RESEARCH OPPORTUNITIES IDENTIFIED DURING THE CASUALTY ANALYSIS OF THE FISHING VESSEL ARCTIC ROSE

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SUMMARY

During the course of the U.S. Coast Guard Marine Safety Center's analysis of the sinking of the fishing vessel ARCTIC ROSE, a broad variety of stability issues were encountered that have not yet been addressed in the research community. The effect of freeboard on static and dynamic stability needs to be studied to ensure minimum reserve buoyancy and limit the effects of water on deck. The area of flooding stability, where a vessel's displacement, centers of gravity, and stability characteristics are constantly changing due to progressive flooding, needs to be further investigated. Time-domain analyses of progressive flooding in a seaway are needed, as are model tests of progressive flooding from the weather deck into interior spaces of a vessel. Additionally, a better understanding is needed on the behavior of the vessel between when the vessel capsizes due to loss of righting arm and sinks because flooding weight exceeds reserve buoyancy, and the attitude of a vessel as it falls through the water column to the ocean floor.

1. INTRODUCTION

The commercial fishing industry continues to be one of the most dangerous industries in the United States. Recent statistics from the U.S. Coast Guard's Marine Safety Office of Investigations and Analysis (G-MOA) show the rate of vessel losses and fisherman deaths in the United States has remained relatively steady over the last seven years [1]. Figure 1 shows the number of U.S. fishing vessel losses and fishermen killed between 1994 and 2000, with a total of 907 vessels lost and 466 fatalities during that time period.

At approximately 3:30 a.m. on April 2, 2001, the 92 foot (waterline length) fishing vessel ARCTIC ROSE disappeared in the Bering Sea, approximately 200 miles west of St. Paul Island, killing all fifteen men onboard. There was no Mayday call heard, nor were any distress signals sighted. The estimated weather at the time of the incident was: winds out of the west at approximately 20 knots, and seas from the south at 8-12 feet, although a front passed through the area about the time of the accident. The U. S. Coast Guard convened a Formal Marine Board of Investigation (FMBI) to determine what happened to the ARCTIC ROSE, why it happened, and how casualties like this can be prevented in the future.

The Marine Safety Center (MSC) provided naval architecture support to the FMBI throughout their investigation. The MSC developed and evaluated 19 scenarios that could have potentially led to the loss of the ARCTIC ROSE, and used a variety of tools to evaluate the likelihood of each scenario, including static righting arm calculations, dynamic stability calculations to evaluate capsize resistance, and progressive flooding

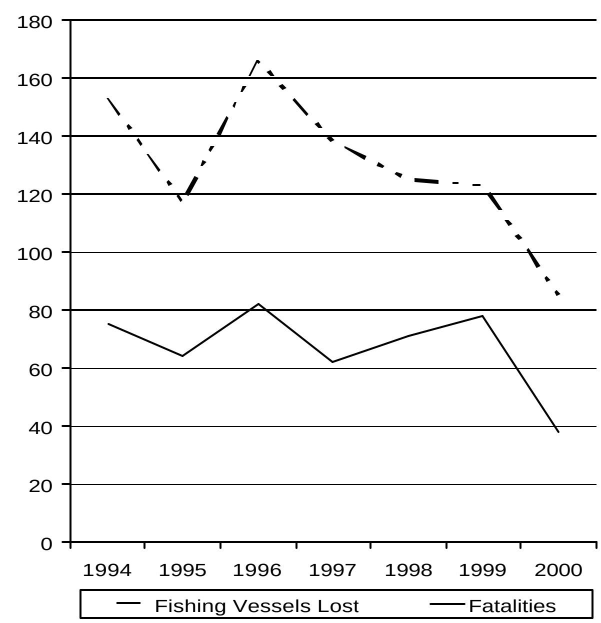

Figure 1. U.S. Fishing Vessel Accidents During The Last Seven Years

calculations to evaluate time to capsize and time to sink. The results of the MSC analysis are shown in Table 1. According to the analysis, the most likely reason the ARCTIC ROSE sank was progressive flooding from the aft weather deck to the processing space through an open door connecting the two areas, and the flooding then progressed to the galley, fish hold, and engine room through non-watertight doors and hatches. A sketch showing the general arrangement of the main deck and below deck of the ARCTIC ROSE was provided to the

FMBI by Jensen Maritime Consultants, Inc., and is included in Figure 2. The progressive flooding scenario that most likely sank the ARCTIC ROSE is very similar to that assumed to have resulted in the loss of the GAUL, a Norwegian trawler that sank in February 1974, killing all 36 men onboard [2].

While the MSC made important strides in increasing the breadth of tools available to the Coast Guard in conducting casualty analysis, a number of questions were left unanswered. The limitations of the MSC casualty analysis tools and a review of the literature have revealed significant research opportunities in evaluating fishing vessel stability, especially while the vessel is experiencing progressive flooding.

2. EFFECT OF FREEBOARD ON STATIC AND DYNAMIC STABILITY

Many of the stability regulations for passenger and fishing vessels have been derived from the results of Dr. Rahola's landmark dissertation, specifically the minimum static righting arm requirements for fishing vessels. [3,4]. However, none of the current stability requirements for fishing vessels include minimum freeboard requirements. The angle of maximum righting arm is required to occur at an angle equal to or greater than 25 degrees. If the maximum righting arm occurs at the deck edge, the freeboard would have to be no less than 0.233 times the beam of the vessel.

