ERDC/CRREL TR-09-4

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

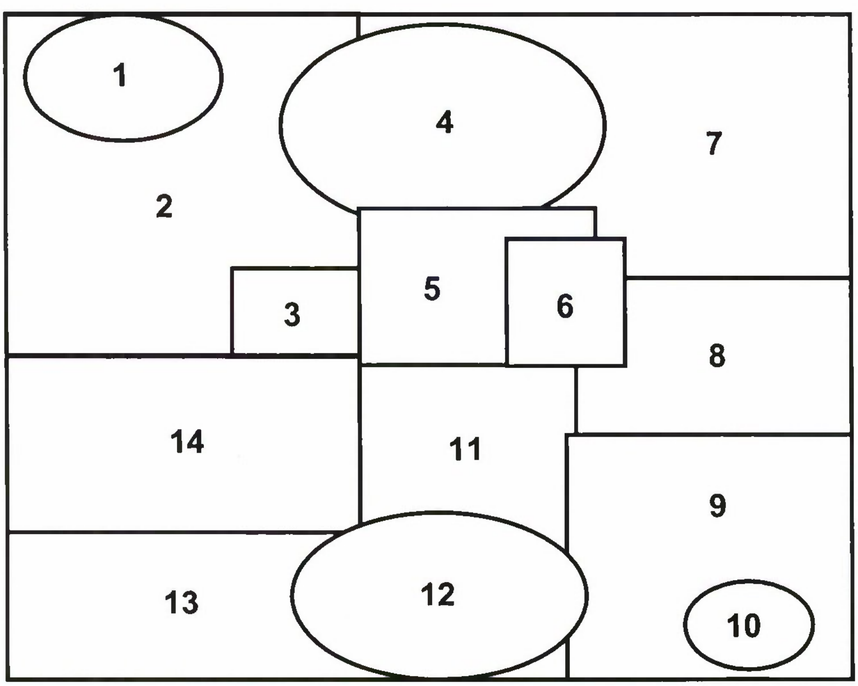
Assessment of Superstructure Ice Protection as Applied to Offshore Oil Operations Safety

Ice Protection Technologies, Safety Enhancements, and Development Needs

Charles C. Ryerson

April 2009

COVER: Ice protection technologies—clockwise from upper left (reprinted with permission):
1. Feltwick Anti-Icing Grate from Innovative Dynamics Inc.
2. *Ocean Bounty* semi-submersible iced in Cook Inlet
3. Microwave Aircraft Icing Detection System (MAIDS) from Intelligence and Information Warfare.
4. QFoil from EGC Enterprises Inc.
5. Chinook Humid Air Deicing from Chinook Mobile Heating and Deicing Corp.
6. Goodrich (Rosemount) Icing Rate Detector from Goodrich Corporation Sensors and Integrated Systems.
7. Manual deicing on USCGC *Midgett*, 1990.
8. Ice Hawk image from Goodrich Corporation Sensors and Integrated Systems.
9. Ice Camera image from MDA Space Missions.
10. Vacca heater from Vacca Inc.
11. Ice-Cat from Trimac Industrial Systems LLC, Infra-Red Technologies.
12. AirPlus! Forced Air Deicing System from Global Ground Support LLC.
13. HotZone Heaters from Schaefer Ventilation Equipment LLC.
14. Radiant Aviation infrared deicing system from Radiant Aviation.



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Abstract: Offshore oil exploration and production operators in high latitude regions recognize icing as a seasonal challenge. Icing is often accepted as an inconvenience, but that tolerance can rapidly become a safety hazard that requires solutions. This report evaluates the superstructure and atmospheric icing hazard on offshore platforms and supply boats with location and operation on the structure. It also explains the potential impact of icing on these locations and operations by icing type: sea spray, snow, glaze, rime, frost, and sleet. Fourteen ice protection technology categories are identified for anti-icing, deicing, and ice detection. These technologies include chemicals, icephobic coatings, structure design, expulsive techniques, heat, high-volume water, air and steam, infrared energy, manual deicing, piezoelectric methods, pneumatic boots, vibration and covers, and as separate categories windows, cables, and ice detection methods. Each technology category is described with regard to products available, current use, engineering design, technology readiness levels, capability at the current level of development for the marine environment, possible use in the marine environment to improve safety, and indications of development necessary to transfer the technology to offshore use. Examples of technology sources are also provided. Suggestions are made with regard to the application of technologies to solve icing safety threats on platforms and supply boats. Technology readiness levels are also summarized. The goal is to provide a technology resource for offshore oil and production operators with icing-related safety requirements.

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Preface

This report was prepared by Dr. Charles C. Ryerson, Research Physical Scientist, Terrestrial and Cryospheric Sciences Branch, U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH.

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This report was prepared under the general supervision of Janet Hardy, Chief, Terrestrial and Cryospheric Sciences Branch, Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; and Dr. Robert E. Davis, Director, CRREL.

At the time this report was published, COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Ryerson (2008) demonstrated through citing reports, and by describing the icing environment and the structure and operation of offshore oil exploration and production platforms, that superstructure and atmospheric icing are a threat to safety and operational tempo. Supply boats are also threatened with superstructure icing because of their small size and low freeboard, analogous to the icing problems of fishing trawlers. Therefore, there is a need for technologies to reduce the safety hazard caused by icing of offshore operations and to maintain productivity during icing events.

In addition to describing the icing problem, the types of icing that can be experienced offshore, and the potential impact of each on offshore structures, Ryerson (2008) provided a brief overview of deicing technologies with a description of their development history, principal of operation, and general application outside and within the marine environment. Examples of developers and vendors were also identified for each technology when possible. In addition, the special cases of cable and window icing were addressed, with a review of technologies that have been applied to deice or anti-ice them. And, because ice protection systems must be activated when icing begins, and deactivated after the threat is over, ice detection technologies were reviewed.

This report provides more information about ice protection technologies identified in Ryerson (2008) from the perspective of their ability to solve critical superstructure icing problems and operational safety needs in offshore operations. Most of these technologies are currently used principally in non-marine environments, though some have been tested in marine applications. Although the focus is on applications in the Beaufort Sea and the Chukchi Sea, applicability to other offshore Alaska locations is also discussed (Figure 1). The goal in this report is to provide information regarding applicability, readiness, and safety impacts of available ice protection technologies, used principally in other applications, and to suggest how they may be transferred to specific applications in the offshore marine environment.

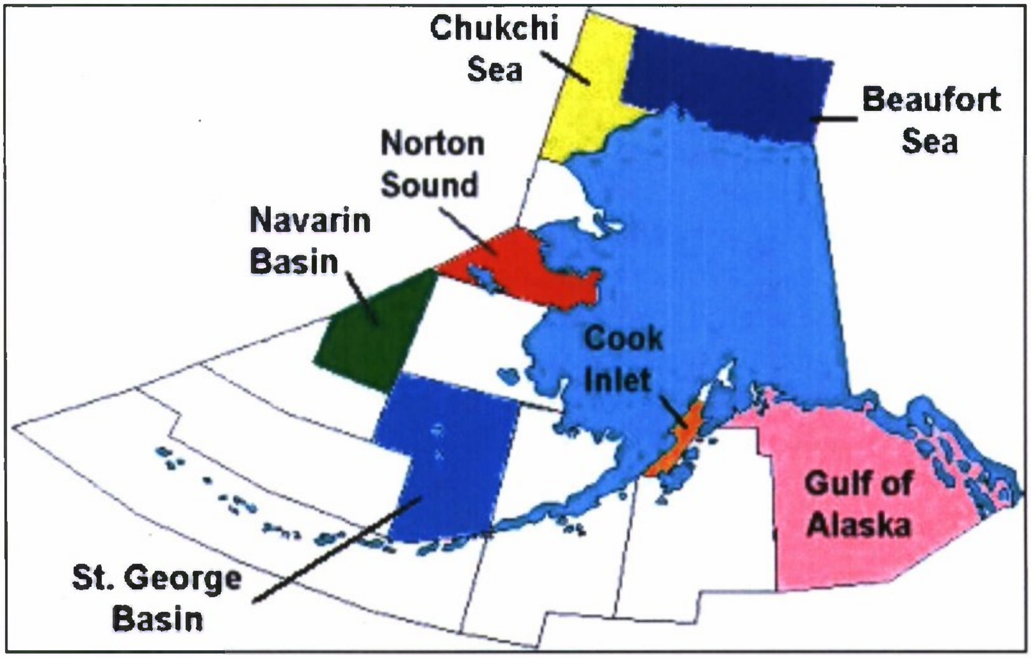

Figure 1. Potential and operational offshore oil exploration and production areas of Alaska (from Appendix C in Paulin 2008).

2 Methodology—Platforms

Engineering information available from developers, manufacturers, vendors, patents, literature, and experience is used to obtain an assessment of the capabilities of ice protection technologies that could be used in the marine environment. Ice protection technologies from other disciplines experiencing icing, especially from the highway, aviation, and electric power transmission industries, are summarized and matched to specific marine icing needs. This is accomplished through the use of criteria that address the current application and operating environment of the technology, engineering principles and design, current level of development expressed as a Technology Readiness Level (TRL), advantages and disadvantages in the current or intended operating environment, maintenance, and acquisition cost and operating cost if available (Graettinger et al. 2002). Information is then provided, as possible, regarding the technology's actual or potential capability in the marine environment.

Evaluation criteria, described below, were addressed through reports about the technologies, sales and engineering literature, Web sites, and patents. Information in some circumstances was available from personal experience. Much information was also acquired through telephone interviews of developers or manufacturer representatives.

Evaluation criteria

1. *Technology Source:* This is the source of the technology if available commercially, or the source of information about the technology. If the technology is not commercially available, then developer or inventor contact information is listed if known. Some items may be common commodity items available from a wide variety of sources. In these situations a representative source is listed—exhaustive lists are not provided in some cases, such as for deicing and anti-icing chemicals, because of the large numbers of vendors.

2. *Intended or Actual Application:* This is a description of the use of the technology as marketed, as used by customers of the company, or as anticipated by the developer in a patent or other documentation. This information provides a baseline for comparison to the marine environment, es-

pecially if the technology was not originally intended for use in the marine environment.

3. *Operating Environment:* The operating environment includes the natural environmental conditions such as temperature and winds, and the type 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 in a narrow range of icing environments. Airflow speed and direction over the device can be important, especially for ice detectors and applications that are sprayed. Operating environment also includes the operational environment of the technology, such as airports or bridge pavements for example.

4. *Engineering Concept:* Engineering concept refers to the physical principles of operation and how those principles are used to prevent ice accretion or remove snow or ice. For example, heat may be used to melt ice or prevent its formation, whereas an expanding pneumatic boot relies upon the brittleness of accreted ice to debond it from substrates. Because many of the technologies are proprietary, some information sources were limited to Web sites and open literature.

5. *TRL:* Technology Readiness Level (TRL) refers to the level of development of the technology as currently available for its intended purpose as defined by the nine TRLs described by Graettinger et al. (2002) for the Army, and used throughout the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD).

6. *Deicing or Anti-icing:* Technologies can deice, anti-ice, or both. Deicing refers to technologies that remove ice after it has accumulated. Anti-icing refers to technologies that prevent any accumulation of ice or snow. Some technologies can either deice or anti-ice, but most cannot do both. There may be advantages and disadvantages to either approach in specific situations; these can be related to power consumption or to potential hazards during operation and to nearby equipment or personnel.

7. *Current Advantages and Disadvantages:* Describes advantages and disadvantages of the technology in its current or intended application. This includes maintenance, initial and operating costs, power requirements, ease of application, operational limitations, and effectiveness for different types of ice or snow.

8. *Current Acquisition Cost:* Acquisition cost for current application if known.

9. *Operational Cost:* Operational cost for current application if known. If possible, operational cost is related to a measure of performance.

10. *Maintenance Requirements:* Maintenance frequency and type required in intended operating environment. Maintenance includes renewing elements of the technology and inspections for safety.

11. *Potential Marine Application and Safety Enhancement:* The *Potential Marine Application and Safety Enhancement* describes the potential utility of the technology in the marine environment. Technologies developed for non-marine environments may not be capable in marine environments where physical properties differ for saline ice versus freshwater ice, wind speeds are often higher, corrosion potential is greater, and the impact of waves and spray can be large. Technologies intended for operation on moving vehicles, such as aircraft, may not function properly in a stationary environment. In addition, the marine environment is a harsh industrial environment, and technologies intended for aviation may not survive physical impact that could occur, for example, in the offshore oil recovery environment. This will also describe where, and sometimes how, safety may be improved by the use of the technology. Quantitative estimation of safety improvement is not provided because baseline quantitative safety information is not available.

12. *Marine TRL:* In this case, TRL refers to the current level of development of the technology if it were applied to the marine environment. For example, a technology that operates successfully in a freshwater environment in moderate winds with ice created from rainfall or cloud droplets may require additional development if applied to the corrosive marine environment with higher wind speeds and the potential of being impacted by heavy spray, or by “green” water (Buchner 2002). Therefore, a technology developed originally for the marine environment could have a *Marine TRL* that is numerically the same as the current *TRL*. A technology developed for non-marine environments will likely have a *Marine TRL* that is numerically smaller than the current *TRL* because additional development may be necessary to make the technology effective in the marine environment. As with the current TRL, the *Marine TRL* refers to the level of de-

velopment of the technology as described by Graettinger et al. (2002) and used throughout NASA and the DoD.

13. *Marine Advantages and Disadvantages:* This criterion describes the ability of the technology to operate in the marine environment, and describes the expected advantages and disadvantages of the technology in a marine application. For example, safety in explosive atmospheres, corrosion potential, maintenance, acquisition and operating costs, ease of application, and effectiveness are all important on platforms and supply boats. This information will be applied to assigning the *Marine TRL*, and assessing the development necessary to use the technology successfully in the marine environment.

14. *Marine Technology Transfer Requirements*: This criterion recommends design changes and testing necessary to apply technology to the marine environment.

Safety enhancement assessment

Potential safety improvements resulting from transferring promising deicing and anti-icing technologies to the marine environment are addressed in relationship to icing conditions found on offshore platforms and the safety risk that specific ice types cause. Scores are provided for ice types and platform work areas or components with regard to their impact on safety. For example, frost has little impact on platform stability or air intakes, but it can cause slippery stairs and decks, a hazard to personnel. Frost is relatively unimportant with regard to its threat to safety of a platform or to the entire crew, but it can threaten the safety of individuals in specific areas. Therefore, the combination of frost with decks provides a relatively low score when compared to decks and snow.

The importance of any technology as applied to a platform, therefore, is a function of ice type versus specific platform locations or operations.

Table 1. Joint safety impacts by ice type and platform component or function, with higher numbers denoting a larger safety hazard.

	Safety Rating	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Hazard rating		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.							

The success of this approach is a function of the assumptions made with regard to the importance of safety hazards created on different parts of platforms by the various forms of ice combined with the assessed potential success of ice protection technologies when applied to the problem. Because all of these assessments are largely qualitative, there is potential for error in assessing the importance of technologies and their potential applications.

Ice hazard ratings

The following superstructure and atmospheric ice threats are described and rated for overall threat to platform safety and operations. A rating of 10 is the highest threat and a rating of 1 is lowest, indicated in parentheses below and in Table 1.

1. *Sea spray ice (10):* Sea spray or superstructure ice (as defined by Ryerson [2008]) can reduce rig stability, potentially damage rig structure due

to changes in stress on members, cause slipping hazards on decks, ladders, handrails, and helicopter pads, make deck cargo unavailable, disable winches, cranes, and antennas, and cover windows, rescue equipment, hatches, firefighting equipment, valves, and radomes. Other areas that can be affected include air intakes, the moon pool, the cellar deck, and legs and deck bracing.

2. *Snow (8):* Snow can contribute considerable weight to a platform and contribute to instability of floating platforms. Snow causes a slipping hazard for personnel on ladders, decks, and helicopter landing pads, can damage or possibly contribute to the collapse of flare booms, prevent the operation of valves, and melt and refreeze on lattice structures causing falling ice chunks that are a hazard to personnel and material.

3. *Glaze (7):* Glaze, deposited from freezing rain, affects principally horizontal surfaces. However, wind and runoff can cause problems with some vertical surfaces, and lattice structures are especially susceptible to freezing rain accretion. Glaze produces personnel slipping hazards on decks, stairs, and helicopter pads, and can disable machinery such as winches and cranes by locking cables in continuous hard ice. Glaze coats antennas and radomes, windows, hatches, rescue and firefighting equipment, and valves. It is a difficult ice to remove because of its high density and hardness.

4. *Rime (6):* Rime ice results from freezing of supercooled fog or cloud drops carried by the wind as described by Ryerson (2008). Objects facing the wind—especially smaller-diameter objects such as railings, antennas, cables, and lattice structures—will usually accumulate the largest rime ice thicknesses. However, wind blowing across a deck can occasionally cause rime accumulation on small roughness elements and produce slippery deck conditions; wind blowing across stairs, especially if constructed as an open grid, can coat stairs with rime and cause falls.

5. *Frost (4):* Frost deposits directly from water vapor onto surfaces forming a deposit that is thin, continuous or discontinuous, with needles oriented away from the surface. Frost forms in two circumstances. On windless nights with clear skies frost often forms on surfaces facing the sky. On days when warmer, moist air moves over surfaces that are cold soaked, frost will form on surfaces that are coldest and with no orientation prefer-

ence. Frost forms on decks, railings, stairs, handles, and cables and presents a slipping hazard for personnel.

6. *Sleet (5):* Sleet, often called ice pellets, forms when raindrops freeze before hitting surfaces. Therefore, sleet usually does not freeze to surfaces; it accumulates on horizontal surfaces such as decks, stairs, hatches, and helicopter landing pads. Sleet produces a slipping hazard and can create a surface that, for personnel, can be similar to walking on ball bearings.

Platform component and function safety ratings

Components and functions of offshore platforms are rated for the magnitude of safety hazard caused if disabled or changed by ice accretions. Components and functions are rated according to the importance of the function or component lost due to ice because of its effect on the survivability or operation of the entire platform, multiple crew members, or individual crew members. Threats to the safety of the entire rig are of greater importance than are threats to the entire crew, which are more important than are threats to individuals, which are more important than are threats to operational tempo or production. From most severe to least severe are threats to rig stability, rig structural integrity (legs and bracing), fire and rescue equipment, communications (antennas, radomes), helicopter landing pad, air intakes, flare boom (explosion or collapse), valves and handles, windows, cranes, winches, stairs (gratings), decks (gratings), railings, hatches, cellar deck, and moon pool.

Following are descriptions of rig, personnel, and production threats and ratings of each with regard to threat to platform safety and operations if disabled. A rating of 10 is the highest threat, and a rating of 1 is lowest, indicated in parentheses below and in Table 1.

1. *Stability (10):* Rigs can be destabilized by large superstructure ice accretions that occur principally below the main deck. However, as experienced on the semi-submersible *Ocean Bounty* in Cook Inlet, Alaska, large amounts of ice can also accrete on the main deck (Figure 17 in Ryerson 2008). Large masses of ice can cause larger rolling moments and decrease freeboard for floating platforms. Differential ice accretion also may cause heeling because most ice typically accretes on the windward side. Although no rig losses have been attributed to ice accretion, rigs have been endangered by ice and action taken to improve sea-keeping ability degraded by ice accretions. Loss of stability has a high hazard rating because destabili-

zation of a rig can cause its loss, the loss of multiple lives, and large oil spills.

2. *Integrity (10):* Integrity refers to structural integrity and the potential for a rig to break up due to structural loads caused by ice on parts of the structure. Crowley (1988) expressed concern that rig structural members are designed to take oscillatory stresses due to wave action, and changes in drag, inertia, diameter, roughness, and flexural response caused by ice accretion on these structures could change the structure's design wave capability. These stresses could cause fatigue and, potentially, loss of a rig. Breakup is a significant hazard because it would cause total loss of the structure, possibly loss of all lives aboard, and potentially massive spills of oil and drilling chemicals.

3. *Fire and rescue (9):* Loss of firefighting capability and encasing of rescue equipment such as life rafts in ice threatens the lives of all crew, and potentially could cause the loss of the platform should fire occur (Figure 2).

Figure 2. Fire extinguisher cabinet (left) and life rafts (right) (Ryerson).

4. *Communications (8):* Loss of communications would be unlikely to cause loss of the platform, but it could risk crew members' lives due to fire, gases, or other major life-threatening event.

Figure 3. Although helicopter landing pads are usually located well above the ocean surface, they are susceptible to snow, rime, glaze, or frost accumulation (courtesy VIH/Cougar Helicopters Inc).

5. *Helicopter landing pad (8):* Loss of the helicopter landing pad due to icing prevents rapid evacuation of injured or endangered crew members and the supply of critical safety items (Figures 3 and 4).

6. *Air intakes (8):* Blockage of air intakes can increase the danger of explosive or poisonous gases stagnating in living areas or in locations with potential ignition sources. In addition, operating machinery often requires ventilation for intake of combustion air, exhaust, and cooling. Loss of ventilation could cause failure of critical services and death to one or more crew members. Loss of power due to machinery shutdown could cause loss of the platform in extreme circumstances.

7. *Flare boom (7):* Flare booms are exposed to icing more than many other structural elements because they extend over the water (Figure 4). In addition, they are typically lattice structures presenting a large surface area for ice and snow accretion. Because they burn off potentially explosive gases, damage to the flare boom structure or blockage of the burner nozzles due to ice before well testing could cause an explosion, fire, or concentrations of toxic gases (Fagan 2004). Ice effects on the boom can cause serious safety threats to personnel and possibly the entire rig.

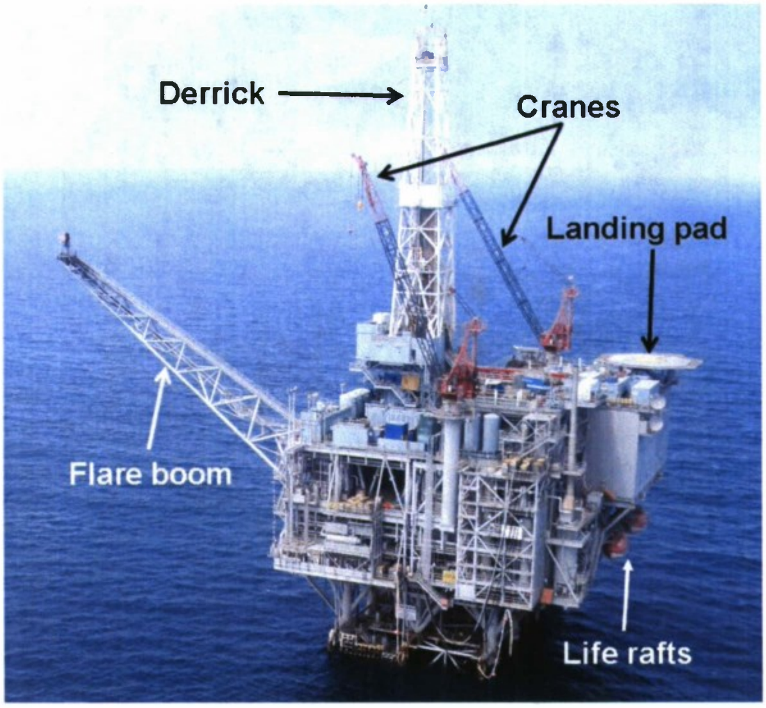

Figure 4. Icing of lattice and safety structures cause high risk (Ryerson).

Figure 5.Valves and controls below the main deck are located in a high-risk superstructure icing area (Ryerson).

8. *Handles, valves (6):* Iced handles and valves may not turn or may be difficult to operate (Figure 5). Frozen valve handles could prevent the operation of a critical component affecting the safety of the rig, or at least of personnel.

9. *Windows (5):* Iced-over windows cause loss of visibility for crane operators and other personnel working within enclosed control stations. Although loss of visibility is a potential threat to life, it is most likely to cause accidents and injuries. However, a crane or similar accident could possibly threaten the platform and entire crew if an explosion or fire occurred.

10. *Cranes (4):* Iced crane components could jam the windlass and cause cables to jump pulleys or to jam in guides causing failure. Though not likely to be life threatening, loss of the crane due to ice could cause injuries or loss of operational tempo (Figures 4 and 6).

Figure 6. Unprotected cables ice readily, and windlasses may become inoperable (Ryerson).

11. *Winches (4):* Ice-jammed winches can prevent operation or cause erratic operation of cranes and other lifting or dragging operations, which could endanger personnel (Figure 6).

12. *Stairs (gratings) (4):* Iced stairs are a fall hazard to individual personnel because they are slippery and can become irregular in shape, causing loss of footing (Figures 2 and 7).

Figure 7. Open grating walkways can rapidly fill with ice caused by sea spray or fog, and nonskid fills with snow or ice rendering it ineffective (Ryerson).

13. *Decks (gratings) (3):* Iced decks, though less dangerous than stairs, are a personnel hazard because of potential falls and because loose equipment often freezes to the deck causing accidents (Figure 7).

14. *Railings (3):* Iced railings are a personnel hazard because they become slippery and can increase in diameter, becoming irregular in shape and difficult to grasp. Even when iced, however, railings still prevent personnel from going overboard unless ice accretion on stairs or decks is thick enough to reduce the effective height of the railings.

15. *Hatches (2):* Removal of hatches can be difficult if not impossible when encased in ice because they become heavier, they become difficult to grasp and lift with hands or mechanical devices, and the ice can act as an adhesive holding hatch covers to the deck.

16. *Cellar deck (1):* Ice will accrete on many small-diameter objects and become a hazard for personnel movement and operation of equipment. Icing of the cellar deck principally reduces operational tempo.

17. *Moon pool (1):* Icing of the moon pool can affect the operation of valves and slip joints. Primarily it is a hindrance to operational tempo.

Platform joint safety rating

Ice type, platform components, and platform functions are combined to provide a qualitative ranking of safety impacts of each ice type on each platform function or component. Table 1 provides ratings that are products of the ice type hazard rating and the platform component or function important to safety if disabled. Scores range from 100 for the most severe icing-related safety hazard to 6 for the least severe rating.

Sea spray icing and platform stability and integrity have the highest joint safety rating because sea-spray-generated ice is most likely to add weight to the structure, add asymmetric ice masses that may cause the platform to heel and lose seaworthiness, and cause platform structural components to fail. Because the entire platform might be lost catastrophically, potentially causing large loss of life and perhaps oil spills, the safety hazard rating is high.

Snow and the flare boom have a joint safety rating of 56 because the flare boom could be damaged by snow, or its function could be impaired by blockage of the burner by snow and ice created by snow. Though an impaired flare boom could endanger the entire platform, it is unlikely to cause loss of the platform or the entire crew. In addition, snow is less likely to cause catastrophic failure than sea spray ice. However, snow is more likely to cause safety threats to the flare boom than rime, for example, because snow can accumulate in larger masses, absorb spray and increase weight, and affect the burner and the boom.

Glaze ice and decks have a joint safety rating of 21 because glaze is a significant hazard to footing, but it will not likely cause loss of life or injure more than a few individuals. In addition, the safety hazard is relatively easily reduced with chemicals or a friction enhancer such as sand, or removed by melting or mechanical methods. In addition, a fall on a deck is less likely to happen or cause injury than a fall on stairs, where the fall could be a considerable distance and head injuries are more likely to occur.

Frost and the helicopter landing pad have a joint safety hazard rating of 32 because frost creates slippery conditions that could cause the helicopter to slide. Personnel could slide and potentially fall overboard because helicopter landing pads have no personnel railing. However, frost is usually not thick, is often short-lived, and is relatively easy to remediate.

The above explanations indicate that there are generally several factors that cause ice type and certain platform components or functions to present a greater or lesser safety hazard when combined. The safety ratings in Table 1 are a result of the author's knowledge of ice, offshore platform components and functions, and indications from references of the impact of ice on platforms. Table 1 should be verified by cold regions offshore platform operators with operational experience on platforms during icing.

3 Methodology—Supply Boats

Technology assessment

The ice protection technologies reviewed for application to supply boats are the same technologies reviewed for application to offshore platform icing. The ice protection evaluation criteria are also the same for supply boats as for offshore platforms. The emphasis in the technology descriptions later in the report is on platforms rather than supply boats because there has been considerably more research conducted on icing of ships and boats than on offshore platforms.

Safety enhancement assessment

Icing processes and impacts on supply boats are somewhat different than on platforms, as elaborated in Ryerson (2008). In general, supply boats are moving structures that interact with the sea differently than do platforms. Unlike platforms, supply boats move and therefore can have a greater or lesser relative movement with the sea and with the wind than a stationary platform (Figure 8). Supply boats are smaller than platforms, thus interact more vigorously with the sea, and have less freeboard. Even large ships can create significant spray, necessary for superstructure icing, when interacting with swells (Figure 9).

The differences in supply boat structure and dynamics require different ice hazard and component and function safety ratings than do platforms. And, as a result, the suite of technologies suited for a supply boat may be different than that for a platform. Overall, a supply boat is less tolerant of icing than a platform, should ice more rapidly, and is considerably more likely to sink due to icing. In addition, the dynamics of the vessel, restricted work areas, weight and size constraints, and power limitations make deicing and anti-icing more difficult on a supply boat than on a platform.

Figure 8. Supply vessel climbing a swell. Note that the fantail is submerged (courtesy VIH/Cougar Helicopters Inc).

Figure 9. Interaction of Canadian Frigate HMS *Fredrickton* with seas. Spray is lofted by bow plunging in the top photo and carried over the ship by the relative wind in the bottom photo (as also illustrated for a trawler by Figure 15 in Ryerson [2008]). Top photo is entitled "A Fine Navy Day!" and bottom photo is entitled "Just a Little Spray. The resulting spray from the ship's bow plowing through the swell is seen crashing against the bridge windows. Truly, evidence of a great Navy day off the coast of Newfoundland." (Both photos courtesy of Provincial Airlines and the Canadian Department of National Defence, http://www.navy.forces.gc.ca/fredericton/0/0-s_eng.asp).

As with platforms, the application of technologies to supply boats is a function of ice type versus specific locations or functions on the boat. And, as with platforms, the potential of a technology to mitigate the hazard is then considered with regard to the combined safety hazard created by ice type and boat function.

Table 2. Joint safety impacts by ice type and supply boat component or function, with higher numbers denoting a larger safety hazard.

	Safety Rating	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Hazard rating		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	
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.							

The success of this approach is a function of the assumptions made with regard to the importance of safety hazards created on different parts of supply boats by the various forms of ice combined with the assessed potential success of the ice protection technology when applied to the problem. Because these assessments are largely qualitative, there is potential for error in assessing importance of technologies and their potential applications.

Ice hazard ratings

The following superstructure and atmospheric ice threats are described and rated for overall threat to supply boat safety and operations. A rating of 10 is the highest threat and a rating of 1 is lowest, indicated in parentheses below and in Table 1.

1. *Sea spray ice (10):* Seas spray, or superstructure ice (as defined by Ryerson [2008]) is the greatest threat to supply boats. Superstructure ice can accumulate rapidly, reduce stability by reducing freeboard and raising center of gravity, and cause the boat to increase its rolling moment until it does not recover. In addition, as with platforms, superstructure ice causes a slipping hazard for personnel on decks, ladders, and handrails, makes

deck cargo unavailable, disables winches, davits, life rafts, and antennas, and covers windows, rescue equipment, hatches, firefighting equipment, and radomes.

2. *Snow (6):* Snow can contribute to instability by absorbing spray, blocking scuppers, and increasing weight. Snow causes a slipping hazard for personnel on decks. Snow is also not saline. Therefore, the larger the contribution of snow to the total water content of ice onboard, the fresher and harder the ice will be, making it more difficult to remove.

3. *Glaze (4):* Glaze deposited from freezing rain affects decks, wheelhouse roofs, antennas, 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 disable antennas, firefighting equipment, and cover windows. However, overall glaze generally contributes little to the weight of a boat.

4. *Rime (3):* Rime ice coats objects facing the wind. On a boat, because the relative wind is typically over the bow or quartering, rime will form on locations with the highest relative wind. Small-diameter objects such as cables, railings, and masts will ice to greatest thickness. Wind blowing across a deck may occasionally cause rime accumulation on nonskid, and wind blowing across ladders can coat them with rime and cause falls. Rime is an inconvenience, and is primarily a personnel hazard.

5. *Frost (2):* Frost forms on decks, railings, stairs, handles, and cables and presents a slipping hazard for personnel.

6. *Sleet (1):* Sleet accumulates on decks, stairs, and hatches. Sleet creates a slipping hazard from rolling of the ice pellets on surfaces.

Supply boat component and function safety ratings

Components and functions of supply boats, as with platforms, are rated for the magnitude of safety hazard caused if hardware or functions are disabled or hindered by ice. Components and functions are rated according to the importance of the function or component lost due to ice because of its effect on the survivability or operation of the boat, multiple crew members, or individual crew members. Threats to the boat's sea-keeping ability are of greater importance than are threats to the entire crew, which are more important than are threats to individuals. From most severe to least severe are threats to supply boat seaworthiness, firefighting equipment and life rafts, communications (antennas, radomes), windows, winches, ladders, decks, railings, and hatches.

Figure 10. Ice-encased life raft (courtesy Kevin F. Plowman, U.S. Coast Guard).

Following are descriptions of ship and crew threats, and ratings of each with regard to threat to safety if disabled. A rating of 10 is the highest threat and a rating of 1 is lowest, indicated in parentheses below and in Table 2.

