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SMALL CRAFT HARDENING FOR ARCTIC OPERATIONS

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SMALL CRAFT HARDENING FOR ARCTIC OPERATIONS

by

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June 2023

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The need for a sustained Naval presence in the Arctic Region has been rapidly increasing due to heightened accessibility caused by melting ice. However, the unforgiving Arctic climate poses various operational hazards that must be addressed to accomplish this. This thesis seeks to identify the key threats posed to ships by the Arctic climate and the best methods to overcome them. This will be carried out through the analysis of military and commercial shipping reports, which outline the critical systems and components that are most at risk. In addition to explaining some solutions discovered by these reports, a deeper investigation into both ship stability and heat transfer will be performed. These studies will utilize modern computational tools to fill gaps in knowledge such as how exactly ice accumulation affects ship stability based on size and if one-dimensional heat transfer calculations are sufficient in defining three-dimensional problems. The implementation of solutions found in this study can enhance the U.S. Navy's presence and effectiveness in the Arctic region.

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SMALL CRAFT HARDENING FOR ARCTIC OPERATIONS

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ABSTRACT

The need for a sustained Naval presence in the Arctic Region has been rapidly increasing due to heightened accessibility caused by melting ice. However, the unforgiving Arctic climate poses various operational hazards that must be addressed to accomplish this. This thesis seeks to identify the key threats posed to ships by the Arctic climate and the best methods to overcome them. This will be carried out through the analysis of military and commercial shipping reports, which outline the critical systems and components that are most at risk. In addition to explaining some solutions discovered by these reports, a deeper investigation into both ship stability and heat transfer will be performed. These studies will utilize modern computational tools to fill gaps in knowledge such as how exactly ice accumulation affects ship stability based on size and if one-dimensional heat transfer calculations are sufficient in defining three-dimensional problems. The implementation of solutions found in this study can enhance the U.S. Navy's presence and effectiveness in the Arctic region.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
ARPA	Arctic Research and Policy Act
ASTM	American Society for Testing and Materials
BRI	Belt and Road Initiative
CDO	Climate Data Online
CGC	Coast Guard Cutter
FPC	fluorocarbon penetrating coating
HVAC	heating, ventilation, and cooling
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MDAT	mean daily average temperature
MDHT	mean daily high temperature
MDLT	mean daily low temperature
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
POSSE	Program of Ship Salvage Engineering
RTOFS	Real-Time Ocean Forecast System
STP	SBIR Transition Program

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I. INTRODUCTION

A. BACKGROUND

The decrease in Arctic Sea ice has increased human traffic throughout the Arctic region. This has led to heightened concern regarding how to best ensure peace and prosperity in the region while also protecting the interests of the United States. As the region sees an increase in military operations, commercial shipping, and mineral exploration, it is becoming ever more vital to ensure that the United States is ready and capable to ensure a favorable balance of power in the region [1]. To best achieve this, the United States is striving to have a sustained Naval presence as well as strong Arctic partnerships. This is especially important due to the current and foreseen impedance caused by Russian and Chinese forces; whose values differ from that of the United States [2]. However, the Arctic environment still poses various significant challenges to Naval ships which must be identified and overcome.

Although the U.S. Navy has been operating in the Arctic region intermittently throughout the past few decades, the vast amount of knowledge gained on necessary system changes has been overshadowed by more pressing national interests abroad. This has resulted in the U.S. military being outpaced by Russia and China in the Arctic region, intensifying the need to dedicate more focus and funding to a more Arctic-capable Navy.

B. DEFINITION AND GEOGRAPHY

Although there are many definitions of the Arctic region, this report will utilize the definition codified in Title 15 of the Arctic Research and Policy Act (ARPA). This defines the “Arctic” as “all United States and foreign territory north of the Arctic Circle and all United States territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers; all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chukchi Seas; and the Aleutian chain” [3]. The U.S. Arctic Research Commission depicts this area holistically in Figure 1 while also providing a more detailed look at the Arctic area of Alaska in Figure 2.

Figure 1. Entire Arctic Area as Defined by ARPA. Adapted from [1].

Credit: US Arctic Research Commission

Figure 2. Arctic Area of Alaska as Defined by ARPA.
Adapted from [1].

C. ENVIRONMENTAL AND POLITICAL IMPORTANCE

As global temperatures have been increasing, the Arctic is becoming more accessible to sea traffic. From various satellite data, the National Aeronautics and Space Administration (NASA) has calculated that Arctic Sea ice has been decreasing by 12.6% per decade, while Antarctica has lost 151 billion metric tons of ice mass since 2002 [4]. This gradual opening of the Arctic region will provide the United States with both new opportunities and challenges in the region.

The rate at which ice is melting through the Arctic region will soon open a new 6,000 km (3,700 mi) northern passage for sea-borne trade, which has been referred to as the "Arctic Silk Road" [5]. This new route will be of key interest to countries such as China, as they will likely utilize it to continue their massive global infrastructure program, the Belt and Road Initiative (BRI). Perhaps even more concerning to U.S. strategic national interests is that China has been working with Russia to increase its presence in the Arctic region through the establishment of multi-use ports, airfields, and energy extraction sites [6]. This will likely threaten the promotion of cooperation and peace in the region in the years to come.

To maintain order in the Arctic region, the Arctic Council was formed in 1996 through the Ottawa Declaration [7]. As one of the eight Arctic states, the Russian Federation helps to create international laws to govern the region. However, considering Russia's recent invasion of Ukraine, this position may give them influence that could prove counter-productive to peace throughout the Arctic region.

D. APPROACH AND CONTRIBUTIONS

For the U.S. Navy to increase its presence and functionality in the Arctic, effective solutions must be identified and implemented. Various organizations across the world have developed methods to better prepare vessels for operation in the Arctic. Through the research of solutions implemented by these groups, a vast amount of knowledge can be gained about effective ways to solve problems. The American Bureau of Shipping (ABS), for example, has devoted a great amount of time to studying and addressing vital problems that ships transiting the Arctic experience. This, in addition to problems experienced and addressed by the U.S. Coast Guard, will be investigated.

In addition, a study on how icing impacts ships differently based on their size will be performed. Although there is historical evidence that can be referenced regarding this problem, a modern computational solution will help to further explain and solidify this relationship. Lastly, a detailed thermal analysis of a common heating solution will be performed. The purpose of this is to investigate if commercial methods of heat transfer calculations are sufficient in describing real-world problems and to determine how effective heating is as a solution for problems that vessels face in the Arctic.

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II. RULES AND REGULATIONS FOR SHIPS OPERATING IN THE ARCTIC

Since the age of sail, lessons have been learned on the Arctic waters by every power that has traversed them. In the modern era, many nations either have a Navy or are invested in international commerce and thus share some experience with the Arctic's harsh environment. Despite the experience, a lack of international regulations for ships transiting the Arctic would eventually cause disaster. In March 1989, the tanker *Exxon Valdez* spilled 11 million gallons of oil into the ocean after running aground in Prince William Sound, Alaska [8].

Following this national ecological disaster, it became clear that there needed to be a more unified approach to ensure the safety of the environment as well as international trade writ large in the Arctic. Thus, the International Maritime Organization (IMO), a specialized agency of the United Nations recognized for providing shipping regulations, decided to step up. The following year, in 1990, the IMO drafted the first nationally recommended provisions for ships operating in the Arctic, although they were not yet mandatory [9]. Nearly 30 years later, these recommended provisions would soon evolve into the IMO's Polar Code, which is now mandatory under various international conventions [10]. The goal of the Polar Code is to ensure a standard for ships that would be operating in the Arctic regions to ensure their safety and to hopefully prevent another environmental disaster. Specifically, the code is concerned with the "design, construction, equipment, operational, training, search and rescue and environmental protection matters relevant to ships operating in the inhospitable waters surrounding the two poles" [10].

A. THE AMERICAN BUREAU OF SHIPPING

While also adhering to the IMO's Polar Code, ABS, founded in 1862, helps to provide engineering solutions and standards for American shipping [11]. Much can be learned from the mistakes and remedies of the commercial shipping industry, especially in the Arctic region. In September 2006, the ABS published a guide for vessels operating in low-temperature environments which was most recently updated in September 2021 [12].

Although not mandatory, this document helps to play a vital role in the safety and operation of vessels in the Arctic region.

Much of the ABS's low-temperature guide is also applicable to the United States Navy. Specifically, it outlines ship-related challenges in the Arctic such as "operation of equipment, systems, structure, vessel maintenance, safety equipment, and crew performance" [12]. These will be examined in depth in addition to some of the problems and solutions the Navy has come up with themselves.

B. POLAR SHIP CATEGORIES

Both the IMO and the ABS categorize Arctic faring ships following what type of waters they intend to operate within. In the case of many U.S. Navy ships, they would be categorized as class C ships; or those designated to "operate in open water or ice conditions less severe than categories A and B" [13]. Each category brings with it a variety of standards for shipbuilding and maintenance that will not be discussed here. However, the definition of the three categories, as well as their equivalencies in Ice Class and ABS Ice Class classifications, can be found in Appendix A.

C. ABS DEFINITION OF TEMPERATURES

Much of the work of the ABS is dependent on the temperature in which a ship and its machinery will be operating. For standardization purposes, they identify vital temperature features such as the design service temperature. The design service temperature can be expressed graphically, as in Figure 3. This utilizes the mean daily high, mean daily average, and mean daily low temperatures (MDHT, MDAT, and MDLT) [12]. The design service temperature would be the lowest MDAT during the months of operation in low temperatures. These temperature averages use over 20 years of data and are specific to every region. Temperature data for most regions can be found publicly using tools like the National Oceanic and Atmospheric Administration (NOAA) Climate Data Online (CDO) [14].

