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United States Coast Guard

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16710/P024492
Serial: A0-2400418
22 February 2024

MEMORANDUM

From: [redacted]
SERT Principal Naval Architect

To: [redacted], LT
CG SECTOR CHARLESTON (spv)

Subj: POST-SINKING STABILITY ANALYSIS OF TUG JACQUELINE A (O.N. 638353)

Ref: (a) Your email dated 31 Aug 2023
(b) Resolve Marine email dated 6 Sep 2023, Regarding JACQUELINE A Weights

1. We have conducted a stability analysis of Towing Vessel JACQUELINE A as you requested in reference (a) and our later discussions. Specifically, you requested an assessment of the vessel's intact stability and progressive flooding rate.

2. I attended the vessel at Steven's Towing in Yonges Island, SC on 19 Oct 2023 and measured the vessel to create a computer model for hydrostatics analysis. No drawings or stability data were available to validate this computer model.

3. Using the observed freeboards and tank soundings within reference (b), we used our model to calculate the vessel's weight and longitudinal center of gravity. We estimated that the weight of the vessel was 146 short tons excluding liquids in tanks. This weight was used with the owner's reported lightship weight of 130 short tons given in reference (b). We assumed that the 16 short ton weight difference included crew effects, spares, food, and other items not included in lightship weight or as liquids inside tanks.

4. Through discussions with your staff, we used a pre-casualty tank loading of JACQUELINE A consisting of:

a. 5,000 gallons of diesel in the outboard fuel tanks
b. 75% loading of fresh water in the potable water tanks

5. Although JACQUELINE A was uninspected at the time of casualty, we used the stability requirements for partially protected routes for new towing vessels in 46 CFR subchapter M as an objective reference standard against which to compare the intact stability in the pre-casualty condition. Our analysis shows that JACQUELINE A satisfied these intact stability criteria in the assumed pre-casualty condition.

6. We used our model to evaluate progressive flooding of the engine room from the lazarette. For this analysis, we used the measured area of the holes through the main deck into the lazarette and the wire runs from the lazarette to the engine room. Vessel motions and waves would have gradually filled the lazarette with seawater until the holes in the deck were submerged. Once the wastage holes in the deck were submerged, our analysis indicates that JACQUELINE A could have sunk by the stern in 9 to 16 minutes.

7. Enclosure (1) is a detailed explanation of our assumptions and analysis. Please contact me if you have questions or need additional information.

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Enclosure: (1) Explanation of Analysis & Assumptions
(2) MSC GHS Output, 31 Jan 2024

1. General Comments Regarding Our Stability Analysis

All references in this analysis are as listed on Marine Safety Center (MSC) Memo, Serial No. A0-2400418 dated 22 Feb 2024.

Creative Systems' General HydroStatics (GHS) software version 18.92 was used for our analysis. Our GHS model was created from direct offset measurements of JACQUELINE A at Steven's Towing in Yonges Island, SC on 19 Oct 2023. A picture of the vessel is shown in Figure 1. Offset measurement was conducted both by conventional tape measure and Light Detection and Ranging (LiDAR). No vessel drawings or prior stability test data were available to validate the model.

JACQUELINE A was an uninspected vessel at the time of the casualty. Existing inspected towing vessel stability criteria is found within 46 CFR subchapter M. In most cases, 46 CFR 144.300 permits operation of existing vessels without any stability documents. We used the intact stability criteria for new towing vessels given in 46 CFR 144.305. For routes on partially protected waters, the stability criteria is given in 46 CFR 170.170, "Weather criteria," and 170.173(e)(1) "Criterion for vessels of unusual proportion and form." We did not evaluate 46 CFR part 173, subpart E, "Towline pull criterion" because the vessel was not engaged in towing at the time of the casualty. We did not evaluate JACQUELINE A using 46 CFR part 174, subpart E, "Intact stability requirements," because the vessel was neither oceangoing nor subject to 46 CFR subchapter I.