Seaworthiness (10): The weight of ice on a ship reduces seaworthiness by reducing freeboard, raising center of gravity, and increasing roll angle. As weight increases, the ship or boat makes larger rolls and eventually does not recover and founders.

Fire and life rafts (9): Fishing trawlers often are lost with all hands because life rafts become encased in ice. Inaccessible life rafts cause crew to be lost with the ship or go into the water, making survival probability low because of potential hypothermia (Figures 10 and 11).

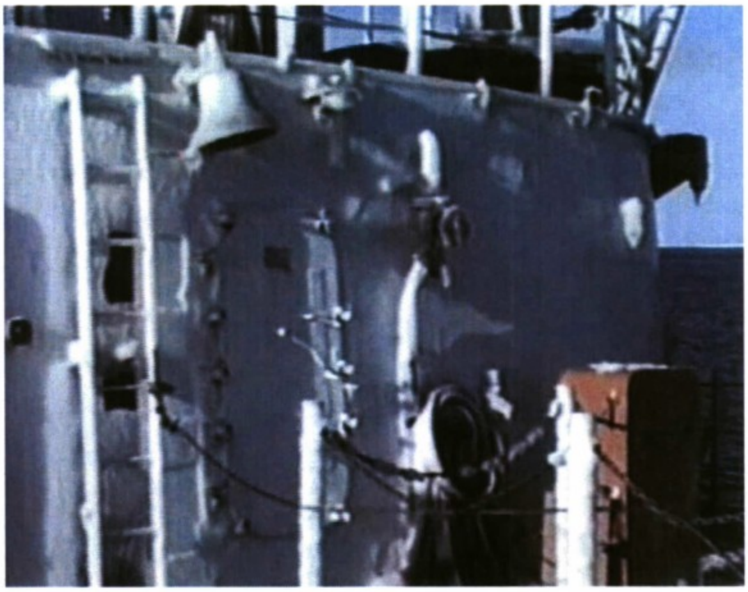

Figure 11. Ice-encased fire valve and ladder on forward bulkhead of Coast Guard Cutter *Midgett*, Bering Sea 1990 (Ryerson).

Communications (8): Inability to call for assistance to other ships or to the Coast Guard due to ice-covered antennas may cause loss of the ship and the entire crew (Figure 12).

Ventilation (8): Ventilation is critical to vessel survival. Ice covering engine inlets causes loss of engine power, which may allow a boat to founder. In addition, lack of ventilation can cause explosions through the accumulation of fuel vapors. Walsh et al. (1993) assessed accretion of ice on a new Navy ship engine intake design.

Windows (7): Windows must remain clear for navigation and keeping the vessel oriented to the seas for proper sea keeping (Figure 12). If the vessel crosses the sea or runs in a following sea, it is more likely to be lost.

Ladders (5): Iced ladders are a personnel safety hazard because they are slippery and become irregular in shape (Figure 11).

Figure 12. Superstructure ice covering bridge windows (courtesy Kevin F. Plowman, U.S. Coast Guard).

Decks and railings (4): Iced decks are a personnel hazard because of potential falls (Figure 13). Heavy spray or "green water" over the decks also threaten to carry personnel overboard. Icing of decks often freezes scuppers, which prevents decks from draining and enhances icing (Figure 13).

Hatches (2): Freezing of hatch covers makes them difficult to remove, an inconvenience rather than a hazard.

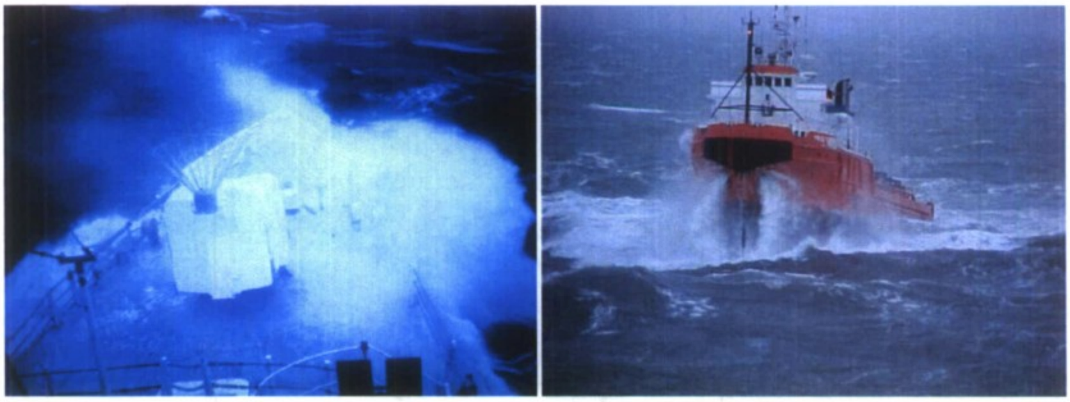

Figure 13. Iced deck receiving spray on Coast Guard Cutter *Midgett* (left) (Ryerson). Supply boat with proper draining forecastle scuppers (right) (courtesy http://www.qsl.net/kc2jpo/index.html).

Supply boat joint safety rating

Ice type and supply boat components and functions are combined, as with platforms, to provide a ranking of safety impacts of each ice type on each function or component. The Table 2 ratings are products of the ice type hazard rating and the boat component or function importance to safety if disabled. Scores range from 100 for the most severe icing-related safety hazard to four for the least severe rating.

Sea spray icing and seaworthiness have the highest joint safety rating because sea-spray-generated ice is most likely to add weight, which lowers freeboard, raises center of mass, and increases maximum roll angle. In the extreme, these factors cause loss of the vessel, possibly with all hands. As a result, this is the highest icing safety rating for a supply boat. Seaworthiness is 60 for snow because it is unlikely that snow would add sufficient weight to a supply boat to cause its loss. However, snow can cause blockage of scuppers and it can absorb sea spray, thus magnifying the icing problem by not allowing sea spray to run off. Glaze, rime, frost, and sleet are expected to provide no threat to supply boat seaworthiness.

Fire and life rafts refer to accessibility of fire protection equipment and life rafts. Each of these functions is affected by the accumulation of superstructure ice, snow, glaze, and rime. However, the significant threat is superstructure spray ice, which can become so thick that firefighting equipment and life rafts would not be available at all. Snow, glaze, and rime would likely not block access to fire equipment or life rafts, but they would hinder access so that the boat might be threatened, or the crew would be threatened if these items could not be accessed in a timely manner.

Communications and ventilation, though much different functions, are similarly important to supply boat safety. Communications allow the vessel, if threatened, to alert potential rescuers that they need assistance. Impaired communications may prevent contact with potential assistance, with the result being a possible loss of the entire crew should the boat sink. Communications also involves the functioning of global positioning system (GPS) or long-range aid-to-navigation (LORAN) locating systems, and emergency position-indicating radio beacons (EPIRBs) signaling maritime distress. Ventilation is vital for supply of air to the engines, and for the exhausting of flammable or toxic gases. Failure of engine power would not allow the boat to maintain heading and could allow it to cross the waves and roll.

Windows are important safety and navigation tools despite navigation equipment on the bridge. Icing can reduce visibility through windows and place the boat at risk.

Iced ladders, decks, and railings are a threat to personnel and are generally not a threat to the survival of the vessel or the crew. Although decks can flood when scuppers freeze and cease draining, which could lead to the loss of the vessel, this would likely be only a contributing factor. Decks, ladders, and railings provide work areas for the crew and contribute to their safety. Slippery decks, ladders, and railings increase the chances of a crew member falling, or possibly going overboard, and increase the difficulty of working on deck. However, these conditions would not threaten the loss of the entire crew. Ladders are inherently more dangerous areas than decks, therefore their safety rating is one point higher.

In general, icing of hatches is an inconvenience rather than a significant safety hazard. Although icing can cause hatches to freeze in place and make them difficult to open or seal when closing, in most icing conditions they are not likely to be opened.

4 Ice Protection Technologies

Ryerson (2008) provided a synopsis of 16 ice protection technologies. This report provides additional information about each technology area; the report also identifies products, developers, and vendors and describes each in more detail. Electrical ice protection technologies, as described by Ryerson (2008), were determined to be another form of thermal deicing. Therefore, they are placed under heat, or included with other technologies when supporting the operation of the other technology. Each technology or product described in the categories are organized according to the description under the platform *Evaluation Criteria* in Section 2.

The following technologies or applications are reviewed:

1. Chemicals and Chemical Distribution
2. Coatings
3. Design
4. Expulsive
5. Heat
6. High-Volume Water, Air, Steam
7. Infrared
8. Mechanical
9. Piezoelectric
10. Pneumatic Systems
11. Vibration and Covers
12. Windows
13. Cables
14. Ice Detection

5 Chemicals and Chemical Distribution

Chemicals are the most widely used ice control technology, and also the most complex with regard to numbers of chemicals, methods of use, suppliers and vendors, and dollars spent to purchase and use them. Chemicals are used most frequently in snow and ice control of highways and aviation operations. However, chemical deicers are also used at sea (Figure 14).

Figure 14. "Ice melt works well! Once the majority of the ice is shoveled off the deck, 'ice melt' is put on the upper decks to prevent people from slipping. Here is Petty Officer Second Class Pennel putting ice melt on the upper decks" on the Canadian Frigate HMCS *Fredericton*. (Photo courtesy PO2 Randell/Lt(N) M. Tremblay and the Canadian Department of National Defence, http://www.navy.forces.gc.ca/fredericton/0/0-s_eng.asp).

Weeping Wing

CAV Aerospace Inc.
2734 Arnold Court
Salina, KS 67401
Telephone: 888-865-5511; 785-493-0946
E-mail: tkssales@weepingwings.com
http://www.weepingwings.com

Intended or Actual Application: CAV Aerospace markets the TKS Ice Protection system, a technology that weeps ice protection fluid slowly onto an aircraft wing, propeller, and the windscreen. The system is activated before entering icing conditions and remains effective throughout an icing encounter. When activated, ethylene glycol ice protection fluid is pumped from a reservoir through pores in the wing leading edge (Figure 15). The slip stream carries the ice protection fluid over the wing protecting the entire surface, rather than only the leading edge, from icing by using the freezing point depression capabilities of the ethylene glycol. If ice forms, the ice protection fluid melts the adhesion layer of ice from the aircraft, whereby perturbations in the airflow will cause the ice to detach itself from the aircraft (Burnside 2008). Ice protection fluid is not heated; all ice protection is accomplished through the freezing point depression characteristics of the glycol mixture. Kilfrost is one of the fluid manufacturers for the TKS Ice Protection system. Examples of aircraft using the TKS system include the Cessna 182, 206, 208B, 210, 300, 350, 400, a variety of Bonanza and Mooney aircraft models, the Cirrus SR22 and SR22G3, the Commander 114B, the Hawker, and various Piper models.

Operating Environment: The TKS system is currently designed for use in specific aircraft models. The TKS system is certified for flight in Federal Aviation Administration (FAA) FAR25, Appendix C icing conditions and provides ice protection to -40°C (FAA 1991).

Engineering Concept: The TKS system protects aircraft from icing by weeping ice protection fluid at a rate of about 6 to 8 liters per hour (L/hr) through porous, laser-drilled titanium panels installed on the leading edges of the wings and horizontal and vertical stabilizers in all known-ice

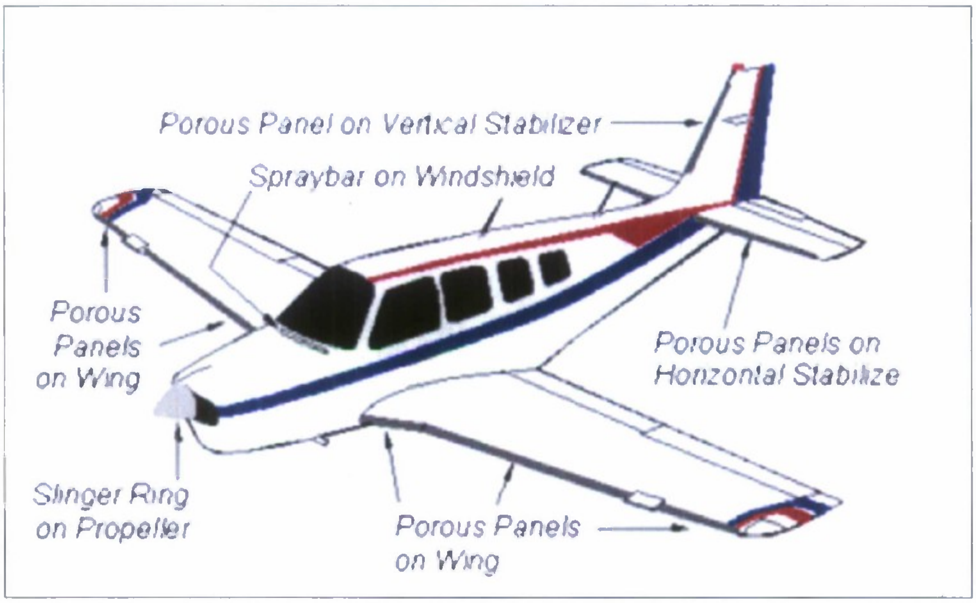

Figure 15. Areas of aircraft weeping deicing fluid for complete TKS installation (courtesy CAV Aerospace Inc.).

certified applications (Figure 16). Protection time is a function of ice protection fluid application rate and storage capacity. Holes through which the glycol- and alcohol-based ice protection fluid is pumped have a diameter of about 0.065 mm providing about 124 holes per cm^2. The holes are small enough that impacting insects do not penetrate the leading edge. A slinger ring keeps the propeller blades protected from ice accretion, and a spray bar protects the windshield through an on-command momentary switch.

The Kilfrost glycol- and alcohol-based ice protection fluid keeps the aircraft nearly ice-free and minimizes runback ice on protected surfaces. Fluid is metered through proportioning units by a small electrical pump. The system is activated before or as icing is encountered, and turned off when leaving icing conditions. The weight of system hardware and ice protection fluid varies with aircraft size, but is typically about 36 to 45 kg. Typical flight duration with onboard ice protection fluid in icing is 1 to 3 hr, depending upon the aircraft model.

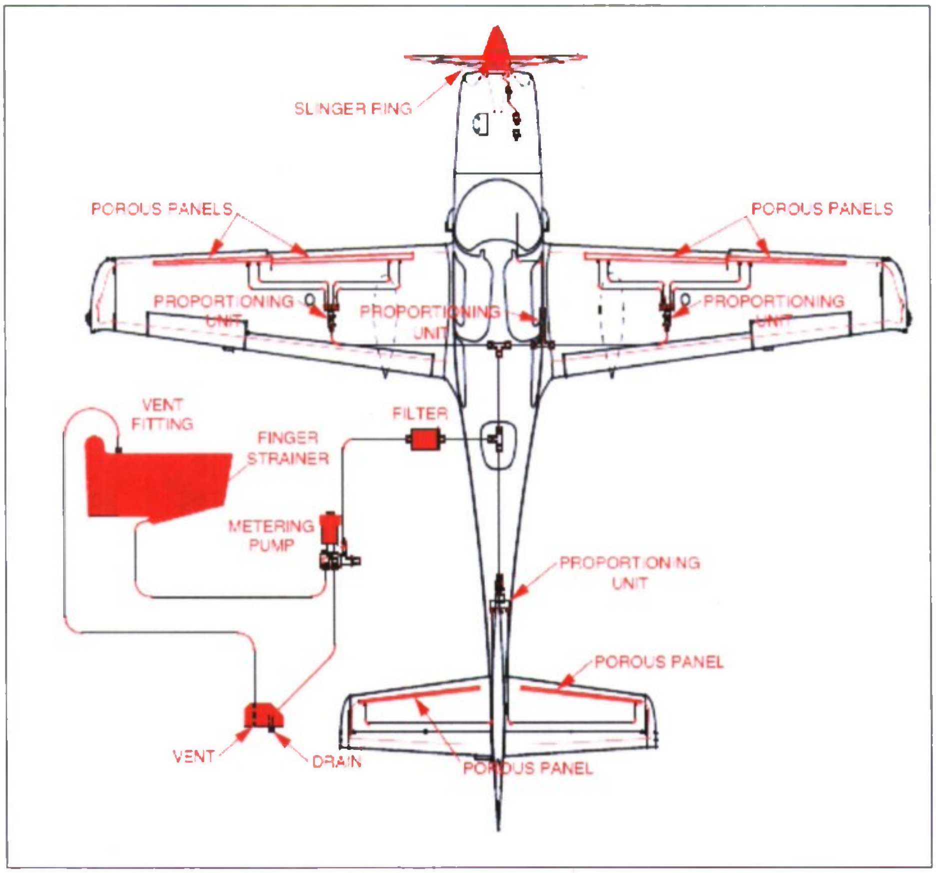

Figure 16. TKS system pumps, valving, lines, and porous panel configuration on light aircraft (courtesy CAV Aerospace Inc.).

Stallabrass (1970) experimented with a variation of the weeping wing concept in outdoor tests, using freshwater ice, but otherwise attempted to simulate marine icing. Glycol was gravity fed from holes at the top of a vertical steel panel wall through holes in a manifold pipe that were 1 mm in diameter. As the glycol flowed down the wall, the individual streams joined, coating the entire wall. Ice formed on the panels as the freezing point depressant was in use. However, the glycol mixed with the ice as it formed, creating a mushy ice that was poorly adhered, or not adhered, to the steel panel upon which the glycol flowed. In a test with 25 mm of ice, about 25% of the panel was free of ice at the end of the test, and the remainder was standing clear of the panel, requiring only an easy hand touch to remove.

TRL: 8–9. Commercial-off-the-shelf (COTS) for specific aircraft models.

Deicing or Anti-icing: Ice protection.

Current Advantages and Disadvantages: The weeping wing system protects all aircraft surfaces where ice protection fluid can flow after being pumped from leading edges or the propeller. The system only protects as long as ice protection fluid is available. Since each aircraft installation is somewhat unique, CAV Aerospace is familiar with how to customize the technology as required. The system operates in icing conditions for which it is certified and has been extensively tested by NASA.

Current Acquisition Cost: A Beechcraft Bonanza A36 TKS kit for known icing conditions (and installation) is $42,300.

Operational Cost: Operational cost is primarily a function of ice protection fluid use rate. Kilfrost costs about $5.80 per liter and usage rate is about 6–8 L per hour, depending upon aircraft model. Ice protection fluid usage rates can increase if system is operated in Maximum mode for deicing. Anti-icing is accomplished in Normal mode.

Maintenance Requirements: The TKS system flushes accumulated debris from the perforated leading edge panels as operated. Glycol, the main ingredient of the ice protection fluid, is a cleaner and does not harm aircraft paint. Periodic exercising of the system is recommended to ensure readiness in flight.

Potential Marine Application and Safety Enhancement: A weeping system of the TKS or Stallabrass (1970) design could deice bulkheads and support structures under the main deck of a platform. A manifold placed above windows may allow window ice protection. The technology could also be used on bulkheads and masts of a supply boat.

Marine TRL: 5. Early design tested by Stallabrass (1970).

Marine Advantages and Disadvantages: System may be inexpensive except for ice protection fluid usage cost. Bulkheads and support structures could be protected. Ice protection fluid on decks is potentially slippery. Ice protection fluid may run overboard and may be considered a hazard depending upon the chemical used. System could keep windows free of ice.

Marine Technology Transfer Requirements: Test with saline ice. Evaluate pollutant effects because glycol is a cleaner. Evaluate effects of glycol under sea ice. Determine ice protection fluid delivery rates necessary to keep surfaces free of ice. Test ice protection fluid friction effects on deck surfaces.

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Feltwick Anti-Icing Grate

Innovative Dynamics Inc.
2560 North Triphammer Rd.
Ithaca, NY 14850
Contact: Joseph Gerardi
Telephone: 607-257-0533
Fax: 607-257-0516
E-mail: idi@idiny.com
http://www.idiny.com

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 (Figure 17). 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.

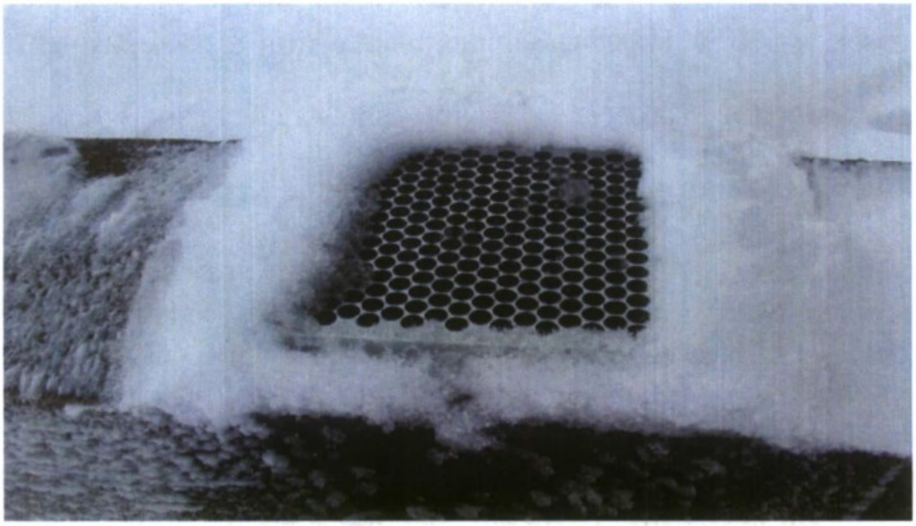

Figure 17. Feltwick prototype melting snow (courtesy Innovative Dynamics Inc.).

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.

A reservoir system feeds all of the wicks, and this can comprise a dedicated layer and/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, due 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 disposed of.

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.

TRL: 6. Lab testing has occurred in winter snow and ice conditions.

Deicing 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 Feltwick 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 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 is 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.

Marine Technology Transfer Requirements: Evaluate system in saline ice and spray conditions. Evaluate system on deck of pitching supply boat. Experiment with a variety of wicking designs to determine most effective system in industrial environment. Explore effects of chemicals and oil on system effectiveness and longevity. In addition, the slipperiness of the anti-icing fluids should be investigated if tracked onto smooth surfaces.

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Fixed Anti-Icing Spray Technology (FAST)

All Weather Inc.
1165 National Dr.
Sacramento, CA 95834
Telephone: 916-928-1000; 800-824-5873
E-mail: info@allweatherinc.com
http://www.allweatherinc.com

Boschung Company Inc.
PO Box 8427 930 Cass St.
New Castle, PA 16101-8427
Telephone: 724-658-3300
E-mail: information@boschungamerica.com
http://www.boschungamerica.com/pages/aboutUs.php

Innovative Dynamics Inc.
2560 North Triphammer Rd.
Ithaca, NY 14850
Telephone: 607-257-0533
E-mail: idi@idiny.com
http://www.idiny.com/weather.html

Odin Systems
PO Box 20247
St. Simons Island, GA 31522
Telephone: 912-638-2400

Quixote Transportation Safety
35 East Wacker Dr.
Chicago, IL 60601
Telephone: 312-467-6750; 800-325-7226
http://www.qttinc.com

Intended or Actual Application: Fixed Anti-Icing Spray Technology (FAST) is a class of systems marketed by several companies to spray anti-icing or deicing fluids onto walkways, roadways, bridges, and other pavement surfaces. Spray nozzles alongside or embedded in the roadway surface are activated either manually or with sensor systems, such as Road Weather Information Systems (RWIS). FAST is more commonly used in Europe than in North America, but several companies listed above market the spray systems and develop sensors.

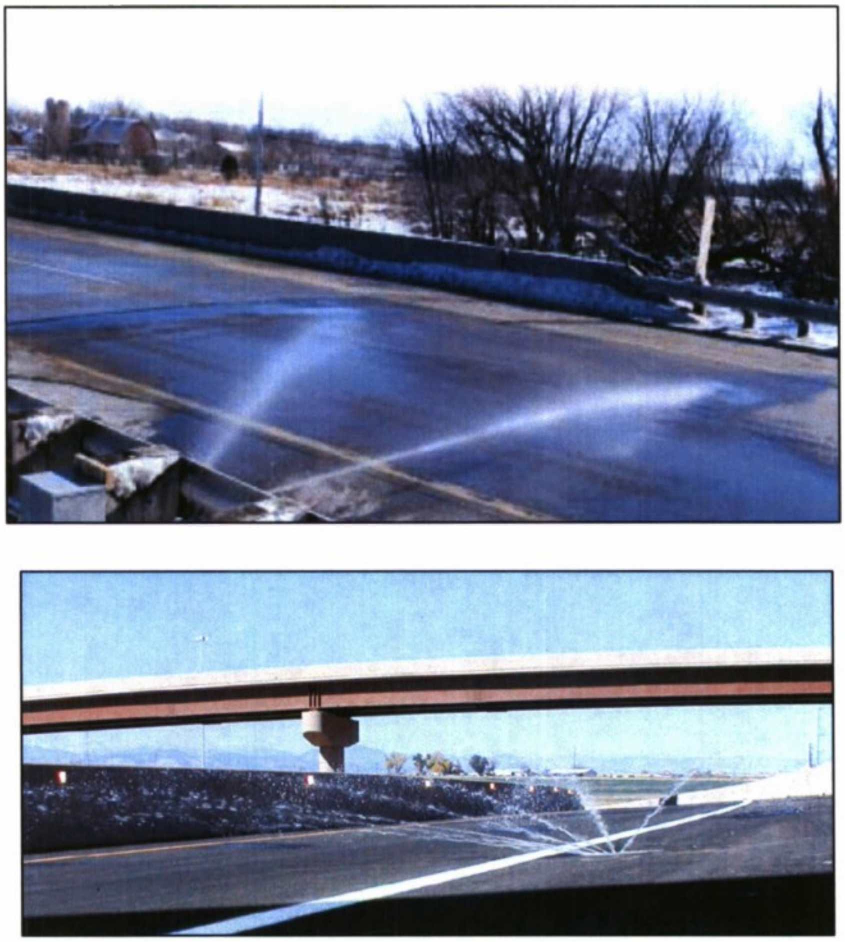

Figure 18. Spray nozzles located alongside (top) and in roadway pavement (bottom) (both images courtesy Quixote Corporation).

Operating Environment: FAST systems are typically designed to spray bridge decks and roadways remotely with deicing or anti-icing fluid. Therefore, they can operate in temperature and precipitation conditions causing snow, frost, ice, or slush and at temperatures as cold as the fluid freezing point depression. Operating temperatures for the FreezeFree system marketed by Energy Absorption Systems Inc. (Quixote Corporation), for example, are -40°C to 60°C (Figure 18). Most systems are activated by automated controllers that monitor active and passive sensors to indicate temperature, the presence of ice, water or deicing chemicals, and other weather conditions. The sensors are either embedded within the pavement or, like those from Innovative Dynamics Inc., placed alongside the area.

Engineering Concept: FAST systems prevent or reduce the formation of snow, ice, and frost on pavement surfaces by anticipating ice and snow conditions and placing a layer of chemical on the roadway surface to reduce ice adhesion. The Minnesota Department of Transportation, for example, tested a FAST system on the I-35W Mississippi River bridge that collapsed on 1 August 2007 (Johnson 2001) (Figure 19). The bridge was susceptible to "black ice" and slippery conditions because of moisture from nearby St. Anthony Falls, nearby industrial sources of moisture, and high traffic volume. The FAST was effective at temperatures to -26°C and below when used with Cryotech CF7, a potassium acetate liquid anti-icing chemical containing no chlorides. They found that the spray system (a Boschung system) effectively deiced the bridge, and used less fluid when operated in an automated mode rather than when manually activated. FAST consists of a pump, a fluid storage tank, a controller, and ice detectors if the system is automated. Spray nozzles can be located on the side of the pavement, or can be embedded in the surface of the pavement (Figures 18 and 19). The systems can be programmed for multiple condition-specific programmed spray routines and are compatible with many liquid deicing chemicals. According to the Johnson (2001) study, the chemical selected is the most important component because it has the potential to make the system perform poorly or successfully. Both Johnson (2001) and Roosevelt (2004), who studied an Odin system installed on Interstate 95 in Virginia, indicate that FAST systems are least effective in heavy snow, where plowing is still necessary. Pinet et al. (2001) also found that potassium acetate is an excellent deicing chemical for use in a FAST system.

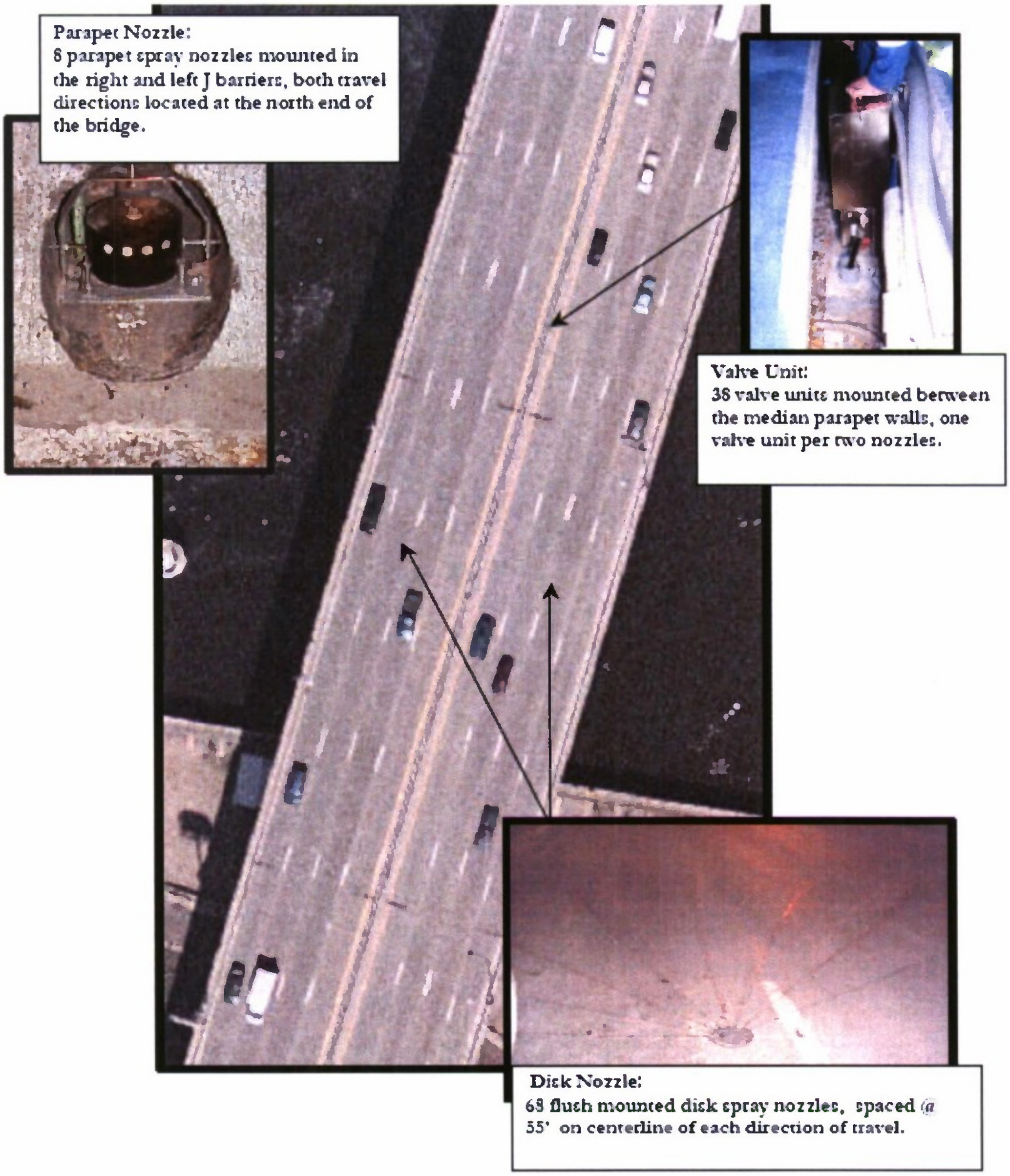

Figure 19. Spray anti-icing system installed on I-35W Mississippi River bridge that collapsed on 1 August 2007 (Johnson 2001).

TRL: 8–9. FAST systems have been available for about 20 years, especially in Europe.

Deicing or Anti-icing: Anti-icing and deicing.

Current Advantages and Disadvantages: FAST systems consume potentially large quantities of deicing chemicals. FAST systems are not as effective on snow as on ice. They are expensive to install, and chemicals can cause corrosion of the system and of the surfaces being protected. Space is required for chemical storage and pumps. Sensors are necessary if the system is intended to be automated. The Minnesota I-35W system reduced winter traffic accidents by 68% (Johnson 2001). Installation may require modifying the roadway surface to bury piping and sensor cables, although designs are available that make this unnecessary.

Current Acquisition Cost: Cost is a function of application. Pinet et al. (2001) in Ontario estimated an installation cost of $239,000 to $300,000 (in Canadian dollars) to protect a 165-m-long by 11.2-m-wide section of concrete highway. Roosevelt (2004) estimated a cost of about $60,000 to install a FAST system on a 10-m-wide by 56-m-long bridge in Virginia. The I-35W bridge installation in Minneapolis cost $618,450 (Johnson 2001). This cost covered installation, hardware, software, the pump house, operation manuals, sensors, and two years of support and training. The area covered was about 595-m long and eight-lanes (approximately 35-m) wide. Installation costs for the three sections, when normalized, range from about $30 to $110 per square meter.

