8+9+10+11+ 12	0.00118	0.000	0.000	0.552	-37.60	3.61a	179.45p	0.00	
8+9+10+11+ 12+i1	0.00039	0.000	0.000	0.552	-47.41	5.72a	179.26p	0.00	
8+9+10+11+ 12+i1+i2	0.00236	0.000	0.000	0.552	-47.41	5.72a	179.26p	0.00	
9+10+11+12+ 13	0.00040	0.000	0.000	0.552	-37.31	3.55a	179.52p	0.00	
9+10+11+12+ 13+i1	0.00149	0.000	0.000	0.552	-46.86	5.59a	179.41p	0.00	
9+10+11+12+ 13+u1	0.00040	0.000	0.000	0.552	-42.72	4.65a	179.52p	0.00	
9+10+11+12+ 13+u1+i1	0.00149	0.000	0.000	0.552	-54.48	7.43a	179.38p	0.00	
		5-division damage:		**0.000**	**Probability of damage:**			**0.006**	

Attained index in this condition: **0.552** **Total probability of damage:** **0.983**
Required index: **0.602**

Distances in FEET. Angles in deg.

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GHS 15.00 **ELFARO321** RUN1
====== Summary Data ======

Calculation method: SDIC
Condition name: Deepest draft (ds) (code 2)
Damage side: Port

Displacement: 34646.4 LONG TONS
Trim: 0.00 degrees
VCG: 38.045 FEET
Free surface moment: 0.0 LONG TONS-FEET
Environment: 1.025

Attained index: 0.552
Overall Required index: 0.602

12/14/16 12:02:00	USCG - MSC, Washington, D.C.	Page 1
GHS 15.00	**ELFARO321**	RUN2

Damage Stability Analysis
GHS DAMSTAB2 Wizard version 13.38S

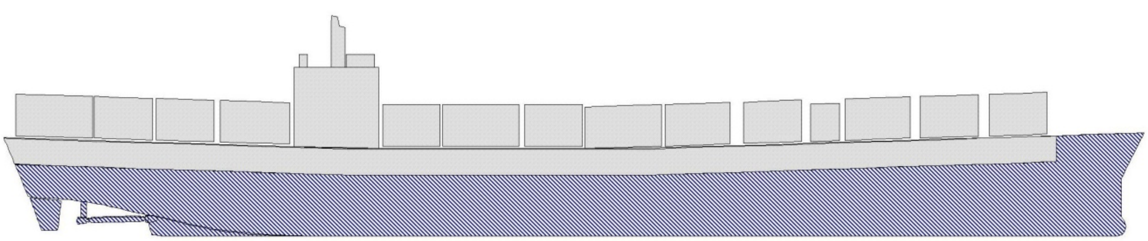
Probabilistic Damage

PORT-side Probabilistic Cargo old SOLAS Reg 25

Light-service draft (dl)

Condition Graphic

Outboard Profile View



12/14/16 12:02:00 USCG - MSC, Washington, D.C. Page 2
GHS 15.00 **ELFARO321** RUN2

DIVISION definitions

Division	Fwd End	Aft End	Wing	HBhd	Parts
1	20.59f	40.00a		51.43	BOSUNSTORES.C CHNLKRFP.C FOREPKTK.C
2	40.00a	68.42a			DTNO1A.C
3	68.42a	99.67a			DTNO1BP-SLOP.P
4	99.67a	212.42a			DBNO1P.P HOLDA.P
5	212.42a	325.17a	23.94 24.00		DBNO2IP.P DB2OP.P HOLDB.S HOLDA.P
6	325.17a	415.92a	26.75		DBNO2AIP.P DB2AOP.P HOLDC.C
7	415.92a	528.67a	26.73		DBNO3IP.P DB3OP.P HOLDD.C VOIDD.C
8	528.67a	613.92a	13.55 20.80		DBNO4P.P LO_SUMP.C ENGINEROOM.C DISTWTR.P HOLDF3RD.P
9	613.92a	638.67a	22.05		DBNO4P.P LO_SUMP.C ENGINEROOM.C DTAFTP.P HOLDF3RD.P
10	638.67a	668.92a	20.05		DTAFTP.P FOSETT.C HOLDF3RD.P STERNTCOMP.C
11	668.92a	694.75a	16.75		DTAFTP.P AFTPEAKCL.C HOLDF3RD.P
12	694.75a	726.75a	14.85		AFTPEAKCL.C AFTPEAKP.P HOLDF3RD.P
13	726.75a	758.75a	5.90	37.50	AFTPEAKCL.C AFTPEAKP.P STEERINGGEAR.C

Distances in FEET.

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GHS 15.00 **ELFARO321** RUN2

Downflooding Points

	Critical Points		**LCP**	**TCP**	**VCP**	**Tank**
(1)	H1-EF-L	FLOOD	102.40a	25.50	64.60	HOLDA.P
(2)	H1-EA-L	FLOOD	193.20a	35.50	61.50	HOLDA.P
(3)	H2-EF-BA	FLOOD	228.90a	45.20	58.60	HOLDB.S
(4)	H2-EA-BA	FLOOD	311.40a	45.50	56.50	HOLDB.S
(5)	H2A-EF-BA	FLOOD	341.70a	45.70	55.90	HOLDC.C
(6)	H2A-EA-BA	FLOOD	402.20a	45.80	55.90	HOLDC.C
(7)	H3-EF-BA	FLOOD	435.20a	46.00	55.90	HOLDD.C
(8)	H3-EA-BA	FLOOD	501.20a	46.00	55.90	HOLDD.C
(9)	H5-EF-BA	FLOOD	674.40a	44.70	61.30	HOLDF3RD.P

Distances in FEET.

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GHS 15.00 **ELFARO321** RUN2

WEIGHT STATUS

Trim: 0.00 deg., Heel: zero

Part	Weight(LT)	LCG	TCG	VCG
WEIGHT	28,673.26	384.83a	0.00	38.55

Distances in FEET.

Draft at LCF: 26.026
Draft at mid subdivision length: 26.026

Condition Graphic - Draft: 26.03 @ 0.00 Trim: 0.00 deg. Heel: zero

Profile View

Plan View

12/14/16 12:02:00 USCG - MSC, Washington, D.C. Page 5
GHS 15.00 **ELFARO321** RUN2

