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United States Coast Guard

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MEMORANDUM

From: S. J. Kelly, CAPT
CG MSC

Reply to (202) 795-6746
Attn of: LT I. A. Oviatt

To: B. E. Welborn, CAPT
CGD EIGHT (dw)

Subj: MSC TECHNICAL REPORT FOR RO/RO GOLDEN RAY CAPSIZING

Ref: (a) CGD SEVEN memo 16732 of 12 Sep 19

1. The Marine Safety Center (MSC) completed a forensic stability analysis in support of the Formal Marine Casualty Investigation into the capsizing of the RO/RO GOLDEN RAY on September 8, 2019, established per reference (a).

2. Documentation of our analysis is provided in a stand-alone MSC technical report, which is included as enclosure (1) to this memorandum.

3. If you have any questions or require additional information, please contact LT Ian Oviatt.

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Encl: (1) MSC Technical Report: GOLDEN RAY Intact Stability dated 26 Aug 2020

U.S. Coast Guard
Marine Safety Center

Technical Report

GOLDEN RAY
Intact Stability

August 26, 2020

CG EX 16 B

Table of Contents

Executive Summary

This report documents a forensic stability analysis of the RO/RO GOLDEN RAY, completed by the Marine Safety Center (MSC) in support of the formal marine casualty investigation into the capsizing that occurred on September 8, 2019.

To aid in the accomplishment of the analysis, MSC independently generated a detailed computer model, and used this model for analyses of vessel hydrostatics and intact stability.

Based on independent calculation and various assumptions detailed in this report, MSC analysis indicates that, if loaded in accordance with the cargo weights detailed on the Brunswick Departure Stowage Plan and the liquid load quantities reported by the IMACS computer prior to the capsize, the GOLDEN RAY did not meet the mandatory requirements of the International Code on Intact Stability (2008). MSC analysis also indicates significant reduction in righting arms due to the centrifugal force experienced by the vessel throughout the turn leading up to the capsize. MSC analysis indicates that these factors combined to produce an extremely low righting energy, preventing the vessel from withstanding further adverse static or dynamic heeling effects, and resulting in the vessel's capsize.

Further analysis was conducted to assess the vessel's intact stability during the two voyages prior to the capsize voyage: Freeport, TX to Jacksonville, FL and Jacksonville FL, to Brunswick, GA. Results indicate that, based on the respective cargo stowage plans and IMACS liquid loading data, although the vessel had more righting energy in these voyages than during the capsize voyage, it did not fully comply with the mandatory requirements of the International Code on Intact Stability (2008) during either preceding voyage.

1. Introduction

1.1. Background

Reference [1] established the formal marine casualty investigation into the capsizing of the RO/RO GOLDEN RAY while transiting St. Simons Sound, Georgia on September 8, 2019. As requested by the members of the investigation team, MSC utilized relevant naval architecture principles to assist with determining the contributing physical and environmental factors which led to the capsize of the vessel.

1.2. Approach

Based on the available documentation, including vessel drawings, stability information, tank loading data, and cargo loading data, MSC completed a series of independent technical analyses. To aid in the accomplishment of these analyses, MSC independently generated a detailed computer model for calculation of vessel hydrostatics and stability.

Section 2 provides an overview of the development of the MSC computer model.

Section 3 documents the methods and assumptions used to generate the loading condition that was applied to the MSC computer model to simulate the capsize voyage condition.

Section 4 provides a primer on basic ship stability and documents the results of the hydrostatic and stability analyses in the loading condition described in Section 3.

Section 5 documents MSC's review of the vessel's stability during the capsize voyage with key data in the vessel's Trim and Stability Booklet.

Section 6 documents and compares the results of MSC's review of vessel stability during the two voyages prior to the capsize voyage.

Section 7 details conclusions based on the analyses contained in Sections 4 through 6.

Section 8 is a listing of references utilized for the analyses.

Appendix A details results of a comparison of the MSC computer model's hydrostatic and tank properties with the vessel's Trim and Stability (T&S) Booklet.

Appendix B provides detailed documentation of the methods, assumptions, and results of the stability analysis for the Jacksonville, FL to Brunswick, GA voyage.

Appendix C provides detailed documentation of the methods, assumptions, and results of the stability analysis for the Freeport, TX to Jacksonville, FL voyage.

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	m	meters
A/B	Above baseline	mm	milimeters
AP	Aft perpendicular	M	Metacenter, bending moment
B	Beam, center of buoyancy	M/E	Maine engine
BL	Baseline (plane)	M.D.O.	Marine Diesel Oil (tank)
BM	Metacentric radius	M.G.O.	Marine gas oil (tank)
CAD	Computer Aided Design (software)	MSC	Marine Safety Center
CL	Centerline (plane)	MT	Metric tons
CYL.O.	Cylinder oil (tank)	MTC	Moment to trim one centimeter
D	Depth	P	Port Side
EDT	Eastern daylight time	PPU	Portable pilot unit
F_B	Force of buoyancy	R	Radius (of turn)
F.W.	Fresh water (tank)	RO/RO	Roll-On/Roll-Off
G/E	Generator Engine	S	Starboard side
H.F.O	Heavy fuel oil (tank)	S.G.	Specific Gravity
FP	Forward perpendicular (plane)	SOLAS	Safety of Life at Sea (conventions)
g	Acceleration due to gravity	T	Draft
G	Center of gravity	TK	Tank
GHS	General Hydrostatics (software)	T&S	Trim and Stability (Booklet)
GM	Metacentric height	TCG	Transverse position of center of gravity
GZ	Righting arm	TPC	Tons per centimeter immersion
IACS	International Association of Classification Societies	UTC	Coordinated universal time
IMO	International Maritime Organization	v	velocity
KG	Vertical (height) position of center of gravity (VCG)	VCB	Vertical (height) position of center of buoyancy
KMt	Height of the metacenter	VCG	Vertical (height) position of center of gravity (KG)
l	Wind heeling arm (lever)	W.B.	Water ballast (tank)
LBP	Length between perpendiculars	W	Weight
LCB	Longitudinal position of center of buoyancy	WL	Waterline
LCF	Longitudinal position of center of flotation	φ	Angle of heel (same as θ)
LCG	Longitudinal position of center of gravity	θ	Angle of heel (same as φ)
L.O.	Lube oil (tank)	Δ	Displacement (weight of ship)
LWL	Length on the waterline	∇	Displacement volume

Table 1-1: Nomenclature

Notes regarding sign convention:

a. All negative TCG measurements indicate port of centerline and positive TCG measurements indicate starboard of centerline.
b. All VCG and KG measurements are references from the keel.
c. All longitudinal measurements are referenced from the aft perpendicular (positive values indicate forward towards bow).

2. MSC Computer Model

2.1. Introduction

To assess the hydrostatics and stability of the GOLDEN RAY, a detailed 3-dimensional computer model of the vessel was created for use with MSC's analysis software GHS (General HydroStatics by Creative Systems, Inc.). All modeling and analyses were completed using GHS Version 16.00. This section describes the development of the MSC GHS computer model for use in subsequent stability analyses.

2.2. Development of the MSC Computer Model

An original computer hull model was developed using the table of offsets [2] as the primary basis for the hull shape. However, some detail was not reflected in the table of offsets at the bow and stern due to the selected station spacing. Additionally, the table of offsets did not provide enough coordinate density to accurately define the bilge radius throughout the midships. As the failure to properly define these hull intricacies has potential to affect the accuracy of the calculated hull areas and volumes in those areas, the General Arrangement [3], Aft End Construction [4], Fore End Construction [5] and Double Bottom Construction [6] drawings were used to supplement the table of offsets when modeling the hull shape.

Hull components were added to provide accurate definition and volumes for the rudder and propeller. Deductions in the hull volume were made to define the bow thruster tunnel and the inset in way of the stern ramp on the starboard aft end of the vessel, as these were not accounted for in the table of offsets. A shell plating thickness of 17 mm on the bottom and 15 mm on the sides was added to account for the average hull plating thickness calculated from the Midship Construction Drawing [7] and Shell Expansion Plans [8]. Coordinates indicating the location of the freeboard deck, which is necessary for analyzing intact stability, were added to the model at a height of 14,300 mm A/B, as indicated in the Damage Control Plan [9]. The A Deck, Navigation Bridge Deck and Compass Deck were added to the model to accurately define the projected lateral area of the vessel. Figure 2-1 shows the MSC GHS computer hull model with all hull refinements incorporated.

Once the hull was modeled, the internal tanks and major compartments were added using the dimensions and locations shown on the General Arrangement, Engine Room Construction [10], Double Bottom Construction, Double Bottom Construction in Engine Room [11], Aft End Construction, Fore End Construction, and Construction Profile & Deck Plan [12] drawings. Figure 2-2 shows the inboard profile and plan views of the MSC GHS computer model with tanks and major internal compartments.

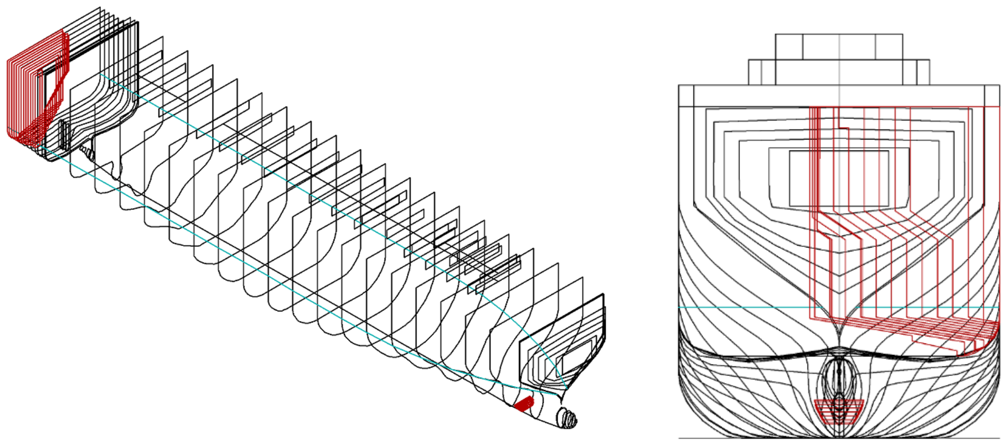

Figure 2-1: The MSC GHS computer hull model, including appendages, freeboard deck (light blue line), deductions for the thruster tunnel and stern ramp inset (red lines), and the top decks.

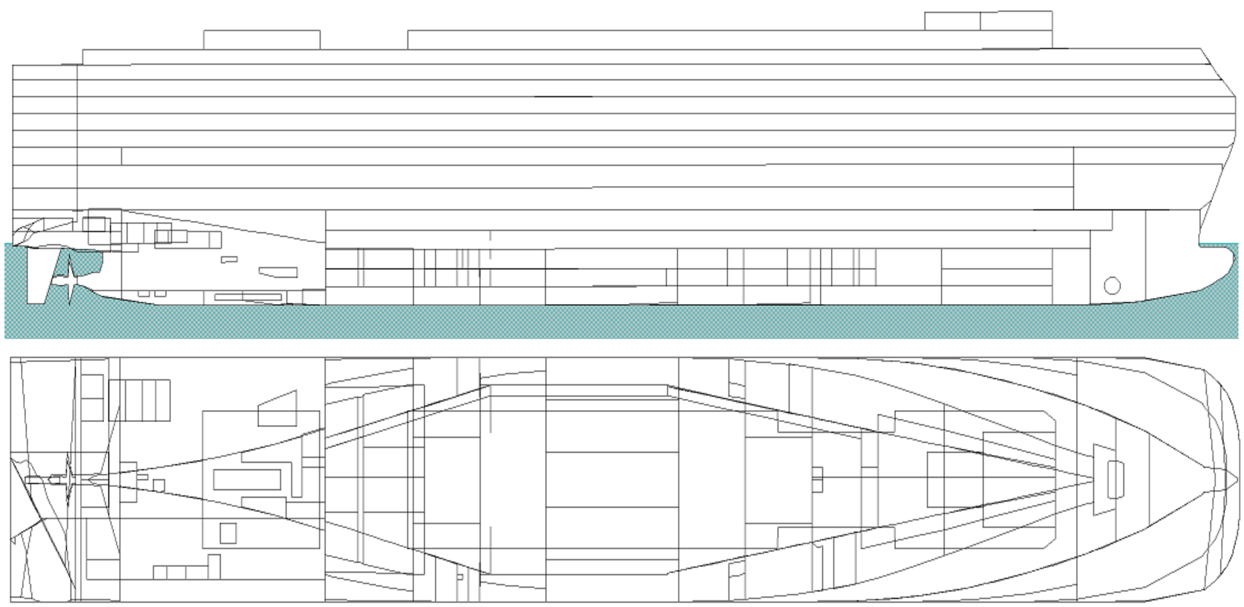

Figure 2-2: Inboard profile and plan views of the MSC GHS computer model showing tanks and compartments.

2.3. MSC Computer Model Comparison with T&S Booklet

A comparison of hydrostatic properties and tank parameters between the MSC computer model and the T&S Booklet [13] was completed. A full description of the results of this comparison is provided in Appendix A. Hull hydrostatic properties between the models aligned closely, with approximately 0.2% difference in calculated displacement at mean drafts between 9.3 m and the extreme Summer load draft of 10.618 m. Some minor discrepancies between tank properties were noted; however, these were considered to be generally inconsequential to results.

2.4. Lightship Weight and Center of Gravity

To perform hydrostatic and stability analyses, the ship's lightship weight (displacement) and location of the center of gravity must be determined and assigned to the model. The lightship weight and centers of gravity were calculated based on a stability test completed on the GOLDEN RAY on October 13, 2017 [14]. Table 2-1 provides a summary of the lightship condition determined for the GOLDEN RAY. These values were assigned to the MSC model for use with all subsequent stability analyses.

	Lightship Condition
Disp. (MT)	21433.0
LCG (m-AP)	85.89
TCG (m-CL)	-0.27
KG/VCG (m-BL)	18.29

Table 2-1: Lightship weight (displacement) and center of gravity approved for the GOLDEN RAY and applied to the MSC computer model.

2.5. Summary

This section provided an overview of the development of the MSC GHS computer model for hydrostatic and stability analyses. Comparisons of hydrostatics and tank properties between the MSC GHS computer model and the T&S Booklet were summarized, with details of this comparison presented in Appendix A.

The lightship displacement and center of gravity of the MSC computer model were assigned in accordance with approved values and used for all analyses in this report.

3. Loading Conditions

3.1. Introduction

This section details the information, methods, and assumptions used to simulate the capsize voyage loads that were applied to the MSC computer model. When available, actual liquid and cargo loading data from the capsize voyage was used. For loads in which no data was available, Sections 5.3 and 5.4 of the T&S Booklet, which detail acceptable benchmark loading conditions for the vessel, were referenced.

3.2. Liquid Loading

Of the 61 tanks listed in the vessel's T&S Booklet, 47 were fitted with automatic tank level indicators which were output through the vessel's Totem Plus IMACS (Integrated Monitoring, Alarm and Control System) software. This software permits real time tank monitoring and records the data in an onboard computer. The list of IMACS monitored tanks includes all ballast, fuel oil, diesel oil and gas oil tanks.

The vessel's IMACS software program files [16] and several years of data files [17] leading up to the capsize were provided to MSC for use in analyzing hydrostatics and stability. A close review of the tank levels during the capsize voyage was conducted. Although various small fluctuations were noted, the loads in the tanks appeared to remain generally constant throughout the voyage. To quantify this, a comparison of the tank load quantities recorded from the approximate departure timestamp (08/09/19 04:00:26 UTC (12:00:26 EDT)) [18] to the values recorded from the pre-capsize timestamp (08/09/19 05:27:51 UTC (01:27:51 EDT)) [19] was completed and is summarized in Table 3-1. The latter timestamp indicates the closest available data to the capsize in which the vessel was at approximately 0° heel. Although the IMACS software indicates that the tank quantities reported are corrected for trim, the values do not appear to be corrected for list, so selecting a timestamp with 0° heel was necessary. The net difference in total liquid weight between the two timestamps, which constitutes approximately 69 MT, is indicative of error associated with automatic tank monitoring. As the net 69 MT difference is less than 0.2% of the 35,000 MT displacement predicted for the capsize voyage, this was considered to be well within the acceptable range of accuracy.

	05:27:51 UTC Load (MT)	04:00:00 UTC Load (MT)	Difference (MT)	Difference %
Ballast	2981.45	2929.04	-52.41	-1.8%
Fuel	891.38	872.95	-18.43	-2.1%
Diesel	321.91	322.95	1.04	0.3%
Misc.	46.29	47.17	0.88	1.9%
Total	**4241.03**	**4172.11**	**-68.92**	-1.6%

Table 3-1: Comparison between tank weights from the vessel's IMACS data files at the 08/09/19 05:27:51 UTC (01:27:51 EDT) (pre-capsize) timestamp and the 08/09/19 04:00:26 UTC (12:00:26 EDT) (departure) timestamp. The loads at the pre-capsize timestamp were applied to the MSC computer model.

The tank quantities from the 08/09/19 05:27:51 UTC (pre-capsize) timestamp were used to assign the liquid loads within the 47 IMACS monitored tanks to the MSC computer model. This was done by inputting the weight of the liquid in each tank that is indicated in the IMACS data file into GHS. The resulting tank fill percentage based on the tank shapes modeled in Section 2 was then calculated using the GHS software, which permits calculation of the resultant free surface inertia of each tank. Applying the tank quantities to the MSC model based on weight eliminates total weight and volume errors associated with differences in tank modeling between the MSC model and the model used to generate the T&S Booklet. Although this method does not eliminate free surface inertia differences associated with tank modeling, the total difference in VCG rise as a result of the free surface inertia difference was determined to be negligible to stability analysis as described in Appendix A.

Some smaller tanks including the lube oil, cooling water, and fresh water tanks were not monitored by the vessel's IMACS software. As such, the loading values for these tanks were assumed to be consistent with the Departure Bunkering Condition detailed in Section 5.3.1 of the T&S Booklet. Table 3-2 shows the liquid load applied for these tanks, which accounted for 7.8% of the total liquid load applied to the model.

	Load Applied (MT)
L.O. Sludge TK (S)	0.0
S/T L.O Sludge TK (C)	0.0
F.O. Sludge TK (S)	0.0
Sewage Holding TK (P)	0.0
S/T Cooling Water TK (C)	30.2
No. 1 F.W. TK (S)	78.2
No. 2 F.W. TK (S)	156.4
M/E L.O. STOR. TK (P)	21.6
M/E. L.O. SET. TK (P)	0.0
G/E L.O. STOR TK (S)	9.7
G/E L.0. SET. TK (S)	0.0
NO. 1 CYL. Oil TK (S)	14.7
NO. 2 CYL. Oil TK (S)	22.0
M/E L.O. Sump TK (C)	26.8
Total	**359.6**

Table 3-2: Liquid loads applied to MSC computer model for small tanks not monitored by IMACS. Values were selected in accordance with the T&S Booklet departure benchmark loading conditions.

3.3. Cargo Loading

MSC was provided with a VIN list [20] itemizing all cargo onboard the vessel along with each item's corresponding intended destination. However, this document did not cite stowage locations or vehicle curb weights. MSC was also provided with the Brunswick Departure Stowage Plan [21], a document which depicts the locations of vehicle groups in defined cargo areas throughout the vessel. Each vehicle group is titled with the port of loading and departure, a rough description of the vehicle models contained therein, and an approximate total weight of the cargo in the group.

To assess the acceptability of the weight estimates in the Brunswick Departure Stowage Plan, a detailed review of the plan was conducted. First, the weight of each vehicle group cited on the plan was assessed to ensure that it was reasonable when considering the description of the vehicles it contained. Of the 76 total vehicle groups detailed on the plan, the weight estimates of all but one group were deemed reasonable. The weight estimate of vehicle group '5A' on the forward end of Deck 5, however, was not: the stowage plan indicated that it contained 14 total vehicles (12 Ram 1500s and 2 Ram 2500s) with a total weight of 154.23 metric tons, as shown in Figure 3-1. With an average curb weight of 2.31 metric tons for the Ram 1500 and 3.09 metric tons for the Ram 2500, MSC calculated an estimated weight for this vehicle group of 33.9 metric tons, which is significantly less than the weight indicated on the stowage plan. As such, the MSC obtained value of 33.9 metric tons was used in lieu of the 154.23 metric tons cited in the Brunswick Departure Stowage Plan for all analysis. Using this lower weight raises the overall cargo VCG by approximately 0.13 m.

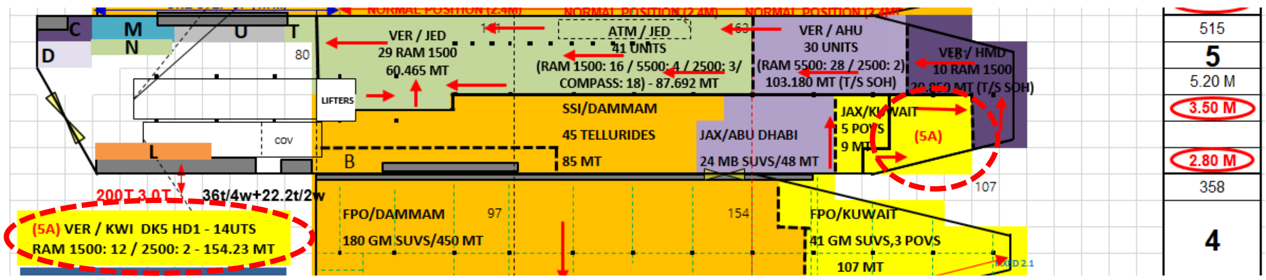

Figure 3-1: Section of Brunswick Departure Stowage Plan indicating vehicle group '5A' (circled in red) contains 14 vehicles weighing 154.23 MT, which was considered unreasonable. A weight of 33.9 MT was applied to the MSC computer model instead.

Next, the sum of the weights of the vehicle groups on the Brunswick Departure Stowage Plan was compared to the estimated total weight of the vehicles on the VIN list. This comparison is summarized in Table 3-3. As the VIN list did not contain vehicle weights, manufacturer's data was used to estimate the curb weight for each vehicle.

	Brunswick Dept. Stowage Plan	Brunswick VIN List	Difference	Difference %
Weight (MT)	8,780.15	8,981.10	200.95	2.2%

Table 3-3: Comparison between total weight on Brunswick Departure Stowage Plan and estimated total weight on Brunswick VIN list.

The Brunswick Departure Stowage Plan weight total, with the MSC modified weight in vehicle group (5A), was approximately 200 metric tons (2.2%) below the estimated weight total of the VIN list. However, this difference is relatively small in comparison to the predicted operating displacement of the vessel (approximately 35,000 MT) at the time of the incident. As such, the weights cited on the Brunswick Departure Stowage Plan, as modified by MSC, were applied to the MSC computer model.

In order to apply the weights of the vehicle groups in accordance with the locations detailed on the Brunswick Departure Stowage Plan, MSC superimposed the stowage plan onto the General Arrangement using Autodesk AutoCAD. The area centroid of each vehicle group was then calculated in AutoCAD and was assumed to represent the LCG and TCG of each vehicle group.

The VCG of each vehicle group was determined by adding the corresponding deck height to a standard, assumed vehicle VCG of 0.57 m above the deck, which is the assumed VCG indicated in Section 3.4.6 of the T&S Booklet for a standard vehicle. Although many of the vehicles onboard the vessel were SUVs, which are likely to have a higher VCG above the deck, the 0.57 m VCG was applied so that any subsequent failure of stability criteria could not be attributed to an error in using an assumed alternative value.

The weights of the vehicle groups were then applied to the MSC computer model in 76 individual point loads at the respective centers of gravity determined by MSC. These loads are summarized by deck in Table 3-4.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
Deck 13	745.60	98.24	0.14	36.82
Deck 12	805.44	102.95	0.72	34.51
Deck 11	951.00	91.03	1.07	32.00
Deck 10	1010.00	91.56	0.28	29.47
Deck 9	1020.00	92.71	-0.33	26.93
Deck 8	995.00	86.31	-0.15	24.41
Deck 7	620.25	96.81	-0.91	21.71
Deck 6 Raised	155.29	25.57	5.97	18.97
Deck 6 Standard	511.00	121.57	3.42	18.27
Deck 5	525.09	102.25	-1.30	14.87
Deck 4	557.00	99.81	0.02	11.82
Deck 3	515.00	99.12	0.00	9.02
Deck 2	174.34	97.63	-0.83	6.12
Deck 1	195.15	94.04	0.12	3.42
Total	**8780.2**	**95.39**	**0.32**	**24.34**

Table 3-4: Cargo weights applied to the MSC model from the Brunswick Departure Stowage Plan summarized by Deck. Deck 6 is subdivided into cargo situated on deck panels which were raised 0.7 m and cargo situated on deck panels which were at the standard height.

It is also important to note that Decks 2, 4, 5, 6, and 8 have the capability of being raised as desired depending on the height of the cargo beneath the deck. According to the Brunswick Departure Stowage Plan, Decks 2, 3, and 4 were at the standard (lowest) height. Three panels in the aft portion of Deck 6 were raised one step up (0.7 m); and, as such, the VCGs of the three corresponding vehicle groups were adjusted accordingly and are itemized according to height in Table 3-4.

Additionally, as the lightship VCG of the vessel is calculated with the vehicle decks at the standard (lowest) heights, it was necessary to account for the resultant rise in VCG from the weight of the raised steel panels. Page 95 of the T&S Booklet details weight moment calculations required for this calculation if the entire liftable portion of Deck 6 was raised. As only several panels on Deck 6 were raised above the standard height, MSC used a proportional weight moment calculation to obtain a rise in VCG of 0.006 m, which was added to the lightship VCG of 18.29 m cited in Section 2 of this report. The new VCG of 18.296 m was used for all further analyses.

3.4. Miscellaneous Deadweight

A review of the T&S Booklet benchmark loading conditions indicated that a number of other miscellaneous deadweight items were accounted for. This includes the weight of the fixed firefighting system's carbon dioxide, swimming pool water weight, provisions, stores, and cargo lashing equipment. These items were assumed to be onboard the vessel at the time of capsize and were therefore applied to the MSC computer model in accordance with the weights and corresponding centers of gravity listed for the Departure Condition detailed on page 266 of the T&S Booklet.

3.5. Final Loading Condition

A summary of the final loading condition applied to the MSC computer model is shown in Table 3-5.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
LTSH	21433.0	85.9	-0.27	18.3
Tanks	4600.8	102.6	1.94	3.9
Cargo	8780.2	95.4	0.32	24.3
Misc. Deadweight	230.4	74.4	-2.33	25.3
Total	**35044.4**	**90.4**	**0.16**	**18.2***

Table 3-5: Final loading condition applied to the MSC computer model.
*VCG includes a 0.215 m free surface correction.

3.6. Summary

This section documented loading conditions applied to the MSC computer model for hydrostatic and stability analyses. Liquid loading was based primarily on readings from the vessel's tank monitoring system data immediately prior to the capsize; however, T&S Booklet departure levels were assumed for small tanks which were not monitored by this system. Cargo loading was modeled based on the Brunswick Departure Stowage Plan. Miscellaneous deadweight items including stores and personal effects were applied to the MSC model based upon assumed departure values.

4. Results

4.1. Introduction

Through proper design, loading and operation, a ship should possess enough reserve buoyancy and stability to ensure that 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 and its contents. 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. A vessel's stability without damage is "intact stability," and is typically evaluated using the vessel's resultant righting arm curve.

This section provides a summary of the resultant hydrostatics and righting arm curve properties obtained for the vessel using the MSC computer model in the loading condition simulated for the capsize voyage. Results are then assessed for compliance with applicable stability requirements. Finally, the results of an assessment detailing the predicted change in the righting arm curve properties as the vessel turns are provided and discussed.

4.2. Loaded Hydrostatics

After the loads described in Section 3 were applied to the MSC computer model, the resultant hydrostatic properties were calculated using GHS.

4.2.1. List

The 0.16 m TCG calculated in Section 3 and applied to the MSC computer model resulted in a list of 4.6° to starboard. This is caused by asymmetric loading of port/starboard tank pairs: the No. 2 and No. 3 starboard ballast tanks were nearly fully loaded, however, the corresponding port tanks were loaded to less than 10% capacity. Additionally, the Brunswick Departure Stowage Plan indicated a starboard cargo TCG, further contributing to the vessel's modeled overall starboard TCG and resultant list. As the 4.6° starboard list calculated by MSC conflicts with the observed list conditions and the heel data reported by the IMACS computer immediately prior to departure, both of which indicated that the vessel left Brunswick without significant list, a further review was initiated to determine possible causes for this inconsistency.

As described in Section 3, the tank values used to load the MSC model were determined primarily from automated readings and were therefore considered unlikely to be the primary cause of the inconsistency between the MSC model list and observed/IMACS heel. Instead, it is likely that variations in the transverse locations of cargo between the Brunswick Departure Stowage Plan and the actual location of the cargo onboard the vessel resulted in the list in the MSC model. As such, the subsequent stability analysis was conducted by applying a zero heel condition to the vessel in accordance with observed and IMACS conditions. This was done by setting the heel of the vessel model equal to zero, allowing it to trim freely in order to remove residual longitudinal moments, and solving for the resultant TCG. This is equivalent to assigning the overall transverse center of the vessel loads such that the resultant heel is equal to

0°, while maintaining other bounded conditions such as tank free surface inertias, displacement, and longitudinal and vertical placement of loads.

4.2.2. Final Hydrostatic properties

The hydrostatic properties with the vessel at zero heel were calculated and are shown in Table 4-1.

	Disp. (MT)	LCB (m-AP)	VCB (m-BL)	LCF (m-AP)	MTC (m*MT/cm)	KMt (m-BL)	GM (m)	TPC (MT/cm)
Disp. (MT)	35044	90.39	5.35	78.06	621.94	19.97	1.76	56.10

Table 4-1: Final hydrostatic properties calculated from the MSC computer model for the vessel in the zero heel condition with the loading applied in Section 3.

4.2.3. Drafts

With the vessel at 0° heel, the resultant drafts calculated using the MSC computer model were compared to the drafts reported by the IMACS departure timestamp (08/09/19 04:00:26 UTC (12:00:26 EDT)), as shown in Table 4-2. The MSC computer model drafts obtained are shown for both salt water and brackish water conditions with a specific gravity of 1.02, which is representative of the water conditions when the vessel left Brunswick. Comparison of the loaded MSC model drafts with IMACS data immediately prior to departure was most appropriate, as the drafts reported by the IMACS while the vessel was underway did not appear consistent or reliable. This may have been due to errors associated with the automatic draft readings system and vessel movement through the water.

The mean draft of the MSC model in brackish water was within 0.03 m of the mean draft reported by the vessel's IMACS software at departure. The mean departure draft reading taken by the crew was 0.08 m higher than the MSC model mean draft in brackish water. However, it should be noted that observed draft readings are subject to the accuracy of the human eye and therefore subject to some error. Overall, because the MSC computer model draft readings aligned within 3% of the IMACS departure drafts, this indicates that a reasonably accurate total deadweight was applied to the MSC computer model.

	MSC Model Salt Water	MSC Model Brackish Water	IMACS Departure	Departure Draft Readings
Taft (m)	9.37	9.39	9.20	9.45
Tfwd (m)	9.26	9.31	9.56	9.40
Tmean (m)	9.32	9.35	9.38	9.43

Table 4-2: Comparison between loaded drafts calculated using the MSC computer model in salt and brackish water (S.G. = 1.02) with IMACS drafts at departure and departure draft readings taken by the vessel crew.

4.3. Intact Stability

Using the MSC computer model, an independent intact stability analysis was conducted, results of which are detailed and discussed in this section.

4.3.1. 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. Internal righting capacity arises from the ship's own weight and buoyant forces, providing a righting moment (see Figure 4-1). 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 4-2 shows a righting arm curve for a notional vessel. A plot of righting moments (righting moment curve) can also be created by simple multiplication of the righting arms with the ship's weight or 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. 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. Since the righting arm curve is simply a scaled version of the righting moment curve (scaled by the displacement or weight of the vessel), it is a principal tool in evaluating the ability of a ship to resist capsizing.

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 is commonly used as the primary means for assessing seaworthiness of all modern vessels.

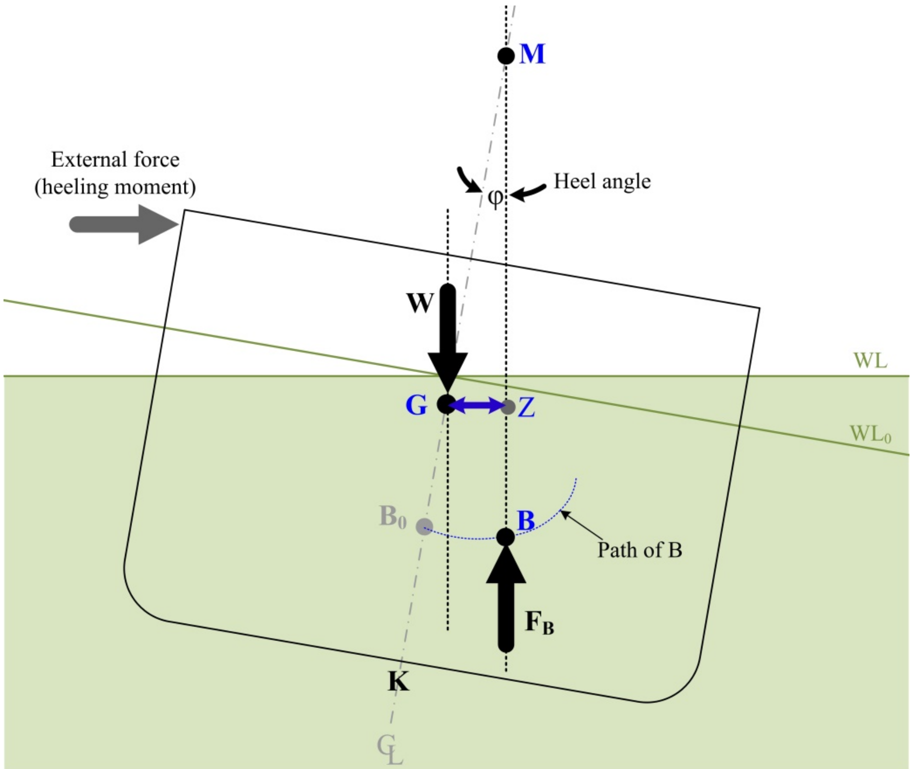

Figure 4-1: Development of righting arms (GZ) (righting moments) with vessel heel due to external forces.

Figure 4-1 includes annotation of an imaginary point through which the line of action of the buoyant forces 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 4-1 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 4-1:

$$GM = GZ/sin\varphi = GZ/\varphi \quad for\ small\ \varphi \ \ (in\ radians) \qquad (4\text{-}1)$$

GM is therefore the initial slope of the righting arm curve. Noting that 1 radian is equal to 57.3°, GM is often annotated graphically on a righting arm curve as shown in Figure 4-2.

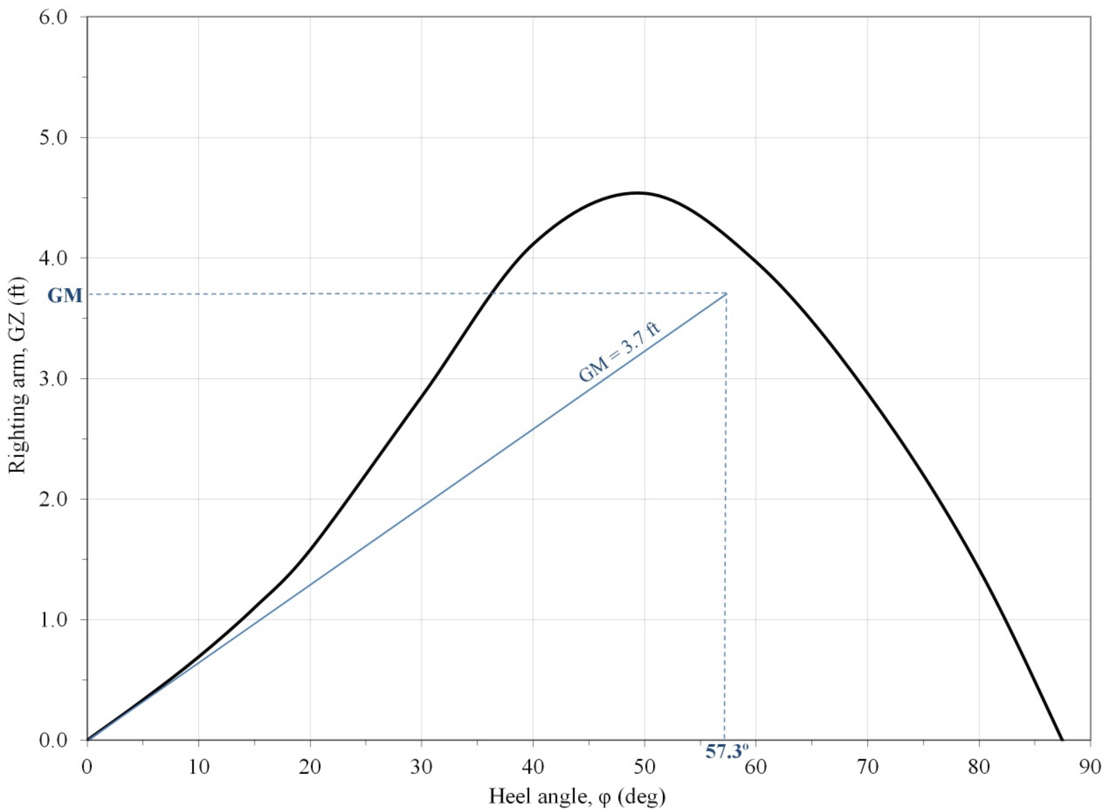

Figure 4-2: A righting arm curve for a notional vessel. GM is the initial slope of the righting arm curve.

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.

Current international intact stability standards are provided in the International Code on Intact Stability, 2008 (2008 IS Code) [22]. The 2008 IS Code includes two parts: "Mandatory Criteria" (Part A) and "Recommendations for Certain Types of Ships and Additional Guidelines" (Part B).

Part A of the 2008 IS Code presents minimum requirements to apply to cargo and passenger ships of 24 m in length and over, and includes two types of intact stability criteria:

(1) Criteria regarding righting arm (lever) curve properties (Section 2.2). The following righting arm criteria are specified:

a. The area under the righting arm curve shall not be less than 0.055 m-radians up to an angle of heel of 30°, and not less than 0.09 m-radians up to an angle of heel of 40° or the angle of downflooding if less than 40°. Additionally the area under the righting arm curve between 30° and 40°, or between 30° and the angle of downflooding if less than 40°, shall not be less than 0.03 m-radians.

b. The righting arm shall be at least 0.2 m at an angle of heel equal to or greater than 30°.

c. The maximum righting arm shall occur at an angle of heel not less than 25°.

d. The initial metacentric height GM shall not be less than 0.15 m.

(2) Severe wind and rolling criteria (Section 2.3). 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" [23]. The criteria are based on an energy balance between beam wind heeling and righting moments, with roll motion also taken into account. The following righting arm criteria are specified, referring to Figure 4-3:

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_{w1}. The angle of heel under action of the steady wind φ_0 shall not exceed 16° 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°, the angle of downflooding, or the angle of second intercept φ_c.

The wind heeling arms (l_{w1} and l_{w2}), calculated in accordance with Section 2.3.2 of the 2008 IS Code, remain constant at all angles of heel.

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.