Operational Cost: Operational cost is a function of the area protected but, most importantly, the weather conditions at the site as expressed by the frequency of frost, freezing rain, freezing drizzle, and snow. The Canadian installation described by Pinet et al. (2001) cost about $12,000 to operate for one winter, which was largely the cost of the potassium acetate sprayed onto the roadway. This operational cost was considered minimal by the authors. The Virginia FAST operators did not maintain a record of winter operational costs (Roosevelt 2004). Johnson (2001) calculated that annual operation of the Minneapolis I-35W bridge was $56,300, of which all except $1050 was for the purchase of 17,000 gallons of deicing chemical. The design life of the Minneapolis system was 15 years.

Maintenance Requirements: The Ontario installation required monitoring chemical levels in tanks, keeping chemicals and electronics separated, and flushing with clear water and changing filters in the spring (Pinet et al. 2001). Johnson (2001) indicates that the Minneapolis I-35W bridge annual maintenance cost was $9725 for one year to replace computer, pump, and valve parts. The Virginia system was not provided with annual maintenance, and several system components were damaged by residual chemicals (Roosevelt 2004). However, it is estimated that $1000 per year should cover necessary maintenance.

Potential Marine Application and Safety Enhancement: FAST could be readily adapted to drilling platforms to protect walkways, stairs, helicopter landing pads, and irregularly shaped machinery components such as winches. It is not clear if the system would be effective with saline ice, near the sea surface, or under platform main decks where most superstructure ice accumulates. However, a spray system may be installed inside lattice structures, such as flare booms and crane booms, to reduce ice loads and to minimize significant ice accumulations that might later fall and become a personnel hazard.

Marine TRL: 5. Systems must be designed for each application. There is no evidence that FAST systems have been tested in the marine environment.

Marine Advantages and Disadvantages: Chemical slipperiness could present a safety hazard, and corrosion could damage equipment. Personnel may need to evacuate the area when spraying occurs. Chemicals would likely be tracked by personnel into areas where chemicals are not desired. Equipment installation may be expensive if piping and spray nozzles are made flush with deck surfaces. However, nozzles mounted on bulkhead surfaces and railings and spraying onto decks may be more cost-effective. The technology, which involves pumping fluids, is well-understood on offshore platforms.

Marine Technology Transfer Requirements: FAST systems should be tested with saline superstructure ice. They should also be evaluated for deicing complex surfaces like winches, and on hardware such as stored piping and life rafts. Fluids should be evaluated for compatibility with marine structures—especially slipperiness and corrosivity. Algorithms for automated FAST systems may need altering for the marine environment.

****

Chloride deicers

Sodium chloride (NaCl)

Cargill Inc.
PO Box 9300
Minneapolis, MN 55440-9300
Telephone: 888-364-7258; 800-227-4455
http://www.cargill.com

Chemical Solutions Inc.
Franklin, MA 02038-0675
Telephone: 508-520-3900
http://www.meltsnow.com/products.htm

Redmond Minerals Inc.
PO Box 219
Redmond, UT 84652
Telephone: 435-529-7402
Fax: 435-529-7486
http://www.iceslicer.com

U.S. Salt Inc.
1020 Black Dog Rd. West
Burnsville, MN 55337
Telephone: 952-890-8448
Fax: 952-890-8493
https://www.ussalt.com

Intended or Actual Application: Sodium chloride (Halite, "rock salt," NaCl) is the most common of the salts used for deicing. The other common deicing salts are magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$). Sodium chloride was first used for roadway ice and snow control in the 1930s, and was widely adopted in the 1960s (Environmental Literacy Council 2002; Viadero 2005). Approximately 8–12 million tons of sodium chloride are used on highways each winter in the United States. Sodium chloride is the least effective salt for melting ice and snow, but it is the most common and least expensive. Because sodium chloride can corrode bridges and vehicles and damage water supplies and vegetation, transportation authorities have sought alternative chemicals, but they are often more expensive.

Operating Environment: Sodium chloride is used to melt and reduce the bond strength of ice and snow globally on roadways, parking lots, and bridges. Salt can be applied as solid granules over a variety of size ranges, or as a brine. As a brine, the optimal 23.3% mixture has a freeze point temperature of -21°C. However, the practical working temperature of sodium chloride ranges between -7°C and -10°C (Greenawalt 2008). Salt is mined in Alberta, New Brunswick, Nova Scotia, New York, Kansas, Louisiana, Ohio, and other areas of the United States and Canada. Solarization is used to produce salt in San Francisco, CA, Salt Lake City, UT, Louisiana, Mexico, and Chile.

Engineering Concept: Bulk ice control salt is a coarse, screened, translucent to white crystalline solid as a highway deicing product (Cargill 2007). Ice and snow melting chemistry works on freezing point depression, a colligative property of solutions. All ice melting salts dissociate into ions as they dissolve into melting ice and snow, which multiplies the molar quantity and multiplies the effect of freezing point depression. Sodium chloride releases a ratio of one sodium ion (Na+) to one chloride ion (Cl-) for twice the effect. Calcium chloride releases one calcium ion (Ca+) for every two chloride ions for three times the effect. However, calcium and magnesium chlorides pose a greater risk than potassium and sodium chlorides because they release twice the number of damaging chloride ions that cause corrosion and damage to plants (Peeples 1998). Table 3 shows the relationship between sodium chloride and other deicing salts and chemicals with regard to effective temperature, corrosion, effects on carpets and floors, effects on vegetation, and effects on the environment. Table 4 shows sources for chloride salts, their optimum eutectic temperature and the concentration at that temperature, usage rates, and cost. Table 5, compiled by Greenventure (2007) from a variety of sources indicated on their Web site, shows the effective usable temperatures of common deicing chemicals including the salts, relative cost, and environmental impact.

TRL: 9. Commercial off-the-shelf.

Deicing or Anti-icing: Anti-icing and deicing.

Current Advantages and Disadvantages: Sodium chloride is inexpensive, easily applied, and is effective at melting and debonding ice at warmer temperatures. However, it is corrosive and damaging to the environment.

Current Acquisition Cost: \$20–\$40 per ton (Minnesota DOT n.d.); \$36 per ton (NCHRP 2007).

Operational Cost: Sodium chloride is used on highways at rates up to nearly 11,000 kg per km (AASHTO 2008), but others recommend 28–84 kg per single lane kilometer (Wisconsin Transportation Center 1996). Typical usage in non-road applications is about 0.25 kg m^{-2} (Hagen n.d.). Operational cost can include application methods and damage caused by impacts on structure corrosion and the environment. No firm cost information is available for these factors except for information available in Tables 3 and 5.

Maintenance Requirements: Reapplication is usually indicated "as needed" due to dilution as ice and snow melt.

Table 3. Selected properties of common and alternative deicing compounds (Koenig and Rupp 1999).

Compound	Effective Temperature, °F*	Effect on: Hardscape	Carpet/ Floors	Vegetation	Environment
Sodium chloride	-6	severe	slight	severe	moderate
Calcium chloride	-67	severe	severe	moderate	slight
Magnesium chloride	-28	severe	severe	moderate	slight
Potassium chloride	+13	severe	slight	moderate	slight
Corrosion-inhibiting salts	depends on compounds	slight/ moderate	varies	depends on compounds	depends on compounds
Calcium Magnesium Acetate (CMA)	+15	slight	moderate	slight	slight/ moderate
Nitrogen salts	variable	none/ severe	moderate	slight	severe
Abrasives	--	slight	moderate	none	slight
Radiation absorbers	--	slight	moderate	slight none	slight

*The effective melting temperature depends on the concentration of the deicing chemical. Values generally represent the lowest effective melting temperature possible with highly concentrated solutions of the compound.

Table 4. General properties of chloride salts (NCHRP 2007).

Material	Chemical Formula	Forms Used	Optimum Eutectic Temperature °C (°F) @ % Concentration [1]	Common Sources	Approximate Annual usage Tonnes (Tons) North America	Median Cost (USD) per Ton (survey of Internet contracts) [2]
Sodium Chloride	$NaCl$	Primarily solid, but increasing use of liquid	-21 (-5.8) @ 23.3%	Mined from natural deposits, solarization of natural brines	21,080,000 (22,291,000) (Salt Institute)	$36
Calcium Chloride	$CaCl_2$	Mostly liquid brine, some solid flake	-51 (-60) @ 29.8%	Natural well brines, by-product of the Solvay process	Not Available	$120
Magnesium Chloride	$MgCl_2$	Mostly liquid brine, some solid flake	-33 (-28) @ 21.6%	Solarization of natural brines, natural well brines, by-product of metallurgical process	Not Available	$95
Blended Chlorides	Varies with product	Solid and liquid	Varies with product	Natural well brines, solarization of natural brines, mined from natural deposits	Not Available	$142

[1] Source: (2)
[2] as of October 2003

Table 5. Characteristics of selected deicing chemicals (Greenventure 2007).

Check the Label For:	Works Down to:	Cost is:	Environmental Impacts:
Calcium Magnesium Acetate (CMA)	-3°C to -5°C	20x more than rock salt	(+) Less toxic — if used sparingly
Potassium Acetate (KAc)	-30°C to -60°C	8x more than rock salt	(+) Less toxic — biodegrades, but lowers oxygen levels in bodies of water
Calcium Chloride (CaCl)	-31°C	3x more than rock salt	(+) Lower rate of application; (+) No cyanide; (−) Chloride impact
Magnesium Chloride (MgCl)	-15°C	5x more than rock salt	(+) No cyanide; (−) Chloride impact
Potassium Chloride (KCl)	-11°C	2.5x more than rock salt	(+) No cyanide; (−) Slightly higher rate of application; (−) Chloride impact — contains 17-56% more chloride ions than other "salt"-type deicers
Urea	-4°C to -7°F	5x more than rock salt	(+) Less corrosive; (−) Slightly higher rate of application; (−) Adds needless nutrients — can be harmful to plants & waterbodies
Sand	Minimal melting effect	≈$3 for a 20 kg bag	(+) Improves traction; (−) Accumulates in streets and streams
Sodium Chloride (NaCl), aka rock salt	-10°C	≈$5 for a 20 kg bag	(−) Contains cyanide; (−) Chloride impact

Potential Marine Application and Safety Enhancement: Sodium chloride can be applied to marine structures to melt ice because seawater salt concentrations are only about 3%, and concentrations for the lowest freezing depression are about 23%. Granular or liquid sodium chloride may be used on decks and stairs. Although liquid could be sprayed on winches and other equipment, corrosion would be enhanced. It may also be possible to spray brine onto lattice structures. However, granular or liquid application for open-grid decks and stairs will be difficult unless they are completely filled with ice.

Marine TRL: 7.

Marine Advantages and Disadvantages: Although sodium chloride is present in seawater at a typical concentration of 3%, seawater freezes at about -2°C. Adding sodium chloride to sea-spray-created superstructure ice, or to fresh-water ice formed from snow, rime, or freezing rain would enhance melting and decrease bond strength, allowing more ready removal. However, adding sodium chloride could increase corrosiveness in an already corrosive environment. Because of corrosivity, sodium chloride should not be used on helicopter landing pads. In addition, salt will be tracked to inside living and working areas. Brine could possibly be sprayed onto vertical surfaces and complex structures, such as winches and lattice frameworks. However, runoff may be so large that deicing in this manner would be ineffective.

Marine Technology Transfer Requirements: Sodium chloride should be evaluated for its effectiveness with saline ice and its applicability to surfaces that are not in horizontal orientation.

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Calcium chloride ($CaCl_2$)

Peters Chemical Company
Mailing address:
PO Box 193
Hawthorne, NJ 07507
Street address:
535 High Mountain Rd. Suite 212
North Haledon, NJ 07508
Telephone: 973-427-8844
http://www.peterschemical.com

The Dow Chemical Company
2030 Willard H. Dow Center
Midland, MI 48674
Telephone: 989-832-1560; 800-441-4369
http://www.dow.com

Intended or Actual Application: Calcium chloride (CaCl2) is one of the most common pavement deicers, and is also commonly mixed with Halite and other chemicals to lower freezing point depression and to increase deicing speed. It is primarily available as a brine rather than as a solid. It is often mixed with granular materials in an optimal 32% solution, such as coal, sand, abrasives, limestone, wood chips, ores, and minerals to keep them free.

Operating Environment: Calcium chloride is effective in snow and ice, and is used on roadway surfaces, in granular materials to keep them ice-free, and in rail cars to keep materials from freezing to the sides. It is typically applied as a liquid, but can be applied as a flake. Calcium chloride is an aggressive deicer. It is hydroscopic so it attracts moisture, which speeds melting, and it is exothermic, releasing considerable heat as it melts into ice and snow; this makes it more effective at low temperatures. Calcium chloride can leave a slippery residue that is difficult to clean. It tends to refreeze quickly and may require frequent reapplication. In addition, it is hygroscopic, which can cause clumping, hardening or even liquefying during storage (Peeples 1998).

Engineering Concept: Calcium chloride is primarily produced from natural well brines and as a by-product of the Solvay process used to produce soda ash. The hygroscopic ability of calcium chloride allows it to melt ice and snow more rapidly than other deicing chemicals because liquid activates the chemical. In addition, the exothermic reaction of calcium chloride is larger than other deicers; it releases 674 J g^{-1} as it dissolves, raising the temperature of the water (Jerico Services 2008). The working temperature of calcium chloride is -31°C and the eutectic temperature is -45°C. Calcium chloride damages leather shoes and gloves (Myhra n.d.).

TRL: 9. Commercial off-the-shelf.

Deicing or Anti-icing: Anti-icing and deicing.

Current Advantages and Disadvantages: Calcium chloride rapidly deices because it is hygroscopic and exothermic. However, it is also expensive and highly corrosive. Because it is readily available as a liquid, calcium chloride can be used to keep loose, granular materials from freezing, and it is often mixed with other deicers, such as sodium chloride, to increase effectiveness.

Current Acquisition Cost: $132 per metric ton in 2003 (NCHRP 2007).

Operational Cost: Calcium chloride requires a lower rate of application than sodium chloride (Table 5). However, it is highly corrosive, occasionally requires more rapid renewal than other deicers, damages floors, carpets and leather goods, is moderately damaging to vegetation, and is only slightly harmful to the environment. Typical application is 35–58 L per lane kilometer, costing about $7.20 per lane kilometer.

Maintenance Requirements: Periodic renewal as the chemical dilutes.

Potential Marine Application and Safety Enhancement: As with sodium chloride, calcium chloride can be applied to marine structures. Granular or liquid calcium chloride may be used on decks and stairs. However, open grids will be difficult for either application unless completely filled with ice. Though liquid could be sprayed on winches and other equipment, corrosion would be enhanced. It may also be possible to spray brine onto lattice structures.

Marine TRL: 7.

Marine Advantages and Disadvantages: Adding calcium chloride to sea-spray-created superstructure ice, or to fresh-water ice formed from snow, rime, or freezing rain should enhance melting and decrease bond strength, allowing more ready removal. However, calcium chloride would increase corrosiveness in an already corrosive environment. Because of corrosivity it should not be used on helicopter landing pads. In addition, it would be tracked to inside living and working areas and damage floors, shoes, gloves, and other leather protective wear. Brine could possibly be sprayed onto vertical surfaces and complex structures, such as winches and lattice frameworks. However, runoff may be so large that deicing in this manner may be ineffective.

Marine Technology Transfer Requirements: Calcium chloride should be evaluated for its effectiveness with saline ice and its applicability to surfaces that are not in horizontal orientation.

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Magnesium chloride ($MgCl_2$)

EnviroTech Services Inc.
PO Box 338
Kersey, CO 80644
Telephone: 800-369-3878
www.envirotechservices.com

Glacial Technologies
12 Delaware Trail
Malvern, OH 44644
Telephone: 330-863-9531
http://www.anti-icers.com

Ice Ban America
100 Volvo Parkway, Suite 200
Chesapeake, VA 23320
Telephone: 888-423-2261
www.iceban.com

Intended or Actual Application: Highway departments often replace sodium chloride and sand with liquid magnesium chloride (MgCl2) as a deicer or anti-icer. The liquid magnesium chloride is sprayed on dry pavement before precipitation in freezing temperatures to prevent snow and ice from adhering to pavement. It also reduces bounce when solid deicers are applied, and it encourages solid particles to stick to the pavement. When used as an anti-icer, magnesium chloride improves highway safety during and after freezing precipitation. However, its high corrosivity, as with all of the chloride-based deicing chemicals, affects electric utilities located along highways. Spray from vehicles carries the chemical into the air to contaminate insulators, causing tracking, arcing, and occasionally pole fires. In addition, enhanced corrosion of steel and aluminum hardware has been observed by electric power companies. However, the amount of corrosion caused by magnesium chloride may be related to the type and amount of corrosion inhibitor used in the deicing fluid.

Operating Environment: Magnesium chloride is used on pavements in ice and snow. The working temperature is -15°C, and the eutectic temperature is -33°C. Like calcium chloride, magnesium chloride can be hazardous to human health and it leaves a slippery residue that is difficult to clean. It tends to refreeze quickly and may require frequent reapplication. In addition, it is also hygroscopic, which increases the rate of melting, but can also cause it to clump, harden, or even liquefy during storage (Peeples 1998).

Engineering Concept: Magnesium chloride has been used as both a deicer in the winter and a chemical that reduces road dust in the summer. Like calcium chloride, magnesium chloride is manufactured or evaporated from naturally occurring brines like the Great Salt Lake in Utah or from brine wells in Michigan. Like calcium chloride, magnesium chloride is exothermic as it dissolves, which helps it melt ice at very low temperatures, but it releases only 43% as much heat per unit weight dissolved as calcium chloride. It can be applied as either a liquid or solid, but as a deicer it is generally used in liquid form. Typical liquid solutions are 25% to 35% magnesium chloride. Because it is an aggressive corrosion chemical, corrosion inhibitors are typically added to liquid forms of the deicer.

TRL: 9. Available commercially off-the-shelf.

Deicing or Anti-icing: Deicing and anti-icing. Magnesium chloride is often used to prewet pavements to reduce ice adhesion before a storm, or to allow a dry ice protection chemical to adhere better.

Current Advantages and Disadvantages: Magnesium chloride deices rapidly because it is hygroscopic and exothermic, but it is slower than calcium chloride. It is less expensive than calcium chloride, but is similarly highly corrosive. Because magnesium chloride is readily available as a liquid, it is used to prewet pavements.

Current Acquisition Cost: Cost per liter is $0.10, according to the Montana Department of Transportation (Blacker 2008).

Operational Cost: Rate of liquid application is 21–81 L per lane kilometer.

Maintenance Requirements: Reapplication as required.

Potential Marine Application and Safety Enhancement: Magnesium chloride may be effective on marine structures. Because magnesium chloride is applied before storms to reduce ice adhesion, this may be the best application on drilling platforms. However, it may be washed off during the icing event, especially on supply boats. Calcium chloride may be used on decks and stairs. However, open grids will be difficult unless completely filled with ice after icing has started. Though liquid could be sprayed on winches and other equipment, corrosion would be enhanced, but with less intensity than sodium chloride or calcium chloride. It may also be possible to spray brine onto lattice structures as an anti-icer.

Marine TRL: 6. Anti-icing chemical performance is less predictable in the marine environment.

Marine Advantages and Disadvantages: Spraying magnesium chloride on marine structures before icing events may decrease ice adhesion, however, spray and wave wash activity may remove the material before it is effective. Magnesium chloride may increase corrosiveness in an already corrosive environment, depending upon the effectiveness of inhibitors in the product used. Because of corrosivity, magnesium chloride should not be used on helicopter landing pads. Magnesium chloride damages floors and carpets, but only has a small impact on the environment. Brine could possibly be sprayed onto vertical surfaces and complex structures, such as winches and lattice frameworks. However, runoff may be so great that deicing in this manner would be ineffective.

Marine Technology Transfer Requirements: Magnesium chloride should be evaluated for its effectiveness with saline ice and its applicability to surfaces that are not in horizontal orientation.

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Potassium chloride (KCl)

Ossian Inc.
PO Box 4076
635 S. Elmwood Ave.
Davenport, IA 52722
Telephone: 800-553-8011
http://www.ossian.com

Redmond Minerals Inc.
PO Box 219
Redmond, UT 84652
Telephone: 435-529-7402
Fax: 435-529-7486
http://www.iceslicer.com

Intended or Actual Application: Potassium chloride (KAc) is typically available in liquid form for application to roads, generally in combination with other chemicals. Potassium chloride is not as effective as other deicers at very low temperatures, making pure potassium chloride impractical unless used with other ingredients (Peeples 1998). Although not commonly used for these reasons, it is the third most effective deicer of the chlorides if it is mixed 50/50 with rock salt. Liquid KAc, 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 has also been used in straight liquid form during anti-icing experiments (Ketcham et al. 1996). Motech, a commercial deicing mix that is a by-product of sugar beet processing, contains potassium chloride. It is also the principle component of Select Liquid deicer by Ossian Inc.

Operating Environment: The effective temperature of potassium chloride is similar to sodium chloride, about -4°C to -13°C. The eutectic temperature of a KAc and water solution is -60°C at a concentration of 49% (Ketcham et al. 1996). It is toxic in low doses (Sharkbytes 2007). However, 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. Potassium chloride is a common fertilizer and is relatively easy to handle and store.

Engineering Concept: Potassium chloride is available as a solid or a liquid in a red grade, which is mined from traditional shaft mines and contaminated with iron, or a white grade, which is solution mined. Potassium chloride must come in direct contact with moisture before it can dissolve into a brine, which makes deicing slower than calcium chloride and magnesium chloride; the latter two are hygroscopic and quickly form a brine. Potassium chloride is also endothermic, requiring that heat be absorbed to go into solution. This is in contrast to calcium chloride and magnesium chloride, which are exothermic, melting ice and snow as they go into solution. Potassium chloride requires 4.4 times more heat to go into solution than does sodium chloride, and it requires 1.6 times more heat than does urea. This lowers the temperature of the water as it forms a brine, slowing the process (MacDonnell 2003).

TRL: 8–9. COTS product.

Deicing or Anti-icing: Deicing and anti-icing.

Current Advantages and Disadvantages: Potassium chloride is corrosive, somewhat toxic, expensive, and has a relatively high working temperature. In addition, it is slower working than exothermic chlorides. Potassium chloride is somewhat less damaging to floors, vegetation, and the environment than are other chlorides. It can be applied as a solid or as a liquid, and it can be readily mixed with other chemicals.

Current Acquisition Cost: Approximately 3–5 times more expensive than calcium chloride.

Operational Cost: Slightly higher rate of application than other deicers, such as sodium chloride.

Maintenance Requirements: Reapplication as required.

Potential Marine Application and Safety Enhancement: Potassium chloride, either alone or mixed with other chemicals, can be applied as a solid or as a liquid, either before or after icing, to walkways, stairs, and work areas. It may be sprayed on bulkheads and lattice structures, but effectiveness is unknown where the liquid could run off before taking effect. Potassium chloride would not be as effective in areas below the main deck where wave wash would readily cause dilution.

Marine TRL: 6.

Marine Advantages and Disadvantages: Corrosion will be enhanced, and the material should not be used where it could contact airframes, such as on the helicopter landing pad. Electrical connections could be damaged. However, as a liquid, potassium chloride could be applied readily to complex surfaces such as windlasses, piping, and lattice structures. Wave wash would be a deterrent to the use of any chemical deicer below the main deck.

Marine Technology Transfer Requirements: Potassium chloride should be evaluated for its effectiveness with saline ice and its applicability to surfaces that are not in horizontal orientation. The effectiveness of potassium chloride when mixed with other chemicals should be investigated.

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Acetate deicers

Calcium magnesium acetate (CMA)

Cryotech Deicing Technology
6103 Orthoway
Fort Madison, IA 52627
Telephone: 319-372-6012; 800-346-7237
E-mail: deicers@cryotech.com
http://www.cryotech.com

Peters Chemical Company
PO Box 193
Hawthorne, NJ 07507
535 High Mountain Rd., Suite 212
North Haledon, NJ 07508
Telephone: 973-427-8844
http://www.peterschemical.com

Intended or Actual Application: Calcium magnesium acetate (CMA) is a relatively new deicing compound manufactured from limestone and acetic acid, and contains no salts. It is used on roads, bridges, parking garages, and anywhere that corrosion and environmental damage are of concern because it causes little damage to concrete and little corrosion to metals (Dalecky et al. 1996; Transportation Research Board 1991; Cryotech 2007). Commonly described as being about as corrosive as tap water, CMA is often used as the corrosion standard by which other deicers are judged (Peters Chemical Company 2008). Corrosivity experiments conducted in Michigan indicate that metals exposed to CMA experience one-third to one-ninth the corrosion of those exposed to road salt. On the basis of weight loss data and general observation, the average corrosion rate of CMA was one-third to one-tenth the corrosion rate of salt for most metals tested, including steel and aluminum. Most CMA specimens exhibit only shallow pitting, compared with deep pitting in specimens exposed to sodium chloride. Despite its low corrosivity, the FAA has not approved CMA for use in areas where aircraft operate (Switzenbaum et al. 1999). It is a slower acting deicer than sodium chloride at temperatures below -5°C (TRB 1991). Although CMA has few negative environmental effects, it is more expensive than most deicers.

Operating Environment: CMA is typically used at a 25% concentration, which provides a freeze point of -18°C. At a 32% concentration, CMA has a freeze point of -28°C (eutectic temperature). The practical working temperature of CMA is about -8°C. CMA is applied to roadway surfaces and therefore is used in snow, freezing rain, and frost. It is used to prewet areas, and it is used during and after storms. CMA can be used as a solid or a liquid. CMA 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. Finally, laboratory tests indicate that CMA has a problem similar to that of the glycols, a high biochemical oxygen demand (BOD). CMA has been found to have a BOD greater than 100,000 ppm. BOD levels greater than 100,000 ppm are considered to be high and likely to cause oxygen depletion of surface water (Fischel 2001).

Engineering Concept: CMA is made by combining dolomitic lime and acetic acid (a principal component of vinegar) and derived from the fermentation of corn (Fischel 2001; Cryotech 2007). Anhydrous calcium magnesium acetate is a solid deicer manufactured by Cryotech Inc. It is also manufactured as a 25% aqueous solution of CMA by weight. Work is in progress to produce acetic acid from other sources, such as municipal and other wastes. However, the new sources may alter CMA's environmental effects.

CMA decreases the bond strength of ice crystals with substrates, and with each other. That is, it reduces the adhesive strength and the cohesive strength of ice crystals making them easier to remove with plows. The performance of CMA has been evaluated, perhaps more than any other highway deicing chemical except for road salt. In general, CMA deices acceptably. However, it works most effectively at temperatures warmer than -5°C, and its effectiveness diminishes in freezing rain and dry snow. If applied before or early in a storm, CMA reduces the bond of ice and snow to substrates, enhancing later cleanup effectiveness (Cryotech 2007). But when applied during or after a storm, it is found to be slower acting than road salt, frequently taking 15–30 min longer to induce melting. CMA leaves a residual on roadways that can have a positive effect for up to two weeks. Therefore, although application rates are larger for CMA than for sodium chloride, subsequent applications are less frequent because of the carry-over effect. Research shows that CMA has few negative environmental effects and is relatively nontoxic (Fischel 2001).

TRL: 8-9. CMA is a COTS product.

Deicing or Anti-icing: Deice, anti-ice, and prewet sensitive areas.

Current Advantages and Disadvantages: CMA is considered a nearly ideal chemical deicer by most users, except that it is expensive and is not effective at low temperatures. In addition, it has a high BOD that damages surface waters by depleting oxygen levels as it rapidly degrades threatening aquatic species and encouraging eutrophication. CMA has low corrosivity and causes little damage to structures or the environment. It can be applied as a solid or a liquid, and it has a residual effect that carries, potentially, through several storms.

Current Acquisition Cost: Cost reports vary. One metric ton of CMA costs $330–$660 as opposed to $22–$77 for salt (Anon 2008). Fischel (2001) reports CMA as costing about $1100 per metric ton.

Operational Cost: Rate of liquid application for anti-icing is 2–4 L per 100 m^2 (Fischel 2001). As a dry chemical, CMA is applied at a rate of about 5–11 kg per 100 m^2. Theoretically, the weight ratio of CMA to road salt needed to obtain equal deicing capability is 1.7:1. Early experiments with CMA in Michigan found that 2.6 times as much CMA as road salt is required to attain reasonably dry pavement, but more recent experience has found a 1:1 ratio satisfactory.

Maintenance Requirements: Reapplication as necessary. Residual effects, however, have required fewer applications than sodium chloride for the same conditions.

Potential Marine Application and Safety Enhancement: CMA should be effective in the marine environment where, as with all chemicals, wave wash may cause significant dilution. Because CMA is available as a solid or a liquid, it can be applied to walkways, stairs, and work areas. CMA should not be applied to helicopter landing pads pending FAA approval. However, because of its low corrosivity and residual effects it may be an ideal chemical to apply to windlasses, fire apparatus, and other equipment readily damaged by corrosion.

Marine TRL: 6. There are no reports of CMA testing in the marine environment.

Marine Advantages and Disadvantages: 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 a large, moving volume 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 the most acceptable of deicing chemicals for marine applications. Since it is available as a solid and as a liquid, application is possible to decks, stairs, work areas, and possibly windlasses and lattice structures.

Marine Technology Transfer Requirements: Research is needed to assess the effectiveness of CMA in marine icing conditions. Its slipperiness should be evaluated as well as its potential for being trapped under sea ice. Studies to determine the effects of CMA on electrical equipment and communications antennas are also necessary.

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Potassium acetate ($KC_2H_3O_2$) or (KAc)

Cryotech Deicing Technology
6103 Orthoway
Fort Madison, IA 52627
Telephone: 319-372-6012; 800-346-7237
E-mail: deicers@cryotech.com
http://www.cryotech.com

Ossian Inc.
PO Box 4076
635 S. Elmwood Ave.
Davenport, IA 52722
Telephone: 800-553-8011
http://www.ossian.com

Seneca Mineral Co. Inc.
8431 Edinboro Rd.
Erie, PA 16509
Telephone: 814-476-0076; 800-291-9222
http://www.senecamineral.com/index.htm

The Blackfoot Company
6061 Telegraph, Suite P
Toledo, OH 43612
Telephone: 419-478-8650
E-mail: info@theblackfootcompany.com
http://www.theblackfootcompany.com/default.htm

Zinkan
1919 Case Parkway North
Twinsburg OH 44087
Telephone: 800-229-6801
http://www.zinkan.com/index.htm

Intended or Actual Application: Potassium acetate is a liquid deicer. It is expensive and is typically used in areas where extreme cold-weather performance is required, such as airports (Greenawalt 2008). It is used primarily as a deicer for Air Force base runways (Fischel 2001). It is safe for the environment and is relatively inexpensive. It is best used as an anti-icier, or to deice thin layers of ice (AFCESA 1995). Recent concerns about corrosion of cadmium and carbon brakes on aircraft has caused the Air Force to recommend washing of aircraft after exposure to runway deicing chemicals such as potassium acetate.

Operating Environment: Potassium acetate has a slight oral toxicity and is moderately toxic to fish and invertebrates (Fischel 2001). It has a high BOD of 148,000, significantly higher than the threshold of 100,000 that is considered harmful. BOD levels greater that 100,000 ppm are considered to be high and likely to cause oxygen depletion of surface water (Fischel 2001). Potassium acetate does little damage to most materials including concrete, metal, and wood. It is claimed to provide effective deicing longer than the chlorides, adheres well to surfaces, and wets and spreads well (Seneca Mineral 2008). Potassium acetate has a corrosion rate similar to distilled water. The eutectic temperature of potassium acetate is -60°C, with an effective temperature of -26°C (Fischel 2001). It has passed SAE AMS 1435 requirements for runway deicing chemicals.

Engineering Concept: Potassium acetate is unique for its benign corrosion properties and low working temperature. Potassium acetate is a mixture of acetic acid (vinegar) and potassium hydroxide. A mix of corrosion inhibitors is added to allow compatibility with concrete, steel, and aviation components. Potassium acetate breaks the bond between pavement and ice or snow. Snowplows can then remove the resulting slush without damage to the runway or excessive wear on the snow removal equipment. Tests at Eielson Air Force Base in Anchorage, AL demonstrated effective clearing of a runway of ice and packed snow when the air temperature was -27°F (Johnson n.d.).

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 sensations of hands and feet, slower heart beat, reduced blood pressure, and irregular heart beat. The effects are probably due to the potassium (Fischel 2001).

TRL: 8–9. CMA is a COTS product.

Deicing or Anti-icing: Deice, anti-ice, and prewet sensitive areas.

Current Advantages and Disadvantages: Potassium acetate is expensive and is therefore a niche product. Although used for runways, it and other runway deicing chemicals are suspected of causing underbelly corrosion, wiring damage, and brake component disintegration in aircraft. Potassium acetate has a high BOD and could cause harm to quiet surface waters and cause eutrophication. Its significant advantages are overall minimal corrosivity and high effectiveness at low temperatures. As a liquid it is easily applied over large areas with spray trucks.

Current Acquisition Cost: $0.86 per liter or $660 per metric ton in 2001. (Fischel 2001).