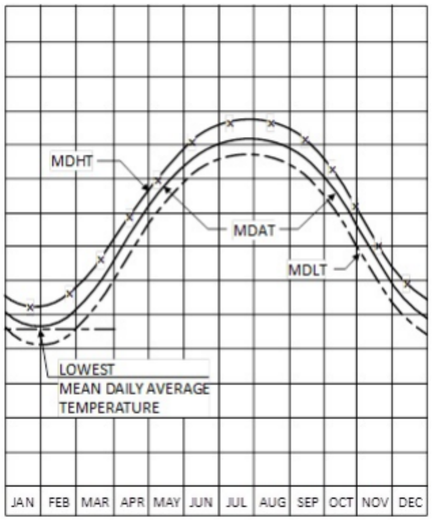

Figure 3. Graphical Representation of Design Service Temperature.
Source: [12].

D. CERTIFICATION PROCEDURE AND ENGINEERING REVIEW

Before a vessel operates in a low-temperature environment, which ABS defines as a temperature at or below -10 °C (14 °F), several steps need to be met for it to be certified [12]. To begin, the vessel must be assigned an ice class notation based on the expected environment of operation, as outlined in Appendix A. The vessel must also prove that the structural material of the hull is adequate for the expected design service temperature. Once this is accomplished, an engineering review must be made for nearly every aspect of the ship, as listed in Appendix B and explained in detail in the low-temperature guide [12]. The split in the flow chart in Appendix B is because personnel training and the outfitting of loose safety gear can be accomplished at two different times depending on the situation.

Perhaps the most vital part of the engineering review, and a possible beneficial addition to Navy regulations, is the winterization plan that must be submitted and reviewed. This seven-part plan is meant to holistically show that a vessel is prepared for the Arctic environment and concludes with a visit from an ABS surveyor for system testing and confirmation. It involves proving the readiness for anti-icing and de-icing, preventing systems from freezing or becoming uncontrollably viscous, heating and ventilation, and how the plan will be tested. It also must include instructions for how vessel personnel will be trained to use the plan. Upon the successful completion of the engineering review, a surveyor will then come to verify that everything in the plan is in place and works as intended before a vessel is given the green light for a cold-weather voyage [12].

Although there may be variation between the standards used for cold weather voyages between the U.S. Navy and the ABS, adoption of the winterization plan and engineering review may better prepare the Navy to accomplish its Arctic endeavors. It would likely take a significant amount of testing, time, and money, but once a winterization plan is completed for a certain class of ships, much of it may apply to the rest of the class or platform.

III. CLIMATE

The Arctic climate is a harsh environment to operate in due to a vast array of conditions. Arctic storms bring rapidly changing temperatures, low visibility, and intense winds. In addition to drifting sea ice, precipitation, low temperatures, and sea state, the Arctic is one of the most treacherous places to operate a ship.

A. ICING BASICS

One of the most significant hazards of operating ships in the Arctic region is topside icing. This phenomenon is characterized by thick layers of ice forming on the "decks, sides, superstructures, hatches, masts, rigging, deck mounted machinery, antennas and combat systems" [15]. Soviet ships and freighters alike have reported accumulating foot-thick ice that has taken days to remove [15]. Figure 4 showcases the extreme impact that topside icing can cause. Depicted in the image is the fore bulkhead of the *Knorr* during a winter expedition in 1997 [16].

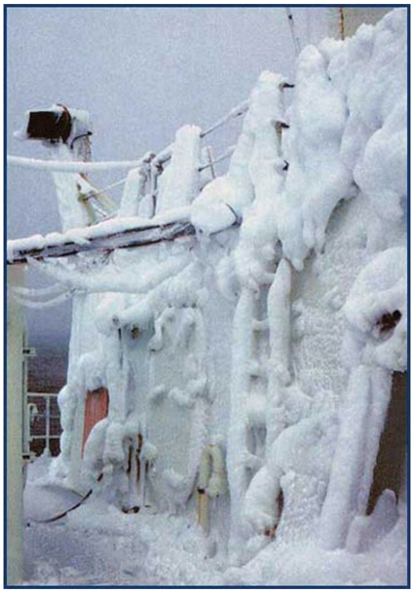

Figure 4. Research Vessel *Knorr*. Source: [16].

Topside icing is a vital issue because it also "increases the ship's displacement, decreases freeboard, obstructs operation of deck machinery, impedes personnel movement on deck, may obstruct air intakes, restricts helicopter operations, disrupts the operation of radio and radars, hampers the deployment of underwater sensors and may interfere with the use of deck mounted weapons" [15]. Furthermore, the added ice can raise the center of gravity of a vessel, reducing its stability. Added weight from ice on superstructures and masts brings the metacentric height of a ship closer to zero. When this happens, it becomes increasingly easier for external forces such as wind and sea state to capsize it. Many smaller vessels have experienced this and have been lost in Arctic storms [15].

1. Types of Icing

The most common type of topside icing is referred to as spray icing. This phenomenon occurs when air temperatures are below freezing and sea spray that lands on ship surfaces freezes on contact [17]. In vessels with low decks, waves can rise high enough to cause flooding. However, as long as the water does not remain stagnant and can be drained or displaced by more waves, it will not be able to firmly bond to the surface and contribute to the icing. There is also a secondary, less common type of topside icing, known as atmospheric icing. This occurs when drops of rain or damp snow land on the ship and freeze [17]. Under most conditions, both types of icing occur simultaneously.

Atmospheric icing poses a significant threat due to the accumulation of ice forming higher up on the masts, rigging, and superstructures of vessels. This is because these areas are hard to reach to prevent or remove ice. Atmospheric icing can be further split into the categories of freezing rain and arctic sea smoke. Freezing rain will cover a ship in a glaze of freshwater ice [17]. Due to the typically low amount of rainfall rates in the Arctic, this effect will not cause severe danger to a vessel. Arctic sea smoke, or frost smoke, can occur when the air temperature is below 0 °C (32 °F) and is at least -9 °C (16 °F) colder than the seawater [17]. In this instance, a smoke-like frost forms that is usually only a few feet thick. This frost is called white frost when it is below eye level and black frost when above. Frost smoke contains supercooled water droplets that will, in the conditions mentioned above, freeze immediately upon contact with surfaces, forming opaque rime ice [17]. Rime ice is more porous than glaze ice and is easier to remove as it requires less force to break apart.

2. Types of Ice Accretion

Depending on the environmental conditions and type of water, several types of ice accretion can occur. These include frost, rime, and glaze. Frost, or hoarfrost are ice crystals that form on surfaces when water vapor sublimates on a surface that is at or below freezing [17]. If this effect occurs directly on the ship's surface rather than on top of the snow, the resulting bond can be extraordinarily strong. Small individual water droplets that become supercooled on surfaces at or below freezing can form rime ice. This can be either a hard ice rime, when freezing is slow, or a soft ice rime when the droplets freeze rapidly [17]. Hard rime is more translucent with a higher density while soft rime has a more delicate structure with a lower density as more air is trapped inside of it. Lastly, glaze occurs when water droplets can form a continuous film over the surface before it freezes. In this case, bubbles can escape, making the resulting ice extremely hard and strongly adhered to surfaces. Larger water droplets increase the likelihood of the formation of glaze ice [17]. The ice's density can vary depending on the concentration of brine in the water. Sea spray will contain brine pockets which makes it weaker than icing caused by freshwater [17].

B. ICING AVOIDANCE

One of the best ways to prevent icing on a ship in the Arctic is to avoid it altogether. This can be done through the use of modern-day methods to calculate, detect, or predict weather across the world. Using this information in addition to understanding how a ship's course can affect icing, routes can be created that will increase the safety of the ship and crew.

1. Predicting Icing

The 1988 Cold Weather Handbook documented methods that were used to prevent and remove ice [15]. Although the method of predicting ice accumulation was suggested, the most recent data and technology were not sufficiently advanced to be utilized confidently. However, modern technology has brought about many advancements in prediction technology. Currently, the most modern system is the NOAA (National Oceanic and Atmospheric) Global Real-Time Ocean Forecast System (RTOFS) [18]. This system provides a forecast of "up to eight days of ocean temperature and salinity, water velocity, sea surface elevation, sea ice coverage, and sea ice thickness" [18]. With the increased ability to predict these various conditions, as well as Artic storms, one of the best ways to combat icing is to plan and avoid adverse conditions entirely. This includes setting courses to minimize wind and bow slamming, which can decrease the amount of sea spray the ship will experience.

2. Calculating Icing

Icing is a complex and multivariable function dependent on various environmental and ship factors. In 1990, Overland presented an algorithm to predict icing [19]. Equation (1) defines the icing predictor variable, PPR, as the rate at which ice is expected to accumulate [19]. This considers the wind speed, V_a, the freezing point of seawater, T_f, the air temperature, T_a, as well as the sea temperature, T_w.

$$PPR = \frac{V_a(T_f - T_a)}{1 + 0.3(T_w - T_f)} \tag{1}$$

This algorithm was developed using data provided by vessels between 20–75 m (66–246 ft) in length and heading directly into the wind, and it will be more accurate in similar situations. Of course, depending on various environmental and ship characteristics, actual icing rates will vary. Furthermore, there are charts called nomograms based on this same research that can be used to predict ice accumulation if calculation is difficult.