PERMEABILITY SETTINGS

Name	Description	Flooded	Normal	Cubic FEET
DBNO1P.P		0.9500	0.9500	11,262.4
DBNO1S.S		0.9500	0.9500	11,262.4
DBNO2IP.P		0.9500	0.9500	14,784.8
ELPITDB.S		0.9500	0.7500	913.3
DBNO2IS.S		0.9500	0.9500	13,628.0
DBNO2AIP.P		0.9500	0.9500	12,129.0
DBNO2AIS.S		0.9500	0.9500	12,129.0
DBNO3IP.P		0.9500	0.9500	15,047.0
DBNO3IS.S		0.9500	0.9500	15,047.0
LO_SETT.P		0.9500	0.9800	630.6
LO_STOR.S		0.9500	0.9800	490.5
POTWTR.S		0.9500	0.9800	2,735.4
DISTWTR.P		0.9500	0.9800	3,224.8
LO_SUMP.C		0.9500	0.9800	551.9
LO_GRAV.C		0.9500	0.9800	539.0
DO.P		0.9500	0.9800	679.1
FOSETT.C		0.9500	0.9800	10,299.4
FWDRAMP.P		0.7000	0.7000	14,972.2
AFTRAMP.P		0.7000	0.7000	11,686.0
HOLDA.P		0.7000	0.8000	193,548.9
FWDRAMPLOW.P		0.7000	1.0000	16,851.5
HOLDB.S		0.7000	0.8000	263,376.9
HOLDC.C		0.7000	0.8000	232,601.3
VOIDD.C		0.9500	1.0000	10,979.1
HOLDD.C		0.7000	0.8000	277,146.9
HOLDF3RD.P		0.7000	0.8000	140,035.7
ERRAMP.P		0.7000	1.0000	11,501.5
ENGINEROOM.C		0.8500	0.8500	212,361.0
DTNO1A.C		0.9500	0.9800	20,210.9
DTNO1BP-SLOP.P		0.9500	0.9800	16,973.2
DTNO1BS.S		0.9500	0.9800	16,973.2
DTAFTP.P		0.9500	0.9800	9,393.8
DTAFTS.S		0.9500	0.9800	9,393.8
CHNLKRFP.C		0.9500	1.0000	3,209.8
FOREPKTK.C		0.9500	0.9800	15,430.6
STEERINGGEAR.C		0.9500	0.9500	25,527.3
BOSUNSTORES.C		0.6000	0.9000	22,696.7
AFTPEAKCL.C		0.9500	0.9500	28,780.5
AFTPEAKP.P		0.9500	0.9500	4,150.2
AFTPEAKS.S		0.9500	0.9500	4,150.2
COFF.P		0.9500	1.0000	401.7
DBNO4P.P		0.9500	0.9800	3,932.2
DBNO4S.S		0.9500	0.9800	3,932.2
DB2OP.P		0.9500	0.9800	9,394.4
DB2OS.S		0.9500	0.9800	9,394.4
DB2AOP.P		0.9500	0.9800	13,461.6
DB2AOS.S		0.9500	0.9800	13,461.6
DB3OP.P		0.9500	0.9800	13,086.5
DB3OS.S		0.9500	0.9800	13,086.5
SECONDDECK.C		0.7000	0.9800	1,082,915.5
STERNTCOMP.C			0.9000	6,776.8

PROBABILISTIC DAMAGE STABILITY
Cargo Vessel Version
Subdivision length: 788.30 Terminals: 20.59f, 767.71a
Breadth: 96.00 Draft: 26.03 Hmax: 48.96

Divisions	P	Smin	P*S*V	A	Depth	Trim	Heel	Range	MaxRA
None	0.00000	1.000	0.000	0.000	26.03	0.00	0.00	33.92	1.55
1	0.06159	1.000	0.062	0.062	27.29	0.15f	0.00	33.54	1.57
2	0.00734	1.000	0.007	0.069	26.98	0.11f	0.00	33.60	1.56
3	0.00882	1.000	0.009	0.078	26.73	0.08f	0.41p	33.20	1.58
4	0.09356	1.000	0.094	0.171	35.36	1.04f	1.77p	27.79	1.20
5	0.06620	1.000	0.066	0.237	35.97	0.99f	9.16p	20.14	0.51
5+i1	0.00005	0.000	0.000	0.237	16.84	4.59f	179.87p	0.00	
5+i1+i2	0.02731	0.000	0.000	0.237	18.10	4.71f	179.72p	0.00	
6	0.04815	1.000	0.048	0.286	30.40	0.32f	10.81p	20.21	0.58
6+i1	0.01545	0.981	0.015	0.301	30.80	0.35f	11.44p	19.24	0.60
7	0.05740	1.000	0.057	0.358	26.96	0.27a	8.42p	22.30	0.66
7+i1	0.02053	1.000	0.021	0.379	27.05	0.29a	9.32p	21.01	0.71
8	0.01965	1.000	0.020	0.398	21.69	1.04a	1.97s	25.73	0.52
8+i1	0.00723	1.000	0.007	0.406	21.54	1.06a	4.37p	23.32	0.48
8+i1+i2	0.01144	1.000	0.011	0.417	21.51	1.07a	4.24p	23.46	0.48
9	0.00300	0.886	0.003	0.420	20.98	1.08a	10.46p	15.68	0.34
9+i1	0.00022	0.864	0.000	0.420	20.82	1.12a	10.86p	15.05	0.33
10	0.00373	1.000	0.004	0.424	25.57	0.08a	3.87p	29.46	1.30
10+i1	0.00063	1.000	0.001	0.424	24.76	0.23a	3.91p	28.88	1.34
11	0.00228	1.000	0.002	0.427	25.57	0.08a	3.87p	29.46	1.30
11+i1	0.00064	1.000	0.001	0.427	24.72	0.23a	4.34p	28.36	1.26
12	0.00262	1.000	0.003	0.430	26.02	0.00	0.04p	33.42	1.21
12+i1	0.00135	1.000	0.001	0.431	25.36	0.12a	0.08p	32.85	1.19
13	0.00112	1.000	0.001	0.432	26.02	0.00	0.04p	33.85	1.52
13+i1	0.00235	1.000	0.001	0.433	25.36	0.12a	0.08p	33.72	1.54
13+u1	0.00112	1.000	0.001	0.433	26.02	0.00	0.04p	33.83	1.52
13+u1+i1	0.00235	1.000	0.001	0.435	25.36	0.12a	0.08p	33.69	1.54
		1-division damage:		**0.435**		**Probability of damage:**		**0.463**	
1+2	0.02990	1.000	0.030	0.464	28.31	0.27f	0.00	33.19	1.58
2+3	0.01392	1.000	0.014	0.478	27.74	0.20f	0.43p	32.82	1.58
3+4	0.03697	1.000	0.037	0.515	36.79	1.21f	2.68p	25.84	1.07
4+5	0.04187	0.000	0.000	0.515	19.40	4.85f	179.67p	0.00	
4+5+i1	0.00004	0.000	0.000	0.515	19.40	4.85f	179.67p	0.00	
4+5+i1+i2	0.03434	0.000	0.000	0.515	21.12	5.02f	179.47p	0.00	
5+6	0.04035	0.000	0.000	0.515	-1.21	2.56f	179.74s	0.00	
5+6+i1	0.00004	0.000	0.000	0.515	61.58	8.66f	178.43p	0.00	
5+6+i1+i2	0.03161	0.000	0.000	0.515	75.17	9.97f	177.97p	0.00	
6+7	0.03928	0.000	0.000	0.515	-13.20	1.15f	180.00s	0.00	
6+7+i1	0.02727	0.000	0.000	0.515	-13.19	1.15f	180.00s	0.00	
7+8	0.02045	0.000	0.000	0.515	-44.85	5.15a	179.60p	0.00	
7+8+i1	0.00722	0.000	0.000	0.515	-46.71	5.63a	178.96p	0.00	
7+8+i1+i2	0.02462	0.000	0.000	0.515	-46.82	5.66a	178.94p	0.00	
8+9	0.00694	0.864	0.006	0.521	20.82	1.12a	10.86p	15.05	0.33

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12/14/16 12:02:00 USCG - MSC, Washington, D.C. Page 7
GHS 15.00 **ELFARO321** RUN2