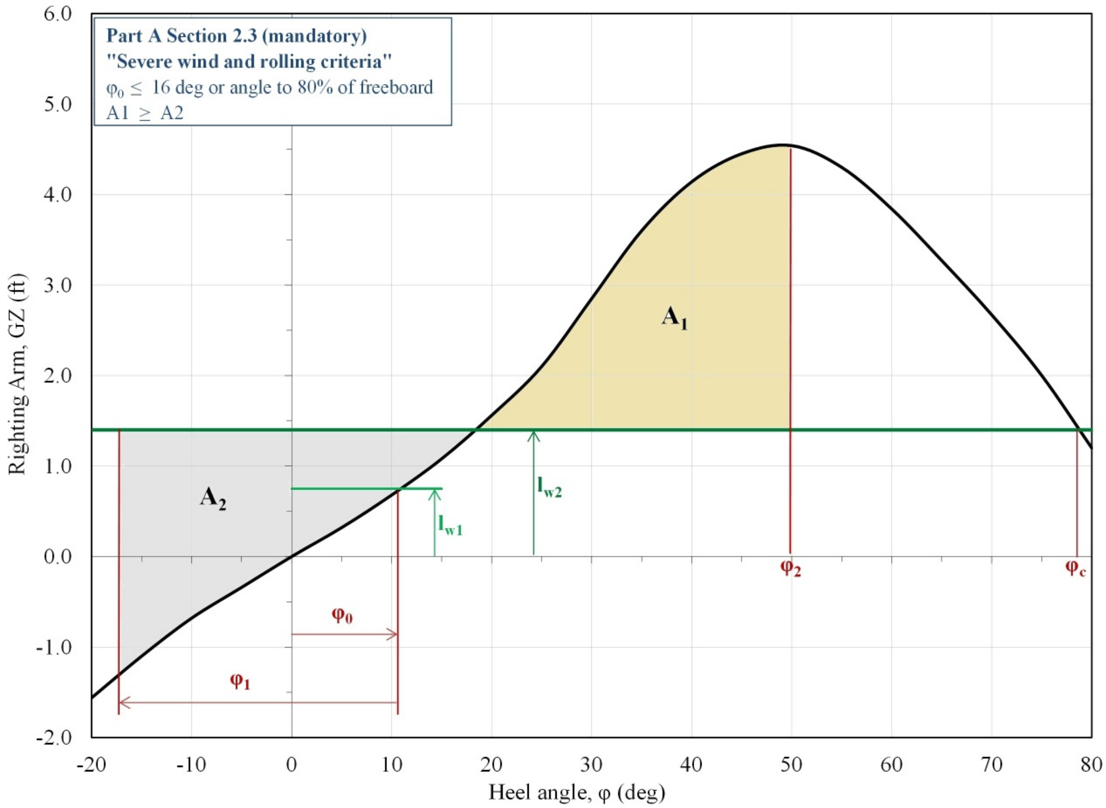

Figure 4-3: IMO severe wind and rolling criteria.

4.3.2. Capsize Voyage Righting Arm Curve Properties

With the MSC computer model loaded for the capsize voyage in accordance with Section 3, and with list set to 0°, righting arm curves were generated for heel to port and starboard. These righting arm curves are shown in Figure 4-4 by the solid green line (heel to starboard) and solid red line (heel to port). For comparison of righting arms with loading conditions which meet regulatory requirements, the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT are also shown (dotted lines).

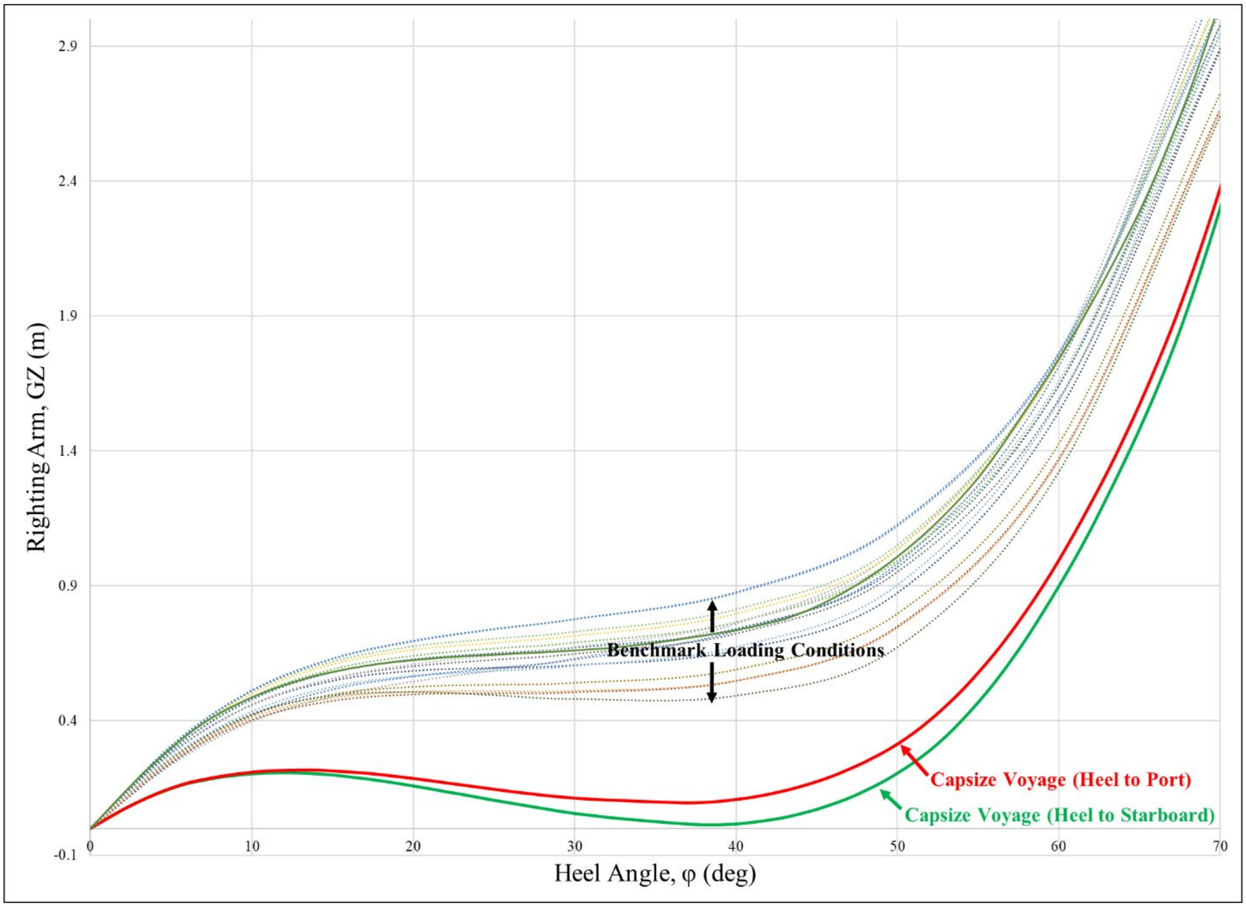

Figure 4-4: Righting arm curves generated for the vessel in the capsize voyage using the MSC Computer model for heel to starboard (solid green line) and heel to port (solid red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

Both righting arm curves produced for the capsize voyage had significantly lower righting arms and area under the righting arm curve than all benchmark conditions from the T&S Booklet. Due to the influence of the inset designed into the hull in way of the stern ramp, the MSC model starboard righting arm curve (green) produced slightly lower righting arm values than the corresponding port righting arm curve (red), particularly above 15° heel. A GM of 1.76 m was calculated from the righting arm curves from the capsize voyage condition.

For the righting arm curves shown in Figure 4-4, the 2008 IS Code mandatory intact stability criteria were applied, with results summarized in Table 4-3. Red background indicates that the attained value does not meet the specific criteria and green background indicates that the attained value meets the specific criteria. Of particular note is the limited area under the righting arm curve of the vessel in the MSC loaded condition between 30° and 40°. This caused failure of several of the IS Code general righting arm curve properties (Part A, Section 2.2). For the IS Code severe wind and rolling criteria (Part A, Section 2.3), the vessel failed to meet the area ratio criteria due to the limited area under the righting arm curve while in the capsize voyage loading condition.

	Units	MSC Loading Condition (Capsize Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties			
Area to 30 degrees	m-rad	0.075	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.079	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.005	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	3.980	At least 0.2 m
Angle of maximum righting arm	deg	80.3	At least 25 deg
Initial GM	m	1.76	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria			
Angle of static heel (φ_0)	deg	6.8	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	Greater than 1

Table 4-3: Results of the assessment of the MSC computer model loaded for the capsize voyage with the mandatory requirements of the 2008 IS Code. Green background indicates that the criteria has been met. Red background indicates that the criteria has not been met.

4.3.3. Stability During a Turn

4.3.3.1. Background

As a ship moves through a turn at velocity, it is subjected to various lateral forces as shown in Figure 4-5. A centrifugal force (red arrow) acts normal to the direction of the ship's forward velocity at the center of gravity of the ship. During a steady turn, there is an essentially equal and opposite force (black arrow) created by the water pressure at the vessel's center of lateral resistance (CLR), a point approximately halfway between the keel and the vessel's waterline. These forces create a heeling moment which acts to heel the vessel in the opposite direction of the turn as shown in Figure 4-5 and calculated below:

$$Turn\ Heel\ Moment = \frac{\Delta \cdot v^2}{g \cdot R}\left(KG - \frac{T}{2}\right)\cos\varphi \qquad (4\text{-}2)$$

As demonstrated in Equation 4-2, the turn heel moment increases as the vessel's forward velocity (v) and center of gravity (KG) increase, and as turn radius decreases.

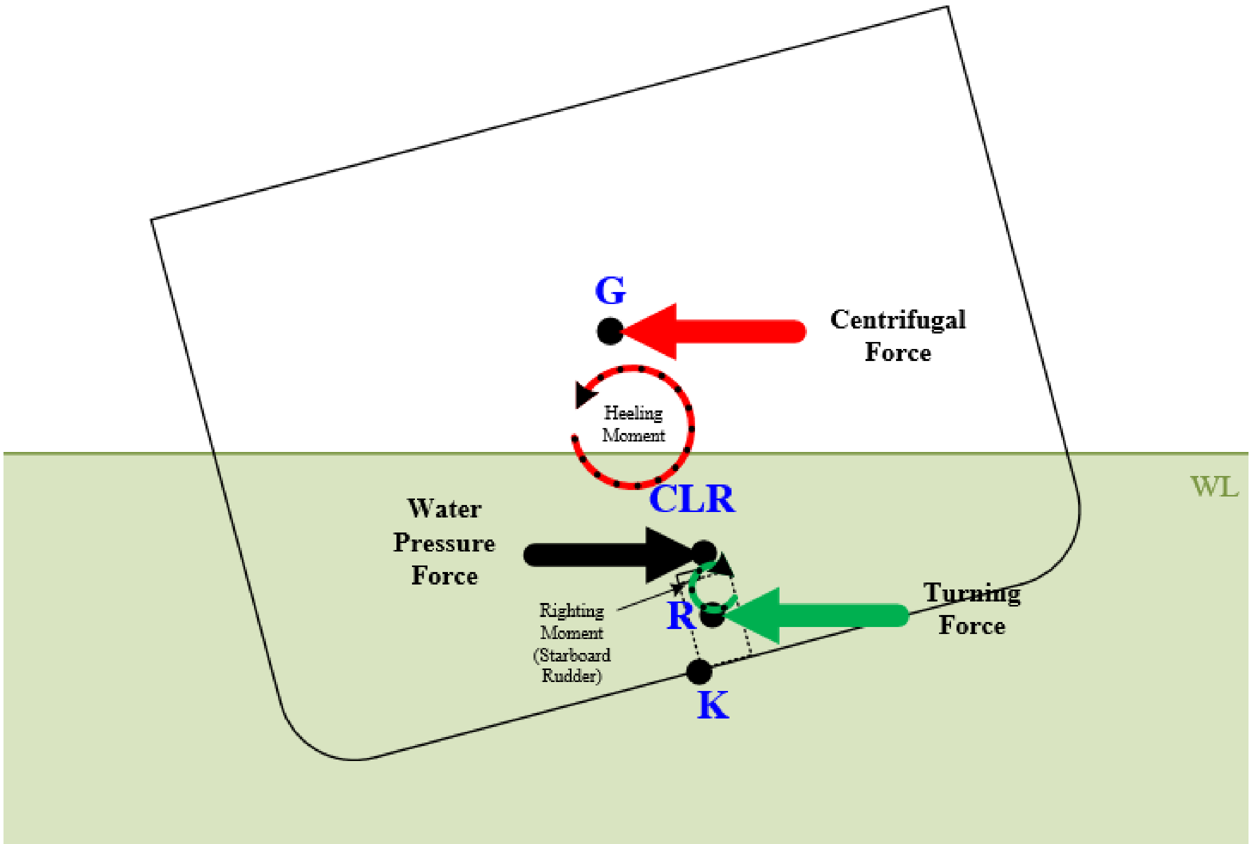

Figure 4-5: Lateral forces on a vessel engaged in a steady turn to starboard with the rudder angled to starboard.

During a turn, a separate moment is created by the turning force from the ship's rudder (green arrow), which is angled to starboard in Figure 4-5, and the water pressure force (black arrow). However, this moment acts opposite to the moment created by the centrifugal force and is typically of significantly less magnitude due to the smaller distance between the centroid of the rudder and the center of lateral resistance. As such, the moment created by the centrifugal force prevails over the moment created by the rudder's turning force. This causes the vessel to heel away from the direction of turn.

The net effect of the heeling moment experienced by a vessel while in a steady turn can be determined by subtracting the moment created by the rudder's turning force from the moment created by the centrifugal force. Dividing by the vessel's displacement results in the corresponding net heeling arms experienced by the vessel while in a turn. The net heeling arms can be subtracted from the vessel's righting arms to obtain a residual righting arm curve for the vessel during a turn, which is useful in assessing the remaining vessel stability. The point at which the residual righting arm curve intersects the x-axis represents the steady heel angle of the vessel during the turn.

As noted above, this analysis is based on the assumption that the vessel is in the steady phase of the turn. It is important to recognize that, just prior to the vessel entering this phase of the turn and settling at the steady heel angle, dynamic effects cause the vessel to heel even further away from the direction of the turn, sometimes by twice as much, as noted by Zubaly [24] and Crane [25]. This is referred to as dynamic overshoot.

As further noted by Zubaly, "If a helmsman were frightened that the ship might capsize when it overshoots its steady heeling angle and were to reduce the rudder angle or reverse the rudder at that point, the dangerous heel would be instantly increased because the opposing rudder force moment would be reduced or reversed."

4.3.3.2. Effect of Turn on Stability During Capsize Voyage (Rudder to Starboard)

The heeling arms during the turn leading up to the capsize were found for the GOLDEN RAY in the MSC loading condition, with the rudder assumed to be angled to starboard, as was necessary to initiate the turn. For these calculations, the radius of the turn was estimated to be between 500 m and 800 m using visual data obtained for the capsize voyage from the portable pilot unit [26], which displays the vessel's turning circle in real time. The portable pilot unit also indicated that the vessel was traveling at a speed of 13.2 knots over ground during the turn, and this speed was assumed for all calculations. The turning heeling arm values at each angle were then subtracted from the port (direction the vessel capsized) righting arm values obtained for the capsize voyage loading condition in Section 4.3.2. This yielded the residual righting arm curve for the vessel while in the turn leading up to the capsize. The residual righting arm curves are shown in Figure 4-6 for a turn radius of 500 m (dashed black line) and a turn radius of 800 m radius (dashed blue line). The righting arm curve obtained by MSC for the vessel in the capsize voyage not engaged in a turn (solid red line) and the righting arm curves from the benchmark conditions in the T&S Booklet with displacements between 32,000 MT and 38,000 MT are also plotted for comparison.

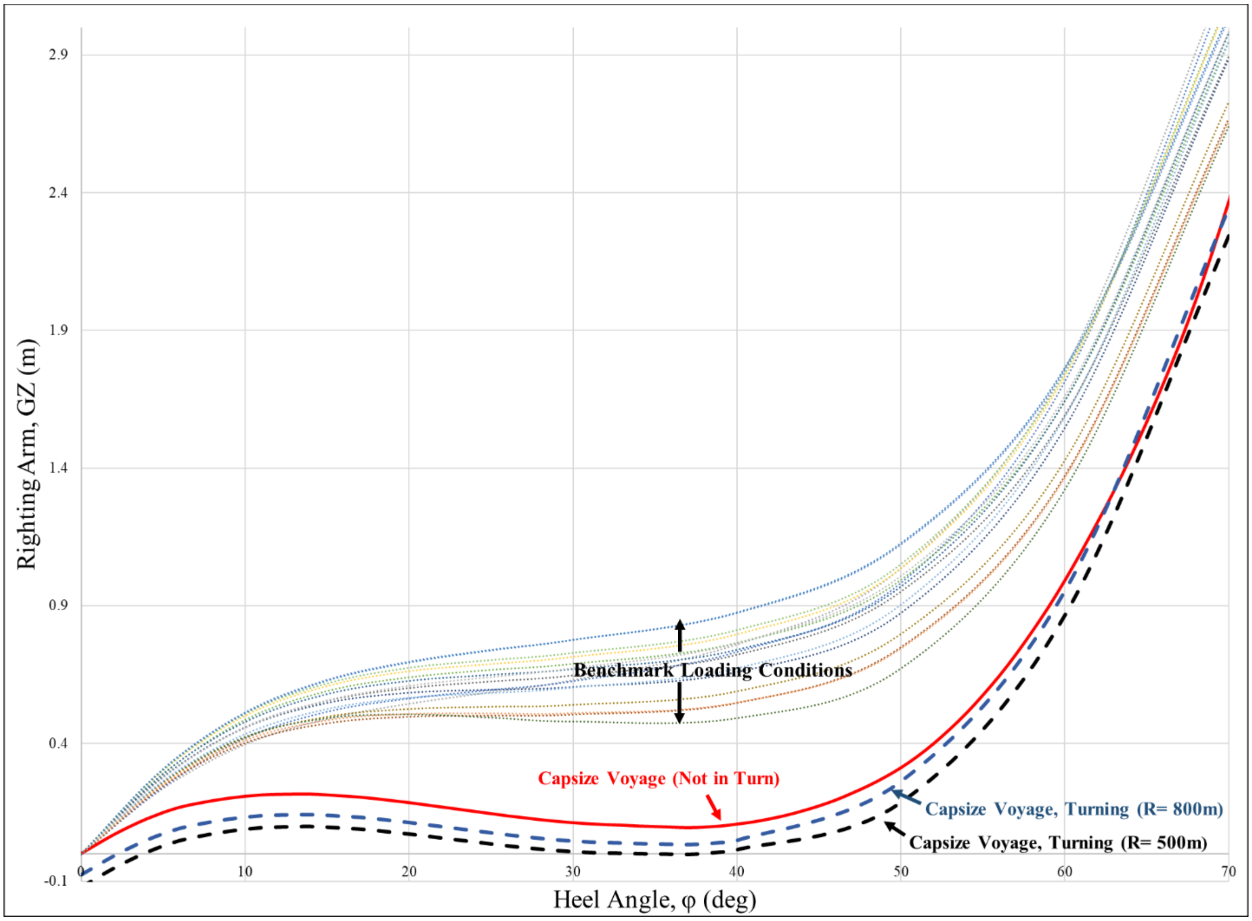

Figure 4-6: Residual righting arm curves for the vessel in the capsize voyage condition while engaged in a steady turn at a radius of 500 m (black dashed line) and 800 m (blue dashed line). Also shown for comparison are the righting arm curves for the vessel in the capsize voyage not engaged in a turn (solid red line) and the righting arm curves for the benchmark loading conditions in the T&S Booklet (dotted lines).

4.3.3.3. Effects of Turn on Righting Arm Curve (Rudder Amidships)

Audio from the portable pilot unit indicates that, while the ship was still in the turn to starboard, a rudder command of "rudder amidships," followed by a rudder command of "port 10" was ordered. As detailed in Section 4.3.3.1, a rudder angled to amidships would eliminate the righting moment from the rudder and therefore further increase the overall turning heeling moment. Residual righting arm curves showing the effect of this principle for the vessel in the capsize voyage for a 500 m turn radius are shown in Figure 4-7. The solid grey line represents the righting arm curve with the rudder amidships.

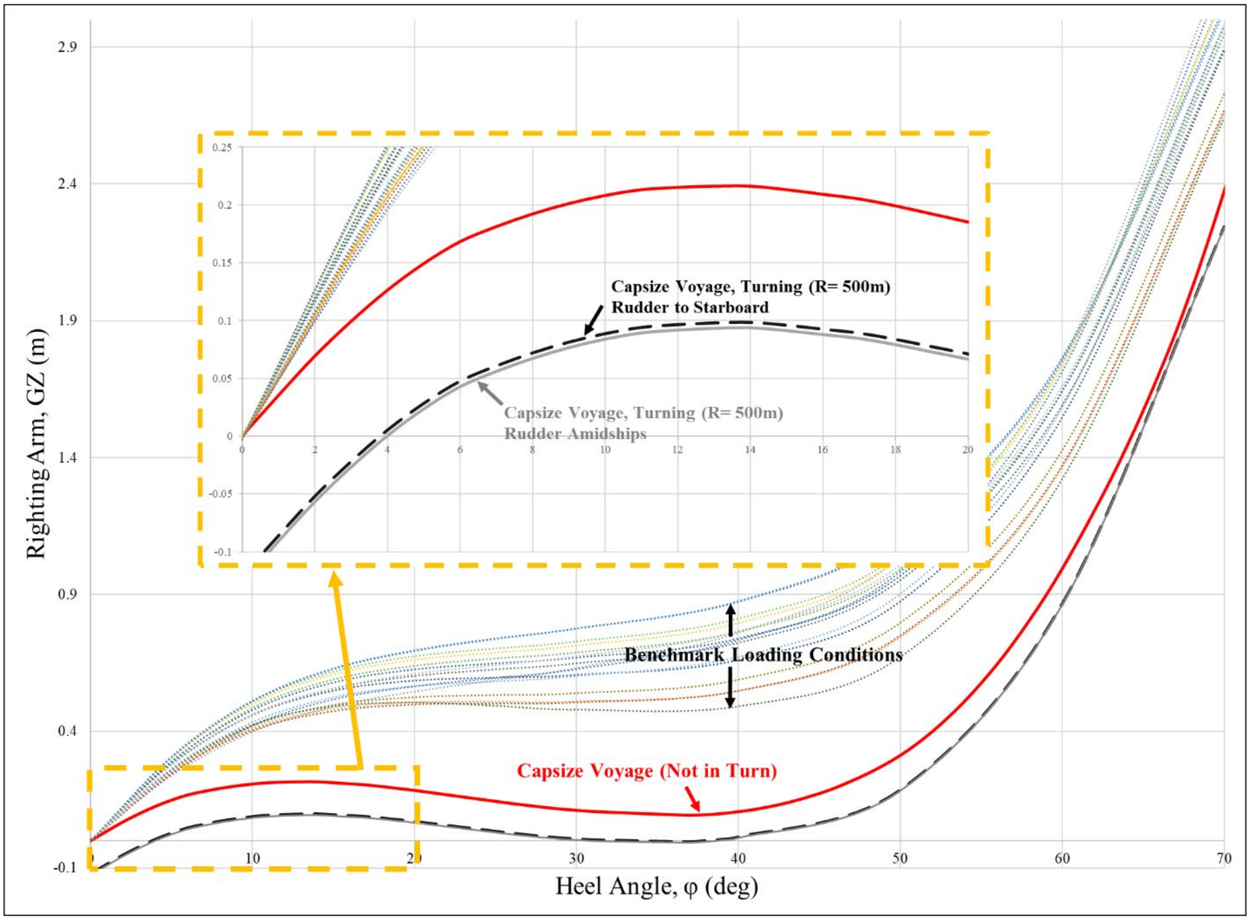

Figure 4-7: Residual righting arm curves for the vessel engaged in a steady turn at a radius of 500 m with the rudder to starboard (dashed black line), and rudder amidships (solid grey line). Also shown for comparison is the righting arm curve for the vessel not engaged in a turn (red line), and the righting arm curves from benchmark conditions in the T&S Booklet with displacements ranging from 32,000 MT to 38,000 MT.

Although the subsequent rudder command of "port 10," would have been expected to further increase the overall turning heeling moment because it would have created an additional capsizing moment from the rudder, the rudder may have no longer been effective at this point due to the heel of the vessel. Accordingly, little or no additional capsizing moment from the "port 10" command would have been created.

It is important to note that Figures 4-6 and 4-7 represent the righting arm curves for the vessel while in the steady turn phase. As noted in Section 4.3.3.1, dynamic effects experienced by the vessel prior to this phase of the turn are likely to have further reduced the righting arms and righting areas calculated in this section.

4.4. Downflooding Angle Analysis

4.4.1. Theory

A downflooding point is an opening in a vessel's hull or superstructure through which flooding into the vessel can take place if the opening becomes immersed. Examples of downflooding points typically include vents, discharges, non-watertight/weathertight doors and hatches, and other similar openings. Openings such as doors and hatches which can be closed watertight or weathertight are not typically considered downflooding points for the purposes of regulatory compliance because it is assumed that these openings are closed when the vessel is underway and brief immersion is not typically expected to lead to significant water ingress.

A downflooding angle is the lowest angle of vessel heel in which any downflooding point is immersed, as shown in Figure 4-8.

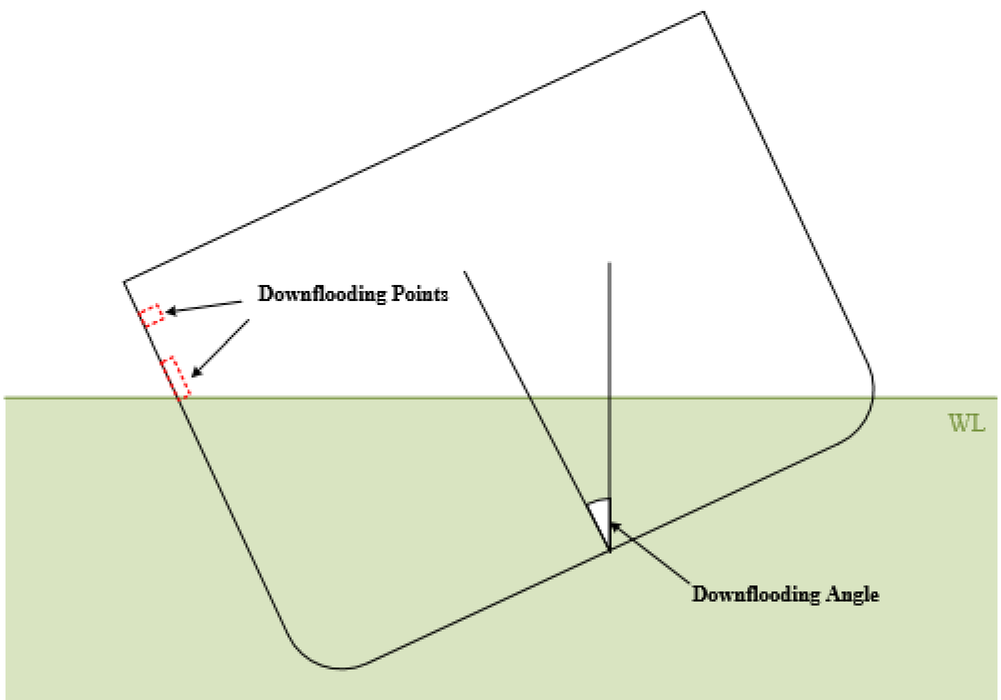

Figure 4-8: Illustration of downflooding points and the downflooding angle for a notional vessel.

The primary danger associated with immersion of downflooding points is progressive decrease in stability due to the addition of weight and free surface moment from seawater flooding into the hull or superstructure. Additionally, if an opening is large enough, there is an added reduction in righting arms and righting energy due to lost waterplane area (area occupied by the hull in a plane perpendicular to the water).

4.4.2. GOLDEN RAY Downflooding Angle

The vessel's T&S Booklet defines a single downflooding point for the GOLDEN RAY: a door on Deck 13 at Fr. -5. The corresponding downflooding angle of the vessel is approximately 83° with the vessel at a mean draft of 9.3 m. Although the GOLDEN RAY has other openings in the side of the hull below the door on Deck 13, they are not required by the IS Code to be considered downflooding points because they can be closed watertight or weathertight. The Pilot Door on Deck 5, Fr. 73, Port, which was reported by the IMACS data to have remained open during the capsize, is one such opening.

4.4.3. Revised Downflooding Angle with Pilot Door Open

An analysis using the MSC computer model was conducted to determine the revised downflooding angle with the Pilot Door on Deck 5, Fr. 73, Port open. Results indicate that, with the vessel in the capsize voyage loading condition, the downflooding angle is reduced to approximately 17° when heeled to port. As the Pilot Door constitutes a large opening, heel during the capsize beyond this downflooding angle would likely have resulted in immediate flooding on Deck 5 and, subsequently, a reduction in righting arms and righting energy at angles of approximately 17° and above.

4.5. Summary

This section introduced fundamental intact stability concepts as related to righting arm curves, followed by the results of MSC's intact stability analysis for the vessel in the capsize voyage loading condition. The moments acting on a vessel during a steady turn were then introduced, followed by the results of MSC's calculation of righting arms due to the effects of the turn prior to the capsize. Finally, an analysis of the GOLDEN RAY's downflooding angle with the pilot door open was presented.

5. Comparison with Trim & Stability Book

5.1. Introduction

A vessel's T&S Booklet is designed to provide stability information to the ship's master to ensure that the vessel has adequate stability prior to departure and throughout each voyage. This section provides an exploration into the basic stability information which could have been ascertained from the T&S Booklet based on the vessel's drafts, liquid loads, and cargo prior to departure from Brunswick for the capsize voyage. Comparison is made between the stability information contained in the T&S Booklet and the vessel's loading condition and MSC calculated stability parameters.

5.2. Minimum Allowable GM Tables

Section 4.7 of the vessel's T&S Booklet contains the minimum allowable GM and maximum allowable KG tables, which are designed to be used by the vessel's master and crew to quickly assess compliance with stability requirements at various levels of draft and trim. The minimum allowable GM and maximum allowable KG required can be ascertained from the tables and compared with the GM and KG calculated using the vessel's loading computer. If the GM and KG values calculated do not meet the required thresholds contained within the tables, then the vessel is not in compliance with the stability requirements of the T&S Booklet and therefore not in compliance with the mandatory requirements of the 2008 IS Code.

MSC utilized the data from the tables in Section 4.7 of the T&S Booklet to obtain the minimum required GM and maximum allowable KG which corresponded to the drafts recorded by the vessel's crew prior to departure: 9.45 m aft and 9.40 m forward. Because T&S Booklet tables are provided with drafts in 0.2 m increments and trim in 1.0 m increments, linear interpolation was necessary to find the corresponding regulatory minimum GM and KG values at the mean draft of 9.425 m and trim of 0.05 m by the stern.

As described in Section 4.3.2, MSC's computer model was used to calculate the predicted GM and KG in the capsize voyage condition. A comparison of the required values with the predicted values calculated using the MSC computer model is shown in Table 5-1 for GM and Table 5-2 for KG. The MSC calculated GM was approximately 31% below the T&S Booklet requirement and the MSC calculated KG was approximately 3.8% higher than the T&S Booklet requirement (both failing).

T&S Min. GM (m)	MSC Calc. GM (m)	Difference (m)
2.54	1.76	0.78

Table 5-1: Comparison of MSC calculated GM for the capsize voyage with the minimum GM required by the T&S Booklet corresponding to the drafts obtained by the ship's crew.

T&S Max. KG (m-AB)	MSC Calc. KG (m-AB)	Difference (m)
17.53	18.20	0.67

Table 5-2: Comparison of MSC calculated KG for the capsize voyage with the maximum KG permitted by the T&S Booklet corresponding to the drafts obtained by the ship's crew.

MSC also used the tables in Section 4.7 of the T&S Booklet to determine maximum GM and minimum KG required using the drafts recorded by the IMACS computer at the departure timestamp (08/09/19 04:00:26 UTC): 9.2 m aft and 9.56 m forward. The resultant values are compared with the predicted MSC calculated values for the capsize voyage in Tables 5-3 and 5-4. The MSC calculated GM was approximately 27% below the T&S Booklet requirement and the MSC calculated KG was approximately 3.9% higher than the T&S Booklet requirement (both failing).

T&S Min. GM (m)	MSC Calc. GM (m)	Difference (m)
2.42	1.76	0.66

Table 5-3: Comparison of MSC calculated GM for the capsize voyage with the minimum GM required by the T&S booklet corresponding to the drafts recorded by the IMACS at the departure timestamp.

T&S Max KG (m-AB)	MSC Calc. KG (m-AB)	Difference (m)
17.52	18.20	0.68

Table 5-4: Comparison of MSC calculated KG for the capsize voyage with the maximum KG required by the T&S booklet corresponding to the drafts recorded by the IMACS at the departure timestamp.

5.3. Benchmark Loading Conditions

Sections 5.3 and 5.4 of the T&S Booklet detail 34 benchmark loading conditions which have been demonstrated to result in adequate vessel stability. Though it is not mandatory that the vessel be loaded strictly in accordance with one of these conditions, because they result in compliance with the 2008 IS Code, they can be used for planning and comparison to the actual/proposed vessel loading condition. The vessel loading information for the capsize voyage was assessed against 2 benchmark conditions which had similar cargo VCGs, 2 benchmark conditions which had similar total liquid loads, and 2 benchmark conditions which had a higher cargo weight.

5.3.1. Benchmark Conditions with Similar Cargo VCG

Table 5-5 provides a comparison between the capsize voyage loading condition and T&S Booklet conditions 17 and 18. All three loading conditions had nearly identical cargo VCGs and similar displacements; however, T&S Booklet conditions 17 and 18 were loaded with over 40% more liquid load than the capsize voyage condition, and approximately 12% less cargo weight. This is important because, as the center of the vessel's liquid load is close to the keel and the center of the cargo is well above the keel, a higher quantity of liquid load onboard and a lower quantity of cargo onboard would lower the overall VCG of the vessel and result in a more favorable righting arm curve.

T&S Condition 17 represents a benchmark departure loading condition and, as such, a high proportion of the total liquid load consists of bunkers (fuel, diesel, gas, etc.). Condition 18 represents a benchmark arrival loading condition which assumes that, as fuel is consumed, ballast is taken on to prevent a rise in the vessel's VCG. The capsize voyage condition had a similar quantity of bunkers to that in T&S condition 18, however, it had nearly 2,500 MT less ballast.

	Ballast (MT)	Bunkers (MT)	Total Liquid (MT)	Cargo Weight (MT)	Cargo VCG (m)	Vessel VCG (m)	Total Disp. (MT)
MSC Capsize Voyage	2981	1619	4601	8780	24.3	18.2	35044
T&S Condition 17	2766	4233	7000	7742	24.2	17.1	36175
T&S Condition 18	5463	1066	6529	7742	24.2	17.0	35704

Table 5-5: Comparison of benchmark loading conditions in the T&S Booklet which had similar cargo VCGs to the cargo VCG of the vessel in the capsize voyage condition. Both benchmark conditions indicate over 40% more total liquid load than the vessel had onboard during the capsize voyage.

5.3.2. Benchmark Conditions with Similar Total Liquid Load

Table 5-6 provides a comparison between the vessel's capsize voyage loading condition with T&S Booklet conditions 13 and 14. All three conditions have a similar quantity of total liquid load. However, conditions 13 and 14, have a cargo VCG that is approximately 20% lower than the cargo VCG of the vessel in the capsize voyage condition. This is because T&S conditions 13 and 14 did not have cargo loaded on decks 11, 12 or 13. As indicated in the Brunswick Departure Stowage Plan, the vessel had approximately 2,500 MT loaded on these decks during the capsize voyage. In addition to a higher cargo VCG, the capsize voyage loading condition had approximately 1,500 MT more cargo weight than that of T&S Booklet conditions 13 and 14, further contributing to an increase in overall vessel VCG and adverse effects on vessel stability.

	Ballast (MT)	Bunkers (MT)	Total Liquid (MT)	Cargo Weight (MT)	Cargo VCG (m)	Vessel VCG (m)	Total Disp. (MT)
MSC Capsize Voyage	2981.45	1619.2	4601	8780	24.3	18.2	35044
T&S Condition 13	320	4233	4553	7267	19.4	17.0	33253
T&S Condition 14	3117	1066.2	4183.2	7267	19.4	16.8	32884

Table 5-6: Comparison of benchmark loading conditions in the T&S Booklet which had similar quantities of total liquid loads to the vessel in the capsize voyage condition. The T&S Booklet conditions indicated an approximately 20% lower cargo VCG.

5.3.3. Benchmark Conditions with Higher Cargo Weight

The T&S Booklet also details several benchmark conditions which have higher cargo weights than that of the capsize voyage. Table 5-7 provides a comparison between the capsize voyage loading condition and conditions 19 and 20. Conditions 19 and 20 have approximately 900 MT more cargo weight than the capsize voyage loading condition (at a similar VCG), but both conditions indicate over 2,900 MT more liquid load required to comply with stability requirements. Consequently, conditions 19 and 20 have higher displacements and drafts.

	Ballast (MT)	Bunkers (MT)	Total Liquid (MT)	Cargo Weight (MT)	Cargo VCG (m)	Total VCG (m)	Total Disp. (MT)
MSC Capsize Voyage	2981	1619	4601	8780	24.3	18.2	35044
T&S Condition 19	3282	4233	7515	9670	24.2	17.2	38619
T&S Condition 20	6601	1066	7667	9670	24.2	16.9	38771

Table 5-7: Comparison of benchmark loading conditions in the T&S Booklet which had higher cargo weights than the vessel in the capsize voyage condition. Conditions 19 and 20 have approximately 900 MT more cargo weight, but have over 2,900 MT more liquid load.

5.4. Summary

This section provided a comparison between the GM and KG required by the T&S Booklet based upon observed and IMACS recorded drafts. The MSC calculated GM and KG did not meet the required thresholds.

Additionally, comparison was made between similar benchmark loading conditions in the T&S Booklet and the loading condition the vessel was in during the capsize voyage. This comparison indicated that the vessel loading during the capsize voyage was not consistent with similar benchmark loading conditions in the T&S Booklet. For conditions with similar cargo VCGs to the capsize voyage loading condition, the comparable benchmark conditions had significantly more liquid load onboard. For conditions with similar total liquid loads, the comparable benchmark conditions had significantly lower cargo VCGs.

6. Stability Comparison to Previous Voyages

6.1. Introduction

This section details the loading conditions applied to the MSC computer model to simulate the two voyages preceding the capsize voyage: Jacksonville, FL to Brunswick, GA (September 7, 2019) and Freeport, TX to Jacksonville, FL (August 30 to September 6, 2019). Resulting righting arm curves are then compared with the righting arm curves generated for the capsize voyage.

6.2. Jacksonville to Brunswick Voyage

An intact stability analysis was conducted for the Jacksonville to Brunswick voyage (voyage prior to the capsize voyage) as detailed in Appendix B.

6.3. Freeport to Jacksonville Voyage

An intact stability analysis was conducted for the Freeport to Jacksonville voyage (two voyages prior to the capsize voyage) as detailed in Appendix C. The loading condition applied for this voyage represents the tank loads present following ballast discharge operations on September 3, 2019.

6.4. Comparison of Righting Arm Curves

Figure 6-1 presents a comparison between the starboard righting arm curves for the vessel while loaded for the Jacksonville to Brunswick, Freeport to Jacksonville, and capsize voyage. Table 6-1 demonstrates a comparison of the vessel's compliance with the mandatory provisions of the 2008 IS Code as evaluated using the MSC computer model. Red background indicates that the attained value does not meet the specific criteria and green background indicates that the attained value meets the specific criteria. Results indicate that, although the vessel was predicted to have had more righting energy in both of the preceding voyages than the vessel had during the capsize voyage, the vessel lacked the righting energy required to comply with the mandatory provisions of the 2008 IS Code during all three voyages.

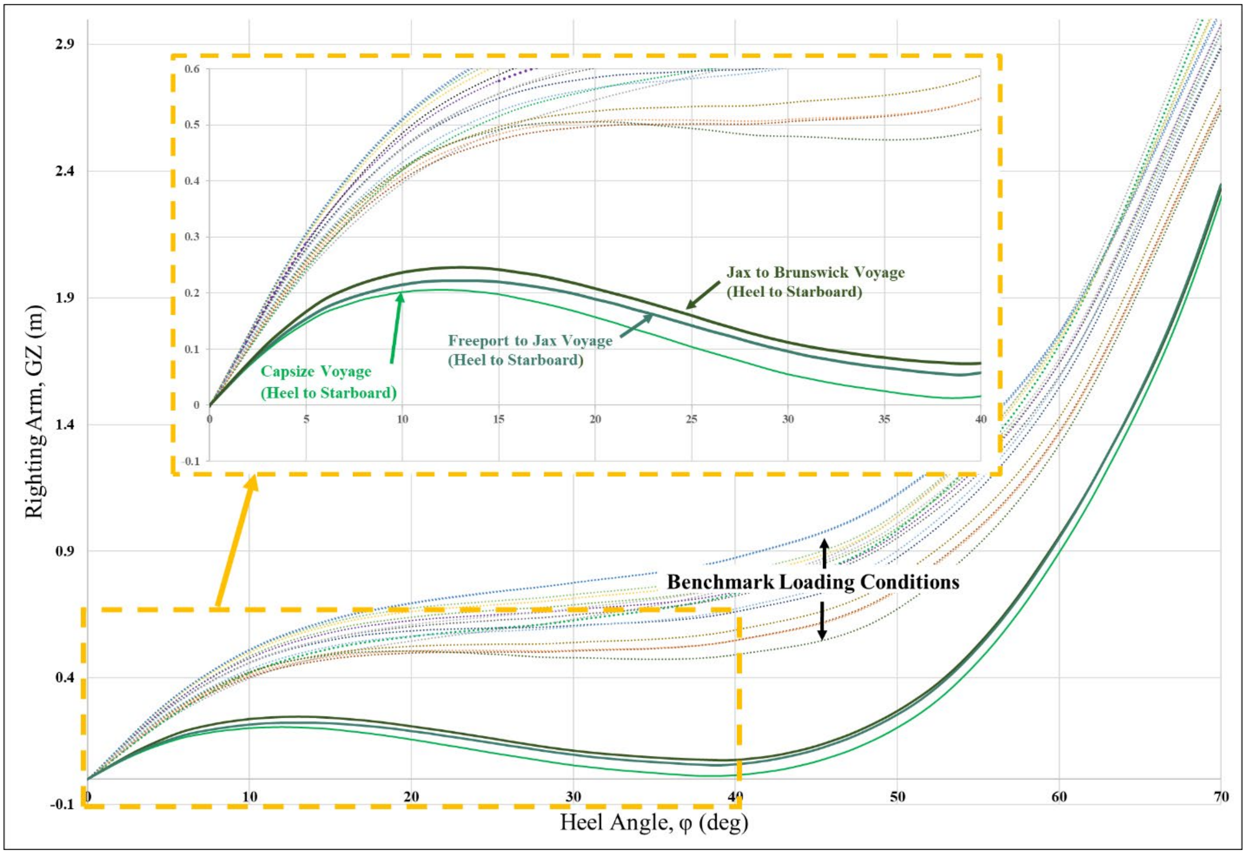

Figure 6-1: Comparison between starboard righting arm curves for the capsize voyage, Freeport to Jacksonville Voyage, and Jacksonville to Brunswick Voyage. Also shown for comparison are the righting arm curves from benchmark conditions in the T&S Booklet with displacements ranging from 32,000 MT to 38,000 MT.