Table 1 was created by Overland by utilizing Equation (1) and correlating the icing predictor variable with a class of icing and its corresponding rate of ice accumulation. This can be used to predict what type of preparation or equipment may be necessary before encountering the conditions.

Table 1. Icing Class and Rate. Adapted from [19].

PPR	<0	0–22.4	22.4–53.5	53.3–83.0	>83.0
Icing Class	None	Light	Moderate	Heavy	Extreme
Icing Rates (cm/hour) (inches/ hour)	0	<0.7 <0.3	0.7–2.0 0.3–0.8	2.0–4.0 0.8–1.6	>4.0 >1.6

As previously mentioned, this data can be more easily understood through an icing nomogram. Figure 5 shows an example nomogram which is set to a specific water temperature and shows icing class curves as a function of wind speed and air temperature. Each nomogram will be set at a certain water temperature.

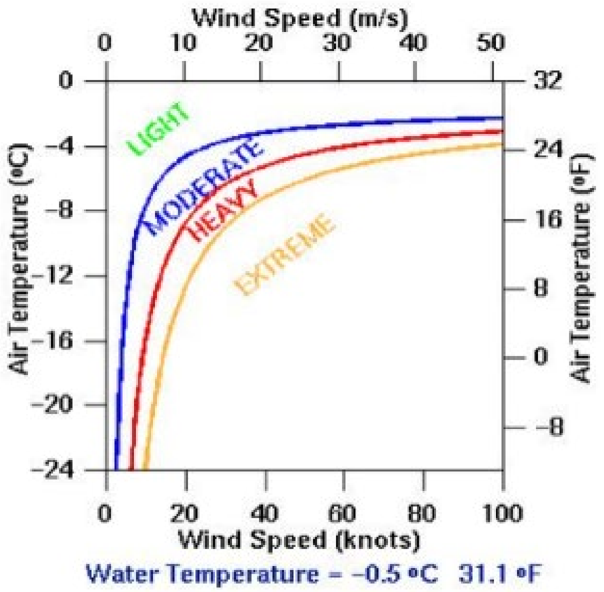

Figure 5. Example Nomogram. Source: [19].

3. Impact of Weather on Ice Deposition

The temperature plays a significant role in how ice will be deposited on a ship. The temperature range in which icing is most severe is between -18–0 °C (0–32 °F) [17]. Furthermore, icing is increased when the sea surface temperature is between 2.2–8.9 °C (28–48 °F) [17]. In air temperatures of around -2 °C (28 °F), spray from the ocean freezes on exposed surfaces of the vessel that are no more than around 15 m (50 ft) above the peak water level [17]. In colder temperatures of around -17 °C (1 °F), the spray may be frozen before contact with exposed surfaces [17]. In this case, dislodged ice may drift around the deck. Wind speeds were observed to cause freezing spray to occur around 9 m/s (18 kts) [17]. The lower the temperature of the air and sea and the quicker the speed of the wind, the faster ice will accumulate. Sea spray is heavily dependent on the height and period of waves, which in turn vary based on the wind conditions. The stronger the winds, the more sea spray and in turn icing will occur. Lastly, the accumulation of ice itself increases the rate at which more ice deposits. This is because the formation of ice on various surfaces increases the area in which more water droplets can land and freeze.

4. Impact of Course on Ice Deposition

It has been observed that most sea spray and subsequent topside icing occur when a ship is heading into the wind at an angle between 15–45° relative to the bow [17]. In this case, there is more icing that occurs on the windward side. In some cases, a decision may have to be made between a smaller, nonsymmetrical accumulation of ice and a greater, symmetrical deposition. Despite this, if the weather and temperature are understood beforehand, as well as how they will impact the type of ship, then an optimal course can be selected to minimize icing.

IV. STABILITY CASE STUDY

A. INTRODUCTION AND HYPOTHESIS

As a vessel transits the Arctic, a significant amount of ice can accumulate along the sides, top, superstructure, and masts. Topside icing is a complex, multivariable problem that impacts ships in many ways. The goal of this section is to compare how ice accumulation affects the stability of ships differently based on their size and other characteristics. The hypothesis of the impact that icing has on ship stability is that it will have a more profound negative impact on smaller vessels than on larger ones. Although larger vessels have an increased area for ice to accumulate and have the capacity to carry a larger load than their smaller counterparts, they also have a larger maximum displacement and will likely experience a smaller shift in their center of gravity. Furthermore, smaller vessels typically have a main deck that is closer to the waterline and will be impacted more by spray icing caused by bow slamming due to the higher quantity of water that will be able to reach the deck and superstructure. The more extreme impact that icing has on the freeboard and center of gravity of smaller vessels will likely result in a smaller righting arm and thus a more detrimental effect on ship stability in comparison to a larger vessel.

The three vessels analyzed will be the Oliver Hazard Perry Class (FFG-7), the Norwegian coastguard vessel *KV Nordkapp*, and the Runnymede Class (LCU-2030). These three vessels were selected due to their range of sizes as well as the availability of loading information. The FFG-7 is the largest with an overall length of 135.64 m (445 ft) and a beam of 13.716 m (45 ft) [20]. The *KV Nordkapp* is slightly shorter with a length 105.05 m (344.65 ft) and a beam of 14.60 m (47.90 ft) [21]. Lastly, the LCU-2030 is the smallest at 54 m (174 ft) long and 13 m (42 ft) wide [22].

B. PROGRAM SETUP

To understand the impact that ice accumulation has on the stability of a vessel, the center of gravity under a specified loading condition must be determined. These loading conditions corresponded to typical values of weight distribution that would be found on a normal vessel. For example, the initial loading case before icing utilized for the FFG-7 model included the weight of various fuels, waters, and miscellaneous tanks. The location and weight of each of these loads were used as inputs in the U.S. Navy's Program of Ship Salvage Engineering (POSSE) software. This program, given a set of inputs, performs numerical integrations, force iterations, as well as a deflection analysis to return useful information about the vessel such as its stability characteristics [23]. POSSE found that the initial loading information for the FFG-7 model resulted in an initial displacement of 4,100,000 kg (4515 tons) and a vertical center of gravity of 5.54 m (18.19 ft) from the keel.

Following this, two more loading conditions were considered. The first was an accumulation of 99,790 kg (110 tons) of ice. This is derived from the experience of the *KV Nordkapp*, which accumulated that amount of ice during a 1987 voyage in just 17 hours [21]. The final condition was an addition of 399,161 kg (440 tons) of ice, four times greater than the first case. Although this final condition is unlikely, it serves as an extreme example of the worst possible icing situation. All three loading conditions were performed for both the FFG-7 and then LCU-2030.

To model the ice accurately in POSSE, its vertical center of gravity must be calculated. The full weight of the ice can then be added into the software as a miscellaneous weight acting through that point to determine its contribution to the change in ship stability. To do this, the side and top view of each vessel were analyzed and broken down into simple geometries. For example, Figure 6 shows the side view of the different surface areas above the water for the FFG-7.

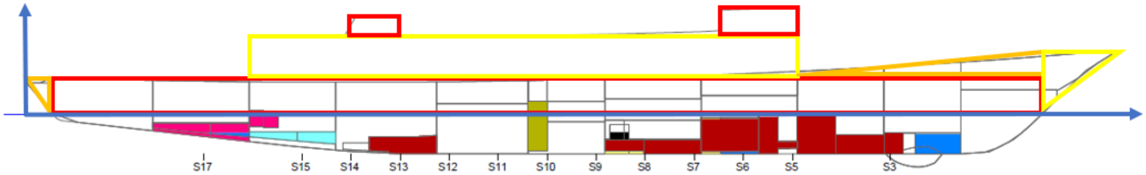

Figure 6. FFG-7 Side View with Basic Geometries.

Each surface area that could accumulate ice needed to be found for both the FFG-7 and the LCU-2030. This includes the port, starboard, fore, aft, and top surfaces. Once each surface area was found, the thickness of the ice could be calculated. This analysis assumed that the ice was deposited at a consistent rate across all available surface areas, resulting in a constant thickness. By dividing the total weight of the ice by its density (around 900 kg/m^3 (56.19 lb/ft^3) for saltwater), the total volume of ice can be found [21]. The overall thickness of ice is then calculated by dividing the volume of ice by the total surface area of the ship. For example, when adding the two specified ice weights, the FFG-7 had an ice thickness of 2.87 cm (1.13 in) and 11.48 cm (4.52 in) respectively.

After the even distribution of the ice, the vertical center of gravity where the weight of ice could effectively be added into the model was found. This was accomplished through a centroidal analysis wherein each surface area holding ice had its vertical centroid calculated, summed, and averaged. Because of the assumption that the ship has no initial heel angle and that the ice thickness is constant, this vertical center of gravity can be used in POSSE for the location of the added ice.

C. ICING PREDICTOR RATE

For reference on how the amount of ice accumulated by the *KV Nordkapp* corresponds to Overland's icing predictor rate from Table 1, an additional calculation was performed. It was assumed that ice accumulated on approximately half of the topside area of the ship, or 766.87 m^2 (8,254.47 ft^2). This area was found by taking half of the overall length multiplied by the beam. This simplification accounts for the added area from the superstructure through the additional, nonexistent area near the bow. Only the front half of the topside area was used because that part of the ship accumulates the vast majority of the ice, making the other half negligible. Although the topside area found is very simplified, the amount of added ice calculated will make a negligible difference to the icing predictor rate.