Operational Cost: Recommended application rates are 3.9 L per 100 m^2 for deicing, and about 1.5 L per 1000 m^2 for anti-icing (The Blackfoot Company 2008).

Maintenance Requirements: Reapplication as necessary.

Potential Marine Application and Safety Enhancement: Potassium acetate is a liquid that is easily applied to walkways, stairs, and work areas. Potassium acetate can be applied to helicopter landing pads because it has been approved by the FAA and the Air Force. However, recent concerns about corrosion effects on aircraft underbellies and electrical components should be a caution to helicopter operators. Potassium acetate may also be an ideal chemical to apply to windlasses, fire apparatus, and other equipment readily damaged by corrosion.

Marine TRL: 6. There are no reports of potassium acetate testing or applications in the marine environment.

Marine Advantages and Disadvantages: The high cost of potassium acetate may not be a significant factor with the potentially small usage rates on marine structures. Except where sea ice is nearby, the high BOD should not be of serious concern. Because it is available as a solid and as a liquid, it is possible to protect decks, stairs, work areas, and possibly windlasses and lattice structures. It is unlikely that frequent wave wash areas can be protected adequately.

Marine Technology Transfer Requirements: Research is needed to assess the effectiveness of potassium acetate in marine icing conditions. Slipperiness should be evaluated for potassium acetate and all deicing and anti-icing chemicals, especially liquids, as should its potential for being trapped under sea ice. Investigations of the effects of potassium acetate on electrical equipment, and communications antennas, are also necessary.

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Sodium acetate ($NaC_2H_3O_2$)

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GeoEnvironmental
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North Oxford, MA 01537
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E-mail: sales@geoenviro.net
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Ossian Inc.
PO Box 4076
635 S. Elmwood Ave.
Davenport, IA 52722
Telephone: 800-553-8011
http://www.ossian.com

Peters Chemical Company
P. O. Box 193
Hawthorne, NJ 07507
535 High Mountain Rd., Suite 212
North Haledon, NJ 07508
Telephone: 973-427-8844
http://www.peterschemical.com

Intended or Actual Application: Sodium acetate is a non-corrosive granulated or liquid used to deice runways, highways, and railroad third rails. It also can be used on catwalks, conveyor belts, and walls. Its primary use is on runways. It is also a preferred chemical for use on roads and parking garages because it does not cause corrosion of steel embedded within concrete (Myhra n.d.). Sodium acetate has become the preferred replacement for urea and glycol-based deicers in some applications (Fyvestar 2008). It has passed SAE AMS 1435 requirements for runway deicing chemicals. Sodium acetate has many of the same environmental benefits as potassium-acetate-based deicers. It is generally non-corrosive, it readily biodegrades, it is non-toxic to animals and aquatic life, and it does not harm vegetation (Switzenbaum et al. 1999).

Operating Environment: Sodium acetate has an effective temperature of -15°C, and an eutectic temperature of -22°C (Fischel 2001). It is available only as pellets and is somewhat dusty in storage. It is effective in ice and snow. As an anti-icer it is applied to surfaces immediately before storms. Sodium acetate activates with a small amount of precipitation on the surface, and is effective in freezing rain, ice, or snow by preventing ice from bonding to substrates. Sodium acetate may also be used to penetrate thick snow packs. Liquid deicers may then be applied that can penetrate to the base of the holes at the snow-substrate interface created by the sodium acetate. Although sodium acetate has little corrosivity, The Boeing Company recently has released advisories specifying that aircraft exposed to sodium acetate be washed (Orison 2008). Comparisons of calcium chloride and sodium acetate performance on roads in Japan indicate that they are similar in deicing performance, but sodium acetate results in significantly less corrosion (Takeshi et al. 2004).

Engineering Concept: Sodium acetate is based on the acetate ion found in vinegar. Its acidity changes when reacted with a base. It can be produced by the reaction of acetic acid with sodium carbonate, sodium bicarbonate, or sodium hydroxide. Corrosion inhibitors are usually included in the material. Sodium acetate exhibits characteristics similar to the other acetate-based deicers. It is expensive, it has a sufficiently high BOD (410 mg g^{-1}) to cause mild oxygen depletion in surface waters, and its toxicity is mild for oral intake and aquatic species (Fischel 2001). The chemical is hygroscopic, which allows it to rapidly produce brine and melt into ice and snow. For this reason it is also exothermic, melting ice and snow as it penetrates by releasing heat. However, the hygroscopicity causes sodium acetate pellets to loosely stick to one another during storage, causing caking (Cryotech 2008).

Sodium-acetate-based deicer solutions, however, have a significant potential to cause alkali-silica reactions in concrete and form a gel-like substance. The gel absorbs water and expands causing the concrete to crack, encouraging freeze-thaw damage, corrosion damage, and possible structural failure (Rangaraju et al. 2006).

TRL: 8–9. COTS product.

Deicing or Anti-icing: Anti-icing and deicing (Fyvestar 2008).

Current Advantages and Disadvantages: Sodium acetate is low in corrosivity, yet performs similarly to calcium chloride. It is effective as a deicer and an anti-icer in ice and deep snow. Although approved for use on runways, it is suspected of causing damage to commercial jets. It is effective to low temperatures, however, it is expensive, especially in solid form.

The acetate-based deicers cause alkali-silica reactions in concrete, which leads to swelling and cracking.

Current Acquisition Cost: Approximately $3.33 per liter (Orison 2008). Sodium acetate pellets are about $110 per 100 kg and more (Fischel 2001).

Operational Cost: In liquid form, sodium acetate is recommended to be applied at a rate of 2 L per 100 m^2 before icing events. Usage rate varies with temperature. In general, an application of 4 L per 100 m^2 is recommended for thin ice and 12 L per 100 m^2 for ice up to 2.5-cm thick (Orison 2008). In pellet form, 3.5 to 10 kg per 100 m^2 is recommended. Near 0°C on thin ice, 1.5 to 2.5 kg per 100 m^2 is recommended. In temperatures colder than -12°C on 2.5-cm ice, 5 to 12 kg per 100 m^2 is recommended (Peters Chemical Company 2008).

Maintenance Requirements: Reapply when new accumulation shows first tendency to bond (Peters Chemical Company 2008) or when friction decreases (Cryotech 2008).

Potential Marine Application and Safety Enhancement: Sodium acetate, as with all chemicals, should be effective in the marine environment where not diluted by wave wash and spray. Because sodium acetate is available as a liquid or a solid, it can be applied easily to many surfaces including walkways, stairs, work areas, and bulkheads. It can be applied to helicopter landing pads since it has been approved by the FAA and the Air Force. However, recent concerns about corrosion effects on certain aircraft indicate that frequent aircraft washing is recommended. It may be prudent to wash off helicopter landing pads after icing events where sodium acetate has been used. Sodium acetate may also be an ideal chemical to apply to windlasses, fire apparatus, and other equipment because of its low corrosivity.

Marine TRL: 6. There are no reports of sodium acetate testing or applications in the marine environment.

Marine Advantages and Disadvantages: The high cost of sodium acetate, like the other acetates, is not a significant factor with the potentially small usage rates on marine structures. Although low corrosivity may make it an acceptable deicing chemical for marine applications, in most marine situations the extreme low-temperature capability will not be used. Because it is available as a solid and as a liquid, application is possible to protect decks, stairs, work areas, and possibly windlasses and lattice structures. It is unlikely that wave-washed areas can be protected adequately. Because the acetate-based deicers cause alkali-silica reactions in concrete, their use should be avoided on platforms with concrete components.

Marine Technology Transfer Requirements: Research is needed to assess effectiveness in marine icing conditions. Slipperiness should be evaluated, especially for the liquid deicer. Effects of potassium acetate on electrical equipment, communications antennas, and aircraft components require study.

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Glycols

Ethylene glycol ($HOCH_2CH_2OH$)

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Fax: 954-603-0534
E-mail: usa.sales@kilfrost.com

Intended or Actual Application: Ethylene glycol was the primary chemical used to deice aircraft until about 10 years ago. Ethylene glycol has been replaced almost completely by propylene glycol deicing fluids in the United States because of its toxicity. Toxicity studies have been performed using pure ethylene glycol, but few studies have been performed using formulated aircraft deicing fluids. The formulations are considered trade secrets, therefore, little information is available about their actual chemical compositions. Although some information is available on compounds included as additives, fluid manufacturers indicate that formulas change often, sometimes as often as every year (EPA 2000).

Operating Environment: All aircraft deicing fluids (ADFs) must lower the freezing point of water to -28°C or lower when applied. A typical deicing fluid contains approximately 50% to 60% glycol after being diluted for application. This concentration will depress the freezing point of water to between -40°C and -46°C. The minimum freeze point for ethylene-glycol-based ADFs (approximately -50°C) occurs when the fluid consists of approximately 60% ethylene glycol and 40% water. Ethylene glycol is highly toxic to aquatic life and mammals. 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 by the U.S. Congress, 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. Ethylene glycol is not believed to be toxic by adsorption through the skin or by breathing air containing its mists or vapors (EPA 2000). Ethylene glycol is relatively non-toxic in the aquatic environment.

Engineering Concept: Glycols are organic compounds in the alcohol class. Alcohols as a rule are polar molecules and tend to have high boiling points and serve as excellent freezing point depressants. Ethylene glycol is completely miscible in water and is a colorless, thick, hygroscopic, bittersweet tasting liquid. It is derived by hydrolysis of ethylene oxide or oxidation of ethylene. It is used in antifreeze, hydraulic brake fluids, as a general heat transfer fluid, and as a chemical intermediate in the production of ethylene-glycol esters, ethers, and polyester fibers and resins. It is widely used in printer, stamp pad, and ballpoint pen inks. It is also used as a stabilizer in latex paints, a softening agent for cellophane, a solvent, a dehydrating agent for natural gas, and as an aircraft and runway deicer.

Ethylene glycol is listed as a hazardous air pollutant under the U.S. Clean Air Act and is considered a hazardous material. Consequently several reporting requirements exist regarding its storage and use. Overall, toxicity exhibited by pure ethylene glycol is significantly lower than the corresponding formulated aircraft deicing fluids. The toxicity of chemicals added to deicing fluids causes the formulated fluids to be more toxic than pure glycol (EPA 2000). Typical materials found within aircraft deicing fluid include ethylene glycol, water, surfactants (wetting agents), corrosion inhibitors, flame retardants, pH buffers, dyes, 1,4-dioxane, and complex polymers (thickening agents) (EPA 2000).

TRL: 8–9.

Deicing or Anti-icing: Deicing and anti-icing.

Current Advantages and Disadvantages: Ethylene glycol is a fast and effective deicer and anti-icer. However, it is slippery, expensive, and toxic. Ethylene glycol is generally no longer available as a deicing fluid in the United States.

Current Acquisition Cost: Similar to propylene-based aircraft deicing fluid when last available.

Operational Cost: Similar to propylene-glycol aircraft deicing fluid when last available.

Maintenance Requirements: Not applicable.

Potential Marine Application and Safety Enhancement: If available, ethylene glycol could be applied to walkways, stairs, work areas, and helicopter landing pads. If aircraft approved, it could be used to deice helicopters if sensitive areas such as rotor heads are avoided (Ryerson et al. 1999). Because it is a liquid, ethylene glycol could be used to deice cranes, lattice structures, and windlasses—although with significant wastage. With spray equipment under deck, ethylene glycol may be used to remove superstructure ice between the main deck and the waterline. It is not recommended to replace glycols formulated for deicing aircraft or pavements with radiator anti-freeze coolant because of differences in formulation and flammability.

Marine TRL: 6. Propylene glycol is not reported to have been tested in the marine environment and is not systematically used for deicing in that application.

Marine Advantages and Disadvantages: Glycol, whether propylene glycol or ethylene glycol, has been used to deice aircraft on aircraft carrier decks and can cause slippery conditions on non-skid surfaces. Glycol is costly and, even though surface areas are small on marine platforms, the cost could be prohibitive. Generally, similar spray equipment could be used on a rig or supply boat as is used at airports, except that equipment would not be truck mounted. Ethylene glycol could potentially be used on communication equipment with no harm. Glycol deicing fluids are suspected of potentially causing harm to composite materials, which could affect structures such as escape pods. Runoff under an ice cover could be an environmental hazard because of high toxicity.

Marine Technology Transfer Requirements: Ethylene glycol should be evaluated with saline ice to determine if its performance degrades. Effects of ethylene glycol on composite materials need to be investigated.

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Propylene glycol ($CH_3CHOHCH_2OH$)

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The Dow Chemical Company
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Telephone: 800-441-4369; 989-832-1560
http://www.dow.com

Octagon Process Inc.
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Telephone: 732 346-8000
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http://www.octagonprocess.com

Intended or Actual Application: Propylene glycol (PG) is currently the primary chemical used for deicing aircraft worldwide (Figure 20). Millions of gallons are used each year at many airports for aircraft and runway deicing. (The Air Force, however, has withdrawn its use of glycol on runways [Air Force 2005]). Approximately 98% of PG is used as aircraft deicing fluid, and only about 2% is used for anti-icing to protect aircraft from re-icing if freezing precipitation is occurring in the time interval between deicing and takeoff. During typical icing conditions 600 to 4000 L of ADF may be used on one commercial jet. Smaller volumes, as little as 40 L, may be used on a small corporate jet (EPA 2000). During severe weather conditions 4000 to 16,000 L may be needed to deice a commercial jet. A commercial jet requires approximately 130 L of fluid for anti-icing after deicing. Frost conditions require 72 to 180 L of deicing fluid, depending on aircraft size (EPA 2000).

Operating Environment: All ADFs must lower the freezing point of water to -28°C or lower when applied. A typical deicing fluid contains approximately 50% to 60% glycol after being diluted for application. This concentration will depress the freezing point of water to between -40°C and -46°C. Propylene-glycol ADFs 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. Propylene glycol is considered relatively safe for mammals, however, ADF additives can be toxic. It can significantly decrease the oxygen in surface waters because it has a high BOD—its primary environmental impact. According to the U.S. Environmental Protection Agency (EPA 2000), as ADFs break down they can release acetaldehyde, ethanol, acetate, and methane—all highly toxic to many aquatic organisms.

When deicing aircraft, basic areas of caution are engine inlets, auxiliary power unit (APU) inlets and exhaust, windows, doors and seals, brakes and landing gear, vents, probes, sensors, cavities, and any opening where sprayed fluid is not allowed. Additionally, composite parts may have limitations regarding deicing fluids and temperatures, such as composite propellers (AEA 2008). These general areas should be avoided, and these limitations may also apply to non-aviation applications. The U.S. Air Force does not anti-ice aircraft because the only fluids available are glycols; there are concerns that anti-icing fluids may degrade aircraft parts, particularly those made from composite materials, when the fluids are left on for extended periods.

Figure 20. "A nasty winter storm blanketed every surface on Tinker Air Force Base with a layer of ice, halting non-critical operations on the base. 552nd Air Control Wing crews were hard at work de-icing jets." (Air Force photo/1st Lt. Kinder Blacke).

Engineering Concept: Neat propylene glycol is a clear, colorless, viscous, hygroscopic, nearly odorless liquid. It is produced by the non-catalytic liquid phase hydration of propylene oxide at 100°C–200°C and purified by distillation or by yeast reduction of hydroxyacetone. It is widely used as a chemical intermediate, 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, an aircraft deicing fluid, and general heat exchanger fluid. The chemical structure of propylene glycol is similar to ethylene glycol except that propylene glycol contains a third carbon atom (Switzenbaum et al. 1999).

Propylene glycol is not currently listed as a hazardous material by any federal or state agencies. The Society of Automotive Engineers publishes standards (SAE AMS 1428 and AMS 1424) for four different types of aviation deicing and anti-icing fluids (SAE 2007a,b). Type I fluids are deicing fluids that have low viscosity. They are used to remove ice and snow. They are typically sprayed on hot (55°C–83°C) at high pressure and they are often dyed orange to aid in identification and application (Figure 20). Type II, III, and IV fluids are non-Newtonian, spray as a low-viscosity liquid, and thicken when resting on the aircraft. The fluids are applied after deicing occurs and during freezing precipitation to protect the aircraft from re-icing between the time that it is deiced 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. The time between application and failure, the holdover time, is a function of the glycol concentration and application thickness of the anti-icing fluid for the temperature and precipitation conditions at that time. If the aircraft takes off before ice again forms, the fluid is designed to shear off of the wing at rotation speed—when the wheels begin to lift from the ground and the aircraft begins to fly. Type II, III, and IV fluids differ by the speed at which they are designed to shear from the wing and the holdover time that they provide. The shear at takeoff is necessary because the FAA and the Air Force require a clean wing before an aircraft attains flight. Removal of the fluid through wind shear forces causes the wing to be cleaned of fluid. Deicing fluids are sold concentrated and are diluted with water according to air temperature.

Overall, similarly to ethylene-glycol-based deicing fluids, the toxicity exhibited by pure propylene glycol is significantly lower than the corresponding formulated aircraft deicing fluids. The toxicity of chemicals added to formulated fluids cause formulated fluids to be more toxic than pure glycol (EPA 2000). Typical materials found within aircraft deicing fluid include propylene glycol, water, surfactants (wetting agents), corrosion inhibitors (including flame retardants), pH buffers, dyes, 1,4-dioxane, and complex polymers (thickening agents in Type II and Type IV ADFs) (EPA 2000). The additives of many deicing and anti-icing fluids, however, have recently been significantly reduced in toxicity.

TRL: 9. COTS.

Deicing or Anti-icing: Deicing and anti-icing.

Current Advantages and Disadvantages: PG is a fast and effective deicer and anti-icer. However, it is slippery, expensive, and has a high BOD. Technology for application to aircraft and runways is well developed. PG is widely available from several vendors.

Current Acquisition Cost: $1.30 to $1.82 per liter (Ritter 2001).

Operational Cost: Typically 40 to 4000 L per application depending upon aircraft size and weather condition. $50 to $7000 per application.

Maintenance Requirements: Repeated deicing is necessary in freezing precipitation if anti-icing fluid fails.

Potential Marine Application and Safety Enhancement: PG can be applied to walkways, stairs, work areas, and helicopter landing pads. It can be used to deice helicopters if sensitive areas such as rotor heads are avoided. Because PG is a liquid, it can be used to deice cranes, lattice structures, and windlasses. However, wastage will be high because of run-off. With spray equipment under deck, PG may be used to remove super-structure ice between the main deck and the waterline.

Marine TRL: 6. PG has not had extensive testing in the marine environment and is not systematically used in that application.

Marine Advantages and Disadvantages: Glycol has been used to deice aircraft on aircraft carrier decks and caused slippery conditions on non-skid surfaces. PG is costly and, even though surface areas are small, its use could be cost prohibitive. Generally, similar spray equipment could be used on a rig or supply boat as is used at airports, except that equipment would not be truck mounted. PG can be used on communication equipment with no harm. PG is suspected of possibly causing harm to composite materials, which could affect structures such as life rafts. Run-off under an ice cover could be an environmental hazard due to high BOD.

Marine Technology Transfer Requirements: PG must be evaluated with saline ice to determine if its performance degrades. Effects of PG on composite materials need to be investigated. The slipperiness of PG on platform and supply boat decks should be quantified. PG additive formulations should be reconsidered for the marine operating environment.

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Miscellaneous deicing chemicals

Sodium formate (HCOONa)

Chemical Solutions Inc.
Franklin, MA 02038-0675
http://www.meltsnow.com/index.htm

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http://www.cryotech.com

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Telephone: 954 603 0533
E-mail: info@kilfrost.com
http://www.kilfrost.com/home

Safeway SF
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Telephone: 49-6196-757-7848
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http://fun.clariant.com/fun/internet.nsf/($lookupdocid)/08F108ACA1356060C125693D0031B7E7

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http://www.theblackfootcompany.com/default.htm

Intended or Actual Application: Sodium formate is a relatively recent chemical introduced into the United States for deicing pavements, including runways. Before the 1990s its primary use was in Europe. It is used by the Air Force to deice runways. The South Dakota Department of Transportation (DOT) has developed an improved roadway deicer, called Ice Shear, comprising sodium acetate and sodium formate. Ice Shear lowers the freezing point of water, penetrates ice, and reduces the ice-pavement bond strength. Ice Shear is available as a solid or as a liquid; it is an effective deicer with low corrosivity (Bang and Johnston 1998). Sodium formate granular deicers with proprietary corrosion inhibitors are used as runway and roadway deicers at airports; they meet the performance and ecological requirements of AMS 1431A. Transport Canada and the FAA recommend sodium formate for general airport use as an effective substitute for urea. Air Force guidance discourages use of solid (granular) deicing/anti-icing agents because they tend to scatter off runways under windy conditions (Air Force 1998).

Operating Environment: Sodium formate has a working temperature of -18°C and a eutectic temperature of -22°C (Cryotech 2008). It has a low BOD (230 mg g^{-1}) and has a neutral pH that reduces corrosion. Sodium formate use for apron, runway, and pavement deicing and anti-icing would reduce the amount of oxygen-demanding compounds released into surface water and may decrease corrosion of metal (Air Force 2005). Sodium formate is dusty in storage and, being hygroscopic, may cake before use (Cryotech 2008). Sodium formate and sodium acetate have similar characteristics.

Engineering Concept: Although sodium formate is classified as a salt, it typically includes a corrosion inhibitor to comply with an SAE specification for airport airside applications. However, it is slowly corrosive of galvanized steel because it reacts with zinc, as do all of the acetates and formats (Reeves et al 2005). The material consists of white granules or crystalline powder and is highly soluble in water.

The South Dakota Department of Transportation Ice Shear formulation appears relatively harmless to aquatic animals and causes minimal toxicity to roadside vegetation; herbaceous (e.g., sunflowers, beans, and lettuce) and woody (e.g., pine seedlings) plants. At low concentrations (less than 2 g kg^{-1} soil) sodium formate seems to work as a fertilizer, promoting the yield of plants. Studies by Bang and Johnston (1998) demonstrate that Ice Shear poses minimal environmental disturbance in both aquatic and terrestrial ecosystems.

TRL: 8. COTS.

Deicing or Anti-icing: Primarily deicing.

Current Advantages and Disadvantages: Sodium formate, though a salt, when formulated with protective additives causes little corrosion, has a relatively low BOD, and is not toxic to aquatic animal life. Sodium formate is effective at low temperatures and has little environmental impact. It is more expensive than other deicers. Takeshi et al. (2004) found that sodium formate had a melt rate that was highest of the non-chloride deicers, and it had a corrosion rate approximately one-half that of sodium chloride. The formates are often used at airports in Europe because they have a weaker odor than acetates (Reeves et al. 2005).

Current Acquisition Cost: Approximately $2000 per metric ton in the United Kingdom (Reeves at el. 2005).

Operational Cost: Application rates are about 50% that of urea. Recommended application rates range from 3.9 to 14.2 kg 100 m^{-2} for 0.8 mm of ice in temperatures ranging from -1.1°C to -6.7°C, to 30.3 to 65.9 kg 100 m^{-2} for 3.2 to 6.4 mm of ice in the same temperature range (AFCESA 1999).

Maintenance Requirements: Costs in the UK are $0.80 for 10 m^2 24 hr^{-1} for anti-icing, and $1.61 for 10 m^2 24^{-1} hr for anti-icing (Reeves et al. 2005).

Potential Marine Application and Safety Enhancement: 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 the airside of airports on taxiways and runways, it is also usable on helicopter landing pads. Its effect on composites is not known.

Marine TRL:6. It is not known whether sodium formate has been used in the marine environment.

Marine Advantages and Disadvantages: Sodium formate can be used on a variety of surfaces of different shapes except perhaps on galvanized steel. It is effective at low temperatures. Because sodium formate is 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.

Marine Technology Transfer Requirements: Sodium formate should be evaluated with saline ice. Its effect on marine materials needs to be evaluated. Its effect on composite materials is also unknown.

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Urea ($CO(NH_2)_2$)

Ossian Inc.
PO Box 4076
635 S. Elmwood Ave.
Davenport, IA 52722
Telephone: 800-553-8011
http://www.ossian.com

Intended or Actual Application: Urea was a common runway deicer, but its use has been prohibited at an increasingly large number of airports because of its environmental impact and the availability of superior deicers. Urea pellets are Air Force approved, but their use is discouraged (Air Force 2003). Urea is available as a liquid and a solid. As a solid, it is available either as a powder that can be mixed with sand, for example, or as small spheres approximately 1.5 mm in diameter. Urea currently is not in use as a road deicer except in the state of Washington, but it is used on airport runways because it is less corrosive than road salt to aluminum airplane bodies (Michigan DOT 1993). Switzenbaum et al. (1999) report that 10 years ago urea was in widespread use at northern airports.

Operating Environment: Urea is effective in ice and snow. The problems with urea are its high working temperature, its high aquatic toxicity, and its high BOD, which causes surface water eutrophication. Eliminating the toxicity requires complicated nitrification/denitrification treatment for waste water. In addition, urea has high eutectic and working temperatures of -12°C and -4°C, respectively. Urea can only depress the melting point of ice about 8°C. Urea pellets are usually not applied when temperatures are below about -4°C (Schueler n.d.). Urea also causes damage to vegetation and surface water by adding excessive nitrates. Ammonia is released into the air when it contacts water, which is toxic in poorly ventilated locations.

It also severely corrodes metals, though it does not harm concrete (Frank 2004). Urea can irritate the nose and cause sore throat, sneezing, coughing, and shortness of breath in humans. Chronic exposure and acute exposure in high concentrations may cause eye damage, skin redness or rash (dermatitis), or emphysema (EPA 2000). Urea is one of the deicers that causes white deposits when tracked onto floors (MacDonnell 2003).

Engineering Concept: Urea is synthesized from ammonia and carbon dioxide. Urea is an organic compound that degrades to ammonia and then to nitrate by soil microorganisms. Urea is typically hydrolized to ammonia in the environment within two to 10 days depending upon temperature (Levelton 2007). Some ammonia may also volatize to the air, though volatization is minimal at temperatures colder than 8°C (EPA 2000). Therefore, this is typically not a problem during winter months when urea is most used, but it may become a problem as temperatures warm in the spring. Although urea itself has relatively low toxicity to terrestrial and aquatic life, ammonia and nitrate are problems. The toxicity of ammonia to aquatic life is relatively high. One study finds that when exposed to as little as 10 ppm of ammonia, one-half of the aquatic biota present will die. The other by-product of urea, nitrate, is a fertilizer that can contaminate water. High nitrate also stimulates alga growth in aquatic systems and accelerates eutrophication. Urea is an endothermic deicer. 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 deicing.

TRL: 8. Urea is a COTS product.

Deicing or Anti-icing: Deicing and anti-icing.

Current Advantages and Disadvantages: Urea is hygroscopic and may harden in storage. It is limited in deicing capability because it is also endothermic, which slows deicing. Urea is effective only at warmer temperatures. It is harmful to aquatic ecosystems and humans, especially as it degrades to ammonia and nitrates.

Current Acquisition Cost: About five times more expensive than sodium chloride or about $25 per 25-kg bag of pellets (Schueler n.d.)

Operational Cost: Urea is used at a rate of 1 kg per 20 m^2 (Hagen n.d.), or 7 to 12 kg per 100 m^2 (Cryotech 2008). The Air Force (AFCESA 1999) recommends application rates ranging from 7.8 to 29.3 kg per 100 m^2 for 0.8 mm of ice in temperatures ranging from -1.1°C to -6.7°C, to 61 to 134 kg per 100 m^2 for 3.2 to 6.4 mm of ice in the same temperature range (AFCESA 1999).

Maintenance Requirements: Periodic renewal as required.

Potential Marine Application and Safety Enhancement: 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 and would not endanger cables and other corrosion-sensitive materials as significantly as alternative materials. In addition, it could be applied to helicopter landing pads, if the material is AMS 1431A-certified for airside use. However, ammonia as a by-product of urea decomposition may be a safety hazard if it concentrates in poorly ventilated areas. Urea and its by-products are also potential threats to human health.

Marine TRL: 5. Performance in the marine environment is unknown.

Marine Advantages and Disadvantages: Urea is not highly corrosive and may be less damaging to infrastructure than some alternative deicers. However, the degradation of urea to ammonia, and its release into the atmosphere, may potentially cause concentrations in poorly ventilated locations on marine structures. Urea is not effective at lower temperatures. Urea and its by-products are potential threats to human health. As with all chemicals, wave wash and spray may significantly dilute and decrease effectiveness.

Marine Technology Transfer Requirements: 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 closer proximity of human activity and the deicer chemical than in roadway and airport applications. The effects of urea on the integrity of composite materials is unknown.

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Agricultural-based chemicals

Sugar-beet-based products

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Intended or Actual Application: Geomelt is a trade name for a sugar-beet-based deicing chemical that is used to deice 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).

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; W. 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 five days so that roads are protected before road crews can apply additional deicer or anti-icer (Wellspring 2008).

Engineering Concept: Geomelt, a by-product of sugar beet processing, is recovered for its deicing 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 due 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 (W. 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).

TRL: 8. Geomelt is a COTS product.

Deicing or Anti-Icing: Deicing 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 usage. Geomelt's low freezing point means less chemical is needed so there is less corrosion of bridges and pavements.

Current Acquisition Cost: Approximately $2 per 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 (W. 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 five days.

Potential Marine Application and Safety Enhancement: Because Geomelt is a liquid, it can be applied to walkways, stairs, work areas, complex structures such as windlasses and stored pipe, and lattice structures such as cranes and flare booms. Spraying under the main deck in areas where superstructure ice accumulates is possible—especially as a deicer. Geomelt operates at low temperatures if needed when a platform is near a landmass or an ice edge.

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 helicopter landing pads is not recommended. Geomelt stores well without fermenting or chemical decomposition. There have been claims of rancid odor and a syrupy consistency (Hollander 2008).

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.

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Corn-based products

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Intended or Actual Application: Caliber M1000 and NC-3000 are corn-based products designed for ice control on roads, bridges, parking lots, and sidewalks. Both chemicals are available only as liquids. The fluids can also be sprayed from trucks or used with automated spray systems such as on bridges. Caliber M1000 penetrates snow packs and ice to break the bond with pavement.

Operating Environment: Caliber M1000 and NC-3000 have eutectic temperatures of -66°C and -40°C, respectively. They are designed to be effective in ice and snow. The deicers are claimed to reduce corrosion of steel, and tests show corrosion rates of Caliber M1000 to be similar to or slightly greater than distilled water. NC-3000 is a non-chloride deicer that has a corrosion rate less than distilled water. Caliber M1000 and NC-3000 prevent bonding of snow and ice to substrates, and are effectively used as deicers and as anti-icers (Glacial Technologies 2008).

Engineering Concept: Caliber M1000 and NC-3000 consist of base stocks processed from starches and sugars from corn. Caliber M1000 consists of 27% magnesium chloride, 6% Caliber carbohydrate with the remainder being water. NC-3000 consists of corn-based stock and potassium acetate. The BOD of NC-3000 is 120,000 ppm, whereas the BOD of M1000 is 34,000 ppm (Glacial Technologies 2008). NC-3000 and Caliber M1000 have no flash point, both chemicals are non-toxic, and both have mild to sweet odors. Both chemicals are claimed to continue functioning at high dilution. There are no nitrates or urea to cause eutrophication of surface waters.

TRL: 8. COTS products.

Deicing or Anti-icing: Deicing and anti-icing.

Current Advantages and Disadvantages: These chemicals are effective at low temperatures, are minimally corrosive, and continue to function with high dilution (Glacial Technologies 2008). They can be used as deicers and anti-icers. Friction characteristics are slightly less than those for a wet road.

Current Acquisition Cost: Approximately $7.00+ per 4 L for NC 3000 (R. Greene, personal communication, 21 November 2008).

Operational Cost: Recommended anti-icing application rate for M-3000 is 50–100 L per lane kilometer, and deicing application rates are 100–220 L per lane kilometer depending upon ice thickness and air temperature. Anti-icing application rates for Caliber M1000 are 50–150 L per lane kilometer, 100–150 L per lane kilometer for deicing, and 35–50 L per lane kilometer for frost prevention. Prewetting requires 12–35 L per lane kilometer (Glacial Technologies 2008).

Maintenance Requirements: Effectiveness at high dilution rate may allow less frequent reapplications.

Potential Marine Application and Safety Enhancement: Caliber M1000 and NC-3000 are liquids that can be applied to walkways, stairs, work areas and complex structures such as windlasses, stored pipe, and lattice structures such as cranes and flare booms. Spraying under the main deck in areas where superstructure ice accumulates is possible except for the potential for spray and waves to remove the chemicals. The claimed continued performance with high dilution may be an advantage in this application.

Marine TRL: 5. Environmental effects and capability in marine environment are unknown.

Marine Advantages and Disadvantages: As liquids, these deicers are of somewhat higher viscosity than other deicing 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 about 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 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 deicing chemicals, friction increases over time—especially after the material dries.

Marine Technology Transfer Requirements: The capabilities of these corn-based chemicals should be evaluated for effectiveness in saline ice and the marine spray environments. The capability of the chemicals on antennas and composites must be evaluated, and friction coefficients validated.

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Alcohol-based products

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Intended or Actual Application: Ice-B-Gone, also marketed as Magic Salt, consists of a sugar base stock of distilled condensed solubles (DCSs), a slurry derived from the making of vodka and rum. 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). The product is also available as a prewetted salt solid labeled Magic Salt.

