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Cold Regions Research and Engineering Laboratory

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Icing Management for Coast Guard Assets

Charles C. Ryerson

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Final report

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Abstract

Global warming is causing greater retreat of the summer Arctic sea ice cover, with several historical minimums within the last decade. Opening of the Chukchi Sea and the Beaufort Sea is expected to cause increased marine and other activity off of the northern Alaska coast and through the Bering Strait. This will require increased Coast Guard presence. Bow spray icing of Coast Guard Cutters decreases safety and risks mission accomplishment. This report reviews documented causes and potential impacts of ship superstructure icing from bow spray and atmospheric sources, and examines the probability of icing in the Chukchi and Beaufort seas. Four classes of Coast Guard Cutters, the *Polar*-Class heavy icebreakers, the *Legend*-Class National Security Cutter—the *Bay*-Class 140-ft icebreaking tug, and the *Juniper*-Class seagoing buoy tender—were examined. Decks were walked, crews interviewed, and questionnaires distributed to determine the impact of icing on cutter components and functions, to learn how icing affects mission success, to determine how ice accumulations are currently prevented or removed, and to seek improved ways of alleviating icing effects. In addition, 12 classes of ice protection technology were reviewed, as were methods of protecting windows and cables from icing, to determine how they may reduce icing hazards. Recommendations for existing cutters are to heat decks, to test and use anti-icing and low ice adhesion coatings, to use low corrosion aircraft and environment safe chemicals and high velocity fluids to de-ice, to protect vessel components with covers, to use expulsive, pulse electro-thermal, and pneumatic technologies on large untrafficked surfaces, and to use infrared heat to protect components and limited deck areas. New cutter designs should incorporate heated decks, splash-resistant bows, and covered masts and boat decks. Cutters need not be completely ice-free in transit and when executing a mission. They must, however, maintain sea keeping ability, stability, and integrity, and full functionality. Hence, cutters must be anti-iced and de-iced underway in heavy weather without stopping or diverting crew resources. Prudent technology investments will allow safer Coast Guard operations in moderate to severe superstructure icing conditions.

Table of Contents

List of Figures and Tables

Figures

Tables

Preface

The work was performed by the Dr. Charles C. Ryerson (Terrestrial and Cryospheric Sciences Branch, Janet Hardy, Chief), US Army Engineer Research and Development Center/Cold Regions and Engineering Laboratory (ERDC/CRREL). The author thanks K. MacDonald for assistance with Appendix B and with tours of the *Polar*-Class icebreakers and *Bay*-Class icebreaking tug. The author also thanks S. Tripp, J. Story and Lt. B. Fike of the Coast Guard Research and Development Center for support and advice, and the crews of the CGC POLAR STAR, CGC HEALY, CGC WAASCHE, CGC MIDGETT, CGC THUNDER BAY, CGC BISCAYNE BAY, CGC MORRO BAY, CGC WILLOW, CGC ALDER and CGC HOLLYHOCK for icing experiences and cutter tours.

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Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
knots	0.5144444	meters per second
pounds (force) per inch	175.1268	newtons per meter
tons (2,000 pounds, mass)	907.1847	kilograms

Definitions

AEMS	Advanced Enclosed Mast System
AOR	Area of Responsibility
ATON	Aids to Navigation
BLRS	Boat Launch and Recovery System
CIC	Combat Information Center
CO	Commanding Officer
CONOPS	Concept of Operations
COTS	Commercial-off-the-shelf
CWIS	Close-in Weapon System
DNV	Det Norske Veritas
EEZ	Exclusive Economic Zone
EM	Electromagnetic
EO	Executive Officer
EPIRBS	Emergency position-indicating radio beacons
FAS	Fueling-at-Sea
FCCS	Flooding Casualty Control Software
FCCS-WIN	Flooding Casualty Control Software–Windows
FLIR	Forward Looking Infrared imagers
FOD	Foreign Object Damage
GPS	Global Positioning System
IR	Infrared
ITO	Indium Tin Oxide
MARICE	Marine Icing project
MFV	Medium size fishing vessel
OPTEMPO	Operational Tempo

PED	Pulse Electro-thermal De-icing
PTFE	Polytetrafluoroethylene
PWCS	Ports, waterways, and coastal security
RAST	Recovery Assist Securing Traversing
SAR	Search and Rescue
SCIF	Sensitive Compartmented Information Facility
TRL	Technology Readiness Levels
TTP	Tactics, Techniques and Procedures
UAV	Unmanned Aerial Vehicle
UNREP	Underway Replenishment
VERTREP	Vertical Replenishment

1 Introduction

Superstructure icing is a significant threat to boats and cutters operating in cold northern waters (Wise and Comiskey 1980; Brown and Roebber 1985). Beyond the current icing threats, forecasters warn that, for the Beaufort and Chukchi sea areas, expected longer sea ice-free periods attributable to global change will be accompanied by longer fetches. Frequent and long duration high winds, combined with extended fetch, produces greater wave heights and will make superstructure icing more severe than it is today (Papineau, n.d.; Paulin 2008; National Energy Board 2011; Wang et al. 2012). In addition, the Bering Sea, the Gulf of Alaska, and coastal waters of western North America, eastern North America to about 38°N Latitude and the Great Lakes are areas where superstructure icing threatens safety (Chatterton and Cook 2008).

Considerable research on superstructure icing caused by sea spray and atmospheric sources was conducted principally by Japanese and Russian researchers in the 1970s and 1980s on fishing trawlers, processing ships, and offshore platforms. Examples include studies by Tabata et al. (1963), Ono (1968), Iwata (1973), and Borisenkov and Panov (1974). In the late 1980s and 1990s, additional research, especially related to characterization of the icing process, physical and mechanical properties of superstructure ice, and modeling was conducted in the US and Canada (Jeck 1984; Ackley 1985; Zakrzewski and Lozowski 1991; Ryerson 1991, 1995; Lozowski et al. 2000; Ryerson and Gow 2000a, b). Considerable research was also conducted during this period on the icing of drill rigs and other stationary sea structures (Itagaki 1984; Minsk 1977, 1984a, b; Horjen and Vefsnmo 1984; Brown and Horjen 1989). More recently a Norwegian project, the Marine Icing (MARICE) project, has attempted to model icing on offshore platform components and ships. Most recently, Ryerson (2008, 2009, 2011) has described ship and offshore platform icing processes, and has analyzed the effects of icing on offshore platform safety and the technologies that may be adapted for preventing, removing, and detecting icing.

Sea spray can produce ice on both decks and superstructures, which may have a major effect on vessel sea keeping and mission success. Typical icing problems encountered are the impairment of stability owing to the raised center of gravity, which increases the rolling moment of the ship; decreased freeboard; and impaired communication, navigation, and radar capabilities caused by antenna icing and ice on wheelhouse windows. Ice accumulation can prevent the functioning of certain deck equipment, such as winches, and it may hinder access to rescue equipment, such as lifeboats and life rafts. Air intakes may become clogged with ice and gangways, decks, and railings covered by ice make it difficult and dangerous to operate safely. Scuppers and drains are often reduced in area and may even completely clog, impairing deck drainage increasing ice accumulation.

Active plunging of ship bows into waves and swells, through displacement, hydrodynamically lofts columns of water that are entrained into the relative wind. That spray is then carried over the superstructure by the relative wind and causes ship icing to be more severe than icing of stationary structures such as offshore platforms (Itagaki 1984; Minsk 1984b). Atmospheric icing, caused by snow, freezing rain, and rime, can also affect safety of operations on decks and equipment (Makkonen 1984).

Ice protection technologies have been evaluated to mitigate superstructure icing (Tabata 1968; Sackinger et al. 1986; Zadra and Pyle 1990). Anti-icing technologies can be used in areas where continuous operations are required, such as navigational equipment and fire lines. De-icing technologies can be used for equipment and areas where some accumulation of ice is tolerable. Significant advances have been made in aviation and power line ice protection technologies, and those technologies have been assessed by Ryerson (2008, 2009, 2011) for their potential use for solving offshore oil platform icing problems. These new technologies are critical because traditional technologies, such as the use of baseball bats and mallets to remove ice, are not compatible with new materials, such as composites used in Coast Guard boats and cutters, and new regulations do not allow the release of hazardous de-icing chemicals into the environment. For example, innovative, electro-expulsive technologies were invented by NASA and matured by industry to become operational on aircraft, and have been assessed for use on ships (Embry et al. 1990). However, this technology is not applicable in all operating environments, such as decks and irregular surfaces, and applications may depend on the physical properties of the accreted ice. Innovative de-icing methods, such as electrical pulse methods developed by Petrenko (Salusbury 2005) for metal surfaces, windows, and cables, may be useful in specific areas. Also, new ice-phobic coatings have been developed (Mulherin 2002; Ayres 2004). Other more traditional de-icing and anti-icing technologies, such as electro-thermal systems, infrared heating, steam lances, and mechanical impact, may also be applicable.

Advances have been made in applying ice-phobic coatings to the marine environment. Though past research has addressed this problem, many new coatings have been developed and tested (Mulherin et al. 1990, Mulherin 2003; Makkonen 2012). Ice-phobic coatings are typically rated for ability to reduce ice adhesion strength to substrates. However, their ability to endure repeated washings by saline water and abrasion before renewal are critical durability concerns for the use of these coatings, as is slipperiness when applied to trafficked areas and ability to function when contaminated. Though ice-phobic coatings do not yet prevent ice formation, they can enhance the effectiveness of anti-icing or de-icing systems (Ferrick et al. 2006a, b; 2012;). In addition, new super-hydrophobic nano-based surfaces have the potential to completely preventing icing.

Knowledge of the presence of superstructure ice, and its thickness and distribution, is critical to the safety of boats and cutters. Though ice accumulation sufficient to threaten ship stability can be visually recognized easily during daylight, small thicknesses of ice sufficient to make decks slippery are less easily seen by eye. In addition, icing at night may not be detected until a significant amount has accumulated. Ice detection technologies have made considerable advances in the last 20 years (Ryerson and Ramsay 2007), but the operating environment of a seagoing boat or ship is hostile. Homola et al. (2006) summarized many ice detection concepts and assessed their near-term application potential to wind turbines. This report will evaluate current ice detection technologies for applicability on boats and cutters (SAE 2004a, b; Yankielun and Ryerson 2003).

In the late 1980s and 1990s, ERDC/CRREL conducted ship superstructure icing research. CRREL also conducted power-line icing, aircraft icing and de-icing, and ice detection and ice protection research for many kinds of structures, using a wide variety of technologies (Ryerson and Koenig 2003; Jones et al. 2004). This knowledge of atmospheric and superstructure icing is used to evaluate options and to provide recommendations. When practical, Technology Readiness Level (TRL) classifications are assigned to each technology and product. TRLs were developed by NASA and are used by the Department of Defense to provide a standardized description of the development stage of technologies from initial concept to proven performance (Graettinger et al. 2002).

US Coast Guard Cutters and boats operating in Arctic waters and mid- to high-latitude winter conditions are particularly vulnerable to superstructure icing, primarily because of the Coast Guard's mission. In addition, icing can have serious impacts on Coast Guard mission performance for the following reasons:

1. Frequency of bow splash is a function of vessel length in a given sea state. Most Coast Guard Cutters and boats are relatively small and may work seas and create splash more frequently than larger cutters. Therefore, similar to fishing trawlers, Coast Guard vessels may ice rapidly.
2. Coast Guard vessels often have low freeboard and, therefore, will have greater danger of icing because spray clouds will easily reach the large areas of superstructures.
3. Coast Guard vessels often need to operate at higher speeds in sea and weather conditions conducive to icing because of Search and Rescue (SAR) missions—enhancing the probability of superstructure icing.
4. Coast Guard missions include Intelligence, Surveillance and Reconnaissance (ISR), law enforcement, and SAR. Therefore, Coast Guard vessels must always be mission-ready. Superstructure icing can compromise mission success by requiring operation at slower speeds, by icing of communications antennas and radars, and by icing of decks and windows.
5. As the Coast Guard has a homeland security mission, consideration should be given to potential thermal infrared (IR) and electromagnetic (EM) signatures from de-icing and anti-icing technologies.
6. Many newer Coast Guard boats and ships have composite structures, antennas, and sensors that are damaged by traditional mechanical de-icing with mallets or baseball bats.

2 Approach

This report describes ship superstructure icing in the Arctic and cold regions, the physics of ship icing, the potential safety impacts of icing, and suggested technical and operational ice protection. The report is in-part an update of market research in anti-icing and de-icing technologies and methodologies work initially conducted in 2008–2009 for offshore platforms. This update will focus on Coast Guard asset applications and Concept of Operations (CONOPS), identifying the applicability for retrofit on existing assets or incorporation in new design. Ice accretion risk matrices will be included for Coast Guard Cutters expected to operate in the Arctic, and recommendations for a best path forward with regard to investing in anti-icing technologies.

The types of ice that form on ships, atmospheric and superstructure icing, and the physics of formation, the physical properties of the ice, where it forms, its magnitude, and frequency are described using literature research, experiences of the author on CGC MIDGETT WHEC-726 in icing conditions in the Bering Sea in 1990, and discussions with Coast Guard personnel experienced in icing. The latter focused on cutters expected to operate in the Chukchi Sea and Beaufort Sea. The known safety hazards of icing by type for ships, and effects on small vessels versus large vessels, are also described.

Safety matrices for Coast Guard Cutters for ship component or function, ice type, and the relative importance with regard to safety are presented. All elements of each matrix are described and, as possible, supported by documented information from experience at sea.

The dynamics of ship superstructure icing are described in the report using literature and experience on the CGC MIDGETT WHEC-726. The physical processes of superstructure icing vary spatially and temporally on a ship, and icing rate is qualitatively related to ship size, speed, headway, temperature, and sea state. This includes the dynamics of how, hypothetically, ice could be forming on one portion of a ship, and eroding on other portions.

Most importantly, de-icing/anti-icing technology matrices are presented (Ryerson 2009, 2011) to be used to select candidate technologies for protecting components or functions of Coast Guard Cutters from icing.

3 Superstructure Icing Types and Processes

Superstructure icing usually refers to one type of icing—that which occurs when sea spray is lofted over the ship and freezes on the superstructure. At sea this is saline water creating saline ice; on lakes and rivers, it is fresh water creating fresh water ice.

Atmospheric ice also forms on ship superstructures: ice that originates from atmospheric sources. Atmospheric ice includes frost, rime, snow, sleet, and glaze. As the moisture source is the atmosphere and not from an ocean or lake surface, all atmospheric ice is fresh water.

The type of icing and its salinity affects where it forms on a ship, the physical properties of the ice, and the difficulty of preventing or removing it. The frequency of formation, the physical properties of the ice (shape, color, density, inclusions, hardness, adhesion strength), and the safety hazards it creates on cutters are also determined by the type of ice. Each ice type creates its own hazards and potentially reduces safety.

3.1 Spray icing

The primary and most hazardous type of superstructure icing is spray icing because of its capability of lofting large volumes of water over large areas of the ship. It reduces the safety of deck operations, and affects the seaworthiness of ships because it raises center of gravity and increases the rolling moment. It also increases ship displacement and decreases freeboard because of the great mass of ice that can accumulate relatively quickly, and quickly encases exposed objects.

3.1.1 Formation process

As with any icing process, icing does not occur unless moisture is available and temperatures are lower than the freezing temperature of the water. The freezing point of sea water depends upon its salinity. In polar regions, sea water salinity is about 35 ppt, and because the freezing temperature of water decreases by 0.28°C (0.5°F) for every 5 ppt increase in salinity, sea water in the polar regions begins freezing at about –1.8°C (28.8°F) (http://nsidc.org/cryosphere/seaice/characteristics/brine_salinity.html).

The primary source of water in spray icing is the lofting of water over the ship's bow as a result of the plunging of the bow into waves and swells. When the bow encounters a wave or swell, it causes a jet or sheet of water to rise above the ocean surface along the hull of the ship, caused by the displacement of the wave by the bow. As the water jet rises, air is entrained, and it begins to break into drops. If the water jet rises nearly to, or above, the bulwarks or the forecastle, the jet of water becomes entrained in the relative wind, and most are carried up the sides of the bow and over the forecastle; many are carried over the ship superstructure. If relative wind speeds and turbulence are sufficiently strong and the ship superstructure is high, the wind can be forced to rise and drops can increase in height. However, typically, the water jet breaks into drops with a broad, and often exponential, drop size spectra and drops fall from the cloud as a function of their fall speeds—determined by their size—larger drops falling out of the cloud more rapidly (Ryerson 1995; Chung et al. 1999).

Figure 3-1. Icing modes. Upper left—lofting—bow of Canadian Frigate HMS *Fredricton* plunging into swell and lofting water jet. Upper right—entrainment—spray is entrained in relative wind and is carried as a pulse of water over the forecastle and is impinging the bridge (upper photos courtesy of http://www.navy.forces.gc.ca/fredericton/0/0-s_eng.asp). Lower image—traverse—fishing trawler in Bering Sea with spray cloud pulse mid-ships (Ryerson 1990).

Figure 3-1 shows the sequence of a typical bow spray event. During lofting, the plunging bow displaces water and jets a sheet of water into the air along the bow perimeter. Entrainment begins as the ship moves under the sheet of water, and wind drag and gravity break the water jet into drops and accelerate the drops in the wind flow. Traverse occurs as the cloud moves aft at the speed of the relative wind—the sum of the wind speed, and the ship speed—if the ship is moving into the wind.

Figure 3-2. Initial plunging of NSC WAESCHE bow in 35- to 40-kt (18- to 20-m/s) winds and 3.5- to 6-m seas with a ship speed of 18 kt (9 m/s) during Tropical Depression Haikui. The beginning of a spray jet is entering the forecastle through the bow chock (courtesy LCDR Reid, CGC WAESCHE 2012).

Though bow spray is the most significant source of spray for superstructure icing, spray does reach the ship from other mechanisms. Water enters the forecastle deck area by falling over the bulwarks, and by passing through chocks through the bulwarks and through the anchor hawse pipes (Fig. 3-2). This water contributes to the initial spray plume as it jets through the openings and into the air. However, the spray event also floods the forecastle, and if the forecastle is constructed to allow water to drain off the sides of the deck, or through scuppers, that water can also be entrained by wind flow and carried over the ship (Fig. 3-3). Though not measured, it is believed that the liquid water content, drop sizes, and drop concentrations of these secondary events are small and contribute little to icing.

Figure 3-3. Water flowing from flooded forecastle on CGC MIDGETT and drops being entrained in wind after bow spray event in Bering Sea (Ryerson 1990).

Spume from breaking waves can also be a source of spray for icing of ships. Water droplets originating at the sea surface result from aerodynamic suction at the crest of capillary waves, bursting of air bubbles at the water surface, and wind-tearing of wave creating whitecaps (Wu 1982), and creating spume. Recent work by Jones and Andreas (2012) estimates that spume begins at wind speeds of about 37 kt (19 m/s), and the drops created at lower wind speeds contribute little to the icing of stationary offshore structures, such as oil drilling platforms. Median volume droplet diameters at the lower wind speeds are typically less than 10 µm, but at wind speeds above 37 kt (19 m/s), spume drops' medium volume diameters were estimated to be about 24 to 37 µm, depending upon height, with the smallest near 40 m above the sea surface. Jones and Andreas (2012) found that the larger spume drops contributed to higher icing rates on stationary platforms.

Ryerson (Ryerson and Gow 2000a, b) observed a nearly continuous spraying of surfaces on the port side of the CGC MIDGETT amidships when the bow wave over-steepened seas from port in the Bering Sea. This continuously breaking wave extending a large portion of the length of the ship was barely visible, but was felt as a continuous light mist or drizzle event (Fig. 3-4). Though liquid water content and drop sizes were small, over time it may have caused sufficient ice accumulation, had conditions been colder than about –1.8°C, to cause a thin layer of ice on decks and bulkheads.

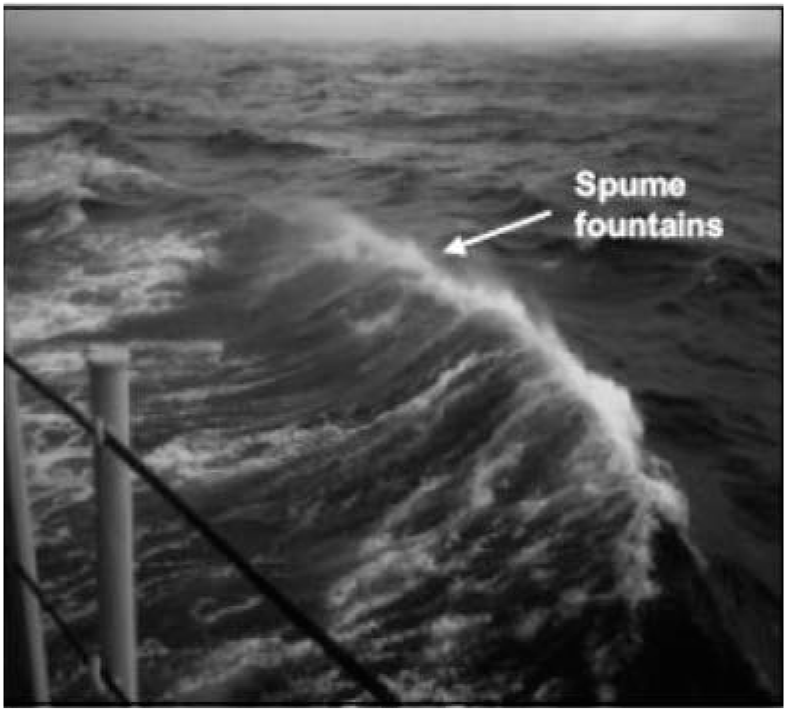


Figure 3-4. Spume fountains midship on port side of CGC MIDGETT caused by bow wave interacting with swell from port, and breaking (Ryerson 1990).

The University of Alberta developed an advanced, time-dependent, three-dimensional ship icing model tuned for specific ships, the CGC MIDGETT and a *Spruance*-Class destroyer, from 1989 through 1992 (Lozowski and Zakrzewski 1993). The model was carefully constructed with the most explicit, deterministic techniques available. One key element of the model is water delivery to the ship from bow–wave collisions. Lozowski and Zakrzewski (1993) carefully reviewed what was known about collision-generated spray (Zakrzewski 1987; Chung and Lozowski 1999; Lozowski et al. 2000), and illustrated the dynamic elements of a bow–wave collision-generated spray cloud in Figure 3-5. The bow–wave collision generates a jet of water that is lofted at A in Figure 3-5. As the jet rises, and is entrained with air as determined in later studies by others (Waniewski et al. 2001, 2002), it breaks into drops, for example at S, because of entrained air, gravity, and the local wind field overcoming water surface tension. The drop is entrained in the true wind (U_{10}) and carried over the ship with a speed and trajectory determined by the relative wind (U_r), and the fall of gravity (V_g), the latter a function of the drop size. The drop, in its flight, traverses over the deck along path D, and strikes the bulkhead at O. During flight, the drop is cooling via evaporation, convection, and radiation, and is decreasing in size by evaporation or aerodynamic breakup unless it coalesces with another drop. When the drop strikes the bulkhead, it splashes and runs down the surface as a film, losing heat via conductive, convective, and radiative losses.

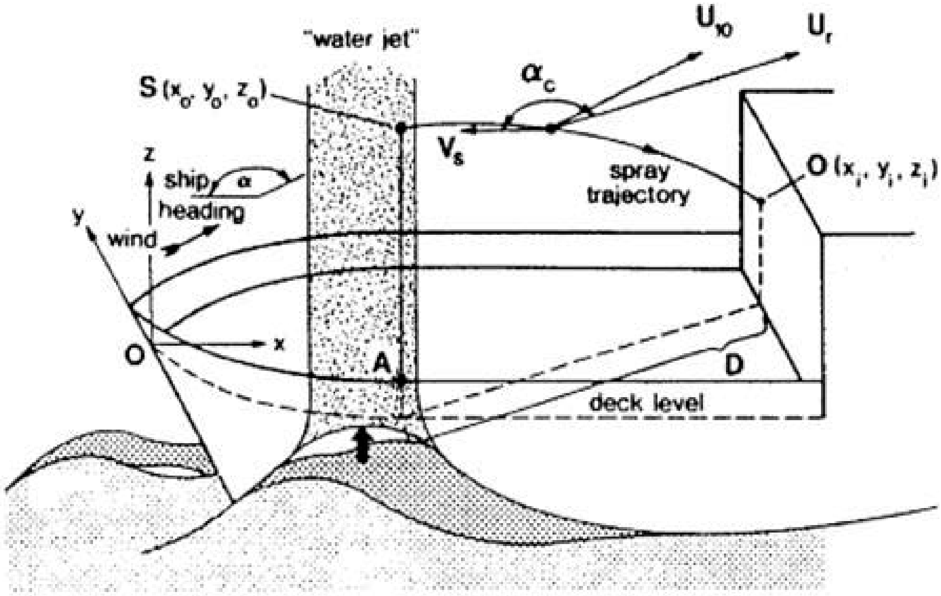


Figure 3-5. Trajectory of one drop from a bow–wave collision-generated spray cloud (from Lozowski and Zakrzewski 1993).

Spray event length can be specified as the duration from the initial lofting of spray by the bow to the exiting of the resulting spray cloud from the stern of the ship. More specifically, it can also mean the duration of spray cloud transit over the ship from the time of drop formation to interception with ship surfaces.

Itagaki (1990) discussed the period of time during which water is deposited at a specific location on a ship. He suggested that spray events last for a few seconds, and specifically from 1 to 10 s, as timed from video taken aboard an unspecified ship. He chose a 5-s duration for modeling.

Ryerson (1995) specified spray duration as time during which spray droplets appeared in the sampling volume of a stroboscopic camera system mounted aft of the forecastle of the CGC MIDGETT, and at the top of the 01 level bulkhead (Ryerson and Longo 1992). An analysis of 37 spray events at a ship speed of about 24 kt (12 m/s) in approximately 3-m seas, and at wave angles of 90 to 70° to the bow, gave spray event durations ranging from 0.47 to 5.57 s, with a mean of 2.73 s (Ryerson 1995). As these measurements were made at a high ship speeds, durations may be shorter than most spray events.

Measurements of spray event duration aboard a Soviet fishing trawler averaged about 2 s duration in unknown weather, sea, and ship speed conditions, as reported by Borisenkov and Panov (1974). And Borisenkov et al. (1975), as related by Zakrzewski (1986), measured spray cloud duration as 5.8 s for a medium size fishing vessel at a speed of 5–6 kt (2.5–3.0 m/s), and wind speed of 19–23 kt (10–12 m/s), and a wave angle of 90–110°.

Zakrzewski (1986) specifies that spray duration, the period of time that water is actually impinging on a ship surface, for a given ship, depends on the ship speed relative to the wave at impact, and the height of the wave and the relative wind speed. He indicated that ship speed and wave height affect the extent and morphology of the spray cloud, in part also because of the hull shape, and that relative wind speed alone determines residence time of the cloud over a specific ship component as drops are accelerated by drag forces against their inertia. Assumptions and parameterizations by Zakrzewski (1986, 1987) of the medium size fishing vessel described by Borisenkov et al. (1975) suggest that, over a range of vessel speeds, spray duration varies primarily with wind speed and heading to the seas, with most spray events lasting 5 to 7 s.

Thomas (1991) assessed the probability of superstructure icing from monitoring bow spray events on two ships, the CGC MIDGETT in the Bering Sea, and the USS *Monterey* in the North Atlantic Ocean. The CGC MIDGETT is a *Hamilton*-Class High Endurance Cutter with a length of 107 m and displacement of 3017 tons, and the USS *Monterey* is a *Ticonderoga*-Class Cruiser with a length of 161 m and a displacement of 9598 tons. Thomas opined that though cold is necessary for the prediction of superstructure icing, the creation of bow spray is a more difficult parameter to predict because it is related to ship design and sea state, and the latter is related to the true wind if there is sufficient seaway. He related total spray events within a 20-minute period at a steady ship speed and heading to ship motion. He stated that relative wind played a role in determining the duration of spray events over a superstructure, and in influencing the cooling and freezing of drops.

Thomas (1991) found that the onset of bow spray is not directly related to true wind or to relative wind—neither alone can cause water to be lofted above the bow; if ship bow motions were insufficient to create spray, then wind alone cannot generate spray clouds. Bow motion was measured by ship pitch and vertical acceleration in the forward part of each ship. Spray was created when pitch was greater than 1.06° and vertical acceleration was greater than 0.19 g's on the CGC MIDGETT, and when pitch was greater than 1.46° and acceleration greater than 0.22 g's on the USS *Monterey*. Apparently, the role of true wind is in creating the sea state, which influences the ship motion at a given speed—which creates the spray events. True wind, therefore, is related to spray frequency. The smaller pitch angle and acceleration required to create spray in the CGC MIDGETT is attributable to the smaller size and freeboard of the Coast Guard Cutter. Generally, the CGC MIDGETT sprays about 8 to 10% more frequently than does the USS *Monterey*. In general bow pitch acceleration was a reasonable predictor of spray event frequency on both the CGC MIDGETT and the USS *Monterey* (Fig. 3-6). Once accelerations crossed the threshold for each ship, correlations were good except at the highest accelerations.

Correlations between significant single bow pitch angles on the CGC MIDGETT were not as strong a predictor of spray event frequency as on the USS *Monterey* (Fig. 3-7). On the latter, bow pitch angle is a better predictor of spray event frequency than is vertical acceleration.

Zakrzewski (1987) also explored spray frequency using information observed and computed from Panov (1971) for Soviet medium-sized fishing trawlers (MFV)—approximately 37 to 61 m long. They found a relationship between the wavelength of the seas and splashing from observations, and did not explicitly consider ship speed. In general, they report that spray frequency was about 6 to 8 per minute in seas of 50-m wavelength, 8–11 per minute in seas of 40-m wavelength, 11–12 per minute in seas of 30-m wavelength, 13–14 per minute in seas of 20-m wavelength, and 15–16 splashes per minute in seas of 10-m wavelength. They also report that spraying occurs approximately with every other bow–wave collision. The

Soviet MFV is much smaller than the CGC MIDGETT or the USS *Monterey*, and it is not clear how comparable ship bow angle and acceleration are to sea wave length. However, in general it appears that smaller MFVs spray more frequently than larger ships owing to the more frequent pitching of smaller ships in a given sea state (Doerry 2008).

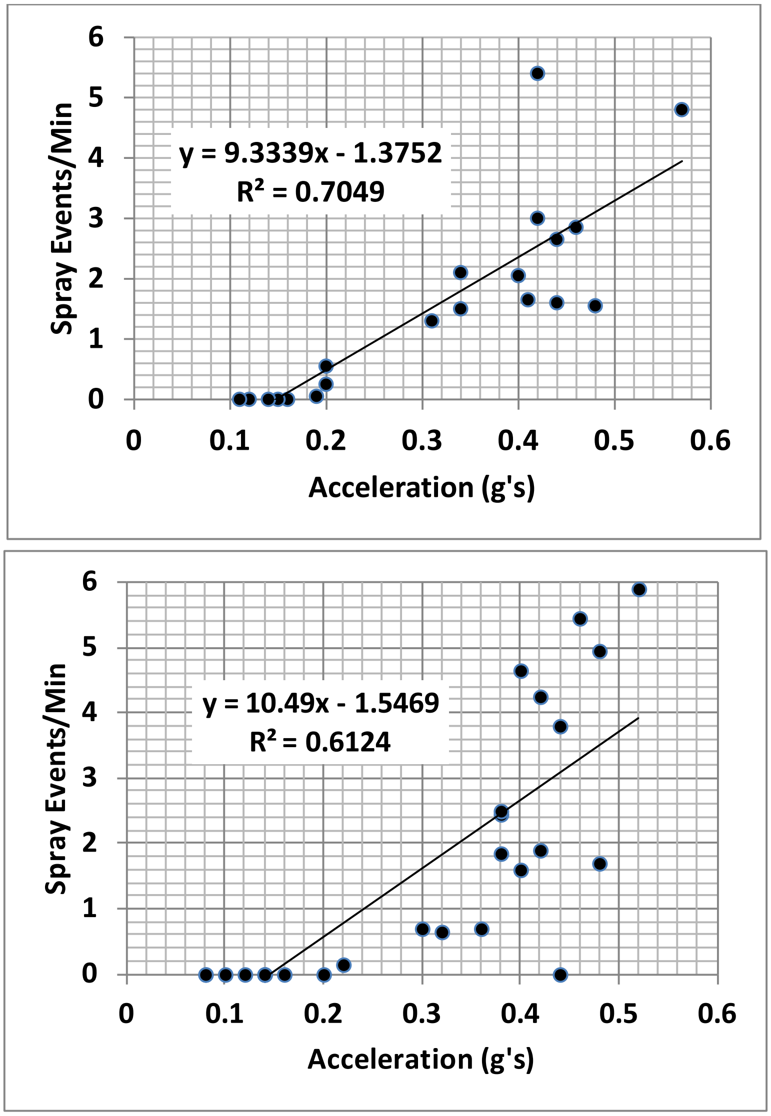


Figure 3-6. Relationship between bow area vertical acceleration and spray frequency on CGC MIDGETT (top) and USS *Monterey* (bottom).

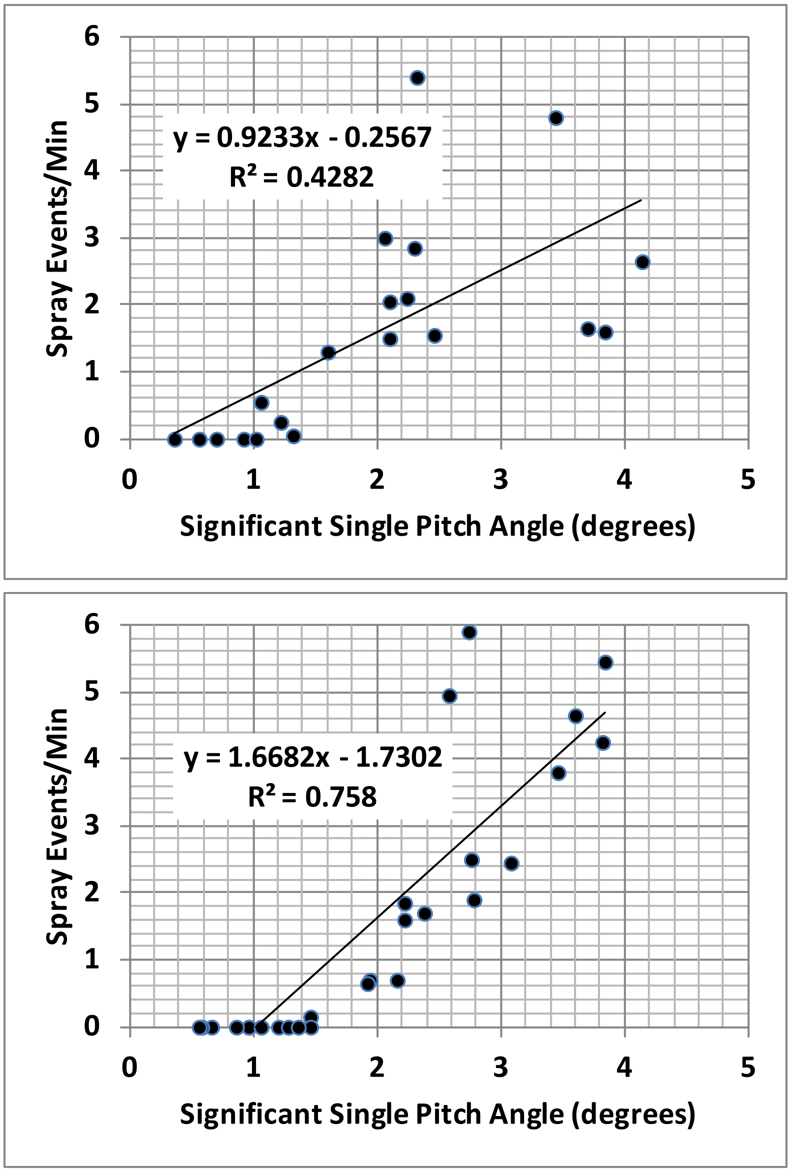


Figure 3-7. Relationship between bow significant pitch angle and spray frequency on CGC MIDGETT (top) and USS *Monterey* (bottom).

During a 1990 research cruise conducted on the CGC MIDGETT in the Bering Sea to validate the University of Alberta model, videos were made of sea spray events from the flying bridge (Fig. 3-8). Ship heading and speed were logged during these periods, and all information was provided to the university. Lozowski and Zakrzewski (1993) developed a classification of spray events using the video information and logs. Length of the spray jets along the bulwarks, *L*, and height above the bulwarks, *H*, were estimated, as was spray cloud duration. The number of spray events summarized was not indicated by the university. However, the events inspect-ed were classified into 11 categories, each with characteristic lengths, heights, and durations (Table 3-1).

Figure 3-8. Spray event image from starboard camera on CGC MIDGETT flying bridge (Ryerson 1990).

In addition, a written description accompanies each class. The authors also related the duration and frequency of spray events respectively to spray class, and to ship speed.

$$\text{Spray duration (s)} = 1.30 + 0.27\,(\text{CLASS} - 1.0) \tag{3-1}$$

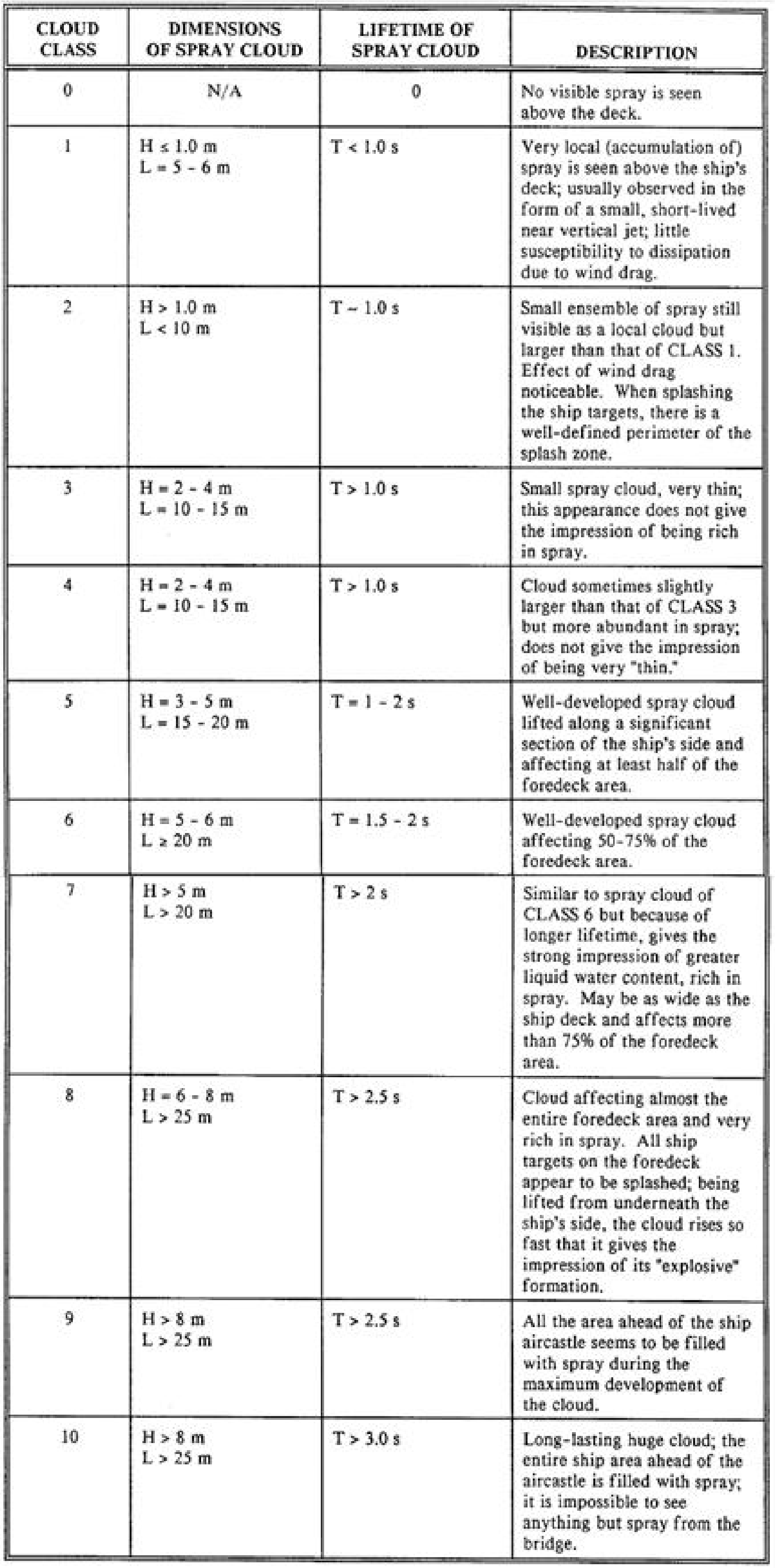
$$\text{Spray frequency/min} = 1.50 + 0.26\,(1.94v_s - 9.0) \tag{3-2}$$

where

v_s = ship speed in m/s.

Oddly, sea state is not a factor in the spray frequency relationship.

Table 3-1. Spray cloud classification for CGC MIDGETT cruise, 1990 (from Lozowski and Zakrzewski 1993).



CLOUD CLASS	DIMENSIONS OF SPRAY CLOUD	LIFETIME OF SPRAY CLOUD	DESCRIPTION
0	N/A	0	No visible spray is seen above the deck.
1	$H \leq 1.0$ m $L = 5 - 6$ m	$T < 1.0$ s	Very local (accumulation of) spray is seen above the ship's deck; usually observed in the form of a small, short-lived near vertical jet; little susceptibility to dissipation due to wind drag.
2	$H > 1.0$ m $L < 10$ m	$T \sim 1.0$ s	Small ensemble of spray still visible as a local cloud but larger than that of CLASS 1. Effect of wind drag noticeable. When splashing the ship targets, there is a well-defined perimeter of the splash zone.
3	$H = 2 - 4$ m $L = 10 - 15$ m	$T > 1.0$ s	Small spray cloud, very thin; this appearance does not give the impression of being rich in spray.
4	$H = 2 - 4$ m $L = 10 - 15$ m	$T > 1.0$ s	Cloud sometimes slightly larger than that of CLASS 3 but more abundant in spray; does not give the impression of being very "thin."
5	$H = 3 - 5$ m $L = 15 - 20$ m	$T = 1 - 2$ s	Well-developed spray cloud lifted along a significant section of the ship's side and affecting at least half of the foredeck area.
6	$H = 5 - 6$ m $L \geq 20$ m	$T = 1.5 - 2$ s	Well-developed spray cloud affecting 50-75% of the foredeck area.
7	$H > 5$ m $L > 20$ m	$T > 2$ s	Similar to spray cloud of CLASS 6 but because of longer lifetime, gives the strong impression of greater liquid water content, rich in spray. May be as wide as the ship deck and affects more than 75% of the foredeck area.
8	$H = 6 - 8$ m $L > 25$ m	$T > 2.5$ s	Cloud affecting almost the entire foredeck area and very rich in spray. All ship targets on the foredeck appear to be splashed; being lifted from underneath the ship's side, the cloud rises so fast that it gives the impression of its "explosive" formation.
9	$H > 8$ m $L > 25$ m	$T > 2.5$ s	All the area ahead of the ship aircastle seems to be filled with spray during the maximum development of the cloud.
10	$H > 8$ m $L > 25$ m	$T > 3.0$ s	Long-lasting huge cloud; the entire ship area ahead of the aircastle is filled with spray; it is impossible to see anything but spray from the bridge.

Figures 3-6 and 3-7 do not indicate the variability of spraying with time. Spraying varies considerably with ship natural or resonance pitch period, which is a function of the distance between ship perpendiculars. However, the actual pitch is strongly influenced by the sea wave period and ship speed across the seas (Doerry 2008). For example, a MFV may have a pitch period of 3.9 s, whereas the CGC MIDGETT has a pitch period of 5.5 s, and the USS *Monterey* a pitch period of 6.4 s. Each of these ships, then, responds to the seas with a different frequency. In general, vessels with a shorter pitch period spray more frequently.

The interaction of the wave period and the ship pitch period, as determined in part by ship speed and heading, also affect spray frequency. Spray rate per minute is an average value. Spraying usually does not occur at constant intervals, but may occur in clusters of many sprays separated by periods of little or no spray. This is caused by the interrelationships of ship pitch period, ship speed, ship heading across the seas, and sea wavelength. The author observed this on the CGC MIDGETT in 1990. The ship pitch would shift over a period of minutes to being in-phase with the waves or swells, and would gradually shift out-of-phase, and again back in-phase over time. When in-phase, the ship would rise on a swell, and sink in a trough, and not create spray for many wave encounters. When out-of-phase, the ship would plunge into each wave and create spray events for nearly every wave or swell.

This clustering of spray events, from frequent to infrequent, affects the icing process. Large amounts of water delivered to ship surfaces over a short period provides little time for heat to be removed from water that has impinged on surfaces. If insufficient heat is removed, water does not freeze, or only small amounts of ice forms. If spray events are spaced farther apart in time, the impinging water then has more time to cool and possibly freeze and create an ice layer, or add to ice previously formed. The rate of freeze must be rapid enough to nucleate water running down bulkheads before it fully runs off.

The size and design of a ship also have other effects upon the rate of superstructure spraying during icing conditions, and the subsequent growth of topside ice.

As described earlier, smaller vessels are immersed with spray more frequently than larger ships because of their lower freeboard and greater pitch frequency. Also, bow spray clouds are more likely to cover the entire superstructure of a small ship with a large spray flux than large ships. This is related to the size distribution of drops in spray clouds. Larger drops have greater fall velocities than small drops. Droplet sizes in spray events can range from less than 10 µm to 3 mm diameter at the bow. As the bow jets break up into drops and they are accelerated by the wind over the ship, they begin to fall. Large drops have higher terminal fall velocities than small drops, but the time, and distance, required to reach terminal velocity is greater for large drops than for small drops (Wang and Pruppacher 1977). Drops smaller than 200-µm diameter accelerate to terminal velocity in less than 0.2 s and over less than 2 m of travel distance. Drops larger than 2-mm diameter require over 1.2 s and over 12 m of fall distance to reach terminal velocity. The terminal fall velocity for a 200-µm diameter drop, however, is only 0.72 m/s, whereas a 2-mm diameter droplet falls at about 6.7 m/s. Therefore, large drops will intercept ship components first, most within 1 to 2 s from a height of 10 m, a large spray event. Small drops beginning flight at 10 m above the ship deck would require over 13 s to fall to the deck. Generally, small drops, such as 200-µm diameter drops, will be carried completely over the ship unless they strike higher portions of the superstructure. For this reason, spray clouds are more likely to transit an entire smaller ship than a larger ship.

The distance that spray moves aft, the portion of the ship that is wetted, is a function of the relative wind speed and the height of the spray jet. The height of the spray jet is a function of true wind speed, ship speed, and ship heading according to Zakrzewski et al. (1988a, b). They also state that wetting of the superstructure is greatest when spray crosses 60 to 70° off the bow because the water source is now closer to the superstructure (Zakrzewski 1987). Drops originating over the bow in head seas potentially must travel farther to reach the superstructure. Head seas may be more likely to allow drops to be carried farther aft, if the spray jet is high enough, because the trajectory will be directly aft. However, ship heading also influences where ice forms on a ship. Quartering seas, or their approximation, cause spray to be carried across the deck and, according to the University of Alberta team, may actually cause more impingement on the opposite side of the ship from where the spray originated than on the near side (Chung and Lozowski 1999). Bales (1985) reports that serious icing can occur 15 to 45° off the bow, causing increased icing on one side of the ship. This can cause a list towards the exposed side and, when combined with an extreme beam wind, could seriously degrade maneuver capability and ship stability.

In additional studies of the distribution of spray flux aft on a ship, Chung and Lozowski (1999) attempted to determine why the water volume deposited by a spray cloud as it moves aft over a superstructure decays exponentially with distance. This relationship is important because it, in part, determines the distribution of ice on the ship. They cite several studies, both on full-size ships and on tow tank models, that demonstrate this relationship; spray flux decreases with a negative exponential relationship as it moves aft. Because "spray clouds are an ensemble of droplets of different sizes," and large drops fall out of the cloud first, they hypothesized that the decrease of water volume deposited by the cloud as it moved aft was a function of the drop size distribution in the initial lofted spray event. They tested this hypothesis with two spray cloud drop size distributions: the classic rainfall Marshall-Palmer distribution and a log-normal distribution determined by Ryerson (1995) on the CGC MIDGETT in 1990. They found that spray clouds had two regimes with regard to liquid water content. The spray cloud is initially uniform vertically and horizontally for 12 m of movement across the ship, depending upon wind speed. In their experiment wind speed was 10 m/s. Thereafter, the decrease of liquid water content of the cloud as it moved aft over the ship best fit the exponential drop size distribution (Ryerson 1995). They do indicate, however, that many more measurements are necessary in a variety of meteorological, oceanographic and ship conditions.

Hull shape also influences the amount of spray lofted over the superstructure. Ships with greater freeboard in the bow area and greater bow flare tend to deflect spray away and reduce entrainment of drops into the relative wind. Sapone (1990), in tow tank experiments, found that bows with increased flare, in this case tested from 35 to 55° flare angles, reduce the wetted area of decks. Greater flare also reduced the volume of spray liquid water reaching decks, reduced the distance spray travelled aft, and produced finer drops at the deck edge than did bows with less flare angle.

Superstructure spray icing occurs when sea water is delivered to the ship superstructure and sufficient heat can be removed from the spray droplets in flight and from the water film on the superstructure after the droplets have collided and splashed, that the water can freeze. Air supercools drops in their first few seconds of flight, but if the sea is too warm, even very cold air may be insufficient to cool drops sufficiently that they freeze after collision. The water may run off the ship without freezing.

Generally, sea temperature must be lower than 5°C for superstructure icing to occur according to Guest (2005; DeAngelis 1974). The Navy indicates that the critical sea water temperatures for superstructure icing in the Gulf of Alaska, the Aleutian Islands, the Bering Sea, and the Arctic is between –2.2 and 8.9°C (Fett et al. 1993; Sechrist et al. 1989). Brown and Agnew (1985), in assessing about 1000 ship icing reports in Canadian water from the 1960s to the 1980s, found that water temperatures were typically 0 to 2°C during icing events. Water temperatures were between approximately 0 and 3°C during two icing events on the CGC MIDGETT in 1990 (Ryerson 1995).

According to the Navy *Forecasters Handbooks* for the Bering Sea, Aleutians, Gulf of Alaska, and the Arctic, air temperatures range between –2 and –18°C for superstructure icing (Fett et al. 1993; Sechrist et al. 1989). They argue that temperatures lower than –18°C cause droplets to freeze before striking the superstructure, and not adhere to the ship, though this latter claim is disputed by Minsk (1977) who indicates that superstructure icing has been reported to temperatures of –29°C. Brown and Agnew (1985) found icing to most typically occur between –5 and –11°C, with extremes down to –13.1°C in non-Arctic Canada, and in the Canadian Arctic between –7.3 and –10°C. Ryerson (1991) found temperatures most associated with superstructure icing off the east coast of Canada in 117 cases to be between –3.5 and –12.6°C, though the maximum was 0°C and the minimum was –20°C. Two icing events were well-documented on a cruise by the CGC MIDGETT in the Bering Sea in 1990 (Ryerson 1995). In the first event, air temperatures ranged from 0 to about –15°C, and in the second event they ranged from about –5 to about –12°C.

Winds may also contribute significantly to icing. Wind helps carry spray over the ship, and may create the seas that cause the spray when the bow pitches into them. In addition, the wind increases convective cooling of the drops. The Navy *Forecasting Handbooks* indicate that faster wind speeds generally see more ice forming (Fett et al. 1993; Sechrist et al. 1989). Brown and Agnew (1985) find winds associated with icing to be typically 50–60 kt (26–31 m/s) off the Canadian east coast, and 30–40 kt (15–20 m/s) in the Arctic. Ryerson (1991) found mean wind speeds of 31 kt (16 m/s) in ship icing off of the Canadian east coast, though speeds did range up to 65 kt (33 m/s). Relative wind speeds on the CGC MIDGETT during the two 1990 icing events ranged between about 10 and 58 kt (5 and 30 m/s), in the first event, and between 10 and 33 kt (5 and about 17 m/s) in the second event.

Wave heights are also important generators of spray. Without waves, bow plunging would not occur to create spray jets and spray clouds. However, ships of different size interact with sea states differently, with smaller vessels creating spray in lower sea states than larger ships because of their greater pitch angle and pitch frequency, and typically lower freeboard. The database analyzed by Brown and Agnew (1985) in Canadian waters includes ships ranging in size from fishing trawlers to cargo ships. They found icing to be associated with seas of 2 to 4 m off the east coast of Canada and in Hudson Bay, but seas of 1 to 12 m in the Scotian Shelf area, the Grand Banks, and off Newfoundland. Seas of 6 to 8 m accompanied icing in the Gulf of St. Lawrence, Labrador Sea, and eastern Arctic. The western Arctic had seas of less than 2.5 m during icing. Ryerson (1991) found that waves averaged about 1.6 m high, and swells 1.8 m off the Canadian east coast during icing. During the 1990 CGC MIDGETT icing events, waves ranged from 1 to 2.5 m high and swells 1 to 3.7 m high in the first icing event, and 0.5 to 1.3 m for waves and 1.3 to 2.5 m for swells in the second icing event.

Guest (2005) provides guidelines relating vessel length, significant wave height, and wind speed to threshold icing conditions on his Navy Postgraduate School web site (Table 3-2)[1].

Icing rates, the result of seas, wind, spray, and cold, are either expressed as a thickness or mass accumulation with time, and are usually expressed for the entire ship. Icing rates suggest how quickly ships may become dangerously loaded with ice. Even small amounts of ice on a ship can reduce the safety of personnel operating on decks, and also degrade optical systems, sensors, and antennas. Icing rates are usually indicators of how quickly seaworthiness may deteriorate, but they are also an indication of the deterioration of ship operations and safety.

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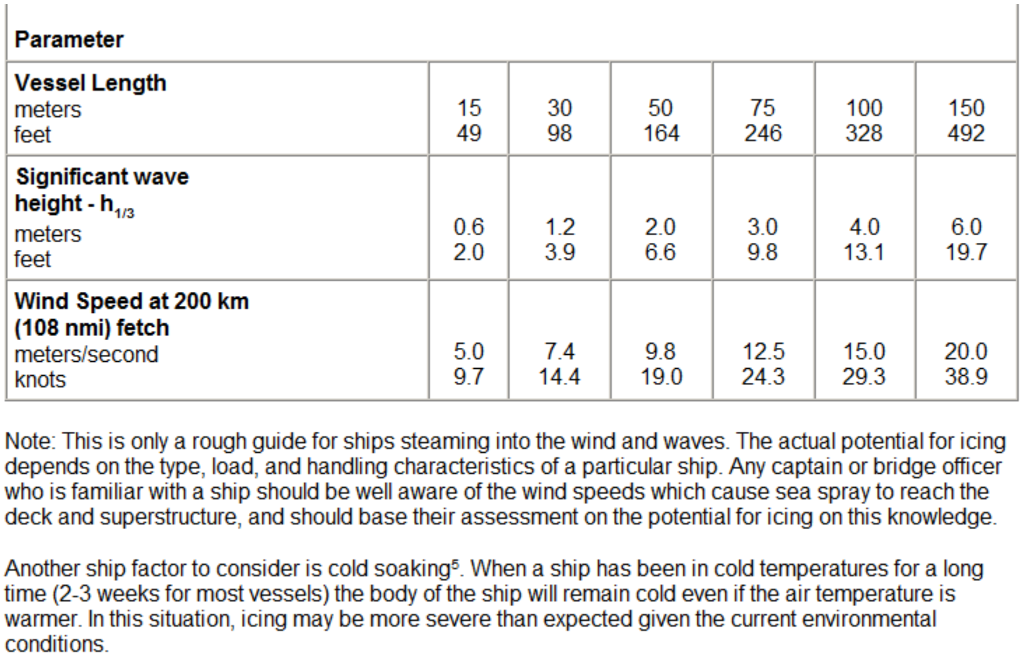
[1] http://www.weather.nps.navy.mil/~psguest/polarmet/vessel/description.html

Table 3-2. Threshold wind speeds for icing to occur on various length ships (from Guest 2005).



Parameter						
Vessel Length meters feet	15 49	30 98	50 164	75 246	100 328	150 492
Significant wave height - $h_{1/3}$ meters feet	0.6 2.0	1.2 3.9	2.0 6.6	3.0 9.8	4.0 13.1	6.0 19.7
Wind Speed at 200 km (108 nmi) fetch meters/second knots	5.0 9.7	7.4 14.4	9.8 19.0	12.5 24.3	15.0 29.3	20.0 38.9

Note: This is only a rough guide for ships steaming into the wind and waves. The actual potential for icing depends on the type, load, and handling characteristics of a particular ship. Any captain or bridge officer who is familiar with a ship should be well aware of the wind speeds which cause sea spray to reach the deck and superstructure, and should base their assessment on the potential for icing on this knowledge.

Another ship factor to consider is cold soaking[5]. When a ship has been in cold temperatures for a long time (2-3 weeks for most vessels) the body of the ship will remain cold even if the air temperature is warmer. In this situation, icing may be more severe than expected given the current environmental conditions.

In the 1950s, after the loss of several fishing trawlers to icing, the British modeled icing of a scale model trawler in a coldroom tank (Fein and Freiberger 1965; Minsk 1977). The vessel was tested with a mast with rigging, and with a tripod mast without rigging. Tests were conducted with water droplets blown against the ship from various directions at an equivalent 45- 55-kt (23- to 28-m/s) wind speed, and an air temperature of –10 to–6°C. Three tests were conducted for each mast configuration: head to wind, wind 30° off of the bow, and stern to wind. In head to wind conditions, the ship lost only about 67% of its metacentric height with the tripod mast as with the rigged mast. In the 30° beam wind, the rigged mast model capsized with less than 50% of the ice that the head wind rigged model had when it capsized. The stern to wind test only lost about 50% of the metacentric height lost in the headwind position because of sheltering of the mast by the superstructure.

Icing rates on ships can be very high. Zakrzewski et al. (1988) and DeAngelis (1974) report that rates of 1 to 3 cm/hour are not uncommon. The NOAA Environmental Modeling Center forecasts superstructure icing for US interests and the system is used by the US Navy.[1]

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[1] http://polar.ncep.noaa. gov/marine.meteorology/vessel.icing/#ani.sice

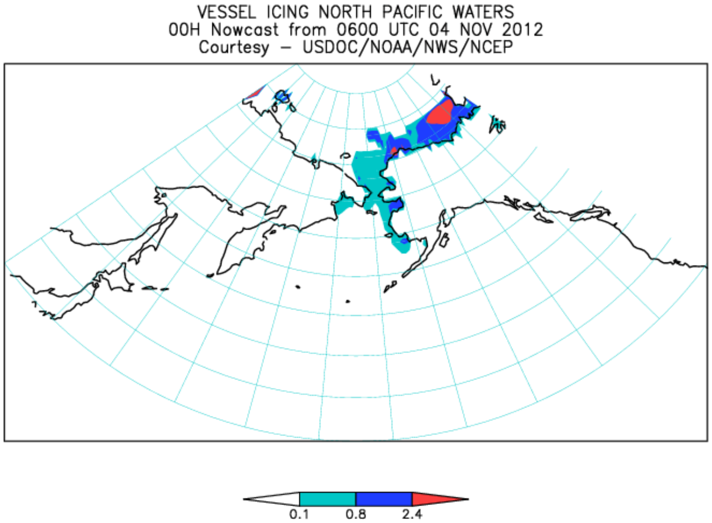


Figure 3-9. Forecast made at 00 hours for 0600 to 1200 hours UTC 4 November 2012 for the northern Pacific and Arctic Oceans. White indicates no or minimal icing, green light icing, blue moderate icing, and red heavy icing (**http://polar.ncep.noaa/**).

NOAA uses algorithms developed by Overland et al. (1986) that relates icing to wind speed at a height of 10 m, the sea water freezing temperature, air temperature at 2 m, and sea surface temperature. Designed from a database of 58 carefully selected cases of trawlers 20 to 75 m in length, the prediction algorithms generate three classes of icing rates. Forecasts are made at 3-hour intervals for 6-hour forecast periods on a 1° latitude by 1° longitude grid globally. Icing rates are predicted in three intervals: light is 0.3 to 2.0 cm of ice in 3 hours, moderate is 2.0 to 6.1 cm of ice in 3 hours, and heavy is greater than 6.1 cm of ice in 3 hours (see also Table 3-3). Forecast maps show areas where each category could occur over 6-hour periods, with forecasts created every three hours out to 168-hours (1-week) (Fig. 3-9). These rates are defined as the “maximum sustained rate for typical Alaskan vessels, 20- to 75-m length, which are not actively avoiding icing through heading downwind, moving at slow speeds or avoiding open seas” (Overland 1990).

Overland re-derived his 1986 algorithms in 1990, but stated that the 1986 algorithms were operationally performing well (Overland 1990). The new derivation accounts for supercooling of drops in flight when sea water temperatures are lower than 2 to 3°C. This required reclassifying icing rates into four categories (Table 3-3).

Table 3-3. Icing rates (cm/hr) developed by various authors. Overland et al. (1986) is used for most NOAA forecasts (extracted from Overland et al. 1986.).

	Light	Moderate	Heavy or severe	Very severe, extreme, very heavy	Extreme
Overland et al. (1986)	<0.7	0.7–2.0	>2.0		—
Overland (1990)	<0.7	0.7–2.0	2.0–4.0	>4.0	—
Lundqvuist and Udin (1977)	0.04–0.17	0.25–0.75	>1.0	—	—
Sawada (1973)	<0.5	0.5–2.0	>2.0	—	—
Kachurin et al. (1974)	—	—	1.8	4.2	—
Mertins (1968)	0.04–0.125	0.17–0.25	0.29–0.58	>0.625	—
Wise and Comiskey (1980)	0.09–0.21	0.21–0.42	0.42–0.63	0.63–1.06	>1.06

Lundqvuist and Udin's (1977) rates were developed for the Baltic Sea, Sawada's (1973) for the Sea of Okhotsk, and Kachurin's et al. (1974) for the Sea of Japan, the Barents Sea, and the Bering Sea (Table 3-3). These were all developed for medium size fishing vessels of about 20- to 75-m length (Overland 1990). Wise and Comiskey (1980) used Mertins' (1968) nomograms and combined them into one based on additional icing reports from the northeast Pacific Ocean. They also included climatologies of the northeastern Pacific Ocean and the northeastern Atlantic Ocean (Feit 1985).

The Alaska NOAA National Weather Service Office uses a variety of techniques for Alaska waters. As do other NOAA offices, the Alaska NWS uses the Overland et al. (1986) algorithms and icing rates. They also remove the Overland et al. (1986) "moderate" category and split it between "light" and "heavy" because most users do not use the "moderate" category. They also predict freezing spray as wind > 7.7 m/s and air temperature < –1°C, and heavy freezing spray as wind > 7.7 m/s and air temperature < –3.4°C and sea surface temperature < 5°C (Curtis 2012).

3.1.2 Location, magnitude, frequency

Sea spray ice accretion rates vary considerably with location on a ship (Ackley 1985). Ice accretion rates are determined by the balance of heat delivery by spray, both sensible and latent, and atmospheric heat removal processes. Figure 3-10 illustrates three icing zones that often occur on all sizes of ships. The maximum accretion zone is where spray delivery matches the atmosphere's ability to remove sensible and latent heat from impinged water at a sufficient rate for all spray to freeze (although some spray remains trapped as brine within the ice). Maximum accretion may take place at bow locations maximally exposed to the wind, such as at the top of the bow and windlass located on the forecastle of the fishing trawler shown in Figure 3-11. However, during heavy spraying, much ice may also accumulate amidships, where the spray flux is smaller and the rate of heat removal by the atmosphere is still large (Fig. 3-10). This is demonstrated by the wheelhouse roof and areas immediately aft of the wheelhouse on the trawler (Fig. 3-11).

Thermally limited accretion (Fig. 3-10) takes place where the spray water delivered exceeds the atmosphere's ability to remove its sensible and latent heat. Thus, ice accretion rates are smaller than water delivery suggests. Large spray fluxes, and thus thermally limited accretions, are normally only found on the bow areas of large ships, even though large volumes of spray can reach farther aft on smaller ships.

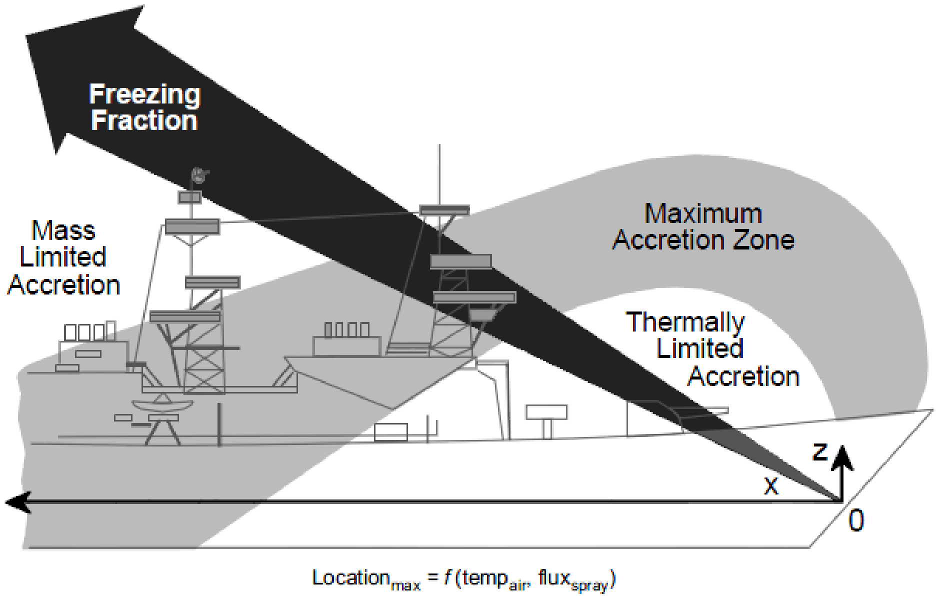


Figure 3-10. Mass and thermally limited accretion zones on a ship during spray-generated superstructure icing. These zones move and change in intensity as ship–sea dynamics and air temperature and wind speed change (after Ackley 1985).

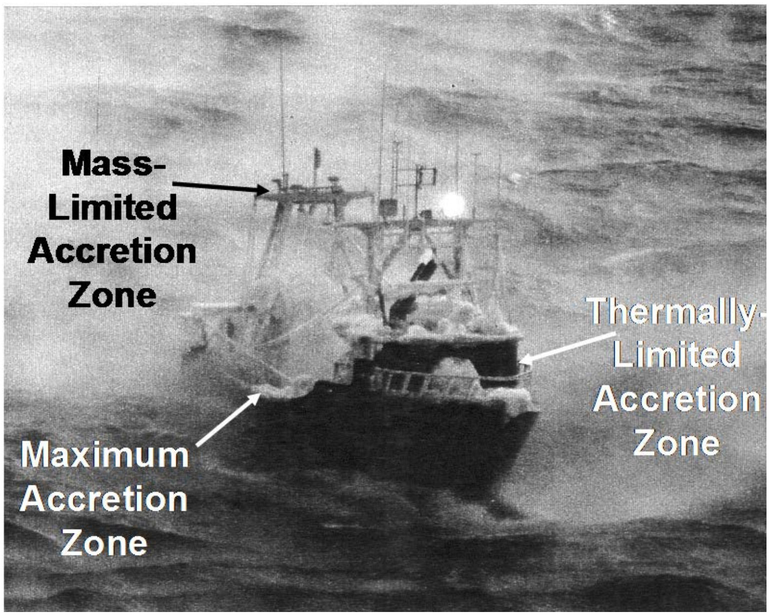


Figure 3-11. Ice accretion zones on trawler in Bering Sea, 1990 (Ryerson 1990).

Figure 3-11 illustrates a situation where thermally limited accretion is restricted primarily to portions of the bow, the forecastle deck, and the forward bulkhead of the trawler. Mass limited accretion generally occurs aft and above the maximum accretion zone because spray generally decreases with distance aft of the bow and above the main deck. The mass limited accretion zone is characterized by water delivery rates, and, thus, sensible and latent heat delivery rates, that are smaller than the atmosphere's ability to remove the heat. All of the spray (except brine concentrated within brine pockets) freezes and ice accretion is limited by available spray. It does not reach its potential thickness as determined by the atmosphere's ability to remove heat.

Mass limited accretion is most dramatically illustrated by the upper portions of the twin masts on the trawler's fantail, where ice thickness decreases with height (Fig. 3-11). The three superstructure icing zones are dynamic, with the amount of superstructure covered by each changing as spray delivery rates and patterns, and atmospheric conditions such as relative wind speed and direction, change. Thus, it is conceivable that ice may be growing on some portions of the superstructure, while on other areas it may be eroding (Ryerson 1995). In addition, depending upon ship size, spray delivery rates, and atmospheric conditions, only one, two, or all three of the zones may be found at any one time on the ship. Often, however, thermally limited accretion occurs in the bow area, transitioning to maximum, and mass limited, accretion zones at higher levels and farther aft. The freezing fraction is defined by the portion of impinging spray water that freezes and forms a matrix that traps brine. Known as spongy ice, for this reason saline sea spray ice generally attains a mass and thickness that is greater than that explained by the latent heat removed.

Zahn and Voelker (1985) report at least five fishing trawlers are lost per year because of superstructure icing (but seven to ten per year have been reported Minsk 1977), all smaller vessels, less than 800 tons. The current loss situation may be smaller owing to better icing forecasts, even though de-icing and anti-icing technologies on ships have improved little over the last 50 years.

As an example of smaller vessels in difficulty because of icing, DeAngelis (1974) elaborates on icing of a fishing trawler, the *Kingston Garnet*, in the Denmark Strait in January 1955. Shrouds, ratlines, masts, and halyards were all solid with ice. The radar mast iced over, and boats and their davits were ice covered. The funnel was frozen, rails were a “solid sheet of ice,” and the front wheelhouse windows held a 10-cm layer of ice. Other fishing trawlers, of 600 to 800 tons displacement, similar to the displacement of the Coast Guard *Bay*-Class or icebreaking tugs, accumulated more than 50 tons of ice in less than 24 hours and sank. Russian, Japanese, and British literature indicates that when air temperatures are immediately below the freezing temperature of seawater, a vessel displacing 300–500 tons will accumulate less than 1 ton of ice per hour in any wind. If temperature drops to −3 to −8°C and winds increase to 8 to 15 m/s, ice accumulation increases to 4 tons per hour or less. At temperatures lower than −8°C and winds greater than 15 m/s, accumulation rates will be more than 4 tons per hour. Translated to thicknesses, icing rates of 8 cm per hour can be tolerated on most vessels for a short time, but greater rates can quickly cause stability problems, and a risk of capsizing.

Chatterton and Cook (2008) wrote a comprehensive analysis of the effects of icing on commercial fishing vessels in US waters. Three accidents were described that were related to icing: the sinking of the *Lady Grace* off Nantucket, the grounding of the *Star Trek* off the Alaska coast, and the sinking of the *Hunter* off the coast of Alaska. All three vessels were small, 23 m long or less. All three vessels operated in icing conditions, and none of the crews or vessels were fully prepared or knew how to operate in icing conditions. In all three cases, NOAA forests had predicted air temperatures, sea surface temperatures, and wind speeds that were beyond the threshold for icing conditions.

On large commercial ships, such as Great Lakes bulk carriers, which generally have high freeboard, icing has caused loading and unloading delays, and tankers crossing the North Atlantic have experienced freezing cargo manifolds and valve actuators.

Russians claim that icing is a danger to ships as large as container ships. Icing of a container ship in a photo (Fig. 3-12) supplied by the Canadian Coast Guard supports this claim. This, and an iced tanker illustrated by Riska (n.d.), demonstrate that large ships with higher freeboard than military craft are capable of heavy superstructure icing. Transport Canada (2011) indicated that container ships are vulnerable to icing of containers on the forecastle deck, and that the ice may be unnoticed even in daylight because of visibility obstruction from the bridge. They cited a 120-m vessel that left Europe with a 0.2 m trim by the stern, and arrived at Quebec City trimmed 4.0 m by the bow, and with a 5° list because of icing. The ship was also directionally unstable when arriving in Canada.

Itagaki (1977), when reviewing Japanese literature on superstructure icing, also cited cases where large commercial ships experienced difficulties from icing. A 9390-ton Japanese freighter left Washington State in January 1967 for Japan loaded with timber. It encountered heavy icing in transit between Attu Island in the Aleutians and Japan. In 60 hours 20 cm of ice accumulated on the forecastle, and the maximum thickness eventually reached 51 cm. The front bridge windows were covered with 41 cm of ice. The ship developed a 10° starboard list under an estimated 200 tons of ice and nearly capsized. In another incident a 17,290-ton vessel accumulated 100 tons of ice in the North Pacific Ocean, requiring 12-hours of de-icing by a 60-person crew.

Figure 3-12. Icing of container ship. At least the forward 53 m of the ship is heavily iced from sea spray ice (from Canadian Coast Guard, http://www.qc.ec.gc.ca/meteo/secrets_stlaurent/vessel_icing_e.htm).

CAPT Garbe (1985) and Rogalski (1985) described icing of the USS *Capadanno*, a FFH 7 Class ship that arrived in Bath, ME, during the winter of 1981–82 with a 5° starboard list and ice at high levels on the superstructure (Fig. 3-13 to 3-18). The ship was near its load limit because of armament changes over its operational lifetime.

Crowley (1988), a retired US Coast Guard Captain and engineer at Bath Iron Works, ME, described the effects of superstructure icing on ships of various sizes. Sea spray icing is the most dangerous form of ship icing, but icing rates are often accelerated by the presence of snow, though the actual mechanism that makes concurrent snow and ice events more severe is unclear. Though in any given event, spray-induced superstructure icing is less severe on larger ships, it can have serious effects. A Finnish container ship, for example, accumulated 25 to 30 mm of ice on decks and winches.

A German freighter sailing between Bremerhaven and Baltimore iced between Cape Farewell, Greenland, and Nantucket, accumulating 250–300 tons of ice forward, and about 100 tons amidships.

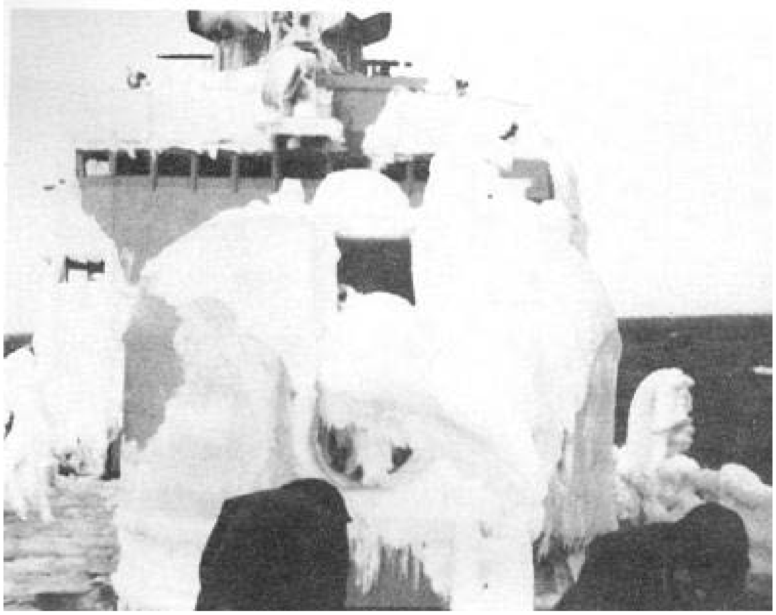


Figure 3-13. Front view of forward gun on USS *Capadanno* (Rogalski 1985).

Figure 3-14. Top view of forward gun on USS *Capadanno* (Rogalski 1985).

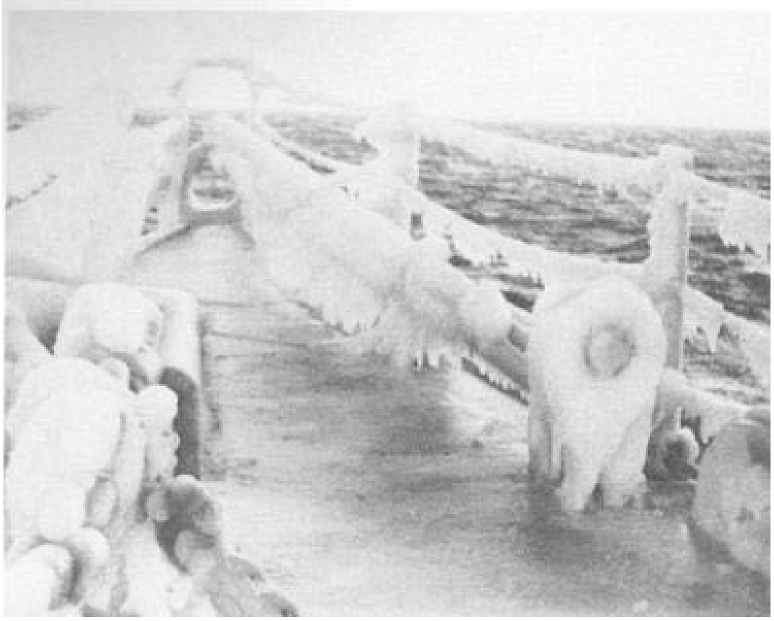


Figure 3-15. Iced over bow on USS *Capadanno* showing chocks, anchor chains, and chain hand rails (Rogalski 1985).

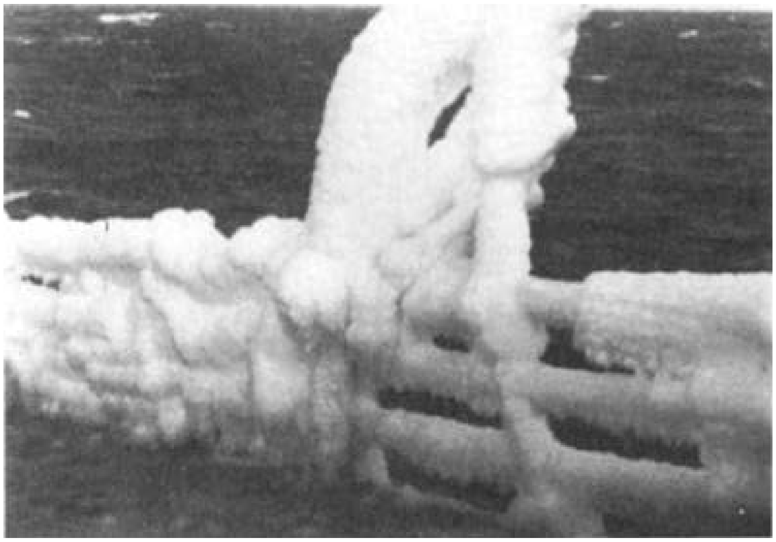


Figure 3-16. Iced over davit and chain hand rails on USS *Capadanno* (Rogalski 1985).

Figure 3-17. Iced over ladder and deck housings on USS *Capadanno* (Rogalski 1985).

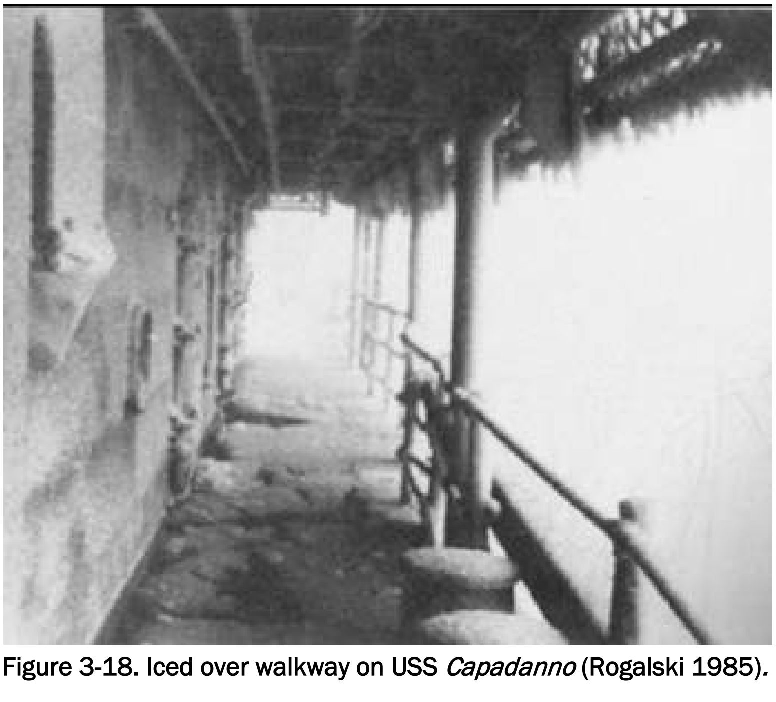


Figure 3-18. Iced over walkway on USS *Capadanno* (Rogalski 1985).

A Navy study by Lee (1986) indicates that the probability of encountering moderate icing at an accretion rate of 0.6 to 1.3 cm per 3 hours in the North Pacific is 20 to 30%, and the probability of heavy icing at a rate of

1.3 to 1.9 cm per 3 hours is 4 to 8% (from Schultz 1989). Icing events can last from several hours to 3 days. Panov (1978), from studies of 494 icing cases on ships of various sizes, but mostly trawlers, assessed the frequency of icing on different parts of a ship. He found that the icing of an entire ship is extremely rare. However, 47% of all cases were iced on the forecastle deck, rigging, superstructure, and the mast; 24% were iced on the forecastle deck and forward mast; and 18% were iced on the superstructure and superstructure decks. The stern and the entire ship only iced during 2% of cases each.

Lundqvuist and Udin (1977) stated that ice accretion starts on the forward part of a ship in the rigging, mast, and superstructure that are not washed by very heavy spray or green water. In general, they said that if ice accumulates primarily on one side, a ship will founder with only about 50% of the ice load that would cause foundering if icing were symmetrical. Minsk (1975), in a summary of the literature, reported that 30 to 70% of ice forms on horizontal surfaces, and 15 to 40% forms on vertical surfaces; 5 to 30% accumulates on complex surfaces, such as deck machinery; and 0 to 30% accumulates on masts, spars, and rigging. Ryerson (1995) found that vertical surfaces accumulated only 71% as much ice as horizontal surfaces on the CGC MIDGETT in the Bering Sea in 1990.

Fisheries and Oceans Canada (2012) warn that icing generally is most severe at the stem, bulwark and bulwark rail, windward side of the superstructure, hawse pipes, anchors, deck gear, forecastle deck and upper deck, scuppers, aerials, stays, shrouds, masts, spars, and associated rigging. They, and Transport Canada (2011), warn that it is also important to keep the anchor windlass free of ice so that the anchor may be dropped in case of emergency. When approaching an area of expected superstructure icing, it is good practice to leave anchors slightly lowered (≈ 0.5 m) in the hawse pipe to pull them free of ice accretion when needed.

3.1.3 Physical properties

Minsk (1977) studied marine icing, principally on offshore platforms, but he also evaluated the icing of ships from literature available. He described marine icing as forming when a supply of water is exposed to a process that extracts thermal energy sufficiently to cause the initiation of crystallization. The transition from water to ice structure requires a stimulus to trigger crystallization; but without a stimulus, fresh water can supercool to between −30 and −40°C before spontaneously freezing.

Freezing can be initiated by mechanical means such as vibration, or by nuclei with crystal structures similar to ice, such as dust, ice crystals, or impurities on the walls of a vessel containing the water. Dissolved impurities cause water to freeze at lower temperatures than pure water. In general, for example, sea water has a salinity of 34 ppt and begins to freeze at approximately –1.9°C. The freezing front rejects the sea salts and pure ice remains in the solid phase. The remaining brine drains or is trapped in brine pockets, which have a lower freezing temperature because of their higher salinity.

Brine pockets weaken the ice. For this reason, in part, sea spray ice on vertical surfaces is often thinner near the top of bulkheads and thicker at the bottom because brine runs down the surface of the ice, and through the ice in brine channels, and freezes at the bottom of the bulkhead. Saline icicles also form in a similar, but more complex, manner. As the ice on the lower part of a structure has a higher brine content, it is also often weaker than ice higher on bulkheads, and ice on decks is often weaker yet, in part for this reason (Minsk 1977).

Though brine pockets and channels are often cited by researchers, brine channels have not been sufficiently visible to be fully understood. Brine pockets and features that appear to be brine channels were visible in ice sampled on the CGC MIDGETT in 1990 (Ryerson and Gow 2000a, b). However, Ozeki et al. (2005) have actually imaged brine channels in saline spray ice that accumulated on a lighthouse on the Japanese coast. Brine channels that had drained were filled with dodecane doped with iron acetylacetonate. Magnetic resonance microscopy was used to image the channels, and maximum intensity projection (MIP) was used to render a cross-section of the spray ice and the channels. A channel network was visible.

Salinity of the sea water is commonly cited as the reason for brine pockets occurring in sea spray ice. However, all ice, fresh or salty, formed from droplets striking surfaces forms pockets of unfrozen water, and this is called spongy ice (Makkonen 1987; Blackmore and Lozowski 2003). Ice sponginess, the incorporation of unfrozen fresh water, brine, or air in the ice, has been observed in hail, in aircraft airfoil ice, and in ship superstructure ice. It has also been observed in floating sea ice that does not form from the accumulation of airborne drops. Lozowski et al. (2000) indicate that up to 50% of an ice mass may consist of unfrozen liquid inclusions.

These inclusions increase the mass of ice on a ship well above that to be expected from thermodynamic theory alone because latent heat is not removed from the unfrozen water. This can cause modelers to significantly under-predict the amount of ice forming on a ship. It also weakens ice cohesive and adhesive strengths by interrupting the ice crystal lattice and by lubricating the ice crystal mass.

The cause of spongy ice is not well understood, and Blackmore and Lozowski (2003) developed a consensus from the literature of other researchers and their own theories about the causes. They believed that if the liquid water content of the spray is large, and the weather is relatively warm, that water on the face of an ice mass accumulating on a bulkhead, for example, supercools. The supercooling stimulates the growth of ice dendrites at the ice–water interface that create tips that entrap water between the ice crystals. Makkonen hypothesized that sea spray icing can have a sponginess of about 26% (Makkonen 1987), though Lozowski et al. (2000) claimed that up to 50% of the ice mass can be unfrozen.

A number of researchers have made measurements of the characteristics of saline superstructure ice in wind tunnels and on ships. Borisenkov and Pchelko (1975) indicated through observations on Russian trawlers at –15°C that ice initially is weak, or “loose,” and can be removed easily. However, the ice hardens over time, in this case in 1.5 to 2 hours, and becomes difficult to remove. The latter is probably ascribable to brine drainage and freezing of the water in the spongy ice making it harder. They also found ice to freeze more slowly on wooden surfaces, but once it forms, it adheres more tenaciously to wooden than to painted metal surfaces.

The University of Alberta constructed a unique wind tunnel, allowing vertical flow sea spray icing, in the late 1980s. That tunnel allowed experiments to be conducted with large drops of saline water, as are observed on ships.

Fukusato et al. (1989) conducted an experiment in the Alberta tunnel to determine the effects of air temperature and wind speed on the characteristics of ice accretion from sea spray. They used mean drop diameters of about 200 μm accumulating on a cylindrical rod placed across the air stream. They observed that, at a temperature of –15°C and a wind speed of 6 m/s, some water did not freeze and flowed off of the surface, forming icicles. At wind speeds greater than 10 m/s, fewer icicles formed as droplets more completely supercooled and ice was created on the upwind side of the cylinder. The lower speed created a wet-growth condition, where some water does not immediately freeze and runs around the object that is icing, causing freezing downstream. The higher wind speed caused most of the water to freeze nearly upon impact, allowing little runback, approaching a dry ice-growth situation.

Experiments with different drop diameters at a wind speed of 6 m/s and temperature of –15°C showed that smaller drops froze more quickly than large drops because the smaller drops supercooled more deeply. Therefore, larger drops caused more wet growth and runback than did small drops because of the larger volume of water within each drop, causing relatively slower cooling and freezing rates.

Additional experiments varied the initial temperature of the droplets, as though from warmer or colder sea water, showed that colder drops caused a smoother ice surface, and warmer drops caused a rougher ice surface—the latter being attributed to incomplete freezing and runback.

Finally, as spray liquid water content increased, ice mass accumulation on the cylinder increased. However, at the larger mass flow rates, considerable water did not freeze in the wet-growth environment, forming some icicles. This created only 40% of an expected increase in ice growth that would happen if all of the impinging water froze. Measurements of the salinity of the ice showed that there was greater salinity in ice formed downstream of the cylinder's leading edge as brine was rejected by ice formation on the leading edge. This is consistent with observations that ice is less saline, and therefore harder and more cohesive and adhesive, higher on bulkheads where brine has had a greater opportunity to drain from ice. They also found that, as water salinity increased drop supercooling also increased.

Additional studies in the University of Alberta sea spray tunnel provided more information about the behavior of spray ice as it freezes (Lock and Foster 1990). In this experiment, ice was accumulated on the forward stagnation point of a 12-cm-diameter steel disc with an insulated back—similar to a ship surface. Spray cloud liquid water contents ranged from 10 to 120 g/m^3, and spray drop diameters were about 500 µm in diameter. For comparison, mean drop diameter on the CGC MIDGETT cruise was

295 µm, median volume diameter was 1094 µm, and liquid water content averaged about 60 g/m^3 (Ryerson 1995).

Lock and Foster (1990) found that spray of fresh water and saline water, the latter with a salt content of 35 ppt, each created spongy ice. They found that the fraction of frozen versus unfrozen water in a mass of fresh water ice and sea water ice did not vary significantly over a range of air temperatures between –5 and –30°C, and over a range of wind speeds between 5 and 25 m/s. The mass ice fraction was about 40 to 55% for fresh water ice and about 30 to 50% for salt water ice, with only about a 10% variation over the full range of temperature or wind speed.

They did find that a morphological change occurred in the ice at temperatures below and above –10°C. At temperatures higher than –10°C (warmer), the ice grows with a columnar crystal structure with the long crystal axis orthogonal to the substrate. The ice accretion appeared glazed on the surface with an occasional pebbly structure. It is believed that this ice forms by anisotropic crystal growth, as dendrites growing into the water film on the ice surface. This ice was somewhat cohesive and fractured when bent along well-defined grain boundaries. Ice forming at temperatures lower than –10°C (colder) produced a surface with a matte surface, and a “mushy” texture. It had a consistency and structural integrity similar to that of a grey paste ready to set. The ice was loosely held together like wet snow or slush. Ice growth in this colder regime is believed to occur on many random nuclei, producing a finer and less cohesive ice structure.

Ryerson sampled ice that formed on the CGC MIDGETT in February and March 1990 in the Bering Sea: 23 samples were removed as slabs of ice from decks, bulkheads, the gun mount and lifelines—all on the ship forecastle because little ice formed elsewhere. Ice temperature was also taken in situ, and samples were sealed in bags for later analysis (Fig. 3-19).

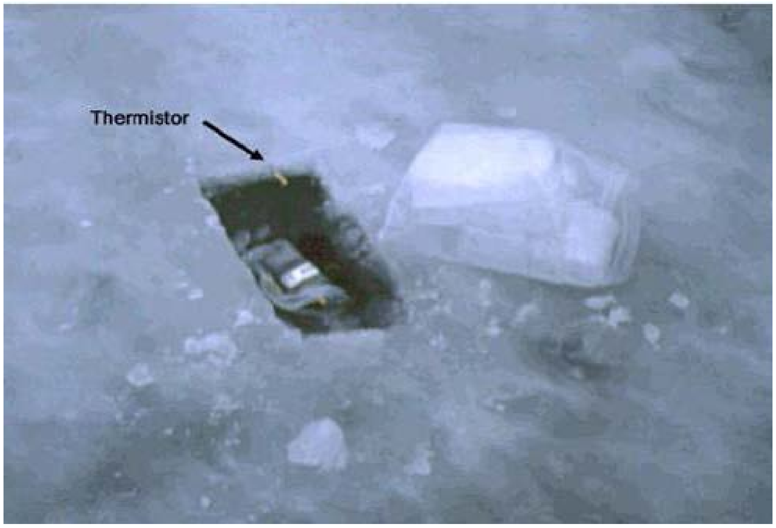


Figure 3-19. Ice samples in a freezer bag, and a thermistor for measurement of in situ ice temperature (Ryerson 1990).

Mean thickness of ice on horizontal surfaces at the end of the February icing event was 2.6 cm, and average vertical surface thicknesses were 2.2 cm. During the March icing event, horizontal surfaces averaged 2.0 cm of ice, and vertical surfaces averaged 1.5 cm, indicating that vertical surface ice was about 75% of the thickness of horizontal surface ice (Ryerson 1995).

Ice properties such as density, salinity, and porosity were measured in a coldroom. Ice density in the CGC MIDGETT's February and March icing events ranged from 0.69 to 0.92 Mg/m^3 (Ryerson and Gow 2000a, b). Ice densities on horizontal surfaces were 1.2 times larger than on vertical surfaces in the February icing event, but there was no significant difference in March. The range of desnities measured on the CGC MIDGETT is similar to those measured aboard ships by the Russians and Japanese (Kultashev et al. 1972; Tabata et al. 1963). Ice density, coupled with thickness, determines the mass of ice at various locations on the ship. It also has a large effect upon the ultimate strength of the ice, and how well it adheres to the substrate (Smirnov 1972).

Salinity during the CGC MIDGETT's two icing events varied with surface orientation. The salinities of horizontal ice samples taken from decks and a hatch ranged from 12.0 to 24.9 ppt and averaged 21.4 ppt. Vertical ice samples were taken from bulkheads, the 5-in. gun, the lifeline, and from icicles (Fig. 3-20). These salinities ranged from 16.7 to 7.0 ppt, and averaged 12.0 ppt (Ryerson and Gow 2000a, b).

Figure 3-20. Lifeline vertical ice sample on the CGC MIDGETT (Ryerson 1990).

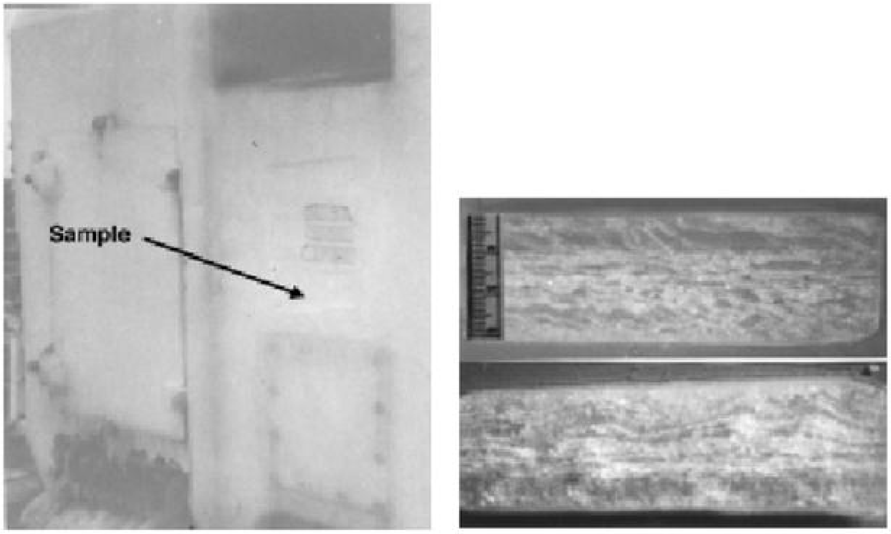
The portion of ice that is not frozen, composing the spongy components, is called porosity. Porosity refers to voids in the ice filled with water, brine, or air. If unfrozen brine eventually drains, as occurs quickly during and immediately after accretion and more slowly later and in cold conditions, the mass of the accretion will be considerably reduced below what thickness alone may suggest. The porosity of ice samples removed from the MIDGETT was computed using equations developed by Cox andWeeks (1983) and Frankenstein and Garner (1967). The volumes computed were estimates because the equations were developed for floating sea ice, not spray ice, and the answers rely upon density, salinity, and temperature measurements that, with all potential errors considered, could cause uncertainty in the porosity estimates. The derived brine volumes and air contents are calculated for the in situ temperature for the accreted ice at the time of sampling.

Porosity on vertical surfaces of the CGC MIDGETT ranged from 19.2 to 50.4% and averaged 30.2%. On vertical surfaces porosity ranged from 16.1 to 31.4%, and averaged 24.6%. A larger percentage of pores were filled with brine on horizontal surfaces than on vertical surfaces (Ryerson and Gow 2000a, b).

Few studies have examined the crystalline structure of ice created from bow spray: only one study by the Japanese and one by the Russians (Ono 1968; Golubev 1972). Several ice structure characteristics were examined from the CGC MIDGETT samples, including ice crystal shape, size, and orientation, and inclusion size and shape. The February icing event is the least difficult to analyze because temperatures were low during the entire period. Warm weather late in the March event complicates understanding of ice characteristics during that event.

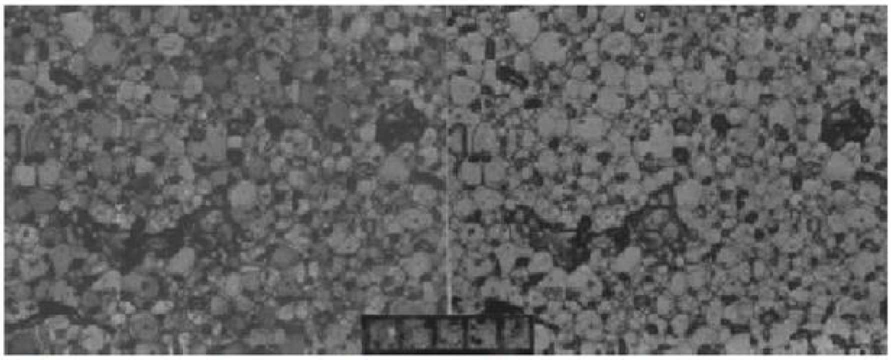
Texturally, CGC MIDGETT ice resembled frazil ice, formed from the consolidation of freely nucleated ice crystals in sea water. The shapes of grains composing the crystalline structure of accreted ice ranged from rounded to polygonal. Gow (Ryerson and Gow 2000a, b) observed that ice formed during the initial stages of accretion frequently displayed a polygonal crystalline structure. This can probably be attributed to thermally driven modification of the original microstructure, caused possibly by heat leaking from the interior of the vessel. This process is generally manifested by the straightening of crystal boundaries, and by the formation of triple junctions intersecting at equilibrium angles of approximately 120°, as observed in thin sections.

No trend towards a preferred orientation of crystallographic c-axes, either in freshly accreted ice or its aged, thermally modified (recrystallized) variant was observed. Mean grain dimensions ranged from a minimum value of 0.56 mm to a maximum of 1.15 mm (Fig. 3-21 and 3-22).



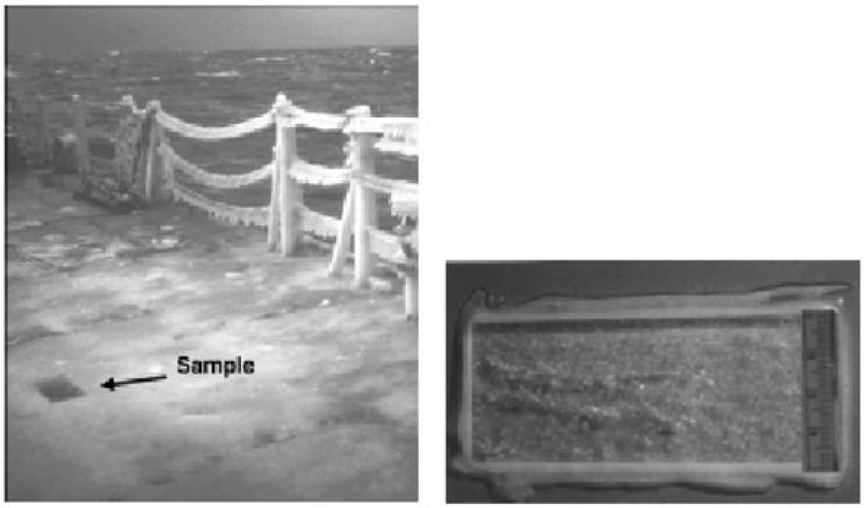
a. Sample location.

b. Thick sections photographed in natural light.



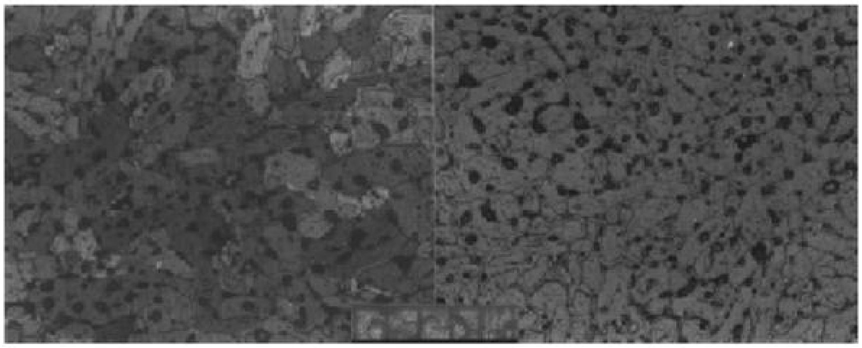
c. Thin sections photographed in natural light (right) and between crossed polarizers (left).

Figure 3-21. Sample taken on the forward face of the 5-in. gun mount under the barrel (scales in millimeters). Layering is strongly developed in this sample (Ryerson and Gow 2000b).



a. Sample location.

b. Thick section photographed in natural light.



c. Horizontal thin sections photographed in natural light (right) and between crossed polarizers (left).

Figure 3-22. Sample taken on the deck 2–3 m to the port of the 5-in. gun base (scales in millimeters). Deck samples were typically wet or saturated because of poor drainage of water across the deck (Ryerson and Gow 2000b).

The only exceptions were one deck sample accreted in very warm weather and an icicle type ice, where the dimensions of the crystals often exceeded several millimeters and where elongation of crystals in a preferred direction was observed (Fig. 3-23). Excluding this one deck sample and the icicles, they found that the mean dimension of crystals accreted on both horizontal and vertical surfaces of the USCGC MIDGETT were similar to those measured by Tabata et al. (1963), but generally much larger than those derived from three-dimensional measurements of crystals reported by Golubev (1972).

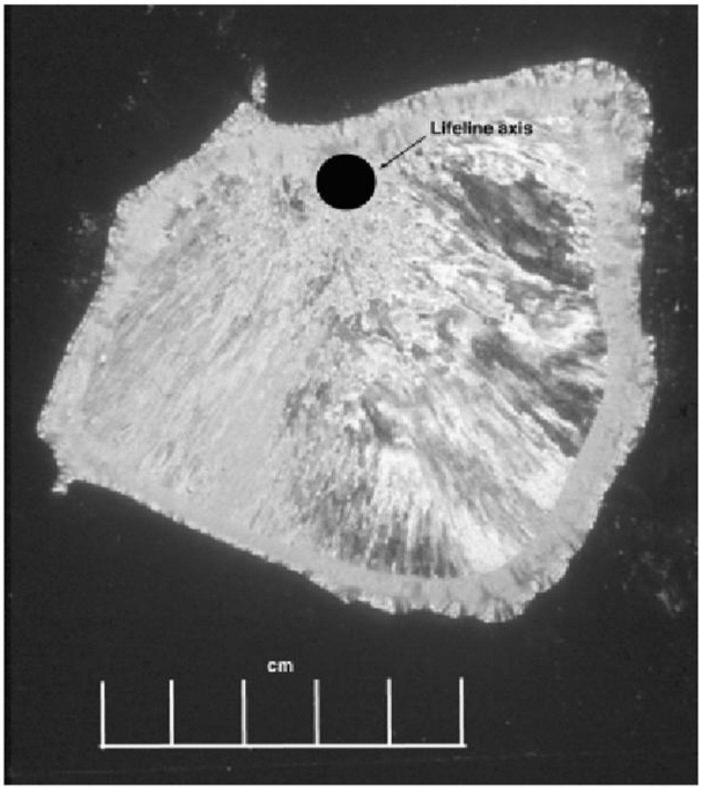


Figure 3-23. Vertical section of icicle removed from port lifeline imaged between cross-polarizers. Note the small, round ice crystals near the lifeline, and the elongated crystals radiating away from it. The outermost layer around that sample is an artifact of mounting the sample on a glass slide (Ryerson and Gow 2000b).

3.1.4 Safety hazards on ship components

Superstructure icing from spray causes safety hazards ranging from complete vessel loss to less serious consequences, such as hazards to individual personnel. Icing of smaller vessels such as fishing trawlers is well documented (Panov 1971; Borisenkov et al. 1974; Minsk 1975), and they are similar in size to smaller Coast Guard vessels such as the 140-ft icebreaking tugs and the 220-ft buoy tenders. However, Coast Guard Cutters' construction differs considerably from fishing trawlers, as do their missions. Coast Guard Cutters are more similar to Navy ships in construction and mission profile than to fishing trawlers. For that reason, documented here are superstructure icing effects on Navy and similar vessels.

The effects of superstructure icing on ship stability and freeboard are well understood threats. However, heated windows can also ice over, safety on deck is greatly reduced for personnel, and operation of winches, windlasses, boats, lifesaving gear, firefighting equipment, and valves is greatly impaired. Radomes can ice, causing blind spots, reducing navigation safety, and radio antennas can short because of the salinity of the ice. Icing can even affect systems below decks. For example, transfer of fuel between tanks can cause tanks to collapse when vents are blocked by superstructure icing (Crowley 1988).

Det Norske Veritas (DNV), an independent Norwegian foundation, manages risk, similar to Lloyds of London and the American Bureau of Shipping. Because superstructure icing and snow produce ice on decks and superstructures, they can affect the stability, safety, and general operation of vessels. Ice covering navigational equipment and deck mechanical equipment reduces safety (Koren 2007). Therefore, DNV has developed the class notation DEICE to ensure operational safety by providing anti-icing requirements for equipment and areas of a ship where continuous operation is required, such as navigational equipment and fire lines, and deicing requirements for equipment and areas where ice accumulation is acceptable (Magelssen 2005). However, the ship must be equipped to de-ice within 4–6 hours of accumulation. DNV's concerns are impairment of stability, impaired navigation caused by inoperable antenna and radar equipment, and icing of wheelhouse windows. Deck equipment, such as rescue equipment, lifeboats, and life rafts may be sufficiently iced that davits are inoperable. Vents and anchors may be ice covered and inoperable, and gangways and railings may be ice-covered, making it dangerous to operate safely on deck. DNV's standards are intended to encourage vessel operators to operate more safely in icing conditions.

Equipment and areas that DNV requires to be anti-iced include the following (Magelssen 2005):

1. Communication equipment and antennas.
2. Radars.
3. Wheelhouse windows.
4. Navigation lights.
5. Cooling water systems.
6. Firefighting equipment.
7. Anchor equipment.
8. Emergency towing apparatus.
9. Air pipe ventilation heads.
10. Lifeboats, davits, rafts, man overboard boats, and launching areas.

11. Escape exits.
12. Storage lockers or rooms for lifesaving or de-icing equipment.
13. Cargo system emergency shutoff or venting valves.

Equipment and areas the DNV requires to be de-iced within 4–6 hours of the end of an icing event include the following (Magelssen 2005):

1. Open deck and extra cargo areas.
2. Gangways, stairways and access to bow.
3. Superstructure.
4. Railings.
5. Outdoor piping.
6. Mooring winches.
7. Deck lighting.
8. Protected locations with heating.
9. Protected covers.

DNV has co-sponsored a program, MARICE (Marine Icing), to improve the understanding of marine icing and to create numerical models for creating real-time icing severity maps (Leirgulen 2012). The program, started in 2009, is in progress.

The American Bureau of Shipping also addresses hazards of superstructure icing on LNG carriers in the Arctic (Legland et al. 2006). As indicated in examples, ice loads on superstructures can be large, and ice weight may exceed the design loads of deck areas. Large deck areas on LNG carriers are inclined at pronounced angles. If layers of heavy ice detach from inclined areas, it can fall onto flat decks, and the impact can exceed design loads. They recommend strengthening flat decks, using fixtures to hold ice in place on inclined surfaces until it can be removed, and providing access to the inclined areas by crew allowing them to remove hazardous ice.

Fein and Freiberger (1965) discussed the effects of icing on ships ranging in size from fishing trawlers to Navy ships. They indicated that increased topside weight from icing not only increases roll period, as indicated by Winegrad (1987), but also increases roll angle, making it easier for wind and waves to capsize a ship. They indicate that ships of destroyer size and smaller will experience a “considerable” reduction in resistance to upsetting by wind and waves with 15 cm of ice. A destroyer-size ship than can withstand a 100-kt (51-m/s) beam wind without ice can only withstand an

80-kt (41-m/s) beam wind with 200 tons, or uniform 15-cm thickness, of accumulated ice. A cruiser that can withstand a 90-kt (46-m/s) beam wind without ice can withstand only 78 kt (40 m/s) with 600 tons of ice, again in a relatively uniform 15-cm layer. They report that the British Navy lost one warship to icing in WWII, size not indicated, but stated that many others may have been close to being lost. The British also state that warships are likely to suffer from icing more than commercial ships. They do not specify how warships suffer more, but it may be because warships generally have lower freeboard than commercial ships, deck operations are more frequent when underway, and antennas and weapons system must be kept operable.

The Russians have indicated that Navy ships can accumulate ice on their sides, decks, superstructure, weapons, masts, and rigging, with increased weight and draft and decreased freeboard. Ice also hinders employment of weapons, impairs operation of deck machinery, and causes loss of radio capability on Navy ships. The Russians also claim that icing can cause loss of stability of larger ships in storms and subsequently cause capsizing (Lyon 1985).

Crowley (1985) described incorporation of superstructure icing into the design of the Navy CG 47 *Ticonderoga*-Class Aegis cruisers at Bath Iron Works. Icing load degraded the intact stability of the ship, maneuverability is degraded, and icing loads significantly increased hull girder hogging loads and stresses. Gas turbine air intakes could be blocked, and weapons handling was hindered by poor footing on ice-covered decks, including torpedoes and Close-In Weapons Systems (CIWS). Firefighting was also hindered by icing, including ice damage to fire mains and reduced access to firefighting equipment.

Icing can also occur on the U.S. Navy's Recovery Assist Securing Traversing (RAST) system that guides helicopters between hangars and launch and recovery positions on the flight deck (Boston 1985). A similar system is installed on the Coast Guard *Legend*-Class National Security Cutter. The Navy determined that there were four potential ways to de-ice the RAST: mechanical, thermal, hydrodynamic, and chemical. Icing of vertical launch system doors, magazine hatches, gun mounts, and cargo gear limit combat capability and helicopter operations (Zahn and Voelker 1986). The Navy found, at least by 1985, that operating radars did not accumulate ice because of their movement and vibration, but idle radars would freeze in place and could not be started.

During Underway Replenishment (UNREP), the Navy found, during fleet exercises, that lines froze hard and could not be deployed. Snow and ice removal required constant manpower using shovels and brooms, steam, firehoses, baseball bats, hammers, ice picks, and ax handles (Lyon 1986). Helicopter operations during Vertical Replenishment (VERTREP) were hindered during northern exercises in 1983 by icing of tie-down padeyes, and chains and chocks required five crew members instead of the normal two for takeoff preparation. Both rough weather and superstructure icing made open deck operations potentially hazardous.