	Units	MSC Loading Condition (Capsize Voyage)	MSC Loading Condition (Jacksonville Voyage)	MSC Loading Condition (Freeport Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties					
Area to 30 degrees	m-rad	0.075	0.095	0.084	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.079	0.110	0.095	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.005	0.015	0.011	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	3.980	4.028	4.056	At least 0.2 m
Angle of maximum righting arm	deg	80.3	80.2	80.4	At least 25 deg
Initial GM	m	1.76	1.91	1.84	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria					
Angle of static heel (φ_0)	deg	6.8	5.5	6.2	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	0 (No Area A1)	0 (No Area A1)	Greater than 1

Table 6-1: Comparison of 2008 IS Code compliance for each voyage. Red background indicates that the attained value does not meet the specific criteria and green background indicates that the attained value meets the specific criteria.

6.5. Stability with Additional Ballast

A review of the vessel's IMACs tank loading data during the Freeport to Jacksonville voyage indicates that the vessel discharged a total of 1492 MT of ballast from 4 large tanks (No. 5 Port D.B., No. 5 Starboard D.B., No. 5 Centerline D.B., and No. 6 Centerline) on September 3, 2019 beginning at approximately 17:00 UTC (13:00 EDT).

An analysis was conducted to determine the theoretical hydrostatics characteristics and vessel stability had the vessel not discharged the ballast from these tanks and had instead maintained that quantity of ballast water in the aforementioned tanks throughout the remainder of the Freeport to Jacksonville voyage and subsequent voyages (Jacksonville to Brunswick, and Capsize Voyage).

Resulting drafts for these theoretical loading conditions are shown in Table 6-2 for salt water conditions. Resulting starboard righting arm curves for each theoretical loading condition (dashed green lines) are shown in Figure 6-2. For comparison, the righting arms curves for the vessel in the actual representative loading conditions for each voyage are also shown (solid green lines).

	MSC Loading Condition (Capsize Voyage) Additional Ballast	MSC Loading Condition (Jacksonville Voyage) Additional Ballast	MSC Loading Condition (Freeport Voyage) Additional Ballast
Taft (m)	9.55	9.64	9.54
Tfwd (m)	9.62	9.31	9.57
Tmean (m)	9.59	9.48	9.55

Table 6-2: Theoretical drafts in salt water during each voyage, had the vessel maintained the additional 1492 MT of ballast that was discharged on September 3, 2019.

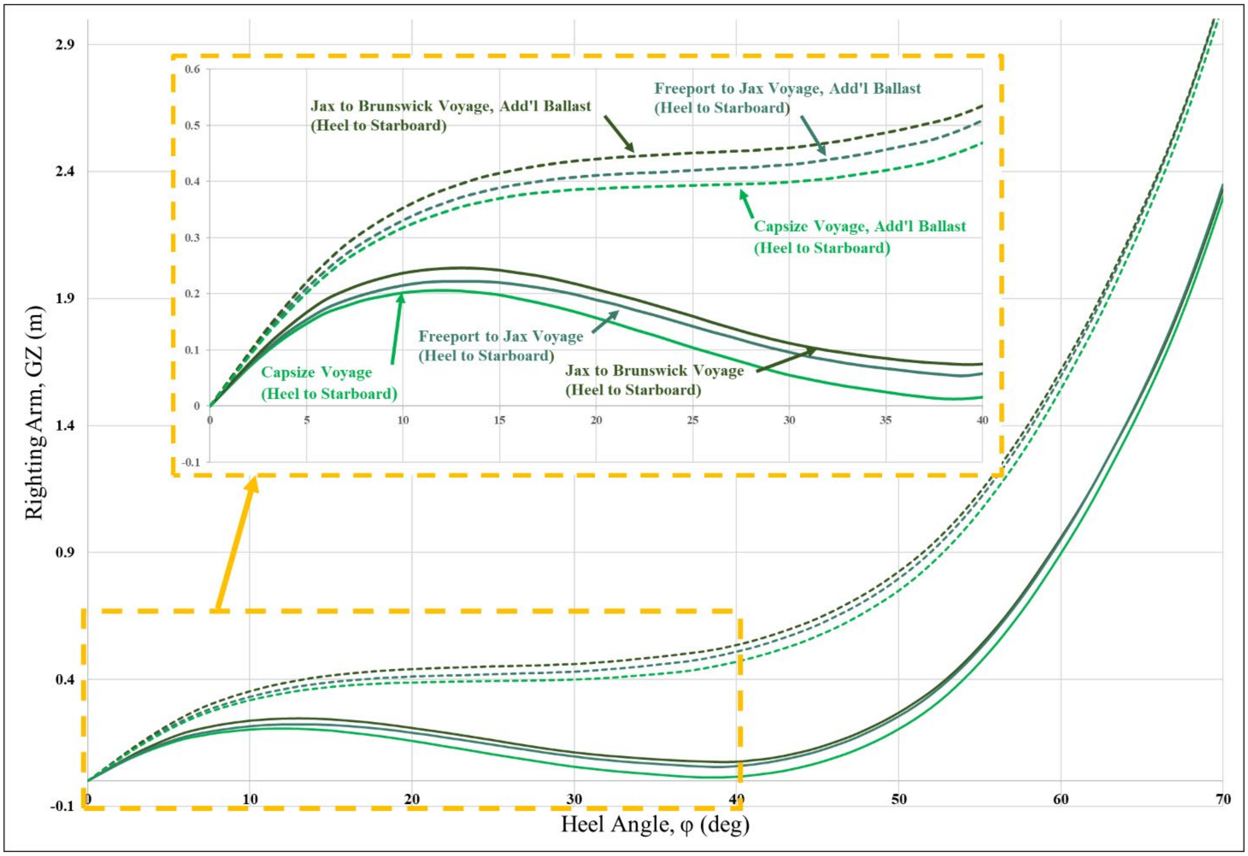

Figure 6-2: Theoretical starboard righting arm curves (dashed green lines) for each voyage with additional 1492 MT of ballast, had it not been discharged. For comparison, the righting arms curves for the vessel in the actual representative loading condition are shown for each voyage (solid green lines).

Table 6-3 shows the vessel's theoretical compliance with the 2008 IS Code during each voyage, had the vessel maintained the additional 1492 MT of ballast. Results indicate that the vessel would have been able to fully comply with the mandatory provisions of the 2008 IS Code. The GM for those voyages ranged from 2.25 m to 2.47 m.

	Units	MSC Loading Condition (Capsize Voyage) Additional Ballast	MSC Loading Condition (Jacksonville Voyage) Additional Ballast	MSC Loading Condition (Freeport Voyage) Additional Ballast	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties					
Area to 30 degrees	m-rad	0.149	0.186	0.174	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.211	0.271	0.254	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.063	0.086	0.080	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	4.439	4.625	4.636	At least 0.2 m
Angle of maximum righting arm	deg	79.4	79.2	79.5	At least 25 deg
Initial GM	m	2.25	2.47	2.40	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria					
Angle of static heel (φ_0)	deg	4.0	3.7	3.9	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	1.77	2.13	2.01	Greater than 1

Table 6-3: Theoretical compliance with the 2008 IS Code during each voyage had the vessel maintained the additional 1492 MT of ballast that was discharged on September 3, 2019. The GM for those voyages ranged from 2.25 m to 2.47 m.

7. Conclusions

The following provides a summary of key MSC observations and conclusions, listed by topic area:

(1) MSC computer model:

a. MSC independently generated a computer model using GHS software. Resultant hydrostatics were generally consistent with the vessel's T&S Booklet.

b. The liquid loads in major tanks onboard the vessel were applied to the MSC computer model in accordance with recorded data from the IMACS computer prior to the capsize. Small tanks not recorded by the IMACS computer were loaded in accordance with T&S Booklet departure condition values.

c. Miscellaneous weights likely to be onboard the vessel during the capsize voyage, such as provisions, stores, and crew effects, were applied to the MSC model in accordance with weights and centers provided in the T&S Booklet.

d. The weights of the cargo applied to the MSC model were in accordance with the weight estimates detailed on the Brunswick Departure Stowage Plan. The total weight applied (8,780.2 MT) was generally consistent with the MSC estimated total weight of the cargo cited on the VIN list applicable to the voyage. The centers of gravity of the cargo applied to the MSC model were in accordance with the vehicle group locations depicted on the Brunswick Departure Stowage Plan.

e. Calculation of hydrostatics of the loaded MSC computer model resulted in drafts which were generally consistent with the drafts reported by the IMACS computer prior to departure from Brunswick. However, the 4.6° starboard list calculated using the MSC computer model was not consistent with observed conditions prior to departure. This indicates a possible anomaly between the TCGs depicted on the Brunswick Departure Stowage Plan and the actual TCGs of the cargo onboard the vessel. To remain consistent with observed conditions, all subsequent stability analysis was conducted with the vessel at zero list, while other bounded stability parameters including displacement, LCG, and VCG were held constant.

(2) Intact Stability Analysis

a. The MSC computer model was used to generate righting arm curves for the vessel as loaded in accordance with provided data for the capsize voyage. The corresponding righting arm properties were calculated and assessed for compliance with the mandatory criteria regarding righting arm (lever) curve properties (Part A, Section 2.2) of the 2008 IMO IS Code. Results indicated that the vessel did not fully meet the requirements of this criteria due to the limited area under the righting arm curve between 30° and 40°.

b. MSC also used the independently generated computer model to assess compliance with the mandatory Severe Wind and Rolling criteria (Part A, Section 2.3) of the 2008 IMO IS Code. Results indicated that the vessel failed this criteria by a significant margin.

(3) Impact of Turn on Stability

a. A ship undergoing a turn experiences a heeling moment due to the resultant centrifugal force. Portable pilot unit recorded data indicated that the capsize occurred during a turn to starboard. MSC calculated the effect that this turn would have had on the righting arm curve using a range of turn radii and the speed of the vessel. Results indicated that the maximum righting arm and righting energy were significantly reduced by the turning heeling moment.

b. MSC also calculated the effect that moving the rudder from starboard to amidships would have had on the righting arm curve. The area under the righting arm curve was calculated to have been further reduced by this helm command, but only by relatively small amounts when compared to the reduction in area under the righting arm curve due to the centrifugal force from the turn.

c. The final area under the righting arm curve due to the combined effects of the way the vessel was loaded during the capsize voyage and the heeling moments experienced during the turn constituted a small fraction of the area under the righting arm curve that the benchmark conditions in the T&S Booklet had. This extreme lack of righting area (and corresponding lack of righting energy) indicates that the vessel had little capability of withstanding further adverse static or dynamic heeling effects. Dynamic overshoot, which causes a vessel entering a turn to heel even further away from the direction of that turn, coupled with any cargo shifting due to heel, are likely to have overcome the remaining righting energy and resulted in the capsize.

d. Additional MSC analysis indicates that with the Pilot Door on Deck 5, Fr. 73, Port open, as was reported by the IMACS data, the downflooding angle of the vessel would be reduced from approximately 83° to 17° of heel. As such, it is very likely that, during the capsize, once a heel angle of 17° was reached, a large amount of seawater immediately flooded into the vessel through this open door, exacerbating the capsize by causing a further reduction in the available righting energy beyond 17°.

(4) Comparison with T&S Booklet

a. MSC also used the tables contained within Section 4.7 of the T&S Booklet to assess whether the vessel was in compliance with the required minimum GM and maximum KG at the corresponding drafts and trim. Results indicated that the GM of the vessel, as calculated by MSC, was approximately 30% below the minimum

GM required by the T&S Booklet and the KG calculated by MSC was approximately 4% above the maximum KG permitted.

b. The cargo and liquid loads onboard the vessel were compared to the cargo and liquid loads in similar benchmark conditions detailed in the T&S Booklet. For conditions with cargo VCGs similar to the cargo VCG of the capsize voyage loading condition, the comparable benchmark conditions had significantly more liquid load onboard. For conditions with similar total liquid loads, the comparable benchmark conditions had significantly lower cargo VCGs. Given the cargo weight and VCG for the capsize voyage, the vessel would have needed significantly more liquid load (fuel or ballast) onboard the vessel to be in compliance with the T&S Booklet and the 2008 IS Code. This additional liquid load would have resulted in an increase in displacement and consequently, an increase in drafts.

(5) Stability During Previous Voyages

a. Using the MSC computer model, subsequent intact stability analyses were conducted using loading data for the vessel in the Jacksonville to Brunswick voyage (voyage prior to the capsize voyage) and in the Freeport to Jacksonville voyage (two voyages prior to the capsize voyage), as detailed in Appendices B and C respectively.

b. Righting arm curves for the vessel in these voyages were calculated and assessed for compliance with the 2008 IS Code. Results indicate that, although the vessel had slightly higher righting arms and righting energy during both the Jacksonville to Brunswick and the Freeport to Jacksonville voyages than the vessel had during the capsize voyage, the mandatory criteria of the 2008 IS Code were not fully met.

c. When contemplating why the vessel did not capsize during the Freeport to Jacksonville or Jacksonville to Brunswick voyage, but did capsize during the Brunswick outbound transit, it is important to understand that stability criteria within the 2008 IS Code is static and includes margins of safety to account for the dynamic responses of a vessel in real-world environmental and operating conditions. Failure of the IS Code criteria does not indicate immediate capsize, but rather, is an indicator that the vessel poses a higher risk of capsize given exposure to certain dynamic conditions such as severe wind, waves and faster speed/tighter radius turns. Because risk is based upon probability, it is possible that GOLDEN RAY, while failing IS Code criteria, could have capsized on a previous voyage if it had been exposed to more severe adverse conditions.

d. Finally, a historical review of the IMACs tank loading data indicates that the vessel discharged approximately 1500 MT of ballast from the No. 5 D.B. and No. 6 tanks on September 3, 2019 during the Freeport to Jacksonville voyage. MSC analysis indicates that, had the vessel not discharged this ballast and had instead kept these tanks filled for the subsequent voyages, it would have fully complied with the 2008 IS Code during the remainder of that voyage and each of the two subsequent voyages, with resulting GM between 2.25 m to 2.47 m, as calculated using the MSC computer model. In this regulatory compliant condition, capsize during the outbound Brunswick transit would more than likely have been prevented.

8. References

1 Formal Marine Casualty Investigation Concerning the Capsizing and Fire of the RO/RO GOLDEN RAY While Transiting St. Simons Sound, Georgia on 08 September 2019, Memorandum from CGD SEVEN (des) to CGD EIGHT (dw), dated September 12, 2019

2 GOLDEN RAY Table of Offsets, File “8151-hull-offset.txt”

3 GOLDEN RAY General Arrangement, Drawing 1A000B001, Rev. Fin, dated November 15, 2017

4 GOLDEN RAY Aft End Construction, Drawing 2A100H001, Rev Fin, dated July 2, 2015

5 GOLDEN RAY Fore End Construction, Drawing 2A600H001, Rev Fin, dated July 3, 2015

6 GOLDEN RAY Double Bottom Construction, Drawing 2A300H001, Rev. Fin, dated July 10, 2015

7 GOLDEN RAY Midship Section, Drawing 1A000H001, Rev. Fin, dated July 27, 2017

8 GOLDEN RAY Shell Expansion, Drawing 1A000H003, Rev. Fin, dated July 27, 2017

9 GOLDEN RAY Damage Control Plan, Drawing 2A000B003, Rev. Fin, dated February 4, 2016

10 GOLDEN RAY Engine Room Construction, Drawing 2A200H002, Rev. Fin, dated July 17, 2015

11 GOLDEN RAY Double Bottom Construction in Engine Room, Drawing 2A200H001, Rev. Fin, dated June 29, 1015

12 GOLDEN RAY Construction Profile & Deck Plan, Drawing 1A000H002, Rev. Fin, dated July 27, 2017

13 GOLDEN RAY Final Trim & Stability Booklet, Document 4A000B012, stamped “Approved” by DNV-GL on December 12, 2017

14 GOLDEN RAY Result of Deadweight Measurement, Document 6A000B003, stamped “Approved” by DNV-GL on November 2, 2017

15 SILVER RAY Result of Inclining Experiment & Deadweight Measurement, Document 6A000B003, stamped “Approved” by DNV-GL on November 2, 2017

16 GOLDEN RAY IMACS Program, File “IMACS_Master.exe”

17 GOLDEN RAY IMACS Recorded Data Files from August 2017 to September 2019

18 GOLDEN RAY IMACS Tank Summary for 08/09/19 04:00

19 GOLDEN RAY IMACS Tank Summary for 08/09/19 05:27

20 GOLDEN RAY B/L Vin List, File “19. VIN LIST G RAY 13.xls”

21 GOLDEN RAY Brunswick Departure Stowage Plan, last modified by Mike Mavrinac (Glovis USA) on September 8, 2019

22 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)

23 Circular MSC.1/Circ 1281, “Explanatory Notes to the International Code On Intact Stability, 2008,” December 9, 2008, International Maritime Organization (IMO)

24 Zubaly, R.B., Applied Naval Architecture, Cornell Maritime Press, 1996, pp. 129-130

25 Moore, C.S., Principles of Naval Architecture Volume III: Motions in Waves and Controllability, Society of Naval Architects and Marine Engineers (SNMAE), 1989, pp. 212-213

26 Portable Pilot Unit Data for Capsize Voyage, File “CG 83 PILOT PPU_wAudio_0134_0144_08SEP19.wmv”

Appendix A: MSC Computer Model Comparison to T&S Booklet

A comparison of hydrostatic properties and tank parameters between the MSC computer model and the T&S Booklet was completed and is detailed in this appendix.

A.1. Hydrostatic Parameters

Table A-1 details key hydrostatic parameters at a draft of 9.3 m in salt water without trim or hull deflection, calculated using the MSC GHS computer model. For comparison, the values in the T&S Booklet [A1] are also provided as well as 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 [A2], which are identical to those in the IACS Unified Requirement L5 applied by classification societies [A3].
The MSC GHS computer model hull hydrostatic properties align closely with those reported in the T&S Booklet at the 9.3 m draft, with all properties falling within the IMO/IACS tolerances. Model hydrostatics at and near this draft are considered to be most critical to subsequent stability analyses, as this was the approximate true mean draft of the vessel prior to the capsize.

	MSC Model	T&S Book	Difference	Difference %	Tolerance
Disp. (MT)	34892.28	34817.00	75.28	0.2%	2%
LCB (m-AP)	90.65	90.82	0.16	0.2%	1% or 50 cm
VCB (m-BL)	5.34	5.32	0.01	0.2%	1% or 5 cm
LCF (m-AP)	78.34	78.07	0.27	0.3%	1% or 50 cm
MTC (m*MT/cm)	653.94	645.60	8.34	1.3%	2%
KMt (m-BL)	19.96	20.13	0.17	0.8%	1% or 50 cm
TPC (MT/cm)	55.92	56.07	0.15	0.3%	NA

Table A-1: Comparison of key hydrostatic properties at a draft of 9.3 m in salt water, without trim or hull deflection. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

As the draft is increased to the extreme Summer load draft of 10.618 m, all properties, with the exception of the moment to trim 1-cm, remain within the IMO/IACS tolerances. Table A-2 summarizes the hydrostatic properties at the 10.618 m draft without trim or hull deflection. The moment to trim 1-cm cited in T&S Booklet at this draft produced a value approximately 2.5% lower than the value produced by the MSC hull model. As MSC did not have access to the model used to generate the T&S Booklet, it was not possible to accurately identify the reason for this difference. However, because the difference in moment to trim 1-cm between the models was only slightly above the IMO/IACS tolerance limit, the other hydrostatic properties aligned well, and the stability analysis was conducted at drafts close to 9.3 m, the slight variation in hydrostatic properties at other drafts was determined to be generally inconsequential to stability results.

	MSC Model	T&S Booklet	Difference	Difference %	Tolerance
Disp. (MT)	42500.68	42428.00	72.68	0.2%	2%
LCB (m-AP)	88.31	88.42	0.10	0.1%	1% or 50 cm
VCB (m-BL)	6.17	6.15	0.01	0.2%	1% or 5 cm
LCF (m-AP)	77.87	77.77	0.10	0.1%	1% or 50 cm
MTC (m*MT/cm)	744.44	725.60	18.84	2.5%	2%
KMt (m-BL)	19.19	19.25	0.06	0.3%	1% or 50 cm
TPC (MT/cm)	58.94	58.89	0.05	0.1%	NA

Table A-2: Comparison of key hydrostatic properties at the extreme Summer load draft of 10.618 m in salt water, without trim or hull deflection. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

A.2. Tank Properties

Tables A-3, A-4, and A-5 detail calculated tank properties of the MSC computer model and T&S Booklet, including 100% volume and center of gravity, and maximum (slack) free surface inertia for the ballast, fuel, and miscellaneous tanks respectively. Also included in these tables 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, sounding tubes, and other internal components. The permeability factors assumed in the original calculation of the tank volumes in the T&S Booklet were not available. However, the permeability factors provided in Tables A-3, A-4, and A-5 were incorporated based upon MSC's review of GOLDEN RAY structural drawings associated with the internal tank structure. In general, double bottom tanks which have significant internal structure which would reduce the volume available for liquid have been assigned a permeability of 0.97 to 0.98 and internal tanks which do not have significant internal structure have been assigned a permeability of 0.99.

(2) A comparison of tank volumes of the MSC GHS computer model with the T&S Booklet shows a number of tanks with differences in excess of the 2% volume tolerance of MSC Circ. 1229. However, as the approach to the subsequent stability analyses utilized tank loading based upon total weight of the liquid, as opposed to the tank fill percentage, these volume differences did not have an effect on the total quantity of liquid modeled onboard the vessel.

(3) Similar to the differences noted with tank volume calculations, review of Tables A-3, A-4, and A-5 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 12 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. Despite the high number of tanks with differing maximum free

surface inertias, the effects that these differences have on intact stability is minimal. The sum of differences in maximum free surface inertias between the MSC GHS model and the T&S Booklet for all tanks totals approximately 570 m^4. At a displacement of 35,000 MT, which is the approximate displacement at which the vessel was operating prior to the capsize, this difference in maximum free surface inertias results in a maximum VCG difference of less than 2 cm. This difference is negligible when considering the effects that the large quantity of RO/RO cargo has on the overall KG of the vessel.

	100% Volume (m^3)		100% LCG (m fwd AP)		100% TCG (m stbd CL)		100% VCG (m abv BL)		Slack (Max) Free Surface (m4)		Permeability Factor		Volume Difference (%)	LCG Difference (%)	TCG Difference (m)	VCG Difference (%)	FS Inertia Difference (%)	Comments/Notes
	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	Tolerance 2%	Tolerance 1% or 50 cm	Tolerance 0.5% of B (0.18 m) or 5 cm	Tolerance 1% or 50 cm	Tolerance 2%	
Ballast Water																		
F.P. TK	434.2	431.0	184.752	184.995	0.000	0.000	8.078	7.911	598.50	594	0.97	NA	0.7%	0.1%	0.00	2.1%	0.8%	Minimal Loading
NO. 1 W.B.TK (C)	314.8	318.2	167.687	167.686	0.000	0.000	4.950	4.951	302.38	304	0.98	NA	1.1%	0.0%	0.00	0.0%	0.5%	Minimal Loading
NO. 2 W.B.TK (P)	363.5	358.2	154.787	154.907	-4.089	-4.152	4.048	4.096	174.76	168	0.98	NA	1.5%	0.1%	0.06	1.2%	3.9%	
NO. 2 W.B.TK (S)	398.7	386.6	154.868	155.115	3.728	3.827	3.813	3.899	256.16	243	0.98	NA	3.0%	0.2%	0.10	2.3%	5.1%	
NO. 3 W.B.TK (P)	778.3	787.5	135.089	135.076	-7.178	-7.144	3.835	3.784	1359.76	1,305	0.98	NA	1.2%	0.0%	0.03	1.3%	4.0%	
NO. 3 W.B.TK (S)	739.7	738.4	135.830	135.964	6.282	6.243	3.452	3.395	1643.50	1,606	0.98	NA	0.2%	0.1%	0.04	1.7%	2.3%	
NO. 4 W.B.TK (C)	379.1	379.2	119.684	119.687	0.000	0.000	1.441	1.461	1801.75	1,758	0.99	NA	0.0%	0.0%	0.00	1.4%	2.4%	
NO. 4 W.B.TK (P)	291.8	297.8	118.977	118.966	-11.537	-11.580	4.118	4.123	238.32	244	0.98	NA	2.1%	0.0%	0.04	0.1%	2.4%	
NO. 4 W.B.TK (S)	344.6	346.1	119.557	119.571	11.676	11.694	4.459	4.421	238.35	244	0.98	NA	0.4%	0.0%	0.02	0.9%	2.4%	
NO. 5 D.B.W.B.TK (C)	482.7	487.6	92.699	92.700	0.000	0.000	1.425	1.425	944.95	922	0.98	NA	1.0%	0.0%	0.00	0.0%	2.4%	
NO. 5 D.B.W.B.TK (P)	449.8	452.7	92.664	92.673	-7.731	-7.720	1.433	1.426	778.36	759	0.98	NA	0.6%	0.0%	0.01	0.5%	2.5%	
NO. 5 D.B.W.B.TK (S)	449.8	452.7	92.664	92.673	7.731	7.720	1.433	1.426	778.36	759	0.98	NA	0.6%	0.0%	0.01	0.5%	2.5%	
NO. 5 W.B.TK (P)	558.8	569.0	92.455	92.442	-14.844	-14.864	4.787	4.768	147.11	151	0.98	NA	1.8%	0.0%	0.02	0.4%	2.6%	
NO. 5 W.B.TK (S)	558.8	563.4	92.455	92.446	14.844	14.872	4.787	4.764	147.11	151	0.98	NA	0.8%	0.0%	0.03	0.5%	2.6%	
NO. 6 W.B.TK (C)	377.5	380.9	65.696	65.700	0.000	0.000	1.423	1.425	1801.76	1,758	0.98	NA	0.9%	0.0%	0.00	0.1%	2.4%	
NO. 6 W.B.TK (P)	333.6	335.1	65.382	65.434	-12.050	-12.144	3.790	3.816	420.06	411	0.98	NA	0.4%	0.1%	0.09	0.7%	2.2%	
NO. 6 W.B.TK (S)	291.9	292.9	65.280	65.332	11.676	11.770	3.505	3.538	419.82	411	0.98	NA	0.3%	0.1%	0.09	0.9%	2.1%	
NO. 7 W.B.TK (P)	491.2	500.2	53.453	53.442	-6.709	-6.789	2.613	2.655	1418.39	1,408	0.98	NA	1.8%	0.0%	0.08	1.6%	0.7%	
NO. 7 W.B.TK (S)	519.4	528.7	53.454	53.423	6.345	6.426	2.548	2.590	1713.66	1,699	0.98	NA	1.8%	0.1%	0.08	1.6%	0.9%	
A.P.TK (C)	338.6	347.4	1.844	1.764	1.446	1.461	10.408	10.443	1487.91	1,443	0.98	NA	2.6%	4.3%	0.02	0.3%	3.0%	Minimal Loading
A.P.TK (P)	454.6	469.3	3.169	3.235	-10.118	-10.175	10.046	10.024	3222.91	3,175	0.98	NA	3.2%	2.1%	0.06	0.2%	1.5%	Minimal Loading
A.P.TK (S)	399.4	418.8	2.862	3.326	11.303	11.342	10.277	10.206	1646.07	1,542	0.98	NA	4.9%	16.2%	0.04	0.7%	6.3%	Minimal Loading

Table A-3: Calculated tank properties of the MSC computer model (grey columns) and T&S Booklet (white columns) for all ballast tanks. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

	100% Volume (m^3)		100% LCG (m fwd AP)		100% TCG (m stbd CL)		100% VCG (m abv BL)		Slack (Max) Free Surface (m4)		Permeability Factor		Volume Difference (%)	LCG Difference (%)	TCG Difference (m)	VCG Difference (%)	FS Inertia Difference (%)	Comments/Notes
	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	Tolerance 2%	Tolerance 1% or 50 cm	Tolerance 0.5% of B (0.18 m) or 5 cm	Tolerance 1% or 50 cm	Tolerance 2%	
Heavy Fuel Oil																		
NO. 1 H.F.O.TK (P)	387.7	375.8	154.283	154.531	-2.564	-2.619	5.968	5.979	229.41	218	0.98	NA	3.1%	0.2%	0.06	0.2%	5.0%	
NO. 1 H.F.O.TK (S)	456.9	459.2	154.498	154.498	2.175	2.175	5.920	5.919	331.31	320	0.98	NA	0.5%	0.0%	0.00	0.0%	3.4%	
NO. 2 H.F.O.TK (P)	405.4	408.9	141.020	141.021	-3.909	-3.932	5.904	5.914	463.72	499	0.98	NA	0.9%	0.0%	0.02	0.2%	7.6%	
NO. 2 H.F.O.TK (S)	577.6	582.6	139.569	139.572	3.683	3.705	5.872	5.881	926.95	875	0.98	NA	0.9%	0.0%	0.02	0.2%	5.6%	
NO. 3 H.F.O.TK (P)	239.1	240.3	57.150	57.150	-2.550	-2.550	5.650	5.650	72.03	70	0.98	NA	0.5%	0.0%	0.00	0.0%	2.8%	
NO. 3 H.F.O.TK (S)	277.1	278.5	57.150	57.149	2.200	2.200	5.650	5.650	112.17	109	0.98	NA	0.5%	0.0%	0.00	0.0%	2.8%	
NO. 4 H.F.O.TK (P)	317.5	319.1	57.461	57.458	-8.369	-8.342	6.317	6.310	524.91	510	0.98	NA	0.5%	0.0%	0.03	0.1%	2.8%	
NO. 4 H.F.O.TK (S)	355.8	358.6	57.435	57.424	8.364	8.359	6.078	6.078	519.34	510	0.98	NA	0.8%	0.0%	0.01	0.0%	1.8%	
NO. 1 H.F.O. SERV. (P)	41.4	39.6	17.325	17.325	-11.500	-11.458	10.950	11.012	35.01	41	0.99	NA	4.3%	0.0%	0.04	0.6%	17.1%	
NO. 2 H.F.O. SERV. (P)	49.7	47.5	14.850	14.850	-11.500	-11.458	10.950	11.012	45.71	49	0.99	NA	4.4%	0.0%	0.04	0.6%	7.2%	
NO. 1 H.F.O. SETT. (P)	41.4	39.6	19.575	19.575	-11.500	-11.458	10.950	11.012	35.01	40	0.99	NA	4.3%	0.0%	0.04	0.6%	14.3%	
NO. 2 H.F.O. SETT. (P)	49.7	47.5	12.150	12.150	-11.500	-11.458	10.950	11.012	45.71	49	0.99	NA	4.4%	0.0%	0.04	0.6%	7.2%	
Diesel Oil																		
M.D.O. STOR.TK (P)	96.0	95.5	48.570	48.570	-8.370	-8.370	7.000	7.000	109.68	112	0.99	NA	0.5%	0.0%	0.00	0.00	2.1%	
M.D.O. STOR.TK (S)	140.8	149.2	48.733	48.659	7.656	7.700	6.511	6.644	141.70	139	0.99	NA	6.0%	0.2%	0.04	0.02	1.9%	
M.D.O. SERV.TK (S)	37.0	35.5	8.550	8.550	2.014	2.000	12.230	12.200	19.94	24	0.99	NA	4.1%	0.0%	0.01	0.00	20.4%	Not loaded
Gas Oil																		
M.G.O.TK (P)	147.6	146.9	48.743	48.742	-2.836	-2.836	5.650	5.650	57.55	57	0.99	NA	0.5%	0.0%	0.00	0.00	1.0%	
M.G.O.TK (S)	152.7	151.9	48.600	48.600	2.200	2.200	5.650	5.650	61.19	60	0.99	NA	0.5%	0.0%	0.00	0.00	1.9%	
M.G.O. SERV.TK (P)	37.0	35.5	8.550	8.550	-2.014	-2.000	12.230	12.200	20.66	24	0.99	NA	4.1%	0.0%	0.01	0.00	16.2%	

Table A-4: Calculated tank properties of the MSC computer model (grey columns) and T&S Booklet (white columns) for all heavy fuel oil, diesel oil, and gas oil tanks. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

	100% Volume (m^3)		100% LCG (m fwd AP)		100% TCG (m stbd CL)		100% VCG (m abv BL)		Slack (Max) Free Surface (m4)		Permeability Factor		Volume Difference (%)	LCG Difference (%)	TCG Difference (m)	VCG Difference (%)	FS Inertia Difference (%)	Comments/Notes
	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	Tolerance 2%	Tolerance 1% or 50 cm	Tolerance 0.5% of B (0.18 m) or 5 cm	Tolerance 1% or 50 cm	Tolerance 2%	
Lubricating Oil																		
M/E L.O. STOR.TK	26.8	24.5	8.100	8.100	-13.510	-13.525	12.200	12.200	12.30	12	0.99	NA	8.6%	0.0%	0.02	0.00	2.4%	
M/E L.O. SETT.TK	23.5	23.4	8.100	8.100	-10.155	-10.150	12.200	12.200	10.95	11	0.99	NA	0.4%	0.0%	0.00	0.00	0.5%	Not loaded
G/E L.O. STOR.TK	10.9	11.0	21.870	21.850	13.550	13.550	10.355	10.350	1.79	2	0.99	NA	0.9%	0.1%	0.00	0.00	11.7%	
G/E L.O. SETT.TK	8.3	8.2	19.170	19.150	13.550	13.550	10.355	10.350	1.37	1	0.99	NA	1.2%	0.1%	0.00	0.00	27.0%	Not loaded
NO. 1 CYL.O.TK	16.6	16.6	27.900	27.900	12.640	12.625	9.850	9.850	7.91	8	0.99	NA	0.0%	0.0%	0.02	0.00	1.1%	
NO. 2 CYL.O.TK	25.2	24.9	23.728	23.741	13.550	13.550	9.574	9.574	5.27	5	0.99	NA	1.2%	0.1%	0.00	0.00	5.1%	
M/E L.O. SUMP.TK	30.5	30.4	33.300	32.922	0.000	0.003	1.175	1.161	24.91	27	0.99	NA	0.3%	1.1%	0.00	0.01	8.4%	
Miscellaneous																		
L.O. SLU.TK	6.3	9.6	30.150	30.224	7.755	9.155	6.950	6.735	5.92	6	0.99	NA	52.4%	0.2%	1.40	0.03	1.4%	Not loaded
S/T L.O.SUMP.TK	2.3	2.5	18.903	18.918	0.809	0.871	1.853	1.851	0.82	1	0.99	NA	8.7%	0.1%	0.06	0.00	22.0%	Not loaded
BILGE HOLD.TK	79.9	74.6	20.218	20.703	-0.019	-0.012	1.355	1.312	75.71	72	0.97	NA	6.6%	2.4%	0.01	0.03	4.9%	Not loaded
OILY BILGE.TK	50.2	48.7	45.170	39.722	-2.157	-1.659	1.345	1.217	121.53	110	0.98	NA	3.0%	12.1%	0.50	0.10	9.5%	
F.O. SLUDGE.TK	16.0	16.8	14.017	13.987	0.380	0.194	8.844	8.840	43.16	43	0.99	NA	5.0%	0.2%	0.19	0.00	0.4%	
SEWAGE HOLD.TK	18.8	20.5	38.894	39.804	-9.228	-9.064	5.207	5.090	43.80	25	0.99	NA	9.0%	2.3%	0.16	0.02	42.9%	Not loaded
CLEAN DRAIN.TK	18.6	18.1	36.627	36.621	3.337	3.341	1.502	1.505	8.03	8	0.99	NA	2.7%	0.0%	0.00	0.00	0.4%	
C.W.DRAIN.TK	25.0	26.5	43.148	43.395	4.419	4.529	1.459	1.582	19.14	18	0.99	NA	6.0%	0.6%	0.11	0.08	6.0%	
F.O.DRAIN.TK	11.7	12.1	44.111	44.296	-2.498	-2.491	1.149	1.185	1.04	1	0.99	NA	3.4%	0.4%	0.01	0.03	3.8%	
Cooling Water																		
S/T C.W.TK	35.4	30.2	10.231	10.349	0.000	0.000	3.823	3.512	3.71	4	0.95	NA	14.7%	1.2%	0.00	0.08	7.8%	
Fuel Oil Overflow																		
NO. 1 F.O.OVER.TK	10.8	10.2	134.550	134.625	-1.050	-1.050	7.003	7.020	0.61	1	0.99	NA	5.6%	0.1%	0.00	0.00	63.9%	
NO. 2 F.O.OVER.TK	18.6	18.6	44.214	44.410	-4.592	-4.675	1.528	1.608	16.45	13	0.99	NA	0.0%	0.4%	0.08	0.05	21.0%	
Fresh Water																		
NO. 1 F.W.TK	81.0	78.2	9.900	9.900	13.000	13.000	11.750	11.850	12.45	12	0.98	NA	3.5%	0.0%	0.00	0.01	3.6%	
NO. 2 F.W.TK	168.3	156.4	9.900	9.900	8.500	5.500	11.850	11.850	99.63	97	0.98	NA	7.1%	0.0%	3.00	0.00	2.6%	

Table A-5: Calculated tank properties of the MSC computer model (grey columns) and T&S Booklet (white columns) for all lubricating oil, miscellaneous, cooling water, overflow, and fresh waters tanks. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

A.3. Appendix References

A1 GOLDEN RAY Final Trim & Stability Booklet, Document 4A000B012, stamped "Approved" by DNV-GL on December 12, 2017

A2 IMO MSC.1/Circ.1229, Guidelines for Approval of Stability Instruments, dated January 11, 2007.

A3 International Association of Class Societies (IACS) Unified Requirement L5: Onboard Computers for Stability Calculations, Corr. 1, dated 2006.

Appendix B: Jacksonville to Brunswick Stability Analysis

An assessment of the GOLDEN RAY's intact stability during the transit from Jacksonville, FL to Brunswick, GA on September 7, 2019 was completed using the MSC computer model described in Section 2 of this report. This Appendix details the loading conditions applied to the model for this voyage and the resultant righting arm curves expected during this voyage.

B.1. Loading Conditions

This section details the information, methods, and assumptions used to simulate the Jacksonville, FL to Brunswick, GA voyage loads that were applied to the MSC computer model. When available, actual liquid and cargo loading data from this voyage was used. For loads in which no data was available, Sections 5.3 and 5.4 of the T&S Booklet, which detail acceptable benchmark loading conditions for the vessel, were referenced.

B.1.1. Liquid Loading

As with the analysis for the capsize voyage, IMACS software data was used to apply the loads to the 47 major tanks in the MSC computer model. The tank quantities from the 07/09/19 05:01:32 UTC timestamp [B1] were used. This timestamp represents tank quantities immediately prior to departure when the vessel was at nearly zero list. Using a timestamp at which the vessel was at zero list reduces error, as the IMACS tank readings do not appear to correct for heel, and using a timestamp immediately prior to departure ensures that an accurate comparison with the vessel's departure drafts can be completed.

A comparison of the tank values applied to the model to the tank values immediately prior to arrival in Brunswick was conducted, the results of which are shown in Table B-1. Based on this data, fuel and diesel quantities appeared to decrease by a small amount throughout the voyage, likely due to liquid load consumption, however the net liquid load decrease of approximately 16 MT is insignificant to stability given the approximately 35,000 MT displacement of the vessel during this voyage.