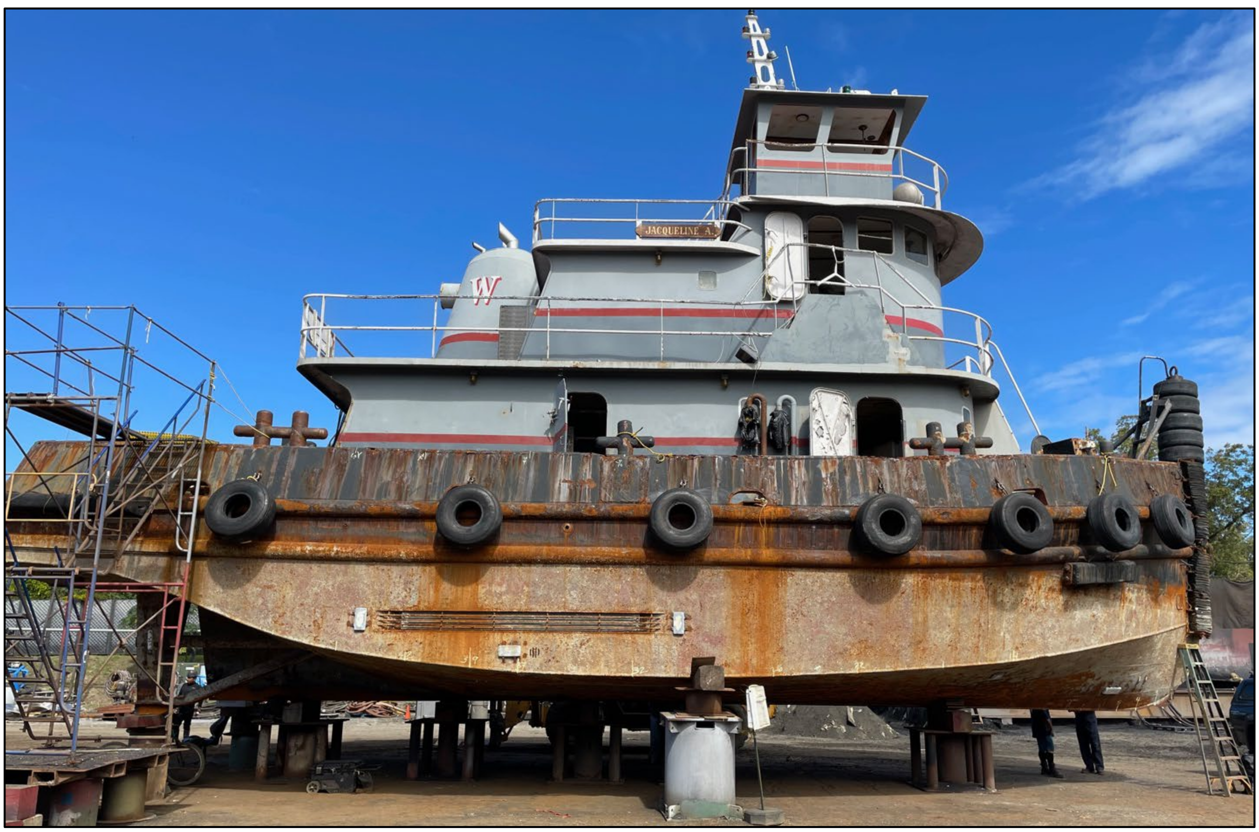

Figure 1: JACQUELINE A at the Steven's Towing Yard on 19 Oct 2023

2. Modeling Procedure

The computer model used throughout this analysis was created by MSC based on the direct measurements of JAQUELINE A on 19 Oct 2023.

LiDAR measurement was performed using the Polycam app on an iPhone 12 Pro. Points were captured by walking around the vessel in video mode. The Polycam app captures the three-dimensional points with LiDAR and then colors the points using the iPhone's camera. A total of 4,160,440 unique points were captured during an approximately 5-minute scan while walking around and under the vessel. Point clouds are shown in Figure 2.

LiDAR points on the starboard quarter showed some inconsistency due to scaffolding next to the vessel in this area (shown in Figure 1). The port side points were used in this area with the assumption that the vessel is symmetric about the centerline.

Using Rhino 3D (version 7), we used the LiDAR points to fit three-dimensional surfaces through the points, creating the hull bottom, sides, and bulwarks (3 surfaces). Offset measurements were less accurate than LiDAR measurements and were used as a secondary check of the surface fit. Once surfaces were complete, a two-dimensional lines plan was created for use as a GHS model. This modeling progression is shown in Figure 3.

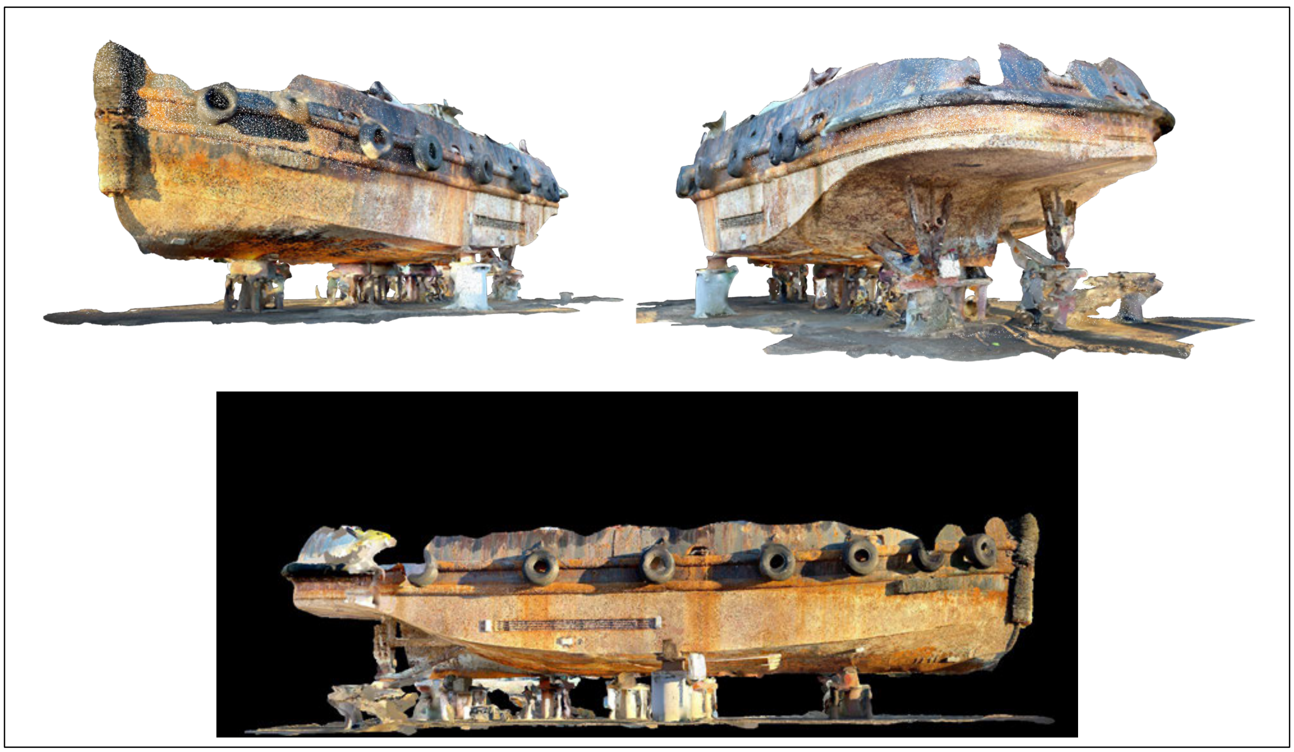

Figure 2: LiDAR Generated 3D Point Clouds of JACQUELINE A

Figure 3: Modeling Progression: Point Cloud and Offsets (top), Surfaces Fit Through Point Cloud and Offsets (middle), Lines Plan (bottom)

For our model, the house structure and bulwarks were not considered to provide any buoyancy. They were included in the model for clarity and regulatory wind calculations. A rendering of the complete Rhino model is shown in Figure 4.