Rogalski (1985) described icing on the US Navy Fast Frigate USS *Capodanno* (FF 1093) over a 12-hour period at night along the Northeast US coast. Conditions were 35- to 45-kt (18- to 23-m/s) winds at Sea State 4, and air temperatures of –18°C. Visibility was 3–6 m in dense sea smoke that extended to 18 to 24 m above sea level. Icing occurred from sea smoke and spray. Ice was 20 cm thick on all horizontal surfaces, and 1.3 to 20 cm thick on vertical surfaces. The effects of ship operation were significant:

1. Ice covered machinery and space ventilation intakes.
2. Service diesel generator air intakes were completely blocked.
3. Ice covered interior and exterior bridge windows faster than window heaters could remove it.
4. The anchor windlass brake froze because of water intrusion.
5. Antennas did not operate properly.
6. Increased superstructure weight caused the ship roll period to change.
7. Weather and seas prevented crew from removing ice.

Figures 3-13 to 3-18 show ice on the USS *Capodanno*'s forward gun and forecastle, rails, chocks, and anchor chain, davits, ladder and side decks.

Other effects of icing on Navy ships, from experience on an unidentified ship, include overhead life rafts completely iced over, rails and antennas iced, and heavy icing on a Forward UNREP station (Fig. 3-24). Non-skid iced readily, and ice adhered strongly to the high roughness surface. Flight decks iced on the stern, and tie down wells filled with water, froze, and were difficult to de-ice. Bridge windows iced over, and spinners intended to remove water readily iced over. Even Navy oilers iced from snow and spray, hindering underway refueling operations (Fig. 3-25 and 3-26).

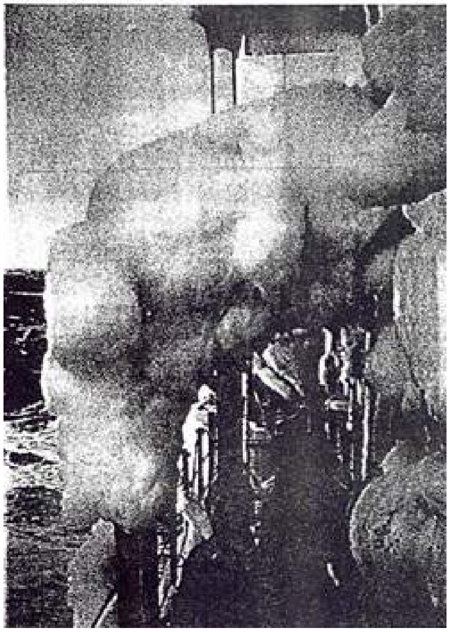


Figure 3-24. Heavily iced Forward UNREP area on unidentified Navy ship (after Winegrad 1987).

Figure 3-25. Navy UNREP tests in the Bering Sea, 1977, on the USS *Roanoke*, a replenishment oiler. Decks are snow and ice-covered (from Miller 2009).

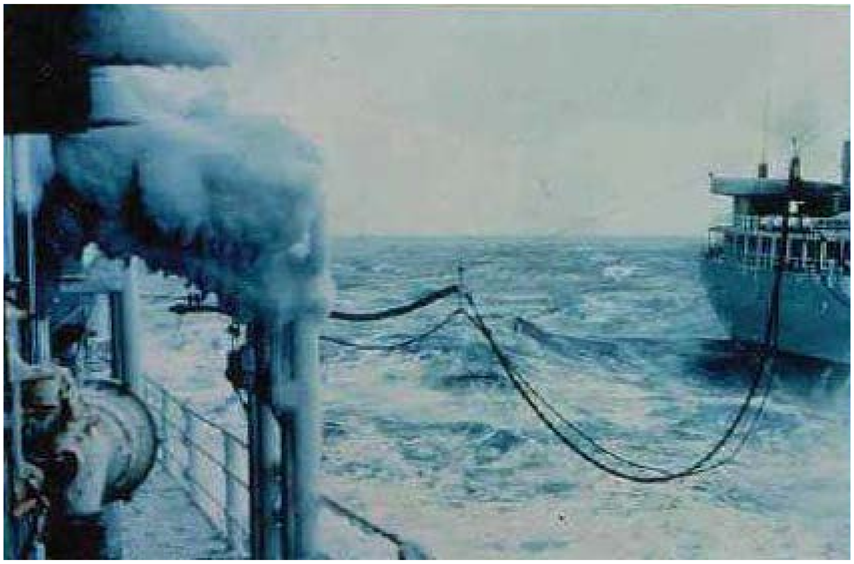


Figure 3-26. Underway refueling during superstructure icing conditions (National Energy Board 2011). Location, ships, and date unspecified.

Miller (2009) also discussed US Navy UNREP procedures, saying that underway replenishment systems are not designed for operating in icing conditions. As the Arctic opens, the Navy will need to operate more frequently in the Arctic Ocean, and warmer weather will allow more superstructure and aircraft icing, according to the Navy Oceanographer / Navigator Rear Admiral Gove (2009). UNREP and VERTREP will not be able to operate in these conditions. UNREP tests in the Bering Sea in 1977 demonstrated that fork trucks cannot operate on icy decks, VERTREP is not possible because of aircraft icing and hazardous deck handling problems, and personnel can have only limited exposure on deck in high wind chill conditions. Miller (2009) suggested housing UNREP machinery in a structure for both refueling and rearming. He indicated that rigging and hoses were difficult to protect, and that considerable research is needed to produce a simple and safe UNREP system that operates in icing conditions. In addition to operating out of enclosed spaces, Miller (2009) suggested keeping weather decks de-iced with breakwaters, water lances, under deck heaters, and canvas covers that are lashed down.

Bales (1983) evaluated the design of Navy ships through their sea keeping capability. She presented a table illustrating the effects of environmental factors, such as sea state, wind, visibility, fog, and five other factors on ship functions, such as speed, maneuverability, detection and communication systems, weapons systems, and ship tactics. Superstructure icing is listed among the 16 environmental factors, and is the only factor to negatively affect all five of the ship functions. She also noted that US destroyers of the

1960s era frequently took green water over the bow, and spray to the bridge. In the same seas, winds, and headings, and at the same speeds, Soviet destroyers took no water over the bow, and occasionally raised spray above the forecastle edge. The Soviet destroyers had better sea keeping capabilities than the US ships. Ships that create less spray will also perform better in superstructure icing conditions by accumulating ice less rapidly.

Winegrad (1987) of the Carderock Division of the Naval Surface Warfare Center, formerly the David Taylor Research Center, described the effects of ice accumulation on US Navy ships. Even moderate-size Navy ships similar to some Coast Guard Cutters, such as a fast frigate, can increase their roll period dramatically as ice accumulates on the forecastle deck (Fig. 3-27). However, the ice accumulations needed to be extreme to reach dangerous roll periods. In addition to changes in center of gravity affecting roll and weight decreasing freeboard, Winegrad (1987) also indicated that ice decreased a ship's wind resistance and increased stability problems.

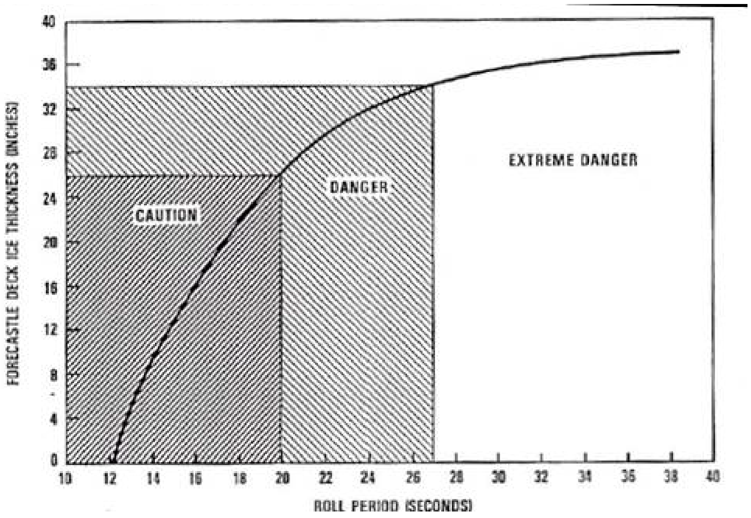


Figure 3-27. Increased roll period with ice accumulation on forecastle deck (after Winegrad 1987).

For a ship or offshore platform, Nedrevåg (2011) provided a thorough review of requirements and concepts for Arctic evacuation systems, lifeboats, and life rafts. Using two types of hazard identification tools, he identified six critical hazards that can affect the successful evacuation and rescue of personnel in Arctic conditions. One of the six most critical hazards identified was sea spray icing of the lifeboat at sea. However, also discussed were sea spray and atmospheric icing of launch equipment, such as davits and slides. For small vessels, such as lifeboats, wind speeds as low as 5 m/s may allow icing to begin (Guest 2005). Of greatest concern was stability of lifeboats in superstructure icing conditions. He argued that lifeboats must be constructed of materials that minimize adhesion of ice, that allow self-shedding of ice by angling sides, by providing hatches to allow manual de-icing, and by minimizing appendages that allow ice to lock to the vehicle. Launch apparatus were threatened by superstructure icing up to 25 m above sea level. Atmospheric icing was also a threat to launch equipment such as winches, pulleys, levers, hooks, and skids. It can also reduce the capability of propulsion equipment, hatches, windows, and other components.

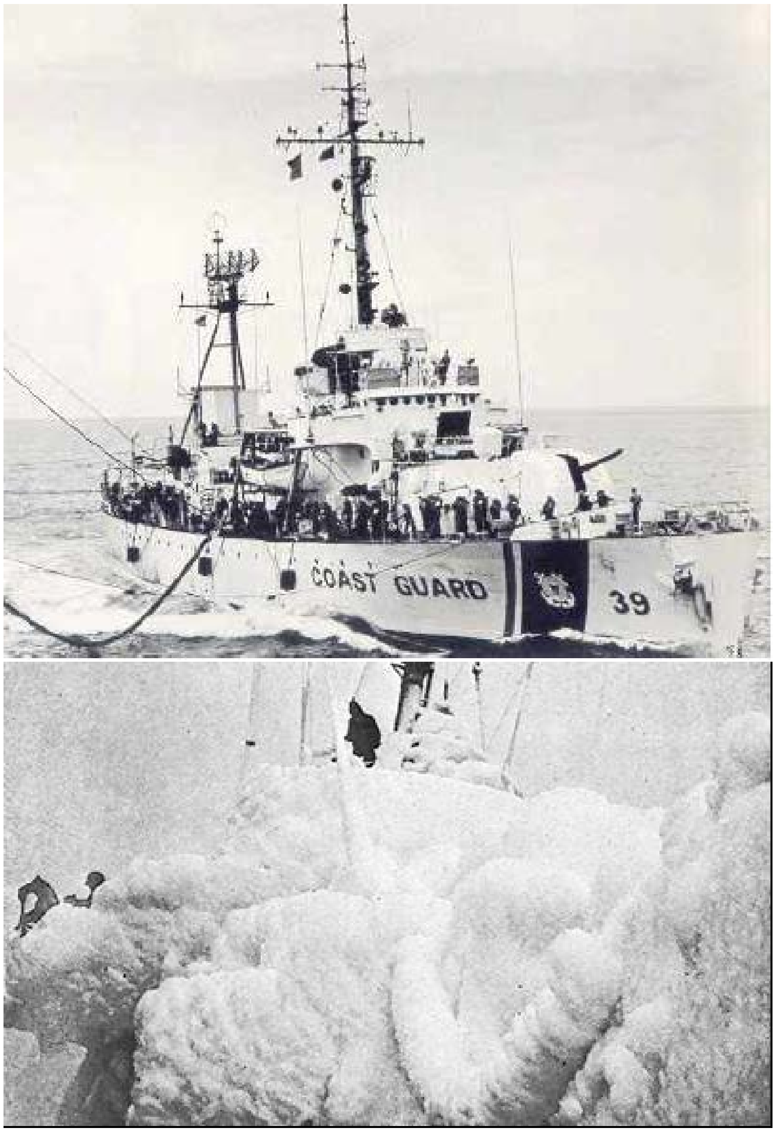


Figure 3-28. Top—CGC OWASCO (US Coast Guard 2013). Bottom—starboard side of CGC OWASCO after accumulating up to 25 cm of ice at Ocean Station "Bravo" (DeAngelis 1974).

DeAngelis (1974) described superstructure icing of fishing trawlers, and icing of the CGC OWASCO, a high endurance cutter similar in length and displacement to today's Medium Endurance Cutters. It accumulated up to 25 cm of superstructure ice at Ocean Station "Bravo" in gales and rough seas (Fig. 3-28). The crew used baseball bats, hammers, pick handles, axes, shovels, and hot water from the engine room to remove ice.

Other Coast Guard Cutters have experienced significant icing, and one may have been lost to icing during World War II. The CGC NANOK and CGC NATSEK were former fishing trawlers. In transit southward along the Labrador coast in December 1942, both ships encountered severe icing. The crew of the CGC NANOK removed ice, and even then, the cutter accumulated sufficient ice to develop a starboard list so severe that water entered the stack temporarily killing the engine. The ship survived; however, the NATSEK disappeared with all hands. Superstructure icing is one possible cause; the other might have been structural failure or grounding (Novak 2005).

Navy ships were compelled to operate in icing conditions routinely during World War II, as did the Merchant Marine convoys crossing the Atlantic Ocean to England and Russia. As an example, the HMS *Leamington* was one of 50 ex-US Navy "flush deck" destroyers given to the Royal Navy by President Roosevelt during the Lend-Lease program. There were not known for their stability, making superstructure icing very hazardous in the North Atlantic if ignored. In January 1943 the HMS *Leamington* had just left port when it began to rapidly ice. The heavy and rapid icing caused a list, and the ship escaped to St. John's Newfoundland to de-ice (Fig. 3-29 through 3-31).

At a 2001 symposium about potential operations in an ice-free Arctic, the Navy outlined missions and needs for operating in the area (National Ice Center 2001). With regard to ship icing, some concerns were aircraft handling on rolling, icy decks, pre-aircraft launch de-icing requirements, deploying sensors and weapons through superstructure icing, personnel safety on moving ice-covered decks, effects of icing on ship radar signature, UNREP, and suitability of air intakes for cold weather performance. They were also concerned with tolerance of weapons systems, boat operations, and personnel safety in wind chill, darkness, and low visibility during icing. Rime ice accumulation high on topside structures was also listed as a concern.

Figure 3-29. De-icing bridge and forecastle of HMS *Leamington* in 1943 using tools not dissimilar to those used today. Photo courtesy of Phil Marley (www.hazegray.org/navhist/canada/bota/rn/leamington/)

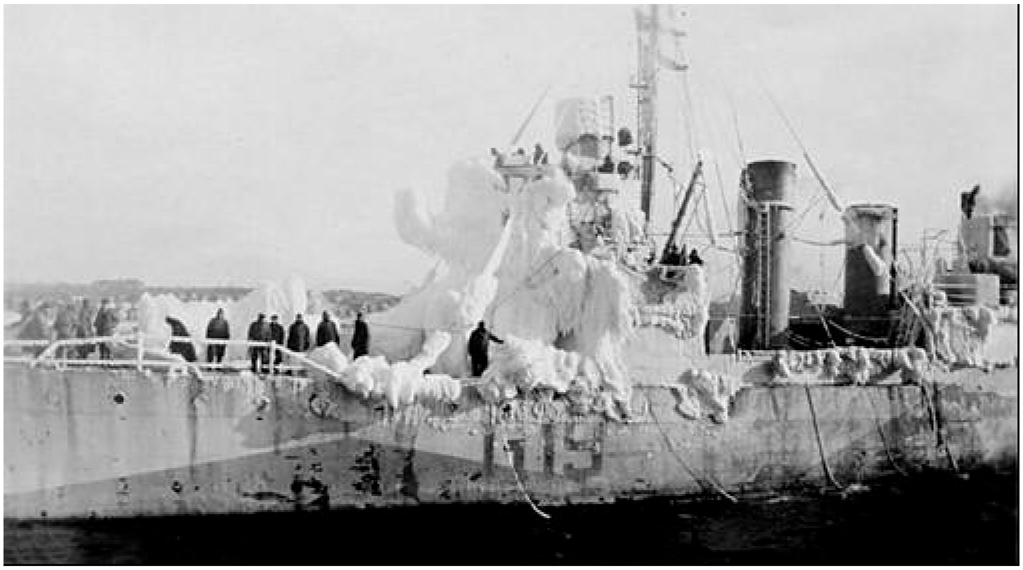


Figure 3-30. Superstructure ice on bridge and forecastle of HMS *Leamington* in 1943. Photo courtesy of Gord Condie and Bill Croshaw (www.hazegray.org/navhist/canada/bota/rn/leamington/).

Figure 3-31. De-icing forecastle of HMS *Leamington*. Photo courtesy of Phil Marley (www.hazegray.org/navhist/canada/bota/rn/leamington/).

The 2001 Navy symposium (National Ice Center 2001) also outlined a need for improved icing prediction models and the increased need to consider ship reserve buoyancy in icing. The latter is addressed by Goldberg and Tucker (1975) and by Koelbel (1977) in earlier publications, where they indicated that two scenarios were considered: 7.6 and 15.2 cm of ice on horizontal and vertical surfaces on weather decks and above at a density of about 0.6. For this weight marine engineers determined ship survivability while rolling in beam winds.

Rogalski (1985) said that the labor required to remove ice from a ship is a strong reason for the US Navy the conduct research and development, and to conduct experiments to improve ice removal techniques. Referring to traditional manual methods of ice removal, such as baseball bats, mallets and shovels, he said that removal rates of 6 to 7 man-hours per ton of ice have been confirmed by ship operators. However, he also said that the removal rate for certain de-icing lances used by foreign operators (but not the US Navy) was 0.6 to 1.8 man-hours per ton.

3.2 Atmospheric icing

Atmospheric icing is the creation of ice from water vapor, supercooled droplets, or ice crystals originating in the atmosphere. Atmospheric icing always produces fresh water ice because the source of the water is the atmosphere. Sea spray icing, whether saline in the oceans or fresh in lakes and rivers, is created from drops that originated from the water surface and were lofted as wind blown spume, or as spray lifted during ship–wave collisions.

Atmospheric icing produces frost, snow, rime, and glaze, and has relatively little effect on ships (Zakrzewski et al. 1988a, b). Overall, it occurs infrequently, depending upon geographic location and time. Nevertheless, it has potential importance because it does degrade the operation of equipment, and it does create safety hazards for personnel. In addition, being of atmospheric origin, it forms on different surfaces or locations on ships than does sea spray icing, and it can be more difficult to remove than saline ice.

Though most reports indicate that about 90% of ship icing events reported worldwide are caused by freezing spray, Brown and Agnew (1985) indicate that icing from atmospheric sources was most common in the Arctic—primarily from rime icing. According to Bales (1985), though most icing is from sea spray, fog and precipitation produce uniform icing over the entire ship, can cover the entire mast, and occurs primarily in the vicinity of land masses and the marginal ice zone.

3.2.1 Frost

Little information is published about frost formation and its effects at sea. However, the author of this report observed frost formation on surfaces of the CGC MIDGETT in the Bering Sea in February and March 1990.

3.2.1.1 Formation process

Frost forms when water vapor deposits (sublimates is also an acceptable term) on surfaces, transitioning directly from water vapor to ice without going through the liquid water phase. Also known as hoarfrost, or “white frost,” it generally forms a thin, low density layer of ice on objects. However, frost can form deposits sufficiently thick that automobiles can slide out of control on frost-covered bridge pavements, and personnel can slide on smooth surfaces that are frost covered.

Frost generally forms when the surface that is forming frost has a temperature that is saturated with respect to ice. At temperatures below 0°C, water can be saturated with respect to water or to ice. Liquid water droplets in clouds that condense at the dew point temperature below freezing, and are saturated with respect to water, are supercooled drops that are important for rime ice formation—discussed later. Ice crystals forming on surfaces that are below freezing, and are cooled to the frost point, produce frost crystals (Ryerson et al. 1994).

Frost forms under generally two conditions. The first, nocturnal radiative hoarfrost, occurs at night in nearly calm, clear sky conditions. The other, attributable to cold-soaking, occurs when a ship transits from a cold location to a warmer, humid location, and can form day or night.

Nocturnal hoarfrost forms if the sky is dry and clear, the winds are near calm, the surface has a high radiative emissivity, and surfaces are oriented with a view factor to the sky. This requires a sky radiative temperature that is lower than the frost point, which is common during the winter. Winds should be nearly calm to prevent the heat lost to radiation from being rapidly replaced by convection. The surface that is frosting should have a high emissivity in the thermal radiation wavelength, from about 8–16 µm wavelengths, to lose heat readily to the sky. Objects need to be oriented towards the sky for maximum cooling.

Ryerson et al. (1994) provide examples of the conditions under which nocturnal radiative hoarfrost forms; however, these are not from over the sea but from inland. They found that frost formation started on cold winter nights when winds at a height of 1 m were less than 0.9 m/s, and skies were clear and had a radiative temperature lower than the air temperature at least 67% of the time. Objects facing the sky that formed frost typically had surface temperatures of about 4.8°C lower than the air. Frost required simultaneous satisfaction of all of the conditions, or it did not form. The condition most difficult to satisfy on a moving ship is the near-calm wind speed. However, low winds speeds may be satisfied on a ship that is stationary.

Ships become cold-soaked at a coastal port, or near the ice edge, and then transit to warmer waters. Portions of the ship with high thermal mass, and that are unheated, will cold-soak over a period of time in a very cold location. If the ship then sails through a warmer region, high humidity above the sea surface may cause the frost point of the air to be higher than cold-soaked portions of the ship. Frost will them form on the cold-soaked surfaces. In cold-soaking conditions, frost will form in higher wind speeds than necessary for nocturnal radiation frost. However, faster moving air warms cold-soaked surfaces more rapidly, decreasing the longevity of frost. Moving air will also carry larger volumes of moist air over cold-soaked surfaces—possibly enhancing frost formation. Though cold-soak frost can occur during daylight hours, sunlight may stop it from forming by heating surfaces.

The cold-soak effect is similar to chilling a glass in a freezer, and then bringing it into a warm, humid room—frost will from on its surface until it warms to above 0°C. A similar condition occurs on the inside of window glass where the temperature on the inside of the glass is lower than the frost point in the warm room because of thermal conduction through the glass to the colder atmosphere on the opposite side.

3.2.1.2 Location, magnitude, frequency

The location, magnitude, and frequency of frost formation on a ship depend upon the type of frost. Nocturnal radiation frost will form on objects oriented to the sky, such as well-insulated decks, railings, cables, antennas, masts, and other materials with poor thermal conductivity or low thermal mass. Dark-colored objects may form frost more rapidly than white objects because black paint typically has a higher thermal emissivity. Because of the need for low winds, frost is not likely to form when a ship is moving. In addition, frost is less likely to form if the sea is warm, though how warm is not known, because the boundary layer within which the ship resides may be too warm—though dew could form.

If the ship is cold-soaked because it has been at a cold port for days, or has been near the sea ice edge during very cold weather, frost may form when the ship moves into warmer water. Areas with high thermal mass that are unheated will frost first, such as the bow area of an ice breaker, heavy steel sections such as mast supports, mooring and anchor hardware, and cranes and davits.

Frost often varies in its coverage spatially. It often forms most strongly on convex surfaces with better exposure to the atmosphere. It will often form first on surfaces that are well insulated—such as wooden decks and stairs. It also will form rapidly where vapor pressure is highest, if temperatures are sufficiently low, such as downstream of vents, and around cold vent openings.

The frequency and location of frost are unknown. Frost is not recorded by weather services, nor is it known to be recorded at sea.

3.2.1.3 Physical properties

Frost typically has a density less than 0.1 g/cm^3 (Ryerson et al. 1994). Frost will add little weight to a ship and grows as clusters of individual crystals following thermal and vapor pressure gradients. Thicknesses are typically less than a few millimeters. Though frost crystals can be easily crushed and “polished,” frost often cannot be removed from surfaces without the use of heat, chemicals, or mechanical scraping. The cohesion of frost is weak, but its adhesion is strong. Frost is often prevented using covers, or by spraying a freezing point depressant, such as glycol, on a surface before the frost forms.

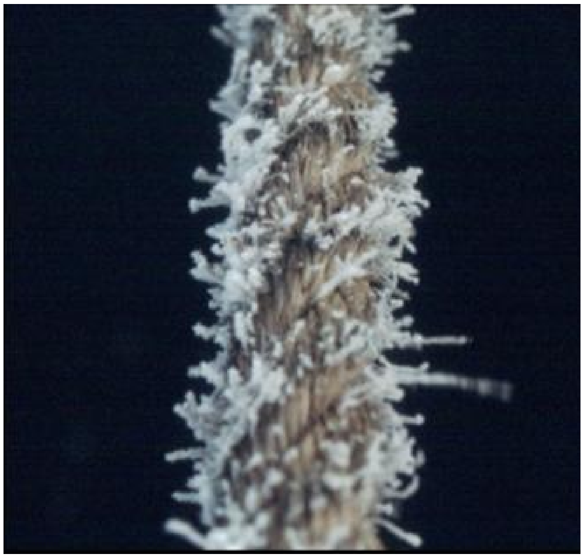


Figure 3-32 Frost formed on rope strands on the CGC MIDGETT, winter 1990 (Ryerson 1990).

This author observed frost formation on rope on the CGC MIDGETT in the Bering Sea in 1990, presumably from nocturnal radiative cooling because the ship had been stationary during the night (Fig. 3-32).

3.2.2 Rime

Rime is a white, friable ice, often resembling feathers, that forms on the upwind side of objects from supercooled cloud droplets striking surfaces in the wind stream. Other than snow, rime is the second most common form of atmospheric ice that affects ships. Rime forms feather-like shapes that grow into the wind (Fig. 3-33 and 3-34).

Figure 3-33. Rime ice feathers growing into wind. Wind is from the left, and wood is about 1.6 cm in diameter (Ryerson, n.d.).

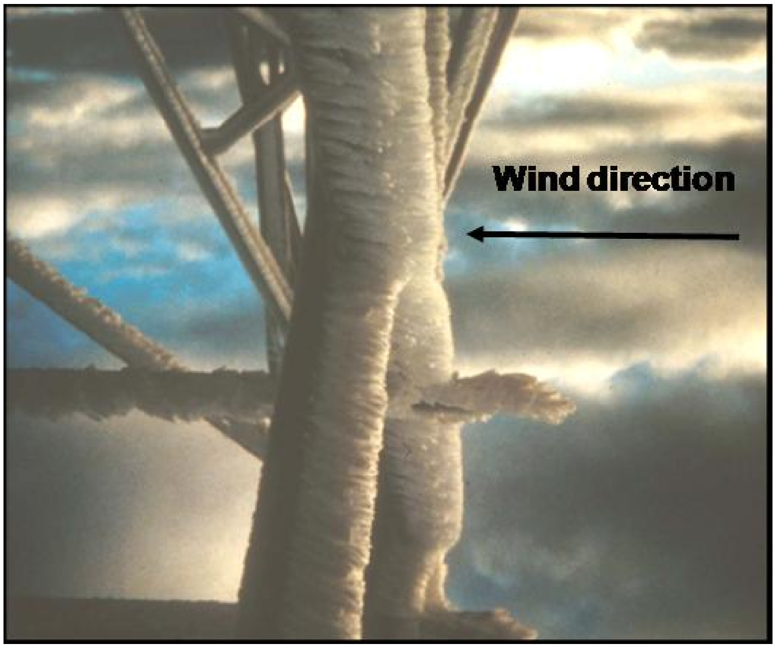


Figure 3-34. Rime ice accumulation on lattice steel structure similar to some components found on ships. Ice on structural shapes is approximately 15-cm thick (Ryerson, n.d.).

3.2.2.1 Formation process

Clouds and fog consist of small drops ranging from approximately 5- to about 50-µm diameter. They are sufficiently small that their fall speed is less than about 0.25 m/s (Houze 1993), making them effectively stationary with regard to falling. Turbulent motion within clouds is sufficient to keep them aloft.

Most cloud and fog drops do not freeze at 0°C; they supercool, and remain liquid. Supercooled drops are metastable, they do not freeze unless they strike objects or encounter a freezing nuclei such as an ice crystal. Supercooling is most common from 0 to about –10°C. At about –10°C, freezing nuclei within droplets become activated and the proportion of liquid drops in a cloud or fog decreases until about –40°C, when homogeneous nucleation takes place.

Over land surfaces, most rime forms where supercooled clouds are most common and winds are high, such as on mountains. Over the sea, rime typically forms within supercooled fog. The formation of rime requires the simultaneous occurrence of four factors: supercooled fog, air temperatures below freezing but higher than –40°C, wind, and objects upon which ice can accumulate.

Though there are at least five types of fogs—upslope fog, frontal fog, radiation fog, advection fog, and convection fog—only the latter two types are common at sea. Advection fog forms when warm, moist air moves over a cold surface, but rarely supercools. Over fresh water, advection fog cannot supercool because water surface temperatures freeze when they cool below 0°C. Over sea water, which freezes at about –2°C, only 2°C of supercooling can occur in the fog under ideal conditions because it cannot cool below the water surface temperature. Therefore, rime ice formation is relatively rare in advection fogs, and when it does occur, extreme icing rates are unlikely.

Convection fog forms when water temperatures are higher than the air passing over them. It is also called evaporation fog, or sea smoke, as air heated by the relatively warm water surface rises from the water surface as “parcels” of air. The warm, humid rising air parcels cool as they rise and reach the dew point, forming fog. If the air temperature is well below 0°C, the fog supercools and will freeze when striking shipboard objects. Deep, vigorous convection fog is the cause of lake effect storms in the Great Lakes and the Sea of Japan, which cause snowfall and icing on downwind shores. Stratus clouds often form a few thousand feet above the water from the rising moisture, and small water spouts have been observed over water surfaces during convection fog. They form because of the extreme convection that can occur. Figure 3-35 shows sea smoke rising around an iced fishing trawler in the Bering Sea in 1990. The trawler was immersed in cold air flowing off of the nearby ice edge. However, the ice on the vessel was caused principally by sea spray and not from convection fog-induced rime ice.

Figure 3-35. Convection fog plumes rising from sea surface in Bering Sea, March 1990 (Ryerson 1990).

Makkonen (1984) reviews studies explaining the formation of convective fog at sea. Convection fog can form to thicknesses of up to 100 m above the sea surface, depending upon the sea surface temperature, the air temperature, and the air relative humidity. If sea water temperatures are between −2 and 15°C, air temperature at a relative humidity of 95% must be 6°C lower than the sea temperature for convection fog to form, and 16°C lower than the sea surface when relative humidity is 0%. For fresh water lakes and rivers, required temperature differences are about 2°C less.

There is also a linear trend between the depth of convection fog and the difference between the sea surface and the air temperature (Makkonen 1984). Generally, as the air becomes colder than the sea surface temperature, from about −2 to –15°C, fog depth increases respectively from about 1 m thick to about 25 m or more thick.

Makkonen (1984) also presents droplet sizes and liquid water contents found in convection fogs. Droplet diameters range from 6 to 120 µm, and liquid water contents vary from 0.01 to 0.30 g/m^3. The drop diameters and liquid water contents are not unlike those found in stratus cloud icing conditions. According to Makkonen (1984), most rime occurs in temperatures between 0 and –15°C.

In general, wind speed has not been found to have any effect on the formation of convection fog (Makkonen 1984). However, relative wind speed does influence the amount of rime ice that will form on a ship. Several factors affect the amount of rime ice, and its density. In general, higher temperatures, higher wind speeds, larger fog drops, and smaller diameter objects on ships cause larger ice accumulations. As air flows around objects, the air stream diverges. If the object obstructing air flow, such as a railing or a sensor, is large and smooth, and wind speed is low and drops are small, drops will be more likely to flow around the object because the inertia of small drops is small, and large, smooth objects divert air flow well ahead of their surfaces allowing drops to move with the air stream (Fig. 3-36). In this case, few drops collect on the surface to produce ice, and collection efficiency is said to be low. However, if wind speeds are high, drops are larger, and objects on the ship have small radii surfaces, there will be insufficient time for drops to divert around the object, and a collision will occur. In this case collection efficiency is high (Fig.3-37).

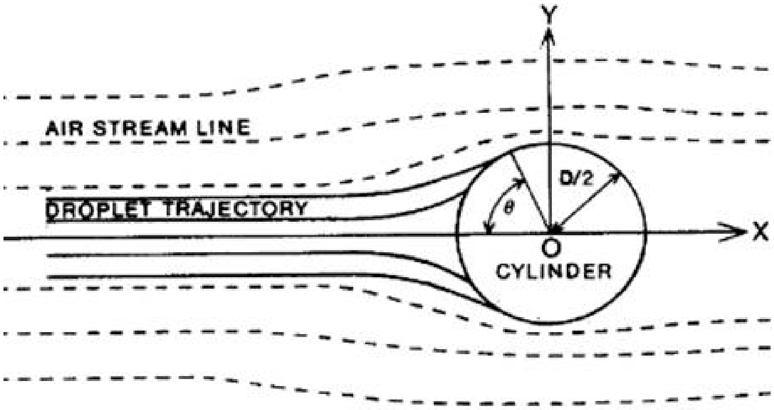


Figure 3-36. Trajectories of droplets around objects (after Makkonen 1984).

Figure 3-37. Rime formation on tower and whip antennas on Mt. Washington, NH. Note thicker rime ice accumulation on small diameter whip antennas than on large diameter tower structure (CRREL, n.d.).

3.2.2.2 Location, magnitude, frequency

Brown and Agnew (1985) report rime accumulations of up to 5.0 cm on trawlers and rigs in the western Canadian Arctic. Reports of riming rates on ships have claimed 10 cm of ice on decks in 12 hours, and 30 cm on rails during the same period (Fett et al. 1993) in dense sea smoke. DeAngelis (1974) indicates that sea smoke can cause relatively rapid ice accumulations, though it does not endanger the seaworthiness of ships.

Geographic patterns of rime icing at sea are unclear because of a lack of measurements and archived analyses.

Makkonen (1984), in a detailed analysis of existing literature, found that most supercooled fogs that may produce rime are in coastal waters, but their frequency is small. The frequency of winter fogs is 0 to 10% in the Gulf of Alaska, 10 to 20% in the Bering Sea, and 10 to 15% in the Beaufort and Chukchi seas. These frequencies may increase as sea ice retreats and open water is exposed for a greater portion of the winter.

3.2.2.3 Physical properties

Rime ice typically is relatively weak and brittle. At its lowest density, it readily breaks from substrates. Rime ice adhesion strength generally increases as its density increases (Makkonen 1984). However, it can have densities and strengths approaching those of glaze ice, which has a density of about 0.91 g/cm^3. The density of rime ice can range from about 0.4 to 0.9 g/cm^3 (Macklin 1962; Williams and Zhang 1996; Vargas et al. 2005).

Large drops in flows with high liquid water contents, higher temperatures, and higher winds produce rime ice that is higher in density—and with greater adhesion strength. These conditions cause larger amounts of water to impinge on objects, requiring more latent heat to be removed from the water for nucleation. The greater amount of liquid water impinging on the surface slows freezing and causes rime having greater density—with densities between about 0.7 and 0.9 g/cm^3. Lower wind speeds, smaller drops, and lower temperatures allow more rapid freezing, which allows more air to be entrained between frozen drops, and lower ice density. In general, according to Makkonen (1984), ice density decreases with decreasing drop impact speed, decreasing droplet size, decreasing air temperature, and decreasing water content.

Relatively few studies have assessed the mechanical properties of rime ice. A study (Cole 2006) on rime ice created in a wind tunnel used a scanning electron microscope and electron backscatter diffraction to measure the diameter and crystal orientation of rime ice. The results showed that crystal sizes are very small, ranging from 50 to 200 µm in diameter. Pore sizes were in two ranges, about 1- to 5-µm diameter, and from 50- to 200-µm diameter. The c-axis was generally 45–90° from the normal to the growth surface.

Cole (2006) also analyzed the wind tunnel ice for bend strength and found that the small grain sizes caused greater increases in ice bend strength than predicted by models.

In general, rime rice is relatively weak and can be broken from surfaces easily if the density is low. If density is near 0.9 g/cm^3, and the ice has feathers that appear nearly clear, it can be extremely strong cohesively and adhesively.

3.2.2.4 Safety hazards on ship components

On a cutter or boat, the relative wind is typically over the bow or quartering; therefore, rime will form on locations with the highest relative wind if there is supercooled fog present. Small-diameter objects, such as cables, railings, and masts, will ice first and to greatest thickness. Wind blowing across weather decks may occasionally cause rime accumulation on non-skid, and wind blowing across ladders can coat them with rime and cause falls. Davits, antennas, masts, and instrumentation on the flying bridge and higher will accumulate rime ice. Cranes and associated cables and booms will readily collect rime. Ladders will accumulate rime, and air intakes, if unheated, may accumulate rime faster than other areas if intake velocities are high. Also, falling rime is a significant hazard to equipment and personnel when thawing begins and large pieces fall from structures (Fig. 3-38).

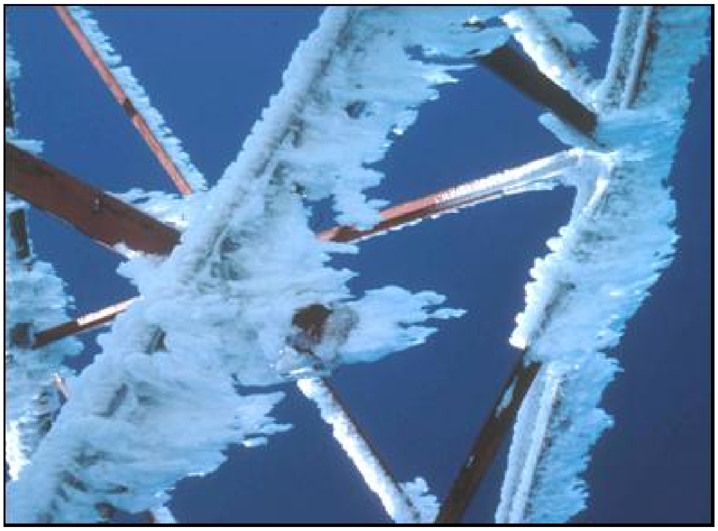


Figure 3-38. Rime ice undergoing sublimation, weakening, and falling from structure (Ryerson, n.d.).

The load of rime ice on objects, despite its smaller density than clear ice, for example, will cause cables to rotate and twist as ice accumulates from the side. Because cables are torsionally weak, as ice accumulates on the side of a suspended cable, the increased mass on one side will cause the iced side to rotate down and expose a new face to icing. This process can continue until the cable rotates several turns. Even though rime ice is brittle, it does not readily fall from cables as it grows, and as the cable twists segments of ice will separate and rotate independently from one another, similar to the rotation of beads on a string if it is twisted.

In addition, rime can form an airfoil shape that causes twisting of cables and antennas and causes cyclic lift gain and loss. Drag caused by the increased diameter caused by the ice thickness can cause whip antennas, for example, and rigging to fail, especially if harmonics occur because of the aerodynamic and weight changes.

It is likely that the greatest danger caused by rime ice on a ship will be when ice falls from overhead. Warming, sunlight, and changes of course that cause wind direction and speed changes, can cause rime ice to fail and fall. Large ice projectiles can injure crew and damage equipment (see Fig. 3-38).

Figure 3-39. Glaze ice on branches. Note the icicles and clarity of the ice (CRREL, n.d.).

Rime alone cannot cause the loss of a vessel. However, it is a safety problem, and can be an inconvenience.

3.2.3 Glaze

Glaze ice is a hard, clear ice that forms from liquid precipitation, supercooled drizzle drops, or rain drops (Fig. 3-39). Though not believed to be frequent at sea because of the warmth of the sea surface, it is a frequent hazard to Coast Guard vessels that operate near coastlines where cold air can move offshore considerable distances. Or it can coat a vessel in port.

3.2.3.1 Formation process

Precipitation drops are larger than cloud drops because they have a fall velocity large enough for them to exit the bottom of a cloud, and have sufficient mass and speed to survive the cloud-to-ground transit and not fully evaporate. Drizzle drops range in diameter from about 50 to 500 µm, and raindrops from 500 to over 5000 µm. Larger raindrops generally do not survive for long because drag forces cause them to break up to smaller sizes.

Freezing drizzle and rain drops form from condensation of cloud drops that subsequently collide, or coalesce, to create larger drops. They can also form from falling ice crystals that collide with supercooled cloud drops and other ice crystals and grow, becoming snow. The snow then melts, forming drizzle or raindrops that can continue to grow through coalescence as they fall. Drizzle is also thought to form in clouds in turbulent conditions.

Freezing drizzle and rain occur when droplets that were created in warm air fall through a layer of cold air and supercool. This is often where warm air is overriding cold air, such as in a warm front or where warm air is overriding cold air trapped in mountain valleys. These are the classic meteorological situations where freezing drizzle or freezing rain form. Drops falling through the cold air supercool, but not sufficiently to freeze before striking objects. The non-classical situation is where supercooled drops within clouds collide and coalesce without freezing, forming supercooled drizzle drops (Cober at al. 2001; Korolev et al. 2002). It is believed that the non-classical process causes freezing drizzle, but perhaps not freezing rain.

Where rime ice is a process in which ice forms via dry growth, glaze is a wet growth process. Dry growth takes place when all liquid water freezes quickly, trapping air within the ice mass and producing no runoff. This produces a lower density, white ice mass because light is scattered by air-filled voids within the ice. Wet ice grows when the water nucleates slowly because the air is warm, drops are large, and liquid water content is high. Air is excluded as the water freezes, and a clear accumulation forms with excess water running off, and perhaps refreezing as icicles (see Fig. 3-39). Glaze ice most probably occurs in air temperatures ranging from 0 to −3°C at sea, in part because air near the surface cannot be much colder than the sea surface temperature (Makkonen 1984). Immediately downwind of land or ice surfaces, however, temperatures can be lower.

3.2.3.2 Location, magnitude, frequency

Glaze ice forms on all horizontal surfaces of a ship that can be reached by precipitation. It also accumulates on the windward side of vertical surfaces, and can completely coat small-diameter objects such as wires and cables. Zakrzewski et al. (1988a, b) indicated that there was no conclusive evidence (in 1988) that freezing rain is a significant problem for ships or rigs, though they also report that, in Russian waters, spray and freezing rain together cause icing during 41% of icing events. Baller (1983) reported accretion of 1 cm or less of glaze ice on rigs. Brown and Mitten (1988) reported glaze accumulations of less than 3 cm on trawlers and rigs off of the Canadian east coast. Makkonen (1984) stated that atmospheric icing is the primary cause of icing on tall stationary sea structures, such as rigs, with supercooled precipitation being a major contributor.

The climatology of freezing precipitation has only begun to be understood in North America in any reliable detail in the last 15 years. The ASCE (ASCE 2010) has created maps of glaze ice accumulation thicknesses with a 50-year mean return interval and associated wind gust speeds. Their maps show ice thicknesses of about 13 mm in the Lake Superior region, increasing to approximately 25 mm in the lower and eastern Great Lakes. Ice thicknesses range from 19 to over 25 mm along the East Coast north of Chesapeake Bay. Thicknesses up to 6 mm occur on a 50-year mean return period as far south as Savannah, GA. Thicknesses start at about 6 mm immediately west of the Mississippi Delta, increase to 12 mm along the western Louisiana coast to approximately Corpus Christi, TX, and decrease again to about 6-mm of ice at Brownsville, TX.

Along the West Coast, the ASCE maps show no icing south of the central Oregon coast, and about 6 mm north to the Canadian border. The Colombia Rover gorge is an exception, with over 32 mm of ice possible. Alaska has insufficient data to form conclusive patterns. However, 50-year mean return period ice thicknesses along the Beaufort and Chukchi sea coasts are about 6 mm, and elsewhere along the southern Alaska coasts range from about 6 t0 12 mm.

With regard to patterns, Bernstein (2000) indicates that a broad maximum of freezing precipitation, which includes freezing drizzle, freezing rain, and ice pellets, extends from the Texas Panhandle to the Great Lakes, with smaller maxima along the eastern slopes of the Appalachian Mountains from New England south to the Carolinas, and again in the Colombia River gorge. Within these areas freezing precipitation can occur approximately 30 to 40 hours/year (Fig. 3-40). This pattern matches the winter storm tracks well.

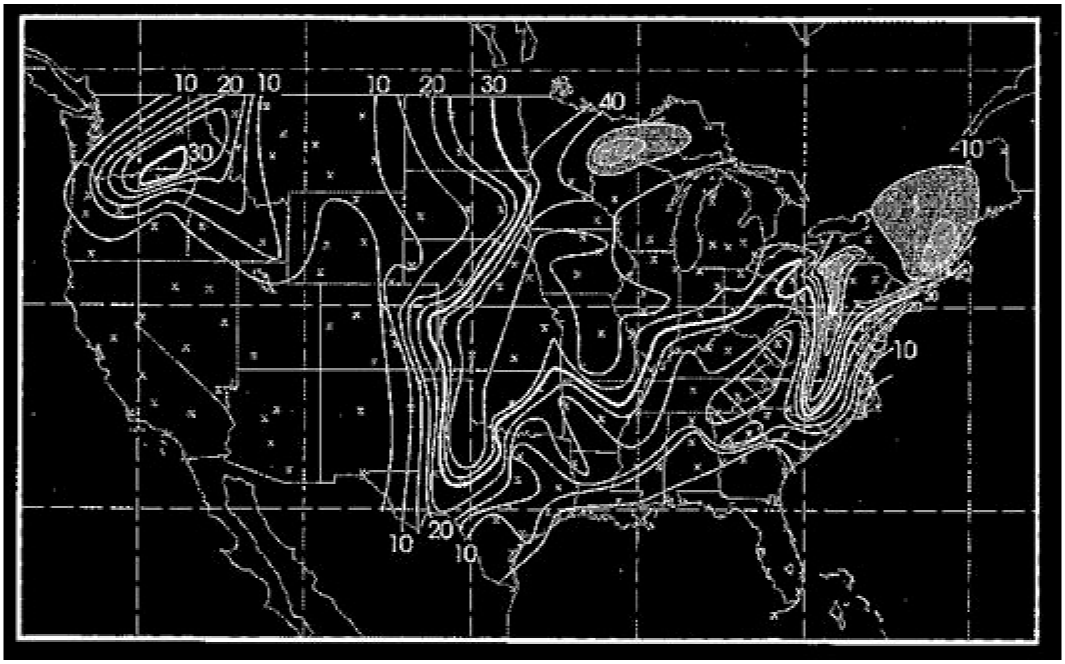


Figure 3-40. Annual hours of freezing precipitation per year from 1961 through 1990 (from http://www.rap.ucar.edu/asr97/supercooled.html).

Bernstein et al. (2007) studied the incidence of precipitation icing from the surface to about 9150 m. They show frequencies of freezing rain and freezing drizzle to be similar in the Great Lakes area and along the Bering Sea coast, with frequencies along the Arctic Ocean coast being about 30% of those in the Bering Sea. In general, maxima moved north into the Arctic in late spring, and south again in early autumn.

3.2.3.3 Safety hazards on ship components

DeAngelis (1974) indicated that freezing rain can coat a ship with freshwater glaze ice that makes operations on decks dangerous, though it does not endanger ship stability. Glaze deposited from freezing rain affects decks, wheelhouse roofs, antennas, valve handles, and hatch covers. However, it will also form on cables and windlasses, preventing them from functioning efficiently. Glaze creates slipping hazards for personnel on decks and ladders and can cause sprained ankles and wrists. Glaze ice can disable antennas, firefighting equipment, and cover windows and helicopter pads.

Glaze, deposited from freezing rain, principally affects horizontal surfaces. However, wind and runoff can cause problems with some vertical surfaces, and lattice structures are especially susceptible to freezing rain accretion. In general, it is very difficult ice to remove because of its high density and hardness.

3.2.4 Snow

Snow is precipitation that is created from ice crystals that form on ice nuclei in the atmosphere, much as frost forms on surfaces. Ice crystals grow large enough to fall, as do raindrops, through collision with other ice crystals which, after accumulating sufficient mass, fall to the Earth's surface before sublimating away. Snow typically coats all horizontal surfaces of ships, especially when in port.

Wet snow has greater adhesive and cohesive characteristics than dry snow and can also accumulate on vertical surfaces and cables. Because wet snow contains water, its dielectric properties are different from dry snow, and may affect radar and radio communication systems.

3.2.4.1 Formation process

Initially, snow forms similarly to frost on ice nuclei with diameters ranging from about 0.01 to 1.0 µm (Schemenauer et al. 1981; Libbrecht 2007) and exist in concentrations of about 100 to 1000 per cm^3 of air. Dust is the source of most ice nuclei, such as clay-silicate particles, industrial air pollutants, and forest fire particles, which have crystal structures similar to ice. Ice nuclei are most active, thus most effective, between –10 and –30°C. Ice crystals that create snow form from direct deposition of water vapor onto ice nuclei.

At about –5°C, ice nuclei begin forming ice crystals a few microns in diameter, which grow initially to about 75 µm. Growth is through diffusion of water vapor to the ice crystal. Within a cloud composed of supercooled water droplets and nascent ice crystals, the ice crystals grow at the expense of the water droplets through the Bergeron process. Because ice is a solid, it exists at a lower energy state than adjacent supercooled liquid water droplets. As the water droplets at the same temperature as the ice crystals have a higher energy state, they also have a higher water vapor pressure. All gasses move from higher pressure to lower pressure. Therefore, water droplets evaporate, humidify the air, which increases vapor pressure, which then causes deposition of water vapor as ice on the ice crystals. Approximately one million cloud droplets must evaporate to make one large snowflake (Libbrecht 2007).

As the crystal grows, a snowflake forms as turbulence carries it through air of different temperatures and humidities. There are many crystal types that form in specific temperature and humidity regimes. The most common are plates, stellars, columns, needles, and capped columns, originally classified by Nakaya in Japan (Schaefer and Day 1981) (Fig. 3-41). Plates form between 0 and –3°C, columns and needles form between –3 and –10°C, plates and dendrites between –10 and –22°C, and plates and columns form when it is colder than –22°C (Schemenauer et al. 1981; Libbrecht 2007). The snowflake, as it falls from a cloud, is often a composite of several of these types, depending upon the multiple environments it has passed through. In addition, it is modified by colliding, or aggregating, with other crystals, and colliding with supercooled water droplets, causing riming of the snowflakes.

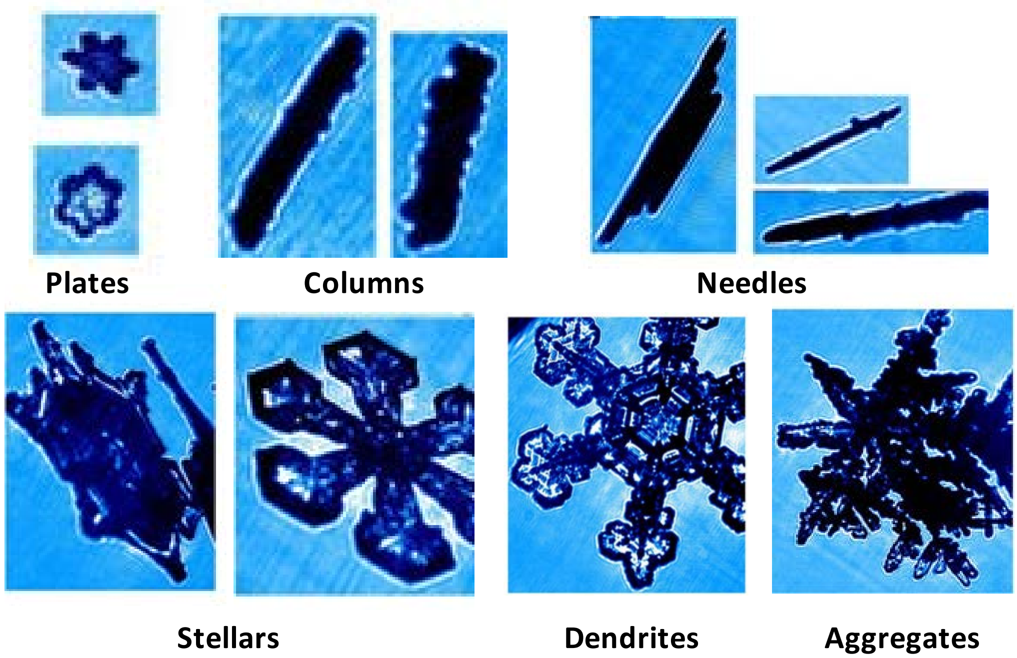


Figure 3-41. Common ice crystals that form snowflakes (Courtesy Stratton Park Engineering, MWISP program).

Most dry snow, when initially deposited, has a density of about 0.1, where 10 cm of snow melt is equal to 1 cm of water. Snowflakes typically grow to 1 to 5 mm in diameter, though very large dendrites can grow to 10 mm diameter (Schemenauer et al. 1981; Libbrecht 2007). Aggregates and stellars are the most common snowflakes, and they generally cause the most rapid snow accumulation rates. If melted, a large snowflake can produce a water droplet about 1 mm in diameter (Schemenauer et al. 1981).

3.2.4.2 Location, magnitude, frequency

In general, snow is a problem on horizontal surfaces such as decks (Fig. 3-42 and 3-43). However, snow also will adhere to vertical surfaces such as bulkheads and horizontal cables, especially if those surfaces are wet, or if it is a wet snow. With regard to height above water level, Fagan (2004) said that snow affects all heights on a drill rig. Multiple forms of icing, such as snow and sea spray, also often occur at the same time to cause multiple problems, especially in the lee of intense winter storms (Brown and Agnew 1985; Brown and Roebber 1985).

Figure 3-42. Navy UNREP tests in the Bering Sea, 1977, on the USS *Taluga*, a fleet oiler. Decks are snow and ice-covered (from Miller 2009).

If care is not taken to remove ice loads after each event, the additive effects could threaten trim and stability. Mycyk (1985) reported that combined snow and sea spray icing was such a problem off the Canadian East Coast that it merited further study. Makkonen (1984) has also shown that snow events are far more frequent than freezing rain and drizzle on Middleton Island in the Gulf of Alaska, and on St. Paul Island in the Bering Sea. Whereas freezing rain and drizzle and ice pellets occur less than 20 hours most winter months, snow occurs from 80 to over 270 hours in some months.

Figure 3-43. Snow accumulation on buoy deck of CGC ALDER (http://www.uscg.mil/d9/cgcAlder/photo_gallery.asp).

3.2.4.3 Physical properties

Snow can fall as one of two general types, depending upon air temperature, which has large effects upon its adhesive and cohesive strength. Wet snow forms when air temperatures near the ground are generally between 0.5 and 2.0°C (Fikke et al. 2008). These layers of warm air are as thin as 100 to 150 m. At sea, this may be a common occurrence in the warm boundary layer near the ocean surface. If the warm layer is too thick, the snowflakes will melt.

When snowflakes encounter the warm air, they begin to melt and form a thin liquid layer on their surface. When these wet drops collide, they stick to one another, and when they collide with a surface, they adhere more strongly because of the surface tension of the water. Wet snow often has a liquid water content between 15 and 40%, but at the wet end of the range, the snow becomes similar to slush and adhesive strength weakens (Fikke et al. 2008). However, Wakahama et al. (1977) claimed that adhesion is high at up to about 20% liquid water content where the snow is nearly saturated (Poots 1986). The strong cohesive and adhesive properties of wet snow were attributed to inter-particle ice bonding by Colbeck and Ackley (1983). They also indicated that this bonding is caused by snow metamorphism that causes snow crystals to become more rounded and fewer in number. This process, and higher wind speeds, also causes density to increase where, at densities above about 0.6 g/cm^3, strength increases as ice crystals establish a continuous network of bonds between snow crystals. The wind causes packing forces in the snow, similar to squeezing a snowball (Makkonen 1984). In general, as the density of ice or snow increases, the adhesion strength increases.

Wet snow, or sticky snow, readily bonds to all surfaces where dry snow does not readily bond, such as bulkheads, antennas, and cables. According to Makkonen (1984), horizontal cables tend to accumulate a greater thickness and weight of wet snow than vertical cables because the cable rotates as snow accumulates, especially if accumulation is from the side in strong winds, and forms a cylindrical deposit that envelopes the cable. Accretion weights can damage lines, and if temperatures decrease below 0°C, the water in the snow can cause high adhesion of the snow to surfaces, making it very difficult to remove.

3.2.4.4 Safety hazards on ship components

Snow can cause problems on ships when underway and when in port. It may be reasonable to form analogues between offshore platform snow issues and cutters in port as they are both stationary.

Brown and Agnew (1985) reported that more than 60% of trawler spray-icing events off of Labrador and Nova Scotia were associated with snow. In February 1985, the semisubmersible platform *SEDCO 710* crew had to shovel 10 cm of snow from the deck. Liljestrom and Lindgren (1983) estimated that snowfall can cause considerable loads on semi-submersibles. For example, they cited the *GVA 5000* semi-submersible, which has a deck area of 80 m^2, and can accumulate a load of about 150 tons with a snow depth of 0.3 m. In general, dry snow does not accumulate on structures at sea but blows off, unless surfaces are wet, and then it forms a porous low-strength accretion (Jorgensen 1982). However, wet snow that does accumulate without the benefit of sea spray can form ice underfoot as it increases in density through crushing and refreezing. Some Coast Guard crews are diligent about keeping decks clear of snow and clear decks when snow reaches a depth of about 5 cm.

Snow causes falling accidents because of slippery conditions and obscuration of steps and objects with less height than the snow depth. Kozo (1986), in assessing the icing hazard in the Chukchi Sea, concluded that snow is not a hazard because it adheres so poorly. Drilling locations in the lee of cold land masses could cause significant quantities of snow to accumulate on decks and machinery as cold air picks up moisture, causing, in effect, “lake effect” snowstorms. This phenomenon is known in the Sea of Japan, for example. It is unknown whether it is a problem in the Beaufort and Chukchi seas.

Snow accumulation on valves may inhibit both their operation and the ability to see position indications. Snow also can affect crane operations because it can create slippery working conditions, and it can melt and refreeze. On open lattice structures, snowmelt can flow into crotches where multiple structural members are fastened, forming large chunks of ice. When thawing occurs, these ice chunks fall bec,oming projectiles that can be a serious hazard to personnel and equipment. This phenomenon has been observed on land-based communication towers where ice balls have punched holes in the roofs of buildings and smashed windows of vehicles (personal communication with N. Mulherin, 1987).

Figure 3-44. De-icing snow-covered port weather deck of CGC MIDGETT in 1990 (Ryerson 1990).

Ryerson observed snow on the CGC MIDGETT in the Bering Sea in February 1990. Though only a few centimeters of snow accumulated, it froze as a solid mass on the non-skid deck, creating dangerous footing. The crew indicated that the snow absorbed light spray after it accumulated, making the entire deposit more difficult to remove. Unnecessary personnel were not allowed on deck, and crew members performing mechanical de-icing (Fig. 3-44) found removing the snow difficult.

4 Cutter Superstructure Ice Risk Analysis

The icing environment, the relatively small size of Coast Guard Cutters, and unique Coast Guard Concept of Operations (CONOPS) make superstructure icing a threat to safety and to Operational Tempo (OPTEMPO). As with aircraft icing, superstructure icing is a product of the environment and of the design of the vehicle that is accumulating the ice and its operation. With aircraft icing, the atmosphere provides the conditions to cause icing by supplying a cold atmosphere and supercooled cloud droplets. There will be no icing unless an aircraft traverses the atmosphere with the icing conditions. Collision of aircraft surfaces with supercooled drops causes ice accumulation. Handling of the aircraft, its speed, attitude, use of flaps, and exposure time all affect the rate of ice accumulation and the ability of the aircraft to continue flying.

For cutter superstructure icing, the atmosphere and the sea provide the conditions conducive to icing. The design and handling of the cutter in the icing conditions determine how rapidly and how much it ices. For example, a small cutter with little freeboard and a hull that creates spray operating at speed in quartering seas may ice more rapidly and dangerously than a slower moving cutter, in head seas, or following seas, with larger freeboard. Icing does not occur in isolation; it is a function of the weather, seas, and vessel design and operation.

This indicates that icing severity may be diminished by avoiding icing conditions, by redesigning or equipping vessels to mitigate icing, and by operating the cutter to mitigate icing. The Coast Guard attempts to avoid icing. However, Coast Guard missions occasionally do not allow cutters to remain in port during dangerous weather. Coast Guard commanders also attempt to mitigate icing through operational procedures that minimize spray generation. The Coast Guard also equips cutters to mitigate icing by occasionally heating decks, by covering deck machinery with tarps, and by heating bridge windows. This analysis used a variety of tools to collect information about the icing threat to Coast Guard Cutters, and evaluates the severity of the icing threat.

4.1 Background

The US Coast Guard is within the Department of Homeland Security (DHS) during peacetime, which has four overarching mission areas: Maritime Safety, Security, Stewardship, and Mission Support. Overall, the Coast Guard has 11 mission areas within the four overarching DHS missions, and in the high latitudes there are nine primary missions: Port and Waterways, Coastal security, Aids to Navigation (ATON), Search and Rescue (SAR), Living Marine Resources, Defense Readiness, Marine Environmental Protection, Ice Operations, and Other Law Enforcement. The type of mission and its urgency may affect how a cutter must operate. Fisheries patrol may allow a cutter to operate at relatively slow speeds for most of the mission and, if icing weather threatens, alter operations to minimize impact. However, if there is an SAR mission, or a Defense Readiness action, if may be necessary to operate in icing weather in such a manner that some ice will accumulate. Although safety is a primary concern when operating cutters, mission focus will vary in priority as circumstances and urgency dictate. The frequency of each mission type and the circumstances at the time vary with the geographic Area of Responsibility (AOR) of each cutter. Therefore, the regional and temporal mission demands may determine how frequently a cutter is exposed to icing conditions, in addition to the frequency of such weather conditions.

In addition to Coast Guard mission profiles and geographic AORs, the Coast Guard operates vessels designed for specific, practical applications, such as breaking floating lake and sea ice and maintaining ATON. Ice breaking, for example, requires hull profiles that are not necessarily compatible with the need to minimize bow spray. Buoy tenders require deck space, machinery, and low freeboard that allow the movement and repair of heavy machinery, yet are prone to ice accumulation. Therefore, the need for specific ship designs can encourage vulnerability to spray, leading to subsequent superstructure icing.

Superstructure icing as a safety threat is consistent with concepts of accident causation. Using material from a wide variety of industrial accidents compiled by the insurance industry, Heinrich (1950) suggested that frequent, minor, unreported events caused by phenomena such as icing may lead to more serious accidents. If allowed to continue, minor reportable accidents or injuries could lead to one or more fatal or catastrophic events. Following this logic, the apparently benign impact of small icing events that are of little threat may ultimately lead to serious icing accidents.

Though Heinrich's theory is controversial and often challenged, it has been widely accepted for over 70 years (Conklin 2007).

Many other theories, such as the confluence of multiple factors commonly used in assessment of aviation accidents, attempt to explain accident causation. Gunter (2008) reviewed theories of accident causation and concluded that the importance of ergonomics and stress is influenced, in part, by the physical environment. These theories of accident causation suggest the potential safety impact of icing in the marine environment. Superstructure icing from snow, glaze, rime, frost, and especially sea spray, were recognized hazards to ships in the 1980s (Jorgensen 1982). Icing hazards identified over 40 years ago still, in large part, exist today. Overall, little systematically collected information about the impact of superstructure or atmospheric ice on Coast Guard Cutter operations is available. We have obtained information in other ways.

4.2 Methodology

This study focuses on anticipated Coast Guard operations in Arctic weather conditions, and especially in the Beaufort and Chukchi seas. The analysis focuses upon four classes of cutters that could be operated in those seas: the heavy and medium *Polar*-Class icebreakers (WAGB-11 and WAGB-20), the *Legend*-Class National Security Cutter (NSC), the 225-ft *Juniper*-Class seagoing buoy tenders (WLB), and the 140-ft *Bay*-Class icebreaking tug (WTGB).

4.2.1 Information gathering

4.2.1.1 Archival information

Some information about Coast Guard icing experiences were obtained from papers published in the open literature. Though little information was available from open sources, some experiences were obtained dating back to World War II and are related in other sections of this report. Little information was available for current cutters except for photographs available on web sites maintained by individual cutter crews.

4.2.1.2 Boots-on-Deck

"Boots-on-Deck" visits were made to each of the four classes of cutters of interest. Each visit involved interviewing officers, chiefs, and bosons about superstructure icing experiences on their cutter class as well as icing experiences on other cutters. Each visit included an extensive tour of the weather decks, noting and photographing areas where ice has or may be expected to affect operations, or may be enhanced by a vessel design characteristic. The ship inspections were typically enhanced by crew members explaining problems they have experienced with icing on forecastle decks, boat decks, and other areas.

4.2.1.3 Questionnaires

A questionnaire was developed to provide to crews to complete after Boots-on-Deck visits. Questionnaires were also sent by Coast Guard Research Center staff to crews working on cutters of the classes of interest that they knew had experienced superstructure icing. Most questionnaires were received from *Juniper*- and *Bay*-Class cutters: a total of 11 were received.

The questionnaires consisted of questions and a risk matrix for completion (see Appendix A). The risk matrix asked respondents to indicate the types of icing experienced on their cutter, such as spray icing, rime, glaze, snow or frost, and to indicate their relative importance in affecting cutter operations. They were also asked what cutter areas or functions were degraded by icing and to indicate their relative importance to safety and mission readiness. A cross-tabulation of the ice type importance and ice impact importance provided a relative indication of the potential impact of icing by types on ship function, and hence on safety.

4.2.2 Analyses

Two types of analyses were conducted from information acquired primarily from the Boots-on-Deck experiences and the questionnaires. The analyses are quantitative only at the nominal and ordinal scales because they were initially based upon qualitative and often subjective information.

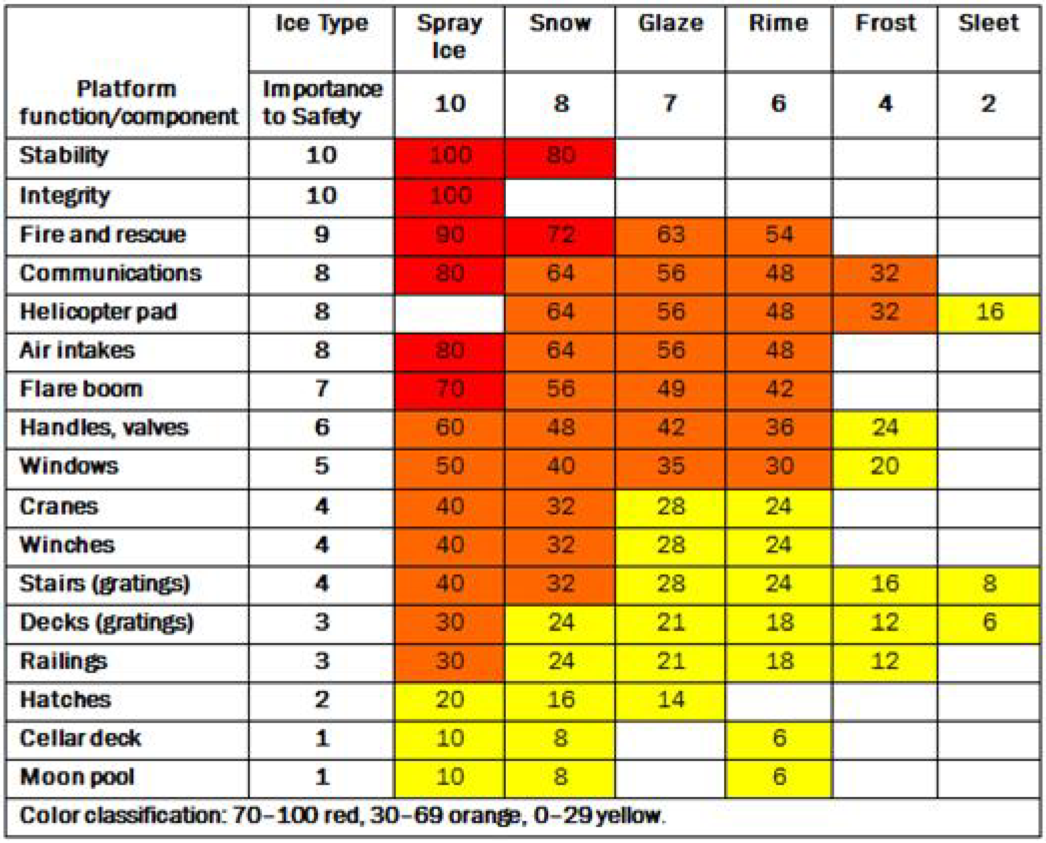
4.2.2.1 Boots-on-Deck summary

The Boots-on-Deck summary is a narrative summarizing information gathered through interviews, photographs, and the questionnaires completed by crew. The summaries identify specific icing issues on each cutter class, and recommendations by crews.

4.2.2.2 Risk matrix

The risk matrix attempts to identify the types of ice that are the greatest threat to the vessel and the areas and functions of the vessel most affected by ice (Ryerson (2009, 2011) (Table 4-1). A cross-tabulation then identifies the importance of ice type versus the areas or functions of the vessel most affected by ice.

Table 4-1. Risk matrix for Arctic offshore platforms.



Platform function/component	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
	Importance to Safety	10	8	7	6	4	2
Stability	10	100	80				
Integrity	10	100					
Fire and rescue	9	90	72	63	54		
Communications	8	80	64	56	48	32	
Helicopter pad	8		64	56	48	32	16
Air intakes	8	80	64	56	48		
Flare boom	7	70	56	49	42		
Handles, valves	6	60	48	42	36	24	
Windows	5	50	40	35	30	20	
Cranes	4	40	32	28	24		
Winches	4	40	32	28	24		
Stairs (gratings)	4	40	32	28	24	16	8
Decks (gratings)	3	30	24	21	18	12	6
Railings	3	30	24	21	18	12	
Hatches	2	20	16	14			
Cellar deck	1	10	8		6		
Moon pool	1	10	8		6		

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

For example, Ryerson (2009) developed a risk matrix for offshore platforms (Table 4-1). The matrix identifies spray icing as most serious, and snow as second most serious. Because spray ice and snow can add many tons of ice to an offshore platform owing to its large weather deck area, then stability was the largest safety concern. Stability was also of greatest concern because its loss would mean losing the entire platform. Other platform functions were less affected by icing, and the remaining forms of ice were also deemed less important to platform function. The resulting cross tabulation matrix indicated the most serious combinations in red and less hazardous combinations in orange and yellow.

4.3 Cutters

4.3.1 *Polar*-Class icebreakers

4.3.1.1 Ship mission and operating environment

The US Coast Guard currently has two heavy polar icebreakers, the CGC POLAR SEA and the CGC POLAR STAR, and one medium polar icebreaker, the CGC HEALY (O'Rourke 2012). Currently, the CGC POLAR SEA is not operational and is not planned to be returned to service. The CGC POLAR STAR was out of service for 7 years and is returning to service after extensive overhaul in 2013 for an additional expected 7–10 years of service life (Fig. 4.1).

Figure 4-1. CGC POLAR STAR heavy POLAR-Class icebreaker. The CGC POLAR SEA and CGC POLAR STAR are of similar design (US Coast Guard, n.d.).

The CGC HEALY is a medium *Polar*-Class icebreaker and is only about 12 years old, compared to over 34 years for the heavy icebreakers (Fig. 4-2). Though somewhat longer and of larger displacement than the heavy icebreakers, it has an icebreaking capacity of 1.4 m at 3 kt (1.5 m/s) compared to 1.8 m at 3 kt (1.5 m/s) for the heavy icebreakers.

Missions of the polar icebreakers are (O'Rourke 2012):

1. Conducting and supporting Arctic and Antarctic scientific research, a significant portion of icebreaker operation, including resupply of McMurdo station.
2. Defending US sovereignty in the Arctic by helping to maintain a US presence.
3. Defending US Polar interests, including interests within the US Exclusive Economic Zone (EEZ) north of Alaska.

4. Monitoring sea traffic in the Arctic.
5. Conducting other typical Coast Guard missions (such as SAR, law enforcement, and protection of marine resources) in Arctic waters, including US territorial waters north of Alaska.

Figure 4-2 Medium POLAR-Class icebreaker CGC HEALY (US Coast Guard, n.d.).

When deployed, each cutter conducts about 1600 to 3800 mission hours per year. The CGC HEALY spends about a quarter of its polar operations hours in transit to and from the operating area or for scientific research. Specifically, this is estimated to be 25% transit time and 75% scientific time. For the heavy icebreakers, polar operations hours are spent transiting to and from the operating area, scientific research, or mobility logistics (icebreaking for re-supply). Specifically, this is 50% transit time, 10% scientific research time, and 40% mobility logistics time (O'Rourke 2012). For all three icebreakers, with mission hours combined over 3 years, only 33 were used for search and rescue operations.

The mission breakdown is important because it indicates potential exposure to superstructure icing. Exposure to superstructure icing would happen primarily during transit time given appropriate seas, weather conditions, and ship operation. Overall, transit times have averaged about 900 to 950 hours per year for the CGC HEALY, and 800 to 1400 hours for the CGC POLAR SEA or CGC POLAR STAR. Exposure to superstructure icing conditions would typically be many fewer hours yearly for each cutter because they are often transiting warm water, and icing is more probable during stormy conditions.

4.3.1.2 Ship design and structure

The polar ice breakers are designed for their missions of breaking ice and supporting scientific research. Ice breaking requires that bows be designed to ride up onto ice and crush it under the ship's weight. Minimizing spray is a much less important need and, therefore, the bows are not designed to suppress spray. The bows of these vessels, especially the CGC POLAR STAR, have little flare to divert spray to the side and keep the decks and superstructure dry (Fig. 4-1 and 4-2).

Supporting scientific research, especially on sea ice, requires lowering scientific equipment to the ice, and retrieving it. This necessitates considerable deck operations and use of cranes (Fig. 4-3). Large, open weather decks are required for storing scientific equipment, and for staging equipment. In addition, personnel need to be able to operate on the decks regularly, and often without lifelines. The open weather decks and complex crane hardware readily accumulate ice from sea spray and snow. These areas, and cranes, which can drop ice on personnel and equipment as it spalls off, must be cleared of ice prior to use for safety.

Figure 4-3. Cranes in use on rear of CGC HEALY during a scientific mission (photo courtesy Bruce Elder, CRREL).

4.3.1.3 Boots-on-Deck observations and icing experience

4.3.1.3.1 CGC HEALY

The CGC HEALY was visited on 30 May 2012 in Seattle. Figure 4-4 shows areas on the CGC HEALY that are considered important superstructure icing areas. Though rime ice has occurred on the ship, and snow is a problem, frost and glaze are not considered problems. Bow spray generated icing is the greatest icing problem on the CGC HEALY. However, though loss of stability is the greatest overall superstructure icing concern for all ships, the CGC HEALY has too much mass for icing to significantly reduce stability. The CGC HEALY has experienced 30 cm of superstructure ice without serious impact.

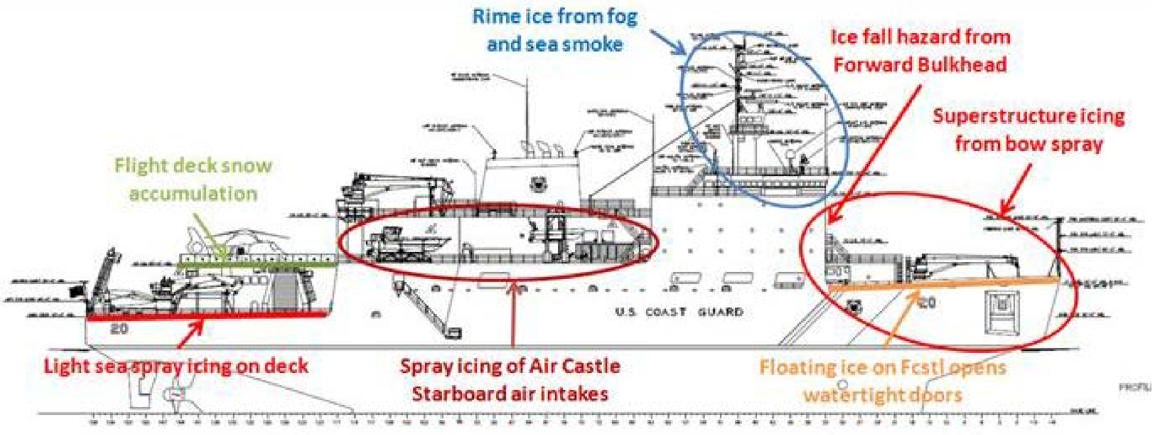


Figure 4-4 Areas of CGC HEALY with icing problems.

The three most important operational areas of the ship that icing affects are the forecastle deck, the flight deck, and the air castles. Loss of forecastle crane, anchors, and the flight deck to icing are also urgent safety issues for SAR operations.

Forecastle icing is primarily from bow spray, but snow can also cover the forecastle deck, especially when operating in ice or when in port. Anchor and crane operations are hindered by forecastle icing, and the forecastle deck is effectively unusable and is secured when iced. Anchor operations affected by icing including the catspaw, making anchor release difficult, the pelican hook, and the wildcat capstan, which raises and lowers the anchor, and the anchor pockets on the sides of the hull (Fig. 4-5). Otherwise, icing of the sides of the hull is not serious.

Figure 4-5. Forecastle anchor and crane hardware are made inoperable by icing (CRREL 2012).

Contributing to forecastle icing is restricted deck drainage from ice and rust (Fig. 4-6). Deck drains are the only way for water to drain from the deck because weather decks have a lip around the edge to prevent spills of chemicals and oils from flowing overboard. Sufficient water floods the deck, especially after ice forms on the deck and builds dams, that sloshing water from ship motion and floating pieces of ice can cause the dogs on the forward bulkhead watertight doors to be pushed open. Water then enters the ship compartments. The remedy currently used is to tie-down the door handles.

Figure 4-6. Deck drains on the forecastle and in the air castles clog due to rust and ice (CRREL 2012).

Icing on the forward bulkhead at the aft end of the forecastle deck can reach the bridge windows (Fig. 4-7). The bulkhead below the bridge is too high to be reached from below for complete manual de-icing, and it is inaccessible from above. Therefore, ice can be a hazard as it falls from higher areas of the bulkhead. In addition, ice forms on the crane mounted on the forecastle, and ice falling from the crane can be a hazard. The crane also cannot be operated when iced. Icing of the forecastle hinders anchoring, mooring, and scientific operations requiring equipment to be craned on and off the ship.

Figure 4-7. High forward bulkhead below bridge cannot be fully de-iced manually (left). Floating ice on forecastle opens watertight doors, allowing water into compartments (right) (CRREL 2012).

At amidships, air intakes in the air castle ice up on the starboard side. On the port side, exhaust ports in the air castle do not ice because they exhaust warm air. Deck drain clogging by ice and rust also causes flooding and ice accumulation in the air castles.

Boat operations take place amidships, but for the most part, these operations have not been affected by icing.

Flight operations are affected by snow on the flight deck. Only snow around the immediate launch area is usually cleared. About 2.5 cm of snow is often left on the flight deck non-skid because of the difficulty of de-icing the rough non-skid. In addition snow is fresh water ice, which is more difficult to remove. However, this residual snow has been demonstrated to have little negative effect.

Though frost is not a reported problem, rime ice occurs on rails, antennas, and other gear above the bridge from convection fog. Rime ice must often be cleared daily from electronic equipment above the bridge.

4.3.1.3.2 . CGC POLAR STAR

Topside icing is rare on the CGC POLAR STAR because action is taken to prevent bow spray in cold conditions by slowing speed or changing course However, it causes problems when it occurs. Atmospheric icing from frost, rime, and freezing rain are of minor concern. Summer fog is worse than winter fog (convection fog), but it decreases in severity as the ship sails north. There are low temperatures and precipitation in the Bering Sea, but it is not an issue for the CGC POLAR STAR as it does not operate there often. The CGC POLAR STAR usually operates far north (or south if in the Southern Hemisphere), where it is colder and there is less precipitation. If they transit through areas with snow, they are moving and it does not accumulate. However, snow can accumulate when in port.

Icing reduces operational capabilities for anything that requires topside (deck) operations, including boat operations and scientific work, such as water sampling. Equipment freezing, hydraulics not operating well in cold (heat taped), ice falling from cranes, and personnel falling are safety issues related to cold and icing. Safety lines, life rings, cleats for boats, and painter lines for launching and retrieving boats can be affected by topside icing.

When spray over the bow is happening, sea water wash on decks becomes more of an issue when the cutter slows down and the reduced ship motion does not slosh water overboard from decks. Deck drains freeze, water accumulates, and there can be flooding of the deck. Plugs of ice can also rupture the deck drains. If the decks ice over, they can become large, slippery areas. The only spray shield is forward of the forecastle crane mount (Fig. 4-8).

Water 1 m deep has been observed on the forecastle deck ahead of the air castle doors. This water has frozen and prevented the air castle doors from being opened, denying access to the forecastle deck. Crew members have been rappelled to the forecastle from the air castle, around the frozen doors, to remove the deck ice freezing the doors shut (Fig. 4-9).

Figure 4-8. Forecastle deck of CGC POLAR STAR (CRREL 2012).

Figure 4-9. Ice accumulates on the forecastle deck ahead of the air castle doors freezing them shut, denying access for anchoring operations (CRREL 2012).

Anchoring is always done from the forecastle. If machinery and hardware that raise and lower the anchors ice up, anchoring can become dangerous, difficult, or impossible (Fig. 4-10). Anchor pockets can also ice and the 9000-lb anchor can freeze in the anchor pocket and cannot be deployed. Ice can build rapidly, and 30 to 46 cm of ice has been observed in the anchor pockets (Fig. 4-11).

Figure 4-10. Anchor hardware including wildcat on left and catspaw on right (CRREL 2012).

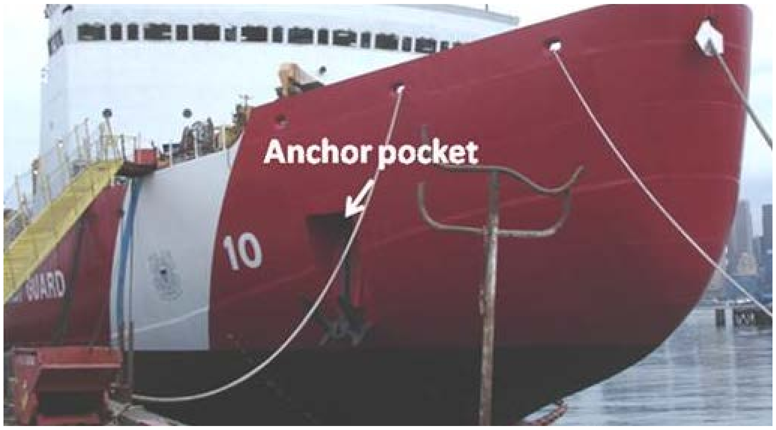


Figure 4-11. Anchor can freeze when drawn into anchor pocket and not release when required (CRREL 2012).

Icing also affects science gear deployment and hardware located along deck edge encourages ice accumulation.

Superstructure icing can accumulate high on the forward bulkhead under the bridge windows where it cannot be reached for manual de-icing (Fig. 4-12). The bridge is 16 m above the waterline and about 9 m above the forecastle deck. This causes a falling ice hazard on the forecastle.

Figure 4-12. Manual de-icing techniques cannot reach high on forward bulkhead causing a falling ice hazard. Ice can also fall from the crane (CRREL 2012).

The CGC POLAR STAR has heated bridge windows and two spinning windows (Fig. 4-13). Window heaters occasionally fail, and there are problems with bridge window wiper failure from ice on moving mechanical parts. Wipers mechanisms should be redesigned to reduce vulnerability to icing. Some sea spray ice accumulates on antennas on the flying bridge and higher, but it is not significant enough to affect their operation (Fig. 4-14).

Figure 4-13. Effective Clearview heated spinning window on Left. Right—complex external wiper mechanism that keeps blades parallel to window edge during stroke, but accumulates ice and freezes (CRREL 2012).

Figure 4-14. Satellite deck electronic equipment is rarely impacted by icing, but is affected by cold (CRREL 2012).

Turbine air intakes circulate heated air and prevent ice accumulation at the inlet. However, unheated tank vents occasionally freeze shut (Fig. 4-15). The hangar and flight deck never ice because of hangar warmth, and heat rising from below decks.

Figure 4-15. Air vents for fuel and water tanks can freeze shut (CRREL 2012).

Open grid composite grating on the fantail, which reduces freezing rate, increases traction because of its grit surface, and allows ice to fall through spaces, improving safety (Fig. 4-16).

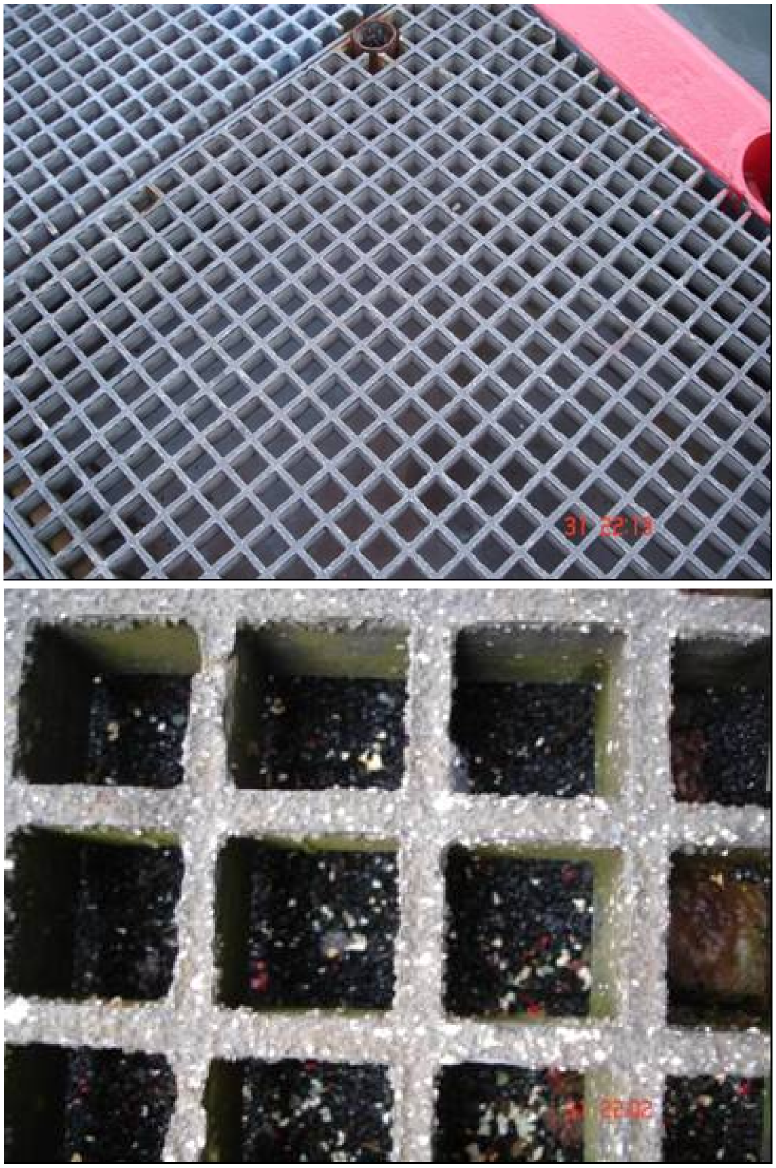


Figure 4-16. Open grid grit-covered composite grating on fantail deck improves footing and allows ice and snow to fall through (CRREL 2012).

Zahn and Voelker (1985) describe several occasions of superstructure icing of the CGC POLAR SEA and the CGC POLAR STAR (Fig. 4-17 and 4-18).

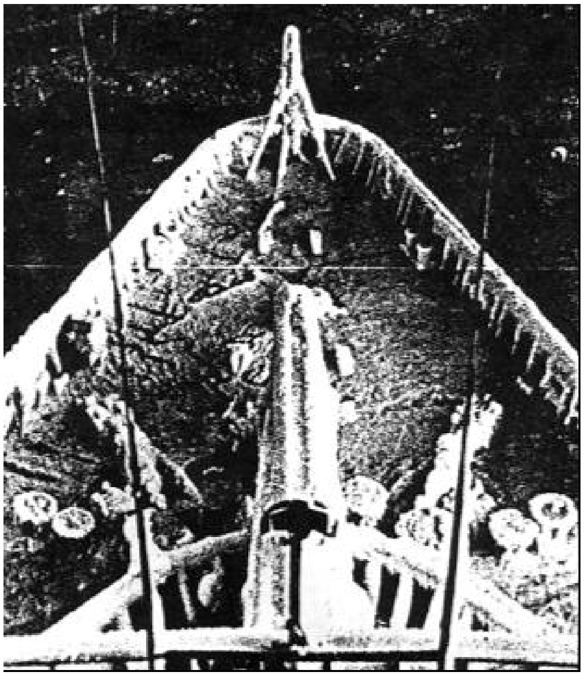


Figure 4-17. View of the CGC POLAR SEA forecastle deck 12-hours after icing ceased in February 1983 (Zahn and Voelker 1985).

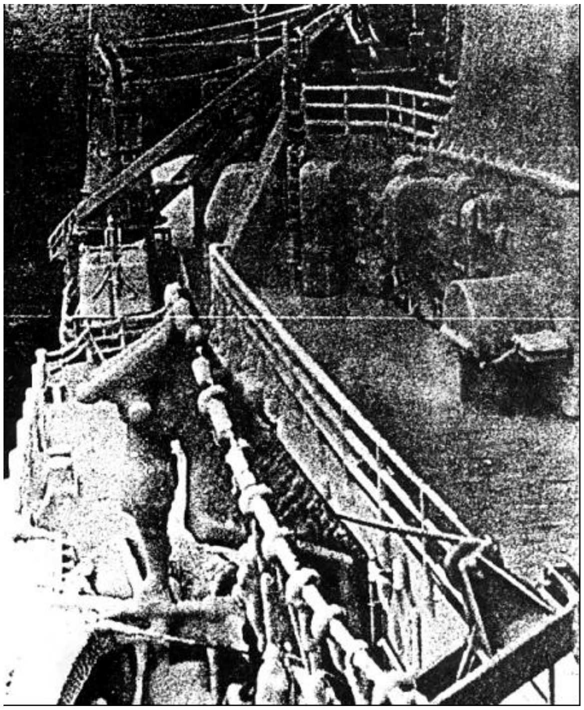


Figure 4-18. Icing of the flight deck and boats and rafts, all which are inoperative, in the February 1983 CGC POLAR SEA icing event (Zahn and Voelker 1985).

On 18 February 1983 as the CGC POLAR SEA was in transit between the Aleutian Islands and ice edge in the Bering Sea in 30–40 kt (15–20 m/s) winds and 3-m seas, icing started. Temperatures fell to –11.2°C, seas rose to 4.3 m, and icing continued for 34 hours. Accumulations of 15 cm were common on all surfaces including railings, and 30 cm accumulated on the forward cargo crane. Less ice accumulated on the 02 and 03 levels, illustrating that icing decreases with height.

On 28 March 1985 the CGC POLAR SEA was in transit from Dutch Harbor to the ice edge. Temperatures dropped to a low of –9°C as wind speeds increased to 28 to 37 kt (14 to 19 m/s) and sea temperatures decreased to 0.6°C. Wave heights varied from 0.5 to 2 m. Light icing occurred during these conditions, with 5 cm forming on the forecastle deck and 1.3 to 5 cm on other decks.

In these icing events, access to the forecastle deck was lost because of freezing of access hatches. Forecastle equipment, including windlasses, chocks, and cargo cranes, were inoperable for 3 weeks or more (Fig. 4-19). Icing of decks aft of the bridge made personnel passage treacherous and incapacitated davits and motor lifeboats.

Figure 4-19. Removing ice from the forward crane, with an axe handle, on the CGC POLAR SEA in 1985 (Zahn and Voelker 1985).

Icing experiences on the CGC HEALY were related by a recent crew member through a questionnaire. Though icing experiences were combined for three cutter classes, the following general observations are believed to be most related to the CGC HEALY. Ice thicknesses to 25 cm were observed on the mast and forecastle. Though several types of ice were observed, sea spray icing typically occurred in seas above 3 m in temperatures lower than –1°C. Icing was observed to be a safety hazard because decks were slippery and injuries could occur from falls, and falling ice was a hazard.

4.3.1.4 Anti-icing and de-icing procedures

On the CGC HEALY course changes and reductions in ship speed are used to reduce water lofted above the bow to minimize icing. This affects the mission, but mission delays are acceptable to reduce the hazard of icing. It is recognized, however, that green water[1] can remove ice because of the additional heat it provides, and it is occasionally intentionally allowed over the bow for de-icing.

De-icing is accomplished with *Ice Melt* (calcium chloride), Mackinaw wooden mallets, baseball bats purchased from sports stores, and plastic deadblow mallets (see Fig. 4-19). The heated bridge windows are effective, though they can overheat and cause damage to the glass. Not keeping up with snow removal causes serious ice removal problems because it evolves to thick ice over time. Removing ice from non-skid is difficult, which is a problem on the flight deck because flight operations cannot take place unless the surface is clean. In general, de-icing is done at the first opportunity with acceptable weather, and most is done with ice hammers on surfaces where people travel, and on the flight deck. Spaded shovels are discouraged for de-icing because they damage non-skid. A de-icing/anti-icing coating mixed with paint that could be applied over the ship would be desirable.

Topside icing is rare on the CGC POLAR STAR, primarily because action is taken to prevent bow spray in cold conditions. The ship slows and changes course to minimize spray when entering an environment where ice could accumulate. Transit speed and environment are used to estimate how much of an impact speed and course changes will have on mission. Marine science technicians (meteorologists) on board predict superstructure icing from weather forecasts. If topside icing has a chance of occurring they will avoid it if possible, and they use Flooding Casualty Control Software (FCCS) to estimate ice effects on ship stability.

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[1] Solid sheets or waves of water not spray. Solid sheets of sea water appear green rather than blue.

The ship also conducts superstructure icing avoidance maneuvers, such as hiding behind islands, during extreme weather. In emergencies, if the ship needs to travel at higher speed, it may take spray causing icing. If there is significant ice accumulation, it must be removed before distress calls can be answered. However, the CGC POLAR STAR has few SAR operations because it is an icebreaker and there are few other vessels in its area of operations.

The ship's crew indicated that anti-icing through design changes would be preferable to de-icing, an example being the open grid composite grating with grit installed on fantail deck area of the CGC POLAR STAR (see Fig. 4-16). Another example of a very successful anti-icing system installed through design change is the heated buoy deck and forecastle deck of the CGC MACKINAW using an electric strip heater system. Baltic ships may have similar electric heat technologies that should be considered.

Wooden baseball bats are used for de-icing the CGC POLAR STAR, as are *Ice Melt* and sand. Heat tape is not used for de-icing; it is used only for keeping hydraulic lines operational. It may be desirable to retrofit existing ships with de-icing equipment because de-icing technologies may be easier to install on an existing ship than are anti-icing technologies.

4.3.1.5 Risk matrix

No risk matrix is available specifically from the CGC HEALY. However, all of the *Polar*-Class icebreakers have similar missions and operating environments. Therefore, the CGC HEALY risk matrix is expected to be similar to that of the CGC POLAR STAR (Table 4-2).

The CGC POLAR STAR risk matrix was developed through a discussion among five senior officers. Sea spray icing was considered the most serious ice type even though it does not occur often in the cutter's mission profile, and because aggressive efforts are taken to minimize icing when in transit.

Table 4.2. Risk matrix for POLAR-Class icebreakers.

	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Cutter function/component	Importance to Safety	10	4	6	3	2	0
Deck machinery	9	90	36	54	27	18	0
Cranes	9	90	36	54	27	18	0
Boats	9	90	36	54	27	18	0
Antennas and electronics	8	80	32	48	24	16	0
Tank valves/vents	8	80	32	48	24	16	0
Bridge windows	8	80	32	48	24	16	0
Bulkheads	8	80	32	48	24	16	0
Deck drains	8	80	32	48	24	16	0
Flight deck	7	70	28	42	21	14	0
Rafts	5	50	20	30	15	10	0
Deck surfaces/ladders	5	50	20	30	15	10	0
Lifelines/railings	5	50	20	30	15	10	0
Fire stations	4	40	16	24	12	8	0
Ventilation	2	20	8	12	6	4	0

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

The primary mission of the icebreakers is in support of Arctic and Antarctic science by providing a logistics platform, and for icebreaking, such as opening channels for supply ships to McMurdo. Though bow spray superstructure icing does not occur when breaking sea ice, it does happen when transiting to the ice edge, despite aggressive attempts to avoid it; it was rated 10 in its impact as an ice type on safety. Snow falls when in transit and when in sea ice, but it generally does not accumulate when in transit, and it is shoveled and decks are sanded when it falls. Snow was not considered a significant hazard as it was rated at only 4 in its impact on safety. Though glaze from freezing rain or freezing drizzle occurs infrequently, it was rated as 6 because it affects antennas and most ship surfaces, makes decks slippery, affects davits, cranes, and other hardware, and is difficult to remove despite the thicknesses being small. Rime and frost had little effect on the icebreakers and were rated 3 and 2 respectively, and sleet had no impact.

Though bow spray is avoided, when it does reach over the bulwarks it affects the forecastle deck and equipment on that deck, including anchoring hardware, the forecastle crane, and science gear on the forecastle. Because science is a primary icebreaker mission, the ability to anchor and work off of the forecastle deck, and use the crane, are all considered critical to the mission. In addition, ice on the forecastle affects the ability to handle the painter when launching the boat. And ice can fall from the crane, creating a personnel hazard on the forecastle deck. All of these areas were rated as

9 in importance to safety if affected by icing; nothing was rated as 10 in importance because superstructure icing is so actively avoided through ship operations in icing weather.

Antennas and electronics were considered critical to safety in all operations, especially with the need to communicate with scientific teams: they were rated as 8 in importance. Tank vents must be kept clear of ice because tanks could collapse when transferring fuel or water in or out, which can cause flooding inside the cutter if they are ruptured. They were therefore rated at 8. Bridge windows are heated and ice rarely reaches that height, so they could have a rating lower than 8. However, if the windows were not heated, or if the window heaters fail, then the importance of icing of the windows became 8. Bulkheads refer primarily to the forward bulkhead, and include the bulkhead doors. The forward bulkhead doors have proven to be a serious problem during icing on the CGC POLAR STAR and on the CGC HEALY, though for different reasons on each ship. On the CGC HEALY the forecastle floods with standing water, causing large pieces of floating ice to hit the handles on the forward bulkhead doors, opening them and allowing water into the ship. On the CGC POLAR STAR drainage of the forecastle deck is also a problem in icing, and thick ice builds at the base of the forward bulkhead at the air castle doors. The air castle doors are the only access to the forecastle, and when the doors are blocked by ice there can be no forecastle operations. Deck drains were also added because their inability to drain deck water properly in icing conditions is a partial cause of other forecastle icing problems.

Flight deck operations were considered critical for taking people who are injured or sick off the ship. However, heat leaking from below the flight deck keeps it sufficiently clear of ice and snow that it received only a risk rating of 7.

Decks must be clear of ice because lifelines are often down when scientific equipment is passed off and on the ship. As deck ice causes slipping and fall hazards, decks and ladders were rated at 5. Life rafts were also rated at 5. Some air intake icing does occur in rough weather. As it is not viewed as a serious problem, it was provided a risk rating of only 2.

4.3.2 *Legend*-Class National Security Cutter

4.3.2.1 Ship mission and operating environment

The National Security Cutter (NSC) is a multi-mission ship intended to replace the aging High Endurance Cutters. The NSC is designed as a command and control vessel that could operate with the Navy in national emergencies. It is intended to be the flagship of the Coast Guard fleet, with better sea keeping, higher speeds, greater endurance and range, and the ability to launch and recover boats, helicopters, and unmanned aerial vehicles (UAV) in higher sea states than previously possible.

The Coast Guard now has three NSCs in service: the CGC BERTHOFF (Fig. 4-20), the CGC WAESCHE, and the CGC STRATTON, all based in Alameda, CA. A fourth ship is under construction, and four more are planned for a total of eight. The cutters are equipped with sophisticated electronic command and control hardware, a Sensitive Compartmented Information Facility (SCIF), a Combat Information Center, and ship survivability equipment such as the Close-in Weapon System (CWIS), or Phalanx, Gatling gun.

Figure 4-20. CGC BERTHOFF (US Coast Guard, n.d.).

The NSC can intercept vessels, rescue swimmers, protect fisheries, and execute maritime homeland security missions, counter terrorism missions, and coastal patrol missions. The overall mission profile is as follows:

1. SAR.
2. Drug interdiction.
3. Migrant interdiction.

4. Ports, waterways, and coastal security (PWCS).
5. Protection of living marine resources.
6. Other and general law enforcement.
7. Defense readiness operations.

The four Coast Guard missions that the NSC will not routinely perform are marine safety, ATON, marine environmental protection, and ice operations. These missions are the responsibility of other Coast Guard vessels, though could occasionally be done by NSCs (O'Rourke 2012).

4.3.2.2 Ship design and structure

The NSCs are 127 m long and displace about 4500 tons, and are similar in length and displacement to the Navy's *Oliver Hazard Perry* (FFG-7) class frigates (O'Rourke 2012). The hull is not ice-hardened and, when operating in cold weather, will not operate near the ice edge or in ice.

The bow is flared, which should divert spray to the sides and help keep the decks and superstructure dry in heavy seas (Fig. 4-21 and 4-22).

Figure 4-21. Flare of CGC WAESCHE bow (Ryerson 2012).

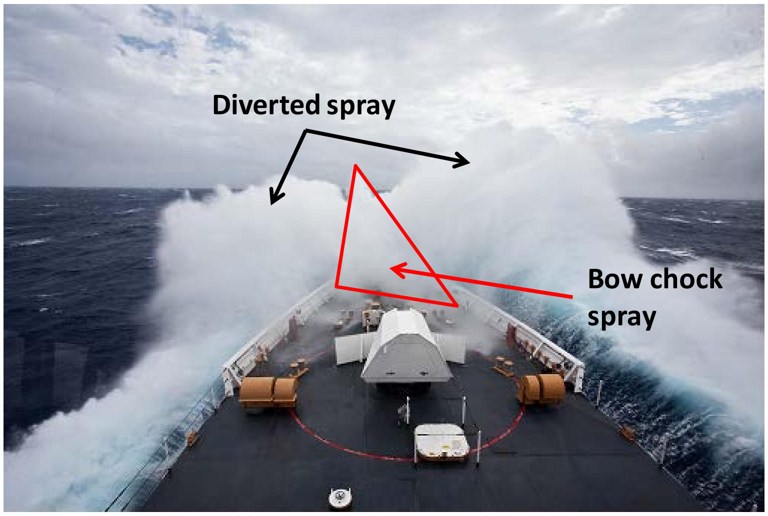

Figure 4-22. Spray diverted away from bow by flare in heavy seas. Note, however, water jetting through the bow chock and wetting the deck (courtesy LCDR Reid, CGC WAESCHE 2012).

In general, operations are required on the forecastle for anchoring and mooring, on the flight deck for helicopter and UAV operations, on the fantail for boat launches, and on the boat deck for boat launches. All of these areas are viewed as having the potential for icing from spray, snow, or water wash if operated in Arctic conditions.

4.3.2.3 Boots-on-Deck observations and icing experience

The NSCs have not operated in extreme cold weather conditions where superstructure icing could take place. Therefore, assessments of possible icing problems on the NSC are from crew members who have experienced icing on other cutter hulls and have extrapolated that experience to the NSC. A Boots-on-Deck visit to the CGC WAESCHE was made on 16 October 2012 in Alameda, CA.

In heavy weather, sea spray covers the forecastle by flowing over the bulwarks and through the bow chock. No water enters the deck through the hawse pipes because they are well-covered at the deck level, and the anchor fits closely into the anchor pockets, reducing water entry (Fig. 4-23 and 4-24). Small drainage holes in the frames where they exit the deck and support the bulwarks are only a few inches in diameter and would likely freeze closed early in an icing event reducing deck drainage and promoting deck ice accumulation (Fig. 4-25). Forecastle deck drains are often not located at the lowest areas of the deck, occasionally protrude from the deck, and are often clogged with rust and debris (Fig. 4-26). The drains are also routed though unheated areas that can cause freezing before the pipe exits the side of the ship near the waterline. Countermeasure wash-down nozzles in decks can freeze shut—but they are not expected to be needed in cold weather (Fig. 4-26). The aft end of the forecastle deck is flush with the ship sides, encouraging drainage of spray off the deck behind the gun and in front of the forward bulkhead.

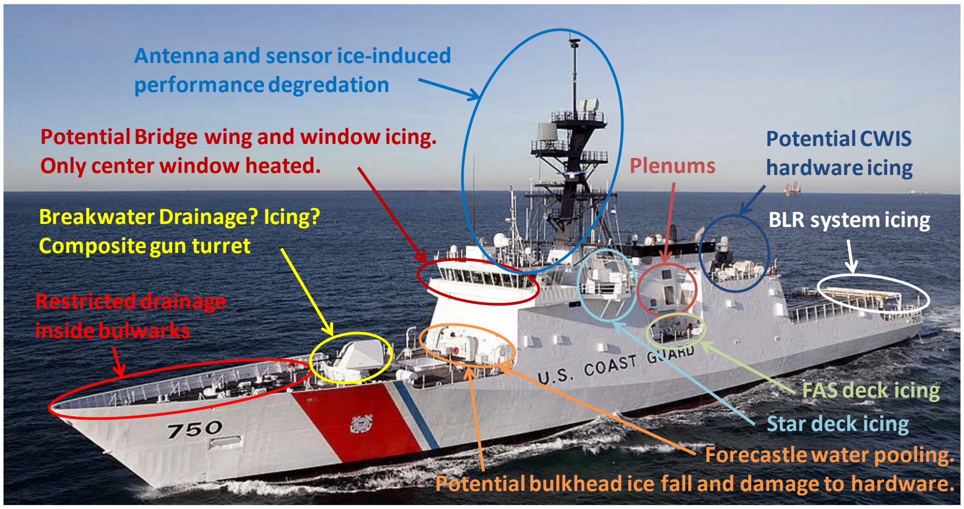

Figure 4-23. Areas of CGC WAESCHE where icing could occur and where icing could hinder operations (image from US Coast Guard).

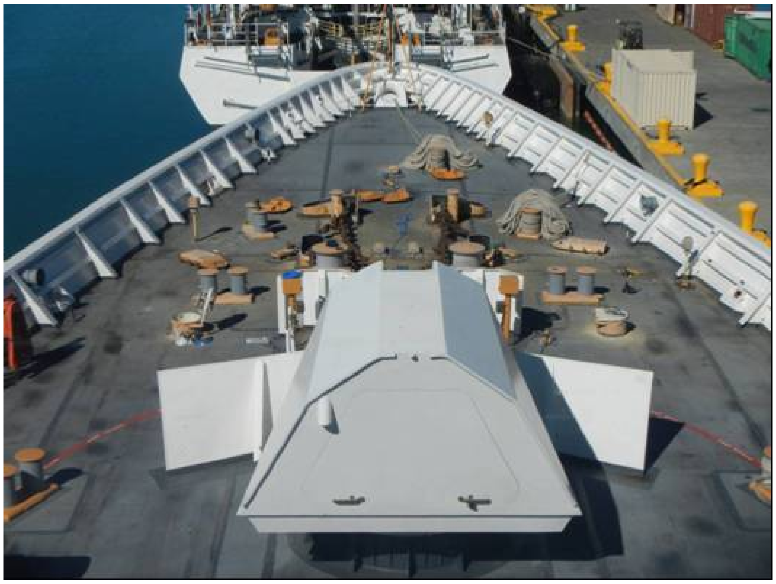

Figure 4-24. Forecastle of CGC WAESCHE showing 57-mm gun (foreground), gun spray shield, anchor release and retrieval hardware, and bollards for securing lines in port or when being towed. The wall around the perimeter of the forecastle deck is the bulwarks, which reduces spray on the deck (Ryerson 2012).

Figure 4-25. Holes in frames promote deck drainage—but may freeze shut (Ryerson 2012).

Figure 4.26. Deck drains are often not located in the lowest areas of the deck, they are often clogged with rust and construction debris, and are routed through cold areas that can cause freezing (left). Countermeasure wash-down deck nozzles could freeze, but are not expected to be needed in cold weather (right) (Ryerson 2012).

Low areas in the forecastle deck prevent full water drainage. Ice can form on non-skid in these areas from any source of water, especially when the ship is not moving. Rolling when underway minimizes this problem by allowing water to slosh and drain.

An enclosed area protecting piping and wires exiting the deck on the aft end of starboard bulwark has one small drain located at the high end and raised off of the deck. This will flood and freeze and ice removal will be difficult (Fig. 4-27). This problem has also been observed on the JUNIPER-Class buoy tenders.

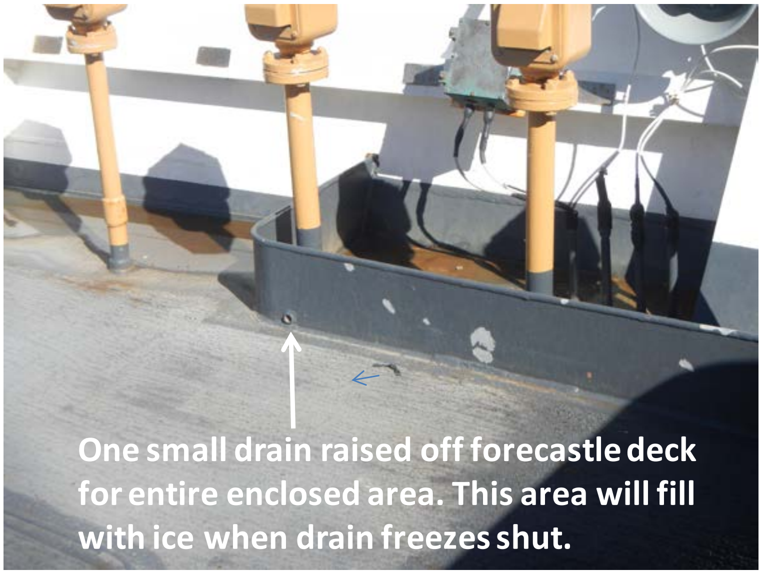

Figure 4-27. Enclosed area at aft end of starboard forecastle with one small drain that can freeze closed (Ryerson 2012).

The CGC WAESCHE has operated in heavy seas during Tropical Depression Haikui. When operating in 5.5- to 6.1-m seas and 35- to 40-kt (18.9- to 20.4-m/s) winds, and cruising at 18 kt (9.2 m/s), bow spray reached the bridge windows (Fig. 4-28). This suggests that, because the bridge is atop the high forward bulkhead, that the entire face of the bulkhead could ice. It would be possible to manually de-ice only the lower portion of the bulkhead because the higher portions are not accessible except via a pipe walkway that could be too ice-covered for safe use (Fig. 4-29).

Figure 4-28. Bow spray striking bridge window in Tropical Depression Haikui (courtesy LCDR Reid, CGC WAESCHE).