While the angle of maximum righting arm may have occurred at or near the angle of deck edge immersion for the vessels studied in Dr. Rahola's dissertation, this is no longer the case for some fishing vessels in the United States. Guidance published by the Coast Guard allows naval architects to include weathertight superstructure as buoyant volume when calculating righting arms [5]. The effect of including the buoyancy of the superstructure of the ARCTIC ROSE on the static righting arm curve is shown in Figure 3.

The superstructure modeled is on top of the main deck, 20 feet in length (1/5 the length of the vessel), 8 feet high and 24 feet wide, the entire beam of the vessel. With the superstructure nonbuoyant, the angle of maximum righting arm is at the angle of deck edge immersion. With the superstructure buoyant, the angle of maximum righting arm is increased to the angle at which the top of the superstructure is immersed. However, if the superstructure cannot physically be kept weathertight due to openings without closures and operational considerations, buoyancy is lost and the naval architect and the master may have a false sense of security as to the vessel's intact stability.

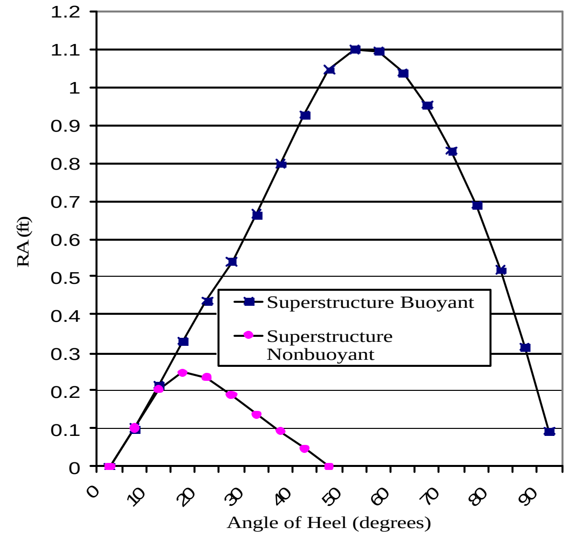

Figure 3. Righting Arm for ARCTIC ROSE Assuming Superstructure Buoyant and Nonbuoyant

While it is possible for a vessel with a significant amount of buoyant superstructure to still meet the CFR requirements with the vessel loaded until the aft deck is below the waterline, the detrimental effects on stability from significant water on deck and bulwark immersion need to be considered when evaluating the stability of the vessel. Much research has been done on the effects of water trapped on deck, and hydrodynamic effects of submerged bulwarks [6,7,8,9]. Additionally, water on deck often leads to progressive flooding into spaces inside the fishing vessel in which watertight doors and hatches have been left open [10], which is precisely the scenario the author believes most likely caused the loss of the ARCTIC ROSE.

The current stability regulations require the naval architect to evaluate the effect of water on deck for new fishing vessels over 79 feet in length. However, this regulation is merely an evaluation of the heeling moment due to water on deck, and demonstrating that the heeling moment due to the water is less than the righting moment of the vessel. For all fishing vessels, additional research is needed on the minimum freeboard necessary to minimize the effect of boarding seas. While it is important to understand the effect water on deck will have on the stability of the vessel, it is just as important to quantitatively evaluate the vessel's ability to prevent water from coming on deck.

The Japanese have developed minimum freeboard requirements for small passenger vessels based on maximum wave heights and passenger movements [11]. It would be beneficial to naval architects designing fishing vessels to have similar minimum freeboard requirements to best balance the vessel's resistance to boarding seas and maximize the amount of fish carried.

3. FLOODING STABILITY

The term 'flooding stability' is used to describe the stability of a vessel in which the displacement, centers of gravity, and righting arm characteristics are changing with time due to the time-dependent addition of flooding water through different compartments of the vessel. Additionally, the term 'capsize' is used to describe when a vessel is heeled over to an angle from which it cannot return upright without assistance from external forces.

3.1 CAPSIZE RESISTANCE ANALYSIS

The MSC conducted a dynamic stability analysis in the roll degree-of-freedom only of the ARCTIC ROSE to evaluate the vessel's capsize resistance, and to determine the vessel's time domain response to excitation by regular (sinusoidal) beam seas.

In order to compute the ARCTIC ROSE's capsize resistance, the MSC calculated the nonlinear safe basin erosion for different frequencies using the techniques originally described in [12] and [13]. Adopting the equation used in [12], the general equation of motion in only the roll degree of freedom accounting for nonlinear damping is:

$$(I + A)\ddot{q} + b_1\dot{q} + b_2\dot{q}\left|\dot{q}\right| + \Delta RA(q) = F_{excitation} \quad (1)$$

where I is the roll moment of inertia, A is the roll added mass, b_1 and b_2 are the damping coefficients, Δ is the displacement, and $F_{excitation}$ is the forcing due to waves. The wind force on the vessel was not included in this analysis. Additionally, the righting arm was not modeled as a fifth-order curve as in [12]. Instead, the righting arm was discretized into 1 degree increments, and a look-up function was utilized to calculate the righting arm at each heel angle. Equation (1) was used to describe the motion of the vessel throughout the capsize resistance analysis, assuming that progressive flooding was not occurring.