Divisions	P	Smin	P*S*V	A	Depth	Trim	Heel	Range	MaxRA
8+9+i1	0.00239	0.702	0.002	0.523	20.57	1.14a	12.21p	12.70	0.25
8+9+i1+i2	0.00699	0.702	0.005	0.528	20.57	1.14a	12.21p	12.70	0.25
9+10	0.00391	0.886	0.003	0.531	20.98	1.08a	10.46p	15.68	0.34
9+10+i1	0.00266	0.886	0.002	0.534	20.98	1.08a	10.46p	15.68	0.34
10+11	0.00334	1.000	0.003	0.537	25.57	0.08a	3.87p	29.46	1.30
10+11+i1	0.00290	1.000	0.003	0.540	23.61	0.44a	4.31p	27.58	1.29
11+12	0.00291	1.000	0.003	0.543	25.52	0.08a	4.14p	29.03	1.22
11+12+i1	0.00302	1.000	0.003	0.546	24.58	0.25a	4.94p	27.47	1.16
12+13	0.00160	1.000	0.001	0.547	26.02	0.00	0.04p	33.42	1.21
12+13+i1	0.00475	1.000	0.002	0.549	25.36	0.12a	0.08p	32.85	1.19
12+13+u1	0.00160	1.000	0.001	0.550	26.02	0.00	0.04p	33.32	1.21
12+13+u1+i1	0.00475	1.000	0.002	0.552	25.36	0.12a	0.08p	32.56	1.18
		2-division damage:		**0.118**	**Probability of damage:**			**0.389**	
1+2+3	0.02208	1.000	0.022	0.574	29.14	0.37f	0.46p	32.35	1.60
2+3+4	0.02196	1.000	0.022	0.596	38.80	1.45f	2.82p	24.47	0.97
3+4+5	0.00000	0.000	0.000	0.596	24.16	5.34f	179.38p	0.00	
3+4+5+i1	0.00000	0.000	0.000	0.596	24.16	5.34f	179.38p	0.00	
3+4+5+i1+i2	0.00189	0.000	0.000	0.596	26.70	5.58f	179.13p	0.00	
4+5+6	0.00000	0.000	0.000	0.596	67.17	9.22f	178.46p	0.00	
4+5+6+i1	0.00000	0.000	0.000	0.596	75.53	10.02f	178.11p	0.00	
4+5+6+i1+i2	0.00326	0.000	0.000	0.596	98.41	12.25f	177.52p	0.00	
5+6+7	0.00049	0.000	0.000	0.596	5.75	2.78f	179.73s	0.00	
5+6+7+i1	0.00000	0.000	0.000	0.596	593.97	64.60f	174.75p	0.00	
5+6+7+i1+i2	0.00556	0.000	0.000	0.596	624.26	69.22f	173.95p	0.00	
6+7+8	0.00000	0.000	0.000	0.596	-64.17	12.99a	177.46p	0.00	
6+7+8+i1	0.00000	0.000	0.000	0.596	-86.15	22.88a	175.95p	0.00	
6+7+8+i1+i2	0.00248	0.000	0.000	0.596	-87.41	23.44a	175.95p	0.00	
7+8+9	0.00100	0.000	0.000	0.596	-46.85	5.62a	178.85p	0.00	
7+8+9+i1	0.00032	0.000	0.000	0.596	-49.12	6.22a	178.15p	0.00	
7+8+9+i1+i2	0.00239	0.000	0.000	0.596	-49.12	6.22a	178.15p	0.00	
8+9+10	0.00550	0.864	0.005	0.601	20.82	1.12a	10.86p	15.05	0.33
8+9+10+i1	0.00204	0.735	0.002	0.603	20.12	1.25a	11.10p	13.40	0.26
8+9+10+i1+ i2	0.00646	0.735	0.005	0.607	20.12	1.25a	11.10p	13.40	0.26
9+10+11	0.00201	0.886	0.002	0.609	20.98	1.08a	10.46p	15.68	0.34
9+10+11+i1	0.00219	0.793	0.002	0.611	17.37	1.86a	5.95p	15.41	0.27
10+11+12	0.00249	1.000	0.002	0.613	25.52	0.08a	4.14p	29.03	1.22
10+11+12+i1	0.00322	1.000	0.003	0.617	23.36	0.48a	5.21p	26.38	1.19
11+12+13	0.00097	1.000	0.000	0.617	25.52	0.08a	4.14p	29.03	1.22
11+12+13+i1	0.00322	1.000	0.002	0.619	24.58	0.25a	4.94p	27.47	1.16
11+12+13+u1	0.00097	1.000	0.000	0.619	25.52	0.08a	4.14p	28.81	1.20
11+12+13+ u1+i1	0.00322	1.000	0.002	0.621	24.58	0.25a	4.94p	27.15	1.12
		3-division damage:		**0.068**	**Probability of damage:**			**0.090**	
1+2+3+4	0.01862	1.000	0.019	0.639	41.25	1.74f	2.96p	22.84	0.86
2+3+4+5	0.00000	0.000	0.000	0.639	31.14	6.05f	179.30p	0.00	
2+3+4+5+i1	0.00000	0.000	0.000	0.639	31.14	6.05f	179.30p	0.00	
2+3+4+5+i1+ i2	0.00080	0.000	0.000	0.639	34.69	6.39f	179.03p	0.00	

continued next page

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GHS 15.00 **ELFARO321** RUN2

Divisions	P	Smin	P*S*V	A	Depth	Trim	Heel	Range	MaxRA
7+8+9+10	0.00001	0.000	0.000	0.639	-46.85	5.62a	178.85p	0.00	
7+8+9+10+i1	0.00000	0.000	0.000	0.639	-53.65	7.38a	177.99p	0.00	
7+8+9+10+ i1+i2	0.00137	0.000	0.000	0.639	-53.65	7.38a	177.99p	0.00	
8+9+10+11	0.00261	0.864	0.002	0.642	20.82	1.12a	10.86p	15.05	0.33
8+9+10+11+ i1	0.00091	0.617	0.001	0.642	17.19	1.88a	7.49p	12.58	0.20
8+9+10+11+ i1+i2	0.00362	0.617	0.002	0.644	17.19	1.88a	7.49p	12.58	0.20
9+10+11+12	0.00149	0.649	0.001	0.645	20.44	1.14a	12.58p	12.00	0.23
9+10+11+12+ i1	0.00208	0.521	0.001	0.646	16.94	1.91a	8.14p	11.14	0.16
10+11+12+13	0.00082	1.000	0.000	0.647	25.52	0.08a	4.14p	29.03	1.22
10+11+12+ 13+i1	0.00285	1.000	0.001	0.648	23.36	0.48a	5.21p	26.38	1.19
10+11+12+ 13+u1	0.00082	1.000	0.000	0.649	25.52	0.08a	4.14p	28.81	1.20
10+11+12+ 13+u1+i1	0.00285	1.000	0.001	0.650	23.36	0.48a	5.21p	25.98	1.12
		4-division damage:		**0.029**		**Probability of damage:**		**0.035**	
7+8+9+10+11	0.00000	0.000	0.000	0.650	-46.85	5.62a	178.85p	0.00	
7+8+9+10+ 11+i1	0.00000	0.000	0.000	0.650	-64.92	10.59a	177.82p	0.00	
7+8+9+10+ 11+i1+i2	0.00052	0.000	0.000	0.650	-64.92	10.59a	177.82p	0.00	
8+9+10+11+ 12	0.00118	0.616	0.001	0.651	20.29	1.18a	12.79p	11.53	0.22
8+9+10+11+ 12+i1	0.00039	0.333	0.000	0.651	16.75	1.93a	9.48p	8.18	0.09
8+9+10+11+ 12+i1+i2	0.00236	0.333	0.001	0.652	16.75	1.93a	9.48p	8.18	0.09
9+10+11+12+ 13	0.00040	0.649	0.000	0.652	20.44	1.14a	12.58p	12.00	0.23
9+10+11+12+ 13+i1	0.00149	0.521	0.000	0.652	16.94	1.91a	8.14p	11.14	0.16
9+10+11+12+ 13+u1	0.00040	0.179	0.000	0.652	19.82	1.21a	14.79p	4.85	0.04
9+10+11+12+ 13+u1+i1	0.00149	0.000	0.000	0.652	-45.31	4.30a	179.45p	0.00	
		5-division damage:		**0.002**		**Probability of damage:**		**0.006**	
8+9+10+11+ 12+13	0.00005	0.616	0.000	0.652	20.29	1.18a	12.79p	11.53	0.22
8+9+10+11+ 12+13+i1	0.00000	0.333	0.000	0.652	16.75	1.93a	9.48p	8.18	0.09
8+9+10+11+ 12+13+i1+ i2	0.00092	0.333	0.000	0.652	16.75	1.93a	9.48p	8.18	0.09
8+9+10+11+ 12+13+u1	0.00005	0.098	0.000	0.652	19.54	1.25a	15.47p	3.15	0.02