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 preferably used as an anti-icer to reduce the volume of material required. As an anti-icer it is effective in ice and snow. It is safe for plants, humans, and animals and does not affect skin, leather, clothing, or carpets. 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 deicers. 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. It is dark brown and sweet-smelling with a molasses-like texture (PRNewswire 2007). These DCSs are combined with magnesium chloride or other chlorides or acetates to create an anti-icing fluid. Ice-B-Gone is typically 50% DCS material and 50% magnesium chloride. The dilution rate is lower, and it remains effective for a longer duration than most deicing 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. It is preceded by a patent by Tóth et al. (1987) based upon observation of the low freezing point of a distillate residue and magnesium chloride mixture in a pond in Hungary. Ice-B-Gone melts ice more rapidly than a 24% sodium chloride brine solution (its optimum) at temperatures warmer than -18°C. However, the concentration of Ice-B-Gone is unspecified. At colder temperatures deice rates are equivalent to one another, and the deice rates are low. BOD is low.

TRL: 8. COTS product.

Deicing or Anti-icing: Primarily 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 deices 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 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 per 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 use of Ice-B-Gone is to treat other materials such as sodium chloride, sand, aggregate, sodium chloride/sand mixtures, and sodium chloride/aggregate mixtures. Thirty-two liters of Ice-B-Gone is normally 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.

Maintenance Requirements: Reapplication as needed. However, residual effects may delay necessary reapplication.

Potential Marine Application and Safety Enhancement: Ice-B-Gone can be used with other chemicals to increase their low temperature effectiveness and their period of effectiveness, and to reduce corrosivity. Applications are decks, walkways, stairs, and irregular surfaces such as windlasses, lattice structures, and safety gear. Effectiveness on superstructure ice below the main deck is a function of the spray environment, although the longer residual effect and greater tolerance for dilution may make Ice-B-Gone and agricultural-based chemicals generally more effective.

Marine TRL: 5. Environmental effects and capability in the marine environment are unknown.

Marine Advantages and Disadvantages: As liquids, these deicers can be sprayed on surfaces of any orientation. They are of somewhat higher viscosity than other deicing 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 deicing chemicals, friction increases over time—and especially after the material dries.

Marine Technology Transfer Requirements: The capabilities of these alcohol-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.

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6 Coatings

The purpose of coatings is to increase the hydrophobicity and icephobicity of surfaces. Although highly hydrophobic surfaces are not necessarily highly icephobic, Farzaneh et al. (2008) suggest that there may be a positive relationship between the two. Many of the materials summarized below claim relatively high icephobity. Some coatings claim anti-icing capability due to superhydrophobicity.

The goal of most coatings is to cause ice to shed off surfaces from its weight alone. For this to occur, the adhesion strength of ice to the substrate must be less than the shear stress that the ice exerts because of its weight. As an example, the adhesion strength of ice to a coating would need to be less than 5 kPa for a 0.6-m-wide ice collar (on a navigation lock wall for example) to fall off a vertical surface under its own weight (Army Corps of Engineers 2006). No material has yet achieved such a low adhesion strength. Consequently, coatings should generally be considered methods of enhancing other ice control methods described in this report.

Rain-X Windshield Treatment

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Intended or Actual Application: Rain-X windshield treatment is intended to improve visibility in wet weather by causing rain water to bead up and reducing the adhesion strength of water droplets to glass surfaces. The beading and reduced adhesion strength allows airflow to carry water drops off of windshields. Rain-X has also been evaluated as an icephobic coating by NASA and by ERDC/CRREL (Ferrick et al. 2008; Deweese et al. 2006; Trigwell and Calle 2006).

Operating Environment: Rain-X is marketed for use on automobile windshields to allow water droplets to clear rapidly from the surface and to provide sufficient visibility enhancement to allow 1-sec additional driver reaction time. Rain-X must be applied in 5°C temperature or warmer, but users claim it is useful in snow and ice. Reviewers state that ice and snow are more easily removed from a Rain-X-treated windshield.

Engineering Concept: Rain-X is a silicone-based product in ethyl and isopropyl alcohol carriers (SOPUS 2007). It is wiped onto glass surfaces, allowed to dry to a haze, and the excess is buffed off. Depending upon exposure to weather, and possible use of windshield wipers, it is reported to remain hydrophobic for a few weeks to a few months. Rain-X was tested as a potential icephobic material for lowering ice adhesion strength on the Space Shuttle external fuel tank on surfaces operating at cryogenic temperatures (Ferrick at al. 2006a,b, 2008; DeWeese et al. 2006; Trigwell and Calle 2006). Hydrophobic tests of the droplet contact angle on Koropon paint showed a mean angle of 81°. Coating the Koropon surface with Rain-X windshield treatment increased the droplet contact angle to 104°.

TRL: 9. COTS.

Deicing or Anti-icing: Deicing. Rain-X windshield treatment is a hydrophobic material that exhibits some icephobic benefits, according to user reports. It allows windshields to be more easily deiced.

Current Advantages and Disadvantages: Rain-X is intended for use on glass surfaces. Other than the NASA studies, performance on other surface materials is unknown (Ferrick at al. 2006a,b, 2008; DeWeese et al. 2006; Trigwell and Calle 2006).

Current Acquisition Cost: Approximately $0.50 to $0.65 per 30 mL COTS in 105- to 210-mL bottles.

Operational Cost: Unknown.

Maintenance Requirements: Coating requires renewal on automobile windshields every few weeks to a few months.

Potential Marine Application and Safety Enhancement: Rain-X may be usable on surfaces other than glass, including bulkheads, antennas, radomes, railings, and lattice structures, but performance is unknown. Performance factors include initial hydrophobicity and icephobicity, and duration of effectiveness. Durability is unknown in wave wash areas, and in areas with frequent spray. Because Rain-X windshield treatment is effective on automobile windshields for several months, it may have special application for window areas that must be kept ice-free.

Marine TRL: 5.

Marine Advantages and Disadvantages: Rain-X has not been formally tested in the saline marine environment. However, there are no reports of ineffectiveness on windshields during the winter in the saline environment caused by road salts. Renewal requirements are unknown for substrates other than glass. However, Rain-X could be effective for readily accessible applications that require easy deicing such as life rafts, gas sensors, firefighting equipment, communications antennas, and other safety-related equipment. Limited durability will restrict Rain-X to application at locations with ready accessibility. Rain-X Hydrophobic Glass Treatment is flammable. Because of its extreme slipperiness, Rain-X Hydrophobic Glass Treatment should not be applied to walkways, stairs, railings, helicopter landing pads, and other surfaces that require high friction to function properly and safely.

Marine Technology Transfer Requirements: The utility of Rain-X on communications antennas should be investigated. The abrasion resistance and durability of Rain-X under a variety of conditions must be formally investigated. Rain-X must be evaluated over substrate materials found on offshore structures. The slipperiness of Rain-X will be critical for its application to walkways, stairs, railings, and helicopter landing pads and should be evaluated.

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NuSil Technology

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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. Several new silicone icephobic coating formulations include a room temperature vulcanizing (RTV) material, a fuel-resistant material, and a material with low volatile organic compounds (VOCs). Table 6 lists several standard and developmental coatings considered for icephobic applications. Preliminary test results show that the new coatings in Table 6 have nominal shear stresses lower than 238 kPa, the shear strength of Teflon (unpublished results).

Table 6. NuSil silicone-based icephobic coatings.

Part Number	Description	Cure
R-2180	2 part, environmental protection	Heat
R-2180-2	Black version of R-2180	Heat
R-3930	1 part Solvent resistant Adheres to difficult substrates w/without a primer	RTV
R-1082	1 part Adheres to difficult substrates w/without a primer	RTV
R-2181	RTV version of R-2180	RTV

R-2180 is the most researched NuSil coating to date and is often used as a benchmark for comparison. The physical properties for R-2180 are listed in Table 7.

Table 7. Typical physical properties of R-2180.

Uncured	
Viscosity	3600 cP
Work time	>72 hr
Cured (30 min @25°C; 45 min @75°C; and 135 min @150°C**)	
40 Durometer, Type A	40
Tensile strength	1700 psi
% Elongation	1050%
Tear strength	300 ppi
Stress @100% strain	150 psi

**The given ramped cure schedule is suggested to remove solvent before elevated temperature cure. (Source: R-2180 product profile; http://www.nusil.com)

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 (Sivas et al. 2007). This value is lower than any previously screened material or coating tested by ERDC-CRREL (Sivas et al. 2007). For comparison, Teflon, the industry low-friction material standard, has an ice adhesion strength of 238 kPa whereas bare aluminum, the test control, has 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 deicing fluids (Hoover et al. 2007).

Operating Environment: Silicones are often chosen for their ability to maintain elastomeric physical properties at extreme temperatures where other adhesives, coatings, or encapsulants would fail. Silicones are often used as mold release agents, waterproof coatings, and biomedical materials because of their highly unusual and desirable surface characteristics (Mark 2004). In general, silicones have a broad thermal operating range, typically from -65 °C to 240°C.

In addition to simulated icing conditions, R-2180 has also been extensively tested in simulated extreme environmental conditions. In Figure 21, the ice adhesion values of freshly applied R-2180 are compared to values of R-2180 that has been distressed to simulate wear, thermal aging, and humidity and salt spray exposure (Sivas et al. 2007; Hoover at al. 2007). Under all 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 1991), however, R-2180 has not been extensively tested in other operating environments.

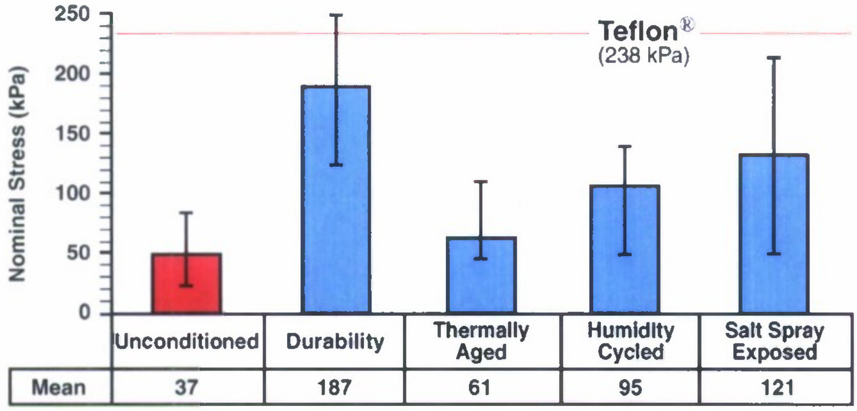

Figure 21. A comparison of the ice adhesion of unconditioned R-2180 compared to simulated exposure of R-2180 to wear (durability) thermal aging, humidity exposure, and salt spay exposure (courtesy NuSil Technology LLC).

Engineering Concept: NuSil R-2180 is applied as a two-part process and must be cured using heat that can be implemented using an autoclave or oven. Table 7 indicates the recommended cure schedule. 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 icephobic coatings listed in Table 6 were developed to achieve easy application and solvent resistance. R-3930 is effectively resistant to solvents that may be useful in aviation environments where surfaces may be exposed to fuels, soaps, and deicing fluids. R-1082 is a one-part material that adheres to difficult substrates and is easily applied through spraying, knife coating, or wiping and can be cured without the addition of heat.

TRL: The TRL for R-2180 is approximately 7–8. The other new coatings under development have a TRL of about 6.

Deicing or Anti-icing: This coating is a deicing technology. It does not prevent ice formation; it does allow ice to break easily from surfaces.

Current Advantages and Disadvantages: R-2180 is erosion resistant and has the lowest ice adhesion strength measured by CRREL. R-2180 must be heated in an oven or autoclave for curing. New formulations currently being performance tested have the capability to room-temperature vulcanize and do not require high temperatures for curing.

Current Acquisition Cost: Unknown.

Operational Cost: None.

Maintenance Requirements: Unknown, function of recoat frequency needed.

Potential Marine Application and Safety Impact: NuSil R-2180 would be useful for coating small parts that would fit in and withstand the temperatures in an autoclave. This includes valves, communication antennas, firefighting equipment, and possibly some rescue equipment such as escape pod doors and hawser components. R-2180 cannot be used for large objects that are not portable, will not fit into an autoclave, and cannot withstand high temperatures. However, another silicone-based coating in Table 6 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 to shed ice from safety equipment.

Marine TRL: 7 for R-2180. TRL 6 for new formulations.

Marine Advantages and Disadvantages: In addition to aviation applications, R-2180 may be useful in the marine environment. The adhesion strength to ice in the saline environment was measured to have a mean adhesion strength of 121 kPa (Hoover et al. 2007). This is higher than for freshwater ice, but still very low. The NuSil icephobic coatings may also be useful on lock walls, electrical transmission lines, roofs, and antennas. However, R-2180 is a two-part material that needs an autoclave for curing limiting application to small articles resistant to heat, which is not ideal for large structures. New formulations, such as R-3930, R-1082, and R-2181 (Table 6), may be applied to larger offshore structure areas and will cure without the addition of heat. At this time, materials performance information is being evaluated but is not available.

Marine Technology Transfer Requirements: Test new formulations in marine and industrial offshore environment. Test all coatings on substrate materials found in the offshore environment. Test new formulations for slipperiness for application to decks, stairs, helicopter pads, and work areas.

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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/or 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 feed line 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.

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 deicing 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 warmer 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°C 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 sec^{-1} 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) (Figure 22). This places SILC immediately below the superhydrophobic regime.

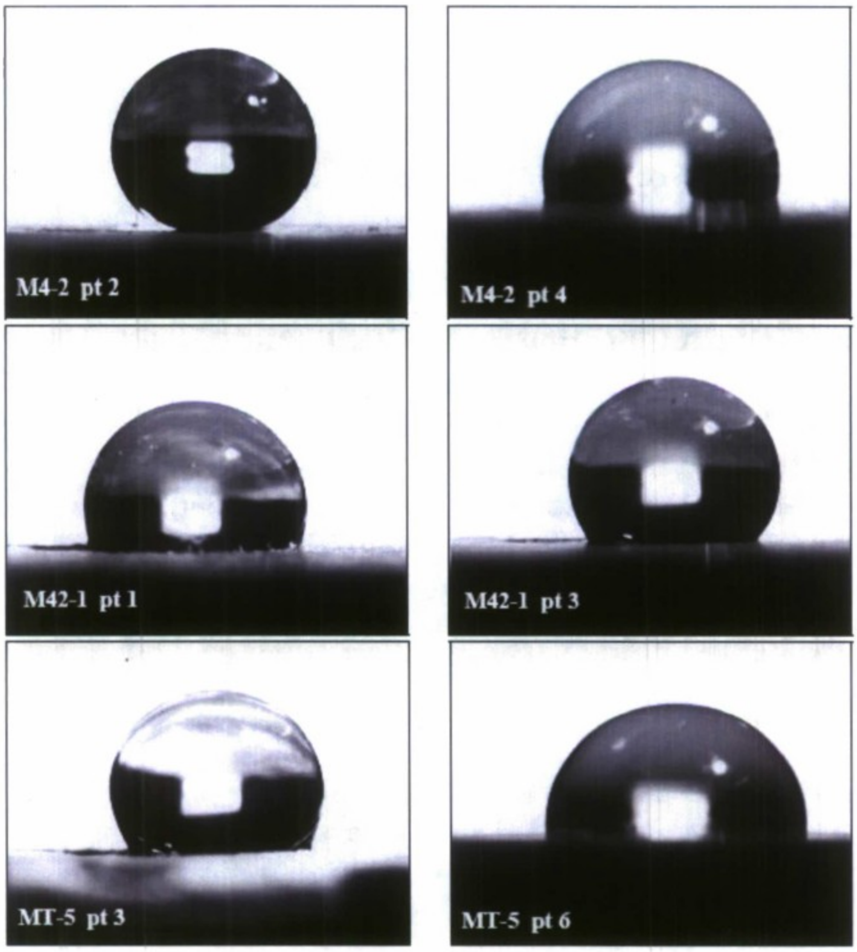

Figure 22. Droplet contact angles for coupons M4-2 after five test cycles (top), M42-1 after four test cycles (middle), and MT-5 after four test cycles (bottom) (Ferrick et al. 2006a,b).

TRL: 5. Depending upon application.

Deicing or Anti-icing: Deicing.

Current Advantages and Disadvantages: Tests have shown SILC to be effective on shuttle fuel tank insulation for 30–60 days. When used informally on an automobile windshield in winter weather, SILC was effective for 2 to 3 months. SILC has been tested for up to five deicing cycles, but is expected to be effective for more deicing cycles. SILC has not been confirmed to be consistently effective at more normal icing temperatures. However, it is effective at cryogenic temperatures. The material is easily applied with a brush.

Current Acquisition Cost: Unknown; patent application pending.

Operational Cost: Renewal rate is unknown.

Maintenance Requirements: None; renewal requirement rate is unknown. SILC has been tested in up to five deicing 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 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 deiced, such as life rafts, gas sensors, firefighting equipment, and communications antennas. 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°C 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.

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ePaint

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Intended or Actual Application: ePaint has, or is developing, several icephobic coatings through U.S. Navy and Air Force Small Business Innovative Research (SBIR) funding. Each has somewhat different characteristics. Navy coating development is completed and is more applicable to the marine environment. The ePaint coatings are dual-acting coatings. They consist of a hydrophobic material coupled with a phase change material (PCM) that expands and causes the material to break the substrate-ice bond. The Navy coating was developed to address sea-spray-created topside icing. The Air Force coating is somewhat more hydrophobic than the Navy coating and is transparent. Either coating could be used on radomes, antennas, power lines, and roofs. It is being considered as a material to protect radar radomes by the U.S. 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. ePaint 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 1991). 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 coatings reduce the adhesive strength of ice using several processes: hydrophobicity, icephobicity, 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 (Figure 23). 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. Tests have shown shear strengths of 28.85 ± 11.8 kPa (M. Goodwin, personal communication, 2 January 2009).

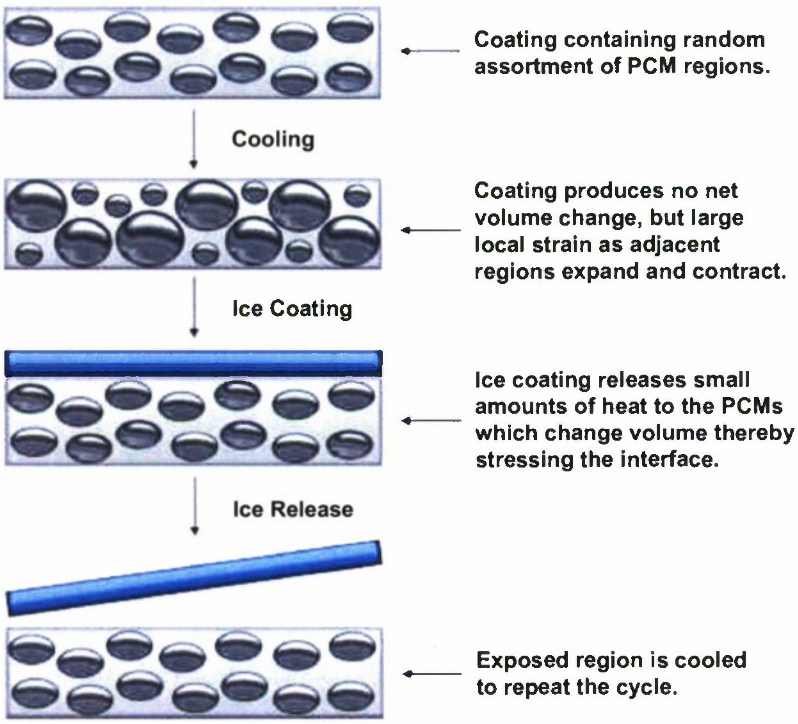

Figure 23. Use of thermal change to create coating mechanical stress and reduce ice adhesion (courtesy ePaint Company).

The material completely comprises solids. It is easily applied with spray or foam brushes. It is a two-part material that has a multiple-hour cure time at room temperature. Cure time increases as temperature decreases. The material can be applied over other paints, steel, aluminum, and composites.

TRL: 8.

Deicing or Anti-icing: Ice resistant—deicing.

Current Advantages and Disadvantages: The coating can be applied by spray or brush as a two-part process 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. The coating loses hydrophobicity after approximately one year.

Current Acquisition Cost: ~\$200 to \$300 per 4 L (4 L covers 65 m^2 to 74 m^2 with a 0.02- to 0.05-mm-thick coating).

Operational Cost: None.

Maintenance Requirements: None (operational life is about one year and requires recoating thereafter).

Potential Marine Application and Safety Enhancement: 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 below the main deck on support areas subject to spray and wave wash to reduce adhesion of superstructure ice.

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 platform and supply boat structures.

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NanoSonic

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Intended or Actual Application: Navy ship bridge window coatings.

Operating Environment: Marine ship topside environment.

Engineering Concept: NanoSonic is developing hydrophobic, anti-fouling, environmentally durable coatings with a wide service temperature range and inherent anti-icing functionality. The concept is to tailor the surface energy of the coating such that aqueous and many solvent-borne materials will not physically or chemically interact with the surface, effectively minimizing droplet contact area and imparting a natural high level of repellency and consequently a shedding, self-cleaning functionality. The coatings are icephobic and have been demonstrated to prevent icing of the coated surface under freezing conditions. The coatings are designed to be highly durable to ultraviolet (UV) radiation, abrasion, and solvents, with anticipated multiple-year lifespan before reapplication. Application is performed at room temperature and pressure, using a number of conventional paint application techniques.

TRL: 4. Coatings have been demonstrated to possess anti-icing capability and saltwater resistance in a laboratory environment that simulates operational conditions.

Deicing or Anti-icing: Anti-icing. Ice formation was mitigated in a laboratory environment at -18°C.

Current Advantages and Disadvantages: The system under development is environmentally robust, being designed for marine environments and high levels of UV, salt, grit, sand, water, and solvent exposure. The system is currently being designed for a three-year lifespan before coating reapplication. Reapplication may require a controlled environment. A detailed qualification plan specifically targeted for marine ship topside applications has been developed for coating analysis. The coatings have passed a number of durability and performance requirements—such as American Society for Testing and Materials (ASTM) D4060 (abrasion resistance), D5402 (solvent resistance), and D3359 (adhesion)—in a laboratory environment simulating accelerated topside exposure.

Current Acquisition Cost: To be determined.

Operational Cost: To be determined.

Maintenance Requirements: The coating system is being designed to require reapplication no more than once every three 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 environments encountered across the globe. The coatings provide good optical transparency on windows and prevent icing in all weather conditions.

Marine TRL: 4. Coatings are specifically designed for marine use.

Marine Advantages and Disadvantages: The coatings provide a level of corrosion protection to underlying components. Application may be performed 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 the coating technologies to determine effectiveness in a shipboard marine environment representative of operational conditions. The coatings will subsequently be field tested and evaluated for return on investment and acquisition costs.

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Microphase Coatings—PhaseBreak ESL

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Intended or Actual Application: The intended applications for Microphase Coatings Inc.'s icephobic coating, PhaseBreak ESL, are wind turbines, general aviation engine inlets, aircraft antennas and other aircraft components, winter sports equipment, railroad equipment, power transmission systems, communication and radar antennas, and ship superstructures. The coating resists abrasion, is hydrophobic causing droplets to have a large contact angle with the surface, and icephobic through release of an encapsulated melting point depressant that migrates to the coating surface and melts ice at the ice-coating interface. For aviation applications, the goal of the technology is to cause ice to break away from the accretion surface with sufficient frequency that only small pieces are dislodged at any time, reducing the probability of foreign object damage (FOD) to aircraft components. Testing has been conducted by North Carolina State University and the U.S. Air Force Research Laboratory, and an earlier version of the coating has been certified by the FAA. PhaseBreak has the following properties: low ice adhesion, good substrate adhesion, high durability, three- to five-year service life, easy application, low odor, easy cleanup, field repairable, and a passed thermal flash test.

Operating Environment: Testing for the NASA Space Shuttle program showed the coating is effective to -40°C temperatures. Other testing demonstrated that icephobicity did not change between -9.4°C and -56.6°C. The material releases the freezing point depression compounds when its temperature cools below about 2°C and the surface is wetted. The coating has been tested on wind turbines in Norway, on aircraft, and on communication antennas. Therefore, PhaseBreak operates in snow, freezing rain, and freezing drizzle conditions near the ground, and in the air, which includes rime ice. Because it is certified for aviation use, it operates satisfactorily in FAA FAR 25 Appendix C conditions that describe cloud droplet spectra, liquid water contents, temperature, and duration of exposure (FAA 1991) (Figure 24). The coating has not been tested in the marine environment, although the developer anticipates that it should be effective in the saline ice. The coating has many potential applications, but longevity is an inverse function of the frequency of wet and cold conditions.

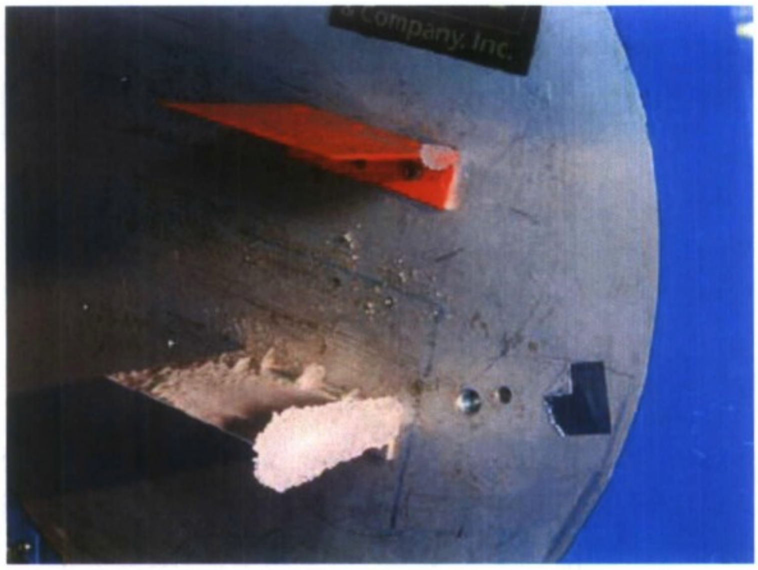

Figure 24. Coated (top, red) and uncoated (bottom) vortex generators after 20-min exposure at -2 °C in an icing wind tunnel. The coating demonstrated is the predecessor coating from which PhaseBreak-ESL was developed (courtesy Microphase Coatings Inc.).

Engineering Concept: Microphase Coatings Inc.'s PhaseBreak ESL is a smooth, hard, white two-part epoxy silicate coating with a unique formulation of epoxy, ethoxy silicates, and freezing point depressants that enable an ambient cure system. PhaseBreak ESL is a product of the sol-gel process where molecular precursors are converted into nanometer-sized particles to form a colloidal suspension, the sol. The sol nanoparticles are then linked in a three-dimensional solid network and the spaces in between are filled with liquid. The solid network is a polysiloxene epoxy resin binder.

The sol-gel chemistry used to create the PhaseBreak ESL facilitates the slow release of three freezing point depressants. The compounds are first chemically reacted with titanium isopropoxide (TIP) and then slowly released through subsequent hydrolysis and condensation reactions as the coating surface wears. This gives the coating its anti-icing properties through the prevention of the nucleation and thus adhesion of ice. The concentration of freezing point depressants is depleted with time and exposure to water; therefore, the rate at which they are released to the surface is critical to both the coating's performance and its lifetime.

Microphase Coatings uses the sol-gel chemistry to control the release rate of the freezing point depressants and their presence on the surface of the coating. Slow release of melting point depressants maintain the coating anti-icing capability, predicted to be three to five years. The service life of the coating depends upon the concentration of melting point depressants, coating thickness, and the frequency of exposure to low temperature and to water.

PhaseBreak ESL is a two-part material mixed immediately before application. It has low VOC release, and is applied by spraying, rolling, or brushing to a thickness of 0.254 to 0.305 mm. It is moisture cured in ambient temperatures in about 1 hr and is usable in 4 hr. The coating can be used over most materials, including steel, aluminum, and composites. PhaseBreak ESL has been tested for flash point (passed), rain erosion (passed 10 min at 223 m sec^{-1} and 4.5 min at 268 m sec^{-1}), resistance to jet fuel and hydraulic fluid (passed), and scrape adhesion (passed).

TRL: 8. PhaseBreak ESL is COTS, but has not been thoroughly tested for effectiveness and durability in all environments.

Deicing or Anti-icing: Deicing. PhaseBreak ESL releases a freezing point depressant when cooled below about 2°C and the surface is wetted.

Current Advantages and Disadvantages: PhaseBreak ESL is COTS and is available in large quantities. It can be applied over many substrates and is moisture cured at ambient temperatures. The freezing point depressants are non-toxic. The material decreases the adhesion strength of ice to substrates making active systems more effective. The material is well-tested in the aviation environment and has been certified by the FAA. The material has a service life that is inverse to its exposure to cold, wet, and icing conditions.

Current Acquisition Cost: Cost is $53 for 1 L from the North Carolina factory.

Operational Cost: None, except for periodic renewal or repair.

Maintenance Requirements: No maintenance, except for renewal or repair.

Potential Marine Application and Safety Enhancement: PhaseBreak ESL would be most effective where access is not easily available by personnel for deicing. This includes lattice structures, such as cranes and the flare boom. The material may reduce ice accretion below the main deck where access is difficult and ice loads can be high. The material could work alone, but, like most coatings, it may be more effective if coupled with an active technology such as heat or electroexpulsive techniques. Bulkheads and hatch covers could be deiced with PhaseBreak ESL, but walkways, helicopter pads, stairs, and railings may become slippery when the material is wet. The material could be used on communications antennas with apparently no degradation of signal quality.

Marine TRL: 6–7. Testing is necessary in the marine environment.

Marine Advantages and Disadvantages: PhaseBreak ESL is hard, non-toxic, and can be applied with common paint spray equipment in various colors. It must be removed by sanding. Because the material is activated when wet and cold, frequent wave wash by cold water near the waterline would shorten service life. Product service life is three to five years depending upon exposure. The material is slippery when wet and should be used on surfaces other than walkways, stairs, and helicopter landing pads. As with many technologies, released ice will accumulate at the base of structures where it must be removed.

Marine Technology Transfer Requirements: PhaseBreak ESL has not been tested in a marine environment and should be tested for capability with saline ice. In addition, for applications subjecting the coating to heavily abrasive and continuous outdoor exposure, specific performance testing is required to determine coating life.

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Seashell Technology

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Intended or Actual Application: Seashell Technology is in Phase II of an Air Force SBIR project, and has proven the concept for an ultrahydrophobic Lotus-leaf-based coating. 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 may reduce ice buildup on surfaces by inhibiting the accumulation of water droplets. Additional testing will demonstrate the coating's anti-icing capability in real-world and icing wind tunnel environments. Research is planned to provide the coating with sufficient abrasion resistance to be applicable to aircraft. The company previously developed a coating that is ultrahydrophobic and provides corrosion protection for marine structures.

Operating Environment: Seashell Technology indicates that the coating was tested in "midwestern winter conditions" and performed successfully in those unspecified conditions. The company indicates that preliminary studies show that the material will perform successfully in snow, rime ice, and clear ice conditions. However, information is not available about the nature of this performance. If certified for use on aircraft, the coating would need to perform acceptably in FAA FAR25 Appendix C supercooled cloud droplet conditions (FAA 1991). Some testing has occurred in an icing wind tunnel, and additional icing wind tunnel testing is planned.

Engineering Concept: The Seashell coating is ultrahydrophobic 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 degrees).

The coating formulations are designed so that the resulting coating surface topology mimics the surface of a Lotus leaf. Lotus leaf surfaces are ultrahydrophobic due 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 and the small surface area presented by the coating to the drop, the droplet is held to the surface with little energy. Figure 25 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 de-

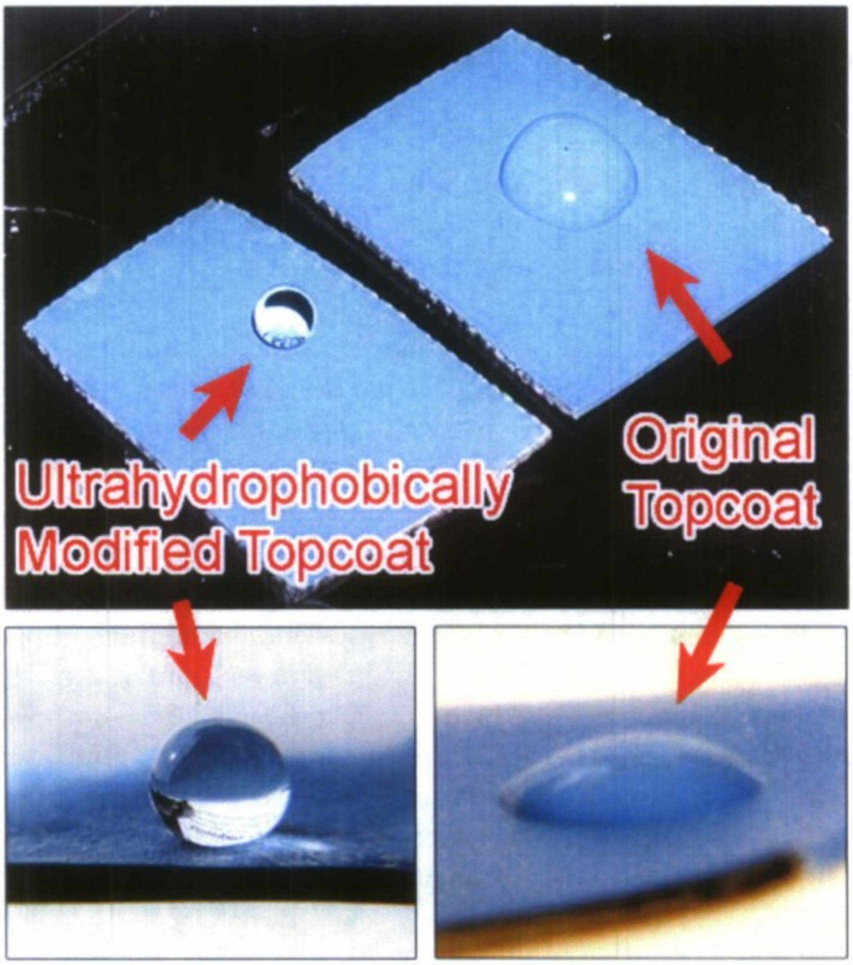

Figure 25. Droplet contact angle on original substrate coating and after coating with Seashell ultrahydrophobic coating (courtesy Seashell Technology, LLC).

tails of the coating are proprietary. Tests of coating longevity under a variety of conditions are planned.