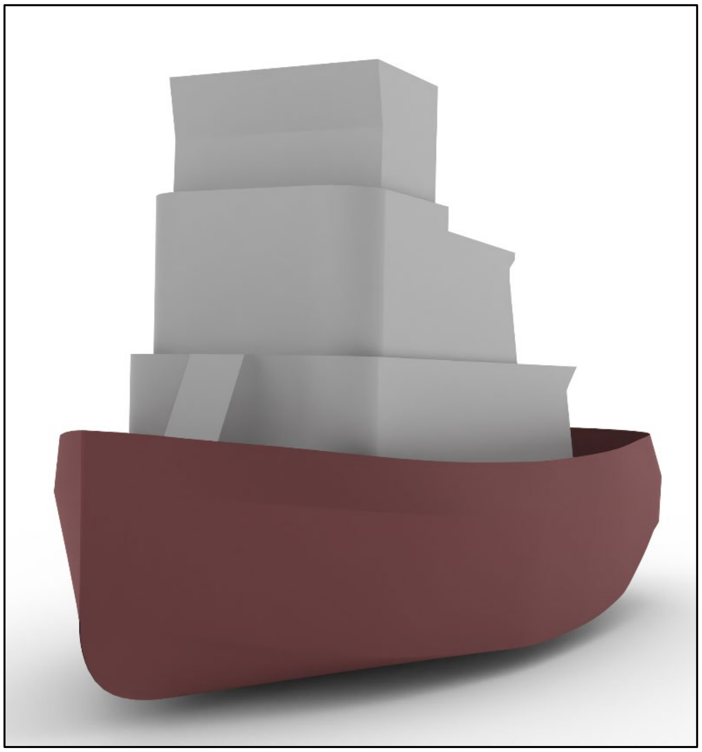

Figure 4: Rhino Rendering of Model

Tanks were modeled using the measured length of each compartment and the width of the fuel tanks. Tank permeability is the percentage of the compartment that can be filled with floodwater. In our model, permeabilities were set to 95% for all tanks and the store room and 85% for the engine room. Figure 5 is a sketch of tank locations and capacities.

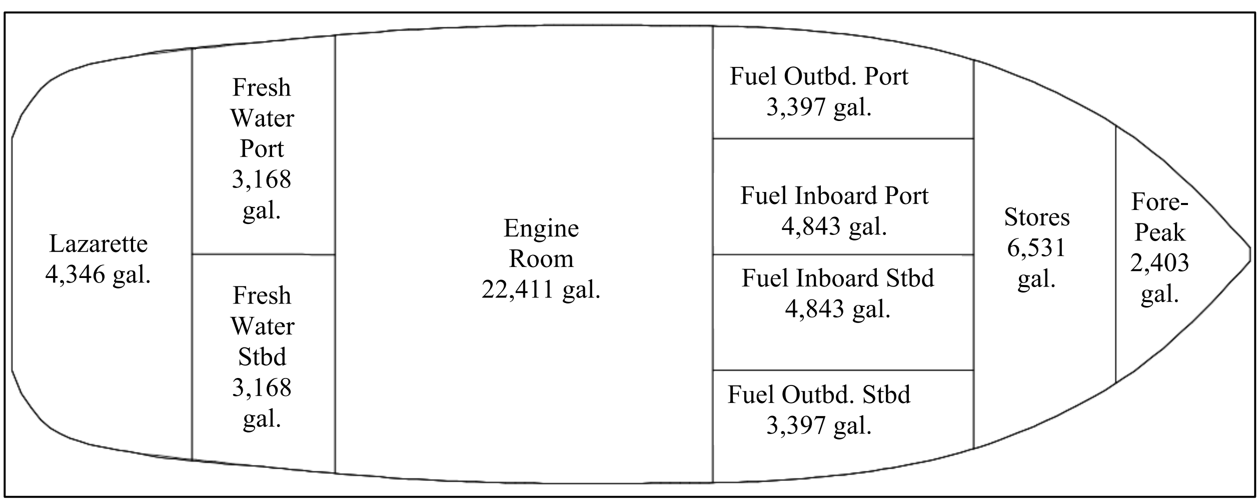

Figure 5: Tank Sketch with Permeable Volumes

A downflooding point is an opening in the vessel that permits the ingress of water to the buoyant hull. Downflooding points include weathertight openings (such as doors that are not fully watertight). Based on our examination of the JACQUELINE A, the lowest intact downflooding points are the doors to the house. These doors were typical weathertight doors with gaskets and two dogs opposite of the hinges. These downflooding points are shown in Figure 6 and Table 1.