	Jacksonville Departure Load (MT)	Brunswick Arrival Load (MT)	Difference (MT)	Difference %
Ballast	2924.33	2920.18	-4.15	-0.1%
Fuel	887.22	875.08	-12.14	-1.4%
Diesel	322.39	321.06	-1.33	-0.4%
Misc.	44.61	46.54	1.93	4.3%
Total	**4178.55**	**4162.86**	**-15.69**	-0.4%

Table B-1: Comparison between tank weights from the vessel's IMACS data files at the 07/09/19 05:01:32 UTC (01:01:32 EDT) (Jacksonville Departure) timestamp and the 07/09/19 21:09:14 UTC (17:09:14 EDT) (Brunswick Arrival) timestamp. The loads at the Jacksonville Departure timestamp were applied to the MSC computer model.

Loads for the smaller tanks including lube oil, cooling water, and fresh water, which were not monitored by the vessel's IMACS software were assumed to be consistent with the Departure Bunkering Condition detailed in Section 5.3.1 of the T&S Booklet. Table B-2 shows the liquid load applied for these tanks, which accounted for 7.9% of the total liquid load applied to the model.

	Load Applied (MT)
L.O. Sludge TK (S)	0.0
S/T L.O Sludge TK (C)	0.0
F.O. Sludge TK (S)	0.0
Sewage Holding TK (P)	0.0
S/T Cooling Water TK (C)	30.2
No. 1 F.W. TK (S)	78.2
No. 2 F.W. TK (S)	156.4
M/E L.O. STOR. TK (P)	21.6
M/E. L.O. SET. TK (P)	0.0
G/E L.O. STOR TK (S)	9.7
G/E L.0. SET. TK (S)	0.0
NO. 1 CYL. Oil TK (S)	14.7
NO. 2 CYL. Oil TK (S)	22.0
M/E L.O. Sump TK (C)	26.8
Total	**359.6**

Table B-2: Liquid loads applied to MSC computer model for small tanks not monitored by IMACS. Values were selected in accordance with the T&S Booklet departure benchmark loading conditions.

B.1.2. Cargo Loading

The Jacksonville Preliminary Stowage Plan [B2] was used to determine the cargo loading applied to the MSC Computer Model. After superimposing the stowage plan onto the General Arrangement, the area centroid of each vehicle group was calculated and was assumed to represent the LCG and TCG of each vehicle group. The VCG of each vehicle group was determined by adding the corresponding deck height to a standard, assumed vehicle VCG of 0.57 m above the deck, an assumption which is consistent with previous analysis contained in this report. The weights of the vehicle groups were then applied to the MSC computer model in 73 individual point loads at the respective centers of gravity. These loads are summarized by deck in Table B-3.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
Deck 13	745.60	98.24	0.14	36.82
Deck 12	535.28	78.87	-3.00	34.51
Deck 11	933.22	89.48	1.22	32.00
Deck 10	1010.00	91.56	0.28	29.47
Deck 9	1020.00	92.71	-0.33	26.93
Deck 8	995.00	86.31	-0.15	24.41
Deck 7	620.25	96.81	-0.91	21.71
Deck 6 Raised	155.29	25.57	5.97	18.97
Deck 6 Standard	511.00	121.57	3.42	18.27
Deck 5	440.09	105.18	-2.90	14.87
Deck 4	557.00	99.81	0.02	11.82
Deck 3	515.00	99.12	0.00	9.02
Deck 2	174.34	97.63	-0.83	6.12
Deck 1	195.15	94.04	0.12	3.42
Total	**8407.2**	**93.53**	**0.02**	**24.09**

Table B-3: Cargo weights applied to the MSC model from the Jacksonville Preliminary Stowage Plan summarized by Deck. Deck 6 is subdivided into cargo situated on deck panels which were raised 0.7 m and cargo situated on deck panels which were at the standard height.

B.1.3. Miscellaneous Deadweight

The weight of miscellaneous deadweight items, including the fixed firefighting system's carbon dioxide, swimming pool water weight, provisions, stores, and cargo lashing equipment, were applied to the MSC Computer model consistent with the values listed for the Departure Condition detailed on page 266 of the T&S Booklet.

B.1.4. Final Loading

A summary of the final loading conditions applied to the MSC Computer model for the Jacksonville to Brunswick voyage is shown in Table B-4.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
LTSH	21433.0	85.9	-0.27	18.3
Tanks	4538.2	102.1	2.26	3.9
Cargo	8407.2	93.5	0.02	24.1
Misc. Deadweight	230.4	74.4	-2.33	25.3
Total	**34608.8**	**89.8**	**0.12**	**18.1***

Table B-4: Final loading condition applied to the MSC computer model for the Jacksonville to Brunswick voyage. *VCG includes 0.247 m of free surface correction.

B.2. Results

B.2.1. Final Hydrostatics

The 0.12 m starboard TCG of the final loading condition applied to the model resulted in starboard heel of 2.9 degrees. However, IMACS data indicates that the vessel did not depart Jacksonville with significant heel. As such, a zero heel condition was applied to the vessel for all subsequent stability analysis. Consistent with previous analysis in this report, this was done by setting the heel of the vessel model equal to zero, allowing it to trim freely in order to remove residual longitudinal moments, and solving for the resultant TCG.

The hydrostatic properties with the loads applied for the Jacksonville to Brunswick voyage with the vessel at zero heel were then calculated and are shown in Table B-5.

	Disp. (MT)	LCB (m-AP)	VCB (m-BL)	LCF (m-AP)	MTC (m*MT/cm)	KMt (m-BL)	GM (m)	TPC (MT/cm)
Disp. (MT)	34609	89.76	5.31	77.55	624.94	20.09	1.91	56.13

Table B-5: Final hydrostatic properties calculated from the MSC computer model for the vessel in the zero heel condition with the loading applied for the Jacksonville to Brunswick voyage.

B.2.2. Drafts

With the vessel at 0 degrees heel, the resultant drafts calculated using the MSC computer model were compared to the drafts reported by the IMACS Jacksonville departure timestamp (07/09/19 05:01:32 UTC) as shown in Table B-6. The MSC computer model drafts obtained are shown for both salt water and brackish water conditions with a specific gravity of 1.01, which is representative of the water conditions at Blount Island Marine Terminal in Jacksonville on September 7, 2019 according to salinity data [B3]. The mean draft of the MSC model in brackish water was within 0.02 m of the mean draft reported by the vessel's IMACS software at departure.

	MSC Model Salt Water	MSC Model Brackish Water	IMACS Departure	Departure Draft Readings
Taft (m)	9.47	9.51	9.49	9.40
Tfwd (m)	8.94	9.07	9.04	9.30
Tmean (m)	9.20	9.29	9.27	9.35

Table B-6: Comparison between loaded drafts calculated using the MSC computer model in salt and brackish water (S.G. = 1.01) with IMACS drafts at departure and departure draft readings taken by the vessel crew.

B.2.3. Jacksonville Voyage Righting Arm Curve Properties

With the MSC computer model loaded for the Jacksonville to Brunswick voyage in accordance with Section B.1, and with list set to 0 degrees, righting arm curves were generated for heel to port and starboard in salt water. These righting arm curves are shown in Figure B-1 by the dark green line (heel to starboard) and dark red line (heel to port). For comparison of righting arms with loading conditions which meet regulatory requirements, the righting arm curves from all

T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT are also shown (dotted lines).

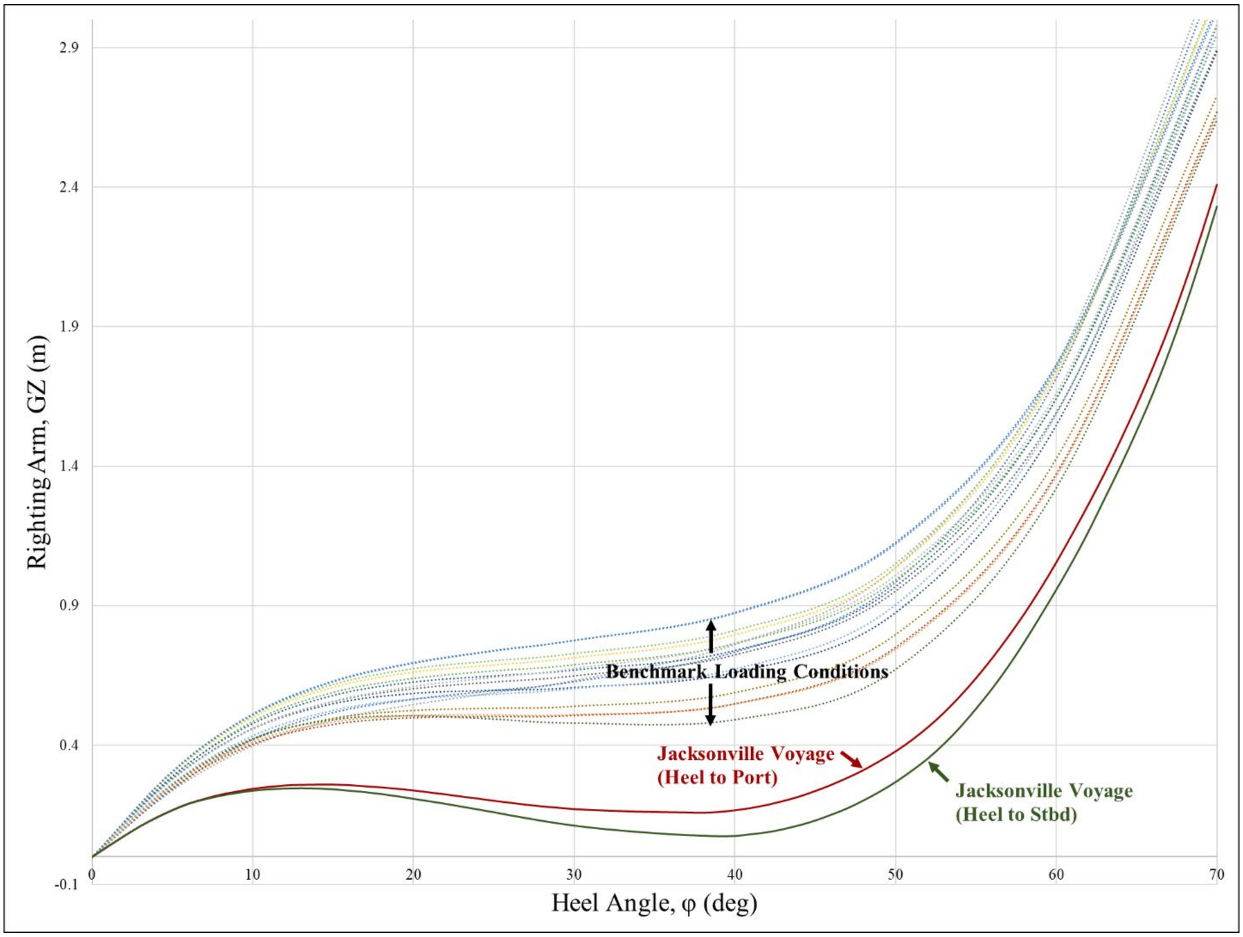

Figure B-1: Righting arm curves generated for the vessel in the Jacksonville to Brunswick voyage condition using the MSC computer model for heel to starboard (dark green line) and heel to port (dark red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

For the righting arm curves in Figure B-1, the 2008 IS Code mandatory intact stability criteria were applied, with results summarized in Table B-7. Red shading indicates that the attained value does not meet the specific criteria and green shading indicates that the attained value meets the specific criteria. For the IS Code general righting arm curve properties (Part A, Section 2.2), the righting arm curve did not meet the required minimum threshold for righting energy between 30° and 40°, and for the severe wind and rolling criteria (Part A, Section 2.3), the vessel failed to meet the Area Ratio threshold.

	Units	MSC Loading Condition (Jacksonville Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties			
Area to 30 degrees	m-rad	0.095	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.110	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.015	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	4.028	At least 0.2 m
Angle of maximum righting arm	deg	80.2	At least 25 deg
Initial GM	m	1.91	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria			
Angle of static heel (φ_0)	deg	5.5	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	Greater than 1

Table B-7: Results of the assessment of the MSC computer model loaded for the Jacksonville to Brunswick voyage with the mandatory requirements of the 2008 IS Code. Green background indicates that the criteria has been met. Red background indicates that the criteria has not been met.

The righting arm curves for the Jacksonville voyage were then compared to the righting arm curves for the capsize voyage generated in accordance with Section 4.3.2 of this report, and are shown in Figure B-2 for heel to starboard and Figure B-3 for heel to port.

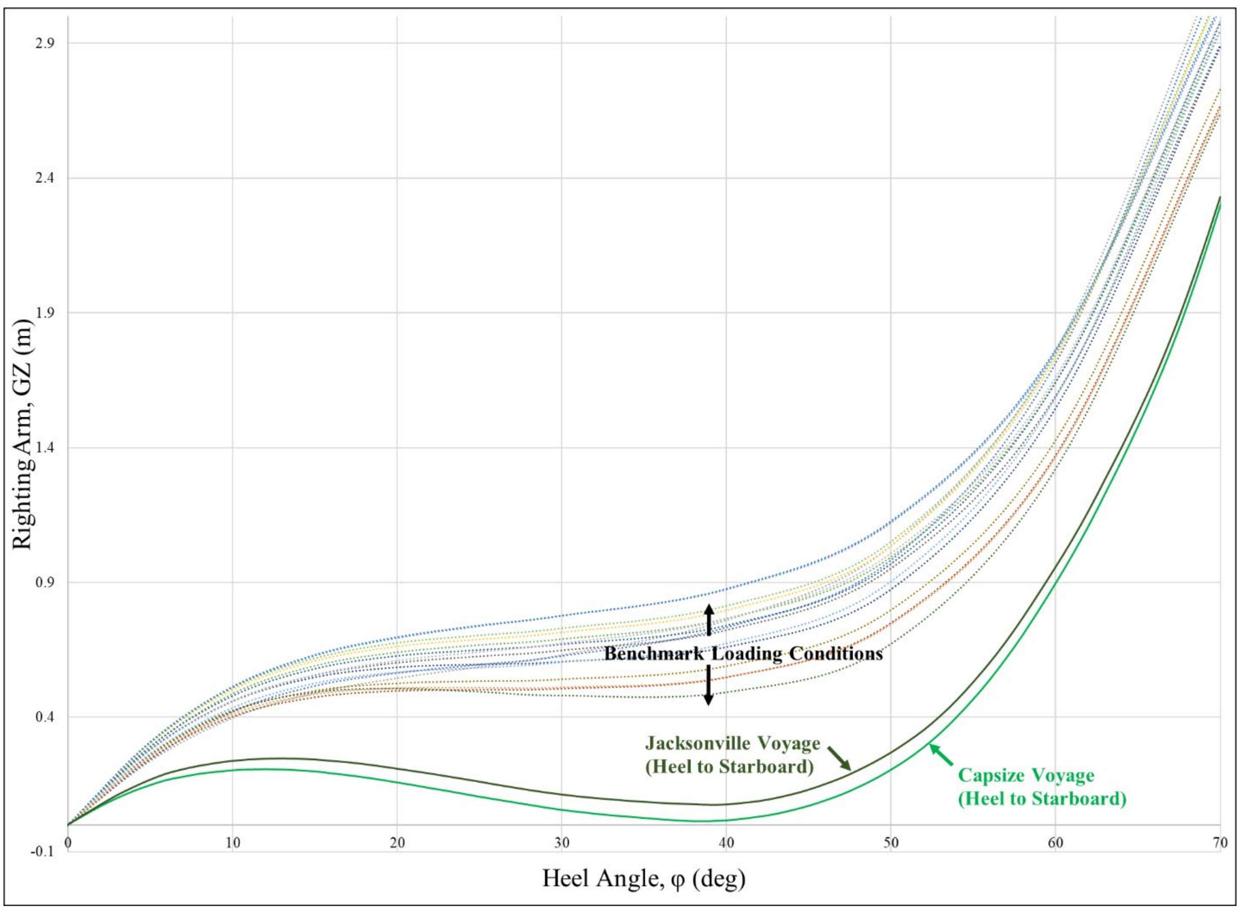

Figure B-2: Comparison of starboard righting arm curves for the vessel in the Jacksonville to Brunswick voyage (dark green line) and in the capsize voyage (light green line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

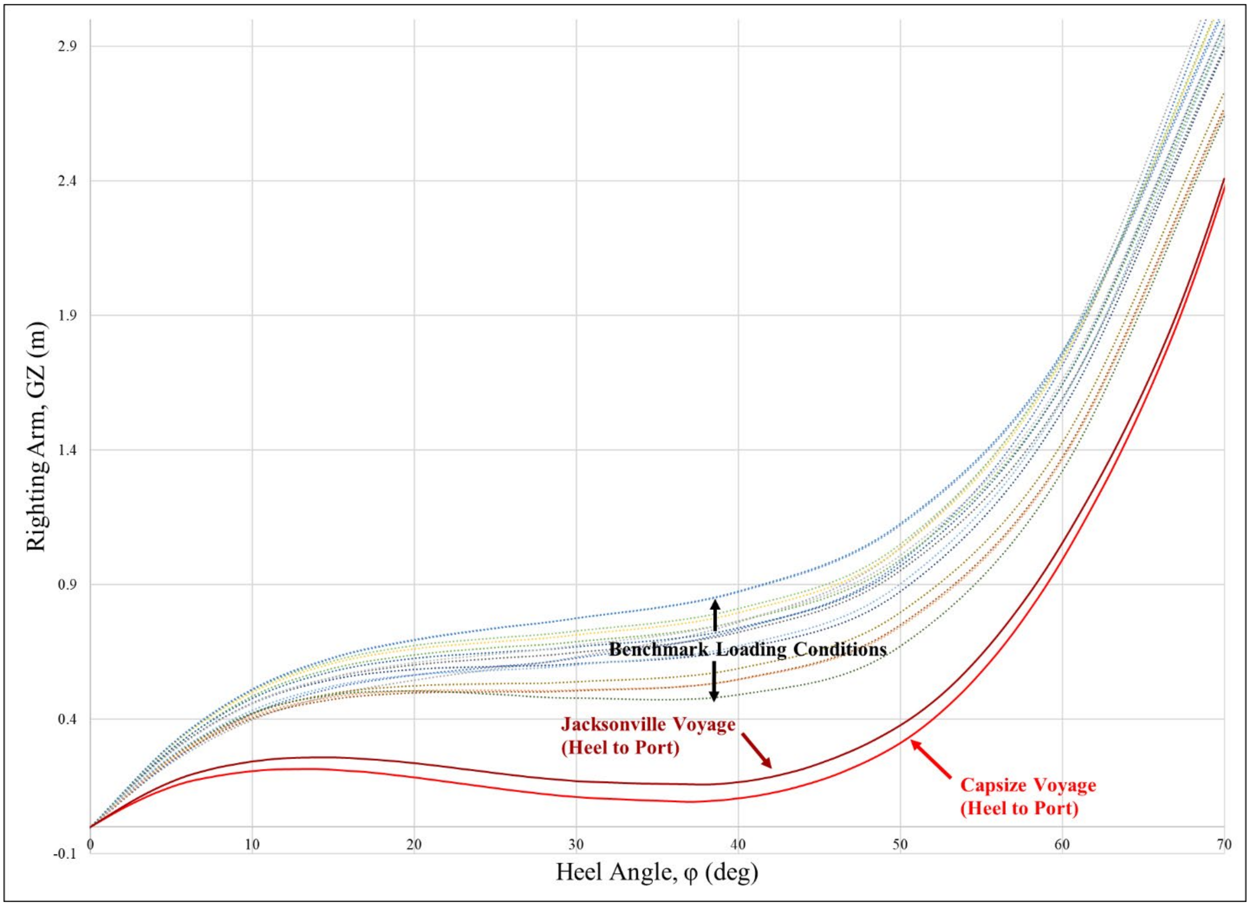

Figure B-3: Comparison of port righting arm curves for the vessel in the Jacksonville to Brunswick voyage (dark red line) and in the capsize voyage (light red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

B.3. Appendix References

B1 GOLDEN RAY IMACS Tank Summary for 07/09/19 05:01:32

B2 GOLDEN RAY Jacksonville Preliminary Stowage Plan

B3 U.S. Geological Survey National Water Information System, Salinity Data for Station "St Johns R Dames Point Bridge at Jacksonville, FL"

Appendix C: Freeport to Jacksonville Stability Analysis

An assessment of the GOLDEN RAY's intact stability during the transit from Freeport, TX to Jacksonville, FL beginning on August 30, 2019 was completed using the MSC computer model described in Section 2 of this report. This Appendix details the loading conditions applied to the model for this voyage and the resultant righting arm curves expected during this voyage.

C.1. Loading Conditions

This section details the information, methods, and assumptions used to simulate the Freeport, TX to Jacksonville, FL voyage loads that were applied to the MSC computer model. When available, actual liquid and cargo loading data from this voyage was used. For loads in which no data was available, Sections 5.3 and 5.4 of the T&S Booklet, which detail acceptable benchmark loading conditions for the vessel, were referenced.

C.1.1. Liquid Loading

As with the analysis for the capsize voyage, IMACS software data was used to apply the loads to the 47 major tanks in the MSC computer model. The tank quantities from the 04/09/19 17:35:39 UTC timestamp [C1] were used. This timestamp represents tank quantities following ballast discharge operations on September 3, 2019, and when the vessel was at nearly zero list. Using a timestamp in which the vessel was at zero list reduces error, as the IMACS tank readings do not appear to correct for heel.

A comparison of the tank values applied to the model to the tank values immediately prior to arrival in Jacksonville was conducted, the results of which are shown in Table C-1. Based on this data, fuel quantity appeared to decrease by a small amount throughout the remainder of the voyage, likely due to liquid load consumption; however the net liquid decrease of approximately 130 MT is insignificant to stability given the approximately 35,000 MT displacement of the vessel during this voyage.

	Mid-Voyage Load (MT)	Jacksonville Arrival Load (MT)	Difference (MT)	Difference %
Ballast	2993.45	2932.97	-60.48	-2.0%
Fuel	970.29	890.63	-79.66	-8.2%
Diesel	321.98	323.82	1.84	0.6%
Misc.	35.45	43.69	8.24	23.2%
Total	**4321.17**	**4191.11**	**-130.06**	-3.0%

Table C-1: Comparison between tank weights from the vessel's IMACS data files at the 04/09/19 17:35:39 UTC (13:35:39 EDT) (mid-voyage) timestamp and the 06/09/19 22:38:28 UTC (18:38:28 EDT) (Jacksonville Arrival) timestamp. The loads at the mid-voyage timestamp were applied to the MSC computer model.

Loads for the smaller tanks including lube oil, cooling water, and fresh water, which were not monitored by the vessel's IMACS software were assumed to be consistent with the Departure Bunkering Condition detailed in Section 5.3.1 of the T&S Booklet. Table C-2 shows the liquid load applied for these tanks, which accounted for 7.7% of the total liquid load applied to the model.

	Load Applied (MT)
L.O. Sludge TK (S)	0.0
S/T L.O Sludge TK (C)	0.0
F.O. Sludge TK (S)	0.0
Sewage Holding TK (P)	0.0
S/T Cooling Water TK (C)	30.2
No. 1 F.W. TK (S)	78.2
No. 2 F.W. TK (S)	156.4
M/E L.O. STOR. TK (P)	21.6
M/E. L.O. SET. TK (P)	0.0
G/E L.O. STOR TK (S)	9.7
G/E L.0. SET. TK (S)	0.0
NO. 1 CYL. Oil TK (S)	14.7
NO. 2 CYL. Oil TK (S)	22.0
M/E L.O. Sump TK (C)	26.8
Total	**359.6**

Table C-2: Liquid loads applied to MSC computer model for small tanks not monitored by IMACS. Values were selected in accordance with the T&S Booklet departure benchmark loading conditions.

C.1.2. Cargo Loading

The Freeport Preliminary Stowage Plan [C2] was used to determine the cargo loading applied to the MSC Computer Model. After superimposing the stowage plan onto the General Arrangement, the area centroid of each vehicle group was calculated and was assumed to represent the LCG and TCG of each vehicle group. The VCG of each vehicle group was determined by adding the corresponding deck height to a standard, assumed vehicle VCG of 0.57 m above the deck, an assumption which is consistent with previous analysis contained in this report. The weights of the vehicle groups were then applied to the MSC computer model in 73 individual point loads at the respective centers of gravity. These loads are summarized by deck in Table C-3.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
Deck 13	745.60	98.24	0.14	36.82
Deck 12	739.74	98.34	-1.89	34.51
Deck 11	933.22	89.48	1.22	32.00
Deck 10	988.00	89.98	0.14	29.47
Deck 9	1020.00	92.71	-0.33	26.93
Deck 8	995.00	86.31	-0.15	24.41
Deck 7	580.25	97.70	-1.76	21.71
Deck 6 Raised	119.29	23.59	10.58	18.97
Deck 6 Standard	500.00	122.68	3.66	18.27
Deck 5	479.12	110.35	-1.15	14.87
Deck 4	557.00	99.81	0.02	11.82
Deck 3	515.00	99.12	0.00	9.02
Deck 2	174.34	97.63	-0.83	6.12
Deck 1	195.15	94.04	0.12	3.42
Total	**8541.7**	**95.36**	**0.11**	**24.33**

Table C-3: Cargo weights applied to the MSC model from the Freeport Preliminary Stowage Plan summarized by Deck. Deck 6 is subdivided into cargo situated on deck panels which were raised 0.7 m and cargo situated on deck panels which were at the standard height.

C.1.3. Miscellaneous Deadweight

The weight of miscellaneous deadweight items, including the fixed firefighting system's carbon dioxide, swimming pool water weight, provisions, stores, and cargo lashing equipment, were applied to the MSC Computer model consistent with the values listed for the Departure Condition detailed on page 266 of the T&S Booklet.

C.1.4. Final Loading

A summary of the final loading conditions applied to the MSC Computer model for the Freeport to Jacksonville voyage is shown in Table C-4.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
LTSH	21433.0	85.9	-0.27	18.3
Tanks	4680.8	102.1	2.04	3.9
Cargo	8541.7	95.4	0.11	24.3
Misc. Deadweight	230.4	74.4	-2.33	25.3
Total	**34885.9**	**90.3**	**0.12**	**18.1***

Table C-4: Final loading condition applied to the MSC computer model for the Freeport to Jacksonville voyage.
*VCG includes 0.250 m of free surface correction.

C.2. Results

C.2.1. Final Hydrostatics

The 0.12 m starboard TCG of the final loading condition applied to the model resulted in a starboard heel of 2.9 degrees. However, IMACS data did not indicate significant heel throughout the voyage. As such, a zero heel condition was applied to the vessel for all subsequent stability analysis. Consistent with previous analysis in this report, this was done by setting the heel of the vessel model equal to zero, allowing it to trim freely in order to remove residual longitudinal moments, and solving for the resultant TCG.

The hydrostatic properties with the loads applied for the Freeport to Jacksonville voyage with the vessel at zero heel were then calculated and are shown in Table C-5.

	Disp. (MT)	LCB (m-AP)	VCB (m-BL)	LCF (m-AP)	MTC (m*MT/cm)	KMt (m-BL)	GM (m)	TPC (MT/cm)
Disp. (MT)	34885	90.37	5.32	78.06	621.50	19.99	1.85	56.03

Table C-5: Final hydrostatic properties calculated from the MSC computer model for the vessel in the zero heel condition with the loading applied for the Freeport to Jacksonville voyage.

C.2.2. Drafts

With the vessel at 0 degrees heel, the resultant drafts calculated using the MSC computer model were compared to the drafts reported by IMACS as shown in Table C-6. The mean draft of the MSC model in salt water was within 0.05 m of the mean draft reported by the vessel's IMACS on September 4, 2019.

	MSC Model Salt Water	IMACS
Taft (m)	9.36	9.44
Tfwd (m)	9.21	9.23
Tmean (m)	9.29	9.34

Table C-6: Comparison between loaded drafts calculated using the MSC computer model in salt water with IMACS drafts on September 4, 2019 at the 04/09/19 17:35:39 UTC timestamp.

C.2.3. Freeport Voyage Righting Arm Curve Properties

With the MSC computer model loaded for the Freeport to Jacksonville voyage in accordance with Section C.1, and with list set to 0 degrees, righting arm curves were generated for heel to port and starboard in salt water. These righting arm curves are shown in Figure C-1 by the teal green line (heel to starboard) and the dark red line (heel to port). For comparison of righting arms with loading conditions which meet regulatory requirements, the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT are also shown (dotted lines).

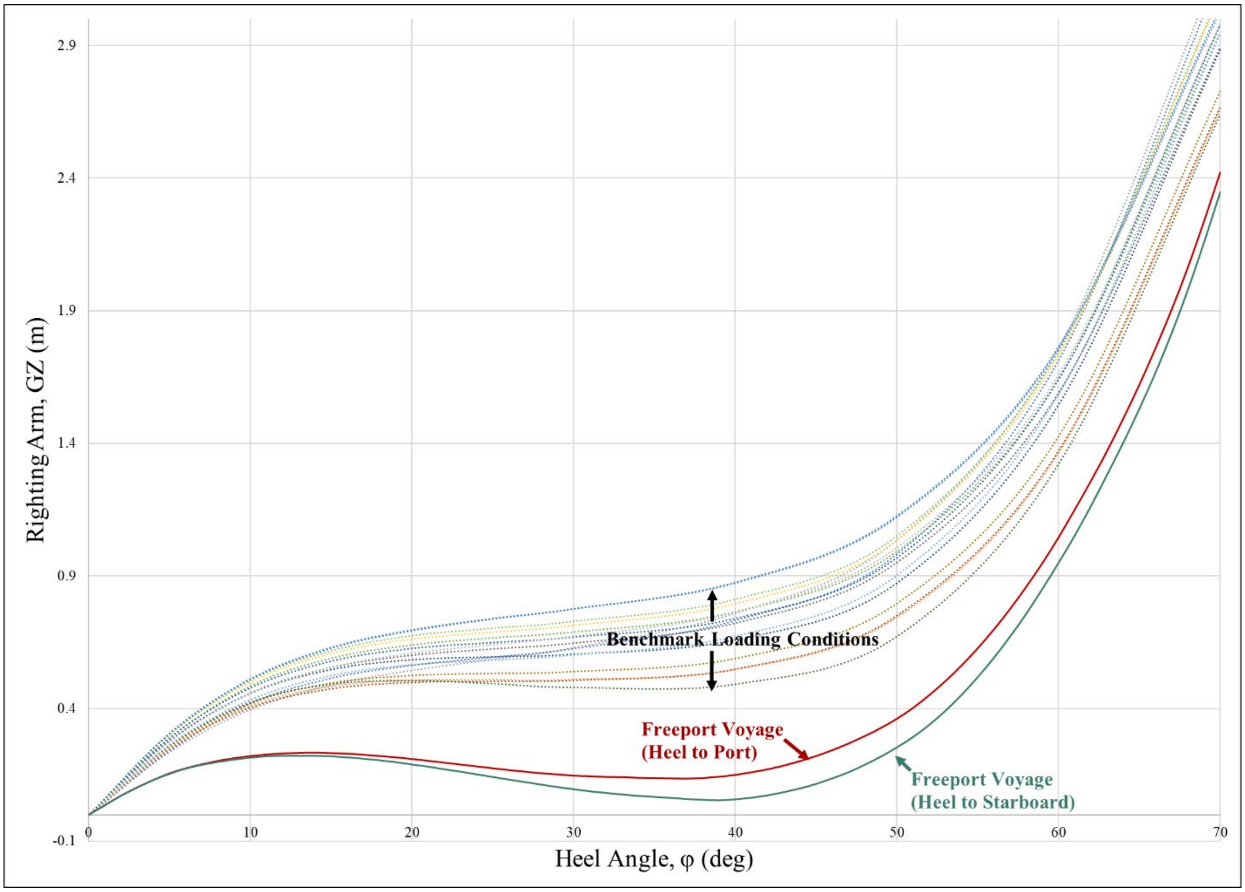

Figure C-1: Righting arm curves generated for the vessel in the Freeport to Jacksonville voyage condition using the MSC computer model for heel to starboard (teal green line) and heel to port (dark red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

For the righting arm curves in Figure C-1, the 2008 IS Code mandatory intact stability criteria were applied, with results summarized in Table C-7. Red shading indicates that the attained value does not meet the specific criteria and green shading indicates that the attained value meets the specific criteria. For the IS Code general righting arm curve properties (Part A, Section 2.2), the righting arm curve did not meet the required minimum threshold for righting energy between 30° and 40°, and for the severe wind and rolling criteria (Part A, Section 2.3), the vessel failed to meet the Area Ratio threshold.

	Units	MSC Loading Condition (Freeport Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties			
Area to 30 degrees	m-rad	0.084	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.095	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.011	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	4.056	At least 0.2 m
Angle of maximum righting arm	deg	80.4	At least 25 deg
Initial GM	m	1.84	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria			
Angle of static heel (φ_0)	deg	6.2	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	Greater than 1

Table C-7: Results of the assessment of the MSC computer model loaded for the Freeport to Jacksonville voyage with the mandatory requirements of the 2008 IS Code. Green background indicates that the criteria has been met. Red background indicates that the criteria has not been met.

The righting arm curves for the Freeport voyage were then compared to the righting arm curves for the capsize voyage generated in accordance with Section 4.3.2 of this report, and are shown in Figure C-2 for heel to starboard and Figure C-3 for heel to port.

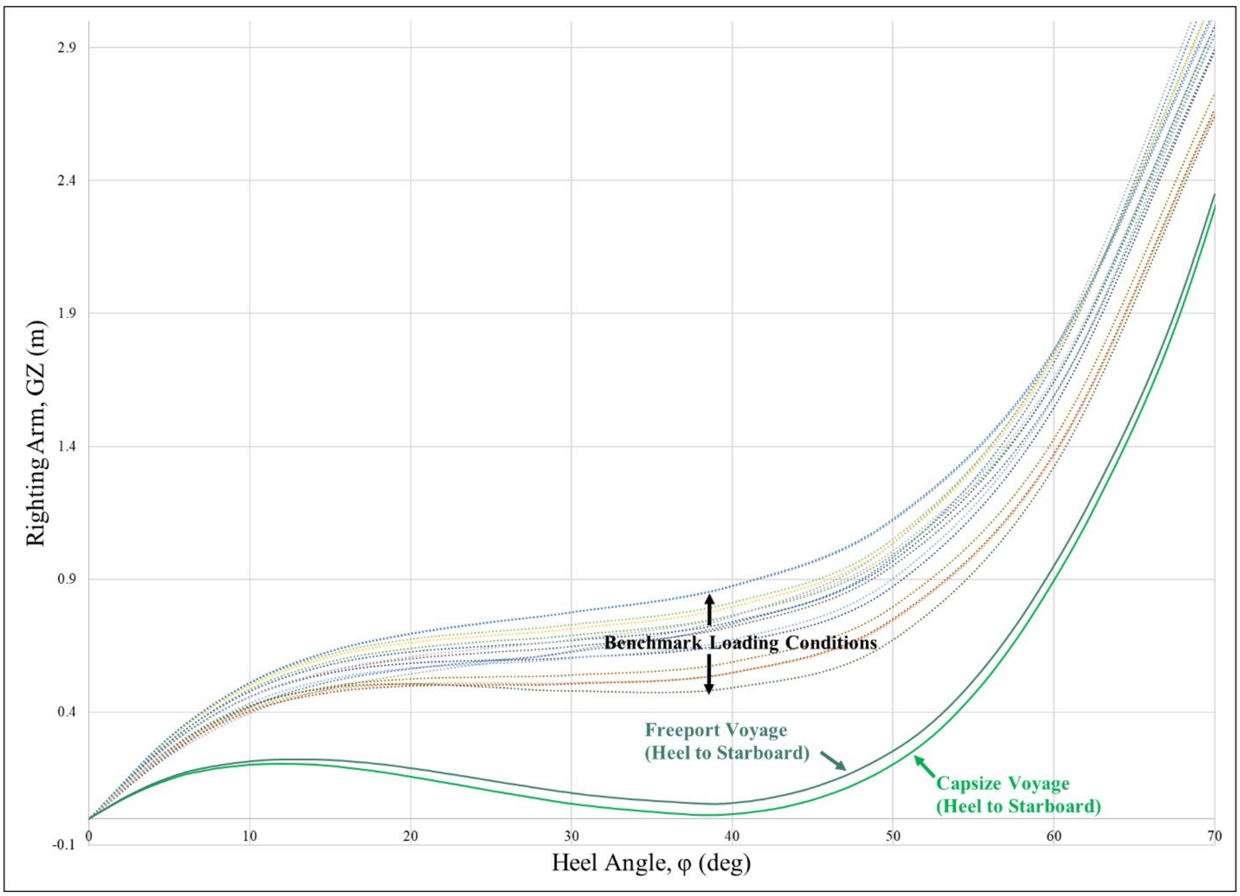

Figure C-2: Comparison of starboard righting arm curves for the vessel in the Freeport to Jacksonville voyage (teal green line) and in the capsize voyage (light green line).

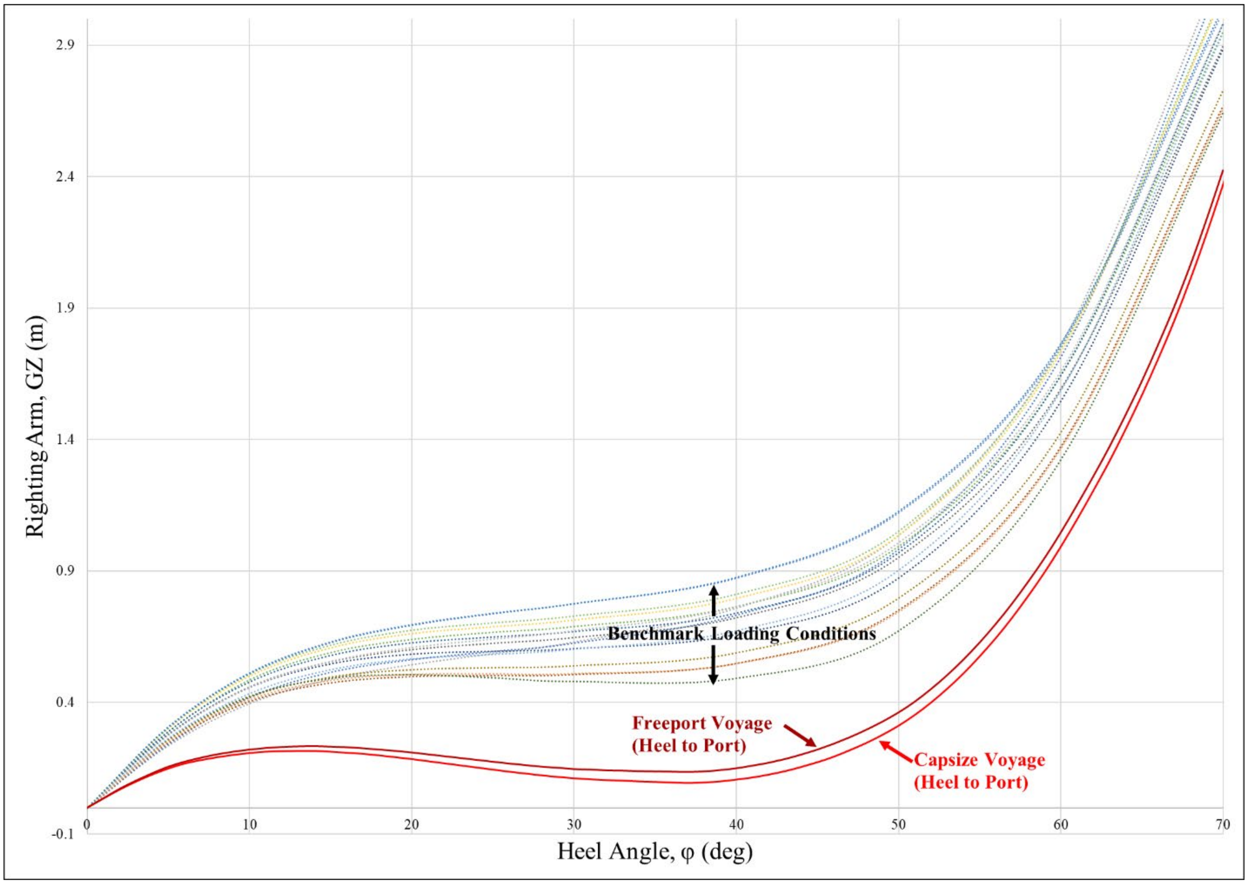

Figure C-3: Comparison of port righting arm curves for the vessel in the Freeport to Jacksonville voyage (dark red line) and in the capsize voyage (light red line).