Using a digitized underwater hull model of the ARCTIC ROSE, the inertia, added mass, nonlinear damping, and wave force terms were calculated from the University of Michigan's SHIPMO program, developed by Dr. Robert Beck and Dr. Armin Troesch [14]. The wave shape was assumed to be a sinusoidal function, and the wave period was bracketed between 8s and 12s, based on the NOAA weather hindcast at the time of the accident.

The righting arms used in the computation were calculated from the estimated load condition at the time of the loss, and are shown in Figure 4. The righting arms were calculated in the intact condition and with 5" of

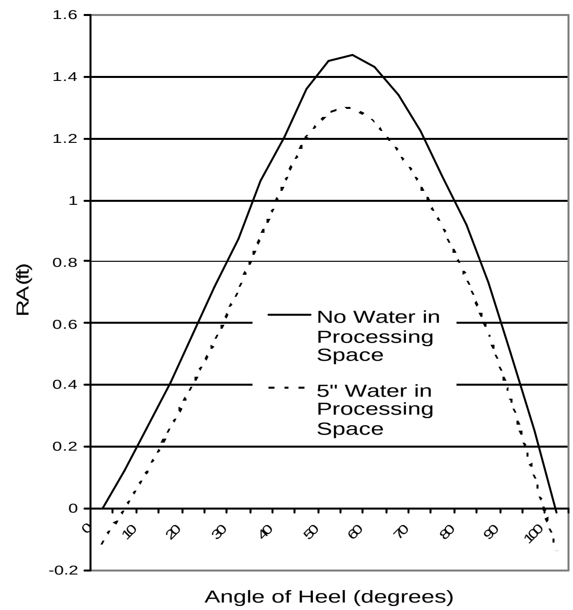

Figure 4. Righting Arms for ARCTIC ROSE in Assumed Condition at Time of Accident

water in the processing space, and were inserted into equation (1) to evaluate the effect of water on deck on the capsize resistance of the vessel. The moment of inertia method was used to calculate the free surface effect from the water in the processing space, and was responsible for most of the reduction in the righting arm.

A time history graph of the ARCTIC ROSE's roll motion for the two studied loading conditions when starting from zero initial conditions, and subjected to a train of eight waves with a period of 12 seconds and wave height of 8 feet is shown in Figure 5.

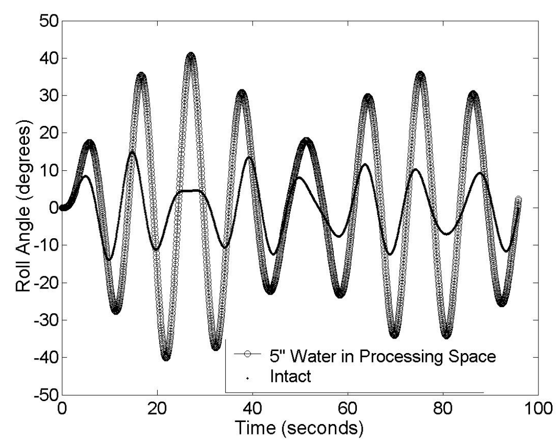

Figure 5. Roll Angle Time History for ARCTIC ROSE, Zero Initial Roll Angle and Roll Velocity, 8 ft Wave Height, 12 s Wave Period

This solution of equation (1) displays the nonlinear response of the vessel, and the increased roll angles of the ARCTIC ROSE due to the water in the processing space. In the intact condition, the maximum roll angle is only about 15 degrees, but with water inside the vessel the maximum roll angle more than doubles to 40 degrees. Based on the freeboard of the vessel at the time of sinking, rolls of at least 23 degrees to each side would have put the open door in the processing space underwater with every roll, increasing the chance of water accumulating inside the processing space and progressively flooding throughout the vessel.

For an 8 second and 12 second wave period, and an eight-wave train of sinusoidal waves, equation (1) was solved for varying initial roll displacement and velocity conditions as described in [12]. If the vessel capsized (as defined by an angle of roll greater than the angle of vanishing stability) at any point during the excitation, the coordinate corresponding to those initial conditions was marked with a black diamond. Otherwise, the vessel is assumed to have "survived" the wave excitation and the coordinate was left blank. Figures 6 through 9 show the safe basins for the ARCTIC ROSE excited by an 8 foot wave height but with different wave periods and different righting arms to reflect the static effect of water in the processing space. The safe basin plots show the vessel's capsize resistance degrades in a similar behavior to those described in [12,13,15].

Figures 10 through 13 show the safe basins for the ARCTIC ROSE excited by a 14 foot wave height but with different wave periods and different righting arms, again to reflect the static effect of water on deck. The safe basins exhibit different degradation behavior based on the frequency of excitation. For reference, the calculated natural period of the ARCTIC ROSE in the assumed loading condition at the time of the sinking was 7.7 seconds.