Figure 4-29. Spray reaches bridge in storms. Ice on high forward bulkhead could fall and damage antennas on bulkhead sides, and valves, wires and small piping lower on bulkhead (Ryerson 2012).

Figure 4-30. Bell and bullhorn cabling, and fire stanchion valves, could be damaged by ice falling from the forward bulkhead (Ryerson 2012).

Because the high forward bulkhead precludes manual ice removal, falling ice could damage antennas positioned under the bridge wing corners (Fig. 4-29). Bullhorn and bell wiring, and fire stanchion valves at the bulkhead base, could be damaged as ice falls from above (Fig. 4-30). In addition, ice falling from the forward bulkhead could damage countermeasure wash-down piping exiting the bulkhead and an antenna mounted on the bulkhead, and ice could coat the antenna, decreasing its sensitivity (Fig. 4-31).

Figure 4-31. Antennas and countermeasure wash-down piping could be damaged by ice falling from the forward bulkhead. Also, antenna performance could be reduced by ice (Ryerson 2012).

Figure 4-32. The 57-mm gun turret is a composite structure and could be damaged by manual de-icing. The spray shield below and forward of the gun may accumulate ice at its base and hinder forecastle deck drainage (Ryerson 2012).

The forecastle-mounted 57-mm cannon has a composite housing that could be damaged by manual de-icing techniques (Fig. 4-32). Some ships cover the forward gun with tarps when at sea. The spray shield forward of the gun mount could also limit deck drainage if ice falls from and accumulates around its base.

There is considerable concern about operation of the boat deck, and boat launch and recovery single point davit in icing conditions. The boat deck receives spray, and is expected to ice. There is much hardware in the area, making manual de-icing difficult and restricting deck drainage. Personnel must position to operate the davit at an exposed control station, and to handle lines over the side—such as painters (Fig. 4-33 and 4-34). Boat launch and recovery at this station is labor intensive and exposed to wind, spray, and cold on the deck, with crew often operating in positions where footing is critical.

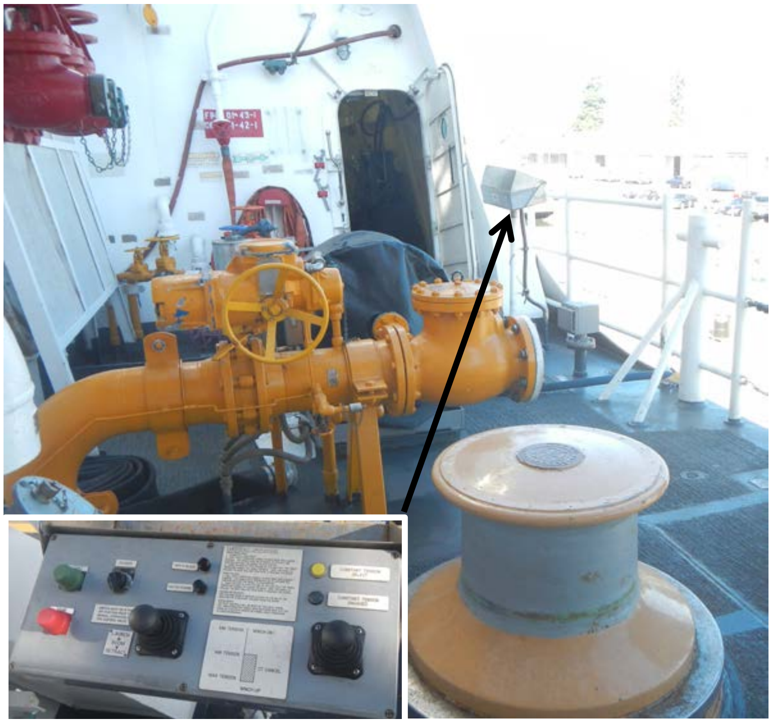

Figure 4-33. The boat deck has considerable hardware, operations involve several personnel, the area receives spray, and icing is expected. Inset shows single davit control station, and arrow shows control station location—on a deck that may be iced (Ryerson 2012).

Figure 4-34. Single davit for launching boat, located one level above boat deck. It is understood that little spray reaches this height, but it is a complex machine that is difficult to keep operating fully in less severe conditions than icing (Ryerson 2012).

An intake for the gas turbine is located on the boat deck (Fig. 4-35). Air passes through an unheated Foreign Object Damage (FOD) screen, through a heated manifold and heat exchanger, and through a louver system into a plenum inside the bulkhead. It was determined from engineering that the system is intended to prevent intake icing, but it has not been tested in actual operating conditions.

Figure 4-35. Gas turbine air intake on boat deck. A heated manifold behind the FOD screen is intended to keep the intake louvers de-iced. It is not clear how the FOD screen is de-iced (Ryerson 2012).

The flight deck, in general, is of little concern for icing. It is recognized that the deck could become snow covered, but it is not viewed as a serious problem. However, several components of the flight deck could experience ice or snow problems. The guidance system for moving helicopters in and out of hangars uses a grooved rail system that would readily fill with snow and ice and would be difficult to clear (Fig. 4-36). However, that system is not used and will be removed. The Navy had concerns about the icing of a similar system, the Recovery Assist Securing Traversing (RAST) system to guide helicopters between hangars and launch and recovery positions on the flight deck. The Navy determined that there were four potential ways to de-ice: mechanical, thermal, hydrodynamic, and chemical (Boston 1985). Icing of the hangar doors is not of concern.

Figure 4-36. Track for guiding helicopters into and out of hangar has not been used, and will be removed. Ice from spray or snow would hinder operation of the system if it were used. Note numerous tie downs in deck that fill with water and could become unusable when frozen (Ryerson 2012).

Rescue team nets along the flight deck perimeter must be lowered for flight operations. Pins used to hold the nets in their retracted position could freeze in-place and become difficult to remove from light spray, or even from snow (Fig. 4-37). However, crew members believe that the rescue nets would not ice sufficiently to cause problems, even when extended. Though stern slamming creates some spray, it is not viewed as significant to superstructure icing, though a cruise of an NSC into the Chukchi Sea and Beaufort Sea in the fall of 2012 found that the stern area can experience significant spray. Electronic gear on the flight deck edge and exposed armored flexible conduit could be damaged from snow shovels or other occasional de-icing (Fig. 4-38). Also, aircraft tie-downs (Fig. 4-36) and non-glare aviation clearance lights (Fig. 4-38) embedded in the flight deck could be easily covered by ice or snow and will require some care when de-icing.

Figure 4-37. Latches for flight ops rescue team nets involve pulling pins that could freeze, making removal difficult (US Coast Guard 2012).

Figure 4-38. Electronic gear and cabling on flight deck could be damaged by snow shoveling. Snow or ice must be removed with care around non-glare landing zone lights for them to be useful (US Coast Guard 2012).

A system that may be significantly compromised by Arctic conditions is the Boat Launch and Recovery (BLR) System in the stern (Fig. 4-39 and 4-40). The system uses a ramp with low friction runners and a winch to launch and recover boats. The lower portion of the ramp, a well at the stern, is always awash so that the boat can enter or depart the stern under power and afloat (Fig. 4-41). Grid mesh walkways on either side of the runners allow footing for personnel ingress and egress. Hydraulic doors close the back of the ramp when the boat is inside, but do not make the ramp well area watertight. Water within the well rises and falls with ship displacement changes—especially in heavy weather with ship heave, pitch, and roll. Cold weather will cause ice to form on all surfaces within the well and ramp area that are awash. This will cause slippery conditions for crew ingress and egress, and could cause launch difficulties if the boat freezes in place. It could cause recovery difficulties if the ramp becomes ice-covered when the boat is away. In addition, splashing of the clamshell doors in the closed or open position could cause ice to accumulate on the doors, or on the transom, hindering door operation. Ice on the transom could prevent the doors from opening or closing (Fig. 4-42).

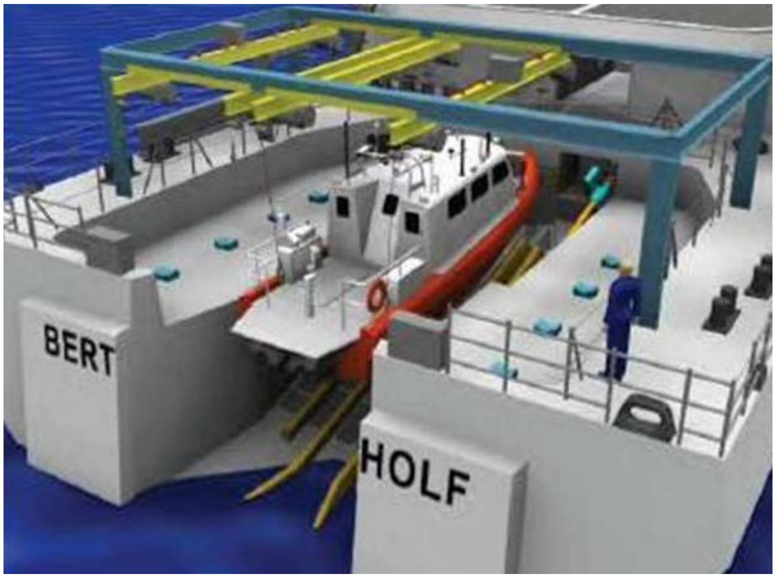

Figure 4-39. The Boat Launch and Recovery System consists of a launch and recovery well and ramp, a winching system, a door system to close the stern, and an overhead crane system for transporting boats to and from cradles (diagram from The *TCG Pulse*, Winter 2011, pages 2–5).

Water in the lower ramp well could freeze in extremely cold conditions (Fig. 4-41). That ice could hinder boat launching, and door opening. If operating in an area with brash ice, the boat could push ice into the well, hindering recovery. Also, ice could jam in the well area causing door closing difficulties. It could be dangerous for personnel to enter the ramp or well area to clear ice because they could slip into the well. The clutter of equipment on deck will make de-icing difficult. However, heat leaking into the area from surrounding mechanical areas may help keep the area de-iced.

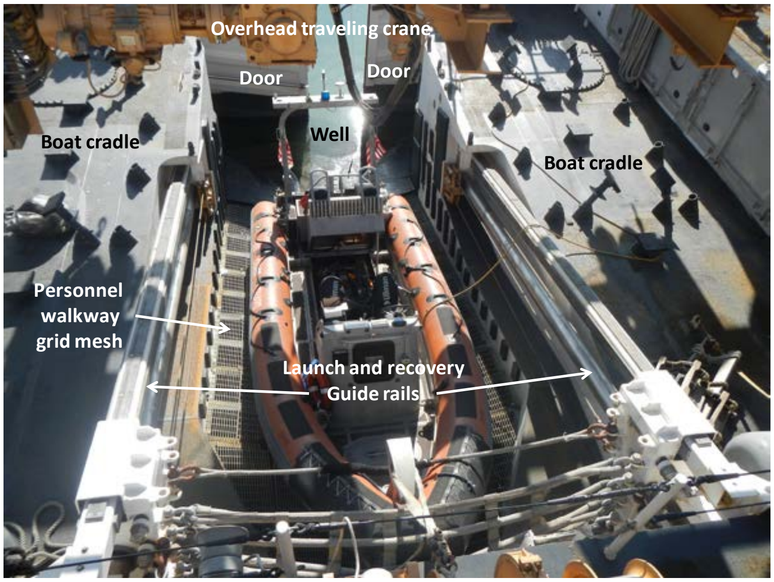

Figure 4-40. Details of BLR system (US Coast Guard 2012).

Figure 4-41. Starboard door of BLR system (US Coast Guard 2012).

Figure 4-42. Details of BLR System stern doors and vulnerable hydraulic door slides and cylinder mechanism outside transom on NSC STRATTON (Ryerson 2012).

An overhead traveling crane system moves boats to storage cradles port and starboard of the ramp well (Fig. 4-43). The overhead crane is a system of exposed rails, racks and gears, winches, cables, and electronics. Spray icing from slamming of the stern could cause difficulties with crane operation. It is not protected from spray and weather elements. It is expected to be replaced with one or two single point davits.

Figure 4-43. BLR system overhead crane (US Coast Guard 2012).

Located above the port hangar is the Close-in Weapon System (CWIS), or Phalanx Gatling gun, co-located with flight control instrumentation for the flight deck (Fig. 4-44). The photo shows a cover removed, above the ammunition feed barrel, which is replaced at sea. However, it also shows ammunition belts where rounds are fed from the magazine to the gun. If sufficient spray occurred in the area, or snow, or freezing rain, the system may malfunction because of ice-induced jamming.

Figure 4-44. CWIS system is located on the port side on top of hangar. Exposed ammunition belts that feed rounds from barrel below gun could jam in icing conditions (Ryerson 2012).

Figure 4-45. Visual approach slope indicator for helicopter landings on flight deck. Bellows icing could hinder movement or puncture bellows (Ryerson 2012).

Also, the helicopter landing aid system, located below the CWIS, could have movement hindered by ice and sustain damage to the bellows (Fig. 4-45).

The Fueling-at-Sea (FAS) deck on the port side could ice from spray or snow. Piping and winches must be kept clear of ice to allow fueling when underway (Fig. 4-46). Plenum screens above FAS deck on port side are not of serious concern (Fig. 4-47). It is assumed that they are exhaust vents, or low-velocity inlets, because they have no heating system nor FOD screens.

Figure 4-46. FAS deck with piping, winches and hardware that could ice, according to crew, and hinder fueling when underway (US Coast Guard 2012).

Figure 4-47. Plenum screens above FAS deck on port side. It is assumed that they are exhaust vents because they do not have FOD screens or heating systems (Ryerson 2012).

NSCs are configured as command and control centers. Therefore, they have a CIC and a SCIF that use tracking and communication systems requiring numerous antennas and sensors above the bridge and on the mast (Fig. 4-48–4-53). This capability must be protected for SAR and other activities because sea spray has been observed to reach the mast and bridge wings. In addition, atmospheric icing in the form of rime and glaze from freezing rain could reduce the effectiveness of antennas, optics, and associated equipment.

Figure 4-48. Mast with walkways and instrumentation, viewed from Boat Deck on starboard side (Ryerson 2012).

Figure 4-49. Mast with walkways and instrumentation, viewed from port (Ryerson 2012).

Figure 4-50. Starboard mast upper cross arm with anemometer (left), and various dipole and other antennas (Ryerson 2012).

Figure 4-51. Starboard mast lower cross arm with camera and antennas (Ryerson 2012).

Figure 4-52. Ship's horn with radar above and anemometer on port cross arm (Ryerson 2012).

Figure 4-53. Radar antenna (left), sensor under platform (right), and radar system on topmast (Ryerson 2012).

Bridge window wipers could freeze in place if not operated during icing conditions (Fig. 4-54). Only the front middle window is heated on the entire bridge.

Figure 4-54. Wiper mechanism on bridge windows (Ryerson 2012).

4.3.2.4 Anti-icing and de-icing procedures

De-icing and anti-icing procedures have not been formally developed for the NSCs beyond techniques and procedures used by crews when experiencing icing on other cutters. However, the Flooding Casualty Control Software (FCCS) icing module is being used to predict ice accumulation on the ship, and to determine the effect of ice load and its distribution on ship stability. Model output is used as an additional tool by commanders to make anti-icing and de-icing decisions.

4.3.2.5 Risk matrix

The CGC WAASCHE crew did not complete a risk matrix, nor were risk matrix elements discussed. The risk matrix below (Table 4-3) was generated from conversations with crew members who were knowledgeable about icing experiences on other cutters, or crew members who speculated about icing. The matrix is also derived from the Boots-on-Deck inspection and other ancillary information.

Table 4-3. Risk matrix for LEGEND-Class National Security Cutter.

	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Cutter function/component	Importance to Safety	10	5	2	3	1	0
Deck surfaces/ladders	9	90	45	18	27	9	0
Bulkheads	8	80	40	16	24	8	0
Antennas and electronics	8	80	40	16	24	8	0
Boats	8	80	40	16	24	8	0
Bridge windows	7	70	35	14	21	7	0
Fueling-at-Sea deck	7	70	35	14	21	7	0
Boat launch and Recovery System (BLRS)	7	70	35	14	21	7	0
Ventilation	6	60	30	12	18	6	0
Flight deck	5	50	25	10	15	5	0

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

The NSC has a mission profile similar to that of the High Endurance Cutters that they are replacing. This keeps the cutters most frequently well out to sea rather than operating near shore in the littoral zone. They, therefore, will be exposed less frequently to conditions in the littoral environment such as glaze from freezing rain or freezing drizzle.

Spray ice has the highest risk rating of ice types because of the amount of ice than can be created, and its saline properties have larger impact upon electronic systems. Snow was listed as second in importance, but significantly less than spray icing because the ship is often moving and less snow accumulates when the ship is in motion. Rime was third in importance because supercooled convection fog may be common, depending upon when and where the NSC is deployed, and rime affects antennas and electronic gear, which are important components of the NSC. Glaze is not expected to occur frequently far at sea.

The forecastle deck has anchoring and mooring equipment, and includes the 57-mm gun. Forecastle decks are typically rendered unusable in superstructure icing conditions, yet its functions are critical to safe ship operations, and to the security and defense readiness missions. The forward bulkhead of the NSC is high, and bow spray does strike the entire bulkhead in high winds and sea states, reaching 30 m above the sea. If it ices, higher areas cannot be manually de-iced, and falling ice could damage antennas, wash down nozzles, wiring, bullhorn, air valves, fire valves, and vents located on or at the immediate base of the bulkhead on the forecastle deck. In addition, personnel operating below the bulkhead could be injured by falling ice.

Part of the NSC's mission is command and control through the SCIF and CIC. This capability requires antennas, radars, Forward Looking Infrared imagers (FLIR), and other sensors and antenna systems that must operate under all conditions. Saline ice accumulation on instruments, and antennas, and meteorological gear on the mast could cause loss of capability through decreased sensitivity or complete loss of the instruments. This equipment is important for mission success and safety, including navigation capability.

The boat deck, located amidships on the starboard side, was of particular interest to several officers who said that the deck, which has considerable hardware for a variety of purposes, must be manned by several crew when launching and recovering the boat from the deck above with the single point davit. Crew must lean over the rail to handle the painter and to assist personnel into or out of the boat. In addition, the control station for the single point davit is located on the starboard main deck. The boat deck receives considerable spray, especially during launch and recovery in higher seas. Many missions require boat launching, which could be hazardous should icing have occurred. Icing could also occur on the turbine engine air inlet in this area. A heat exchanger is located over the bulkhead vent opening to provide de-icing heat. However, an unheated FOD screen with a relatively fine mesh on the cold side of the heat exchange could ice and may require periodic de-icing.

Bow generated spray readily reaches the bridge windows in heavy weather. Though all bridge windows have wipers and washers, only the center window is heated. Therefore, the bridge windows will ice over in freezing spray conditions, and wipers may freeze in place. Ice-free bridge windows are of high priority on most cutters.

Crew members familiar with icing indicated that the FAS deck must be kept clear at all times. Located amidships on the port side, numerous valves and vents must be kept ice-free. Snow is also expected to cause problems with this area.

Icing of the flight deck was not of serious concern on the NSC. The flight deck is protected from spray, and ice is not expected to accumulate on the hangar doors. Though snow could accumulate on the flight deck (non-skid is a difficult surface to de-ice and shovel snow from), snow was also considered of little concern. There could be difficulty with releasing the nets lowered around the flight deck during flight operations, and landing lights embedded in the deck could be difficult to keep clear of ice and snow, especially if they are converted to colder LED lights. Though rails for the helicopter Recovery Assist Securing Traversing (RAST) system are embedded in the flight deck and could easily clog with ice or snow, the system is not used and is scheduled for removal.

Though the BLRS is not a traditional superstructure icing problem, the boatswains expressed considerable concern about it. Superstructure icing from snow, rime, or spray could impede the gantry system for moving boats between cradles and the launch ramp; the system will be replaced in several years by two single-point davits. The greatest concern is ice formation within the launch ramp area, which is not watertight, and holds water in a well between the boat and the clamshell doors on the transom. Water within the well can freeze, brash ice could be pushed into the well upon boat recovery, and stern splash could ice the clamshell doors and mechanisms, causing them to not open or close completely. In addition, there was concern for personnel safety as crew need to traverse inclined grates between the ship deck and the boat that could ice over. A fall in this area could cause the victim to slide into the launch ramp well, or slide off of the fantail into the sea, creating a man-overboard incident.

4.3.3 140-ft *Bay*-Class icebreaking tug

4.3.3.1 Ship mission and operating environment

The Coast Guard operates a fleet of four 140-ft *Bay*-class (WTGB) icebreaking tugs on the East Coast based in ME, CT, and NJ, and five in the Great Lakes based in MI, WI, and OH (Fig. 4-55). They were commissioned between 1979 and 1988 and are a multi-mission craft. Their primary mission is icebreaking, and each vessel averages about 184 hours per year (CGC MORRO BAY stationed in New London, CT) to 594 hours per year (CGC KATMAI BAY stationed in Sault Ste. Marie, MI) executing the mission, depending upon the area of operation (Cross 2005).

Figure 4-55. *Bay*-class 140-ft CGC BRISTOL BAY (US Coast Guard, n.d.).

Along the East Coast much of the 140's icebreaking time is used to open waterways for bringing fuel oil barges into Boston, New York, Portland, Albany, and through the Cape Cod Canal. They also keep ports open for fishing boats and ferryboats (Morgan 2011). On the Great Lakes, the 140s are used in Operation Taconite in the western Great Lakes to maintain taconite movement, and in Operation Coal Shovel in the eastern Great Lakes to maintain coal movements. The 140-ft tugs are a primary Great Lakes icebreaking asset, in addition to the CGC MACKINAW. Operations in the Great Lakes require breaking of fresh water ice, considerably harder than first-year sea ice.

Overall, there are 12 missions assigned to the 140-ft *Bay*-Class tugs. However, the primary missions are Ice Operations, SAR, Pollution Response, ATON, and Law Enforcement. Of those missions, ice operations are most demanding and require the most mission time.

Despite the primary missions assigned, a compilation of mission hours spent by all nine of the 140-ft cutters over 10 years shows that about 95% of the mission hours conducted by the class are (Cross 2005):

1. Ice Operations	31.5%
2. Support (training, public affairs, etc.)	23.8%
3. Ports, Waterways, Coastal Security	18.7%
4. ATON	14.6%
5. Living Marine Resources	6.3%

Ice operations specifically require transits in cold conditions, those periods when superstructure icing is most likely from bow spray and atmospheric sources. Transit in support of the ice breaking mission is most likely to expose the cutters to icing; icebreaking itself does not cause icing exposure except from snow, frost or glaze.

4.3.3.2 Ship design and structure

The 140-ft icebreaking tugs have an 11.4-m bean with a displacement of 662 tons. They can cruise at a maximum speed of 14.7 kt (7.5 m/s), and can break 46 to 51 cm of ice. Icebreaking is aided by a unique low-pressure bubbler system that forces air around the hull and reduces friction between the hull and the ice.

Overall, the cutter creates considerable spray in transit. The hull has little rake, and freeboard is small; approximately 3 m at the bow to the top of the bulwarks, and approximately 1.5 m amidships (see Fig. 4-55). Bow spray superstructure icing is a significant problem in the Great Lakes. Waves “kick-up” on the shallower lakes, such as Lake Erie, quickly and the west–east orientation of the main axes of lakes Superior, Erie, and Ontario provides a long fetch that creates significant waves. Cutters traveling east to west have the greatest probability for significant spray generation because of the long lake fetches, and because predominant winds are from west to east.

On the East Coast the cutters are exposed to extreme cold as continental air moves seaward. In addition, they operate in bays, estuaries, and in locations surrounded by land, such as the Hudson River. These environments do not often provide waves that create bow spray, but snow, freezing rain and freezing drizzle, and frost are more common. In addition, the cutter moves relatively slowly when icebreaking, providing little opportunity for relative wind to blow snow off of the decks.

The short length of the cutter and its low freeboard provide sea keeping characteristics similar to that of a fishing trawler. Compared to a fishing trawler or crabber that has more rigging and may have crab pots stacked on deck, raising center of gravity, the 140 has a relatively low center of gravity. However, it may interact with seas as vigorously as a fishing trawler, creating spray as often. Therefore, it may be appropriate, for guidance, to apply forecasts used by NOAA that are based on fishing trawler icing experiences to the 140-ft icebreaking tug.

4.3.3.3 Boots-on-Deck observations and icing experience

A Boots-on-Deck visit on CGC THUNDER BAY in Rockland, ME, provided discussions of icing experiences, a risk matrix, and images from a guided tour by the Commanding Officer (CO) and Executive Officer (EO). Ship officers had experience with fresh and salt water superstructure icing.

Spray and ice have been observed as high as the flying bridge on the CGC THUNDER BAY, though usually not higher. Spray typically tapers off towards the stern as shown with the blue lines in Figure 4-56. More pronounced bow flare might deflect spray away from the ship and reduce icing, as might a spray deflector on the bow. A blue dodge (tarp) is placed on the railings on the 01 and 02 levels above the forward bulkhead to protect bridge windows, and antennas, Global Positioning System (GPS), and navigation systems above the bridge. Ice adheres to the dodges in morning, but the sun quickly warms them and the ice falls off (Fig. 4-55 and 4-56).

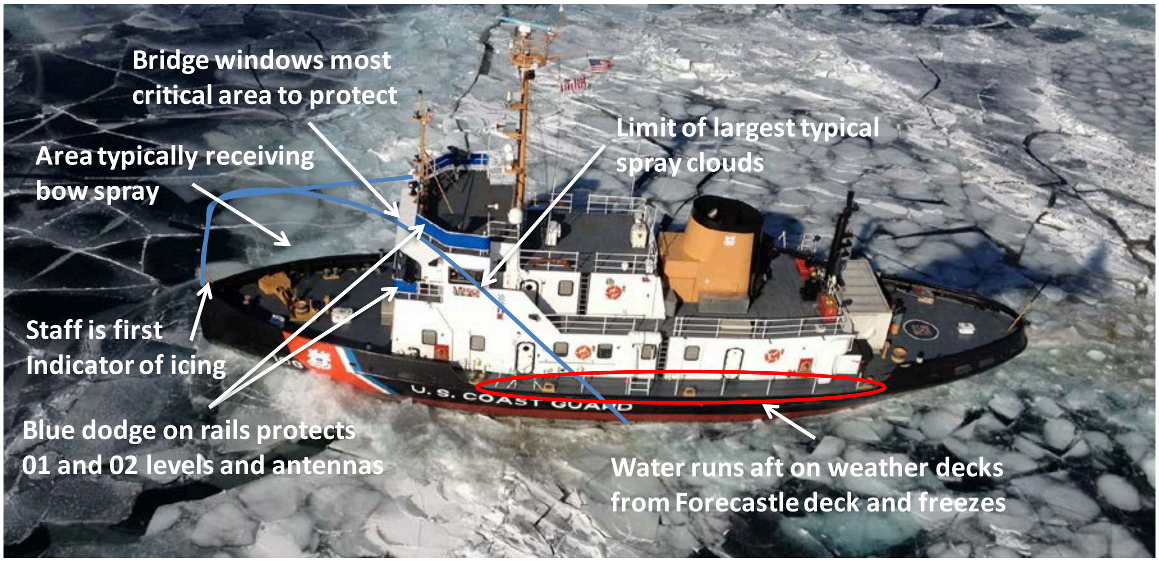

Figure 4-56. Locations of spray and icing characteristics on the CGC THUNDER BAY (US Coast Guard, n.d.).

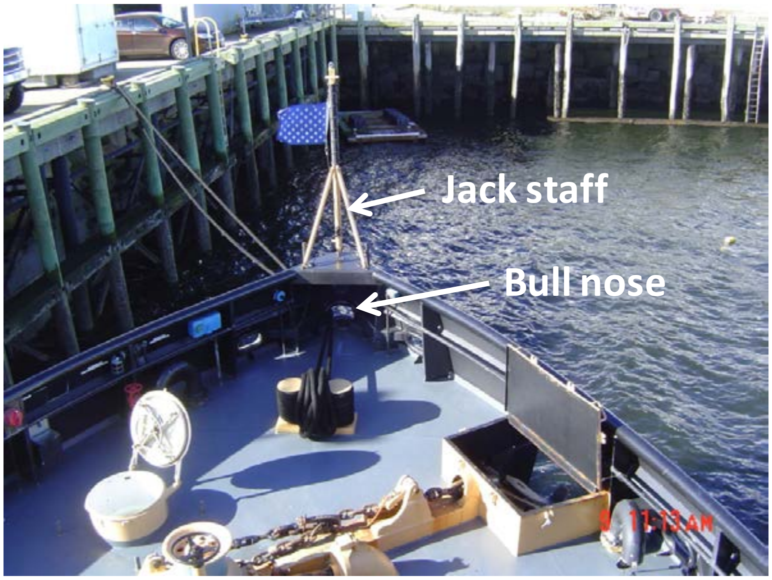

Figure 4-57 Initial icing is observed on jack staff, in bull nose, and on sides of hull (CRREL 2012).

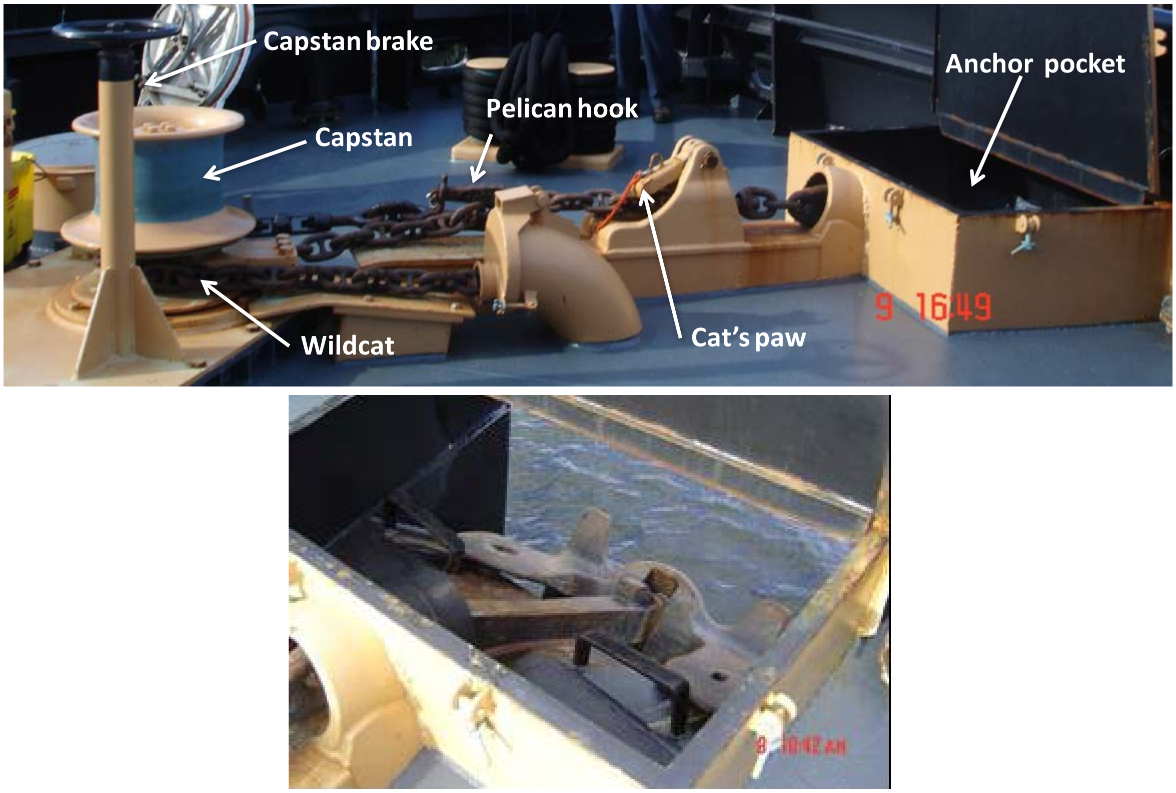

Figure 4-58. Anchor hardware that ices on the forecastle deck (CRREL 2012).

Generally, the sides of the hull, the bull nose, and the Jack staff ice on the forecastle first. The Jack staff is typically watched as an indicator; it is usually the first sign of icing (Fig. 4-57). Also, the anchor cannot be released until its hardware is de-iced. Anchor chain wound around the wildcat freezes, and the actual anchor freezes in place (Fig. 4-58). The cats paw and pelican hook both ice and must be de-iced for anchor use. Anchor detail is a high safety issue owing to frequent navigation of the ship in proximity to shoal water. Mooring is also difficult when equipment is iced because of deck ice, iced chocks, and iced bits. Hammers are used to de-ice the chocks when they occasionally freeze.

The CGC BISCAYNE BAY in Lake Superior shows how serious icing of the forward bulkhead can become (Fig. 4-59, upper left). Bridge windows are clear via window heaters, but the window wipers are iced, as are the ship's bell and horn. Window wipers will freeze unless they are kept running during freezing spray conditions. The ice-free bridge and forward bulkhead of CGC THUNDER BAY are shown for comparison (Fig. 4-59, upper right). During de-icing the crew can reach most of the forward bulkhead from below—and the remainder can be reached from the 01 level walkway in front of bridge windows (Fig. 4-59, bottom). In this situation freezing spray reached the radar but little spray reached the spar on the mast.

The highest locations on the ship always have highest priority for de-icing because of the negative stability caused by ice weight raising the ship's center of gravity. For this same reason, icing of the forecastle and main deck improves ship stability. Priorities for de-icing are 1) the forward bulkhead and 02 level decks and 2) the forecastle, side, and then other weather decks (Fig. 4-59).

Flying bridge electronics are more affected by cold than by ice. They are not turned off when cold weather is expected because they may not start after cold-soaking. The ship's horn and enunciator often fail in icing conditions (Fig. 4-59 and 4-60).

Figure 4-59. Iced bridge and flying bridge on CGC BISCAYNE BAY in Lake Superior (upper left). Ice free bridge and flying bridge on CGC THUNDER BAY for comparison (upper right). Bottom image shows height to which de-icing can occur from the forecastle deck. (CGC BISCAYNE BAY photos courtesy LCDR Godwin, USCG; CGC THUNDER BAY photos by CRREL 2012).

Figure 4-60. Spray and icing reached the ships horn about 15 ft above the flying bridge on the CGC BISCAYNE BAY (see Fig. 4-59). This photo is of the CGC THUNDER BAY (CRREL 2012).

Shear of the forecastle deck encourages drainage; there is no need to improve drainage of the forecastle deck or of any of the ship. Drain blockage is not a problem. However, excess water draining from the forecastle deck runs aft as a “river” of water along the side weather decks and causes ice accumulation on those decks (Fig. 4-56, 4-61 and 4-62). A lip along the deck edge prevents water from running off of the cutter; the lip prevents spills of fuel and other chemicals from reaching the ocean. However, the deck lip causes flooding and icing of side weather decks, which is a safety issue.

Figure 4-61. Lip along deck edge prevents pollutants spilled on deck from reaching the sea (left image). However, it also reduces deck drainage allowing greater ice accumulation on side weather decks except where there are drains, which never freeze or clog on the THUNDER BAY (right image) (CRREL 2012).

Spray reaches as far aft as the boat deck on the main deck, sometimes allowing several inches of ice to accumulate (Fig. 4-62). Icing prevents boat launching from the starboard 01 level boat deck, even though icing is rare on the 01 level. The main deck below the boat deck ices where crew needs to work loading or unloading the boat, and manning the painter. Handling a painter on an iced deck is extremely dangerous. Boat launches are cancelled when decks are iced except under the most extreme of circumstances. Weather decks are always secured during and after icing because crew can slip overboard under lifelines. A buddy system is used whenever personnel enter decks in icing conditions.

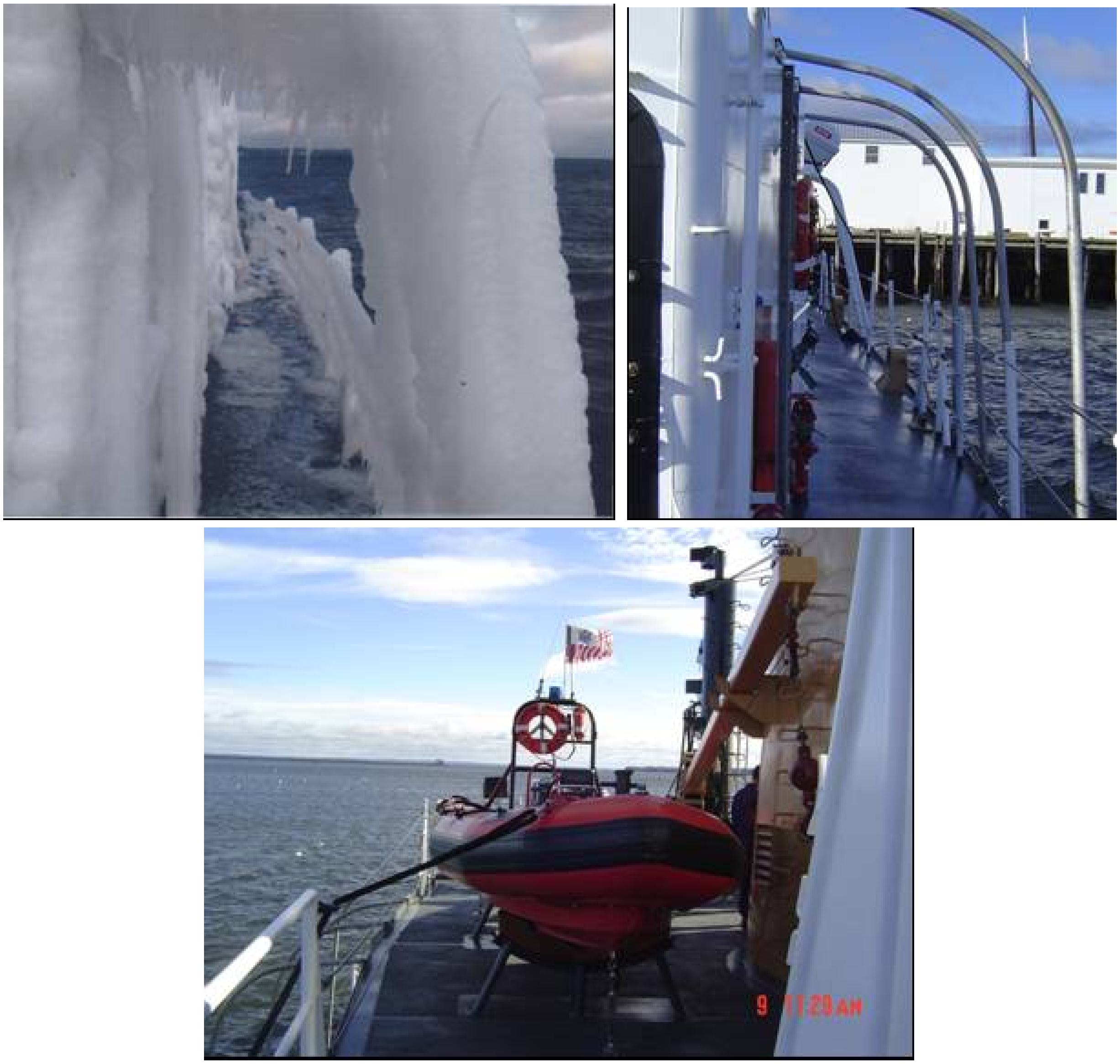

Figure 4-62. Icing of CGC BISCAYNE BAY in Lake Superior (upper left). Same area without ice on CGC THUNDER BAY (upper right). The cradled boat on the 01 level boat deck does not ice, and is covered by a tarp in icing conditions (bottom). (CGC BISCAYNE BAY photo courtesy LCDR Godwin, USCG; CGC THUNDER BAY photo CRREL 2012).

Weather deck de-icing, or anti-icing, is encouraged by the use of space heaters below deck. Space heater output is increased during icing, often making below decks uncomfortably warm, to encourage warming decks from below (Fig. 4-63).

Figure 4-63. Space heater used to heat space under forecastle deck to reduce icing and help de-icing (CRREL 2012).

Weather deck fire stations are closed during winter because they freeze in place and cannot be used (Fig. 4-64). In addition, initial fire response by crew could be inhibited by slippery conditions on deck. Fuel and sewage valves and vents, and fire valves, become covered with ice, especially forward of amidships. In addition, double braided line remains flexible in icing conditions, but synthetic line freezes hard and is unusable (Fig. 4-65). Tarps are often placed over lines and other hardware to keep them free of ice (Fig. 4-66). Life rafts, which cannot be covered with tarps, may also not release properly and could be frozen in place by freezing spray.

Figure 4-64. Valves and vents become ice covered forward of amidships (left image). Fire hoses are removed before winter because they freeze in place (right image) (CRREL 2012).

Figure 4-65. Synthetic line (wound around cleat) freezes hard; double braided line on ladder stays flexible in cold weather (CRREL 2012).

Figure 4-66. Gun mount covered with tarp to reduce icing and other weather effects (CRREL 2012).

The following paragraphs describe experiences and opinions about freshwater and saltwater superstructure icing by *Bay*-Class crews. Some experiences relate to the Great Lakes and others to oceanic locations.

Icing is very dynamic; 1.5- to 1.8-m seas on Lake Ontario have a short period and create much spray. However, a following 4.6-m sea may create no spray. Occasionally, large volumes of spray are allowed over the forecastle to remove or prevent ice by flooding the deck with warm water. The primary difference between fresh and salt water icing is the temperature at which it begins. Saline spray icing is most serious from January through March, under clear skies and –2.2 to –1.1°C temperatures. Icing begins at 1.1 to 1.7°C in fresh water; whereas icing is of no concern at these temperatures in salt water. Fresh water ice accumulates faster, adheres more firmly, lasts longer, and is more difficult to remove than salt water ice.

A clear sky indicates that there will be icing, as a clear sky lowers temperatures. Surfaces facing the sky ice first on clear nights because of radiative cooling. If there is cloud cover there is often no icing. The ship also loses heat and noticeably ices faster in very cold weather.

No rime ice has been observed on the CGC THUNDER BAY, and the ship has experienced only about 1 hour of freezing rain, creating only small amounts of glaze ice. The crew begins shoveling snow when no more than 5 cm accumulates. The ship is also heated when there is snow to cause melt. The boiler is running if the captain knows and believes there will be snow.

Other icing experiences on the *Bay*-Class icebreaking tugs were provided from questionnaires distributed to the crews of several cutters. Icing experiences were provided by the CGC BISCAYNE BAY, home port of St Ignace, MI. The BISCAYNE BAY's primary area of responsibility is the upper Great Lakes (lakes Michigan, Huron, and Superior; Godwin 2012). The following events are paraphrased from experiences.

Over 3 years, the cutter experienced some topside icing on at least 50 occasions. Most icing events were minor (less than 2.5 cm thick), but there was significant icing on at least a dozen occasions. Icing on the Great Lakes is different from icing in salt water; temperatures need not be as low, and the ice is harder (Godwin 2012).

> Most icing occurs during open water transits in the months between November and April. The WTGB creates significant spray in seas as small as 4 ft. Air temperatures at or below freezing, with any significant wave action, requires caution when transiting open water. Most icing forms on the forward half of the ship, but when proceeding with the waves and wind

> off one side of the ship, icing will occur more on the windward side (Godwin 2012).

The most extreme icing was experienced when crossing Lake Superior in December (Godwin 2012). A trip that would normally require less than 24 hours required 4 days.

> The first day the cutter encountered 20 kt winds from the north with corresponding seas ranging from 6 to 8 ft and temperatures hovering around 30°F. The cutter sailed from Sault Ste Marie, MI, to Marquette, MI, and had to anchor and remove up to 6 in. of ice from the forward half of the ship (superstructure up to 01 deck, main deck and bulwarks). It required approximately 3 hours to remove the ice using large mallets and shovels. On day two the cutter reached the eastern tip of the Keweenaw Peninsula in 25-kt winds from the north with seas building to 10 ft and temperatures in the mid-twenties before anchoring and removing another 6–8 in. of ice from the forward half of the ship (Godwin 2012).

On day three the cutter attempted to reach the north shore of the lake in hopes of reaching calmer seas in the lee of the shore but could only make it half way before finding refuge in a bay at Isle Royale. Seas were 3 to 3.7 m, with temperatures about –5°C. The cutter spent most of the day diving into the seas and iced less than previous days, perhaps because water washing over the deck was warmer than the air and prevented freezing. However, approximately 5 to 10 cm of ice still needed to be removed from the forward half of the ship (Godwin 2012).

> Day four was by far the worst for icing. When the BISCAYNE BAY departed Isle Royale the temperature had fallen to 10°F and the wind had shifted to the northwest at 25–30 kt. The cutter made it to the north shore before tracking west for Duluth. The seas were still 4 ft but the high winds created a very fine spray that swept across the ship, especially the forward starboard side. Ice formed quickly and 7 hours into the transit, 6 to 8 in. of ice had formed on the forecas-

> tle and starboard side of the ship. We had a 5° starboard list and we slowed to remove the ice before proceeding further. Temperatures by this time had fallen to near 0°F. After two hours, enough ice had been removed to continue the trip. The cutter safely moored 4 hours later and the following day the crew removed the remaining ice that reached as high as the flying bridge. After all the ice was removed, the freeboard rose 1.5 ft. During this and every other icing experience, the Engineer Officer provided continual stability calculations allowing management of operational risk and minimize ice build-up when possible (Godwin 2012).

According to LTC Godwin (2012), commander of the BISCAYNE BAY for 3 years:

> Icing negatively impacted just about every aspect of shipboard life. Ship stability was the most critical element to manage when experiencing icing and required constant monitoring using the Shipboard Command and Control System (SCCS) program coupled with prudent seamanship. Managing operational risk vs gain is also critical when considering whether to operate in icing conditions. Prudence would often necessitate delaying or cancelling a mission. Once icing did occur, everything became more difficult; doors would freeze shut, ventilation would get obstructed, windows would cover limiting visibility, decks became dangerous to traverse, life rafts became frozen in, small boats became useless, falling ice became a safety hazard, and sensitive electronic equipment became damaged. Icing made it most difficult to do anything on deck such as mooring, anchoring, or even simply conducting a round of the ship. There were several instances when freezing spray remained for a month or more. Attempting to remove it would have caused damage to equipment. Even when being cautious while removing ice, equipment was damaged, paint chipped, and even external piping cracked.

LCDR Wyatt (2012) relates experiences with icing on the original CGC MACKINAW, on the 65-ft (19.8-m) Small Harbor Tugs, and the 140-ft (42.7-m) icebreaking tug CGC MORRO BAY. It is unclear which experiences relate to which vessel. The CGC MORRO BAY operated in the Hudson River and within District 1 offshore and in the St. Lawrence Seaway and the Great Lakes. Sea spray icing was his primary concern, with freezing rain second. Topside ice from snow or frost was not an issue; most snow accumulated while moored and the decks were kept shoveled. Ice thicknesses have ranged from a light glaze less than 0.6 cm thick, to ice over 30 cm thick. Ice covered the rigging, rails, superstructure, mast, antennas, decks, bow, and the windward side of the hull. He states that the following is associated with icing: cold (below 0°C) + wind and seas (forward of the beam) + speed = topside icing.

LCDR Wyatt (2012) says that exterior work by the crew becomes extremely hazardous during and after icing events. Heavy ice on deck equipment (windlass, davit, etc.) prohibits use of that gear until it is de-iced. Forward weather decks are the most affected, and the mast and rigging to a lesser degree. He adds that:

> Adding uncontrolled topside weight quickly becomes a serious stability issue to the point where loss of the vessel is a possibility. A crew responding to an urgent SAR is less likely to stop and take the time needed to clear topside ice before it becomes a stability concern. I've seen post SAR photos of 44-ft motor life boats with so much topside ice it was listing at the pier.

4.3.3.4 Anti-icing and de-icing procedures

On the CGC THUNDER BAY, ship speed is decreased under icing conditions to reduce spray. Reducing speed or altering course to reduce the rate of growth is also a tactic used by LCDR Wyatt on the CGC MORRO BAY (Wyatt 2012). Ship speed on the CGC THUNDER BAY is selected to reduce rolling and spray, and ship speed is adjusted to synchronize ship motion with the seas to reduce spray. Bats, shovels, and urethane mallets are used to remove ice. *Ice Melt* (a mix of sodium chloride and magnesium chloride) does not work well on decks if applied after ice accumulates. *Ice Melt* is typically applied before icing to reduce ice adhesion.

The CGC BISCAYNE BAY avoided icing by not sailing in icing conditions. However, they also used alternative routes, taking advantage of lees, slowed down, altered course to provide a better ride, and used equipment covers and canvas dodgers.

Despite avoidance of icing, de-icing was often necessary on the CGC BISCAYNE BAY. LCDR Godwin (2012) states that:

> Crew fatigue was a major concern in managing operational risk. After battling heavy seas, sea sickness, and hours of watch, the removal of ice was an all-hands event. The cutter kept a healthy supply of 5-lb composite mallets and snow shovels for ice removal evolutions. Additionally, we kept a supply of aircraft anti-icing fluid to be used on windows and sensitive electronic equipment. The anti-icing fluid was applied by commercially purchased hand-held sprayers.

LCDR Godwin (2012) continues:

> Removing the ice was a time-consuming evolution that often took hours of back-breaking work in frigid conditions and dangerous working conditions. We experienced one personnel mishap due to falling ice (bruised hand and wrist). Preferably, icing should be considered during ship design and construction, especially if the ship is destined to operate in a cold weather environment.

LCDR Wyatt (2012) of the CGC MORRO BAY indicates that:

> It can be dangerous to put crew members on deck to de-ice. The first line of defense is to reduce speed and/or alter course to reduce the amount of spray and slow the rate of ice formation. If that isn't an option you will eventually have to turn to put the winds aft of the beam and run down swell at slow speed to give the crew a stable platform while they go out and knock the ice off. Ideally, remove weight high and outboard first to improve stability but they may have to concentrate

> on the deck first to ensure they don't slide and fall as the ship rolls, and ice falling from the rigging is always a safety concern.

He details de-icing procedures by stating that “it is dangerous, labor intensive, and time consuming. Basically, the crew is out on a slippery, lumpy ice rink with lots of tripping hazards, swinging heavy impact weapons, sometimes in the dark while the ship rolls about at random intervals.” If ice is not removed by the first blow of an ice mallet or similar device, it must be struck multiple times until it is removed. “Usually all available hands” are necessary “to get it done as quickly/safely as possible.” Occasionally someone tries to speed up the process and hurts themselves, a shipmate, equipment, or a combination of all three.

A steam lance is an excellent de-icing tool if steam is available. However, as steam is generally not available on modern cutters, wooden baseball bats and plastic sledge hammers are used to reduce the risk of damaging paint under the ice. Plastic snow shovels and brooms are used to remove ice from the deck once it is broken (Wyatt 2012). Once decks are safe to walk on, all the other ice can be removed such as from life rafts, damage control fittings, superstructure, mast/rigging/antennas, boats, hand rails, scuppers/deck drains, and the hull. Antennas and radar domes are easily damaged by manual de-icing, but they are usually hard to reach. And engine room air intakes need to be protected if they are subject to icing (not a problem on the CGC MORRO BAY) (Wyatt 2012).

As observed on the CGC THUNDER BAY, sunlight encourages natural ice melting on the CGC MORRO BAY, especially over dark paint even when the air temperature is well below freezing. Tarps over deck equipment keep spray from freezing inside small moving parts (Wyatt 2012). They also prevent damage to equipment from over-zealous de-icing procedures, such as de-icing an anchor windlass with a propane torch and causing bearing seizure.

In new design, electric heating elements could be installed along the main exterior walkways, to improve safety, and on the mast, which is difficult to reach for manual ice removal. Adequate generator capacity would be needed with a thermostat to prevent burnout when conditions warm, as occurs with heated bridge windows. See Figure 4-78 as an example of heated window overheating on a *Juniper*-Class cutter.

4.3.3.5 Risk matrix

Risk matrices were developed by crew, or former crew, of three 140-ft icebreaking tugs—the CGC THUNDER BAY, the CGC BISCAYNE BAY, and the CGC MORRO BAY. Though respondents from the CGC BISCAYNE BAY and the CGC MORRO BAY addressed icing on other cutter types in narrative, they had explicit and relatively more recent experiences in the 140s. Therefore, their matrices were combined with the CGC THUNDER BAY matrix to produce the combined matrix. The CGC THUNDER BAY and CGC MORRO BAY are based on the East Coast, and the CGC BISCAYNE BAY is based at St. Ignace, MI, between Lake Huron and Lake Michigan. Therefore, the matrix combines experiences from ships based in both salt water and fresh water (Table 4-4).

Table 4-4. Risk matrix for BAY-Class 140-ft icebreaking tug (blue font indicates cutter function; black indicates cutter components).

	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Cutter function/component	Importance to Safety	10	7	4	3	2	1
Stability	10	100	70	40	30	20	10
Damage Control	10	100	70	40	30	20	10
Domestic Icebreaking	10	100	70	40	30	20	10
SAR	10	100	70	40	30	20	10
Mooring/navigation/piloting	10	100	70	40	30	20	10
Rafts	10	100	70	40	30	20	10
Deck Surfaces/ladders	9	90	63	36	27	18	9
Bridge windows	9	90	63	36	27	18	9
Hatches	9	90	63	36	27	18	9
Bulkheads	9	90	63	36	27	18	9
Fire stations	9	90	63	36	27	18	9
Boats	7	70	49	28	21	14	7
Deck machinery	7	70	49	28	21	14	7
Antennas and electronics	7	70	49	28	21	14	7
Lifelines/railings	5	50	35	20	15	10	5
Deck Drains	5	50	35	20	15	10	5
Tank valves/vents	4	40	28	16	12	8	4

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

Spray ice is considered the most important form of icing because of the amount of ice it can deposit on the cutter, and the impact that it has on operations. Snow and glaze are also important because these cutters operate near-shore and in rivers and bays that are dominated by weather that occurs over land surfaces. Near-surface thermal conditions far at sea are modified by the water and make glaze less common. In addition, these cutters often operate at low speed breaking ice; therefore, snow is more likely to accumulate on decks. Bow spray ice accretion has a rating of 10 for its effects on stability, life rafts, damage control, domestic icebreaking, SAR and mooring, navigation, and piloting. Stability was highly rated by all three cutters. The addition of domestic icebreaking to the list, and its high rating, suggests that attempting icebreaking with superstructure icing on the vessel may be hazardous. Snow has a lesser impact on the six 10-rated items, but still very important.

The deck surfaces and ladders, bridge windows, bulkheads, doors and hatches, and fire stations, which could also fall under damage control, are rated as 9 in their importance if hindered by icing. The need to have decks and bridge windows clear of ice has also been emphasized in discussions and written narratives by 140-ft icebreaking tug operators.

Boat operations, deck machinery, and antennas and electronics averaged 7 in importance to icing effects. However, the importance by each cutter varied considerably, ranging 3 to 10 for boat operations to less for the others. All other items on the list had lower ratings for importance to safety if iced.

Rime, frost, and sleet have very little impact, as ice types, on the operations of the 140-ft icebreaking tugs. And, for spray icing, operations in the Great Lakes in fresh water are nearly always expected to cause more severe conditions than saline spray icing because of fresh water's higher freezing temperature and greater hardness and adhesion strength, especially when initially formed.

It is clear that bow-spray generated ice and snow are the greatest icing-related threats to safety on the 140s. With regard to cutter functions and components, ship survivability (including stability, damage control, fire response, life rafts, and mast electronics), ability to accomplish key missions (icebreaking, SAR and mooring, navigation, and piloting), and the ability to see through windows, communicate, and access main decks are of greatest concern.

4.3.4 225-ft *Juniper*-Class seagoing buoy tender

4.3.4.1 Ship mission and operating environment

The Coast Guard operates 16 *Juniper*-Class buoy tenders (WLB) on the East Coast, the West Coast, the Gulf of Mexico, the Great Lakes, Alaska, and Guam. Commissioned between 1996 and 2004, they are a modern fleet of cutters that operates in a wide range of environments, with a primary mission of maintaining ATON. The WLBs are multi-mission vessels, performing ATON, icebreaking, SAR, homeland security, law enforcement, and marine environmental protection (Fig. 4-67).

Figure 4-67. CGC OAK showing spray generated in calm seas and forecastle crane in parked position over buoy deck when underway (US Coast Guard, n.d.).

The WLBs have an ice-strengthened hull that allows some icebreaking capability. Therefore, five of the cutters have some experience breaking ice, and cold weather experience at sea when superstructure icing could happen. These cutters include the CGC ALDER in Duluth, MN, the CGC HOLLYHOCK in Port Huron, MI, the CGC ELM in Atlantic Beach, NC, the CGC JUNIPER in Newport, RI, and the CGC WILLOW in Newport, RI (Cross 2005). In addition, the CGC FIR in Astoria, OR, and the CGC HICKORY, the CGC MAPLE, the CGC SPAR and the CGC SYCAMORE located in Homer, Sitka, Kodiak and Cordova, AK, respectively, would all be expected to have potentially experienced superstructure icing.

4.3.4.2 Ship design and structure

The *Juniper*-Class cutters are among the most advanced Coast Guard vessels. With a length of 225 ft (68.6 m), a beam of 46 ft (14 m), and displacing 2000 tons, the cutters have a large deck area consisting of a forecastle deck and a buoy deck forward of the forward bulkhead. They are rated for a speed of 15 kt (7.7 m/s). The hull is designed to break 36 cm of fresh water ice at 3 kt (1.5 m/s) continuous speeds, and 0.9 m of packed fresh water ice by ramming.

The cutter is one of the most advanced vessels afloat with regard to computers, navigation, environmental protection, and remote monitoring systems. The Integrated Ship Control System coordinates radar, satellite navigation, and computer generated charts with the controllable pitch propeller, rudder, and thrusters. These tools allow the cutter to maintain station within a 5-m circle without human intervention, even in heavy weather for buoy tending, SAR, or any station-keeping task. This suggests the importance of keeping electronic gear and antennas free of ice.

The bow has a small rake and relatively high freeboard. The forecastle and buoy decks share a 20-ton capacity long-reach crane, and numerous vents and typical anchoring and mooring hardware providing surfaces to collect ice and impede water drainage. In addition, the buoy deck, a location where heavy hardware is dragged and maintained, is coated with a corrosion-resistant galvanized surface rather than non-skid, which may allow it to be more slippery when iced. However, it also may also be easier to remove ice from the smoother surface.

The short length of the cutter and its low freeboard at the buoy deck may cause sea keeping characteristics similar to that of a fishing trawler. Fishing trawlers and crabbers have more rigging, and may have crab pots stacked on deck raising center of gravity. The WLB has a relatively high superstructure and the forward crane, which may also give it a relatively high center of gravity. Therefore, it may be appropriate to apply forecasts used by NOAA that are based on fishing trawler icing experiences to the 225-ft seagoing buoy tender.

4.3.4.3 Boots-on-Deck observations and icing experience

A Boots-on-Deck visit on the CGC WILLOW in Newport, RI, provided discussions of icing experiences with cutter officers, with suggestions for preventing icing. A tour of the cutter decks was also conducted to observe areas where icing has caused problems, and to seek an understanding of the working environment and construction of each area.

The CGC WILLOW experienced a bow spray icing event in 2010 that accumulated 5 cm of ice on the forecastle deck and hardware. Most bow spray icing occurs on the forecastle and buoy decks (Fig. 4-67–4-71). The forecastle deck has mooring, anchoring, fueling, and vent hardware, in addition to the crane. Ice accumulates on the anchor windlass, catspaw, and pelican hook (Fig. 4-72). All items must be de-iced before use.

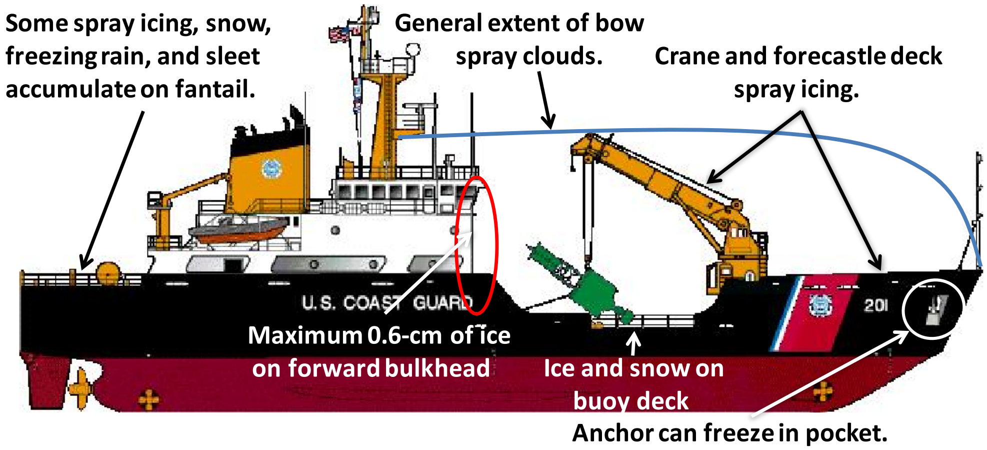

Figure 4-68. Ice accretion characteristics of 225-ft seagoing buoy tender GCG WILLOW and suggested ice protection (US Coast Guard, n.d.).

Figure 4-69. Bow plunging and spray generation on the CGC ALDER. Note the white spray shield on the deck ahead of the crane. The CGC WILLOW has no forecastle spray shield, but icing experience suggests that it is desirable (http://www.uscg.mil/d9/cgcAlder/photo_gallery.asp).

Figure 4-70. Forecastle (forward) covered with non-skid, and the zinc-covered buoy deck (aft) of the CGC WILLOW. The crane is rotated 180° when the vessel is in-transit (Ryerson 2012).

Figure 4-71. Light ice accumulation on the forecastle of a 225 (**http://www.uscg.mil/d9/cgcAlder/Photo_gallery2.asp**).

Figure 4-72. Wildcat (upper left), catspaw (upper right) and pelican hook (bottom) require de-icing before releasing anchor (Ryerson 2012).

Snow is also a safety problem, and it accumulates on the vessel in port and in transit. All weather decks, including the buoy deck and flying bridge, accumulate snow. Snow has accumulated on forward bulkhead to 0.6-cm thickness. Icing is worse when spray occurs on snow. A slush and snow cover 5–7.5 cm thick is a hazard (Fig. 4-73).

Figure 4-73. Operations on snow-covered buoy deck of the CGC ALDER (http://www.uscg.mil/d9/cgcAlder/Photo_gallery2.asp).

The zinc plated buoy deck is a hazardous surface when iced and lifelines are down for buoy retrieval or deployment operations (Fig. 4-74).

Figure 4-74. Officer indicating windlass and aft-facing bulkhead area at forward end of buoy deck that ices heavily from sea spray (Ryerson 2012).

When it sleets decks must be salted to prevent safety problems. Rime icing has not been observed on the CGC WILLOW, but freezing rain has been experienced, even far at sea. Glaze from freezing rain accumulates on all horizontal surfaces, and flags freeze solid. Light freezing rain has been observed by some crew when sailing on the Hudson River, but on another class of cutter.

If the crane is covered with freezing rain-created glaze ice, it can be used, though ice fall is a hazard. If the crane ices with sea spray ice the ATON mission cannot be accomplished without de-icing the crane and buoy deck (Fig. 4-75). When the crane is lifting 45,000 lb from one side, the ship can list 9°, and the crew cannot operate on an iced deck with a 9° list as the buoy deck is coated with zinc, not non-skid. In addition, VERTREP is refused when underway if icing is happening because of dangerous deck conditions. Safety also decreases when drains and open scuppers are clogged by ice, and because buoy deck drains are susceptible to clogging by debris created from buoy maintenance.

Figure 4-75. Sheets of ice can fall from the crane after icing. The crane is parked over the buoy deck when in transit, 180° from view above, which makes falling ice a hazard when that deck is used before de-icing the crane (Ryerson 2012).

The boat deck is not a problem in icing conditions, and engine vents are well-protected from spray as they face aft. Both are also protected by the superstructure, and the boat, all or in part, is covered with a tarp when underway. However, tarps accumulate snow and glaze ice, which must be removed to free the boat for use.

The ship's horn fails in snow, freezing rain, sleet, and spray icing, and the searchlights ice over. The mast is internally heated in cold weather, and radio and radar operation are not affected by icing (Fig. 4-76 and 4-77). In addition, incandescent lights stay de-iced from their heat. New LED lights, however, may ice over because they provide little heat (Fig. 4-76).

Figure 4.76. Incandescent Law Enforcement beacons stay deiced when in operation, but may not if converted to LEDs. Horns on mast fail in snow, freezing rain and sleet (Ryerson 2012).

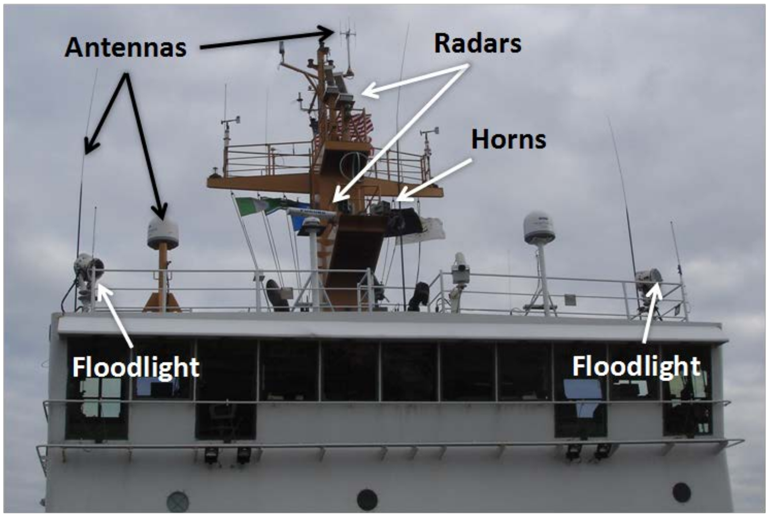

Figure 4-77. Electronics are affected by cold and must be kept running continuously. Floodlights ice over, and horns fail in icing, but radars and antennas are little affected by ice (Ryerson 2012).

Bridge windows are electrically heated. The heated windows and wipers are integral units (Fig. 4-78 and 4-79). When heated windows fail, it is often attributable to controller failure. Another cause of window failure occurs when the window heaters are used with no air moving across them, as when in port (Fig. 4-78).

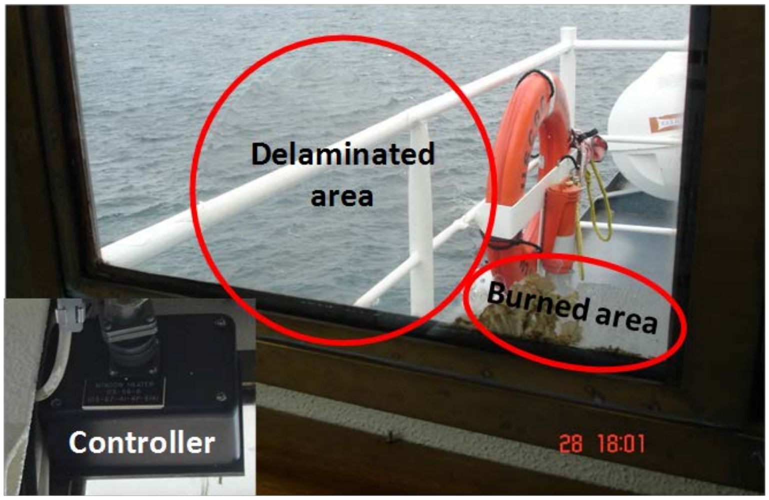

Figure 4-78. Delaminated and burned heated window, perhaps from failed controller or from operation when cutter is stationary (Ryerson 2012).

Figure 4-79. Complex window washer/wiper mechanisms freeze and fail on other cutters, but CGC WILLOW has had no problems with them because little icing occurs at the bridge as it is so high and located so far aft (Ryerson 2012).

Life rings ice to the ship and must be kept free for SAR and man overboard events. Emergency position-indicating radio beacons (EPIRBS) also freeze in place; they must release automatically if the vessel sinks (Fig. 4-80 and 4-81). Hydrostatic releases on life rafts must release when submerged 0.9–1.2 m and may fail if covered with glaze or spray ice. The Navy cold weather operations manual also highlights this problem. Exterior fire stations are also drained for cold weather operations.

Figure 4-80. Life ring on aft rail of forecastle deck in area that ices heavily from spray (Ryerson 2012).

Figure 4-81. Hydrostatic life raft releases can ice and fail if vessel sinks (left), and EPIRBs can freeze in-place and not release if vessel sinks (right) (Ryerson 2012).

Other icing experiences on the *Juniper*-Class 225-ft seagoing buoy tender, related below, were provided from questionnaires distributed to the crews of several cutters. Three sets of icing experiences were provided by the CGC ALDER, home port of Duluth, MN. The cutter's area of responsibility is primarily Lake Superior. A questionnaire was also provided by the CGC HOLLYHOCK based in Port Huron, MI.

A former commanding officer of the CGC ALDER provided experience with icing from 2006 through 2009 (Wirth 2012). During that time, the cutter experienced moderate to severe topside icing from sea spray. This is caused in part by the fresh water of the Great Lakes, which freezes at a higher temperature than salt water, and cold air from the surrounding continental land mass. This combination led to rapid ice accumulation overnight, in moderate seas and typically head winds, on everything forward of the forward bulkhead (frame 57). (Frame 57 is the location of the forward bulkhead, the aft end of the buoy deck.)

Conditions associated with icing included air temperatures below –1°C, with colder air causing more severe icing. In the most severe cases, air temperatures were near –10°C or lower, with lake temperatures below 4.5°C; the closer the water temperature was to freezing, the more severe were the conditions. Also needed are moderate to high relative wind speeds greater than 10–15 kt (5.1–7.7 m/s), with head seas large enough to create spray that can then blow back on the cutter. Although following seas can ice, they generally do not result in very severe conditions owing to the height of the fantail (Wirth 2012). Another CGC ALDER respondent also observed glaze ice, snow, and frost on the cutter (Durley 2012).

Ice forms extensively on the anchor ground tackle and controls forward of frame 25 first, and then spreads to the deck and gunwales on each side. Under prolonged conditions, ice would spread aft on the buoy deck and over all items on it as well. Icing began on items above and off the deck and would progress onto the deck itself and literally coat all steel surfaces of the cutter forward of and on frame 57. Large accumulations of ice would form on the life rails and lifelines, gripes, safety nets across the buoy ports, the crane, and crane pedestal, all horizontal surfaces, the ground tackle, and the jack staff. In extreme cases the shipping ports (scuppers) would form icicles more than 2.4 m long and others would clog with ice, resulting in standing water sloshing around on the forecastle until a port was opened up, which was infrequent (but precipitation or extended exposure to icing conditions would result in this). Ice thickness ranged from about 5 to 30 cm, with some areas greater in severe cases (Wirth 2012).

Hantzmon (2012) observed up to 25 cm of ice on the CGC ALDER and CGC HOLLYHOCK in Lake Superior, with ice forming on masts, staffs, and decks. However, despite these accumulations the 225s are stable with ice loads. The thickness of ice has no appreciable effect on cutter stability other than making it slightly bow heavy, which is correctable by ballasting. It also made walking difficult and hazardous. In addition, Special Sea Detail and Anchoring/Mooring Details are more hazardous and time consuming as gear begins to freeze and adhere to other objects or the deck.

On the CGC ALDER in Lake Superior, ice made transit of weather decks by crew unsafe, and took the buoy deck out of commission until it was cleared of all ice. Sea keeping on the very stable 225 was not affected. Ice forms on many areas of the 225s, including the forecastle, buoy deck, superstructure, and fantail (Durley 2012). All bits forward on the forecastle were unusable when iced in and it took a concerted effort to clear the bits to allow mooring. Communications were not affected, and life rafts and davits were high enough that they didn’t usually ice, though the decks would be ice-coated, which would limit boat operations until they were cleared. As for ventilation, the conditions that caused icing also required the cutter to isolate nearly all outside supply vents to limit entry of frigid air (sometimes −23.5°C or lower) (Wirth 2012).

On a 225 the forecastle and buoy deck are the most affected by icing. Boat operations are postponed until ice is cleared (Wirth 2012). Icing affects the operation of pumps normally left outside and stored externally on the cutter during warm weather, but must be moved inside for the winter season. Antennas and other communication lines ice heavily and impact communications. The boats normally must be winterized, and are considered out of commission for the winter season unless necessary for emergencies. When coated by ice, all external lines, safety chains, and life-lines do not provide the best prevention of accidents for safety and survivability at sea. Several respondents also commented on the dangerous footing on decks during icing (Hantzmon 2012; Wirth 2012)

In SAR missions, boat use is limited because the boat could have iced davit controls or ice build-up on the boat itself, especially if the cover has blown off. Other SAR equipment, including pumps and cargo nets, may also be frozen into out-of-commission status (Wirth 2012). When responding to SAR and sailing at top speed, the cutter becomes iced, unless it is calm and there is no wind, which is not normally a SAR condition. When on scene the ice may cause the crew response to be more dangerous for rescuing SAR victims (Wirth 2012).

4.3.4.4 Anti-icing and de-icing procedures

Several questionnaire respondents indicated that icing can also be avoided or minimized operationally. When attempting to avoid icing or minimize accumulation, judging the best actions to take is often difficult. If the ship is operated at a higher speed, more spray is generated and more relative wind is created, but the cutter is exposed to the conditions for less time. At lower speeds, there is less spray and wind, but a longer exposure time (Hantzmon 2012; Wirth 2012). In one case, overnight a 225 became coated in ice despite a very low speed of less than 6 kt (3.1 m/s). Air temperatures were near –10°C, lake temperature was near 7.5°C, winds were about 20 kt (10.2 m/s), and seas were a light 0.6- to 0.9-m chop. However, the course was into the seas and winds, and this generated enough spray to "mist" the hull in cold water. In 12 hours overnight 7–10 cm of ice accumulated over everything (Wirth 2012).

Cold hampers ice removal and increases the fatigue factor of the crew removing ice, so one must find a balance. Several times anchoring was prohibited by the amount of ice on the ground tackle on the bow and this was very dangerous for the crew to operate. As the ice melted, the water got into the anchor chain controls and crew members without proper gloves insulated against electric were shocked several times (Durley 2012).

Ice can reside on the ship throughout the winter, but decks and a majority of the hull are kept de-iced when in port. It became part of standard operations on the CGC ALDER to have rubber hammers and have all hands muster to remove as much ice as possible from the cutter prior to mooring in homeport or other locations. With less ice, operations are safer, and the cutter is more stable when underway (Durley 2012). If ice thickness became 5 cm or more when underway, the CGC ALDER was slowed and crew would remove ice when underway for safety. Major work areas were cleared with *Ice Melt* (decks only), scrapers, bats, axe handles, mallets, billy clubs, sledges, and shovels. Occasionally, a metal tool was used on a painted deck (the buoy deck is not painted) and damaged the painted non-skid below, or a blow torch-like tool attached to a propane tank (called a thunder torch) was used to melt ice (Wirth 2012). Though blow torches are dangerous, they often need to be used on ratchets and other deck equipment to make them safe to operate. As *Ice Melt* washes over the side, environmental factors concerning de-icing chemicals used need to be examined—especially when in waters of other nations.

Most deck machinery is covered with tarps all year; they are very effective at preventing icing of hardware, and ice is easily removed from tarps (Fig. 4-82). Though the 225s have electrical space heaters, they only provide interior heat—they have not proven effective for heating decks above interior spaces as has been done with the 140-ft icebreaking tug.

Figure 4-82. Blue tarps used for covering deck machinery (Ryerson 2012).

De-icing can break equipment and injure personnel. Slips, falls, and sprained ankles and wrists happen, and eye safety gear must be worn because of flying ice. Fatigue is a concern during de-icing. Ice removal is an all-hands-on-deck situation and is very difficult. Personal Protective Equipment (PPE) is vital, including cold weather gear, Carharts, mustang suits, boots, under armor, gloves, hats, balaclavas, eye goggles, and Yak Tracks or similar boot gripping systems (Fig. 4-83). Iced decks are very slippery, and crew exert themselves and sweat profusely, and then chill if they rest in the frigid conditions (Wirth 2012).

Figure 4.83. Removing about 2–5 cm of fresh-water ice from the CGC ALDER'S buoy deck using shovels and wooden mallets. Note the personal protection equipment necessary for safety (http://www.uscg.mil/d9/cgcAlder/Photo_gallery.asp).

Overall, de-icing is labor intensive. A 140-ft ice-breaking tug with 15 cm of ice on the forward one-half of the ship required 2–3 hours to de-ice. The 86-m CGC ALEX HALEY based in Kodiak, AK, required 30 crew 4–5 hours to de-ice the ship from the flight deck forward. One report from a 225 indicates needing 1 hour for 10 to 20 crew members to de-ice the cutter. Often de-icing must be done during SAR missions, which requires stopping to do the job.

Priorities for ice protection include the following:

1. Main Decks, especially the buoy deck and the forecastle deck for making rounds, safely loading stores, working aids to navigation, and securing things to the main deck.
2. Bow for anchoring and safety, including anchors and wildcat.
3. Navigation equipment: bridge windows often experience failed heaters and become iced (Fig. 4-84), radar, communications, Automatic Identification System (AIS), antennas.
4. Safety equipment: fire main, life rafts, boats, stokes-liters, life rings, safety chains, life-lines, davit controls, boats, P-100 pumps.
5. Superstructure.
6. Hull if it can be reached.
7. Air castles and fantail; slippery decks will cause more man-over-board situations.

Figure 4-84. Seaclear after-market adhesive electric window heater to replace failed window heaters (Ryerson 2012).

For improving ice protection, the CGC WILLOW crew suggested that lessons could be learned by working with the Canadian Coast Guard. For example, they do not turn off electronic systems and allow them to cold-soak in the Arctic—they are always powered.

As smaller “optimally manned crews” and automation occur, fewer personnel are available to de-ice. Many respondents and interviewed crew indicated that heated weather decks are needed with the following priorities:

a) the main weather decks for damage control and SAR activities, and b) the buoy deck. The CGC MACKINAW is the example to follow for electrically heated decks. In addition, heated bulkheads and a heated mast would be useful on the Great Lakes. However, an engineer offered that it is only practical to add heated decks to new ships. Wiring an older ship would cause maintenance problems because of wiring accessibility. The Coast Guard did a study of the cost of adding heat to the decks of 225s. It would cost $750,000 per ship. It may be less expensive to build heated decks into a new cutter.

Another frequent suggestion was to control spray creation and the flow of spray over the ship. One respondent suggested that it would be good if cutters had a design added to their bows to prevent the majority of bow spray from rising over the bow. Though somewhat unclear, another stated that a new design for the bow, such as the Great Lakes ships use, might be useful in a future design of icebreakers and buoy tenders operating in cold weather. The reference may be to the very high bow and bulwarks of the new *Trillium* Class of ships operating on the lakes. Also, the Danish Navy Surface Force has a ship with a covered forecastle and a covered boat launch area.

Additional suggestions for improving de-icing and anti-icing on the 225s include the use of special anti-icing/de-icing materials (Durley 2012), and steam wands to rapidly remove large pieces of ice from the superstructure. Steam wands would require a low cost boiler with a dedicated steam line and hose. Steam does not introduce a large volume of water that standard pressure washers do, and they were an effective method of de-icing when ships were powered by steam (Wirth 2012). And, all fire hoses need better protection, such as tarps or metal covers (Fig. 4-85).

Figure 4-85. Proper metal cover for fire hose and valve on weather deck (Ryerson 2012).

4.3.4.5 Risk matrix

Four *Juniper*-Class respondents' matrices were combined to produce the matrix below. In combining the matrices, similar topics were collapsed together to refine the cutter function/component list. Weightings for each cutter component/function and for each ice type were averaged, and the matrix products were created from the weightings (Table 4-5). The CGC ALDER and the CGC HOLLYHOCK are both based in the upper Great Lakes; therefore, the matrix reflects primarily experiences with fresh water icing in the Great Lakes. Though several respondents had experience with salt water icing, that experience may not be reflected in the matrix.

Table 4-5. Risk matrix for JUNIPER-Class seagoing buoy tender (blue font indicates cutter function; black indicates cutter components).

	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Cutter function/component	Importance to Safety	9	5	5	4	3	3
Seakeeping/stability/integrity	10	90	50	50	40	30	30
Functionality	10	90	50	50	40	30	30
Fire stations	10	90	50	50	40	30	30
Rafts	10	90	50	50	40	30	30
Antennas and electronics	9	81	45	45	36	27	27
Deck surfaces/ladders	9	81	45	45	36	27	27
Buoy deck	8	72	40	40	32	24	24
Cranes	8	72	40	40	32	24	24
Lifelines/railings	8	72	40	40	32	24	24
Deck Machinery	8	72	40	40	32	24	24
Boats	7	63	35	35	28	21	21
Hatches	7	63	35	35	28	21	21

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

Spray ice had the greatest importance to safety, as may be expected. However, it has a value of 9 because three respondents rated it as 10, and one rated it as 7. However, the differences become much larger for the other ice types. The importance of snow averaged as 5, but respondent ratings ranged from 1 to 8, and the same is true for glaze ice resulting from freezing rain or freezing drizzle. Rime averaged 4, with respondent scores ranging from 0 to 10. And frost and sleet both averaged 3 with respondents ranging from 0 to 8.

Three of the four respondents indicated that sea keeping, stability, and integrity were of highest importance as they involve the survivability of the entire cutter. Icing does cause smaller vessels that are similar in size to the 140s and the 225s to founder, making these topics high safety concerns. Functionality, though not defined, was also rated highest by a commanding officer, which may imply the ability of the cutter to perform its basic missions effectively.

Fire stations and rafts were also rated as 9 and 10 by two respondents, in part because of their impact on safety and crew survival. Antennas and electronics, ladders and stairs, and decks were rated as 9 with regard to effects on safety when iced. One to three respondents provided ratings for these items, either 8 or 9 by each. This is certainly expected for decks because within narratives several respondents expressed concern about crews operating on slippery decks and being injured when de-icing.

Buoy deck operations and the crane, railings, and deck gear and ground tackle averaged 8 in importance to safety, and individual respondents rated them from 7 to 9. Though the buoy deck and crane can be considered out of commission when iced, when this is the case, the cutter cannot accomplish its important ATON mission.

4.4 Use of risk matrices

The risk matrix is intended to provide an ordinal method of semi-quantifying superstructure ice type versus functions and components of a ship. Therefore, ranking superstructure ice by type with regard to importance to safety and operations indicates which ice type requires greatest attention to improve safety and OPTEMPO. It does not quantify, however, how much more important one ice type is than another, for at this time there is not sufficient information to make such a judgment.

For example, if ice created from bow spray is rated as 10, and snow is rated as 5, this does not imply that the impact of snow on safety is 50% that of bow spray ice. It does suggest that ice created from bow spray is a much greater hazard to ship safety and function than snow, but no more. The risk ratings are derived from icing observations in the operational environment by crew, and are based upon a range of experiences in different environments, saline and fresh, on the cutter class of interest.

Ship functions and components affected by icing were similarly ranked in an ordinal manner by crew. Through their operational experiences aboard a variety of cutters, but focusing on the cutter class of interest, crew respondents provided their opinions of how safety and function were compromised by icing. Though the importance of each area of the ship, or ship function, is perceived differently by each respondent, based upon their duty on the cutter and their experience, the goal was to obtain as reliable a picture as possible about the effects of icing on each cutter class.

The reliability of the risk matrix is, in part, also a function of the sample size of respondents and their experiences with superstructure icing on the cutter class of interest, and on other cutters and environments. In general, reasonably good sampling was accomplished for the *Polar*-Class icebreakers, the 140s and the 225s. Sampling was less complete for the NSC.

The *Polar*-Class icebreakers were represented by the only two operational vessels in the class: the CGC HEALY and the CGC POLAR STAR. We were able to interview crew on the deck of the CGC HEALY, and walk the decks with officers having superstructure icing experience. In addition, we received one questionnaire from a CGC HEALY crewmember who commented on experiences on several classes of cutters, but did not complete a risk matrix. On the CGC POLAR STAR, we also had a deck tour with a very ice-knowledgeable officer and the benefit of an extended interview with five senior officers with icing experience. Though the crew did not complete a questionnaire or a risk matrix, many elements of the questionnaire were covered in the interview, and an oral risk matrix was completed, which is presented with minor changes in this report. Therefore, the risk matrix for the *Polar*-Class icebreakers was completed primarily by the CGC POLAR STAR crew. However, it was slightly modified to represent both vessels. As the missions and physical characteristics of the two ships are so similar, the risk matrix may be considered well representative of both cutters.

Overall, the most important considerations on the polar ice breakers were sea spray icing, and secondarily glaze. The most important areas and functions compromised by superstructure icing include forecastle deck hardware and operations, boat operations, and forward bulkhead doors, vents, bridge windows, and communication antennas and whistles.

The National Security *Legend*-Class Cutters have not been operated in superstructure icing conditions, and few of the crew of the CGC WAESCHE had icing experience. However, a Boson with icing experience provided a detailed tour of the ship and explained where problems might be expected. No questionnaire or risk matrix was completed by those interviewed for the NSC. A crewmember also demonstrated the icing module of the Flooding Casualty Control Software–Windows (FCCS-WIN) model, and an officer later sent images of spray reaching the bridge windows in a tropical depression, indicating that spray can readily reach the bridge and potentially cause icing. As there are no experiences with icing of the *Legend*-Class Cutters, the risk matrix was developed from the interview and deck-tour information. Overall, however, the NSC risk matrix cannot be interpreted with the same level of confidence as those of the polar icebreakers, the 225 and the 140.

Bow spray icing and snow are of greatest concern for the NSC. Also, as on the other cutters, there is considerable concern for icing on the forecastle deck, and on the forward bulkhead. In addition to ground tackle icing, the 57-mm gun mount could become inoperable by icing, and ice falling from the forward bulkhead could damage wiring, piping, valves, and antennas on and at the base of the bulkhead. The boat deck at the main deck level was of great concern because of spray where the single davit operator, crew launching and retrieving the small boat, and the painter handlers must work. Icing was expected there by designers, because a turbine engine inlet on an adjacent bulkhead had a de-icing manifold/heat exchanger installed to prevent icing. Because one role of the cutter is as a command center, there is concern about antennas on the forward bulkhead and mast icing, the fueling at sea deck icing, and the bridge windows icing. In the latter, only the center window on the entire bridge is heated. Finally, though not specifically a superstructure icing problem, there was great concerned expressed about operations of the BLR System in cold weather.

The crews of the 140-ft *Bay*-Class icebreaking tugs are well-experienced in icing conditions and interviews with the crew, and the risk matrix created by the CO and EO of the CGC THUNDER BAY, and questionnaires and risk matrices completed by crew members of the CGC BISCAYNE BAY and CGC MORRO BAY provide highly reliable information. However, most experience of the CGC BISCAYNE BAY and CGC MORRO BAY is in fresh water icing. CGC THUNDER BAY has experience in both fresh and salt water icing.

Bow spray icing and snow are of greatest concern to the 140s. And, because of their small size, low freeboard, and bows that generate considerable spray at low speeds and small seas, the effect of icing on stability is a great concern, as is the ability to conduct the mission if the vessels are iced. Damage control, navigation, visibility through bridge windows, and deck operations are also compromised by icing. Other major concerns include boat operations, communications, and anchor hardware operation. Overall, these vessels, in part because of their small size, but also because of their operations in the Great Lakes, have a greater icing threat than the larger cutters.

The *Juniper*-Class 225-ft seagoing buoy tender also had strong response from crews of several cutters. Senior officers on the CGC WILLOW provided thorough explanations of icing problems experienced on the 225s and other cutters in fresh and salt water. However, additional information was provided by crews from the CGC ALDER and the CGC HOLLYHOCK operating in the Great Lakes. Though no questionnaires or risk matrices were completed by CGC WILLOW personnel, questionnaires and risk matrices were completed by several CGC ALDER and one CGC HOLLYHOCK crew member. Therefore, the confidence in the *Juniper*-Class risk matrices is high, though the emphasis is on fresh water icing which is overall more severe than sea water icing.

As with the 140s, the 225s are relatively small ships with bows that have little flare. Though the bow freeboard is relatively high, they generate considerable spray, and there is much hardware on the forecastle and buoy decks to ice. As one respondent indicated, icing begins on objects elevated from the deck, and eventually works its way down to the deck. The 225s provide many opportunities for this to occur. In addition, the 225s' ATON mission requires work on decks that have no non-skid, can be ice or snow-covered, and may tilt considerably when crane lifts are occurring with no or minimal lifelines along the side.

The small size, and the low buoy deck freeboard, makes stability a concern in heavy icing, but less of a concern than on other cutters because of the low level of the buoy deck. In addition, decks need to be kept clear of icing, as does overhead gear, such as cranes that must be de-iced to prevent falling ice hazards. Fire-fighting equipment and rafts are a concern if iced, as is ground tackle used for anchor detail.

Overall, the risk matrices show the importance of ice type versus ship components and functions that are most affected by icing. The cross-tabular matrix derived by multiplying the ice type threat score by the function or component importance indicates, again in relative ordinal terms, the conditions, and parts and functions, of a cutter that require the greatest attention to maintain mission integrity and vessel and personnel safety.

5 Ice Protection Technologies

Ice protection refers to a range of technologies that protect a structure from consequences of icing that can cause failure in its ability to function as designed. This can include anti-icing, de-icing, or ice detection. Some of the technologies may be applied to a structure after it is fabricated, and others must be designed into structures. The term “ice protection” originated in the aviation industry, and literally refers to a suite of technologies that, acting as a system, protect structures from the performance impact of icing.

The role of anti-icing technologies is to prevent ice from forming on a surface. This can generally be done in one of two ways: preventing the surface from being wetted by supercooled water drops or covered with snow or frost crystals, or by preventing surfaces from cooling below the freezing temperature of water. These technologies can be chemicals, coatings, design, thermal, or infrared. However, there are de-icing technologies that can be operated such that they are nearly anti-icing technologies, even though they allow some ice to accumulate on the surface.

De-icing technologies, by definition, allow some accumulation of ice on a surface. They then remove the ice from the surface using a variety of methods. Some de-icing methods require that considerable ice accumulate on the surface before it is removed; others require little accumulation. If the component or function being protected is tolerant of some ice for a period, then de-icing technologies may be appropriate, and at times more efficient, because they often operate only periodically rather than continuously.

Ice detection technologies are generally used to energize active anti-icing or de-icing systems. If the system is man-in-the-loop, then humans may be the ice detector. However, ice detection usually means an instrument. Ice detectors, depending on the technology, can detect only the accumulation of ice, but some systems can also detect the presence of ice on a surface and indicate when the surface has been cleaned by an anti-icing or de-icing system.

Anti-icing and de-icing technologies can also be passive or active. Passive systems require no electrical, thermal, or hydraulic power and perform their duties without receiving commands from a human or automated ice detector. However, passive systems give users no control over how much and when ice is removed. And, the surface may not be completely clean after the ice is removed. Coatings that reduce ice adhesion, or the new nano-based anti-icing coatings, are classic passive technologies.

Active systems require a source of power to operate. They provide the user with control over when anti-icing or de-icing occurs and, therefore, also control how clean the surface is. Active systems also allow for de-icing, for example, of several areas at the same time to maintain balance or symmetry. Active systems are often aided by passive systems. For example, an active system may be covered with a coating that reduces ice adhesion, which makes de-icing cleaner and may use less power.

Not all ice protection technologies work with all ice types, and certainly not in all applications. For example, some technologies perform better with glaze ice, spray ice, rime or glaze ice from freezing rain because they originate as supercooled drops, and may not perform well with snow or frost, which arrive or form on the surface as ice crystals. Also, fresh water spray generated ice is harder, less flexible, and adheres to substrates more firmly than does saline spray-generated ice. Physics suggests that some technologies may perform better with one ice type than another.

Therefore, to date, no ice protection technology has been a panacea. That is, no technology works well in all icing conditions and in all applications. Claims by developers and marketers that their technologies solve all icing problems must be investigated to determine what this means, for they are either making claims that are exaggerated, or they are making claims for specific applications that may not have been clearly specified.

5.1 Methodology

Ryerson (2008, 2009) comprehensively reviewed ice protection technologies that were available from the aviation, power transmission, highway, and the marine areas. These technologies were reviewed with regard to the applications intended by their developers, and for their potential application to the marine environment. The reviews, which were written using open literature from published research papers or, for specific products, with the developers or marketers, provided information about the principles behind the functions of the technology, applications, costs, availability, and whether they were available as commercial-off-the-shelf (COTS) products. Their potential for use in the marine environment was evaluated, and the possible pros and cons of their use in the marine environment were outlined. Technology Readiness Levels (TRL) were also provided for the original commercial application, and for possible use in the marine environment. Ryerson (2009) also showed whether the technologies were de-icing, anti-icing, or ice detection technologies, and gave sources to contact for their acquisition.

This review updates the 2009 (Ryerson 2009) report. The update includes changes in products or suppliers since the 2009 report was published. However, it also includes new technologies that have emerged since 2009, or were unknown to the author at that time. The author has also reviewed the availability of the technologies on the World Wide Web. In some cases, it is not clear whether some of the developers or marketers that were available in 2009, at the beginning of the Great Recession, are still in business. We did not receive responses from a number of companies when attempting to update their technology's development, availability, and pricing. We have included technologies that may not be available as COTS products as of this writing if they were a technology that was thought to be potentially effective on a Coast Guard Cutter. New and updated technology descriptions may be found in Appendix B.

Companies were contacted to obtain updates about their technology, but also to include a thorough description in this report in the same manner as they appear in the 2009 report. Also, written permission was required to include descriptions of their product in the report. This legal requirement for publication could not be satisfied if a response was not available from the company after repeated attempts. Therefore, those technologies that could not be updated and included as full descriptions in this report are cited in the narrative, but information is obtained from the report by Ryerson (2009), and referenced as such, or has been obtained from other public sources..

A variety of new technologies have also developed since 2009, and they are included if information could be obtained. Most notably is the rapid development of nano-based coatings with claimed anti-icing properties. Many of these new technologies remain under development and most are not yet COTS products. Numerous academic papers have been written that are available in the open literature. In these cases, many of the descriptions are only from this open literature, whereas additional information about availability of products was obtained, as available, from the developers.

The organization of technologies here closely mirrors that in Ryerson (2009) because, by maintaining the original organization, reference is more clearly made to the 2009 report.

As in the 2009 report, information is provided about technologies that range from the nascent to mature. Some of the newest ideas under development may prove to be the most promising. As the intent of this report is to provide information to the reader that can be used to plan future research, development, testing, and evaluation (RDT&E), it is necessary to describe technology that, at this time, appears promising, and that should be watched, and perhaps nurtured if it shows promise for application to ships and the Coast Guard.

5.2 Chemicals

Chemicals are among the most common of de-icing and anti-icing technologies. They are used heavily in keeping pavements ice free, and in de-icing aircraft on the ground, and in some cases in the air. They are also used on board ships, especially to de-ice decks. For example the US Coast Guard uses a generic term called *Ice Melt* to refer to chemicals obtained in hardware stores for de-icing pavements, as does the Canadian Navy (Ryerson 2009).

De-icing and anti-icing chemicals vary widely in their characteristics. Some chemicals are solids and others are liquids, some are endothermic and others are exothermic, and they all vary in their impact on the corrosion of structures and hazard to the environment. In addition, their cost is highly variable, and though many are marketed and distributed nationally from one or a few manufacturing sites, others are bulk commodities sold in the thousands of tons or gallons, and are regionally marketed.

Though most of this summary focuses of the types of chemicals available and their characteristics with regard to ice control, several products are described that possess unique application methods, and are described for their potential ability to function in the marine environment.

5.2.1 Application technologies

There are a variety of application technologies, in addition to manual methods, that depend upon whether the chemical is solid or liquid. Solid and liquid chemicals are typically used on highways and are spread from trucks using procedures and techniques that are well-established in the highway industry, and are described by Ketcham et al. (1998). Most of these methods are not readily transferable to the marine environment.

Automated methods of distributing chemicals that are most likely to be usable in the marine environment use liquids. Liquids can be sprayed, can be applied by capillary activity, and can be weeped onto surfaces. All of these systems are available commercially, and some have been developed for marine applications.

Weeping systems can be used for anti-icing or de-icing, though they are typically most effective in the former use. Weeping systems slowly pump a freezing point depression fluid through a porous surface or holes in a manifold, or from spray nozzles, enabling it to flow over a surface by gravity or by air flow, such as over an airfoil (Fig. 5-1). Supercooled water, or cold spray, mixes with the freezing point depressant preventing the impinging water from freezing. However, the diluted freezing point depressant must maintain a sufficiently low freezing temperature that nucleation does not occur.

A weeping wing de-icing-anti-icing system was developed for aircraft in the mid-1930s in England. Manufactured by TKS, Inc., during World War II, the product is still used on aircraft, is available and sold by CAV Aerospace in the US (www.weepingwings.com/mx/hm.asp?id=home). The system is used on a wide range of light single and twin engine aircraft, and was used on the Predator UAV.

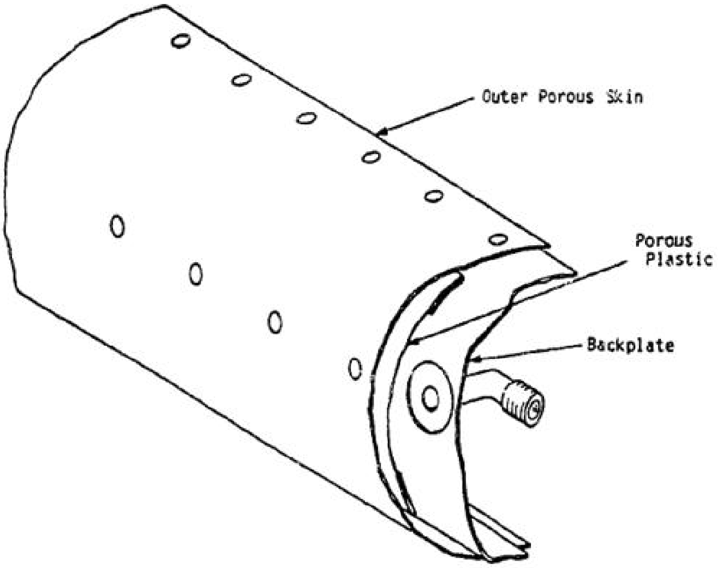

Figure 5-1. Cross section of airfoil leading edge with manifold and holes for weeping freezing point depressant (FAA 1991a).

In anti-icing mode, the system is actuated prior to entering icing conditions, allowing the surface to be covered with freezing point depressant. The system remains operating until icing conditions cease. In de-icing mode, the system is actuated after ice has accumulated. The fluid flow weakens the ice bond and, for aircraft, airflow eventually carries the ice away. Overall, however, the system is more reliable in anti-ice mode; there are conditions where the system will not remove ice that formed before fluid flow started.

Though many freezing point depressant fluids are possible, glycol is most commonly used. It is less flammable than some alternatives, such as alcohol, and actually cleans surfaces. In addition, a fluid is required that has a viscosity that readily flows onto the surface, but also clings to the surface and does not develop a low viscosity quickly as it is diluted by water, which would cause it to be lost in the aircraft airstream.

The disadvantages of weeping systems for aircraft are weight, and limited fluid capacity, and, therefore, the time that protection is available. Use on a ship would not be limited by weight, though fluid capacity could be a limitation. Another limitation on a ship may also be loss of fluid into lake or seawater where it would be a pollutant. However, a freezing point depressant developed for de-icing using pressure washers, Harmony Deicing

Fluid (Appendix B, www.idealsolutionsonline.us), is certified safe for seawater and, if viscosities were appropriate, may be useful for a shipboard system.

A weeping system could be used on ship windows, bulkheads, and perhaps even applied to deck machinery with an appropriate nozzle design. And, if technically feasible, the Countermeasures Washdown System installed on some Coast Guard Cutters, such as the National Security Cutters, could be used to apply fluids to surfaces (Fig. 5-2).

Figure 5-2. Coutermeasure Washdown System in operation on CGC BERTHOLD (Coast Guard photo).

However, consideration of using a weeping system on a ship should include the chance of spray washing fluid away, or diluting sufficiently that it is ineffective. In addition, some freezing point depressants are slippery and could cause footing hazards on decks. The system may not be effective, especially if sprayed, in higher winds. Finally, fluids would be needed that could be allowed to flow overboard into seawater or lake water.

Another technology that sprays freezing point depressants on surfaces is Fixed Anti-Icing Spray Technology (FAST). Marketed by a variety of companies (Ryerson 2009; Ward 2002; see Table 5-1), FAST systems utilize fixed nozzles located along the edges of a bridge or other pavements to spray fluid when actuated either manually or automatically. For highway use, they are commonly linked to Road Weather Information Systems (RWIS), and as systems they are more common in Europe than in North America. They have, in some cases, been found to be more effective at clearing roads of ice and snow than truck-based systems (Ward 2002). Spray durations are typically only a few seconds, making fluid use relatively small. Several systems use potassium acetate as the freezing point depressant and commonly protect areas as large, or larger than, the forecastle area of a Coast Guard Cutter. Fluids are not heated, and they cannot make pavements slippery. However, traffic flow is used to aid in fluid distribution via the tracking and spraying by vehicle tires. Installations have fluid tanks, pumps, and piping to the nozzles. If the fluid is stored diluted, rather than neat, there is no need for external water supplies, and the fluid will not freeze unless temperature drops below its freezing point. If technically feasible, the Countermeasures Washdown System installed on some Coast Guard cutters, such as the National Security Cutters, could be used to apply fluids to surfaces (Fig. 5-2).

Stationary or truck-mounted booms with spray nozzles are typically used to de-ice and anti-ice aircraft before flight. One truck-mounted system used by the US Air Force, the Global Air Plus!, uses high velocity air with no fluid, fluid injected in air, or fluid only to de-ice aircraft (Appendix B). Similar systems, with re-engineering, may be usable on vessels.

A non-spray chemical de-icing and anti-icing system designed for ships is the Feltwick Anti-Ice Grate (Appendix B, www.IceSight.com). The 2.5-cm thick Feltwick Anti-Ice Grate was designed for use on ship decks, and in non-marine applications, to prevent ice and snow accumulation. The Feltwick Grate is an anti-slip grate or tile surface, with a wick beneath the surface. The wick can be felt, an open-cell rigid foam, or a porous ceramic. Wicks can be placed in the cavities of a grate or in holes in a tile, or use homogeneous porous materials. The bases of the wicks are submerged in an anti-icing fluid that is also a freezing point depressant, typically potassium acetate because of its low corrosivity, so that the fluid is drawn the top surface of the wick. The anti-icing fluid at the mat surface prevents snow and ice accumulation. The reservoir can be periodically replenished using a pump, or fluid could be supplied by pouring from the top. Even though snow and ice melted will dilute the fluid in the mat reservoir, the developer indicates that evaporation between icing events will re-concentrate the fluid and lower the freezing point. The technology has been tested in snow and ice.

5.2.2 Chemical technologies

Applying chemicals to surfaces to prevent or remove ice and snow is the most common of ice-protection technologies. It is likely that more dollars are spent on ice-control chemicals than any other ice-protection technology because of the large volume of materials needed. Chemicals are used principally to control ice and snow adhesion to pavements and to aircraft. Chemicals are used in small volumes to control icing of ship decks.

Chemicals are available as solids and liquids, which affect their application technique and the types of surfaces that they can be used on to protect. More importantly, they are available in a wide variety of chemical compounds, with characteristics that makes them more or less attractive in specific applications. This summary is organized by chemical families. All of the chemicals described are available as COTS products. However, because they are often bulk-commodities, availability can vary regionally. A more detailed summary of de-icing and anti-icing chemicals is found in Ryerson (2009). A comprehensive assessment of the environmental impacts of 26 commercially available and experimental aircraft and runway de-icing and anti-icing fluids can be found in a study by the Transportation Research Board (University of South Carolina 2008).

5.2.2.1 Chlorides

Four chloride de-icing chemicals are available for ice and snow control: sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$) and potassium chloride (KCl). All four chemicals are called salts, but sodium chloride is the most common of the four chemicals used for de-icing. Though sodium chloride is the least expensive, thus the most common ice control chemical with approximately 8–12 million tons used annually to de-ice roads in the US, it is the least effective of the chlorides.

Available in solid granules or as a brine, NaCl is used to melt ice and snow, and to reduce its bond strength with pavements. The optimal brine concentration is 23.3%, which has a freeze point of –21°C. However, the practical working temperature of NaCl ranges between –7 and –10°C (Greenawalt 2006). Ice and snow melting chemistry works via freezing point depression, a colligative property of solutions. All ice melting salts dissociate as ions as they dissolve into melting ice and snow, which multiplies the molar quantity and the freezing point depression. NaCl releases a ratio of one sodium ion (Na^+) to one chloride ion (Cl^-), whereas $CaCl_2$ releases one calcium ion (Ca^+) for every two chloride ions. However, $CaCl_2$ and $MgCl_2$ pose a greater risk than KCl and NaCl because they release twice the number of damaging chloride ions that cause corrosion and damage to plants (Peeples 1998). Therefore, the lowest possible melting temperature possible with highly concentrated solutions are −21°C for NaCl, −55°C for $CaCl_2$, −34°C for $MgCl_2$, and −11°C for KCl (see also Table 3 in Ryerson 2009).

Overall, sodium chloride is effective at de-icing at higher temperatures, but it is highly corrosive and damaging to the environment. As sea water has a sodium chloride concentration of only 3%, the 23% concentration needed for de-icing enhances the corrosion of ship components even though they are constantly immersed in sea spray and salt air. As a liquid it can be sprayed onto decks, deck machinery, and stairs, and as a solid it can be used on decks. However, as a chemical it can be readily washed off of surfaces, or diluted, by spray. In addition, it should not be used on flight decks because of its corrosiveness to aircraft, and it will damage floors when tracked inside the ship.

Calcium chloride is a common pavement de-icer, and is often mixed with granular materials such as sand, coal, ores, and other materials in a 32% solution to keep them ice free, or for use as traction aides on pavements. Typically available as a liquid, but also as a flake solid, calcium chloride is an aggressive de-icer. It is hygroscopic, so it attracts moisture, which speeds melting, and it is exothermic, releasing considerable heat as it melts into ice and snow. The hygroscopic ability of calcium chloride allows it to melt ice and snow more rapidly than other de-icing chemicals because liquid activates the chemical. In addition, the exothermic reaction of calcium chloride, larger than other de-icers, releases 674 J/g as it dissolves, raising the temperature of the water (Jerico Services 2008).This exothermic capability allows it to rapidly melt into ice and snow and makes it more effective at low temperatures. It is more effective than sodium chloride, which is endothermic. However, it tends to refreeze quickly, potentially requiring frequent reapplications. Its optimal working temperature is −31°C (Ryerson 2009).

Calcium chloride can leave a difficult to clean slippery residue on floors, and it damages leather shoes and gloves (Myhra, n.d.). It is hygroscopic, which can cause clumping, hardening, or even liquefying during storage (Peeples 1998). It is also expensive and highly corrosive and should not be used on flight decks where helicopter downwash could loft the material onto aircraft surfaces. As it is available as a liquid, it could be sprayed onto deck machinery to hasten de-icing, though with a danger of increased corrosion. And, as with other chemicals, it can be diluted or removed by bow spray (Ryerson 2009).

Magnesium chloride is a popular pre-storm treatment for highways. Sprayed onto pavements as a liquid, it reduces the adhesion of ice and snow to pavements, and it reduces "bounce" when solid de-icers are later applied. Its working temperature is –15°C, and its eutectic temperature is –34°C. Similarly to calcium chloride, it has an exothermic reaction with water, but releases only 43% as much heat per unit weight as it dissolves. It is usually applied as a liquid at 25 to 35% concentration, though it is also available as a solid. It refreezes quickly and may require frequent reapplication.

Magnesium chloride is highly corrosive, and road spray of the chemical is responsible for damaging electric utility insulators along highways, causing arcing, tracking, and occasional pole fires. Corrosion inhibitors are often added to the liquid form of the chemical. However, as with the other chlorides, it should not be applied to flight decks where residue can be blown onto aircraft. Like calcium chloride, magnesium chloride leaves a slippery residue that is difficult to clean. If applied before an icing event, it may reduce ice adhesion strength to decks, bulkheads, and other hardware.

Potassium chloride itself is a relatively poor de-icing chemical at very low temperatures, making it impractical without being mixed with other chemicals, such as sodium chloride (Peeples 1998). Liquid KCl, containing a 50% concentration by weight plus corrosion inhibitors, is used as a prewetting agent with dry salt or as a straight chemical application. It is also mixed with agricultural base-stocks to reduce corrosivity and decrease freezing point temperature. Motech, a commercial de-icing mix that is a by-product of sugar beet processing, contains potassium chloride. It is also the principal component of Select Liquid de-icer by Ossian Inc (Ryerson 2009). Though the effective temperature of KCl is about –11°C, its eutectic temperature is –60°C at a concentration of 49% (Ketcham et al. 1996). Like sodium chloride, potassium chloride is endothermic and it is not hygroscopic; it requires 4.4 times more heat to go into solution than does sodium chloride. This lowering of the temperature as it forms brine is a negative feedback process that slows de-icing speeds.

Though potassium chloride is toxic in low doses (Young 2007), it is not a skin irritant and is only mildly harmful to vegetation. Potassium chloride is highly corrosive, containing more chloride ions than other salts, but is only slightly damaging to floors or to the environment. It is also used as a common fertilizer and is therefore relatively easy to handle and store (Ryerson 2009).

Potassium chloride can be applied as a liquid and sprayed onto walkways, stairs, and bulkheads, though it would run off of the latter quickly. The chemical can damage aircraft owing to corrosivity so it should not be used on flight decks or any electrical connections. It can be sprayed on deck machinery with the additional danger of corrosion, but it can also be easily diluted or removed by sea spray.

Overall, the four chloride de-icers are widely available, relatively inexpensive, but highly corrosive. There are potentially better chemicals available for de-icing in the marine environment.

5.2.2.2 Acetates

Acetate-based de-icing chemicals are often used because of their overall low corrosivity of metals. For example, Calcium Magnesium Acetate (CMA), manufactured from limestone and acetic acid (vinegar) or the fermentation of corn, contains no salts and is safely used on any surface where corrosion of metal is of concern. The corrosion rate of CMA on aluminum and steel is typically very low, about 10 to 33% of that of sodium chloride (Ryerson 2009). However, it is a slow de-icing chemical at temperatures lower than –5°C (TRB 1991). CMA is usually used at a 25% concentration, yielding a minimum melting temperature of –18°C. CMA is typically used on roadways, and is used to pre-wet areas before and during storms. It is available as a liquid or a solid and is likely to be safe in most situations. However, it is best to avoid high concentrations in natural waters, such as poorly flushed ponds or when large quantities of CMA could drain beneath floating ice covers. In addition, CMA has the capability of heavy-metal mobilization, and it has a very high Biological Oxygen Demand (BOD), causing oxygen depletion of surface waters. However, it is relatively non-toxic (Fischel 2001).

CMA reduces the adhesion strength of ice to substrates. It also leaves a residue on pavements that can protect them for up to 2 weeks. Its effectiveness is lower in dry snow and freezing rain than in other conditions, though no explanation as to why is available. CMA is very expensive, costing about 10 times more per ton than sodium chloride.