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Divisions	P	Smin	P*S*V	A	Depth	Trim	Heel	Range	MaxRA
8+9+10+11+ 12+13+u1+ i1	0.00000	0.000	0.000	0.652	-45.63	4.38a	179.30p	0.00	
8+9+10+11+ 12+13+u1+ i1+i2	0.00092	0.000	0.000	0.652	-45.63	4.38a	179.30p	0.00	
			6-division damage:	**0.000**		**Probability of damage:**		**0.001**	

Attained index in this condition: **0.652** **Total probability of damage:** **0.984**
Required index: **0.602**

Distances in FEET. Angles in deg.

U.S. Department of Transportation
United States Coast Guard

Commandant
United State Coast Guard

2703 Martin Luther King Ave SE
Washington, DC 20593-7501
Staff Symbol: CG-INV
Phone: (202) 372-1032
Email: jason.d.neubauer@uscg.mil

16732
26 Jan 2017

MEMORANDUM

NEUBAUER.JASON.D.1170236480 Digitally signed by NEUBAUER.JASON.D.1170236480
DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USCG, cn=NEUBAUER.JASON.D.1170236480
Reason: I am the author of this document
Date: 2017.01.26 14:32:10 -05'00'

From: J. D. Neubauer, CAPT
COMDT (CG-INV)

To: CG MSC

Subj: MSC LUBE OIL SYSTEM COMPUTER MODELING AND ANALYSES OF THE SS EL FARO, O. N. 561732

Ref: (a) COMDT (DCO) memo 16732 of 08 Oct 2015

1. In accordance with reference (a), the Marine Board of Investigation (MBI) is investigating the sinking of the SS EL FARO and loss of her 33 crew members on October 1, 2015. Based on new information gathered from Simplified Voyage Data Recorder (SVDR) listening sessions, it appears that a loss of lube oil was directly involved in the EL FARO's critical loss of propulsion. The MBI has already begun work with David Karnes of your staff to model the lube oil system in Rhino Marine for further analysis of the impacts of list and trim on the system. The work completed to date suggests that approved lube oil sump operating levels would not allow continued operation at 15 degrees of static list, a requirement in the applicable 1973 ABS Steel Vessel Rules. The scope of this work may be more time consuming than originally anticipated, which warrants another formal request to MSC. As a result, I request MSC provide additional technical assistance in support of the investigation.

2. Specifically, I request that the MSC complete the following computer modeling and analyses to support the MBI's analysis of the lube oil system:

    a. Complete Rhino Marine model of the lube oil sump, gravity tank, and storage tank.

        (1) The model should include critical piping for the sump and two tanks that may be impacted by list or trim. These modeled pipes may be modeled within the sump and tanks without modeling the rest of the piping. At a minimum, the following pipes must be modeled:

            1. Sump suction

            2. Sump return from gravity tank

            3. Gravity tank supply

            4. Gravity tank overflow

            5. Storage tank gravity drain pipe

b. Provide analysis for determination of potential impacts to lube oil system from list and trim to include loss of lube oil suction or pocketing within gravity or storage tanks rendering them less effective. This analysis should include the following inputs:

   (1) Sump levels including high level capacity 2020 gallons, operating level capacity 1426 gallons, low level capacity 724 gallons, and the loading specified in the loading condition for the accident voyage.

   (2) Gravity tank and storage tank levels as loaded in the accident voyage.

   (3) Following conditions should be analyzed:

      1. 15 degrees list to port and starboard with no trim

      2. 15 degrees list to port and starboard evaluated with 3.5 feet aft trim.

      3. 15 degrees list to port and starboard and trim 5 degrees forward and aft

      4. 18 degrees list to port and starboard evaluated with 3.5 feet aft trim.

      5. Trim 5 degrees forward and aft with no list.

c. Provide animated sequence for the accident voyage condition which shows the lube oil sump level as list changes incrementally (no more than 5 degree increments) from 0 to 20 degrees to port.

3. MSC will have access to all information available to the MBI, including all materials provided by the parties in interest (PII), other MBI exhibits, and public hearing witness transcripts.

4. Please provide the results of your technical reviews and analyses in the form of a collection of screen shots suitable for use as MBI exhibits and figures within the Report of Investigation (ROI) in addition to the animation requested. It is important to note that MSC's work will be provided to the National Transportation Safety Board (NTSB) and may be included in the NTSB's report of investigation and posted on their public docket.

#

U.S. Department of Homeland Security
United States Coast Guard

Commanding Officer
United States Coast Guard
Marine Safety Center

US Coast Guard Stop 7430
2703 Martin Luther King Jr. Ave
Washington, DC 20593-7430
Staff Symbol: MSC-1
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Email: msc@uscg.mil

16732/P019910
Serial: C3-1700713
03 Apr 2017

MEMORANDUM

From: J.W. Mauger, CAPT
CG MSC

Reply to Attn of: David Karnes
(202) 795-6789

To: J.D. Neubauer, CAPT
COMDT (CG-INV)

Subj: MSC LUBE OIL MODELING AND ANALYSES OF THE SS EL FARO, ON 561732

Ref: (a) Your memo 16732 of January 26, 2017

1. Reference (a) requested that the Marine Safety Center (MSC) complete main lube oil system computer modeling and related analysis in support of the Marine Board of Investigation (MBI) investigating the sinking of the SS EL FARO and loss of her 33 crew members on October 1, 2015, and provide results in the form of screen shots (visualizations).

2. A discussion of this work and our results is attached as the enclosure to this memorandum. If you have any questions or need additional information, please contact Mr. David Karnes.

#

Enclosure: SS EL FARO Lube Oil Modeling and Static Analyses Results

SS EL FARO LUBE OIL MODELING AND STATIC ANALYSES RESULTS

1. Introduction

This enclosure discusses the source material and methodology used by the Marine Safety Center (MSC) in modeling and analyzing lube oil levels for three tanks that are part of the EL FARO's main lube oil system, along with the results of this effort. Static tank levels in relation to associated pipe openings (e.g., suction and drain piping) were examined for different combinations of tank loading volumes and vessel list and trim conditions. This work was conducted in support of the Marine Board of Investigation's (MBI's) investigation of the EL FARO's sinking, as requested by CG-INV memorandum 16732 dated January 26, 2017.