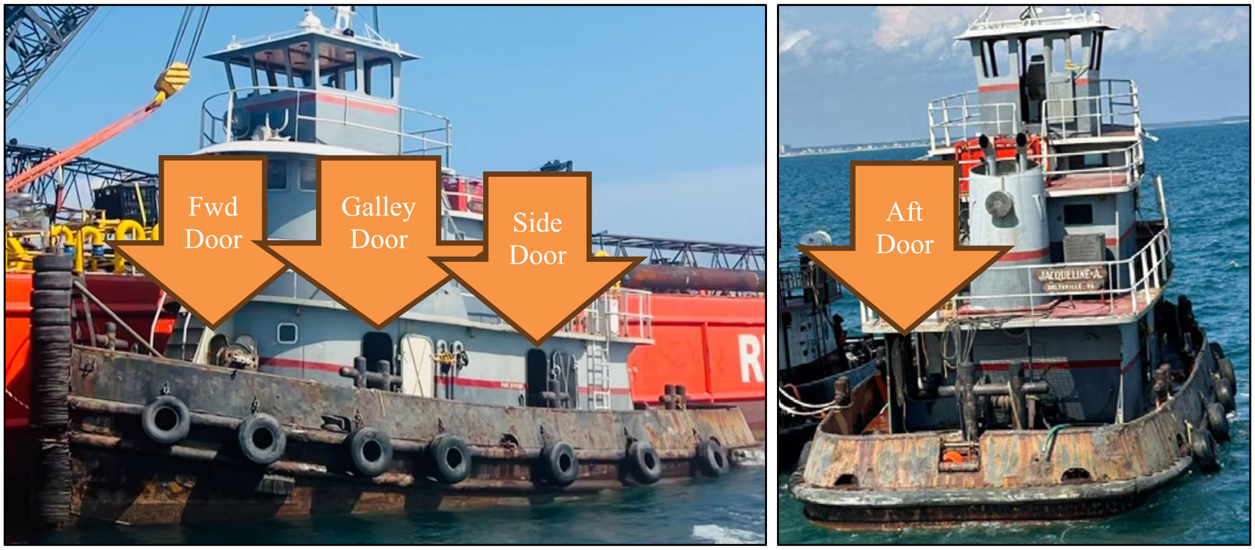

Figure 6: Refloated Condition Pictures with Downflooding Points Indicated

Downflooding Point	Connected Compartment	Longitudinal Position (feet from bow)	Transverse Position (feet from centerline)	Vertical Position (feet above baseline)	Height Above Deck (feet)	Distance from Deck Edge (feet)
Fwd Door (port only)	Stores	9.50	1.53	11.25	1.77	7.00
Galley Door	House	17.50	6.73	10.80	1.50	4.00
Side Door	Engine Room	35.00	7.09	10.30	1.33	3.25
Aft Door (port only)	Engine Room	42.75	4.00	10.87	1.08	4.00

Table 1: Downflooding Points (Intact/Non-Damaged Condition Only)

In addition to normal downflooding points, JACQUELINE A had deck wastage near the stern that would allow downflooding into the lazarette. Three large holes were observed and measured. These holes are considered in our downflooding/sinking analysis but not in the intact stability analysis. Hole location is shown in Figure 7 and Table 2.

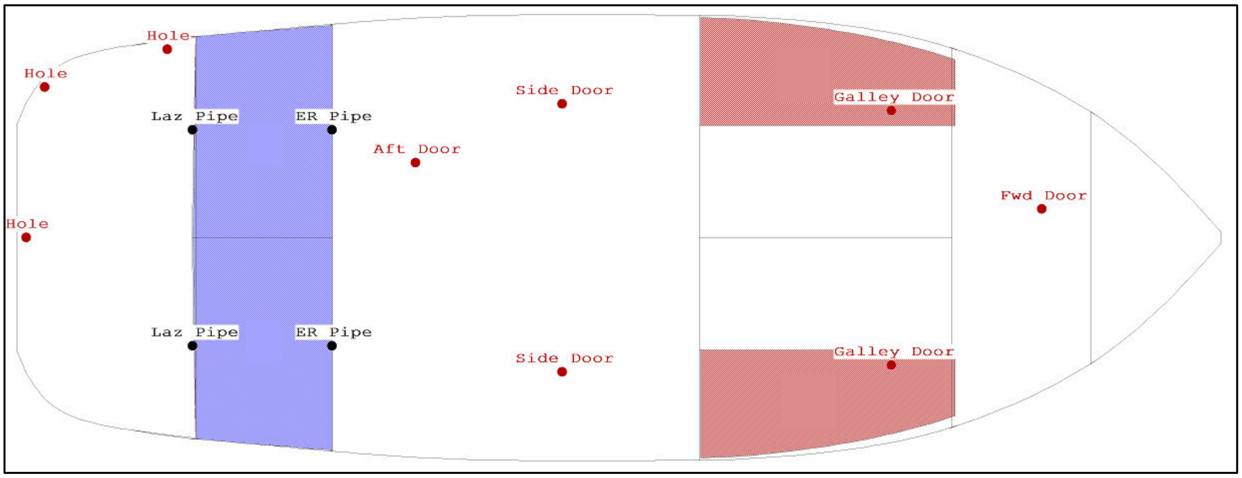

Figure 7: Plan View Sketch of Downflooding Points, Holes, and Tanks

Downflooding Point	**Connected Compartment**	**Longitudinal Position** (feet from bow)	**Transverse Position** (feet from centerline)	**Vertical Position** (feet above baseline)	**Size of Hole**
Deck Hole Aftmost	Lazarette	63.5	Centerline	9.27	2" diameter circular Appx. 12.6 sq.in
Deck Hole Port Quarter	Lazarette	62.5	8.0 port	9.20	5" diameter circular Appx. 78.5 sq.in
Deck Hole Port Aft	Lazarette	56	10.0 port	9.16	9" x 4" rectangular Appx. 50.3 sq.in

Table 2: Downflooding Points from Deck Wastage

The final flooding points that we considered are the wire runs that connect the lazarette to the engine room. These port and starboard wire runs are 4” inside diameter pipe that are 6-1/2” below the bottom of the deck and 5’ 8-7/8” off centerline in the aft bulkhead of the engine room and the forward bulkhead of the lazarette. These points were modeled as cross-flooding points where the contents of the Lazarette can progressively flood into the Engine Room.

An iterative time-stepped approach was used to evaluate this effect using the Bernoulli flow equation. At each iteration:

- The lazarette is flooded through openings on deck. The volume of water that enters the lazarette is a function of head (depth below the outside waterline), opening size, and time step.
- Hydrostatic (head) pressure is calculated at the engine room end of the pipe based on its height below the external waterline.
- A volume of water enters the engine room as a function of head, opening size, and time step. The formula is:

$$flow/timestep = \sqrt{head} * opening\ area * \sqrt{2 * gravitational\ acceleration}$$

- This formula yields the same result as equation 1-4.1 in the U.S. Navy Salvor’s Handbook:

$$flow\ rate\ (gpm) = 3600 * hole\ area\ (ft^3)\ \sqrt{head\ (ft)}$$

3. Assumed Loading Condition at the Time of the Casualty

No stability or weight data was known to exist prior to our stability analysis. The owner reported a lightship weight of 130 short tons to the salvage company, and absent information to the contrary, we assumed this value in our analysis. We used the free-floating condition after salvage to calculate the weight of JAQUELINE A from freeboards. This condition was reported by the salvor, Resolve Marine Group, as shown in Table 3. Sounding locations within tanks were chosen as their lowest point. For the Forepeak, Stores, and Fuel Tanks the lowest point in the tank is located at the aftmost inboard (closest to centerline or centerline, as appropriate) point. For the Lazarette and Water Tanks, the lowest point for measuring soundings is the forward most centerline point. The engine room’s lowest point was chosen at the centerline of the midlength of the engine room, 37.55 feet aft of the bow. After refloating, all tanks were assumed to contain seawater.