CMA could be applied to decks, stairs, deck machinery, and any other equipment threatened by corrosion. However, it is considered slippery. It is approved by the Federal Aviation Administration, and, therefore, should be usable on flight decks. CMA's high cost may have little impact in marine environments because of the small areas requiring ice protection. In addition, a high BOD is less of a negative factor in the marine environment because runoff will rapidly mix within large, moving volumes of water. However, loss of CMA under floating ice may provide some environmental risk. The low corrosivity and low impact on equipment and personnel may make it an acceptable ship de-icing chemical.

Potassium acetate is an expensive liquid de-icer mix of acetic acid (vinegar) and potassium hydroxide that is best used where extreme cold weather performance is required (Greenawalt 2006). According to the Air Force, it is best used to de-ice thin ice layers, or as an anti-icer, though the Air Force uses it primarily as a de-icer (AFCESA 1995; Fischel 2001). The chemical has a slight toxicity, and a BOD that is about 800,000 mg/L, meaning that it will cause oxygen depletion in surface waters (University of South Carolina 2008; Fischel 2001). The eutectic temperature of potassium acetate is about −60°C, with an effective temperature of about −26°C (Fischel 2001). Fischel defines the effective temperature of a de-icing chemical as "an empirical value that describes the lowest temperature for practical use of a de-icer and considers ice melting ability, anti-icing ability, type of precipitation and application rates." In addition to extreme low temperature capability, potassium acetate adheres well to surfaces, wets and spreads well, and has corrosion rates to metal that are extremely low.

Though approved by the Society of Automotive Engineers as a runway de-icing fluid, potassium acetate has been found to cause severe corrosion and disintegration of aircraft carbon brakes. In addition, it has caused aircraft underbelly corrosion and wiring damage (Shi 2008). However, added corrosion inhibitors allow compatibility with concrete, steel, and aviation components, though it is not clear that all of these corrosion problems have been solved.

Inhalation of potassium acetate may cause irritation of the nose, throat, and respiratory tract. It may also cause mild irritation to skin, eyes, and digestive tract. The effects of potassium acetate in young children or adults with kidney or heart disease include irritation and inflammation of the stomach lining, muscular weakness, burning, tingling, and numbness of hands and feet, slower heart beat, reduced blood pressure, and irregular heart beat. The effects are probably attributable to the potassium (Fischel 2001).

Potassium acetate is easily sprayed onto decks and stairs, and according to the Air Force and FAA it can be used on aircraft landing areas. The high cost of the chemical, $660 per metric ton in 2009 (Ryerson 2009), limits its use. However, usage on a ship would likely be quite small.

Sodium acetate is another low-corrosion, granulated or liquid de-icer that is used principally on runways. It is also made with acetic acid, vinegar that is reacted with sodium carbonate, sodium bicarbonate, or sodium hydroxide. The material often includes additional corrosion inhibitors. Its low corrosivity to steel embedded within concrete makes it popular for deicing pavements and bridges. However, Boeing recommends that its aircraft be washed after exposure to the chemical (Orison 2010).

Sodium acetate's effective temperature is −15°C, with a eutectic temperature of −22°C (Fischel 2001). It is typically applied before storms, and is activated by the moisture in the precipitation to reduce the bond strength of ice or snow. The chemical is hygroscopic and exothermic, allowing it to rapidly produce brine, and melt holes in ice and snow. However, the hygroscopicity can cause stored, granulated chemical to cake (Cryotech 2008).

Sodium acetate has a moderate BOD of about 800,000 mg/L (University of South Carolina 2008). It causes damaging alkali–alkali reactions in concrete. The reaction causes formation of a gel that swells and cracks the concrete (Rangaraju et al. 2006).

Sodium acetate is usable on a ship, except caution should be exercised on flight decks. It can be applied to decks, deck machinery, and stairs. However, as with any chemical used where there is foot or vehicular traffic, it should be tested for slipperiness.

Overall, the acetates are attractive for their non-corrosivity, and their overall low temperature capability. However, their high BOD and potential for damaging aircraft means that they should be carefully considered before use.

5.2.2.3 Glycols

Two glycols have commonly been used for formulating de-icing and anti-icing fluids, primarily for use on aircraft. Ethylene glycol was a common preflight de-icing chemical because of its ability to work at low temperatures. However, its toxicity has caused it to be replaced with propylene glycol. Today, nearly all preflight de-icing and anti-icing of aircraft are conducted with propylene glycol.

Pure glycols are not used for de-icing. Glycols are mixed with other chemicals that are surfactants, corrosion inhibitors, flame retardants, thickening agents, de-foamers, pH modifiers, dyes, oils, antioxidants, and antimicrobial agents (University of South Carolina 2008). These additional chemicals, though improving the performance of the fluids, also contribute to their impact on the environment. For example, though propylene glycol as a chemical is often placed in food and skin care products, the additives are often toxic. The additives in most de-icing and anti-icing fluids are trade secrets and are rarely known by users.

Ethylene glycol has a low freezing point, approximately –50°C at a ratio of 60% glycol and 40% water (Ryerson 2009). As glycols break down in the environment, they can release by-products such as acetaldehyde, ethanol, acetate, and methane that are considered highly toxic to many aquatic organisms. Ethylene glycol is also classified as a hazardous air pollutant and is required to be reported by users under the *Comprehensive Environmental Response, Compensation and Liability Act* (EPA 2000). Ethylene glycol has been proven to be toxic to mammals, especially humans, when directly ingested. However, it is not considered toxic by adsorption through the skin or by breathing air containing its mists or vapors (EPA 2000) (Ryerson 2009).

Glycols are organic compounds in the alcohol class, which, as a rule, are polar molecules with high boiling points and excellent freezing point depression. Ethylene glycol is miscible in water and is a colorless, thick, hygroscopic, bittersweet tasting liquid. It is used as engine antifreeze, in hydraulic brake fluids, and as a general heat transfer fluid. It is widely used in inks, as a stabilizer in latex paints, a cellophane softening agent, a dehydrating agent for natural gas, and as an aircraft and runway de-icer. As a de-icer, it is rapid, but it is slippery on decks and expensive. The US Navy has experienced aircraft sliding on rolling aircraft carrier decks after the use of glycol de-icing fluids, even on non-skid surfaces. On ships ethylene glycol could be used to de-ice cranes, deck machinery, and communications gear—although possibly with significant wastage. However, it should be used cautiously on composite structures where it can cause swelling and delamination.

Currently, propylene glycol is the most commonly used fluid for de-icing and anti-icing aircraft worldwide. Millions of gallons are consumed each winter; 98% of the use is for de-icing, and only 2% is used for anti-icing (Ryerson 2009). De-icing a single commercial transport aircraft once can require 4000 to 16,000 L of propylene glycol and water mix. It is also used as a humectant in foods, an emollient in cosmetic and pharmaceutical creams, a latex paint additive, an inhibitor of fermentation and mold growth, a plasticizer for resins, paper, brake and hydraulic fluids, a non-toxic antifreeze in breweries and dairy establishments, an air sterilizer in the vapor form for hospitals and public buildings, and general heat exchanger fluid (Switzenbaum et al. 1999; Ryerson 2009).

Propylene-glycol aircraft de-icing fluids (ADF) require a greater concentration of glycol than ethylene-glycol ADFs to attain the same freezing point depression. The minimum freeze point for propylene-glycol-based ADFs (–60°C) is lower than that for ethylene-glycol-based ADFs, but occurs at a higher glycol concentration. A 50 to 60% propylene glycol concentration will provide a melting temperature of –40 to –46°C.

Though propylene glycol is not toxic, its additives often are. According to the US Environmental Protection Agency (EPA 2000), as ADFs break down they can release acetaldehyde, ethanol, acetate, and methane—all highly toxic to many aquatic organisms. In addition, propylene glycol has a high BOD, typically about 1 million mg/L, versus about 500,000 mg/L for ethylene glycol (University of South Carolina 2008).

In general, on aircraft propylene glycol should not be sprayed into engine inlets, auxiliary power unit (APU) inlets and exhaust, windows, doors and seals, brakes and landing gear, vents, probes, and sensors. In addition, it can also damage composites by causing swelling and delamination (AEA 2012).

Type I de-icing fluids are used to de-ice aircraft and have low viscosity. They are used to remove ice, snow, and frost. They are typically sprayed on hot (55–83°C) and they are often dyed orange to aid in identification and application. Type II, III, and IV anti-icing fluids are non-Newtonian, spray as a low-viscosity liquid, and thicken when resting on the aircraft. The fluids are applied after de-icing during freezing precipitation to protect the aircraft from re-icing between the time that it is de-iced and when it takes off. This anti-icing fluid absorbs freezing precipitation and melts it or prevents it from freezing. If the fluid becomes too diluted, ice begins to reform and the fluid is said to fail (Ryerson 2009).

Overall, for ship use, propylene glycol is costly and, even though surface areas are small, its use could be cost-prohibitive. Generally, similar spray equipment could be used on a ship as is used at airports, except that equipment would not be truck mounted. A small, portable, heated pressure washing system may be sufficient. Propylene glycol can be used on communication equipment with no harm, but it could harm composite materials, such as those used in life rafts. Glycol should be evaluated with saline ice to determine if its performance degrades. Effects of glycol on a variety of composite materials need to be investigated. Slipperiness on decks should be quantified, and alternative additive formulations should be considered for the marine operating environment.

5.2.2.4 Bio-based chemicals

Within the last decade there has been rapid development creating new de-icing and anti-icing chemicals, primarily for roads, by combining sugar-based agricultural by-products with traditional freezing point depressants. Agricultural by-products that are used as base stock include sugar beets, corn, and by-products of alcohol beverage production (Ryerson 2009). The synergistic effect of the carbohydrate base stock and added chloride or acetate-based chemicals lowers the freezing point below that of either material, therefore requiring less chemical for a given application than chlorides or acetates used alone (W. King, personal communication, 24 November 2008; Ryerson 2009). These chemical combinations are effective at low temperatures, are minimally corrosive, and continue to function with high dilution, even through several storms without being re-applied. They typically dilute less rapidly than non-agricultural-based products, and they de-ice more rapidly than sodium chloride at temperatures higher than –18°C. Friction is generally higher than pavement surfaces when the surface is dry and relative humidity is low. However, when wet, these chemicals are typically similar to or only slightly more slippery than a water-wet pavement. Overall, the chemicals are generally safe for plants and animals, are not harmful to clothing, carpets, and other surfaces, have very low corrosivity, and low BODs (Ryerson 2009). The materials do not ferment, attract insects, or decay.

The sugar beet-based products are available primarily in the Midwest where sugar beets are grown. It is often mixed with sodium chloride and magnesium chloride and used by road departments in MI, IN, and OH (Road Solutions 2008; Conkey 2008). There are also experiments being conducted using sugar beet-based fluids to keep stainless steel cable-stayed bridge stays de-iced, and it is used on pavements by the Ohio Department of Transportation (D. Nims, personal communication, 20 February 2013). Depending upon the formulation, versions of the beet-based fluid are effective to –32°C and are about 80% less corrosive than sodium chloride alone (Wellspring 2008; W. King, personal communication, 24 November 2008). The beet-based material is stable and does not ferment or chemically break down rapidly after application (W. King, personal communication, 24 November 2008). This chemical stability also allows the beet-based material to store well, with a long shelf life, and allows for a diversity of applications because it is a liquid; material can be sprayed on surfaces of any orientation. Lower corrosivity protects materials such as cables. Its effects on composite integrity and on communications and surveillance antenna performance are unknown. Because the material is not certified for use on aircraft, use on helicopter landing pads is not recommended. It stores well without fermenting or chemical decomposition, but there have been claims of rancid odor and a syrupy consistency (Hollander 2008).

The corn-based products are also available primarily in the Midwest, and available only as liquids (Ryerson 2009). The material penetrates snow and ice to break the adhesive bond to substrates. Eutectic temperatures can be as low as –40 to –66°C, and the materials are typically a mixture of the corn-based stock and either magnesium chloride or potassium acetate. The BODs are low, the materials are non-toxic and have no flash-point, but they do have mild, sweet odors (Ryerson 2009). The material can be used as an anti-icer if applied before icing begins, or as a de-icer. As liquids, these de-icers are of somewhat higher viscosity than other de-icing liquids, which may allow them to adhere more effectively to non-horizontal surfaces. The low corrosivity should allow applications with less concern about damage to materials such as cables. Impact on composite material integrity is unknown, as is usability on communications and surveillance antennas. Because the materials are not certified for use on aircraft, use on helicopter landing pads is not recommended. Although the friction coefficient of surfaces decreases when these chemicals are initially applied, as is true with most de-icing chemicals, friction increases over time—especially after the material dries.

The alcohol-based fluids consist of a sugar base stock of distilled, condensed solubles (DCSs), a slurry derived from vodka and rum production (Ryerson 2009). The DCS liquid is mixed with magnesium chloride, or other materials such as sodium chloride or sand, for anti-icing of roads, bridges, parking lots, and sidewalks (J. Parker, personal communication, 24 November 2008). A typical mixture is 50% DCS material and 50% magnesium chloride. The alcohol-based products have effective temperatures lower then –18°C, and eutectic temperatures of about –42°C. It is safe for humans and for the environment, BODs are low, no special handling equipment is required, and it is water soluble and biodegradable. Corrosion rates are about 3% that of sodium chloride (Sears 2008). The material is dark brown and somewhat sweet smelling. As liquids, these de-icers can be sprayed on surfaces of any orientation, though they are of somewhat higher viscosity than other de-icing liquids, which may allow them to adhere more effectively to non-horizontal surfaces. The low corrosivity should allow application to materials such as cables with less concern for damage. The effects on composite materials are unknown, as is usability on communications and surveillance antennas. Because the materials are not certified for use on aircraft, use on helicopter landing pads is not recommended. Although the friction coefficient decreases when these chemicals are initially applied, friction increases over time—especially after the material dries.

Prior to use on ships, the capabilities of these bio-based chemicals should be evaluated for effectiveness in saline ice and marine spray environments. The capability of the chemicals on antennas and composites must be evaluated, and corrosivity and friction coefficients should be verified.

5.2.2.5 Miscellaneous

Several other chemicals are also available for de-icing. Two are relatively recent introductions; the third, urea, is in general declining usage.

Sodium formate is a relatively new de-icing chemical in the US, being used extensively in Europe in the 1990s (Ryerson 2009). It is intended for pavements, is available as solid granules or a liquid, and meets FAA and Air Force runway de-icing requirements. Though classified as a salt, it has low corrosivity with the appropriate corrosion inhibitor additives. However, it is slowly corrosive of galvanized steel because it reacts with zinc, as do all of the acetates and formates (Reeves et al. 2005). Takeshi et al. (2004) report that sodium formate has a corrosion rate approximately one-half that of sodium chloride.

Sodium formate has a working temperature of –18°C and a eutectic temperature of –22°C (Cryotech 2008). Takeshi et al. (2004) found that sodium formate has a melt rate that is the highest of the non-chloride de-icers. It has a low BOD (230 mg/g) and has a neutral pH. Sodium formate is dusty in storage and, being hygroscopic, may cake before use (Cryotech 2008). A special formulation used by the South Dakota Department of Transportation is relatively harmless to aquatic animals and causes minimal toxicity to roadside herbaceous (e.g., sunflowers, beans, and lettuce) and woody (e.g., pine seedlings) plants. At low concentrations (less than 2 g/kg of soil) sodium formate is a fertilizer, promoting the yield of plants.

Sodium formate is available as a solid or liquid so it can be applied to horizontal and irregular surfaces. It can be applied to walkways, stairs, and work areas, and potentially to windlasses and lattice structures. Because it can be used on runways and taxiways, it is also usable on helicopter landing pads. Its effect on composites is not known. Being a chemical, it may be readily diluted by spray and wave wash. Its ice melt rate is nearly as fast as the chlorides without many of the negative effects of chlorides. It is relatively expensive and requires large applications when the ice is thick and the temperature is low.

One of the problems with chemicals is their interaction with the environment, generally as an aquatic toxin or as a material with a high BOD (University of South Carolina 2008). Other concerns are corrosion of aircraft and electrical components, and damage to pavement materials (Shi 2008). A new de-icing fluid, Harmony, has been designed to be safely washed overboard from marine structures without regulation. Though the chemical content is proprietary, it is considered safe for discharge into seawater because it is compliant with *The Harmonised Offshore Chemical Notification Format* (HOCNF) 2000 of the *Oslo and Paris Commission* (OSPAR [http://www.ospar.org/]). The overall goal of OSPAR *Using the Ecosystem Approach* to manage human activities affecting the maritime area is to conserve marine ecosystems and safeguard human health. When practicable, another goal is to restore marine areas that have been adversely affected in the Northeast Atlantic by preventing and eliminating pollution and by protecting against the adverse effects of human activities. To this end, the Harmony fluid is on the *Pose Little or No Risk to the Environment* (PLONOR) certified List of Substances/Preparations Used and Discharged Offshore (PLONOR registration number 24991). This certifies that the fluid minimizes damage to biodiversity and ecosystems, does not contribute to human-induced eutrophication, does not contribute hazardous substances to the marine environment, and does not add radioactive substances to marine waters.

The Harmony fluid is intended for use in heated pressure washers for cutting or washing ice and snow from marine structures. With a freezing point of to –27.7°C at a 50% concentration with water, it is intended to prevent re-freeze as ice is removed from surfaces. A residual of the de-icing fluid remains on surfaces to provide an anti-icing effect during the next icing event. The chemical can clean decks, ladders, bulkheads, cranes, windlasses, and other ship equipment.

Urea was a common runway de-icer, but its use has been prohibited at an increasingly large number of airports because of its environmental impact and the availability of superior de-icers. However, recent surveys show that it is still used by airports despite adverse environmental impacts (Shi 2008). Urea is available as pellets or as liquid. It is effective in ice and snow, but its eutectic and working temperatures are only –12 and –4°C respectively (Ryerson 2009). Urea is an endothermic de-icer. That is, as it forms brine, it absorbs heat and cools ice and snow (Cryotech 2008). Therefore, the formation of brine is a negative feedback process that slows de-icing.

Urea has high aquatic toxicity, and a high BOD that causes surface water eutrophication and damages vegetation and surface water by adding excessive nitrates. Ammonia, which is toxic in poorly ventilated areas, is released into the air when urea contacts water. Urea also severely corrodes metals (Frank 2004), and it can irritate the nose and cause a sore throat, sneezing, coughing, and shortness of breath. Chronic exposure and acute exposure in high concentrations may cause eye damage, skin redness or rash (dermatitis), or emphysema (EPA 2000). Urea also causes white deposits when tracked onto floors (MacDonnell 2003). Urea is hygroscopic and may harden in storage.

Urea can be applied as a liquid or a solid, and it is often applied with sand to improve traction—important on walkways, stairs, and work areas. As a liquid, urea could be applied to windlasses, lattice structures, and other irregularly shaped structures. It is relatively non-corrosive, when compared to the chlorides, and lessens the chance of corrosion failure of cables. In addition, it could be applied to flight decks if it is certified for aviation use. Testing the capability of urea in the marine icing environment is necessary. The effects of urea and its by-products on human health should be explored because of the potential proximity of human activity and the chemical is greater on ships than on roadways and airports. The effects of urea on the integrity of composite materials are unknown.

Table 5-1. Summary of de-icing chemicals.

Product	Source	Description	Information
Sodium chloride, Calcium chloride, Magnesium chloride	Cargill Salt PO Box 5621 Minneapolis, MN 55440-5621 Tel: 888-385-SALT (7258)	Solid and liquid ice melting chemicals	Ryerson (2009) www.cargill.com/salt/contact-us/index.jsp
TKS weeping wings	CAV Aerospace Inc. 2734 Arnold Court Salina, KS 67401 Telephone: 888-865-5511; 785-493-0946 E-mail: tkssales@weepingwings.com	TKS weeping wing system and Kilfrost de-icing fluid	Ryerson (2009) www.weepingwings.com
Calcium Magnesium Acetate, Ethylene glycol, Magnesium Chloride, Potassium Acetate, Potassium Chloride, Propylene glycol, Sodium Acetate, Sodium Chloride, Sodium Formate, Urea	Chemical Solutions Inc. Franklin, MA 02038-0675 Tel: 508-520-3900	Solid and liquid de-icing and anti-icing chemicals	Ryerson (2009) www.meltsnow.com/products.htm

Product	Source	Description	Information
Safewing® Octaflo EG® Max Flight® Safeway®	Clariant Corporation 625 E. Catawba Ave. Mt. Holly, NC 28120 Tel: 704-822-2677 Fax: 704-822-2193	Ethylene glycol and Propylene glycol de-icing and anti-icing fluids, Potassium acetate and Potassium formate runway de-icing materials	www.aviation.clariant.com
Cryotech E36® Cryotech NAAC® Cryotech BX36® Cryotech CF7® Cryotech CMA® Cryotech CMA40® Polar Plus® Polar Guard® Polar Guard Advance®	Cryotech De-icing Technology 6103 Orthoway Fort Madison, IA 52627 Tel: 319-372-6012; 800-346-7237 Fax: 319-372-2662	Solid and liquid de-icers: Potassium acetate, Calcium magnesium acetate, Sodium acetate, Propylene glycol, Sodium formate	Ryerson (2009) www.cryotech.com/
Ice Slicer road salt Sodium chloride, Caliber M-1000, Meltdown, Magnesium chloride, Calcium chloride, Potassium chloride	EnviroTech Tel: 800-369-3878 info@iceslicer.com	Solid and liquid de-icing chemicals, ice sensors, FAST spray systems	Ryerson (2009) www.envirotechservices.com
Enviro-MLT	GeoEnvironmental 157 Southbridge Rd. North Oxford, MA 01537 Tel: 800-853-5393 sales@geoenviro.net	Sodium acetate liquid de-icer	Ryerson 2009) www.geoenviro.net
Harmony De-icing Fluid	Mike Sweetman, Managing Director Ideal Solutions 730 Enterprise Drive, Lexington, Kentucky 40510 Tel: 866-673-3963 Cell: 502-316-1663 Fax: 859-266-2717 msweetman@idealsolutionsonline.us	COTS de-icing fluid	Appendix B www.idealsolutionsonline.us
Feltwick Anti-Icing Grate	Innovative Dynamics Inc. 2560 North Triphammer Rd. Ithaca, NY 14850 Tel: 607-257-0533 Contact: Joseph Gerardi Fax: 607-257-0516	Deck and stair anti-icing mats	Appendix B www.IceSight.com/
ProMelt Slicer MAG® Magic Salt	Innovative Surface Solutions 454 River Road Glenmont, NY 12077 Tel: 518-729-4319 Fax: 518-729-5181	Liquid and solid bio-chemicals mixed with magnesium chloride, sodium chloride, calcium chloride or potassium chloride.	www.innovativecompany.com
Kilfrost	Kilfrost, Inc. 6250 Coral Ridge Drive, Suite 130, Coral Springs, Florida 33076 Tel: 1-877-U-KILFROST (1-877-854-5376), 954-282-5050 Fax: 954-282-5049 Usa.sales@kilfrost.com	Ethylene glycol de-icing fluid	Ryerson (2009) www.kilfrost.com/

Product	Source	Description	Information
WinterGreen® Ice-Foe® Triple Melt® Eco Melt® Hammer® Walkway® CMA1000® MAC® Peldow® Select® Ice Guard®	Ossian Inc. PO Box 4076 635 S. Elmwood Ave. Davenport, IA 52802 Tel: 800-553-8011 icemelt@ossian.com	Solid and liquid de-icing and anti-icing chemicals	Ryerson (2009) www.ossian.com
Sodium chloride, Calcium chloride, Magnesium chloride, Potassium chloride, Urea, Sodium acetate, Calcium magnesium acetate, Potassium acetate	Peters Chemical Co. PO Box 193 Hawthorne, NJ 07507 535 High Mountain Rd. Suite 212 North Haledon, NJ 07508 Tel: 973-427-8844 Fax: 973-427-7748 Harold@peterschemical.com	Solid and liquid de-icing and anti-icing chemicals	Ryerson (2009) www.peterschemical.com
Ice B'Gone Magic	Sears Ecological Applications Co., LLC 1914 Black River Blvd. Rome, NY 13440 Tel: 888-847-3226	Bio-based solid and liquid de-icers with magnesium chloride.	Appendix B Ryerson 2009 www.IBGMagic.com/ www.seaco.com
Alpine RF-11™	Seneca Mineral Co. Inc. 8431 Edinboro Rd. Erie, PA 16509 Tel: 814-476-0076; 800-291-9222 Fax: 814-476-0066 senecamineral@gmail.com	Solid and liquid de-icers: Potassium acetate,	Ryerson (2009) www.senecamineral.com
Geomelt® Biomelt® Green Paws® Ice-Ax® Ecosalt®	SNI Solutions 205 N Stewart St. Geneseo, IL 61254 Tel: 309-944-3168 Fax¨309-944-4620 mike@snisolutions.com	Liquid and granular bio-based de-icer with Sodium/Calcium/Magnesium chlorides	Ryerson (2009) www.snisolutions.com
Propylene glycol and ethylene glycol de-icing and ant-icing fluids	The Dow Chemical Company Tel: 989-832-1560, 800-447-4369 Fax: 989-832-1465	Aircraft de-icing and anti-icing fluids	Ryerson 2009) www.dow.com/aircraft/
Sodium chloride, Calcium chloride, Magnesium chloride	U.S. Salt Inc. 1020 Black Dog Rd. West Burnsville, MN 55337 Tel: 952-890-8448 Fax: 952-890-8493	Solid de-icing chemicals	Ryerson (2009) www.ussalt.com
Geomelt® Geosalt® Ecosalt® Iceax® Geoblends®	WellSpring Management Oak Park, IL 60301 Tel: 708-383-0835 Fax: 703-383-3468 info@wellspringltd.com	Liquid and granular bio-based de-icer with Sodium/Calcium/Magnesium chlorides	Ryerson (2009) www.wellspringltd.com/

5.3 Coatings and surface treatments

Developers have long sought to eliminate icing problems on all structures by either changing the surface of the structure's substrate material or by adding a coating. These techniques, or surface treatments, have long been considered the "holy grail" of icing because they are passive, requiring no power to be effective. That is, they are always available to reduce the icing threat, requiring little, or only occasional, attention from users, relying upon surface characteristics to reduce ice adhesion strength or prevent icing, and wind, gravity, solar radiation, or physical geometry to assist.

The traditional intent has been to develop coatings that reduce the adhesion strength of ice to a surface and either reduce the effort to remove ice, or reduce the adhesion strength sufficiently that ice falls off as it accumulates. These would be self-cleaning, or ice-phobic, surfaces because ice would form, and then the ice would self-shed and fall away under its own weight. Because ice-phobic surfaces also are often hydrophobic, they do have the potential to reduce icing amounts. However, ice-phobic surfaces typically do not prevent icing (Anderson and Reich 1997; Mulherin and Haehnel 2003), and, in general, hydrophobic surfaces (those that repel water) are not necessarily also ice-phobic.

Most claimed ice-phobic surfaces are not highly ice-phobic, most do not have longevity, and require frequent maintenance or cleaning to maintain low ice adhesion, and many are not easily applied. Mulherin and Haehnel (2003) state that ideal coatings significantly reduce ice adhesion, are durable, are low in cost, and are easy to apply.

Within the last 5-years there has been dramatic growth in development of materials or surface treatments with nano-scale topographic surfaces that reduce ice adhesion, prevent icing, or both. Nano-based anti-icing surface treatments and coatings are an active area of basic and applied research that hold promise, but are generally not proven technologies in the operational environment. Developments are rapid and issues are many, but they hold some promise of reducing icing more effectively than any materials to date.

5.3.1 Fresh water ice adhesion

In general, the adhesion of ice to a solid substrate is a function of a combination of the following five factors: electrostatic forces, hydrogen bonding, Van der Waals forces, mechanical interlocking, and a liquid-like layer. Of these forces, the liquid-like layer and mechanical interlocking may be the most important. Makkonen (2012) provided a thorough and clear discussion of the mechanisms controlling ice adhesion, and their magnitude in somewhat different terms. Overall, he explained that the work of ice adhesion is related to the surface tension of water in contact with the surface, if the water were melted. That is, as the contact angle of a water droplet with a surface increases, ice adhesion decreases. For example, if a drop stands as nearly a sphere on a surface that is difficult to wet, its contact angle with the surface approaches 180° and ice adhesion would be low. However, if the drop lies flat on a surface that is easily wetted, the angle approaches 0°, and ice adhesion would be high.

Though the relationship between drop contact angle and ice adhesion exists, it is not the only factor that affects ice adhesion. Ice can also fail in adhesion to a surface through either brittle or ductile failure (Makkonen 2012). When the substrate is flexible or the ice is near 0°C, the interface between the ice and the substrate fails as a ductile material—there is no brittle failure. If the substrate is rigid or the ice is cold, failure is typically in the brittle mode. Cold ice often also has lower adhesion strength than warm ice.

The morphology of a substrate surface also plays a large role in ice adhesion. In general, large substrate surface areas adhere to ice more strongly than substrates with small ice contact areas. For example, ice that forms bubbles between itself and the interface will have a smaller adhesion strength than does ice that has no bubbles, because the bubbles decrease contact area with the surface; the surface contact area is < 1. On the other hand, if a substrate is macroscopically or microscopically rough, that substrate has a larger surface area than a smooth, polished surface. If ice forms on the surface with an area > 1 with no air bubbles at the ice–substrate interface, ice adhesion increases through mechanical locking. Generally, also, ice formed from droplets colliding with a substrate form smaller ice crystals than water frozen in bulk, and attempts have been made to relate crystal size with adhesion strength. Menini et al. (2011) provide evidence that the greater the ice crystal size is, the lower is the ice adhesion. However, Makkonen (2012) states that if the contact areas are the same, crystal size shows no effect experimentally.

Ice is also claimed to have a liquid-like layer on its surface, and at contacts with substrates, that affects adhesion strength. Makkonen (2012) explained that the edges of an ice mass have net inward molecular forces, into the ice mass, because the molecular strength between ice and itself is higher than between ice and other materials. This inward pressure is excess pressure on the surface, and is similar to an external pressure exerted on the ice surface. This pressure reduces the melting temperature of the ice, called pressure melting, and allows a thin film of water to form on the ice. This liquid-like layer film, nanoscale in thickness, is thickest near 0°C, and decreases in thickness and disappears at about –13°C. The liquid-like layer is similar to placing a wetting layer between the ice and the substrate, and increases the contact area between them, increasing ice adhesion. This corresponds to an increase in ice adhesion down to the temperature at which the liquid-like layer disappears.

After ice forms, if the temperature decreases and the ice cools, the ice and the substrate both contract as they cool. If the ice and the substrate contract at different rates, then stress will accumulate between the substrate and the ice, creating stress cracks in the ice. Stress cracking is more pronounced if cooling occurs quickly rather than slowly. The stress cracks provide starting places for cracking or peeling of ice from a substrate. Though stress cracking increases as deeper cooling occurs, it does not seem to counteract the increase of ice adhesion as it cools because of the disappearance of the liquid-like layer (Makkonen 2012).

Overall, ice adhesion theory is insufficiently well understood to reliably model adhesion strength according to Makkonen (2012). Therefore, measurements are relied upon to determine ice adhesion, and even measurements are difficult to make consistently. In addition, the method of making the measurement can have a large influence on the values obtained.

In general, ice adheres to substrates with an adhesive strength that ranges from near 0 to about 1 MPa, depending upon the substrate material. According to Makkonen (2012), 1 MPa is nearly the cohesive strength of ice, so if adhesion strength is very high, ice often fails cohesively before it fails adhesively. This, of course, leaves a residual of ice on surfaces that must be removed in a separate process. Generally, it is believed that ice fails along cracks or dislocations, causing weak areas that propagate cracks when stress is applied.

Typical fresh water adhesion strengths with substrates increase as temperature decreases to about –13°C, and then again decrease (Makkonen 2012). However, typical adhesions strengths are, at–10°C, with steel about 500 kPa, with glass about 450 kPa, and with Teflon® about 50 kPa.

In general, it is difficult to link theory and practice for ice adhesion. Ice occurs in many forms—frost, snow, rime, glaze, and spray ice—substrates have surface irregularities and contaminants, and few surfaces are absolutely flat. Therefore, the importance of each factor affecting ice adhesion strength varies with the surface and icing situation. Overall, Menini et al. (2011) summarized that the primary causes of ice adhesion are chemical, electrostatic, liquid-like layer, and mechanical interactions between the ice and the substrate; ice-phobic surfaces must address all of these factors if they are to be successful.

5.3.2 Salt water ice adhesion

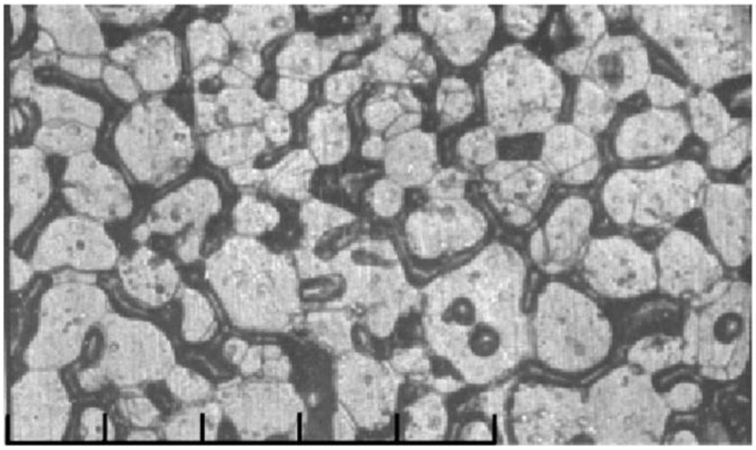

Figure 5-3. Thin section of saline ice sampled from a bulkhead on the CGC MIDGETT in March, 1990 in the Bering Sea illustrating grains (light color) encircled by large channelized networks (dark) filled with brine (scale in millimeters) (from Ryerson and Gow 1990b).

The controls of salt water adhesion are dominated by a brine layer that forms at the ice–substrate interface. As ice crystals form, they exclude impurities from the ice. Salt, as an impurity, then concentrates in unfrozen water that migrates to spaces between the ice crystals, and forms pockets of brine. These small reservoirs are initially filled with concentrated salt water, but gradually drain and fill with air, especially if they are located on an inclined surface where gravity can cause drainage (Fig. 5-3) (Ryerson and Gow 1990a). There is no ice in the brine pockets. Therefore, where brine pockets intersect the substrate, there is less is contact area between the ice and the substrate, and ice adhesion decreases.

The reduced contact area between ice and substrates caused by brine pockets is, however, only part of the process. As ice decreases in temperature, more brine is excluded from the ice, and the brine pockets are squeezed by the continuously freezing ice. Some brine is forced out of the brine pockets, and other flows out because of gravity. This causes a thin layer of brine to form on the ice surface, and along the interface between the ice and the substrate. This decreases adhesion strength, much as does the liquid-like layer of water that forms on fresh water ice.

The brine layer that forms on the ice surface, and at the ice–substrate interface, however, is much thicker than that of the liquid-like layer on fresh water ice. Whereas the liquid like layer may be only 0.01 µm thick, the brine layer thickness varies from 0 µm thick when the ice initially freezes, to a maximum of about 120 µm. It is generally thickest a few to 10°C below the freezing point, depending upon the salinity. The thickest water layer is often greater than the substrate surface roughness. However, it is believed that the brine layer may not always be continuous, causing ice adhesion to vary over the surface. In general, the higher the salinity is, the farther the ice must be cooled to maximize the brine layer thickness.

In general, the adhesion strength of saline ice is only about 10 to 20 kPa at temperatures higher than –10°C. The strength of saline ice begins to rapidly increase at temperatures lower than about –20°C, reaching an adhesion strength of nearly 300 kPa at –50°C (Makkonen 2012).

5.3.3 Ice-phobic surfaces

Ice-phobic surfaces traditionally reduce the adhesion strength of ice to a substrate. Though ice-phobic suggests that ice might not form, there is a new class of materials that prevent ice formation and may reduce ice adhesion, classified as anti-icing surfaces. Because, as used here, ice-phobic materials reduce ice adhesion, ice must first form. They may then be considered as materials that assist de-icing, as they reduce the amount of energy necessary to remove ice.

A goal of ice-phobic coating developers has been to create a surface that is effectively anti-icing. That is, if ice adhesion strength is sufficiently low, ice should detach from a surface immediately after it nucleates from its own weight. And, many believe that hydrophobic surfaces are also ice-phobic because hydrophobic surfaces reject water. However, ice-phobic coatings typically do not prevent icing (Anderson and Reich 1997; Mulherin and Haehnel 2003), and, in general, hydrophobic coatings (those that repel water) are not necessarily also ice-phobic.

Makkonen (2012) calculated the thickness of ice necessary for gravity to remove ice from its weight alone. He claims that the typical better coatings have an adhesive strength of about 100 kPa. An adhesive strength of 100 kPa requires about 10 m of ice to accumulate before it detaches because of its own weight. The best coating measured by CRREL has an adhesion strength of about 37 kPa (Ryerson 2008). Even that low strength requires about 0.35 m of ice to be self-shedding. Though these low adhesion strengths provide a significant aid to manual or other forms of de-icing, anti-icing from controlling adhesion strength alone, using coatings, is not currently available (Farzaneh 2008). Mulherin and Haehnel (2003) summarized ideal properties of ice-phobic surfaces. They must have the 1) capacity to significantly reduce ice adhesion strength, 2) durability or longevity, 3) cost effectiveness, and 4) ease of application. This is in addition to the normal requirement of coatings to protect against corrosion, wear, erosion, and UV degradation, and to release as few VOCs as possible when applied (Menini et al. 2011).

Ice-phobic coating technology varies widely in material properties, chemistry, and design. Most coatings are of a single chemical compound that is applied to surfaces by spraying or brushing. They may also be substances such as plastics that can be structural materials themselves. For example, Teflon® has been found to have one of the lowest ice adhesion strengths of all materials (Frankenstein and Tuthill 2002; Mulherin and Haehnel 2003). Mulherin and Haehnel (2003) also indicate that polyethylene has an adhesive strength similar to Teflon® (Boluk 1996). However, Teflon® is soft and is not generally durable. Other non-durable materials that have demonstrated very low adhesion values include silicone grease (Boluk 1996) and lithium grease (Laforte et al. 2002). Greases typically wash from surfaces, and are often removed with the ice (Ryerson 2008). Their utility on a ship would be limited because spray, and occasional green water, would wash them away.

Of more durable materials, the polysiloxanes have some of the lowest ice adhesion strengths (Frankenstein and Tuthill 2002). However, some siloxanes, such as Kiss-Cote (Ryerson 2009), were found to increase mean adhesive strength when coated over some paints, and decrease it when coated over other paints (Mulherin and Haehnel 2003). This suggests that coatings should not be applied blindly to materials with the expectation of a specific performance, but should be evaluated in the operating environment where they will be used. It is prudent to test with the specific materials of interest before making large investments. Also, the effects of weathering on the ice adhesion strengths of coatings should be investigated during testing.

Among materials having the lowest adhesion strengths ever measured at CRREL are a silicone by NuSil Technology (Sivas et al. 2007) at 37 kPa compared to Teflon®'s average adhesion strength of 238 kPa (see Appendix B), and PCM Marine™ by ePaint at 5.5 kPa (see Appendix B). Even after roughening with sandpaper and weathering to simulate thermal and humidity cycling and salt spray, the adhesion strength of NuSil R-2180 was always lower than that of unweathered Teflon® (Ryerson 2009).

Ferrick et al. (2008, 2012) evaluated a series of coatings at cryogenic temperatures for the space shuttle fuel tank icing problem. The control was Koropon coated aluminum, as is found on the shuttle fuel tank. Coatings tested included lithium grease, Braycote, and a mix of Braycote and Rain-X with powdered MP-55 Teflon included. The Rain-X with Teflon MP-55 showed adhesion strengths that were approximately 10% of that of the control with consistent results during repeat testing. They recommend continued testing to refine optimal formulation, application, cure, and durability questions.

Another approach to reducing ice adhesion strength, using nanotechnology, is to embed capsules of anti-icing compound within an icephobic coating material (Microphase 2008). With Air Force Small Business Innovation Research (SBIR) funding, Microphase Coating, Inc., created a coating with low ice adhesion that is erosion-resistant and renewable, and has high adhesion to substrates. The coating is composed of epoxy, silicate mesh, and freezing-point depressants in embedded nanocapsules. As the coating erodes, the capsules break and ooze freezing point depressant at the ice–coating interface, thereby intending to reduce ice accretion rates (see Appendix B).

More recently, commercially available polymers such as fluorinated polyhedral oligomeric silsesquioxane (fluorodecyl POSS) and poly(ethyl methacrylate) (PEMA) have been investigated, along with nearly 20 other materials, for their ability to lower ice adhesion strength to smooth surfaces. POSS is a low-surface-energy additive, related to the silicones, that enhances water repellency. It is a hybrid material that is intermediate between silica and silicone (Lichtenhan et al. 2001) and can be readily coated onto metal and other surfaces. The authors examined the relationship between water wettability and ice adhesion strength on smooth surfaces. Tests were conducted in a cold chamber, with water poured onto the test substrates. Ice adhesion for bare steel averaged 698 kPa at –10°C. The lowest ice adhesion was from 80/20 and 70/30 mixes of PEMA and flourodecyl POSS at about 165 kPa. The authors believe that the PEMA–flourodecyl POSS combination yielded the minimum ice adhesion strength attainable by reducing the water wettability of smooth surfaces, and that any additional reduction in adhesion strength is only attainable by adding micro- or nano-scale texture to the surface.

Menini et al. (2011) claimed that two materials were the best candidates for very low surface energy coatings: polydimethyle-siloxane (PDMS or silicone), and Teflon® (polytetraflouroethylene [PTFE]). Overall, they stated that the silicones (PDMS) performed better than the PTFE, and they were all easily applied as paints. However, PDMS has relatively poor wear characteristics and is best suited for temporary conditions. Menini et al. (2011) claimed that Wearlon, a silicone-based material, had about 10% of the ice adhesion strength of bare aluminum (Fortin et al. 2011). The company claims the Super F-1 material can be used on any surface with icing problems, including ships; only greases and lubricants, at best temporary, performed better of 24 materials tested. Menini et al. (2011) also indicated that some researchers have mixed PDMS and polyflourocarbon (PFC) materials and created very low ice adhesion strengths. Several of these mixtures of different formulations either reduced or fully prevent wet snow accumulations, and decreased ice adhesion 2 to 25 times less than PTFE.

5.3.4 Anti-icing surfaces

In recent years there have been new attempts to develop surface treatments that either reduce ice adhesion or, more desirably, completely prevent icing. That research has focused on biomimicry to create surfaces that are super-hydrophobic, as is exhibited by some plants, such as the Lotus leaf, and by some insects (Fig. 5-4). That is, some surfaces have a self-cleaning effect where surface energy is very low, wettability is low, and droplets roll off of surfaces with very small inclinations, carrying debris with them. A surface that has a contact angle approaching 0° is considered super-hydrophyllic—or water loving (Dodiuk et al. 2012). Contact angles less than 90° are hydrophilic (Fig. 5-5).

Figure 5-4. Water pool on Lotus leaf showing high drop contact angle (photo Ryerson 2012).

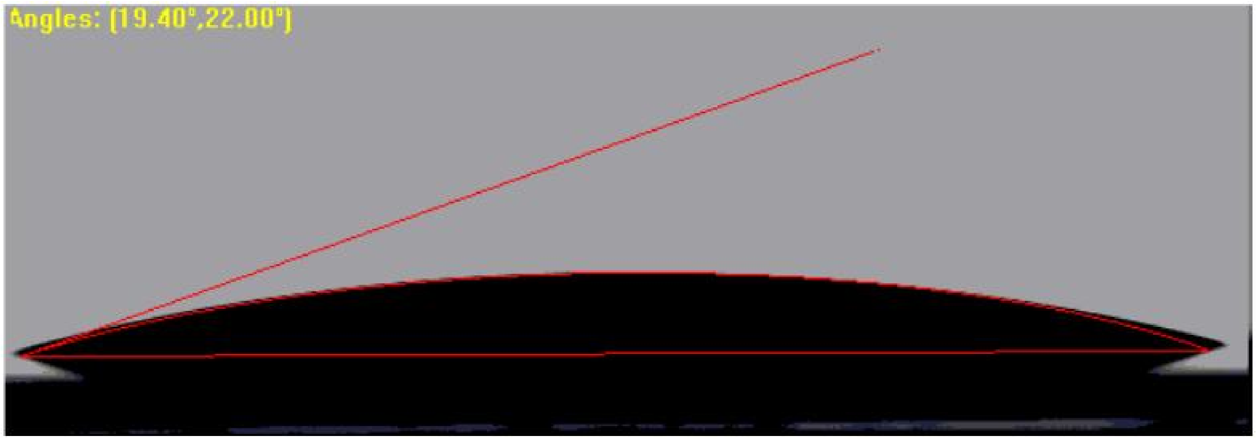

Figure 5-5. Hydrophyllic drop with a contact angle of about 20° (image courtesy University of Center for Integrative Nanotechnology Sciences, University of Arkansas at Little Rock, 2010).

Hydroplyllic surfaces are high energy surfaces, where the adhesion between the drop and the surface, or substrate, is high. Hydrophobic surfaces, water-repelling surfaces, have drop contact angles between 90 and

150°. These angles are about the highest that can be achieved using chemistry on a flat surface according to Meuler et al. (2010). Higher angles, from 150 to 180°, are considered super-hydrophobic, or sometimes ultra-hydrophobic (Fig. 5-6). Many researchers have found super-hydrophobic surfaces to also exhibit anti-icing characteristics and some also exhibit ice-phobic properties when ice does accumulate on their surfaces.

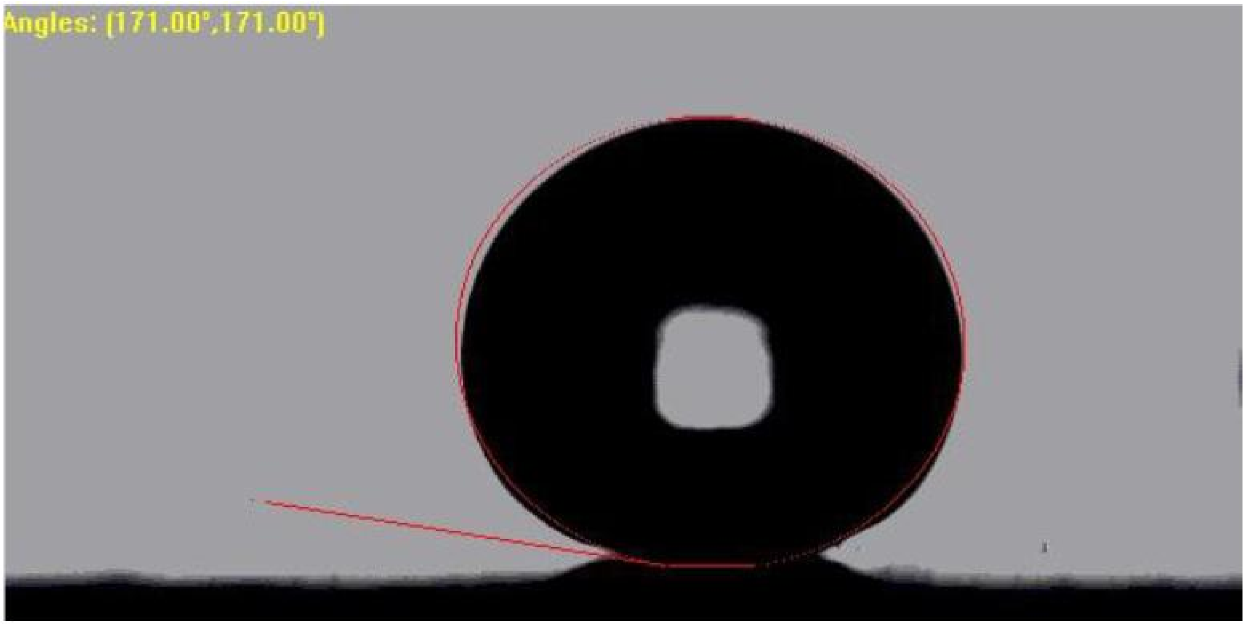

Figure 5-6. Super-hydrophobic drop with a contact angle of 171° (image courtesy Center for Integrative Nanotechnology Sciences, University of Arkansas at Little Rock, 2010).

As indicated, the Lotus leaf self-cleaning effect serves as a natural model for understanding the behavior of super-hydrophobic surfaces. Dodiuk (2012) explained that the leaf is super-hydrophobic using two mechanisms. It consists of a base layer that has a morphology consisting of roughness elements that are 5 to 10 µm high and 10 to 15 µm apart. Atop this relief layer is a layer of waxy, hydrophobic crystals that are only nanometers in diameter. The waxy hydrophobic material repels water and produces a drop contact angle of over 150°, and the micro- and nano-roughness elements decrease the contact area between the drops and the leaf surface. This operates much as a bed of nails, or "Fakir" bed (Fig. 5-7), by reducing the adhesion of drops to the surface. The drops, then, can easily roll or slide across the leaf surface. The angle that the surface must be tilted to make the drops mobile is a critical measure of the hydrophobicity of the surface, as is contact angle hysteresis, the difference between the advancing and receding contact angle of the drop as it moves across the surface. The more similar the leading and departing angles are, the more mobile the drops usually are.

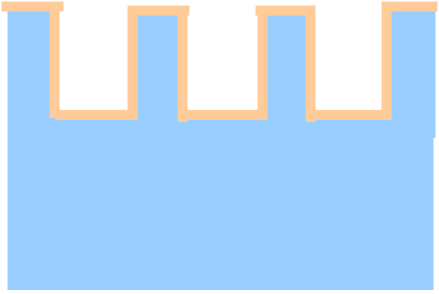

Figure 5-7. Close view of nano-texture surface with conformal coating of polymer or silane (courtesy Center for Integrative Nanotechnology Sciences, University of Arkansas at Little Rock).

Dodiuk (2012) continued that super-hydrophobic surfaces can be created in various ways and using various materials. He said that texture can be created using vapor deposition, calcinations, anodization, plasma or chemical etching, and replication of nano-templates. Nilsson et al. (2010) have even used sandpaper successfully to create topography on Teflon that is a super-hydrophobic surface, and Lambourne and Taylor (2011) proposed, in a patent, using lasers to etch or melt relief into plastic and metal surfaces. Most of these methods, however, require many steps, harsh chemicals and solvents, and complex processes and equipment (Dodiuk 2012).

Chemistries used with the topography to make surfaces super-hydrophibic include alkanes, silicones, and fluorine-based materials, as described for ice-phobic coatings by Menini et al. (2011). Dodiuk (2012) indicated from testing that a trifluoro cyclopentyl POSS was particularly effective as a surface coating, and it was transparent at low concentrations and still effective. However, as a chemical-covered smooth surface cannot attain drop contact angles greater than 120°, roughening the surface is necessary to create higher contact angles and to create the Cassie effect (Dodiuk 2012). Figures 5-8 to 5-10 show examples of different types of nano-surfaces used for super-hydrophobicity and anti-icing experiments, greatly magnified.

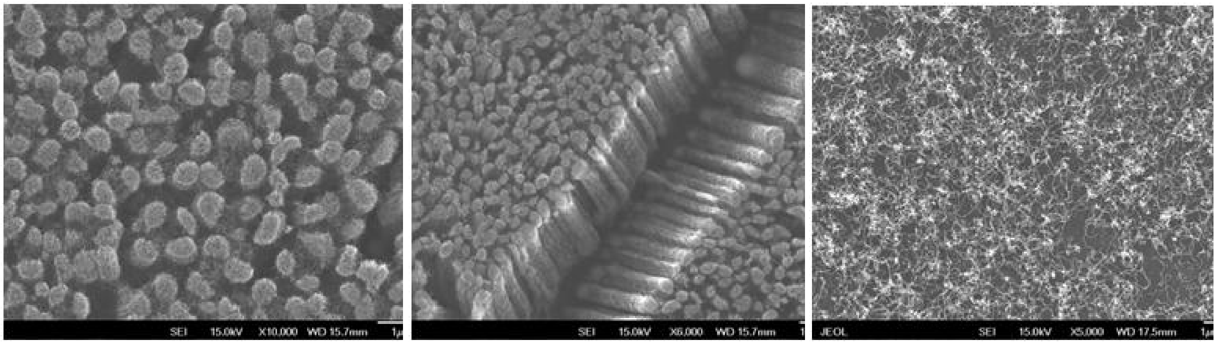

Figure 5-8. Scanning electron microscope top view of vertically oriented carbon nano-tubes (left), vertically oriented carbon nano-tube pillar structure (center), and randomly dispersed carbon nano-tubes (right) (images courtesy Center for Integrative Nanotechnology Sciences, University of Arkansas at Little Rock).

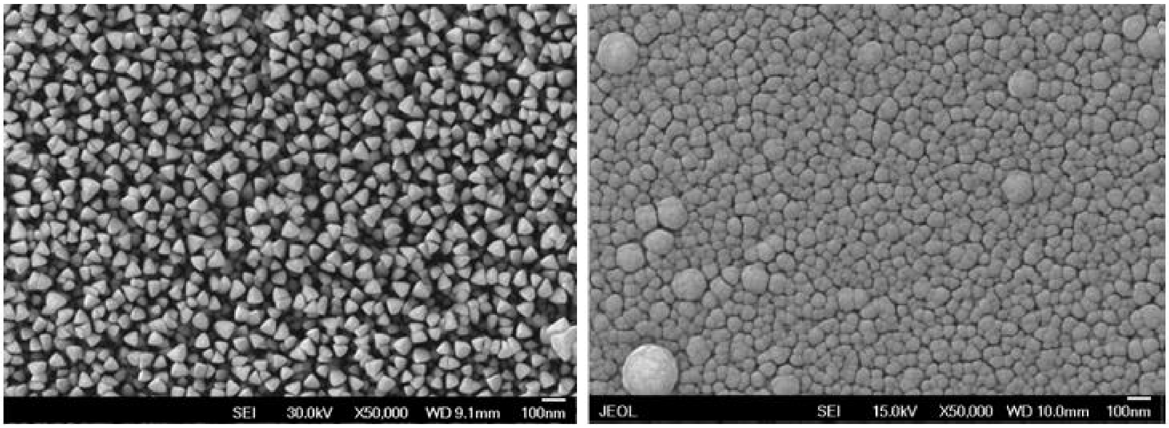

Figure 5-9. Scanning electron microscope top view of Tungsten nanorods (left) and top view of Aluminum nanorods (right) generated using glancing angle sputtering techniques (images courtesy Center for Integrative Nanotechnology Sciences, University of Arkansas at Little Rock).

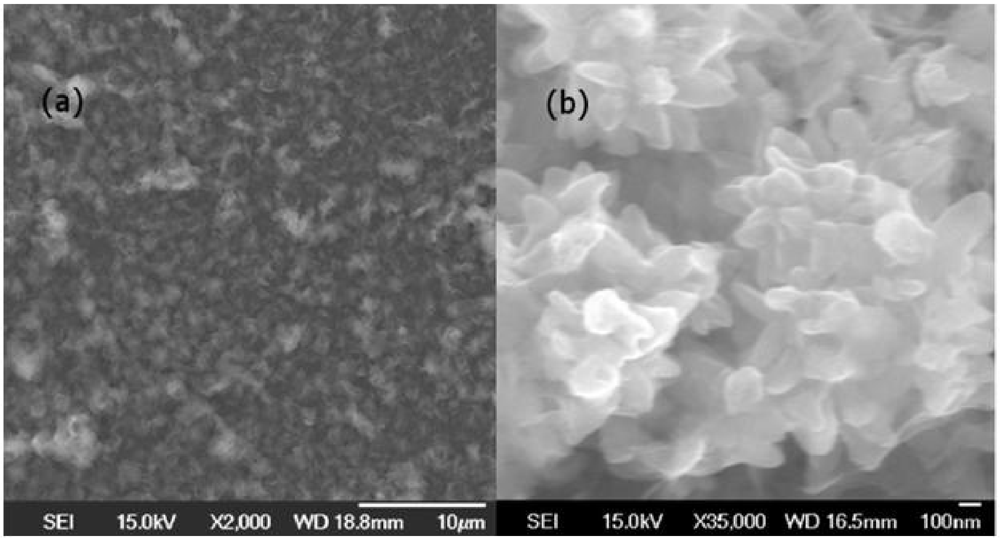

Figure 5-10. Scanning electron microscope morphology for large scale Zirconium Oxide (ZnO) structured surface (left) and nanoprotrusions on ZnO seeds in enlarged image (right) (images courtesy Center for Integrative Nanotechnology Sciences, University of Arkansas at Little Rock).

Super-hydrophic surfaces are low energy surfaces. They have low wettability and high drop contact angles that are greater than 150°. They also must be able to be shed from the surface through gravity or air flow before they freeze to be considered anti-icing surfaces. Hydrophyllic surfaces have high adhesion forces requiring high external forces to move drops because they are pinned strongly to the surface, according to the Wenzel model (Fig. 5-11). Drops on super-hydrophic surfaces are pinned less strongly to the surface and have less surface area in contact with the surface, as described by the Cassie-Baxter model (Fig. 5-11) (Antonini et al. 2011). For this reason, on hydrophilic surfaces, drops stay attached to the surface or move slowly in the direction of the external force, and the drop can have enough time to freeze. A drop impinging on a super-hydrophobic surface can bounce multiple times from the surface and return without freezing (Fig. 5-12). This allows drops to become entrained in the airstream and be carried away, or to fall from the surface if it is near-vertical. Jung et al. (2012) have studied the shear forces necessary to move a drop across a super-hydrophobic surface and actually cause it to be carried off of the surface, and Antonini et al. (2011) has demonstrated that the critical air velocity to cause initial movement for a small drop is 20 m/s on hydrophyllic surface, and only 5 m/s on a super-hydrophobic surface, meaning that the ratio between pressures needed to move the drops is a ratio of 1:16. Therefore, water droplets are shed by air flow more rapidly and at lower wind speeds from super-hydrophobic surfaces than from hydrophilic surfaces. This can be rapid enough that shedding occurs before the drops freeze, preventing icing.

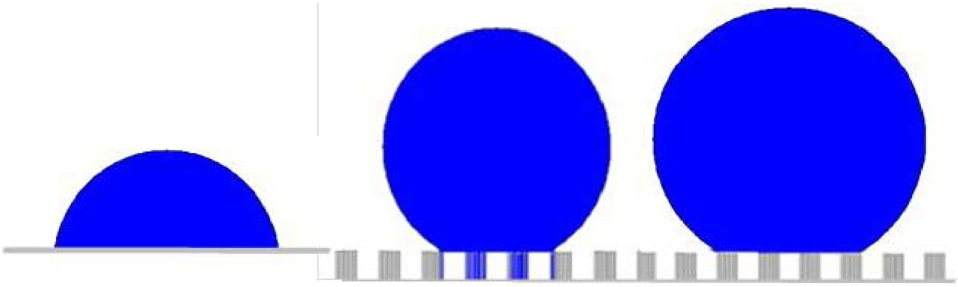

Figure 5-11. Droplet on a smooth hydrophyllic surface (left), at Wenzel state (middle), and at Cassie-Baxter state (right) (Ryerson 2013).

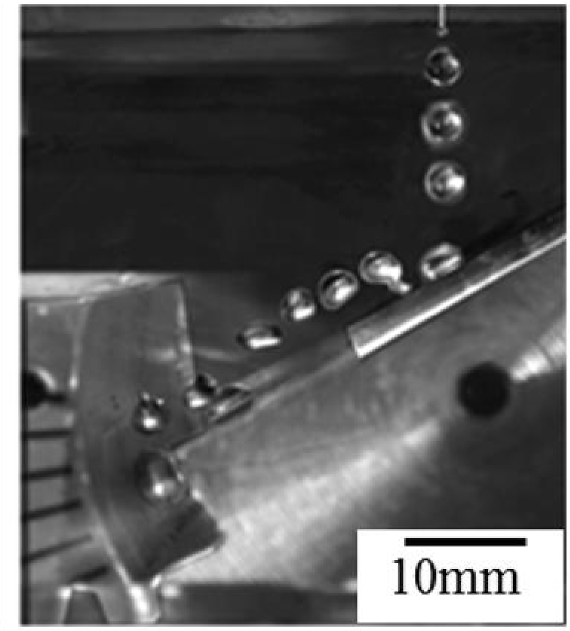

Figure 5-12. Droplets bouncing from an acetone-treated carbon nano-tube surface tilted at 30°. Drops and substrates were at −8°C, and drops fell from a 25-mm height attaining an impact speed of about 0.7 m/s (courtesy Center for Integrative Nanotechnology Sciences, University of Arkansas at Little Rock, 2011; see also Zheng et al. 2011).

Related experiments by Xiao and Chaudhuri (2012) at Washington State University indicated that a combination of micro- and nano-scale roughness created high contact angles, weak adhesion forces, and thus a short residence time for drops on a surface experiencing high air flow rates, at aircraft speeds. They called this a hierarchical structure, which is made from polymer-F-POSS composite. They claimed that this is a durable anti-icing surface; the micro- and nano-surfaces make a multi-scale surface that promotes low drop adhesion, slow freezing, and durability.

As in many disciplines, theory has followed development, and theory is necessary to take technology past initially rudimentary development. Bahadur et al. (2011) at Harvard University conducted a theoretical study, using modeling, of the dynamics of ice formation on super-hydrophobic surfaces, backed by evidence from earlier laboratory work. They modeled the effects of droplet impact dynamics, heat transfer, and drop heterogeneous nucleation on nano-based super-hydrophobic surfaces to determine under what conditions drops bounce away from a super-hydrophobic surface (see Fig. 5-12), or freeze in-place. They found three steps in the process.

1. When droplets strike a super-hydrophobic surface, momentum causes the drops to spread out, with the area of coverage a function of the drop volume. With the assumption of no friction on the surface, the drop then retracts because of surface tension. Drop collision speed has no effect on the process—expansion and retraction are completely governed by the water's surface tension.
2. As the drop is expanding and retracting, the water contacting the nano-columns conducts heat to the surface, the substrate, through the columns, and through the air trapped beneath the drop and between the columns (Fig. 5-11, see Cassie-Baxter state) (Bahadur et al. 2011). Under the assumption that the substrate is colder than the droplet, most heat is conducted through the contact points of the drop and the columns into the substrate. Little heat is conducted into the air from the perimeter of the drop that is not contacting the surface.
3. As most heat is conducted out of the drop through the nano-surface column tops, freezing begins first at those locations. Heterogeneous nucleation begins at the column tops, and propagates through the drop as a freezing front. These nucleation points on the column tops appear as hemispherical caps of ice. If freezing occurs, it happens during the drop retraction phase.

The Harvard models predict the critical temperatures when freezing starts and pins drops to the surface (Bahadur et al. 2011). The critical temperature is a function of surface morphology and chemistry, and the thermal diffusivity of the drop and of the substrate. Lower substrate diffusivity causes a slower freezing speed, and column morphology, height, width, and spacing affect hydrophobicity, and thus drop expansion and retraction speed. The substrate temperature is more important than the air temperature in determining whether a drop will freeze. The Harvard researchers found the critical temperature, in their models and experiments, to be between –20 and –25°C (Bahadur et al. 2011) when freezing starts and pins drop to the surface.

Alizadeh et al. (2012), at General Electric, added that lower temperatures increase the viscosity of water, slowing spreading and retraction times when droplets collide with super-hydrophobic surfaces. This increases the contact time of the droplet with the surface, increases cooling, and also increases the probability of freezing and pinning to the surface. They also indicated that there was no difference between the spreading and retraction times of salt water (salinity not specified, but freezing point −30°C) versus fresh water.

Harvard University has also investigated how the design of super-hydrophic surface geometries can minimize drop freezing, especially at collision speeds up to 90 to 135 m/s (Mishchenko et al. 2010). They state that a uniform topography pattern prevents localized uncontrolled freezing of drops to the surface. However, geometry can be modified to promote direction-dependent wetting if that is desired. They found that closed-cell geometries, such as walls around courtyards, are more effective at preventing freezing at higher velocities than are columns because the walled brick-shaped or honeycomb-shaped areas trap air. The walled structures are also more mechanically robust, easily reproduced at large scales, and can be easily tuned for specific material and chemical properties.

Cao et al. (2009) have used nano-particle–polymer composites to create surfaces that anti-ice in the laboratory and in actual freezing rain storms. They claim that the anti-icing properties of super-hydrophobic surfaces, or coatings in their application, are a function of the surface super-hydrophobicity, caused by chemical coatings, and the size range of the nano-particles. They find that two sizes of nano-particles are needed to be most effective. They also found that ice does not form on surfaces with 20- and 50-nm-diameter particles, and that ice formation increases rapidly when particle sizes are larger than 50 nm. The dual-size surfaces have large water contact angles, and only 15% of the water is in contact with the substrate. They show that icing probability increases nearly exponentially when particles increase in diameter from about 50 to over 10,000 nm. Outdoor experiments in freezing rain storms with a satellite dish coated with 50-nm-diameter particles on one side, and no coating on the other, showed no ice accumulation on the coated side, and considerable ice formation on the uncoated side (see Appendix B, Ross Technology).

However, there are also other complexities to designing anti-icing super-hydrophobic surfaces. Alizadeh et al. (2012), at General Electric, documented, as have others (Zheng et al. 2011), that supercooled droplets can sit on cold, supercooled surfaces for long periods, such as 60 s, without freezing. This freezing delay mechanism is commonly attributed to the insulating effect of the droplet standing atop the narrow columns of the nano-surface with little contact area to conduct heat into the substrate (Cao et al. 2009; Zheng et al. 2011). Alizadeh et al. (2012) indicate that it can take about 20 s for a droplet to cool to the substrate temperature when perched on a super-hydrophobic surface. The droplet then can sit on the surface for additional time before freezing. For example, they found that droplets sitting on a substrate, with a drop contact angle greater than 150°, can delay freezing for more than 2.5 minutes. They indicate that unspecified drop sizes, surface chemistries, and temperatures all have strong effects on drop nucleation speed, with nucleation speed being delayed longer at higher temperatures because droplet heat loss to the air is more important at lower temperatures than at higher temperatures.

Jung et al. (2012) found that drops can also freeze to super-hydrophobic surfaces under certain environmental conditions, defeating their capability. Jung found that when very dry air, in this case dry nitrogen, was flowed over a surface with supercooled drops sitting on a super-hydrophobic surface, the drops would freeze from homogeneous nucleation. Initially, the droplets cooled via contact with the rough, nano-based super-hydrophobic surface. However, flow of the dry nitrogen caused rapid evaporation on the upwind side of the drop, and sufficient cooling that it initiated nucleation on the drop’s upwind side. They calculated the drop surface temperature to decrease from evaporation in airflow of 30% relative humidity from –15 to –15.34°C. They also found that a super-hydrophobic surface that was pre-wetted by condensation at a relative humidity of 100% dramatically increased droplet adhesion, and prevented roll-off. The onset of drop motion in the saturated condition required twice the air velocity required for the dry condition.

Frost formation was also found to cause surfaces to lose their super-hydrophobic characteristics, and become hydrophyllic in studies, by Varanasi et al. (2010) and by Kulinich et al. (2010). Varanasi et al. (2010) developed a coating consisting of silicon posts fabricated using photolithography, and coated with a thin hydrophobic chemical. Cooling the surface to –5°C and increasing chamber vapor pressure until saturation with respect to ice was reached caused frost formation on all post tops, sidewalls, and valleys. All frosted surfaces became hydrophyllic and lost their super-hydrophobic properties. This caused increased surface contact area for droplets and a Wenzell drop contact surface (see Fig. 5-11). Droplets colliding with the surface did not bounce and became pinned (frozen) to the surface. This indicates that nano-based super-hydrophobic surfaces in saturated conditions in subfreezing temperatures could become ineffective as anti-icing surfaces, and as ice-phobic surfaces, with potential very high ice adhesion strengths. Kulinich et al.'s (2010) results were similar on aluminum surfaces coated with flouropolymers embedded with Zirconium oxide nano-particles, etched aluminum coated with fluorodecyl-triethoxsysilane (FAS-17), and etched aluminum coated with stearic acid (SA). As condensation time increased, drop contact angles decreased, contact angle hysteresis increased, icing time decreased from 35 to less than 15 minutes, and de-icing shear stress increased from about 30 to about 55 kPa.

The threat of super-hydrophobic surfaces being rendered ineffective by frost prompted Kim et al (2012) at Harvard University to develop a new type of surface that prevents frost and dramatically reduces the adhesion strength of ice that forms on the surface. They theorized that drop contact angle is not the most important factor to consider in developing effective anti-icing and low ice adhesion surfaces; it is to minimize the difference between the droplet advancing and receding angles, contact angle hysteresis. They also hypothesized that the rough, high surface area nano-based surfaces traditionally used increased contact area sufficiently that they encouraged frost formation. This causes ice to lock to the rough surface increasing ice adhesion (Varanasi et al. 2010).

Kim et al. (2012) developed an extremely smooth surface with low wettability to reduce contact angle hysteresis, delaying frost formation, and reducing ice adhesion. They developed a Slippery, Liquid-Infused Porous Surface (SLIPS) that can be fabricated on metals by electrodepositing highly textured polypyrrole (PPy) onto aluminum substrates followed by fluorination of the surface and infiltration with a lubricant. Their goal was to develop a surface that had a lubricating fluid (unspecified) that is immiscible, with a chemical affinity to the substrate that is greater than its affinity to water or ice, all against a surface of nano-structures that increase the surface area for adhesion and retention of the lubricating fluid. The surface can be applied over large areas of any shape, it is anti-corrosive, can be applied at low temperature, and is non-toxic. In testing, drops formed on the surface and grew until they slid off. At a tilt angle of 90° all drops larger than ~600-μm (0.6-mm) diameter slid off, whereas only drops larger than 5-mm diameter slid off of untreated aluminum. Long exposure to –10°C temperatures and 60% relative humidity eventually caused the SLIPS surface to accumulate ice. Ice that formed produced large, isolated patches of ice with an adhesion strength of only 15.6 kPa, as low as the lowest ice-phobic coatings currently available. Therefore, the SLIPS coating has some anti-icing capability, and ice-phobic characteristics.

Though some nano-based super-hydrophobic surfaces are anti-icing, there are also claims that they are ice-phobic; that is, they possess lower ice adhesion strengths. Kulinich et al. (2010) and Kulinich and Farzaneh (2011) conducted experiments with several super-hydrophobic nano-surfaces to determine their ice adhesion strength. However, because durability is critical to the utility of surfaces exhibiting anti-icing and low ice adhesion properties, they assessed the change in ice adhesion strength during multiple de-icing cycles in simulated freezing rain conditions. For some samples, they also evaluated the effects of condensation on the surfaces prior to ice formation in a similar manner to Varanasi et al.'s (2010) work.

In initial tests aluminum surfaces were prepared in three ways: coated with flouropolymers embedded with Zirconium oxide nano-particles, etched aluminum coated with fluorodecyl-triethoxsysilane (FAS-17), and etched aluminum coated with stearic acid (SA). All surfaces initially had droplet contact angles greater than 150°, and contact angle hysteresis values ≤5°. The prepared samples were then exposed to freezing rain conditions in an icing centrifuge with water droplets of about 80-µm diameter. After ice had accumulated, despite their anti-icing properties, which was not commented on nor tested, they were de-iced and the shear stress required to de-ice was measured.

Each of the three surface types initially had ice adhesive strengths ranging from 25 to 75 kPa. However, after 24 icing and de-icing procedures, shear stress for de-icing increased to 180–200 kPa. Droplet contact angles had decreased to ~140°, and contact angle hysteresis had increased to about 15°. The authors hypothesized that the highest nano-spires became embedded in the ice as it froze in a partial Wenzel state (see Fig. 5-11), and the spires were broken off during de-icing. In addition, droplets hitting the surface at higher velocities have also broken the nano-surfaces. Therefore, each subsequent icing and de-icing cycle caused droplets to settle deeper into the nano-surface creating a more complete Wenzel-type contact. The authors considered these surfaces to be too weak for use in natural icing conditions.

Kulinich and Farzaneh (2011) subsequently tested more durable materials created by depositing a PTFE material on an aluminum oxide underlayer, which showed little deterioration after 14 de-icing cycles. This work suggests, however, that careful development and testing is necessary to create coatings, or surface treatments, that are effective and durable as anti-icing and de-icing materials.

The studies by Kulinich et al. (2010) and Kulinich and Farzaneh (2011) and others of surface durability after many de-icing cycles, and the effects of condensation or frost on surface ice-phobicity and anti-icing capability, prompted Kulinich et al. (2010) to raise doubts about the use of superhydrophobic surfaces as universal anti-icing materials. In addition, surface durability, freedom from contamination, cost and ease of application, adhesion to the substrate, resistance to corrosion and UV degradation, thermal cycles, and abrasion and wear must be considered. Much work is necessary before nano-based anti-icing and ice-phobic coatings are sufficiently proven to be useful in the operating environment. Some materials may be near TRL 7 or 8, but independent test and evaluation will demonstrate this with more confidence.

Ryerson (2009) presented information available in 2009 about coatings that were either ice-phobic or had anti-icing properties. Updates and new coating products are presented in Appendix B and Table 5-2. Information on some products was updated for this report, but others were not because of time available, inability to obtain timely responses, or because no update was necessary.

Table 5-2. Coating sources.

Product	Source	Description	Information
AeroKret	Analytical Services & Materials Inc. ATTN: Dr. Sivakumar, Senior Research Scientist 107 Research Drive Hampton, VA 23666 757-865-7093, Ext. 304 aerokret@asm-usa.com	Siloxane-based nano-coating, Anti-icing	Appendix B www.asm-usa.com
Wearlon Super F1-ICE	Nick Patenaude Ecological Coatings, LLC P.O. Box 4202 Clifton Park, NY 12065 Tel: 518-383-9585 wearlon@wearlon.com	Latex ice-phobic coating	www.wearlon.com/Eice.htm
Rain-X	Illinois Tool Works	COTS hydrophobic coating	Ryerson (2009)

Product	Source	Description	Information
ISurGuard™	Innovative Surface Technologies, Inc. 1000 Westgate Drive, Suite 115 Saint Paul, MN 55114 Patrick E. Guire, Ph.D., President Tel: 651-209-9757, Ext 11 info@isurtec.com	Hydrophobic, oleophobic anti-icing coating.	Appendix B www.isurtec.com
KISS-COTE	KISS Polymers LLC PO Box 274087 Tampa, FL 33688-4087 Tel: 813-962-2703 info@kisspolymers.com	Silicone-based polymer de-icing, ice shedding coating	Appendix B www.kisspolymers.com
PhaseBreak ESL	Microphase Coatings Inc. 170 Donmoor Court Garner, NC 27529 Telephone: 919-779-7679 E-mail: sales@microphasecoatings.com; info@microphasecoatings.com	COTS anti-icing and ice-phobic coating with freezing point depressant	Appendix B www.microphasecoatings.com/
Hybridsil	NanoSonic Inc. PO Box 618 Christiansburg, VA 24068 Tel: 540-953-1785 mbortner@nanosonic.com	Anti-icing super-hydrophobic and ice-phobic coating for ship bridge windows	Ryerson (2009) www.nanosonic. com
R-1009 R-1082 R-3930 R-3975 R-2180	NuSil Technology LLC 1050 Cindy Lane Carpinteria, CA 93013 Tel: 805-684-8780 Fax: 805-566-9905 ad@nusil.com	Ice-phobic RTV silicone coating	Appendix B www.nusil.com
NASA Shuttle Ice Liberation Coating (SILC)	Mr. Trent M. Smith Mail Stop FA-A Bldg: M6-0399 (HQ) Room: 3361J Kennedy Space Ctr, FL 32899 Tel: 321-867-7492 trent.m.smith@nasa.gov	Ice-phobic mixture of Rain-X and 20% to 50% by weight PTFE	Appendix B
PCM Marine™	ePaint Company Alex Welsh, President 25 Research Rd. East Falmouth, MA 02536 Tel: 508-540-4812 Contact: Mike Goodwin E-mail: epaint@epaint.com	Hydrophobic and ice-phobic coating	Appendix B www.epaint.com
Anhydra	Oceanit Corporate Headquarters 828 Fort Street Mall Suite 600 Honolulu, Hawaii 96813 Tel: (808) 531-3017 Fax: (808) 531-3177 Cindy Matsuki Deputy Director of Business Development Phone: (808) 531-3017 Fax: (808) 531-3177 Email: cmatsuki@oceanit.com	Ice-phobic coating	Appendix B www.oceanit.com
NeverWet	Ross Nanotechnology LLC PO Box 646 Leola, PA 17540 Tel: 866-383-7066 ajones@rosstechnology.com	Super–hydrophobic and oleophobic coating	Ryerson (2009) www.neverwet.com

Product	Source	Description	Information
Hydrobead	Seashell Technology, LLC 3252 Holiday Ct. #115 La Jolla, CA 92037 Tel: 858-638-0315 Fax: 858-638-0376 info@seashelltech.com www.seashelltech.com	COTS nano-based anti-icing and ice-phobic coating	Appendix B www.seashelltech.com www.hydro-bead.com
WC-1 (ICE)	21st Century Coatings Inc. 4701 Willard Ave., Suite 109 Chevy Chase, MD 20815 Telephone: 301-654-0099 301-873-5230 E-mail: 21stcenturycoatings@gmail.com	Clear, low surface energy de-icing coating	Appendix B www.fpu-coatings.com
SLIPS	Robert Cunningham Platform Development Director Wyss Institute for Biologically Inspired Engineering Harvard University Center for Life Science Boston, 5th Floor 3 Blackfan Circle Boston, MA 02115 Tel: 617-432-1761 robert.cunningham@wyss.harvard.edu	Slippery, Liquid-Infused Porous Surface, development company being formed	www.wyss.harvard.edu

5.4 Covers

Covers, tarps, or “blue dodges” are commonly used by the Coast Guard and the Navy to protect ship hardware when underway. Coast Guard crews routinely cover deck machinery with tarps. Protective covers are typically constructed of a lightweight, strong, waterproof, fire-retardant, and flexible material such as duck cloth, sail cloth, or polyurethane. The US Navy (1988) recommends that boats, davits, capstans, and windlasses, and all outdoor command, control, and communication stations be covered when transiting cold regions.

Zadra and Pyle (1990) used Navy guidance to determine the effectiveness of covers in superstructure icing conditions by covering a variety of hardware items on the CGC MIDGETT forecastle in a 1990 cruise in the Bering Sea. They covered a safety rail, vent duct, capstan, and anchor control rod wheel with flexible, Hypalon-coated nylon fabric, DuPont’s chlorosulfonated polyethylene (CSPE) synthetic rubber (CSM), noted for its resistance to chemicals, temperature extremes, and ultraviolet light. It is a common material for making inflatable boats and roofing (Ryerson 2009). The Hypalon covers remained flexible in the cold and remained resistant to tearing. De-icing ease was a function of how tightly the Hypalon was attached to protected hardware. Hypalon that was loosely attached was easily de-iced because the material could be bent and deformed (Fig. 5-13).

Figure 5-13. Tarp-covered anchor capstan on CGC MIDGETT, 1990 (Ryerson 2009).

Material that was tightly wrapped was as difficult to de-ice as objects that were not covered. Makkonen (1984) reported that attempts have been made to use flapping and flexible materials, but have met with little success. Jorgensen (1982) recommends the use of tarps that vibrate because of ship motion, and reports that tarps have been successful for de-icing when provided with the proper coatings.

Tarps loosely tied to encourage anti-icing and more effective de-icing may be carried away by wind. Tarps must be placed before storms or they are ineffective, and they are difficult to install in high winds. Fitted tarps (Fig. 5-14) may remain in place more effectively in winds, but being tight, they may not de-ice as well. Tarps are relatively inexpensive ice protection for items requiring little use during storms. However, items covered with tarps are usually unavailable for use until uncovered.

Figure 5-14. Coast Guard Dolphin helicopter with fitted tarps covering windscreen, engine intakes, and ducted tail fan on CGC MIDGETT, 1990 (Ryerson).

Figure 5-15. Cover over gun mount on CGC THUNDER BAY (Ryerson).

Tarps can be used to protect relatively small objects (Fig. 5-15). However, tarps can temporarily cover helicopter landing pads when not in use. Tarps can also cover safety equipment, but should not render it inaccessible.

Tarp performance in icing conditions may be improved by coating or imbedding them with a a super-hydrophobic material that repels water, prevents ice, and reduces the adhesion strength of ice. Hydrobead™, a product developed by Seashell Technology that sprays on surfaces, is one such example (http://www.hydro-bead.com/purchase.html). Another example is a material patented by Simpson (2009) that can be embedded in fabrics to make them super-hydrophobic.

Ozeki and Yamamoto (2006) and Ozeki et al. (2010) conducted field observations of the effectiveness of various tarp materials to protect lighthouses in the Sea of Japan near the Kuril Islands, where coastal sea spray icing is heavy. Both fresh water and sea spray icing tests were conducted. Tests compared ice adhesion strength on stainless steel to covers made from nylon, polyurethane, and fluoroethylene plastics, and a super-hydrophilic plastic. Laboratory tests of adhesion strength showed that fresh water ice had an adhesion strength of about 325 kPa, and the polyester, fluoroethylene, and nylon ranged from 150 to 200 kPa. Sea water, however, had much lower adhesion strengths, with the maximums being about 75 kPa for Nylon and about 25 kPa for polyester. The adhesion strength of saline spray ice with fluroethylene and the super-hydrophilic material were nearly 0 kPa. It is believed that the hydrophilic material's ice adhesion strength was so low because it allows a film of brine water draining from the ice to be maintained between the material and the ice.

Despite low cost, tarps have disadvantages. They require time to install, remove, and repair. They require storage space. They must be dried before storage or they can mold or rot. Time for tarp placement and removal can be wasted if anticipated icing does not occur.

If tarps are desired, it may be best to determine ideal tarp weights and materials for use. Users should also develop tie-down procedures, fitted covers, and covers coated with a material that prevents icing or dramatically reduces ice adhesion. Table 5-3 lists tarp sources.

Table 5-3. Tarp sources.

Product	Source	Description	Information
Aircraft covers	Kennon Aircraft Covers 2071 North Main St. Sheridan, WY 82801 Tel: 307-674-6498 Fax: 307-674-7182	COTS hydrophobic coating	www.militaryaircraftcovers.com

5.5 Design

Ship design can minimize superstructure icing. Design can reduce icing by preventing water from reaching the superstructure, a passive approach. Or, it can incorporate active and passive anti-icing and de-icing technologies into the structure. Either strategy could be effective. However, any ship design is a compromise. Few ships can do everything well; naval architects conduct a cost–benefit analysis to design characteristics into the vessel that best allow it to execute its mission, and to be cost-effective to build and to operate. If anti-icing or de-icing is not a high priority, or if designing ice protection capability into the vessel compromises mission effectiveness or cost, then the anti-icing feature may be abandoned.

There are several ways to minimize icing by minimizing bow spray, and they all involve changes in bow design. For example, the Navy's new USS *Independence* littoral combat ship is a trimaran design by General Dynamics with a narrow monohull and two outriggers (Fig. 5-16).

Figure 5-16. US Navy littoral combat ship USS *Independence* with trimaran hull with significant rake and tumblehome (US Navy).

The ship is reported to handle well in high seas because of its wide beam. More importantly, for icing, its long, narrow bow has considerable rake and tumblehome that deflect spray and reduce horizontal deck area where ice can accumulate. Though ice can accumulate on the hull sides, especially in the tumblehome area, an anti-icing coating or active de-icing technology, such as an electro-expulsive system (Embry et al. 1990), could readily remove ice. However, the trimaran bow design would be impractical for icebreaking, and would not provide forward deck area for the ATON mission. However, a buoy deck could be placed on the fantail. And, it may be possible to break ice with a narrow hull to create an initial channel that would be widened as the hull progressed through the ice.

A somewhat less radical departure from current design, but still a dramatic change, would be to enclose the forecastle deck with a cover that would prevent wetting of the deck, such as the Ultstein X-bow (Fig. 5-17).

The X-bow is similar to a submarine bow, and is reported to have better sea keeping capabilities than conventional bows (Fig. 5-18).

Figure 5-17. Vigor Offshore Patrol Cutter featuring the Ulstein X-Bow(R) (Image courtesy Vigor Ship Yards 2013).

Figure 5-18. X-bow in foreground generally creates less spray than conventional bow in background, which was moving more slowly than the foreground ship.[1]

An enclosed bow would keep the forecastle, deck machinery, and forward bulkhead dry, and perhaps warm. A variant may be an effective ice-breaking bow. However, it would be ineffective for ATON work, and the buoy deck would need to be located aft of the main superstructure. However, that location would protect the buoy deck and crane from superstructure icing and may be configured similarly to supply boats for the offshore oil industry, which have the cargo deck aft of the superstructure.

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[1] http://www.youtube.com/watch?v=GJsogw9fHE0

The sides of the X-bow, however, may ice from spray that can freeze on the upper areas of the bow. Those areas are not accessible for manual de-icing. Therefore, anti-icing or de-icing systems may need to be installed in these areas. For example, anti-icing or low-ice-adhesion coatings would be appropriate, especially as they would receive little abrasion in the upper bow area except from spray. And, active anti-icing or de-icing could be accomplished with electro-expulsive or pulse-type heating systems, both which are now appearing in aircraft applications.

The Danish *Thetis*-Class patrol vessels are designed for Greenland patrols and, along with other Danish patrol vessels, are outfitted for Arctic operations. The forecastle deck of the HMDS *Vædderen*, for example, is enclosed and is believed to be heated (Fig. 5-19). Hulls are ice-hardened and portions are of a double-hull design, and the mast is fully enclosed.

Figure 5-19. HMDS *Vædderen*, a 3500-ton displacement ice-strengthened patrol vessel of the Danish Coast Guard (USCG photo).[1]

Other, new Danish patrol boat designs include a stern-located launch and recovery bay for the 12-m Landing Craft Personnel (LCP), located within enclosed space under the helicopter landing pad (Fig. 5-20 and 5-21). In addition, a roll-up door on the starboard superstructure stows two rigid-hull inflatable boats (RHIB) and davits to minimize icing.

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[1] http://chuckhillscgblog.net/2012/01/25/the-case-for-bigger-opcs/

Figure 5-20. Danish *Knud Rasmussen*-Class inspection ship with enclosed starboard small boat stowage and launch facilities to minimize superstructure icing effects. (image courtesy Stephen Priestley—Canadian American Strategic Review www.casr.ca/).

Figure 5-21. Danish *Knud Rasmussen*-Class inspection ship with stern covered small boat launch and recovery system (image courtesy Defence Command Denmark).

Coast Guard crews suggest controlling spray creation and flow over the ship. For example, a new bow bulwarks design similar to that used by some Great Lakes freighters might be useful for ice-breakers and buoy tenders operating in cold weather environments. The new *Trillium* Class of self-unloading ships operating on the Great Lakes appears to have, in addition to the normally high bow found on Great Lakes freighters, an added high bulwarks protecting the forecastle deck.

Cleaner ship design also minimizes superstructure and atmospheric icing. For example, fishing trawlers lose stability relatively rapidly in icing because of the large surface area exposed high above the waterline. Masts, rigging, cranes, railings, ladders, and fire stanchions all add to the surface area that ices. If ships were constructed with less surface area, there will only remain relatively large, curved or flat surfaces. Takeuchi (1979) demonstrated that snow accretion can be minimized on flat surfaces by altering wind flow by shifting the stagnation point and making snow strike the surface at an acute angle and not stick. This technology may be applicable to large flat areas of ships. Rigging and mast area should be minimized, with a strongly flared bow to deflect spray, and greater freeboard to minimize spray. Lyle (2001) recommended designing increased buoyancy into vessels to accommodate ice accretion. He indicated that some offshore oil supply vessels are designed to accommodate 0.3 m of accreted superstructure ice.

Design can also minimize superstructure ice accretion and, to a lesser extent, atmospheric ice accretion from snow, rime, and freezing rain. Ice loads from superstructure ice, rime, and freezing rain result from supercooled drops moving with the wind and striking structure elements with various collection efficiencies (Ryerson 2008). Collection efficiency is a function of wind speed, droplet size, and target diameter—with higher winds, larger drops, and smaller target diameters causing increased collection efficiency and, typically, increased ice accretion. Ships dominated by small-diameter elements, such as I-beam edges, cables, pipes, and support braces, will typically ice fastest and have larger ice loads per unit area than structures without the small-diameter elements. Structures with large-diameter or flat surfaces will generally have fewer icing problems.

The presence of many small-diameter shapes, such as cables, piping, and railings, contribute to ice accumulation. Figure 5-22 illustrates the effect of the cluttered forward bulkhead on the CGC MIDGETT in 1990 after an icing event in the Bering Sea. Ice accumulates on smaller objects and bridges and locks around the objects making de-icing more difficult. Overall, uncluttered design reduces icing challenges. Many of the new ships designed for Arctic operations contain design elements that reduce the impact of cold on operations, such as the Danish patrol craft (Fig. 5-19 through 5-21). These include covered walkways and covered work areas, covered boat launch and storage areas, and covered masts. These design elements also reduce surface area exposed to icing but, as importantly, reduce the efficiency with which small droplets collide with surfaces and freeze by eliminating large areas of exposed piping, wiring, and other small-diameter materials.

Figure 5-22. Forward bulkhead of CGC MIDGETT after ice had been removed from fire valves and hoses (Ryerson).

De-icing and anti-icing systems can also be more readily integrated into a ship at design and initial build. The Arctic Stena drill ship *MAX*, for example, was designed with wind walls to protect work areas, and de-icing by flushing decks with warm water (Pakarinen 2006).

The Navy's Arctic Patrol Vessel design is resilient to the Arctic environment (Fig. 5-23). It is designed for a minimum operating temperature of −40°C, operation in sea state 6 and survivability in sea state 8+, operation in the Marginal Ice Zone, and resistance to topside icing (Byers et al. 2009). Topside icing received close attention; deck machinery is enclosed, and nano-based coatings are planned to prevent icing. Small liquid-to-air heat exchangers will capture heat from the Diesel engine exhaust for heating the main deck, equipment enclosures, railings, and the the Advanced Enclosed Mast System (AEMS). The AEMS protects radar and sensor antennas in a carbon fiber housing, providing protected access for servicing the interior systems without exposure to weather. It also protects the radar and sensor systems and minimizes superstructure ice accumulation.

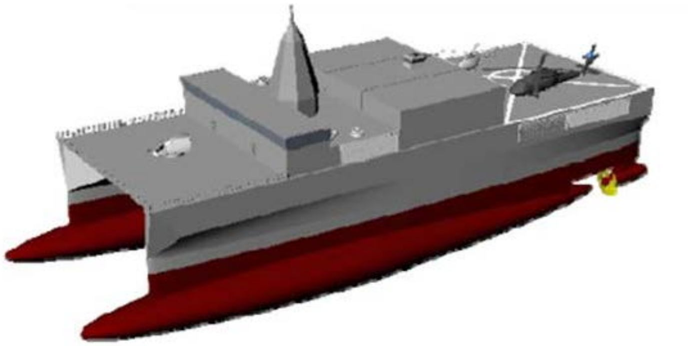


Figure 5-23. Navy Arctic Patrol Vessel design (Byers et al. 2009).

Thomas (1987) provided a comprehensive analysis of design considerations for Navy ships intending to operate in the Arctic, in either the North Atlantic Ocean or the North Pacific Ocean. He listed 26 areas of a ship that required specific attention, most which are relevant to Coast Guard Cutters. The abridged list that pertains to superstructure icing and to Coast Guard Cutters includes:

1. Radar and electronic warfare systems.
2. Communication equipment.
3. Navigation systems.
4. Air traffic control systems.
5. Helicopter recovery systems.
6. Gun systems.
7. Torpedo launch systems.
8. Chaff launcher systems.
9. Missile systems.
10. NBC warfare systems including wash down systems.
11. Mooring systems.
12. Small boat launch and recovery systems.
13. Small boat equipment.
14. Cargo handling equipment.
15. UNREP equipment.
16. Fuel transfer systems.
17. Ventilation systems.
18. Gas turbine intakes.
19. Damage control equipment and fire fighting systems.
20. Lookout positions.
21. Life saving and survival equipment.
22. Weather access doors and ladders.

Thomas (1987) recommended that heating systems be built into most of the systems listed above during ship design to protect to temperatures of at least −20°C. He added the following:

1. Deck personnel should be provided with spaces for temporary shelter, and with nearby facilities for stowage of de-icing equipment (baseball bats, mallets, ax handles, shovels).
2. Bridge and lookout areas should be enclosed and heated, with heated windows and wipers with de-icing spray nozzles.
3. The forecastle deck should be as free of hardware as possible, and have high bulwarks or freeboard to reduce spray.
4. Decks should have non-skid and covers to protect hardware from spray and ice. Capstans, windlasses, winches, cable reels, and searchlights, for example, should have snug fitting covers. Hawse pipe openings should also be covered. Moving parts of machinery should be heavily greased, and UNREP equipment should be operable without removing gloves.
5. Boats should be covered with tarps to well below the gunwales. Sheaves of boat falls should be covered. Life raft hydrostatic pressure release mechanisms should be covered, but should not prevent operation of the releases.
6. Flight decks should be heated or covered with tarps, and cables should be greased.
7. Ventilation and exhaust openings should not be placed in the forecastle area because of spray icing, and ventilation openings should be placed in locations protected from spray, such as the lee of the superstructure. Some inlets on weather decks can be heated.
8. Gas turbine engine inlets should be sheltered from spray and blowing snow, with carefully designed bypass systems.
9. Rigging should be nylon-coated to reduce ice adhesion.

5.6 Expulsive

Expulsive systems are capable de-icing, and effectively anti-icing, by using the inertia of ice to overcome its adhesion strength. Conceived in the 1930s by a German expatriate in London, the technology was not tested until the 1970s by the Soviets (Wolverton 2009). Development began in earnest in the 1990s using a variety of approaches, one which was developed and patented by NASA Ames (Haslim and Lee 1987), and others later by Adams et al. (1989) at Goodrich, Pisarski at Goodrich (1994), Goldberg (1997), Cox & Company (Al-Khalil et al. 1999), and Gerardi and Ingram at Innovative Dynamics, Inc. (2000). Expulsive de-icing systems, also called Electro-Impulse De-Icing (EIDI) systems or Electro-Expulsive De-icing Systems (EEDS), are actually mechanical de-icing systems because a sudden impulse is provided to the ice, which subsequently debonds, shatters, and is expelled from the surface (FAA 1991b).

In general, expulsive systems consist of an electromagnetic coil placed on the backside of the substrate requiring de-icing (Fig. 5-24). Typically, this surface is the leading edge of an aircraft wing, but it can be other surfaces. According to a FAA description of the technology, the system typically consists of an electromagnetic coil behind a metal surface, but separated from the surface. An electrical system with a powerful storage capacitor powers the system. When the capacitor is charged, a rapid high voltage is applied to the coil for about 0.5 ms (Fig. 5-25). The electrical discharge induces a magnetic field in the coil, and induces an opposite polarity magnetic field in the aircraft skin. The opposite polarities repel, and the aircraft skin accelerates outward less than 0.25 mm at a peak force of about 2000 N. As the aircraft skin accelerates outward, so does ice attached to the skin. When the wing surface stops accelerating outward, the ice will continue to move and will peel off of the aircraft skin if the ice adhesion strength is not too strong.

The EIDI system developed by Innovative Dynamics Inc. for use on aircraft and ships operates as described above, but its actuators, the wire-wound coils, are embedded within a thin metal strip that can be placed around hatches and doors to keep them free of ice (Appendix B, Table 5-4) (Gerardi and Ingram 2000). It could be usable on other relatively flat surfaces. The Cox & Company system (Ryerson 2009) also has coils situated inside the wing leading edge (Al-Khalil et al. 1999). However, for aircraft use, a heater strip is also placed along the stagnation zone on the leading edge to melt a strip in the ice, creating a parting strip because air flow will hold ice against that surface even when it is loosened. A heater strip would probably not be required in a cutter application because of the lower air speeds and lack of airfoils.

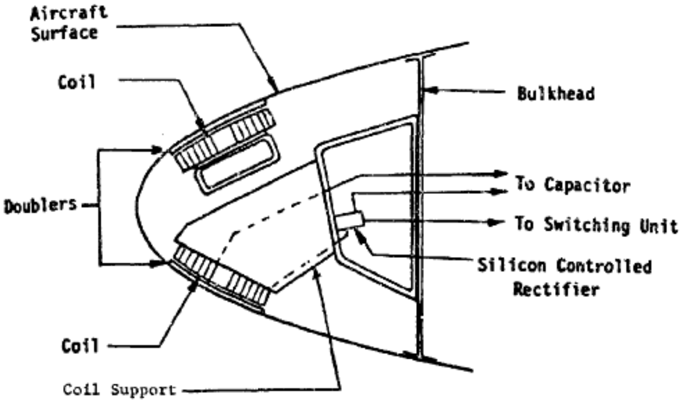


Figure 5-24. EIDI system installed in aircraft wing leading edge (FAA 1991b).

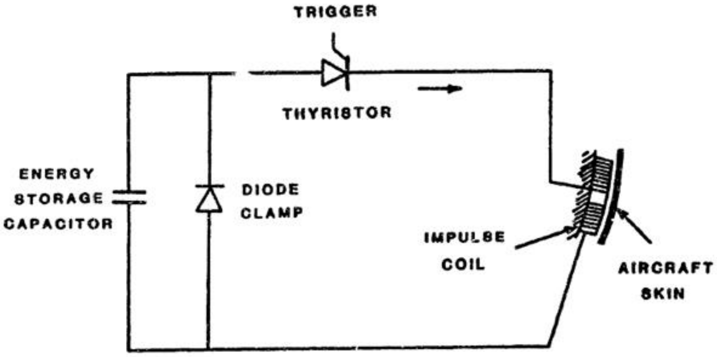


Figure 5-25. Basic EIDI electrical circuit (FAA 1991a).

Haslim and Lee at NASA Ames (1987), Adams et al. (1989) at Goodrich, Pisarski at Goodrich (1994), and Goldberg (1997) took a different approach to actuator design. Instead of deforming the aircraft surface, they developed systems that used flat conductors laid over one another in varying geometries, but electrically isolated, with currents flowing in opposite directions. The opposite flowing currents create like polarities in the stacked, but electrically separated strips, which rapidly drives them apart (Fig. 5-26). This produces a thinner installation, and one that can be laid over the leading edge of a wing or other surface as a sheet or cuff (Fig. 5-27).

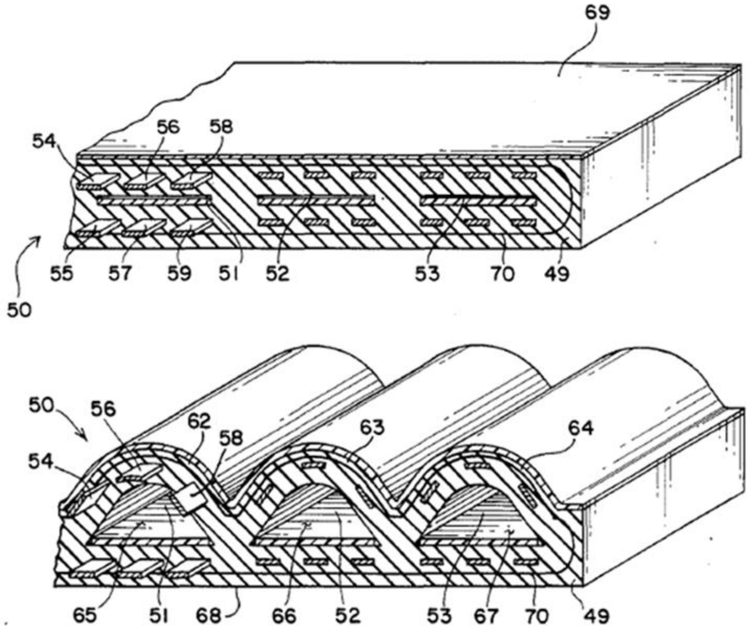


Figure 5-26. Electroexpulsive mat in relaxed form (top). Conductors 54, 56 and 58 acquire a magnetic polarity opposite of 55, 57 and 59 when energized. Item 52 is a gap that allows the mat to expand when actuated, 59 is the surface upon which ice accumulates, and the mat is attached to the substrate below 49. Bottom, mat is energized and has expanded and accelerated ice from surface 69 (Haslim and Lee 1987).

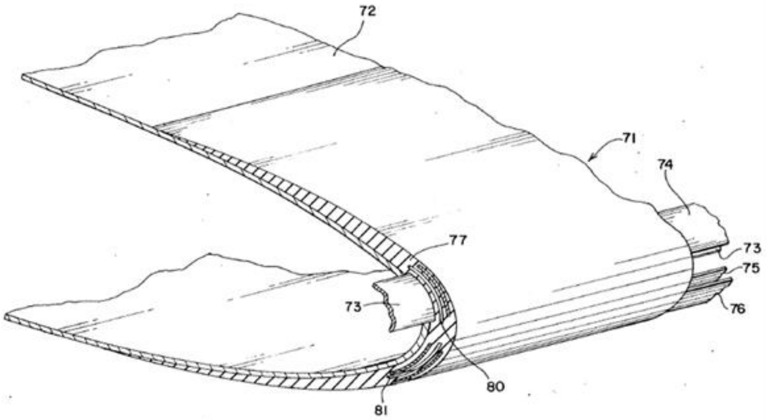


Figure 5-27. Electro-expulsive mat, of Haslim and Lee (1987) design, attached as cuff to airfoil leading edge. Items 73 through 76 are the conductors.

The Haslim and Lee (1987) patent has been commercialized by Ice Management Systems (Appendix B, Table 5-4). For aircraft, the system is a composite, leading-edge cuff with the conductive actuators embedded internally in a carbon-fiber structure. The system is being applied to four unmanned aerial vehicle systems, and being considered for other air-frames. It is being evaluated by the US Army Corps of Engineers for use on navigation lock walls to remove Zebra Mussels and ice, and has been successfully tested in CRREL coldrooms for removing ice from lock walls. For aircraft, it requires no modification of the wing for the cuff, which fairs into the airfoil surface, though wiring would be required. When actuated, 500 V at 8000 to 10,000 A are fed to the system for 1–2 ms, which extends the cuff 2 to 2.5 mm and accelerates the cuff surface, and the ice, at about 60,000 g. The system can de-ice several inches of ice, or more, according to CRREL lock wall tests, and requires only 700 W/m^2 for each firing. When fired frequently, expulsive systems can essentially function as anti-icing systems. System de-icing effectiveness improves even further if the surface is coated with an ice-phobic material.

Table 5-4. Electro-expulsive sources.

Product	Source	Description	Information
Electro-Mechanical Expulsive De-icing System (EMEDS) with Electro-Thermal Subsystems	Cox & Company Inc. 1664 Old Country Rd. Plainview, NY 11803 Tel: 212-366-0200 Fax: 212-366-0222; 212-366-0283	Hybrid anti-icing EMEDS with electr-thermal subsystem (ETIPS) for improved ice release	Appendix B www.coxandco.com
Electro-expulsive de-icing system (EEDS)	Ice Management Systems Inc. 27449 Colt Court Temecula, CA 92590 Tel: 951-676-2751 Fax: 951-694-0097 Contact: Mark Bridgeford	Mat type EEDS for application to variety of surfaces	Appendix B www.ims-ess.com
Electro-Impulse De-icing (EIDI)	Innovative Dynamics Inc. 2560 North Triphammer Rd. Ithaca, NY 14850 Tel: 607-257-0533 Contact: Joseph Gerardi Fax: 607-257-0516	Perimeter and surface expulsive de-icing systems	Appendix B www.IceSight.com

In 1991, when expulsive systems were being first seriously developed, the FAA considered their advantages to be low power use, reliable de-icing (though not tested on saline ice), that were non-intrusive, and low maintenance (FAA 1991). Embry et al. (1990) and Foster-Miller (2004) have proposed use of expulsive systems for marine applications. Foster-Miller proposed the use of EEDS on Navy ships to de-ice composite panels that will not tolerate the forces of traditional mechanical de-icing techniques. The expulsive system designed by NASA (Haslim and Lee 1987) has a low radar cross section, low RF and infrared signatures, requires little power, and is applicable to protection of structures in addition to aircraft. Embry et al. (1990) described testing of a system on an Alaskan Patrol Vessel, which was not wholly successful when metal panels covering the expulsive system surface did not expel all ice. This was attributed to characteristics of the metal covering and an inadequate power supply. They also tested the system successfully in heavy icing conditions on Mt. Washington, NH. They proposed applications to the hatches of the Navy Vertical Launch System located on the forecastle of cruisers and destroyers to replace the current thermal de-icing system that is highly visible in the infrared. They also suggested applications to weather deck doors, masts and antennas, gas turbine intakes, flight decks, bridge windows, containers on commercial ships, deck machinery, fishing gear, and safety equipment, such as lifeboats. The system is most successful, however, on flat or surfaces and convex surfaces; it is more difficult to apply to compound curves and concave surfaces.

5.7 Heat

Heat is one of the most common methods of anti-icing or de-icing. Aircraft use heat to prevent icing of leading edges, electrical transmission lines are heated through joule heating, ships use heat tapes on hatches, and windows are heated. However, heat is expensive and consumes large amounts of energy, especially when anti-icing areas exposed to wind and spray. And, for military use, heat can be hazardous because it makes objects more detectable with infrared imagers and targeting technologies. Therefore, there has been significant development of anti-icing and de-icing technologies that do not use heat. However, heat has not been abandoned as an ice control measure, but its control has become highly refined in recent years, and that is where most of the technological developments are taking place. In addition, heating can use a variety of media, including electrothermal systems, infrared energy, hot water, and hot air.

Energy usage is in part a function of whether a system anti-ices or de-ices. Anti-icing systems are not required to melt ice; they only need to keep the surface warmer than 0°C. Heating 1 g (about 1 cm^3) of water 1°C requires about 4.2 J/g of energy. Melting 1 g of ice requires approximately 335 J/g, 80 times as much. Therefore, it appears that keeping a surface warm may be more energy efficient. However, surfaces that are continually impinged with spray, and experience high relative winds at low air temperatures, such as the forward bulkhead of a ship, require considerably more energy.

De-icing requires that ice be melted. However, once ice has accumulated, depending upon the shape of the surface, little energy may be necessary to remove it. If the surface is relatively smooth, flat, and vertical, only sufficient heat is necessary to break the adhesive bond of ice to the substrate. This requires melting only 1 mm or less of ice. In addition, heat losses are smaller because convective losses are smaller; there is less convective loss at the ice–substrate interface because the substrate is protected from wind flow by the ice. If the ice–air interface is not heated, then convective losses are minimal. All of this requires, however, that ice be heated to at least 0°C.

There is another method of removing ice from heating that is even more efficient. This does not require ice to be heated to melting, but simply that ice is heated at the ice–substrate interface until its vapor pressure rises to above that of the vapor pressure of the air. If the ice is heated several degrees, its vapor pressure will rise and ice will begin to sublimate at the ice–substrate interface. Though this may be a slow process, especially because air initially has poor circulation at the ice–substrate interface, as sublimation progresses the ice erodes and its bond to the substrate weakens allowing the ice to eventually fall from the surface. Ice and snow are cleared from automobiles in this manner on sunny, very cold days. This method can also be used to prevent frost, a technique used to keep a telescope free of frost at the French–Italian Concordia Station on Dome C in Antarctica (Strassmeier et al. 2010).

5.7.1 Electro-thermal systems

Electro-thermal systems are typically the least expensive to apply, but the most expensive to operate. Therefore, there has been considerable development to make electro-thermal systems more efficient.

Electro-thermal resistance heating, or joule heating, is 100% efficient. Nichrome wire, as found in electric heaters, or materials such as carbon layers, are commonly used as conductors. Ships often use heating cables to prevent icing of hatches and bulkhead doors. The Navy uses electric resistance heaters embedded in the edges of the hatch assembly of the Vertical Launch System (VLS) on destroyers and cruisers (Embry et al. 1990). A classic example of electro-thermal de-icing is the heating elements bonded to the interior of automobile rear windows. A similar technology is applied to aircraft propellers, such as on the C-130, and especially to helicopter rotor blades, such as on the Apache, the Black Hawk, and the Sikorsky A-76 (Ryerson 2008).

Traditional electro-thermal systems heat a surface to a temperature controlled by a thermostat, and cycle on and off, or limit current to maintain temperature. However, ice-melting cables are available that are self-controlling without the need for a thermostat. Expansion and contraction of a microscopic conducting material between two copper buss wires controls the current flowing between the bus wires, and the heat produced. Warmth increases the spacing between the microscopic heating elements and reduces electrical continuity and heating, and cold causes contraction and greater electrical conductivity and heating (Raychem 2008) (see Table 5-5). An optional automatic controller can energize the system when low temperatures and precipitation are detected, or only when low temperatures are detected. The heating cables are intended for embedding in concrete, but may be adaptable for other applications, such as placement immediately under ship weather and buoy decks. Watt density requirements to keep concrete ice-free varies from 323 W/m^2 at –7°C in winds of 2.2 m/s to 861 W/m^2 at a temperature of –23°C in winds of 8.9 m/s (Raychem 2008).

Ice-free decks are critical to safety when anchoring, mooring, during search and rescue, in scientific missions, and during ATON operations. Heated decks are very desirable in the Coast Guard, and many interviewed crew cited the current CGC MACKINAW as an excellent example of the capability that should be placed on cutters operating in superstructure icing conditions. The CGC MACKINAW has electrically heated forecastle and buoy decks, a system that was designed and built into the vessel during construction. The desirability of heated decks on the 225-ft *Juniper*-Class seagoing buoy tender resulted in a Coast Guard study that indicated the cost of retrofitting heated decks to these cutters was $750,000 per vessel. Cost, and difficulties retrofitting and maintaining such a system, has prevented retrofits. However, mats are now available for heating decks that use electric heat trace embedded within a polymer that can be custom fit to deck surfaces. The heat trace is self-regulating and draws more or less power as temperature changes. The mats conform to Det Norske Veritas (DNV) Category I and Category II requirements for anti-icing and de-icing, and draw about 200 to 385 W/m^2 (Advanced Mat Systems 2013.) (see Table 5-5 and Appendix B).

Efficiency improvements have been attained for electro-thermal systems by combining them with hydrophobic and super-hydrophobic coatings (Fortin et al. 2011; Antonini et al. 2011a, b). Independent experiments in icing wind tunnels showed that power required for electro-thermal anti-icing was reduced by 80% (Antonini et al. 2011b), and 13 to 33% by Fortin et al. (2011) using super-hydrophobic materials. These are examples where passive coatings and active electro-thermal systems can be used together to advantage.

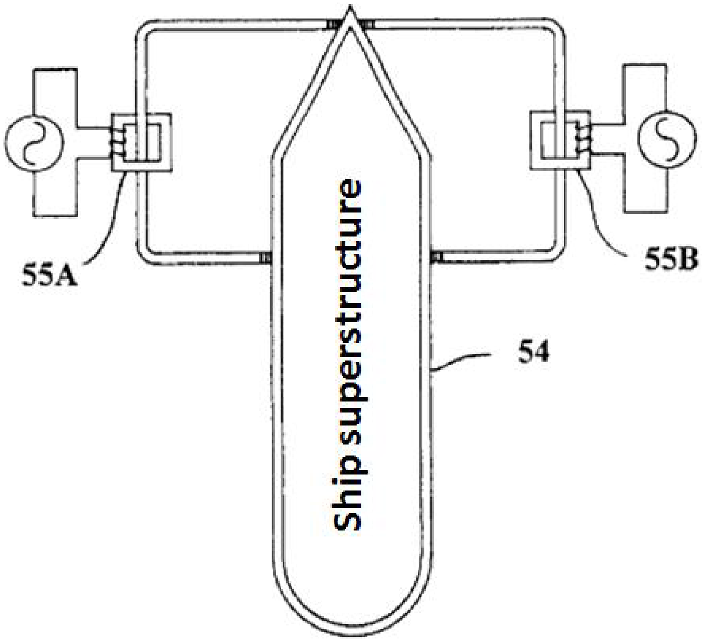


Figure 5-28. Application of Granborg (2002) patent to a ship superstructure. Item 54 is the ship structure, and items 55A and 55B are transformers connected to generators.