2. Overall Approach

From source material provided through the MBI, the MSC created a three-dimensional computer model of the three tanks and certain associated piping using Robert McNeel & Associates' Rhinoceros (Rhino) software version Rhino 5. The modeled tanks were: 1) the main lube oil system sump (referred to on various drawings and throughout this enclosure as "the sump"); 2) the gravity tank; and 3) the storage tank. After finalizing this Rhino model, referred to as "the MSC model" in this enclosure, lube oil level visualizations were produced by listing and trimming the MSC model for selected loading volumes, and capturing the resulting lube oil levels through screen shots. The analysis was limited to constant loading volumes and static list and trim conditions only, with the understanding that dynamic factors (e.g., sloshing or changing sump and tank loading volumes due to movement of lube oil throughout the system) would have to be considered in any comprehensive analysis of lube oil system performance.

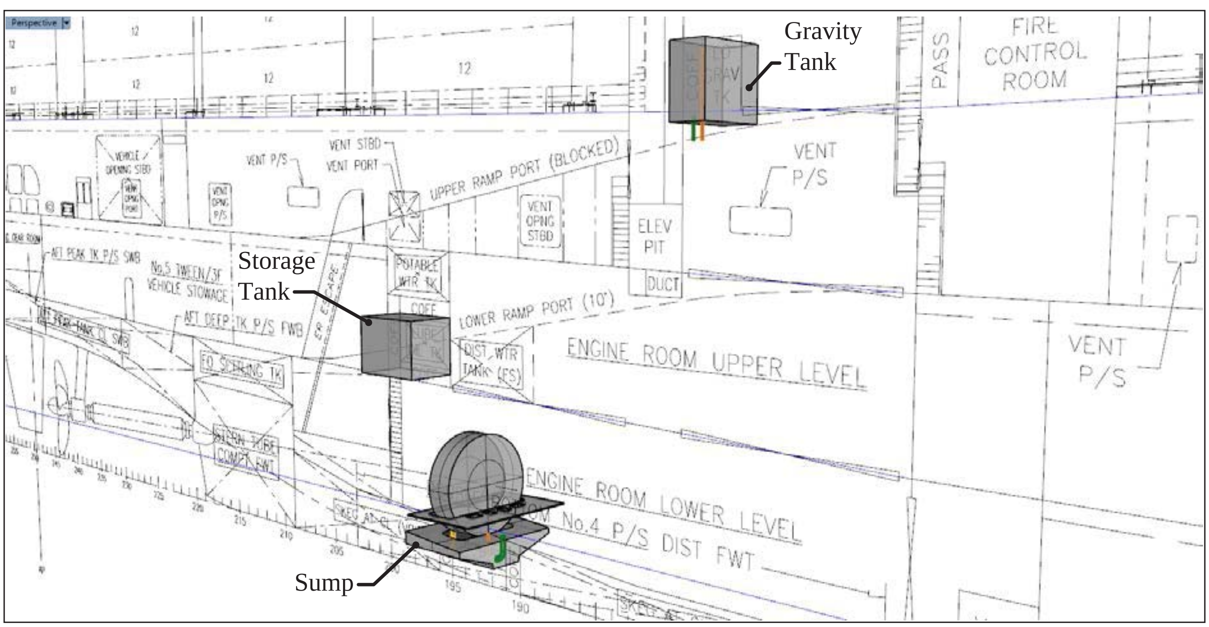

Figure 1. MSC Model and EL FARO Inboard Profile [1]

[1] Inboard profile taken from a general arrangement drawing for the EL FARO (MBI Exhibit 007). The MSC concluded that the drawing contains vertical scaling errors (see Section 2.2 of MSC Technical Report "SS EL FARO Stability and Structures" dated March 22, 2017). Accordingly, while useful for visualization purposes, this drawing was not used for the lube oil modeling and analysis work. Figure 1 shows the modeled components in their correct locations relative to the vessel's baseline as depicted on the drawing.

3. Source Material

The MSC used the drawings listed in Table 1, and information from sister vessel SS EL YUNQUE's lube oil sump sounding table (MBI Exhibit 350) and the EL FARO CargoMax printout for the accident voyage (MBI Exhibit 059), to create the MSC model and complete the subsequent work. Although the drawings were in some cases difficult to read and contained minor scanning distortions, they were sufficiently legible for the import, scaling, and overlay operations used in the MSC model's development.

Table 1. Lube Oil System Source Drawings

Drawing	Used to Model:		
	Sump	Gravity Tank	Storage Tank
Connections on Lube Oil Sump Tank Drawing, Drawing 663-904-04, Alt 9, dated February 25, 1972, Sun Shipbuilding & Dry Dock Co. (MBI Exhibit 408)	X		
Diagrammatic Arrangement of Lubricating Oil System Drawing, Drawing 663-904-100, Alt 5, dated April 27, 1972, Sun Shipbuilding & Dry Dock Co. (MBI Exhibit 352)	X	X	
Lube Oil Service System Drawing, Drawing 663-904-01, Sheet 4 of 5, Alt 18, dated (illegible), Sun Shipbuilding & Dry Dock Co. (MBI Exhibit 409)		X	
Conns. on Lube Oil Gravity-Storage Tanks Drawing, Drawing 663-904-06, Alt 7, dated January 21, 1972, Sun Shipbuilding & Dry Dock Co. (MBI Exhibit 410)		X	X

4. Sump Modeling

The lube oil sump is located beneath the main reduction gear, extending longitudinally from frame 191 to frame 195, and vertically from 3.5 feet (ft) above the baseline up to the level of the upper inner bottom plating. It is of complex shape, with the top sloped relative to the vessel's baseline. The sump model includes the suction pipe and gravity tank return pipe (gravity tank overflow). The turbine foundation, bull gear casing, and the return pipe from the main unit were also included, although they had no effect on the lube oil level analysis, to help visualize the sump's orientation. An isometric view of these components from the MSC model is shown in Figure 2.

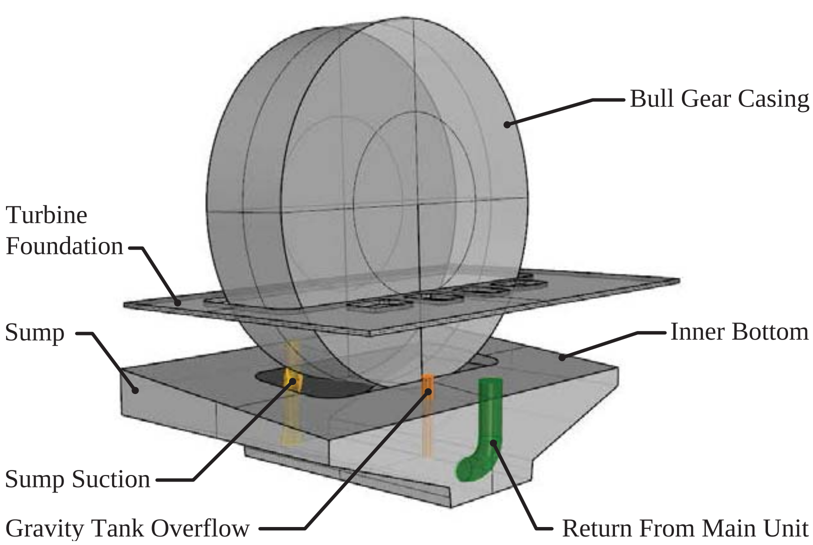

Figure 2. Lube Oil Sump and Related Components

Because complete information on framing and other components internal to the sump was lacking, a permeability factor of 93.5% was used to account for potentially unusable volumes. This factor was derived from a comparison of MSC model data with data from the EL YUNQUE lube oil sump sounding table (MBI Exhibit 350), as shown in Figure 3.[2]