The majority of ice that is formed during topside icing is mostly glaze ice, having a varying concentration of saltwater and a nominal density of around 900 kg/m^3 (56.19 lb/ft^3) [21]. By dividing the weight of accumulated ice that the *KV Nordkapp* experienced by the ice density and topside area, the total ice thickness after 17 hours is found to be 14.46 cm (5.69 in). Utilizing Table 1, this ice thickness corresponds to an icing rate of 0.85 cm/hr (0.33 in/hr). According to Overland, this would correspond to a moderate icing rate. It is worth noting that Table 1 was based on the icing rates experienced by vessels up to 75 m (246 ft) in length while the *KV Nordkapp* is 105.05 m (344.65 ft). A smaller vessel under similar conditions may experience a higher icing rate due to the closer proximity between its topside area and the water level.

D. KV NORDKAPP CENTER OF GRAVITY

For the *KV Nordkapp*, the average vertical center of gravity of the added ice was found to be 11.557 m (37.917 ft) above the keel based on the stability manual of the ship [21]. Also, according to the stability manual, the maximum vertical center of gravity to maintain the stability of the ship was recorded at 6.691 m (21.95 ft) [21]. Before icing, the ship's initial displacement was 3,250,000 kg (3579 tons), which resulted in a center of gravity of 6.395 m (11.14 ft) [21]. The final center of gravity of the vessel was found to be 6.594 m (21.63 ft), an increase of 3.1% and just 1.45% shy of resulting in an unstable equilibrium [21]. Furthermore, the metacentric height was reduced from 1.137 m (3.73 ft) to 0.915 m (3.00 ft), a significant decrease of 19.5% [21]. These values found in the case study will be utilized for comparison to the two differently sized vessels to determine the impact that similar icing has on stability.

E. RESULTS AND COMPARISON

The three loading conditions that were analyzed in the POSSE software were the uniced case, 99,790 kg (110 tons) of ice added, and 399161 kg (440 tons) of ice added. These are represented in the first column of Table 2 as loading conditions 1, 2, and 3, respectively. Table 2 shows the resulting center of gravities and metacentric heights for the FFG-7 and LCU-2030. From the first loading condition to the second for both vessels, the metacentric height decreased by 12%. This was less than the *KV Nordkapp*, as its metacenter decreased by 19.5% under the same conditions. Going all the way to the third loading condition caused the metacentric height of the FFG-7 to decrease by 2% more than the LCU-2030, at a 44% and 42% reduction respectively. However, the difference in the change of the center of gravity was more consistent across the three vessels. At the second loading condition, the LCU-2030 had a center of gravity increase of 3.9%, the *KV Nordkapp* increased by 3.1%, and the FFG-7 increased by 2.4%.

Table 2. Resulting POSSE Date for the FFG-7 and LCU-2030.

Vessel (Loading Condition)	**Center of Gravity m (ft)**	**Metacentric Height m (ft)**
FFG-7 (1)	5.54 (18.19)	1.19 (3.92)
FFG-7 (2)	5.68 (18.63)	1.05 (3.46)
FFG-7 (3)	6.04 (19.82)	0.67 (2.20)
LCU-1030 (1)	3.66 (12.00)	4.18 (13.73)
LCU-1030 (2)	3.80 (12.47)	3.67 (12.03)
LCU-1030 (3)	4.11 (13.49)	2.45 (8.03)

One of the easiest ways to determine how much of an impact the change in center of gravity and metacentric height have on the stability of a vessel is the impact that it has on the righting arm of the vessel given varying degrees of heel. The less stable a vessel is, the smaller its righting arm will be, causing it to capsize at lower heel angles. When a vessel is affected by an outside force, its equilibrium will respond in one of three ways. If the vessel has a stable equilibrium and it heels so that its center of buoyancy shifts to a new position, a righting moment is imparted that will return the ship to its original position. If the vessel has a neutral equilibrium, a heel angle would not be accompanied by any righting moment and the vessel would remain in a new position. If the vessel has an unstable equilibrium, a displacement will cause the ship to continue to move farther away from its equilibrium, eventually causing it to capsize if not corrected.

Figure 7 shows the righting arm graph across various degrees of heel angle for the FFG-7 under the three ice different loading conditions. As expected, the vessel is the most stable in its original loading condition with a metacentric height of 1.19 m (3.92 ft), as seen by the uppermost solid curve. The two dashed curves beneath it represent the first and second loading conditions of the vessel, the addition of 99,790 kg (110 tons) and 399161 kg (440 tons) of ice respectively. Even under the most severe loading condition, the righting arm of the FFG-7 never becomes negative, meaning that it would be able to recover from even a 60° heel angle.

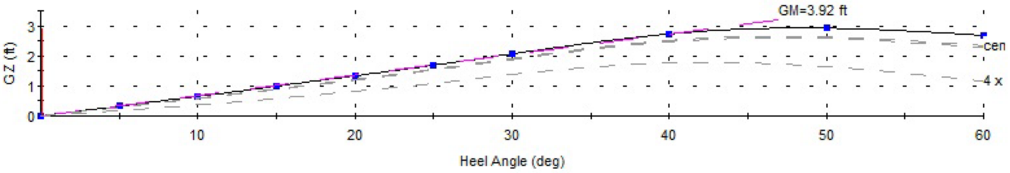

Figure 7. Righting Arm for Varying Heel Angles for the FFG-7.

Figure 8 displays the resulting righting arms for the LCU-2030 given the same loading conditions. Here, the LCU-2030 shows that it would have a negative righting arm above certain heel angles given each loading condition. This means that based on its center of gravity and metacentric height, there exists a threshold heel angle that would capsize the vessel unless immediate preventative actions were taken. In loading condition 3, the LCU-2030 would capsize at a heel angle of 40°, while it would take a heel angle of 62.5° to capsize the vessel in loading condition 1.

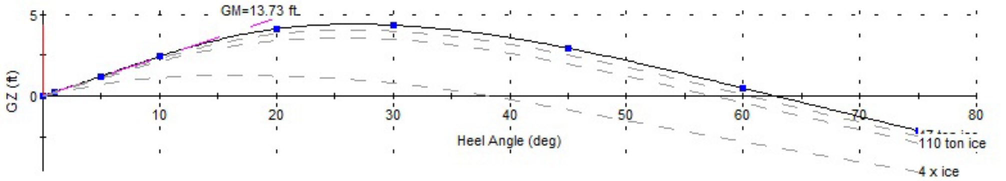

Figure 8. Righting Arm for Varying Heel Angles for the LCU-2030.

It is clear that the smallest vessel, the LCU-2030, had its stability decrease the most compared to the two larger vessels under the same loading conditions. This can be seen through its higher relative increase in center of gravity as well as the severely reduced heel angle required to capsize at greater loading conditions. It is also apparent that the size of a vessel does have a significant impact on the change of the center of gravity under similar icing conditions. This change was found to be the most severe for the smallest vessel and the least severe for the largest as predicted. The change in metacentric height was somewhat erratic and likely impacted more by the different form factor of the vessels.

Overall, sailors operating vessels in the Arctic need to understand the conditions in which their ships may be in danger of capsizing. This analysis showed that the smaller the vessel, the lesser the amount of ice accumulation it would take to negatively impact its stability.

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V. VESSEL TYPE

A. VESSEL SIZE

Differently sized vessels are often disproportionately affected by the Arctic environment. Utilizing his findings from Equation (1), Overland calculated the combination of wave height and wind speed that would cause severe icing based on the length of the vessel. This assumes that the air and water temperatures were within their threshold to cause icing and that the fetch of the wind, or unobstructed length traveled over the water, was 200 km (108 nmi) [24]. Under these conditions, a 15 m (49 ft) vessel would experience severe icing with a wave height of 0.6 m (2 ft) combined with a wind speed of 5 m/s (9.7 kts) [24]. For a vessel 10 times larger than this, it would take 10 times the wave height and four times the wind speed [24] to produce a similar severity of icing. These predictions reveal that the conditions required to cause severe icing are much easier to reach with smaller vessels, making it a much more pressing issue. This means that the smaller the vessel, the more frequently active measures will need to be taken to remove ice. A full table of Overland's threshold findings can be found in Appendix C.

Especially for smaller ships, accumulated ice significantly reduces freeboard which may cause longitudinal pitching to immerse the deck edge, resulting in flooding that would increase the center of gravity. The center of gravity is further increased as ice is deposited along the superstructure and masts, making capsizing more likely. Ships with large superstructures and low freeboard, such as destroyers, are more at risk for this occurrence [17]. This is why some destroyer classes have been designed with specific bows and hulls to help negate this effect. Larger ships, such as aircraft carriers, are more likely to experience a shift in their transverse center of gravity. This is due to the more rapid accumulation of ice on the windward side of the vessel, eventually causing a list [17]. It is important to know what rates at which a vessel will experience icing and the effect that added weight will have on the vertical and transverse center of gravities. The more knowledgeable a crew is on what risks their vessel may be predisposed to, the better equipped they may be to alter their course to help alleviate the issue.

B. MULTI VS. SINGLE-PURPOSE CRAFT

Most commercial shipping vessels were created for a single route and are equipped to operate within specific environments. As a result, they are equipped with permanent modifications that serve to optimize the efficiency of their single purpose. The equipment and technology that can assist with the Arctic's climate can be heavy and sometimes difficult to install. Vessels whose primary goal is to operate in Arctic environments often have the advantage of being built from the ground up with the necessary equipment and technology. In contrast, most Naval vessels are expected to be able to operate across multiple different environments to accomplish a variety of missions. Due to this, it would likely be unwise to install permanent technological Arctic modifications to a Naval vessel that did not intend to operate primarily or indefinitely in extremely cold temperatures. The added modifications and equipment would add weight and possibly limit the ability of the ship to operate in different temperatures. Rather, for current existing Naval vessels that intend to operate in the Arctic, the changes made would ideally be temporary and easily installed and removed.