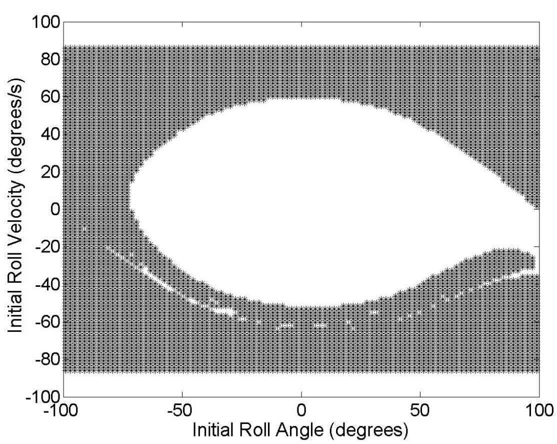

Figure 6 Safe Basin Plot for ARCTIC ROSE, Intact Condition, 8 ft Wave Height, 12 s Wave Period

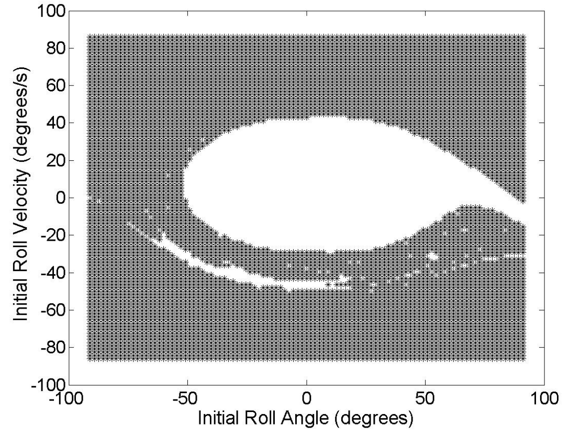

Figure 7. Safe Basin Plot for ARCTIC ROSE, 5" Water in Processing Space, 8 ft Wave Height, 12 s Wave Period

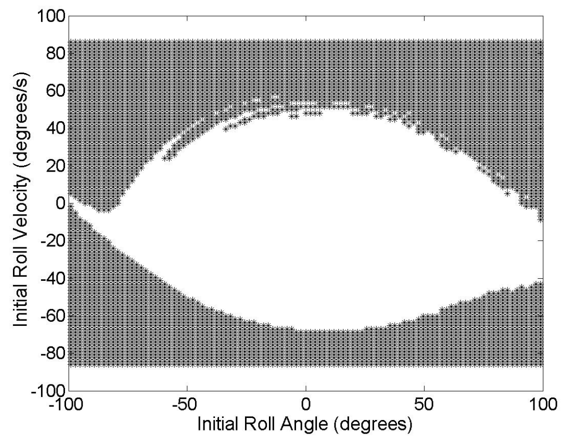

Figure 8. Safe Basin Plot for ARCTIC ROSE, Intact Condition, 8 ft Wave Height, 8 s Wave Period

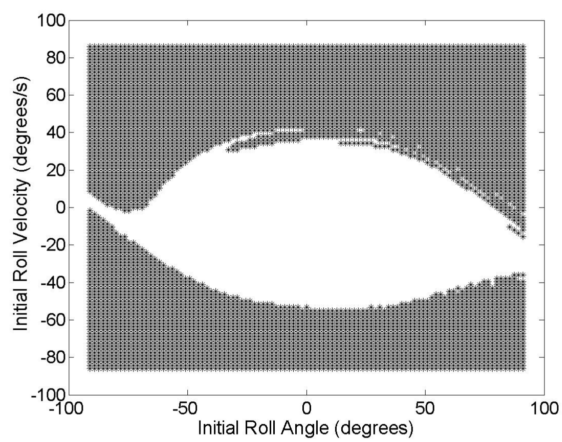

Figure 9. Safe Basin Plot for ARCTIC ROSE, 5" Water in Processing Space, 8 ft Wave Height, 8 s Wave Period

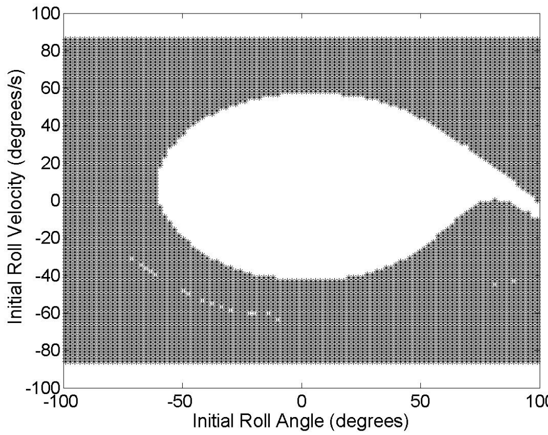

Figure 10. Safe Basin Plot for ARCTIC ROSE, Intact Condition, 14 ft Wave Height, 12 s Wave Period

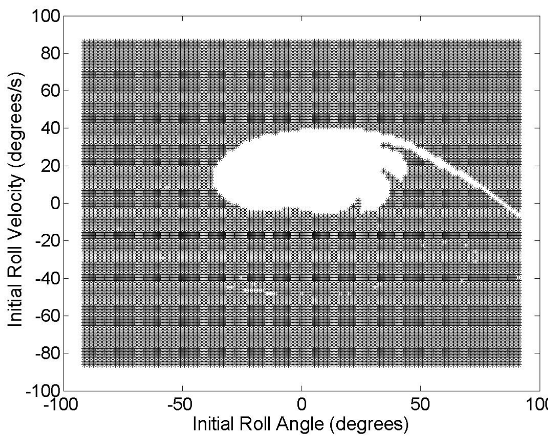

Figure 11. Safe Basin Plot for ARCTIC ROSE, 5” Water in Processing Space, 14 ft Wave Height, 12 s Wave Period