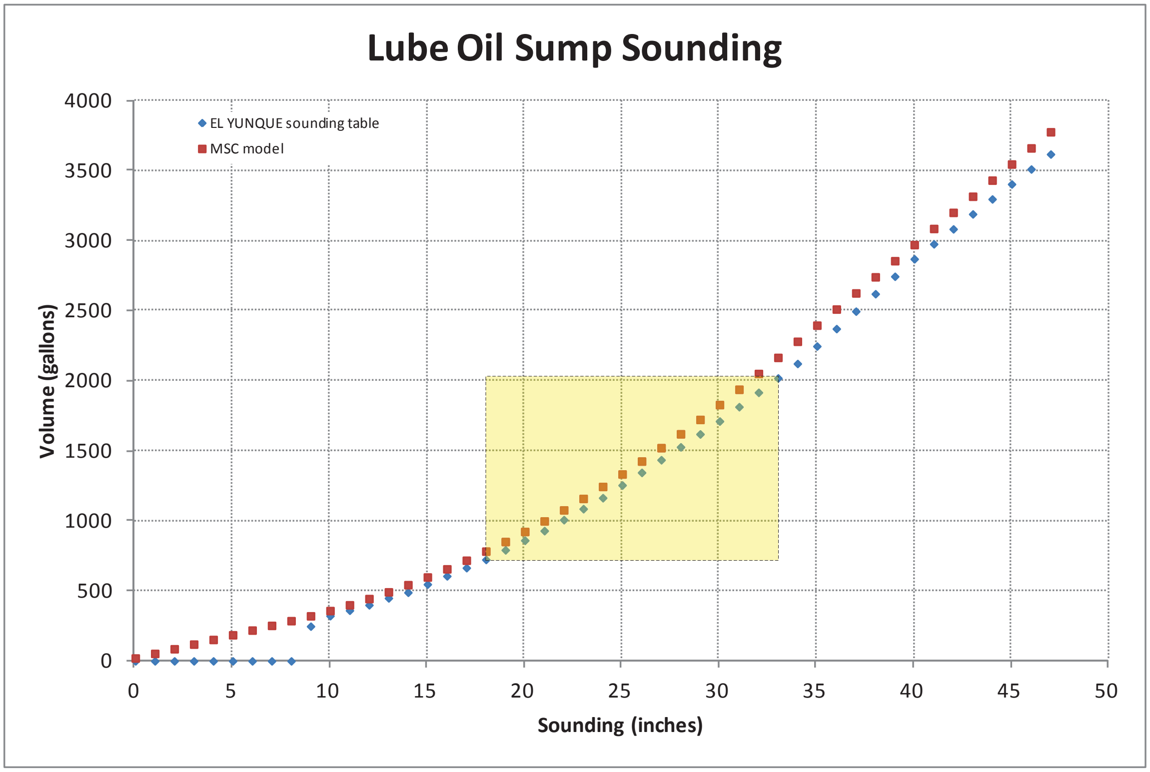

Figure 3. Lube Oil Sump Volumetric Comparison

5. Gravity Tank Modeling

The gravity tank is located on the main deck, extending longitudinally from aft of frame 177 to aft of frame 179, and is centered on the vessel's centerline. It is rectangular in shape with dimensions 5.0 ft (length) x 10.0 ft (width) x 9.0 ft (height). The tank model includes the overflow and supply pipes. Use of a permeability adjustment was not pursued, because analysis was ultimately limited to levels corresponding to the pipe opening locations as discussed in paragraph 7, which are unaffected by permeability considerations. An isometric view of the gravity tank and overflow and supply pipes from the MSC model is shown in Figure 4.

[2] The CG-INV memorandum requested the MSC address an operating range of loading volumes corresponding to that specified in MBI Exhibit 352, and highlighted in yellow within the dashed rectangle in Figure 3. The permeability factor of 93.5% estimated for this range is consistent with the presence of large longitudinal girders and other framing structure within the sump, based on MBI Exhibit 408.

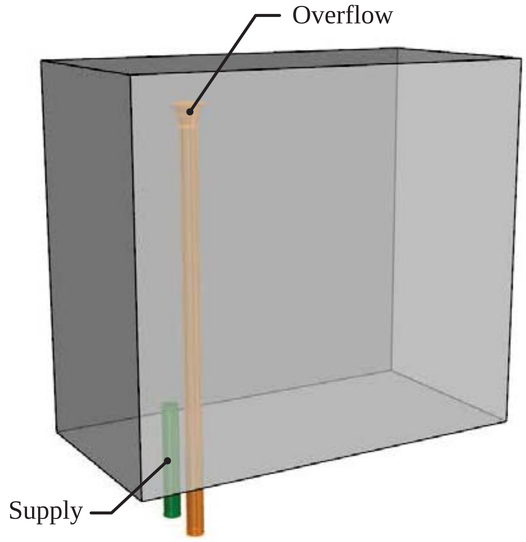

Figure 4. Gravity Tank [3]

6. Storage Tank Modeling

The storage tank extends longitudinally from frame 195 to frame 199, transversely from the vessel's centerline to 7.0 ft outboard to starboard, and vertically from a cofferdam located on the third deck to a height 8.0 ft above. It is rectangular in shape with dimensions 11.0 ft (length) x 7.0 ft (width) x 8.0 ft (height). The tank model includes the drain pipe. As was the case with the gravity tank, no permeability adjustments were made. An isometric view of the storage tank and drain pipe from the MSC model is shown in Figure 5.

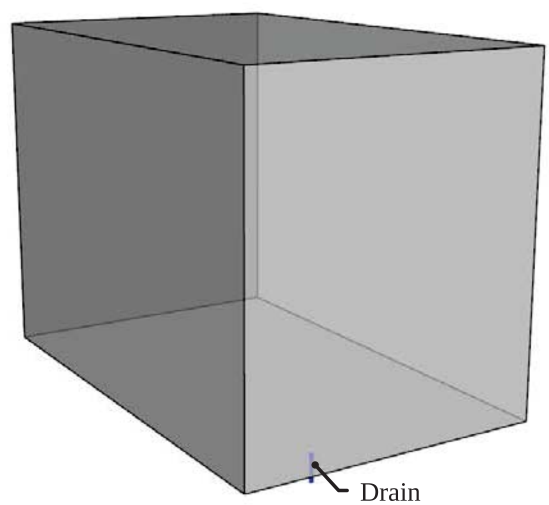

Figure 5. Storage Tank

[3] Figures 4 and 6 reflect the 2 inch correction in the vertical location of the overflow pipe opening discussed in paragraph 9 b.