It would likely be easier to build Naval vessels from the ground up whose primary objective is to operate indefinitely in the Arctic. This has the benefit of removing the need for the modification or installation of technology on current Naval vessels. However, this may not be practical due to the amount of funding, time, and resources needed to accomplish such a task.

C. TRANSITIONING

Due to the nature of their work, Naval vessels may be expected to operate both in the Arctic and in other climates within small time frames. This would necessitate the transiting of vessels between a much larger range of temperatures than would normally be experienced. As a result, for ships in this situation, there would be an increased thermal load on nearly every exterior and interior material and component onboard. Especially for composite materials, an increase in thermal loading over time can decrease material properties, thus reducing their lifespan. It may be prudent to determine how much impact, if any, transitioning between warm and extremely cold temperatures has on these critical ship components. If there is a significant reduction in the expected lifetime for some composite materials or components, this could become a supporting argument for either building or assigning ships to operate primarily or indefinitely in the Arctic region.

D. COLD SOAKING

Cold soaking is defined as the long-term exposure of a ship to subzero temperatures and freezing seas [15]. This process takes two to three weeks to occur as the ship's exterior and interior spaces reach an equilibrium where the net heat transfer rate is zero and the heat on the ship remains constant [15]. Initially, the exterior of the ship will reach an equilibrium with the ambient temperature. It will take a longer time for heat to leave spaces that are farther inside. Cold soaking causes some phenomena that may need to be addressed and mitigated.

1. Exterior Effects

Engines and equipment on the exterior of a vessel will experience a tightening in lines that carry viscous fluids. This, in addition to an increase in the viscosity of fuels and oils, can lead to the sluggish performance of machinery or a complete inability to operate. To help mitigate this, some lines may need to be heated by external means. Also, Arctic-grade oils and fuels should be utilized to minimize the viscosity changes caused by cold temperatures [15]. Lastly, some machinery may need time to idle before warming up enough to perform its intended task.

2. Interior Effects

The sudden decrease in seawater and ambient air temperatures will likely harm internal spaces as they slowly reach equilibrium. One of the most pertinent issues is the formation of condensation on air and seawater pipes as well as on the surfaces of cold interior spaces. This is caused by the large difference in temperature between the warmer inside air and the suddenly colder surfaces of pipes and walls. This condensation could damage electrical systems, cause water damage, or create slippery surfaces [15]. Being able to monitor, control, or mitigate this condensation through resistive heaters or constant inspection is vital during the cold soaking process.

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VI. TOPSIDE ICING SOLUTIONS

A. COATINGS

1. Ice-Phobic Coatings

Surfaces at risk for icing can be covered in various coatings or chemicals. The purpose of this is to inhibit the accumulation of ice by making topside surfaces slick and nonporous. This limits the ability of water and ice to bond with the covered material, thus causing the required force for removal much lower. Such coatings are not considered a prevention mechanism for icing, but they can help mitigate the difficulty in the removal process.

To select the proper coating, there are a few items that must be taken into consideration. Regarding the coating itself, it must be able to adequately prove to inhibit the accumulation of ice to some degree and result in easier ice removal. It must also be non-reactive to the materials to which it is applied. A corrosive coating would lead to a shortening of the lifespan of the surfaces it was in contact with. As a result, the location in which a coating is to be applied needs to be selected carefully. Testing would need to be carried out to determine how a coating would react to the different types of materials found on the decks, masts, and superstructures of vessels. This includes what thickness the coating should be applied for optimal results. Furthermore, if a coating is slippery, then the application in areas where personnel transit may cause additional risk. The use of solid chemicals to assist in ice removal or prevention is preferable in transit areas while chemicals that can be sprayed are preferred for more sensitive technology as well as hard-to-reach areas. The cost and weight of the coating is also important. Each time ice is removed, it will remove some of the protection itself, resulting in the need to reapply. With the limited storage and weight capacity of a ship, the coating should be selected to not surpass these limitations. Lastly, consideration should be taken for the health and environmental effects of the chemical that is used. Some ice-phobic coatings can be harmful if they are ingested, inhaled, or come into contact with skin. All of the coatings that are used will eventually be deposited in the ocean, so utilizing an eco-friendlier chemical would be less harmful to the environments in which it is used.

The two primary coatings used by the Navy for many decades were fluorocarbon penetrating coating (FPC) and Vellox-140 [15]. Although these two chemicals proved to assist in the removal of ice, a wide range of chemicals could be used based on the expected environment or weight and storage limitations. Examples of these other chemicals are sodium chloride, calcium chloride, and urea [25]. While sodium chloride the cheap and calcium chloride is fast acting, both are more corrosive than urea [25].

2. Modern Ice-Phobic Coatings

The U.S. Navy SBIR Transition Program (STP), interested in creating a more effective coating for icing on the superstructure, has invested in various companies to find a solution. One such contract was awarded to NanoSonic, Inc. to create a spray-deposited chemical for U.S. Navy ships operating in Arctic environments [26]. The goal of this project was to create an aerosol that would cause ice adherence strength of less than 30 kPa (4.35 psi), to be able to operate in temperatures down to -30 °C (-22 °F) in salt and fresh water, and to be affordable and easy to apply [26]. The product they created, shown in Figure 6, was able to meet various American Society for Testing and Materials (ASTM) environmental durability tests and demonstrated low ice adhesion, high-velocity rain durability, corrosion protection, and various other benchmarks [27]. NanoSonic, Inc. based its coating on siloxane and fluorinated organic systems [28]. They also claim that their product has no significant environmental or mechanical effects [28].

Figure 9. HybridShield Icephobic Coating. Source: [27].

3. Hull Coatings

Due to the different conditions experienced by a ship operating in the Arctic, a protective coating can be used to cover the hull as a base layer before the application of ice-phobic coatings. The goal of this coating is to protect against corrosion while maintaining a smooth hull that minimizes friction [12]. These coatings are often made of epoxy, polyester, or vinyl resins [12]. Epoxy resins can be reinforced with glass flakes but may become brittle over time and can eventually crack and lose their bond with the material on which they were applied [12]. If a hull coating is applied, the thickness should be adequate to ensure that it will not need to be reapplied too frequently. Often the manufacturer of a hull coating will provide recommendations as to what the thickness should be. Furthermore, if a hull coating is going to be used in addition to an ice-phobic coating, it must be chemically compatible to guarantee proper adhesion and no corrosion.

To ensure the effectiveness of a coating, various testing standards can be applied. These tests measure vital features such as hardness, adhesion, anti-corrosion properties, and the environmental character of the coatings [12]. A full table of ABS-suggested tests for hull coatings can be found in Appendix D.

Ice-phobic and hull coatings have proven their usefulness in combating icing and improving a ship's efficiency and survivability in the Arctic. However, to use them as effectively as possible, there must be a vast amount of testing done to determine their impact on the durability and effectiveness of ship materials and systems. As there are a wide variety of modern coatings available, an analysis of the types of conditions expected during Arctic operations should be used to determine what coatings to bring, how much to use, and where to apply them. Hull coatings may or may not be suitable for the operation of Naval vessels due to their wide-ranging use. This method is most effective for ships that do not need to transition frequently between warmer and colder environments.

B. MANUAL TOPSIDE ICE REMOVAL METHODS

The removal of ice from the topside of a ship often requires a very manual effort. This necessitates the use of items such as baseball bats, mallets, ice picks, shovels, and brooms [25]. In addition to these items, heat sources may need to be utilized such as portable hair dryers, heat guns, steam hoses, and steam lances [25]. This list of items is not exclusive and anything that can be useful in the removal of ice should be considered. The selection of these items should be chosen with the consideration of space, weight, electrical load, and necessity based on predicted environmental and icing conditions. Care should always be taken as some of these manual ice removal methods can be destructive to some materials or systems on a ship if used improperly.

C. COMPOSITE THERMAL LOADING

There are a significant number of components and areas on the topside of a ship that are made of composite materials. These materials often have a lower threshold for thermal and mechanical loading than steel. Specifically, repeated thermal loading can lead to lower mechanical properties and result in brittle fracture, buckling, or a lower life span. Unless necessary, the use of manual and thermal loading of composite materials to remove ice should be avoided. One possible alternative is the use of pneumatically inflated rubber pillows that can be installed on superstructures to help remove ice while avoiding the loads that would be caused by manual removal methods [12].

D. HEAT TRACING

An effective solution to icing and temperature control is the use of electrical resistance heat tracing. The goal of heat tracing is to control the temperature across piping or surfaces through the use of a resistant element and a self-regulating polymer [29]. As seen in Figure 7, a lower temperature causes the polymer to create conductive pathways through which current can flow and produce heat through the resistant element. However, once the temperature levels increase to a certain level, the pathways become shorter and eventually stop the flow of current, thus ceasing heat production.