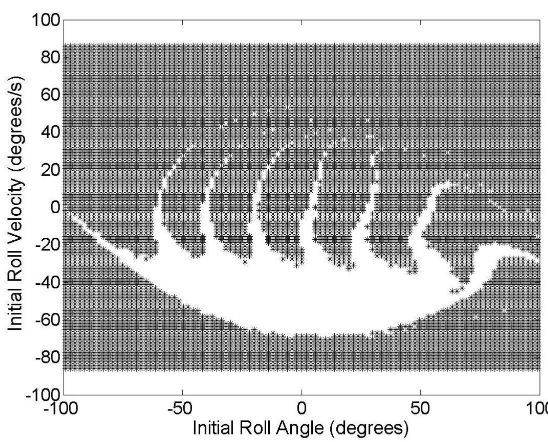

Figure 12. Safe Basin Plot for ARCTIC ROSE, Intact Condition, 14 ft Wave Height, 8 s Wave Period

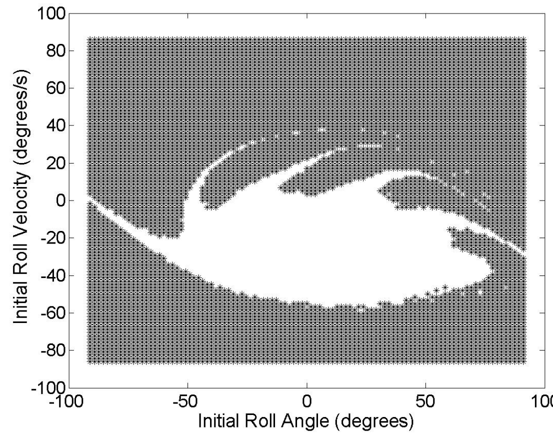

Figure 13. Safe Basin Plot for ARCTIC ROSE, 5” Water in Processing Space, 14 ft Wave Height, 8 s Wave Period

The integrity curve shown in Figure 14 was calculated using the techniques described in [12]. It shows the number of unmarked coordinates, or safe points, in the safe basin for the corresponding wave height. The wave height at which the lines decrease sharply is the critical height, beyond which the capsize resistance decreases greatly. For the ARCTIC ROSE, this critical wave height was approximately 10 feet.

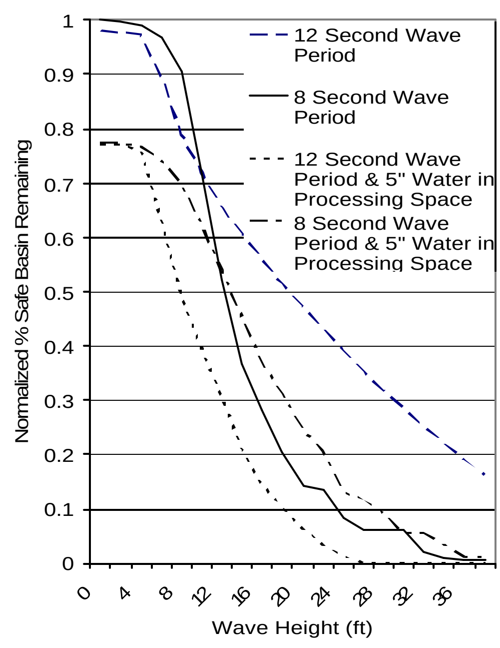

Figure 14. Integrity Curve for ARCTIC ROSE

Further research in the use of transient capsize diagrams and nonlinear safe basin erosion is still needed, especially in the areas of coupling water on deck with capsize resistance. Specifically, the author took a simplistic approach to the water on deck by merely reflecting the reduction of stability in the stiffness term of equation (1). However, by numerically modeling the shallow water flow and calculating the transverse force of the shallow water as described in [16] and [17], a much more accurate assessment of the effects of entrained water on the capsize resistance of the vessel is possible. Additionally, as the seas on the night of the loss of the ARCTIC ROSE were described by other vessels in the area as confused, incorporating the effect of random beam seas using techniques outlined in [18],[19], and [20], coupled with water on deck, would greatly increase the ability to quantify the capsize resistance of these vessels. Modeling the wave force from breaking waves instead of a regular sinusoidal wave train would also more closely simulate the real-world conditions in which the ARCTIC ROSE operated [21].

3.2 ANALYSIS OF FLOODING STABILITY FOR VESSELS

Working with Dr. Bruce Johnson, Professor Emeritus at the U.S. Naval Academy and Chairman of the SNAME Ad Hoc Panel on Fishing Vessel Operations and Safety, the MSC performed a progressive flooding analysis to determine how quickly the ARCTIC ROSE could capsize once progressive flooding began. Using a simplified time-stepping approach to calculate the static righting arms for increasing flooding loads, the righting arms for each time step were calculated based on the vessel's position on the wave, flooding water height and location, and the free surface effect of the water. The amount of water flooding from one space to another was calculated based on the difference in water height between spaces at open doors or hatches. The results show the ARCTIC ROSE most likely capsized between 1 minute 40 seconds and 2 minutes 40 seconds after progressive flooding began, due largely to the free surface effect of the water trapped inside the vessel.