Freeboard at Tow Bitt	6’	Corresponds to a draft of 4.5’
Freeboard at Amidships	3’	Corresponds to a draft of 5.9’
Freeboard at Stern	2’	Corresponds to a draft of 7.3’
Forepeak Tank Sounding	1”	<1 gallon
Stores Sounding	Estimated at 3”	3 gallons
Inboard Fuel Starboard	Unable to Sound	Assumed 2”, 2 gallons
Outboard Fuel Starboard Sounding	7.5”	51 gallons
Inboard Fuel Port	Unable to Sound	Assumed 2”, 2 gallons
Outboard Fuel Port Sounding	1”	1 gallon
Engine Room Sounding	Estimated 3-5”	31 gallons
Water Tank Starboard	0”	Empty
Water Tank Port	7”	5 gallons
Lazarette	1”	3 gallons

Table 3: Refloated Condition Freeboard and Tank Summary from Resolve Marine

For the free-floating condition, fixed weight represents a combination of lightship weight and other solid weights onboard. To calculate this weight and its longitudinal center of gravity (LCG), we subtracted the liquid load from the observed displacement. Using the assumed 130 short tons for lightship weight and a conservative estimate of 70% of the hull depth for vertical center of gravity (VCG), we calculated the fixed weights shown in Table 4.

Fixed Weight	Weight (short tons)	Longitudinal Center of Gravity, LCG (feet aft of bow)	Transverse Center of Gravity, TCG (feet stbd of center line)	Vertical Center of Gravity, VCG (feet above base line)
Light Ship	130.00	33.28	0.00	5.40
Unknown Fixed Weight	16.16	33.28	-0.10	5.40

Table 4: Fixed Weights Calculated from Refloated Condition

Although the 16.16 short ton fixed weight is unknown, it would normally include items such as spare parts, crew effects, food, and other solid weights that are not accounted for as liquids in Table 3. Vessels also tend to gain weight over their lifetime and the unknown fixed weight also includes this weight growth. Because the VCG of the unknown fixed weight could not be determined, we used a range of values in our analysis.

The assumed centers of gravity of the lightship weight and the unknown fixed weights both contribute to the total center of gravity. These unknown centers of gravity lead to uncertainly in the analysis. To address this uncertainty, we used the following methods:

- We assumed that the VCG of the lightship and fixed weight were always the same.[1]
- VCG heights from 4.5 to 6.75 feet were investigated in 3-inch increments.
- LCG positions in the post-casualty refloated condition were assumed to be the furthest aft extent of LCG (because the vessel sank by the stern and unsecured items would have shifted aft).
- Two additional LCG positions were investigated by shifting only the "unknown fixed weight" forward in 4-foot increments.[2]
- We assumed the vessel had negligible heel in the pre-casualty condition. To achieve this, the transverse centers of gravity (TCG) of fixed weight items was assumed to be zero.

The reported pre-casualty tank loading was 75% capacity in the water tanks and 5,000 gallons of total fuel split evenly between the two outboard fuel tanks. This represents a total liquid weight of 37.98 short tons.

Using the reported tank loading and the assumed range of LCG and VCG, we generated a total of 30 pre-casualty conditions as shown in Table 5. These conditions encompass the range of likely centers of gravity for JACQUELINE A.

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[1] VCG of variable and lightship weight are both unknown. To avoid having two unknowns, one fixed weight VCG was chosen.

[2] From freeboards, we can accurately calculate the total LCG. By assuming 130 short tons for the lightship, we can isolate the light ship's LCG from the unknown fixed weight. This allows us to reasonably shift LCG ensuring that it falls within a range that is plausible from the refloated condition.

Weight Item	**Volume**	**Weight (short tons)**	**Longitudinal Center of Gravity, LCG (feet aft of bow)**	**Transverse Center of Gravity, TCG (feet from centerline)**	**Vertical Center of Gravity, VCG (feet above baseline)**
Light Ship		130	33.28	0.00	4.50 4.75 5.00 5.25 5.50 5.75 6.00 6.25 6.50 6.75
Unknown Fixed Weight		16.16	33.28 29.00 25.00	0.00	
Starboard Fuel Oil Outboard	2,500 Gallons	9.07	21.96	8.23 stbd	4.45
Port Fuel Oil Outboard	2,500 Gallons	9.07	21.96	8.23 port	4.45
Starboard Fresh Water	2,376 Gallons	9.91	50.60	5.22 stbd	5.61
Port Fresh Water	2,376 Gallons	9.91	50.60	5.22 port	5.61
Total Weight		*184.14*	*33.84* *33.65* *33.48*	*0*	*4.61* *4.70* *4.79* *4.87* *4.96* *5.05* *5.14* *5.23* *5.32* *7.79*

Table 5: Range of Pre-casualty Conditions Investigated. Each of the Values in the Highlighted Cells is Used.

4. Intact Stability Evaluation

We evaluated the intact stability criteria for a new towing vessel on partially protected routes for each of the 30 pre-casualty loading conditions shown in Table 5. In each of the fully intact pre-casualty conditions investigated (without holes in the deck to the Lazarette) JACQUELINE A satisfied the 46 CFR 170.170 "Weather criteria" and 46 CFR 170.173(e)(1) "Criterion for vessels of unusual proportion and form." The stability of JAQUELINE A was satisfactory for the intact requirements of 46 CFR subchapter M for partially protected routes.