Granborg (2002) proposed an electro-thermal approach in a patent that does not require additional heating elements to be added to a structure; the structure itself serves as the heating element (Fig. 5-28). Granborg proposed passing alternating current through the skin of a structure, with the inherent resistivity of the structure elements providing the heating. The frequency of the alternating current should be high enough to cause the majority of the current to pass through the skin of the structure causing surface heating. Essentially, the structure becomes part of a closed circuit originating in the secondary winding of a transformer. Granborg (2002) claimed that the technology can be used to heat engines before starting, antenna towers, oil drilling platforms, aircraft wings, and ship superstructures. Currents could be several hundred amps at less than 1 V.

The most current electro-thermal developments cleverly control the current through the heating elements to maximize results with the least consumption of energy. In some cases, they also use unique heating elements. In all cases the placement of the heating element on the structure, and its unique operations, create large energy savings.

Petrenko et al. (2003) developed a concept that reduces power usage by supplying only sufficient energy to a surface for a short time to melt a thin layer of ice at the heater surface (Ryerson 2009). The Pulse Electrothermal De-icing (PED) concept can be applied to nearly any structure, and is essentially a heat, and therefore power, control strategy. The technology requires that a thin-film heater be applied to a surface, and that the ice accumulates on the heater. This allows the heater energy to be applied directly to the ice, when energized, rather than needing to be conducted through several millimeters of substrate before reaching the ice. The speed of the heating, and the power supplied both also contribute to energy savings. A high power pulse, of low voltage and high amperage, is applied to the heater for a few seconds or less. This pulse rapidly heats the ice–heater interface and melts a layer of ice a few microns thick—but sufficient to reduce ice adhesion strength. The ice then falls from the surface, or is carried away by wind flow or centrifugal force. The concept has been applied to a variety structures, including to windows covered with clear electrically conducting film.

Goodrich has developed a Low Power Electro-thermal De-icing (LPED) system for use on aircraft—but it could be applied to the marine environment—and uses the Petrenko et al. (2003) PED concept (Ryerson 2009; Table 5-5). It consists of standard electric heating elements mounted on the substrate requiring de-icing, but electrically isolated from the ice. The system is used in de-icing mode because ice that has accumulated on the surface before the system is energized is an extremely effective thermal insulator that reduces heat loss in the aviation environment, but also in any environment where wind and water are impinging on the surface. On an aircraft, strip heaters are periodically energized with short, intense pulses of power supplied by charged capacitors. These short, intense power pulses heat for only 1.4 s every 3 minutes. Only sufficient heat is applied to weaken the adhesive ice bond. Power consumption is reduced below that of a typical electro-thermal system by 20 to 90%. The system would be most effective on ship bulkheads and other vertical surfaces where gravity could carry ice away.

Other companies are using rapid heating strategies to reduce energy consumption, but using new, innovative conductors. QFoil and ThermaWing use a graphite-based thermoelectric heater that is attached, using adhesive, to the leading edge of an airfoil, aircraft or wind turbine, or any other surface that must be protected from icing (Ryerson 2009; Table 5-5). The heating material is thin, flexible, and lightweight, and consists of a rolled carbon conductive core sandwiched between Kapton, polymer films, metal foil, quartz, or ceramic. A thin sheet-metal cover protects it in heavy industrial environments. Also, the surface can be covered with heat-conducting and ice-phobic Tedlar. Heating is similar to the PED concept; current is applied to create a rapid thermal rise, as rapid at 56°C/s. This causes a thin layer of ice to melt at the heater surface, which causes the ice to lose adhesion strength and be carried away. Watt density is 6 W/cm^2 or less, and can be controlled with location by varying the thickness of the carbon conductor.

Battelle has also used the PED concept for heating the leading edges of unmanned aerial vehicles to anti-ice and de-ice (Warwick 2012). However, the Battelle surface consists of conducting carbon nano-tubes mixed into aircraft paint to create a light weight, low power, anti-icing coating that is easily applied and repaired. Initially, a primer is applied to the substrate, and the nano-based conducting paint is sprayed over the primer. A soy-based protective layer is painted over the conducting layer, and standard topcoat paint is applied last. The system is 0.5 to 0.75 mm thick and, according to Battelle, is four times more efficient than other electro-thermal systems. Current applications are for aircraft, but the technology may be applicable to ships, especially bulkheads and surfaces that are unlikely to be abraded or punctured.

5.7.2 Hot air

Despite the low heat capacity of air, and its low thermal conductivity, hot air is still a practical method of anti-icing and de-icing. The most familiar hot air de-icing systems are the automobile windshield defroster, and home forced-air heating systems. Both systems are inexpensive, reliable, and mechanically simple.

Hot air anti-icing systems are also used in aviation to anti-ice the engine inlets, windscreens, and main wing and empennage leading edges (Fig. 5-29). The hot air source of these systems is bleed air from the turbofan engines. Bleed air is high pressure, high temperature air, ranging from 200 to 250°C at 275 kPa, that is bled off after the engine compressor stages, but before fuel is injected in the burners. However, the new Boeing 787 does not de-ice with bleed air, but uses separate electrically driven compressors to supply hot air.

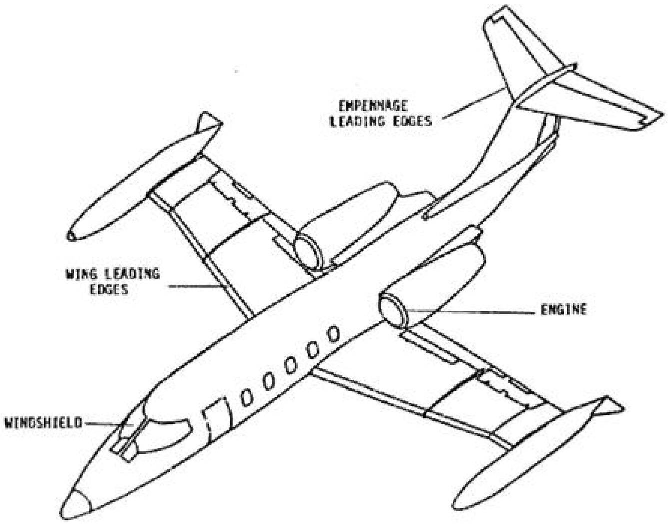


Figure 5-29. Aircraft components using hot air for anti-icing (FAA 1991b).

Airframe manufacturers are actively seeking alternatives to bleed air for de-icing. De-icing is most needed at departure and approach when aircraft are flying low and slow and are most frequently in icing conditions. Bleed air can use up to 10% of engine power at takeoff, when power is needed for flight, and engines are typically at idle on approach and little bleed air is available. In addition, for military aircraft, hot surfaces are not compatible with stealth goals.

Windows are heated with hot air using two approaches. The least common method is to blow hot air between two panes of a double-pane window (Fig. 5-30a). Though effective, dirt and oils can accumulate inside the window, and heating is most effective at the bottom of the window where air enters. The technology is also noisy. The second method uses an external blast system to remove ice and water drops from windscreens (Fig. 5-30b). Air is blown along the outside of a window, from bottom to top; the system also typically replaces windshield wipers.

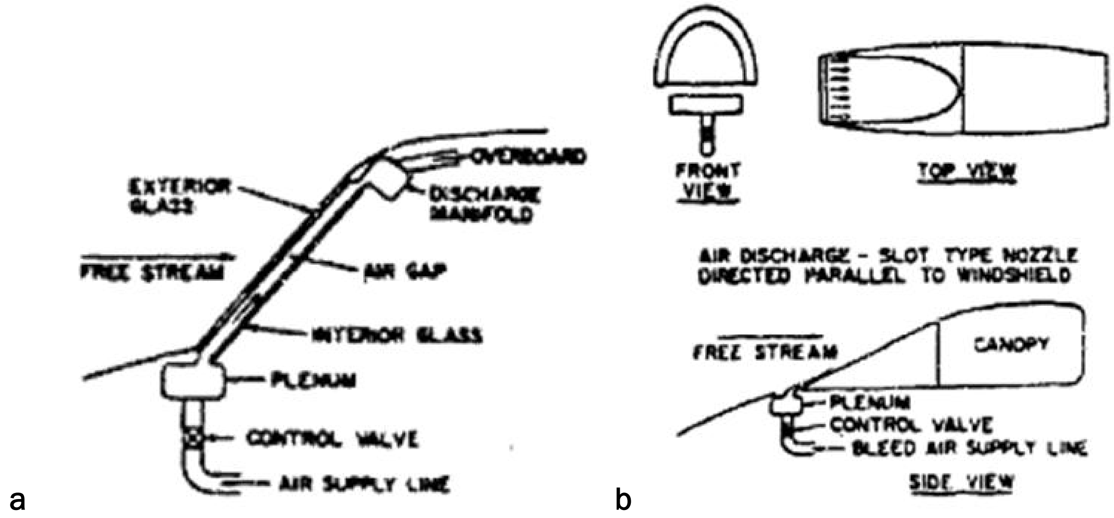


Figure 5-30. Hot air wind de-icing between double panes (a) and using an external air blast (b) (FAA 1991b).

Aircraft leading edges are air-heated using a variety of designs, but most commonly they use a piccolo tube located within and parallel to the leading edge (Fig. 5-31). The piccolo tube, a tube with holes along one side, directs hot air from the bleed air system to the back of the leading edge. Most systems are evaporative, that is they become sufficiently hot, about 150 to 225°C, to evaporate water droplets before than can run back to unheated portions of the wing and form ice there. The "runback" ice also causes loss of lift and control authority, and increases drag even though it is not on the leading edge.

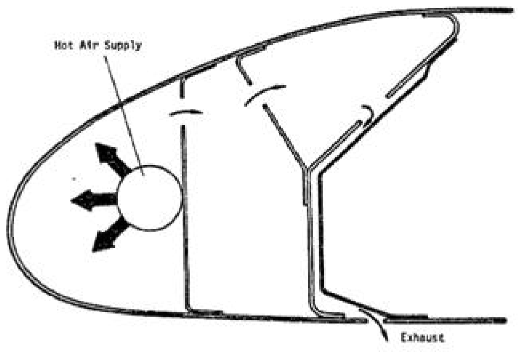


Figure 5-31. Hot air supply for a wing leading edge is distributed through a piccolo tube (FAA 1991a).

Figure 5-33. Buddy Start De-icing Nozzle used to de-ice a Black Hawk blade during a de-icing experiment (Ryerson et al. 1999).

Hot air is also used to de-ice aircraft before flight (Ryerson et al. 1999). Bleed air can be tapped from aircraft Auxiliary Power Units (APU), or Aircraft Ground Power Units (AGPU) and ducted through a hose to a nozzle that can be held and directed by personnel. Army UH-60 and AH-64 helicopters, and the C-130 and C-17 fixed-wing aircraft, are equipped with the Rockwell Collins Buddy Start system (Ryerson 2009) (Fig. 5-32). The Buddy Start system typically uses the auxiliary power unit (APU) bleed air and electrical power from a live aircraft to start the APU of an aircraft with no battery power. Bleed air is sent from the live aircraft to the dead aircraft through an approximately 10-cm-diameter fabric hose. A nozzle added to the system, called the Buddy Start Hose De-icing Kit, allows limited de-icing. The de-icing kit is a 0.5-m-long handheld aluminum nozzle with a 6.4-cm diameter. A ball valve controls air flow. Air temperatures at the nozzle have been measured as high as 167°C, and at a distance of 0.4 m, temperature decreased to about 133°C, and to about 100°C at 0.6 m (Ryerson et al. 1999).

The Air Force has experimented with the use of jet engines mounted on trucks to blow warm air across the wings of snow-covered aircraft at Elmendorf Air Force Base in Alaska. The Navy also has experimented with the use of jet engines mounted on “yellow gear,” equipment used to move aircraft, to de-ice aircraft carrier decks. A jet engine was aimed at the flight deck at a low angle, and the surface removed ice by heating and by the force of the high velocity air flow.

Another clever system uses warm and humid air for ground de-icing. The Chinook Mobile Heating and De-icing (MHD) system delivers warm, humid air to the iced aircraft surface (Ryerson 2009). Usable with any frost, snow, or ice, the system supplements warm air, flowing at relatively low velocity and low temperature, 40 to 85°C, with latent heat of condensation when the warm, moist air condenses on the snow or ice surface. Directed to the ice surface by fabric ducts, approximately 2500 J of energy are released to the iced surface for every gram of water condensed, sufficient to melt about 7.5 g of ice. De-icing times vary with air temperature and wind speed. In demonstrations on aircraft wings, frost required 2–3 minutes to de-ice and dry, 1.6–2 mm of ice required 5–8 minutes to de-ice and dry, and 2–4 cm of snow required 14 minutes.

Though not strictly hot air, steam has been used successfully to heat pipe railings of fishing or crabbing vessels in Alaskan waters (Jim Stone, personal communication, Alaska Bering Sea Crabbers, 17 December 2012). Steam is circulated through the railings similarly to steam heating systems in buildings.

5.7.3 Hot water

Water is an effective means to de-ice and anti-ice because of its large heat capacity. There are several methods of delivering water to surfaces requiring protection, generally through heat exchangers that heat the substrates. The other method used is to flood surfaces with warm or hot water to prevent ice, or to remove it.

The Federal Aviation Administration allows the use of hot water to de-ice aircraft using a variation of the flooding approach (FAA 2000). In a series of experiments, hot water at a temperature of 60°C was applied to plates contaminated with ice in air temperatures as low as −9°C at wind speeds of 2.8 m/s. De-icing was considered successful if a surface experiencing an ice accretion rate of 0.25 (cm/cm^2)/hr would de-ice and remain de-iced for 3 minutes or longer. Hot water performed acceptably, similarly to Type I de-icing fluids under the same conditions.

Ryerson et al. (1999) also experimented with hot water to de-ice Black Hawk helicopters coated with 1–2 mm of clear ice at an air temperature of −2°C. Water used for de-icing was heated to approximately 45°C and delivered by a prototype of the Army's Aircraft Cleaning and De-icing System (ACDS) that was designed primarily to clean helicopter engines. The experiments showed water to refreeze on the blade surfaces before running off, and water often refroze on the underside of the blades where no ice previously had been.

Water will not freeze if there is more energy in the water than can be removed by conduction, radiation, convection, and evaporation. Therefore, various techniques have been tried, or are used, to flood decks with warm water. Green water over the bow can prevent deck icing, and it can remove existing ice. If deck drainage is adequate, large volumes of seawater are sufficiently warm to melt existing ice, or mechanically remove it. It can also prevent icing by adding sufficient heat to the deck, even if its temperature is near freezing, to prevent ice formation (Fig. 5-33). This procedure has been used on occasion to remove ice from the forecastle of the CGC HEALY.

Figure 5-33. Though the deck hardware and bulwarks are freezing, and even the scuppers are frozen shut, sufficient water is flowing over the deck to keep it largely free of ice. Heat from below decks could also be a contributing factor (from CRREL).

De-icing trials on the Navy harbor tug *Keokuk* at Portsmouth, NH, in January 1976 included a deck flushing system (Kenney 1976). Pipes 3.8 cm in diameter with 6-mm holes drilled every 20 cm were attached to the sides of the afterside deck, and seawater was to be pumped through fire mains. It was hypothesized that seawater flowing over the deck would prevent spray from impacting the cold deck and freezing. However, the experiment could not be conducted because the air temperature was −20°C, and the fire mains froze. However, Alaskan crab boats have used a similar technique by placing fire hoses on the weather decks below the railings, and have pumped seawater onto the decks at high pressure and high volume.

This technique has prevented ice formation on decks (Jim Stone, personal communication, Alaska Bering Sea Crabbers, 17 December 2012).

AMI Exchangers, Ltd., manufactures a heat exchanger system specifically designed to de-ice decks of tankers, gas carriers, container ships, and survey vessels with warm sea water (www.ami-exchangers.co.uk). The heat exchanger is connected to the ship steam or other heating system, and to the ship fire main system. The system can operate to −45°C, and can be used to clear ice from decks, forecastle winches and windlasses, and anchors.

Any water-based de-icing system using heat exchangers and piped systems must have the capability of being completely drained when not in use. Or, it will be necessary to use a freezing point depressant to keep the water from freezing.

5.7.4 Heat pipes

Heat pipes are a heat transfer device that use both thermal conductivity and phase transitions to transport heat from one location to another without using an external power source. Heat can be transferred over considerable distances, such as from the engine room of a ship to components on the deck or in the superstructure. A heat pipe, which can be a flat structure that does not resemble a pipe, has three components: an evaporator, an adiabatic section, and a condenser (Beltran and Falabella 1989). A working fluid with a low vaporization temperature, such as ammonia, is vaporized in the evaporator. The vapor travels to the cold condenser end and releases latent heat, and returns to the evaporator by capillary action through a wick. Canadians have experimented with heat pipes to keep buoys de-iced using sea water as the heat source (Larkin and Duboc 1976). Beltran and Falabella (1989) propose using heat pipes to de-ice vessels.

Beltran and Falabella (1989) claimed that heat pipes were nearly maintenance-free, had good thermal response times, removed substantial amounts of energy from low temperature sources, and were flexible in design. They cited applications for heat pipes such as de-icing pavements, and the buoy work by Larkin and Duboc (1976). They also cited work by Japanese researchers using heat pipes to successfully de-ice the decks of fishing trawlers (Matsuda et al. 1981).

Beltran and Falabella (1989) focused on heat pipe use to de-ice US Navy vessels, and provided an example design for a helicopter hangar door that will not operate if ice is greater than 6 mm thick. They showed a design where heat pipes could be built into the doors, and draw heat from warm air inside the hangar to the outside surface. Though simply not insulating the door completely may accomplish the same objectives, it is possible that the cold inside surface would frost and cause other problems. They also suggested that ship pipe railings and decks could be de-iced, and that heat pipes could also draw waste heat from the engine room area and pipe it to needed areas higher on the ship.

5.8 High velocity fluids

High-velocity fluids have been used for years to successfully de-ice aircraft, ships, Coast Guard Cutters, and navigation locks to remove ice and snow (U.S Navy 1989; Mackes 1989; Hanamoto 1977; Frankenstein and Tuthill 2002; Ryerson and Koenig 2003; Wyderski et al. 2003). Steam lances were commonly used to de-ice during WWII in winter convoys across the Atlantic Ocean, and especially in the Arctic convoys to Russia (Kemp 1993). When ships were steam powered, de-icing with steam lances was relatively common because ice could be cut from surfaces in large pieces (Løset 1985). This saves time and energy because the entire ice mass does not require melting, only a narrow kerf needs to be cut that is sufficient to loosen the ice from the substrate and from surrounding ice masses.

Hanamoto (1977) and Frankenstein and Tuthill (2002) summarized experiments using high-pressure water to cut ice from lock walls. A pump of approximately 100 hydraulic horsepower (about 75 kW) was used to create water pressures of approximately 60 MPa using nozzles 2.18 mm in diameter. Penetration of freshwater ice ranged from 0.6 m per pass to 0.76 m per pass. Standoff distances were 0.6 to 0.9 m, and allowed traverse rates of about 0.8 m/min (Hanamoto 1977). Coherent jets produce the best results; and experimenters found that temperature, wind direction, and wind speed are critical to success. High winds allow water spray to blow back and refreeze onto the surface, and low temperatures slow cutting. Low temperatures and a narrow kerf cut (0.5 to 1.0 cm) can allow water to refreeze in the cut, though one vendor markets a fluid to prevent refreezing in pressure washing systems (described below and Appendix B). In Japan Takahashi et al. (2004) found that lower pressures (14 MPa) can also cut ice at a 0.5-m standoff distance. Overall, water pressure cutting of ice is a viable method of removing large masses of ice.

Water jets can cut deeply into dry ice, but not deeply into ice floating in water, such as on a flooded deck, because the water quickly disperses the jet's energy. The reaction force of high-velocity water jet nozzles is often too great to be handheld, especially if the operator is on a slippery deck. In addition, high pressure flow could damage glass, composites, and paint, and can be a hazard to personnel if mishandled.

Derbidge et al. (1989) demonstrated an experimental high pressure (517–862 kPa) flash flow system for de-icing that operated between 122 and 133°C (see Ryerson 2008, p. 84, for photo). The system was intended to operate from a ship fire main and use a portable heater to raise water temperature, but not convert the water to steam, allowing sea water to be used. The result is a two-phase flow with about 10% steam that, in experiments, removed ice faster than a 28-MPa water jet. Tests showed the ability to remove ice 10 cm thick and to remove up to 186 cm^2 of ice per second. It is unknown whether a planned prototype to demonstrate on a ship was built or used.

Bojun and Si (1990) described experiments using a steam lance to cut ice. A small boiler with a super-heater was used to create dry steam at a pressure of 0.6 MPa. A wand was fitted with an array of up to 34 nozzles that was capable of cutting a 15- to 20-cm-wide slot with an ice removal rate of 0.002 to 0.003 m^3/min. Energy use calculations indicated that the ice was not melted, but was eroded by the steam jet; energy use was only about 10% of that necessary to melt the same volume of ice.

High velocity air, water and steam jets may be difficult to manage on slippery, crowded decks, narrow walkways, and in close quarters. In addition, they are closely related to manual methods because they must be operated by personnel exposed to the elements, occasionally on rolling decks. These technologies can be used to de-ice decks, railings, bulkheads, flight decks, stairs, walkways and work areas, piping, and valves. High-velocity jets may not be safe to use on safety equipment, sensors, antennas, horns, life rafts, and boats, especially if the latter are of composite construction. Steam jets are also potentially harmful to personnel, could shatter windows, and may damage items that cannot tolerate high temperatures. Boilers also present the danger of a possible explosion if improperly maintained and managed.

Several high velocity fluid technologies are available commercially. Some are intended for the marine environment, and others may be adapted. The

Air Force uses a truck-mounted low-pressure, high-velocity system to de-ice aircraft. The Global AirPlus! System uses a highly efficient nozzle developed by the Air Force that can be operated in three modes from its truck-mounted cab (Appendix B; Table 5-6; Ryerson 2009). A high-velocity air mode removes loose snow and ice; this is the preferred de-icing mode because glycol de-icing fluids are not used. In the second mode fluid, heated to 80°C, is injected into the air stream and abrades and erodes snow, and melts thin ice and frost. Fluid use in this mode is minimal and is used whenever air alone is not effective (Fig. 5-34). If air with fluid injection is not effective, additional fluid is sprayed from an adjoining fluid-only nozzle. In addition to the Air Force, several airlines are using the AirPlus! System to de-ice. Elements of the system could be mounted on a Coast Guard Cutter, perhaps with the nozzle mounted on a crane, and the spray nozzle used to de-ice the forecastle and buoy decks from the crane control station.

Figure 5-34. Global AirPlus! System removing snow from helicopter in Eglin Air Force Base McKinley Climatic Chamber (Ryerson).

One problem with spray de-icing systems is dealing with the environmental consequences of any freezing point depressant fluids used. Land-based operations must prevent propylene glycol-based de-icing fluids from reaching surface waters. And many nations have restricted the loss of fluids into their ocean waters. Freezing point depression fluids are now available that can flow, according to international agreements, into ocean water (for example see Harmony, Appendix B). These fluids are designed for use with heated pressure washing systems such as used to de-ice the Coast Guard HH-65 Dolphin helicopter aboard the CGC MIDGETT in 1990 (Fig. 5-35). Propylene glycol was the only fluid available at that time, but today fluids are available that are not considered environmental hazards. Table 5-6 lists a high velocity fluid that is currently available, and Appendix B provides a full description.

Figure 5-35. Coast Guard helicopter being de-iced with a heated pressure washing system using a de-icing fluid. Note the engine inlet covers (Ryerson).

Table 5-6. High velocity fluid sources.

Product	Source	Description	Information
AirPlus!	AirPlus! Forced Air De-icing System Global Ground Support LLC 540 East 56 Highway Olathe, KS 66061-4640 Tel: 913-780-0300	Forced air and fluid de-icing system	Appendix B www.global-llc.com
Harmony De-icing Fluid	Mike Sweetman, Managing Director Ideal Solutions 730 Enterprise Drive, Lexington, Kentucky 40510 Tel: 866-673-3963 Cell: 502-316-1663 Fax: 859-266-2717 msweetman@idealsolutionsonline.us	COTS de-icing fluid	Appendix B www.idealsolutionsonline.us
Sioux Pressure Washers & Steam Cleaners	Sioux Corporation One Sioux Plaza Beresford, SD 57004 Tel: 888-763-8833 Fax: 605-763-3334	Heated pressure washers and steam cleaners for de-icing	www.sioux.com/thawing-de-icing-systems-applications.html

5.9 Infrared and lasers

5.9.1 Infrared

Infrared heating is a well-developed technology used in space heating and industrial processes. Infrared is a remote method of heating, where the heat source can be located at a distance from the surface being heated. Infrared technology requires an emitter of energy, and an absorber. However, all transmission of infrared energy is radiative. That is, no medium, such as a solid or a fluid, is necessary to transmit the energy. And, most often, transmission is hindered by absorption in the atmosphere or by spray, precipitation, or fog that may pass between the emitter and the absorber.

All objects that are warmer than absolute zero, 0 K, emit radiation. As objects warm, the amount of energy that can be emitted increases, and the wavelength of that radiated energy shortens. Therefore, objects such as the Sun have a surface temperature of about 6000 K. According to Planck's Law, the flux of energy at any wavelength is a function of the temperature of the object. The peak energy is emitted at a wavelength described by Wein's Law, where the peak wavelength of emission in microns is equal to $2897/T$, where T is temperature in Kelvins. Therefore, an object emitting with 100% efficiency, a black body, at a temperature of 6000 K, such as the Sun, provides maximum radiative flux at a wavelength of about 0.5 µm, which is approximately the color green in the visible spectrum, and emits about 7.3×10^7 W/m^2. Objects, such as the Earth's surface, may have a temperature of about 288 K, and emit about 390 W/m^2 most strongly at a wavelength of about 10 µm. Infrared systems used for heating and deicing operate at temperatures of 670 K to about 1270 K. Therefore, they emit most strongly from about 5.8-µm to about 2.23-µm wavelengths respectively. Energy emission then ranges from about 1.2×10^4 W/m^2 for the colder emitter to about 1.5×10^5 W/m^2 for the hotter emitter.

Most natural objects have an emissivity and absorptivity of about 0.8 and higher, or 80% and higher efficiency. Most paints also have emissivities and absorptivities of 90% and higher. Polished metals, however, generally have absorptivities of about 10% or less—they absorb 10% or less of the infrared energy reaching them. For many materials, the absorptivity varies over the infrared wavelength range. In general, infrared energy impinging on an ice surface is absorbed at the surface. The attenuation depth of ice for the absorption of infrared energy, in the 3- to 14-µm spectral region, is less than a millimeter based on the calculated absorption coefficient (Koenig and Ryerson 2011) (Fig. 5-36). Therefore, objects cooler than about 1000 K emit peak infrared flux in wavelengths that are absorbed most strongly by ice. Most of the infrared energy in these wavelengths reaching ice that is not absorbed near the surface is reflected. Therefore, little infrared energy is transmitted through clear ice to the substrate where it could be absorbed. If this were to happen, warming of the substrate could occur, causing melting of a thin layer of ice against the substrate. Then, as with pulse electro-thermal de-icers, a thin water layer could form that would reduce ice adhesion strength until it released from the substrate. Because about two-thirds of infrared energy in the 3- to 14-μm spectral region is absorbed in the upper millimeter of the ice, melting occurs from the air–ice interface in, rather than from the substrate–ice interface out.

At the air–ice interface, the sum of the spectral radiance reflected, absorbed, and transmitted by the ice must account for all the energy impinging on the interface. Absolutely clear, bubble and defect-free ice is transmissive at visible wavelengths, and it is possible to transmit most energy in these wavelengths through ice to heat the substrate (Koenig and Ryerson 2011). However, to have the peak emitted radiance from a heater in the visible wavelengths requires a high heater operating temperature, approximately that of the Sun's surface. Operating a heater at these high temperatures is both impractical and potentially a safety issue.

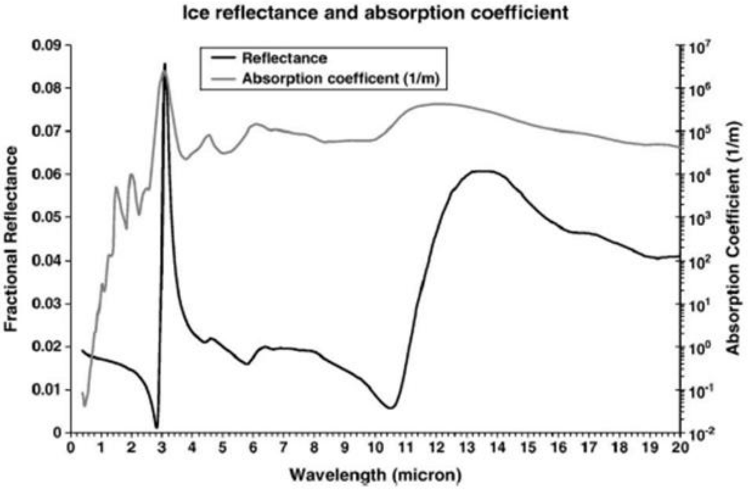


Figure 5-36. Reflectance and absorption for fresh water ice (based on Warren 1984; Koenig and Ryerson 2011).

The characteristics of ice melt rate, as indicated by mass change, are illustrated in Figure 5-37 for the case of melting 47 mm of clear, fresh water ice at an emitter temperature of 1114 K with a peak-emitted radiance at 2.60 µm. Ice was placed on a load cell at 1133 minutes on the time scale, and melting began and continued for about 90 minutes. Infrared melting is not rapid, but it is effective. However, melting of snow with infrared energy is slower than melting ice.

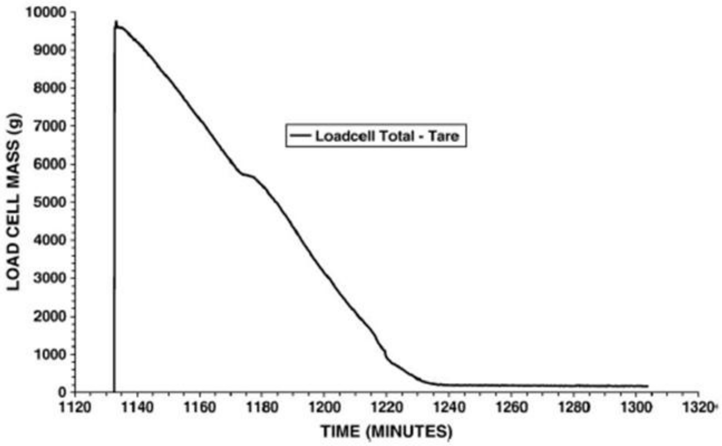


Figure 5-37. Melting of 47-mm thick fresh water ice at emitter temperature of 1114 K (2.60-µm wavelength of maximum emission) (Koenig and Ryerson 2011).

Though infrared energy does not penetrate ice well, and especially if it is not transparent and has defects, the substrate becomes the absorber once the ice has melted and any remaining water evaporates. If the substrate is a painted surface with an absorptivity of 90%, it will absorb most of the impinging energy. And, depending upon its thermal diffusivity, it may heat rapidly. This may be helpful on steel and aluminum surfaces where heat can prevent additional icing. However, if the substrate is a composite material, for example, its thermal diffusivity is low, and it will heat rapidly. Because composites remain intact via internal adhesives, they may soften and delaminate. Therefore, it may be prudent to monitor the temperatures of thermally sensitive surfaces if infrared energy is used to prevent overheating.

The structural properties of a surface, however, are also important in determining the temperature of a surface after ice melts and water evaporates. Figure 5-38 shows a thermal trace of temperature on the surface of a composite helicopter blade during infrared de-icing; the blade had about 2 mm of clear ice. Initially, the ice heats to about 0°C, and remains there from about minutes 2 through 9. The surface temperature will not rise above 0°C because all absorbed energy is used in the latent heat of melting. Once the ice melts, water is evaporated, and energy is absorbed by the latent heat of vaporization. However, once the water fully evaporates the dry substrate heats rapidly, at an average rate of about 2°C/min until the infrared heater is turned off. If the warm surface loses energy through convection and radiation as rapidly as it is receiving energy, heating will slow and perhaps stop, which may be why the heating curve began to flatten in Figure 5-38 before the heater was turned off. The danger is that some portions of a surface may de-ice before others under the infrared heaters. If this happens, and the heaters continue to be powered until all ice is removed, the areas that de-iced and dried first could overheat. For these reasons, it may be best that substrates be reflective in the infrared wavelengths, or made of a material that is not heat sensitive, so that they will not overheat.

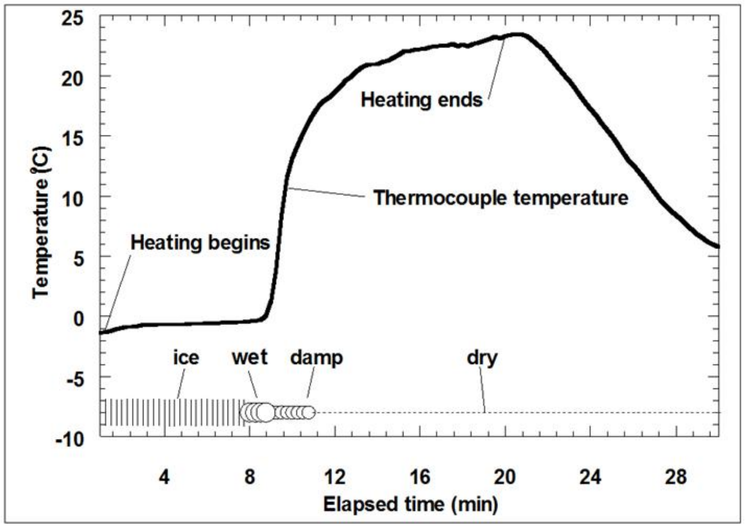


Figure 5-38. Temperature history of composite helicopter blade during infrared de-icing (Ryerson 1999).

The US Navy has assessed infrared heaters for shipboard de-icing or anti-icing (Mackes 1989). Issues such as exposure of personnel, corrosion resistance, explosion hazards, element shattering because of sudden inundation of emitters with sea spray, and performance being degraded by accumulation of salt on emitters were examined. No major issues were identified, but Mackes (1989) also indicated that a full Navy system safety review would be necessary before applying infrared technologies to ships.

Several infrared technologies have demonstrated de-icing capability. The Schaefer Ventilation HotZone heater is available in a variety of sizes for spot heating a small area, to heating the entire entrance foyer of a building. Emitters operate with electricity or gas (Ryerson 2009; Table 5-7). A unique egg-crate, or “lobster-eye,” lens system directs the infrared energy to allow nearly spot heating at greater distances than systems without lenses (Fig. 5-39). Koenig and Ryerson (2011) evaluated the effectiveness of the lenses over coated and uncoated aluminum substrates with and without the lenses. Experiments were conducted at distances of 0.6, 0.46, and 0.30 m between the heater and the iced substrate. Ice thickness was about 8 mm in each test. After normalizing for variability in ice thickness, de-icing took about 24% as long with the lens than without the lens. That is, the lens increased the de-icing rate by about 4.1 times. According to Koenig and Ryerson (2011), a focusing lens infrared heater is a promising technology that could allow more efficient radiant energy de-icing. The electric emitter could be easily operated in the field, and the lens system may provide more rapid de-icing with less energy. In addition, the lens system did allow more rapid de-icing at a greater distance than did the system without the lens attached.

Figure 5-39. HotZone lobster eye lens that focuses infrared energy (Ryerson, n.d.).

Larger infrared systems are gas-fired. They are available as small portable systems to large systems controlled by a hydraulic boom (Fig. 5-40, Table 5-7). They operate over a variable temperature range using a gas-fueled catalyst that has no open flame. The variable temperature capability allows the Ice-Cat to be regulated to not exceed a set maximum temperature for the heated surface. Infrared sensors located within the Ice-Cat heater array detect the apparent radiant temperature of the heated surface, and signal the Digital Temperature Controller (Ryerson 2009). The controller then regulates fuel delivery to the panel as necessary to maintain a not-to-exceed temperature for the surfaces being heated. In an experiment conducted at Eglin Air Force Base's McKinley Climatic Laboratory, Ryerson et al. (2003) concluded that the Trimac Ice Cat thermal control does reduce maximum substrate temperatures after de-icing, though temperatures can still occasionally exceed the set temperature. Ideally, thermal sensors could scan or image the de-icing surface, locate the highest temperature, and maintain that temperature below the set temperature of the Ice Cat. This is a difficult task considering the potential variations of surface geometry, thermal structure, and radiative absorptivities and emissivities.

Figure 5-40. Ice Cat de-icing helicopter tail boom in Eglin Air Force Base McKinley Climatic Chamber (Ryerson).

The largest infrared facilities can de-ice an entire aircraft at once before flight. Radiant Aviation has developed a gas-fired infrared heater system that hangs an array of heaters from the roof of a space-frame structure. The heaters are configured to accommodate any shape of aircraft that can fit into the structure (Fig. 5-41; Table 5-7; Ryerson 2009). The heaters are then fired to accommodate the shape of the aircraft that "drive through" the structure. The system is designed to be placed over an asphalt surface that has high absorptivity for infrared energy, but a relatively low thermal mass. Therefore, ice on top of the aircraft is melted by the direct infrared illumination of heaters. Water running off the aircraft wings, or icicles that may have formed under the aircraft, are melted away by infrared energy reradiated from the asphalt surface up to the bottom of the aircraft. Ryerson et al. (1999) describe experiments de-icing Army helicopters within a prototype Radiant Aviation system at Buffalo International Airport. Each helicopter was coated with 1–2 mm of clear ice using a fire truck, and about 1 cm of natural, wet snow also coated the helicopters in separate events. Two power densities were tested from the infrared heaters: about 945 W/m^2, and 440–630 W/m^2. Removing wet snow or ice sufficiently to ready the aircraft for flight required about 15–25 minutes. Shadowed areas were either wet or retained some slush after this time. Energy usage was very low to de-ice the aircraft, using gas valued at a few tens of dollars.

Figure 5-41. Radiant Aviation system with snow-covered Army Black Hawk helicopter at Buffalo International Airport (Ryerson).

Most of the applications reported above are aircraft-oriented. However, in 1989, Schultz and Minnick (1989) reported on the conduct and conclusions of feasibility studies of the possible use of infrared heaters to de-ice the UNREP decks of Navy ships. The feasibility study drew the following conclusions without any testing aboard a ship. The preferred use of infrared heaters was to anti-ice by keeping the area requiring protection sufficiently warm to prevent icing. The feasibility study did indicate, however, that infrared heaters could be used, with reasonable results, for de-icing. Though they concluded that infrared would be an obvious ship retrofit operation, infrared could compete favorably with the installation of underdeck strip or contact heaters in new construction. They saw the largest limitation of infrared heating systems for anti-icing as the relatively proximity they needed to the surface being heated, making application to large areas of open deck, such as a buoy deck or forecastle deck, difficult. However, focusing infrared heaters, such as the HotZone heater, were not available in 1989, and may provide greater opportunities for heating larger deck areas.

The heating capacity required to keep decks and equipment at an UNREP station at a temperature above the freezing point of sea spray and atmospheric precipitation in Arctic temperature and wind conditions was judged as high, requiring infrared heaters with the highest output and the highest efficiency. The study recommended the use of electric quartz lamps fitted with Vycor sleeves to limit the high light levels emitted by the quartz tubes. The study recommended that infrared heating anti-icing should be demonstrated and further evaluated aboard ships.

Overall, infrared is an effective method of de-icing and ant-icing. It is remote, enabling surfaces where in situ heaters cannot be installed to be protected by an overhead or wall-mounted heater. Though somewhat slow, infrared provides design flexibility. It does, however, create some hazard if the hot heaters are struck by large volumes of cold water that could cause thermal shock. Also, wind can cool surfaces faster than infrared systems can heat them, so testing would be necessary in extreme conditions.

5.9.2 Lasers

Lasers have attracted considerable interest as potential de-icing devices. Their ability to focus energy, and potentially penetrate clear ice in a variety of wavelengths has caused considerable patent and research activity. Lane and Marshall (1976) did early tests evaluating the use of lasers to damage ice and loosen it from substrates at CRREL. They used a Nd:Glass laser operating at a wavelength of 1.06 µm, and a Ruby laser operating at a wavelength of 0.6943 µm, to irradiate clear fresh water ice grown upon substrates of asphalt, brass, concrete, aluminum, steel, and stone. General results were that a single pulse, delivered through the ice to the interface between the ice and the substrate at a power density of 108 to 109 W/cm^2, produced fractures 0.1 to 2 cm in diameter for all substrates. Damage to ice occurred only when samples were 1.5- to 2-cm thick. They speculated that scanning may create fractures over the entire ice interface surface and allow the ice to be removed.

In 1989, Schultz and Minnick (1989) reported on assessment of the possible use of lasers to de-ice the UNREP decks of Navy ships. Neodymium lasers were selected for assessment because they operate at infrared wavelengths. Saline ice readily absorbs infrared energy, as does clear fresh water ice. In addition, neodymium lasers, which operate at 1.06 µm wavelength, allow the beam to be delivered to the deck area by optical fiber, and they are durable and require little maintenance. However, the power required, and the wavelength, make these lasers Class 4, a significant eye safety hazard, requiring eye protection. The Navy did not intend to use lasers to completely remove all ice. The intent was to cut, melt, or shatter grooves in superstructure ice, enabling other technologies, such steam lances or pressure washers, to remove the remainder.

The feasibility study considered the use of lasers to melt or fracture ice as technically feasible. Laser safety concerns, and an economic analysis, indicated that a portable high-pressure washer would likely provide better de-icing performance, with fewer safety and operational concerns, at about 10 to 20% of the cost of a laser de-icing system—in 1989 dollars. However, it was recommended that a prototype infrared anti-icing and de-icing system of limited scope be installed as a test unit aboard a ship scheduled for a northern latitude deployment. It is unknown whether the recommended testing occurred aboard a ship.

There has been continued activity to develop lasers systems for aircraft since the 1989 Navy study. SunLase, Inc., developed a patented concept of de-icing aircraft using a powerful stationary CO_2 laser operating at 50 to 100 kW. It would utilize a series of mirrors to reflect and aim laser beams at the aircraft (Nunnally 1998). The mirrors would scan the aircraft with laser energy, but would also focus the energy to an intensity of about 100 kW/m^2, or about 100 times the intensity of sunlight at the equator. Wavelengths of 10 to 11 µm would be absorbed by ice and snow, but would be reflected by the aircraft surface and prevent damage to the aircraft paint, skin, and other hardware. The inventor claims that an aircraft could be de-iced in 5–20 minutes with this system. There is no indication that the system has been demonstrated. A similar technology by SunLase in a later patent (Nunnally 2001) proposes to mount lasers on the aircraft, and, as for the ground-based de-icing system proposed in 1998, use mirrors to direct laser beams to de-ice wing leading edges that ice during flight.

A somewhat similar patent by Vega and Vega (1990) proposes to de-ice aircraft surfaces using CO_2 infrared lasers mounted on booms that would be traversed over aircraft surfaces. Power and coolant air would be supplied to the laser heads to power the lasers, but also to cool aircraft surfaces and to suppress any fire. A suction system would also draw melted water from the aircraft surface. There is also no evidence that this system has been demonstrated.

Qi et al. (2010) modeled and experimented with using Neodymium:YAG and CO_2 lasers to remove or loosen ice from electrical transmission lines in China. Their simulations showed that the most powerful laser power density was most effective for de-icing power lines. They found that the CO_2 laser melted clear ice from the transmission line more slowly, in layers. The Neodymium:YAG laser heated the entire volume of ice and caused it to loosen from the power line, apparently from thermal stress, making it easily removed using mechanical methods. Also in China, Zhang et al. (2010) describe the design and simulation of a Diode laser system operating at 0.980 µm wavelength and 300 W of maximum power to de-ice electrical transmission lines. They claim that the shorter wavelength should more easily penetrate clear ice, and should successfully de-ice power systems.

Table 5-7. Infrared de-icing sources.

Product	Source	Description	Information
Radiant 1000 Radiant 2000 Radiant 3000 Radiant 4000	Radiant Aviation Services, Inc. Tim Seel, Engineering 2041 Niagara Falls Blvd., Niagara Falls, New York 14304 Tel: 716 636-5375 (Office) Tel: 716 903-3351 (Mobile) tseel@radiantaviation.com	Infrared aircraft de-icing drive-through systems	Ryerson (2009) www.radiantenergycorp.com/
HotZone Heater	Radiant Optics Inc. 19510 144th Ave. NE Suite B7 Woodinville, WA 98072 Tel: 425-806-3990 Fax: 425-806-3991	Infrared electric or gas heater with focusing lens	Ryerson (2009) http://www.radiantoptics.com
Ice-Cat Gas-Cat	Trimac Industrial Systems, LLC Infra-Red Technologies 12601 Kaw Dr. Bldg C Bonner Springs, KS. 66012 Contact: Robert Heinzinger Tel: 800-830-5112 sales@trimacsystems.com	Catalytic gas-fired portable infrared systems	Ryerson (2009) www.infra-red.com/

It may be possible to adapt a laser-based system to ships. The US Navy believed in 1989 that testing aboard ship would be a useful exercise, though it may not be cost effective. Overall, to date, laser systems, though appealing for their ability to scan a structure and de-ice, still are not proven for their de-icing efficiency, speed, or cost-effectiveness. It still may be too exotic for application aboard ships.

5.10 Manual de-icing

Manual, generally mechanical or kinetic, de-icing methods are still the primary method of removing ice from all types of vessels, from the smallest fishing trawler to the largest, most sophisticated Navy vessel. By definition, nearly all manual de-icing methods are innovative because there are few devices manufactured specifically for de-icing ships, though there are a few exceptions.

As an example, Winegrad (1987) described in detail the icing of the USS *Bache* in the 1960s, a DD-470 *Fletcher*-class destroyer. Ice thicknesses over the ship are estimated from photographs to range from about 4 to over 20 cm. Winegrad (1987) described the tools used to de-ice the ship, with the caution that at temperatures lower than –10°C, ice forming on surfaces remains soft or pulpy for only about 1 hour and must be removed quickly before a firm bond forms between the ice and the substrate.

The USS *Bache's* decks were slippery from the icing, making the manual de-icing more dangerous. Ice adhered strongly to the deck non-skid surface because of its roughness. Ice accumulated in flight deck tie-downs, on bridge windows, and heavily on the UNREP deck area.

A rubber mallet was used to de-ice the main gun on the forecastle, but a metal hammer was used to de-ice the signal light mount. Deck ice was loosened with urea pellets and sodium chloride, ice chipping tools, pry and wrecking bars, and baseball bats. However, the end of the baseball bat was used to knock ice off the non-skid rather than swinging the bat like a club. Life rails and other structures, however, were de-iced by swinging ax handles and baseball bats, though Winegrad (1987) cautioned that this could damage ship components. A steam lance and a push broom were used to push ice from the flight deck, followed by flushing using a fire hose and shovels to remove slush. Winegrad (1987) suggests that pressure washers with pulsed spray may be promising tools.

Winegrad (1987) says that the British Navy uses nylon-headed mallets to remove ice from vertical surfaces, life rails, and stanchions. The British found ice removal by hand to be difficult from fittings, electrical enclosures, lights, and drains. Steam jets were used to remove ice from air intakes and boat davits.

The US Coast Guard uses principally manual methods for de-icing on the high endurance cutters, the polar icebreakers, the 225-ft *Juniper*-Class buoy tenders and the 140-ft *Bay*-Class ice-breaking tugs. Coast Guard vessels experience sea spray icing in salt water, but fresh water icing in the Great Lakes, and occasionally in some bays, estuaries and rivers, such as the Hudson. Fresh water ice adheres more strongly to surfaces, and is harder. Saline superstructure ice hardens with time and if temperature decreases, enhancing brine drainage, it approaches freshwater ice in its mechanical properties (Ryerson and Gow 2000).

Manual de-icing is dangerous, labor intensive, and time consuming. After icing events, the weather decks are unsafe, and if there is a buoy deck it is often out of commission. De-icing is a safety concern as slippery, horizontal surfaces are a major hazard at sea; safely operating on deck is perhaps the biggest issue. Basically, the crew is out on a slippery, lumpy ice rink with lots of tripping hazards. They are swinging heavy impact weapons, sometimes in the dark, while the ship rolls, causing accidents. According to veteran Coast Guard crews, sooner or later “someone will try and speed up the process and either hurt themselves, a shipmate, damage something, or a combination of all three.”

In responses from questionnaires, former COs indicated that crew fatigue was also a major concern in managing operational risk. After battling heavy seas, sea sickness, and hours of watch, the removal of ice is an all-hands event. Removing the ice is a time-consuming evolution that often requires hours of back-breaking work in frigid and dangerous working conditions. For example, on a 225-ft *Juniper*-class buoy tender normally all of the ATON detail (10–12 members) works at de-icing. In another example, the 225-ft buoy tenders can be de-iced in 1 hour by 10–20 crew members using manual methods and chemicals. Usually, all available hands are mustered to de-ice as quickly and safely as possible, especially prior to mooring in port or other locations. Areas required to perform the mission can be cleared in 30–45 minutes, depending upon the ice thickness. Thicker ice and deeper snow required more time and effort. The rule of thumb is to hit the ice, and if it doesn't break off, hit it again. In general, ice is very difficult to remove.

Coast Guard crews further explain that Personnel Protective Equipment (PPE) is vital. This includes cold weather gear, such as Carharts, mustang suits, boots, under armor, gloves, hats, balaclavas, and eye goggles. Yak Tracks or similar boot gripping systems are necessary because iced decks are very slippery. Crew exert themselves and sweat profusely, and then chill if they rest. A larger concern in addition to safety is the time taken away from doing the mission so that the crew can clear decks of snow and ice.

At sea large deck work areas are cleared with chemicals (*Ice Melt*). Metal tools damage paint and non-skid. Occasionally, a propane blow torch-like tool called a thunder torch is used. Additionally, some Coast Guard Cutters maintain a supply of aircraft de-icing fluid to be used on windows and sensitive electronic equipment with a commercially purchased hand-held sprayer. A steam lance also works well, but the number of steam fired cutters is small so it’s normally done with wooden baseball bats and plastic sledge hammers to reduce the risk of damaging the paint under the ice.

Sometimes ice from freezing spray will remain for a month or more on cutters because attempting to remove it can cause damage to equipment. Even when being cautious while removing ice, equipment is damaged, paint chipped, and even external piping cracked. Ideally, ice weight is removed high and outboard first to improve stability. However, crew may need to concentrate on the deck first to ensure they don’t slide and fall as the ship rolls. Ice falling from the rigging is a safety concern. Once decks are safe for walking, ice can be removed from life rafts, fittings, the superstructure, masts, rigging, antennas, small boats, hand rails, scuppers, deck drains, and the hull. Antennas and radar domes are easily damaged by manual de-icing, but they are also usually hard to reach.

The Naval Arctic Manual from NATO (2007) recommends that a variety of equipment be stowed aboard ship for de-icing. These include baseball bats, fiber brooms, wire brooms, nylon mallets, rawhide mallets, wooden mallets, snow shovels, steel grain scoops, special foot gear that grip ice, portable heat guns and hair driers, and steam lances and hose if steam is available. In addition, they recommend stocking calcium chloride, sodium chloride, denatured ethyl alcohol, isopropyl alcohol (for windows), urea pellets, ethylene glycol, garden sprayers, protective gear such as boots, gloves and goggles, and a 55-gallon drum of unspecified de-icer. They caution that glycol makes decks slippery, and solid de-icer pellets should not be used on flight decks where they could become flying projectiles. The US Navy indicates that “since battling ice is....open to human ingenuity,” ice removal equipment should include, but not be limited to the items listed above (US Navy 1988).

Special tools were developed by CRREL under Navy sponsorship for manual de-icing. Zadra and Pyle (1990) report on the effectiveness of these tools for removing ice from the CGC MIDGETT in the Bering Sea in February and March 1990. These included chisel point spud bars, ice chisels such as those used to create holes for ice fishing, and a unique five-point chisel. The tools demonstrated aboard the CGC MIDGETT were selected as a result of prior evaluations by Rand et al. (1989) at CRREL of ice removal rates by hand picks, ice breakers, pneumatic chippers, heat mats, heat guns, spud bars, a hot water drill, and the five-point chisel. The chisel point spud bar, the ice chisel, and the five point chisel were found to remove ice 5 to 10 times faster than the other tools. The shipboard experiments found that the spud bar and ice chisel effectively broke ice into pieces that could be easily pushed overboard. However, the tools damaged the nonskid if they penetrated to the deck when dropped to break ice.

The most effective tool was the five-point chisel. Its tines and the chisel head width allowed it to break and rapidly remove ice from vertical surfaces (see Figure 64, Ryerson 2009). However, it still required about 20 minutes to remove 10 cm of ice from a 2-m^2 deck area (Zadra and Pyle 1990; Ryerson, personal observation, 1990). It was lightweight and did not damage nonskid. The five-point chisel was the only method useful for removing ice from the 5-in. gun turret, which had a composite housing that would have been damaged by mallets and baseball bats.

Plastic-headed mallets are specifically manufactured for de-icing ships, and they are available from various ship suppliers. The five-point chisel must be fabricated because it is not commercially available. Baseball bat manufacturers, upon inquiry, do not know if their bats are being used for de-icing, and are not known to specifically manufacture bats for the purpose. However, ship crew have specified informally that wooden bats are preferred over metal bats because they cause less damage to ship components.

Automated de-icing and anti-icing methods can replace manual de-icing on many parts of ships. Manual de-icing decreases OPTEMPO by requiring vessels to seek shelter so that crew can operate on slippery decks. It also takes crew away from other mission-critical tasks because de-icing is a mission-critical task necessary for ship survivability. Though it is unlikely that the need for some manual de-icing can be completely eliminated without substantial ship redesign, it can be minimized. In addition, tools more effective than those used today, that may better utilize the physical properties of the ice, could be developed.

5.11 Piezoelectric

Piezolecetric technologies use the inertia of ice, and its adhesion to substrates, to de-ice, and potentially anti-ice. Several groups have attempted to develop piezoelectric de-icing systems: FBS, Inc., and Penn State University, through Army funding, Creare, Inc., through NASA funding (Ryerson 2009), and independently NASA (Fink and Banks 1985) and Le Docte (2011). The goal of these efforts was to reduce the energy needed to de-ice airfoil surfaces. Energy required is about 5 to 10% of that of traditional electro-thermal systems, with wattages typically less than 1 W/cm^2 (Overmeyer et al. 2012; Palacios et al. 2010).

Piezoelectric crystals create electrical current when they are bent, and they also bend when electrical current is applied. In the latter use, they are structured as actuators that are attached to a deformable surface, or a surface that is readily vibrated at high frequency. When a metal or composite surface is vibrated or deformed at very high frequencies, for example at 20–30 kHz, ice can be detached from a surface if the shear stress created by the substrate movement can overcome the adhesive strength of the ice to the substrate through the inertia of the ice (Ryerson 2009). The engineering goal of the technology is to guide ultrasonic energy created at a few discrete actuators located on a surface to locations where ice accretes. The energy must create surface shear waves sufficiently strong to debond ice from the substrate by overcoming the ice adhesive strength and, simultaneously, not create shear forces damaging to the structure. Ice thicknesses of freezer ice and impact ice in the Penn State University Adverse Environment Rotor Test Stand (AERTS) facility removed using piezoelectric systems have ranged from less than 1 to over 7 mm thick (Overmeyer et al. 2012).

Anti-icing experiments have suggested that ice can be prevented from forming by maintaining high frequency vibrations as supercooled water accumulates on a surface. As water accumulates, it freezes, but the ice does not adhere owing to the high shear forces. In the operational environment, air flow or gravity would remove the loose ice particles (Palacios et al. 2008). Li et al. (2010) also describe experiments modifying frost formation on metal surfaces with 20-kHz ultrasound frequencies propagated through a 600- by 60- by 6-mm-thick copper plate. They found that the size of ice crystals was much smaller when frost formed during ultrasound excitation, crystal shape was erratic, and crystals tended to grow horizontally rather than vertically. Also, frost formation thickness with ultrasound actuated was about 20% of that formed without ultrasound. However, there did not appear to be a significant difference in frost coverage area with or without ultrasound.

Prior to physical testing, finite element models can be used to predict horizontal shear waves, and calculate the frequencies and wave phase velocities that would provide the highest shear concentration coefficients between the ice and the substrate, and the least shear between layers of the composite. In the case of work conducted by FBS, Inc., and Penn State University, model and experimental results agreed within 5% (Palacios et al. 2008).

Piezoelectric technology has the capability of de-icing areas much larger than the actuator area through careful actuator placement and frequency tuning

The capability of the technology on flat and curved surfaces of metal free to vibrate, at metal thicknesses to 9 mm, has been demonstrated (Ryerson 2009). However, it is currently unknown whether the technology would be capable in areas of thicker steel. In addition, bracing, complex shapes, and corners may be stiff enough to absorb, reflect, or redirect ultrasonic energy. The technology has not yet been tested over areas larger than 1 m across, nor has it been evaluated with saline ice. Saline ice is softer than clear, fresh water ice, and the shear forces between the ice and substrate may be absorbed by liquid layers at the ice–substrate interface. The technology, considering the capability known, may be most applicable on lighter structures, such as radomes, antennas, doors, hatches, and windows. However, windows should be tested for potential breakage, and though ice may be debonded from decks, stairs, and the helicopter deck, the technology provides no mechanism for removing ice debris from those horizontal surfaces—shoveling or scraping would be necessary. In addition, ice debris falling from non-horizontal surfaces should be considered.

There are currently no known manufacturers of piezoelectric de-icing systems. However, a system was reported to be in development for unmanned aerial vehicles in 2008 (Ryerson 2008).

Table 5-8. Ultrasonic sources.

Product	Source	Description	Information
Ultrasonic de-icing development	FBS Incorporated 3340 West College Ave. State College, PA 16801 Tel: 814-234-3437 Fax: 814-234-3457 info@fbsworldwide.com	Ultrasonic de-icing and ice detection	Appendix B www.fbsworldwide.com

5.12 Pneumatic

Pneumatic boots were the first method developed to de-ice aircraft wings in flight when introduced by Goodrich in March 1931 (Wolverton 2009). They are an old, but still very accepted, effective, and common technology, typically used on turboprop aircraft. Pneumatic boots are a mechanical de-icing system that are periodically inflated causing ice to break, and then to be peeled off of the surface by the air flow. On aircraft they cover about 15% of the wing chord, starting at the leading edge, and their internal, inflatable tubes are usually oriented spanwise, but can be oriented chordwise (FAA 1991b) (Fig. 5-42).

Pneumatic de-icers have been called boots because they are very thin, 2 to 2.5 mm, bonded directly to the aircraft skin, and can be readily removed for repair. Relatively inexpensive, they consist of layers of elastomers and rubber-coated nylon fabric that are cured together with heat and steam, similar to construction of an automobile tire (Ryerson 2009). The fabric layers are stitched together to form internal tubes that manifold together and inflate to 124 kPa when actuated. Approximate air volume requirements are 0.158 m^3/m^2 of coverage. When deflated, a vacuum source can quickly remove the air and flatten the de-icer; partially inflated tubes perturb airflow over wings. Boots can be inflated and deflated in as little as 2 s, and maximum surface movement is typically 9.5 mm (FAA 1991b).

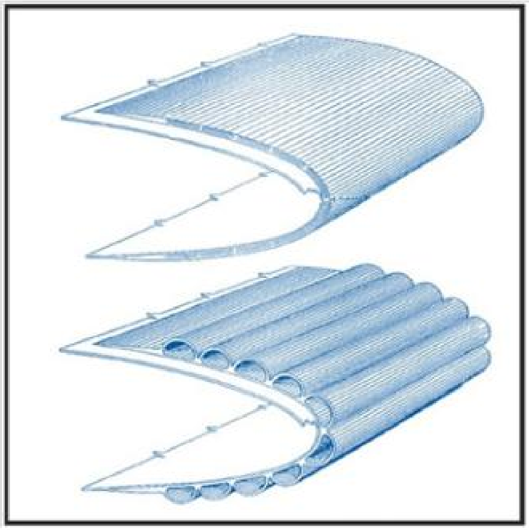


Figure 5-42. Spanwise de-icing boots on airfoil leading edge, deflated (top) and inflated (bottom) (image courtesy United Technologies Corporation Aerospace Systems, Ryerson 2009).

De-icing boots rely on a coating of ice to be effective. The ice has to be sufficiently thick to break and be carried away by the air stream. This capability varies with ice type. Much concern has revolved around how much ice should be allowed to accumulate on boots before they are actuated. Too little ice may cause the ice to ride the boot surface and crack, but not peel off and be carried away leaving residual ice on the boot. If too much ice is allowed to accumulate, flight qualities may be degraded by drag from ice roughness and change in airfoil shape and ice may not be fully removed. Current FAA guidance is to activate “modern” de-icing boots at the first sign of icing and not wait for a specific thickness of ice to accumulate (Pellicano 2007). Considerable icing wind tunnel work and flight testing has been conducted to answer these questions (Hill et al. 2006) (Fig. 5-43).

Pneumatic boots have other non-aviation uses. At CRREL, Ackley et al. (1973) designed a pneumatic boot system to remove snow and ice from TACAN antennas (Fig. 5-44). Experiments showed that greater ice thicknesses required greater air pressures to break the ice, as high as 206 kPa to break ice of 31.2 mm thickness. Boot inflation times were about 30 s. The radome was a flexible, black thermoplastic material. The boot was successful at removing rime and “extensive” accumulations of hard glaze ice. Operation of the boot compressed air inflation and deflation system was controlled by an ice detection system.

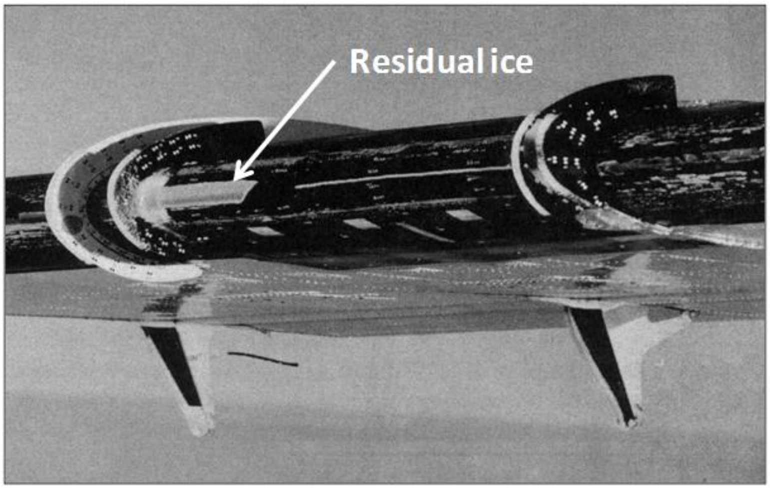


Figure 5-43. Residual ice (light areas) on de-icing boot (black surface) (image courtesy NASA Glenn Research Center Icing Branch).

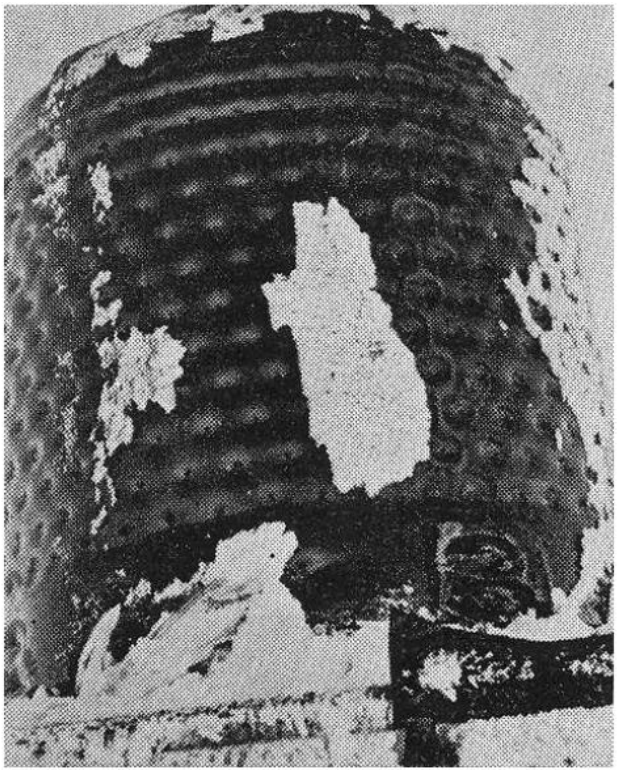


Figure 5-44. De-icing boot covering TACAN antenna successfully removed ice. However, note considerable residual ice (Ackley et al. 1973).

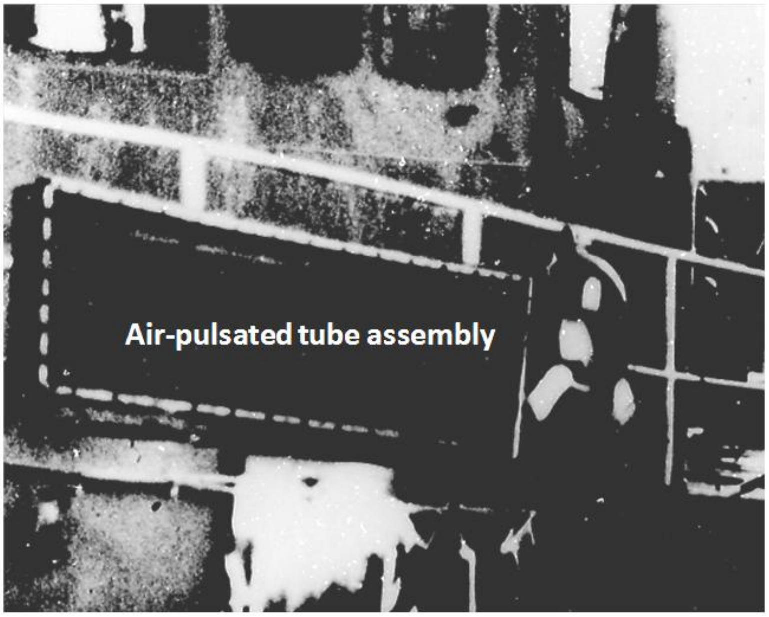


Figure 5-45. Air-pulsated tube assembly located on the 01-level rails forward of the pilot house (Kenney 1976) (best image available).

Kenney (1976) installed two pneumatic devices on the Navy tug *Keokuk* for trials at Portsmouth, NH. One device, an air-pulsated tube assembly, was installed at the 01 level beneath the bridge, and was three roughly 1- by 2-m panels of inflatable tubes made from neoprene rubber (Fig. 5-45). Alternate tubes were pressurized and vented, creating an undulating surface. Two of the three panels also had a Teflon®-based coating applied to their surfaces to reduce ice adhesion.

The second pneumatic device was approximately 2- by 6-m in size, and consisted of urethane-coated Dacron® fabric sewn and cemented to form a series of tubes (Fig. 5-46). The system was designed to allow alternate tubes to be inflated to shear ice away. A low adhesion Teflon®-based coating was also applied to 50% of the tube assembly.

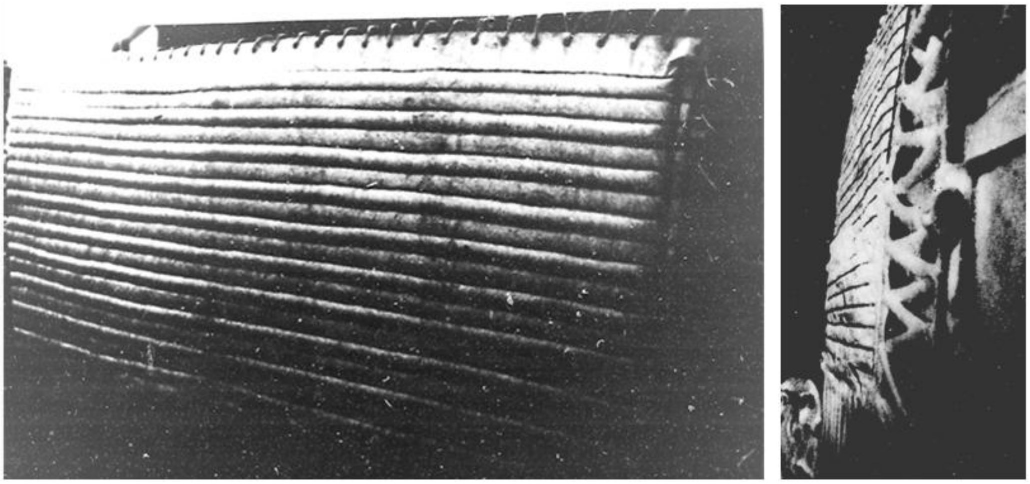


Figure 5-46. Pneumatic de-icing boot tube assembly located on the starboard side of the Keokuk in a location exposed to sea spray, left, with system under test on right (Kenney 1976) (best image available).

Successful sea trials were conducted in late January 1976 at an air temperature of –20°C, a sea temperature of 9°C, a sea state of 3 diminishing to 2, a ship speed of 10 kt (5.1 m/s), and an wind speed of 35 kt (17.9 m/s). Both types of pneumatic devices successfully sheared a 1.6-mm-thick ice layer. A 3.2-mm ice thickness left small areas of residual ice in areas not treated with an ice-phobic coating; the coated areas completely cleared. A final test on both devices with 25 mm of ice produced complete shedding from both panels. Experiments were then stopped because overall ice accumulation on the tug had created a 0.6-m loss of draft in the bow, causing a loss of maneuverability.

Kenney (1976) concluded from the sea trial that the pneumatic devices performed well. He claimed the following advantages of the pneumatic devices: they required less power than an equivalent area thermal system, they are easily stowed if necessary, they are easily operated, and they are attached to the ship’s air supply. They also could, in his estimate, be easily adapted to cover flat, cylindrical, spherical, and other curved surfaces, such as hatch covers, doors, masts, and radar antennas. Clearly, they would also be effective on bulkheads if the tubes could be fitted around existing hardware often attached to bulkheads.

Stallabrass (1970) had conducted a study of devices that might protect ships in an earlier test that was conducted outdoors and in a large wind tunnel, and not aboard a ship nor with saline ice. Stallabrass used tap water to create ice, which is harder and more tenacious than saline ice.

A 0.9- by 1.2-m pneumatic assembly was constructed of rubber matting with integral inflatable tubes (Fig. 5-47). It was designed to be wrapped around a 30.5-cm diameter mast in the wind tunnel, or exposed vertically on a flat surface, such as a bulkhead, in the outdoor test. The boot was not glued to the mast, but laced. It was also exposed in the wind tunnel such that it could be rotated and therefore iced on all sides, simulating icing that could occur as a ship changed course.

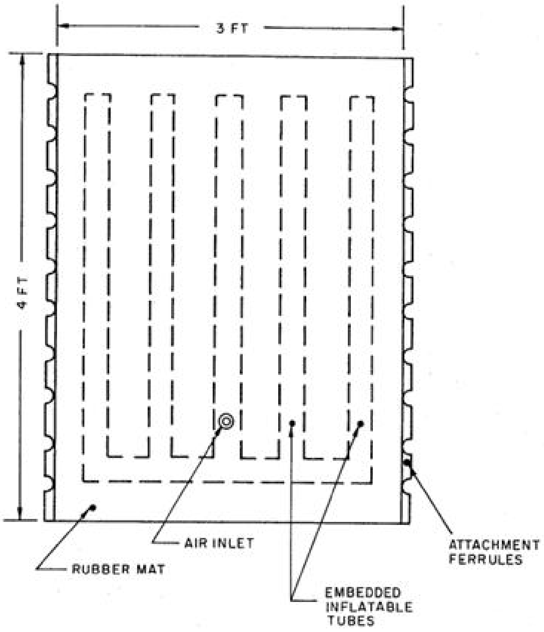


Figure 5-47. Pneumatic assembly used for mast and bulkhead tests inside wind tunnel, and in outdoor tests by Stallabrass (1970).

Tests were done with ice encompassing all sides of the mast boot, and ice accumulated on only one side. Wind tunnel tests were conducted in temperatures ranging from –9 to –23°C, and ice thicknesses formed on the mast boot ranged from 1.3 to over 12 cm. Wind speeds in all tests were 27 m/s (52 kt). Six de-icing tests were conducted, and ice was shed successfully in each test (Fig. 5-48).

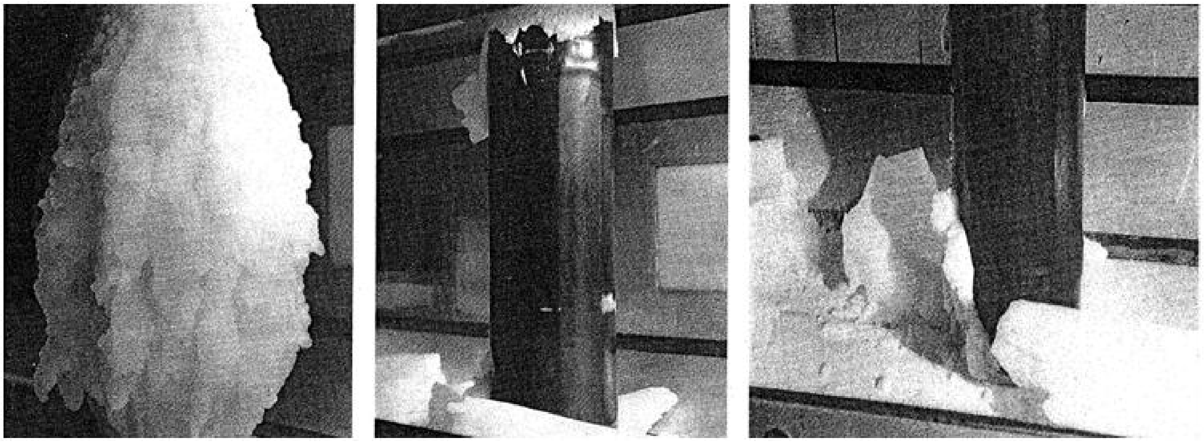


Figure 5-48. Results of wind tunnel mast pneumatic de-icing were all successful. In this case ice thicknesses up to 12 cm were fully removed using an air pressure of only 104 kPa for fresh water ice (Stallabrass 1970).

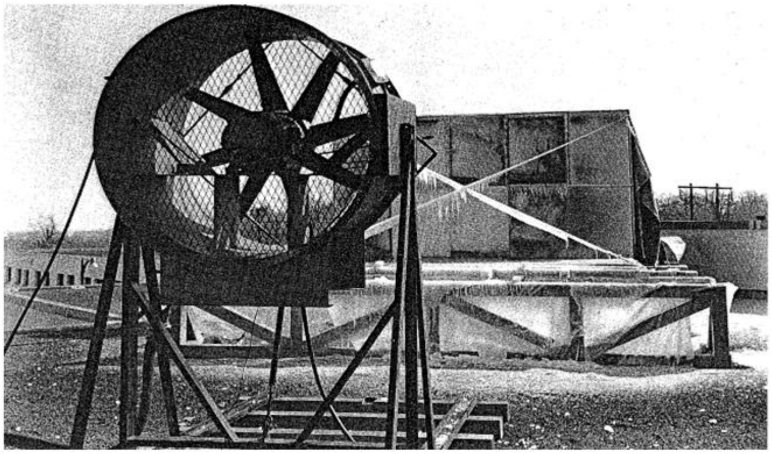


Figure 5-49. Outdoor test arrangement with fan and spray nozzles in foreground, and test stand in background (from Stallabrass 1970).

The pneumatic assembly was attached to a vertical wall for the outdoor tests to simulate exposure on a forward-facing bulkhead (Fig. 5-49). Test ice accumulation temperatures ranged from –4 to –18°C, with de-icing occurring at similar temperatures. Ice thicknesses on the pneumatic panel ranged from about 2.5 to 10 cm. Water was sprayed onto the panels with the assistance of a fan, but winds speeds were highly variable because of the influence of natural winds.

De-icing was accomplished with air pressures of about 104 kPa as was used on the wind tunnel mast test. Ice was shed fully from the pneumatic system, using only one inflation, with an ice thickness of 2.5 to 7.5 cm. However, when ice thickness increased to 10 cm, three inflations were required. The first inflation loosened most of the ice but it remained attached at the edges. The second inflation caused small pieces to break away, and the third inflation removed most of the ice. Stallabrass (1970) concluded that the small size of the panel caused ice to be anchored more firmly at the edges, and had the panel area been larger, de-icing would not have required three inflations with the 10-cm ice thickness.

Stallabrass (1970) concluded that the most effective of the de-icing methods tested was pneumatic, on both the mast and on the flat surface. The occasional failure of the pneumatic devices to shed ice immediately was attributed to the small area of the pneumatic unit, with ice bridging to adjacent surfaces preventing rapid removal. He also indicated that the buffeting of a ship in seas should cause more rapid removal of the ice. Stallabrass concluded that the disadvantages of pneumatic systems are their cost, contrary to Kenney's (1976) conclusions 6 years later, the likelihood of boots being damaged in or adjacent to work areas and the accumulation of ice debris on decks beneath bulkheads. Though there was a minor advantage for those boots covered with the low ice adhesion material, it was not notable in the conclusions.

CRREL conducted a series of pneumatic de-icing tests on navigation lock walls at Sault Sainte-Marie, MI, to remove collar ice (Ackley et al. 1973; Hanamoto 1977). Because of the severe abrasion that would be experienced by moving vessels, boots were actually 25-cm diameter fire hoses protected by flexible metal covers. Air pressures of 0.55 MPa were used to inflate the hoses, allowing ice up to 30 cm thick to be removed with two to four inflation cycles.

Pneumatic de-icing boots are a time-tested basic technology (Table 5-9), though questions still arise about how to use them most effectively. Boots could be used to protect large flat or simple curved areas (concave or convex) such as bulkheads and masts. They can protect antennas and guy wires, and they may be able to protect lattice structures if the boot covered the lattice framework. Boots cannot be used on walkways or in work areas where they could be readily damaged. They cannot be used over irregularly shaped machinery easily. However, they can remove considerable ice thicknesses, and if designed similarly to lock wall de-icers, they may function successfully in the wave wash area along the hull. They can be coated with ice-phobic materials to improve ice release. They are not a source of ignition for volatile gases and they provide no electrical hazard in a wet, saline environment.

Table 5-9. Pneumatic boot sources.

Product	Source	Description	Information
De-icing boots	AirSuppliers 4200 North Main St., Suite 220 Fort Worth, TX 76161 Tel: 800-888-0431 orders@airsuppliers.com	Aircraft de-icing boot supplies	www.airsuppliers.com
De-icing boots	Ice Shield 93 Nettie Fenwick Rd. Fenwick, WV 26202-4000 Tel: 304-846-6636; 800-767-6899 info@iceshield.com	Aircraft de-icing boot suppliers	www.iceshield.com
De-icing boots	United Technologies Corporation Aerospace Systems Ice Protection Systems Sensors & Integrated Systems 1555 Corporate Woods Pkwy, Uniontown, OH 44685 Tel: 330-374-3040	De-icing boot custom design and fabrication	Ryerson (2009) www.utcaerospacesystems.com

5.13 Vibration

Vibration involves the use of low frequency, high amplitude motions to remove ice. Piezoelectric devices are proving effective in the laboratory, but they use high frequency and low amplitude motions of substrates to remove ice.

The purpose of any vibration method is to reduce the adhesion strength of ice to substrates. This is often accomplished by low frequency bending of surfaces. For example, striking the hood of an ice-covered automobile is often sufficient to dislodge ice because the ice is stiffer than the sheet metal. The difference in stiffness, or motion, causes the adhesive strength of the ice to the substrate to be overcome. The ice is then loose and can be brushed away.

Large areas of automobile sheet metal panels are not typically stiff, and they are often relatively flat. Ship components are often relatively flat, but they are also relatively stiff. Therefore, removing ice from surfaces would require significant forces to cause panels, such as deck and bulkhead surfaces, to deform sufficiently for ice removal. In addition, there would need to be few mechanical protrusions, such as piping, to which the ice could adhere. There are several experimental examples of vibration experiments to remove ice that have failed.

Kenney (1976), in experiments aboard the tug boat *Keokuk* in Portsmouth, NH, vibrated a plywood–fiberglass panel sandwich as one of several experiments to find solutions to icing on ships. The system failed to anti-ice or to de-ice. Mulherin (personal communication, 2008) experimented with two approaches, a shaker attached to a stiff beam, and a shaker attached to a flexible 34-m lattice communication tower (Mulherin and Donaldson 1988). Intense shaking of the stiff steel beam failed to remove ice, though some cracking of the clear ice was observed. However, shaking of the tower did remove small amounts of ice ice—especially when the tower's resonant frequency was reached and it flexed. Unfortunately, the flexing that allowed most ice removal also broke welds and destroyed the tower's structural integrity. However, ice was successfully removed from the tower's guy wires.

Complex structures such as lattice towers allow ice to mechanically adhere by wrapping around surfaces. Vibration and resulting flexure of the structure is typically insufficient to completely remove ice—especially without damaging the structure. Therefore, research has also been conducted on the flexing of other materials, such as tarps, to remove or prevent ice. Makkonen (1984) reports that attempts were made to use flapping and flexible materials at sea to reduce icing, but with little success. However, Jorgensen (1982) recommends the use of tarps that vibrate because of ship motion, and reports that tarps have been successful for de-icing when provided with the low ice adhesion coatings. Field observations of tarp materials in icing conditions by Ozeki and Yamamoto (2006) and Ozeki et al. (2010) showed that the adhesion strengths of sea spray ice with fluroethylene and a super-hydrophilic material were nearly 0 kPa. Because ice adhesion would stiffen tarps and prevent them from vibrating in wind, a tarp with a low adhesion coating, coupled with wind-induced vibration, may be sufficient to prevent icing. In general, though not strictly vibration, ice is more easily removed from flexible tarps than from inflexible surfaces.

If vibration were an effective method of removing ice from ships, then bow slamming and the resulting ship-wide shocks may be considered sufficient to remove ice. However, no one has reported ice being removed from ships by the accelerations and vibrations of slamming. Therefore, low frequency and high amplitude vibration is considered to be an ineffective method of de-icing.

5.14 Optics and windows

Windows are critical surfaces to keep clear of ice because of their impact on safety if obscured. In addition, they are difficult to de-ice because of the probability of breakage. Heat through the use of hot air or electrical conduction is the primary method of de-icing or anti-icing optical materials. However, fluids are also used to de-ice windows, and more recently several optically clear low ice adhesion and anti-icing coatings appear to offer some capability.

Automobile windshields and aircraft are the common users of hot air to de-ice (SAE 2004a, b; FAA 1991b; Liardi 1970). In motor vehicles air is circulated through a heat exchanger that is heated by engine coolant. A fan pulls the air through the heat exchanger and blows it onto the inside of the windscreen. Though slow because of the need to warm the engine and heat the coolant, and because air is a poor heat transfer medium, it is simple and effective for demisting, defogging, de-icing and anti-icing windshields.

Light, piston-driven aircraft draw warm air from heat exchangers surrounding exhaust components and blow it onto the back of windscreens similarly to automobile defrosting systems. However, they are typically ineffective and warm very small areas. Higher performance aircraft draw hot bleed air between two panes of windshield glass. These latter systems are not used frequently because of excessive noise, leakage, accumulation of dirt, dust, and oil, and stress problems resulting from temperature gradients in the windshield panes (FAA 1991b). Aircraft windscreens are also heated externally by blast air for anti-icing. Usually used in very high performance aircraft instead of windshield wipers to remove rain from windscreens, bleed air is discharged at the base of the windshield by a wide, but narrow depth nozzle that directs air parallel to the windshield surface. Because in most cases rain removal air flow requirements exceed windshield anti-icing requirements, they also provide de-ice and anti-ice capability by keeping the windscreen warm and dry (FAA 1991b).

Electrical heating of windows to defog, demist, de-ice, and anti-ice is generally more rapid than hot air. Small window areas, such as for cameras or sensors, can be heated by surrounding the window frame with a strip heater. This was done on the CGC MIDGETT to successfully keep camera housing windows de-iced in a winter Bering Sea deployment (Fig. 5-50). In automobiles, wires, such as Nichrome, are attached across windows to heat the rear window glass or the lower portion of windshields to keep windshield wipers from freezing to the glass. The wires are either attached to the interior of the glass where they are less vulnerable to damage, or sandwiched between layers of glass. Some automobiles, and aircraft and some Coast Guard Cutter bridge windows, sandwich optically clear conductive material between layers of glass to heat the entire window. The conductive material is commonly indium tin oxide (ITO), which heats when a current is passed through it. Developed in the 1930s, and used extensively in aircraft during WWII, heated glass is even used in supermarket freezer display case windows.

Figure 5-50. Camera housing window with glass perimeter electrically heated on CGC MIDGETT (Ryerson 1990).

Aircraft electrically heated windows typically require a power input of 0.5 to 0.7 W/cm^2 for most icing conditions (SAE 2004a, b). Controller failure can cause overheating and glass cracking or breakage as happens on aircraft and Coast Guard Cutters. Figure 5-51 shows delaminated and burned glass from assumed controller failure on a 225-ft *Juniper*-Class seagoing buoy tender. In addition, heated windows operated without air flow over the surface on Coast Guard Cutters also causes window overheating. However, electrically heated windows are effective as indicated by the electrically heated windscreen on the NASA Twin Otter icing research aircraft (Fig. 48, Ryerson 2008) and on the CGC BISCAYNE BAY.

Figure 5-51. Delaminated area of window, opposite fingertip, showing optical distortion, and burned area below finger (Ryerson 2012).

Aftermarket, clear adhesive, electrically powered window heaters, such as from Seaclear, are available for use without replacing damaged windows, or for heating windows that do not have built-in heating systems. Cessna aircraft also provides an electrical windshield heater manufactured by Pittsburg Plate Glass (PPG) for external application to Cessna 300 and 400 series aircraft (see Fig. 80 in Ryerson 2009). The Hot Strip system is a 15-cm-wide by about 60-cm-long Plexiglas window overlay that allows visibility in icing conditions.

The Petrenko at al. (2003) PED system can also be used to de-ice window glass coated with ITO (Ryerson 2008). The sharp electrical pulse rapidly heats the conductor and a thin layer of ice sufficiently to release the ice from the surface. The rapid pulse reduces heat loss to the glass and the ice, using most of the energy for latent heat to melt the ice at the interface rather than raise the ice and window temperature. However, the external conductor is subject to abrasion damage being on the exterior of the glass.

Fluids are also used to de-ice and anti-ice glass surfaces on automobiles and aircraft. Ice Free is a propylene glycol-based anti-icing fluid that evolved from aircraft de-icing fluids, and developed by NASA Ames Research Center (NASA 2006). It should be applied before an icing event to reduce ice adhesion to windshields, but can also be used to de-ice after icing. The fluid has a minimum usable temperature of −7°C, and was intended to be commercially available in 2008 (Ryerson 2009). Microheat has patented a system, reported to be used in some General Motors products, to preheat windshield de-icer fluid to remove ice and snow, and insects during the summer. Previously marketed as the "Hot Shot," the device either heated windshield washer fluid electrically or by the engine cooling system.

CAV Aerospace, manufacturer of the TKS weeping wing de-icing system designed to protect airfoils, also protects windscreens. A separate sprayer system allows ethylene glycol to be sprayed onto the aircraft windscreen from a reservoir to de-ice or anti-ice in flight. The minimum operating temperature of the TKS glycol, 406B Kilfrost, is −60°C.

Windows could also be de-iced with fluids using techniques tested by Stallabrass (1970). One method was similar to the weeping wing approach, where a manifold placed above a bulkhead wept glycol over a vertical panel. The discharge holes from the manifold were oriented so that the individual streams of glycol from each hole merged and covered the entire panel. Spray striking the panel diluted the glycol and lowered its freezing point temperature. The weeping glycol either prevented icing on portions of the vertical panels, or it weakened the bond of the ice sufficiently that it fell away when slightly touched. Manifolds weeping de-icing fluid could be placed above windows to keep them ice-free, or make them easy to de-ice. Stallabrass (1970) thought that the approach would be best used on small components, such as radomes and inflatable life raft containers. Its disadvantage was that it would leave a slippery glycol residue on decks. However, other fluids may be available to replace glycol, as described earlier.

Coatings are also available that are optically clear, or nearly so, and that reduce ice adhesion strength. At least five products are transparent, and several claim to be optically clear and can be used on windows.

The NASA Shuttle Liberation Coating (SILC) material, a mixture of Rain-X and Polytetrafluoroethylene (PTFE), has been informally tested on automobile windshields over a period of months. Windshield optical clarity was not degraded. Though not tested in the marine environment, tests showed no ice or snow adhesion to windshields (see Appendix B; Ryerson 2009).

KISS-COTE 1063 also performed well in CRREL tests over aluminum substrates, with average shear strength of 388 kPa (Army Corps of Engineers

2006). KISS-COTE was developed, in part, for improving the speed performance of boats. Correctly applied, the coatings are a monomolecular layer approximately 120 Å thick, allowing them to be optically clear and invisible to the eye, even improving transmission of visible light on coated surfaces (see Appendix B; Ryerson 2009).

Initially, ePaint coatings were developed through Navy and Air Force funding for use, in part, in the marine environment. A transparent, flexible, hydrophobic, and ice-phobic coating, ePaint PCM Marine™ is transparent and can be applied to windows. Surfaces coated with PCM Marine™ are non-wetting; water beads and runs off the surface. Ice accretion results demonstrate very little ice accumulation on the surfaces coated with PCM Marine™. Ice that does accumulate is easily removed. Ice adhesion measurements indicate that minimal force is required to remove accreted ice, 5.5±3.9 kPa (Dixon 2011; see Appendix B; Ryerson 2009).

Nanosonic HybridSil® Hydrophobic has been designed as an anti-fouling, environmentally durable, optically transparent coating with a wide service temperature range and inherent anti-icing functionality. HybridSil® Icephobic has been designed for aircraft and aerospace applications requiring durability in particle and rain erosion environments while providing passive anti-icing and low ice adhesion protection. HybridSil® hydrophobic coatings are optically transparent on windows with negligible optical aberrations (see Appendix B; Ryerson 2009).

Innovative Surface Technology's ISurTec nano-textured super-hydrophobic coatings are used to modify surfaces such that they do not wet, but shed water and aqueous solutions. The super-hydrophobic nano-textured coatings use the "Lotus Effect" to produce super-hydrophobicity, and with additives' oleo-phobicity. All of the coatings available are ice-phobic with several having optical clarity (see Appendix B).

Oak Ridge National Labs has also developed a method for coating optical surfaces with a durable, transparent super-hydrophobic thin-film material (Riggs et al. 2012). Though not tested for anti-icing capability or ice-phobicity, the coating is also anti-reflective, UV-opaque, and self-cleaning. The ~20-nm nano-structures are sufficiently small not to interfere with visible light and produce no scattering. Applications are expected to be automobile windshields, building windows, specialty optics, and solar and military optical components (Fig. 5-52).

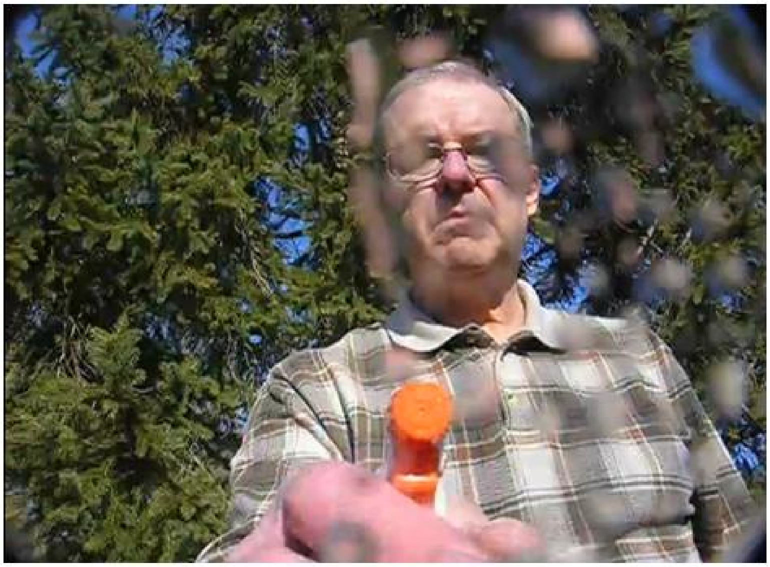


Figure 5-52. Window being sprayed with water. Left side of image is coated with Oak Ridge National Labs transparent coating and right side is uncoated.
https://www.youtube.com/watch?v=s3XWKEvzbGk

Figure 5-53. Spinning window on bridge of the 225-ft seagoing buoy tender CGC WILLOW (Ryerson 2012).

Ships commonly use spinning windows to keep water and ice from obscuring windows. Spinning windows have a circular frame, and a circular glass pane on the outside of the standard glass window spins rapidly to keep water off the window. These windows are installed in the bridge area (Fig. 5-53) (US Navy 2005). Kenney (1976) found that spinning windows failed to stay ice-free during de-icing tests on the tugboat *Keokuk*. Table 5-10 gives window protection technology sources.

Table 5-10. Window protection technology sources.

Product	Source	Description	Information
Superhydrophobic coatings	John T. Simpson, Ph.D. Technology Inventor / Consultant American AquaTech LLC Knoxville, TN Tel: 865-806-8343 Information@americanaquatech.com Tel: 865-898-9615 jsimpson@americanaquatech.com	super-hydrophobic coatings and optics	www.americanaquatech.com/
TKS weeping wings	CAV Aerospace Inc. 2734 Arnold Court Salina, KS 67401 Telephone: 888-865-5511; 785-493-0946 E-mail: tkssales@weepingwings.com	TKS weeping wing system and Kilfrost de-icing fluid	Ryerson (2009) www.weepingwings.com
PCM Marine™	ePaint Company Alex Welsh, President 25 Research Rd. East Falmouth, MA 02536 Tel: 508-540-4812 Contact: Mike Goodwin E-mail: epaint@epaint.com	Hydrophobic and ice-phobic coating	Appendix B www.epaint.com
ISurTec coatings	Innovative Surface Technologies, Inc. 1000 Westgate Drive, Suite 115 Saint Paul, MN 55114 Tel: 651-209-9757 Fax: 651-209-9759 info@isurtec.com		Appendix B www.isurtec.com
Hybridsil	NanoSonic Inc. PO Box 618 Christiansburg, VA 24068 Tel: 540-953-1785 mbortner@nanosonic.com	Anti-icing super-hydrophobic and ice-phobic coating for ship bridge windows	Appendix B www.nanosonic.com
NASA Shuttle Ice Liberation Coating (SILC)	Mr. Trent M. Smith Mail Stop FA-A Bldg: M6-0399 (HQ) Room: 3361J Kennedy Space Ctr, FL 32899 Tel: 321-867-7492 trent.m.smith@nasa.gov	Ice-phobic mixture of Rain-X and 20% to 50% by weight PTFE	Appendix B

5.15 Cables

Cables are a challenge to de-ice or anti-ice. They are thin and therefore accumulate ice relatively efficiently. Ice mechanically wraps itself around cables. Cables are often either located where they cannot be reached easily for manual de-icing, or they operate through sheaves and on windlasses, such as on cranes. Methods have been developed to de-ice cables, especially cables on electrical transmission lines. Excellent reviews for electric power transmission cable de-icing are provided by Laforte et al. (1998) and Farzaneh et al. (2008).

On ships, cables or lines are found as rigging on masts, antennas, and lifelines (Fig. 5-54). Their round shape and stranding cause ice to lock to their surfaces. However, cables are also torsionally weak. Therefore, ice often accumulates on one side if the cable is orthogonal to the wind. The side where ice accumulates is heavy, causing it to rotate down owing to gravity. New ice then accumulates on the windward side, which again causes the cable to rotate down. Eventually, sufficient ice may accumulate that the cable may rotate several times, forming a multi-layer wrapping of ice around its circumference (Kuroiwa 1965). Cables can also develop an airfoil shape as ice accumulates, causing the cable to lift in the wind. As the cable lifts it rotates because of the torsional weakness, which changes the angle of attack, decreasing lift. The cable then drops. This alternating cycle of lift and fall is called galloping, which can tear cables loose from anchors. In addition, tower guy wires, or rigging, with cables attached at steep angles, may partially shed of ice. If ice sheds near the bottom of the cables and not near the top, then ice near the top may weaken if melt begins and slide down the cable and shear the anchor away, causing the tower or mast to collapse.

Figure 5-54. Sea spray ice on CGC MIDGETT cable lifelines (Ryerson 1990).

Pneumatic boots, expulsive systems, heat, coatings, and vibration and related kinetic activities can be used to anti-ice or de-ice cables. Govoni and Franklin (1992) developed a pneumatic boot for de-icing cables (Fig. 5-55 and 5-56). The pneumatic boot wrapped around the cable and was inflated at 15-minute intervals for 15-s durations in tests on Mount Washington, NH, in heavy rime icing and glaze conditions. The 14-m-long by 1.0-cm-diameter guy wire encased in the boot was least successfully de-iced when it was covered with soft rime ice. The boot was most successful shedding hard rime and glaze. It is likely that new sea spray ice will be mechanically most similar to soft rime, but if allowed to age should become quite hard and de-ice more successfully.

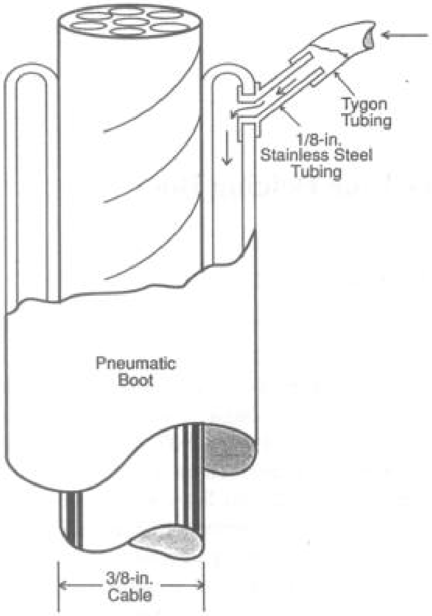


Figure 5-55. Cross-section of pneumatic cable de-icer from Govoni and Franklin (1992).

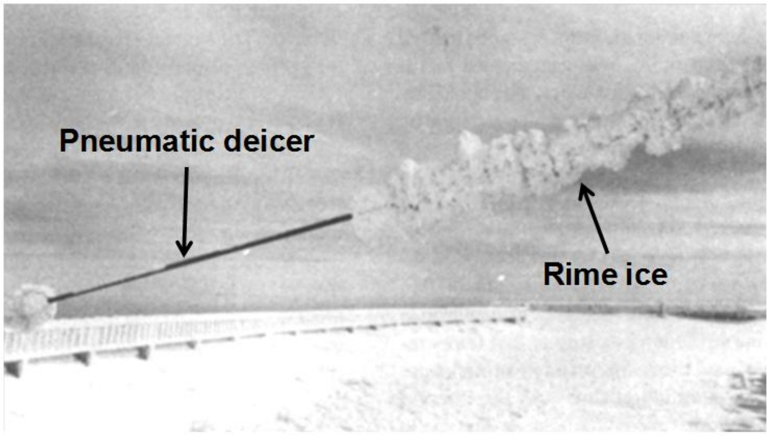


Figure 5-56. Rime ice on unprotected cable, and de-iced cable where pneumatic device has been actuated, during Mount Washington tests (Govoni and Franklin 1992).

Though pneumatic boots could be used on mast guy wires, and antennas, they cannot be used to de-ice cables that pass through sheaves. Boots may also be adaptable to pipes.

An electro-expulsive system was developed for use on cables in Quebec, Canada, by Laforte et al. (1995) at Déglaçage Industriel, Inc. The system consists of a pair of wires that are wound around and encircle the cable, protecting all sides (Allaire and LaForte 2001, 2003). The system is flexible and bends with the cable that is protected. Though originally intended to protect electrical transmission lines, ice created problems for road traffic on the new Great Belt suspension bridge connecting East and West Denmark. Rime and glaze formed on bridge cables, and when the sun warmed the ice during the day, heavy pieces fell onto the roadway forcing the bridge to close for hours (Ryerson 2009). The cable expulsive system has been placed experimentally on the upper 100 m of two vertical hangars next to a tower (Laursen 2004; Laursen and Zweig 2007). For 3 years the system successfully de-iced the cable hangars, but an extreme ice event with over 50-mm thickness caused the system to fail (Laursen and Zweig 2007; Kleissle and Georgakis 2010).

The expulsive system consists of two insulated strips of copper-ribbon wire stacked together and wrapped in a spiral around the external layer of the cable and connected at one end (Laforte et al. 1995). The other end is connected to an impulse current generator. The actuator wires must be tightly wrapped around the cable (see Ryerson 2009, Fig. 87). When energized with a pulse of current, the wires repel one another and exert a force outward from the conductor. Tests have shown that the system can de-ice a 260-m cable (Farzaneh et al. 2008). The expulsive system consumes about 0.01 times the power of conventional heating methods and does not cause radio frequency interference.

Though Laforte believes that the system could be applied in the marine environment (Laforte et al. 1995; Allaire and LaForte 2001, 2003), the system is electrical and will require appropriate wiring for safety. It is unclear how effective it will be with fresh, soft sea spray ice. It is potentially usable on safety railing cable, rigging and antennas, but could not be used on cables used for lifting or pulling or used in sheaves and windlasses.

Coatings have long been considered ideal for protecting cables, especially electrical transmission lines. Baum et al. (1988) described experiments with a variety of materials for reducing ice adhesion on electrical transmission lines. The only coatings that they found viable were formulations of polyethylene with additives that would exude to the surface and reduce ice adhesion like a layer of oil. However, these coatings are sacrificial and require periodic renewal.

Laforte et al. (1998) reviewed of transmission line de-icing technologies and found no acceptable coatings available at the time. Solid coatings had adhesion strengths 20 to 40 times too great for gravity or wind to remove ice. Viscous coatings needed frequent renewal and were thus impractical. Laforte et al. (1998) concluded that coatings were ineffective in decreasing ice adhesion to cables, and only partially successful in decreasing the adhesion of wet snow to cables.

Farzaneh et al. (2008), in a detailed and comprehensive review of overhead line de-icing and anti-icing technologies, also found no currently available coatings adequate to keep ice from forming on cables. However, they indicated that there is promise in new super-hydrophobic materials because there is a positive relationship between hydrophobicity and icephobicity. In addition, drops may be able to roll off surfaces before freezing.

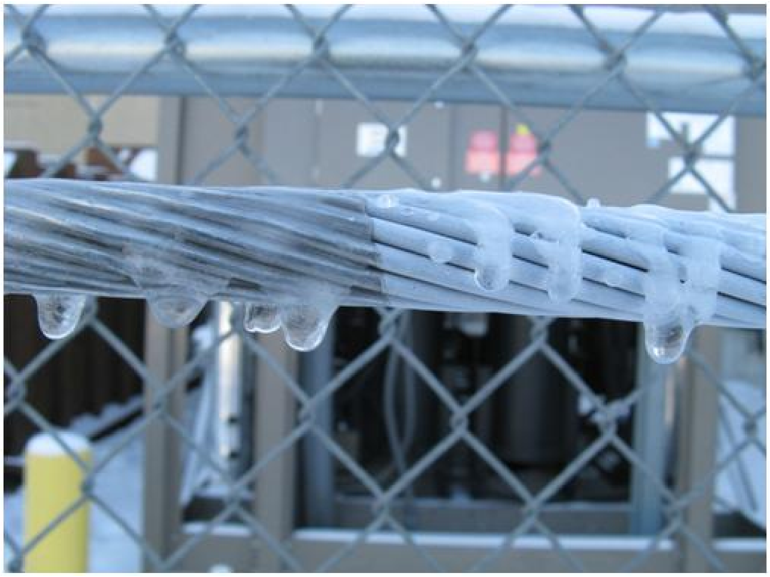


Figure 5-57. Electrical transmission line coated with ISurTec coating right, with bare aluminum surface on left (image courtesy Innovative Surface Technologies, Inc.).

Two organizations have demonstrated nano-based super-hydrophobic coatings for protecting cables in simulated and actual freezing rain conditions. Innovative Surface Technologies, Inc., has developed a super-hydrophobic coating that can be applied with a brush or a roller, and retained 70% of its original water repellency capability after 3 years of outdoor testing. Droplets bounce off when striking the surface and run off without freezing. On coated cables, some water is caught within the cable strands, but most runs off without encasing the cable in ice (Fig. 7-57).

Oak Ridge National Laboratory has also developed a nano-based superhydrophobic coating that is also transparent and can be brushed or sprayed onto nearly any surface. Tests on electrical transmission lines show that ice forms loosely on coated line, and does not form icicles (Fig. 5-58) (Simpson 2013). Drop contact angles are typically 160 to 175°, and the super-hydrophobicity reduces corrosion.

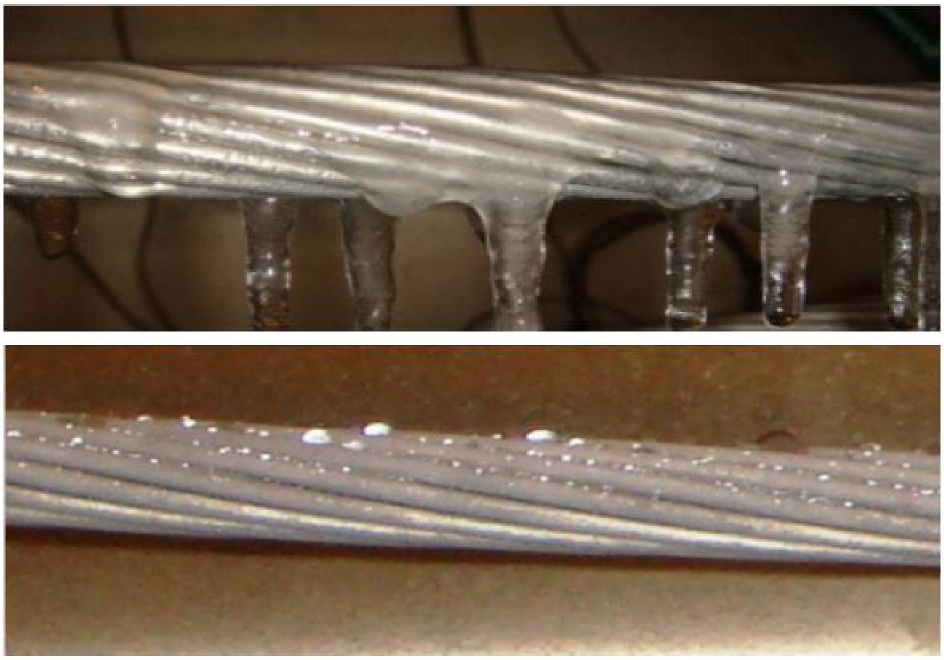


Figure 5-58. Simulated clear icing on untreated electrical transmission line (top image), and on treated line (bottom image) (Simpson 2013; Oak Ridge National Lab).

Heating has been used for de-icing and anti-icing electrical transmission lines for many years. Farzaneh (2008) describes many of the methods currently in use. However, all methods require that the cables be energized, which is not practical in a marine environment, especially on ships. The most common and oldest method is Joule heating (Ryerson 2009). The simplest Joule method is to electrically overload the line that is icing by shifting load from other lines to the iced line. With sufficient electrical load, the additional current heats the line to cause ice melting. Other approaches include short-circuiting the line, and isolating a section of line and creating a DC current loop that causes heating. Joule heating methods are used worldwide and are well-accepted as transmission line de-icing methods.

An electrical method that has proven successful and cost-effective on suspension bridge cables is the Pulse Electro-thermal De-icing (PED) methods developed by Petrenko and associates (Petrenko et al. 2003). In a demonstration, several cables and a pylon on Denmark's Great Belt Bridge, the cables, and a pylon, were covered with an electrically conductive foil. When icing occurs, a rapid, high-current pulse is sent through the conductive film to melt a thin layer of ice causing adhesive strength to decrease and the ice to fall. According to Kleissle and Georgakis (2010), the PED approach is effective in keeping the bridge components ice-free. Though it is not clear whether ice mechanically wrapped around the cable will release using this technique, the technology apparently is successful in icing on the Great Belt Bridge.

The PED approach is potentially applicable to lifelines, crane hoisting cables, and ship rigging. However, cables would require electrical isolation before being energized, and salt in ice may cause current leakage to areas where current flow is not desired.

Mechanical de-icing methods are also potentially applicable to cables on ships. Mechanical methods include expulsive (covered separately), roving ice cutters, and systems that shock the cable with a large pulse of mechanical energy. On ships, the use of baseball bats on lifelines or rigging are classical mechanical methods. Kleissle and Georgakis (2010) even report that baseball bats are used on the George Washington suspension bridge to remove ice by striking vertical hangar cables.

Shock waves, vibration, and twisting of cables all are mechanical. Govoni and Ackley (1986) hypothesized that natural cable twisting did cause some ice shedding of cables on Mount Washington, NH. However, though Laforte et al. (1998) suggest that cable twisting methods weaken cables and are difficult to apply, Allaire and Laforte (2003) designed a system that slowly twists cables about their longitudinal axis, and then suddenly releases them. A manual version of the method was successfully demonstrated on electrical transmission lines, and an automated technique is planned (Laforte et al. 2005).

Hydro-Quebec has developed an ice cutter robot that crawls along cables and removes ice (see Farzaneh et al. 2008, Fig. 6.2). Although effective, it may be difficult to reach cables for applying such an apparatus. A similar ice-cutter crawler system has been proposed for the removing ice and snow from cable stays of the new Port Mann Bridge in Vancouver, WA (Lus and Williams 2013).

Two systems have been developed to mechanically impact cables and remove ice. BC Hydro has developed a knotted rope with a weight that a helicopter can pull over the cable. Each knot catches the cable, and then releases it, causing the cable to rise and drop breaking ice off from the impacts. Hydro-Quebec has developed a system that is attached to a cable called a DAC (De-icer Actuated by Cartridge). An attached gun fires blank rounds to create shock waves that remove ice from cables (Leblond et al. 2005) (see Farzaneh et al. 2008, Fig. 6.4). The DAC device is not permanently attached to the cable, but is pulled up to the cable and held in place with a rope as needed. The Protura Automatic Ice Control (AIC) shakes ice from cables at 1.5 to 8 Hz with cable displacements of 10 to 30 cm (see Farzaneh et al. 2008, Fig. 6.6). It is essentially a low frequency, high amplitude vibration system. The system successfully removes ice accretions, is easily installed on cables, and is powered from an external source.