C.3. Appendix References

C1 GOLDEN RAY IMACS Tank Summary for 07/04/19 17:35:39
C2 GOLDEN RAY Freeport Preliminary Stowage Plan

U.S. Coast Guard
Marine Safety Center

Technical Report

GOLDEN RAY
Intact Stability

August 26, 2020

CG EX 16 B

Table of Contents

Executive Summary

This report documents a forensic stability analysis of the RO/RO GOLDEN RAY, completed by the Marine Safety Center (MSC) in support of the formal marine casualty investigation into the capsizing that occurred on September 8, 2019.

To aid in the accomplishment of the analysis, MSC independently generated a detailed computer model, and used this model for analyses of vessel hydrostatics and intact stability.

Based on independent calculation and various assumptions detailed in this report, MSC analysis indicates that, if loaded in accordance with the cargo weights detailed on the Brunswick Departure Stowage Plan and the liquid load quantities reported by the IMACS computer prior to the capsize, the GOLDEN RAY did not meet the mandatory requirements of the International Code on Intact Stability (2008). MSC analysis also indicates significant reduction in righting arms due to the centrifugal force experienced by the vessel throughout the turn leading up to the capsize. MSC analysis indicates that these factors combined to produce an extremely low righting energy, preventing the vessel from withstanding further adverse static or dynamic heeling effects, and resulting in the vessel's capsize.

Further analysis was conducted to assess the vessel's intact stability during the two voyages prior to the capsize voyage: Freeport, TX to Jacksonville, FL and Jacksonville FL, to Brunswick, GA. Results indicate that, based on the respective cargo stowage plans and IMACS liquid loading data, although the vessel had more righting energy in these voyages than during the capsize voyage, it did not fully comply with the mandatory requirements of the International Code on Intact Stability (2008) during either preceding voyage.

1. Introduction

1.1. Background

Reference [1] established the formal marine casualty investigation into the capsizing of the RO/RO GOLDEN RAY while transiting St. Simons Sound, Georgia on September 8, 2019. As requested by the members of the investigation team, MSC utilized relevant naval architecture principles to assist with determining the contributing physical and environmental factors which led to the capsize of the vessel.

1.2. Approach

Based on the available documentation, including vessel drawings, stability information, tank loading data, and cargo loading data, MSC completed a series of independent technical analyses. To aid in the accomplishment of these analyses, MSC independently generated a detailed computer model for calculation of vessel hydrostatics and stability.

Section 2 provides an overview of the development of the MSC computer model.

Section 3 documents the methods and assumptions used to generate the loading condition that was applied to the MSC computer model to simulate the capsize voyage condition.

Section 4 provides a primer on basic ship stability and documents the results of the hydrostatic and stability analyses in the loading condition described in Section 3.

Section 5 documents MSC's review of the vessel's stability during the capsize voyage with key data in the vessel's Trim and Stability Booklet.

Section 6 documents and compares the results of MSC's review of vessel stability during the two voyages prior to the capsize voyage.

Section 7 details conclusions based on the analyses contained in Sections 4 through 6.

Section 8 is a listing of references utilized for the analyses.

Appendix A details results of a comparison of the MSC computer model's hydrostatic and tank properties with the vessel's Trim and Stability (T&S) Booklet.

Appendix B provides detailed documentation of the methods, assumptions, and results of the stability analysis for the Jacksonville, FL to Brunswick, GA voyage.

Appendix C provides detailed documentation of the methods, assumptions, and results of the stability analysis for the Freeport, TX to Jacksonville, FL voyage.

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	m	meters
A/B	Above baseline	mm	milimeters
AP	Aft perpendicular	M	Metacenter, bending moment
B	Beam, center of buoyancy	M/E	Maine engine
BL	Baseline (plane)	M.D.O.	Marine Diesel Oil (tank)
BM	Metacentric radius	M.G.O.	Marine gas oil (tank)
CAD	Computer Aided Design (software)	MSC	Marine Safety Center
CL	Centerline (plane)	MT	Metric tons
CYL.O.	Cylinder oil (tank)	MTC	Moment to trim one centimeter
D	Depth	P	Port Side
EDT	Eastern daylight time	PPU	Portable pilot unit
F_B	Force of buoyancy	R	Radius (of turn)
F.W.	Fresh water (tank)	RO/RO	Roll-On/Roll-Off
G/E	Generator Engine	S	Starboard side
H.F.O	Heavy fuel oil (tank)	S.G.	Specific Gravity
FP	Forward perpendicular (plane)	SOLAS	Safety of Life at Sea (conventions)
g	Acceleration due to gravity	T	Draft
G	Center of gravity	TK	Tank
GHS	General Hydrostatics (software)	T&S	Trim and Stability (Booklet)
GM	Metacentric height	TCG	Transverse position of center of gravity
GZ	Righting arm	TPC	Tons per centimeter immersion
IACS	International Association of Classification Societies	UTC	Coordinated universal time
IMO	International Maritime Organization	v	velocity
KG	Vertical (height) position of center of gravity (VCG)	VCB	Vertical (height) position of center of buoyancy
KMt	Height of the metacenter	VCG	Vertical (height) position of center of gravity (KG)
l	Wind heeling arm (lever)	W.B.	Water ballast (tank)
LBP	Length between perpendiculars	W	Weight
LCB	Longitudinal position of center of buoyancy	WL	Waterline
LCF	Longitudinal position of center of flotation	φ	Angle of heel (same as θ)
LCG	Longitudinal position of center of gravity	θ	Angle of heel (same as φ)
L.O.	Lube oil (tank)	Δ	Displacement (weight of ship)
LWL	Length on the waterline	∇	Displacement volume

Table 1-1: Nomenclature

Notes regarding sign convention:

a. All negative TCG measurements indicate port of centerline and positive TCG measurements indicate starboard of centerline.
b. All VCG and KG measurements are references from the keel.
c. All longitudinal measurements are referenced from the aft perpendicular (positive values indicate forward towards bow).

2. MSC Computer Model

2.1. Introduction

To assess the hydrostatics and stability of the GOLDEN RAY, a detailed 3-dimensional computer model of the vessel was created for use with MSC's analysis software GHS (General HydroStatics by Creative Systems, Inc.). All modeling and analyses were completed using GHS Version 16.00. This section describes the development of the MSC GHS computer model for use in subsequent stability analyses.

2.2. Development of the MSC Computer Model

An original computer hull model was developed using the table of offsets [2] as the primary basis for the hull shape. However, some detail was not reflected in the table of offsets at the bow and stern due to the selected station spacing. Additionally, the table of offsets did not provide enough coordinate density to accurately define the bilge radius throughout the midships. As the failure to properly define these hull intricacies has potential to affect the accuracy of the calculated hull areas and volumes in those areas, the General Arrangement [3], Aft End Construction [4], Fore End Construction [5] and Double Bottom Construction [6] drawings were used to supplement the table of offsets when modeling the hull shape.

Hull components were added to provide accurate definition and volumes for the rudder and propeller. Deductions in the hull volume were made to define the bow thruster tunnel and the inset in way of the stern ramp on the starboard aft end of the vessel, as these were not accounted for in the table of offsets. A shell plating thickness of 17 mm on the bottom and 15 mm on the sides was added to account for the average hull plating thickness calculated from the Midship Construction Drawing [7] and Shell Expansion Plans [8]. Coordinates indicating the location of the freeboard deck, which is necessary for analyzing intact stability, were added to the model at a height of 14,300 mm A/B, as indicated in the Damage Control Plan [9]. The A Deck, Navigation Bridge Deck and Compass Deck were added to the model to accurately define the projected lateral area of the vessel. Figure 2-1 shows the MSC GHS computer hull model with all hull refinements incorporated.

Once the hull was modeled, the internal tanks and major compartments were added using the dimensions and locations shown on the General Arrangement, Engine Room Construction [10], Double Bottom Construction, Double Bottom Construction in Engine Room [11], Aft End Construction, Fore End Construction, and Construction Profile & Deck Plan [12] drawings. Figure 2-2 shows the inboard profile and plan views of the MSC GHS computer model with tanks and major internal compartments.

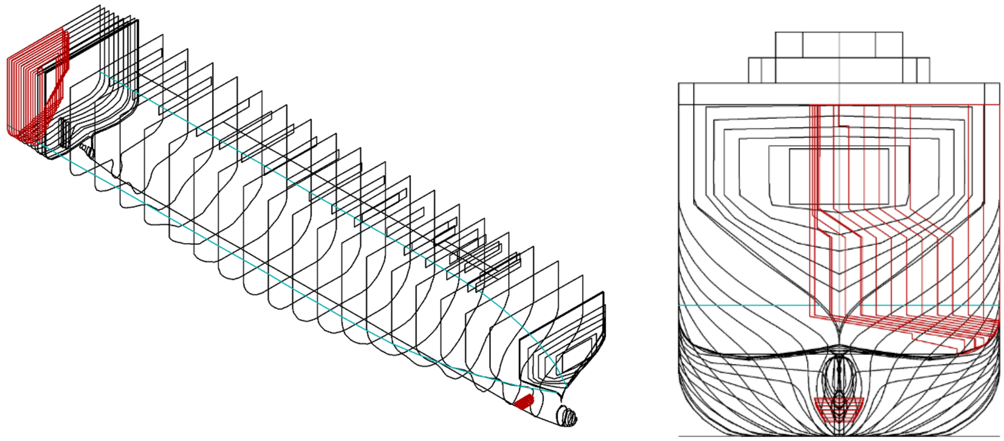

Figure 2-1: The MSC GHS computer hull model, including appendages, freeboard deck (light blue line), deductions for the thruster tunnel and stern ramp inset (red lines), and the top decks.

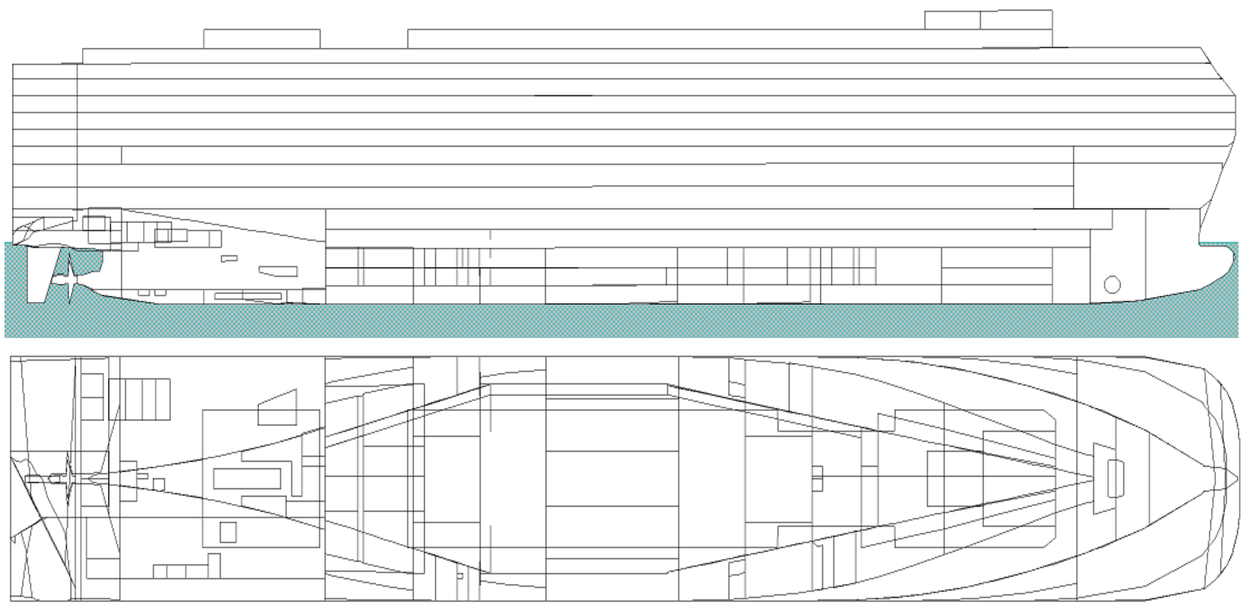

Figure 2-2: Inboard profile and plan views of the MSC GHS computer model showing tanks and compartments.

2.3. MSC Computer Model Comparison with T&S Booklet

A comparison of hydrostatic properties and tank parameters between the MSC computer model and the T&S Booklet [13] was completed. A full description of the results of this comparison is provided in Appendix A. Hull hydrostatic properties between the models aligned closely, with approximately 0.2% difference in calculated displacement at mean drafts between 9.3 m and the extreme Summer load draft of 10.618 m. Some minor discrepancies between tank properties were noted; however, these were considered to be generally inconsequential to results.

2.4. Lightship Weight and Center of Gravity

To perform hydrostatic and stability analyses, the ship's lightship weight (displacement) and location of the center of gravity must be determined and assigned to the model. The lightship weight and centers of gravity were calculated based on a stability test completed on the GOLDEN RAY on October 13, 2017 [14]. Table 2-1 provides a summary of the lightship condition determined for the GOLDEN RAY. These values were assigned to the MSC model for use with all subsequent stability analyses.

	Lightship Condition
Disp. (MT)	21433.0
LCG (m-AP)	85.89
TCG (m-CL)	-0.27
KG/VCG (m-BL)	18.29

Table 2-1: Lightship weight (displacement) and center of gravity approved for the GOLDEN RAY and applied to the MSC computer model.

2.5. Summary

This section provided an overview of the development of the MSC GHS computer model for hydrostatic and stability analyses. Comparisons of hydrostatics and tank properties between the MSC GHS computer model and the T&S Booklet were summarized, with details of this comparison presented in Appendix A.

The lightship displacement and center of gravity of the MSC computer model were assigned in accordance with approved values and used for all analyses in this report.

3. Loading Conditions

3.1. Introduction

This section details the information, methods, and assumptions used to simulate the capsize voyage loads that were applied to the MSC computer model. When available, actual liquid and cargo loading data from the capsize voyage was used. For loads in which no data was available, Sections 5.3 and 5.4 of the T&S Booklet, which detail acceptable benchmark loading conditions for the vessel, were referenced.

3.2. Liquid Loading

Of the 61 tanks listed in the vessel's T&S Booklet, 47 were fitted with automatic tank level indicators which were output through the vessel's Totem Plus IMACS (Integrated Monitoring, Alarm and Control System) software. This software permits real time tank monitoring and records the data in an onboard computer. The list of IMACS monitored tanks includes all ballast, fuel oil, diesel oil and gas oil tanks.

The vessel's IMACS software program files [16] and several years of data files [17] leading up to the capsize were provided to MSC for use in analyzing hydrostatics and stability. A close review of the tank levels during the capsize voyage was conducted. Although various small fluctuations were noted, the loads in the tanks appeared to remain generally constant throughout the voyage. To quantify this, a comparison of the tank load quantities recorded from the approximate departure timestamp (08/09/19 04:00:26 UTC (12:00:26 EDT)) [18] to the values recorded from the pre-capsize timestamp (08/09/19 05:27:51 UTC (01:27:51 EDT)) [19] was completed and is summarized in Table 3-1. The latter timestamp indicates the closest available data to the capsize in which the vessel was at approximately 0° heel. Although the IMACS software indicates that the tank quantities reported are corrected for trim, the values do not appear to be corrected for list, so selecting a timestamp with 0° heel was necessary. The net difference in total liquid weight between the two timestamps, which constitutes approximately 69 MT, is indicative of error associated with automatic tank monitoring. As the net 69 MT difference is less than 0.2% of the 35,000 MT displacement predicted for the capsize voyage, this was considered to be well within the acceptable range of accuracy.

	05:27:51 UTC Load (MT)	04:00:00 UTC Load (MT)	Difference (MT)	Difference %
Ballast	2981.45	2929.04	-52.41	-1.8%
Fuel	891.38	872.95	-18.43	-2.1%
Diesel	321.91	322.95	1.04	0.3%
Misc.	46.29	47.17	0.88	1.9%
Total	**4241.03**	**4172.11**	**-68.92**	-1.6%

Table 3-1: Comparison between tank weights from the vessel's IMACS data files at the 08/09/19 05:27:51 UTC (01:27:51 EDT) (pre-capsize) timestamp and the 08/09/19 04:00:26 UTC (12:00:26 EDT) (departure) timestamp. The loads at the pre-capsize timestamp were applied to the MSC computer model.

The tank quantities from the 08/09/19 05:27:51 UTC (pre-capsize) timestamp were used to assign the liquid loads within the 47 IMACS monitored tanks to the MSC computer model. This was done by inputting the weight of the liquid in each tank that is indicated in the IMACS data file into GHS. The resulting tank fill percentage based on the tank shapes modeled in Section 2 was then calculated using the GHS software, which permits calculation of the resultant free surface inertia of each tank. Applying the tank quantities to the MSC model based on weight eliminates total weight and volume errors associated with differences in tank modeling between the MSC model and the model used to generate the T&S Booklet. Although this method does not eliminate free surface inertia differences associated with tank modeling, the total difference in VCG rise as a result of the free surface inertia difference was determined to be negligible to stability analysis as described in Appendix A.

Some smaller tanks including the lube oil, cooling water, and fresh water tanks were not monitored by the vessel's IMACS software. As such, the loading values for these tanks were assumed to be consistent with the Departure Bunkering Condition detailed in Section 5.3.1 of the T&S Booklet. Table 3-2 shows the liquid load applied for these tanks, which accounted for 7.8% of the total liquid load applied to the model.

	Load Applied (MT)
L.O. Sludge TK (S)	0.0
S/T L.O Sludge TK (C)	0.0
F.O. Sludge TK (S)	0.0
Sewage Holding TK (P)	0.0
S/T Cooling Water TK (C)	30.2
No. 1 F.W. TK (S)	78.2
No. 2 F.W. TK (S)	156.4
M/E L.O. STOR. TK (P)	21.6
M/E. L.O. SET. TK (P)	0.0
G/E L.O. STOR TK (S)	9.7
G/E L.0. SET. TK (S)	0.0
NO. 1 CYL. Oil TK (S)	14.7
NO. 2 CYL. Oil TK (S)	22.0
M/E L.O. Sump TK (C)	26.8
Total	**359.6**

Table 3-2: Liquid loads applied to MSC computer model for small tanks not monitored by IMACS. Values were selected in accordance with the T&S Booklet departure benchmark loading conditions.

3.3. Cargo Loading

MSC was provided with a VIN list [20] itemizing all cargo onboard the vessel along with each item's corresponding intended destination. However, this document did not cite stowage locations or vehicle curb weights. MSC was also provided with the Brunswick Departure Stowage Plan [21], a document which depicts the locations of vehicle groups in defined cargo areas throughout the vessel. Each vehicle group is titled with the port of loading and departure, a rough description of the vehicle models contained therein, and an approximate total weight of the cargo in the group.

To assess the acceptability of the weight estimates in the Brunswick Departure Stowage Plan, a detailed review of the plan was conducted. First, the weight of each vehicle group cited on the plan was assessed to ensure that it was reasonable when considering the description of the vehicles it contained. Of the 76 total vehicle groups detailed on the plan, the weight estimates of all but one group were deemed reasonable. The weight estimate of vehicle group ‘5A’ on the forward end of Deck 5, however, was not: the stowage plan indicated that it contained 14 total vehicles (12 Ram 1500s and 2 Ram 2500s) with a total weight of 154.23 metric tons, as shown in Figure 3-1. With an average curb weight of 2.31 metric tons for the Ram 1500 and 3.09 metric tons for the Ram 2500, MSC calculated an estimated weight for this vehicle group of 33.9 metric tons, which is significantly less than the weight indicated on the stowage plan. As such, the MSC obtained value of 33.9 metric tons was used in lieu of the 154.23 metric tons cited in the Brunswick Departure Stowage Plan for all analysis. Using this lower weight raises the overall cargo VCG by approximately 0.13 m.

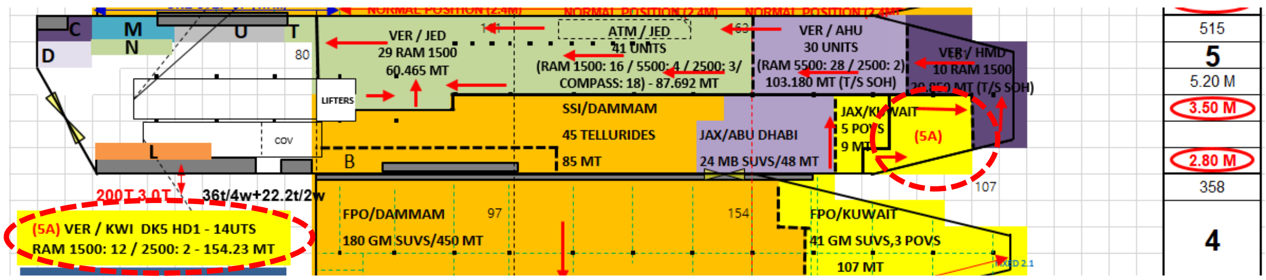

Figure 3-1: Section of Brunswick Departure Stowage Plan indicating vehicle group ‘5A’ (circled in red) contains 14 vehicles weighing 154.23 MT, which was considered unreasonable. A weight of 33.9 MT was applied to the MSC computer model instead.

Next, the sum of the weights of the vehicle groups on the Brunswick Departure Stowage Plan was compared to the estimated total weight of the vehicles on the VIN list. This comparison is summarized in Table 3-3. As the VIN list did not contain vehicle weights, manufacturer’s data was used to estimate the curb weight for each vehicle.

	Brunswick Dept. Stowage Plan	Brunswick VIN List	Difference	Difference %
Weight (MT)	8,780.15	8,981.10	200.95	2.2%

Table 3-3: Comparison between total weight on Brunswick Departure Stowage Plan and estimated total weight on Brunswick VIN list.

The Brunswick Departure Stowage Plan weight total, with the MSC modified weight in vehicle group (5A), was approximately 200 metric tons (2.2%) below the estimated weight total of the VIN list. However, this difference is relatively small in comparison to the predicted operating displacement of the vessel (approximately 35,000 MT) at the time of the incident. As such, the weights cited on the Brunswick Departure Stowage Plan, as modified by MSC, were applied to the MSC computer model.

In order to apply the weights of the vehicle groups in accordance with the locations detailed on the Brunswick Departure Stowage Plan, MSC superimposed the stowage plan onto the General Arrangement using Autodesk AutoCAD. The area centroid of each vehicle group was then calculated in AutoCAD and was assumed to represent the LCG and TCG of each vehicle group.

The VCG of each vehicle group was determined by adding the corresponding deck height to a standard, assumed vehicle VCG of 0.57 m above the deck, which is the assumed VCG indicated in Section 3.4.6 of the T&S Booklet for a standard vehicle. Although many of the vehicles onboard the vessel were SUVs, which are likely to have a higher VCG above the deck, the 0.57 m VCG was applied so that any subsequent failure of stability criteria could not be attributed to an error in using an assumed alternative value.

The weights of the vehicle groups were then applied to the MSC computer model in 76 individual point loads at the respective centers of gravity determined by MSC. These loads are summarized by deck in Table 3-4.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
Deck 13	745.60	98.24	0.14	36.82
Deck 12	805.44	102.95	0.72	34.51
Deck 11	951.00	91.03	1.07	32.00
Deck 10	1010.00	91.56	0.28	29.47
Deck 9	1020.00	92.71	-0.33	26.93
Deck 8	995.00	86.31	-0.15	24.41
Deck 7	620.25	96.81	-0.91	21.71
Deck 6 Raised	155.29	25.57	5.97	18.97
Deck 6 Standard	511.00	121.57	3.42	18.27
Deck 5	525.09	102.25	-1.30	14.87
Deck 4	557.00	99.81	0.02	11.82
Deck 3	515.00	99.12	0.00	9.02
Deck 2	174.34	97.63	-0.83	6.12
Deck 1	195.15	94.04	0.12	3.42
Total	**8780.2**	**95.39**	**0.32**	**24.34**

Table 3-4: Cargo weights applied to the MSC model from the Brunswick Departure Stowage Plan summarized by Deck. Deck 6 is subdivided into cargo situated on deck panels which were raised 0.7 m and cargo situated on deck panels which were at the standard height.

It is also important to note that Decks 2, 4, 5, 6, and 8 have the capability of being raised as desired depending on the height of the cargo beneath the deck. According to the Brunswick Departure Stowage Plan, Decks 2, 3, and 4 were at the standard (lowest) height. Three panels in the aft portion of Deck 6 were raised one step up (0.7 m); and, as such, the VCGs of the three corresponding vehicle groups were adjusted accordingly and are itemized according to height in Table 3-4.

Additionally, as the lightship VCG of the vessel is calculated with the vehicle decks at the standard (lowest) heights, it was necessary to account for the resultant rise in VCG from the weight of the raised steel panels. Page 95 of the T&S Booklet details weight moment calculations required for this calculation if the entire liftable portion of Deck 6 was raised. As only several panels on Deck 6 were raised above the standard height, MSC used a proportional weight moment calculation to obtain a rise in VCG of 0.006 m, which was added to the lightship VCG of 18.29 m cited in Section 2 of this report. The new VCG of 18.296 m was used for all further analyses.

3.4. Miscellaneous Deadweight

A review of the T&S Booklet benchmark loading conditions indicated that a number of other miscellaneous deadweight items were accounted for. This includes the weight of the fixed firefighting system's carbon dioxide, swimming pool water weight, provisions, stores, and cargo lashing equipment. These items were assumed to be onboard the vessel at the time of capsize and were therefore applied to the MSC computer model in accordance with the weights and corresponding centers of gravity listed for the Departure Condition detailed on page 266 of the T&S Booklet.

3.5. Final Loading Condition

A summary of the final loading condition applied to the MSC computer model is shown in Table 3-5.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
LTSH	21433.0	85.9	-0.27	18.3
Tanks	4600.8	102.6	1.94	3.9
Cargo	8780.2	95.4	0.32	24.3
Misc. Deadweight	230.4	74.4	-2.33	25.3
Total	**35044.4**	**90.4**	**0.16**	**18.2***

Table 3-5: Final loading condition applied to the MSC computer model.
*VCG includes a 0.215 m free surface correction.

3.6. Summary

This section documented loading conditions applied to the MSC computer model for hydrostatic and stability analyses. Liquid loading was based primarily on readings from the vessel's tank monitoring system data immediately prior to the capsize; however, T&S Booklet departure levels were assumed for small tanks which were not monitored by this system. Cargo loading was modeled based on the Brunswick Departure Stowage Plan. Miscellaneous deadweight items including stores and personal effects were applied to the MSC model based upon assumed departure values.

4. Results

4.1. Introduction

Through proper design, loading and operation, a ship should possess enough reserve buoyancy and stability to ensure that 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 and its contents. 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. A vessel's stability without damage is "intact stability," and is typically evaluated using the vessel's resultant righting arm curve.

This section provides a summary of the resultant hydrostatics and righting arm curve properties obtained for the vessel using the MSC computer model in the loading condition simulated for the capsize voyage. Results are then assessed for compliance with applicable stability requirements. Finally, the results of an assessment detailing the predicted change in the righting arm curve properties as the vessel turns are provided and discussed.

4.2. Loaded Hydrostatics

After the loads described in Section 3 were applied to the MSC computer model, the resultant hydrostatic properties were calculated using GHS.

4.2.1. List

The 0.16 m TCG calculated in Section 3 and applied to the MSC computer model resulted in a list of 4.6° to starboard. This is caused by asymmetric loading of port/starboard tank pairs: the No. 2 and No. 3 starboard ballast tanks were nearly fully loaded, however, the corresponding port tanks were loaded to less than 10% capacity. Additionally, the Brunswick Departure Stowage Plan indicated a starboard cargo TCG, further contributing to the vessel's modeled overall starboard TCG and resultant list. As the 4.6° starboard list calculated by MSC conflicts with the observed list conditions and the heel data reported by the IMACS computer immediately prior to departure, both of which indicated that the vessel left Brunswick without significant list, a further review was initiated to determine possible causes for this inconsistency.

As described in Section 3, the tank values used to load the MSC model were determined primarily from automated readings and were therefore considered unlikely to be the primary cause of the inconsistency between the MSC model list and observed/IMACS heel. Instead, it is likely that variations in the transverse locations of cargo between the Brunswick Departure Stowage Plan and the actual location of the cargo onboard the vessel resulted in the list in the MSC model. As such, the subsequent stability analysis was conducted by applying a zero heel condition to the vessel in accordance with observed and IMACS conditions. This was done by setting the heel of the vessel model equal to zero, allowing it to trim freely in order to remove residual longitudinal moments, and solving for the resultant TCG. This is equivalent to assigning the overall transverse center of the vessel loads such that the resultant heel is equal to

0°, while maintaining other bounded conditions such as tank free surface inertias, displacement, and longitudinal and vertical placement of loads.

4.2.2. Final Hydrostatic properties

The hydrostatic properties with the vessel at zero heel were calculated and are shown in Table 4-1.

	Disp. (MT)	LCB (m-AP)	VCB (m-BL)	LCF (m-AP)	MTC (m*MT/cm)	KMt (m-BL)	GM (m)	TPC (MT/cm)
Disp. (MT)	35044	90.39	5.35	78.06	621.94	19.97	1.76	56.10

Table 4-1: Final hydrostatic properties calculated from the MSC computer model for the vessel in the zero heel condition with the loading applied in Section 3.

4.2.3. Drafts

With the vessel at 0° heel, the resultant drafts calculated using the MSC computer model were compared to the drafts reported by the IMACS departure timestamp (08/09/19 04:00:26 UTC (12:00:26 EDT)), as shown in Table 4-2. The MSC computer model drafts obtained are shown for both salt water and brackish water conditions with a specific gravity of 1.02, which is representative of the water conditions when the vessel left Brunswick. Comparison of the loaded MSC model drafts with IMACS data immediately prior to departure was most appropriate, as the drafts reported by the IMACS while the vessel was underway did not appear consistent or reliable. This may have been due to errors associated with the automatic draft readings system and vessel movement through the water.

The mean draft of the MSC model in brackish water was within 0.03 m of the mean draft reported by the vessel's IMACS software at departure. The mean departure draft reading taken by the crew was 0.08 m higher than the MSC model mean draft in brackish water. However, it should be noted that observed draft readings are subject to the accuracy of the human eye and therefore subject to some error. Overall, because the MSC computer model draft readings aligned within 3% of the IMACS departure drafts, this indicates that a reasonably accurate total deadweight was applied to the MSC computer model.

	MSC Model Salt Water	MSC Model Brackish Water	IMACS Departure	Departure Draft Readings
Taft (m)	9.37	9.39	9.20	9.45
Tfwd (m)	9.26	9.31	9.56	9.40
Tmean (m)	9.32	9.35	9.38	9.43

Table 4-2: Comparison between loaded drafts calculated using the MSC computer model in salt and brackish water (S.G. = 1.02) with IMACS drafts at departure and departure draft readings taken by the vessel crew.

4.3. Intact Stability

Using the MSC computer model, an independent intact stability analysis was conducted, results of which are detailed and discussed in this section.

4.3.1. 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. Internal righting capacity arises from the ship's own weight and buoyant forces, providing a righting moment (see Figure 4-1). 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 4-2 shows a righting arm curve for a notional vessel. A plot of righting moments (righting moment curve) can also be created by simple multiplication of the righting arms with the ship's weight or 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. 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. Since the righting arm curve is simply a scaled version of the righting moment curve (scaled by the displacement or weight of the vessel), it is a principal tool in evaluating the ability of a ship to resist capsizing.

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 is commonly used as the primary means for assessing seaworthiness of all modern vessels.

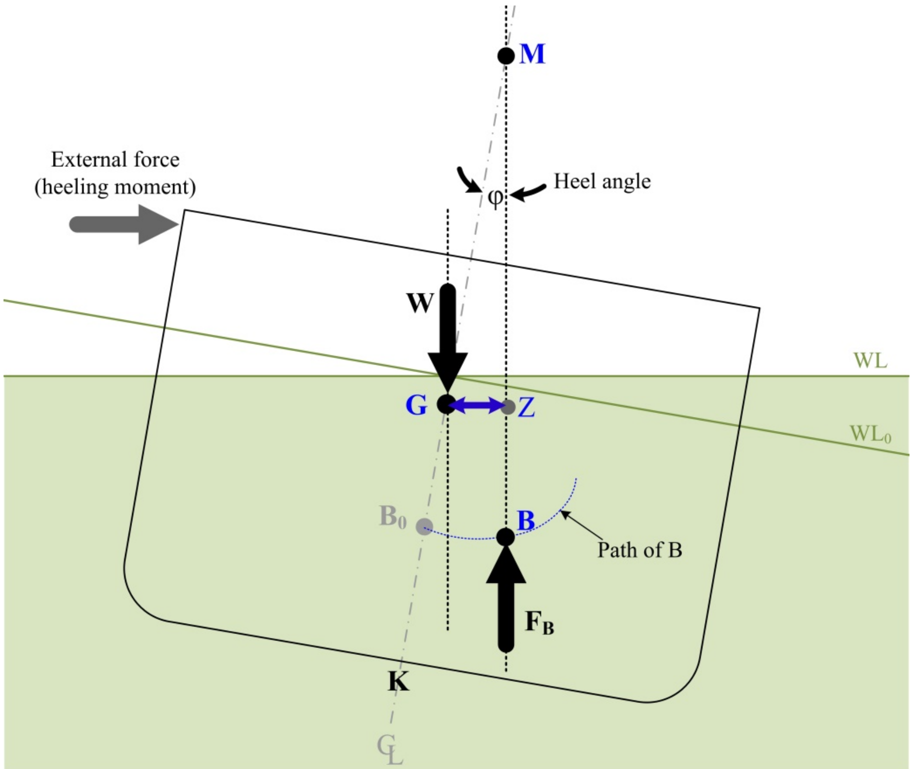

Figure 4-1: Development of righting arms (GZ) (righting moments) with vessel heel due to external forces.

Figure 4-1 includes annotation of an imaginary point through which the line of action of the buoyant forces 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 4-1 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 4-1:

$$GM = GZ/sin\varphi = GZ/\varphi \;\; for\ small\ \varphi \;\; (in\ radians) \qquad (4\text{-}1)$$

GM is therefore the initial slope of the righting arm curve. Noting that 1 radian is equal to 57.3°, GM is often annotated graphically on a righting arm curve as shown in Figure 4-2.

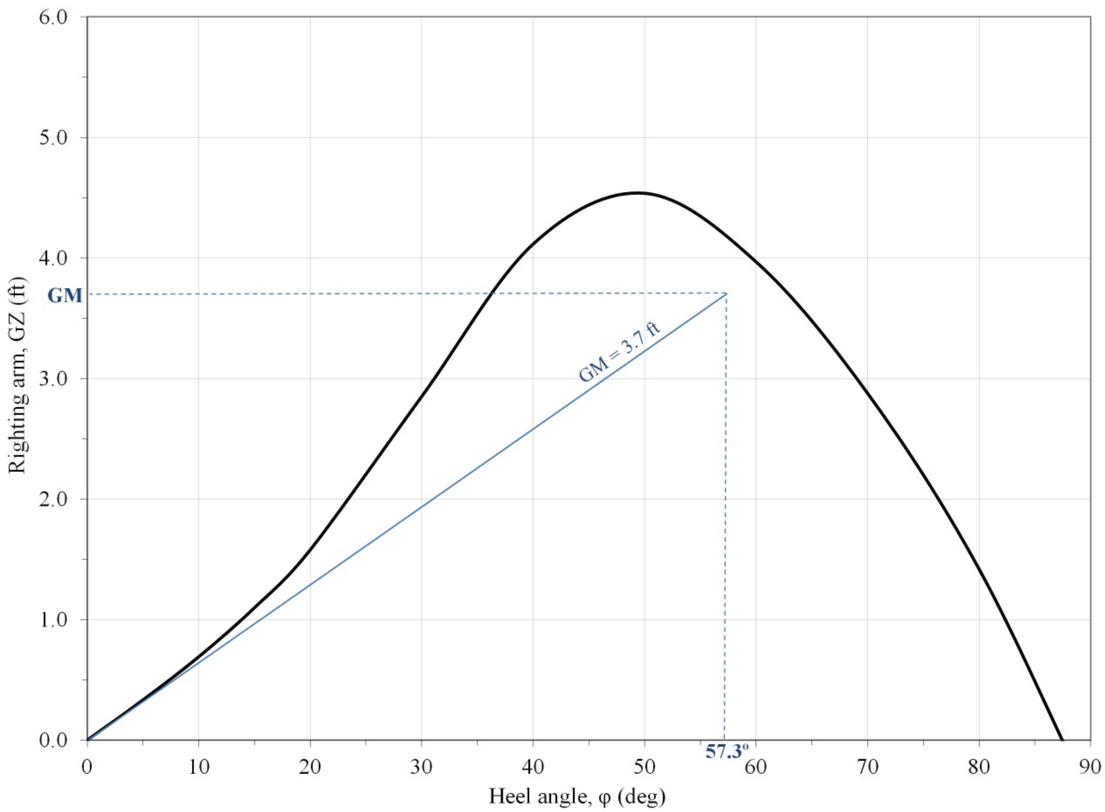

Figure 4-2: A righting arm curve for a notional vessel. GM is the initial slope of the righting arm curve.

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.

Current international intact stability standards are provided in the International Code on Intact Stability, 2008 (2008 IS Code) [22]. The 2008 IS Code includes two parts: "Mandatory Criteria" (Part A) and "Recommendations for Certain Types of Ships and Additional Guidelines" (Part B).

Part A of the 2008 IS Code presents minimum requirements to apply to cargo and passenger ships of 24 m in length and over, and includes two types of intact stability criteria:

(1) Criteria regarding righting arm (lever) curve properties (Section 2.2). The following righting arm criteria are specified:

   a. The area under the righting arm curve shall not be less than 0.055 m-radians up to an angle of heel of 30°, and not less than 0.09 m-radians up to an angle of heel of 40° or the angle of downflooding if less than 40°. Additionally the area under the righting arm curve between 30° and 40°, or between 30° and the angle of downflooding if less than 40°, shall not be less than 0.03 m-radians.

b. The righting arm shall be at least 0.2 m at an angle of heel equal to or greater than 30°.

c. The maximum righting arm shall occur at an angle of heel not less than 25°.

d. The initial metacentric height GM shall not be less than 0.15 m.

(2) Severe wind and rolling criteria (Section 2.3). 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" [23]. The criteria are based on an energy balance between beam wind heeling and righting moments, with roll motion also taken into account. The following righting arm criteria are specified, referring to Figure 4-3:

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_{w1}. The angle of heel under action of the steady wind φ_0 shall not exceed 16° 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°, the angle of downflooding, or the angle of second intercept φ_c.

The wind heeling arms (l_{w1} and l_{w2}), calculated in accordance with Section 2.3.2 of the 2008 IS Code, remain constant at all angles of heel.

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.

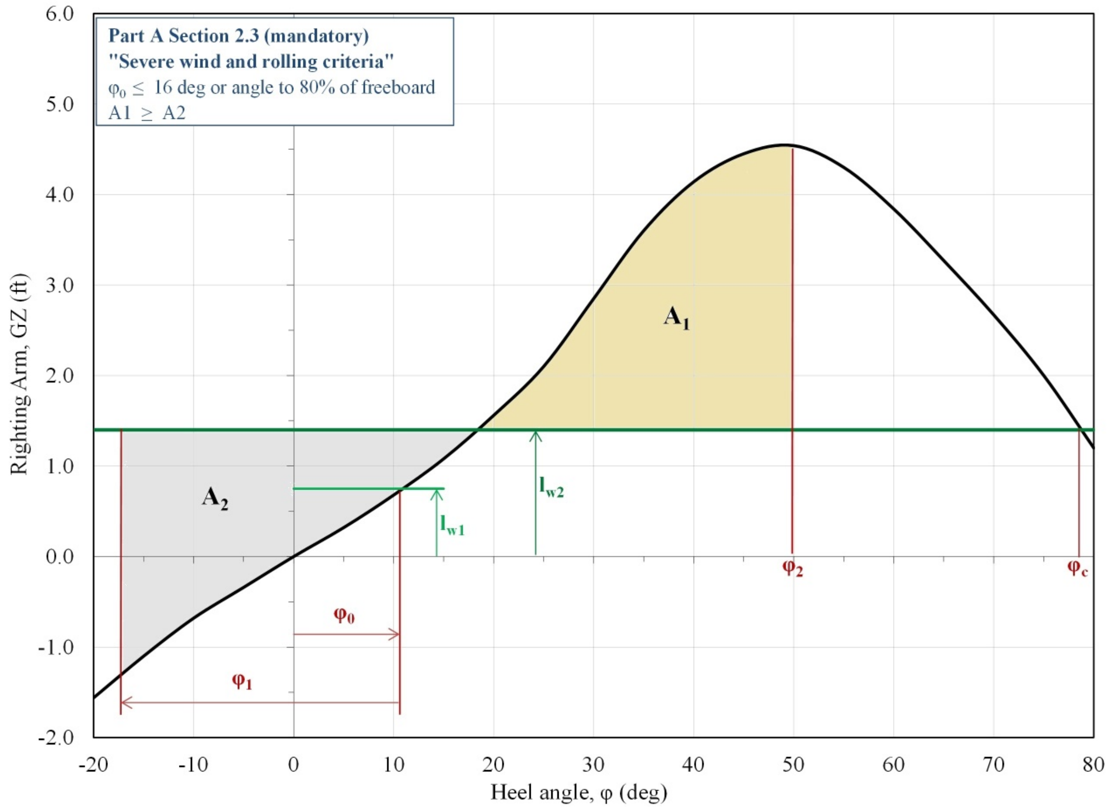

Figure 4-3: IMO severe wind and rolling criteria.