TRL: 4–5. Coating is in Phase II SBIR development. Surfaces can be coated for testing purposes at this writing.

Deicing or Anti-icing: Deicing, and possibly anti-icing, capability. In general, coatings reduce ice adhesion strength and do not prevent the formation of ice. However, if this coating operates as planned, it may be sufficiently hydrophobic that when drops strike the surface they are insufficiently bound to adhere strongly when frozen.

Current Advantages and Disadvantages: Until additional engineering and performance information is available, the full advantages and disadvantages of the final product are unknown. The system is a hydrophobic water-repellent coating and may be icephobic.

Current Acquisition Cost: Unknown. The developer's intent is for the coating to be cost competitive with "most paints."

Operational Cost: None—passive technology.

Maintenance Requirements: Unknown. Periodic cleaning or renewal may be necessary. Longevity testing has not been conducted. The effects of oils and materials other than fresh or saltwater on the coating's hydrophobic characteristics are unknown.

Potential Marine Application and Safety Enhancement: A coating can be applied to most surfaces, except, perhaps, windows (unless the coating is transparent) and possibly walkways (if the material is slippery). If the material is sufficiently flexible and abrasion resistant, it 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. If resistant to wave impact and droplet erosion, the material may be able to reduce ice accumulation on support structures below the main deck. It may also assist ice removal on supply boats.

Marine TRL: 4–5. Seashell Technology indicates that the coating has been tested and works effectively in fresh and saline water.

Marine Advantages and Disadvantages: The technology has the potential to assist active deicing and anti-icing technologies in an offshore environment. In addition, the technology could be sufficiently icephobic that it prevents the formation of ice on platforms and supply boats with the structure's intrinsic operational vibration. Recoating frequency, resistance to abrasion and wave wash effects, and friction characteristics for personnel and equipment will affect where the material is used and its practicality. The effects of abrasion, oils, and other materials on the coating's hydrophobic characteristics are unknown.

Marine Technology Transfer Requirements: The ability to withstand abrasion, friction characteristics, 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 windows, and its ability to assist a variety of active deicing and anti-icing technologies, should also be evaluated.

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Nanohmics

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Intended or Actual Application: Nanohmics is in early development of a tape that can be imprinted with a biomimetic superhydrophobic surface. The tape will be superhydrophobic, erosion resistant, and inexpensive. The initial goal is to provide ice protection for helicopter blade leading edges. The material could function alone or in concert with an active deicing/anti-icing technology for increased efficiency and effectiveness.

Operating Environment: The material is intended to perform successfully in clear ice and rime ice, and resist erosion by sand and dust at near supersonic blade speeds. If certified for use on commercial aircraft, the coating would need to perform acceptably in FAA FAR25 Appendix C supercooled cloud droplet conditions where drop size, liquid water content, temperature, and exposure duration are specified (FAA 1991).

Engineering Concept: Nanohmics will use nanoimprint lithography to etch a superhydrophobic surface topography into the surface of a hard coating material such as aluminum nitride. Using proprietary deposition methods, depositing the hard coating onto flexible substrates in the form of a robust superhydrophobic adhesive tape will allow the material to be directly applied to surfaces requiring ice protection. The imprinted topography will prevent interstitial wetting and hence induce a superhydrophobic character to the material.

TRL: 2. The material requires demonstration of proof-of-concept.

Deicing or Anti-icing: Deicing.

Current Advantages and Disadvantages: Advantages of the super-hydrophobic tape include hard coating for durable performance, imprint features that provide hydrophobicity and low droplet roll-off angles, and ready application of the material to substrates that are not highly irregular or have high surface roughness. The material is still in concept phase and has no supporting scientific data for hydrophobicity or icephobicity. Due to the development stage, the material is not yet available for testing.

Current Acquisition Cost: Unknown—in early development.

Operational Cost: Unknown—in early development.

Maintenance Requirements: Projected to have low maintenance requirements. Replacement rates will be a function of the abrasive environment.

Potential Marine Application and Safety Enhancement: Hydrophobic tapes are expected to have low maintenance cycles; low manufacturing costs will allow coverage of large areas of marine structures.

TRL: 1. The material requires demonstration of proof-of-concept.

Marine Advantages and Disadvantages: The tape surface may not be practical for application to walkways, stairs, or helicopter landing pads. The material is unlikely to be applicable to highly irregular surfaces such as cables, windlasses, and lattice structures. Its longevity in marine environments is unknown. The material will need adhesive and conformal characteristics to be applied usefully to marine structures.

Marine Technology Transfer Requirements: The ability to resist the forces of wave impact if applied near waterlines, and the general industrial environment of marine structures, require investigation. Although hydrophobic, the icephobic character of the tapes must be demonstrated. Investigation of resistance to chemicals, conformality to irregular surfaces, and adhesion capability is necessary.

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21st Century Coatings Inc.

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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 U.S. Naval Research Laboratory (NRL). NRL has tested these coatings for 20 years. Thirteen FPU coatings are provided for the marine environment, each with specific characteristics for the intended environment. The applications and characteristics include icing (FPU WC-1 (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), mechanical toughness, thermal and ultraviolet resistance, and flexibility. Applications include ship topside areas, wave wash areas (splash zone) 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 helicopter 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).

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.

TRL: 8. The product is COTS.

Deicing or Anti-icing: Deicing.

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, the material cost varies from \$13.45 to \$16.14 per 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: WC-1 (ICE) was designed by the Navy for use in the marine environment. The coating is usable on ships and platforms, and it appears to be resistant to wave wash when applied near the water surface. Therefore, it may be applicable to the lower decks of marine platforms and to supply vessels where frequent sea spray occurs. It may also be used on bulkheads, irregular surfaces such as lattice structures, cables and windlasses, and antennas. It is unclear whether WC-1 (ICE) with non-skid additives would provide safe footing in passageways, stairs, decks, and work areas.

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. However, tests with saline ice are not available. An enhanced formula of FPU WC1 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 icephobic properties, friction characteristics for foot and vehicular traffic, and effects on communication antenna performance.

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KISS Polymers LLC

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Intended or Actual Application: KISS-COTE silicone-based polymer coatings are one-molecule thick and are smooth-feeling, slippery, dry, non-toxic, waterproof materials. Coatings are applied at room temperature by spraying a liquid or dabbing a gel and rubbing the surface with a clean cloth. Applications include all exterior surfaces of automobiles, including chrome, glass, and paint, boat hulls for anti-fouling and increased speed, teeth for reducing dental disease, aircraft to increase speed and reduce ice adhesion, and a variety of medical applications. KISS Polymers indicates that airline tests showed the products to be effective in preventing ice from sticking and accumulating on aircraft. However, they emphasize that their coating products are not a substitute for onboard aircraft anti-icing and deicing equipment, although pilots report reduced usage of deice boots when they are coated with KISS polymers. 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, reducing surface friction and drag while protecting the coated material with easy-to-apply non-stick polymers that are superhydrophobic, shedding water and ice, as well as most other detritus and environmental debris.

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, mildew resistant, reduce friction, promote a clean and healthy surface, are environmentally friendly, and work on metal, wood, fabrics, plastic, and glass. In addition, they 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 (Figure 26).

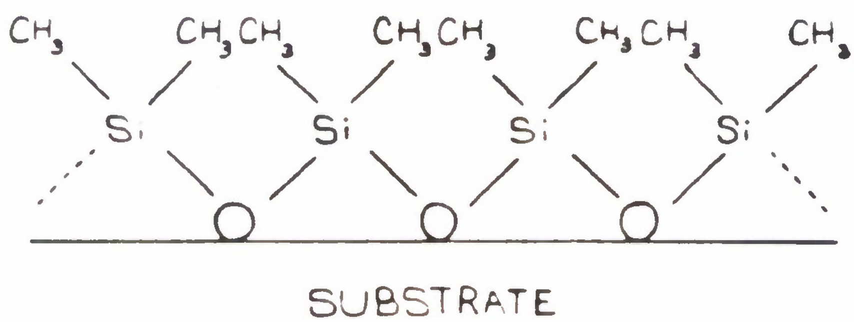

Figure 26. Self-bonding inert polymers present a non-stick face to the environment (CH4 methyl groups) with a strong but thin intermediary (Si Silicon) and a reactive side (O Oxygen) that bonds to the substrate surface (courtesy KISS Polymers LLC).

The resulting coatings exhibit most of the temperature, pressure, and chemical resistance, and water-repellent properties of silicone-base 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 nearly invisible to the eye.

TRL: 9. KISS-COTE products are COTS.

Deicing or Anti-icing: Deicing, ice-shedding.

Current Advantages and Disadvantages: KISS-COTE is water repellent, exhibits icephobic 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.

Current Acquisition Cost: Varies according to formulation and end use. Industrial versions cost approximately \$1.08–\$1.61/m^2.

Operational Cost: Requires no special equipment or environment for application. KISS-COTE Self-Bonding Polymers require no chemical pretreatments, no heat, no pressure, no curing time, and little technique sensitivity (the less you use, the easier the application and the better the performance). Due 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 antifouling 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 applied on steel structures below the main deck to assist the release of ice from platform legs, braces, and piping. It may also be sprayed on irregular surfaces such as lattice structures and windlasses.

TRL: 7. Although KISS-COTE is available as a COTS product for boat hull applications, coating radomes, and construction materials and does exhibit hydrophobic and icephobic characteristics, its use on drill rig surfaces with larger quantities of ice and irregular surfaces should be demonstrated. 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 so actual coating costs are nominal. Because coated surfaces exhibit reduced drag and surface friction, 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. The longevity of KISS-COTE over typical offshore platform substrates should be investigated. The ice adhesion strength of saline ice to KISS-COTE should be tested.

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Ross Technology—NanoSH

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Intended or Actual Application: The Ross Technology NanoSH superhydrophobic coating is being developed to provide corrosion resistance, to improve performance of boats by reducing drag, and to decrease 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. NanoSH was a 2008 R&D 100 award winner (R&D Daily 2008). NanoSH was developed in collaboration with the University of Pittsburg and Oak Ridge National Laboratory.

Operating Environment: Ross Technologies has not identified specific operating environments for NanoSH. 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 (Figure 27) (Ross Technologies 2009). Coated model boats also showed an average 7%–8% increase in speed over uncoated hulls, and coated magnesium also showed less corrosion than uncoated magnesium when similarly exposed (Ross Technologies 2009).

Figure 27. Ice-free NanoSH-coated surface (right) and ice-covered uncoated surface (left), of satellite dish after freezing rain storm (image courtesy Ross Technologies).

Engineering Concept: NanoSH is a powder coating that reduces total energy at the water-interface surface. Using a borosilicate, the nanostructure NanoSH 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.

TRL: 4.

Deicing or Anti-icing: Anti-icing.

Current Advantages and Disadvantages: The coating prevents icing by causing drops to roll off the surface. The NanoSH 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 superhydrophobic, is unknown. Conditions required for applying the coating to substrates and the adhesion strength of ice to NanoSH 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, too early in development.

Maintenance Requirements: Unknown, too early in development. No testing has been performed to determine how long coating is effective. Only durability tests relative 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 freshwater droplets and causes them to roll off surfaces, preventing ice formation. NanoSH could be used on inclined surfaces, and surfaces exposed to wind, which could cause drops to roll from surfaces before freezing. Ice may form on horizontal, protected surfaces. Bulkheads, cables, and safety gear, such as fire-fighting equipment and escape pods, are potential applications.

Marine TRL: 3.

Marine Advantages and Disadvantages: NanoSH 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 NanoSH, its durability, the longevity of its hydrophobic capabilities, its ability to work in saltwater, 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 assess ice adhesion strength. Determine slipperiness of coating. Assess compatibility with communication antenna performance characteristics.

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7 Design

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Intended or Actual Application: Offshore platform design can have a large impact on superstructure ice accretion and, to a lesser extent, atmospheric ice accretion from snow, rime, freezing rain, or frost. 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. Platforms or supply boats dominated by small-diameter elements such as I-beam edges, cables, pipes, and support braces will, all considered, ice fastest and have larger ice loads than structures without the small-diameter elements. Structures with large-diameter or flat surfaces will generally have fewer icing problems. Current design practices appear to minimally consider superstructure and atmospheric ice problems. The focus of most high Arctic offshore platform design is to resist or dissipate forces caused by dynamic sea ice loading. Because superstructure icing and rime, freezing rain, snow, and frost are not likely to displace floating sea ice as a dominating design criterion, it is useful to compare examples of current and recommended platform design practices and assess the tendency of each to ice.

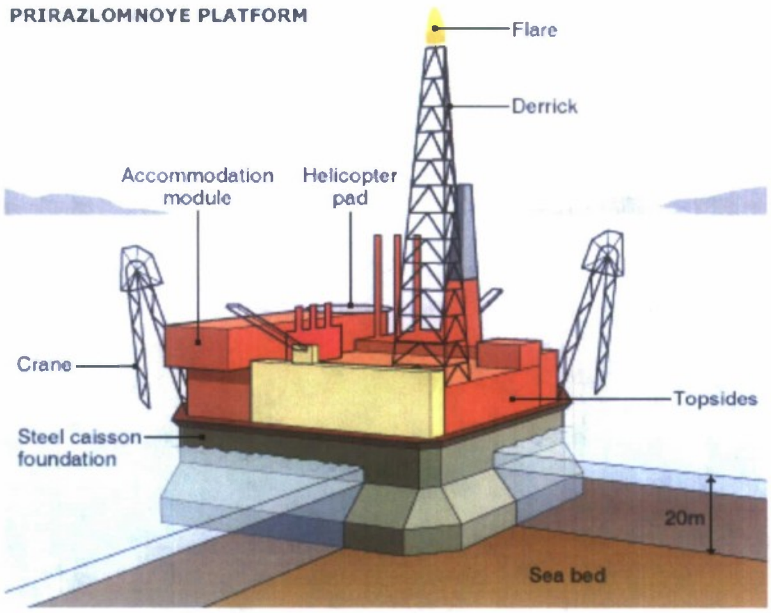

Figure 28. Prirazlomnoye oil field gravity caisson platform for the Russian Arctic shelf in the southeast Barents Sea (Paulin 2008).

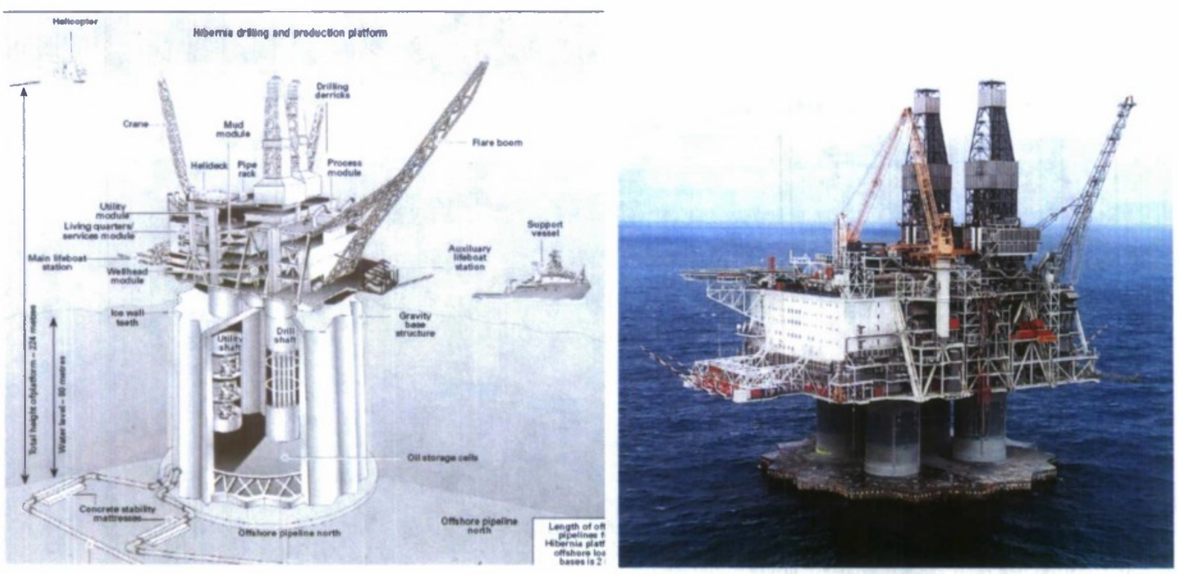

Figure 29. Hibernia gravity-based structure 315 km east-southeast of St. John's, Newfoundland, Canada (Paulin 2008).

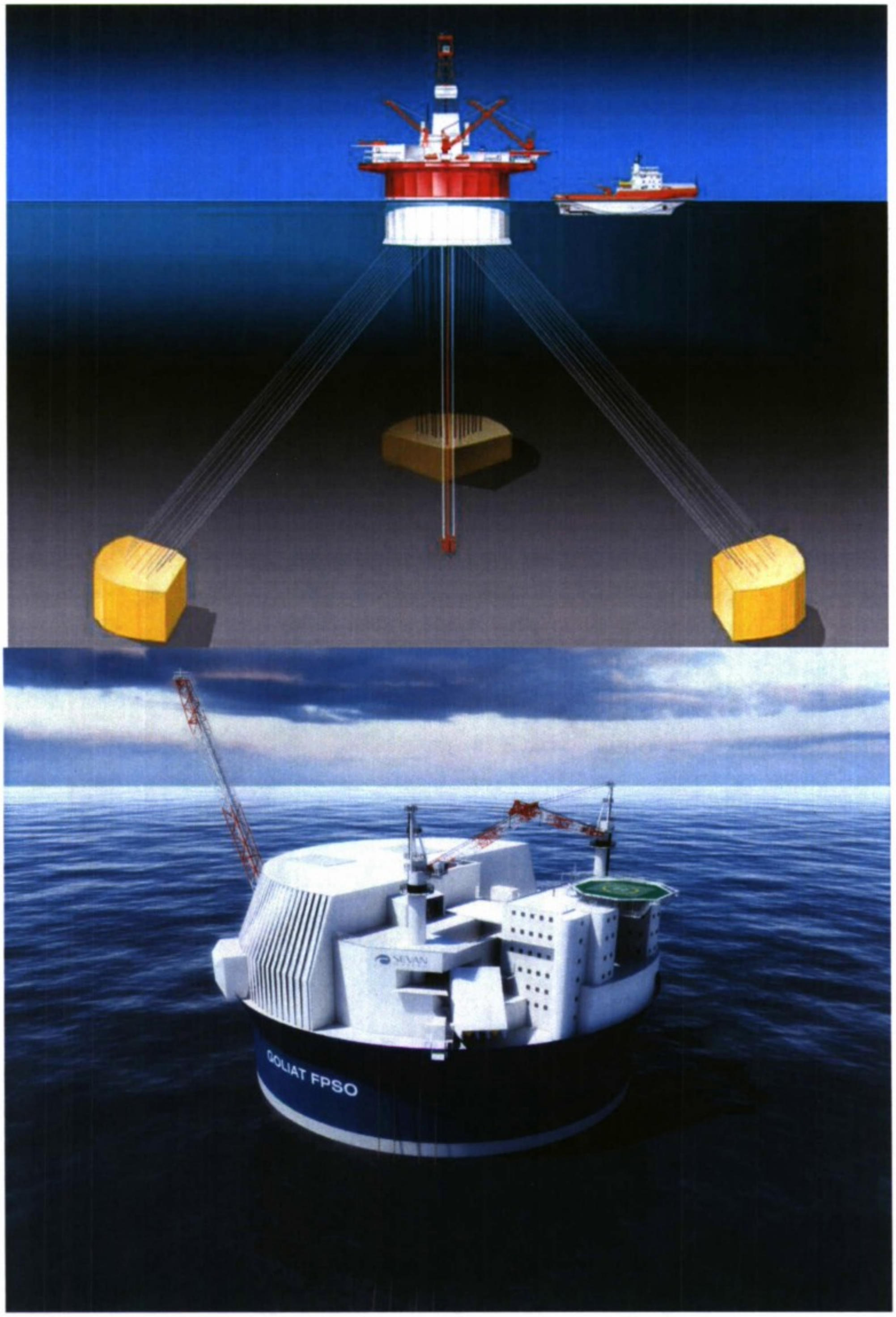

Figure 30. Arctic semi-rigid floater for exploration in water depths of 80 to 500 m (top) (Paulin 2008). The Sevan Marine FPSO (bottom) is a concept for a similar structure for the Goliat Field located north of Norway. The Sevan design focuses on minimizing superstructure icing and on creating an optimal working environment by locating all equipment in enclosed areas. The process modules are arranged with a top cover and transparent walls allowing gas releases to be ventilated (courtesy Sevan Marine).

Figure 31. Steel stepped gravity base structure developed for the Grand Banks of Newfoundland (left) (Paulin 2008) and similar Berger/Abam proposed arctic drilling structure for the deeper water of the Beaufort Sea (right) (Berger/Abam 2008).

Figure 32. Semi-submersibles *Henry Goodrich* (left) and *Erik Raude* (right), both late-generation Arctic designs. However, note hardware below *Erik Raude* main deck that may be susceptible to superstructure icing (both images Paulin 2008).

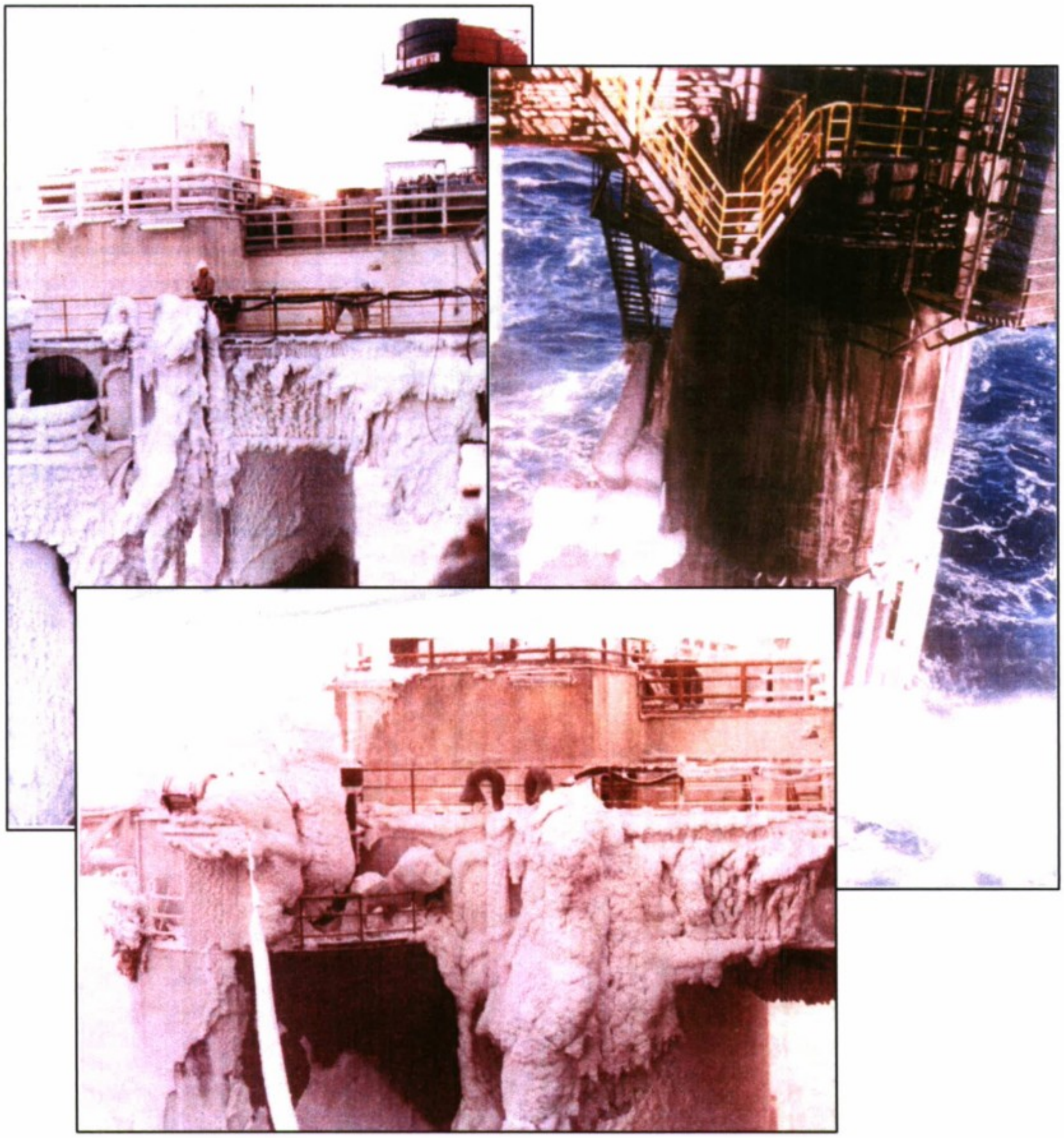

Figure 33. Icing of semi-submersible *Ocean Bounty* in Cook Inlet, Alaska. Note larger accretions and less self-shedding on more complex and smaller-diameter structures (courtesy C. Miller, U.S. Department of Interior Minerals Management Service).

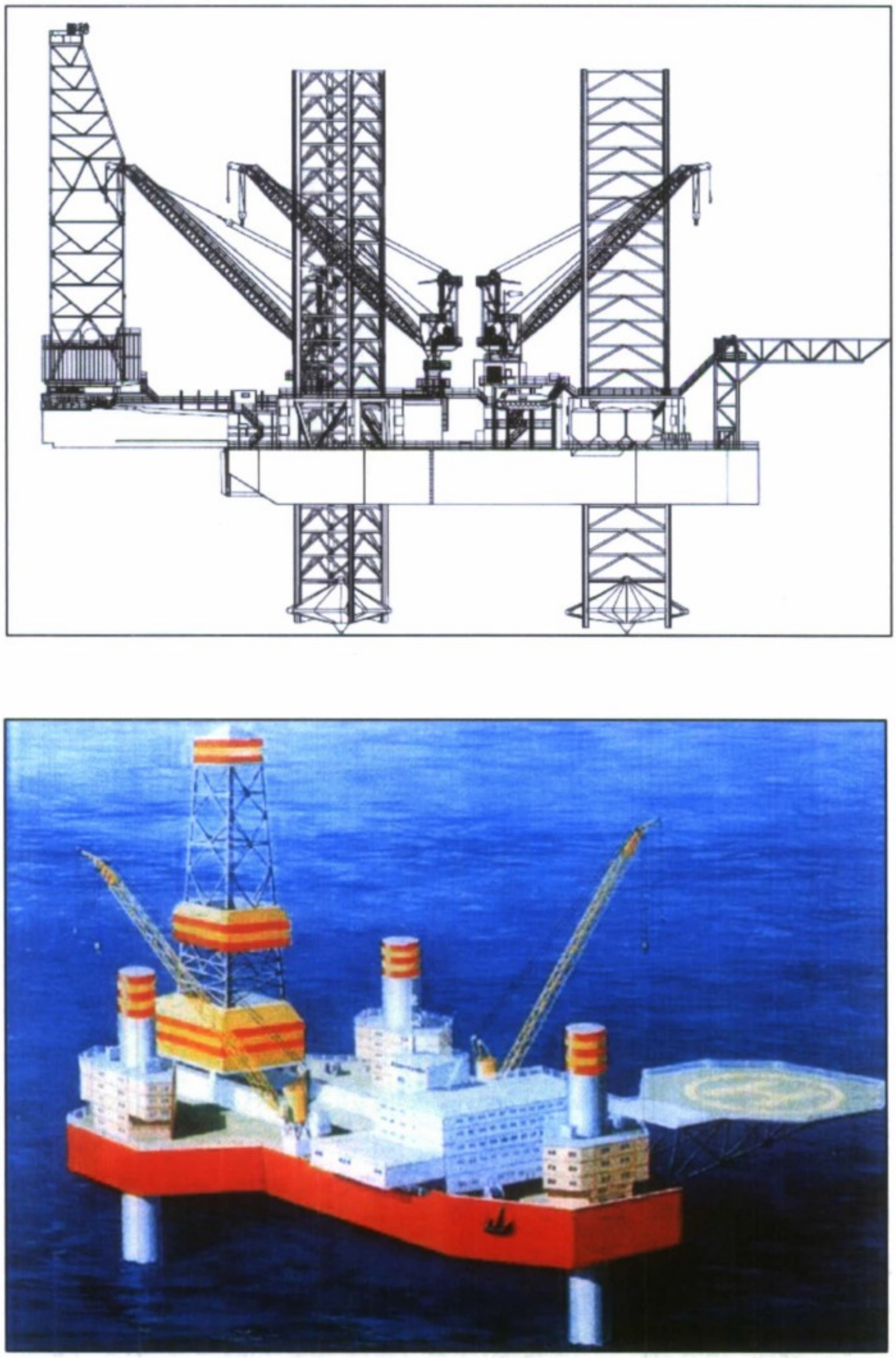

Figure 34. Traditional Gorilla class jack-up platform with lattice structure legs (top) versus new Russian ice-resistant jack-up rig *Arktlcheskaya* (below). Ice resistant refers to forces imposed by floating sea ice. However, the new design should also experience less superstructure ice accretion with its large-diameter, smooth exterior legs (images from Paulin 2008).

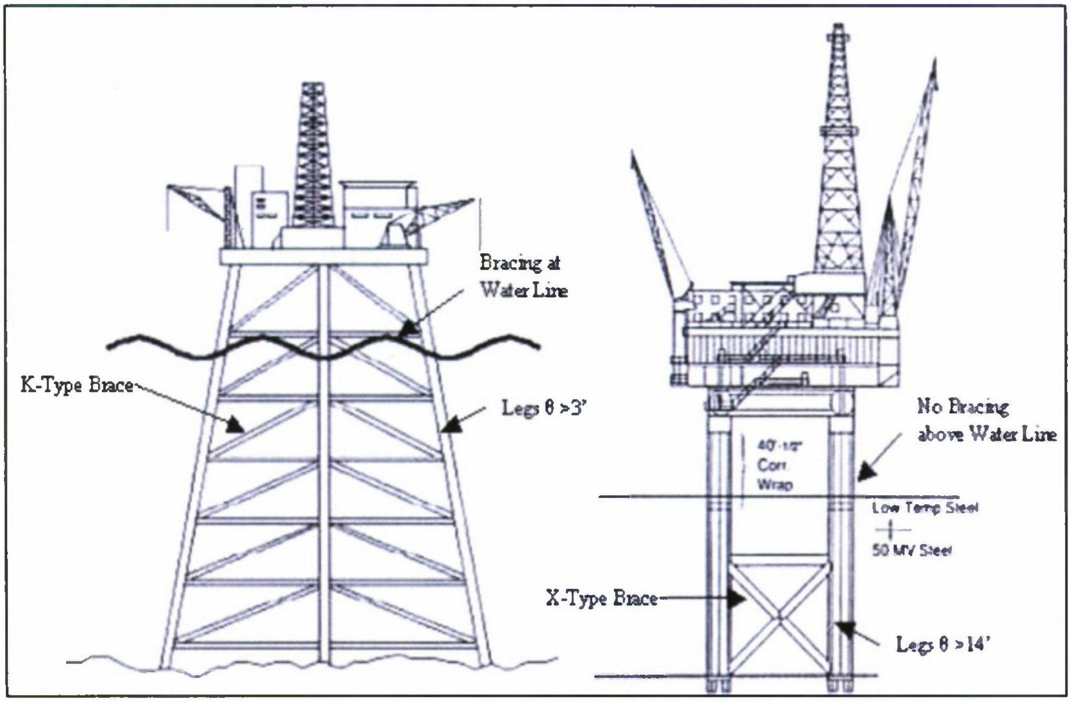

Figure 35. Conventional K-brace jacket structure (left) versus the X-brace jacket structures found in Cook Inlet, Alaska (right) (Paulin 2008). The braces of the K-brace structure at the waterline experience higher floating sea ice and wave loads. The cleaner design of the Cook Inlet structures should experience less superstructure ice accretion.