Mechanical methods are often difficult to apply because they must be either permanently installed, or the cable must be accessible after icing has occurred. Mechanical methods may cause cable fatigue from twisting, shocks, or vibration. Mechanical methods are easily understood and require generally minimal capital investment. Mechanical methods can be used to de-ice most cables, guys, and lifelines. Soft, newly formed sea spray ice may not respond as well to mechanical de-icing methods as hard, fresh water ice such as forms from bow spray in the Great Lakes. Table 5-11 provides sources for cable de-icing.

Table 5-11. Sources for cable de-icing.

Product	Source	Description	Information
Superhydrophobic coatings	John T. Simpson, Ph.D. Technology Inventor / Consultant American AquaTech LLC Knoxville, TN Tel: 865-806-8343 Information@americanaquatech.com Tel: 865-898-9615 jsimpson@americanaquatech.com	super-hydrophobic coatings and optics	www.americanaquatech.com/
Electro-expulsive cable de-icing	Déglaçage Industriel DGI Inc. 246, rue Régent Chicoutimi (Québec) G7G 2V7 CANADA Tel: 418-690-2472 Fax: 418-690-2472 jllafort@uqac.uquebec.ca	Cable electro-expulsive de-icing system	Ryerson (2009) www.hydroquebec.com/transenergie/en/detenteurs/dgi.html
Cable ice-cutting crawler	Hydro-Québec Headquarters 75 René-Lévesque Blvd. West Montréal, Québec, Canada H2Z 1A4 Tel: 800-790-2424	Ice cutting crawler	Ryerson (2009) www.hydroquebec.com/en/index.html
ISurTec coatings	Innovative Surface Technologies, Inc. 1000 Westgate Drive, Suite 115 Saint Paul, MN 55114 Tel: 651-209-9757 Fax: 651-209-9759 info@isurtec.com	ISurTec nanotextured super-hydrophobic coatings	Appendix B www.isurtec.com
Protura Automatic Ice Control (AIC)	Protura AS Olav Brunborgs Vei 4 1396 Billingstad, Norway Tel: 47-66-77-45-20 E-mail: firmapost@protura.no	Cable vibration system	Ryerson (2009) www.protura.no/startpage.html
PED de-icing	Victor F. Petrenko, PhD Thayer School of Engineering Dartmouth College Hanover, NH Tel: 603-646-0296 victor.f.petrenko@dartmouth.edu	Pulse electrothermal de-icing technology	Ryerson (2009)

5.16 Ice detection

Ice detection is an important element of any ice protection system. These systems are used to alert operators that ice is accumulating and may indicate when ice protection measures should be taken. Ideally, ice detection systems will indicate when and where ice is forming on a structure, the amount or rate of ice accumulation, and the successful removal of the ice when the ice protection system is activated. They should also indicate if any residual ice remains after the ice protection technology has been activated.

One type of ice detector is the human in the loop. Humans can see ice accumulation and activate ice protection systems when necessary. Many aircraft operate in this manner. However, operators cannot often see ice as it forms. Ice may be forming in locations that are visually inaccessible to the operator, or it may be accumulating at night when it cannot be seen without the use of lights. However, fog and spray may also partially obscure ice, and thickness may not even be fully evident visually. Therefore, ice detection systems may be helpful in many situations.

Ice detectors can detect the presence of ice optically. They can detect the mass, stiffness, or electrical properties of ice. They can also detect the presence of conditions conducive to icing, and not the ice itself, by detecting the properties of clouds or precipitation. Detection, in the broadest sense, can even be icing forecasts or analyses of the conditions conducive to icing over a large area through the use of meteorological and, in the case of ships, sea state models.

In addition, different ice detection technologies provide different information. Some ice detectors only indicate that ice is forming, but do not indicate that ice is residing on a surface, or that it is removed. Some ice detectors do indicate when ice forms, how long it remains, and when it is removed. Some can provide an indication of ice thickness—either indirectly or directly. Ice detectors can also be point or area measurement devices. Point devices must be located where they represent the surfaces of interest on the structure accurately. Also, some ice detectors conform to surfaces, allowing ice to accumulate on their sensors as it does on other portions of the structure. Other ice detectors are geometrically and materially quite different from the structure they represent.

The accuracy of ice detectors is also important. Ice detectors are not completely accurate at all times. They can provide false positives and false negatives, the latter being perhaps most serious because the ice detectors is reporting no ice when there is ice. Ice detectors are classified here by how they detect ice, through its optical properties, electrical properties, mechanical properties, or thermal properties. Excellent reviews of ice detection technologies are provided by Fikke et al. (2006) for electrical transmission line applications, by Jackson and Goldberg (2007) and the SAE (2004a, b) for aviation applications, and by Homola et al. (2006) for application to wind turbines.

Five optical ice detectors are currently mature technologies, but not all are commercial off the shelf, and one is under development. The Ice Hawk, marketed by the Sensors and Integrated Systems division of United Technologies Aerospace Systems (formerly Goodrich), was developed to show the location of ice on aircraft before, and after preflight de-icing (Ryerson 2008, 2009). Ryerson et al. (1999) used it to find ice on Army helicopters after infrared de-icing. It was also evaluated by the US Air Force during de-icing tests (Wyderski et al. 2003) and by the FAA to determine how well it compared to tactile tests of ice presence (Bender et al. 2006). The system is compact and can be hard-mounted to view the forecastle area of a ship, or hand-held for walk-around inspections.

The Ice Hawk detects ice by analyzing the polarization of eye-safe laser light reflected from surfaces. If no ice is present, the backscattered light is not changed in polarization and the processor maps pixels as having no ice. Where ice is present, the polarization of the reflected light is rotated and the pixels are mapped as an image of the structure with the location of the ice (see Fig. 89, Ryerson 2009). The Ice Hawk is optimized to detect a minimum ice thickness of 0.5 mm reliably. However, a new variant of this technology has been developed that reliably detects even thinner ice. Additionally, the Ice Hawk has the ability to detect ice through materials on the ice surface, such as de-icing fluid and anti-icing fluid, hydraulic fluid, and fuel. Specifications indicate an imaging range of 2 to 23 m, and the area viewed from a distance of 23 m is approximately 9 by 14 m. These viewing ranges and areas can be easily changed for other applications. The capability of the system with sea spray ice is unknown. However, experiments by Ryerson et al. (1999) demonstrated capability with clear fresh water ice or snow.

The MDA Information Systems (MacDonald, Dettwiler, and Associates, Ltd.) Ice Camera maps the location and thickness of ice on surfaces. The system measures near-infrared wavelengths to detect ice, water, and de-icing fluids on surfaces. A low-power (<100 W) Xenon strobe emits short-wave infrared energy, and a focal plane array sensor and optical filters collect energy reflected from the surface in the 1.1- to 1.4-µm region. The spectral contrast of the multiple wavelengths changes as the infrared energy passes through the ice or fluids and indicates what material is at the surface (Meitzler et al. 2007) (see Fig. 94, Ryerson 2009). For water- and glycol-based de-icing and anti-icing fluids, the spectral contrast is negative and becomes more negative with increase in fluid thickness. The contrast of ice, however, is positive and increases nearly linearly with ice thickness. The system includes a weather-resistant sensor head that shelters a multispectral camera and infrared illuminator, a display, and a controller (see Fig. 95, Ryerson 2009). The camera generates digital video of the surface that is color enhanced where ice exists to represent thickness (see Fig. 93, Ryerson 2009). The thickness range of clear ice detected is 0.2 mm to approximately 75 mm. The system can also be used to estimate the ice and water content of slush. Operational range is typically up to 80 m but ranges up to 2 km have been achieved with special configurations. System weight is a design parameter, but is typically 5–15 kg. The system was successfully tested by NASA to inspect the Space Shuttle external fuel tank for ice formation prior to launch. Test measurements of ice thickness and location at a distance of 7.6 m were successful, and NASA considered developing a program to further the technology (Moss et al. 2007). The system has been tested with clear ice, snow, and frost.

AirDat LLC has developed a sensor for detecting ice and other atmospheric conditions as part of their Tropospheric Airborne Meteorological Data Reporting (TAMDAR) system. The small, compact TAMDAR sensor is designed for use on aircraft, and a smaller unit has been designed for use on UAVs, the TAMDAR-U sensor (R. Ferguson, personal communication via email, 27 September 2012) (see Fig. 101, Ryerson 2009). The TAMDAR sensor is now installed on about 250 aircraft. The ice detector protrudes from the skin of aircraft into the air stream, and ice is detected by the obscuration of two independent infrared emitter/detector pairs mounted in a leading edge recess of the probe. Internal heaters melt the ice when the infrared beams are interrupted with 0.5 mm of ice. The icing portion of the detector has been tested in icing wind tunnels and has passed FAA requirements. Because the sensor is designed for aircraft installation, it requires air flow from a consistent direction to operate with maximum accuracy. Daniels et al. (2004) provide a thorough review of its performance.

AirDat provides weather forecasts for aviation and offshore oil rig operators. Some of the data for these forecasts are provided by the TAMDAR sensor, which is provided as part of AirDat's severe weather forecast service. Ship operators may benefit from a combination of real time shipboard TAMDAR observations and specialized icing (and other severe weather) forecasts powered by those data in combination with other data sources (R. Ferguson, personal communication via email, 27 September 2012).

Vaisala markets several optically based remote and in-situ sensors for use with Road Weather Information Systems (RWIS) that indicate the presence of, and the thickness of, ice. In situ sensors are buried in pavement with the top of the sensor flush with the road surface; they are designed to accommodate wear from tires and snowplows and tolerate contact with road chemicals and abrasives. The in situ sensors (DRS511/DRS511B) uses optical detection, surface conductivity, electrochemical polarizability, surface capacitance, surface temperature, and ground temperature at a depth of 6 cm to report pavement surface condition (dry, moist, wet, moist with chemicals, wet with chemicals, frost, snow, and ice), water layer thickness (0 to 8 mm with 0.1-mm accuracy), ice thickness (with lesser accuracy), chemical concentration (0 to over 200 g/L) and chemical amount (g/m^2) at 10% accuracy, and freezing point depression to 10 to 15% accuracy (Haavisto et al. 2000). The system cannot measure snow and slush thickness. It is necessary for the sensor to communicate with a Vaisala Road and Runway Surface Analyzer (ROSA) to report all of the conditions listed. The ROSA and DRS511 system can also estimate road surface friction, or perhaps deck friction, to an accuracy of about 97% when ice layer thickness is greater than 0.05 mm. Vaisala indicates that road friction typically decreases rapidly at an ice thickness of about 0.05 mm (Haavasoja et al. 2002).

The remote sensors (DSC111 and DST111) provide optical detection of ice, snow, or frost, and provide an assessment of pavement friction (Haavasoja 2006) (see Fig. 103 and 104, Ryerson 2009). The DSC111 transmits with an eye-safe laser beam at about 1.4-μm wavelength (near infrared) at a 30° or higher angle to the road surface and senses an area of about 0.1 m^2. Energy reflected from the road surface differentiates among frost, water, slush, and black ice, and provides time-series of the thickness of water and ice. Friction is estimated from the relative proportion of ice versus water on the pavement (Coffey 2008). Water and ice thickness are measured to a maximum thickness of 2 mm, and snow water equivalent to 1 mm, all with a 0.01-mm resolution. The system operates unimpaired in fog and falling snow. These remote systems are used in Canada, the US, Finland, Sweden, Germany, and the UK. The systems would be useful for showing the conditions of walkways, stairs, decks, and possibly bulkheads. The in situ instrument may be useful on flight decks. The systems are useful for indicating incipient icing, and the changing conditions of surfaces after anti-icing or de-icing technologies have been employed.

United Technologies Corporation Aerospace Systems (formerly Goodrich) Sensors and Integrated Systems is developing a small optical system that does not detect ice accretion directly, but measures the cloud properties that produce icing. The Optical Icing Conditions Detector (OICD) is a lidar-based instrument that distinguishes ice crystals from liquid water droplets using circularly polarization (Anderson et al. 2011). The sensor can also measure optical extinction in clouds, and from that information can also quantify cloud water content if cloud drop size information is available. The OICD is a short-range, about 30 m, polarimetric lidar that samples the passing airstream along the leading edge of a wing, for example, from a flush-mounted location in the aircraft skin (Ray et al. 2009). The instrument is not yet commercially available, but it has been tested in the NASA Glenn Icing Research Tunnel and on University of North Dakota research aircraft. Test results show that the instrument can discriminate between pure-ice, pure-liquid, and mixed-phase clouds. Accurate measurements of cloud density have also been demonstrated, as has indication of cloud water content when drop size information is available from other measurements. However, the ability of the OICD to measure drop size information for calculating liquid water content is under development (Anderson et al. 2011).

Several technologies use the electrical properties of ice, versus air, to determine the presence and, in some cases, the thickness of ice. For example, the Microwave Aircraft Icing Detection System (MAIDS) was developed as a prototype through NASA funding to detect thin layers of ice versus water (or de-icing fluid), or a mixture of ice and water (or de-icing fluid) (Ryerson 2009). The flush-mounted system provided a continuous-wave microwave signal that is split into a sensor path and a reference path. It computes the magnitude and phase of the sensor signal relative to the reference signal to determine when water or ice, or both, are present (see Fig. 98 and 99, Ryerson 2009). The system is flush with the surface where ice is being detected and is therefore less easily damaged than other detectors, and may be applied to bulkheads. It is not known if the system functions in saline environments or interferes with communication and control electronics.

United Technologies Corporation Aerospace Systems (formerly Goodrich) Sensors and Integrated Systems supplies the SMARTboot for aircraft ice detection and protection, combining inflatable pneumatic boots and a wide-area flush-mounted ice detection system (Ryerson 2009). The system detects and measures ice accretion, indicates when to activate boots, confirms de-icing boot inflation, detects residual ice, and verifies ice removal. Because aircraft tail surfaces cannot be seen by pilots, and tailplane stalls are a cause of icing accidents, SMARTboot was designed to automatically trigger boot inflation on boot-protected horizontal and vertical stabilizers.

The SMARTboot ice detector is typically embedded within the flexible material of a de-icing boot (Napert 1998; Pruzan et al. 1993). However, it can be removed from the boot and attached anywhere on the aircraft as an ice detector. The detector consists of conductive strips of graphite strands built into conductive rubber (see Fig. 100, Ryerson 2009). When ice forms on the surface, one of the electrodes (the driver or positive electrode) sends a signal to the receiving electrode and impedance is measured between the electrodes, which provides the thickness of the ice. The sensor covers a 232-cm^2 area. Although the SMARTboot ice detector was originally designed as a wide-area sensor for pneumatic de-icers, very thin sensor patches (1.0-mm thick) have been successfully developed for sensing ice buildup on other surfaces (Ryerson 2009). One application uses patches applied to non-de-iced surfaces of a UAV to warn the remote pilot operators when ice is forming, but it may be adapted to many other surfaces inexpensively on a ship if the impedance-based technology is compatible with the saline marine environment.

Some systems rely upon the mechanical properties of ice. NanoSonic has developed a sensor that will measure the icing environment in remote locations. NanoSonic's Metal Rubber sensor technology sensor is of a non-intrusive appliqué format that is readily applied to highly curved surfaces, and to nearly any substrate material (M. Bortner, personal communication via email, 4 February 2013). The Metal Rubber material is piezo-resistive; electrical resistance changes in response to physical and mechanical deformation, and it is capable of sensing changes in environmental conditions, such as wind speed, temperature or ice accretion through induced changes in shear and normal forces at the appliqué surface.

The Metal Rubber sensor has been demonstrated in an icing wind tunnel, responding in near-real-time to temperature and wind speed changes with and without ice accretion. Test conditions spanning –20 to –3°C in wind speeds of 45 to 90 m/s. The capability to withstand buildup of ice (up to ~1.3 cm thick) was tested without loss of sensitivity, coupled with the capability to withstand thermal shock of 116°C hot air impingement when removing frozen ice caps at −20°C. The Metal Rubber sensor is currently at TRL 5 (M. Bortner, personal communication via email, 4 February 2013).

FBS, Inc., is developing a wide-area ice detection system based upon its piezoelectric high-frequency de-icing technology. The ultrasonic de-icing actuators can be used to initially detect ice formation using techniques similar to those utilized in ultrasonic non-destructive testing. Alternatively, other specially designed, low-profile, lightweight ultrasonic actuators can be used for highly sensitive, wide-area, guided wave ice sensing. The technology is in early stage of development, but testing is promising (Borigo 2013).

The Rosemount ice detector is one of the original, and most widely used, ice detection technologies. Rosemount ice detectors sample the icing environment at the probe location, and users must determine how representative the measurements are to other locations (Ryerson and Ramsay 2007). The fundamental technology has evolved into a suite of detectors that operate in many environments, such as on aircraft in flight, on wind turbines, on offshore platforms, in freezing rain, and in heavy riming conditions near the ground (Ryerson and Ramsay 2007; Claffey et al. 1995; Ryerson and Longo 1992; Minsk 1985). The National Weather Service's Automated Surface Observing System (ASOS) operates Rosemount freezing rain detectors at over 600 locations to detect the onset of freezing rain, and ultimately its magnitude (Ryerson and Ramsay 2007) (Fig. 5-59).

Figure 5-59. Model 872E3 ice detector used at 600 National Weather Service ASOS sites (left; Ryerson, n.d.), and the new 0872N1 ice detector intended for severe ground-based icing conditions on communications towers and at mountain meteorological sites (right) (image courtesy United Technologies Sensors Division).

The UTC Rosemount icing detector senses ice mass accumulation on a 25-mm-long by 6-mm-diameter cylindrical probe (usually oriented vertically, or nearly vertical, in non-aircraft applications) that vibrates axially at a nominal 40 kHz when ice-free due to magnetostriction (Jackson and Goldberg 2007) (see Fig. 97, Ryerson 2009). When rime, glaze, or frost accumulates on the probe, the mass of the ice causes the probe frequency to decrease. Typically, at a preset frequency below the nominal 40 kHz, after between 0.5 and 2.0 mm of ice accumulates, depending upon the model and the ice density, a heater is activated for a period of up to 90 s that melts the ice and returns the frequency to 40 kHz. Following a de-icing cycle, the probe typically cools below freezing and resumes the reporting of ice accretion in a few seconds on aircraft-mounted units or in less than 5 or 6 minutes on ground-based units. Occasionally, with air temperature near freezing, light precipitation, and low wind speeds, ground-based sensors may require more time for the probe to cool below 0°C (Ryerson and Ramsay 2007). The probe is sensitive to any type of ice that adheres to its surface and rarely gives a false signal of icing (Jackson and Goldberg 2007; Ramsay 1997; Claffey et al. 1995; Ryerson 1990; Baumgardner and Rodi 1989; Tattelman 1982; Ryerson and Claffey 1995; Ryerson et al. 1994).

The UTC Rosemount ice detector indicates when icing is occurring, and the rate of icing at the probe. Relationships between the probe and other objects are only correlative and depend upon their relative exposure and shape of the objects versus the ice detector, and the ice detector calibration. The probes cannot indicate how much ice is on objects after icing ceases. The instruments are easily installed and operated, but they are easily damaged if the probe is struck. The UTC detectors could be placed over decks to determine potential icing of work areas or walkways, or near flight decks. The probe may be overwhelmed in heavy icing, but they rarely give false alarms. The detectors should be tested in saline icing conditions because fresh saline ice may not couple strongly to the probe.

The freezing process involves the flux of large amounts of thermal energy. Water, in the liquid state, is at a higher energy level than ice at the same temperature. Freezing water requires liberation of latent heat from the water sufficient that nucleation occurs. Water has to cool, or supercool, for freezing to occur. Once freezing begins, latent heat is released and conducted into substrates and convected into the atmosphere. Approximately 80× more heat is liberated freezing a mass of water than is liberated when cooling that same mass of water by 1°C. Therefore, even if water is supercooled, for example to –10°C, some of the latent heat released when nucleation begins is used to heat the water to 0°C. This heating can be detected with thermal infrared sensors, the foundation of an ice detector developed by Visidyne, Inc., with NASA funding, for helicopter blades. The technology was originally developed and patented by Massachusetts Institute of Technology (Dershowitz and Hansman 1991; Hansman and Dershowitz 1994).

Visidyne demonstrated a prototype sensor on a Robinson R22 helicopter on the ground with blades rotating and the aircraft sprayed with a snowmaking gun. In the prototype, a passive infrared sensor operating in the mid-wave infrared region, at wavelengths of 3–5 μm, scanned the leading edge of the rotor blades as they rotated through the sensor field of view (See Fig. 105, Ryerson 2009). When ice accreted, the region where the freezing occurred became warmer than the surrounding surface due to the release of latent heat of fusion (see Fig. 106 and 107, Ryerson 2009). Because icing occurs principally on the leading edge, much of the blade surface remained clear of ice and a temperature gradient developed across the blades. The infrared sensor measured the temperature difference between leading and trailing edges of each blade to determine whether icing was occurring. The technology indicated when ice is accumulating, but only when the water is supercooled before freezing. The technology does not indicate how long resides on the surface after accumulation. It also does not indicate when ice is removed by a de-icing technology. However, it may be an effective method of detecting ice accumulation on helicopter and UAV blades and wings because they do not liberate latent heat when they accumulate. It would not be effective for detecting the accumulation of snow, sleet, or frost. The system may not be effective in a heavy spray environment due to water flowing over the ice surface. Also, the optics could become covered with spray or salt, causing obscuration. Table 5-12 summarizes sources for ice detectors.

Table 5-12. Sources for ice detectors.

Product	Source	Description	Information
TAMDAR	AirDat LLC 2400 Perimeter Park Dr., Suite 100 Morrisville, NC 27560 Telephone: 919-653-4351	Optical ice detector and forecast services	Appendix B www.airdat.com
Ultrasonic de-icing development	FBS Incorporated 3340 West College Ave. State College, PA 16801 Tel: 814-234-3437 Fax: 814-234-3457 info@fbsworldwide.com	Ultrasonic de-icing and ice detection	Appendix B www.fbsworldwide.com Ryerson (2009)
Ice Camera	MacDonald, Dettwiler and Associates Ltd MDA Space Missions 9445 Airport Rd. Brampton, Ontario, Canada L6S 453 Contact: Dennis Gregoris and Frank Teti E-mail: dennis.gregoris@mdacorporation.com Telephone: 905-790-2800 Fax: 905-790-4400	Imaging ice detection system	www.mdacorporation.com
Metal Rubber sensor	NanoSonic Inc. PO Box 618 Christiansburg, VA 24068 Tel: 540-953-1785 mbortner@nanosonic.com	Metal Rubber ice sensor	www.nanosonic.com Ryerson (2009)
Ice Hawk Rosemount ice detector	United Technologies Corporation Aerospace Systems Sensors and Integrated Systems 14300 Judicial Rd. Burnsville, MN 55306 Telephone: 952-892-4300	Imaging ice detection system, Rosemount ice detector	www.utcaerospacesystems.com Ryerson (2009)
SMARTboot ice detector	United Technologies Corporation Aerospace Systems Sensors and Integrated Systems 1555 Corporate Woods Pkwy, Uniontown, OH 44685 Tel: 330 374 3295 Fax: 330 374 2290	Imaging ice detection system, Rosemount ice detector	www.utcaerospacesystems.com Ryerson (2009)
DRS511 DRS511B DSC111 DST111	Vaisala Inc. Boulder Operations, PO Box 3659 194 South Taylor Ave. Boulder, CO 80307-3659	RWIS road condition detectors	www.vaisala.com/en/roads Ryerson (2009)
Helicopter ice detector	Visidyne 111 South Bedford St. Suite #103 Burlington, MA 01803 Tel: 781-273-2820 Fax: 781-272-1068	Infrared latent heat helicopter ice detector	www.visidyne.com Ryerson (2009)

6 Coast Guard Cutter Ice Protection

A large number of technologies are available for protecting structures from icing. Many of the technologies available are presented in this report and in Ryerson (2009). Though the technologies presented were developed for a wide range of applications, many are usable in the marine environment, and those that may apply to Coast Guard Cutters are highlighted here.

The US Coast Guard has considerable superstructure icing experience. In most years the *Polar*-Class heavy ice breakers, the *Hamilton*-Class High Endurance Cutters, the *Bay*-Class icebreaking tugs, the *Juniper*-Class seagoing buoy tenders, and numerous cutters and boats assigned to cold deployment areas experience some amount of superstructure icing. Though difficult, and a risk to mission accomplishment, Coast Guard personnel have learned to cope with superstructure icing through use of appropriate Tactics, Techniques and Procedures (TTP). Cutters and boats have stayed safe despite mission impacts by icing in the Great Lakes, on the East Coast, and in the Gulf of Alaska and the Bering Sea. However, safety may be improved, mission success more assured, and the less known icing hazards of the Beaufort and Chukchi seas dealt with if technologies beyond avoidance and manual methods were applied to Coast Guard assets.

Below, each technology area is briefly summarized with regard to their positive and negative characteristics as applied to Coast Guard Cutters. Also provided is the how and where they may be applied to Coast Guard assets. This is followed with technology matrices for each of four cutter classes addressing applications that will provide the most benefit for least cost, and technologies that can be retrofit to existing cutters, versus designed into new cutters. Suggestions for incorporating ice protection into new designs are also made.

6.1 Ice protection technology synopses

6.1.1 Chemicals and chemical distribution

Chemicals are the most widely used ice and snow control technologies, and they are used by the US Navy, the US Coast Guard, and Canadian Forces to control ice on vessel decks. Most ship-board use of chemicals is for de-icing after a superstructure icing event has occurred, and not before or during icing events. Chemicals melt through the ice, reduce adhesion to decks, and break the ice into pieces. Most chemicals are difficult to apply to vertical surfaces and to open grid decks and ladders. A problem that is always present with chemicals is that it is difficult to prevent some of the material for escaping overboard as either runoff, or with the pieces of ice that are removed after loosening with chemicals and shoveled overboard.

Currently, solid chemicals are hand broadcast onto ship decks. However, there are at least three other methods of spreading chemicals on ships. Fixed or portable spray systems can distribute chemicals over ship surfaces prior to or during icing, or for cutting through ice after it accumulates. For anti-icing or de-icing it may be possible to adapt the Countermeasure Washdown System for spraying de-icing or anti-icing fluids. High relative winds over the bow, however, could hinder proper chemical distribution and cause considerable loss overboard because the Countermeasure Washdown System spray is so fine. Alternatively, a Fixed Anti-Icing Spray Technology (FAST), such as used on some highway bridges, could be plumbed into the ship for spraying anti-icing chemicals onto decks and bulkheads. However, anti-icing fluids may make decks slippery, and it would likely be washed off of the ship during heavy spray events, or be sufficiently diluted as to fail. Pressure washing wands can also be used to de-ice, with freezing point depressant chemicals, which are safe for spillage into water bodies, used to hasten ice cutting and prevent refreeze.

Weeping wing technologies could be easily adapted to bulkheads and bridge windows. They are currently being considered to protect cable stay bridges from icing. Dripping fluid lowers the freezing point temperature of spray after it mixes with the fluids, preventing icing and reducing adhesion when ice does form, as successfully demonstrated in a Canadian test (Stallabrass 1970). However, fluid could flow onto decks and may make them slippery, but may also reduce deck icing. Special mats are also available for placement on decks that are filled with de-icing fluid and used to keep decks clear of ice and snow without using heat or other power.

Though the chlorides are the most commonly used chemicals, they are also highly corrosive and environmentally damaging. Of the chlorides, the most rapid are calcium chloride and magnesium chloride because they are exothermic. However, none of the chlorides should be used near the flight deck because of corrosivity. To prevent errors, it is best to stock one de-icing chemical that can be used anywhere safely.

The acetates have relatively low corrosivity, but they are expensive and generally have high BODs. Any of the three acetates, calcium magnesium acetate (CMA), potassium acetate, and sodium acetate, can be used on flight decks. However, they damage cadmium plating and aircraft carbon-carbon brakes, so aircraft should be washed after exposure.

Ethylene and propylene glycol have been used to de-ice and anti-ice aircraft for decades. They are available only as liquids, are slippery, and have high BODs. It is not clear how well they cut into ice unless heated; de-icing fluids are heated to 80°C when applied. If used when a ship was in port, they could be a significant pollutant of harbor waters.

Sodium formate, available as a liquid or a solid, melts ice rapidly and has low corrosivity. It can be used on FAA and Air Force runways, so also on ship flight decks, and has a low BOD. Though expensive, it may be an effective ship de-icing chemical.

Urea was once a commonly-used de-icing chemical on highways and airport runways. However, it has too many disadvantages for ship use. It is corrosive, is a slow melter, has a high BOD, and decomposes into toxic ammonia gas, which could be a hazard if it leaked into a ship interior.

The bio-based chemicals, using corn, sugar beet, alcohol, and glycerin base stocks, are very popular for high de-icing and anti-icing because of their low corrosivity, fast de-icing rates, and longevity. Most mix traditional chemicals, such as acetates and chlorides with the bio-material, but the mixture has lower corrosion rates than the raw chemicals. At least one bio-based product is an effective de-icer with no added traditional de-icing chemicals.

6.1.2 Chemical applications to cutters

Chemical application methods most suited to ships are manual broadcasting of solid chemicals, and weeping of liquid chemicals down antennas, bulkheads, and bridge windows to prevent icing and reduce ice adhesion. The most practical and least damaging chemical is sodium formate, available as a solid or liquid. The bio-based chemicals should be tested as alternates. Heavy de-icing should be considered with a heated pressure washer and a de-icing fluid suited for that application that can be released into water bodies without harm.

6.1.3 Coatings and surface treatments

Ice-phobic coatings promise to prevent icing by lowering adhesion strength sufficiently that the ice falls from surfaces from its own weight, and perhaps with the aid of air flow and vibration. Coatings have been tested for aircraft engine inlets that promise to release ice in small enough pieces that no engine damage is done. Several coatings have reached adhesion strengths of less than 10 kPa, potentially easing manual de-icing, and assisting automated kinetic methods such as electro-expulsive, piezoelectric, pneumatic, and perhaps covers such as tarps.

Though coatings often perform well in tests, such as CRREL's Zero Degree Cone Test, ship board long term testing, such as for an entire winter, is strongly recommended to determine how the coating performs through multiple icing events and after being abraded and soiled by ship operations. Also, ease of application, repair, recoating, and removal require investigation. On the National Security Cutter, the signature of the coating may also be a factor with the threat of anti-ship weapons. Ice-phobic coatings may not be sufficiently durable for decks, and some have the potential of making decks slippery. Materials can be added to some coatings to aid traction—and it is not clear whether the additives may increase mechanical adhesion of ice. Also, colors available, color durability, and transparency of coatings should be considered as ship color is important.

A new class of coatings, or surface treatments, is anti-icing coatings—most based on biomimetric nano-technologies using the Lotus leaf, or Cassie-Baxter effect. True anti-icing surfaces are a developing technology that holds considerable promise. Though many materials are still "laboratory phenomena," others are available, or nearly available for purchase. Theory is still being actively developed regarding how these surfaces actually prevent icing, but most are super-hydrophobic and some are also ice-phobic. The Cassie-induced super-hydrophobicity reduces contact of the drop with the substrate, reducing heat loss to the substrate, therefore delaying freezing. It also allows drops to readily slide off of surfaces, some at tilt angles of only a few degrees. Several super-hydrophobic coatings are also transparent and promise to keep surfaces clean, water-free, and ice-free. Durability is a serious question and the nano-materials used, the chemical matrix bonding the nano-materials to the substrate, and hydrophobic coatings often applied over the nano-material, are all factors. Contamination and abrasion are also issues with these surface treatments because damage to the nano-topography, even through multiple icing events, may reduce anti-icing capability. Some researchers have hypothesized that droplets striking nano-surfaces at high velocity could defeat the Cassie effect, as could contamination by oils or wetting agents. However, some coatings are super-hydrophobic and super-oleophobic (oil resistant), which may allow resistance to contamination.

6.1.4 Application of ice-phobic coatings to cutters

Ice-phobic coatings are a mature technology, even though materials with lower ice adhesion strengths are continually being developed. Therefore, though laboratory testing is useful, testing can typically begin with shipboard coupons. Ice-phobic coatings are best applied to bulkheads, masts, antennas, cables, deck machinery, boats, and hulls. However, if applied to antennas, the dielectric properties of the coating should be investigated. In addition, several coatings are transparent, but their effects on optical clarity, and compatibility with windshield wipers, washer fluid, and heated windows should be investigated before application.

Anti-icing surface treatments should be thoroughly laboratory tested before being tested aboard ships. Multiple down-select criteria and stages of testing should be done before commitment to large areas of ships. Anti-icing coatings may not be successful on decks, where there is opportunity for heavy abrasion and contamination. However, they may be very successful on bulkheads, lifelines, windows, antennas, masts, davits, tarps, and other surfaces that must be kept ice-free. Though deck testing would be useful, the technology does not appear sufficiently durable for that application and could be slippery.

6.1.5 Covers

Covers, or tarps, provide a degree of protection from icing. Though relatively inexpensive, they are labor intensive, they do not protect unless emplaced before icing begins, and they prevent use of the covered object when the tarp is in place. However, when the cover is removed, the protected surface should be immediately available for use. The Coast Guard often covers deck machinery and sensors, and the US Navy recommends the use of tarps to cover boats, davits, capstans, and windlasses, and all outdoor command, control, and communication stations.

Fitted tarps are most effective because they are less likely to be carried away by wind or green water. And, they may be more quickly installed as the shape of the cover conforms to the object being protected, and fasteners are customized for the application. Placement should prevent spray and water from blowing under the tarp, or condensation from occurring under the tarp; either may cause the cover to freeze to the protected object. Freezing has proven to be a problem for helicopter blade covers; if installed when the blades are wet, they freeze in place and are not removable.

Low ice adhesion materials, and anti-icing materials, are becoming available for manufacturing into tarps, or sprayed onto the surface of existing tarps. Japanese studies have showed that nylon and polyester tarp materials have the lowest ice adhesion strengths. And, for saline ice, when fluroethylene and super-hydrophyllic materials were applied to tarps, saline ice simply fell off.

6.1.6 Applications of covers to cutters

Despite low cost, covers require crew time to install, remove, and repair, and they require storage space. They must be dried before storage or they can mold or rot. Time for tarp placement and removal can be wasted if anticipated icing does not occur. Users should also develop tie-down procedures, design fitted covers, and purchase covers with a material that prevents icing or dramatically reduces ice adhesion.

6.1.7 Design

Design can be a practical method of reducing icing problems. However, it is only practical, and perhaps only cost-effective, when new ships are being designed, or when existing ships are being upgrade or refitted. Ships can be designed to function more effectively in cold, and operate with reduced superstructure icing. However, the US Coast Guard conducts missions in environments ranging from polar to tropical. In addition, Coast Guard Cutters may be assigned to a cold weather mission immediately followed by a tropical mission. Therefore, Coast Guard Cutter design must not be focused on solving only problems for one environment; they must be multi-environment ships. Exceptions may be cutters designed specifically for cold weather duties. The *Polar*-Class icebreakers, the *Bay*-Class icebreaking tugs, and the *Juniper*-Class seagoing buoy tenders are often, but not always, assigned to cold locations.

Cutters can be designed to minimize icing by designing bows with more rake and higher bulwarks to deflect spray away from the ship before being caught in the relative wind and carried over the ship. Soviet ships were noted by US Navy personnel, for example, to be more seaworthy than US ships when sailing together in the 1980s; the Soviet ships plunged into seas less often and created less spray. The Navy's new littoral combat ship, the USS *Independence*, has some hull features, though radical, that may be worthy of consideration.

A bow–forecastle cover that extends to the bridge, such as the Ulstein X-bow or the covered forecastle deck of the Danish HMDS *Vædderen*, would prevent icing of the forecastle deck. A covered forecastle deck would also provide more covered work area, may reduce hull stresses when the ship plunges into seas by lifting less water, and could deflect air flow and spray around the ship. However, it may make use of deck machinery more difficult, would not allow use of cranes or UNREP and VERTREP on the forecastle deck, and would complicate placement of a gun on the forecastle deck. Also, a bulbous covered forecastle deck, such as the X-bow, does not allow access to the exterior for de-icing should it be necessary, requiring the use of passive anti-icing coatings or automated systems such as electro-expulsive, piezo-electric, or thermal systems. New Danish patrol boats also include covered bays for boats along the ship sides, and within the stern.

Other design changes to minimize icing and de-icing difficulties are to reduce exterior piping, wiring, and associated clutter. In general, many of the design changes that reduce a ship's radar signature are also changes that should minimize areas where ice can accumulate and lock to surfaces.

The most frequently mentioned design change by Coast Guard personnel to minimize icing is to provide heated decks similar to those on the CGC MACKINAW. Decks would need to be heated only sufficiently to prevent icing to minimize energy consumption. Heated decks would reduce the mass of ice accumulated on the ship, provide a safe deck for crews to use for de-icing other portions of the cutter, and would assure timely mission accomplishment by reducing time necessary to de-ice—time when the cutter is often not underway. An electrically heated system as used on the CGC MACKINAW would be designed into a new cutter; it would be impractical to retrofit such a system into existing ships because of cost and maintenance issues caused by poor access. However, as a retrofit, decks could be heated electrically with commercial pads that are designed for ship and offshore platform use, and are fastened to the weather decks. Decks could also be covered with pads available commercially that are filled with a freezing point depressant that is then wicked to the pad surface to melt ice and snow.

6.1.8 Applications of new designs to cutters

Design changes are necessary for any new cutters developed for Arctic use. Minimizing spray, covering the forecastle deck and boats, minimizing design clutter, and heating decks are changes to consider for minimizing superstructure icing.

6.1.9 Expulsive systems

Expulsive systems are electro-kinetic de-icing systems. They rapidly accelerate the surface on which the ice has accumulated, and the ice, and then suddenly stop the substrate motion. The moving ice has inertia, and when the substrate stops moving the ice's inertia overcomes the ice-substrate adhesion strength and the ice is released. Electro-expulsive systems are actuated by electromagnetic coils or flat, repulsing magnetic plates. Capacitors are discharged into the coils or plates to "fire" the system. Power consumption is very low, and there is no electromagnetic interference created—the systems have been successfully tested on manned and unmanned aircraft. On an aircraft ejected ice is carried away in the wind; on a cutter it would fall to the deck from bulkheads, but may be carried away by spray and deck wash.

Traditional electro-expulsive systems must be built into the vessel—necessitating that they be installed in new ship designs. However, they could be retrofitted by installing false bulkheads outboard of existing bulkheads. One system is supplied as a thin laminate that is glued to surfaces such as bulkheads and masts. It has been applied to the leading edge of unmanned aircraft and is thin enough not to require fairing. It can also be covered with thin metal to minimize impact damage, though that could make it less effective.

6.1.10 Expulsive system applications to cutters

Electro-expulsive could be an effective de-icing technology on X-bows, but it is insufficiently durable for use on decks. Suggested uses on ships have been bulkheads, hatches, doors, masts, gas turbine intakes, and safety equipment such as life rafts. However, the technology should be tested for effectiveness on fresh, soft saline ice.

6.1.11 Heat

Heat can be supplied to anti-ice and to de-ice by electro-thermal systems, infrared energy, hot air, and hot water. Electro-thermal systems are most common on ships—being used to heat hydraulics and to anti-ice around door and hatch seals. Localized protection of door and hatch seals can continue to be heated by electro-thermal systems, such as with heat tape. However, Department of Defense designers have been seeking solutions to keeping surfaces ice-free that do not use heat because of the signature provided for heat-seeking targeting systems.

Several new electro-thermal technologies are commercially available, or in development but near commercial availability, that use the PED concept developed by Petrenko et al. (2003). The PED concept nearly eliminates the high energy consumption of traditional electro-thermal systems by deicing instead of anti-icing. It also eliminates most of the thermal signature problem by rapidly heating, for several seconds, the ice–substrate interface to melt a thin layer of ice and reduce ice adhesion strength sufficiently that the ice falls or is carried away from the surface by wind. The ice-free substrate then rapidly cools to ambient temperature. This is accomplished by placing the heating elements nearly on the surface to be protected, with a thin electrical and mechanical protective layer, such as paint or a polymer, separating the electrical elements from the ice. Therefore, the ice is rapidly heated rather than the material in which heaters are traditionally embedded.

There are three products commercially available, and a fourth in late development, that use the PED concept. In several designs the heating materials are supplied as either a thin, rolled carbon film with an adhesive for attachment to surfaces, or as a material that can be sprayed onto surfaces in layers. Any of the technologies could be used for protecting large areas such as bulkheads, masts, doors, and ventilation louvers. Though the materials could be damaged if impacted, performance is not affected, and surface repair is relatively easily accomplished. They also are designed to operate on 28 VDC, though at high amperage, for periods of only several seconds, making them relatively safe in the ship environment.

Hot bleed air is used to anti-ice aircraft leading edges, engine inlets, and windscreens, and engine coolant heat is used to de-ice automobile windshields. A commercially available nozzle is available to attach to turbine engine bleed air systems for de-icing Army helicopters. Though requiring a duct system, hot air may be obtained from ship gas turbine engines and ducted to the base of bridge windows or to deck areas for attaching hoses and nozzles for spot de-icing of sensors, lights, and other equipment where manual, kinetic de-icing may not be practical. However, bleed air is available from gas turbines only when they are running, and if the cutter is diesel-powered and supplemented with gas turbines, such as is the National Security Cutter, the turbines may not be used when icing is occurring, and especially if crew are on-deck de-icing.

Therefore, hot air supplied by bleed air may not be practical on cutters. However, the Navy's proposed Arctic Patrol Vessel design does use small liquid-to-air heat exchangers to capture heat from diesel engine exhaust for heating the main deck, equipment enclosures, railings, and the Advanced Enclosed Mast System (AEMS). Such technology could be used on a Coast Guard Cutter, but would be difficult to retrofit; it would need to be part of a new design.

A hot air concept has been proposed, however, for retrofit heating of Coast Guard Cutter decks. A space between the deck and the interior insulation could be constructed, especially forecastle and buoy decks. Warm air could be circulated through the space, perhaps from engine waste heat, during cold weather providing heated decks and anti-icing (S. Tripp, personal communication, January 2013). In warm weather the spaces could be opened to allow for air circulation and deck cooling.

The FAA has proposed de-icing aircraft with hot water without using a freezing point depressant. Though that approach has mixed success on aircraft, warm water can be used to prevent or reduce icing on ships. If air temperatures are not too low, if sea water temperatures are not too low, and if deck drainage is good, sea water can be pumped over the decks to prevent or reduce icing. Large volumes of sea water flowing over the decks adds sufficient heat that freezing cannot occur. However, water must be allowed to drain overboard before it freezes. Deck flooding from green water over the bow, and heat leaking through the decks from below, may be sufficient to keep decks clear of ice even though deck machinery ices (see Fig. 5-33). Occasionally, cutter operators have deliberately allowed green water over the bow to reduce icing. Fire mains have been used to successfully flood the decks of fishing trawlers and keep them ice-free, and experiments have been proposed to do this experimentally on ships, but very low temperatures froze the fire mains. There is also a heat exchanger manufactured in the UK that is designed to use waste engine heat to further warm sea water before pumping it over decks.

Heat pipes have been proposed for use in de-icing portions of ships because heat can be readily transported from heat sources to icing areas. However, the technology, though mature for civil engineering work in permafrost, would require engineering into a new ship design. It doesn't appear to offer advantages sufficient for consideration over alternative technologies.

6.1.12 Heat applications to cutters

Electro-thermal systems that use the PED concept, thin conductors that can be cemented to bulkheads or spray-on conductors, can be used on bulkheads, doors, masts, gas turbine intakes, and safety equipment such as lifeboats. The technology is not sufficiently robust for use on decks. However, heated pressure washers, especially using a freezing point depressant that is safe for drainage overboard, would be useful for de-icing decks and deck machinery, and possibly bulkheads.

6.1.13 High velocity fluids

High velocity fluids have aided ship de-icing for many years, and have a role in the future. In the past, steam lances have been a favored de-icing tool, and were readily available because most ships were steam powered. CRREL and others have conducted extensive experiments using steam jets to remove ice from lock walls. However, steam is no longer available on ships, except from small steam jennys. The advantage of steam is that ice can be easily cut away in large pieces and there is no residual fluid, such as freezing point depressants, to flow overboard as a pollutant.

Today, combinations of high pressure air, water, or heated freezing point depressants are favored for de-icing. The Air Force, and many commercial airfields, uses trucks that provide a combination of high velocity air, air and de-icing fluid, or de-icing fluid alone on aircraft. If the aircraft is covered with dry snow, then air may be sufficient to remove the snow, with a light de-icing fluid to melt any residual. If the snow is wet, or there is ice, then de-icing fluid injected into the air often provides sufficient force to melt and remove ice. If that fails, they use only de-icing fluid.

As Coast Guard Cutters are often in port, or are at sea but relatively near-shore, snow can accumulate. However, it is generally not considered a serious problem because it can be readily cleared or shoveled. Therefore, high pressure air may not be often used for de-icing onboard cutters.

6.1.14 Applications of high velocity fluids to cutters

High velocity liquids could be useful if heated, especially for cutting through thick ice so that it can be removed quickly in large pieces. Pressure washers are used on offshore platforms, and on *Juniper*-Class seagoing buoy tenders for ATON work. In cold weather pressure washing water may refreeze, even if heated. Therefore, new fluids that are internationally certified for disposal into sea water without harm are available for use in heated pressure washers. Heated pressure washers are a viable technology for de-icing cutters if the washer is installed on the ship and hoses of sufficient length are available to reach all iced areas. However, pressure washers should be used with caution around personnel, windows, vents, fire and rescue apparatus, lights, sensors and antennas.

6.1.15 Infrared and lasers

Infrared energy is used for de-icing of walkways and aircraft, and has been recommended for use on ships by the US Navy. In involves heating an emitter to radiate at wavelengths absorbed by ice with sufficient energy to melt ice. This requires an emitter operating at about 400 to 1000°C.

Infrared emitters can be either gas-fired or electrically powered. Open flames are dangerous on a ship, as are exposed electrical elements. Shipboard infrared heaters should be electric elements enclosed inside a metal housing with a glass cover that will not shatter from thermal shock if struck by spray. Infrared heaters should also not be located where they could be struck by green water, or where the location to be de-iced or anti-iced is a great distance from the heater. Infrared radiation follows the inverse square law, where the resulting radiation intensity is inversely proportional to the square of the distance from the emitter. Therefore, doubling the distance between the emitter and the item being heated means that the radiation intensity becomes only 25% as strong. Objects at great distance cannot be practically heated with infrared energy. However, at least one available infrared heater is focused with an aluminum, egg-crate shaped “lobster eye” that dramatically decreases loss of radiation intensity with distance. These focusing heaters could be used to keep specific limited areas of ships de-iced, such as bridge wings, locations in front of bulkhead doors, such on the forecastle forward bulkhead, stairs, the flying bridge and its electronics, horns and antennas, and air vents and intakes. Also, the UNREP deck, and boat launch and recovery areas, could be anti-iced with infrared heaters.

Infrared heaters could be readily retrofitted to existing ships, and they can double as heaters to keep crew warm at lookouts and other stations, and where repairs are necessary. Infrared is effective because it directly heats objects that absorb the radiation, rather than heating the air. However, infrared emitters create a strong signature for anti-ship weapons. In addition, though wind does not affect the intensity of infrared radiation, it does cause convective cooling of the surface being heated, and therefore will be less effective in areas where relative winds are strongest.

The US Navy has considered the use of lasers for de-icing ships, and CRREL has experimented with laser de-icing. Though there are many patents for de-icing aircraft with lasers, there is no laser de-icing system available commercially, and they have not been demonstrated as a practical de-icing device.

6.1.16 Applications of infrared and lasers to cutters

Infrared heaters have localized spot applications to cutters. This includes boat decks, UNREP decks, stairs, sensors, and perhaps bridge window wipers.

6.1.17 Manual

Manual, usually kinetic, methods are the traditional way of de-icing ships. It involves the use of ax handles, ice mallets, hammers, baseball bats, and shovels to break ice from surfaces and move it overboard. Solid chemicals, such as sodium chloride and calcium chloride, are often used to aid loosening ice from decks and ladders. Though effective, manual de-icing is slow, dangerous, mission-compromising work. Crews become fatigued, and the ship must slow or seek shelter to allow crew onto the slippery decks. Special tools were developed by CRREL and the Navy in the 1980s and tested on the CGC MIDGETT, including a five point chisel that was found useful by the crew, but does not appear to have been adopted by the Navy or the Coast Guard.

Though automated methods may make de-icing safer and more rapid, some manual de-icing will be needed for many years. Low ice adhesion and anti-icing coatings can possibly greatly speed and decrease the danger of manual de-icing. Heated decks would probably be the greatest benefit because they would significantly decrease ice mass on ships, decrease surface area requiring de-icing, and significantly increase the safety of working on the deck.

6.1.18 Applications of manual de-icing to cutters

Overall, some manual de-icing will be needed on most ships even if automation is used. No single automated method will be able to remove all ice; manual methods will likely be needed to supplement where automated methods are not effective.

6.1.19 Piezoelectric

Piezoelectric de-icing technology has been attempted experimentally by several organizations, and it may be successfully applied to aircraft. Actuators vibrate surfaces at 20–30 kHz to de-ice by using the inertia of ice to overcome adhesion strength. Ice has been debonded from steel up to 9 mm thick. In addition, there is evidence that the technology can reduce icing severity if operated as icing occurs. Still at a relatively early stage of development, the technology will be developing and could be used on antennas, radomes, and other easily vibrated surfaces. The technology could be greatly assisted if surfaces were coated with low ice adhesion coatings. It is a technology that should be monitored.

6.1.20 Application of piezoelectric de-icing to cutters

The technology should be watched as it develops. Applications include radomes and other thin materials.

6.1.21 Pneumatic

Pneumatic de-icing has been used on aircraft since the 1930s, and is still a common technology. Pneumatic boot panels for de-icing ship bulkheads and masts have been evaluated in fresh and saline ice with considerable success. The technology involves placing inflatable boot panels on a bulkhead, either permanently or seasonally, and inflating them when ice accumulates. On aircraft, inflation normally occurs when 1.5 cm of ice thickness or less accumulates. On ships more ice could be allowed to accumulate; up to 7.5 cm of fresh water ice was successfully shed from flat panels in Canadian tests, and up to 12 cm was shed from a round mast.

Pneumatic boots are a simple technology consisting of a source of compressed air, and a controller for adding or evacuating air. On aircraft a vacuum pump is often used to fully deflate boots so they conform more closely to wing surfaces for better aerodynamics. A vacuum pump may be helpful on ship systems also, as an incompletely deflated boot will not inflate as far when ice shedding is needed, and therefore may not be as effective. Ice falling from the boots would accumulate at the base of the bulkheads they are protecting. Fallen ice could be shoveled away, or it could melt if the decks are heated. Pneumatic boots may also be difficult to place on bulkheads covered with exterior piping, wiring, and antennas such as the National Security Cutter's forward bulkhead.

Pneumatic systems are inexpensive, and they can be easily damaged; but they can also be easily repaired, much like tire inner tubes. Their performance can also be enhanced by coating their surfaces with a silicone or other material that reduces ice adhesion. It is unknown whether boots are available in colors. Black boots may not be acceptable on the bulkheads of white ships.

6.1.22 Application of pneumatic de-icing to cutters

Boots are a technology that should be considered for use on bulkheads, masts, and radomes. They are a well proven and inexpensive technology. Heated decks and pneumatic boots on bulkheads could solve part of the problem of large ice masses accumulating on Coast Guard Cutters.

6.1.23 Vibration

Low frequency, high amplitude vibration is not likely to be a useful de-icing technology for use on ships. Ship structures are relatively stiff and do not easily vibrate. Even the slamming of ship hulls into heavy seas is not an effective method of removing ice. The only application may be the de-icing of cables.

6.1.24 Applications of vibration to cutters

No applications to cutters, except perhaps for de-icing cables.

6.1.25 Optics and windows

Windows can be de-iced or anti-iced with electrical heating, hot air, fluids, or coatings. Electrical heating can be current resistance systems installed directly into windows and window frames, or retrofit systems that adhere to the window with adhesives, such as SeaClear window heaters now used by the Coast Guard. If these systems can be maintained so as not to overheat and damage glass causing discoloration and delamination, their use should be continued. Their advantage is that they keep windows clear of ice continuously except for occasions when ice builds from the window edges over the perimeter of the glass.

The pulse electro-thermal de-icing system, as designed for glass surfaces, is energy efficient, but it requires that ice accumulate on the glass because it is not continuously electrically energized. If continuously energized, it would become similar to traditional resistance window anti-icing systems. As it requires ice to accumulate, the windows would become obscured for a time between de-icing cycles. The technology could be used for less important windows, such as peripheral bridge windows and the windows of cranes and other areas where the need to use windows is occasional.

Hot air blowing over the inside of windows is effective in automobiles. However, it is unlikely that it would be as effective with the thicker, laminated, thermopane glass used on ships. Hot air could be blown between window panes, but that has proven difficult on aircraft because of dirt accumulation and noise. Similar problems would occur on ships. Hot air blowing at high velocity on the outside of windows is used on aircraft, and could be effective on ships if a high volume source of hot air were available. Bleed air could be available when gas turbines are operating, but not when diesels are operating—the most probable source of power during icing conditions when ship speeds would likely be slower. Hot air blowing on the outside of windows could, however, solve a secondary problem—the icing of window wipers.

Windows could be de-iced using fluids that, like the weeping wing system, drip a freezing point depressant over the glass and prevent icing, or at least reduce the adhesion strength of ice to glass. Canadian tests showed that this technology reduced ice adhesion strength to bulkhead surfaces dramatically. However, fluids on windows, though they may be clear, may distort optics and reduce acuity (Fig. 6-1). If this approach were used, fluids would need to be tested on windows in a laboratory before use onboard cutters. However, hot fluids could be sprayed on windows, and wipers, and wiped off, and could perhaps be effective as on some automobiles.

Figure 6-1. De-icing fluid residue on the cockpit windows of an Air Force jet caused the fluid to be rejected for operational use (US Air Force).

Coatings that claim to be optically clear are available for reducing ice adhesion to glass or for preventing icing entirely by being super-hydrophobic, causing drops to roll off of the glass before freezing. Optically clear window coatings, if they are durable and do not degrade from weather or ultraviolet light, could be combined with the current heated windows. Coatings could also be placed on window wiping mechanisms to reduce icing of moving parts.

Bridge window wipers have proven troublesome on several Coast Guard Cutters, especially articulating wipers designed to keep blades parallel to the window edge. Wiping mechanisms corrode and accumulate ice and stop working. The rubber blades also freeze to the windows if they are not heated. Heaters should be placed inside the wiping mechanisms if the windows are not heated, and hot air, hot fluid, or infrared energy could be played onto the wipers to prevent icing. Ordinary window glass does not absorb infrared, so infrared energy should not overheat windows and cause damage, though this should be tested if coatings are placed on the windows.

6.1.26 Optics and windows de-icing applications to cutters

The most expedient window ice protection system would be to use, or improve maintenance on current heated windows, install more electrically-heated windows, and use anti-icing coatings to assist the heaters. Coatings, heat, or hot fluids should be considered for keeping wiping systems operating in icing conditions.

6.1.27 Cables

Cables are challenging to de-ice or anti-ice. They are generally located too high for manual de-icing, and they often run through sheaves and over a windlass. In addition, they often rotate because ice usually accumulates asymmetrically; therefore, ice wraps around the cable, mechanically locking it in place. Pneumatic boots, expulsive systems, heat, coatings, and kinetic methods have all been evaluated, or are in use, to protect cables from icing.

A pneumatic de-icing boot for cables was tested by CRREL on Mt. Washington, NH, that worked successfully. It was only tested for proof of concept, longevity was not evaluated. It could be a viable solution for antennas and guy wires that are not abraded or run through sheaves. It would, however, require some laboratory and development work. Maintenance, installation cost, and operation are all relatively low technology and low in cost.

An electro-expulsive system was developed in Canada for use on cables, and has been tested on a Danish suspension bridge. It operates similarly to panel type expulsive systems and removes ice when it receives a high voltage charge. However, it has not received a large amount of testing. It would require extensive testing with saline and fresh water ice before being used operationally.

Electric transmission cables are heated using a variety of methods, such as by overloading the lines and transmitting carrier currents. When the lines heat they can either anti-ice or de-ice. However, the lines lengthen as they heat, and if used as guy wires, could loosen. Cables heated electrically would require isolation from the ship, requiring non-conducting anchors.

Ice bridging the anchors would be conductive, especially as it melted, which could cause an electrical hazard. It may be possible to heat some cables, however, by wrapping them with heat tape or similar.

The PED technology has been used to successfully de-ice cables on a bridge in Denmark. It requires placing a conductive foil around the cable and electrically isolating it. Testing would be required to determine if this would be practical on a ship.

Several new nano-based anti-icing coatings in development may be viable for protecting cables. They have been placed on transmission line cables and tested in simulated freezing rain conditions. Ship superstructure icing from bow spray is very similar to freezing rain, so the anti-icing coating technologies may be very useful for cables that run through sheaves and wind around windlasses.

Manual technologies may also be used to de-ice cables. Systems that twist and shock cables, or use a permanently mounted vibrator, have proven effective. However, they could fatigue the cables if they are anchored guy wires or antennas, and could cause undesirable vibrations in structures that they are supporting. Most of these mechanical techniques require the cable to be accessible to personnel, and they also require them to be relatively taut. Some of these techniques may be useful and should be considered, but their use would likely be limited on ships.

6.1.28 Applications of cable de-icing to cutters

It is recommended that the anti-icing coating developments be monitored and tested for use on cables aboard ships. Though wear will be an issue for any coating, it could be readily renewed, and even an abraded coating may partially protect and perform better than no coating, and be more environmentally acceptable than slushed (greased) cables.

6.1.29 Ice detection

Ice detection is useful for alerting crews that icing is occurring in locations that cannot be easily observed. On ships, most superstructure icing occurs in the bow area forward of the bridge, so icing will likely be observed by watches. However, electronics sensitive to icing, and icing at night or in fog or heavy weather that obscures vision, may benefit from ice detectors.

Ice detectors are classified in this report as detecting the optical properties, the electrical properties, the mechanical properties, or the thermal properties of ice. Ice detectors on ships must be robust and able to withstand impacts of spray or green water, and possibly mechanical impacts from de-icing. For these reasons some detectors are not practical to use on ships.

There are a variety of optical ice detectors, and two are remote sensing imaging devices. Conceivably, if the range of the sensor is appropriate to the size of the cutter, an imaging system on the bridge or the mast could monitor the forward portion of the ship. Two systems use infrared and polarimetry to show where ice has formed. One of the technologies provides an indication of thickness up to 75 mm, a thickness that may begin creating concern for vessel safety.

Three other optical sensors are point sensors, though one is a stand-off instrument that typically detects icing on pavements from a location on the side of the highway. The other relates ice accumulation on the sensor that obscures a light beam to icing at other locations. Finally, an optical sensor is in late development for use on aircraft that does not directly detect ice, but detects the cloud properties that cause ice. Though appealing, it may have a greater research utility than an operational utility, except that it can provide a useful indication that spray is being carried over the ship. Sensors located at several locations from the bridge to the stern could indicate how far aft spray is reaching, and its severity. All optical sensors must be provided a method of keeping optics free of salt residue or they may not function properly.

One sensor detects the impedance of ice, but may require tuning for saline versus freshwater ice. It is made of rubber and flexible conducting materials and therefore should be robust, and relatively inexpensive. It also is small, and should be placed in several locations on a cutter to provide spot indications of the presence of ice.

The remaining practical sensors use the mechanical properties of ice to indicate its presence. One uses piezoelectric technology to measure the pressure or stiffness of forces on its surface. It is in development, and tests have indicated that it can provide measures of wind speed, temperature, and ice accumulation. The technology development should be monitored; it could be located unobtrusively at several locations on a cutter.

The most commonly used detector senses the mass of ice on a probe, and is used on most commercial transport aircraft. It relies, in part, on the ability of the ice to adhere to the probe so that its mass can decrease the frequency of the probe. If the ice does not adhere well to the probe, the ice will not be detected. For example, the probe does not detect water droplets, but it does detect ice. However, it is not known how well it will detect young salt water ice because there is much water and brine drainage, which may partially decouple the probe from the ice. Laboratory tests should be conducted to determine if this is a factor. The probe is also easily damaged if struck when manually de-icing the ship.

6.1.30 Applications of ice detectors to cutters

One problem is where to place an ice detector on a ship. Icing high on the superstructure is dangerous, but usually first occurs forward and on lower areas of the ship. And, icing tends to form most rapidly on objects most exposed to the air, such as deck machinery, and less on decks where flooding occurs and heat leaks through the deck from below. Point measurement devices must be carefully located to detect ice earliest, or at least before it threatens ship safety. For this reason, though most expensive, the wide area ice imaging systems may be most practical for ship-board use, if ice detectors are needed at all. The other most viable technologies are small, spot detectors that are made from metal or rubber.

6.2 Retrofit ice protection technology application

The 12 ice protection technologies were assigned to each cutter component in the cutter safety matrices. The technologies that were considered applicable to each cutter function or component were assigned arbitrary values from 1 to 5, with 1 being the best choice for solving the icing problem considering technology maturity, availability, and applicability. An empty cell indicates that a technology does not apply to a specific function or a component. The best technologies are those with the smallest non-zero values. The values suggest priority in which technologies should be selected for evaluation and sea trials.

Dollar costs are not available for many of the technologies; many are still in development, others must be custom produced for marine use, and many require laboratory and field testing before application. The technology priorities suggest the desirability of a technology for the specific application. The priorities are intended to provide the Coast Guard with the best protection for the investment, though true costs for many of the technologies are unknown.

The following discussion suggests retrofit technologies that could be applied to current cutters, and a separate discussion suggests technologies that should be applied to new cutter designs. Each technology and its priority are discussed with regard to components requiring ice protection identified by crews of each of the four cutter classes to provide an indication of why the selection and priority was made.

6.2.1 POLAR-Class icebreakers

The POLAR-Class icebreakers have 14 components that were judged by interviewed crews to hinder operations when iced. These components are listed in the safety matrix in Table 4-2 and in the technology matrix (Table 6-1). Descriptions of ice protection technologies that can be used to protect each component in the POLAR-Class technology matrix are found in Section 6.3.

Table 6-1. Technology matrix for POLAR-Class icebreakers.

Cutter function/component	Importance to Safety	A	B	C	D	E	F	G	H	I	J	K	L
Deck machinery	9	3	1	2			2		5				
Cranes	9		1		2	2	4		5				
Boats	9	2	1	2		2	3	2	4				
Antennas and electronics	8		1	2		2		4	5	4	3		2
Tank valves/vents	8		1			2	3		4				
Bridge windows	8	3	1			1		4	5				
Bulkheads	8		1		2	2	3		4		2		
Deck drains	8	2	2			1							
Flight deck	7	3	4			1	2		5				
Rafts	5		1		2	3		3	4				
Deck surfaces/ladders	5	1	4			1	3	4	5				
Lifelines/railings	5		1				2		4		4		
Fire stations	4	2	1	1		2	3	4	5				
Ventilation	2		1		2	2	5	4	5	3			

A—chemicals; B—coatings; C—covers; D—expulsive; E—heat; F—high velocity fluid; G—infrared; H—manual; I—piezoelectric; J—pneumatic; K—vibration; L—detectors.

6.2.2 LEGEND-Class National Security Cutters

The National Security cutters have nine components that were judged by interviewed crews to be important for protection from icing. These components are listed in the safety matrix in Table 4-3 and in the technology matrix (Table 6-2). Descriptions of ice protection technologies that can be used to protect each component in the POLAR-Class technology matrix are found in Section 6.3.

Table 6-2. Technology matrix for LEGEND-Class National Security Cutters.

Cutter function/component	Importance to Safety	A	B	C	D	E	F	G	H	I	J	K	L
Deck surfaces/ladders	9	1	4			1	3		5				
Bulkheads	8		1		2	2	4		5		2		
Antennas and electronics	8		1	2		2		4	5	4	3		2
Boats	8	2	1	2		1	3	2	4				
Bridge windows	7	3	1			1		4	5				
Fueling-at-Sea deck	7	2	1	2		1	3	3	4				
Boat launch and Recovery System (BLRS)	7	1	2	1	2	1	3	2	4				
Ventilation	6		1				3	1	4	3			
Flight deck	5	3	4			1	2		5				

A—chemicals; B—coatings; C—covers; D—expulsive; E—heat; F—high velocity fluid; G—infrared; H—manual; I—piezoelectric; J—pneumatic; K—vibration; L—detectors.

6.2.3 *Bay*-Class icebreaking tug

The BAY-Class icebreaking tug crews identified five functions, in blue font in Table 6-3, and 14 components, in black font, that were judged to be important to protect from icing. These are also listed in the safety matrix in Table 4-4. Descriptions of ice protection technologies that can be used to protect each component in the BAY-Class technology matrix are found in Section 6.3.

Functions are essential to cutter survivability and mission effectiveness. However, functions are not physical entities that can be protected from icing. Each function requires components to operate successfully for the function to be executed. Below, the ship components that are necessary for each function are identified. This will enable ice protection technologies to be selected to ensure the execution of each function.

Table 6-3. Technology matrix for BAY-Class icebreaking tug.

Cutter function/component	Importance to Safety	A	B	C	D	E	F	G	H	I	J	K	L
Stability	10	2	1		2	1	2		3	2	1		2
Damage Control	10	2	1	2	2	1	2	4	4	2	2		
Domestic Icebreaking	10	2	1	2	2	1	2		3		2		
SAR	10	2	1	2	2	1	2	2	3		2		2
Mooring/navigation/piloting	10	1	1	1	3	1	3	2	4		2		3
Rafts	10		1		2	3		3	4				
Deck Surfaces/ladders	9	1	4			1	3	5	5				
Bridge windows	9	3	1			1		4	5				
Hatches	9		1		2	2	3		4		3		
Bulkheads	9		1		2	2	3		4		3		
Fire stations	9	2	1	1		2	3	4	5				
Boats	7	2	1	2		1	3	2	4				
Deck machinery	7	3	1	2			2		5				
Antennas and electronics	7		1	2		2		4	5	4	3		2
Lifelines/railings	5		1				2		4		4		
Deck Drains	5	2	2			1							
Tank valves/vents	4		1		2	2	3	4	4				

A—chemicals; B—coatings; C—covers; D—expulsive; E—heat; F—high velocity fluid; G—infrared; H—manual; I—piezoelectric; J—pneumatic; K—vibration; L—detectors.

6.2.3.1 Stability

Stability is a broad function that involves many ship components. Stability principally involves the mass of ice accumulation on the superstructure, and where it is located. Large ice mass lowers vessel freeboard and ice located higher on the superstructure raises center of gravity. The areas accumulating the greatest mass of ice are generally the forecastle deck, the side weather decks, and forward bulkheads. Therefore, to maintain stability those areas should be kept de-iced.

6.2.3.2 Damage control

Damage control is a relatively broad area, but includes fire protection and other emergencies. It requires rapid access to most areas of the cutter to alleviate the effects of damage. This requires that deck firefighting equipment, alarms, and communication equipment (1 MC) all be free of ice.

6.2.3.3 Domestic icebreaking

Domestic icebreaking requires that the cutter be fully operational, have correct freeboard and metacentric height, and have complete navigation and communication capability. Therefore, decks and bulkheads, antennas, navigation lights, and windows must all be kept ice free.

6.2.3.4 Search and rescue

SAR requires a ship that is capable of transiting quickly, often in challenging weather and seas, capable of maneuvering and navigating precisely in limited areas, and capable of operations on deck. And, the ship must be a stable platform without the additional weight and stability losses caused by ice. Therefore, decks, bulkheads, boat deck areas, and antennas, navigation, floodlights, windows, and deck machinery should be kept ice free. Ice detectors should also be used to alert the crew of icing, especially during night SAR missions.

6.2.3.5 Mooring/navigation/piloting

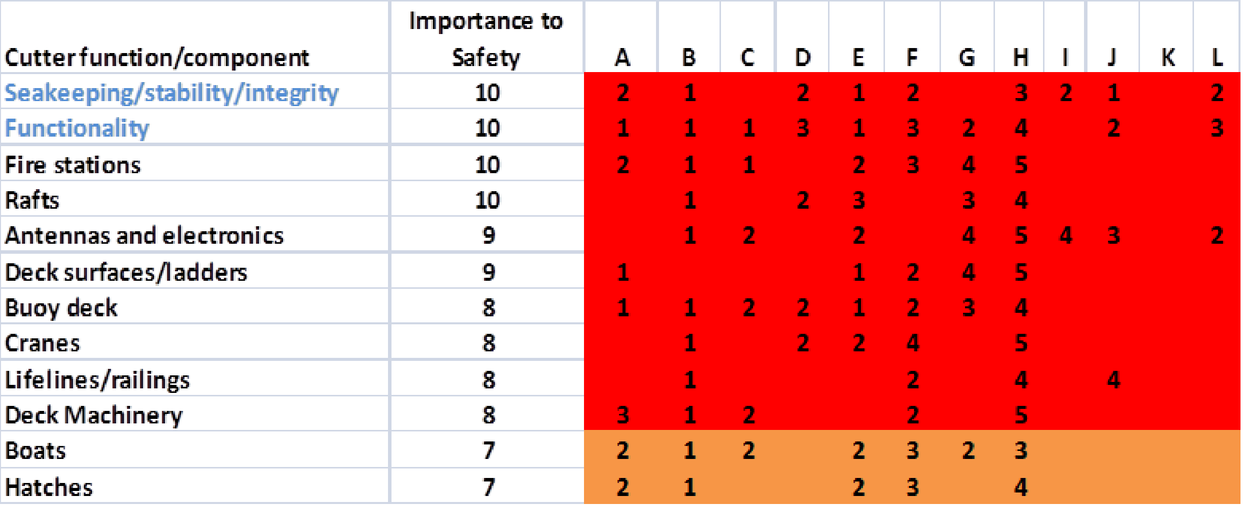
The requirements for mooring, navigation, and piloting suggest low-speed operations, perhaps after icing at sea. This requires maintaining visibility through windows, freeboard, and good stability, operating navigation and communication gear, floodlights, and access to decks for anchoring and mooring operations. Ice detectors would indicate whether ice has accumulated in critical areas, especially at night, before conducting mooring, navigation, and piloting operations.

6.2.4 JUNIPER-Class seagoing buoy tender

The JUNIPER-Class seagoing buoy tender has two functions, in blue font in Table 6.4, and 10 components that were judged by interviewed crews to be affected by icing. These functions or components are tied to the safety matrix in Table 4-5.

Functions are essential to cutter survivability and mission effectiveness. However, functions are not physical entities that can be protected from icing. Each function requires components to operate successfully for the function to be executed. Below, the ship components that are necessary for each function are identified. This will enable ice protection technologies to be selected to ensure the execution of each function.

Table 6-4. Technology matrix for JUNIPER-Class seagoing buoy tender.



Cutter function/component	Importance to Safety	A	B	C	D	E	F	G	H	I	J	K	L
Seakeeping/stability/integrity	10	2	1		2	1	2		3	2	1		2
Functionality	10	1	1	1	3	1	3	2	4		2		3
Fire stations	10	2	1	1		2	3	4	5				
Rafts	10		1		2	3		3	4				
Antennas and electronics	9		1	2		2		4	5	4	3		2
Deck surfaces/ladders	9	1				1	2	4	5				
Buoy deck	8	1	1	2	2	1	2	3	4				
Cranes	8		1		2	2	4		5				
Lifelines/railings	8		1				2		4		4		
Deck Machinery	8	3	1	2			2		5				
Boats	7	2	1	2		2	3	2	3				
Hatches	7	2	1			2	3		4				

A—chemicals; B—coatings; C—covers; D—expulsive; E—heat; F—high velocity fluid; G—infrared; H—manual; I—piezoelectric; J—pneumatic; K—vibration; L—detectors.

6.2.4.1 Sea keeping/stability/integrity

Sea keeping, stability, and integrity are a combination of broad ship survivability functions that involve many ship components. They principally involve the mass of ice accumulation on the superstructure, and how high it is located. Large ice masses lower vessel freeboard, and ice located higher on the superstructure raises center of gravity. The areas accumulating the greatest mass of ice are generally the decks and bulkheads as they occupy the largest areas on the superstructure. Therefore, to maintain stability those areas should be kept deiced.

6.2.4.2 Functionality

Functionality is interpreted here as the ability of the cutter to perform its assigned mission, ATON. For buoy tending that requires capable mooring, navigation, and piloting at relatively low-speeds, perhaps after icing at sea. This requires visibility through windows, freeboard and good stability, operating navigation and communication gear, floodlights, cranes, boats, and access to decks for anchoring and mooring. Ice detectors would indicate to crew whether ice had accumulated in critical areas, especially at night, before mooring, navigating, and piloting.

6.3 Component ice protection

Component ice protection is described below in order of decreasing importance for ice protection on the four cutter classes collectively. The 18 components, including the components necessary for functions, rank with 10 being most important, and 1 least important. Bulkheads, deck surfaces, cranes, and antennas and electronics ranked in the nines. Boats, rafts, fire stations, deck machinery, the buoy deck, hatches, and bridge windows ranked in the eights. The fueling-at-sea deck and the boat launch and recovery system on the National Security Cutter ranked in the sevens. Deck drains, flight decks, tank valves/vents, and lifelines/railings ranked in the sixes. Ventilation ranked last at four.

6.3.1 Bulkheads (rank 9.4)

Bulkheads, and bulkhead doors, can be protected with anti-icing and low adhesion ice-phobic coatings. However, the low adhesion coatings would still require an active or manual method for ice removal. Expulsive, adhesive PED heating, and pneumatic systems are all viable active devices that could be supplemented with low adhesion coatings. High velocity fluids may also de-ice bulkheads and doors, but it may be difficult to reach high bulkhead areas such as on the forward bulkhead of the POLAR-Class cutters and the NSC because of the high fluid pressures and length of wand necessary. Though manual de-icing is viable, it is only useful for bulkheads within reach of hand-held tools.

Heating strips or expulsive systems could be used to keep dogs and seals ice-free on bulkhead doors. Expulsive, adhesive PED heating, and pneumatic systems each could allow ice to accumulate in front of doors as the ice falls off, and possibly block the door. This could also happen with low ice adhesion coatings, and already happens when forecastle deck ice accumulates in front of bulkhead doors. If fired frequently enough, however, the expulsive technology could be most effective here because it can remove thin layers of ice and scatter the ice debris a considerable distance from doors—perhaps reducing the probability of blockage.

6.3.2 Decks (rank 9.3)

Decks are best anti-iced and de-iced with heat. Though heated decks could be a refit procedure, heated mats are available for ship decks, as are mats filled with de-icing chemicals. These mats are designed for the marine environment, and they do not require a ship redesign for application, but they must be fastened to the ship deck, and wired to the ship's electrical system. They can also be used on ladders. Another approach not requiring a major refit is to place air channels on the underside of the deck above the existing deck insulation, and blow hot air through the channels. This could be very effective at modest cost, but could cause condensation under the deck if the warm air were too humid.

Chemicals are now frequently used directly on deck surfaces; however, they can cause corrosion and they can be tracked into the ship, damaging interior floors. High velocity fluids can also effectively de-ice decks, though control of freezing point depressants may be necessary. Infrared heaters would be useful in limited areas such as boat decks and UNREP areas. However, they would not be effective on the forecastle deck in high relative winds and in heavy spray. Coatings can be tested on decks, but they may not wear well, and some may be slippery. Manual de-icing is also effective, but slow and difficult on non-skid.

6.3.3 Cranes (rank 9.3)

Cranes are complex structures that are difficult to reach. Anti-icing coatings are the first choice for cranes, as they can be used on all surfaces: booms, cables, and associated hardware. Use of ice-phobic coatings to reduce ice adhesion in high places may actually increase danger of ice falling unexpectedly unless the locations can be reached with long poles or other apparatus to knock the ice off. Expulsive and heat, and possibly pneumatic systems, are a second choice for cranes because the technologies can be placed on flat or round boom surfaces and can be momentarily powered to shed ice. They should be supplemented with low adhesion ice-phobic coatings on their surfaces. High velocity fluids can be effective on cranes, but many crane components are difficult to reach, and a long wand may be difficult to use with the high fluid velocities. Manual de-icing of cranes is dangerous and slow and not recommended except in easily reached locations.

6.3.4 Antennas and electronics (rank 9.1)

Anti-icing coatings, followed by low ice-adhesion coatings, are the best ice protection for communications and navigation systems electronics and antennas. Anti-icing coatings would prevent ice, remove dirt, and keep surfaces dry. Any use of coatings on antennas and radomes would require testing for appropriate dielectric properties so as not to degrade antenna performance more than necessary. Heat is also a useful and easily applied anti-icing capability. Anti-icing is preferred to de-icing for communications and navigation systems because it assures that they are always operating at peak capability. A permanent weather-proof cover with a heated interior could also be applied to protect the mast, electronics, and antennas if deigned similarly to the Navy's Arctic Patrol Vessel's Advanced Enclosed Mast System (Fig. 5-23). Ice detectors should be included with antenna and electronics anti-icing and de-icing technologies because the hardware is often located on masts and out of visual range—especially at night. Ice detectors are important, even if passive anti-icing coatings are used, so as to alert watches to check periodically for any possible accumulations. Pneumatic systems are also capable of de-icing antennas, depending upon the complexity of antenna shape. Piezoelectric systems can be used for de-icing, but it is not a near-term technology and has probable capability limited to lighter radomes and antennas. Manual de-icing is difficult in the remote places where antennas are located.

6.3.5 Boats (rank 8.7)

The boat deck and all associated hardware must be clear of ice for boat launch and recovery. Davits must be ice free, and the deck must be clear where the painters are handled. The variety of surfaces and hardware make de-icing and anti-icing more complicated. Anti-icing coatings are a first choice for ice protection, though the technology needs some additional time to mature. Coatings should be tested for slipperiness before applying to decks, but they can be used on other surfaces. If it snows, anti-icing coatings are potentially less effective because they generally excel at repelling water droplets rather than ice crystals. An ice-free weather deck, boat deck, and forecastle deck for using the painter would be a significant advantage, and could be provided by heated mats, chemical mats, or circulating warm air under the deck surface after moving insulation without significant ship refitting—though this could cause condensation under the deck. Icing of the weather deck below the boat deck is especially a problem on the BAY-Class icebreaking tug because there are no air castles, and water runs from the forecastle deck along the side weather decks and freezes. Chemicals, covers, heat, and infrared are secondary methods. Chemicals can be used for deck de-icing, and possibly de-icing of davits and other hardware. Covers can protect portions of single point davits, or other types of davits. Small electrical patch heaters can protect control stations for davit systems, such as on the National Security Cutter. Infrared heaters could also be used to keep the deck and all other hardware on the boat deck anti-iced. High velocity fluids are a useful aid to manual de-icing.

6.3.6 Rafts (rank 8.5)

Life rafts are stored in composite containers, and are designed to automatically release when submerged. For these reasons, coatings, especially anti-icing but also low ice adhesion, ice-phobic coatings, and expulsive systems, are the best ice protection solutions. Coatings will protect the rafts and release mechanisms. Expulsive systems can be used to protect raft containers by removing and distributing small ice pieces away from the rafts. However, expulsive may be only used on the larger surfaces of the raft containers. Heat may also be used to keep the release mechanisms anti-iced. Application of heat to these small, delicate materials may be difficult. Infrared may be a partial solution. Manual de-icing is the least effective viable ice protection technology for rafts because of the small, easily damaged parts.

6.3.7 Fire stations (rank 8.3)

Covers and anti-icing and ice-phobic coatings are most the effective ice protection measures for fire-fighting equipment. The best covers are metal or composite cabinets that are internally heated, or coated with an anti-icing or low ice adhesion material. Hoses and brass fittings are easily damaged and a cabinet would also provide mechanical protection. Heating only needs to keep hoses and equipment warmer than 0°C to prevent freezing, which reduces power requirements. Compatibility testing would be necessary before using chemicals or coatings on fire hoses. High velocity fluids could be used for de-icing, but with care because of the potential for damaging hardware. Infrared heat could prevent icing, but the temperature of some surfaces could become too high, causing damage; testing again would be necessary. Manual de-icing can easily cause damage to components, though ice-phobic coatings may lessen the chance for damage.

6.3.8 Deck machinery (rank 8.0)

Deck gear and ground tackle are critical to anchoring and maneuvering around buoys and other navigation aids for the ATON mission, when placing scientific gear, and in SAR. Anti-icing coatings, or low ice-adhesion coatings, can be placed on anchoring hardware, including the catspaw, the wildcat, the pelican hook, anchor chain, and the anchor and anchor pocket. Coatings will be damaged in the harsh, abrasive deck machinery environment, but enough surfaces may retain coatings even after equipment is used to provide value in preventing icing. Covers, especially if coated with anti-icing or ice-phobic materials, can prevent icing, and heated high velocity fluids can rapidly cut away large amounts of ice if machinery is not covered. Chemicals could also be useful here, but slower than high velocity fluids and possibly damaging to bearings, brakes, and other gear. Manual de-icing would be aided by ice-phobic coatings. Heated decks would greatly assist anchor detail by providing safe deck footing, and it would possibly heat some of the deck machinery.

6.3.9 Buoy deck (rank 8.0)

The buoy deck is preferably anti-iced or de-iced with heat, as requested by many Coast Guard crew during interviews. The model to follow in deck de-icing is the heated deck system on the CGC MACKINAW*;* its capability is widely respected among Coast Guard personnel. Though heated decks are a refit procedure, heated mats are available for ship decks, as are unheated mats filled with de-icing chemicals. Designed for ship and offshore platform use, these mats do not require ship redesign, but they must be fastened to the ship deck, and wired if necessary. They can also be used on ladders, and some models of heated mats, which can be used on the floors of drilling platforms, may be tough enough for use on the buoy deck. Vents may also be placed above existing deck insulation to allow passage of warm air for heating the underside of the deck. However, conditions would need to be monitored to avoid excessive condensation under the deck. Chemicals are frequently used on decks; however, they can cause corrosion and other damage to metals and deck machinery, and they can be tracked and damage interior floors. High velocity fluids can also effectively de-ice the buoy deck and assist manual de-icing.

6.3.10 Hatches (rank 8.0)

Anti-icing coatings, as for most surfaces, may be the best ice protection for hatches. However, active de-icing systems including PED or expulsive mats could be effective. These systems must allow ice to accumulate first, and hatches, being horizontal, will not allow ice to fall off if loosened. In this regard expulsive may be the most effective active system because it will break the ice into small pieces and scatter them. High velocity fluid would be effective for de-icing hatches, especially as they can accumulate considerable ice thicknesses. Heat tape and expulsive systems can also be used to keep latches and seals from becoming inoperable. Manual de-icing is effective, but slow. Tarps are not recommended because hatches are egress routes.

6.3.11 Bridge windows (rank 8.0)

All bridge windows should be heated. For example, on the National Security Cutter, only the center window is heated. Heat and coatings are the best methods of keeping windows ice-free. Heat and anti-icing coatings would be an excellent combination if wipers do not remove the coatings, though wiper use may not be necessary with super-hydrophobic anti-icing coatings because droplets immediately roll from the surface, and typically also provide a cleaning action. Fluid chemicals can also anti-ice or de-ice windows, but can obscure vision when applied, such as when using the weeping technique, and, unless removed with wipers, may reduce optical qualities. Infrared heat could be used for de-icing and for keeping wiper systems warm and working. Bare window glass reflects infrared energy; therefore, infrared may not be effective for anti-icing windows because the glass will not absorb the energy—unless the surface absorptivity is modified by a coating. Infrared could de-ice windows because the ice will absorb the energy until it has melted away. Manual de-icing is slowest and most dangerous of the window ice protection technologies, in part because forward bridge windows are often difficult to reach by personnel, except on the BAY-Class tugs.

6.3.12 Fueling-at-sea (FAS) deck (rank 7.0)

The FAS deck is a relatively small area that must be ice-free when in use. However, fuel vapors may concentrate in the area and consideration must be given to safety with high temperature technologies, such as infrared. Anti-icing and low adhesion coatings would either prevent icing, or aid mechanical de-icing methods. A heated deck surface would dramatically improve safety and could be provided by heated mats. Or, chemical anti-icing mats could be used to keep the deck ice-free. Chemicals spread on the deck surface could be an alternative to heated or chemical mats, and covers could protect piping and valves. Manual de-icing is a viable option, but possibly damaging to piping and valves.

6.3.13 Boat Launch and Recovery System (BLRS) (rank 7.0)

The BLRS is a complex system in the National Security Cutter stern that includes an over-head crane, a wet well, hydraulically operated clamshell doors that open to the sea, and a boat ramp. De-icing and anti-icing in the crowded, machinery filled area will be difficult. The best protection may be provided by anti-icing and ice-phobic coatings, heat, chemicals, and covers. Heated decks would cause a dramatic improvement where a fall could cause serious injury or death. Deck heating could most quickly be provided by electrically heated mats. Chemically anti-iced mats may also be viable. Heat could also be used for specific hardware, such as the outside of the transom where the clamshell doors ride and could freeze to the ship, on the boat ramp to prevent the boat from freezing to the ramp, and on the rails that draw the boat up onto the launch ramp. However, heat loss would be very high in any area where sea water can flow over heated surfaces and communicate with water outside of the ship, such as in the launch well. Infrared heaters could prevent icing on the overhead crane because of the many irregular surfaces. Coatings could also be used on nearly all hardware where personnel footing would not be compromised. Use of anti-icing and low ice adhesion coatings in the boat launch well could be helpful, but may also cause slippery surfaces. Covers for the boats, winches, and associated hardware forward of the boat ramp may be necessary. Heated high velocity fluids would be useful for de-icing the entire BLRS area, except that care would be needed when deicing the many electrical and hydraulic components of the system. Manual de-icing would be difficult in the cluttered area filled with easily damaged hardware.

6.3.14 Deck drains (rank 6.5)

Deck drain freezing is often the cause of forecastle and other weather deck icing, and flooding at the forward bulkhead of the POLAR-Class icebreakers. Though drain clogging from rust and debris must be dealt with separately, heat is the most effective method of preventing drain freezing. Chemicals and anti-icing coatings may be effective secondary methods. However, chemicals would be constantly washed out—and into sea, lake or river water—requiring renewal during icing events with automatic dispensers. Super-hydrophobic anti-icing coatings could be applied inside the drain and piping; demonstrations have shown that water flows more rapidly and freely through pipes with interiors coated with super-hydrophobic materials, and they often prevent corrosion.

6.3.15 Flight deck (rank 6.0)

The flight deck is a large surface that should not be slippery from coatings and should have no loose ice particles that can be ingested by helicopter engines or hit blades. Anti-icing is the best technology for flight decks because the deck is always ready when needed. Therefore, the most effective anti-icing technology for flight decks is heat. Heat will keep the surface ice-free and dry. Heating the flight deck may require a significant refit because heated mats may not be appropriate there, with the need to tie down aircraft and roll them over the surface. The capability of heated mats should be investigated carefully before operational testing. High velocity fluids are a secondary de-icing solution because few chemicals are left on the surface, though the large surface area may make de-icing slow. Freezing point depressant fluids used in high velocity systems should be approved for use around aircraft. Though effective, using chemicals for de-icing is slow, the chemicals leave the ship with the ice, and they must be aircraft-safe. Note that even aircraft-safe chemicals should be washed from aircraft as soon as possible. Chemicals can also make the flight deck slippery. Manual de-icing is an alternative that works, but is slow and labor intensive.

6.3.16 Tank valves/vents (rank 6.0)

Ventilation louvers and screens can be coated with anti-icing materials or low adhesion, ice-phobic materials. Anti-icing coatings are also useful for tank valves and vents because their complex shapes can lock ice to surfaces. Anti-icing coatings may prevent ice accumulation completely. Infrared heat can also be used to anti-ice vents and valves, though infrared emitters should not be located where combustible gasses could concentrate. High velocity fluids would readily remove ice from these complex surfaces, though care is necessary not to inject de-icing fluids into vents. Manual de icing is an effective although slow and potentially damaging alternative.

6.3.17 Lifelines/railings (rank 6.0)

Anti-icing and low ice adhesion coatings are the first priority for lifelines. Anti-icing coatings will prevent ice, and low adhesion, ice-phobic coatings will ease its removal, but may not help when ice wraps around cables. High velocity fluids can be used to cut large pieces of ice from lines more effectively than manually striking them with tools. Pneumatic systems designed for cables may be applied to some lifelines, but it may be difficult to plumb air lines, and the rubber boots may be easily damaged. Electro-expulsive systems also may be used if they are not damaged; railings are frequently handled and subject to abrasion when in port. Heat tape could be laid inside of rigid railings. Though effective, manual de-icing is the poorest approach because of the difficulty of de-icing thin, flexible materials.

6.3.18 Ventilation (rank 4.0)

Ventilation system openings can be coated with anti-icing coatings or low adhesion coatings, adhesive PED heaters, or expulsive mats. However, ice would fall to decks and require removal unless decks are heated. Piezoelectric actuators, when sufficiently developed, may also perform well for de-icing relatively lightly made louvers. Infrared heat could be used to anti-ice vents, perhaps even from inside the ship if aimed over the louver surfaces, and if the louvers were coated with a high absorption paint. Manual de-icing could damage relatively delicate vent louvers.

The National Security Cutter boat deck turbine intake is a large structure that is currently protected from icing by passing air through a heat exchanger. This has not been operationally tested, and a bird screen covers the unheated side (exterior) of the intake. It is anticipated that the bird screen will ice. The screen can be coated with anti-icing coatings or low adhesion coatings. Infrared heaters could also be played on the surface of the screen to prevent icing, but high air flows through the vent may diminish the effectiveness of infrared. When piezoelectric devices are perfected, they may be able to de-ice the screen with ultrasonic vibration—an excellent application of that technology given the light structure of the screen and the need to allow air to move freely through. High velocity fluid could be used to de-ice the screen periodically, but bypass air should be used when de-icing with fluids to prevent water and chemicals from entering the intake. Manual de-icing of the screen is also possible. However, it would be necessary to keep ice pieces small enough to not cause damage if carried in the in-take airstream.

6.4 Recommended retrofit technology investment strategy

Until existing Coast Guard Cutters are due for a major refit, the most economical way to add anti-icing and de-icing capability is by retrofitting. That is, by applying coatings or hardware to existing cutter designs while minimizing large installation costs. Many products will need to be custom made or designed for specific ship needs, so costs are difficult to estimate.

When comparing one technology versus another, state of development—which affects cost and availability—must also be considered.

In general, the most important goals of the Coast Guard with regard to superstructure icing should be to allow as little ice as possible to accumulate. Keeping decks and forward bulkheads at all levels clear of ice would accomplish this. This should reduce weight of ice accumulation by about 60 to 70%, depending upon the cutter design, allow improved cutter stability in icing, and allow much safer operations on deck should remaining ice be manually removed.

6.4.1 Priority no.1—heated decks

Decks can be kept ice free by heating. Though costly with regard to power consumption, deck heat is not needed unless freezing spray is hitting the ship, or freezing or frozen precipitation is falling, so power is used only when there is a need to prevent ice. In general, there are three practical ways of heating the decks. The first and most thorough is through redesign and significantly refitting the ship with an electrical deck heating system similar to that installed on the CGC MACKINAW.

The second approach is to create a heated channel deck (S. Tripp, personal communication, January 2013) for existing cutters. Similar in design to installing attic ventilation channels in an existing roof on a house, this would involve creating an air space above the interior insulation below the deck. Heated air can then be forced through the channels during icing, and unpowered at other times. During warm weather the interior could be cooled by ventilating the space.

Anti-icing mats are also commercially available for placement on ship decks. One is not heated, but is a 2.5-cm thick structure with a wear surface, and an interior reservoir for holding a freezing point depression liquid, and a wicking material for transporting the freezing point depressant to the mat surface. Their durability is unknown, and it is not known how easily they would be diluted with spray water. However, they require no power, only periodic replenishment of fluid.

Electrically heated mats designed for the marine environment are also available. Powered by 110-VAC or 220-VAC current, they can be heated to any temperature desired. They are available in a variety of watt densities, and they are sufficiently rugged for use on the drilling floor of an oil rig;

and may be sufficiently rugged for use on a buoy deck. The mats can be fastened to decks, but are removable for deck maintenance. They can also be applied to stairs. The mats have been used operationally in the offshore environment.

6.4.2 Priority no.2—coatings

Anti-icing and low ice adhesion coatings are available for use on most ship surfaces except decks, though some suppliers claim that their products can be used on decks. Many coatings will change the color of the ship, so an inquiry is necessary to determine if coatings are available in the desired colors or available as a clear coat for application over existing paint. Low ice-adhesion coatings are a generally more mature technology, with many COTS products available. Several anti-icing coatings are available commercially. However, the characteristics of many of these coatings, and even of many low ice adhesion coatings, are unknown regarding ease of application, repair, recoating, removal, longevity, durability, and capability. Most super-hydrophobic anti-icing coatings are currently under development, or they will be custom designed for the use. Most low ice-adhesion coatings can be applied to coupons and tested operationally with no laboratory work. However, anti-icing coatings may require some preliminary laboratory work before testing at sea. Anti-icing theory is still being developed, so there is still not a full understanding of how anti-icing coatings work, and what makes them fail. For example, some developers recognize that condensation and frost can cause anti-icing coatings to fail, and coatings are being developed to address that problem. Failure because of condensation could be a significant problem in the saline marine environment where salt crystals quickly coat most surfaces, and, being hygroscopic and in a humid environment, they may quickly cause condensation.

6.4.3 Priority no. 3—chemicals and high velocity fluids

If decks are not heated and anti-iced, then chemicals and high velocity freezing point depressant fluids from heated pressure washers can be used for de-icing. A preferred chemical is sodium formate for its low corrosivity and its potential for doing little harm to the environment and personnel. Other choices may be the acetates, though they have a high BOD, and the bio-based chemicals. However, chemicals will enter water bodies when de-icing, unless pressure washers are used without a freezing point depressant, or chemicals are used that are permitted for drainage into water bodies.

6.4.4 Priority no.4—covers

Covers are a cost-effective solution to preventing ice on deck machinery and other limited-size devices. Fitted covers are faster to apply and remove, both important because covers that are not used because they are awkward are of no value. Covers should be acquired that have anti-icing or low ice adhesion coatings built into the material. Though such material has been patented and others tested, none could be located that are commercially available.

6.4.5 Priority no.5—expulsive, PED heat, pneumatic

Expulsive, PED, and pneumatic systems all are technologies that can be applied to bulkheads, doors, masts, and any other surface without many penetrations and interruptions and are not decks. The most easily used expulsive systems may be those that are thin mats and can be applied to relatively flat or convex surfaces with adhesive. Expulsive systems de-ice vigorously, so personnel should not stand in front of expulsive systems when they fire. They are very effective de-icers, but should be tested with fresh saline ice which is softer than fresh water ice, and could absorb some of the mechanical pulse. Pulse electro-thermal de-icing is available using carbon sheets covered with plastic films and held to surfaces with adhesive. They are also available as conductive carbon nanotubes that are sprayed onto a surface and covered with a dielectric paint and a color coat. The ship surface could retain its color and the heating material would become nearly invisible, and could be carried over more complex surfaces than sheet materials. PED does require surfaces to be sufficiently inclined, and smooth, that ice easily sheds when a thin layer is melted. Pneumatic systems require relatively large, nearly flat and steeply inclined surfaces to allow shed ice to fall off. They must be used in locations where there are no or few interruptions of the surface by wiring, plumbing, or doors. Pneumatic is effective and inexpensive, but can be easily damaged, though also easily repaired. Except for the painted carbon nanotube PED technology, all of the materials may change the color of the ship surface.

6.4.6 Priority no.6—infrared

Infrared emitters can be used to melt ice in limited areas such as stairs and boat and UNREP decks. Infrared can also be used to keep fire equipment and other hardware warm and anti-iced. Infrared keeps personnel warm, but the high temperature of the emitters suggests that they should not be used in areas where flammable gasses could concentrate.

6.4.7 New design ice protection technology application

Some ice protection technologies should be incorporated into new ship designs, and may be applied at major refits. These systems are impractical to retrofit.

Heated decks should be incorporated into new ship designs, or a vent channel deck heated design could be applied in a major refit. Heated deck designers should consider ease of access to electrical components for repair or replacement. Heated decks should include, at a minimum, the forecastle deck, the buoy deck if present, all side weather decks, the flight deck, and boat, UNREP, refuel and BLRS decks.

A covered bow should be considered for new cutters. Concepts such as used by the Danish HMDS *Vædderen*, or the X-bow would prevent the forecastle deck, the forward bulkhead, and ground tackle from icing, and may reduce icing farther aft. The bow cover itself may require de-icing or anti-icing using heat or expulsive technologies, or anti-icing coatings.

Additional flare should be designed into bows to deflect splash to the sides before being caught in the relative wind that flows up the sides of the bow and over the superstructure. In addition to hydrodynamic design, computational fluid dynamics (CFD) should be used to model two-phase flow over the bow and the superstructure in a variety of seas, relative wind speeds, and headings. In addition, raised bulwarks may also deflect spray and prevent it from being carried over the ship. The *Trillium* class Great Lakes boats are an example of ships with large, raised bulwarks.

Boat decks and boat launch areas should be covered and inside the ship. Interior locations and exterior doors prevent ice accumulation on boats, davits and other launch and control gear. It would make boat launching safer and maintenance less fatiguing. It may be possible to place an aircraft hangar type structure over the BLRS on the National Security Cutter to reduce problems with freezing. The boat launch design of the Danish *Knud Rasmussen* class inspection ship should be considered.

Masts with their electronics, communications and navigation equipment should be enclosed. The Danish HMDS *Vædderen*, the *Knud Rasmussen* class inspection ship, or the US Navy's Arctic Patrol Vessel design should be considered. The enclosed mast provides a dry work area. Icing of the surface can be prevented by heating the interior, as required, and applying an anti-icing coating to the exterior.

7 Arctic Superstructure Icing Climatology

The rapid retreat of sea ice during the summer in the Arctic Ocean is increasing the area and time period during which marine interests can operate. The portion of the Arctic Ocean abutting the northern coast of Alaska includes the Chukchi Sea on the northwest, and the Beaufort Sea on the northeast (Fig. 7-1). According to a National Research Council (2012) assessment of the state of the Arctic Sea ice, September 2012, the month with historically the lowest sea ice amount at the end of the summer melt season, had the lowest area of ice since satellite observations began in 1979 (Perovich et al. 2012). This was 18% less area than the previous September extreme minimum in 2007, and the last 6 years have had the lowest minimums in the 1979–2000 satellite record (Fig. 7-2 and 7-3). The 2012 minimum was 49% less in area than the 1979–2000 average. The maximum annual sea ice extent is usually observed in March.

Figure 7.1. Approximate locations of Chukchi Sea and Beaufort Sea (adapted from en::commons:Image:Chukchi Sea map.png created by Norman Einstein, 31 May 2006).

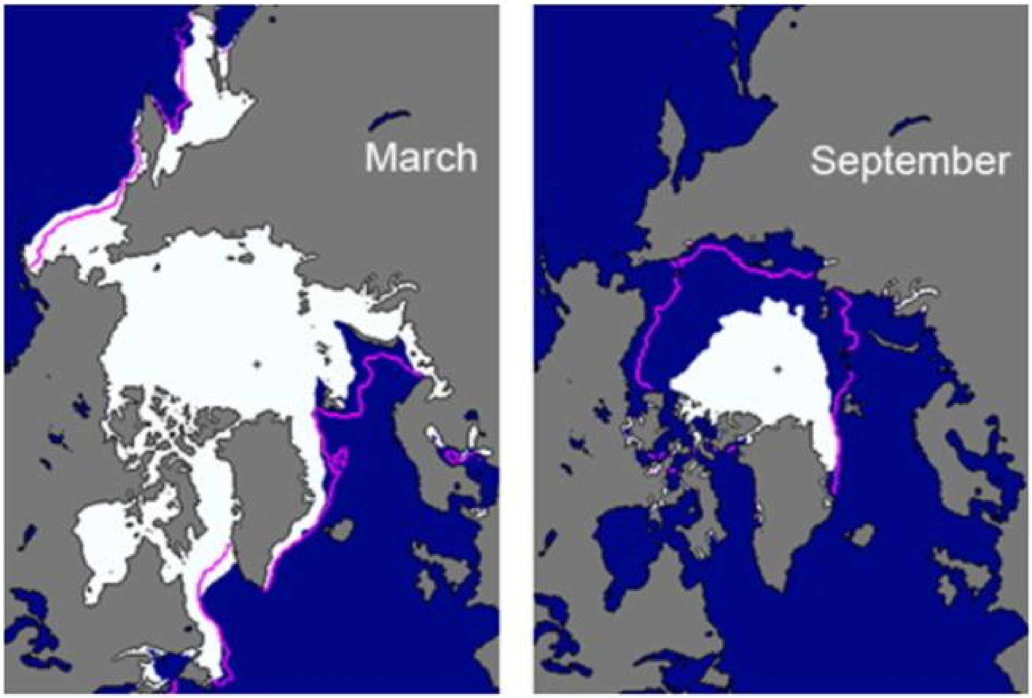


Figure 7-2. Change in sea ice extent March to mid-September 2012 (from Perovich et al. 2012).

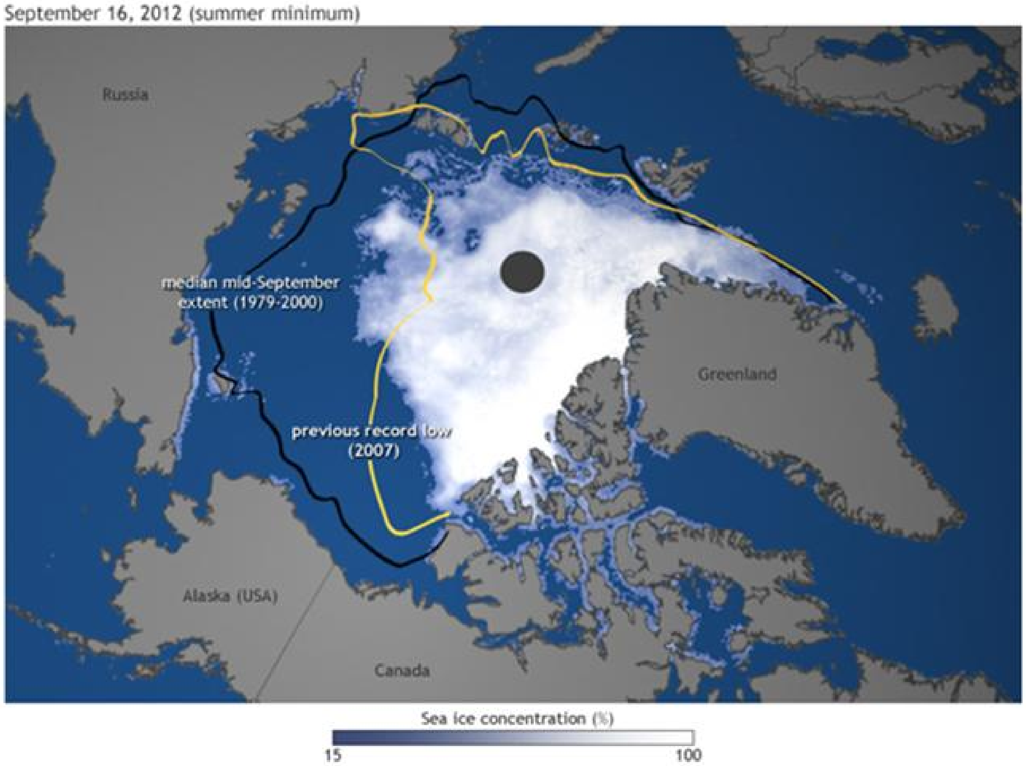


Figure 7-3. September 2012 sea ice extent compared to mid-September median 1979–2000 and previous minimum in September 2007 (from Goldman 2012).

Compared to the 1979–2000 average, the March sea ice coverage has decreased 2.6% in area per decade, but the September area has decreased on average 13% per decade (Perovich et al. 2012). A severe August storm also broke up and scattered melting ice in the Chukchi Sea in 2012, further decreasing the area. Therefore, the areal loss of ice between the March coverage and the September coverage was also the largest ever recorded. The loss occurred in all regions except for the Bering Sea during the winter. In addition, about 75% of the sea ice is now first-year ice, younger and thinner than multi-year ice, and is thus likely thinner on average than it was in 1988 according to Perovich et al. (2012).

This rapid annual decrease in ice area, a rate that is increasing, and models by the US National Snow and Ice Data Center, suggest that the Arctic will be consistently ice-free during the summer by 2030, though most models predict this as occurring from about 2050 to 2100 (US Coastal Response Research Center 2009). This decrease in ice cover will lengthen the shipping season, shorten sea routes by allowing ships to traverse the Arctic rather than taking other routes, and will allow more rapid oil development in the Arctic, notably in the Beaufort and Chukchi seas (US Coastal Response Research Center 2009). Offshore exploratory drilling took place in the Chukchi Sea during the summer of 2012.

This anticipated increase in activity off of the northern Alaska coast has prompted the US Coast Guard and the US Navy to plan for future activity in the area. According to the US Coastal Response Research Center (2009), the US Coast Guard recognizes that increased fishing, mineral exploration, shipping, and tourism will require increased SAR, environmental response, reconnaissance and surveillance, and a maritime presence. The Coast Guard's 17th District has been operating in the Arctic Ocean for several summers, and conducted Arctic Shield 2012 for outreach and to assess their operations and capabilities in the area.

The US Navy has considered Arctic operations, and has identified why US forces may need to operate in an ice-free Arctic. They concluded that there is only one reason to increase operations in the Arctic Ocean in 2025 to 2020, and that is increased access to the area (National Ice Center 2001). More specifically, the Navy anticipates presence in the area will be needed because of increased economic activity—such as opening of the Northwest Passage, increased fishing and oil drilling activity, increased need for law enforcement, and increased security needs. However, despite these predictions by the US Navy in 2001, more recent studies suggest that there is not strong commercial interest in the Arctic by ship operators. In a survey of shipping companies to determine their interest in developing activities in the Arctic, Lasserre and Pelletier (2011) found that the shipping industry has a negative perception of future Arctic shipping. Furthermore, Northern Hemisphere shipping companies and container companies have little interest in Arctic transit. They feel that there is debatable profitability in using Arctic routes and because of this there is no increase in orders for ice-class ships for the Arctic. This is despite over a 25% reduction in distance traversing the Arctic versus the Suez or Panama canals between Yokohama and London.

If there is increased activity by commercial interests, by the US Navy, and by the US Coast Guard in the Beaufort Sea and Chukchi Sea, this will increase the opportunity for ships to be affected by superstructure icing. The Arctic will remain a cold region even with a summer ice-free Arctic Ocean. Though summer temperatures are expected to increase by 1–2°C, and winter temperatures by 8–9°C, in the winter the entire Arctic Ocean basin will still be ice-covered.

According to the US Navy, as summers become more ice-free, sensible and latent heat fluxes into the boundary layer will increase heating and humidifying of the lower atmosphere. This will make the lower atmosphere less stable, increase cloudiness, decrease visibility, and increase the probability of freezing mist (rime ice) and freezing drizzle. This will cause increased vessel and aircraft icing (National Ice Center 2001). Increased cloudiness will also occur over a larger portion of the year as ice melt happens earlier and freeze-up happens later.

The temperature differences between land and water are also likely to increase, which will increase baroclinicity. Increased baroclinicity, coupled with the greater humidity at the surface, which increases instability, and the greater vorticity in the polar regions will cause increased cyclogenesis: more frequent polar lows. These polar cyclonic systems, and Sub-Polar Lows, are small and intense and are expected to increase the rate and amount of snow and liquid precipitation, and the wind and wave conditions conducive to ship icing (National Ice Center 2001).

As examples, two severe storm systems occurred in coastal northern Alaska in November 2011 and August 2012. The November 2011 event started in the Bering Sea as one of the most powerful extra-tropical cyclones on record. Beginning in the western Pacific Ocean, it entered the Bering Sea and deepened with a pressure equivalent to a Category 3 hurricane. The storm's forward speed exceeded 100 km/hr, and passed through the Bering Strait and entered the Chukchi Sea. The storm created wind gusts exceeding 144 km/hr (Overland et al. 2012). The second storm occurred in August 2012, and was responsible for breaking up melting sea ice as mentioned above. The storm was one of the strongest to affect the Arctic Ocean in several decades (Overland et al. 2012).

Ship icing is expected to be of greater concern, especially near cold, continental land masses—such as along the northern coast of Alaska. Ship, aircraft, and weapon systems design and operation will need to be altered to accommodate this increased superstructure icing. The Navy anticipates limitations in launching aircraft, helicopters, and UAVs because of ship motion from the increased storm activity and longer fetches, and problems with in-flight icing. Ice-covered decks will be a personnel hazard, especially when operating in high winds, darkness, and low visibility on pitching decks (Fig. 7-4). UNREP will be more difficult for all of these reasons, as will boat operations (Fig. 7-5). Flight decks will require built-in de-ice capability, and ice accretion models will be needed to predict the probability of superstructure icing (National Ice Center 2001).

Figure 7-4. Operations on pitching, ice-covered decks at night will be dangerous for personnel (National Ice Center 2001).

Figure 7-5. UNREP during superstructure icing conditions (National Ice Center 2001).

Paulin (2008) conducted an extensive study of conditions that would be experienced in various Arctic locations by oil exploration, drilling, and production facilities, including the Beaufort and Chukchi Seas. Paulin (2008) indicated that the Beaufort and Chukchi Seas are shallow over the continental shelf, with water depths ranging from 10 to 60 m to 380 km offshore. Generally, waves increase in height more rapidly in shallow water than in deep water, and superstructure icing is in-part a function of wave height. Waves are likely to be largest when maximum sustained winds from a narrow range of directions blow over a large fetch. This will occur in the Beaufort Sea and the Chukchi Sea in late summer and early fall when open water areas are largest. Also, breaking waves, and thus greater spray generation from spin drift, take place when wave height is about 80% of water depth or greater (Paulin 2008), though spin drift is expected to contribute little to ship icing compared to bow spray generation.

Atmospheric icing is also expected to be more frequent in the more ice-free Beaufort and Chukchi Seas. Atmospheric icing is common where cold air moves over warm water causing convection fog. This will happen where cold air is flowing off of sea ice as it reforms in the fall, or along the coast where cold air can flow offshore under warmer air. Glaze or sleet can form when rain or drizzle originates in the warm, overrunning air and falls through the cold layer at the surface. Snow squalls may also occur as a result of storm activity or localized convection as cold air moves over relatively warm water, causing local instability, and from the increased probability of severe cyclonic activity or Sub-Polar Lows.

7.1 Chukchi Sea

The Chukchi Sea is a marginal sea of the Arctic Ocean on the northwest coast of Alaska. Its western boundary is Wrangel Island and the De Long Strait between Wrangel Island and the Siberian mainland. Its eastern boundary is Point Barrow, AK, beyond which lies the Beaufort Sea. The southern boundary is where the Arctic Circle passes through the Bering Strait (see Fig. 7-1). The Chukchi Sea is very shallow; 56% of it is less than 50 m deep, allowing sea state to increase relatively quickly if free of ice cover. There are also few islands for taking refuge from heavy seas in icing conditions.

Whereas historically the Chukchi Sea is ice-covered as far south as Wrangel Island into late September, when ice begins to again grow, during late summer 2012 nearly the entire sea was ice free, except perhaps for northernmost areas (Perovich et al. 2012). This provides a long east–west fetch, approximately 1000 km, allowing waves created in west to east winds to enter the eastern Chukchi Sea and western Beaufort Sea. Wind and waves are significant factors in generating spray for superstructure icing. Wang et al. (2102) projected that sea ice cover will continue to decrease in the Chukchi Sea through mid-century, with freeze-back being delayed until December.