4.3.2. Capsize Voyage Righting Arm Curve Properties

With the MSC computer model loaded for the capsize voyage in accordance with Section 3, and with list set to 0°, righting arm curves were generated for heel to port and starboard. These righting arm curves are shown in Figure 4-4 by the solid green line (heel to starboard) and solid red line (heel to port). For comparison of righting arms with loading conditions which meet regulatory requirements, the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT are also shown (dotted lines).

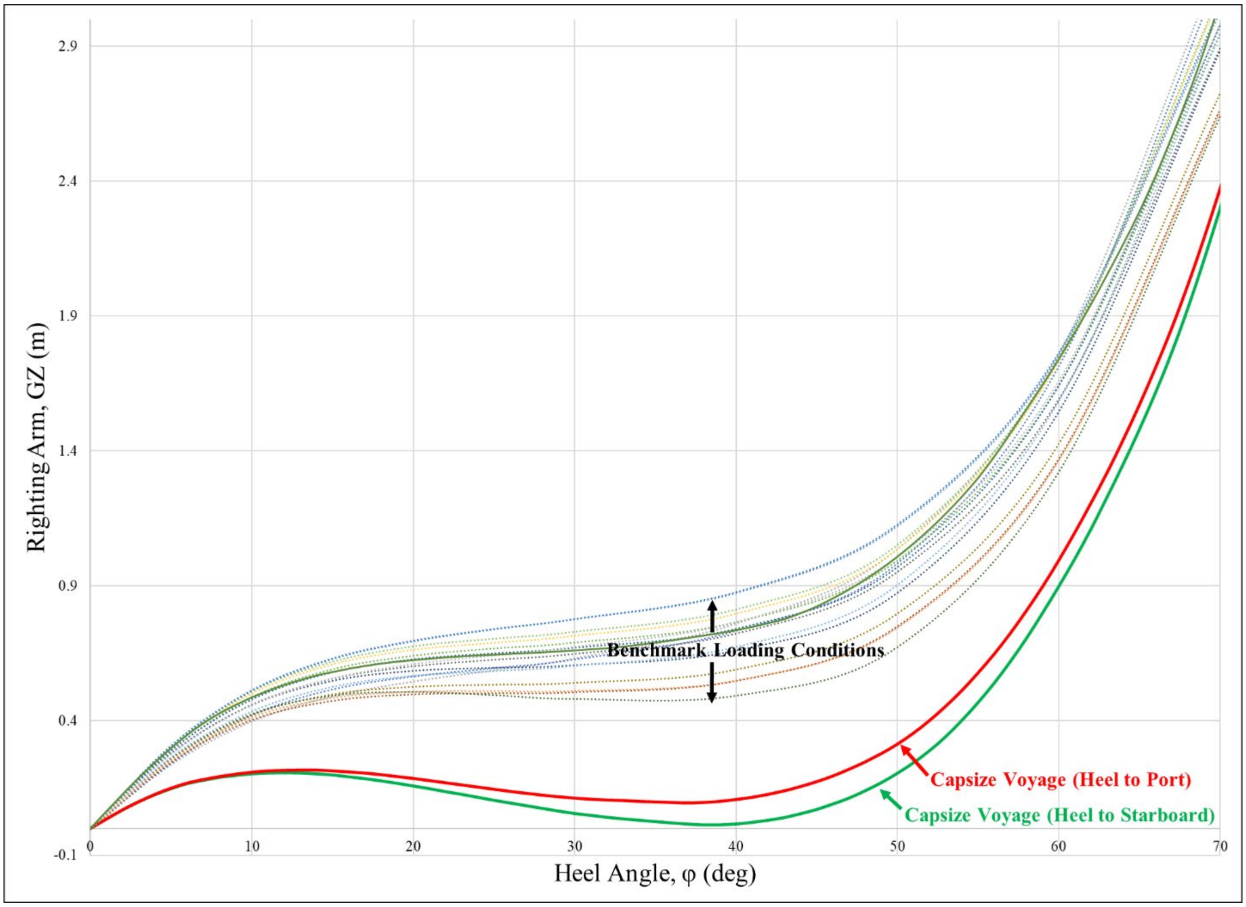

Figure 4-4: Righting arm curves generated for the vessel in the capsize voyage using the MSC Computer model for heel to starboard (solid green line) and heel to port (solid red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

Both righting arm curves produced for the capsize voyage had significantly lower righting arms and area under the righting arm curve than all benchmark conditions from the T&S Booklet. Due to the influence of the inset designed into the hull in way of the stern ramp, the MSC model starboard righting arm curve (green) produced slightly lower righting arm values than the corresponding port righting arm curve (red), particularly above 15° heel. A GM of 1.76 m was calculated from the righting arm curves from the capsize voyage condition.

For the righting arm curves shown in Figure 4-4, the 2008 IS Code mandatory intact stability criteria were applied, with results summarized in Table 4-3. Red background indicates that the attained value does not meet the specific criteria and green background indicates that the attained value meets the specific criteria. Of particular note is the limited area under the righting arm curve of the vessel in the MSC loaded condition between 30° and 40°. This caused failure of several of the IS Code general righting arm curve properties (Part A, Section 2.2). For the IS Code severe wind and rolling criteria (Part A, Section 2.3), the vessel failed to meet the area ratio criteria due to the limited area under the righting arm curve while in the capsize voyage loading condition.

	Units	MSC Loading Condition (Capsize Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties			
Area to 30 degrees	m-rad	0.075	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.079	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.005	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	3.980	At least 0.2 m
Angle of maximum righting arm	deg	80.3	At least 25 deg
Initial GM	m	1.76	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria			
Angle of static heel (φ_0)	deg	6.8	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	Greater than 1

Table 4-3: Results of the assessment of the MSC computer model loaded for the capsize voyage with the mandatory requirements of the 2008 IS Code. Green background indicates that the criteria has been met. Red background indicates that the criteria has not been met.

4.3.3. Stability During a Turn

4.3.3.1. Background

As a ship moves through a turn at velocity, it is subjected to various lateral forces as shown in Figure 4-5. A centrifugal force (red arrow) acts normal to the direction of the ship's forward velocity at the center of gravity of the ship. During a steady turn, there is an essentially equal and opposite force (black arrow) created by the water pressure at the vessel's center of lateral resistance (CLR), a point approximately halfway between the keel and the vessel's waterline. These forces create a heeling moment which acts to heel the vessel in the opposite direction of the turn as shown in Figure 4-5 and calculated below:

$$Turn\ Heel\ Moment = \frac{\Delta \cdot v^2}{g \cdot R}\left(KG - \frac{T}{2}\right)\cos\varphi \qquad (4\text{-}2)$$

As demonstrated in Equation 4-2, the turn heel moment increases as the vessel's forward velocity (v) and center of gravity (KG) increase, and as turn radius decreases.

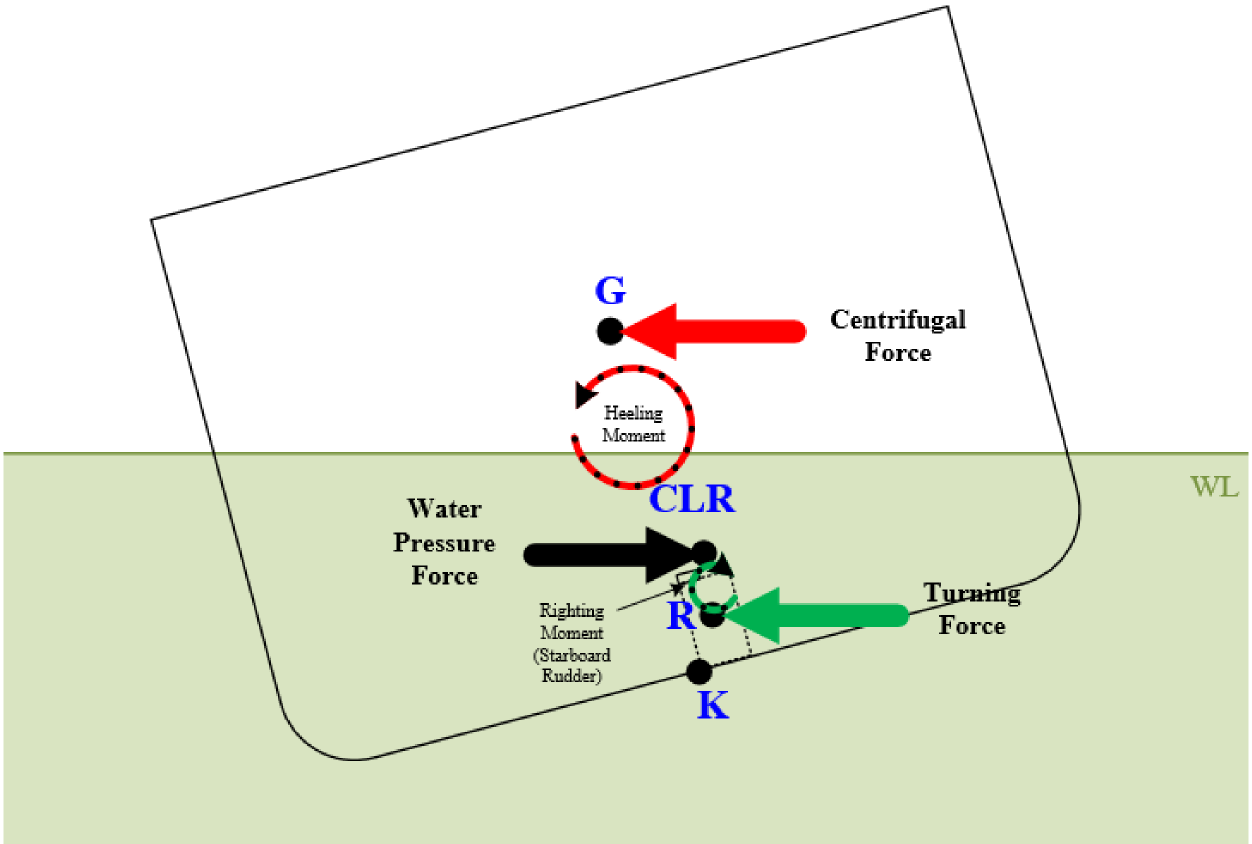

Figure 4-5: Lateral forces on a vessel engaged in a steady turn to starboard with the rudder angled to starboard.

During a turn, a separate moment is created by the turning force from the ship's rudder (green arrow), which is angled to starboard in Figure 4-5, and the water pressure force (black arrow). However, this moment acts opposite to the moment created by the centrifugal force and is typically of significantly less magnitude due to the smaller distance between the centroid of the rudder and the center of lateral resistance. As such, the moment created by the centrifugal force prevails over the moment created by the rudder's turning force. This causes the vessel to heel away from the direction of turn.

The net effect of the heeling moment experienced by a vessel while in a steady turn can be determined by subtracting the moment created by the rudder's turning force from the moment created by the centrifugal force. Dividing by the vessel's displacement results in the corresponding net heeling arms experienced by the vessel while in a turn. The net heeling arms can be subtracted from the vessel's righting arms to obtain a residual righting arm curve for the vessel during a turn, which is useful in assessing the remaining vessel stability. The point at which the residual righting arm curve intersects the x-axis represents the steady heel angle of the vessel during the turn.

As noted above, this analysis is based on the assumption that the vessel is in the steady phase of the turn. It is important to recognize that, just prior to the vessel entering this phase of the turn and settling at the steady heel angle, dynamic effects cause the vessel to heel even further away from the direction of the turn, sometimes by twice as much, as noted by Zubaly [24] and Crane [25]. This is referred to as dynamic overshoot.

As further noted by Zubaly, "If a helmsman were frightened that the ship might capsize when it overshoots its steady heeling angle and were to reduce the rudder angle or reverse the rudder at that point, the dangerous heel would be instantly increased because the opposing rudder force moment would be reduced or reversed."

4.3.3.2. Effect of Turn on Stability During Capsize Voyage (Rudder to Starboard)

The heeling arms during the turn leading up to the capsize were found for the GOLDEN RAY in the MSC loading condition, with the rudder assumed to be angled to starboard, as was necessary to initiate the turn. For these calculations, the radius of the turn was estimated to be between 500 m and 800 m using visual data obtained for the capsize voyage from the portable pilot unit [26], which displays the vessel's turning circle in real time. The portable pilot unit also indicated that the vessel was traveling at a speed of 13.2 knots over ground during the turn, and this speed was assumed for all calculations. The turning heeling arm values at each angle were then subtracted from the port (direction the vessel capsized) righting arm values obtained for the capsize voyage loading condition in Section 4.3.2. This yielded the residual righting arm curve for the vessel while in the turn leading up to the capsize. The residual righting arm curves are shown in Figure 4-6 for a turn radius of 500 m (dashed black line) and a turn radius of 800 m radius (dashed blue line). The righting arm curve obtained by MSC for the vessel in the capsize voyage not engaged in a turn (solid red line) and the righting arm curves from the benchmark conditions in the T&S Booklet with displacements between 32,000 MT and 38,000 MT are also plotted for comparison.

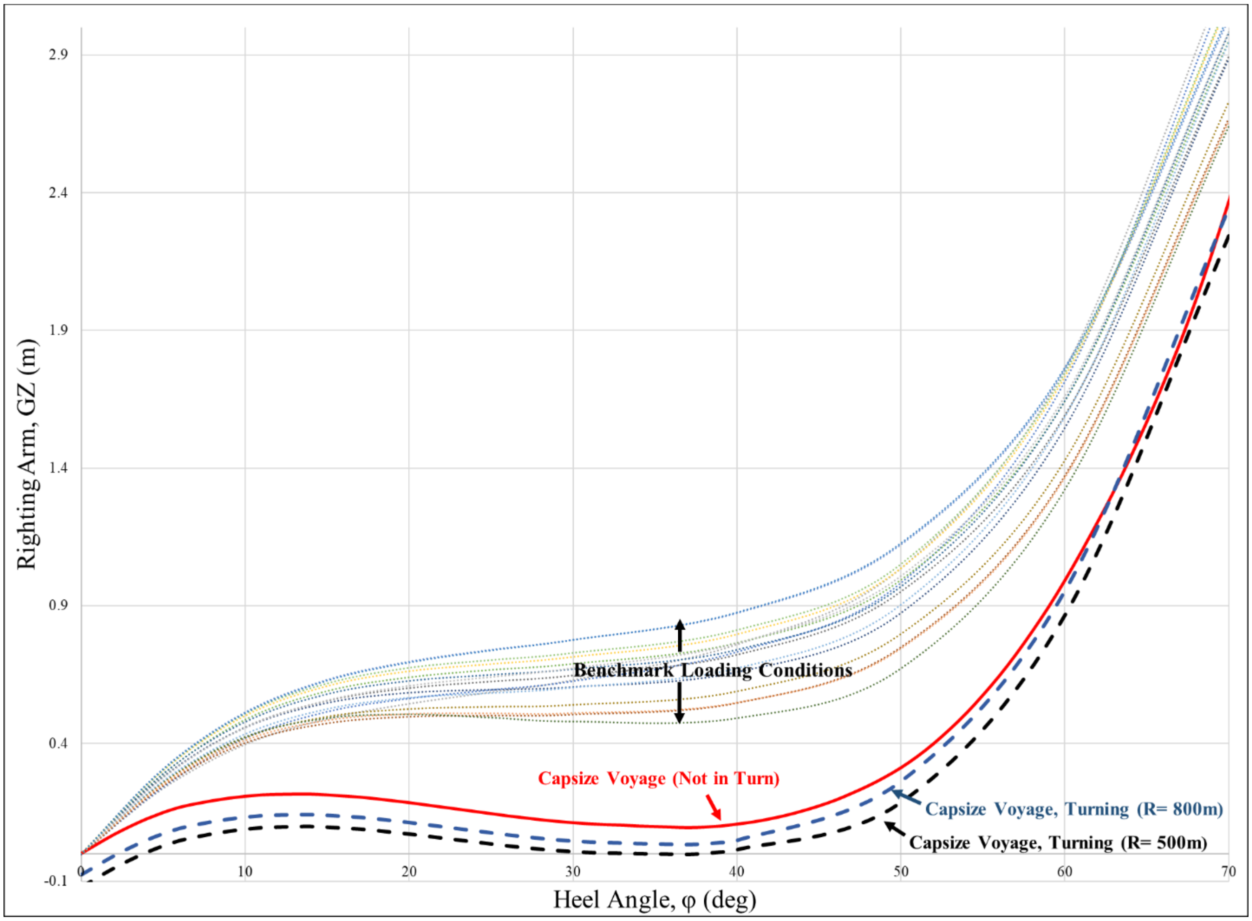

Figure 4-6: Residual righting arm curves for the vessel in the capsize voyage condition while engaged in a steady turn at a radius of 500 m (black dashed line) and 800 m (blue dashed line). Also shown for comparison are the righting arm curves for the vessel in the capsize voyage not engaged in a turn (solid red line) and the righting arm curves for the benchmark loading conditions in the T&S Booklet (dotted lines).

4.3.3.3. Effects of Turn on Righting Arm Curve (Rudder Amidships)

Audio from the portable pilot unit indicates that, while the ship was still in the turn to starboard, a rudder command of “rudder amidships,” followed by a rudder command of “port 10” was ordered. As detailed in Section 4.3.3.1, a rudder angled to amidships would eliminate the righting moment from the rudder and therefore further increase the overall turning heeling moment. Residual righting arm curves showing the effect of this principle for the vessel in the capsize voyage for a 500 m turn radius are shown in Figure 4-7. The solid grey line represents the righting arm curve with the rudder amidships.

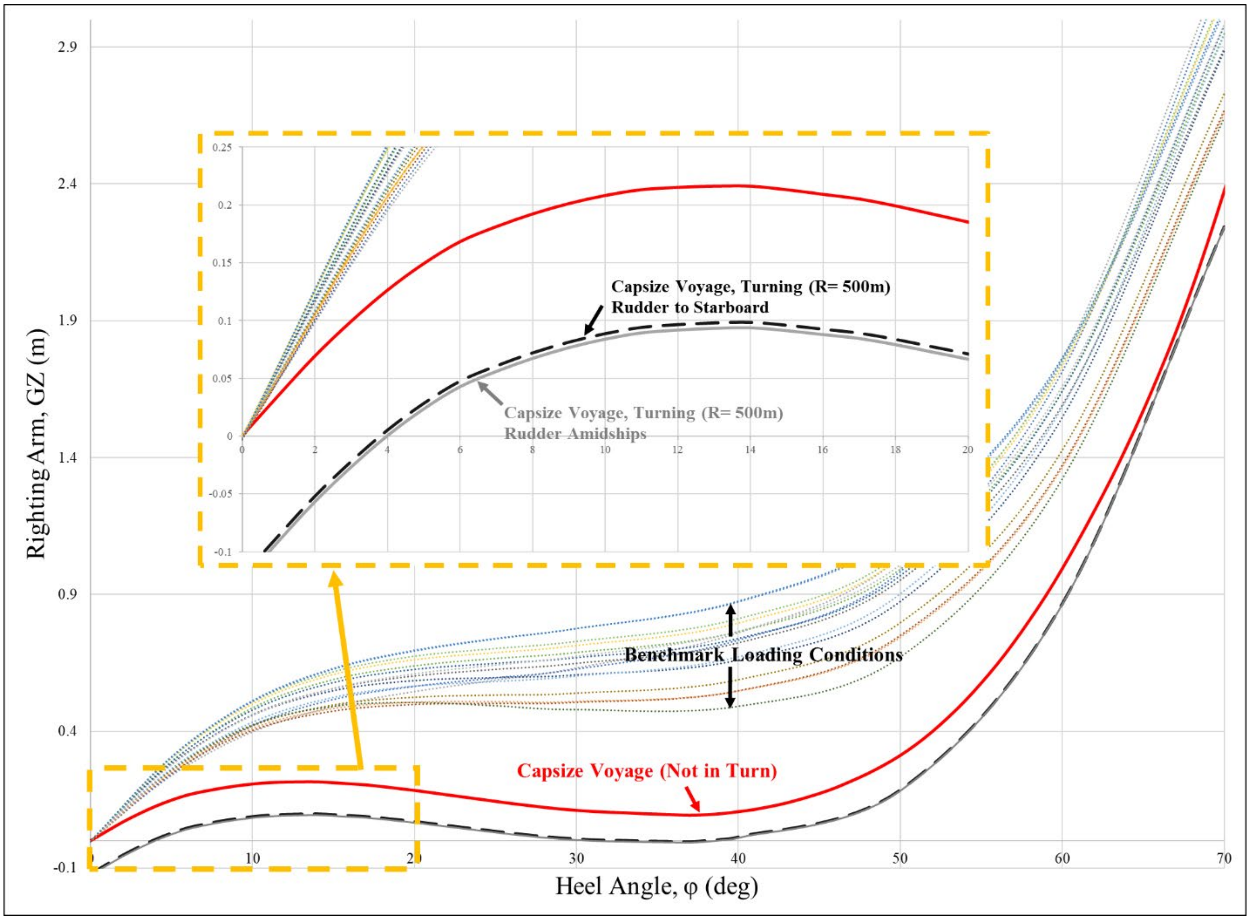

Figure 4-7: Residual righting arm curves for the vessel engaged in a steady turn at a radius of 500 m with the rudder to starboard (dashed black line), and rudder amidships (solid grey line). Also shown for comparison is the righting arm curve for the vessel not engaged in a turn (red line), and the righting arm curves from benchmark conditions in the T&S Booklet with displacements ranging from 32,000 MT to 38,000 MT.

Although the subsequent rudder command of "port 10," would have been expected to further increase the overall turning heeling moment because it would have created an additional capsizing moment from the rudder, the rudder may have no longer been effective at this point due to the heel of the vessel. Accordingly, little or no additional capsizing moment from the "port 10" command would have been created.

It is important to note that Figures 4-6 and 4-7 represent the righting arm curves for the vessel while in the steady turn phase. As noted in Section 4.3.3.1, dynamic effects experienced by the vessel prior to this phase of the turn are likely to have further reduced the righting arms and righting areas calculated in this section.

4.4. Downflooding Angle Analysis

4.4.1. Theory

A downflooding point is an opening in a vessel's hull or superstructure through which flooding into the vessel can take place if the opening becomes immersed. Examples of downflooding points typically include vents, discharges, non-watertight/weathertight doors and hatches, and other similar openings. Openings such as doors and hatches which can be closed watertight or weathertight are not typically considered downflooding points for the purposes of regulatory compliance because it is assumed that these openings are closed when the vessel is underway and brief immersion is not typically expected to lead to significant water ingress.

A downflooding angle is the lowest angle of vessel heel in which any downflooding point is immersed, as shown in Figure 4-8.

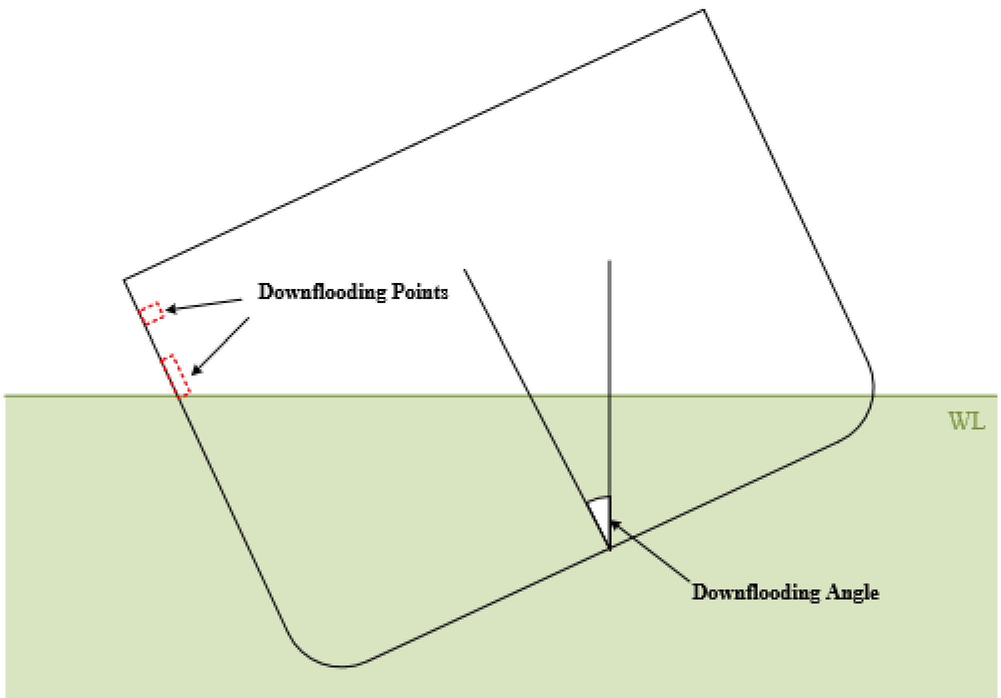

Figure 4-8: Illustration of downflooding points and the downflooding angle for a notional vessel.

The primary danger associated with immersion of downflooding points is progressive decrease in stability due to the addition of weight and free surface moment from seawater flooding into the hull or superstructure. Additionally, if an opening is large enough, there is an added reduction in righting arms and righting energy due to lost waterplane area (area occupied by the hull in a plane perpendicular to the water).

4.4.2. GOLDEN RAY Downflooding Angle

The vessel's T&S Booklet defines a single downflooding point for the GOLDEN RAY: a door on Deck 13 at Fr. -5. The corresponding downflooding angle of the vessel is approximately 83° with the vessel at a mean draft of 9.3 m. Although the GOLDEN RAY has other openings in the side of the hull below the door on Deck 13, they are not required by the IS Code to be considered downflooding points because they can be closed watertight or weathertight. The Pilot Door on Deck 5, Fr. 73, Port, which was reported by the IMACS data to have remained open during the capsize, is one such opening.

4.4.3. Revised Downflooding Angle with Pilot Door Open

An analysis using the MSC computer model was conducted to determine the revised downflooding angle with the Pilot Door on Deck 5, Fr. 73, Port open. Results indicate that, with the vessel in the capsize voyage loading condition, the downflooding angle is reduced to approximately 17° when heeled to port. As the Pilot Door constitutes a large opening, heel during the capsize beyond this downflooding angle would likely have resulted in immediate flooding on Deck 5 and, subsequently, a reduction in righting arms and righting energy at angles of approximately 17° and above.

4.5. Summary

This section introduced fundamental intact stability concepts as related to righting arm curves, followed by the results of MSC's intact stability analysis for the vessel in the capsize voyage loading condition. The moments acting on a vessel during a steady turn were then introduced, followed by the results of MSC's calculation of righting arms due to the effects of the turn prior to the capsize. Finally, an analysis of the GOLDEN RAY's downflooding angle with the pilot door open was presented.

5. Comparison with Trim & Stability Book

5.1. Introduction

A vessel's T&S Booklet is designed to provide stability information to the ship's master to ensure that the vessel has adequate stability prior to departure and throughout each voyage. This section provides an exploration into the basic stability information which could have been ascertained from the T&S Booklet based on the vessel's drafts, liquid loads, and cargo prior to departure from Brunswick for the capsize voyage. Comparison is made between the stability information contained in the T&S Booklet and the vessel's loading condition and MSC calculated stability parameters.

5.2. Minimum Allowable GM Tables

Section 4.7 of the vessel's T&S Booklet contains the minimum allowable GM and maximum allowable KG tables, which are designed to be used by the vessel's master and crew to quickly assess compliance with stability requirements at various levels of draft and trim. The minimum allowable GM and maximum allowable KG required can be ascertained from the tables and compared with the GM and KG calculated using the vessel's loading computer. If the GM and KG values calculated do not meet the required thresholds contained within the tables, then the vessel is not in compliance with the stability requirements of the T&S Booklet and therefore not in compliance with the mandatory requirements of the 2008 IS Code.

MSC utilized the data from the tables in Section 4.7 of the T&S Booklet to obtain the minimum required GM and maximum allowable KG which corresponded to the drafts recorded by the vessel's crew prior to departure: 9.45 m aft and 9.40 m forward. Because T&S Booklet tables are provided with drafts in 0.2 m increments and trim in 1.0 m increments, linear interpolation was necessary to find the corresponding regulatory minimum GM and KG values at the mean draft of 9.425 m and trim of 0.05 m by the stern.

As described in Section 4.3.2, MSC's computer model was used to calculate the predicted GM and KG in the capsize voyage condition. A comparison of the required values with the predicted values calculated using the MSC computer model is shown in Table 5-1 for GM and Table 5-2 for KG. The MSC calculated GM was approximately 31% below the T&S Booklet requirement and the MSC calculated KG was approximately 3.8% higher than the T&S Booklet requirement (both failing).

T&S Min. GM (m)	MSC Calc. GM (m)	Difference (m)
2.54	1.76	0.78

Table 5-1: Comparison of MSC calculated GM for the capsize voyage with the minimum GM required by the T&S Booklet corresponding to the drafts obtained by the ship's crew.

T&S Max. KG (m-AB)	MSC Calc. KG (m-AB)	Difference (m)
17.53	18.20	0.67

Table 5-2: Comparison of MSC calculated KG for the capsize voyage with the maximum KG permitted by the T&S Booklet corresponding to the drafts obtained by the ship's crew.

MSC also used the tables in Section 4.7 of the T&S Booklet to determine maximum GM and minimum KG required using the drafts recorded by the IMACS computer at the departure timestamp (08/09/19 04:00:26 UTC): 9.2 m aft and 9.56 m forward. The resultant values are compared with the predicted MSC calculated values for the capsize voyage in Tables 5-3 and 5-4. The MSC calculated GM was approximately 27% below the T&S Booklet requirement and the MSC calculated KG was approximately 3.9% higher than the T&S Booklet requirement (both failing).

T&S Min. GM (m)	MSC Calc. GM (m)	Difference (m)
2.42	1.76	0.66

Table 5-3: Comparison of MSC calculated GM for the capsize voyage with the minimum GM required by the T&S booklet corresponding to the drafts recorded by the IMACS at the departure timestamp.

T&S Max KG (m-AB)	MSC Calc. KG (m-AB)	Difference (m)
17.52	18.20	0.68

Table 5-4: Comparison of MSC calculated KG for the capsize voyage with the maximum KG required by the T&S booklet corresponding to the drafts recorded by the IMACS at the departure timestamp.

5.3. Benchmark Loading Conditions

Sections 5.3 and 5.4 of the T&S Booklet detail 34 benchmark loading conditions which have been demonstrated to result in adequate vessel stability. Though it is not mandatory that the vessel be loaded strictly in accordance with one of these conditions, because they result in compliance with the 2008 IS Code, they can be used for planning and comparison to the actual/proposed vessel loading condition. The vessel loading information for the capsize voyage was assessed against 2 benchmark conditions which had similar cargo VCGs, 2 benchmark conditions which had similar total liquid loads, and 2 benchmark conditions which had a higher cargo weight.

5.3.1. Benchmark Conditions with Similar Cargo VCG

Table 5-5 provides a comparison between the capsize voyage loading condition and T&S Booklet conditions 17 and 18. All three loading conditions had nearly identical cargo VCGs and similar displacements; however, T&S Booklet conditions 17 and 18 were loaded with over 40% more liquid load than the capsize voyage condition, and approximately 12% less cargo weight. This is important because, as the center of the vessel's liquid load is close to the keel and the center of the cargo is well above the keel, a higher quantity of liquid load onboard and a lower quantity of cargo onboard would lower the overall VCG of the vessel and result in a more favorable righting arm curve.

T&S Condition 17 represents a benchmark departure loading condition and, as such, a high proportion of the total liquid load consists of bunkers (fuel, diesel, gas, etc.). Condition 18 represents a benchmark arrival loading condition which assumes that, as fuel is consumed, ballast is taken on to prevent a rise in the vessel's VCG. The capsize voyage condition had a similar quantity of bunkers to that in T&S condition 18, however, it had nearly 2,500 MT less ballast.

	Ballast (MT)	Bunkers (MT)	Total Liquid (MT)	Cargo Weight (MT)	Cargo VCG (m)	Vessel VCG (m)	Total Disp. (MT)
MSC Capsize Voyage	2981	1619	4601	8780	24.3	18.2	35044
T&S Condition 17	2766	4233	7000	7742	24.2	17.1	36175
T&S Condition 18	5463	1066	6529	7742	24.2	17.0	35704

Table 5-5: Comparison of benchmark loading conditions in the T&S Booklet which had similar cargo VCGs to the cargo VCG of the vessel in the capsize voyage condition. Both benchmark conditions indicate over 40% more total liquid load than the vessel had onboard during the capsize voyage.

5.3.2. Benchmark Conditions with Similar Total Liquid Load

Table 5-6 provides a comparison between the vessel's capsize voyage loading condition with T&S Booklet conditions 13 and 14. All three conditions have a similar quantity of total liquid load. However, conditions 13 and 14, have a cargo VCG that is approximately 20% lower than the cargo VCG of the vessel in the capsize voyage condition. This is because T&S conditions 13 and 14 did not have cargo loaded on decks 11, 12 or 13. As indicated in the Brunswick Departure Stowage Plan, the vessel had approximately 2,500 MT loaded on these decks during the capsize voyage. In addition to a higher cargo VCG, the capsize voyage loading condition had approximately 1,500 MT more cargo weight than that of T&S Booklet conditions 13 and 14, further contributing to an increase in overall vessel VCG and adverse effects on vessel stability.

	Ballast (MT)	Bunkers (MT)	Total Liquid (MT)	Cargo Weight (MT)	Cargo VCG (m)	Vessel VCG (m)	Total Disp. (MT)
MSC Capsize Voyage	2981.45	1619.2	4601	8780	24.3	18.2	35044
T&S Condition 13	320	4233	4553	7267	19.4	17.0	33253
T&S Condition 14	3117	1066.2	4183.2	7267	19.4	16.8	32884

Table 5-6: Comparison of benchmark loading conditions in the T&S Booklet which had similar quantities of total liquid loads to the vessel in the capsize voyage condition. The T&S Booklet conditions indicated an approximately 20% lower cargo VCG.

5.3.3. Benchmark Conditions with Higher Cargo Weight

The T&S Booklet also details several benchmark conditions which have higher cargo weights than that of the capsize voyage. Table 5-7 provides a comparison between the capsize voyage loading condition and conditions 19 and 20. Conditions 19 and 20 have approximately 900 MT more cargo weight than the capsize voyage loading condition (at a similar VCG), but both conditions indicate over 2,900 MT more liquid load required to comply with stability requirements. Consequently, conditions 19 and 20 have higher displacements and drafts.

	Ballast (MT)	Bunkers (MT)	Total Liquid (MT)	Cargo Weight (MT)	Cargo VCG (m)	Total VCG (m)	Total Disp. (MT)
MSC Capsize Voyage	2981	1619	4601	8780	24.3	18.2	35044
T&S Condition 19	3282	4233	7515	9670	24.2	17.2	38619
T&S Condition 20	6601	1066	7667	9670	24.2	16.9	38771

Table 5-7: Comparison of benchmark loading conditions in the T&S Booklet which had higher cargo weights than the vessel in the capsize voyage condition. Conditions 19 and 20 have approximately 900 MT more cargo weight, but have over 2,900 MT more liquid load.

5.4. Summary

This section provided a comparison between the GM and KG required by the T&S Booklet based upon observed and IMACS recorded drafts. The MSC calculated GM and KG did not meet the required thresholds.

Additionally, comparison was made between similar benchmark loading conditions in the T&S Booklet and the loading condition the vessel was in during the capsize voyage. This comparison indicated that the vessel loading during the capsize voyage was not consistent with similar benchmark loading conditions in the T&S Booklet. For conditions with similar cargo VCGs to the capsize voyage loading condition, the comparable benchmark conditions had significantly more liquid load onboard. For conditions with similar total liquid loads, the comparable benchmark conditions had significantly lower cargo VCGs.

6. Stability Comparison to Previous Voyages

6.1. Introduction

This section details the loading conditions applied to the MSC computer model to simulate the two voyages preceding the capsize voyage: Jacksonville, FL to Brunswick, GA (September 7, 2019) and Freeport, TX to Jacksonville, FL (August 30 to September 6, 2019). Resulting righting arm curves are then compared with the righting arm curves generated for the capsize voyage.

6.2. Jacksonville to Brunswick Voyage

An intact stability analysis was conducted for the Jacksonville to Brunswick voyage (voyage prior to the capsize voyage) as detailed in Appendix B.

6.3. Freeport to Jacksonville Voyage

An intact stability analysis was conducted for the Freeport to Jacksonville voyage (two voyages prior to the capsize voyage) as detailed in Appendix C. The loading condition applied for this voyage represents the tank loads present following ballast discharge operations on September 3, 2019.

6.4. Comparison of Righting Arm Curves

Figure 6-1 presents a comparison between the starboard righting arm curves for the vessel while loaded for the Jacksonville to Brunswick, Freeport to Jacksonville, and capsize voyage. Table 6-1 demonstrates a comparison of the vessel's compliance with the mandatory provisions of the 2008 IS Code as evaluated using the MSC computer model. Red background indicates that the attained value does not meet the specific criteria and green background indicates that the attained value meets the specific criteria. Results indicate that, although the vessel was predicted to have had more righting energy in both of the preceding voyages than the vessel had during the capsize voyage, the vessel lacked the righting energy required to comply with the mandatory provisions of the 2008 IS Code during all three voyages.

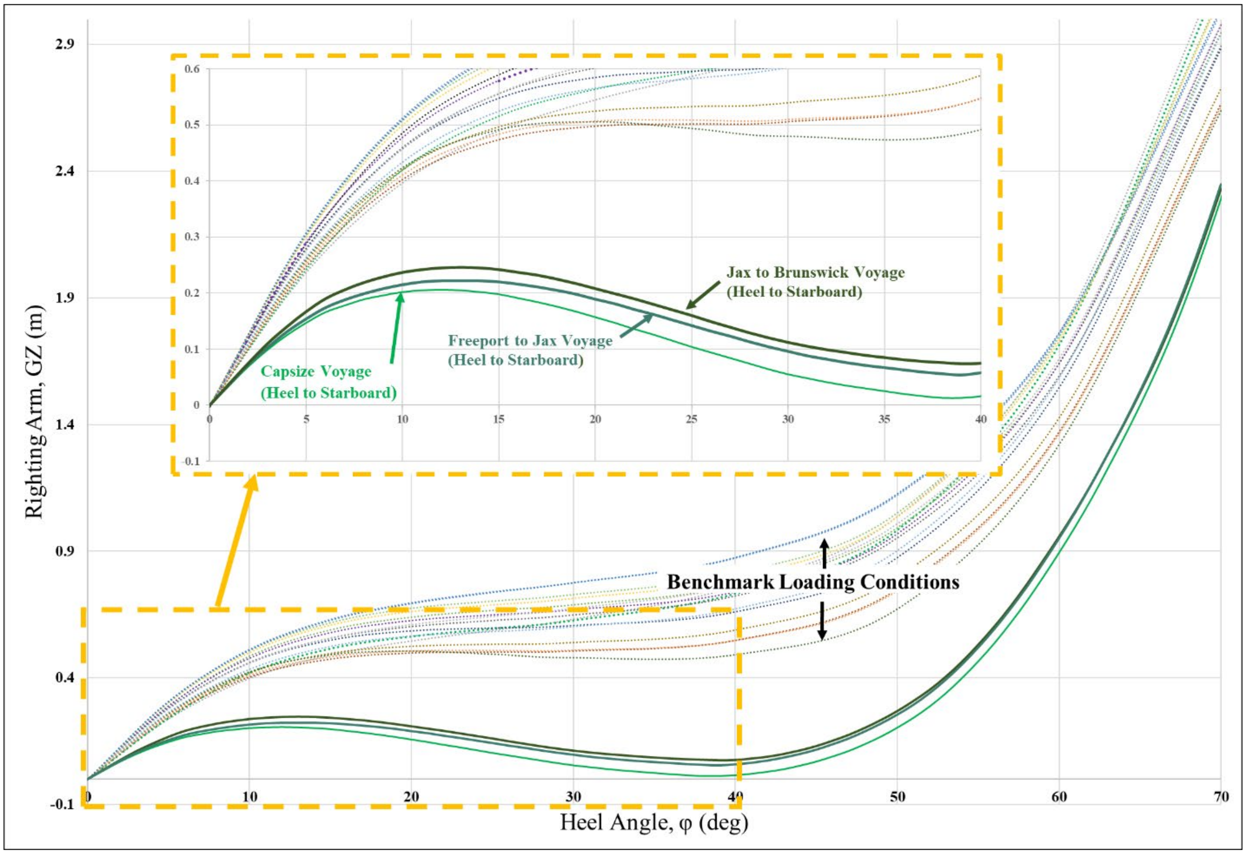

Figure 6-1: Comparison between starboard righting arm curves for the capsize voyage, Freeport to Jacksonville Voyage, and Jacksonville to Brunswick Voyage. Also shown for comparison are the righting arm curves from benchmark conditions in the T&S Booklet with displacements ranging from 32,000 MT to 38,000 MT.