7. Tank Loading Volumes and List and Trim Conditions

The CG-INV memorandum requested the MSC consider multiple combinations of tank loading volumes and list and trim conditions. For the sump, all combinations were analyzed as requested. However, based on preliminary modeling, the MSC concluded that the requested gravity and storage tank loading volumes for the accident voyage did not yield meaningful results.[4] Given that lube oil movement between tanks was not taken into account in the MSC's analysis, levels corresponding to the height of the gravity tank's supply and overflow pipe openings and the storage tank's drain pipe opening were examined. The resulting analysis showed pocketing effects, which could result in either increased, or decreased, effective lube oil capacity depending on the pipe opening location of interest and list and trim conditions. These are illustrated in Figure 6.

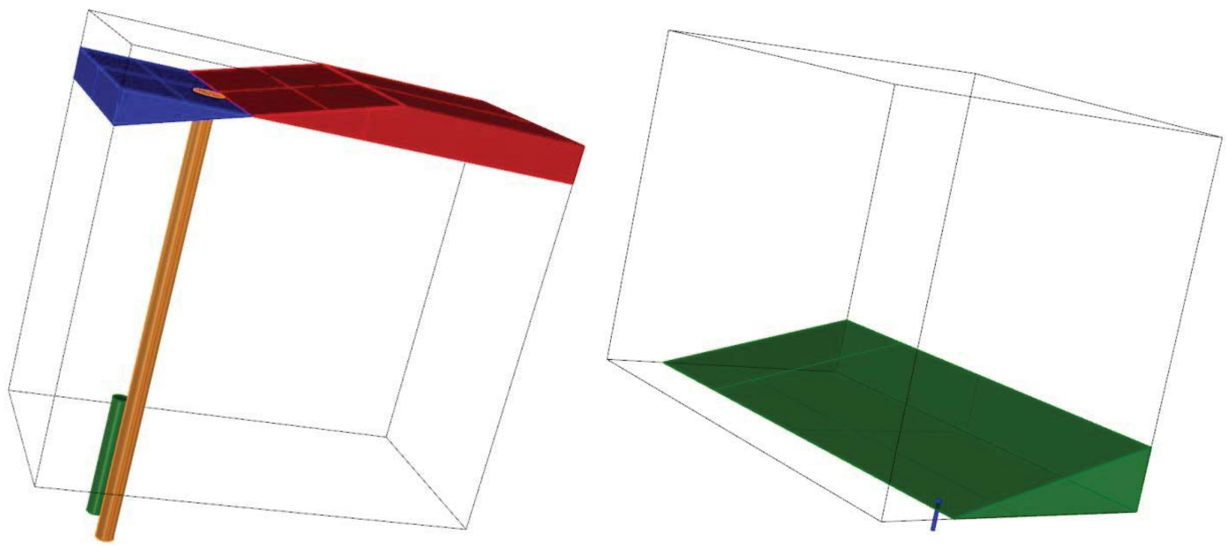

Figure 6. Isometric Views of Gravity Tank (left) and Storage Tank (right) Pocketing 15° Port List; 3.5 ft (0.3°) Aft Trim [5]

[4] Assumed accident voyage departure loading volumes for the gravity and storage tanks were 99.7% and 70.3% full, respectively, as listed in the CargoMax printout for the accident voyage (MBI Exhibit 059). The gravity tank overflow pipe opening is well below the 99.7% loading level, and the tank would rapidly drain to the opening level when filled. The storage tank drain pipe opening is near the bottom of the tank, and would not be uncovered for any of the requested vessel list and trim conditions with the 70.3% loading volume.

[5] The volume shown in red represents the additional lube oil which would be accommodated as the vessel approaches this 15° list condition from 0° list, with the tank continuously filling via the supply pipe. The volume in blue represents the lube oil lost through the overflow pipe under this scenario.

8. Creating Visualizations

After finalizing the MSC model's geometry, it was rotated to the various list and trim conditions specified in the CG-INV memorandum. Lube oil levels were simulated at each list and trim condition, using the specified loading volume or the vertical pipe opening location, as appropriate. This was done manually by bounding the volume of interest with a horizontal plane, and adjusting that plane upward or downward until the sump volume below the plane, as calculated by Rhino, matched the specified loading volume, or the lube oil level coincided with the corresponding pipe opening, as appropriate. The visualizations were created by taking screen shots capturing the resulting levels for each orientation, with the lube oil shown in green except where noted. The requested animation for sump levels was created by compiling a sequence of screen shots at 1° list increments.

9. Results

a. Preliminary Results

In consultation with the MBI, the MSC expedited model development, and provided preliminary visualizations to support the February 2017 MBI public hearing, recognizing that this work was based on modeling information and other data that had not been verified. The MBI presented selected visualizations at the hearing (MBI Exhibit 323), including the requested animation. The MSC also provided the MBI with a document containing images from drawings used in the MSC work (MBI Exhibit 324).

b. Final Results

The MSC reviewed the MSC model, loading volumes, and list and trim conditions used in creating the preliminary visualizations presented at the hearing. During this review, the MSC identified an error of approximately 6% in the lube oil sump accident voyage departure loading volume, which was used to develop the animated visualization, and a 2 inch error in the vertical location of the gravity tank overflow pipe opening. The corrected loading volume shows potential loss of suction in the sump at an 18° static list (as opposed to 19° in the animation), and the corrected overflow pipe location shows a slightly reduced pocketing effect in the gravity tank. Otherwise, the MSC verified the accuracy of the preliminary results provided to the MBI in support of the hearing. The key visualizations stemming from this work are related to sump levels, and are provided as separate figures below, along with an accompanying discussion.[6]

(1) <u>Design Low Level Capacity</u> The following three figures are for the sump at a loading volume of 724 gallons (18 inch sounding), which is the design low level capacity noted in MBI Exhibit 352, and for which applicable rules for lube oil system design require continued operation under certain combinations of list and trim, as indicated in the CG-INV memorandum. Although visualizations for the vessel in a starboard list condition are not included, the MSC model showed the

[6] The visualizations in Figures 7 through 11 are all from the perspective of an observer forward of the sump looking aft horizontally through the sump from a significant distance to avoid distortion effects. Trim angles are relative to the vessel's baseline, so with 0° trim and 0° list, the vessel is on an "even keel". The outlines of the sump's forward and after boundaries appear as light gray lines against the white background in the visualizations.

suction pipe opening to be fully immersed when in a 15° starboard list for all three trim conditions shown in these figures.

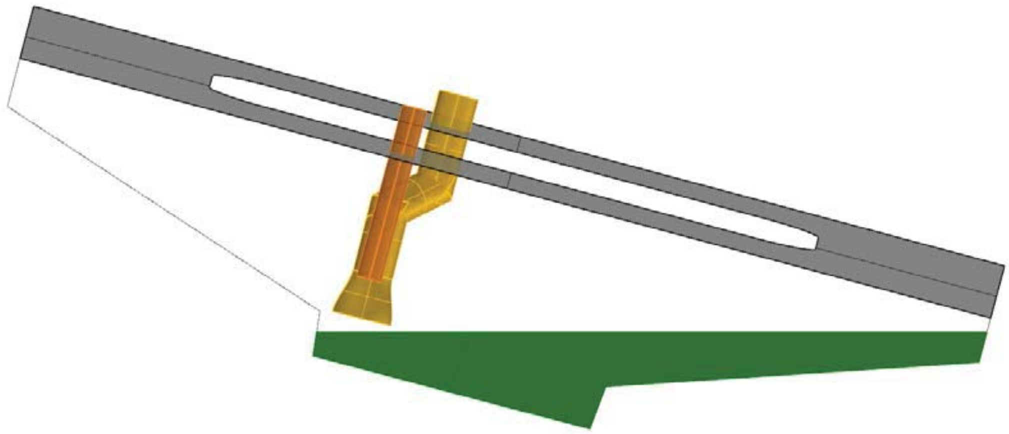

Figure 7. End View of Sump for the Design Low Level Capacity
15° Port List; 0° Trim