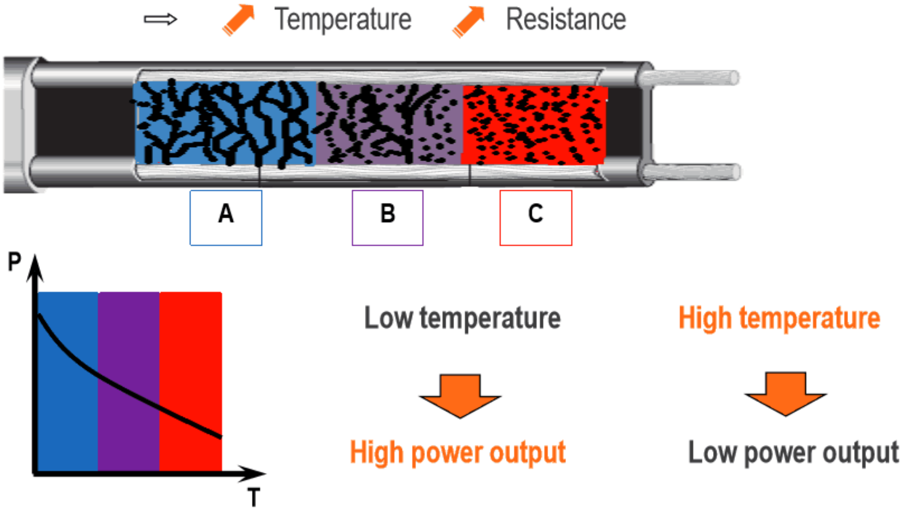

Figure 10. Depiction of How Temperature Affects Heat Trace Cables. Source: [29].

This relatively low-cost solution can adhere to various ship systems to ensure safe operations or minimal ice adhesion at the minimum anticipated temperature. If heat tracing is used, the ABS winterization plan requires the documentation of an electrical single-line diagram [12].

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VII. HEAT TRANSFER CASE STUDY

A. MATERIAL, DIMENSIONAL, AND ENVIRONMENTAL SPECIFICATIONS

To select the proper grade of heat trace cable, calculations must be done for the area in which they are intended to be used. Heat trace cables can be installed in any location that is expected to have a problem due to icing or low temperatures. This can include but is not limited to piping, exterior surfaces, and hatches. The ultimate goal of a heat trace cable is that an equilibrium is reached wherein the heat lost is equal to the heat provided while a specified, desired temperature is reached.

To find the necessary heat output of a heat trace cable in the worst condition, this section will analyze an uninsulated 0.3048 m (1 ft) section of a copper pipe. First, hand calculations will be performed to determine the amount of heat necessary to prevent water from freezing given three ambient temperatures. Many heat trace companies utilize a one-dimensional heat transfer calculation to determine the cable necessary [29]. The results found will be compared to a steady-state thermal analysis under the same conditions performed by the ANSYS engineering simulation program.

To keep the water from freezing, an inside temperature of 2 °C (35.6 °F) was specified. The ambient temperature was set to -10, -20, and -30 °C (14, -4, and -22 °F) to determine what amount of heat would be lost at various temperatures. The conduction coefficient of the copper pipe was 398 W/m-K (2762.12 BTU-in/hr-ft^2-R) [30]. The convection coefficient of the air was set to 15 W/m^2-K (2.643 Btu/hr-ft^2-R). This value was selected based on common a convection coefficient for air given free convection [31]. This assumes that the heat transfer is occurring on a pipe that is contained within the ship, likely in an unheated location. Lastly, the thermal analysis performed is at a steady state and the water modeled has no velocity, mirroring the worst case of an unheated pipe that is infrequently used.

B. ONE-DIMENSIONAL THERMAL ANALYSIS

For this case, a one-dimensional heat transfer analysis in cylindrical coordinates was carried out. In this instance, there is only heat transfer in the radial direction while neglecting the heat transfer in the axial direction. Although the heat does vary in the axial direction, the ANSYS results will show whether or not this assumption can be used. Equation (2) shows the thermal resistance through the copper pipe, where $\mathrm{D_o}$ and $\mathrm{D_i}$ are the outside and inside diameters, k_c is the conduction coefficient of copper, and L_p is the length.

$$R_{t,cond} = \frac{ln\,(\frac{D_o}{D_i})}{2*\pi*k_c*L_p} \tag{2}$$

Equation (3) documents the thermal resistance of convection between the copper pipe and air, where h_{air} is the convection coefficient of the air.

$$R_{t,conv} = \frac{1}{h_{air}*\pi*D_o*L_p} \tag{3}$$

Equation (4) finds the net heat transfer rate by taking the difference between T_w, the temperature of the water at the outer wall of the pipe, and T_a, the temperature of the air. This is then divided by R_{total}, the total thermal resistance provided by both conduction and convection.

$$Q_{out} = \frac{T_w - T_a}{R_{total}} \tag{4}$$

Given the specified parameters, $R_{t,cond}$ is equal to 0.000293 K/W, $R_{t,conv}$ is found to be 1.37 K/W, and R_{total} results in 1.371 K/W. This reveals that the thermal resistance due to the conduction through the copper pipe is negligible in comparison to that due to convection. Given these values, Table 3 shows the resultant heat lost at varying ambient temperatures following Equation (4).

To input the heat flux of the cable into ANSYS, the surface area of the heat trace cable must be found. This is done through Equation (5), which calculates the length of the cable, L_c, that is used when wrapping around the length of the pipe [32].

$$L_c = \frac{L_p}{P} * \sqrt{(\pi * D_o)^2 + P^2} \tag{5}$$

Here, P represents the specified pitch of the coil.

Given the parameters previously outlined, the length of the cable utilized to wrap around the pipe section was found to be 1.0 m (3.28 ft). To find the area that is in contact with the pipe, L_c is multiplied by the diameter of the heat trace coil, resulting in a value of 0.0508 m^2 (0.547 ft^2). The outer surface area of the coil is found by multiplying L_c with half of the coil circumference, resulting in an area of 0.0798 m^2 (0.859 ft^2). By dividing the heat loss, Q_{out}, by the sum of these surface areas, the necessary heat flux, q_{in}, of the heat trace cable can be found. Table 3 shows the one-dimensional heat loss and necessary heat flux for each ambient temperature. These will be referenced as thermal conditions 1, 2, and 3 during the ANSYS thermal analysis.

Table 3. Variation of Heat Loss and Minimum Heat Flux.

Ambient Temperature °C (°F)	**Heat Loss Q_{out} W (Btu/hr)**	**Heat Flux q_{in} W/m^2 (Btu-hr-ft^2)**
-10 (14)	8.75 (29.86)	67.00 (21.24)
-20 (-4)	16.05 (54.76)	122.89 (38.96)
-30 (-22)	23.30 (79.50)	178.41 (56.56)

C. ANSYS THERMAL ANALYSIS

For the ANSYS simulation, the copper pipe was first modeled in SOLIDWORKS. It had an outside diameter of 5.08 cm (2 in) and an inside diameter of 4.06 cm (1.6 in), as shown in Figure 11. Figure 12 shows the heat trace cable modeled as a helical coil with a diameter of 1.52 cm (0.6 in) and a pitch of 5.08 cm (2 in), dimensions that are similar to those commonly utilized [33]. The helical coil was intersected by the copper pipe so that its widest point was in contact with the outside surface of the pipe.

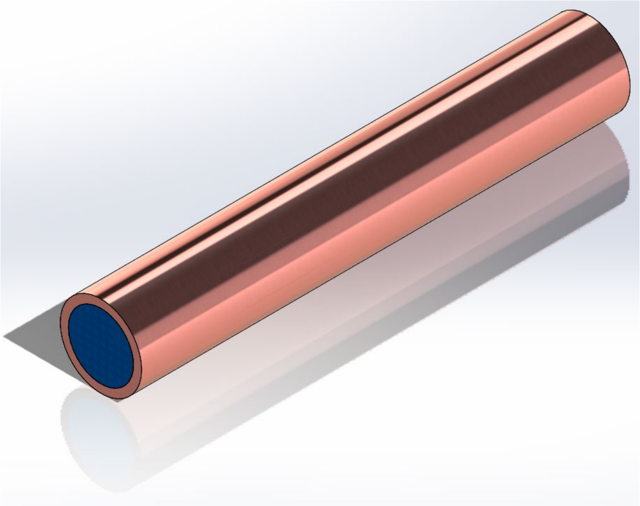

Figure 11. SOLIDWORKS Model of Copper Pipe and Water.

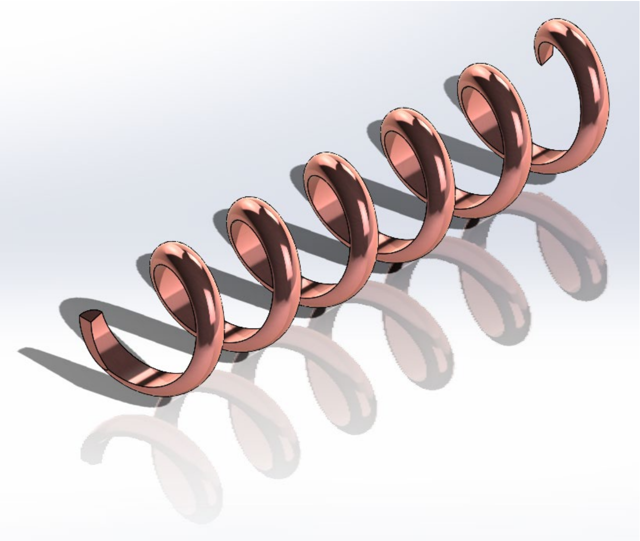

Figure 12. SOLIDWORKS Model of Heat Trace Cable.

Both bodies were imported into ANSYS and a mesh was created for each of them for the program to solve the steady-state thermal problem using a finite element analysis. The mesh utilized 2,336,503 elements with 9,196,909 nodes, and is shown in Figure 13 with a scale of 0.100 m (0.328 ft).