	Units	MSC Loading Condition (Capsize Voyage)	MSC Loading Condition (Jacksonville Voyage)	MSC Loading Condition (Freeport Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties					
Area to 30 degrees	m-rad	0.075	0.095	0.084	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.079	0.110	0.095	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.005	0.015	0.011	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	3.980	4.028	4.056	At least 0.2 m
Angle of maximum righting arm	deg	80.3	80.2	80.4	At least 25 deg
Initial GM	m	1.76	1.91	1.84	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria					
Angle of static heel (φ_0)	deg	6.8	5.5	6.2	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	0 (No Area A1)	0 (No Area A1)	Greater than 1

Table 6-1: Comparison of 2008 IS Code compliance for each voyage. Red background indicates that the attained value does not meet the specific criteria and green background indicates that the attained value meets the specific criteria.

6.5. Stability with Additional Ballast

A review of the vessel's IMACs tank loading data during the Freeport to Jacksonville voyage indicates that the vessel discharged a total of 1492 MT of ballast from 4 large tanks (No. 5 Port D.B., No. 5 Starboard D.B., No. 5 Centerline D.B., and No. 6 Centerline) on September 3, 2019 beginning at approximately 17:00 UTC (13:00 EDT).

An analysis was conducted to determine the theoretical hydrostatics characteristics and vessel stability had the vessel not discharged the ballast from these tanks and had instead maintained that quantity of ballast water in the aforementioned tanks throughout the remainder of the Freeport to Jacksonville voyage and subsequent voyages (Jacksonville to Brunswick, and Capsize Voyage).

Resulting drafts for these theoretical loading conditions are shown in Table 6-2 for salt water conditions. Resulting starboard righting arm curves for each theoretical loading condition (dashed green lines) are shown in Figure 6-2. For comparison, the righting arms curves for the vessel in the actual representative loading conditions for each voyage are also shown (solid green lines).

	MSC Loading Condition (Capsize Voyage) Additional Ballast	MSC Loading Condition (Jacksonville Voyage) Additional Ballast	MSC Loading Condition (Freeport Voyage) Additional Ballast
Taft (m)	9.55	9.64	9.54
Tfwd (m)	9.62	9.31	9.57
Tmean (m)	9.59	9.48	9.55

Table 6-2: Theoretical drafts in salt water during each voyage, had the vessel maintained the additional 1492 MT of ballast that was discharged on September 3, 2019.

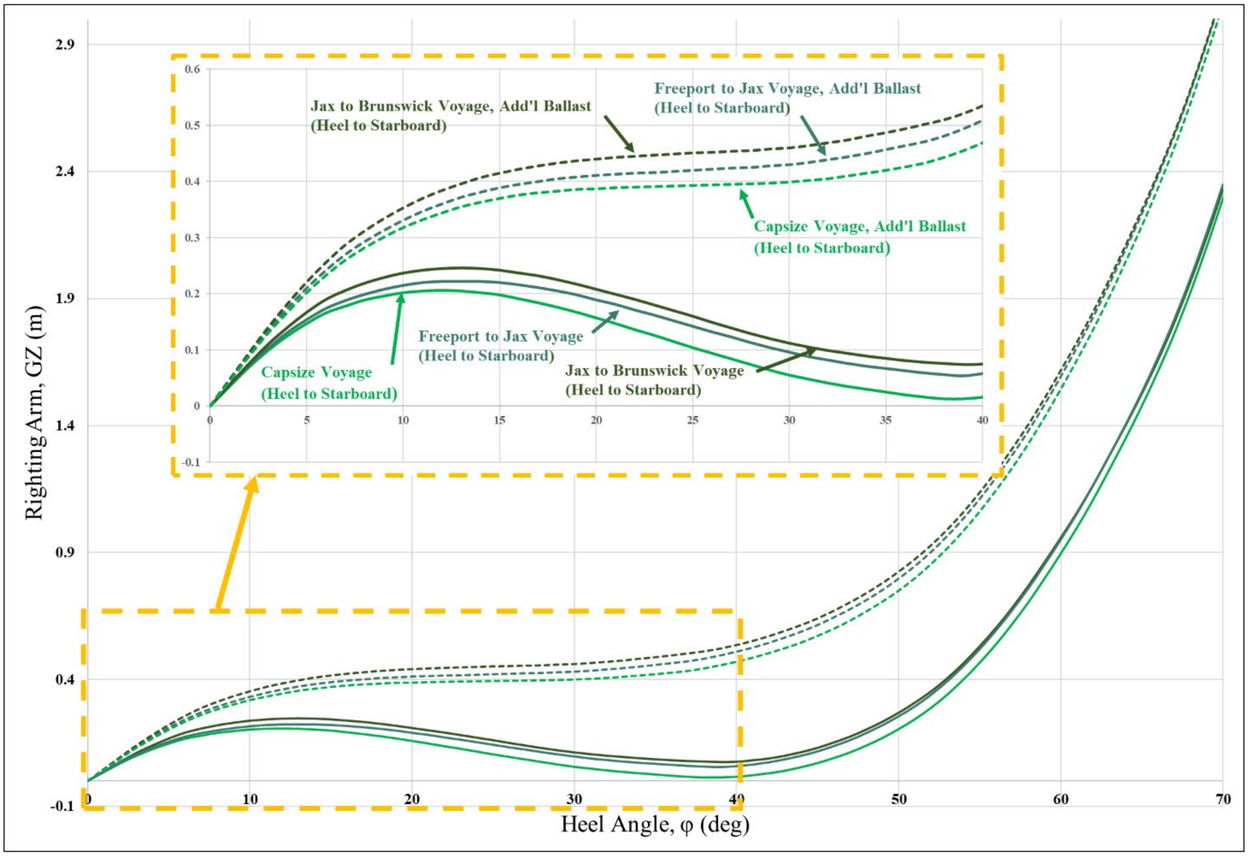

Figure 6-2: Theoretical starboard righting arm curves (dashed green lines) for each voyage with additional 1492 MT of ballast, had it not been discharged. For comparison, the righting arms curves for the vessel in the actual representative loading condition are shown for each voyage (solid green lines).

Table 6-3 shows the vessel's theoretical compliance with the 2008 IS Code during each voyage, had the vessel maintained the additional 1492 MT of ballast. Results indicate that the vessel would have been able to fully comply with the mandatory provisions of the 2008 IS Code. The GM for those voyages ranged from 2.25 m to 2.47 m.

	Units	MSC Loading Condition (Capsize Voyage) Additional Ballast	MSC Loading Condition (Jacksonville Voyage) Additional Ballast	MSC Loading Condition (Freeport Voyage) Additional Ballast	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties					
Area to 30 degrees	m-rad	0.149	0.186	0.174	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.211	0.271	0.254	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.063	0.086	0.080	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	4.439	4.625	4.636	At least 0.2 m
Angle of maximum righting arm	deg	79.4	79.2	79.5	At least 25 deg
Initial GM	m	2.25	2.47	2.40	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria					
Angle of static heel (φ_0)	deg	4.0	3.7	3.9	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	1.77	2.13	2.01	Greater than 1

Table 6-3: Theoretical compliance with the 2008 IS Code during each voyage had the vessel maintained the additional 1492 MT of ballast that was discharged on September 3, 2019. The GM for those voyages ranged from 2.25 m to 2.47 m.

7. Conclusions

The following provides a summary of key MSC observations and conclusions, listed by topic area:

(1) MSC computer model:

a. MSC independently generated a computer model using GHS software. Resultant hydrostatics were generally consistent with the vessel's T&S Booklet.

b. The liquid loads in major tanks onboard the vessel were applied to the MSC computer model in accordance with recorded data from the IMACS computer prior to the capsize. Small tanks not recorded by the IMACS computer were loaded in accordance with T&S Booklet departure condition values.

c. Miscellaneous weights likely to be onboard the vessel during the capsize voyage, such as provisions, stores, and crew effects, were applied to the MSC model in accordance with weights and centers provided in the T&S Booklet.

d. The weights of the cargo applied to the MSC model were in accordance with the weight estimates detailed on the Brunswick Departure Stowage Plan. The total weight applied (8,780.2 MT) was generally consistent with the MSC estimated total weight of the cargo cited on the VIN list applicable to the voyage. The centers of gravity of the cargo applied to the MSC model were in accordance with the vehicle group locations depicted on the Brunswick Departure Stowage Plan.

e. Calculation of hydrostatics of the loaded MSC computer model resulted in drafts which were generally consistent with the drafts reported by the IMACS computer prior to departure from Brunswick. However, the 4.6° starboard list calculated using the MSC computer model was not consistent with observed conditions prior to departure. This indicates a possible anomaly between the TCGs depicted on the Brunswick Departure Stowage Plan and the actual TCGs of the cargo onboard the vessel. To remain consistent with observed conditions, all subsequent stability analysis was conducted with the vessel at zero list, while other bounded stability parameters including displacement, LCG, and VCG were held constant.

(2) Intact Stability Analysis

a. The MSC computer model was used to generate righting arm curves for the vessel as loaded in accordance with provided data for the capsize voyage. The corresponding righting arm properties were calculated and assessed for compliance with the mandatory criteria regarding righting arm (lever) curve properties (Part A, Section 2.2) of the 2008 IMO IS Code. Results indicated that the vessel did not fully meet the requirements of this criteria due to the limited area under the righting arm curve between 30° and 40°.

b. MSC also used the independently generated computer model to assess compliance with the mandatory Severe Wind and Rolling criteria (Part A, Section 2.3) of the 2008 IMO IS Code. Results indicated that the vessel failed this criteria by a significant margin.

(3) Impact of Turn on Stability

a. A ship undergoing a turn experiences a heeling moment due to the resultant centrifugal force. Portable pilot unit recorded data indicated that the capsize occurred during a turn to starboard. MSC calculated the effect that this turn would have had on the righting arm curve using a range of turn radii and the speed of the vessel. Results indicated that the maximum righting arm and righting energy were significantly reduced by the turning heeling moment.

b. MSC also calculated the effect that moving the rudder from starboard to amidships would have had on the righting arm curve. The area under the righting arm curve was calculated to have been further reduced by this helm command, but only by relatively small amounts when compared to the reduction in area under the righting arm curve due to the centrifugal force from the turn.

c. The final area under the righting arm curve due to the combined effects of the way the vessel was loaded during the capsize voyage and the heeling moments experienced during the turn constituted a small fraction of the area under the righting arm curve that the benchmark conditions in the T&S Booklet had. This extreme lack of righting area (and corresponding lack of righting energy) indicates that the vessel had little capability of withstanding further adverse static or dynamic heeling effects. Dynamic overshoot, which causes a vessel entering a turn to heel even further away from the direction of that turn, coupled with any cargo shifting due to heel, are likely to have overcome the remaining righting energy and resulted in the capsize.

d. Additional MSC analysis indicates that with the Pilot Door on Deck 5, Fr. 73, Port open, as was reported by the IMACS data, the downflooding angle of the vessel would be reduced from approximately 83° to 17° of heel. As such, it is very likely that, during the capsize, once a heel angle of 17° was reached, a large amount of seawater immediately flooded into the vessel through this open door, exacerbating the capsize by causing a further reduction in the available righting energy beyond 17°.

(4) Comparison with T&S Booklet

a. MSC also used the tables contained within Section 4.7 of the T&S Booklet to assess whether the vessel was in compliance with the required minimum GM and maximum KG at the corresponding drafts and trim. Results indicated that the GM of the vessel, as calculated by MSC, was approximately 30% below the minimum

GM required by the T&S Booklet and the KG calculated by MSC was approximately 4% above the maximum KG permitted.

b. The cargo and liquid loads onboard the vessel were compared to the cargo and liquid loads in similar benchmark conditions detailed in the T&S Booklet. For conditions with cargo VCGs similar to the cargo VCG of the capsize voyage loading condition, the comparable benchmark conditions had significantly more liquid load onboard. For conditions with similar total liquid loads, the comparable benchmark conditions had significantly lower cargo VCGs. Given the cargo weight and VCG for the capsize voyage, the vessel would have needed significantly more liquid load (fuel or ballast) onboard the vessel to be in compliance with the T&S Booklet and the 2008 IS Code. This additional liquid load would have resulted in an increase in displacement and consequently, an increase in drafts.

(5) Stability During Previous Voyages

a. Using the MSC computer model, subsequent intact stability analyses were conducted using loading data for the vessel in the Jacksonville to Brunswick voyage (voyage prior to the capsize voyage) and in the Freeport to Jacksonville voyage (two voyages prior to the capsize voyage), as detailed in Appendices B and C respectively.

b. Righting arm curves for the vessel in these voyages were calculated and assessed for compliance with the 2008 IS Code. Results indicate that, although the vessel had slightly higher righting arms and righting energy during both the Jacksonville to Brunswick and the Freeport to Jacksonville voyages than the vessel had during the capsize voyage, the mandatory criteria of the 2008 IS Code were not fully met.

c. When contemplating why the vessel did not capsize during the Freeport to Jacksonville or Jacksonville to Brunswick voyage, but did capsize during the Brunswick outbound transit, it is important to understand that stability criteria within the 2008 IS Code is static and includes margins of safety to account for the dynamic responses of a vessel in real-world environmental and operating conditions. Failure of the IS Code criteria does not indicate immediate capsize, but rather, is an indicator that the vessel poses a higher risk of capsize given exposure to certain dynamic conditions such as severe wind, waves and faster speed/tighter radius turns. Because risk is based upon probability, it is possible that GOLDEN RAY, while failing IS Code criteria, could have capsized on a previous voyage if it had been exposed to more severe adverse conditions.

d. Finally, a historical review of the IMACs tank loading data indicates that the vessel discharged approximately 1500 MT of ballast from the No. 5 D.B. and No. 6 tanks on September 3, 2019 during the Freeport to Jacksonville voyage. MSC analysis indicates that, had the vessel not discharged this ballast and had instead kept these tanks filled for the subsequent voyages, it would have fully complied with the 2008 IS Code during the remainder of that voyage and each of the two subsequent voyages, with resulting GM between 2.25 m to 2.47 m, as calculated using the MSC computer model. In this regulatory compliant condition, capsize during the outbound Brunswick transit would more than likely have been prevented.

8. References

1 Formal Marine Casualty Investigation Concerning the Capsizing and Fire of the RO/RO GOLDEN RAY While Transiting St. Simons Sound, Georgia on 08 September 2019, Memorandum from CGD SEVEN (des) to CGD EIGHT (dw), dated September 12, 2019

2 GOLDEN RAY Table of Offsets, File "8151-hull-offset.txt"

3 GOLDEN RAY General Arrangement, Drawing 1A000B001, Rev. Fin, dated November 15, 2017

4 GOLDEN RAY Aft End Construction, Drawing 2A100H001, Rev Fin, dated July 2, 2015

5 GOLDEN RAY Fore End Construction, Drawing 2A600H001, Rev Fin, dated July 3, 2015

6 GOLDEN RAY Double Bottom Construction, Drawing 2A300H001, Rev. Fin, dated July 10, 2015

7 GOLDEN RAY Midship Section, Drawing 1A000H001, Rev. Fin, dated July 27, 2017

8 GOLDEN RAY Shell Expansion, Drawing 1A000H003, Rev. Fin, dated July 27, 2017

9 GOLDEN RAY Damage Control Plan, Drawing 2A000B003, Rev. Fin, dated February 4, 2016

10 GOLDEN RAY Engine Room Construction, Drawing 2A200H002, Rev. Fin, dated July 17, 2015

11 GOLDEN RAY Double Bottom Construction in Engine Room, Drawing 2A200H001, Rev. Fin, dated June 29, 1015

12 GOLDEN RAY Construction Profile & Deck Plan, Drawing 1A000H002, Rev. Fin, dated July 27, 2017

13 GOLDEN RAY Final Trim & Stability Booklet, Document 4A000B012, stamped "Approved" by DNV-GL on December 12, 2017

14 GOLDEN RAY Result of Deadweight Measurement, Document 6A000B003, stamped "Approved" by DNV-GL on November 2, 2017

15 SILVER RAY Result of Inclining Experiment & Deadweight Measurement, Document 6A000B003, stamped "Approved" by DNV-GL on November 2, 2017

16 GOLDEN RAY IMACS Program, File "IMACS_Master.exe"

17 GOLDEN RAY IMACS Recorded Data Files from August 2017 to September 2019

18 GOLDEN RAY IMACS Tank Summary for 08/09/19 04:00

19 GOLDEN RAY IMACS Tank Summary for 08/09/19 05:27

20 GOLDEN RAY B/L Vin List, File "19. VIN LIST G RAY 13.xls"

21 GOLDEN RAY Brunswick Departure Stowage Plan, last modified by Mike Mavrinac (Glovis USA) on September 8, 2019

22 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)

23 Circular MSC.1/Circ 1281, "Explanatory Notes to the International Code On Intact Stability, 2008," December 9, 2008, International Maritime Organization (IMO)

24 Zubaly, R.B., Applied Naval Architecture, Cornell Maritime Press, 1996, pp. 129-130

25 Moore, C.S., Principles of Naval Architecture Volume III: Motions in Waves and Controllability, Society of Naval Architects and Marine Engineers (SNMAE), 1989, pp. 212-213

26 Portable Pilot Unit Data for Capsize Voyage, File "CG 83 PILOT PPU_wAudio_0134_0144_08SEP19.wmv"

Appendix A: MSC Computer Model Comparison to T&S Booklet

A comparison of hydrostatic properties and tank parameters between the MSC computer model and the T&S Booklet was completed and is detailed in this appendix.

A.1. Hydrostatic Parameters

Table A-1 details key hydrostatic parameters at a draft of 9.3 m in salt water without trim or hull deflection, calculated using the MSC GHS computer model. For comparison, the values in the T&S Booklet [A1] are also provided as well as 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 [A2], which are identical to those in the IACS Unified Requirement L5 applied by classification societies [A3].
The MSC GHS computer model hull hydrostatic properties align closely with those reported in the T&S Booklet at the 9.3 m draft, with all properties falling within the IMO/IACS tolerances. Model hydrostatics at and near this draft are considered to be most critical to subsequent stability analyses, as this was the approximate true mean draft of the vessel prior to the capsize.

	MSC Model	T&S Book	Difference	Difference %	Tolerance
Disp. (MT)	34892.28	34817.00	75.28	0.2%	2%
LCB (m-AP)	90.65	90.82	0.16	0.2%	1% or 50 cm
VCB (m-BL)	5.34	5.32	0.01	0.2%	1% or 5 cm
LCF (m-AP)	78.34	78.07	0.27	0.3%	1% or 50 cm
MTC (m*MT/cm)	653.94	645.60	8.34	1.3%	2%
KMt (m-BL)	19.96	20.13	0.17	0.8%	1% or 50 cm
TPC (MT/cm)	55.92	56.07	0.15	0.3%	NA

Table A-1: Comparison of key hydrostatic properties at a draft of 9.3 m in salt water, without trim or hull deflection. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

As the draft is increased to the extreme Summer load draft of 10.618 m, all properties, with the exception of the moment to trim 1-cm, remain within the IMO/IACS tolerances. Table A-2 summarizes the hydrostatic properties at the 10.618 m draft without trim or hull deflection. The moment to trim 1-cm cited in T&S Booklet at this draft produced a value approximately 2.5% lower than the value produced by the MSC hull model. As MSC did not have access to the model used to generate the T&S Booklet, it was not possible to accurately identify the reason for this difference. However, because the difference in moment to trim 1-cm between the models was only slightly above the IMO/IACS tolerance limit, the other hydrostatic properties aligned well, and the stability analysis was conducted at drafts close to 9.3 m, the slight variation in hydrostatic properties at other drafts was determined to be generally inconsequential to stability results.

	MSC Model	T&S Booklet	Difference	Difference %	Tolerance
Disp. (MT)	42500.68	42428.00	72.68	0.2%	2%
LCB (m-AP)	88.31	88.42	0.10	0.1%	1% or 50 cm
VCB (m-BL)	6.17	6.15	0.01	0.2%	1% or 5 cm
LCF (m-AP)	77.87	77.77	0.10	0.1%	1% or 50 cm
MTC (m*MT/cm)	744.44	725.60	18.84	2.5%	2%
KMt (m-BL)	19.19	19.25	0.06	0.3%	1% or 50 cm
TPC (MT/cm)	58.94	58.89	0.05	0.1%	NA

Table A-2: Comparison of key hydrostatic properties at the extreme Summer load draft of 10.618 m in salt water, without trim or hull deflection. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

A.2. Tank Properties

Tables A-3, A-4, and A-5 detail calculated tank properties of the MSC computer model and T&S Booklet, including 100% volume and center of gravity, and maximum (slack) free surface inertia for the ballast, fuel, and miscellaneous tanks respectively. Also included in these tables 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, sounding tubes, and other internal components. The permeability factors assumed in the original calculation of the tank volumes in the T&S Booklet were not available. However, the permeability factors provided in Tables A-3, A-4, and A-5 were incorporated based upon MSC’s review of GOLDEN RAY structural drawings associated with the internal tank structure. In general, double bottom tanks which have significant internal structure which would reduce the volume available for liquid have been assigned a permeability of 0.97 to 0.98 and internal tanks which do not have significant internal structure have been assigned a permeability of 0.99.

(2) A comparison of tank volumes of the MSC GHS computer model with the T&S Booklet shows a number of tanks with differences in excess of the 2% volume tolerance of MSC Circ. 1229. However, as the approach to the subsequent stability analyses utilized tank loading based upon total weight of the liquid, as opposed to the tank fill percentage, these volume differences did not have an effect on the total quantity of liquid modeled onboard the vessel.

(3) Similar to the differences noted with tank volume calculations, review of Tables A-3, A-4, and A-5 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 12 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. Despite the high number of tanks with differing maximum free

surface inertias, the effects that these differences have on intact stability is minimal. The sum of differences in maximum free surface inertias between the MSC GHS model and the T&S Booklet for all tanks totals approximately 570 m^4. At a displacement of 35,000 MT, which is the approximate displacement at which the vessel was operating prior to the capsize, this difference in maximum free surface inertias results in a maximum VCG difference of less than 2 cm. This difference is negligible when considering the effects that the large quantity of RO/RO cargo has on the overall KG of the vessel.

	100% Volume (m^3)		100% LCG (m fwd AP)		100% TCG (m stbd CL)		100% VCG (m abv BL)		Slack (Max) Free Surface (m4)		Permeability Factor		Volume Difference (%)	LCG Difference (%)	TCG Difference (m)	VCG Difference (%)	FS Inertia Difference (%)	Comments/Notes
	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	Tolerance 2%	Tolerance 1% or 50 cm	Tolerance 0.5% of B (0.18 m) or 5 cm	Tolerance 1% or 50 cm	Tolerance 2%	
Ballast Water																		
F.P. TK	434.2	431.0	184.752	184.995	0.000	0.000	8.078	7.911	598.50	594	0.97	NA	0.7%	0.1%	0.00	2.1%	0.8%	Minimal Loading
NO. 1 W.B.TK (C)	314.8	318.2	167.687	167.686	0.000	0.000	4.950	4.951	302.38	304	0.98	NA	1.1%	0.0%	0.00	0.0%	0.5%	Minimal Loading
NO. 2 W.B.TK (P)	363.5	358.2	154.787	154.907	-4.089	-4.152	4.048	4.096	174.76	168	0.98	NA	1.5%	0.1%	0.06	1.2%	3.9%	
NO. 2 W.B.TK (S)	398.7	386.6	154.868	155.115	3.728	3.827	3.813	3.899	256.16	243	0.98	NA	3.0%	0.2%	0.10	2.3%	5.1%	
NO. 3 W.B.TK (P)	778.3	787.5	135.089	135.076	-7.178	-7.144	3.835	3.784	1359.76	1,305	0.98	NA	1.2%	0.0%	0.03	1.3%	4.0%	
NO. 3 W.B.TK (S)	739.7	738.4	135.830	135.964	6.282	6.243	3.452	3.395	1643.50	1,606	0.98	NA	0.2%	0.1%	0.04	1.7%	2.3%	
NO. 4 W.B.TK (C)	379.1	379.2	119.684	119.687	0.000	0.000	1.441	1.461	1801.75	1,758	0.99	NA	0.0%	0.0%	0.00	1.4%	2.4%	
NO. 4 W.B.TK (P)	291.8	297.8	118.977	118.966	-11.537	-11.580	4.118	4.123	238.32	244	0.98	NA	2.1%	0.0%	0.04	0.1%	2.4%	
NO. 4 W.B.TK (S)	344.6	346.1	119.557	119.571	11.676	11.694	4.459	4.421	238.35	244	0.98	NA	0.4%	0.0%	0.02	0.9%	2.4%	
NO. 5 D.B.W.B.TK (C)	482.7	487.6	92.699	92.700	0.000	0.000	1.425	1.425	944.95	922	0.98	NA	1.0%	0.0%	0.00	0.0%	2.4%	
NO. 5 D.B.W.B.TK (P)	449.8	452.7	92.664	92.673	-7.731	-7.720	1.433	1.426	778.36	759	0.98	NA	0.6%	0.0%	0.01	0.5%	2.5%	
NO. 5 D.B.W.B.TK (S)	449.8	452.7	92.664	92.673	7.731	7.720	1.433	1.426	778.36	759	0.98	NA	0.6%	0.0%	0.01	0.5%	2.5%	
NO. 5 W.B.TK (P)	558.8	569.0	92.455	92.442	-14.844	-14.864	4.787	4.768	147.11	151	0.98	NA	1.8%	0.0%	0.02	0.4%	2.6%	
NO. 5 W.B.TK (S)	558.8	563.4	92.455	92.446	14.844	14.872	4.787	4.764	147.11	151	0.98	NA	0.8%	0.0%	0.03	0.5%	2.6%	
NO. 6 W.B.TK (C)	377.5	380.9	65.696	65.700	0.000	0.000	1.423	1.425	1801.76	1,758	0.98	NA	0.9%	0.0%	0.00	0.1%	2.4%	
NO. 6 W.B.TK (P)	333.6	335.1	65.382	65.434	-12.050	-12.144	3.790	3.816	420.06	411	0.98	NA	0.4%	0.1%	0.09	0.7%	2.2%	
NO. 6 W.B.TK (S)	291.9	292.9	65.280	65.332	11.676	11.770	3.505	3.538	419.82	411	0.98	NA	0.3%	0.1%	0.09	0.9%	2.1%	
NO. 7 W.B.TK (P)	491.2	500.2	53.453	53.442	-6.709	-6.789	2.613	2.655	1418.39	1,408	0.98	NA	1.8%	0.0%	0.08	1.6%	0.7%	
NO. 7 W.B.TK (S)	519.4	528.7	53.454	53.423	6.345	6.426	2.548	2.590	1713.66	1,699	0.98	NA	1.8%	0.1%	0.08	1.6%	0.9%	
A.P.TK (C)	338.6	347.4	1.844	1.764	1.446	1.461	10.408	10.443	1487.91	1,443	0.98	NA	2.6%	4.3%	0.02	0.3%	3.0%	Minimal Loading
A.P.TK (P)	454.6	469.3	3.169	3.235	-10.118	-10.175	10.046	10.024	3222.91	3,175	0.98	NA	3.2%	2.1%	0.06	0.2%	1.5%	Minimal Loading
A.P.TK (S)	399.4	418.8	2.862	3.326	11.303	11.342	10.277	10.206	1646.07	1,542	0.98	NA	4.9%	16.2%	0.04	0.7%	6.3%	Minimal Loading

Table A-3: Calculated tank properties of the MSC computer model (grey columns) and T&S Booklet (white columns) for all ballast tanks. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

	100% Volume (m^3)		100% LCG (m fwd AP)		100% TCG (m stbd CL)		100% VCG (m abv BL)		Slack (Max) Free Surface (m4)		Permeability Factor		Volume Difference (%)	LCG Difference (%)	TCG Difference (m)	VCG Difference (%)	FS Inertia Difference (%)	Comments/Notes
	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	Tolerance 2%	Tolerance 1% or 50 cm	Tolerance 0.5% of B (0.18 m) or 5 cm	Tolerance 1% or 50 cm	Tolerance 2%	
Heavy Fuel Oil																		
NO. 1 H.F.O.TK (P)	387.7	375.8	154.283	154.531	-2.564	-2.619	5.968	5.979	229.41	218	0.98	NA	3.1%	0.2%	0.06	0.2%	5.0%	
NO. 1 H.F.O.TK (S)	456.9	459.2	154.498	154.498	2.175	2.175	5.920	5.919	331.31	320	0.98	NA	0.5%	0.0%	0.00	0.0%	3.4%	
NO. 2 H.F.O.TK (P)	405.4	408.9	141.020	141.021	-3.909	-3.932	5.904	5.914	463.72	499	0.98	NA	0.9%	0.0%	0.02	0.2%	7.6%	
NO. 2 H.F.O.TK (S)	577.6	582.6	139.569	139.572	3.683	3.705	5.872	5.881	926.95	875	0.98	NA	0.9%	0.0%	0.02	0.2%	5.6%	
NO. 3 H.F.O.TK (P)	239.1	240.3	57.150	57.150	-2.550	-2.550	5.650	5.650	72.03	70	0.98	NA	0.5%	0.0%	0.00	0.0%	2.8%	
NO. 3 H.F.O.TK (S)	277.1	278.5	57.150	57.149	2.200	2.200	5.650	5.650	112.17	109	0.98	NA	0.5%	0.0%	0.00	0.0%	2.8%	
NO. 4 H.F.O.TK (P)	317.5	319.1	57.461	57.458	-8.369	-8.342	6.317	6.310	524.91	510	0.98	NA	0.5%	0.0%	0.03	0.1%	2.8%	
NO. 4 H.F.O.TK (S)	355.8	358.6	57.435	57.424	8.364	8.359	6.078	6.078	519.34	510	0.98	NA	0.8%	0.0%	0.01	0.0%	1.8%	
NO. 1 H.F.O. SERV. (P)	41.4	39.6	17.325	17.325	-11.500	-11.458	10.950	11.012	35.01	41	0.99	NA	4.3%	0.0%	0.04	0.6%	17.1%	
NO. 2 H.F.O. SERV. (P)	49.7	47.5	14.850	14.850	-11.500	-11.458	10.950	11.012	45.71	49	0.99	NA	4.4%	0.0%	0.04	0.6%	7.2%	
NO. 1 H.F.O. SETT. (P)	41.4	39.6	19.575	19.575	-11.500	-11.458	10.950	11.012	35.01	40	0.99	NA	4.3%	0.0%	0.04	0.6%	14.3%	
NO. 2 H.F.O. SETT. (P)	49.7	47.5	12.150	12.150	-11.500	-11.458	10.950	11.012	45.71	49	0.99	NA	4.4%	0.0%	0.04	0.6%	7.2%	
Diesel Oil																		
M.D.O. STOR.TK (P)	96.0	95.5	48.570	48.570	-8.370	-8.370	7.000	7.000	109.68	112	0.99	NA	0.5%	0.0%	0.00	0.00	2.1%	
M.D.O. STOR.TK (S)	140.8	149.2	48.733	48.659	7.656	7.700	6.511	6.644	141.70	139	0.99	NA	6.0%	0.2%	0.04	0.02	1.9%	
M.D.O. SERV.TK (S)	37.0	35.5	8.550	8.550	2.014	2.000	12.230	12.200	19.94	24	0.99	NA	4.1%	0.0%	0.01	0.00	20.4%	Not loaded
Gas Oil																		
M.G.O.TK (P)	147.6	146.9	48.743	48.742	-2.836	-2.836	5.650	5.650	57.55	57	0.99	NA	0.5%	0.0%	0.00	0.00	1.0%	
M.G.O.TK (S)	152.7	151.9	48.600	48.600	2.200	2.200	5.650	5.650	61.19	60	0.99	NA	0.5%	0.0%	0.00	0.00	1.9%	
M.G.O. SERV.TK (P)	37.0	35.5	8.550	8.550	-2.014	-2.000	12.230	12.200	20.66	24	0.99	NA	4.1%	0.0%	0.01	0.00	16.2%	

Table A-4: Calculated tank properties of the MSC computer model (grey columns) and T&S Booklet (white columns) for all heavy fuel oil, diesel oil, and gas oil tanks. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

	100% Volume (m^3)		100% LCG (m fwd AP)		100% TCG (m stbd CL)		100% VCG (m abv BL)		Slack (Max) Free Surface (m4)		Permeability Factor		Volume Difference (%)	LCG Difference (%)	TCG Difference (m)	VCG Difference (%)	FS Inertia Difference (%)	Comments/Notes
	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	MSC GHS	T&S	Tolerance 2%	Tolerance 1% or 50 cm	Tolerance 0.5% of B (0.18 m) or 5 cm	Tolerance 1% or 50 cm	Tolerance 2%	
Lubricating Oil																		
M/E L.O. STOR.TK	26.8	24.5	8.100	8.100	-13.510	-13.525	12.200	12.200	12.30	12	0.99	NA	8.6%	0.0%	0.02	0.00	2.4%	
M/E L.O. SETT.TK	23.5	23.4	8.100	8.100	-10.155	-10.150	12.200	12.200	10.95	11	0.99	NA	0.4%	0.0%	0.00	0.00	0.5%	Not loaded
G/E L.O. STOR.TK	10.9	11.0	21.870	21.850	13.550	13.550	10.355	10.350	1.79	2	0.99	NA	0.9%	0.1%	0.00	0.00	11.7%	
G/E L.O. SETT.TK	8.3	8.2	19.170	19.150	13.550	13.550	10.355	10.350	1.37	1	0.99	NA	1.2%	0.1%	0.00	0.00	27.0%	Not loaded
NO. 1 CYL.O.TK	16.6	16.6	27.900	27.900	12.640	12.625	9.850	9.850	7.91	8	0.99	NA	0.0%	0.0%	0.02	0.00	1.1%	
NO. 2 CYL.O.TK	25.2	24.9	23.728	23.741	13.550	13.550	9.574	9.574	5.27	5	0.99	NA	1.2%	0.1%	0.00	0.00	5.1%	
M/E L.O. SUMP.TK	30.5	30.4	33.300	32.922	0.000	0.003	1.175	1.161	24.91	27	0.99	NA	0.3%	1.1%	0.00	0.01	8.4%	
Miscellaneous																		
L.O. SLU.TK	6.3	9.6	30.150	30.224	7.755	9.155	6.950	6.735	5.92	6	0.99	NA	52.4%	0.2%	1.40	0.03	1.4%	Not loaded
S/T L.O.SUMP.TK	2.3	2.5	18.903	18.918	0.809	0.871	1.853	1.851	0.82	1	0.99	NA	8.7%	0.1%	0.06	0.00	22.0%	Not loaded
BILGE HOLD.TK	79.9	74.6	20.218	20.703	-0.019	-0.012	1.355	1.312	75.71	72	0.97	NA	6.6%	2.4%	0.01	0.03	4.9%	Not loaded
OILY BILGE.TK	50.2	48.7	45.170	39.722	-2.157	-1.659	1.345	1.217	121.53	110	0.98	NA	3.0%	12.1%	0.50	0.10	9.5%	
F.O. SLUDGE.TK	16.0	16.8	14.017	13.987	0.380	0.194	8.844	8.840	43.16	43	0.99	NA	5.0%	0.2%	0.19	0.00	0.4%	
SEWAGE HOLD.TK	18.8	20.5	38.894	39.804	-9.228	-9.064	5.207	5.090	43.80	25	0.99	NA	9.0%	2.3%	0.16	0.02	42.9%	Not loaded
CLEAN DRAIN.TK	18.6	18.1	36.627	36.621	3.337	3.341	1.502	1.505	8.03	8	0.99	NA	2.7%	0.0%	0.00	0.00	0.4%	
C.W.DRAIN.TK	25.0	26.5	43.148	43.395	4.419	4.529	1.459	1.582	19.14	18	0.99	NA	6.0%	0.6%	0.11	0.08	6.0%	
F.O.DRAIN.TK	11.7	12.1	44.111	44.296	-2.498	-2.491	1.149	1.185	1.04	1	0.99	NA	3.4%	0.4%	0.01	0.03	3.8%	
Cooling Water																		
S/T C.W.TK	35.4	30.2	10.231	10.349	0.000	0.000	3.823	3.512	3.71	4	0.95	NA	14.7%	1.2%	0.00	0.08	7.8%	
Fuel Oil Overflow																		
NO. 1 F.O.OVER.TK	10.8	10.2	134.550	134.625	-1.050	-1.050	7.003	7.020	0.61	1	0.99	NA	5.6%	0.1%	0.00	0.00	63.9%	
NO. 2 F.O.OVER.TK	18.6	18.6	44.214	44.410	-4.592	-4.675	1.528	1.608	16.45	13	0.99	NA	0.0%	0.4%	0.08	0.05	21.0%	
Fresh Water																		
NO. 1 F.W.TK	81.0	78.2	9.900	9.900	13.000	13.000	11.750	11.850	12.45	12	0.98	NA	3.5%	0.0%	0.00	0.01	3.6%	
NO. 2 F.W.TK	168.3	156.4	9.900	9.900	8.500	5.500	11.850	11.850	99.63	97	0.98	NA	7.1%	0.0%	3.00	0.00	2.6%	

Table A-5: Calculated tank properties of the MSC computer model (grey columns) and T&S Booklet (white columns) for all lubricating oil, miscellaneous, cooling water, overflow, and fresh waters tanks. Also included are the calculated differences and tolerances based on the IMO and IACS guidelines.

A.3. Appendix References

A1 GOLDEN RAY Final Trim & Stability Booklet, Document 4A000B012, stamped "Approved" by DNV-GL on December 12, 2017

A2 IMO MSC.1/Circ.1229, Guidelines for Approval of Stability Instruments, dated January 11, 2007.

A3 International Association of Class Societies (IACS) Unified Requirement L5: Onboard Computers for Stability Calculations, Corr. 1, dated 2006.

Appendix B: Jacksonville to Brunswick Stability Analysis

An assessment of the GOLDEN RAY's intact stability during the transit from Jacksonville, FL to Brunswick, GA on September 7, 2019 was completed using the MSC computer model described in Section 2 of this report. This Appendix details the loading conditions applied to the model for this voyage and the resultant righting arm curves expected during this voyage.

B.1. Loading Conditions

This section details the information, methods, and assumptions used to simulate the Jacksonville, FL to Brunswick, GA voyage loads that were applied to the MSC computer model. When available, actual liquid and cargo loading data from this voyage was used. For loads in which no data was available, Sections 5.3 and 5.4 of the T&S Booklet, which detail acceptable benchmark loading conditions for the vessel, were referenced.

B.1.1. Liquid Loading

As with the analysis for the capsize voyage, IMACS software data was used to apply the loads to the 47 major tanks in the MSC computer model. The tank quantities from the 07/09/19 05:01:32 UTC timestamp [B1] were used. This timestamp represents tank quantities immediately prior to departure when the vessel was at nearly zero list. Using a timestamp at which the vessel was at zero list reduces error, as the IMACS tank readings do not appear to correct for heel, and using a timestamp immediately prior to departure ensures that an accurate comparison with the vessel's departure drafts can be completed.

A comparison of the tank values applied to the model to the tank values immediately prior to arrival in Brunswick was conducted, the results of which are shown in Table B-1. Based on this data, fuel and diesel quantities appeared to decrease by a small amount throughout the voyage, likely due to liquid load consumption, however the net liquid load decrease of approximately 16 MT is insignificant to stability given the approximately 35,000 MT displacement of the vessel during this voyage.

	Jacksonville Departure Load (MT)	Brunswick Arrival Load (MT)	Difference (MT)	Difference %
Ballast	2924.33	2920.18	-4.15	-0.1%
Fuel	887.22	875.08	-12.14	-1.4%
Diesel	322.39	321.06	-1.33	-0.4%
Misc.	44.61	46.54	1.93	4.3%
Total	**4178.55**	**4162.86**	**-15.69**	-0.4%

Table B-1: Comparison between tank weights from the vessel's IMACS data files at the 07/09/19 05:01:32 UTC (01:01:32 EDT) (Jacksonville Departure) timestamp and the 07/09/19 21:09:14 UTC (17:09:14 EDT) (Brunswick Arrival) timestamp. The loads at the Jacksonville Departure timestamp were applied to the MSC computer model.