Fontneau (1990) mapped frequencies of wind speeds in the Chukchi Sea between Wrangell Island and Point Barrow to 75°N latitude, and in the southern Chukchi Sea to the Bering Strait. If August and September represent the historic period of greatest open water, then wind speeds between 5.7 and 10.8 m/s occur from 30 to 45% of the time in the Chukchi Sea. Wind speeds from 10.8 to 17.0 m/s occur 5 to 15% of the time.

Fontneau (1990) also compiled wave statistics for open water periods. The greatest wave heights were in August, possibly because of the longer fetches during August, but also possibly because of storminess. In most areas of the Chukchi Sea waves were less than 0.5 m in height 30 to 68% of the time. They ranged from 1 to 1.5 m in height 22 to 42% of the time. Waves between 2 and 2.5 m occurred 6 to 18% of the time, and waves higher than 3 to over 5 m occurred 2 to 9% of the time.

Fontneau (1990) showed the major storm tracks across the Chukchi Sea, which occur primarily during periods of open water when atmospheric instability is greatest (Fig. 7-6). The storms all follow tracks over long fetches of open water, providing the opportunity for higher seas in the eastern Chukchi Sea; this is especially a problem for vessels attempting to reach the Bering Sea in early fall when air temperatures are falling and cold air could be flowing over the sea from the ice edge or land.

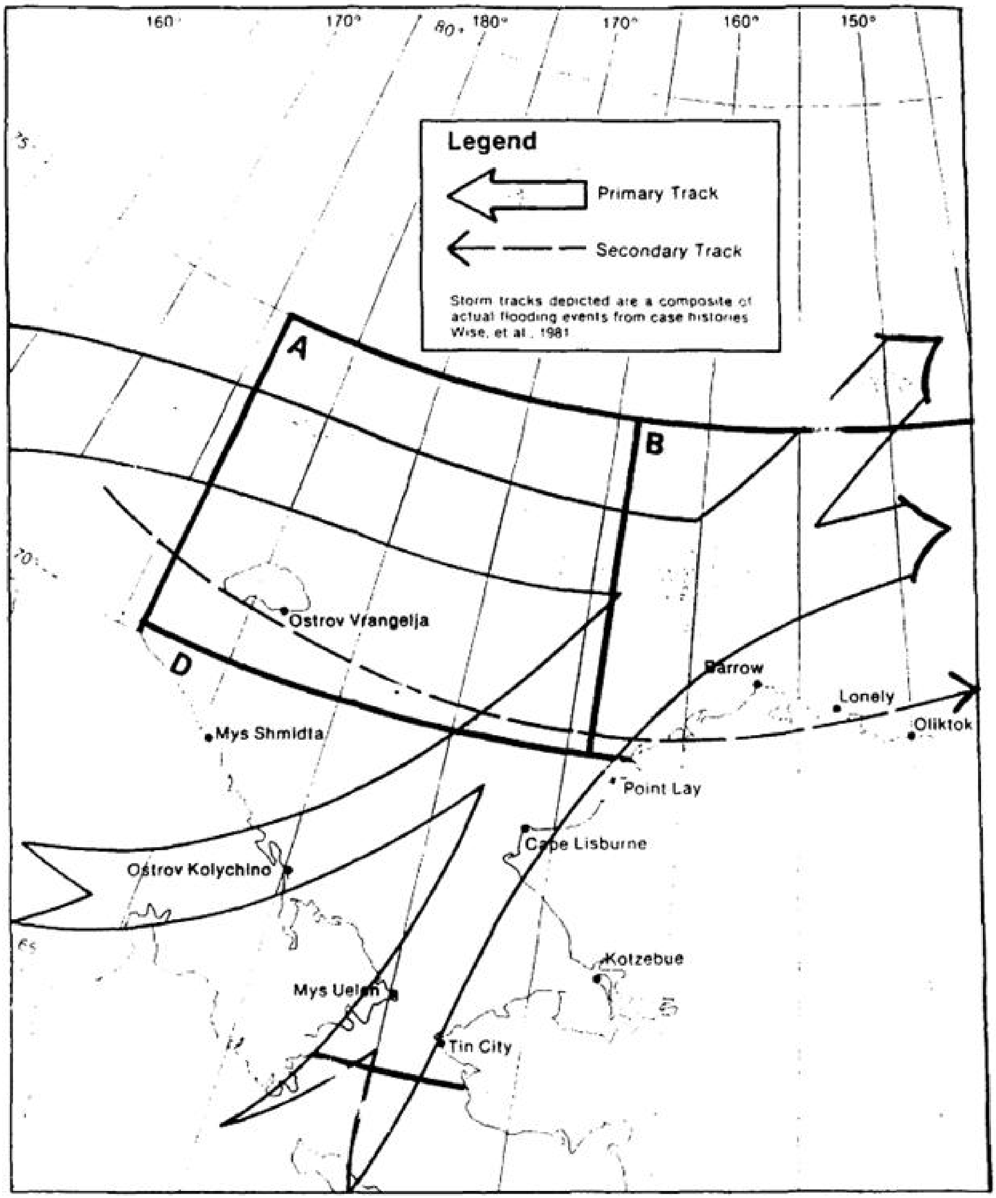


Figure 7-6. Primary storm tracks over the Chukchi Sea (Fontneau 1990).

Zakrzewski (1986) related significant wave height to wind speed and to fetch in work on superstructure icing for the Pacific Marine Environmental Laboratory (Fig. 7-7). His work suggests that significant wave heights could readily reach 2.5 to 6 m for 5 to 15% of the time and perhaps higher during Polar Lows, in rough agreement with Fontneau's work.

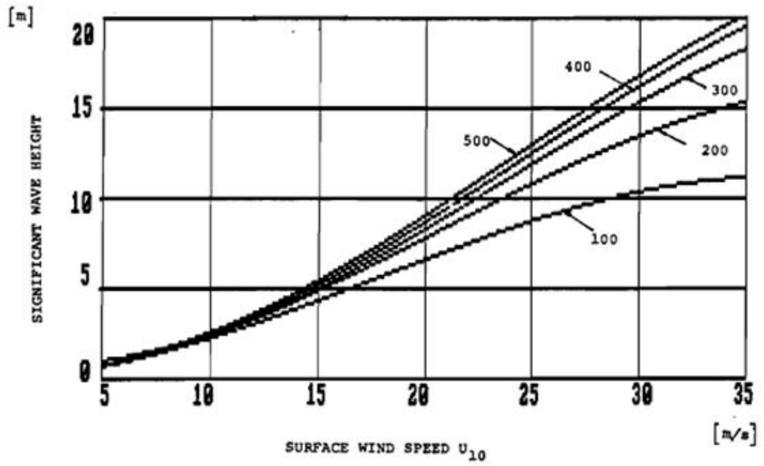


Figure 7-7. Significant wave height as a function of surface wind speed and fetch (in nautical miles) (from Zakrzewski 1986).

Today, air temperatures are highest in August, and hover between 2 and 4°C 20 to 30% of the time between Wrangell Island and Point Barrow, and average near 0°C about 40 to 50% of the time near 75° N latitude. Fontneau (1990) shows that, before 1990, minimum temperatures in July or August could drop below –1 or –2°C, potentially allowing icing. Sea ice begins to refreeze in September when historically minimum air temperatures have been –4 to –8°C over open water.

Wang et al. (2012) suggest that in the future air temperatures could be up to 5°C higher over the Chukchi Sea in late fall. Though sea water temperatures are not an important contributor to superstructure icing rates, sea water temperatures currently reach their high of about 2°C in August, cooling to –1°C by December, a trend that will continue. Sea surface temperatures are not projected to rise above 4°C, even in mid-summer, by mid-century.

Large-scale severe storms also occur in the Chukchi Sea, though they are not frequent. Often called Polar Lows, or Sub-Polar Lows, because they are relatively small, very intense sub-synoptic scale cyclonic systems, they can overcome small vessels with superstructure icing. Fett and Kozo (1992) described larger storms having diameters of about 1000 km that develop over the central Arctic. They can cause winds of greater than 26 m/s over long fetches of open water, create seas over 8 m in height, and can require

1 to 10 days to grow. Fett and Kozo (1992) described the meteorological evolution of one of these severe Arctic storms that sank a fishing trawler by superstructure icing south of the Aleutian Islands in January 1989. In this case there was strong cold air advection from Alaska that caused wind speeds of 31 m/s, air temperatures of –14°C, conditions that produced a forecast for heavy icing. Papineau (n.d.) argued that powerful Arctic storms pose a significant risk to ships all months of the year with open water in the Chukchi and Beaufort seas. Moderate to high wind speeds in Arctic storms, coupled with long durations of high winds, cold sea surfaces, and increased storm intensity, cause risk of superstructure icing.

The US Navy indicates that the northern Bering Sea and the southern Chukchi Sea are areas of heavy icing (Fig. 7-8) (Sechrist et al. 1989). Superstructure icing has not historically been a frequent problem in the Chukchi Sea because it has been open for only a few months each year, fetches have been relatively short, and there has been little need to transit the area by sea. Nevertheless, Borisenkov et al. (1975) recorded 100 cases of superstructure icing in the Kara, Laptevykh, East Siberian, and Chukchi seas over an unspecified time period. All of these cases occurred between 15 June and 15 September.

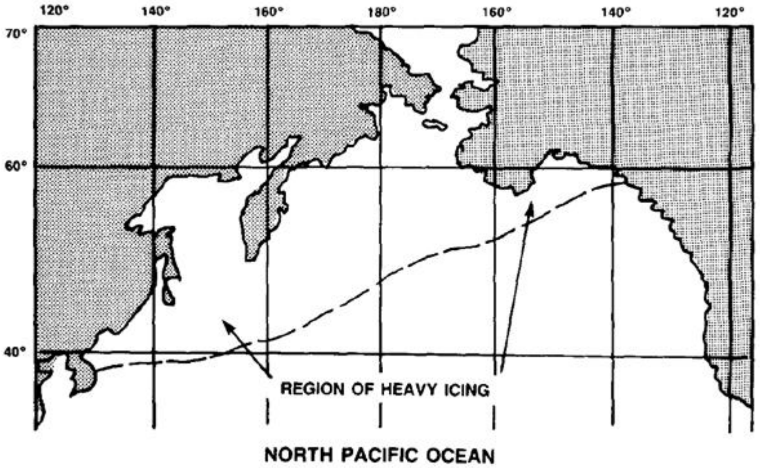


Figure 7-8. Regions of heavy icing according to the US Navy (1988).

Kozo (1986) constructed monthly contour maps of icing intensity frequency for the northern and southern Chukchi Sea, and the Hope Basin immediately north of the Bering Strait. Two sources of information were used to create the maps. The monthly positions of the 63% coverage ice edge were used to determine where open water was located. Sea surface, air, and wind speeds were used to calculate icing intensities using a nomogram developed by Comiskey (Kozo 1986). Wind speeds were divided into those below 14 m/s, and between 14 and 25 m/s. The World Meteorological Organization lists 14 m/s as the onset of dangerous wind speeds, and 25 m/s as the onset of storm level winds. Kozo (1986) also divided the north and south Chukchi Sea at the 50-m isobath because shallower water, for a given gravity wave, will create higher surface waves and more icing in the southern Chukchi Sea.

Five categories of icing intensity were mapped by Kozo (1986). Light icing accumulates less than 1.25 cm of ice per hour; moderate icing accumulates 1.26 to 2.53 cm per hour; heavy icing accumulates 2.54 to 3.78 cm per hour; very heavy icing 3.81 to 6.32 cm per hour; and extreme icing greater than 6.35 cm per hour.

Fontneau (1990) interpreted Kozo's (1986) resulting 18 maps in the following way. No icing can occur from October through April because of complete sea ice cover. In May, moderate to heavy icing is possible in the Hope Basin immediately north of the Bering Strait at minimum air temperatures and winds greater than 14 m/s. In June moderate to heavy icing can occur in the entire Chukchi Sea if sea ice recedes far enough. July icing is restricted to light or moderate, except near the sea ice edge, often near 70°N, because air temperatures are too high. Cooling weather in August increases the chance for moderate icing in minimum air temperatures and winds greater than 14 m/s. In September a change to heavy superstructure icing exists from the ice edge to the Siberian Coast and Cape Lisborne and north of Kotzebue Sound, with moderate icing possible southward to the Bering Strait.

The Committee for Maritime Services to Support Polar Resource Development, for the National Academy of Sciences (1981), assessed periods of navigation and weather hazards in the Chukchi Sea. They said that the period of navigation is from mid-July through mid-October. They indicated that fogs were frequent over ice-free water, and that superstructure icing was very severe in mid-spring and fall.

All of these indications of superstructure icing are over 20 to 30 years old. The Arctic has warmed considerably in the last 2–3 decades; temperatures are higher and there is more open water area. With continuing trends, superstructure icing may decrease in intensity during mid- to late-summer, but icing frequency and intensity may increase in November and December as the navigation season potentially lengthens.

7.2 Beaufort Sea

As with the Chukchi Sea, the Beaufort Sea is a marginal sea of the Arctic Ocean. It borders the north coast of Alaska east of Point Barrow, and the Northwest Territories, the Yukon, and the western end of the Canadian Archipelago (see Fig. 7-1). Overall, the Beaufort Sea is deeper than the Chukchi Sea, with a narrow, shallow coastal shelf of 40- to 75-km width and 20- to 90-m depth that rapidly drops offshore to submarine canyons (MMS 1985). Also, unlike the Chukchi Sea, the Beaufort Sea has many islands that may offer ships protection from severe weather.

Few weather and ship superstructure icing observations have been made in the Beaufort Sea because the area is relatively uninhabited, and historically sea ice has not retreated off shore for large distances. In general sea ice retreat is greater in the eastern Beaufort Sea north of Canada than it is between Point Barrow and the Canadian border (MMS 1985). In some years the ice edge does not retreat far from shore, and loose, moving pack ice along the ice edge makes traversing the coast by ship difficult. As an index, the distance from Point Barrow to the ice edge at the time of greatest melt back, mid-September, has varied from 0 km (41% of the time) to over 240 km over a 29-year period before 1985 (MMS 1985). In September 2012, of course, the ice edge had retreated farther from the coast than ever before recorded.

Open water encourages storm activity because the ocean surface is warmer than the ice cover, and evaporation humidifies the boundary layer and encourages instability. Figure 7-9 shows that polar lows track along the Beaufort Sea coast during the open water period of the year. These lows can bring rapid pressure drops, strong winds, moderate to heavy snow, and can form quickly and last less than one to several days (Canadian Coast Guard 2012). They are also accompanied by large temperature drops in the lee of the storms—where superstructure icing is most common (Fett and Kozo 1992). No comprehensive studies had been conducted by 1975 of the synoptic conditions bringing superstructure icing conditions to the Beaufort Sea. However, Berry et al. (1975) concluded that the synoptic conditions observed during icing off the Canadian east coast, off Japan, and in the Barents Sea can be applied to the Beaufort Sea. In these areas icing is usually limited to areas behind low pressure systems, and often lee of a trailing cold front. A wind shift, temperature drop, and often a wind speed increase are associated with this sector of the storm. Ryerson (1991) found similar conditions associated with trawler icing off the Canadian east coast.

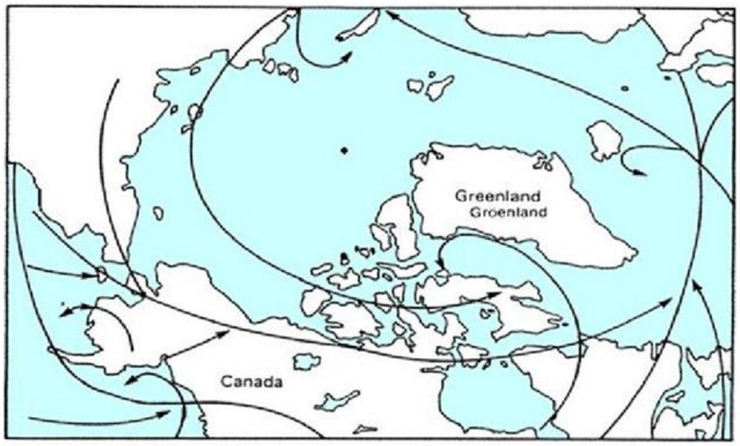


Figure 7-9. Principal summer storm tracks in the Beaufort Sea area (from Canadian Coast Guard 2012)[1].

In addition to storms, a study for the former Minerals Management Service of the Department of Interior (MMS 1985) claimed that the most common meteorological cause of superstructure icing in the western end of the Beaufort Sea is to have wind blow from cold land or pack ice toward open water with a fetch sufficient to produce waves, and spray when encountered by a ship. Farther from the ice edge or shore, the temperature of the air rises to near the water temperature, so the probability of icing decreases. Occasionally, freezing rain, and rime ice from sea smoke, has also occurred on ships in the Beaufort Sea.

According to the National Academy of Sciences (1981), the Beaufort Sea is open to unescorted navigation in August and September only. They indicate that the threat of superstructure icing is very severe in early fall until freeze-up. All other Beaufort Sea superstructure icing risk assessments have been conducted in Canadian studies, and have focused on the Beaufort Sea east of the US–Canadian border. In general, the Canadian Coast Guard indicates that 25–50 hours of superstructure icing occur annually in the eastern Beaufort Sea. They also indicate that ice accretion rates can

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[1] Copy of an official work that is published by the Government of Canada; the reproduction has not been produced in affiliation with, or with the endorsement of the Government of Canada.

exceed 2 cm/hr, with accumulations of over 25 cm of ice on a ship not uncommon (Canadian Coast Guard 2012).

In 1975 the Canadian Atmospheric Environment Service assessed weather, waves, and superstructure icing in the eastern Beaufort Sea (Berry et al. 1975). They developed a climatology of superstructure icing using the Mertins (1968) algorithm that calculates ice accretion rates on slow moving fishing trawlers as a function of air temperature, sea water temperature, and wind speed. Calculations were done for an area between the US–Canadian border and Amundsen Gulf, Northwest Territories. They used 14 years of hourly wind speeds and air temperatures from Cape Perry, and 13 years from Sachs Harbour. September and October were analyzed, and sea water temperature was assumed to be 1.0°C in September and 0°C in October. Only September and October were analyzed because only those two months had sufficient open water to allow waves, and therefore spray, to form when traversed by a trawler. Land-based wind speed measurements were multiplied by 1.3 to represent winds over water. Total hourly observations for Cape Parry were 20,496, and for Sachs Harbour, 19,032. Cape Parry is farther south and should represent the southern portion of the Beaufort Sea, and Sachs Harbour the northern portion. For the analysis, September and October data were combined. The results were the average duration in hours of specified accretion rates, the total number of occurrences, the maximum duration in hours for specific icing rates, and return periods for maximum ice thickness per storm. Icing rates were 1 to 3 cm/day for light icing, 4 to 6 cm/day for moderate icing, 7 to 14 cm/day for severe icing, and greater than 15 cm/day for very severe.

Icing in the Cape Parry area occurred during 13% of all hours analyzed. Light icing occurred during 7% of all hours, moderate icing during 4% of all hours, severe during 2% of all hours, and very severe during 0.1% of all hours (Berry et al. 1975). At Sachs Harbour, icing occurred during 16% of all hours, with 6% being light, 3% moderate, 4% severe, and 1% very severe. Icing event duration was typically about 12 hours for the smallest intensity to 1 hour for the greatest intensity. Intensity ranged from less than 10 mm/day to 360 mm/day.

The return period for ice accumulation per storm indicates that Sachs Harbour, located farther north, has more significant ice accumulations (Table 7-1). An ice accumulation of 10 cm on a vessel is considered dangerous (Berry et al. 1975, as cited from Shekhtman 1968). Ice thicknesses of 10 cm per storm have a return period of 2 years at Cape Parry, and twice this amount every 10 years. At Sachs Harbour 10 cm thickness per storm is exceeded every 1.1 years. Though, according to Berry et al. (1975), the frequency in the Beaufort Sea is not very high, there is a potential for dangerous icing in the months of September and October.

Table 7-1. Return period of maximum ice accumulation per storm (cm).

	Return Period in Years							
	2	5	10	15	20	25	50	100
Cape Parry	11.4	11.8	22.4	24.9	26.6	28.0	33.5	36.2
Sachs Harbour	17.3	26.0	31.8	35.1	37.4	39.1	44.6	49.9

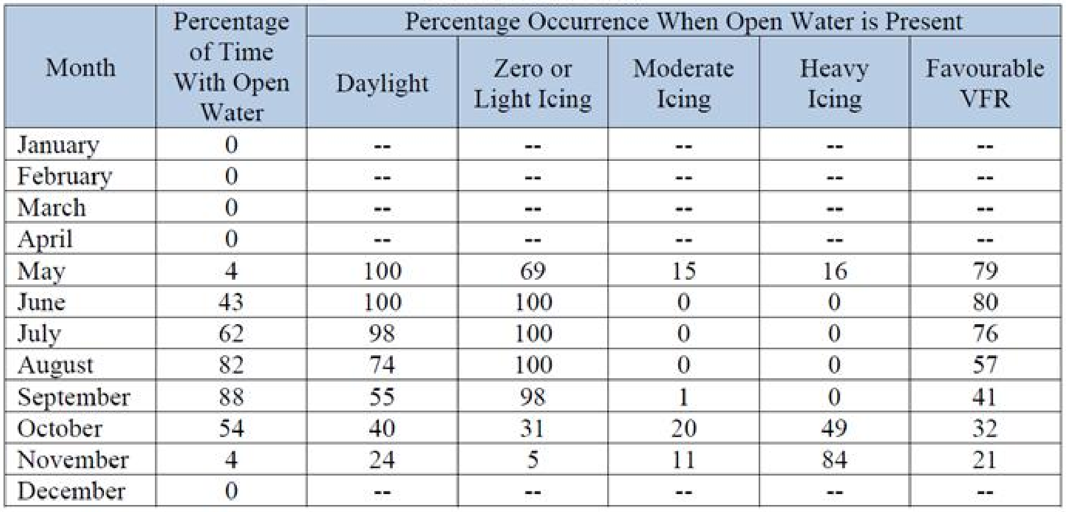
In another analysis of the probability of icing in the Beaufort Sea, the Canadian National Energy Board sponsored a study to evaluate gaps in oil spill response in the Canadian Beaufort Sea and Davis Strait (National Energy Board 2011). The objective of the study was to “Provide estimates about when and how long primary recovery and clean-up techniques of mechanical recovery, dispersants, and in-situ burning would be unavailable due to environmental factors such as adverse ice conditions, fog, darkness, higher sea states, etc.” Twenty years of environmental data, from 1989 through 2008, were used in the analysis assessed at two locations in the Beaufort Sea approximately north of the MacKenzie River delta in the Northwest Territories of Canada. The database was developed using Meteorological Service of Canada hindcast techniques, and accounts for the significant retreat of sea ice cover in the last several decades.

Superstructure icing was computed using the National Oceanographic and Atmospheric Administration’s National Weather Service Environmental Modeling Center’s vessel superstructure icing algorithm. The algorithm was developed by Overland et al. (1986), and relates icing rate to wind speed, the freezing temperature of sea water, air temperature, and sea surface temperature. The method is designed for trawlers 20 to 75 m in length underway at normal speeds in open seas and not heading downwind. The three icing rate categories are; light—less than 0.7 cm/hr, moderate—0.7 to 2.0 cm/hr, and heavy—greater than 2.0 cm/hr (National Energy Board 2011).

Information about percentage of time with open water, percentage of time with daylight, superstructure icing intensities, and favorable Visual Flight

Rule (VFR) conditions were computed to determine the limitations posed by these environmental factors on oil spill cleanup. Computations were made for near offshore and far offshore. Table 7-2 and Table 7-3 show similar information, except for differences in ice cover near shore and far off shore. The near-shore location is approximately 70 km north–northwest of Tuktoyaktuk, Northwest Territory (70°N, 113.95°W) (Fig. 7-10). The far shore location is about 80 km north of the near-shore location (70.75°N, 135.9°W) (National Energy Board 2011).

Table 7-2. Occurrences of open water, daylight, icing, and Visual Flight Rules conditions for aircraft near offshore in the Beaufort Sea (from National Energy Board 2011).



Month	Percentage of Time With Open Water	Percentage Occurrence When Open Water is Present				
		Daylight	Zero or Light Icing	Moderate Icing	Heavy Icing	Favourable VFR
January	0	--	--	--	--	--
February	0	--	--	--	--	--
March	0	--	--	--	--	--
April	0	--	--	--	--	--
May	4	100	69	15	16	79
June	43	100	100	0	0	80
July	62	98	100	0	0	76
August	82	74	100	0	0	57
September	88	55	98	1	0	41
October	54	40	31	20	49	32
November	4	24	5	11	84	21
December	0	--	--	--	--	--

The near shore location shows open water 7 months of the year, May through November (Table 7-2). The table also shows that daylight decreases after June, and favorable VFR conditions also decline, especially during the fall. The remaining columns provide the threat of superstructure icing in the three intensity categories described above. In May zero or light icing conditions occur about 66% of the time, and 15 and 16% of the time moderate or heavy icing occur, respectively. Only zero to light superstructure icing is experienced from June through September. October and November are the most dangerous icing months, when heavy icing can occur 49 and 84% of the time, probably because the ice has retreated as far as possible by October, and cold air is beginning to intrude (National Energy Board 2011). In November, moderate or heavy icing occurs 95% of the time.

Table 7-3 Occurrences of open water, daylight, icing, and Visual Flight Rules conditions for aircraft far offshore in the Beaufort Sea (from National Energy Board 2011).

Month	Percentage of Time With Open Water	Percentage Occurrence When Open Water is Present				
		Daylight	Zero or Light Icing	Moderate Icing	Heavy Icing	Favourable VFR
January	0	--	--	--	--	--
February	0	--	--	--	--	--
March	0	--	--	--	--	--
April	0	--	--	--	--	--
May	0	--	--	--	--	--
June	23	100	100	0	0	80
July	47	98	100	0	0	77
August	65	74	100	0	0	56
September	79	55	99	1	0	41
October	46	40	28	21	51	33
November	5	23	4	8	88	20
December	0	--	--	--	--	--

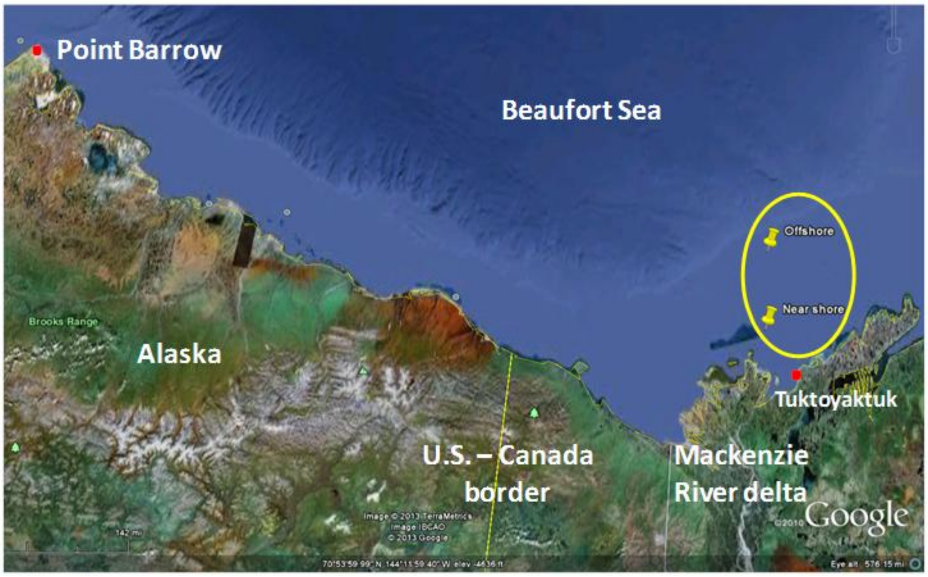


Figure 7-10. Near shore and off shore locations circled in yellow (image from Google Earth).

Far offshore, closer to the ice edge, conditions are somewhat less severe, except in October and November (Table 7-3). The number of open water months decreases to 6—the site is ice-covered in May. Daylight and VFR flying conditions are very similar monthly to the near shore location. And, as with the near shore location, superstructure icing is predominantly zero or light from June through September. As with the near-shore location, October and November are the most dangerous superstructure icing months, with 72% of icing being moderate or severe in October, and 96% in these categories in November (National Energy Board 2011).

These two studies of Beaufort Sea superstructure icing were conducted 36 years apart. Both show superstructure icing to be most serious primarily at the end of the open water season, with a slight peak in early spring. The later study reflects the greater period of open water now most frequent in the Beaufort Sea. Though both studies rely on icing algorithms related to icing of fishing trawlers, they are relatable to the smaller vessels operated by the US Coast Guard, except that Coast Guard Cutters must often sail at higher speeds. Therefore, during high speeds such as used in SAR missions, it may be prudent to treat these results as conservative.

8 Recommendations and Conclusions

Global warming is causing greater retreat of the summer Arctic sea ice cover, with several record historical minimums within the last decade. Opening of the Chukchi Sea and the Beaufort Sea, and the Arctic Ocean in general, is expected to cause increased marine and other activity off of the northern coast of Alaska and through the Bering Strait. This will require increased Coast Guard presence during open water periods.

If warm season marine activity increases as expected, then a hazard that will impact commercial and Coast Guard assets is superstructure icing. Though the Arctic is warming sufficiently to cause significant warm season sea ice retreat, sea surface temperatures will largely remain within a few degrees of freezing, and the increase in fetch and the high frequency of storms and moderate to strong winds will make superstructure icing a danger (Papineau, n.d.).

Though safety is a priority, the US Coast Guard must maintain a presence in Arctic waters to accomplish its many missions, some which require operations in severe weather. And, the Coast Guard generally operates relatively small vessels, boats and cutters, which are generally more susceptible to superstructure icing than large ships.

Nearly all ship de-icing is now done manually, with some ship-specific technological help such as deck heating systems. The Coast Guard will be able to accomplish Arctic missions with greater safety and more expeditiously if modern technology is used for de-icing and anti-icing. Technologies that do not require crew to be on deck in severe weather, at night, and on slippery surfaces would be of value.

It is unlikely that cutters need to be completely free of all ice when in transit and when executing a mission. They do, however, need sea keeping ability, stability, and integrity, and they need full functionality. That is, they need to maintain communications and surveillance capability, to launch boats, break ice, maintain buoys, address damage control, and accomplish any major mission need. Therefore, there is a need to de-ice and anti-ice the vessel when underway in heavy weather without slowing or stopping or diverting crew resources for de-icing. Therefore, the goal is keeping cutters seaworthy and functional while underway.

Keeping cutters seaworthy and functional while underway may be done in the following way. It may be acceptable to remove 60 to 80% of the ice mass, especially from decks, high locations, and from boats, the flight deck, electronics gear, and damage control equipment. This can be done on cutters in three ways in the following priority:

1. Decks should be anti-iced using heat to reduce vessel weight, to lower center of gravity, to melt ice that falls from other surfaces to decks, and to maintain a safe deck working environment.
2. Electronics gear, antennas, lights, ground tackle, boats, and safety equipment should be de-iced or anti-iced with localized anti-icing or de-icing technologies as appropriate for the specific technology and location.
3. Bulkheads should be anti-iced or de-iced using expulsive, PED, or pneumatic technology to lower weight and center of gravity.

Most vessels, even smaller Coast Guard Cutters, will ice primarily in their forward areas—perhaps in the forward 40 to 60% of the ship length. Therefore, decks on the forward part of the ship, but also including boat launch and flight deck areas farther aft, should be given highest ice protection priority. This will remove considerable weight, improving cutter seaworthiness and stability, and provide a safe topside operating environment. De-icing or anti-icing electronics, mooring and navigation, safety and boat launch hardware will improve safety and allow mission success. Deicing forward bulkheads, last in priority, will contribute to safety by reducing weight. Each cutter class will require a detailed prioritization, but these general priorities, it is believed, would be a sound investment strategy.

Though new technologies are capable of keeping the majority of ice off of cutters, manual de-icing of smaller areas will be necessary. The cost to benefit of using automation to de-ice or anti-ice all vessel surfaces, except perhaps using anti-icing coatings if they prove successful, would not likely support investment. The goal is not a completely clean ship, but a ship that is seaworthy and is functional.

Climatologies suggest that superstructure icing will be a safety problem in the Chukchi and Beaufort seas for at least 2 months of the open water season. Icing has a high probability of being moderate to severe. Prudent Coast Guard investment in superstructure ice abatement technology, initially on a trial or test and evaluation basis, is recommended.

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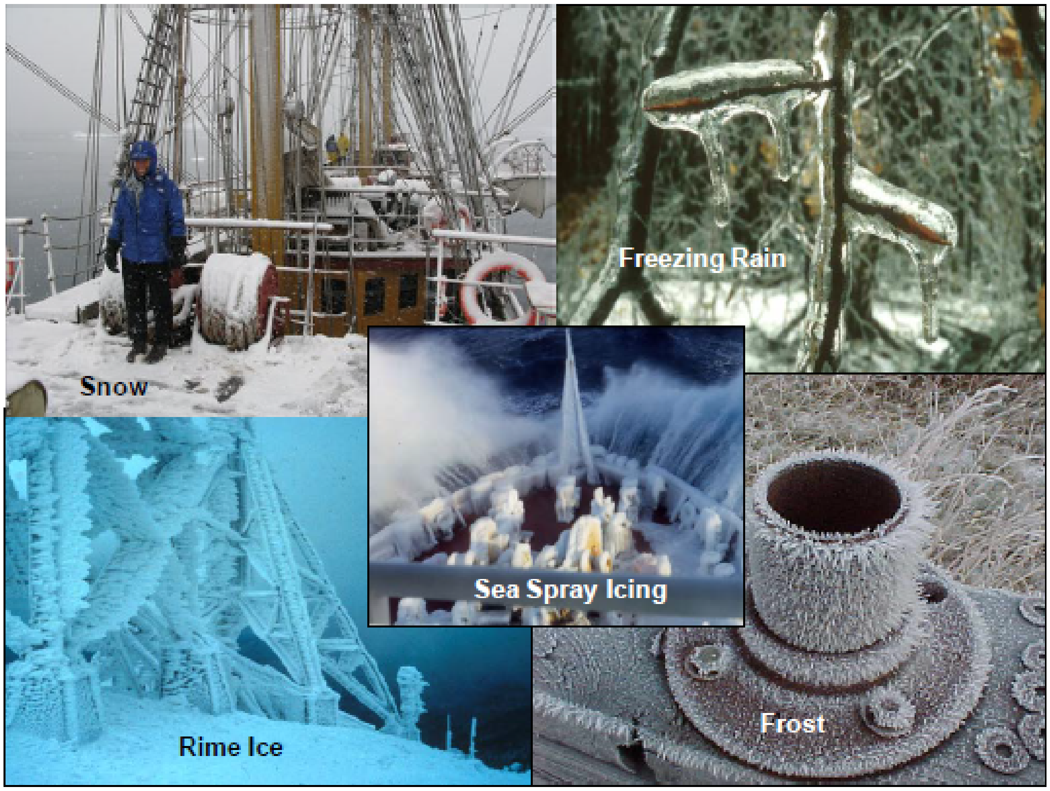
Appendix A: U. S. Coast Guard Superstructure Icing Email Questionnaire

U. S. Coast Guard Superstructure Icing
Email Questionnaire

October 2012

U.S. Coast Guard Research and Development Center
U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory

The U.S. Coast Guard R&D Center and the U. S. Army Corps of Engineers Cold Regions Research & Engineering Laboratory are jointly developing a roadmap for addressing superstructure icing as a safety and operational problem. We wish to understand how superstructure icing from sea spray, snow, freezing rain, rime, and frost may reduce mission safety and efficiency. Your responses will allow us to assess where resources should be invested to provide operational or materiel solutions. Interviews have indicated that icing impacts and solutions are mission and cutter-class specific.



1) Cutter class, cutter name (optional)?

2) What is your cutter's mission?

3) **Icing experiences at sea?**
   a. What is your experience with superstructure icing from freezing spray, glaze, rime, snow, frost?
   b. Class of cutter and geographic location?
   c. What kind of icing was experienced (see photos above for reference)?
   d. Where did ice form on the ship?
   e. What thicknesses of ice formed?
   f. What conditions were associated with icing (cold, wind, seas, ship speed, heading or operations)?

4) **Icing effects?**
   a. What were the effects of icing on safety? Sea keeping? Operations? Communications? Ventilation? Life rafts? Davits?
   b. Operationally, what areas of Coast Guard cutters are most impacted by icing?
   c. What were the effects of icing on SAR (if applicable)?
   d. What were the effects of icing on flight operations (if applicable)?
   e. How long did ice reside on the ship, and why? Was ice removal hindered by extreme cold, heavy seas, large ice thickness, mission, safety?

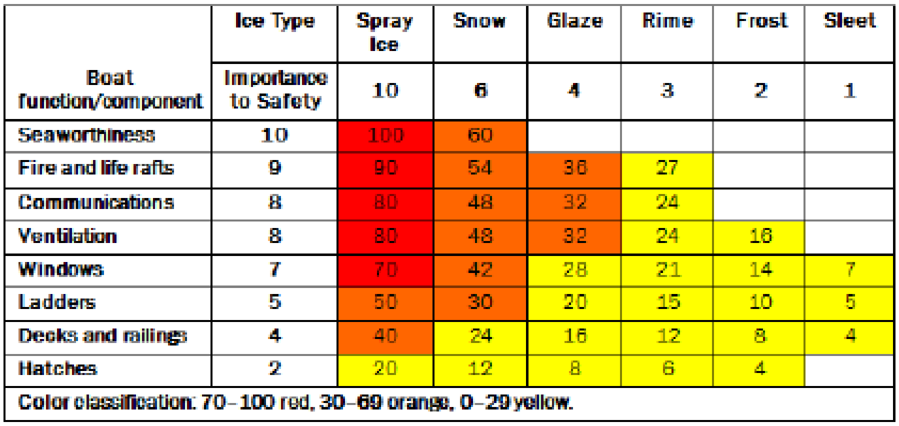
5) **Ice protection?**
    a. What methods were used to remove ice and how much time and how many crew were required?
    b. How difficult was ice removal?
    c. What tools were used to remove ice?
    d. What portions of a cutter need to be protected from ice, ranking from most important (1) to least important?
    e. What areas of CG ships may require special anti-icing/deicing attention due to materials or function (composites), sensors (fire), activity (decks), function (ventilators, fire)?
    f. Do you have ideas of how to protect a ship from icing? Manual methods? Automated? Crew-activated?

6) **Other comments?**
    a. What icing experiences have you had on other ships?
    b. What models, forecast tools, or "rules of thumb" do you use to predict icing?
    c. Are you aware of any documentation of ship icing events such as photos? Videos? Reports?
    d. Additional comments?

7) **Safety matrices:** Safety matrices relate the significance of icing threats to specific components or functions of a structure or a vessel. The two safety matrices below are examples for a supply boat and for an offshore platform. Matrix columns are labeled as spray ice, snow, glaze, rime

and sleet and are hazard-rated from 10 to 1, with 10 having the most impact to offshore structures, and 1 having the least impact. Matrix rows represent components or functions of an offshore structure or vessel which, if compromised by ice or snow, degrades safety of operations. The safety rating number refers to the importance of that component or function with regard to the safety of the entire structure or vessel if compromised by ice or snow. Therefore, seaworthiness is rated at 10 because impacts of icing on seaworthiness can be catastrophic, whereas impacts on railings may be relatively minor. Rows and columns are multiplied to determine relative importance of ice type and function/component pairs. On supply boats, for example, snow effects on communications provides a joint risk factor of 48. Red cells indicate high risk, orange moderate risk, yellow low risk, and white no risk.

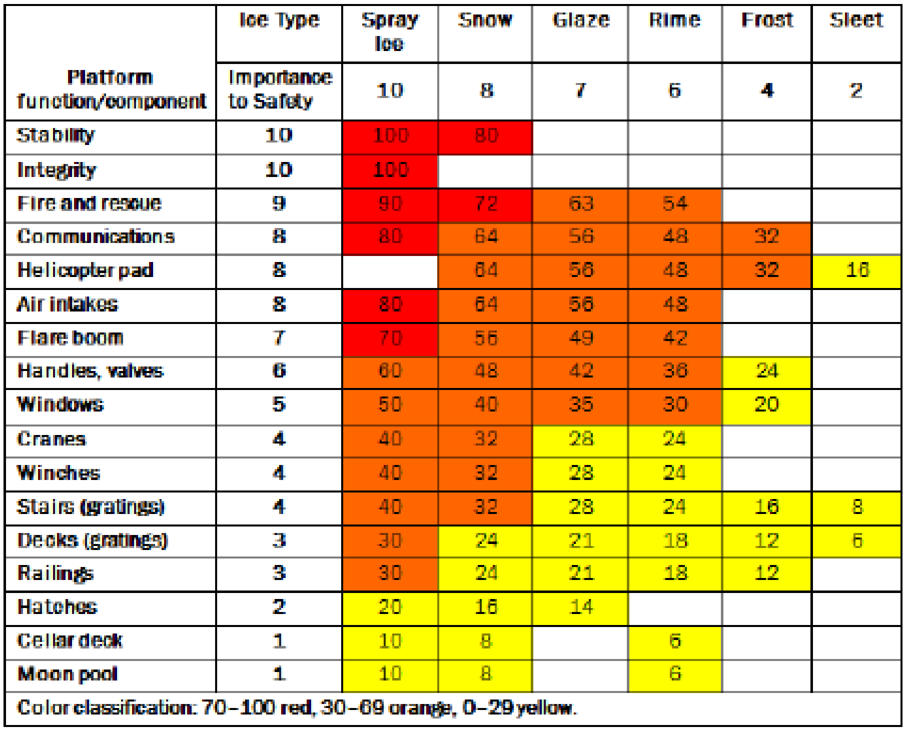
Safety matrix for oil industry supply boat.



Boat function/component	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
	Importance to Safety	10	6	4	3	2	1
Seaworthiness	10	100	60				
Fire and life rafts	9	90	54	36	27		
Communications	8	80	48	32	24		
Ventilation	8	80	48	32	24	16	
Windows	7	70	42	28	21	14	7
Ladders	5	50	30	20	15	10	5
Decks and railings	4	40	24	16	12	8	4
Hatches	2	20	12	8	6	4	

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

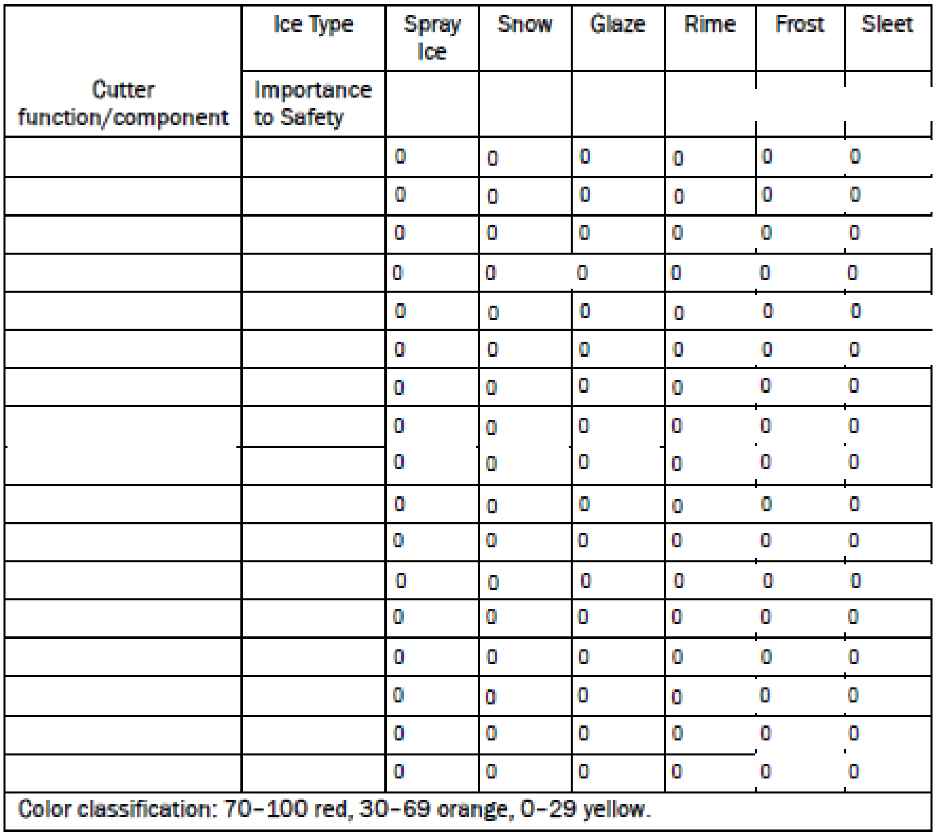
Safety matrix for stationary offshore oil platform.



Platform function/component	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
	Importance to Safety	10	8	7	6	4	2
Stability	10	100	80				
Integrity	10	100					
Fire and rescue	9	90	72	63	54		
Communications	8	80	64	56	48	32	
Helicopter pad	8		64	56	48	32	16
Air intakes	8	80	64	56	48		
Flare boom	7	70	56	49	42		
Handles, valves	6	60	48	42	36	24	
Windows	5	50	40	35	30	20	
Cranes	4	40	32	28	24		
Winches	4	40	32	28	24		
Stairs (gratings)	4	40	32	28	24	16	8
Decks (gratings)	3	30	24	21	18	12	6
Railings	3	30	24	21	18	12	
Hatches	2	20	16	14			
Cellar deck	1	10	8		6		
Moon pool	1	10	8		6		

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

Complete the safety matrix below for your cutter using the examples above. If possible, use experiences of this ship, or your knowledge of operations of this cutter class, to develop the matrix. You may give any value to each icing type that you wish, with 10 as most impact, and 1 as least. Also list cutter components or functions impacted by icing and number them from 10 as most important to the cutter's safety if compromised, to 1 as least important to safety if compromised. Multiply rows by columns to determine relative importance of ice type versus cutter function or component.



	Ice Type	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Cutter function/component	Importance to Safety						
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
Color classification: 70–100 red, 30–69 orange, 0–29 yellow.							

Comments:

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Appendix B: Technology summaries

Contents

Figures

Tables

Chemicals[1]

Innovative Dynamics, Inc.—Feltwick Anti-Icing Grate

Innovative Dynamics Inc.
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Intended or actual application

Innovative Dynamics Inc. (Innovative Dynamics Inc. 2007) has developed a system called the Feltwick Grate to create an anti-icing and anti-slip surface for marine and non-marine applications (Fig. B-1). The Feltwick grate surface consists of a robust grating or tiles that wick an anti-icing fluid to the icing-prone surface from a reservoir layer located beneath. Feltwick is designed for use on walkways, stairs, and in work areas. The system is passive and self-regulating. Fluid can be supplied from a remote location by pump if necessary.

Operating environment

The Feltwick Grate was designed for ship decks and other non-marine surfaces. It has been tested successfully in snow and freshwater ice. The system will operate in temperatures as low as the chemical freezing-point depressant used in the system.

Engineering concept

The Feltwick Grate exploits wicking action, which utilizes a porous material such as felt, open-cell rigid foam, or a porous ceramic that is incorporated within an anti-slip grating or tile matrix. Wicks can be placed in the cavities of a grate or in holes in a tile, or use homogeneous porous materials. The bases of the wicks are submerged in the anti-icing fluid such that it is drawn to the top surface of the wick. Thus, the formation of ice or accumulation of snow is prevented.

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[1] See also Ryerson (2009)

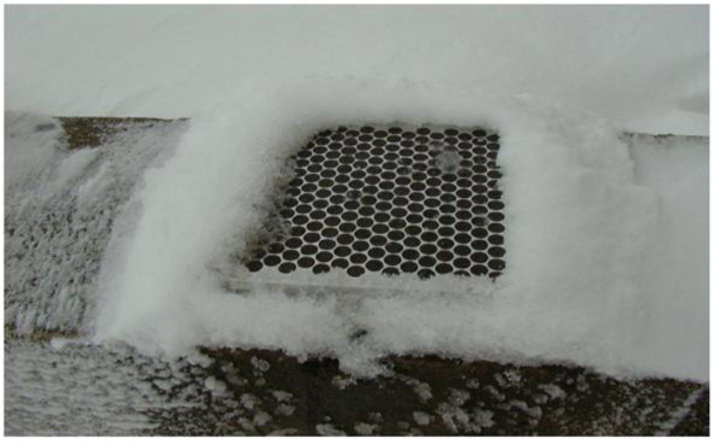

Figure B-1. Feltwick Grate.

A reservoir system feeds all of the wicks, and this can comprise a dedicated layer or be tied into an adjacent or remote reservoir via pumping. Recessing the wicks immediately below the surface of a grating allows the fluid to reach the icing substrate while minimizing tracking.

A key capability of the system is that the meltwater can be absorbed along with the diluted anti-icing fluid, rather than flowing to adjacent surfaces where it could cause other problems. Furthermore, owing to the naturally intermittent nature of icing events, the large surface area of the system will evaporate the meltwater. Thus, the full potency of the anti-icing fluid is maintained, and the meltwater is discarded.

The Feltwick Anti-Icing Grate has been tested with potassium acetate, which is a highly effective freezing point depressant. Its hygroscopic nature maintains the appropriate chemical potency in a changing moisture environment. It cannot dry out or over-dilute from humidity. Potassium acetate has a sufficiently low corrosivity so that it can be used on aircraft runways as well; it is applied as a liquid to temperatures as low as −29°C.

Technology readiness level

TRL: 6. Lab testing has occurred in winter snow and ice conditions.

De-icing or anti-icing

Anti-icing.

Current advantages and disadvantages

The Feltwick Anti-Icing Grate protects walkways, stairs, and potentially landing pads. The system requires level surfaces for optimal operation. The system consumes fluid, though slowly, so replenishment would be needed. Extreme cases of precipitation or wave wash could over-dilute the fluid to render the system momentarily ineffective. IDI indicates that the system is damage tolerant and would continue to be effective if punctured or otherwise damaged. The Feltwick Grate is about 2.5-cm thick, but this will depend on the reservoir capacity and performance requirements. Thicker versions can absorb more meltwater, and perform longer without replenishment, but the space may not be available.

Current acquisition cost

Unknown, in development.

Operational cost

Function of performance level.

Maintenance requirements

None other than fluid replenishment. Wicks may need to be back-flushed if performing in a dusty environment.

Potential marine application and safety enhancement

The Felt-wick Anti-Icing Grate may be effective on walkways, stairs, ship decks, and work areas. It may also be applicable to helicopter landing pads. Feltwick technology would improve the safety of individuals, groups of personnel, and possibly helicopter flight operations.

Marine technology readiness level

Marine TRL: 5.

Marine advantages and disadvantages

System may be diluted by sea spray. System would protect only horizontal surfaces such as decks, walkways, stairs, and perhaps helicopter landing pad. Effects of saline spray on anti-icing fluid are unknown. System presents no electrical or explosive hazards. System has low complexity, suggesting low cost and low maintenance requirements. System is largely passive except for need to replenish fluid.

Sears Ecological Applications Co., LLC—Ice-B-Gone

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Intended or actual application

Ice-B-Gone, also marketed as Magic-O, is sold as a liquid, and under the names Magic Salt and Ice B' Gone Magic, the liquid Ice B' Gone is used to treat rock salt to enhance its performance, and is usually sold in 50-lb bags and is also available in bulk quantities. There are some additional products that are sold under private labels in the form of bagged salt as well.

The liquid is a combination of sugar sources—molasses, corn, grain, cane sugar or other low molecular weight Carbohydrate sources, and is mixed with magnesium chloride or other materials such as sodium chloride brines or sand for anti-icing of roads, bridges, parking lots, and sidewalks.

All of these products are allowed to bear the EPA's "Design for the Environment" logo, having met the EPA's stringent requirements for this designation- the primary driver being lower corrosion (approximately 70%) and lower salt usage (approximately 30%).

Operating environment

Ice-B-Gone has an effective temperature colder then -18°C, and a eutectic temperature of about –42°C. Ice-B-Gone is often used as an anti-icer to reduce the volume of material required. Direct liquid applications are used in areas where tracking or harmful environmental effects of rock salt are to be avoided. As an anti-icer or a de-icer, it is effective in ice and snow. It is safer for plants, humans, and animals and does not affect skin, leather, clothing, or carpets unless exposed for an unreasonable time. No special handling equipment is required. Ice-B-Gone is water soluble and biodegradable. Corrosion rates of Ice-B-Gone are about 3% that of sodium chloride (Sears 2008). Upon application, friction is reduced below that of a wet pavement as with most fluid chemical de-icers. However, the friction coefficient becomes larger than that of a dry pavement when the surface dries and the relative humidity drops below 50% (Sdoutz 2006).

Engineering concept

Ice-B-Gone is a complex aqueous solution containing carbohydrates (sugars), proteins, and other organics derived from the fermentation and distillation processes of agricultural products, or from refined and consistent sources such as molasses and corn syrup. It is dark brown and sweet-smelling with a molasses-like texture (PRNewswire 2007). These sugar sources are combined with magnesium chloride or other chlorides or acetates to create an anti-icing fluid. Typical blend ratios of Ice-B-Gone, depending on the sugar source, range from 20–50% sugar source and 50–80% magnesium chloride. With 45–50% de-icing solids in the blend, the dilution rate is lower, and it remains effective for a longer duration than most de-icing chemicals. Ice-B-Gone is based on the concept that “low molecular weight carbohydrates when used with an inorganic freezing point depressant such as a chloride salt has a synergistic effect upon freezing point depression” (Hartley and Wood 2005). This conclusion was drawn from laboratory research conducted by Sears Petroleum & Transport Corporation.

Liquid Ice-B-Gone, in its typical blend, melts ice more rapidly than a 24% sodium chloride brine solution (its optimum) at temperatures higher than −18°C. At lower temperatures de-icing rates continue more slowly for Ice B’ Gone, but Sodium Chloride brines will have stopped working all together. BOD is low.

Technology readiness level

TRL: 8. COTS product.

De-icing or anti-icing

Both de-icing and anti-icing.

Current advantages and disadvantages

Ice-B-Gone dilutes less rapidly than non-agricultural-based products. It has a residual effect and functions at low temperatures. It de-ices more rapidly than sodium chloride at temperatures warmer than –18°C. Friction is higher than pavement surfaces when dry and relative humidity is low. However, when it is wet, Ice-B-Gone is slightly more slippery than a water-wet pavement.

Current acquisition cost

About $100 per 1000 kg of treated Ice-B-Gone rock salt. Ice-B-Gone typically costs $15/1000 kg more than standard rock salt (Phillips 2008). Maine DOT reports Ice-B-Gone costs $1.20 for 4 L (Colson 2006).

Operational cost

The primary uses of Ice-B-Gone are as a direct liquid application or to treat other materials such as sodium chloride, sand, aggregate, sodium chloride/sand mixtures, and sodium chloride/aggregate mixtures. Normally 32 L of Ice-B-Gone is applied per 1000 kg of material. The treated material is then spread, normally at a rate of 60 kg per lane kilometer and up to 150–200 kg depending upon conditions. As salt brine use has increased, Ice B' Gone has also been found to be an effective performance enhancer at rates as low as 5%, and as temperatures drop, up to 30%, thus reducing Brine's severe tendency to refreeze.

Maintenance requirements

Reapplication as needed. However, residual effects may delay necessary reapplication. Ice-B-Gone prevents ice and snow from bonding to the surface, thus minimizing the buildup of hard pack and ice.

Potential marine application and safety enhancement

Ice-B-Gone can be directly sprayed on surfaces in its liquid form, or it can be used with other chemicals to increase their low temperature effectiveness and their period of effectiveness, and to reduce corrosivity. With its sugars base, it has a slightly tacky consistency that helps it to adhere to contact surfaces. Applications are decks, walkways, stairs, and irregular surfaces such as windlasses, lattice structures, and safety gear. Effectiveness on superstructure ice is a function of the spray environment, although the longer residual effect, tackiness and greater tolerance for dilution may make Ice-B-Gone and agricultural-based chemicals generally more effective.

Marine technology readiness level

Marine TRL: 5. Environmental effects and capability in the marine environment are unknown. However, note the EPA's DfE designation for these products, discussed above.

Marine advantages and disadvantages

As liquids, these de-icers can be sprayed on surfaces of any orientation. They are tacky and of somewhat higher viscosity than other de-icing liquids, which may allow them to adhere more effectively to non-horizontal surfaces. The low corrosivity should allow applications to materials such as cables with less concern of damage. Impact on composite material integrity is unknown, as is usability on communications and surveillance antennas. Because the materials are not certified for use on aviation airside, use on helicopter landing pads is not recommended. Although the friction coefficient decreases when these chemicals are initially applied, as is true with most de-icing chemicals, friction increases over time—especially after the material dries.

Marine technology transfer requirements

The capabilities of these Carbohydrate-based chemicals should be evaluated for effectiveness in saline ice and marine spray environments. The capability of the chemicals on antennas and composites must be evaluated. Corrosivity claims should be verified, especially in a saline environment.

SNI Solutions—Geomelt and Biomelt

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Intended or actual application

Geomelt is a trade name for a sugar-beet-based de-icing chemical that is used to de-ice roads. Developed in the early 1990s, Geomelt is often mixed with sodium chloride (Geomelt S, Geomelt NB, and Geosalt), and magnesium chloride (Geomelt M). Geomelt is used by road departments in Michigan, Indiana, and Ohio, and other Midwestern states where sugar beets are grown and processed (Road Solutions 2008; Conkey 2008). The synergistic effect of the carbohydrate base stock and added chloride or acetate-based chemicals lowers the freezing point below that of either material, therefore requiring less Geomelt for a given application than most other chemicals (W. King, personal communication, 24 November 2008). A new product has also been developed, Biomelt AG64, that is superior to Geomelt, because it melts ice without the addition of chlorides (W. King, personal communication, 6 October 2012).

Operating environment

Depending upon the formulation, versions of Geomelt are effective to −32°C and are about 80% less corrosive than sodium chloride alone (Wellspring 2008; King, personal communication, 24 November 2008). Geomelt reduces corrosion on bridges and concrete pavement, reduces the bounce of dry materials applied with liquid Geomelt, and provides a persistence effect that can remain for up to 5 days so that roads are protected before road crews can apply additional de-icer or anti-icer (Wellspring 2008). Biomelt AG64 has a freezing point of −40°C, and does not contribute to corrosion of steel because it has no chlorides.

Engineering concept

Geomelt, a by-product of sugar beet processing, is recovered for its de-icing capabilities. Sugar beets are processed at plants in the Midwest where they are pulped and water is used to extract sugar compounds. A residue of the process is mixed with magnesium chloride, calcium chloride, sodium chloride, or potassium acetate. The persistence effect of Geomelt, when combined with chlorides, is attributable to its ability to stabilize the hygroscopic nature of the chlorides, making them last longer on surfaces. This also makes them less likely to decrease friction coefficients as temperature approaches 0°C, and makes them more likely to retain hygroscopic properties as temperatures fall. The beet-based material is stable and does not ferment or chemically break down rapidly after application (King, personal communication, 24 November 2008). This chemical stability also allows Geomelt to store well providing a long shelf life, and allows for a diversity of applications. Geomelt reduces the bond of ice and snow to pavements. Geomelt does not permanently stain carpets or flooring, and all forms reduce the amount of chlorides applied to roads (Road Solutions 2008). Biomelt AG64 is a natural deicing/anti-icing liquid derived from an agricultural by-product (sugar beet molasses) blended with a proprietary polyol (W. King, personal communication, 6 October 2012).

Technology readiness level

TRL: 8. Geomelt is a COTS product.

De-icing or anti-Icing

De-icing and anti-icing.

Current advantages and disadvantages

Full environmental effects are unknown, but apparently there is less environmental impact than from other materials because Geomelt's increased effectiveness requires less harmful traditional chemical use. Geomelt’s low freezing point means less chemical is needed so there is less corrosion of bridges and pavements.

Current acquisition cost

Approximately $2/4 L plus shipping costs.

Operational cost

Application rates are approximately 4 L per 300–400 m^2 for anti-icing. Application rates approximately double for deicing (King, personal communication, 24 November 2008).

Maintenance requirements

Residual effects require less immediate reapplication during a storm or in storms that follow. Residual effects can remain for 5 days.

Potential marine application and safety enhancement

Because Geomelt is a liquid, it can be applied to walkways, stairs, work areas, and complex structures such as windlasses and cranes. Geomelt Biomelt operate at low temperatures if needed when a vessel is near a landmass or an ice edge. It may be possible to apply Biomelt AG64 to ship decks via a sprayer system that is timed or metered similar to systems used on bridge decks and overpasses during winter to prevent freezing of roadway surfaces.

Marine technology readiness level

Marine TRL: 5. Capability in the marine environment is unknown.

Marine advantages and disadvantages

Because Geomelt is a liquid, material can be sprayed on surfaces of any orientation. Lower corrosivity protects materials such as cables. Its effects on composite integrity and on communications and surveillance antenna performance are unknown. Because the material is not certified for use on aircraft, use on flight decks is not recommended. Geomelt stores well without fermenting or chemical decomposition. There have been claims of rancid odor and a syrupy consistency (Hollander 2008). Biomelt AG64 may have a tendency to dilute quickly in severe marine storm conditions, being totally water soluble.

Marine technology transfer requirements

Geomelt's capability in the marine saline and spray environment should be investigated. Slipperiness of material when used on walkways, stairs, and work areas is unknown in saline conditions. Residual effect should be quantified. Impact of antenna performance and composite material integrity should be investigated.

Coatings and surface treatments[1]

21st Century Coatings Inc.—Industrial and Marine Coatings

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[1] See also Ryerson (2009).

Intended or actual application

21st Century Coatings of America (21st Century Coatings Inc.) offers a variety of non-stick fluorinated polyurethane (FPU™) industrial and marine coatings manufactured under license from the US Naval Research Laboratory (NRL). NRL has tested these coatings for 20 years. There are 13 FPU™ coatings for the marine environment, each with specific characteristics for the intended environment. The applications and characteristics include icing (FPU WC1 (ICE)™), corrosion reduction with and without non-skid characteristics, and drag and non-toxic fouling release. Versions are optimized for thermal resistance, abrasion resistance, optical transparency (WC-1 (ICE)™ is not transparent, it is opaque and also available in white), mechanical toughness, thermal and ultraviolet resistance, and flexibility. Applications include ship topside areas, wave wash areas (splash zone—FPUWC15™) below the waterline, mechanical areas, and tank and hull spaces. Each coating has ideal characteristics for specific marine applications; all characteristics are not available for all coatings. Rigorous tests have been conducted on Sikorsky helicopter radar radomes, and on wind turbines for ice release where FPU WC-1 (ICE) ™ and FPU WC15™ surpassed all other coatings in performance. The WC-1 (ICE)™ is less fluorinated than the WC15™, therefore in harsher environments the WC15™ will perform better because of the higher contents of fluorinated polyol. In addition, the FPU™ coatings provide barrier-effect corrosion protection due to their impermeability, long service life because of their ability to withstand heat, UV radiation, and mechanical damage, easy cleaning, reduced drag, and lack of toxicity.

Operating environment

The 21st Century Coatings FPU™ ice coating is applicable to steel, aluminum, fiberglass, concrete, and previous finishes. The coating is chemically stable (non-reactive), highly abrasion resistant, and not permeable to oxygen and water. It reduces corrosion, is non-stick and resists soiling, is abrasion and moisture resistant, and expels no toxic chemicals. In addition, because it is a weather-resistant non-ablative coating, no material is released into the environment from an eroding coating. It is effective on ice (and probably snow) and has passed performance tests to −40°C.

Engineering concept

WC-1 (ICE) ™ is a modified fluoropolyurethane two-component solvent-based topcoat. "It combines the advanced technology of Fluoropolyol Resin, PTFE™, Fluoroalkylsilane and Dimethyl Siloxane, into a thin film coating system applicable to a variety of properly prepared substrates" (21st Century Coatings 2008). These materials form a low surface energy film that has icephobic characteristics (21st Century Coatings 2008). The NRL formulas allow the two-part WC-1 (ICE)™ coating to be applied as a thin film, without heat curing and using conventional painting equipment, but heat-cured formulas are available. The material requires cleaning and abrading of surfaces to which it will be applied and, typically, application of a primer. Total dry thickness of the coating and primer is about 50–76 µm (2–3 mils). The material is designed for spray application, but small areas can be brushed. Typical coverage is 8.15 m^2/L unthinned with a 25% Loss Factor (21st Century Coatings 2008). It is important to note that the total topcoat thickness should be more that the normal 2–3 Mils and applied in 2 or 3 coats in Arctic conditions whereby non-skid and de-icing are accounted for simultaneously. A water tank on the vicinity of the Thruway in Westchester County has been treated with the FPU™ series and is still performing after 12 years of service (pollution, UV exposure, rain, snow, etc.). Only a few gallons were required for repairs when the County designed a new logo that they wanted to show on the tank.

Tests of WC-1 (ICE)™ by CRREL using a zero degree cone test on aluminum at −40°C produced a low average shear stress between ice and substrate of 320 kPa. The shear stress range for the four tests was from 183 to 429 kPa (21st Century Coatings 2008). This is compared to an adhesive strength of ice to bare aluminum of about 560 kPa. The FPU™ coatings have also passed ASTM tests for corrosion resistance (ASTM B 117) to salt fog, weathering (ASTM D 2794), impact resistance (ASTM D2794), chemical resistance (DIN 50018, ASTM D 4060, ASTM D 4585), flexibility and adhesion (ASTM D 4541), and additional ASTM and MIL-SPEC tests by the Navy for resistance to petroleum products, resistance to sewage, contamination of potable water, and retention of protective qualities in maritime conditions.

Technology readiness level

TRL: 8. The product is COTS.

De-icing or anti-icing

De-icing.

Current advantages and disadvantages

WC-1 (ICE)™ has one of the lower ice adhesion strengths tested in the CRREL zero degree cone test facility. The material has passed numerous tests for resistance to most of the harsh conditions encountered in the marine environment. The material is applied by spray with surface preparation (cleaning and abrasion followed by a primer). It is not known how long the material retains its lower ice adhesion strength characteristics in harsh conditions. It is unknown how the material, a dielectric, affects antenna operation; its slipperiness for work areas and walkways is unknown if used without the manufacturer-supplied traction enhancement additives.

Current acquisition cost

Depending on volume of orders and DFT 2MILS DFT, the material cost varies from \$13.45 to \$16.14/m^2·

Operational cost

None—a passive material.

Maintenance requirements

Low maintenance cost, easy repair on-site, little down time for coated surfaces. Wind turbine manufacturer was attracted to on-site repair capability without need to dismantle blades for repairs.

Potential marine application and safety enhancement

FPU™ was designed by the Navy for use in the marine environment. The coating is usable on ships, and it appears to be resistant to wave wash when applied near the water surface. It may also be used on bulkheads, irregular surfaces such as lattice structures, cables and windlasses, and antennas. It is not yet clear whether WC-1 (ICE)™ with non-skid additives would provide safe footing in passageways, stairs, decks, and work areas. Rigorous tests were performed by the Navy on the periscopes and antennas of the US Trident Submarines. The FPU™ characteristics of resisting immersion in salt water for over 6 months, coupled with its non-dielectric capabilities, were the main elements of performance in harsh conditions. This was continued by official tests performed by the Royal British Navy on the Aircraft Carrier *Royal Ark*.

Marine technology readiness level

TRL: 8. WC-1 (ICE)™ is a COTS product intended for the marine environment.

Marine advantages and disadvantages

WC-1 (ICE)™ has one of the lower ice adhesion strengths tested in the CRREL zero degree cone test facility in freshwater ice. Tests with saline ice are not available. An enhanced formula of FPU WC15™ has been used in seawater intake structures for over 12 years of successful performance, but in a non-icing environment. Other tests also indicate that the coating has a long lifetime in the non-icing marine environment. The material has passed numerous tests for resistance to most of the harsh conditions encountered in the marine environment. The material is applied by spray to surfaces prepared by cleaning, abrasion, and a coat of primer. It is not known how long the material retains its low ice adhesion strength characteristics in harsh marine conditions, its affects on antenna operation, and its slipperiness for work areas and walkways if used without traction enhancement additives.

Marine technology transfer requirements

WC-1 (ICE)™ should be tested in icing marine conditions for longevity of ice-phobic properties, friction characteristics for foot and vehicular traffic, and effects on communication antenna performance.

Analytical Services & Materials Inc—AeroKret Coating

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Intended or actual application

AeroKret coating from Analytical Services & Materials (AS&M) is a two layer coating consisting of an epoxy based primer, which bonds to most materials, followed by a flexible erosion-resistant nano-composite topcoat (Fig. B-2). It is designed to absorb and dissipate the impact energy of sand, water droplets, and other materials that typically erode coatings. The topcoat consists of a chemically inert and stable hydrophobic Siloxane nanocomposite matrix with high corrosion, erosion, cavitation, UV, and saltwater resistance, and low bio-fouling and ice adhesion. It is intended for marine structures above and below the water line, fan blades, compressor blades, heat exchangers, wind turbine blades, piping, and most metal surfaces. In marine applications it provides easy bio-foul release, reduces pitting and galvanic corrosion of aluminum hulls, may dampen vibration, and reduces rudder and drive train cavitation. It can coat antennas, radomes, hulls, propellers and propeller shafts, rudders, and sonar domes, and can also offers blast damage mitigation (Sivakumar 2012).

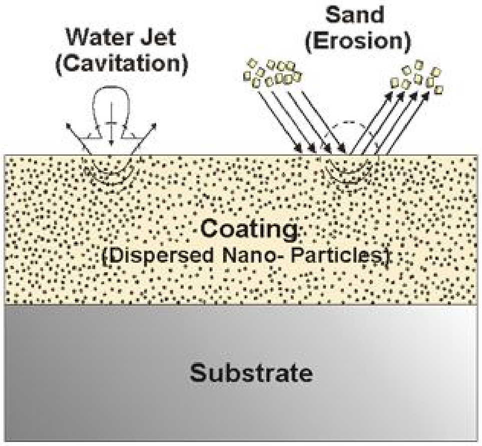

Figure B-2. AeroKret coating design.

Operating environment testing

AeroKret can be used in fresh and sea water. It is non-toxic, and its properties are unaffected from –71 to 200°C. ASTM Test G76 shows that its erosion rate (at 600 ft/s using 120 grit alumina) is about 6% that of steel, 7% of Titanium, and 12% of Aluminum. Unlike metals, the erosion rate of AeroKret coating is not sensitive to impingement angle. ASTM test B117 showed no blisters or other corrosion damage when coated over steel or aluminum after a 30-day exposure to 5% salt fog. Weight loss due to cavitation in ASTM test G32 (500 W, 20 KHz, 2 hours) showed 2.5% the weight loss of aluminum, 10% of nickel, and 30% of stainless steel. Mandrel test bends showed no loss of adhesion at a 2-mm radius. In ice aggregation tests, when compared to 13 other unspecified products, AeroKret showed the lowest ice accumulation, ranging from approximately 70% of the aggregation of the next lowest material, to about 13% of the highest aggregating material (Sivakumar, 2012). Figure B-3 shows AeroKret ice aggregation test results, in grams, with 13 other coated surfaces. Tests were made at –5°C at an air speed of 75 m/s, over a 5-s period. AeroKret is item number 13. In a biofouling patch test under on a boat hull, the coating was found to reduce adhesion of bio-foulants for at least 1 year.

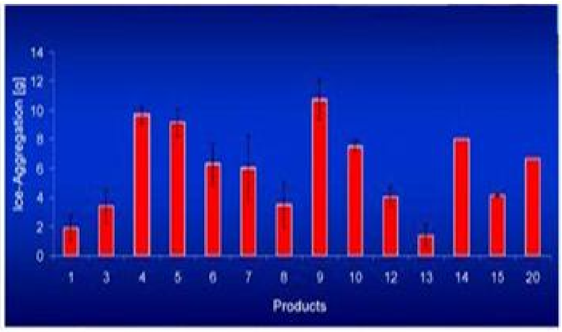

Figure B-3. Ice aggregation test results.

Engineering concept

AeroKret consists of a 2 part flexible epoxy-based primer, and a 1-part siloxane-based (Si-O-Si) nano-composite topcoat. The coating is normally applied around 70 ± 10°F, and also cured under ambient conditions. As the coating properties are insensitive to temperatures, they can also be applied at low temperatures, but the curing will need more time. The primer can be brushed or sprayed using a commercial High Volume Low Pressure (HVLP) gun and the topcoat can be sprayed using a commercial airless gun or applied as a paste. Application preparation requires the surface to be cleaned, degreased, and sand blasted or scuffed with abrasive. The primer is then applied and cured for 24 hours at room temperature or for about 2 hours at 110°C. The topcoat is then applied and cured for a minimum of 1 to 3 days, depending upon coating thickness, with a preferable cure time of 5 days. Typical primer thickness is 2 to 4 mils, and that of topcoat is 5 to 80 mils, which depends on the application.

The Siloxane topcoat has a strong, internal Silicon-Oxygen bond, giving the material thermal and oxidative stability. It has high bonding strength with a variety of materials including steel, aluminum, stainless steel, nickel, titanium, and composites. It has peal resistance and good edge retention, and is inert and non-toxic. Tests at the University of Buffalo indicate that it has low surface energy, and is hydrophobic with a contact angle of 109.8°. The dielectric constant is 2.65 at 10 GHz, and 2.68 at 96 GHz, allowing it to be applied on radomes and antennas with little signal loss. Topcoat colors can be tailored to customer requirements.

Technology readiness level

TRL: 8–9.

De-icing or anti-icing

Anti-icing through lower ice accumulation, and de-icing through lower ice adhesion.

Current advantages and disadvantages

AeroKret is easily field repaired and recoated, and adherent to most materials with high thermal, oxidative, and hydrolytic stability, and low ice accumulation and adhesion. It is also hydrophobic, weathering-, moisture- and salt-water-resistant, erosion-, corrosion- and cavitation-resistant, and inexpensive.

Current acquisition cost

Not specified and will be quoted on inquiry. Primer, as parts A and B, is available in quart or gallon cans. Topcoat is available in 1- to 5-gal. cans.

Operational cost

Application-specific, depending upon operating conditions.

Maintenance requirements

Field repair and recoating techniques have been established. AeroKret can be repaired as needed.

Potential marine application and safety enhancement

AeroKret can be applied to the hull, superstructure and antennas of a ship. It decreases ice accumulation and ice adhesion, and is hydrophobic in fresh water and salt water. It is corrosion and impact resistant, effective over a wide range of temperatures, and applicable to the harsh weather and industrial environment of ships.

AeroKret, in black and white colors, is being operationally tested on steel plates and pipes mounted on crab boats in the Bering Sea. Its effectiveness is being determined for preventing superstructure icing and reducing ice adhesion, and its ability to survive manual de-icing techniques with sledgehammers.

Marine technology readiness level

Marine TRL: 8–9. Being a research and development company, Analytical Services and Materials, Inc., can work closely with customers to optimize coatings for specific applications.

Marine advantages and disadvantages

AeroKret can be easily applied in the marine environment, requiring room temperatures and dry, clean conditions. It may be usable on many vessel surfaces, and provides reduced ice accumulation and ice adhesion when compared with other unspecified materials. It may be sufficiently durable for highly abrasive environments with heavy impacts such as buoy decks and forecastles. It is easily field-repaired. It has a relatively long cure time, and requires a two-part base-coat and a separate topcoat.

Marine technology transfer requirements

The performance of its anti-icing and ice adhesion lowering properties should be formally tested in simulated conditions and field conditions.

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ePaint Company—PCM Marine™

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Intended or actual application

*e*Paint has developed novel ice-phobic coating technology through US Navy and Air Force Small Business Innovative Research (SBIR) funding. A transparent, flexible, hydrophobic and icephobic coating with dynamic ice-shedding properties was developed, PCM Marine™.

Surfaces coated with PCM Marine™ are non-wetting; water beads and runs off the surface. Ice accretion results demonstrate very little ice accumulation on the surfaces coated with PCM Marine™. Ice that does accumulated on these coating surfaces is easily removed by ice-shedding properties of the coating technology. Ice adhesion measurements indicate that minimal force is required to remove accreted ice, 5.5±3.9 kPa (Dixon et al. 2011).

*e*Paint ice-phobic coating technology comprises a hydrophobic material coupled with a phase change material that expands and causes the material to break the substrate-ice bond. PCM Marine™ was developed for the Navy to address sea-spray-created topside icing. The Air Force coating (PCM 3000) is somewhat more hydrophobic than the Navy coating and is rain erosion resistant. Either coating could be used on radomes, antennas, power lines, and roofs. *e*Paint ice-phobic coating technology is being considered as a material to protect radar radomes by the US Department of Transportation. An ice protection vendor is testing the material for aircraft use.

Operating environment

The operating environment is a function of the application. Testing has occurred on ships and aircraft components. *e*Paint indicates that it performs well at sea and is performing well in the aviation environment in initial tests. Aviation applications would require the ability to operate in FAA FAR 25 Appendix C conditions or similar (FAA 1991a). The shipboard applications require the ability to withstand sea spray and saline conditions. Although it is recommended for roofs, transmission lines, and other ground-based applications, there is no indication that testing has yet occurred in these environments.

Engineering concept

The ePaint ice-phobic surface reduces the adhesive strength of ice using several processes; hydrophobicity, ice-phobicity, and differential expansion/contraction. The epoxy-like coating surface is hydrophobic, creating a droplet contact angle between approximately 90 and 135°. Hydrophobicity reduces the droplet contact area by providing fewer points of attachment to the surface, reducing ice adhesion strength. Secondly, the coating includes phase change material that is thermally activated. As the coating cools below 0°C the epoxy-like material contracts, and the embedded solid phase change material expands, causing little net change in the surface area of the coating. However, as ice accretes, liberated latent heat from the ice warms the coating surface. This causes the phase change material to warm and to expand (Fig. B-4). The simultaneous contraction of the epoxy-like material and expansion of the phase change material causes shear stress within the coating and failure of the ice–substrate adhesion bond.

Ice-shedding properties were qualified at the Anti-Icing Materials International Laboratory (*AMIL*), associated with the *University of Quebec*. Results from Centrifuge Ice Adhesion Testing (CAT) testing at AMIL confirm that *e*Paint ice-phobic coating technology is ice-phobic. AMIL reported an Adhesion Reduction Factor (ARF) of 39.0 for PCM 3000. The ARF is calculated by comparing average shear stress to remove ice by centrifugal force measured using three coated aluminum test surfaces to the average stress measured on three bare aluminum controls, the higher the ARF, the more ice-phobic the coating. The ARF of Teflon is roughly 7.0. Only sacrificial coatings, such as lithium and silicone grease, achieve an ARF greater than 30.0. Based on results from AMIL, ice shedding properties of PCM-based ice-phobic coatings exceed that of all other commercially available products. PCM-based ice-phobic coatings yield a durable more permanent solution to the icing problem than soft silicone or grease-based sacrificial coatings.

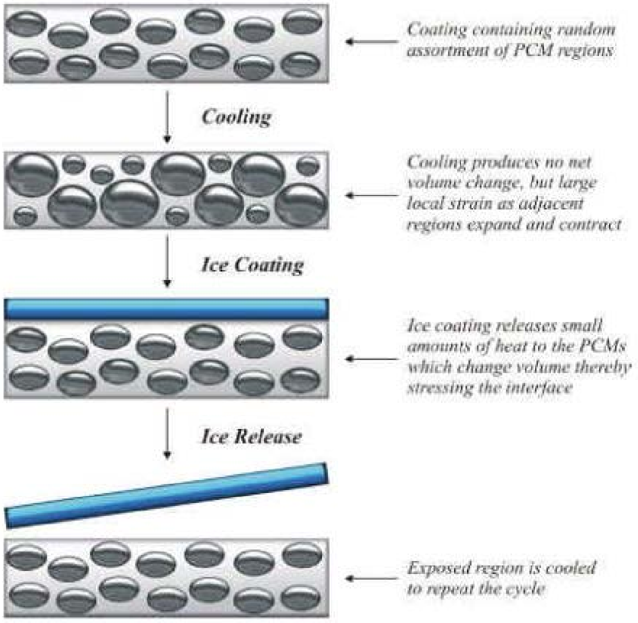

Figure B-4. Use of thermal change to create coating mechanical stress and reduce ice adhesion.

The material completely comprises solids. It is easily applied with spray or foam brushes. It is a two-part material that has a three hour pot-life and four hour cure time at room temperature. Cure time increases as temperature decreases. The material can be applied over other paints, steel, aluminum, and composites.

Technology readiness level

TRL: 7+.

De-icing or anti-icing

Ice resistant—de-icing.

Current advantages and disadvantages

The coating can be applied by spray or brush as a two-part process that applies over steel, aluminum, composites, and other coatings. Cure time is several hours at room temperature, increasing at cooler temperatures. Heat decreases cure time. The material has good abrasion resistance, is corrosion resistant, and protects paints and substrate materials. The material is optically clear, or can be tinted.

Current acquisition cost

About $299/4 L (4 L covers 65 to 74 m^2 with a 0.02- to 0.05-mm-thick coating).

Operational cost

None.

Maintenance requirements

None (operational life is about three years and requires recoating thereafter).

Potential marine application and safety enhancement

It may be applied to antennas, radomes, windows, railings, bulkheads, and lattice structures. The surface is slippery so it is not recommended for walkways or stairs. The material could also be used on areas subject to spray and wave wash to reduce adhesion of superstructure ice.

Marine technology readiness level

Marine TRL: 7+.

Marine advantages and disadvantages

See *Current Advantages and Disadvantages* because this product is intended for the marine environment.

Marine technology transfer requirements

Test on Coast Guard cutters.

Innovative Surface Technologies, Inc.—ISurTec Nanotextured Super-hydrophobic Coatings

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Intended or actual application

The ISurTec nanotextured super-hydrophobic coatings are used to modify surfaces such that they do not wet but rather shed water and aqueous solutions. Under freezing rain conditions, for example, they have been shown to substantially reduce the buildup of ice on coated metal compared to a non-coated control. The photo below shows a braided aluminum electrical transmission line (ETL) which is coated (right side, white) to repel water (Fig. B-5). Iced water was sprinkled onto it after the ETL had equilibrated to ambient winter temperature well below freezing. Water penetrated the non-coated portion (left) and it was encased in ice. Ice built up on the coated ETL section only where drops managed to seat themselves on its top in grooves between the braids, and freeze there.

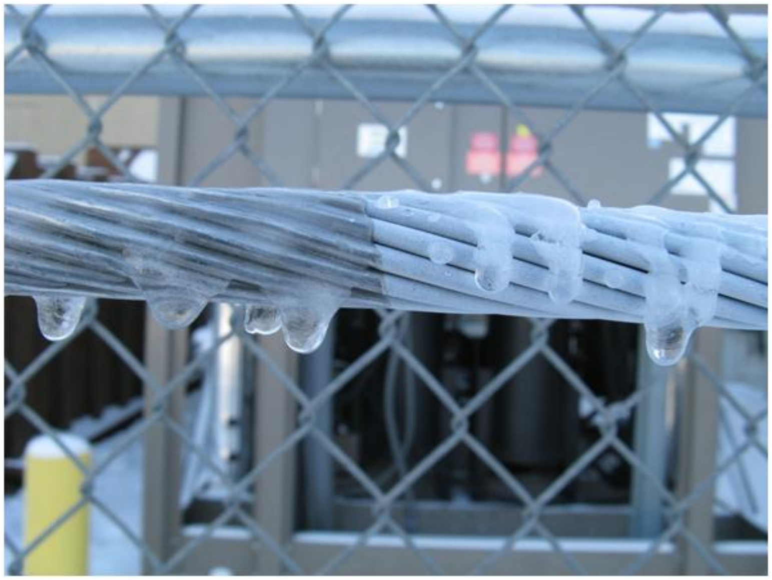

Figure B-5. ETL coated with ISurTec coating right, with bare aluminum surface on left.

Operating environment

This nanotextured coating technology in its current embodiments is not tailored to a specific environment or type of ice. It is anti-icing as opposed to de-icing in that it limits wetting by water that would otherwise freeze on contact. Its operating principle is the same indoors or out.

Wind might interfere with spray application; if so a brush or roller could be used. Wind is not likely to interfere with the coating's performance. Experience of *applying* this nanotextured coating out-of-doors is limited; however, the surface to be coated should be within the range of ambient temperatures at which a particular formulation's solvent will evaporate. With a selection of solvents and binder polymers to choose from, it may be possible to tailor coatings to demanding environments.

Engineering concept

The super-hydrophobic nanotextured coatings act according to what is sometimes called the "Lotus Effect," in which a surface presents rough features of a size hierarchy from micrometers down to nanometers, combined with a hydrophobic polymer film. Appropriate additives can confer oleophobicity as well. Any of Innovative Surface Technologies' water-repelling coatings can be considered ice-phobic, and several varieties have been formulated with regard to durability, optical clarity, and adhesion to certain substrates. Some have an oil-repelling quality as well.

Water contacting such a surface touches points of the hydrophobic features but owing to surface tension does not penetrate the air spaces between them (Fig. B-6). Water's interaction with the coating is largely with the air held within it, and a super-hydrophobic condition is established. Under freezing rain conditions, raindrops tend to bounce away before freezing can occur.

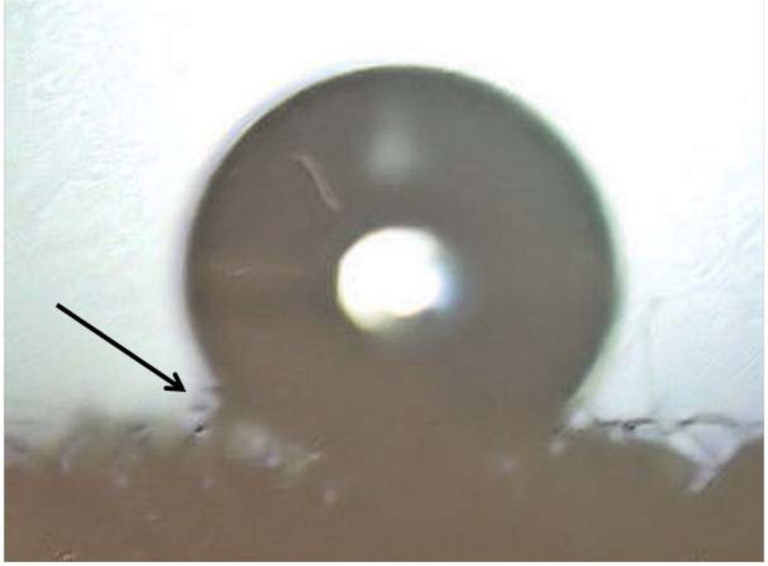

Figure B-6. Arrow indicates the air space where air is trapped beneath the droplet maintaining high hydrophobicity.

Figure B-6 shows a drop of water placed on fabric coated with the omniphobic formulation, to resist oily substances as well as water. The arrow indicates air space underneath the spherical drop, held within the fabric.

Technology readiness level

TRL 7 in the sense that the coatings have been shown to reduce icing under outdoor conditions of freezing rain.

De-icing or anti-icing

The nanotextured coatings reduce or prevent the buildup of ice on surfaces, and as such are considered anti-icing.

Current operating characteristics

The nanotextured coatings constitute a passive anti-icing system, and power requirements are demanded only in their production and application. Application can be by spray, roller or brush, and dip or spin-coating where practical (generally on small objects). It is more effective at repelling wet, heavy snow than dry, light powder. Where snow and ice do manage to cling, the coatings tend to lock it in place during melting, which can be a plus in terms of safety.

Current acquisition cost

Unknown.

Operational cost

Operational costs once surfaces are coated would be largely limited to any re-application if necessary. The coatings are largely self-cleaning and retained ~70% of original water repellency through a 3-year outdoor test. What defects arise through hail, etc., can be easily repaired by touching-up affected areas, and photochemical curing by sunlight.

Maintenance requirements

Inspection of coated surfaces can involve merely testing them with a stream of water, which will roll off a fully intact super-hydrophobic coating, but adhere to any exposed substrate. Renewal entails re-application. Frequency of renewal may depend entirely on traffic and environment.

Potential marine application and safety enhancement

In a marine environment as in a terrestrial one the coatings have potential to reduce buildup of ice on metal and other surfaces, and so enhance safety against hazards the ice can cause. Their water-repellent quality is resistant to corrosion by salt water, and to a forceful stream of water. The nanotexture may also provide a measure of safety against falling ice and snow, as under melting conditions it tends to retain any that has managed to cling to a coated structure.

Marine technology readiness level

Marine TRL: 6, as coatings have not been field-tested in a marine environment.

Marine compatibility

Undetermined; however data suggest a probability of compatibility.

Figure B-7 is from Day 0 of a corrosion-resistance study in which aluminum coupons were partially immersed in Congo Red dye solution in water. The coupon on right (labelled A01) was first coated with an ISurTec® nanotextured super-hydrophobic composition. It may be apparent from the deformation of the air/water/coating three-way interface that the coating itself is not wet.

Figure B-7. Start of corrosion test with ISurTec–coated aluminum on right, bare aluminum on left.

A year later the dye salt has precipitated from its water and the non-coated aluminum is well corroded; the coated (A01, now on the left) much less so (Fig. B-8).

Figure B-8. After 1 year of immersion, the bare aluminum coupon (right) is well-corroded, and the ISurTec-coated coupon (left) has minimal corrosion.

Marine technology transfer requirements

Evaluate effectiveness of nanotextured coatings in superstructure icing conditions. Evaluate coating durability. Evaluate ease of applying coatings. Evaluate compatibility of coatings with active de-icing systems used on cables, such as expulsive, mechanical, and electrical systems.

KISS Polymers LLC—KISS-COTE

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General overview

KISS-COTE is a silicone-based polymer coating that is only one-molecule thick and made of smooth-feeling, slippery, dry, non-toxic, waterproof materials. Coatings are applied at room temperature by spraying a liquid or dabbing a gel and removing the excess with a clean cloth. The coating has a variety of uses in many industries including: marine, aviation, boating, transportation, munitions, mold release agents and other non-stick applications, dental, and medical.

KISS-COTE was originally developed to keep dental plaque from sticking to teeth, blood cells from sticking to cardiovascular devices, and as an artificial skin to promote wound healing. Testing with pathogenic (disease causing) bacteria and other materials showed nothing would stick to coated materials, tests in various diameter flow cells showed that surfaces treated with KISS-COTE exhibited significant reduction in surface friction and drag. The Navy and CALSPAN suggested looking at barnacles and other marine life, which have the stickiest and strongest cements known to man. Marine field tests and commercial use showed barnacles, zebra mussels, and other fouling marine organisms would not stick to coated surfaces or were very easy to remove. In addition, coated boats exhibited reduced friction and drag with increased performance. As a result, first commercial uses were in marine, aircraft, car, and other high performance racing and as a release agent in freeze casting and other molding processes.

Ice release/anti-icing applications include actual use in aerospace (KISS-COTE prevents frost and ice from forming on acrylic and other clear viewing surfaces, among other things), high altitude munitions (preventing explosives from sticking to high altitude bomb casings), as long-lasting release agents in freeze casting processes, to prevent fouling of snow-making equipment, and to reduce friction and resulting force required to cut or drill frozen materials and to extend the functional life of coated materials. KISS-COTE has been shown to be effective in reducing ice build-up on boats, dams and locks, windscreens, and radomes. Airline tests showed the products to be effective in preventing ice from sticking and accumulating on aircraft. Pilots report reduced usage of de-ice boots and reduced icing when their aircraft and other aerospace vehicles are coated with KISS polymers. Other applications include all exterior surfaces of a variety of vehicles, such as boats, planes, trucks, and automobiles, including metal, glass, plastic, and paint. On boat hulls, cars, fan blades, and other moving vehicles and their component parts KISS-COTE provides an anti-fouling and fouling-release surface with reduced friction and drag, resulting in increased speed.

It has been shown that it has beneficial biomedical applications, such as on teeth for reducing dental disease, on skin for reducing sun and wind burns and frost-bite, prevents actinic and radiation damage (such as preventing skin burns on patients undergoing radiotherapy for cancer treatment, helps promote healing on burns and cuts, and reduces bacterial growth to make surfaces hygienic and for treating infections, and a variety of medical applications. Overall, KISS Polymers reports that in the biomedical, marine, aerospace, and munitions environments their coatings reduced drag at the solid–fluid interface, reduced cleaning requirements, reduced ice adhesion, and increased water shedding (KISS Polymers 2008).

KISS-COTE is available as MegaGuard Ultra LiquiCote and MegaGuard Ultra Release Liquid for industrial applications (including aerospace, construction, general, commercial, and military aviation); KSBP and KSBP SpeedCote for high performance uses; and KISSCARE Ultra for biomedical applications. Each is an easy-to-apply non-stick polymer that improves clarity of visual surfaces, increasing transmissivity of visible light through glass, acrylic, and other optical materials while reducing fouling and cleaning requirements.

Operating environment

KISS-COTE “lasts as long as the surface layer of the substrate upon which it is placed” (KISS Polymers 2008). However, if it is applied over unstable or poor-quality surfaces (like old oxidized paint), it will have a reduced life expectancy. KISS-COTE Polymers withstand extreme heat and cold and are non-toxic. In addition, the coatings are easily cleaned, water repellent, and mildew resistant. They reduce friction, promote a clean and healthy surface, and are environmentally friendly. KISS-COTE is effective on metal, wood, fabrics, plastic, cement, and glass. It even works on porous substrates such as sand. In addition, the coatings are tolerant of prolonged exposure to chemicals.

Engineering concept

KISS-COTE Polymers are environmentally safe and securely bond to the substrate they protect. They comprise a polymer, poly(dimethyl siloxane), that is one of the least reactive silicones known. KISS-COTE is made by modifying the polymerization process by adding inhibitors that halt the cross-linking process at a preselected point. This leaves a material with highly reactive sites on the polymer chain for bonding to substrates, reacting with the substrate to bond, while presenting an inert non-stick non-wetting, friction-reducing layer to the environment that contacts the coated surface (Fig. B-9).

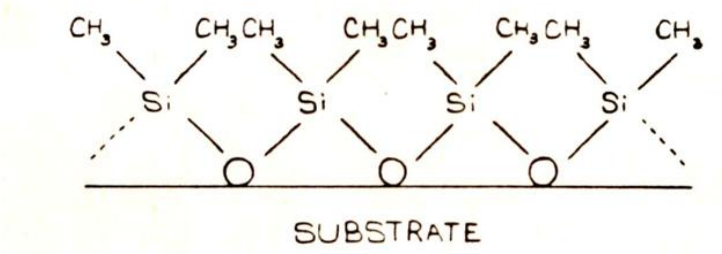

Figure B-9. Self-bonding inert polymers present a non-stick face to the environment (CH_4 methyl groups) with a strong but thin intermediary (Si Silicon) and a reactive side (O Oxygen) that bonds to the substrate surface (courtesy KISS Polymers LLC).

The resulting coatings exhibit most of the temperature, pressure, and chemical resistance, and water-repellent properties of silicone-based polymers, yet they stick to surfaces and do not migrate as does silicone. Correctly applied, the coatings are a monomolecular layer approximately 120 Å thick, allowing them to be optically clear and invisible to the eye, even improving transmission of visible light on coated surfaces. KISS-COTE provides a water/ice-shedding non-stick surface that is easy to apply, and makes ice that may form (such as on static surfaces) easier to remove. KISS-COTE attracts oxygen to its surface layer and has a high contact angle to fluids (super-hydrophobic), altering the type of frost or ice layer that may form with lower bond strength and ease of removal of ice, and its non-stick surface makes removal of frozen materials or any other detritus easier.

KISS-COTE treated surfaces have a low surface energy and high contact angle (Fig. B-10) to most all fluids and other materials, making them difficult to wet, super-hydrophobic, and having non-stick easy-to-clean surface finishes, no matter what substrate they are applied to. Because the KISS-COTE treated surface exhibits the most inert surface layer known, materials do not chemically bond to it. Only mechanical retention can occur, which is easily overcome due to the poor adaptation of the adherent materials to the coated surface.

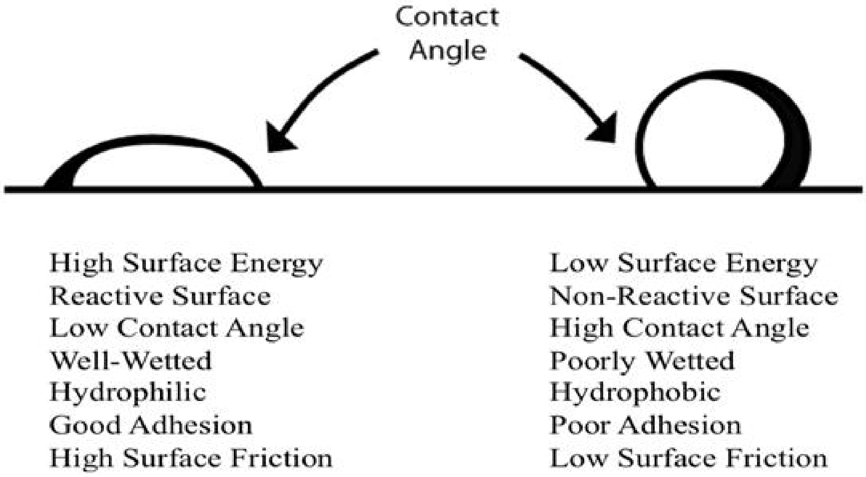

Figure B-10. KISS-COTE treated surfaces have a low surface energy and high contact angle

Technology readiness level

TRL: 9. KISS-COTE products are COTS.

De-icing or anti-icing

De-icing, ice-shedding.

Current advantages and disadvantages

KISS-COTE is water repellent, exhibits ice-phobic characteristics, and is applicable over many types of materials. It is clear for application to windows, and as a liquid it could be applied to irregular materials. Its longevity is a function of the quality of the substrate to which it is applied. Application is easy and quick and can be done in most environments. Its primary disadvantage is it prevents adherence of labels and decals, so areas where these are to be applied should not be coated.

Current acquisition cost

It varies according to formulation and end use. Industrial versions cost approximately \$1.08–\$1.61/m^2.

Operational cost

It requires no special equipment or environment for application. KISS-COTE Self-Bonding Polymers require no chemical pre-treatments, no heat, no pressure, no curing time, and little technique sensitivity (the less you use, the easier the application and the better the performance). Owing to its reduced friction, coated objects exhibit less drag, resulting in improved performance: such as increased engine power, higher object speed, and reduced operating and maintenance costs (which offset the cost of the coating).

Maintenance requirements

The life expectancy of the anti-fouling and non-stick character is determined by the quality of the substrate to which it is applied. A 9 to 12 month lifespan over existing ablative anti-fouling paint is reported by users in saltwater environments. KISS-COTE has a 10-year life rating for use on radomes and other telecommunication equipment. The KISS-COTE is also used on most underwater lenses (such as turbidity sensors) and deepwater sleds used by National Oceanic and Atmospheric Administration (NOAA) and others.

Potential marine application and safety enhancement

KISS-COTE is sold for application to boats and other marine surfaces, both above and below the waterline, for fouling release and drag reduction. It may be applied to bulkheads, windows, antennas, life raft hulls, and other relatively smooth materials. It may also be sprayed on irregular surfaces such as windlasses.

Marine technology readiness level

TRL: 7. KISS-COTE is available as a COTS product for boat hull applications, coating radomes, and construction materials and does exhibit hydrophobic and ice-phobic characteristics. Its use on Coast Guard Cutter surfaces with larger quantities of ice and irregular surfaces might require supplemental ice release systems. However, current use in other applications (such as freeze casting of ceramics, ice release on bridge cables, and radomes) suggests good performance may be achieved.

Marine advantages and disadvantages

KISS-COTE is expensive per unit volume, but very small amounts are required for coating, making actual coating costs nominal. KISS-COTE should not be applied to smooth weight-bearing walkways because they will be slippery, but it works well on non-skid textured floor materials. KISS-COTE should not be applied where adhesion of other materials to its surface is required, such as labels and signage. Longevity is a function of the substrate quality. It is able to reduce aerodynamic and hydrodynamic drag, and therefore may be slippery for use on smooth decks, walkways, and work areas. It is environmentally safe and easily applied.

Marine technology transfer requirements

The friction characteristics of KISS-COTE should be investigated for use on walkways and stairs. It is recommended that any weight bearing walkways be textured as coated surfaces exhibit reduced friction and may be slippery. The longevity of KISS-COTE over typical Coast Guard Cutter substrates and the ice adhesion strength of saline ice to KISS-COTE appears substantial, but testing for individual applications is recommended.

MicroPhase—PhaseBreak Flex MPD

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Intended application

PhaseBreak Flex MPD is an anti-icing coating intended to be used on surfaces and structures that may accumulate ice due to snow, freezing rain, and spray. PhaseBreak Flex MPD was developed as a very low ice adhesion coating that can be used on static or slow moving structures that do not benefit from high speed air flow to help remove ice. PhaseBreak Flex MPD is not intended to be used on flight control surfaces or leading edges of aircraft due to the possibility of rain erosion of the coating.

Operating environment

PhaseBreak Flex MPD is intended to be used in operational environments of 50 to −40°C. Anti-icing properties are effective from 2 to −40°C. The coating helps release glaze ice, rime ice, and sea spray. As the ice adhesion value for this product is very low, the coating helps remove ice with limited assistance from airstream flow or mechanical vibration.

Engineering concept

PhaseBreak Flex MPD is a tough, silicone-based coating that contains a melting point depressant (MPD). This MPD melts ice that accumulates on the surface of the coating, allowing the ice to be easily shed away. The MPD is reacted with a titanate compound to control the release of the MPD.

The ice adhesion value of the silicone coating is quite low even without the presence of the MPD, as a result, the coating will continue to provide some protection once the MPD has been depleted from the coating.

Technology readiness level

TRL: not provided. The coating is available in production quantities from MicroPhase Coatings, Inc. As this is a new product field trial data are not available at this time, although some trials are in the early stages. There are no significant laboratory data to provide.

De-icing or anti-icing

The coating is intended to shed ice as it begins to accumulate on a surface, thus acting as an anti-icing coating.

Current operational characteristics

The coating is applied using standard High Volume Low Pressure (HVLP) spray equipment. To ensure good adhesion to substrates a primer needs to be applied to the substrate. MPCI recommends using PhaseCoat Primer for this application. PhaseCoat primer is a one part epoxy coating that provides excellent adhesion to a variety of substrates.

Anti-icing properties are effective to −40°C. Below this temperature the MPD will no longer be effective.

Operational cost

Cost for the coating is $300/gal. Additionally there will be costs associated with application and substrate preparation.

Maintenance requirements

There are no maintenance requirements for the coating once it has been applied, other than to repair areas that have been damaged due to mechanical impact.

Potential marine application

PhaseBreak Flex MPD will be suitable for marine applications. The coating should not be used on surfaces where foot traffic is expected due to the possibility of creating slip hazards. The coating is flammable when sprayed, so precautions should be taken to prevent open flames or sparks, and ensure all equipment is properly grounded.

Because the coating is silicone based, it will have very limited combustion properties once properly cured. Consequently, it will not significantly contribute as a fuel source to an on board fire.

Marine technology readiness level

No data have been accumulated at this time to provide a TRL for the marine environment.

Marine compatibility

The coating is suitable to be used in a marine environment. No adverse effects will occur due to UV exposure, salt spray, or chemicals used to clean the ship. As the coating is silicone based it will not provide a significant fuel source for accidental fires. Additionally, the coating is very flexible and will not crack or delaminate due to vibration, twisting or bending of the substrate material.

PhaseBreak Flex MPD is not intended to be used to prevent corrosion. A good corrosion protection coating should be applied over the substrate before the PhaseBreak MPD is applied.

Marine technology transfer requirements

No changes of the coating formulation or application are anticipated for use of this product in marine applications.

NanoSonic Inc.— HybridSil® Hydrophobic and HybridSil® Ice-phobic Coating

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Intended or actual application

Navy ship bridge window coatings, and aircraft structure coatings.

Operating environment

Marine ship topside environment, and FAA aircraft icing conditions.

Engineering concept

NanoSonic is developing two materials of interest for anti-icing applications. HybridSil® Hydrophobic has been designed as an anti-fouling, environmentally durable, optically transparent coating with a wide service temperature range and inherent anti-icing functionality. The concept is to tailor the surface energy and morphology of the coating such that aqueous and many solvent-borne materials will minimize physical and chemical interactions with the surface, effectively minimizing contact area and imparting a natural high level of repellency and consequently a shedding, self-cleaning functionality.

HybridSil® Ice-phobic has been designed for aircraft and aerospace applications requiring durability in particle and rain erosion environments while providing passive anti-icing and low ice adhesion protection. HybridSil® Icephobic is a translucent coating designed to passively reduce the temperature at which ice accretion is observed, as well as substantially reduce ice adhesion in aggressive, very low temperature freezing conditions. The coating is not exfoliating and does not rely on cohesive coating failure / coating shedding to work, but rather is designed with a unique morphology to enable a long term, durable passive coating solution with excellent rain and particle erosion resistance. Additionally, HybridSil® Ice-phobic is capable of being strained to very high percentages repeatedly in sub-freezing conditions without delamination or failure, and is capable of adhering to nearly any metallic, polymeric, or ceramic substrate.

Both coatings are ice-phobic and have low ice adhesion. HybridSil® Hydrophobic has been demonstrated to prevent icing of the coated surface over selected freezing conditions on prototype window assemblies, as observed during thermal cycle testing per MIL-W-18445D. HybridSil® Ice-phobic has been demonstrated to prevent and mitigate icing buildup under certain aviation icing conditions and temperatures where ice accretion is typically observed, coupled with demonstrated low ice adhesion in aggressive, low temperature icing and erosion environments. HybridSil® Ice-phobic performance has been demonstrated within third party icing wind tunnel testing environments.

The coatings are designed to be highly durable to ultraviolet (UV) radiation, abrasion, and solvents, with an anticipated multiple-year lifespan before reapplication is necessary. Application is performed at room temperature and pressure, using a number of conventional paint application techniques.

Technology readiness level

TRL: 6. Coatings have been demonstrated to possess anti-icing capability and saltwater resistance in simulated operational environments on representative prototype models / assemblies.

De-icing or anti-icing

Anti-icing, low ice adhesion. HybridSil® Ice-phobic has third party quantitative ice adhesion measurements indicating reduced ice adhesion, and icing wind tunnel testing indicating mitigation of ice formation under certain aircraft icing conditions. HybridSil® Hydrophobic mitigated ice formation in simulated prototype window laboratory testing during thermal cycling.

Current advantages and disadvantages

Both HybridSil® variants are environmentally robust, being designed for marine and aircraft environments. High levels of resistance to UV, salt, grit, sand, water, and solvent exposure have been designed into the coatings. The system is currently being designed for a 3–7 year lifespan before reapplication. Reapplication may require a controlled environment. A detailed qualification plan specifically targeted for marine ship topside applications is currently underway for HybridSil® Hydrophobic coating analysis. Detailed qualification analyses are underway for HybridSil® Ice-phobic aerospace applications. The coatings have passed a number of durability and performance requirements—such as American Society for Testing and Materials (ASTM) G155 (accelerated weathering), G73 (rain erosion), G76 (particle erosion), D4060 (abrasion resistance), D5402 (solvent resistance), and D3359 (adhesion)—in a laboratory environment simulating accelerated exposure.

Current acquisition cost

To be determined. Preliminary cost analysis suggests comparable cost to current high performance aerospace coatings when produced through pilot scale manufacturing.

Operational cost

To be determined.

Maintenance requirements

The coating systems are being designed to require reapplication no more than once every 3 years.

Potential marine application and safety enhancement

This technology is designed for use over a wide temperature range and wide set of environmental conditions (e.g., wind, rain, salt spray) representative of marine and aerospace environments encountered across the globe. HybridSil® Hydrophobic coatings specifically provide excellent optical transparency on windows with negligible optical aberrations.

Marine technology readiness level

Marine TRL: 6. HybridSil® Hydrophobic coatings are specifically designed for marine use. HybridSil® Ice-phobic has been designed for aerospace applications.

Marine advantages and disadvantages

Both HybridSil® coatings provide a level of corrosion protection to underlying components. They may be applied using conventional deposition techniques and may be deposited in a wide variety of conditions, providing the capability for reapplication in the field.

Marine technology transfer requirements

NanoSonic is currently qualifying both coating technologies to determine effectiveness in a shipboard marine environment representative of operational conditions. Field testing is anticipated in 2013 and 2014 for both coating variants and evaluated for return on investment and acquisition costs.

NASA—Shuttle Ice Liberation Coating (SILC)

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Intended or actual application

The Shuttle Ice Liberation Coating (SILC, pronounced "silk") was developed to reduce ice formation and adhesion on the NASA Space Shuttle external fuel tank. Development was initially focused on reducing ice adhesion on Koropon-primed aluminum surfaces of liquid oxygen feed line brackets (DeWeese et al. 2006; Ferrick et al. 2006a, b). The challenge was to find a coating material that would reduce ice formation and ice adhesion at cryogenic temperatures. The resulting ice release at low speed under gravity and induced vibration loading, very early in the launch, would minimize potential damage to the shuttle's thermal tiles from foreign object damage (FOD). The coating needed to be durable, with wind, rain, sunlight, and multiple cryogenic cycle tolerance, and with substrate materials compatibility. The best formulation was a mix of Rain-X and powdered Teflon. Developers have informally tested SILC on automobile windshields. Several organizations have expressed interest in testing SILC for aviation and marine applications.

Operating environment

The operating environment is cryogenic temperatures at about −83°C on the exposed part of the shuttle liquid oxygen feedline bracket. Frost is formed from the atmosphere and water freezes when cold components intercept condensed water running down from higher locations. The material has also been formally and informally tested in cold chambers at −10°C and on automobiles in typical winter weather with rain and snow. SILC is transparent when buffed and SEM-XPS analysis has shown the coating to be present after buffing.

Engineering concept

SILC is a mixture of commercial Rain-X and 20 to 50% by weight Laurel Products Ultraflon MP-55 polytetrafluoroethylene (PTFE). MP-55 is a micropowder of loose agglomerates of submicron-sized particles with an average size of 4.0 µm (minimum particle size of 0.2 µm) and a density of 300 g/L. When not dispersed within Rain-X, the PTFE particles are made to break down producing a high specific surface area forming a lubricious and uniform coating. This material combination was the best of many mixtures of different materials tested by NASA and CRREL for reducing ice adhesion to Koropon-coated aluminum at cryogenic temperatures of –112°C (Ferrick et al. 2006a, b, 2008).

Coating was lost during each cycle of de-icing during tests, but the amount of coating lost from the coupon surfaces following each successive test cycle decreased with each cycle. The loss of coating indicates that failure of the bond of ice to the substrate occurred within the coating rather than at the ice-coating interface. Standardized coating application with a foam brush provided consistent and reproducible surface coverage, and a mixture of 60% Rain-X with 40% MP-55 was judged most effective from experiments. The ice adhesion to coated coupons with Koropon, Kapton tape, Kapton film, and Fire-X (fire-retardant paint) surfaces was a small fraction of the adhesion compared to uncoated coupons of the same materials. The coating showed outstanding performance and durability through five cycles of ice growth and adhesive failure (Ferrick et al. 2006a, b).