There is a significant gap in the literature concerning progressive flooding and the dynamic response of a vessel. Analytical methods still need to be developed to evaluate the dynamic flooding stability of vessels, and model testing would also need to be done to validate the flooding stability models. The ability to quantify the effects of progressive flooding is sorely needed; of the 423 U.S. fishing vessels lost while underway or maneuvering between 1994 and 2000, 43% (182 vessels) were due to flooding and capsizing [1].

4. POST-CAPSIZE BEHAVIOR OF FISHING VESSELS

The U.S. Coast Guard's Commercial Fishing Vessel Safety program has always stressed to fishermen that their fishing vessel is its' own best lifeboat [22]. While the focus of the program is preventing the vessel from capsizing, predicting the behavior of the vessel after it capsizes is also extremely important. Recent casualties such as the capsizing of the passenger vessel EL TORO II and the fishing vessel TWO FRIENDS highlight that if the vessel capsizes, inverts 180 degrees, and continues to float, people thrown overboard have a chance to escape from the water and minimize their chance of dying due to exposure and hypothermia [23]. Additionally, air trapped in the hull may provide fishermen still inside the vessel time to escape from the vessel.

4.1 BEHAVIOR OF VESSEL AFTER CAPSIZING BUT WHILE BUOYANT

Due to the location of the ARCTIC ROSE in the Bering Sea, the U.S. Coast Guard was unable to arrive onscene until over 3 hours after the vessel's Emergency Positioning Indicator Radio Beacon (EPIRB) began broadcasting its alarm. When the search aircraft and nearby fishing vessels approached the last-known location of the vessel, the vessel had already sunk. As it was not possible to determine the attitude of the vessel on the water's surface once it capsized, and the subsequent flooding rates into the hull and superstructure, the MSC was unable to estimate how long the ARCTIC ROSE remained buoyant after capsizing.

The stability of capsized fishing vessels has been studied to some extent by Mr. Terrence Hall [24]. However, depending on the force of flooding water and the centers of gravity and buoyancy for the vessel, once the angle of heel exceeds the angle of vanishing stability, a vessel in a seaway may not invert to 180 degrees immediately. Additionally, progressive flooding through openings in the hull and superstructure assure the vessel will ultimately sink.

An excellent example of two fishing vessels of similar proportion, form, and stability characteristics that capsized and sank in different ways can be found in the U. S. Coast Guard Formal Marine Board of Investigation report on the loss of the crabbing vessels AMERICUS and ALTAIR [25]. The AMERICUS and ALTAIR were sister vessels, built in Anacortes, Washington at the same yard within a few years of one another. On February 14, 1983, the ALTAIR and AMERICUS departed Dutch Harbor, Alaska. The ALTAIR disappeared, and is assumed to have capsized and sank. The capsized hull of the AMERICUS was seen floating until it sank on February 16, 1983. The Formal Marine Board of Investigation, assisted separately by Dr. Bruce Adee and Mr. Fisker-Anderson, determined that both vessels were overloaded, and that the ALTAIR's stability was more compromised than that of the AMERICUS. However, the factors that caused the AMERICUS to capsize and remain afloat for two days, while the ALTAIR capsized and sank within a few hours have never been determined.

Understanding the behavior of a vessel once it capsizes, but before the vessel sinks due to progressive flooding, could lead to vessel designs that do not sink immediately after capsizing, providing fishermen with an increased chance of survival.

4.2 VESSEL SINKING AFTER FLOODED DISPLACEMENT EXCEEDS RESERVE BUOYANCY

Using side-scan sonar and remote-operated underwater vehicles, the Formal Marine Board of Investigation found the ARCTIC ROSE in 422 feet of water. The vessel was resting upright on her keel and starboard bilge keel. The vessel appeared to be intact, with no signs of external damage to the hull or superstructure, and the windows in the pilothouse were all intact. Additionally, whether based on the water depth or the fact that no air was trapped in the hull, there were no signs of compartment implosion like those found on the GAUL [26]. However, the MSC was unable to determine how the ARCTIC ROSE flooded such that the vessel landed upright on the ocean bottom after falling to a depth four times its length. Knowing how the vessel flooded would have helped pinpoint which openings in the hull and superstructure were critical in allowing flooding water into the hull, and would have helped determine if human error was responsible for the sinking. Conversely, if analysis showed flooding of certain compartment combinations would prevent the vessel from settling on her keel, then the investigators could at least determine how the vessel did not sink. While there is published research on the stability of submarines and submersibles, most research efforts have concentrated on vessels with neutral or positive buoyancy [27].

The modeling of a flooded vessel falling through a column of water is not an elementary task, and would have to account for a number of factors, including the form of the hull and superstructure, the arrangement of compartments inside the vessel, the depth of water, and the location of the centers of gravity and buoyancy. The exterior form of the hull and superstructure will influence the drag of the vessel as it falls through the water. The arrangement of compartments will affect the rate of flooding through a number of variables. The location and size of openings into each compartment will influence how quickly water enters and air escapes from the space. The depth of water will be critical in determining the amount of time the vessel takes to fall through the water, and if a terminal velocity is reached by the time the vessel reaches the ocean floor. The location of the centers of buoyancy and gravity will constantly change as the vessel falls through the water as the vessel continues to lose buoyancy due to escaping air and incoming water.