Loads for the smaller tanks including lube oil, cooling water, and fresh water, which were not monitored by the vessel's IMACS software were assumed to be consistent with the Departure Bunkering Condition detailed in Section 5.3.1 of the T&S Booklet. Table B-2 shows the liquid load applied for these tanks, which accounted for 7.9% of the total liquid load applied to the model.

	Load Applied (MT)
L.O. Sludge TK (S)	0.0
S/T L.O Sludge TK (C)	0.0
F.O. Sludge TK (S)	0.0
Sewage Holding TK (P)	0.0
S/T Cooling Water TK (C)	30.2
No. 1 F.W. TK (S)	78.2
No. 2 F.W. TK (S)	156.4
M/E L.O. STOR. TK (P)	21.6
M/E. L.O. SET. TK (P)	0.0
G/E L.O. STOR TK (S)	9.7
G/E L.0. SET. TK (S)	0.0
NO. 1 CYL. Oil TK (S)	14.7
NO. 2 CYL. Oil TK (S)	22.0
M/E L.O. Sump TK (C)	26.8
Total	**359.6**

Table B-2: Liquid loads applied to MSC computer model for small tanks not monitored by IMACS. Values were selected in accordance with the T&S Booklet departure benchmark loading conditions.

B.1.2. Cargo Loading

The Jacksonville Preliminary Stowage Plan [B2] was used to determine the cargo loading applied to the MSC Computer Model. After superimposing the stowage plan onto the General Arrangement, the area centroid of each vehicle group was calculated and was assumed to represent the LCG and TCG of each vehicle group. The VCG of each vehicle group was determined by adding the corresponding deck height to a standard, assumed vehicle VCG of 0.57 m above the deck, an assumption which is consistent with previous analysis contained in this report. The weights of the vehicle groups were then applied to the MSC computer model in 73 individual point loads at the respective centers of gravity. These loads are summarized by deck in Table B-3.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
Deck 13	745.60	98.24	0.14	36.82
Deck 12	535.28	78.87	-3.00	34.51
Deck 11	933.22	89.48	1.22	32.00
Deck 10	1010.00	91.56	0.28	29.47
Deck 9	1020.00	92.71	-0.33	26.93
Deck 8	995.00	86.31	-0.15	24.41
Deck 7	620.25	96.81	-0.91	21.71
Deck 6 Raised	155.29	25.57	5.97	18.97
Deck 6 Standard	511.00	121.57	3.42	18.27
Deck 5	440.09	105.18	-2.90	14.87
Deck 4	557.00	99.81	0.02	11.82
Deck 3	515.00	99.12	0.00	9.02
Deck 2	174.34	97.63	-0.83	6.12
Deck 1	195.15	94.04	0.12	3.42
Total	**8407.2**	**93.53**	**0.02**	**24.09**

Table B-3: Cargo weights applied to the MSC model from the Jacksonville Preliminary Stowage Plan summarized by Deck. Deck 6 is subdivided into cargo situated on deck panels which were raised 0.7 m and cargo situated on deck panels which were at the standard height.

B.1.3. Miscellaneous Deadweight

The weight of miscellaneous deadweight items, including the fixed firefighting system's carbon dioxide, swimming pool water weight, provisions, stores, and cargo lashing equipment, were applied to the MSC Computer model consistent with the values listed for the Departure Condition detailed on page 266 of the T&S Booklet.

B.1.4. Final Loading

A summary of the final loading conditions applied to the MSC Computer model for the Jacksonville to Brunswick voyage is shown in Table B-4.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
LTSH	21433.0	85.9	-0.27	18.3
Tanks	4538.2	102.1	2.26	3.9
Cargo	8407.2	93.5	0.02	24.1
Misc. Deadweight	230.4	74.4	-2.33	25.3
Total	**34608.8**	**89.8**	**0.12**	**18.1***

Table B-4: Final loading condition applied to the MSC computer model for the Jacksonville to Brunswick voyage. *VCG includes 0.247 m of free surface correction.

B.2. Results

B.2.1. Final Hydrostatics

The 0.12 m starboard TCG of the final loading condition applied to the model resulted in starboard heel of 2.9 degrees. However, IMACS data indicates that the vessel did not depart Jacksonville with significant heel. As such, a zero heel condition was applied to the vessel for all subsequent stability analysis. Consistent with previous analysis in this report, this was done by setting the heel of the vessel model equal to zero, allowing it to trim freely in order to remove residual longitudinal moments, and solving for the resultant TCG.

The hydrostatic properties with the loads applied for the Jacksonville to Brunswick voyage with the vessel at zero heel were then calculated and are shown in Table B-5.

	Disp. (MT)	LCB (m-AP)	VCB (m-BL)	LCF (m-AP)	MTC (m*MT/cm)	KMt (m-BL)	GM (m)	TPC (MT/cm)
Disp. (MT)	34609	89.76	5.31	77.55	624.94	20.09	1.91	56.13

Table B-5: Final hydrostatic properties calculated from the MSC computer model for the vessel in the zero heel condition with the loading applied for the Jacksonville to Brunswick voyage.

B.2.2. Drafts

With the vessel at 0 degrees heel, the resultant drafts calculated using the MSC computer model were compared to the drafts reported by the IMACS Jacksonville departure timestamp (07/09/19 05:01:32 UTC) as shown in Table B-6. The MSC computer model drafts obtained are shown for both salt water and brackish water conditions with a specific gravity of 1.01, which is representative of the water conditions at Blount Island Marine Terminal in Jacksonville on September 7, 2019 according to salinity data [B3]. The mean draft of the MSC model in brackish water was within 0.02 m of the mean draft reported by the vessel's IMACS software at departure.

	MSC Model Salt Water	MSC Model Brackish Water	IMACS Departure	Departure Draft Readings
Taft (m)	9.47	9.51	9.49	9.40
Tfwd (m)	8.94	9.07	9.04	9.30
Tmean (m)	9.20	9.29	9.27	9.35

Table B-6: Comparison between loaded drafts calculated using the MSC computer model in salt and brackish water (S.G. = 1.01) with IMACS drafts at departure and departure draft readings taken by the vessel crew.

B.2.3. Jacksonville Voyage Righting Arm Curve Properties

With the MSC computer model loaded for the Jacksonville to Brunswick voyage in accordance with Section B.1, and with list set to 0 degrees, righting arm curves were generated for heel to port and starboard in salt water. These righting arm curves are shown in Figure B-1 by the dark green line (heel to starboard) and dark red line (heel to port). For comparison of righting arms with loading conditions which meet regulatory requirements, the righting arm curves from all

T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT are also shown (dotted lines).

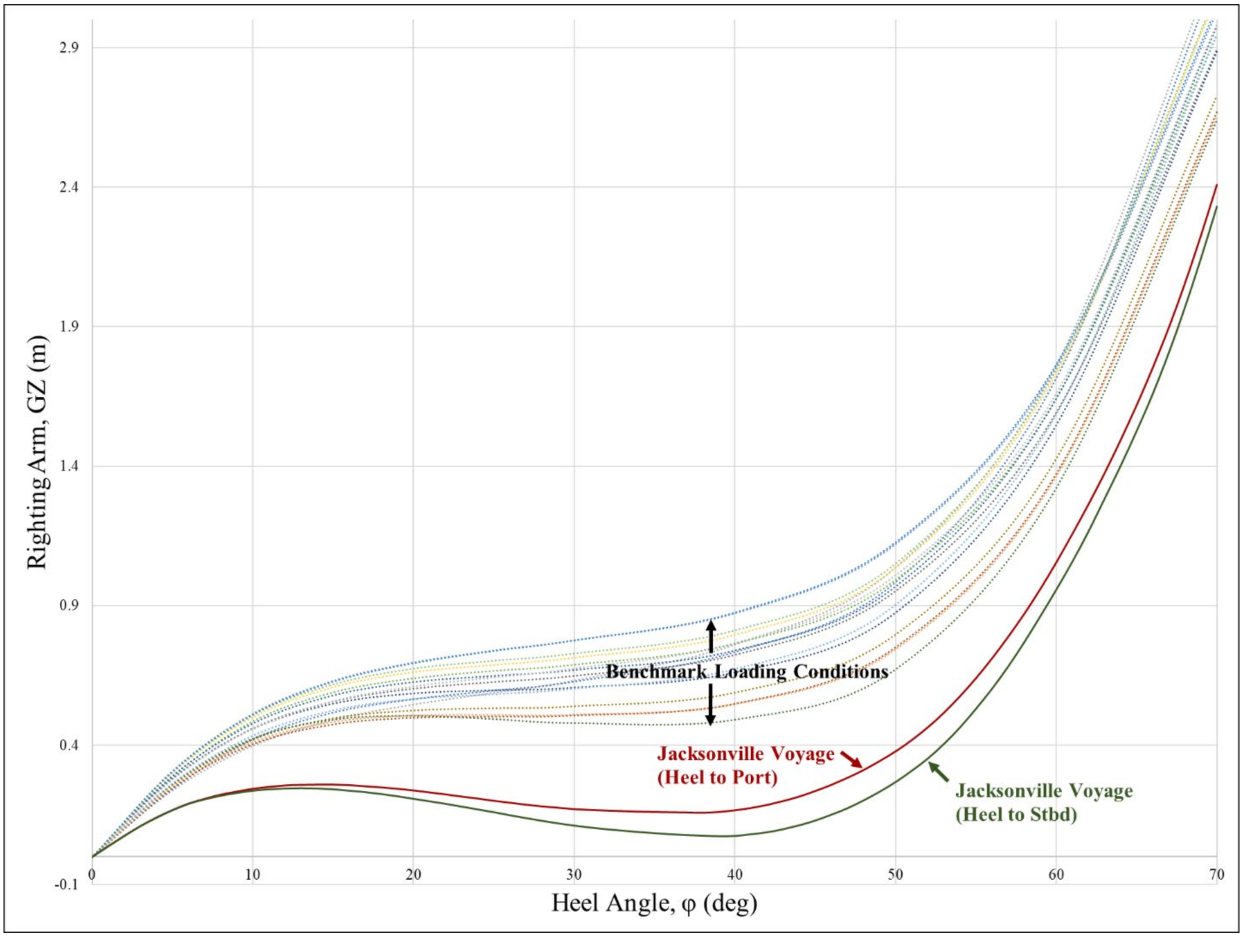

Figure B-1: Righting arm curves generated for the vessel in the Jacksonville to Brunswick voyage condition using the MSC computer model for heel to starboard (dark green line) and heel to port (dark red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

For the righting arm curves in Figure B-1, the 2008 IS Code mandatory intact stability criteria were applied, with results summarized in Table B-7. Red shading indicates that the attained value does not meet the specific criteria and green shading indicates that the attained value meets the specific criteria. For the IS Code general righting arm curve properties (Part A, Section 2.2), the righting arm curve did not meet the required minimum threshold for righting energy between 30° and 40°, and for the severe wind and rolling criteria (Part A, Section 2.3), the vessel failed to meet the Area Ratio threshold.

	Units	MSC Loading Condition (Jacksonville Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties			
Area to 30 degrees	m-rad	0.095	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.110	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.015	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	4.028	At least 0.2 m
Angle of maximum righting arm	deg	80.2	At least 25 deg
Initial GM	m	1.91	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria			
Angle of static heel (φ_0)	deg	5.5	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	Greater than 1

Table B-7: Results of the assessment of the MSC computer model loaded for the Jacksonville to Brunswick voyage with the mandatory requirements of the 2008 IS Code. Green background indicates that the criteria has been met. Red background indicates that the criteria has not been met.

The righting arm curves for the Jacksonville voyage were then compared to the righting arm curves for the capsize voyage generated in accordance with Section 4.3.2 of this report, and are shown in Figure B-2 for heel to starboard and Figure B-3 for heel to port.

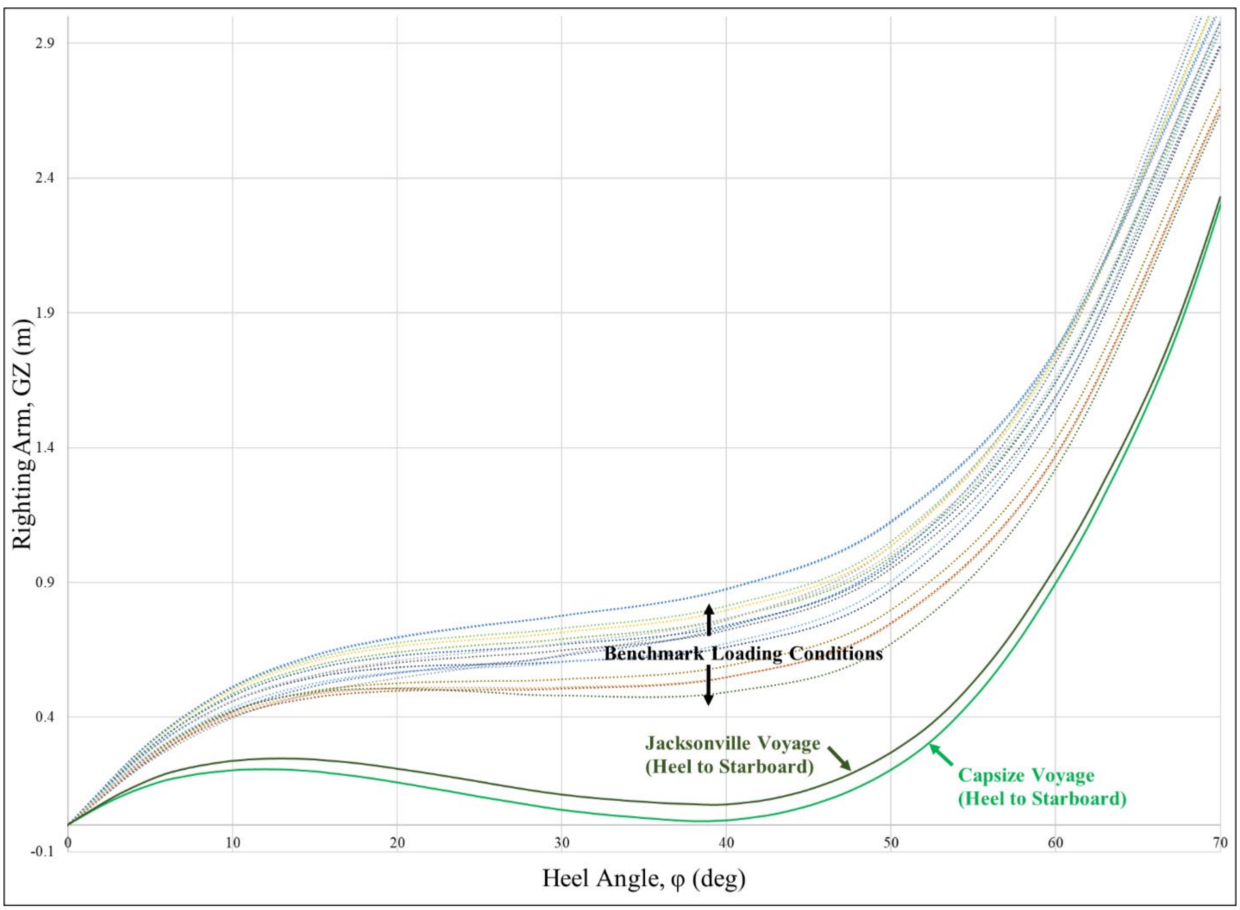

Figure B-2: Comparison of starboard righting arm curves for the vessel in the Jacksonville to Brunswick voyage (dark green line) and in the capsize voyage (light green line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

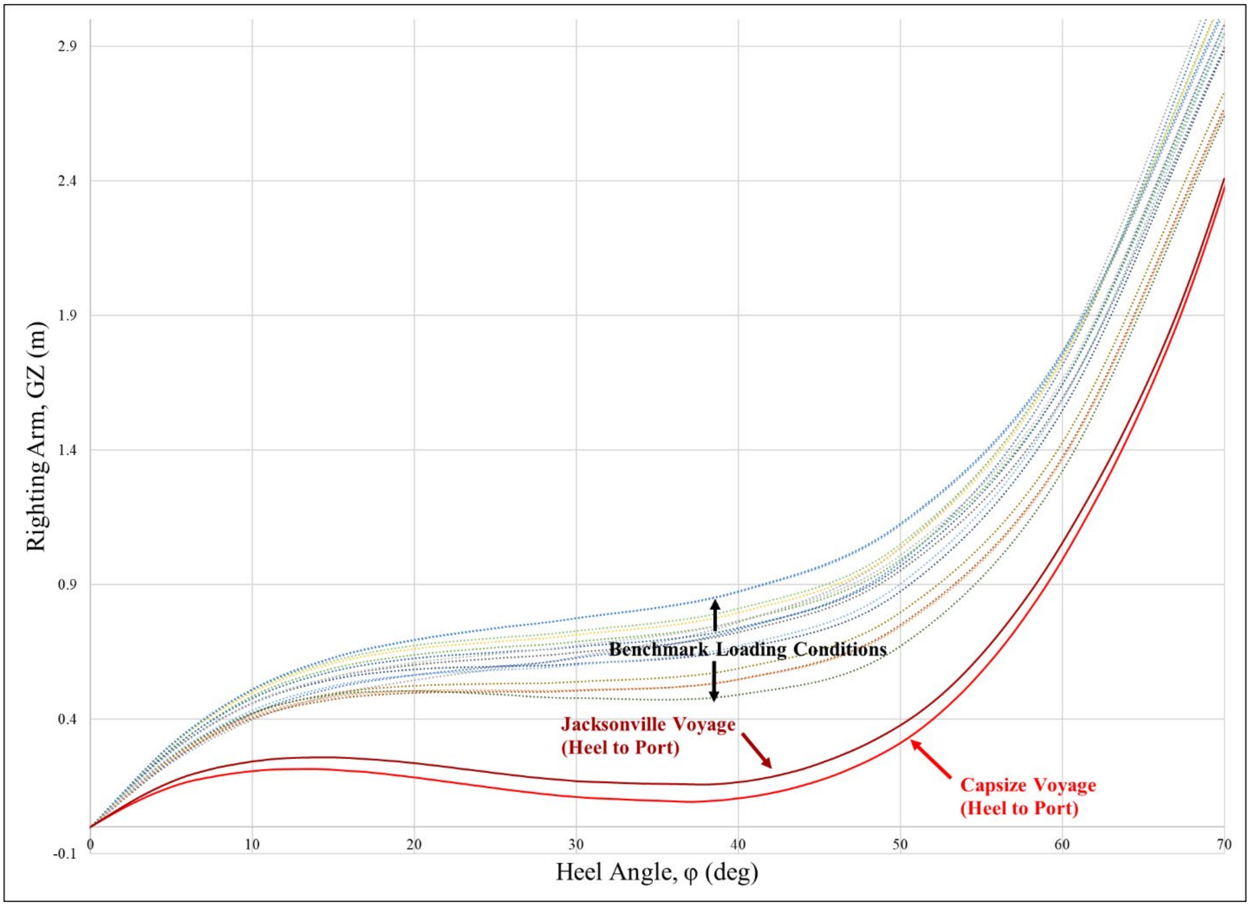

Figure B-3: Comparison of port righting arm curves for the vessel in the Jacksonville to Brunswick voyage (dark red line) and in the capsize voyage (light red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

B.3. Appendix References

B1 GOLDEN RAY IMACS Tank Summary for 07/09/19 05:01:32
B2 GOLDEN RAY Jacksonville Preliminary Stowage Plan
B3 U.S. Geological Survey National Water Information System, Salinity Data for Station "St Johns R Dames Point Bridge at Jacksonville, FL"

Appendix C: Freeport to Jacksonville Stability Analysis

An assessment of the GOLDEN RAY's intact stability during the transit from Freeport, TX to Jacksonville, FL beginning on August 30, 2019 was completed using the MSC computer model described in Section 2 of this report. This Appendix details the loading conditions applied to the model for this voyage and the resultant righting arm curves expected during this voyage.

C.1. Loading Conditions

This section details the information, methods, and assumptions used to simulate the Freeport, TX to Jacksonville, FL voyage loads that were applied to the MSC computer model. When available, actual liquid and cargo loading data from this voyage was used. For loads in which no data was available, Sections 5.3 and 5.4 of the T&S Booklet, which detail acceptable benchmark loading conditions for the vessel, were referenced.

C.1.1. Liquid Loading

As with the analysis for the capsize voyage, IMACS software data was used to apply the loads to the 47 major tanks in the MSC computer model. The tank quantities from the 04/09/19 17:35:39 UTC timestamp [C1] were used. This timestamp represents tank quantities following ballast discharge operations on September 3, 2019, and when the vessel was at nearly zero list. Using a timestamp in which the vessel was at zero list reduces error, as the IMACS tank readings do not appear to correct for heel.

A comparison of the tank values applied to the model to the tank values immediately prior to arrival in Jacksonville was conducted, the results of which are shown in Table C-1. Based on this data, fuel quantity appeared to decrease by a small amount throughout the remainder of the voyage, likely due to liquid load consumption; however the net liquid decrease of approximately 130 MT is insignificant to stability given the approximately 35,000 MT displacement of the vessel during this voyage.

	Mid-Voyage Load (MT)	Jacksonville Arrival Load (MT)	Difference (MT)	Difference %
Ballast	2993.45	2932.97	-60.48	-2.0%
Fuel	970.29	890.63	-79.66	-8.2%
Diesel	321.98	323.82	1.84	0.6%
Misc.	35.45	43.69	8.24	23.2%
Total	**4321.17**	**4191.11**	**-130.06**	-3.0%

Table C-1: Comparison between tank weights from the vessel's IMACS data files at the 04/09/19 17:35:39 UTC (13:35:39 EDT) (mid-voyage) timestamp and the 06/09/19 22:38:28 UTC (18:38:28 EDT) (Jacksonville Arrival) timestamp. The loads at the mid-voyage timestamp were applied to the MSC computer model.

Loads for the smaller tanks including lube oil, cooling water, and fresh water, which were not monitored by the vessel's IMACS software were assumed to be consistent with the Departure Bunkering Condition detailed in Section 5.3.1 of the T&S Booklet. Table C-2 shows the liquid load applied for these tanks, which accounted for 7.7% of the total liquid load applied to the model.

	Load Applied (MT)
L.O. Sludge TK (S)	0.0
S/T L.O Sludge TK (C)	0.0
F.O. Sludge TK (S)	0.0
Sewage Holding TK (P)	0.0
S/T Cooling Water TK (C)	30.2
No. 1 F.W. TK (S)	78.2
No. 2 F.W. TK (S)	156.4
M/E L.O. STOR. TK (P)	21.6
M/E. L.O. SET. TK (P)	0.0
G/E L.O. STOR TK (S)	9.7
G/E L.0. SET. TK (S)	0.0
NO. 1 CYL. Oil TK (S)	14.7
NO. 2 CYL. Oil TK (S)	22.0
M/E L.O. Sump TK (C)	26.8
Total	**359.6**

Table C-2: Liquid loads applied to MSC computer model for small tanks not monitored by IMACS. Values were selected in accordance with the T&S Booklet departure benchmark loading conditions.

C.1.2. Cargo Loading

The Freeport Preliminary Stowage Plan [C2] was used to determine the cargo loading applied to the MSC Computer Model. After superimposing the stowage plan onto the General Arrangement, the area centroid of each vehicle group was calculated and was assumed to represent the LCG and TCG of each vehicle group. The VCG of each vehicle group was determined by adding the corresponding deck height to a standard, assumed vehicle VCG of 0.57 m above the deck, an assumption which is consistent with previous analysis contained in this report. The weights of the vehicle groups were then applied to the MSC computer model in 73 individual point loads at the respective centers of gravity. These loads are summarized by deck in Table C-3.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
Deck 13	745.60	98.24	0.14	36.82
Deck 12	739.74	98.34	-1.89	34.51
Deck 11	933.22	89.48	1.22	32.00
Deck 10	988.00	89.98	0.14	29.47
Deck 9	1020.00	92.71	-0.33	26.93
Deck 8	995.00	86.31	-0.15	24.41
Deck 7	580.25	97.70	-1.76	21.71
Deck 6 Raised	119.29	23.59	10.58	18.97
Deck 6 Standard	500.00	122.68	3.66	18.27
Deck 5	479.12	110.35	-1.15	14.87
Deck 4	557.00	99.81	0.02	11.82
Deck 3	515.00	99.12	0.00	9.02
Deck 2	174.34	97.63	-0.83	6.12
Deck 1	195.15	94.04	0.12	3.42
Total	**8541.7**	**95.36**	**0.11**	**24.33**

Table C-3: Cargo weights applied to the MSC model from the Freeport Preliminary Stowage Plan summarized by Deck. Deck 6 is subdivided into cargo situated on deck panels which were raised 0.7 m and cargo situated on deck panels which were at the standard height.

C.1.3. Miscellaneous Deadweight

The weight of miscellaneous deadweight items, including the fixed firefighting system's carbon dioxide, swimming pool water weight, provisions, stores, and cargo lashing equipment, were applied to the MSC Computer model consistent with the values listed for the Departure Condition detailed on page 266 of the T&S Booklet.

C.1.4. Final Loading

A summary of the final loading conditions applied to the MSC Computer model for the Freeport to Jacksonville voyage is shown in Table C-4.

	Weight (MT)	LCG (m-AP)	TCG (m-CL)	VCG (m-AB)
LTSH	21433.0	85.9	-0.27	18.3
Tanks	4680.8	102.1	2.04	3.9
Cargo	8541.7	95.4	0.11	24.3
Misc. Deadweight	230.4	74.4	-2.33	25.3
Total	**34885.9**	**90.3**	**0.12**	**18.1***

Table C-4: Final loading condition applied to the MSC computer model for the Freeport to Jacksonville voyage. *VCG includes 0.250 m of free surface correction.

C.2. Results

C.2.1. Final Hydrostatics

The 0.12 m starboard TCG of the final loading condition applied to the model resulted in a starboard heel of 2.9 degrees. However, IMACS data did not indicate significant heel throughout the voyage. As such, a zero heel condition was applied to the vessel for all subsequent stability analysis. Consistent with previous analysis in this report, this was done by setting the heel of the vessel model equal to zero, allowing it to trim freely in order to remove residual longitudinal moments, and solving for the resultant TCG.

The hydrostatic properties with the loads applied for the Freeport to Jacksonville voyage with the vessel at zero heel were then calculated and are shown in Table C-5.

	Disp. (MT)	LCB (m-AP)	VCB (m-BL)	LCF (m-AP)	MTC (m*MT/cm)	KMt (m-BL)	GM (m)	TPC (MT/cm)
Disp. (MT)	34885	90.37	5.32	78.06	621.50	19.99	1.85	56.03

Table C-5: Final hydrostatic properties calculated from the MSC computer model for the vessel in the zero heel condition with the loading applied for the Freeport to Jacksonville voyage.

C.2.2. Drafts

With the vessel at 0 degrees heel, the resultant drafts calculated using the MSC computer model were compared to the drafts reported by IMACS as shown in Table C-6. The mean draft of the MSC model in salt water was within 0.05 m of the mean draft reported by the vessel's IMACS on September 4, 2019.

	MSC Model Salt Water	IMACS
Taft (m)	9.36	9.44
Tfwd (m)	9.21	9.23
Tmean (m)	9.29	9.34

Table C-6: Comparison between loaded drafts calculated using the MSC computer model in salt water with IMACS drafts on September 4, 2019 at the 04/09/19 17:35:39 UTC timestamp.

C.2.3. Freeport Voyage Righting Arm Curve Properties

With the MSC computer model loaded for the Freeport to Jacksonville voyage in accordance with Section C.1, and with list set to 0 degrees, righting arm curves were generated for heel to port and starboard in salt water. These righting arm curves are shown in Figure C-1 by the teal green line (heel to starboard) and the dark red line (heel to port). For comparison of righting arms with loading conditions which meet regulatory requirements, the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT are also shown (dotted lines).

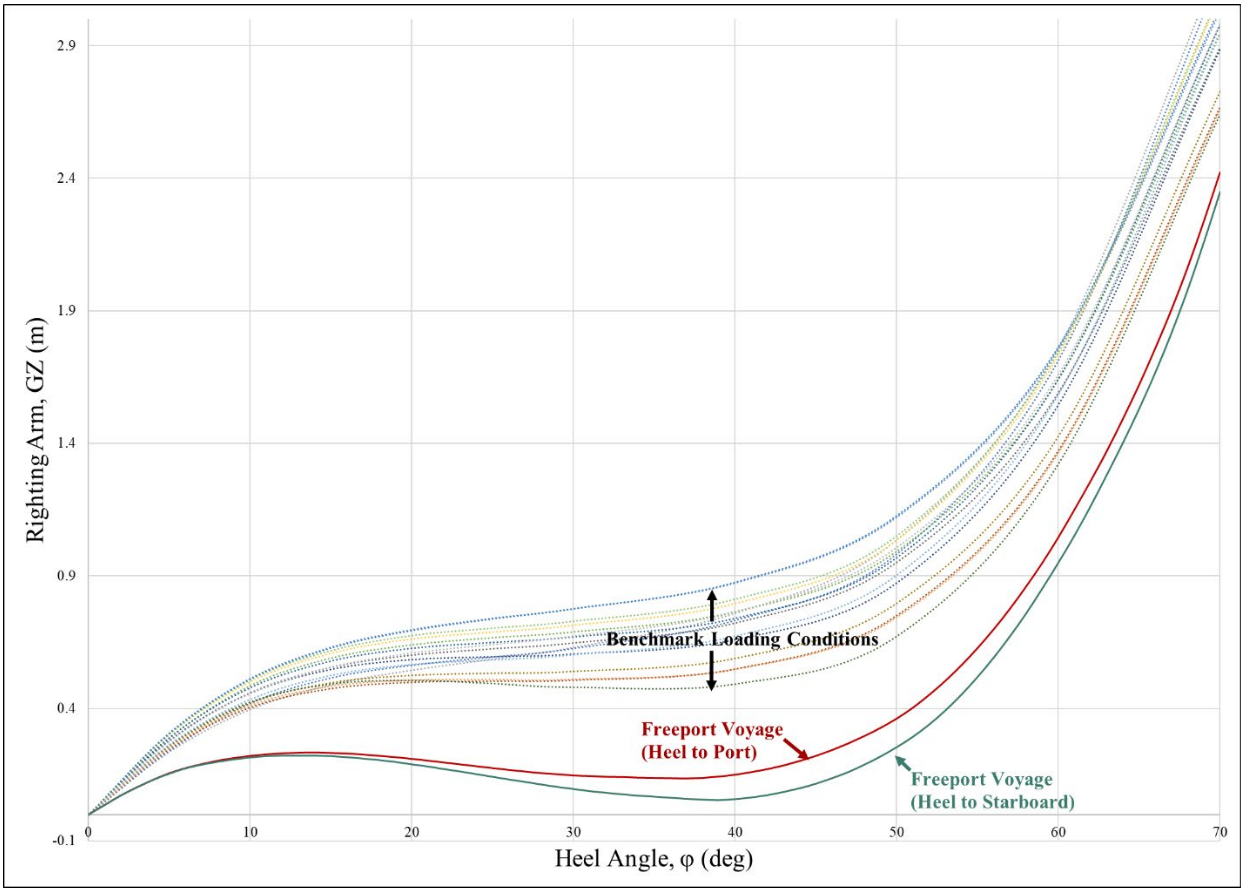

Figure C-1: Righting arm curves generated for the vessel in the Freeport to Jacksonville voyage condition using the MSC computer model for heel to starboard (teal green line) and heel to port (dark red line). Also shown for comparison are the righting arm curves from all T&S benchmark conditions with displacements between 32,000 MT and 38,000 MT (dotted lines).

For the righting arm curves in Figure C-1, the 2008 IS Code mandatory intact stability criteria were applied, with results summarized in Table C-7. Red shading indicates that the attained value does not meet the specific criteria and green shading indicates that the attained value meets the specific criteria. For the IS Code general righting arm curve properties (Part A, Section 2.2), the righting arm curve did not meet the required minimum threshold for righting energy between 30° and 40°, and for the severe wind and rolling criteria (Part A, Section 2.3), the vessel failed to meet the Area Ratio threshold.

	Units	MSC Loading Condition (Freeport Voyage)	Required Value
Part A Section 2.2 - Criteria regarding righting arm curve properties			
Area to 30 degrees	m-rad	0.084	At least 0.055 m·rad
Area to 40 degrees/downflooding	m-rad	0.095	At least 0.09 m·rad
Area between 30 and 40 degrees/downflooding	m-rad	0.011	At least 0.03 m·rad
Maximum righting arm at 30 degrees or greater	m	4.056	At least 0.2 m
Angle of maximum righting arm	deg	80.4	At least 25 deg
Initial GM	m	1.84	At least 0.15 m
Part A Section 2.3 - Severe wind and rolling criteria			
Angle of static heel (φ_0)	deg	6.2	Not to exceed 16 deg or angle for 80% of angle to deck edge immersion
Area ratio (A_1/A_2)	m-rad	0 (No Area A1)	Greater than 1

Table C-7: Results of the assessment of the MSC computer model loaded for the Freeport to Jacksonville voyage with the mandatory requirements of the 2008 IS Code. Green background indicates that the criteria has been met. Red background indicates that the criteria has not been met.

The righting arm curves for the Freeport voyage were then compared to the righting arm curves for the capsize voyage generated in accordance with Section 4.3.2 of this report, and are shown in Figure C-2 for heel to starboard and Figure C-3 for heel to port.

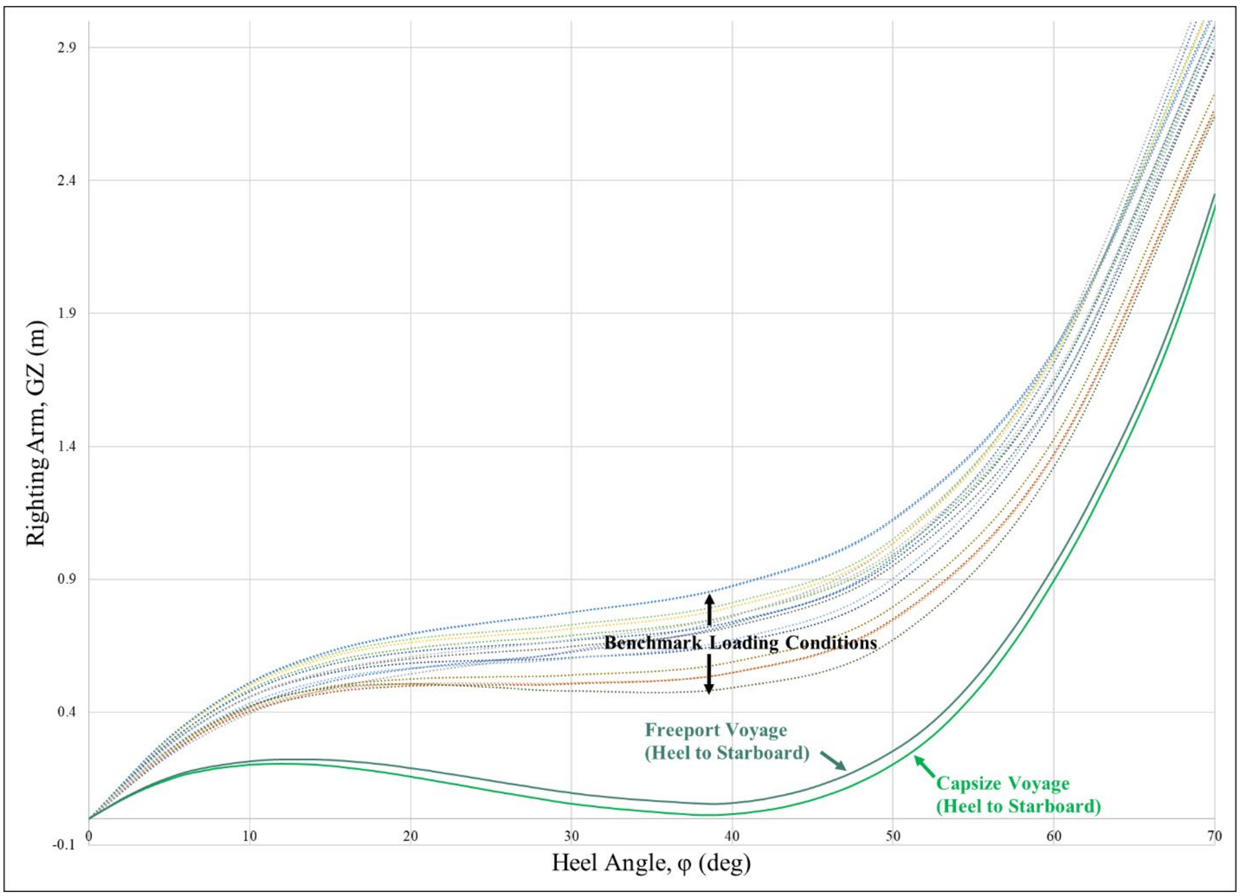

Figure C-2: Comparison of starboard righting arm curves for the vessel in the Freeport to Jacksonville voyage (teal green line) and in the capsize voyage (light green line).

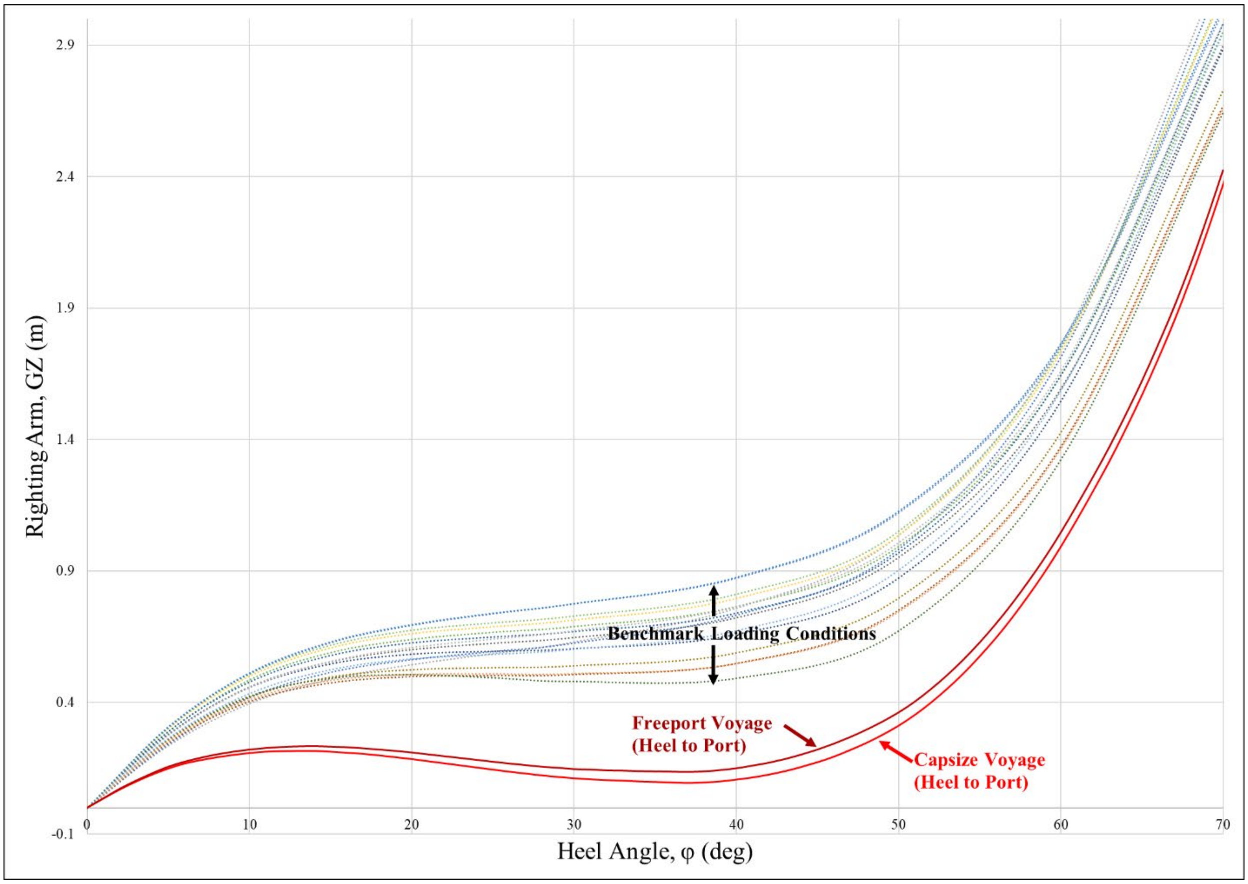

Figure C-3: Comparison of port righting arm curves for the vessel in the Freeport to Jacksonville voyage (dark red line) and in the capsize voyage (light red line).

C.3. Appendix References

C1 GOLDEN RAY IMACS Tank Summary for 07/04/19 17:35:39

C2 GOLDEN RAY Freeport Preliminary Stowage Plan