5. Time to Sink Analysis

We used our model to perform a quasi-static analysis to determine the time it would take for JACQUELINE A to sink due to progressive flooding in the lazarette through wire runs to the engine room.

In each of the investigated loading conditions the deck and holes to the lazarette were above the waterline. In the pre-casualty condition, our model indicated that the holes were 10" to 1'2" above the waterline when the lazarette was empty. We assumed that seawater on deck from waves and the pitching and heeling motions of the vessel would gradually and intermittently fill the lazarette through the holes with seawater. However, our analysis does not include vessel motions or waves and we could not model this intermittent flooding from waves and motions.

To model progressive flooding, we used a starting condition where the lazarette was partially flooded. This flooding caused the model to trim aft, increase the aft draft, and submerge the holes in the deck. We started our analysis with enough lazarette flooding so that the holes were 1/2" below the static waterline. This occurs with between 2,086 gallons to 3,194 gallons in the lazarette depending on the pre-casualty (unflooded) trim as shown in Table 6.

Pre-casualty Aft Trim	Pre-casualty Hole Position Above Waterline	Amount of Seawater in Lazarette to Submerge Aft Wastage Hole by 1/2"
3' 4"	10"	2,086 - 2,259 gallons
2' 11"	1'	2,594 - 2,738 gallons
2' 6"	1' 2"	3,042 - 3,194 gallons

Table 6: Time Step Starting Condition Hole Location and Floodwater in Lazarette

We used GHS to evaluate the formula shown in Section 2 using 3 seconds as a time step. With the aftmost hole in the deck 1/2" below the surface, the initial flooding rate into the lazarette is approximately 80 gallons per minute. In this condition, the port quarter hole is also submerged 3/8" below the waterline. At the starting depth, the initial flooding rate through the larger port quarter hole is 480 gallons per minute for a total of 560 gallons per minute.

As the lazarette floods through the holes in the deck, the vessel's draft and aft trim increase, moving the hole deeper and increasing the flooding rate. The rate of flooding, aft trim, and mean draft increase with time. Our analysis shows that the third deck hole in the port side aft submerges after 45-48 seconds. At this point, the total flooding rate into the lazarette has increased to 1,700 gallons per minute and the lazarette floods completely within 90 seconds.

Because of the aft trim in all conditions, no engine room flooding occurs until the lazarette is 100% full. This is because the wire runs are near the top forward bulkhead of the lazarette. This is the last location of the lazarette to fill when the vessel has aft trim. Additionally, the wire runs, normally level with no trim, are angled upward to the engine room with aft trim. This requires the lazarette to be fully submerged to have external head pressure forcing water up the wire runs into the engine room.

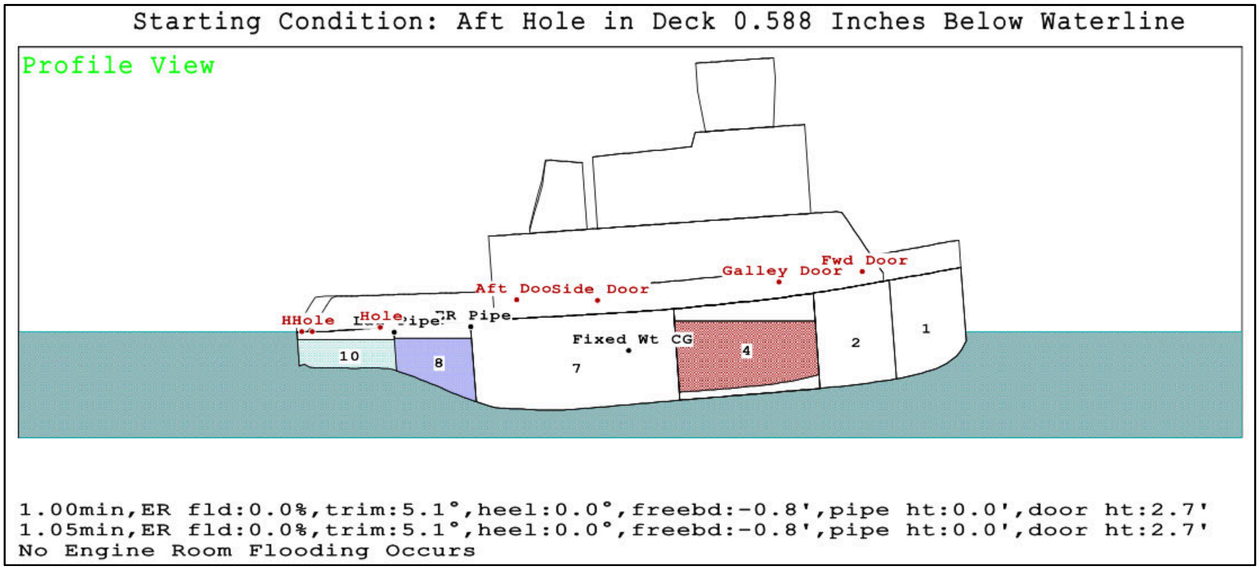


Figure 8: Timestep Analysis Showing Initial Lazarette Flooding Resulting in No Flooding of the Engine Room (Fixed VCG 5.25', Variable LCG 25')

Once the lazarette floods completely, the engine room begins flooding only if the model's aft trim is greater than 5 feet and the deck edge at the stern is 10" below the waterline. Because JACQUELINE A's engine room did flood, we can dismiss these cases where the engine room does not flood. These cases are the least trimmed cases with VCG less than 5.5 feet.

Flooding of the engine room from the lazarette through the two wire runs begins when there is head pressure at the outlet of the wire run pipes. Table 7 shows a typical flooding sequence.

Once the waterline reaches a normal downflooding point (the aft door was the lowest in all cases evaluated), flooding rates increase rapidly. The aft door was 2' wide which would result in a flooding rate over 5,000 gpm when the door sill was 1' below the waterline. Flooding through the door would rapidly fill the house and engine room to sink the tug. We stopped the progressive flooding analysis when the aft door sill was 1' below the waterline.