Operating Environment: Paulin (2008) conducted an extensive study of conditions that would be experienced in various Arctic locations by exploration, drilling, and production facilities, including the Beaufort and Chukchi Seas, the focus of this report (Figure 1). Paulin (2008 [Table 4.1]) indicates that in the Beaufort and Chukchi Seas at water depths from 10 to 60 m, and distances from 10 to 380 km offshore, the governing design parameters for structures will be multiyear ice and weak foundations. In the Beaufort Sea at depths of 200 m and distance from shore to 90 km, the dominant design parameters are first-year sea ice ridges and small multiyear floes. Duration of ice cover in the Beaufort Sea is typically 9–10 months with occasional ice brought in by winds during the summer (Paulin 2008). Typical ice cover in the Chukchi Sea is 7–10 months with about 20% coverage during the summer. He indicates in his summary that multiyear ice drives design when that ice is likely to be present. In these locations, wave loads are small by comparison. Structures located in the Navarin Basin and the North Aleutian Basin (Figure 1), however, experience greater loads from waves than from the occasional first-year ice found in the area. Both areas of the latter are open water for about eight months.

Superstructure icing will be a function of expected wave height, and therefore wave forces. Waves are likely to be largest when maximum sustained winds from a narrow range of directions occur over a large fetch. In sea ice areas this may occur in the later summer and fall when open water areas are largest. Breaking waves, and thus greater spray generation from spin drift, also occur when wave height is about 80% or greater of water depth (Paulin 2008). When supercooled, spray freezes on structures and forms greater ice thicknesses on smaller-diameter objects.

Atmospheric icing is common where cold air moves over warm water causing sea smoke, which is fog comprising cloud-size water droplets. Sea smoke and fog create rime ice on superstructure surfaces, with the largest ice thicknesses forming on smaller-diameter objects. Snow squalls also occur as a result of storm activity or localized convection as cold air moves over relatively warm water surfaces. Frost will occur if the structure has become cold soaked and warm moist air moves over the platform, or if calm conditions occur and surfaces chill from exposure to a clear night sky. Glaze or sleet occurs when rain or drizzle falls through a layer of air at the surface that is below freezing. This would most likely occur near where air is moving from over cold sea ice or cold land masses to the open ocean. The design of platforms and supply boats can either encourage or discourage superstructure and atmospheric icing.

Engineering Concept: Paulin (2008) identifies several types of structures appropriate for each geographic area around Alaska based upon the ice loads, wave loads, foundation conditions, water depth, and distance offshore. All locations with substantial ice forces require a structure that is anchored to the ocean floor. Therefore, all recommended designs are either gravity structures or are floaters anchored to the sea floor with tension cables.

Shallow water structures located in areas frequented by multiyear ice are recommended to be gravity structures with broad bases that are nearly the same diameter from the sea floor to the main deck (Figure 28) (Paulin 2008). Gravity-based structures, such as those planned for the Russian Prirazomlnoye field (Zolotukhin 2008), have relatively smooth sides below the main deck and nearly vertical walls with a main deck that may or may not substantially overhang the base (Figure 28). As waves strike these structures, spray will be carried around—and over—the superstructure by the wind. The nearly vertical sides are smooth and free of elements that will encourage ice accretion. However, the main deck is much closer to the water surface than many other deigns allowing larger quantities of spray, and possibly green water, to reach the top of the main deck. The Hibernia structures off the east coast of Canada are also gravity structures (Figure 29). These structures are designed with a broad base that is substantially under the water surface, with large-diameter tubular legs supporting the main deck that is cantilevered and a large distance from the water surface. Although the base and support legs are large and relatively clean structures with few areas for large ice quantities of superstructure ice to accumulate, the remaining superstructure is complex and presents numerous small elements for ice accretion (Figure 29).

Mid-depth structures in multiyear ice locations have designs recommended as in Figure 30. These are floating structures that are anchored to the ocean floor with cables and can be used in many environments, including the North Sea (Sevan Marine 2007). Sevan Marine claims that their cable-guyed structure could operate in 3000 m of water. The floating structure is round with smooth, large-diameter sides that are vertical with a cantilevered main deck flared outward (Figure 30). In addition, most working areas of the Sevan Marine FPSO (floating production, storage, offloading) vessel are enclosed to reduce superstructure icing and are designed to allow light in and ventilate gases out for a comfortable and safe working environment. The main deck can provide as much as 20 m of freeboard. Although 100-year extreme wave heights in the Beaufort Sea and 10-year extreme wave heights in the Chukchi Sea can exceed the freeboard, in most storms large quantities of supercooled liquid water may not reach the main deck, minimizing superstructure icing danger.

Deeper water structures in sea ice locations have recommended designs such as those shown in Figure 31. These steel stepped gravity base (SSGB) structures provide a wide, heavy foundation that can cope with a variety of foundation conditions (Paulin 2008). Structure diameter necks to a minimum near the sea surface to minimize sea ice and wave loads. The Arctic drilling structure proposed by Berger/Abam for the deeper water of the Beaufort Sea is an example (Figure 31). It is expected that superstructure icing would be minimal below the main deck because of the 30-m freeboard, the relatively small perimeter where wave impacts occur, and the cantilevered main deck with a relatively smooth and featureless underside. The flared sides and cantilevered main decks of this and the previous two structure types are reminiscent of a ship bow flare's ability to deflect spray.

Structures in areas with little or no floating sea ice may have nearly any design depending upon water depth, wave forces, and other factors. Structures could be floaters or semi-submersibles, jack-ups, or jacket structures. Floaters used in Arctic environments can often remain on station in the most extreme storm conditions. However, they must abandon wells when threatened with moving sea ice. Examples of modern dynamically positioned semi-submersibles are Ocean Rig's *Eric Raude* (Ryerson 2008; Paulin 2008) and the *Henry Goodrich* (Figure 32) operated by Trans-Ocean. These rigs are supported by four to six large-diameter steel legs and have relatively clean areas below the main deck. Although this design should minimize ice accretion, there is sufficient bracing and piping to create an opportunity for significant ice accretion (Figure 32). The rigs can operate in waves of 14 m and survive waves of 24 to 32 m. The main deck of the *Eric Raude* is 13.5 m above the sea surface. The *Ocean Bounty*, a semi-submersible located in Cook Inlet in the 1980s, experienced serious superstructure icing despite its relatively clean design. Storms caused ice accretion of up to 1-m thickness on more complex portions of the structure, such as piping, railings, and stairways (Figure 33). At specific locations on the structure, ice was thinnest on smoother, larger-diameter surfaces where ice had occasionally shedded under its own weight (Figure 33). Ice accumulations on smaller-diameter structures mechanically locked to the structure, which made self-shedding less probable and manual ice removal more difficult.

Jack-up structures are usable in waters up to 150-m deep (Paulin 2008). However, although they can be used in cold waters where significant superstructure icing could occur, they are not typically designed to withstand forces greater than those imposed by first-year sea ice and waves, and then only in light load conditions. Therefore, Paulin (2008) indicates that jack-up structures would be inappropriate in the Beaufort and Chukchi Seas because of their poor response to dynamic ice loads. However, they could be located in the Bering Sea and perhaps the Gulf of Alaska with some technological advances—both locations where superstructure icing is also common.

The structure of a traditional jack-up makes it susceptible to superstructure icing. The lattice structure of jack-up legs present an excellent opportunity for ice accretion and bridging from one relatively small-diameter support member to another. The result could be ice filling in at least part of the leg framework and increasing load on the structure. For these reasons, a jack-up may accrete large masses of superstructure ice on the legs (Figure 34). However, new Russian ice-resistant jack-up rig designs, such as the *Arkticheskaya*, now under construction, are designed to operate in ice flows 0.5-m thick by providing jacketed legs (Paulin 2008) (Figure 34). Smooth, large-diameter jacketed legs without sharp corners or radii should accrete less superstructure ice and shed what does accrete more readily than open lattice designs.

Jacket structures are most common in warm locations such as the Gulf of Mexico. There are also jacket structures in Cook Inlet, Alaska (Paulin 2008). Jacket structures in warm locations often have numerous support legs and considerable bracing, piping, and other hardware below the main deck. Cook Inlet jacket structures have larger diameter (greater than 4.3-m diameter rather than about 1 m) ice-reinforced legs and bracing only below the water surface to reduce ice impact on bracing (Figure 35). Paulin (2008) indicates that jacket structures could be used in the Bering Sea under light first-year ice loads and water depths of less than 60 m. However, they are unsuitable in the Beaufort and Chukchi Seas with the large multiyear ice loads and multiyear ridges. Because jacket structures can be used in areas experiencing superstructure icing, such as the Bering Sea and Cook Inlet, Arctic designs without above-water bracing and with larger-diameter legs will lessen the accumulation of superstructure ice; there is less surface area, structure diameters are larger, and there is less opportunity for ice to bridge structural elements and lock to the structure.

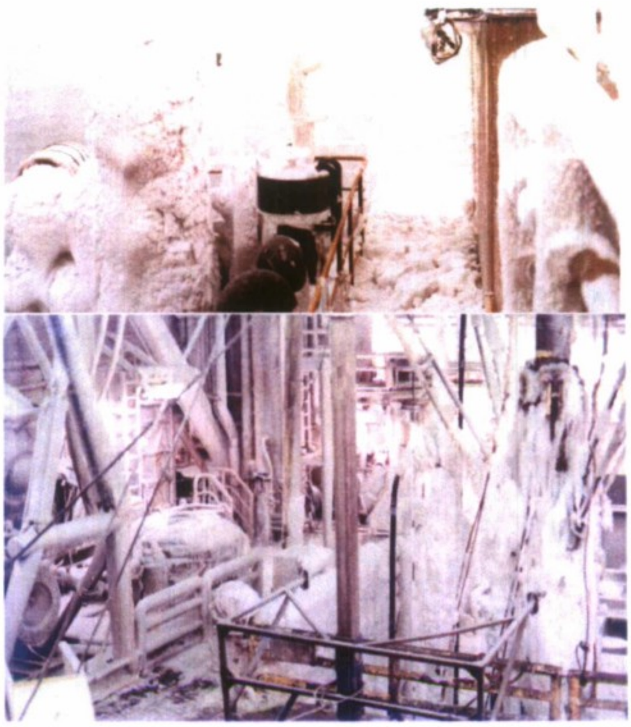

Figure 36. Ice accretion on smaller objects on the *Ocean Bounty*, with mechanical locking of ice around some objects (courtesy C. Miller, U.S. Department of Interior Minerals Management Service).

Structures of all Arctic designs, however, are generally complex topside of the main deck, and occasionally below the main deck. Superstructure ice can accumulate in significant quantities topside in strong storms. However, atmospheric icing such as snow, rime, frost, and freezing rain glaze accumulations can also accumulate. The presence of many small-diameter shapes such as cables, piping, and railings contribute to ice accumulation. Figure 36 illustrates how ice accumulates on smaller objects, and bridges and locks around objects making deicing more difficult. Overall, uncluttered design reduces icing challenges.

Many of the new platform designs also contain design elements that reduce the impact of cold on operations. These include covered walkways and covered work areas, including placement of sheathing over the derrick (Figure 30). 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 lattice structure, piping, wiring, and other small-diameter materials.

TRL: 6–7. Platform design is well-developed, and at least one example of many designs has been tested in Arctic conditions. Few platforms have been specifically designed to reduce superstructure icing because the most demanding design criteria are floating sea ice and wave loads.

Deicing or Anti-icing: Newer Arctic platform designs are, advertently or inadvertently, designed to potentially minimize superstructure icing with fewer above-water braces, large freeboard between the ocean surface and decks, and large-diameter legs or other supports. However, topside icing from spray and atmospheric sources can still be significant because of the complexity of the structure. Cleaner design with less surface area and fewer complex shapes reduces icing and makes its removal less challenging.

Current Advantages and Disadvantages: New generations of Arctic platforms are being designed to reduce ice and wave forces. These designs contain elements that may also reduce superstructure icing below the main deck. Covered work areas, walkways, stairs, and derricks that protect from the cold may also reduce snow and ice accretion above the main deck.

Current Acquisition Cost: Embedded within rig cost.

Operational Cost: Unknown.

Maintenance Requirements: Unknown.

Potential Marine Application and Safety Enhancement: Reduction in superstructure icing and atmospheric icing above the main deck will reduce the probability of rig loss and will improve safety conditions for personnel in work areas, under the derrick, and on stairs. However, safety gear may not be better protected, and the moon pool area may ice.

TRL: 5–6. Few, if any, elements of rigs are being designed to specifically alleviate superstructure and atmospheric icing except, perhaps, the Sevan FPSO (Figure 30). Reduction of superstructure and atmospheric icing is a consequence of design to survive floating sea ice and wave forces.

Marine Advantages and Disadvantages: See above—same as *Current Advantages and Disadvantages.*

Marine Technology Transfer Requirements: Evaluate design changes for alleviating effects of floating ice and wave forces for synergistic effects on superstructure and atmospheric ice accumulation. Assess design elements intended to alleviate cold effects for its ability to alleviate icing. Model superstructure and atmospheric icing of platforms.

8 Expulsive Deicing Systems

Expulsive deicing technologies have a long history (Wolverton 2009). However, they are now being accepted as deicing technologies that can be applied to a variety of icing problems. They have the potential to keep surfaces ice-free with little energy use when compared to heating surfaces to melt ice. Expulsive systems hold significant promise for the marine environment.

Electro-Impulse Deicing (EIDI)

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Intended or Actual Application: Innovative Dynamics Inc. (Innovative Dynamics Inc. 2007) has developed Electro-Impulsive Deicing (EIDI) systems in collaboration with the NASA Glenn Research Center and Lockheed 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 deicing 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 deicing and anti-icing systems must meet for certification (FAA 1991). 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 cold 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 sec^{-1} (Innovative Dynamics Inc. n.d.).

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 (Figures 37 and 38).

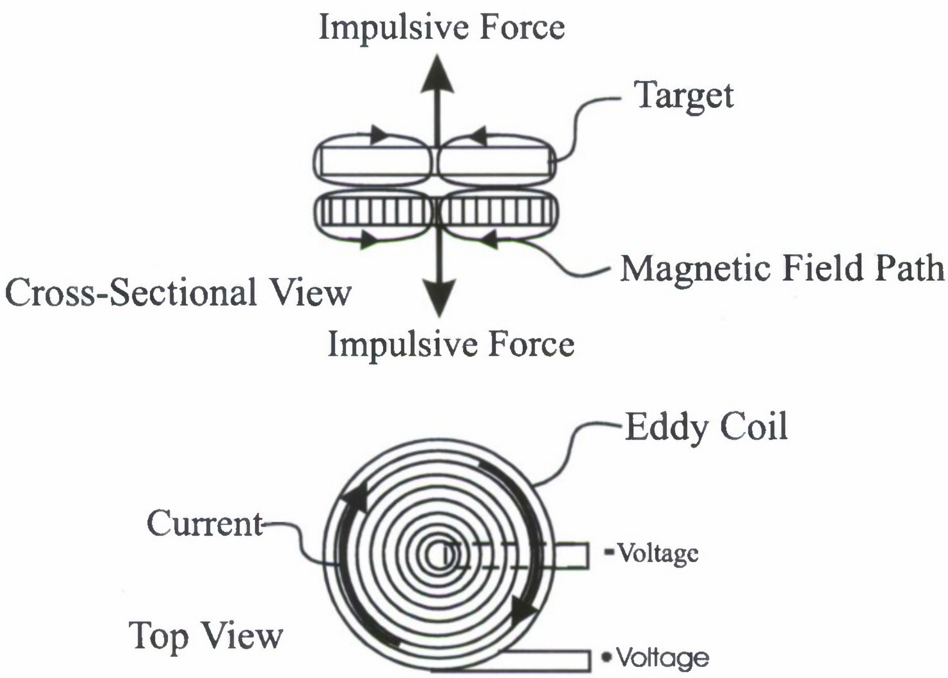

Figure 37. Diagram of EIDI coil. Coil is positioned in close proximity to target surface and discharged with high current impulse source. Magnetic field lines induce currents in target surface to cause rapid shock to pulverize surface ice accumulation (courtesy Innovative Dynamics Inc.).

Figure 38. Single actuator under 3.2-mm metal plate with 25-mm ice sheet (top). Actuator breaking ice sheet (bottom). (Images courtesy Innovative Dynamics Inc.)

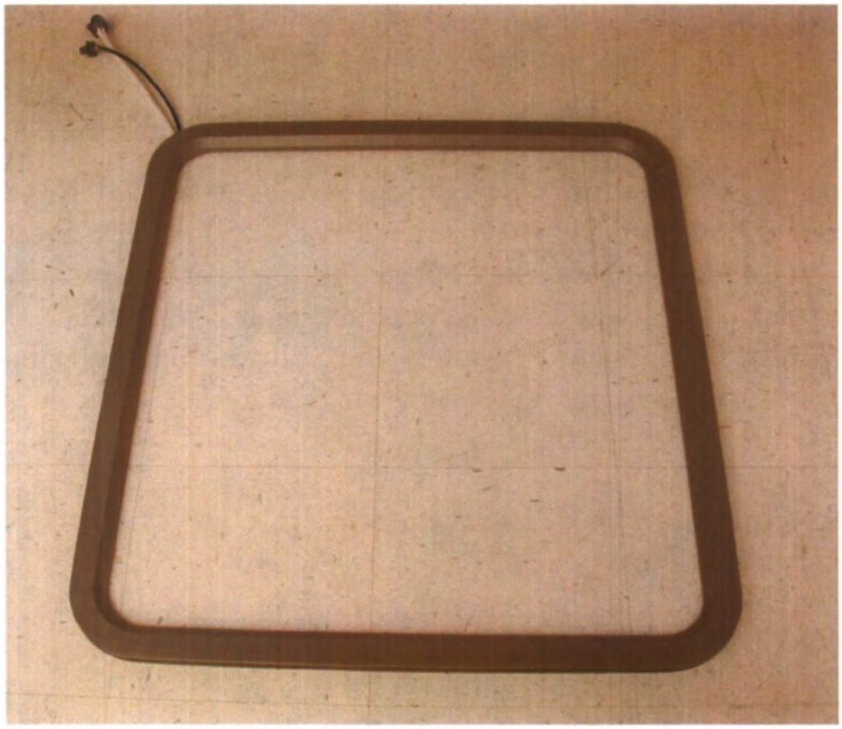

Figure 39. One-piece EIDI ship hatch deicer used to break ice accretion and allow hatch to be easily opened (courtesy Innovative Dynamics Inc.).

Figure 40. Multiple actuators integrated into a one-piece ship hatch deicer seal (courtesy Innovative Dynamics Inc.).

TRL: 8. System is currently available for aircraft.

Deicing or Anti-icing: Deicing.

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 deicing of bulkheads, potentially support structures under the main deck of a platform, and hatch covers (Figures 39 and 40).

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.

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Electro-Mechanical Expulsive Delcing System (EMEDS) with ElectroThermal Subsystems

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Intended or Actual Application: Cox & Company has developed a low-power deicing system that can be used with or without thermal electrical subsystems. Existing applications are used on aircraft where power availability is low and the need to keep airfoil leading edges ice-free is necessary. In its basic configuration, EMEDS is capable of removing ice accumulations to a relatively low thickness, nominally of the order 1.5 mm distributed over the surface to be protected. This level of protection is dependent upon the frequency of operation; the residual and intercycle ice may exceed this amount. In some cases, this is not sufficient to satisfy the aerodynamic requirements of the applications and EMEDS is then combined with electrothermal ice protection subsystems to provide the level of ice protection required.

The type of ElectroThermal Ice Protection System (ETIPS) to be used in combination with EMEDS is dependent upon the level of ice protection required, and may be either Anti- or De-Icing operational mode. The particular type of operation is dependent upon the requirements of the application.

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-only systems that use considerably greater power than does the EMEDS/ETIPS combination.

EMEDS cannot remove very low levels of ice accumulations such as frost or "sandpaper ice." In those instances for which it is necessary to provide a "clean surface," EMEDS can be combined with an anti-icing ETIPS. In this approach, electrothermal heater strips are located at or near the apex of the leading edge to prevent the formation of ice in this critical part of the airfoil—the anti-icing ETIPS prevents ice from accumulating in this area. Because the anti-icing ETIPS surfaces are maintained at low temperatures—only slightly above freezing—the system operates as a running-wet anti-icer and impinging water flows downstream where it freezes. The EMEDS technology is strategically located aft of the electrothermal system where water collects and freezes after running back from the heated parting strip area. The ice accumulations are subsequently removed by periodical operation of EMEDS. In this approach, the heated strip extends over the full length of the span and, as a result, it is important that the anti-icing ETIPS operate in a running-wet mode to reduce the power required. This system has been called the "Hybrid EMEDS Ice Protection System," and is shown in Figure 41 below. This system is described by Al-Khalil in his AIAA paper (Al-Khalil 2007).

Another version combines a deicing ETIPS with EMEDS (Figure 42). It uses less power than the hybrid system described above because the electrically heated area is a small fraction of that for the anti-icing hybrid described above. 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. In this configuration, the electrically powered heaters are divided spanwise and are powered in coordination with the EMEDS actuators that are located within the heated area. Ice is permitted to form for a limited time, and ice removal proceeds spanwise to perform clean ice removal. This system is called the Thermal Mechanical Expulsive Deicing System (TMEDS) (Al-Khalil 2007).

Operating Environment: The operating environment is the aircraft icing environment as defined by FAA Federal Aviation Regulation (FAR) 25 Appendix C (FAA 1991). In FAR 25 Appendix C, cloud water contents range from approximately 0.2 g m^{-3} to 3.0 g m^{-3}. Mean effective drop diameters range from about 15 to 50 µm, and temperatures range from 0°C to -30°C. Although 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 operate on the leading edges of fixed-wing aircraft.

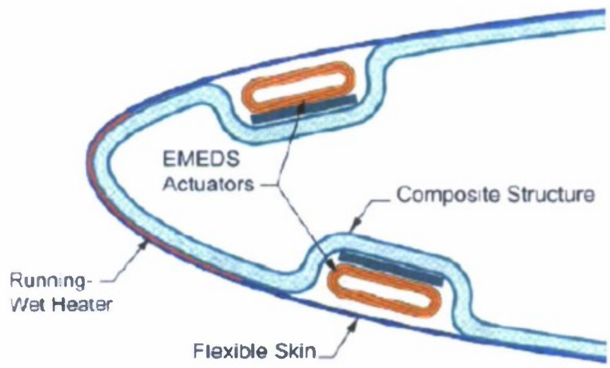

Figure 41. EMEDS/run-wet hybrid anti-icing ETIPS. EMEDS is the Electro-Magnetic Expulsion Deicing System component (courtesy Cox & Company Inc.).

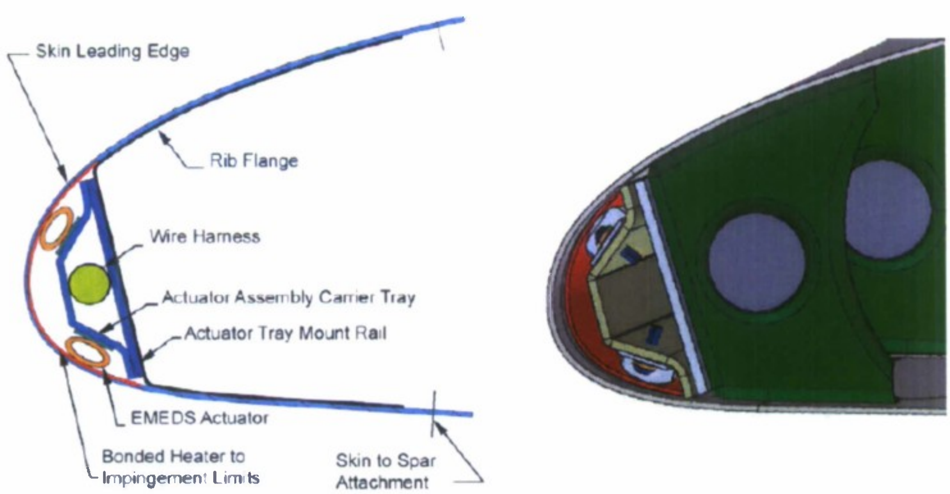

Figure 42. EMEDS/ETIPS deicing TMEDS configuration in an airfoil (courtesy Cox & Company Inc.).

Engineering Concept: The primary concept is to combine either an anti-icing or deicing technology with a primary low-power deicing technology (EMEDS) and to coordinate their operation to achieve relative degrees of ice protection and surface condition as permitted or required by the particular application.

EMEDS

A critical component of EMEDS is the actuator (Figure 43). A high-voltage, but very short, electrical charge is released from an Energy Storage Bank, which is essentially a bank of capacitors. A 1-µs duration high-current electrical pulse delivered to the actuators in carefully controlled timed sequences generates opposing electromagnetic 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 0.005 sec. Ice as thin as 1.5-mm thick can be shed. The EMEDS has been demonstrated on 0.40-mm-thick stainless steel skins and on aluminum skins 1.0-mm thick or thinner (Figure 41).

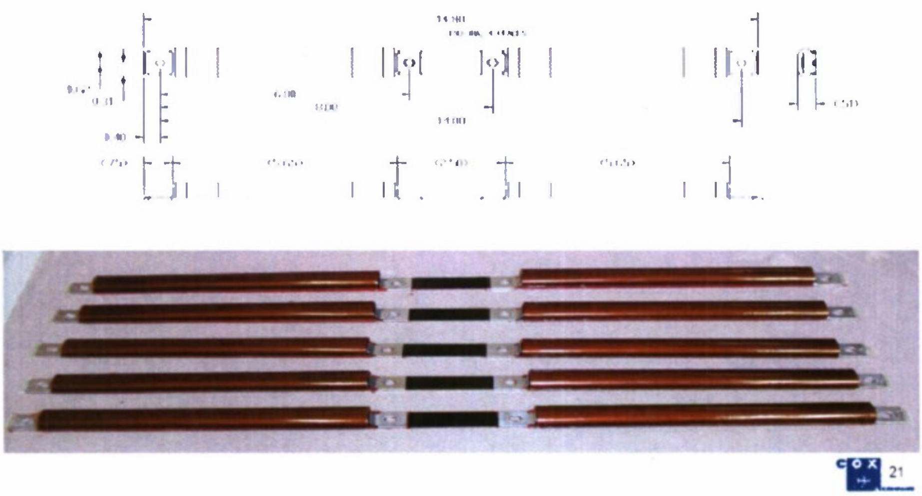

Figure 43. EMEDS actuator in TMEDS (courtesy Cox & Company Inc.).

EMEDS/Anti-icing ETIPS

The EMEDS/Anti-icing combination is designed to keep the leading edge free of ice to reduce aerodynamic effects caused by surface roughness and then to remove ice that forms from the water that runs back onto the downstream unheated surface and accumulates until removed by the EMEDS as shown in Figure 41.

The run-wet anti-icing heater prevents ice from accumulating on the ice impingement region of the leading edge, while permitting run-back ice to 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, typically 1.3 mm or less.

EMEDS/Deicing ETIPS

As opposed to the previous case in which the leading edge is continuously heated, this approach subdivides the span into segments that include both ETIPS heaters and EMEDS actuators (Figure 42). 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. The run-wet system is always heated in the roughness-sensitive zone. In this configuration, ice is permitted to accumulate to within acceptable limits, and is removed periodically. The use of heat to reduce bond strength increases the effectiveness of the expulsive system and causes more complete deicing. 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 (Al-Khalil 2007).

TRL: 5–6. Both EMEDS and EMEDS/Anti-icing ETIPS "Hybrid" are currently in production and service on aircraft certified by the FAA and other authorities for Flight into Known Icing. The EMEDS/Deicing ETIPS has been tested in a wing at full scale in an icing wind tunnel.

Deicing or Anti-icing: As determined by requirements of the application. EMEDS is primarily deicing.

Current Advantages and Disadvantages: 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 side of the surface skin. Therefore, it is not readily retrofitted, but it is easily built into airfoils at the initial phase of aircraft design. 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.

Current Acquisition Cost: Competitive. 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 platforms and supply boats. The system may not be usable on complex surfaces or walkways, but could be useful on bulkheads and hatches and possibly below the main deck to protect support structures near the sea.

Marine Advantages and Disadvantages: The system would allow efficient deicing 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 TRL: 4.

Marine Technology Transfer Requirements: 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.

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Electroexpulsive Deicing System (EEDS)

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Intended or Actual Application: The Ice Management Systems (IMS) electroexpulsive deicing system (EEDS) technology was invented by NASA Ames (Haslim and Lee 1987) for deicing 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 deicing the walls of navigation locks on the Illinois River and was demonstrated at Lock 25 on the Mississippi River at Rock Island (Figure 44).

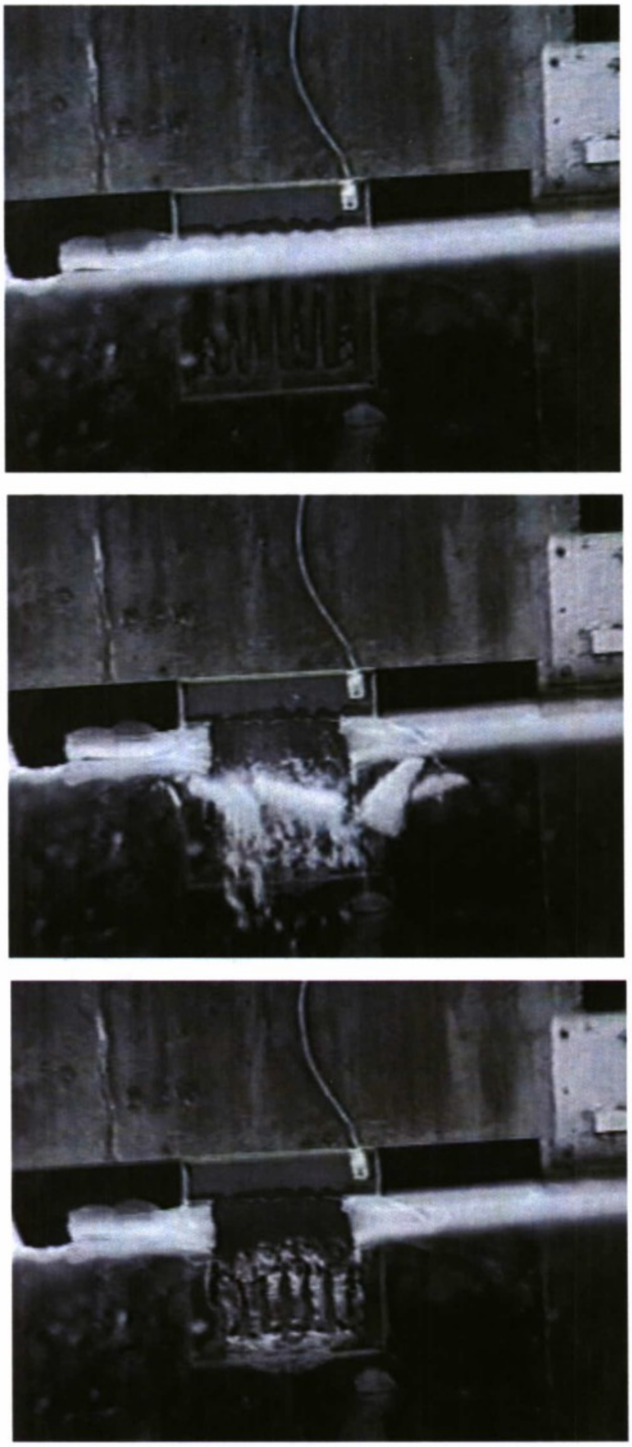

Figure 44. A nominal 1-m square EEDS on the Mississippi River lock wall removing collar ice with a single pulse (courtesy N. Mulherin 2008). Sequence is from top image before pulse, to middle image during the pulse, and bottom image after the pulse.

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 vehicles (UAVs). 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 in the wave wash area of an offshore platform. 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 electroexpulsive deicing systems 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 amps 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 sec 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 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. Voltages and amperages can vary based on the need. The system creates no electromagnetic interference (EMI) or radio frequency interference (RFI), 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 and have not failed. 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. Icephobic coatings have been placed experimentally on the cuff surface to assist ice release.

TRL: 8.

Deicing or Anti-Icing: The IMS EEDS principally deices and leaves 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 deice and anti-ice capability. The EEDS can be readily combined with icephobic 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 product is not COTS. As an example, the acquisition cost of designing and installing a system on a 10-m wingspan aircraft is about \$50,000–\$75,000 depending upon required features. 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 W RMS (IMS 2007). Power consumption is about 450 W 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-sec 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 in the superstructure ice accretion zones underneath the main deck of a platform. The EEDS could be placed on a subframe and wrapped around the platform legs. The technology could also be used on railings, hatch covers, and bulkheads. The system will form ice debris after firing, and will cause ice pieces to fly during firing, 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 the leg and support area of a platform below the main deck. 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 falls off the platform.

Marine TRL: 5.

Marine Advantages and Disadvantages: No problems in saline environment; EEDS should operate successfully, even on handrails and tight radii. Effects of soft marine sea ice on deicing needs to be tested. The system could work in wave wash areas near a rig base. 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 deiced, 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, and the adhesion strength of saline ice and its variation with age, temperature, and salinity. Electronics should be placed in waterproof boxes.

9 Heat

There are two ways to prevent icing; prevent water from striking the surface or warm the surface above 0°C so that water cannot freeze. Heat is the most common defense against icing, but it is often the most costly. And, the application of heat can have unintended undesirable consequences such as runoff of meltwater from heated areas to unheated areas where it refreezes. Considerable innovation has improved the efficiency of heating technologies. This section presents many of these new, innovative technologies.