Formal and informal testing was also conducted at higher than cryogenic temperatures. Tests conducted in New Orleans, where the shuttle external fuel tank is fabricated, showed an 80% reduction in adhesion strength at temperatures of –12 to –7°C. Informal tests on automobile windshields (the material can be buffed to be optically clear) also suggested that ice adhesion was low; ice and snow did not adhere. However, tests on an aircraft wing at Eglin Air Force Base at speeds of 40–45 m/s caused considerable splash when drops impacted the wing leading edge. Water from the splash landed farther aft on the wing chord and runback occurred providing mixed results. Additional testing is planned to assess the effects of abrasion when used on helicopter blades.

Water drop contact angle with substrates is a measure of the hydrophobicity of a material. Depending upon the number of icing events, contact angles varied in tests from a high of 150 to a low of 103° (Ferrick et al. 2006a, b) (Fig. B-11). This places SILC immediately below the super-hydrophobic regime.

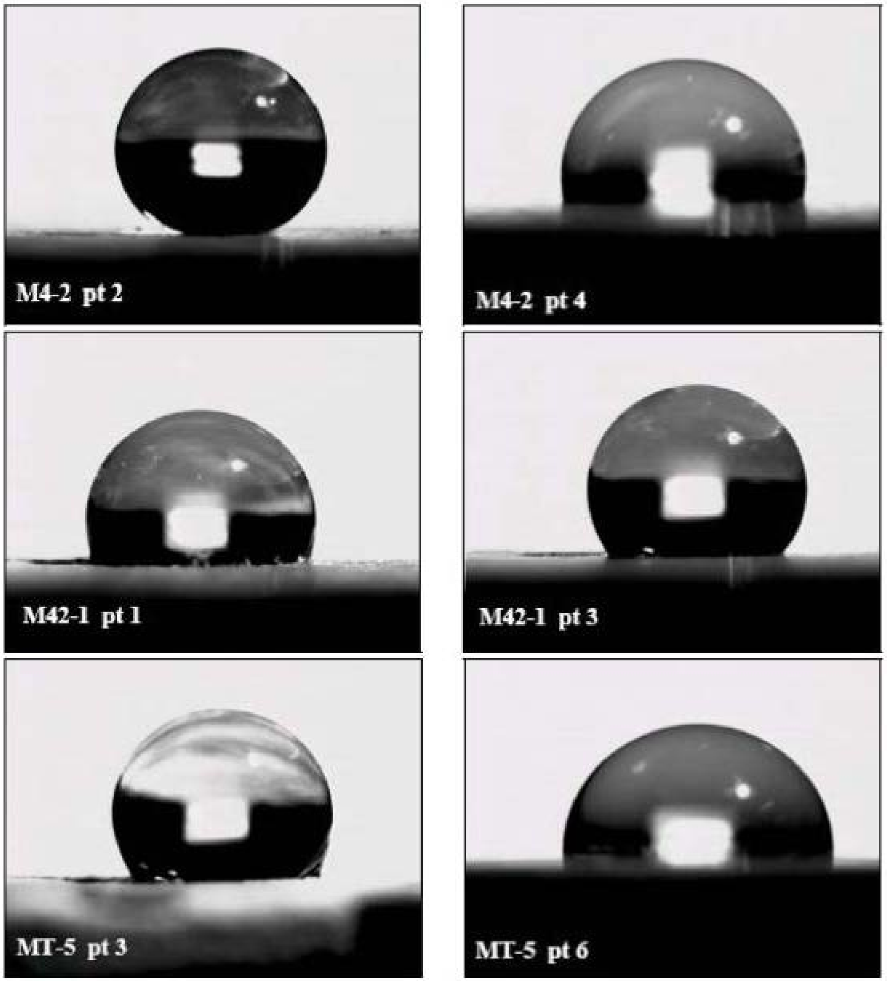

Figure B-11. Near minimum and maximum contact angles for coupons M4-2 after five test cycles (top), M42-1 after four test cycles (middle), and MT-5 after four test cycles (bottom).

Technology readiness level

TRL: 5. Depending upon application.

De-icing or anti-icing

De-icing.

Current advantages and disadvantages

Tests have shown SILC to be effective on shuttle fuel tank insulation for 30–60 days. When used informally on automobile windshields in winter weather, SILC was effective for 2 to 3 months. SILC has been tested for up to five de-icing cycles, but is expected to be effective for more de-icing cycles. The ice liberation characteristics of SILC were tested on Kapton®

which is used around the Space Shuttle liquid hydrogen umbilical. Ice formed using spray techniques developed at Eglin Air Force Base's McKinley Climatic Laboratory consistently released under uniaxial applied vibrations (Fig. B-12). The material is easily applied with a brush.

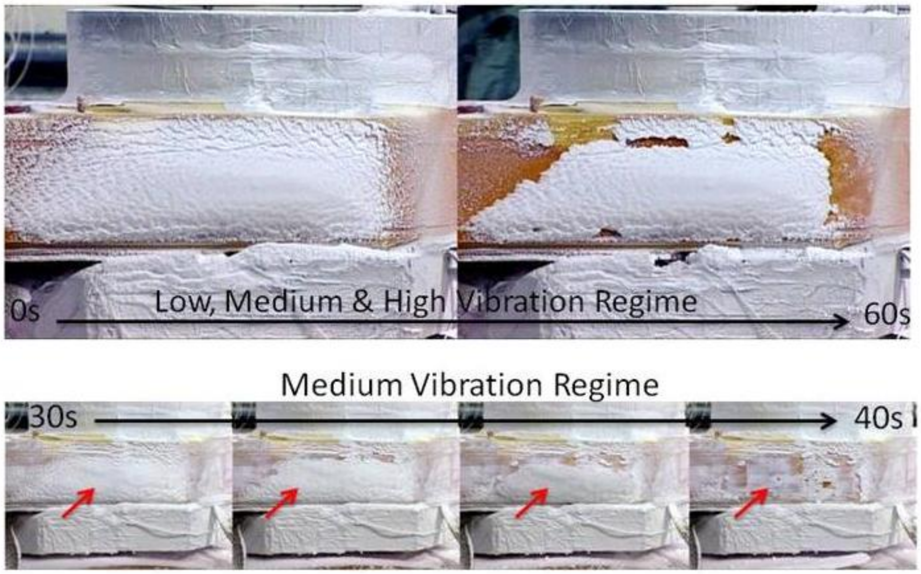

Figure B-12. Low Density Spray Ice remaining mostly adhered to uncoated Kapton® surface, West test zone (top) and Low Density Spray Ice Releasing from SILC-coated Kapton® surface, West test zone.

Current acquisition cost

Unknown, patent applied for, U.S. Patent Application 2008/0286473.

Operational cost

Renewal rate is unknown.

Maintenance requirements

None, renewal requirement rate is unknown. SILC has been tested in up to five de-icing events and was effective during the last event.

Potential marine application and safety enhancement

Potentially, SILC could be used at any location where other coatings could be used, with similar cautions. This includes bulkheads, antennas, radomes, railings, and lattice structures. It is not known whether the material is slippery without additional testing. Although the developers speculate that SILC may be effective in wave wash areas, durability is unknown.

SILC is effective on automobile windshields for several months, so it may have special application for window areas that must be kept ice-free.

Marine technology readiness level

Marine TRL: 4.

Marine advantages and disadvantages

SILC may be effective for windows, but renewal requirements are unknown. Ice adhesion is very low; if SILC is effective with saline ice, it could be effective for safety equipment that must be easily de-iced, such as life rafts, gas sensors, firefighting equipment, and communications antennae. Durability will limit SILC to applications at locations with ready accessibility.

Marine technology transfer requirements

SILC needs to be verified for its capability in saline ice, rime, and snow conditions at temperatures between 0 and –40°C. The abrasion resistance and durability of SILC under a variety of conditions must be investigated. SILC must be evaluated over substrate materials found on offshore structures. Evaluation of the slipperiness of SILC will be critical for its use on walkways, stairs, railings, and helicopter landing pads.

NuSil Technology LLC—Silicone-Based Coatings

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Intended or actual application

NuSil Technology offers a family of silicone-based coatings intended to reduce the adhesion of ice to aerodynamic surfaces and structures, such as aircraft components manufactured from aluminum or composite materials. These silicone coatings are formulated as high-tear-strength elastomers, tailored for unique conditions and environments. Table B-1 lists several standard coatings considered for ice-phobic applications. Properties include fuel resistance and low volatile organic compounds (VOCs). Preliminary test results (Table B-2) show that the new coatings in Table B-1 have nominal shear stresses lower than 238 kPa, the shear strength of Teflon (unpublished results).

Table B-1. NuSil silicone-based ice-phobic coatings.

Part Number	Description	Cure
R-1009	1 part Excellent adhesion to unprimed substrates Especially broad operating temperature range	RTV*
R-1082	1 part Excellent adhesion to unprimed substrates	RTV
R-3930	1 part Fuel and solvent resistant Excellent adhesion to unprimed substrates	RTV
R-3975	1 part Fuel and solvent resistant Excellent adhesion to unprimed substrates Especially broad operating temperature range	RTV
R-2180	2 part Accelerated cure	Heat

* Room Temperature Vulcanizing

R-2180 is the most researched NuSil coating to date and is often used as a benchmark for comparison. In a study conducted by ERDC-CRREL, R-2180 was measured to have an ice adhesion strength of 37 kPa and a standard deviation of 14 kPa. This value is lower than any previously screened material or coating tested by ERDC-CRREL (Burkitt et al. 2010). For comparison, Teflon®, the industry low-friction material standard, exhibits an ice adhesion strength of 238 kPa; whereas bare aluminum, the test control, shows an ice adhesion strength of 1575 kPa, and bare carbon steel has an ice adhesion strength of 1414 kPa. R-2180 is also shown to withstand sand erosion and is resistant to many fuels, lubricants, cleaners, and de-icing fluids (Hoover et al. 2007).

Table B-2. NuSil silicone-based ice phobic coatings.

Typical Properties	R-1009 RTV Silicone Coating	R-1082 RTV Silicone Coating	R-3930 RTV Fuel Resistant Coating	R-3975 RTV Fuel Resistant Coating	R-2180 Heat Curing Silicone Coating
Viscosity	6,500 cPs 6,500 mPas	750 cPs 700 mPas	1080	1600	3600 cPs 3600 mPas
Non-Volatile Content	31%	29%	60%	60%	20%
Work Time	>72 hours	N/A	N/A	N/A	>72 hours
Solvent	VM&P Naptha (R-1001)	Xylene (R1-1001)	Tert Butyl Acetate (R2-1001)	Tert Butyl Acetate (R2-1001)	Xylene (R1-1001)
Cure Schedule (days @ ambient temperature & humidity)	7	5	3	3	*See Below
Specific Gravity	1.10	1.09	1.36	1.29	N/A
Durometer, Type A	40	25	35	23	40
Tensile Strength	1200 psi 8.3 MPa	1,425 psi 9.8 MPa	850 psi 5.9 MPa	425 psi 2.9 MPa	1,700 psi 11.7 MPa
Tear Strength	95 ppi 16.8 N/mm	125 ppi 22.0 kN/m	50 ppi 8.8 kN/m	Min. 35 ppi 6.2 kN/m	300 ppi 52.9 kN/m
% Elongation	650	950	400	400	1050
Recommended NuSil Primer**	SP-120 SP-121	SP-120 SP-121	SP-120 SP-121	SP-120 SP-121	SP-270

*30 min @ 25°C (77°F), 45 min @ 75°C (167°F), and 135 min @ 150°C (302°F).

**Some bonding applications may require use of a primer. NuSil Technology recommends the primers listed in the above table.

Operating environment

Silicones are often chosen for their ability to maintain elastomeric physical properties at extreme temperatures in which other adhesives, coatings, or encapsulants would fail. Silicones are used as mold release agents, waterproof coatings, and biomedical materials because of their highly unusual and desirable surface characteristics In general, they have a broad thermal operating range, typically from –65 to 240°C.

In addition to simulated icing conditions, R-2180 has also been extensively tested in simulated extreme environmental conditions. In Figure B-13, the ice adhesion values of freshly applied R-2180 are compared to values of R-2180, which has been distressed to simulate wear, thermal aging, and humidity and salt spray exposure (Hoover at al. 2007). Under all of these simulated conditions, R-2180 continues to perform better than Teflon®. These results suggest that silicone-based coatings may be effective in liquid water contents, droplet sizes, and temperatures defined by FAA FAR25 Appendix C (FAA 1991a).

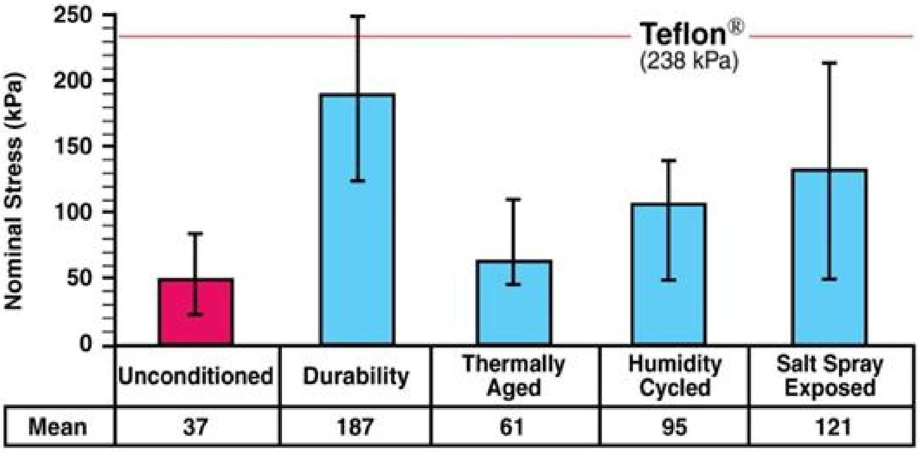

Figure B-13. A comparison of the ice adhesion of unconditioned R-2180 to simulated exposure of R-2180 to wear (durability) thermal aging, humidity exposed, and salt spray exposure.

Engineering concept

NuSil R-2180 is applied in a two-part process and must be cured using heat that can be implemented using an autoclave or oven. Compatibility with substrate surfaces varies with the material. When coating a surface with R-2180, a coupling agent is typically used as a primer before application to increase the adhesion of the coating to the surface.

Several new ice-phobic coatings, listed in Tables B-1 and B-2, were developed to achieve easy application and solvent resistance. These can be cured without the addition of heat. First, R-3930 and R-3975 are effectively resistant to solvents that may be useful in maritime as well as aviation environments wherein surfaces may be exposed to fuels, soaps, and de-icing fluids. Second, both R-1082 and R-1009 bond to difficult substrates, but corrosion is less of a threat with R-1009, which uses an oxime rather than an acetoxy cure. These two coatings can be pigmented and are easily applied through spraying. Knife coating can also be a viable application process if the substrate is a small, flat surface.

Figure B-14 displays ice-phobic performance results for R-2180, R-3930, R-3975, R-1009, and R-1082. Using the Zero Degree Cone Test, these silicone coatings were evaluated alone as well as in combination with R-1182. The red bars on the graph represent these latter results; the blue bars, the ice-phobic coatings by themselves. R-1182 is a one-part, fast cure RTV complementary silicone coating that prevents the silicone from being a particle gatherer. R-1182 can be walked on and is easy to clean.

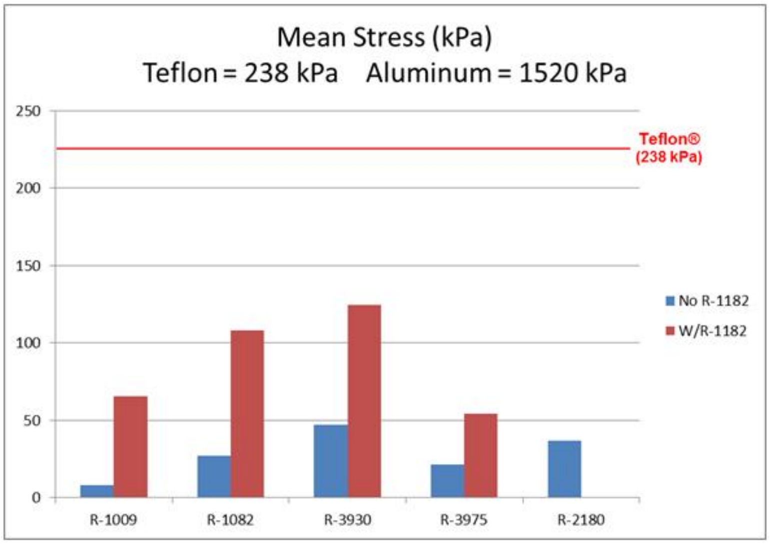

Figure B-14. Ice adhesion results for silicone ice-phobic materials with and without R-1182 on bare 2024 aluminum.

Technology readiness level

TRL: 8–9.

De-icing or anti-icing

These coatings are de-icing technologies. They do not prevent ice formation, but they do allow ice to break easily from surfaces. As shown in Figure B-13, R-1009 exhibited the overall lowest ice adhesion strength measured by CRREL. R-3975 had the lowest ice adhesion strength of the two fuel resistant coatings, as well as the lowest overall result when the coatings were tested in combination with R-1182. R-3975 also showed the lowest discrepancy in ice adhesion strength from being tested alone to being evaluated with R-1182 coated on top.

Current advantages and disadvantages

R-2180 must be heated in an oven or autoclave for curing, unlike R-1009, R-1082, R-3975, R-3930, and R-1182, which can room temperature vulcanize and thus do not require high temperatures for curing. All of the coatings are erosion resistant. Compared to the other ice phobic coatings, R-3975 and R-3930 have lower elastomeric properties—a tradeoff for their resistance to fuel and organic solids. Please note that these coatings now have over 8 years of flight heritage with the United States government on military aircraft.

Current acquisition cost

Contact NuSil Technology at +1(805)684-8780.

Operational cost

Contact NuSil Technology at +1(805)684-8780.

Maintenance requirements

Vary by coating and environment.

Potential marine application and safety impact

NuSil's R-2180 would be useful for coating small parts that would fit into and withstand the temperatures reached inside an autoclave. This includes valves, communication antennas, firefighting equipment, and possibly some rescue equipment, such as escape pod doors and hawser components. R-2180 is not recommended for large objects that are not portable or will not fit into an autoclave, or for objects that cannot withstand high temperatures. However, the other silicone-based coatings featured in this section may provide an alternative solution for larger surfaces or surfaces that cannot withstand heat. The low adhesion strength of ice to these coatings may help reduce the effort needed to shed ice from safety equipment.

Marine technology readiness level

Marine TRL: 7.

Marine advantages and disadvantages

R-2180 may be useful in marine as well as aviation applications. In the saline environment, the adhesion strength of ice to R-2180 was cited at 121 kPa (Hoover et al. 2007). This is higher than for freshwater ice, but still very low. It should be noted that aside from testing in simulated marine environments, R-2180 does not have the history of use in marine applications that it has in the aircraft industry. R-2180 is also a two-part material that requires heat to cure, limiting application to small articles resistant to heat, which is not ideal for large structures. NuSil recommends a ramped cure from 30 minutes minimum at ambient temperature and humidity, to 45 minutes at 75°C (167°F), and ending in 135 minutes at 150°C (302°F). New formulations, such as R-3975 and R-1082, may be applied to larger offshore structure areas and will cure without the addition of heat. NuSil's silicone ice-phobic coatings may also be useful on lock walls, electrical transmission lines, roofs, and antennas.

Marine technology transfer requirements

Test new elastomeric formulations in marine and industrial offshore environments for slipperiness in application to decks, stairs, helicopter pad, and work areas. Test all coatings on substrate materials found in the offshore environment.

Oceanit Laboratories, Inc.—Anhydra coating

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Intended or actual application

Anhydra technology is intended to be used as a water repellant, corrosion resistant, ice-phobic, and super-hydrophobic coating for protecting metal structures exposed to water (fresh or salt) ice at extreme temperatures (−25 to 70°C).

Operating environment

The operating environment for the developed coating will be rain, snow, fresh and sea water, mist, fog and icy conditions.

Engineering concept

Anhydra works on the principle of creating extreme surface roughness combined with a low surface energy coating, resulting in a surface unfavorable for water or ice crystals to adhere.

Technology readiness level

TRL: 4.

De-icing or anti-icing

Anhydra is an anti-icing/ice-phobic coating that would prevent the formation of ice on the coated surface.

Current operating characteristics

Anhydra is a coating on metal surfaces to prevent ice formation. It does not require any power for operation.

Current acquisition cost

Not yet available.

Operational cost

Not yet available.

Maintenance requirements

The Anhydra coating is expected have a long operational life (at least 24 months) with no intermediate maintenance required.

Potential marine application and safety enhancement

Anhydra coating is expected to be an exterior coating on marine vessels, pipes, shafts, propellers, decks, deep sea and oil/gas pipelines etc., and can be used in extreme environments.

Marine technology readiness level

Marine TRL: 4.

Marine compatibility

Preliminary experiments conducted on the Anhydra coating proves that it is compatible with the marine environment (seawater, pH and temperatures –20 to 40°C). Oceanit is currently investigating the production and application cost of the coating technology for marine application.

Marine technology transfer requirements

The Anhydra coating technology is designed for use in marine environments and hence no technology transfer is required.

Ross Technology—NeverWet SE

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http://www.rosstechnology.com/

Intended or actual application

The Ross Technology NeverWet SE super-hydrophobic coating is being developed to provide corrosion resistance, to improve performance of boats by reducing drag, and decreasing icing on overhead transmission cables, satellite dishes, antenna towers and aircraft. This technology also may reduce the friction of liquid flow through pipes and protect metals from corrosion. NeverWet SE was a 2008 R&D 100 award winner (R&D Daily 2008). NeverWet SE developed in collaboration with the University of Pittsburg and Oak Ridge National Labs.

Operating environment

Ross Technologies has not identified specific operating environments for NeverWet SE. However, informal testing in freezing rain storms with the coating applied to a satellite dish and a metal plate show significantly less ice accumulation on coated areas, assuming that both areas were similarly exposed (Fig. B-15) (Ross technologies 2009). Coated model boats showed an average 7–8% increase in speed over uncoated hulls. Coated magnesium also showed less corrosion than uncoated magnesium when similarly exposed (Ross Technologies 2009).

Figure B-15. Ice-free NeverWet SE coated surface (right), and ice-covered uncoated surface (left), of satellite dish after freezing rain storm (Image courtesy Ross Technologies).

Engineering concept

NeverWet SE is a powder coating that reduces total energy at the water-interface surface. Using a borosilicate, the nanostructure NeverWet SE surface consists of more than one million spiked cones per square centimeter (R&D Daily 2008). These cones achieve a water droplet contact angle of 160 to 165° by preventing water from entering pores between the spiked cones. The coating uses the Lotus leaf effect to reduce droplet adhesion. Air is trapped throughout the porous amorphous silica, which also provides thermal and electrical insulation and reduces water-based corrosion. Ice formation on surfaces is prevented because of the high contact angles of drops to the surface, causing drops to roll off before they freeze and adhere. The company has not conducted tests of the adhesion strength of ice, if it forms, to the surface.

Durability of the coating's ability to remain on a substrate has been evaluated using a rubbing test. A 500-g weight with fabric on the bottom is rubbed over the coating. Change in rubbing resistance is a measure of durability. However, results are not yet available that indicate how long a coating will remain on a surface, or how long it will remain effective as a hydrophobic material operationally.

The coating can be applied to surfaces by spraying, brushing or dipping. However, required conditions of the substrate and temperatures for application are not specified.

Technology readiness level

TRL: 4.

De-icing or Anti-icing

Anti-icing.

Current advantages and disadvantages

The coating prevents icing by causing drops to roll off of the surface. The NeverWet SE also reduces corrosion and friction of fluids with the surface. The durability of the material with regard to its ability to remain attached to substrates, and its ability to remain super-hydrophobic are unknown. Conditions required for applying the coating to substrates and the adhesion strength of ice to NeverWet SE are unknown. Only informal testing of anti-icing capability has occurred.

Current acquisition cost

Coating costs are application dependent and are provided on a case by case basis.

Operational cost

Unknown, it is too early in development.

Maintenance requirements

Unknown, as it is too early in development. No testing has been performed to determine how long coating is effective. Only relative durability tests to other coatings have been conducted. The ability to repair the material in the field is unknown.

Potential marine application and safety enhancement

The Ross Technologies coating resists the adhesion of fresh water droplets and causes them to roll off of surfaces preventing ice formation. NeverWet SE could be used on inclined surfaces, and surfaces exposed to wind, which could cause drops to roll from surfaces before freezing. Bulkheads, cables, safety gear such as firefighting equipment and life rafts, and possibly decks are potential applications.

Marine technology readiness level

Marine TRL: 3.

Marine advantages and disadvantages

NeverWet SE reduces ice accretion by causing drops to roll-off before they freeze. A similar capability for saline water would reduce ice accretion on surfaces where water could drain freely. The adhesion strength of ice to NeverWet SE, its durability, the longevity of its hydrophobic capabilities, its ability to work in salt water, the adhesion of wind-blown drops, and the effects of contaminants on the surface are unknown.

Marine technology transfer requirements

Assess coating longevity. Assess coating compatibility and effectiveness on variety of substrates. Determine coating capability with saline water, and ice adhesion strength. Determine slipperiness of coating. Assess compatibility with communication antenna performance characteristics.

Seashell Technology LLC—Hydro-bead

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Intended or actual application

Seashell Technology, after completion of an Air Force SBIR Phase II project, initialized the commercial sale of a super-hydrophobic (ultra-hydrophobic) Lotus-leaf-based coating branded under the trade name Hydro-bead (www.hydro-bead.com). When unfrozen water droplets strike the coating, the water droplets bead into spheres and roll off the surface. Applications include any structures that ice, including fixed-wing aircraft, wind turbines, roofs, and offshore structures. The coating reduces ice buildup on vertical or near vertical surfaces by inhibiting the accumulation of water droplets and greatly reduces the ice adhesion to the surface. Testing has shown that the ice adhesion can be reduced by up to a factor of 11 times relative to the adhesion to ice on bare aluminum. Additional testing has demonstrated the coating's anti-icing capability in real-world and icing wind tunnel environments. Research is ongoing on demonstrating the ice-phobic coating on aircraft and remotely piloted aircraft (RPA). The company also has a commercially available two part super-hydrophobic coating that offers superior corrosion protection for marine structures.

Operating environment

The coating was tested in "Midwestern winter conditions" and performed successfully. The company indicates that preliminary studies show that the material will perform successfully in snow, rime ice, and clear ice conditions. Testing at the NASA Glenn Icing Research Tunnel and at the Cox & Company icing research tunnel has shown that the ice-phobic coating enhances anti-icing performance when used in conjunction with other anti-icing systems (e.g., electro-expulsive systems). If certified for use on aircraft, the coating would need to perform acceptably in FAA FAR25 Appendix C super-cooled cloud droplet conditions (FAA 1991a).

Engineering concept

The Seashell coating is super-hydrophobic and mimics the well-known Lotus leaf effect. Water droplets lying on the coating surface exhibit a contact angle with the surface greater than 150°. The droplets are nearly spheres and roll off the coated surface at low sliding angles (<5°).

The coating formulations are designed so that the resulting coating surface topology mimics the surface of a Lotus leaf. Lotus leaf surfaces are super-hydrophobic owing to surface topography that consists of a dense population of topographic peaks with air within valleys between the peaks. Droplets attach to the peaks and due to water surface tension the droplet is held to the surface with little energy. Figure B-16 shows a drop of water on a surface with high adhesive energy without the Seashell coating (right), and with the Lotus leaf effect and low surface energy caused by the Seashell coating (left). The coating is being developed using procedures similar to any paint, allowing it to be used in any application where most paints are used. Additional details of the coating are proprietary. Tests of coating longevity under a variety of conditions have been completed.

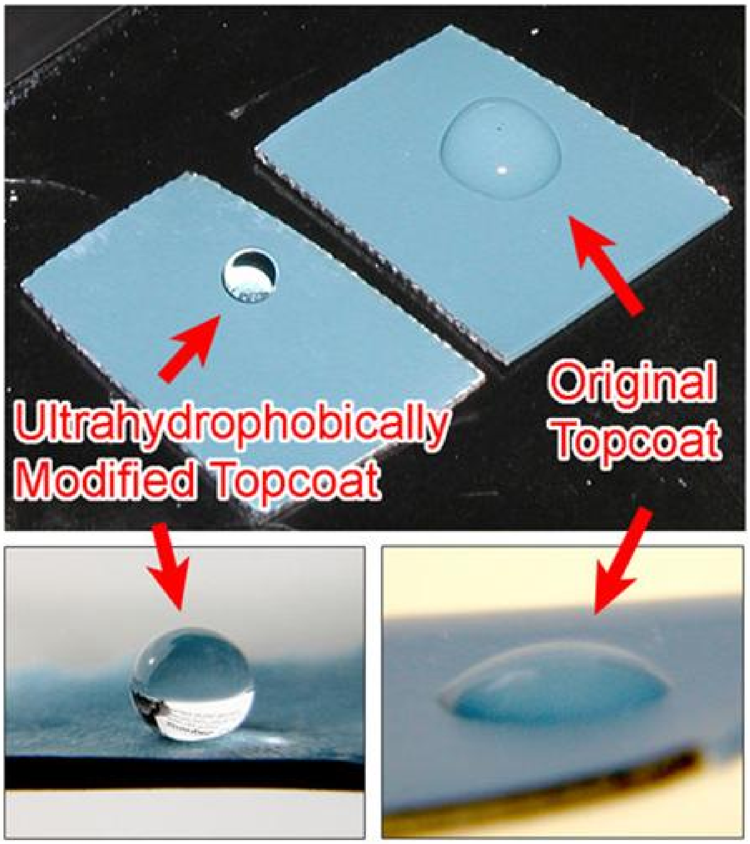

Figure B-16. Droplet contact angle on original substrate coating and after coating with Seashell super-hydrophobic (ultra-hydrophobic) coating.

Technology readiness level

TRL: 6. Coating has been demonstrated on model airfoils under simulated icing at accredited icing research centers.

De-icing or anti-icing

Hydro-bead is de-icing capable when used with other de-icing systems to minimize power requirements associated with ice removal. The coating is anti-icing capable when used to minimize power requirements of anti-icing systems by minimizing supercooled water wetting of a surface. In general, coatings reduce ice adhesion strength and do not prevent the formation of ice on horizontal surfaces or at air flow stagnant locations such as the leading edge of an aircraft wing.

Current advantages and disadvantages

Advantages include reducing ice adhesion and power consumption for ice removal when used in conjunction with de-icing and anti-icing equipment. Ice buildup is also minimized under vertical or semi-vertical conditions (roofs or other inclines). Disadvantages include the need for maintenance coatings if the super-hydrophobic property of the coating is diminishing.

Current acquisition cost

The coating is competitively priced with similar paint systems like marine and aircraft coatings.

Operational cost

None—passive technology.

Maintenance requirements

Periodic cleaning or renewal may be necessary depending on the application. Longevity test results are similar or better than other paints. Oils and other apolar materials can wet the surface and will need to be cleaned to restore the super-hydrophobic property of the coating.

Potential marine application and safety enhancement

The coating can be applied to most surfaces, except windows, as the coating is not transparent. The coating is very useful to maintain traction on wet walkways since water does not fully wet the surface. The coating could be applied to cables. If applied to bulkheads and overhead surfaces with walkways or work areas beneath, ice could fall and accumulate on those surfaces, causing a potential hazard. The material should reduce ice accumulation on support structures below the main deck. It may also assist ice removal on supply boats.

Marine technology readiness level

Marine TRL: 6. Seashell Technology indicates that the coating has been tested and works effectively in fresh and saline water. The coating has been used on boat hulls to minimize drag.

Marine advantages and disadvantages

The technology has the potential to assist active de-icing and anti-icing technologies in an offshore environment. In addition, the technology could be sufficiently ice-phobic that it prevents the formation of ice on Coast Guard cutters with their intrinsic operational vibration. Recoating frequency, resistance to abrasion and wave wash effects will affect where the material is used and its practicality. The effects of abrasion, oils, and other apolar materials on the coating's surface will diminish the superhydrophobic characteristics and may require cleaning or recoating to restore performance.

Marine technology transfer requirements

The ability to withstand abrasion, renewal requirements, resistance to wave wash, and effectiveness with saline ice must be investigated through a controlled test and evaluation program. If used on communication antennas, the material's dielectric properties will need to be investigated and tailored to the application. The potential use of the coating on cables and its ability to assist a variety of active de-icing and anti-icing technologies should also be evaluated.

Covers

See Ryerson (2009).

Expulsive[1]

Cox & Company, Inc.—Electro-Mechanical Expulsive De-icing System (EMEDS) with Electro-Thermal Subsystems

Cox & Company Inc.
1664 Old Country Rd., Plainview, NY 11803
Tel: 212-366-0200
Fax: 212-366-0222; 212-366-0283
http://www.coxandco.com

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[1] See also Ryerson (2009).

Intended or actual application

EMEDS (Electro Mechanical Expulsion De-icing System) is a Low Power Ice Protection System that is proprietary to Cox & Company. EMEDS can be applied either independently or in combination with an Electro-Thermal Subsystem. EMEDS is in production and development for use on aircraft certificated to FAR 23 and FAR 25 requirements for Flight into Known Icing. It is currently in development and production on military aircraft for which ice protection is essential to mission completion. The military applications include transport category aircraft and Unmanned Aircraft Systems (UAS).

While the applications to this point have been for use on aircraft, there are no issues that would prohibit its application elsewhere, including shipboard applications. These applications are currently under study.

Operating environment

For aviation applications, the operating environment is the aircraft icing environment as defined by FAA Federal Aviation Regulation (FAR) 25 Appendix C (FAA 1991a). In FAR 25 Appendix C, cloud water contents range from approximately 0.2 to 3.0 g/m^3. Mean effective drop diameters range from about 15 to 50 µm, and temperatures range from 0 to –30°C. Though aircraft can encounter larger drops, such as supercooled drizzle and supercooled rain, the FAA does not require aircraft to be certified to those conditions. Therefore, ice protection systems are not tested in those conditions even though the ice protection system design may protect from large drop conditions. The system is designed to protect the leading edges of lifting and stabilizing surfaces of fixed-wing aircraft.

Shipboard applications may encounter other environmental conditions, such as water spray that are defined by similar parameters.

Engineering concept

The Engineering Concept and purpose is to provide acceptable levels of ice protection using the least amount of power. Whenever the degree of ice protection is not sufficient using EMEDS exclusively, then it is possible to combine either anti-icing or de-icing heater technology with EMEDS and to coordinate their operation to achieve an acceptable level of ice protection with the least amount of power.

EMEDS description

EMEDS is a de-icing system that removes ice by using sequentially fired actuators to apply small displacement, high acceleration impulses to the leading edge skin of a wing or aerodynamic surface. Ice is accreted on the leading edge skin and is removed in a timed sequence where individual actuators are fired in a pre-programmed pattern characterized by a firing rate and a cycle rate which is the time required to complete the deicing of all of the aircraft's surfaces. Once a cycle is completed the system may start again at the beginning or may wait for some time for the ice to reach a critical height.

EMEDS is composed of the following basic components.

- De-icing Control Unit (DCU). The DCU controls the distribution and timing of energy within the system. It conventionally provides Built-in-Test and continuous monitoring of the health and operation of the system. It receives power from the aircraft (in this case) which it then distributes to the ESB.
- Energy Storage Bank (ESB). The ESB is essentially a bank of capacitors that accumulates electrical energy and solid state switches that distribute a high current pulse to each.
- EMEDS Actuator. The actuator is the critical component upon and around which EMEDS is configured. The actuator is a printed electrical circuit that is rolled into a cylindrical shape approximately 0.5 in. diameter in cross section. The actuator is shown in Figures B-17 and B-18. This particular actuator is the base-line design, but actuators of other designs have been developed and are in current use. They all have the same basic configuration and operating principle.

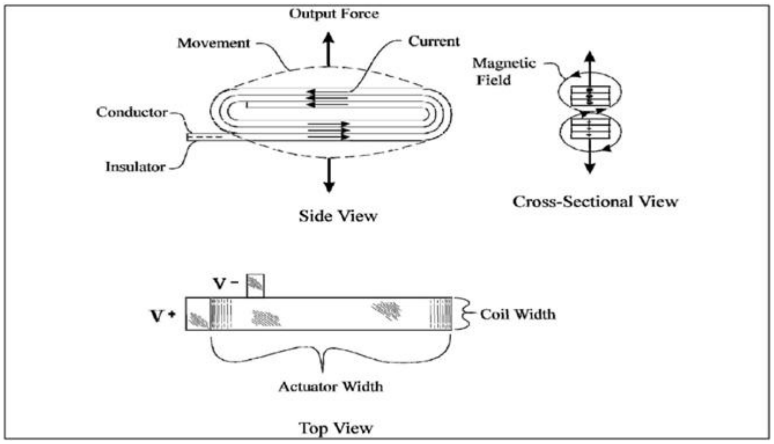

Figure B-17. EMEDS Actuator side, plan and cross section views.

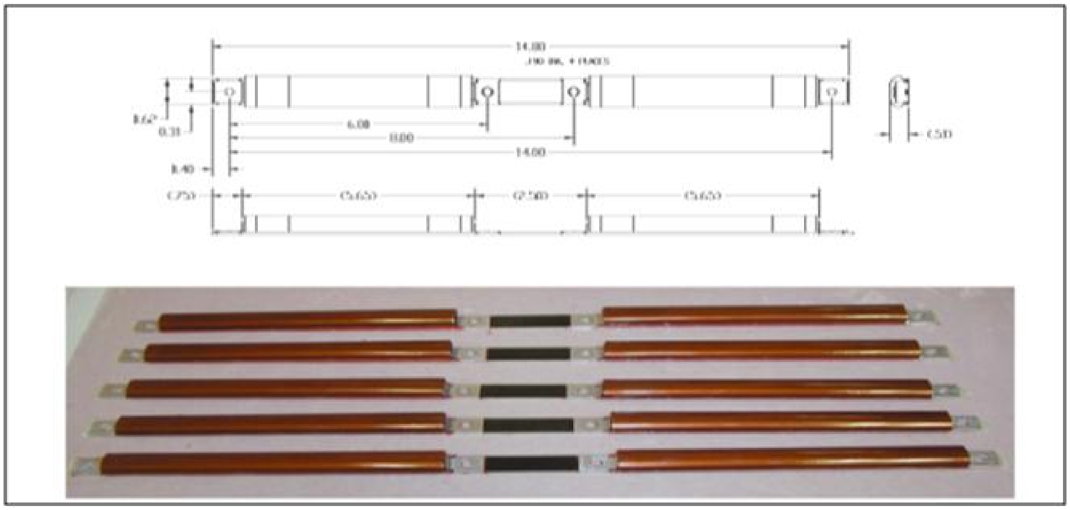

Figure B-18. EMEDS actuator dimensions (Al-Khalil 2007) and photograph.

Actuator operation

A 100-μs duration high-current electrical pulse delivered to the actuators from the ESB at the direction from the DCU in carefully controlled timed sequences generates opposing electro-magnetic fields that cause the actuators to change shape rapidly. This change of the actuator shape is transmitted to the erosion shield causing it to flex, resulting in acceleration-based debonding of accumulated ice on the erosion shield. The accreted ice is shattered and carried away in the slip stream. The skin accelerates and deflects approximately 0.635 to 1.02 mm in less than 0.001 s. Ice as thin as 1.5 mm can be shed. The EMEDS has been demonstrated on 0.40-mm-thick stainless steel skins, aluminum skins 1.0-mm thick, and composite skins of equivalent thickness (Fig. B-19).

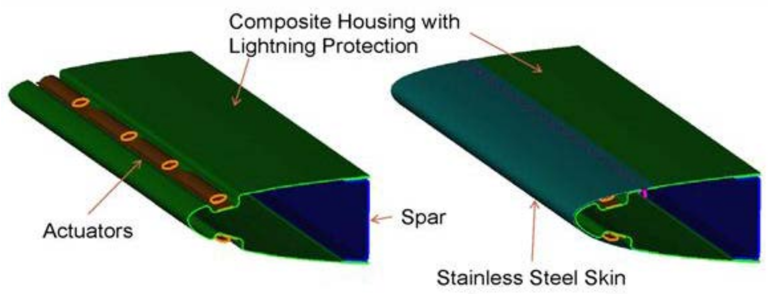

Figure B-19. Composite LEA with metallic external surface.

The remaining EMEDS component is the Leading Edge Assembly (LEA), which is the aircraft structure into which the EMEDS actuator is mounted. In non-aviation applications, the assembly may take different forms and functions primarily as the Actuator Housing Assembly.

The LEA is a structural member of the aircraft and is modified or purpose designed to restrain the actuator in both chord- and span-wise positions. It also provides structural support against which the actuator exerts downward (or upwards as may be the case) force. The LEA includes a semi-rigid external surface upon which ice accumulates. As the actuator fires, it flexes the external surface just enough to cause the ice to debond. The external surface is sufficiently rigid to retain its aerodynamic shape and is sufficiently flexible (“semi-rigid”) enough to remove ice whenever the actuator strikes the inside surface.

Another LEA of conventional aircraft structure fabricated from aluminum is shown in Figure B-20. The thickness of the aluminum skin where the actuators are located is tailored to be sufficiently flexible while retaining basic structural rigidity required, satisfying aerodynamic requirements.

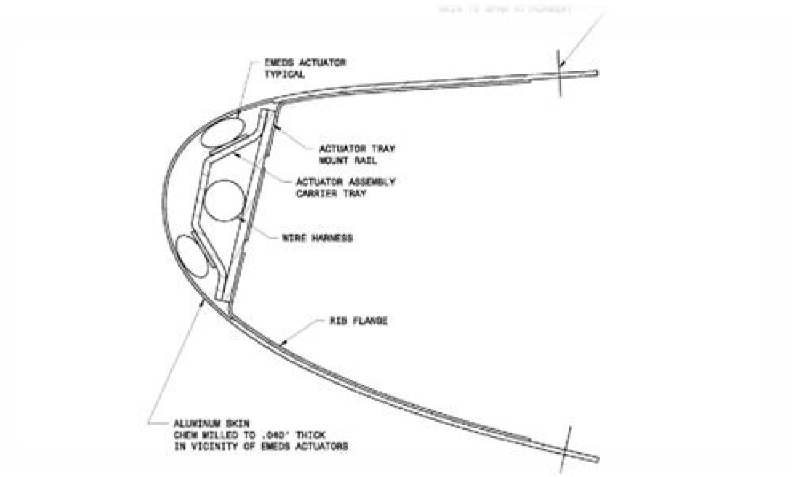

Figure B-20. Conventional aircraft construction LEA.

The LEA shown in Figure B-20 has two rows of EMEDS actuators mounted onto Actuator Assembly Trays which are attached onto truncated wing-ribs.

The LEAs shown in these figures are typical of existing EMEDS applications. Both show two rows of EMEDS actuators. In some installations, only one row is required. Both LEA configurations shown have metallic external surfaces. Others use composite external surfaces.

EMEDS/ETIPS combinations

The degree to which the ice removal capabilities of EMEDS are acceptable is determined by the aerodynamic requirements of the surface and the extent to which these requirements are compromised by ice accumulations. In some cases, the ice removal capabilities of EMEDS may not be sufficient to satisfy the aerodynamic requirements of the applications and EMEDS is then combined with Electro-Thermal Ice Protection subsystems to provide the level of ice protection required. For example, no de-icing system is capable of providing anti-icing levels of ice protection. In cases in which protection to this degree is required, then EMEDS is combined with an appropriate Electro-Thermal Ice Protection System (ETIPS). The particular aerodynamic requirements as well as the available electrical power availability are factors in determining the type of ETIPS is appropriate; anti-icing or de-icing.

Combining EMEDS with an ETIPS of either anti- or de-icing mode will require more power than EMEDS alone, but the level of protection often approaches that of thermal systems that use considerably greater power than does the EMEDS/ETIPS combination.

Every aeronautical ice protection system, including EMEDS, is intended to satisfy an aerodynamic requirement. EMEDS as shown in the preceding installations is capable of removing ice accumulations to a relatively low level, nominally of the order 1.5 mm distributed over the protected surface. Aircraft for which this level of protection is satisfactory are currently in operation and certificated to FAA requirements. In a non-aeronautical application, the requirement may be the removal of ice formations on other critical surfaces.

EMEDS/anti-icing ETIPS

The EMEDS/Anti-icing combination is designed to keep the roughness sensitive zone of the leading edge free of ice. This type of ice that commonly has the texture of sand paper, can pose significant aerodynamic hazards. As EMEDS cannot remove very low levels of ice accumulations, an anti-icing heater is placed on the non-breeze side of the leading edge within zone to be protected to prevent the formation of this ice. The chordwise extent of the anti-icing heater is limited to the roughness sensitive zone and the power level is only sufficient to prevent ice formation. Because the heater does not cover the full chord of the leading edge, the water will freeze at some point downstream. This is the chordwise point at which the EMEDS actuator is located.

In this application, EMEDS does not remove ice accumulation from within the impingement zone, but only the runback-refreeze ice that accumulates aft of the heated zone.

This system has been called the “Hybrid EMEDS Ice Protection System,” and is shown in Figure B-21. This system is described by Al-Khalil in his AIAA paper (Al-Khalil 2007).

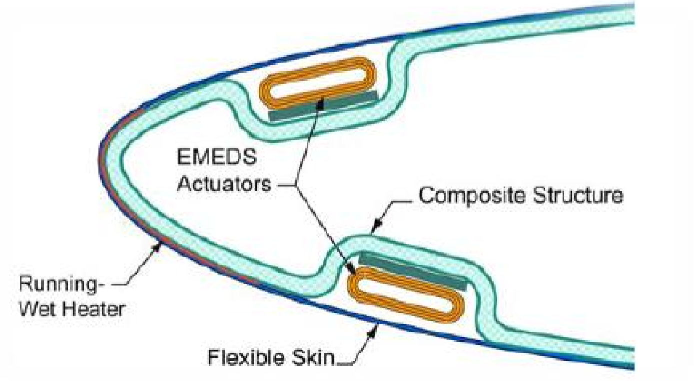

Figure B-21. EMEDS/Run-wet Hybrid Anti-Icing ETIPS (from Al-Khalil 2007). EMEDS is the Electro-Magnetic Expulsion De-icing System component.

To summarize, the running-wet anti-icing heater prevents ice from accumulating within the ice impingement region of the leading edge and allows run-back ice form directly downstream of the heated leading edge roughness-sensitive zone. This ice is removed by lower power EMEDS periodically before it can grow to a size that causes aerodynamic losses.

This type of Hybrid Anti-icing EMEDS is in production and service on FAA certificated aircraft.

TMEDS—Thermal Mechanical Expulsive De-icing System

Another EMEDS/ETIPS is a combination of de-icing ETIPS with EMEDS. It uses less power than the Anti-ice Hybrid System described above because the electrically heated area is a small fraction of that used by for the anti-icing hybrid. This application is suitable for airfoil sections that are tolerant of more ice residuals than the anti-icing hybrid, but less so than the conventional EMEDS-only applications. As opposed to the anti-icing hybrid configuration in which the leading edge is continuously heated span-wise, this approach subdivides the span into segments that include both ETIPS heaters and EMEDS actuators. The heaters and EMEDS actuators are operated in a coordinated fashion to improve the ice-release performance of the EMEDS actuator by reducing the ice adhesive bond through the application of local heat. For the case of the anti-icing hybrid, the leading edge is heated continuously. In this configuration, ice is permitted to accumulate to within acceptable limits, and is removed periodically. This periodic heating reduces the ice surface bond strength and improves EMEDS effectiveness which results in more efficient and complete de-icing. At near-freezing ambient temperatures the system requires 1.5-sec heating. Near –30°C, each zone requires about 5-sec of heating to melt the interface ice. This system is called the Thermo-Mechanical Expulsion De-icing System (Al-Khalil 2007) or TMEDS.

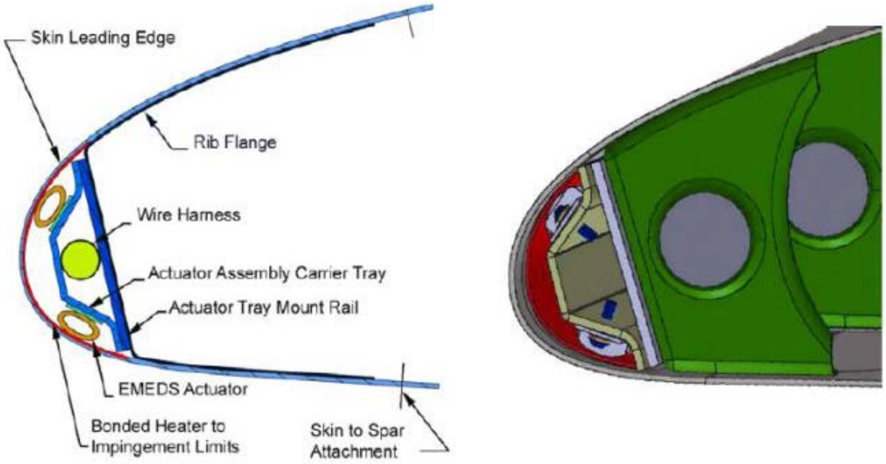

Figure B-22. EMEDS/ETIPS DE-icing TMEDS configuration in an airfoil (from Al-Khalil 2007).

A typical TMEDS installation is shown in Figure B-22. This installation is for a conventional rib and skin construction and uses an Actuator carrier Tray mounted onto truncated ribs. TMEDS is also in development and production on aircraft that are fabricated from composite materials.

Technology readiness level

TRL: 5–6. EMEDS, EMEDS/Anti-Icing ETIPS “Hybrid,” and TMEDS are currently in development, production, and service on aircraft certificated by the FAA and other authorities for Flight into Known Icing.

De-icing or anti-icing

As determined by requirements of the application. EMEDS is a de-icing system that can be combined with either an Anti- or De-icing ETIPS.

Current advantages and disadvantages

The system removes thin layers of ice and leaves little residual. Power consumption is lower as compared to thermal systems that provide equivalent levels of ice protection. The system requires that the aircraft structure be designed to accommodate the EMEDS actuators and, as the case may be, electrical heaters bonded to the non-breeze of the surface skin. While it is not readily retrofitted, it is easily built into airfoils at the initial phase of aircraft design or into existing structures with reasonable levels of modification.

Acquisition cost

Competitive with existing alternate ice protection systems. Each application is a custom design and fabrication.

Operational cost

Heater power density is about 5.4 W/cm^2. Simulation of four technologies protecting a 50,000-cm^2 area showed that electro-thermal evaporative anti-icing consumed 160 kW, the run-wet system Hybrid consumed 55 kW, the low-power TMEDS required only 18.4 kW (Al-Khalil 2007), and the EMEDS alone consumed <1 kW.

Maintenance requirements

There is no regularly scheduled maintenance for existing aircraft installations.

Potential marine application and safety enhancement

The EMEDS/ETIPS hybrid combinations could be built into flat panels for use on ships. The system may not be usable on complex surfaces or walkways, but could be useful on bulkheads and hatches and possibly on hulls below the main deck near the sea. In the event that ice accumulation on power system air intakes poses difficulties, EMEDS/ETIPS may offer a way to remove ice formations before they can grow to unacceptable sizes, while using very low levels of power.

Marine advantages and disadvantages

The system would allow efficient de-icing and would clean areas thoroughly. However, the thin skins, if necessary in a non-aviation application, may be susceptible to damage in the heavy industrial environment, and from potential wave impact if used near the sea surface. The EMEDS will allow ice debris to form at the base of vertically oriented surfaces if used on bulkheads. If used on flat surfaces such as hatches, the system has no method of removing loose ice from the surface without a slip stream. Electrical safety would need to be considered in a saline environment. System capability with the different physical properties of sea spray ice is unknown.

Marine technology readiness level

Marine TRL: 4.

Marine technology transfer requirements

A test and development is necessary to determine the effectiveness of the system in the marine environment. This would include testing in saline ice conditions, electrical safety, evaluation of robustness of the system in a marine and heavy industrial environment, and evaluation of the potential for application to surfaces of various shapes and orientations.

Ice Management Systems Inc.—Electro Expulsive De-icing System (EEDS)

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The IMS Electro-Expulsive De-icing System (EEDS) technology was invented by NASA Ames (Haslim and Lee 1987) for de-icing and anti-icing aircraft. Development of the technology from a prototype through commercialization was attempted by several companies, but IMS is the only successful vendor of the technology. The IMS technology is being used operationally on aircraft. The IMS EEDS has been tested in icing tunnels for proof of concept using Hunter UAV, Lancair 4P, and Cessna 337 airfoils and Westland Helicopter rotor blades and engine cooling duct. The IMS EEDS was also tested for de-icing the walls of navigation locks on the Illinois River and was demonstrated at Lock 25 on the Mississippi River at Rock Island (Fig. B-23). The company is now in production on four Unmanned Aerial Systems (UAS) programs: MQ-1, MQ-9, Watchkeeper, and TAI Anka. Applications for new UAS programs and commercial programs are in process.

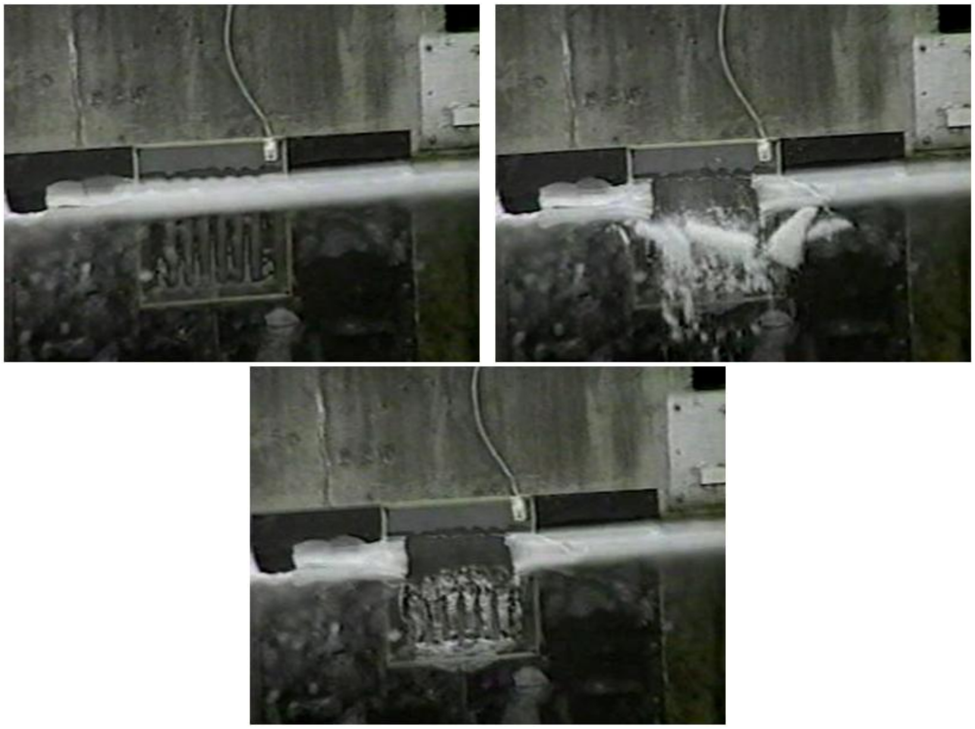

Figure B-23. Nominal 1-m square EEDS on the Mississippi River lock wall removing collar ice with a single pulse (courtesy N. Mulherin 2008). Sequence is from first from left image before pulse, to second image during the pulse, and last image after the pulse.

Operating environment

The IMS EEDS has been used in atmospheric icing conditions on airfoils in glaze (clear ice) and rime icing conditions—principally on unmanned aerial systems (UASs). It has also been used in navigation locks to remove ice that adheres to lock walls and prevents lock gates from fully opening. Although the system tolerates the frequent flooding of a lock, it operates most successfully when used in the atmosphere rather than under water. Therefore, the technology could operate on ship hulls. Though the technology is claimed to be applicable to the marine environment and usable on marine hatch covers and antennas (IMS 2007), and more (Embry et al. 1990), the technology has not been tested in the saline environment and with superstructure ice formed with seawater.

Engineering concept

The fundamentals of EEDS are explained by Ryerson (2008). The EEDS comprises two electrically conductive strips sandwiched between layers of carbon fiber or fiberglass sheet material (IMS 2007). Electrical current passed through the conductors (up to 500 V at 8000–10,000 A for 1–2 ms) causes magnetic fields to form in the two conductors that repulse and push the two conductors apart with an acceleration of up to 60,000 g with a cuff movement of 2 to 2.5 mm. The system is typically pulsed every 45–90 s in an aircraft ice accretion event.

The IMS EEDS conforms best to flat and convex surfaces such as the leading edge of airfoils. It is more difficult to apply to compound curves and concave surfaces. The leading edge cuff is typically structural carbon fiber or fiberglass. The system consists of two components; a power system comprising controllers and capacitors, and the EEDS cuff system. In addition, there are cables, ice detectors, indicators, and controllers. Because of the potential for electrical leakage should the surface be damaged, the system has a smart box controller that identifies electrical leaks, opens, and shorts, and disarms the portion of the system that fails. In addition, the capacitors are always discharged until the activation event. Voltages and amperages can vary based on the need. Electromagnetic interference (EMI) or radio frequency interference (RFI) are controlled through judicious use of grounding, shielding and filters, and all aircraft requirements have been passed to Mil Std 461 requirements (DoD 1999).

The IMS EEDS cuff mean time between failures (MTBF) is at least 144,000 cycles, or typically a 15-year service life. However, cuffs have been tested at over 250,000 firings without failure. Capacitors are rated at 1 million cycles. The EEDS is used primarily on composite structures, but can also be used on metal. Fatigue testing for composite materials is planned over a range of temperatures. No composite material has been known to fatigue with the system.

Technology readiness level

TRL: 8.

De-icing or anti-icing

The IMS EEDS principally de-ices and leaves very little residual ice. However, a form of anti-icing can occur if the system is cycled with sufficient frequency that insignificant ice accretes between cycles.

Current advantages and disadvantages

The EEDS has de-ice and anti-ice capability. The EEDS can be readily combined with ice-phobic coatings for greater efficiency. The system easily conforms to flat and simple convex surfaces, but concave and complex surface shapes are also achievable.

Current acquisition cost

The active surface is not COTS. However, the power system may be, depending upon the application. As an example, the acquisition cost of designing and installing a system on a 10-m wingspan aircraft is about $250,000-$500,000 depending upon requirements. Flat panels in a non-aviation application may be less costly.

Operational cost

Based on the ice protection performance requirements and system configuration of the airframe determined by analysis or test, system power requirements range from 300 to 700 watts RMS (IMS 2007). Power consumption is about 450 W average for an entire aircraft for one pulse. Laboratory and field tests by CRREL measured the system's power consumption using a recording wattmeter, and showed that a nominally 1-m^2 panel used approximately 700 W/m^2 during each 10-s charging cycle prior to firing (Mulherin and Miller 2003).

Maintenance requirements

Capacitors must be replaced after about 1 million pulses. There is no other maintenance aside from periodic inspections.

Potential marine application and safety enhancement

The IMS EEDS would be effective for the superstructure ice accretions and could be used on railings, hatch covers, and bulkheads. The system will form ice debris after firing, and will cause ice pieces to fly during activation; therefore, it should be located where equipment and crew cannot be affected by flying ice or by ice debris lying on decks or stairs. The IMS EEDS is sufficiently robust for potential application to areas with spray and wave splash. It could also be used on railings and other structural elements where heavy impacts would not occur, and where the surface would not be cut or penetrated. It should be applied in locations where flying ice is not a hazard and where ice debris accumulation would be a hazard.

Marine technology readiness level

Marine TRL: 5.

Marine advantages and disadvantages

No problems are anticipated in the saline environment; EEDS should operate successfully, even on handrails and tight radii. Effect of soft marine sea ice on de-icing needs to be tested. The system could work in wave wash areas. It may not be practical to use where ice projectiles could injure personnel and ice debris could litter work areas, clog machinery, or endanger personnel. The technology is proven to work in a harsh fresh-water environment in locks.

Marine technology transfer requirements

The IMS EEDS is not COTS—it must be packaged for each operating environment. Elements of design include the shape and size of the area to be de-iced, the adhesion strength of the ice to the surface, and the structure to which the EEDS panels must be attached. Analyses would be required to determine the effects of wave and floating sea ice impacts if placed on hulls, and the adhesion strength of saline ice and its variation with age, temperature, and salinity. Electronics should be placed in waterproof boxes.

Innovative Dynamics, Inc.—Electro-Impulse De-icing (EIDI)

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Intended or actual application

Innovative Dynamics Inc. (Innovative Dynamics Inc. 2007) has developed Electro-Impulsive De-icing (EIDI) systems in collaboration with the NASA Glenn Research Center and Lock-heed Martin for use on aircraft and ships. A version of the system is currently in use on the horizontal stabilizer of the Raytheon Premier I business jet, and another version has been demonstrated for de-icing ship hatches. The EIDI system uses electromagnetic coils underneath a rigid or semi-rigid icing-prone surface to produce an impulsive force sufficiently large to debond and expel the ice. A variation of the EIDI system has been commercialized.

Operating environment

The primary application is for in-flight aircraft icing, but a version is developed for ships at sea. The technology was originally designed for FAA FAR25 Appendix C conditions, which all aircraft de-icing and anti-icing systems must meet for certification (FAA 1991a). The EIDI system is capable of expelling thin ice, which is more difficult than expelling thicker ice. However, due to the salinity of sea spray superstructure ice, which is naturally softer, the shock effect of an expulsive system may be partially absorbed, lessening its effectiveness.

An EIDI system was designed for ship icing conditions with air temperatures as low as $-40°C$, a saltwater content of 65 g/m^3, an average drop diameter of 300 µm, and a wind speed of 25 m/s.

Engineering concept

The system operates by using electromagnetic coils located behind the surface by inducing strong and sudden magnetic forces from a high-current DC pulse through the coil. This results in the rapid acceleration and flexure of the icing surface, causing the debonding and expulsion of the ice (Fig. B-24 and B-25).

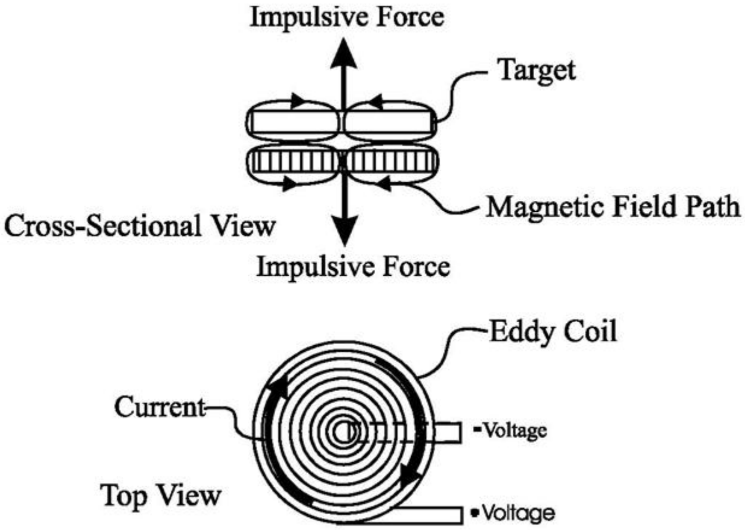

Figure B-24. Diagram of EIDI coil. Coil is positioned close to target surface and discharged with high current impulse source. Magnetic field lines induce currents in target surface to cause rapid shock to pulverize surface ice accumulation (courtesy Innovative Dynamics Inc.).

Figure B-25. Single actuator under 3.2-mm metal plate with 25-mm ice sheet (top). Actuator breaking ice sheet (bottom). (Images courtesy Innovative Dynamics Inc.)

Technology readiness level

TRL: 8. System is currently available for aircraft.

De-icing or anti-icing

De-icing.

Current advantages and disadvantages

Ice can be shed in a variety of thicknesses. The system has been evaluated successfully in saline ice and for application to ship hatches, but certain details are proprietary. Although fundamental design work has been accomplished, specific applications require some redesign. The system utilizes high voltage—a potential safety concern—but requires less power compared to electrothermal systems and features a low IR signature.

Current acquisition cost

Unknown. Some redesign is necessary for each specific application.

Operational cost

Unknown.

Maintenance requirements

System may be cycle limited due to high-voltage charging capacitors, though it has been certified on aircraft for hundreds of thousands of actuation cycles.

Potential marine application and safety enhancement

The EIDI system would allow energy-efficient automated de-icing of bulkheads, potentially support structures under the main deck of a platform, and hatch covers (Fig. B-26 and B-27).

Figure B-26. One-piece EIDI ship hatch de-icer used to break ice accretion and allow hatch to be easily opened (courtesy Innovative Dynamics Inc.).

Figure B-27. Multiple actuators integrated into a one-piece ship hatch de-icer seal (courtesy Innovative Dynamics Inc.).

Marine technology readiness level

Marine TRL: 6.

Marine advantages and disadvantages

The system can only perform with a flexible icing substrate—not directly with the very thick plate or structures typical of marine applications. A special flexible icing substrate “skin“ may be needed, which is on the order of a few millimeters thick; the actuators are located between this and the original structure. The surface may need reinforcement for use in the heavy industrial environment. The system will generate ice debris, which, for example, will deposit at the base of vertically oriented surfaces such as bulkheads.

Marine technology transfer requirements

Tests have been performed in a simulated marine environment with sea ice mixtures at a range of temperatures, but additional testing would be appropriate. Additional research would be required to achieve a robust and electrically safe system for operation in a marine and heavy industrial environment. Application to surfaces of various shapes and orientations would also require investigation.

Marine technology transfer requirements

Evaluate system in saline ice and spray conditions.

Heat[1]

Advanced Mat Systems, Inc.—Arctic Pad

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Intended or actual application

In cold climates, the formation of ice on ships, offshore platforms, and land-based facilities can create serious problems, impacting the safety of personnel and the economy of operations. AMS™ has developed a heated traction mat for decks called the Arctic Pad™. Arctic Pads are self-regulating heated traction pads that prevent ice and snow accumulation while protecting personnel from slip-fall accidents and injuries. The Arctic Pad has been developed to provide an all-season non-slip surface for industry and operators both onshore and offshore where and when operations take place in cold or arctic conditions. The secondary purpose of the

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[1] See also Ryerson (2009)

Arctic Pad is to provide an alternative to, or augment of, traditional anti-icing and de-icing systems currently being utilized throughout the marine industry. Typical applications include ship decks, stairways, platforms and landings, and flight decks.

Operating environment

The operating environment includes natural environmental conditions, such as temperature and winds that produce the types of ice the technology is designed to combat such as glaze, rime, or sea spray ice. The design of the device may be tailored for a certain type of ice, or may operate over a broad range of icing environmental or operating conditions.

Engineering concept

The Arctic Pad is a mat encapsulating self-regulating Electrical Heat Trace (EHT) within a variety of robust polymer blends. The Arctic Pad is designed to reduce the rate of energy consumption by insulating against conductive heat losses. By taking into account the various brands, wattages and supply voltages of EHT, the design process takes into account the ambient temperatures, the risk of icing, snowfall, the application or intended use and the source or availability of power before a particular EHT type is selected for use.

When energized, the self-regulating EHT automatically adjusts the thermal output in relation to the surrounding ambient temperatures (Fig. B-28). The self-regulating core, combined with the insulation properties of the pad polymers and polymer blends, reduces rapid heat loss. As a result once Arctic Pads reach their optimal operating temperature they move into a cycle of maintenance.

Watt densities at initial inrush current range from 256 to 385 W/m^2, depending upon the operating environment. However as Arctic Pads are purpose-built the watt densities can vary dependent on the project requirement. Voltages range from 110 VAC to 277 VAC.

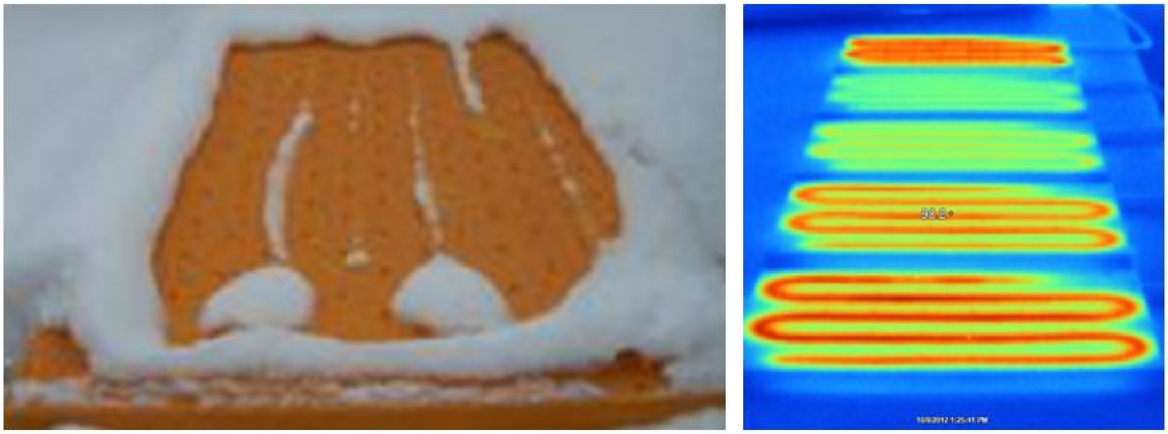

Figure B-28. Heated Arctic Pad melting snow cover on left, thermal image of Arctic Pads on right indicating different operating temperatures as a result of the five different Watt densities.

Technology readiness level

TRL: 9. The Arctic Pad is commercially available and is currently used in the Oil & Gas industry with installations onboard a semi-submersible drilling platform (Norway) as well onboard a long haul tugboat operating in AK. The Arctic Pad has been qualified through test and demonstration and proven through successful mission operations.

De-icing or anti-icing

The Arctic Pad provides de-icing and anti-icing through controls and design.

Current advantages and disadvantages

The Arctic Pad is simple to install and uses common power supply voltages. It is safe for use in hazardous installations, and is applicable to both temporary and permanent installations. It can be custom manufactured to meet specific requirements. The pads have been used in heavy work areas such as drilling rig floors by using heavier duty polymer that includes fire retardant and UV resistant materials (Fig. B-29). Arctic Pads are always fastened to ship decks when there is a risk of sea spray or green water moving them, and pads on stair treads are always mounted.

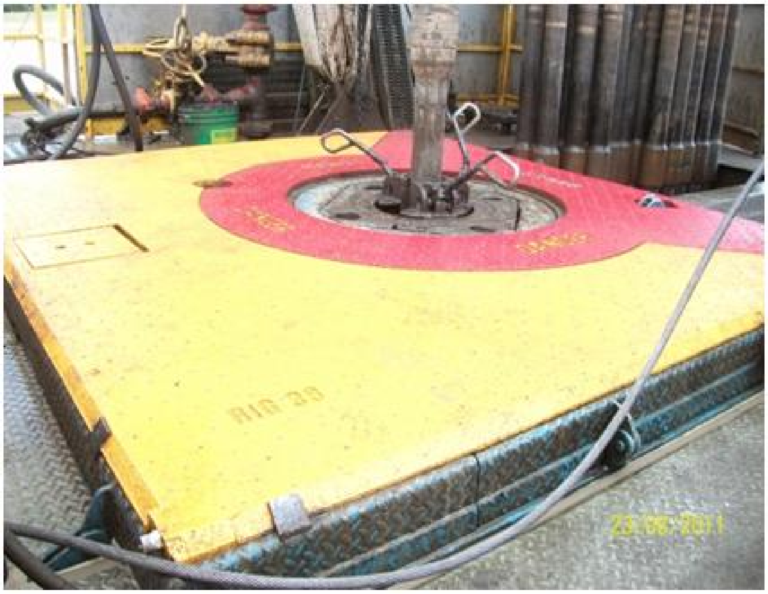

Figure B-29. Arctic Pad installed on land-based drilling rig floor in Alberta, Canada.

Current acquisition cost

Average costs range from \$1000 to \$2000/m^2 depending upon the application and the polymer requirements.

Operational cost

Operational cost is related to desired performance. This includes whether the Arctic Pad is used for anti-icing or de-icing, and the weather conditions to which they are exposed.

Maintenance requirements

Maintenance includes renewing elements of the technology and inspections for safety. The Arctic Pad has been developed to operate in the heavy industrial environment of the oil drilling industry.

Potential marine application and safety enhancement

The Arctic Pad was specifically and firstly designed to prevent slip and fall accidents and injuries. Therefore by providing a high traction non-slip surface and including a heat element the co-efficient of friction can be maintained.

Marine technology readiness level

TRL: 9.

Marine advantages and disadvantages

The Arctic Pad is designed and marketed for the offshore marine environment. It is a relatively inexpensive and easily adaptable system for heating decks. Mats are removable for deck corrosion inspection and repainting as necessary.

Marine technology transfer requirements

Technology has been demonstrated in marine environment.

EGC Enterprises Inc.—QFoil

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http://www.egc-ent.com/html/qfoil_2.html

Intended or actual application

QFoil is a electro-thermal thin-film heater technology intended for ice protection applications that allow rapid temperature rise with a low-watt density. QFoil is thin, flexible, durable, and lightweight. Variations of QFoil have been applied to aircraft wing deicing, blades of wind turbines, automobile mirror heaters, food service warming trays, and plastics welding. It has potential application to a variety of icing environments (Bernthisel and Biller 2003).

Operating environment

QFoil has the potential to operate in most icing environments, including snow, freezing rain or freezing drizzle, rime, or clear ice. The thin-film heater can be constructed using Kapton, polymer films, metal foil, quartz, and ceramic; it can be configured for surfaces that are not flat such as airfoil leading edges. QFoil has an 800°F operating temperature limitation in oxidizing environments (>2000°F in non-oxidizing environments). It is subject to damage in a heavy industrial environment unless covered with thin protective layer(s) (example: sheet metal). QFoil may be supplied in sizes ranging from 6.4 cm^2 to 3 m^2 (1.2- by -2.4 m) (Bernthisel and Biller 2003, EGC Enterprises 2008).

Engineering concept

QFoil heaters are thin, approximately 0.25-mm-thick laminate structures (Fig. B-30). The rolled vermiform graphite serpentine heater conductor is typically laminated and sealed between an electrically insulating outer layer, and an electrically insulating bottom layer. The outer layer materials can be thermoplastic or thermoset polymers that are thin and therefore conduct heat well. The outer layer may also be Tedlar, a material with ice-phobic properties. The QFoil flexible graphite conductor allows a more rapid temperature rise when power is applied than conventional heaters. Rapid thermal rise is typically more pronounced as the surface area to be heated increases in size. Thermal rise can be as rapid as 56°C/s. The energy requirement to produce rapid rises in temperature is claimed to be less than that required for electrical metallic heating systems. QFoil can be configured to evenly heat an entire surface area to within ±3% temperature stability by changing the thickness, width, and density of the flexible graphite during manufacture. Typical watt density is 6 W/cm^2 or less. Voltages can range from less than 12 V (DC) to 480 V (AC). Maximum continuous temperatures are about 276°C, with short maxima to 318°C (Bernthisel and Biller 2003; EGC Enterprises 2008). QFoil is available with a peel-and-stick backing, or it can be applied to substrates with epoxy or RTV silicone.

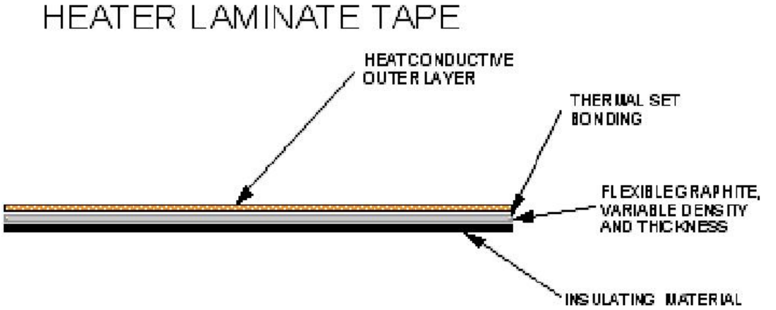


Figure B-30. Components of QFoil laminate sandwich.

Technology readiness level

TRL: 7–8. QFoil is COTS. However, each heater is custom manufactured to user requirements.

De-icing or anti-icing

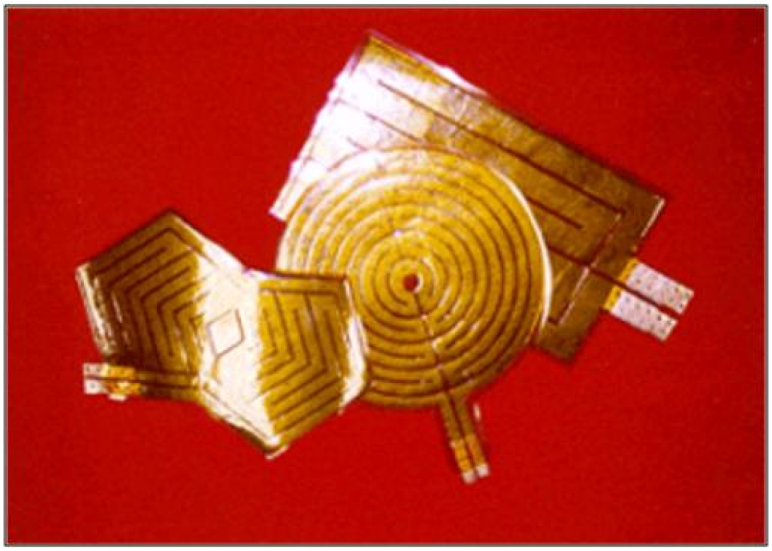
De-ice or anti-ice.

Current advantages and disadvantages

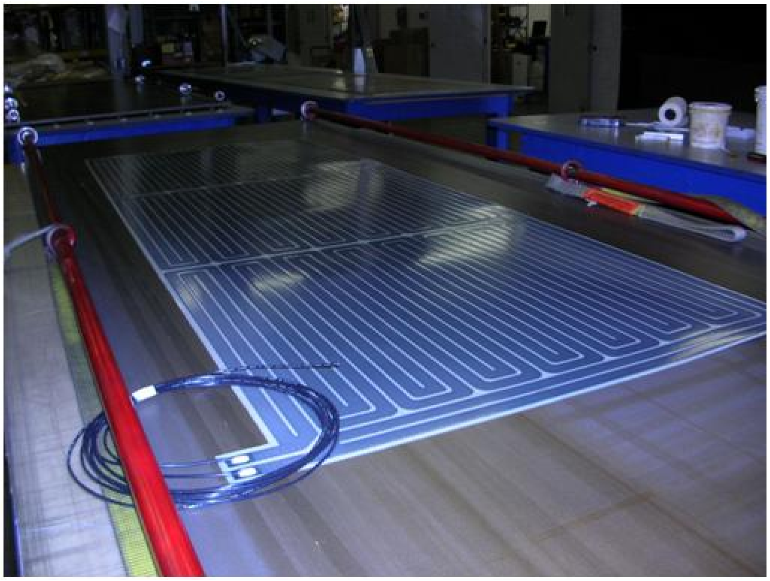
Rapid heating allows low-cost deicing by heating foil quickly to melt ice at the ice–foil interface. Thin, flexible material allows application to curved surfaces, and a peel-and-stick option allows quick application. The plastic surface could be penetrated easily, causing a shock hazard unless fused and equipped with ground fault protection. The foil may not apply with complex curves. QFoil is available in a variety of custom sizes and watt densities. The heaters may be operated over a wide range of voltages. Controllers are available from other vendors.

Current acquisition cost

\$300 to \$450 per m^2. The 0.6- by 1.8-m heaters in Figure B-31 each cost between \$270 and \$465 depending upon quantity ordered.



a.



b.

Figure B-31. Small QFilm heater areas (a), and 0.6- by 1.8-m section (b), both showing serpentine heater conductors and electrical connections.

Operational cost

Operational cost is a function of the cost of electricity, and whether QFoil is used in deicing or anti-icing mode.

Maintenance requirements

None except for periodic checks of functioning, electrical leakage, and connector strain relief.

Potential marine application and safety enhancement

QFoil is not currently used in a marine environment. However, it is anticipated to be applicable to bulkheads outside of heavy work areas and support structures under the main deck. Use on walkways, stairs, and other areas with frequent and potentially damaging mechanical impact is not recommended. QFoil would be best applied to relatively smooth, flat surfaces or curved surfaces without compound curves. QFoil cannot be applied easily to lattice structures or to cables or windlasses.

Marine technology readiness level

Marine TRL: 5–6. QFoil should be tested in an actual or simulated marine environment.

Marine advantages and disadvantages

QFoil can be used in deice or anti-ice mode. QFoil uses less energy than other resistance heating systems, and has potential for the most energy savings when operated intermittently in deice mode. Application is relatively easy.

Marine technology transfer requirements

Investigation of the best method of attaching QFoil to ship surfaces is needed. QFoil should be tested in a marine icing environment to determine effects of wave and heavy spray impacts.

High velocity fluids[1]

Global Ground Support, LLC—AirPlus! Forced Air De-icing System

Global Ground Support LLC
540 East 56 Highway, Olathe, KS 66061-4640
Tel: 913-780-0300
http://www.global-llc.com

Intended or actual application

The Air Force has used high-pressure air to clear snow from aircraft wings, and the Navy has used jet engine exhaust to clear aircraft carrier decks (Mackes 1989). Global AirPlus! is a commercial truck-mounted high-velocity air system used by the Air Force (Fig. B-32). Equipped with a boom-mounted cab and blower with fluid nozzles, the system operates in any of three modes. A high-velocity air mode removes loose snow and ice. Air alone is the preferred de-icing mode because hazardous and costly glycol de-icing fluids are not used. Fluid injection into the air stream abrades and erodes snow, and melts thin ice and frost. Fluid use in this mode is low, and is used whenever air alone is not effective. If air with fluid injection is not effective, additional fluid is sprayed from a separate nozzle (Wyderski et al. 2003).

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[1] See also Ryerson (2009).

Figure B-32. Air Force Global AirPlus! system. Larger nozzle blows air or air and de-icing fluid mist (bottom). Smaller nozzle sprays de-icing fluid at low velocity (top).

Operating environment

High-velocity air can clear loose snow and, with injected fluid or by working the edges, packed snow and ice. The Global AirPlus! high-velocity low-pressure system can be used at any ambient temperature, but may be compromised by high winds. Heated de-icing fluid, either injected into the airflow or sprayed separately in larger volumes, can assist with snow and ice removal. The airflow is about 0.9 Mach; loose objects caught in the air stream, such as loosened sheets or chunks of snow or ice, can be lofted. However, test results and actual industry usage demonstrates that these projectiles end up falling relatively short distances from the aircraft surfaces. Placement of the nozzle at high angles to large, nearly flat surfaces at very short distances may damage some types of surfaces, but typical industry standard practices for safe de-icing distances shows this to not be a problem or concern. Sound volume requires hearing protection if personnel are not at a safe working distance from the air nozzle. Though the system is truck mounted, it may be possible to place it on a smaller moving platform.

Engineering concept

A high-velocity air mode operating at a velocity of 313 m/s and a pressure of 53.7 kg/m^2 removes loose snow and ice. Air alone is the preferred de-icing mode because hazardous and costly glycol de-icing fluids are not used. Fluid injection into the air stream abrades and erodes snow, and melts thin ice and frost. Fluid use in this mode is low and is used whenever air alone is not effective. If air with fluid injection is not effective, additional fluid is sprayed from a separate nozzle. Fluid is heated to 80°C before entering either of the two nozzles (Wyderski et al. 2003). AirPlus! uses a heavy-duty, continuous rated, centrifugal blower (a super charger) that is belt driven by a hydraulic motor. The blower, located on a truck boom, is a lightweight modular assembly enclosed in a shatter-proof shield for safety and insulated for noise reduction. In a study sponsored by Transport Canada, Dawson (2000) evaluated characteristics of the AirPlus! System. At a 0.9-m distance and a 45° angle of incidence (typical of aircraft de-icing operations), the force on a sensor disk was 3.5 kPa. The maximum recorded force (produced with a nozzle distance of 0.3 m and a 90° angle of incidence) was 9 kPa. Forces at a nozzle distance of 0.3 m created pressures about 40% greater than at 0.9 m. The system removed loose snow, wet snow, and ice satisfactorily when de-icing fluid (25 L/min) was injected into the air stream. Air alone had difficulty coping with ice and heavy, wet 10-cm-deep snow in tests at Eglin Air Force Base (Ryerson et al. 2003). Dawson (2000) measured noise levels greater than 85 dBA at 5 m from the vehicle perimeter. However, noise levels at all locations, including the operator bucket, could be controlled to acceptable levels by wearing hearing protectors. Removal of thin ice with the air/fluid combination resulted in small coin-sized pieces of ice being lifted from the wing and blown away to fall near the wing perimeter. Snow was removed primarily by erosion with forced air only, and the resulting separate snow crystals were blown away from the wing. Occasional clumps of snow were lifted and fell near the wing perimeter. The average horizontal velocity of ice particles was computed to be about 7 m/s. The forced air de-icing system presented no significant hazards from ice and snow projectiles.

Technology readiness level

TRL: 8-9. Global AirPlus! is a COTS product.

De-icing or anti-icing

De-icing and anti-icing.

Current advantages and disadvantages

The system is truck mounted. There is moderate hazard from flying ice and snow particles for personnel located downstream. Hearing protection is necessary for all personnel working near the system. The system reduces de-icing fluid use, especially in snow clearing conditions where fluid use is typically high. The nozzle must be located within about a meter of the surface to be effective.

Current acquisition cost

Unknown.

Operational cost

Cost of fuel for truck and de-icing or anti-icing fluid used.

Maintenance requirements

Maintenance to truck and blower and hydraulic equipment. Unknown.

Potential marine application and safety enhancement

The fundamental forced air and spray system may be located on a ship without the truck body. Air and fluid would need to be piped to locations on the ship where the de-icing capability was needed. It may de-ice bulkheads, decks, and helicopter landing pads. If capable in superstructure ice and sufficiently transportable, it may be able to de-ice areas under the main deck of offshore platforms.

Marine technology readiness level

Marine TRL: 4–5. Basic elements of the AirPlus! System could be reengineered for use on a ship. Testing of the reengineered system should be made in simulated and actual marine environments.

Marine advantages and disadvantages

The system may not be as effective with saline superstructure ice, which is heavy and often wet and perhaps more similar to the wet snow tested at Eglin Air Force Base. The system is currently large and is not readily transported on a ship. The nozzle may need to be hard-mounted for safety, rather than hand-held. Flying ice and snow and noise levels could be concerns on a cutter.

Marine technology transfer requirements

The system must be tested for its capability to remove superstructure ice—both young ice and older, harder ice—over a variety of thicknesses. The system should be reduced in size. Methods of reaching all areas on a cutter must be investigated.

Ideal Solutions—Harmony De-icing Fluid

Ideal Solutions
Contact: Mike Sweetman, Managing Director
730 Enterprise Drive, Lexington, Kentucky 40510
Tel: 866-673-3963
Cell: 502-316-1663
Fax: 859-266-2717
E-mail: msweetman@idealsolutionsonline.us
www.idealsolutionsonline.us

Intended or actual application

Superstructure ice may be removed from offshore structures by hydraulic blasting with pressure washers to cut through the ice and remove large pieces using relatively little energy (Ryerson 2008; Hanamoto 1977; Mackes 1989). A primary cause for the discontinuation of development of hydraulic blasting for ice removal offered by offshore operators is the refreezing of discharged water. Cleared surfaces containing residual blasting water, given sufficiently cold outside ambient temperatures, can quickly refreeze presenting safety hazards. Heretofore, adding anti-freezing additive chemicals, similar to aviation de-icing fluids, to the discharge water has been prohibited by maritime environmental regulation.

Ideal Solutions has developed Harmony De-icing Fluid, an environmentally acceptable chemical additive which prevents refreezing of discharge water. The fluid has been designed for use primarily as an anti-freezing agent with typical industrial pressure washing equipment, which they also provide. The solution can be heated, which aids the de-icing process. The solution is intended for use on offshore platforms and ships, and can be used in existing on-board pressure washing systems.

Operating environment

Harmony de-icing fluid has the potential to operate in most icing environments including snow, freezing rain or freezing drizzle, rime, or fresh or saline bow-spray caused superstructure ice. The fluid can be used with typical pressure washing equipment in temperatures to –27.7°C. Lower freeze points are available with stronger concentrations; however, viscosity increases and pumping equipment should be tested first. The material is certified as safe for marine environments and can be allowed to flow overboard.

Engineering concept

Harmony De-icing Fluid has a freezing point of –27.7°C when combined with fresh water or sea water at a ratio of 50% chemical/50% water. Importantly, Harmony De-icing Fluid is considered safe for discharge into seawater because it is compliant with *The Harmonised Offshore Chemical Notification Format* (HOCNF) 2000 of the *Oslo and Paris Commission* (OSPAR [http://www.ospar.org/]). It is on the *Pose Little or No Risk to the Environment* (PLONOR) certified List of Substances / Preparations Used and Discharged Offshore.

Technology readiness level

TRL: 8.

De-icing or anti-icing

Primarily, de-icing.

Current operating characteristics

Harmony De-icing Fluid has been designed for use with typical industrial pressure washing equipment primarily as an anti-freezing agent. Heating of the solution is beneficial to the de-icing process. In tests conducted at the US Army Armament Research, Development and Engineering Center, Picatinny, NJ, a 10-ft foot by 4-ft by 4-in.-thick ice mass was created in a cold chamber. The 4-in. thick fresh water ice was pierced in 15 s by the heated fluid. Once the ice was penetrated larger ice pieces broke apart readily (Fig. B-33). The entire ice mass was broken and cleared away in 70 s utilizing 4.8 gal./min of fluid volume at 3500 psi, 145°F fluid temperature. This rate of ice removal is about 3.1 min/ton of ice, but rates will vary with ice properties, temperatures, water pressure, and ice geometry.

Figure B-33. Ice being removed from a surface with heated Harmony De-icing Fluid from pressure washer at Picatinny RD&E Center tests.

Harmony De-icing Fluid also has some anti-icing properties from proprietary salts that remain on the surface. It provides a non-freezing barrier for as long as it resides on a surface.

The Harmony system requires heated, pressurized water spray. Recommended is use of 8 gal./min of water flow at a minimum of 2500 psi using a 0° (straight line “laser-like”) spray nozzle for cutting and dislodging ice deposits. An all-electric pressure system with these capacities requires 72 Kw with a 480/3 phase service. It will draw 104.8 A. This system will deliver approximately 125°F water to the spray wand (depending upon feed water temperature). A separate diesel or natural or LP gas burning heating system can be used in line with a stand-alone pumping system, reducing electrical consumption significantly. These heaters use a “forced flame against steel coil” design, so it is necessary to consult regulations for allowances for flame type heaters.

Blasting and removal of ice can be accomplished with lesser flow, pressure and heat capabilities if necessary.

Current acquisition cost

Harmony de-icing fluid is available as a 50/50 premix, 50% Harmony and 50% water, or as a 100% Harmony concentrate. Harmony must be diluted (50/50) to ensure proper viscosity for use through pumping systems. Approximate cost for 1 gal. of Harmony de-icing fluid premix is $5.50 per minimum 275-gal. tote without shipping. Contact Ideal Solutions Harmony concentrate costs. The product is currently not COTS.

Operational cost

Given the unpredictable nature of ice accumulations including their makeup, their thickness and their positioning, pressure washer characteristics and operator technique, it is difficult to render a static value to cost of operation. It is also highly recommended that, if possible, a two stage, cost-saving procedure be followed including:

Stage1

Allow the heated, high pressure spray with *water only* to do the bulk of the work disintegrating and dislodging ice deposits.

Stage 2

Follow-up with the Harmony fluid to flush away lesser remaining ice and leave a clear surface which is exposed only to the Harmony residual.

The cost of running the pressure washer would depend on electrical costs and if use of a separate diesel or natural gas or LP gas heater is permitted. The Harmony fluid is equally effective mixed with fresh water or salt water, though salt water has an adverse effect on the longevity of pressure washer systems. If seawater is used a thorough flushing with fresh water after every use is recommended.

Maintenance requirements

None, except for pressure washer maintenance.

Potential marine application and safety enhancement

The Harmony De-icing Fluid is intended for use in the marine environment for removing superstructure ice from offshore platforms and ships.

The de-icing fluid complies with international regulations for discharge into sea water and fresh water and is considered to pose no risk to the marine environment. The fluid freezing point is −27.7°C when mixed 50/50 with fresh or sea water. With a pressure washer, the fluid penetrates ice and allows sections to be carved away from a surface. Energy is saved by not requiring that the ice be completely melted. The system can clean decks, ladders, bulkheads, cranes, windlasses and other ship equipment of ice to improve personnel safety. Residual water on the de-iced surface will not freeze if the freezing point depression of the residual fluid is lower than the air temperature.

Marine technology readiness level

Marine TRL: 8.

Marine compatibility

The technology is developed for and is certified compatible with the marine operating and natural environments. Some nations are sensitive to chemicals flowing into water even if certified as safe according to the US Coast Guard. It is unknown if the fluid leaves a slippery residue on de-iced surfaces or causes corrosion. Operation of pressure washers can cause personnel and materiel damage if not carefully handled. Ice broken from surfaces with high pressure fluids can cause flying ice shards necessitating eye and face protection.

Marine technology transfer requirements

Development of procedures for most efficiently removing ice with pressure washers is needed. Ship-board testing in an operation environment is recommended.

Infrared and lasers

See Ryerson (2009).

Piezoelectric[1]

FBS Inc.—Piezoelectric Anti-Icing System

FBS, Inc.
3340 West College Ave., State College, PA 16801
Tel: 814-234-3437
E-mail: cjborigo@fbsworldwide.com
http://www.fbsworldwide.com

Intended or actual application

FBS, Inc. and the Pennsylvania State University, via a Phase II SBIR contract (contract no. W911W6-08-C-0064) from the Army Aviation Applied Technology Directorate (AATD), a Phase II NAVAIR SBIR contract (contact no. N68335-11-0442), and a Phase I SBIR contract (contract no. FA8650-12-M-5159), have shown that by introducing sufficient ultrasonic shear stresses to a host structure/ice interface, instantaneous ice delamination is possible. The work has focused on composite and metallic helicopter blades, composite fixed-wing remotely piloted aircraft composite wings and engine inlets, and metallic fixed-wing commercial aircraft leading edges and engine inlets. The technology utilizes one or more piezoelectric actuators on metal or composite structures such as plates and airfoils, and drives the airfoil into steady-state ultrasonic vibration. Using this approach, large area de-icing has been demonstrated using only 50–100 W of power (<1.5 W/in.^{2}) supplied to the ultrasonic actuators. This concept was demonstrated on airfoil sections subjected to realistic impinging ice conditions in Goodrich's icing/wind tunnel as well as in Penn State's Adverse Environmental Rotor Test Stand (AERTS). The goal of the technology development is to reduce the energy required to de-ice aircraft using a non-thermal method. Similar low-profile lightweight ultrasonic sensors can be used for wide-area ice sensing by utilizing transient guided wave propagation.

Operating environment

The technology is intended to be used in flight on fixed-wing aircraft and on rotorcraft. Therefore, the technology must operate within the thermal and moisture regimes of flight. In addition, it must survive the forces op-

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[1] See also Ryerson (2009).

erating on helicopter blades and the hazards of aviation operations such as greases, fuels, and abrasion due to sand, dust, ice crystals, and raindrops.

Engineering concept

The engineering goal of the technology is to guide ultrasonic energy created at a few discrete actuators located on the airfoil through the entire structure by utilizing ultrasonic resonance. The energy must create interface shear and normal stresses via ultrasonic vibration sufficiently strong to crack and debond ice from the substrate and, simultaneously, not create shear forces internal to the composite airfoil structure sufficient to damage the materials. Full structural coverage is achieved with a combined frequency-sweeping and dynamic focusing/phasing procedure in which phase delays and frequency shifts are applied to the actuator driving signals to alter the vibration focal points. Extensive finite element modeling and experimental testing has been conducted to evaluate actuator design and location, as well as bonding and actuator integration methods.

The technology operates by bonding or embedding one or more small actuators to or within the surface requiring ice protection (Fig. B-34 through B-36). Frequency tuning, actuator phasing, and placement of actuators can be used to optimize the location and magnitude of shear forces between ice and the substrate. The de-icing actuators can also be used to initially detect ice formation using techniques similar to those utilized in ultrasonic non-destructive testing. Alternatively, other specially-designed low-profile lightweight ultrasonic actuators can be utilized for highly-sensitive wide-area guided wave ice sensing.

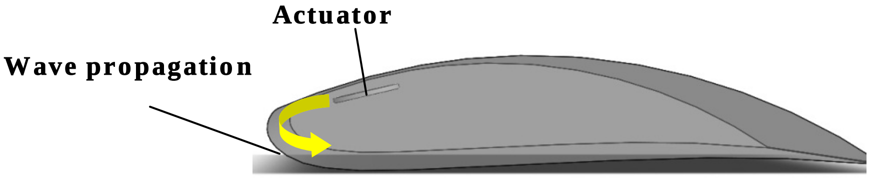

Figure B-34. Schematic of piezoelectric anti-icing system on airfoil.

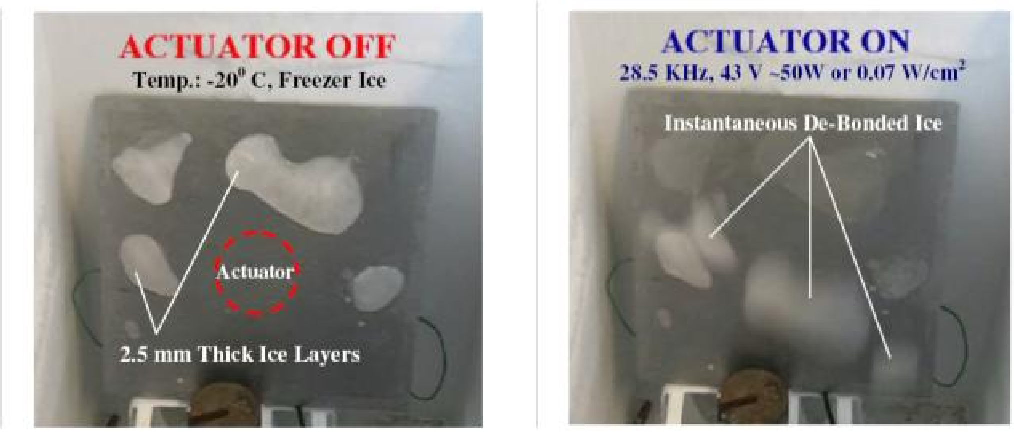

Figure B-35. Ice bonded to plate top, with actuator location indicated on back of plate. Instant of ice debonding and falling upon activating actuator (Palacios et al. 2008).

Figure B-36. (Left) An airfoil specimen exposed to realistic impinging ice conditions in Goodrich's wind/ice tunnel. Ice forms on the leading edge with no ice protection. (Right) Same airfoil exposed to the same icing conditions but with the ultrasonic ice protection system turned on. Note only a thin film of ice is formed on the leading edge. The actuators are embedded inside of the leading edge (not shown).

Operating environment

The technology is intended to be used in flight on fixed-wing aircraft and on rotorcraft. Therefore, the technology must operate within the thermal and moisture regimes of flight. In addition, it must survive the forces operating on helicopter blades and the hazards of aviation operations such as greases, fuels, and abrasion due to sand, dust, ice crystals, and raindrops.

Engineering concept

The engineering goal of the technology is to guide ultrasonic energy created at a few discrete actuators located on the airfoil through the entire structure by utilizing ultrasonic resonance. The energy must create interface shear and normal stresses via ultrasonic vibration sufficiently strong to crack and debond ice from the substrate and, simultaneously, not create shear forces internal to the composite airfoil structure sufficient to damage the materials. Full structural coverage is achieved with a combined frequency-sweeping and dynamic focusing/phasing procedure in which phase delays and frequency shifts are applied to the actuator driving signals to alter the vibration focal points. Extensive finite element modeling and experimental testing has been conducted to evaluate actuator design and location, as well as bonding and actuator integration methods.

The technology operates by bonding or embedding one or more small actuators to or within the surface requiring ice protection (Fig. B-34 through B-36). Frequency tuning, actuator phasing, and placement of actuators can be used to optimize the location and magnitude of shear forces between ice and the substrate. The de-icing actuators can also be used to initially detect ice formation using techniques similar to those utilized in ultrasonic non-destructive testing. Alternatively, other specially-designed low-profile lightweight ultrasonic actuators can be utilized for highly sensitive wide-area guided wave ice sensing.

Technology readiness level

TRL: 4–5. The system has been taken through proof-of-concept in laboratory tests and rotating tests under realistic environmental conditions.

De-icing or anti-icing

De-icing.

Current advantages and disadvantages

The technology has the capability of de-icing areas much larger than the actuator area through actuator placement, frequency tuning, and actuator phasing by generating a steady-state ultrasonic vibration condition. The technology has been successfully demonstrated on materials such as 9-mm-thick steel plates, suggesting that it may be possible to place actuators directly on ship surfaces to protect large areas, rather than covering the entire surface to be protected as is necessary with many other technologies. The vibration frequencies are in the ultrasonic regime (20–60 kHz) and there is therefore no concern of structural resonance issues, which would arise at much lower frequencies for the structures of interest. However, the technology generally performs best on thinner, less-rigid structures. Electrical isolation, electromagnetic interference and radio frequency interference (EMI-RFI) characteristics, and longevity of actuators are currently unknown.

Current acquisition cost

Unknown, development stage too early to estimate.

Operational cost

Modeling indicates about 9 W/m^2 (Palacios et al. 2008).

Maintenance requirements

Unknown, development stage too early to estimate.

Potential marine application and safety enhancement

The capability of the technology on flat and curved surfaces of metallic and composite structures, at metal thicknesses to 9 mm, has been demonstrated. This may accommodate some surfaces of ships. However, it is currently unknown whether the technology would be capable in areas of thicker steel. In addition, bracing, complex shapes, and corners may be stiff enough to hinder ultrasonic vibration. The technology has not yet been tested over large areas, nor has it been evaluated with saline ice. The technology, considering the capability known, may be most applicable on decks, bulkheads, hatches, stairs, flight decks, antennas, radomes, and windows. However, windows should be tested for potential breakage, and though ice may be debonded from decks, stairs, and the helicopter deck, the technology provides no mechanism for removing ice debris from those horizontal surfaces. In addition, ice debris falling from non-horizontal surfaces should be considered. The potential benefits of utilizing larger higher-power actuators have not yet been evaluated because of the requirements for lightweight low-power actuators for the aircraft platforms for which the technology was developed.

Marine technology readiness level

Marine TRL: 3–4.

Marine advantages and disadvantages

Anticipated advantages in the marine environment include the potential for de-icing large areas without requiring de-icing hardware to cover large areas and the potential ability to protect areas below the main deck down to the waterline. Electrical systems would require isolation in the wet, saline environment. Capability to debond soft saline ice from substrates would require demonstration.

Marine technology transfer requirements

Significant testing is necessary to develop appropriate and robust actuators. Modeling of surfaces to be protected is necessary to tune frequency, power, and actuator location to optimize de-icing. Assessment of technology capabilities on complex surfaces such as corners, braced metal surfaces, and hulls will be necessary for ship applications. Assessment of the technology capability in saline ice is needed, as is the EMI/RFI signature of the system.

Pneumatic

See Ryerson (2009).

Optics and windows

See Ryerson (2009).

Cables

See Ryerson (2009).

Ice detection[1]

AirDat LLC—TAMDAR

AirDat LLC
2400 Perimeter Park Drive, Suite 100
Morrisville NC 27560
919-653-4351
http://www.airdat.com

Intended or actual application

TAMDAR (Tropospheric Airborne Meteorological Data Reporting) is an atmospheric monitoring system that uses sensors mounted on ordinary commercial aircraft for data gathering to provide improved weather forecasts. An ice detector is built into the sensor package along with instruments to measure humidity, pressure, temperature, winds, turbulence, location, time, and altitude. TAMDAR is installed on about 250 aircraft operating throughout North America including Alaska, Mexico, and the Caribbean, and installations on aircraft have begun in Europe. There is also a new TAMDAR-U sensor available for use on smaller unmanned aerial vehicles (UAV). Data from the flying sensors enhance AirDat's ability to forecast atmospheric conditions where icing conditions may be a concern.

Operating environment

The system operates on commercial airliners so it must withstand temperatures, pressures, and airspeeds in all phases of flight. The sensor must operate in FAA FAR25 Appendix C icing conditions.

Engineering concept

The ice detector resides within a small sensor package that protrudes from the skin of aircraft into the air stream. Ice is detected by the obscuration of two independent infrared emitter/detector pairs mounted in a leading edge recess of the probe (Fig. B-37). Internal heaters melt the ice when the infrared beams are interrupted. The system can record 0.5 mm of ice. The icing portion of the detector has been tested in icing wind tunnels and has passed FAA requirements. As with other aviation ice detector applications, the sensor requires air flow over the sensor body from a consistent direc-

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[1] See also Ryerson (2009).

tion to operate with maximum accuracy. Daniels et al. (2004) provide a thorough review of instrumentation performance.

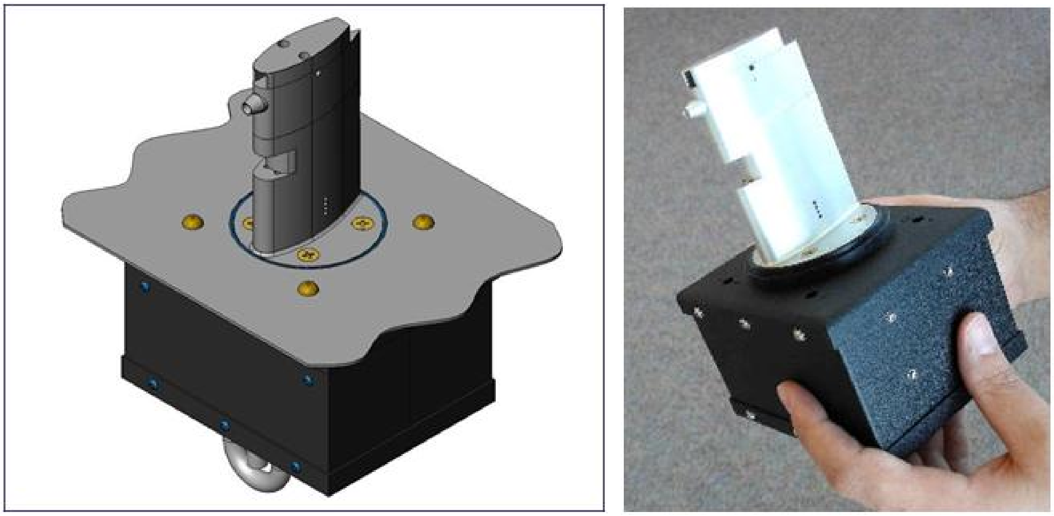

Figure B-37. Drawing of TAMDAR sensor head (left), and sensor head mounted under aircraft wing (right) (images courtesy AirDat LLC).

Technology readiness level

TRL: 9. TAMDAR has been certified for several transport aircraft models.

De-icing or anti-icing

Ice detector and more.

Current acquisition cost

AirDat does not sell the sensors, but will cooperate with aircraft operators on installation of sensors and related satellite communication system. AirDat's ground-based data processing systems perform quality assurance, archiving and distribution of TAMDAR data in near real time. AirDat also assimilates the TAMDAR data into high-resolution atmospheric models and creates custom output as required.

Operational cost

The power consumption with deicing heaters powered off is 10 W, and with heaters on is 280 W.

Maintenance requirements

AirDat monitors all sensors continuously and will advise the aircraft operator if maintenance is required. The sensor requires little maintenance. Some operations are possible to perform in the field, but AirDat maintains a Return Merchandise Authorization (RMA) process for replacement sensors if factory service is required.

Current advantages and disadvantages

TAMDAR is a well-studied system with known accuracy and operating characteristics. It is designed for aircraft mounting and operation. AirDat indicates that TAMDAR data is equal to or better than radiosonde data, and produces superior forecast accuracy when properly assimilated into high-resolution models. Because of the two-way satellite communication system, AirDat can monitor and administer the lifecycle of its sensors remotely, including changes to calibration or sampling rate.

Potential marine application and safety enhancement

A TAMDAR sensor head redesigned for use on a ship or a cutter could provide icing rates at a number of locations along with temperature and other weather information. AirDat would consider development of a special sensor for marine-based applications if a business case could be made. AirDat can provide real time condition reports via Internet and superior high-resolution weather forecasts if aircraft operating regularly in the area are equipped with TAMDAR. Of value to ship operators may be a combination of real time shipboard TAMDAR observations integrated with other shipboard weather observations, such as wind, that could be used to create specialized icing (and other severe weather) forecasts. With the TAMDAR satellite links information could be transmitted to each ship.

Marine technology readiness level

Marine TRL: 5. Not tested in marine environment.

Marine advantages and disadvantages

The sensor is designed for airflow from one direction but could be adapted for stationary use. System provides multiple weather variables. System may become clogged with salt particles, especially the small-diameter air circuits. A suitable housing would be required to protect internal sensor components from corrosion. A sensor designed for marine applications is recommended for anything other than temporary use.

Marine technology transfer requirements

Evaluate technology in marine environment. Address wind direction requirements and assess whether system could be aspirated for stationary applications.

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14. ABSTRACT

Global warming is causing greater retreat of the summer Arctic sea ice cover; with several historical minimums within the last decade. Opening of the Chukchi Sea and the Beaufort Sea is expected to cause increased marine and other activity off of the northern Alaska coast and through the Bering Strait. This will require increased Coast Guard presence. Bow spray icing of Coast Guard Cutters decreases safety and risks mission accomplishment. This report reviews documented causes and potential impacts of ship superstructure icing from bow spray and atmospheric sources, and examines the probability of icing in the Chukchi and Beaufort Seas. Four classes of Coast Guard Cutters, the POLAR-Class heavy icebreakers, the LEGEND-Class National Security Cutter, the BAY-Class 140-ft icebreaking tug, and the JUNIPER-Class seagoing buoy tender were examined. Decks were walked, crews interviewed, and questionnaires distributed to determine the impact of icing on cutter components and functions, to learn how icing affects mission success, to determine how ice accumulations are currently prevented or removed, and to seek improved ways of alleviating icing effects. In addition, 12 classes of ice protection technology were reviewed, as were methods of protecting windows and cables from icing, to determine how they may reduce icing hazards. Recommendations for existing cutters are to heat decks, to test and use anti-icing and low ice adhesion coatings, to use low corrosion aircraft and environment safe chemicals and high velocity fluids to de-ice, to protect vessel components with covers, to use expulsive, pulse electrothermal, and pneumatic technologies on large untrafficked surfaces, and to use infrared heat to protect components and limited deck areas. New cutter designs should incorporate heated decks, splash-resistant bows, and covered masts and boat decks. Cutters need not be completely ice-free in transit and when executing a mission. They must, however, maintain sea keeping ability, stability, and integrity, and full functionality. Hence, cutters must be anti-iced and de-iced underway in heavy weather without stopping or diverting crew resources. Prudent technology investments will allow safer Coast Guard operations in moderate to severe superstructure icing conditions.

15. SUBJECT TERMS

Anti-icing
Atmospheric icing
Beaufort Sea
Chukchi Sea
Coast Guard Cutter
De-icing
Ice protection
Ship superstructure icing

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