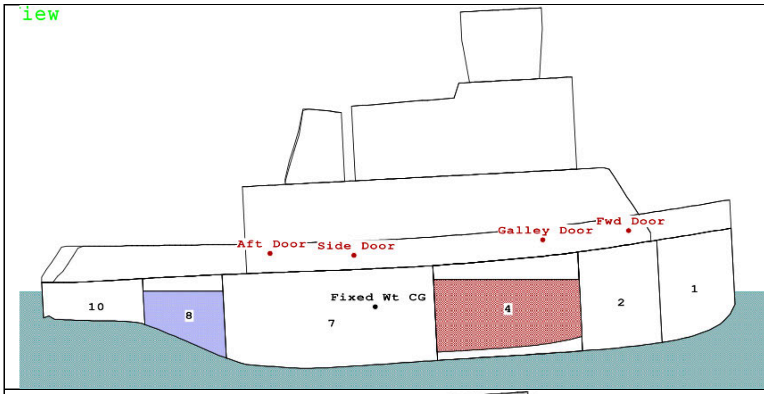
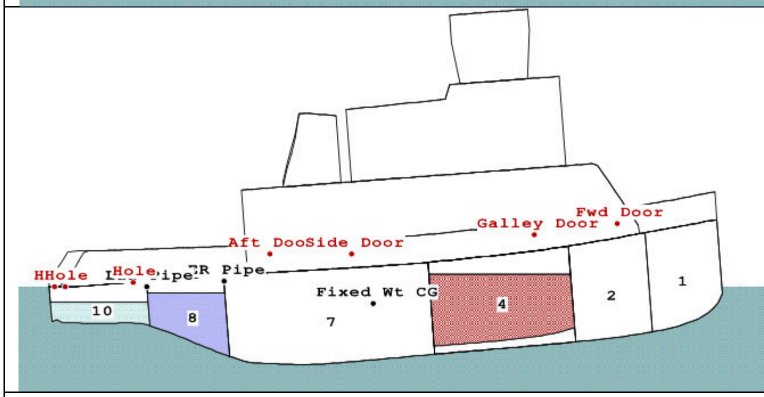
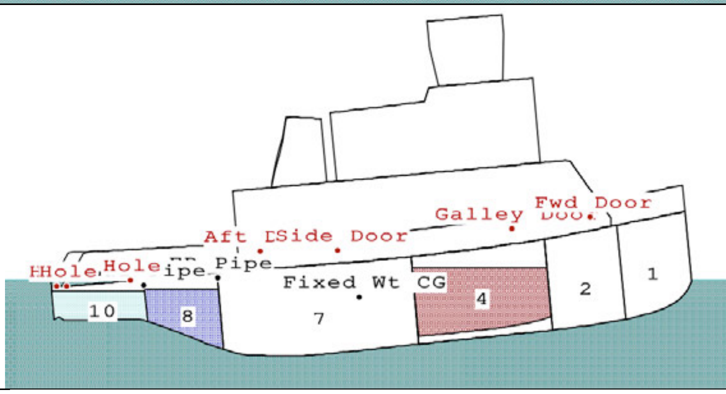
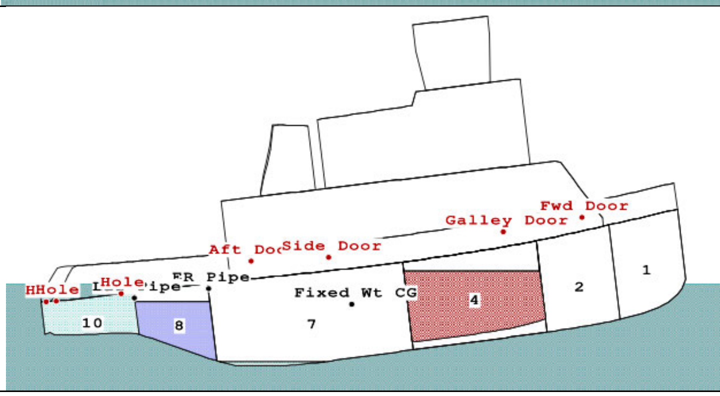
	Initial, Pre-casualty Condition with no Lazarette Flooding
	Time = 0 Aft Hole in Lazarette is 1/2" below waterline due to intermittent Lazarette flooding from waves. This is the starting point for the quasi-static progressive flooding analysis. Lazarette is 50% flooded Flooding Rate is appx. 560 GPM)
	After 1 Minute: Lazarette is 76% flooded Flooding Rate is 2,000 GPM Trim is 5.2° Aft Hole: 8" below Waterline Engine Room is 0% Flooded
	After 90 Seconds: Lazarette is 100% flooded Trim is 6.8° Aft Hole: 1'10" below Waterline Engine Room is <1% Flooded ER Flooding Rate is 460 GPM

Table 7: Example Progressive Flooding Analysis for Fixed VCG 5.5', Fixed Unknown LCG: 33.276'