5. CONCLUSIONS

The U.S. Coast Guard Marine Safety Center utilized a number of different tools to evaluate the most likely causes of the disappearance of the ARCTIC ROSE and its fifteen man crew. However, a number of questions went unanswered because the analytical techniques needed to answer these questions were beyond the current state of research. More research is needed in the capsize resistance and dynamic stability of a vessel while progressive flooding is occurring. Additionally, a better understanding is needed of a vessel's behavior after capsizing, until the vessel either reaches an equilibrium position on the ocean surface or comes to rest on the ocean floor.

During the 1994-2000 time period, the loss of 190 U.S. fishing vessels was attributed to capsizing, flooding, or severe weather. Continuing the extensive efforts to better understand the dynamics of fishing vessels, especially in the flooding condition, will help naval architects design safer vessels, assist fishermen in understanding how to prevent their vessels from sinking, and ultimately save lives.

6. DISCLAIMER

It must be emphasized that the opinions expressed in this paper are solely those of the author and are not necessarily those of the Marine Safety Center or the United States Coast Guard.

7. ACKNOWLEDGEMENTS

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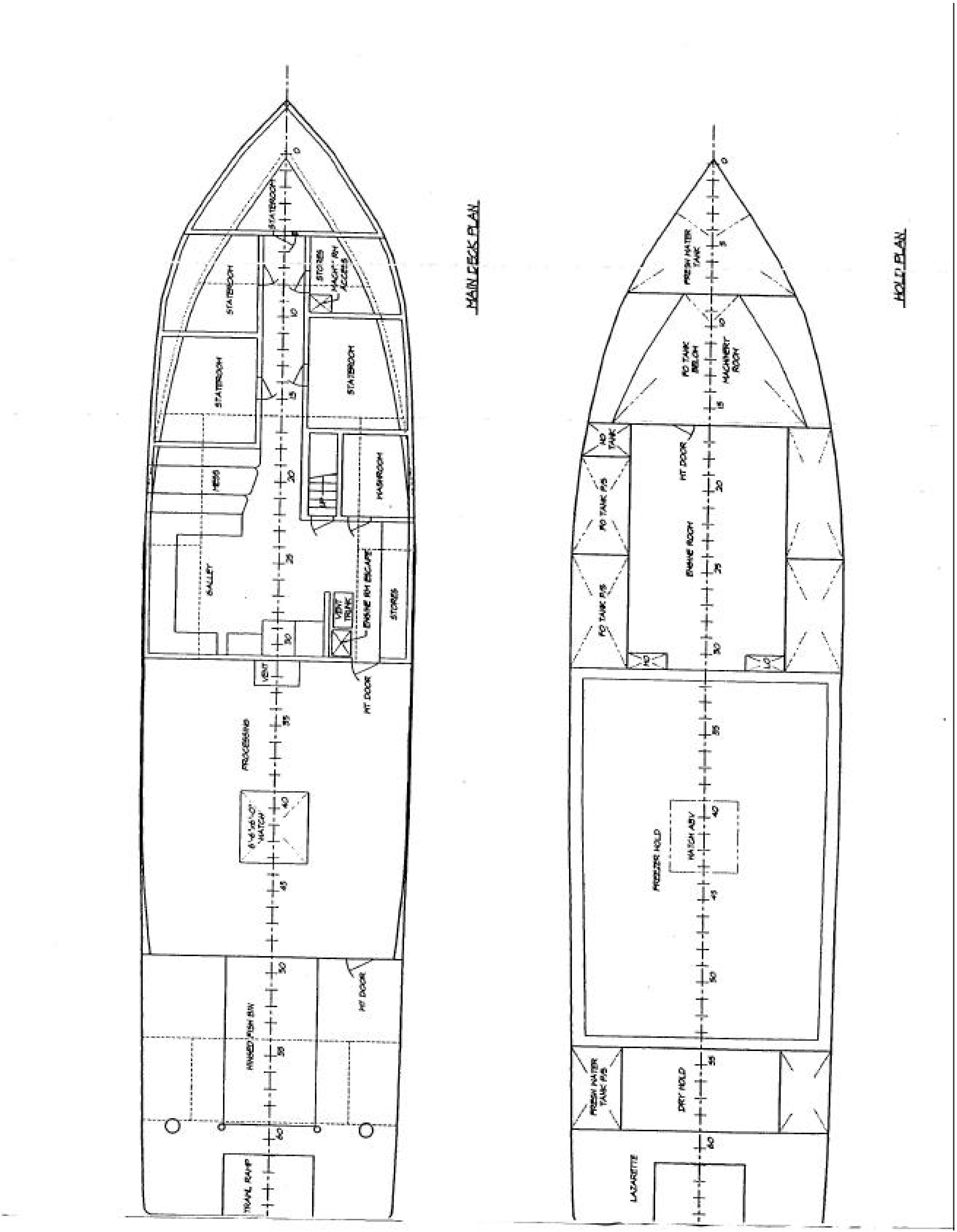