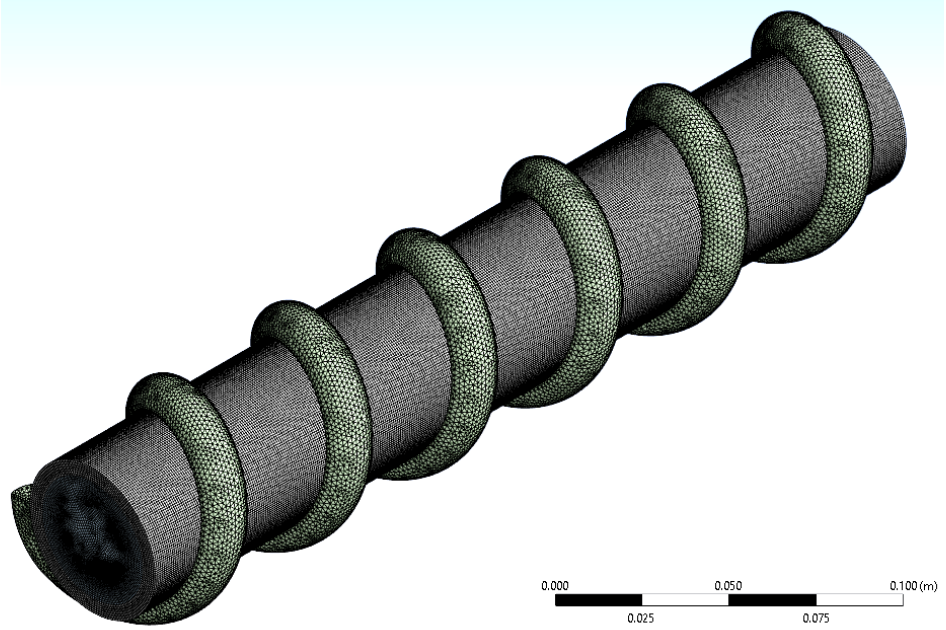

Figure 13. ANSYS Mesh.

Next, the materials were selected and the thermal properties utilized in the hand calculation were applied. The heat trace cable was also modeled as copper due to its advanced thermal properties. The six faces that coincided with each end were defined as perfectly insulated which was the boundary condition that was set for the thermal analysis. A convection model was included for the outside surface of the copper pipe. The two variables that were changed for each run were the heat flux at the inner and outer surface of the heat trace coil as well as the ambient air temperature. The values that were selected matched the three thermal conditions that were found from the one-dimensional heat transfer calculations found in Table 3.

Table 4 shows the minimum and maximum temperature results that were found utilizing the ANSYS steady-state thermal analysis at each of the three original thermal conditions. A fourth condition is added in Table 4 to determine what minimum heat flux was necessary to accomplish at least the desired temperature with an ambient temperature of -10 °C (14 °F). This condition found that if a heat flux of 210 W/m^2 (66.61 Btu-hr-ft^2) is utilized, the minimum design temperature can be reached.

Table 4. ANSYS Temperature Results.

Thermal Condition	**Minimum Temperature °C (°F)**	**Maximum Temperature °C (°F)**
1	-6.03 (21.15)	-6.05 (21.11)
2	-2.72 (27.10)	-2.75 (27.05)
3	0.52 (32.94)	0.57 (33.03)
4	2.38 (36.28)	2.44 (36.39)

Figure 14 shows the resultant temperature gradient of the geometries after the equilibrium was reached. The simplification of utilizing a one-dimensional analysis of this problem appears to not be too inaccurate in the sense that the variation of temperature in the axial direction is almost zero. However, there are heat loss terms that are not accounted for in some of the simplified hand calculations as the heat flux supplied by the coil was not enough to keep the water from freezing during the first and second thermal conditions. Likely the largest source of error in the hand calculations is the assumption that all of the heat generated by the coil is enough to offset the heat loss due to convection. In reality, a significant amount of the heat generated by the cable is also lost due to convection, which is likely why it was not successful in reaching the design temperature of 2 °C (35.6 °F).

Lastly, this analysis did not consider the inclusion of insulation on the copper pipe and the heat trace cable. In an insulated system, the thermal resistance due to convection would be significantly reduced, resulting in a lower heat flux necessary to keep the water from freezing.

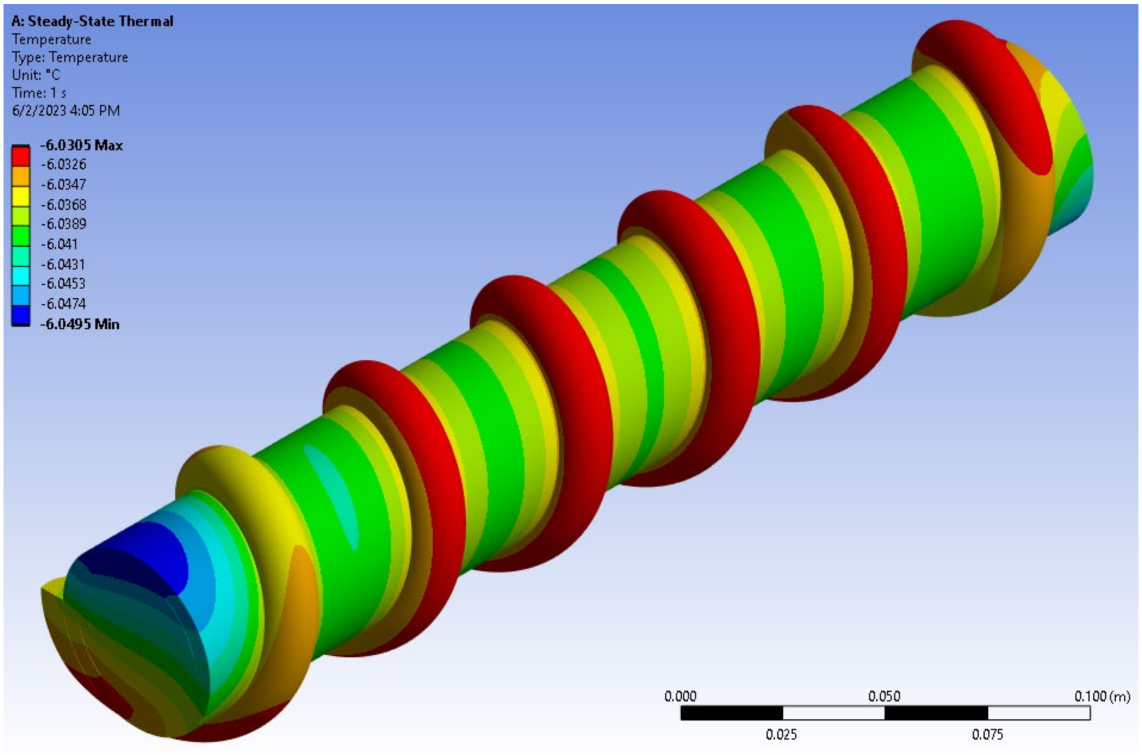

Figure 14. ANSYS Result of Thermal Condition 1.

Although the use of a one-dimensional analysis is a helpful tool, it neglects to consider some important modes of heat transfer and results in a potentially misleading heat flux for the heat trace cable. To better predict what type of heat trace cable should be used, either a more involved calculation should be performed that includes the heat loss from the cable, or a finite element analysis solver such as ANSYS should be utilized. This thermal analysis can be applied to determine the necessary heat flux to prevent any desired fluid from freezing or becoming uncontrollably viscous, such as hydraulic fluid. A thoughtful calculation to determine what type of heat trace cable should be used for each system that needs it will likely prevent damage and save significant costs and resources.

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VIII. WINTERIZATION OF VITAL SYSTEMS

A. HEATING, VENTILATION, AND COOLING (HVAC)

The goal of HVAC onboard a ship is to regulate the climate within ship spaces to ensure a hospitable living environment. However, most shipboard HVAC systems onboard U.S. Navy ships have not been designed to operate efficiently in low-temperature environments and will likely not be robust enough to achieve their goal. In addition to this, there is a much larger temperature gradient between the atmospheric conditions and the inner ship areas when in the Arctic, making it especially difficult to control the temperature and humidity onboard.

To explore the HVAC problems that vessels would experience in cold weather, the Coast Guard Cutter (CGC) *Bertholf* participated in Operation Arctic Shield in 2012 and created a list of design and operational issues [34]. Current HVAC systems onboard the *Bertholf* had been designed to operate at -18 °C (0 °F), which would be very inefficient in much colder temperatures. Based on historic temperature data available for the areas in which they were to operate, they assumed that the worst temperature they were likely to encounter was around -40 °C (-40 °F). This temperature was used to calculate what needed to change to ensure that the HVAC system could still operate in these conditions.

The analysis performed on the HVAC system determined that the electrical load that would be placed on the HVAC system at the minimum expected temperature would be greater than what they could provide. This means that many of the preheaters, reheaters, and unit heaters would need to be replaced. However, it was noted that although the HVAC system would need to be improved to be able to operate at this temperature, it does not need to be modified to operate in that condition indefinitely.

One attribute that contributes to the difficulties of operating HVAC systems in the Arctic is the lack of cold weather insulation. A possible low-cost insulation solution that has been utilized by liquefied natural gas (LNG) tankers is the use of spray foam insulation consisting of polyurethane and a polymeric coating [35]. The spray foam completely bonds to surfaces to prevent moisture buildup, is noncorrosive and watertight, and increases efficiencies due to enhanced low-temperature insulation [35]. In addition, this system requires very low maintenance and is relatively easy to install.