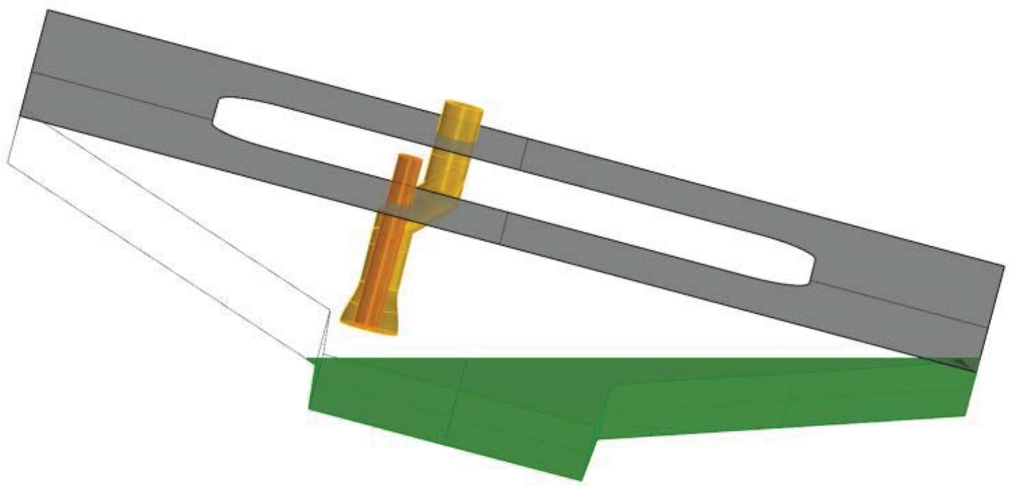

Figure 8. End View of Sump for the Design Low Level Capacity
15° Port List; 5° (64.2 ft) Trim by the Bow

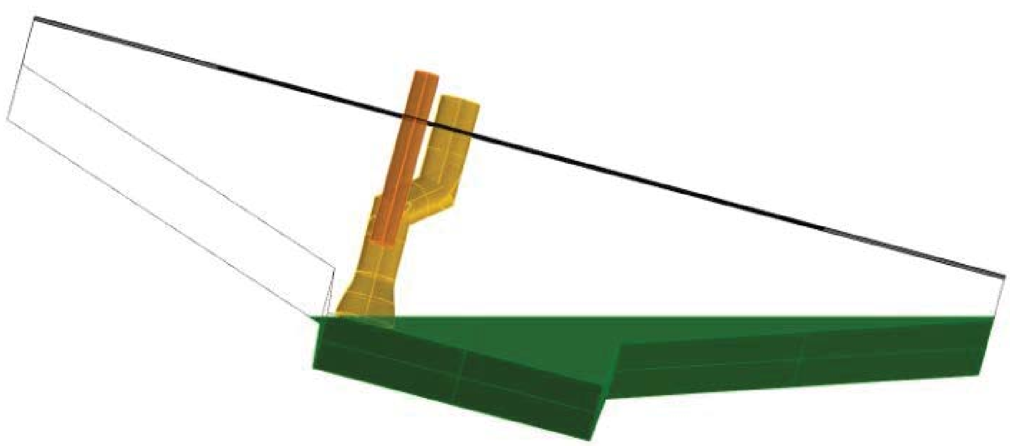

Figure 9. End View of Sump for the Design Low Level Capacity
15° Port List; 5° (64.2 ft) Trim by the Stern

(2) Accident Voyage Departure Loading The following two figures are for the sump at the accident voyage departure loading volume of 163.8 ft^3, as taken from the EL FARO CargoMax printout for the accident voyage (MBI Exhibit 059). These visualizations have been corrected from those used in the animation presented at the MBI public hearing. Both depict a trim of 5 ft by the stern, which corresponds to an angle of 0.4°. Figure 11 shows the suction pipe opening breaking the lube oil surface, indicating a potential loss of suction at an 18° static list (as opposed to 19° shown in the animation). Per the CG-INV memorandum request, starboard list conditions were not examined for this trim.

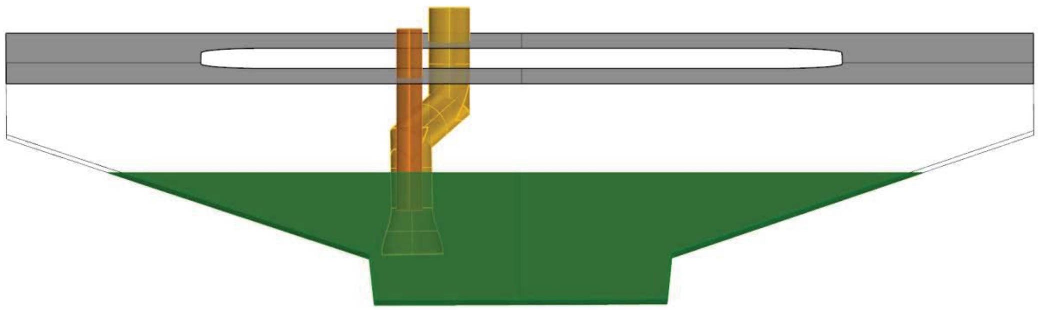

Figure 10. End View of Sump for the Accident Voyage Departure Loading
0° List; 5 ft (0.4°) Trim by the Stern

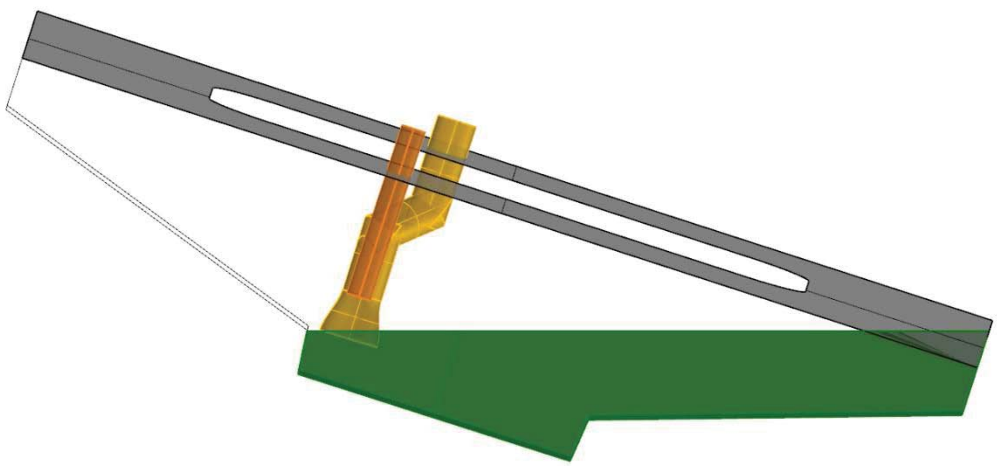

Figure 11. End View of Sump for the Accident Voyage Departure Loading
18° Port List; 5 ft (0.4°) Trim by the Stern