Figure 2. General Arrangements of Main Deck and Below Deck of ARCTIC ROSE

Scenario That Could Lead to the Loss of the ARCTIC ROSE	Assumptions	Findings	Likelihood
Progressive Flooding - No Initial Flooding in Lazarette - Processing Space, Galley, Engine Room, and Fish Hold Flood	ARCTIC ROSE in damaged condition; Aft starboard door in processing space open and hatch to fish hold allows progressive flooding; Doors leading to engine room and galley allow progressive flooding	ARCTIC ROSE would capsize between 1 minute 40 seconds and 2 minutes 43 seconds after progressive flooding begins, and the ARCTIC ROSE would sink between four minutes and eight minutes after progressive flooding began	Most Likely
Progressive Flooding - No Initial Flooding in Lazarette - Processing Space and Fish Hold Flood	ARCTIC ROSE in damaged condition; Aft starboard door in processing space open and hatch to fish hold allows progressive flooding	ARCTIC ROSE would capsize approximately 3 minutes 23 seconds after progressive flooding begins, and the ARCTIC ROSE would sink approximately 25 minutes 35 seconds after progressive flooding began	Likely
Progressive Flooding - Initial Flooding in Lazarette - Processing Space, Galley, Engine Room, and Fish Hold Flood	ARCTIC ROSE in damaged condition; Aft starboard door in processing space open and hatch to fish hold allows progressive flooding; Doors leading to engine room and galley allow progressive flooding	ARCTIC ROSE would capsize approximately 2 minutes 30 seconds after progressive flooding begins, and the ARCTIC ROSE would sink approximately 5 minutes 19 seconds after progressive flooding began	Likely
Progressive Flooding - Initial Flooding in Lazarette - Processing Space and Fish Hold Flood	ARCTIC ROSE in damaged condition; Aft starboard door in processing space open and hatch to fish hold allows progressive flooding	ARCTIC ROSE would capsize approximately 2 minutes 53 seconds after progressive flooding begins, and the ARCTIC ROSE would sink approximately 13 minutes 11 seconds after progressive flooding began	Likely
Through Hull Fitting Failure - Rudder Post in Lazarette	ARCTIC ROSE in damaged condition; Lazarette and Dry Stores Flood	ARCTIC ROSE met damage stability requirements when lazarette and dry stores flooded.	Unlikely
Through Hull Fitting Failure - Shaft in Fish Hold	ARCTIC ROSE in damaged condition; Fish Hold Floods	ARCTIC ROSE met intact and damage stability requirements when lazarette and dry stores flooded.	Unlikely
Through Hull Fitting Failure - Shaft or Sea Water Suction in Engine Room	ARCTIC ROSE in damaged condition; Engine Room and Machinery Space Flood	ARCTIC ROSE met intact and damage stability requirements when lazarette and dry stores flooded.	Unlikely
Struck Object or Collision	ARCTIC ROSE in damaged condition; Forepeak damaged or Wing Fuel Oil Tanks Damaged	ARCTIC ROSE met almost all intact stability and all damage stability requirements when lazarette and dry stores flooded.	Unlikely
Water Trapped on Aft Deck	ARCTIC ROSE in intact condition; Water trapped on aft deck and cannot escape from freeing ports or stern ramp	ARCTIC ROSE's stability would be severly reduced, but water would clear quickly out freeing ports and aft stern ramp	Unlikely
Overloaded - Unaccounted Weight Growth Since Inclining	ARCTIC ROSE in intact condition	Weight additions to ARCTIC ROSE did not significantly change the stability characteristics of the vessel since the 1999 stability report	Unlikely
Rogue Wave - Capsizing of ARCTIC ROSE	ARCTIC ROSE in intact condition; Very large wave rolls ARCTIC ROSE to angle of vanishing stability	Rogue wave would have to be at least 50 feet high to capsize ARCTIC ROSE	Very Unlikely
Loss of Keel Ballast	ARCTIC ROSE in intact condition; Keel ballast falls off ARCTIC ROSE	ARCTIC ROSE's stability would not be significantly affected by loss of ballast, and no evidence of structrual damage	Very Unlikely
Overloaded - Excess Cargo on Deck or in Fish Hold	ARCTIC ROSE in intact condition	ARCTIC ROSE was not overloaded at time of casualty	Very Unlikely
Structural Failure	ARCTIC ROSE in damaged condition	ARCTIC ROSE did not appear to suffer a structural failure	Very Unlikely
Synchronous Roll	ARCTIC ROSE in intact condition	ARCTIC ROSE was not in synchronous roll conditions	Very Unlikely
Severe Wind Capsizes ARCTIC ROSE	ARCTIC ROSE in intact condition; Strong wind heels ARCTIC ROSE to angle of vanishing stability	100 knot wind would be insufficient to capsize ARCTIC ROSE	Very Unlikely
Rogue Wave - Swamping of ARCTIC ROSE	ARCTIC ROSE in intact condition; Aft starboard door in processing space open and hatch to fish hold allows progressive flooding	ARCTIC ROSE would have to take on 500 tons of water in one wave period for vessel to be swamped	Very Unlikely
Trawling Net Snags on Bottom	ARCTIC ROSE in intact condition	ARCTIC ROSE was most likely not fishing at time of accident	Very Unlikely
Overloaded - Icing	ARCTIC ROSE in intact condition	ARCTIC ROSE was most likely not in icing conditions	Very Unlikely

Table 1. Results Of MSC Analysis of 19 Possible Scenarios That Could Lead to the Loss of the ARCTIC ROSE