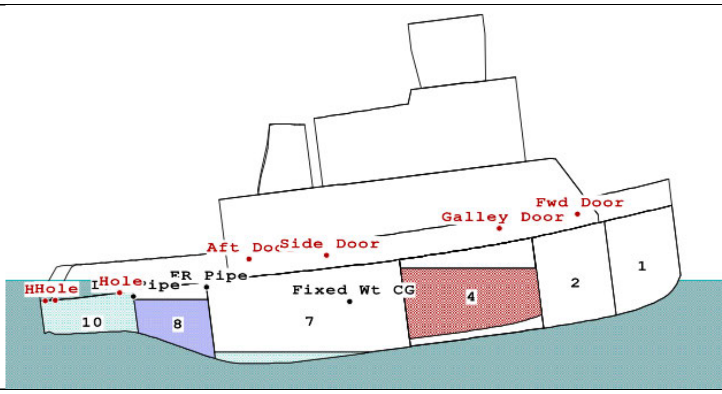
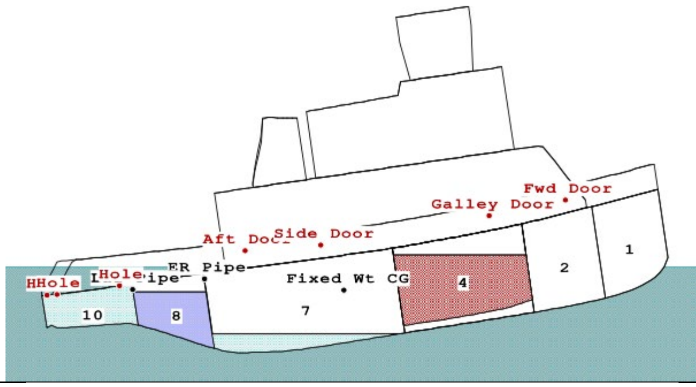
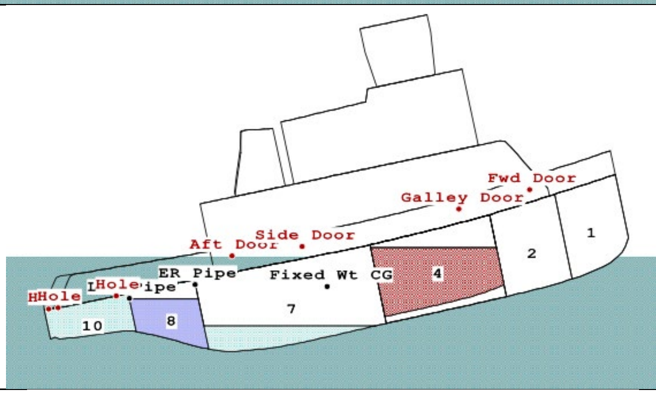
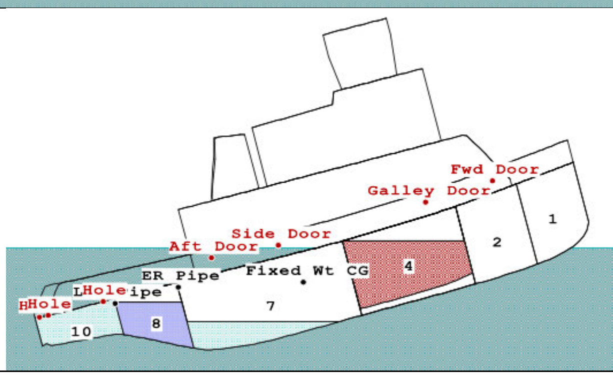
	After 3 Minutes: Lazarette is 100% flooded Trim is 7.1° Aft Hole: 2’2” below Waterline Engine Room is 2% Flooded Flooding Rate is 530 GPM
	After 6 Minutes: Lazarette is 100% flooded Trim is 8.3° Aft Hole: 3’ below Waterline Engine Room is 6% Flooded Flooding Rate is 710 GPM
	After 9 Minutes: Lazarette is 100% flooded Trim is 12° Aft Hole: 6’ below Waterline Engine Room is 12% Flooded Flooding Rate is 1,100 GPM Aft Door at Waterline
	After 9:36 (end of analysis) Lazarette is 100% flooded Trim is 15° Aft Hole: 8’3” below Waterline Engine Room is 13% Flooded Wire Run Flooding Rate is 1,300 GPM Aft Door is 1’ Below Waterline Door Flooding Rate is >5,000 GPM (not modeled/rapid sinking)

Table 7: Example Progressive Flooding Analysis for Fixed VCG 5.5', Fixed Unknown LCG: 33.276' (cont’d)

Progressive flooding results that ended in capsize were dismissed as implausible because JACQUELINE A sank upright in 35' feet of water with near zero heel. Dismissing results where capsize or no engine room flooding occurs allowed us to validate the starting center of gravity, limiting it to a range of reasonable VCG and LCG. A summary of results, with implausible conditions highlighted yellow, is shown in Table 8.

Fixed Unknown LCG (ft)► / Fixed VCG (ft) ▼	33.276	29	25
4.5	11 min Door 1' Below Surface	15.95 min Door 1' Below Surface	1.05 min No ER Flooding
4.75	10.65 min Door 1' Below Surface	15.45 min Door 1' Below Surface	1.05 min No ER Flooding
5	10.3 min Door 1' Below Surface	14.9 min Door 1' Below Surface	1 min No ER Flooding
5.25	9.95 min Door 1' Below Surface	14.4 min Door 1' Below Surface	1.05 min No ER Flooding
5.5	9.6 min Door 1' Below Surface	14 min Door 1' Below Surface	23.2 min Capsize
5.75	9.25 min Door 1' Below Surface	13.45 min Capsize	21.6 min Capsize
6	8.9 min Door 1' Below Surface	12.75 min Capsize	20.25 min Capsize
6.25	8.45 min Capsize	12.1 min Capsize	19.05 min Capsize
6.5	7.9 min Capsize	11.4 min Capsize	17.95 min Capsize
6.75	7.4 min Capsize	10.8 min Capsize	16.85 min Capsize

Table 8: Summary of Progressive Flooding Times from Deck Hole Immersion to Final Condition (Aft Door 1' Below Waterline, No Further Flooding, or Capsize). Results Highlighted Yellow are Not Plausible

6. Conclusions

Our analysis indicated that, at the time of the casualty, JACQUELINE A was a stable vessel that would have satisfied the 46 CFR Subchapter M intact stability criteria for partially protected routes. Wastage holes in the deck over the lazarette, in the area with the lowest freeboard, could result in gradual, intermittent entrance of seawater into the lazarette as the result of waves. Eventually, holes in the deck would be submerged allowing constant floodwater to enter the lazarette and progressively flood through wire runs into the engine room. Once the holes in the deck are submerged, our analysis indicates that progressive flooding leads to sinking of the tug by the stern in 9-16 minutes.