For current operational vessels, it is important to study the necessary electrical load HVAC systems would require in extremely low-temperature environments as well as the impact of utilizing enhanced cold weather insulation such as spray foam. One possible goal would be to meet the ABS requirements for ship spaces, where heating systems need to adequately maintain an internal temperature of 20 ℃ (68 ℉) with a relative humidity of between 30%–70% at the minimum anticipated temperature [12].

B. PIPING, TANKS, AND CONDENSERS

Piping and tanks throughout the ship have the risk of freezing and bursting. It is important to recognize what water lines are used minimally or not at all as they have the highest risk of this occurring [12]. To negate this, ABS recommend the use of heat tracing on the majority of vital ship piping [12]. For ballast water tanks that will be subjected to temperatures below -30 ℃ (-22 ℉), steam heating coils are expected to be installed. Cold weather may create a low-pressure vacuum in condensers [12]. To prevent this, an external heating system or low-temperature grade refrigerant must be used to maintain temperatures to promote condenser operation and efficiency. In most cases, the installation of heat tracing cables will be able to prevent fluid-related issues throughout a vessel when operating in the Arctic.

IX. CONCLUSION

A. FINDINGS AND RECOMMENDATIONS

During an Arctic voyage, there are a significant number of challenges that present themselves. These issues, although potentially deadly, are not novel. By analyzing the solutions to these problems that have been discovered and implemented by other organizations, a meaningful plan can be developed to prepare the U.S. Navy to increase its presence and effectiveness in the Arctic Region. By honing a holistic winterization plan for vessels similar to the one employed by ABS, ships and their crew can have the necessary equipment and training for the Arctic environment. Through the testing of how a ship's components, materials, and coatings react to the Arctic environment, more concrete solutions can be found and employed. In addition, being able to predict the temperature and weather using modern technology is vital to be able to create a course that will minimize the dangers of icing and freezing.

A more complete understanding was reached regarding the importance of ship size in the context of icing. Smaller vessels will have a greater increase in their vertical center of gravity, resulting in less overall stability. This knowledge should be used to educate sailors on the importance of ice removal, especially on smaller ships. Lastly, the thermal analysis of heat trace cables shows that one-dimensional models, while useful, fail to fully outline real-world situations. Using a computational tool such as ANSYS to model areas in which heat trace cables are intended to be employed will aid in the selection of the proper cable. Through the implementation of the findings in this work, the U.S. Navy can be better equipped to prepare ships and sailors to traverse the Arctic region.

B. FUTURE WORK

The use of heating solutions such as heat tracing likely alters the thermal signature of a vessel. If heat tracing was utilized on the outside of the ship such as on the masts, superstructure, or railings, the ship would possibly have a thermal signature that is more visible. In an environment where it is important to remain undetected, this could prove to be detrimental. As a result, it is important to discover the degree to which thermal signatures are changed through the Arctic climate when using external heating methods. If the change is large enough, it may merit the selection of an external solution other than heat tracing.

The mechanical and thermal loading of many materials and systems is increased for Arctic vessels transiting between climates and when deicing. What remains to be seen is how much of an impact there is on materials that are more vulnerable to this effect such as composites. The lifespan of composite materials and components utilized on Naval vessels should be tested in a variety of thermal and mechanical loading conditions to determine this.

APPENDIX A. POLAR SHIP CATEGORIES

Table 5. Equivalence of Polar Ship Categories across Various Organizations. Adapted from [13].

Category	**Description**	**Ice Class**	**Approximate Correspondence of other ABS Ice Class Notations**
A	Designed for operation in Polar waters in at least medium first-year ice which may include old ice inclusions	IACS PC1, PC2, PC3, PC4, PC5	ABS Ice Class A5, A4, A3, A2, A1
B	Designed for operation in Polar waters in at least thin first-year ice which may include old ice inclusions	IACS PC6 – PC7	ABS Ice Class A0 ABS Baltic Ice Class 1AS
C	Designed to operate in open water or ice conditions less severe than those included in Cat A or B	Scantlings adequate for intended ice types and concentrations	ABS First-year Ice Class B0, C0, D0, E0 ABS Baltic Ice Class IA, IB, IC

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APPENDIX B. CERTIFICATION PROCEDURE

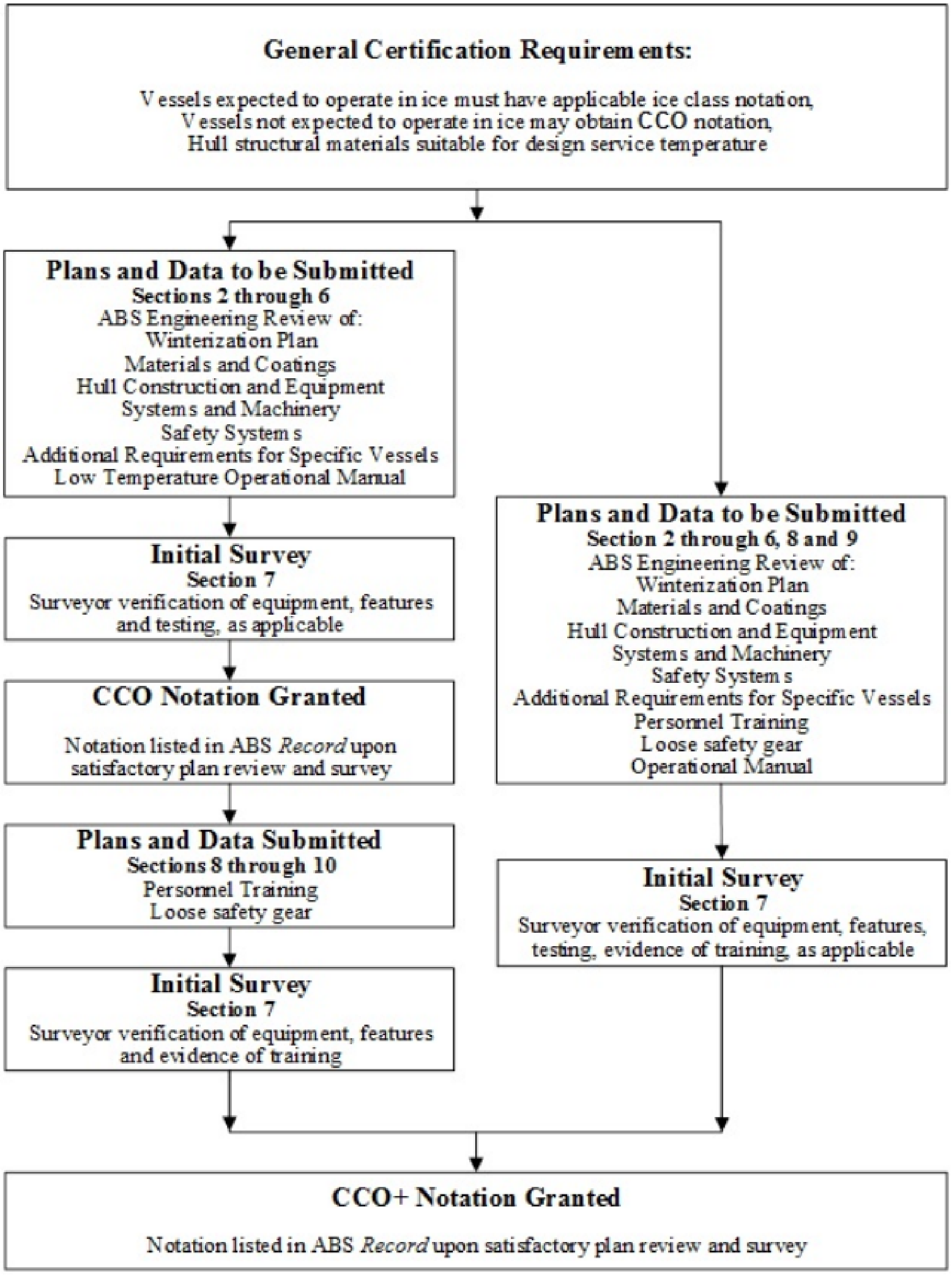

Figure 15. ABS Certification Procedure for Cold Weather Voyages. Source: [12].

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APPENDIX C. THRESHOLD FOR SEVERE ICING

Table 6. Threshold Wind Speeds and Wave Heights for Severe Icing on Various Length Ships. Adapted from [24].

Vessel Length m (ft)	Wave Height m (ft)	Wind Speed m/s (kt)
15 (49)	0.6 (2)	5 (9.7)
30 (98)	1.2 (3.9)	7.4 (14.4)
50 (164)	2 (6.6)	9.8 (19)
75 (246)	3 (9.8)	12.5 (24.3)
100 (328)	4 (13.1)	15 (29.3)
150 (492)	6 (19.7)	20 (38.9)

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APPENDIX D. HULL COATING TEST STANDARDS

Table 7. ABS Suggested Test Standards for Cold Weather Hull Coatings. Adapted from [12].

Property	Test Standard
Abrasion Resistance	ASTM D 4060 Taber Abrasion
Impact Resistance	ISO 6272–93
Hardness	ISO 2815
Scratch Resistance	ISO 1518
Adhesion	ISO 4624
Friction	ASTM D 4518–91
Anti-corrosion properties	As advised by NORSOK M-501
Environmental Character	A High Solids Content (preferably Solvent Free or Ultra High Solids), as a minimum to be in compliance with the VOC Regulations applicable at location of application, and not containing biocides, tin or copper compositions is to be considered
Resistance to Cavitation damage	ASTM G 32

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