Chinook MHD humid air deicing

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http://www.chinookmhd.com/products.html

Intended or Actual Application: Chinook Mobile Heating and Deicing Corporation (Chinook MHD) has developed a technology that delivers warm, humid air to iced surfaces via a truck-mounted delivery head (Figure 45). The initial commercially developed application is for fixed-wing aircraft deicing. The technology has been demonstrated on a variety of aircraft types at Dorval Airport in Montreal in overnight settings with prototype equipment. A concept of operations (CONOPS) in the daily operational environment has been developed with a major commercial airline to allow deicing at the gate. A helicopter has been deiced in demonstration.

Figure 45. Chinook MHD delivery heads for wings (top) and engine inlets (bottom) (courtesy Chinook MHD).

Operating Environment: The Chinook MHD system is intended for use with any kind of ice, frost, or snow. It is designed for operation at commercial airports, initially on fixed-wing aircraft. The system has been demonstrated in winds up to 12 m sec^{-1}.

Engineering Concept: The Chinook MHD deices by delivering heat to snow, ice, or frost surfaces. Non-condensing warm to hot humid air is delivered to the surface through ducts and directed by a specially designed fabric delivery head. Humidification occurs in a vehicle that carries a heater, a humidification chamber, and a boom with the delivery head on the end. Figure 46, based on the saturation vapor pressure curve, indicates that humid air at any given air temperature and moisture content delivers many times more thermal energy to the ice or snow surface than does hot air alone. Latent energy is provided to the air when it is humidified at the rate of approximately 2500 Joules per gram of water vaporized. That energy is then provided, through latent heat of condensation, to the snow or ice surface because the snow or ice is colder than the saturation vapor pressure of the air. As a result, water is condensed on the snow or ice surface during the process, and the large amount of latent energy released during condensation rapidly melts the ice and snow without causing a large temperature rise—important for temperature-sensitive aircraft components.

Deicing occurs by placing a delivery head over or in front of the surface to be deiced. The delivery head inflates as warm, moist air is pumped into it, and, in some applications, a circumferential skirt is used to contain and direct the humid air and heat to the iced surface. Moist air, at a temperature of 40°C to 85°C, exits holes in the delivery head fabric and heats the snow or ice surface. Moisture content provided to the delivered air is a function of the amount of melting required. After deicing, the surface is dried by sending only warm dry air through the delivery head. For frost removal, moisture content may be reduced to very low levels.

Deicing times vary with air temperature and wind speed. In demonstrations on aircraft wings, frost required 2–3 min to deice and dry, 1.6–2 mm of ice required 5–8 min to deice and dry, and 2–4 cm of snow required 14 min.

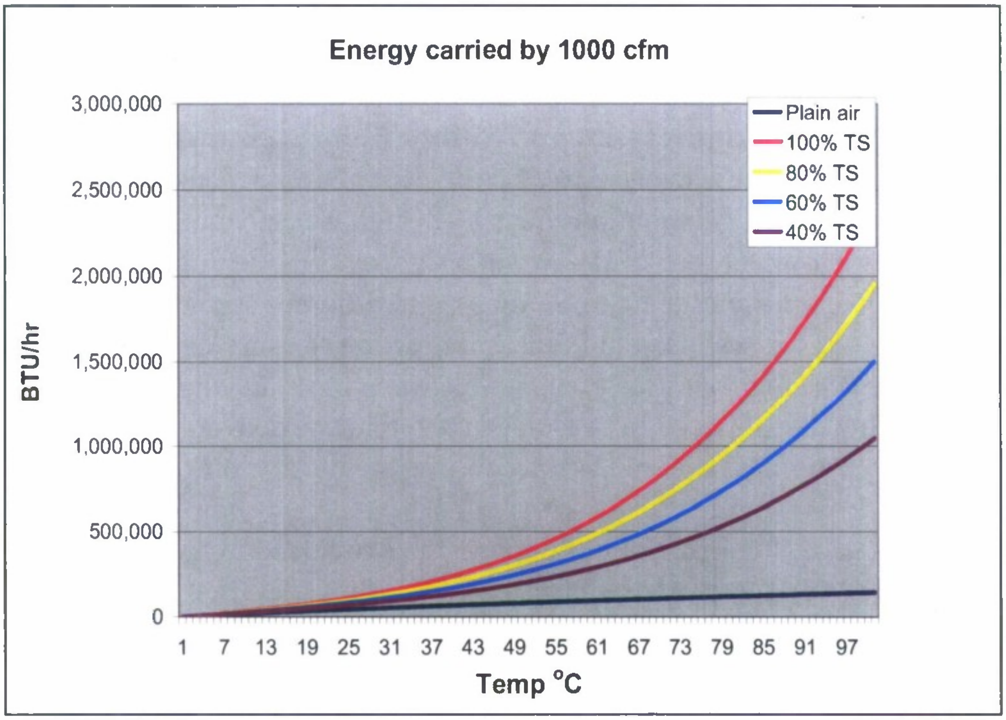

Figure 46. Heat available for deicing at given temperatures at differing relative humidities (courtesy Chinook MHD).

TRL: 7–8. The system will be used operationally during the 2008–2009 winter deicing season.

Deicing or Anti-icing: Deicing.

Current Advantages and Disadvantages: The system melts snow and ice rapidly and dries the surface. There is no risk of overheating surfaces because surfaces do not warm above the delivered air temperature. The delivery head is lightweight and can be made to conform to many surface shapes, such as bulkheads and air intakes. Water does fall below the melting surface and can refreeze. A boom truck maneuvers the delivery head, and it is subject to high wind forces. The system does not require deicing fluids that present a costly cleanup and pollution hazard.

Current Acquisition Cost: The Chinook MHD system cost is expected to be comparable to the cost of a high-end deicing fluid application truck.

Operational Cost: System operation is less expensive than deicing fluid; costs are for fuel, water, and different delivery heads for different applications, such as wings versus engine inlets.

Maintenance Requirements: Airflow, heating, and vaporization mechanicals require maintenance.

Potential Marine Application and Safety Enhancement: The Chinook MHD system could be used to deice decks, walkways, bulkheads, air intakes, windlasses, helicopter landing pads, windows, and smaller safety-related items. However, the system would require portability and it would require a delivery head that could be adapted to different applications. It is unclear whether the system could function near the sea surface because it would experience higher winds and possible wave wash. Furthermore, surfaces requiring deicing need to be shaped such that the delivery head and skirts could encompass the iced surface during the deicing process.

Marine TRL: 4. No testing or development has occurred in the marine environment.

Marine Advantages and Disadvantages: Portability and a system to deliver the large volumes of warm, moist air is necessary. The system involves no coatings or chemistry that must be reapplied or captured. No significant modifications to platform surfaces would be necessary. The system is COTS for aircraft, but requires testing and development for offshore platforms. The system would need to be deployed to critical platform areas. It is unclear how the technology would be applied to supply boats.

Marine Technology Transfer Requirements: Evaluate the technology in the crowded, somewhat cluttered environment of an offshore platform. Experiment with control of delivery head location from a crane. Evaluate effects of wind on system control. Determine if the technology can be applied between the main deck and the ocean surface to remove superstructure ice.

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Rockwell Collins Buddy Start Deicing Nozzle

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Intended or Actual Application: The Buddy Start deicing nozzle is a handheld unit that uses hot air at high velocity to blow snow off aircraft surfaces and to melt ice and snow from aircraft surfaces. The nozzle can be connected by a hose to an Airstart ground support unit that supplies compressed air to start turbine engines, or from an aircraft auxiliary power unit (APU). The nozzle is used for deicing wings and rotor blades, to cool braking surfaces, and to deice any other objects near aircraft. The nozzle is compact, lightweight, and inexpensive (Figure 47).

Figure 47. Buddy Start deicing nozzle. Hose attaches to far end. Operator guides nozzle with foreground handle and controls air volume with rear handle (courtesy Rockwell Collins ElectroMechanical Systems).

Operating Environment: The Buddy Start deicing nozzle is a handheld unit that can be used in any environment where a high-velocity source of hot air is available, though the intended environments are aircraft service areas at airports and aircraft in expeditionary environments with minimal ground support. It can be used with snow or any type of ice in wet or dry conditions and at any temperature.

Engineering Concept: The Buddy Start nozzle is an approximately 0.5-m-long handheld aluminum nozzle with a top-mounted handle that operates a ball valve to control airflow, and a handle near the 6.4-cm-diameter nozzle exit for directional control. The nozzle controls the velocity and direction of airflow. The ability to remove snow and ice is a function of air velocity, air temperature, and the operator's skill. For example, Ryerson et al. (1999) found that directing the nozzle at a low angle with the surface allowed air to penetrate under ice edges and lift it from the surface.

Air temperature and velocity exiting the nozzle is a function of the air source capability, the length of supply hose, and the ambient air temperature. Ryerson et al. (1999) found temperature, depending upon the hot air source, can be high enough to possibly overheat composite surfaces. However, air temperature and velocity decreases rapidly with nozzle distances from surfaces. For example, in one test at a distance of 0.4 m, air temperature was about 133°C and decreased to about 100°C at 0.6 m (Ryerson et al. 1999).

Curry (1998) conducted a series of tests with prototypes of the Buddy Start deicing nozzle at Cairns Airfield in Alabama, and in the Eglin Air Force Base McKinley Climate Chamber under conditions representative of winter. In 10°C air temperatures and winds of 6.5 m sec^{-1}, temperatures at the nozzle mouth ranged from 104°C to 188°C; at a distance of 61 cm from the nozzle, air temperatures ranged from 62°C to 104°C. Curry (1998) also found that the nozzle could be difficult to use in slippery conditions because of the force of air exiting the nozzle, operating the nozzle was fatiguing, and the nozzle was best operated with one person controlling the nozzle, a second controlling the air source, and a safety officer. Operators were rotated after approximately 15 min of operation during the tests due to fatigue. Curry (1998) also observed that ice was most efficiently removed when the operator used the hot air to loosen the ice so that it could be removed in pieces rather than melted.

TRL: 9. Commercial off-the-shelf.

Deicing or Anti-icing: Deicing only.

Current Advantages and Disadvantages: The Buddy Start deicing nozzle is an inexpensive COTS product that is robust and requires little training. It can be used to deice complex, heat-resistant surfaces if a high-volume hot air source is available. However, high temperatures, which are not a function of the nozzle but of the air source, can cause damage to materials if the system is not used with caution. For example, operators tend to operate the nozzle close to surfaces to hasten ice melting, which also allows potential heat damage to substrates. In addition, high air velocities can be hazardous to personnel operating on slippery surfaces, and to both personnel and equipment due to lofted ice particles.

Current Acquisition Cost: ~$3500 (quantity of less than 10).

Operational Cost: Function of cost of operating air source and cost of personnel. The system requires manual operation.

Maintenance Requirements: Maintain hose and hose-to-nozzle connection integrity.

Potential Marine Application and Safety Enhancement: The Buddy Start deicing nozzle could be used to advantage on offshore platforms and supply boats for deicing small areas and complex surfaces that are not sensitive to overheating. A high-volume, high-velocity hot air supply would be necessary with sufficient hose to reach objects. Army tests by Curry (1998) used hose up to 37-m long. If they are accessible, objects such as antennas, firefighting equipment, valves, windlasses, air intakes, stairs, and life rafts would be practical to deice with the Buddy Start nozzle. The nozzle could provide a significant personnel safety enhancement with regard to deicing these small but critical areas.

Marine TRL: 7.

Marine Advantages and Disadvantages: The Buddy Start deicing nozzle is relatively immune to damage from saltwater, cold, and the marine environment, in general, being constructed largely of aluminum. It is inexpensive, requires minimal training, and can be used to deice complex shapes. However, heat-sensitive surfaces should be avoided, surfaces requiring deicing must be accessible by personnel, and personnel are exposed to weather conditions when deicing.

Marine Technology Transfer Requirements: None except for a provision for a high-volume, high-velocity hot air supply at required locations on offshore platforms and supply boats, and proper training.

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QFoil

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Intended or Actual Application: QFoil is a electrothermal 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 the blades of wind turbines, automobile mirror heaters, food service warming trays, and plastics welding. It has potential application to a variety of icing environments.

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) (e.g., sheet metal). QFoil may be supplied in sizes ranging from 6.4 cm^2 to 3 m^2 (1.2-by-2.4 m) (EGC Enterprises 2008).

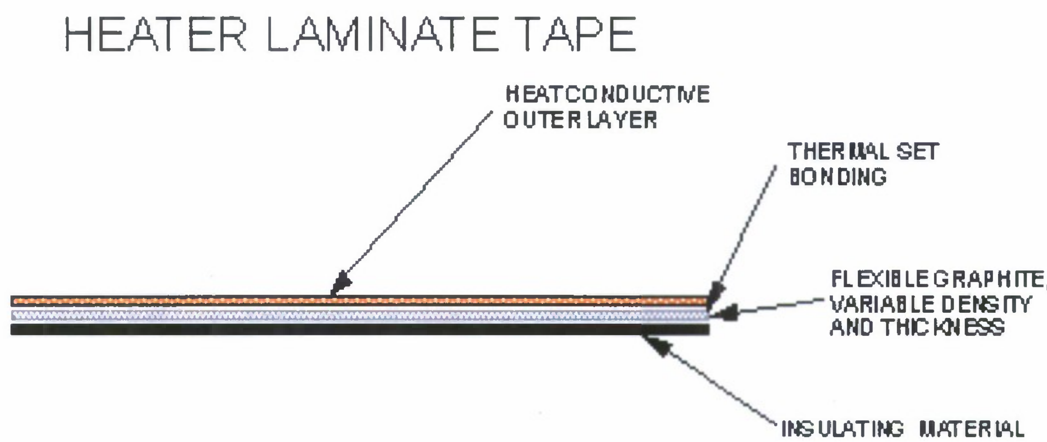

Figure 48. Components of QFoil laminate sandwich (courtesy EGC Enterprises Inc.).

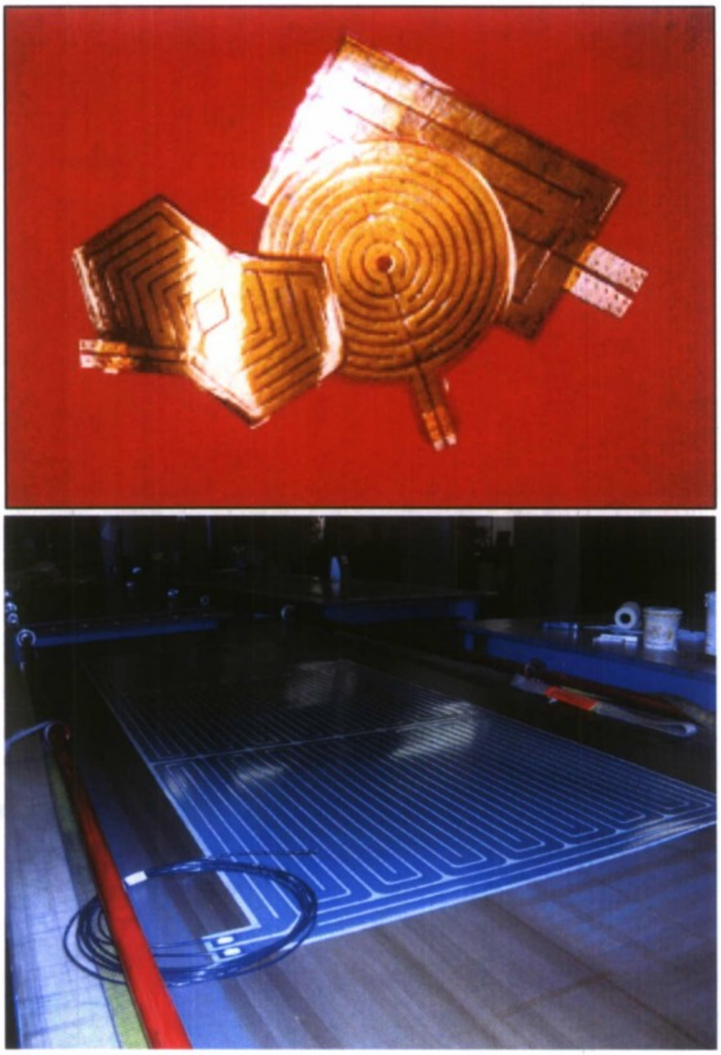

Figure 49. Small QFilm heater areas (top) and 0.6- by 1.8-m section (bottom), both showing serpentine heater conductors and electrical connections (courtesy EGC Enterprises Inc.).

Engineering Concept: QFoil heaters are thin, approximately 0.25-mm-thick laminate structures (Figure 48). 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 icephobic 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 sec^{-1}. 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 (EGC Enterprises 2008). QFoil is available with a peel-and-stick backing, or it can be applied to substrates with epoxy or RTV silicone.

TRL: 7–8. QFoil is COTS. However, each heater is custom manufactured to user requirements.

Deicing or Anti-icing: Deice 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 be applied to 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 49 each cost between \$270 and \$465 depending upon quantity ordered.

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 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 drilling platform surfaces is needed. QFoil should be tested in a marine icing environment to determine effects of wave and heavy spray impacts.

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ThermaWing—Kelly Aerospace Thermal Systems

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Intended or Actual Application: ThermaWing is a graphite-based thermoelectric heater that protects the leading edge of airfoils. The system's laminated geometry is designed specifically for aircraft wings and propellers. In that configuration it provides more heat on the leading edge than areas aft of the leading edge. It is currently designed for specific airframes such as the Cessna 350 and 400 and the Lancair IV kit plane. On aircraft the system anti-ices the stagnation zone, a narrow parting strip area on the leading edge of the airfoil, and deices other areas of the leading edge by periodically and rapidly heating; this causes melt only at the ice-heater interface. The loosened ice, which is not allowed to grow thick, is carried away by the slip stream, minimizing water runback on unprotected areas of the wing.

Figure 50. ThermaWing being applied to an airfoil leading edge (courtesy Kelly Aerospace Thermal Systems).

Operating Environment: ThermaWing is designed to operate on the leading edges of aircraft flight surfaces and propellers in rime ice and clear ice. It also has been tested on engine inlets, and is being considered for deicing wind turbine blades. The heater components are flexible graphite sheets bonded to surfaces that ice (Figure 50). The heater surface is covered with a polymer for low-speed applications, and is covered with a metal shield for speeds greater than 150 m sec^{-1}. The propeller version of ThermaWing also operates on the blade leading edge—an abrasive environment with high radial forces. The system anti-ices the parting strip on the most forward portion of the airfoil, and deices areas farther aft in rime and clear ice conditions at aircraft speeds and at temperatures found in 14 USC 25 Appendix C (FAA FAR25 Appendix C). The system relies upon slip stream airflow to carry away ice that has been debonded by the rapid heating process.

Engineering Concept: ThermaWing is an electrothermal deicing system that differs dramatically in design from traditional aircraft electrothermal systems. Traditional electrothermal systems, such as those found on the Black Hawk helicopter blade leading edge, heat nichrome or similar wires embedded 2–3 mm under the leading edge wear strip. The ThermaWing system for low-speed surface applications is covered with a thin heat-conducting material called Tedlar. The heater is a flexible graphite foil that varies in thickness depending upon the watt density, or temperature, required at any location on the surface. Below the heater is an electrically insulating layer; the entire multilayer system is bonded to the exterior of any surface with an adhesive tape. Construction of high-speed ThermaWing heaters replaces the Tedlar with a protective metallic sheath.

Material physical properties of the graphite foil allow it to heat quickly for a near-instantaneous rise in temperature. Coupled with the thin, low-mass material, the heater-substrate interface heats rapidly, reduces the ice adhesive strength, and allows slip stream airflow to carry the ice away. Because only a thin layer of ice and heater material is heated, energy usage is low. The heater operates with 70 V (DC) on aircraft on some General Aviation aircraft or 200 VAC 3 phase on transport category aircraft.

ThermaWing uses a zoned heater controlled by a processor. The wing leading edge is kept warm, continually melts ice, and "runs wet." Aft of the leading edge is a shedding zone that is kept below freezing, causing water that runs back from the leading edge to freeze and collect as ice. During deicing, the temperature of the aft shedding zone is increased, releasing the ice bond and shedding the ice. When power is removed from the heater the shedding areas again freeze and collect ice until the next deice cycle. System operation can be as short as a few seconds to deice any one heater segment or about one minute to deice an entire single engine aircraft. The system is self-healing if damaged.

TRL: 8. System must be tailored to the intended application.

Deicing or Anti-icing: Anti-icing along the parting strip, with deicing on the remaining heater surface.

Current Advantages and Disadvantages: System must be tailored to specific applications but is otherwise a COTS product. System is lightweight, relatively low in power consumption, and easily applied to aircraft surfaces. System successfully protects aircraft surfaces. System functions well with metal or composite substrates.

Current Acquisition Cost: Kelly Aerospace Thermal System's ThermaWing system for the Columbia 300/350/400 costs between $24,000 and $27,000, depending on the airplane's air conditioning unit (Burnside 2008).

Operational Cost: Unknown. Depends upon on required watt density, area of coverage, and deicing frequency.

Maintenance Requirements: Unknown.

Potential Marine Application and Safety Enhancement: ThermaWing components could be applied to flat and curved surfaces that are relatively smooth and oriented vertically or at a steep angle. A smooth, steep surface will allow ice to slide off the heater when the ice bond is decreased. Surfaces that could be deiced are areas below the main deck on the support structure if mechanical elements are smooth and simple in shape. Bulkheads and other vertically oriented smooth surfaces could be deiced.

Marine TRL: 6. A prototype system exists but would require testing in the marine environment.

Marine Advantages and Disadvantages: System relies upon air flow or gravity to remove ice in its most energy-efficient mode because the heater only decreases ice adhesive bond strength sufficient for it to fall away from the substrate. The potential for electrical shock must be addressed for saline environments, especially if punctured. The effect of mechanical impacts is unknown. The system cannot be used easily on complex surfaces.

Marine Technology Transfer Requirements: Evaluate the system in a marine environment on both a platform and a supply boat. Evaluate capability in high-spray, wave-washed zones. Assess ease of damage and electrical protection. Assess need to change methods of attaching ThermaWing material to platform and boat superstructures. Assess potential for helicopter ice protection.

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Low-Power Electrothermal Deicing (LPED)

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Intended or Actual Application: The Goodrich Low-Power Electrothermal Deicing (LPED) system was developed to reduce power consumption below that of the typical electrothermal system by 20% to 90%. The primary application for this system is on critical aircraft surfaces that are exposed to icing conditions in flight. LPED incorporates a pulsed deicing concept jointly developed with Victor Petrenko of Dartmouth College (Petrenko 2005).

Operating Environment: LPED is designed to minimize power requirements for electrothermal (electrical) ice protection systems. The operating environment for application and certification on aircraft is defined by FAA FAR Part 25 Appendix C. However, LPED is also applicable for icing conditions that exceed this environment.

Engineering Concept: LPED uses electrical heating elements attached to or installed within a structure requiring ice protection (Figure 51).

LPED is primarily a deicing system, i.e., some ice is allowed to accumulate on the surface of the structure being protected. The reason for this is that ice is an extremely good thermal insulator. For the aircraft application, in-flight thermal losses are very high. The ice layer greatly reduces thermal losses at the structure/ice interface. Short pulses of high intensity heat applied at this interface rapidly melts a thin layer and the ice is quickly removed. Electrical power is cycled to individual heating elements in rapid succession. Thus, deicing of an entire structure can be accomplished quickly. For the aircraft application it has been shown to effectively remove frost as well as thick ice.

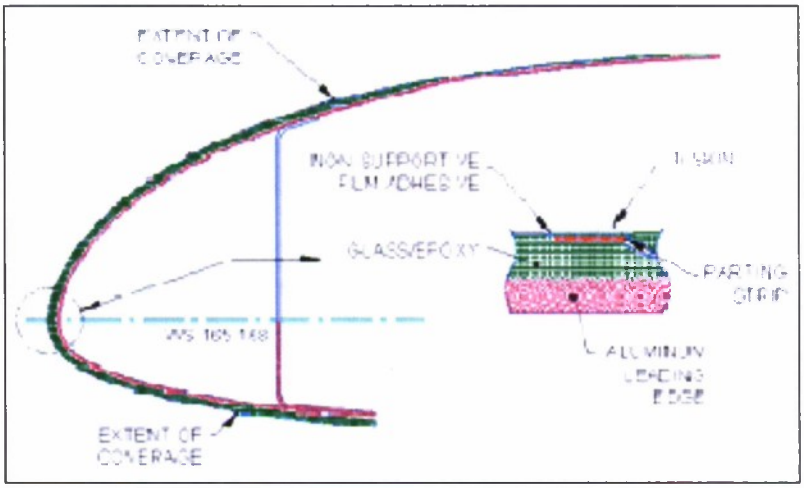

Figure 51. Typical LPED heater cross-section (courtesy Goodrich Corporation).

Figure 51 above shows one configuration of LPED integrated into a wing leading edge structure that was successfully tested within the Goodrich Icing Wind Tunnel and in flight on a twin engine business aircraft. A run-wet anti-icing titanium parting strip heater 1.6-cm wide by 0.14-mm thick is located at the stagnation region of the airfoil. This parting strip breaks ice caps that may form over the leading edge, allowing the slip stream to reach the edge of ice farther aft on the leading edge. Adjacent to and parallel to the leading edge, strips of heaters are periodically energized with short intense pulses of power in an anti-ice mode to cause melt at the ice-heater interface, allowing the slip stream to remove the accumulated ice. Extremely thin layers of ice can be removed in this manner with low power consumption. The anti-ice parting strip is pulsed at a constant power density, but with an on-time varying as a function of air temperature. The deice strips are pulsed every 3 min for a duration of 1.4 sec. Energy pulses are supplied through a controller with banks of ultra-capacitors.

The system has been tested on a 1.7-m-long full wing section in the Goodrich icing wind tunnel. Power requirements varied from 1926 W at temperatures between -20°C and -12°C to 1394 W at temperatures warmer than -7°C. Wraparound coverage was 30.3 cm. The system was also installed and flight tested on the wings of a General Aviation aircraft. The heater fully protected the outboard half of each wing using less continuous power than a handheld hair dryer. The system performed very well, removing thin and thick ice accretions.

TRL: 6. The LPED system has been successfully tested in flight on a General Aviation aircraft. It will require some modification for application to marine vessels or offshore oil platforms. However, continuous power drawn from the electrical system is greatly reduced as compared with conventional electrothermal heaters.

Deicing or Anti-icing: Deicing is the preferred method so as to minimize electrical power requirements. The aircraft wing application requires use of a parting strip anti-icer because aerodynamic forces (wind stream) tend to hold the ice cap in place even if the ice/surface bond has been destroyed. Lower wind speeds and positive effects of gravity for marine applications should negate the need for use of anti-icing strips in most applications. However, thin anti-icing strips are often used on the periphery edges of heaters to prevent ice bridging over from unheated structures.

Current Advantages and Disadvantages: The system was originally designed and tested specifically for aircraft application; but it is believed that it can be readily adapted for other (marine and oil rig) applications. Reduction in continuous power draw (amperage) versus a conventional plug-in heater (operating directly off the electrical system) is a distinct advantage.

Current Acquisition Cost: Estimate $300 to $3000 per square meter depending on the complexity of the structure, number of heaters, sophistication of switching gear, etc.

Operational Cost: Average power consumption is less than 0.23 W/cm^2 at -20°C.

Maintenance Requirements: Periodically replace damaged heaters, switching gear and storage banks (capacitors). It is suggested that switching gear and storage banks be installed in areas protected from external environments (salt spray, etc).

Potential Marine Application and Safety Enhancement: The LPED could be applied to flat and curved surfaces oriented vertically or at a steep angle. A smooth, steep surface will allow ice to slide off the heater when the ice bond is decreased because there will be no slip stream to carry shed ice particles away. Areas below the main deck on the support structure could be deiced if the system could be electrically isolated from water. Bulkheads and other vertically oriented smooth surfaces could be deiced. Periodically replace damaged heaters, switching gear and storage banks (capacitors). It is suggested that switching gear and storage banks be installed in areas protected from external environments (salt spray, etc).

Marine TRL: 4. The system can be adapted to marine applications and would require testing in the relevant environment.

Marine Advantages and Disadvantages: The LPED system has been specifically designed for aircraft application. However, it is believed that it could be adapted for marine applications. The heater element and electrical controls can be readily isolated from saline environments and personnel. It is not recommended for use in areas where floating sea ice can regularly impact the heater. The system can effectively reduce the ice bond; gravity or other mechanical forces will remove the ice from the heater surface. Falling ice may accumulate at the base of bulkheads and other objects.

Marine Technology Transfer Requirements: The system should be evaluated in a marine environment for electrical isolation, cost of application, and operation over large areas.

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Pulse electrothermal deicing

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Intended or Actual Application: Ice Engineering LCC has developed a new electrothermal deicing concept that saves energy and could be applied to deicing airfoils, ships, offshore structures, towers, buildings, road signs, windows, and other structures (Petrenko et al. 2003). The technology has been successfully demonstrated on windows, and has been tested on facsimiles of structure walls. The technology reduces the bond of ice to the substrate, and then utilizes gravity, air flow over the ice, or centrifugal force in the cases of rotating objects, such as helicopter and wind turbine blades, to cause ice removal.

Operating Environment: Pulse electrothermal deicing has the potential to operate successfully in most icing environments. The technology requires that a thin-film heater be placed directly on the surface that accretes ice rather than several millimeters or more under the ice accretion surface as with other electrothermal technologies. This requires that electrical currents be kept small enough so that they present no hazard to personnel or to equipment, or that a dielectric material with a high thermal conductivity electrically isolate the heater conductors from the ice surface.

Engineering Concept: The pulse electrothermal technique differs from other electrothermal deicing techniques in two ways. The technique operates with a thin-film heater located on the surface being iced, and provides a short, high-power pulse of electricity to the heater to cause deicing. By applying a high-power pulse of a few seconds duration or less, the heater heats with sufficient speed to produce a water film about 2-μm thick at the heater-ice interface (Petrenko et al. 2003). This water film thickness reduces the ice adhesion strength enough so that it can be easily removed. The speed of heating also reduces the heating of the ice or the substrate under the heater. This is because the ice is loosened and the heater is turned off before thermal conductivity can cause loss of much heat into the materials. Only enough energy is used to supply the needs of latent heat to melt the approximately 2-μm ice thickness, and minimal heat is lost for unneeded heating. This makes the pulse method considerably more efficient than traditional electrothermal methods. Petrenko et al. (2003) indicate that this efficiency is enhanced by increasing the heating power density and decreasing the heater energized pulse time.

TRL: 6. System has been tested in a high-fidelity environment.

Deicing or Anti-icing: Deicing.

Current Advantages and Disadvantages: The system must be tailored to specific applications—it is not a COTS product. The concept is low in power consumption and has been integrated into products by other companies. The concept can protect many surfaces, including windows if they are coated with a transparent conductor such as tin oxide. High thermal conductivity dielectric material must be placed over the heater if it requires electrical current isolation.

Current Acquisition Cost: Unknown—each application is unique.

Operational Cost: Unknown. Depends upon on watt density, area of coverage, and deicing frequency.

Maintenance Requirements: Unknown.

Potential Marine Application and Safety Enhancement: Pulse electrothermal deicing could be applied to surfaces oriented vertically or at a steep angle. A smooth, steep surface will allow ice to slide off the heater when the ice bond is decreased because there will be no slip stream to carry shed ice particles away, but ice would fall in walkways or work areas below and would require removal. Areas below the main deck on the support structure could be deiced if the system were electrically isolated from water. The system may not be suitable for surfaces where contact could be made by personnel, or where industrial activity could cause damage.

Marine TRL: 5. A prototype system exists but would require testing in the marine environment.

Marine Advantages and Disadvantages: The concept relies upon gravity to remove ice because the heater only decreases ice adhesive bond strength, but does not melt the ice completely. The potential for electrical shock must be addressed for saline environments. The system can be used to keep windows deiced.

Marine Technology Transfer Requirements: Evaluate the concept in a marine environment on both a platform and a supply boat. Assess ease of damage and electrical protection. Design robust hardware and test for extended time period.

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10 High-Velocity Water, Air, Steam

Steam lances have been used and recommended, but rarely tested formally, for marine icing applications. And, because steam is now a less common source of propulsion at sea than in the past, the ready availability of steam is diminishing. High-velocity steam and water have been formally tested for deicing navigation lock walls where ice forms large collars in the fluctuating waterline area, narrows the lock, and prevents gates from fully opening. High-velocity low-pressure air jets have recently become available for rapidly removing snow from aircraft and reducing the use of expensive and environmentally threatening deicing fluid. Though not discussed here, there have been occasional tests using turbine engine exhaust to remove snow from surfaces in military environments. Variations of these technologies may be of value for deicing offshore structures.

High-velocity water and steam

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http://www.meritpump.com/Kobe_Pumps/kobe_pumps.html

Intended or Actual Application: High-velocity steam and water have long been used on ships and on locks and dams to remove ice and snow (U.S Navy 1989; Mackes 1989; Hanamoto 1977; Army Corps of Engineers 2006; Frankenstein and Tuthill 2002). At one time steam was readily available for tapping from Navy ship boilers and therefore was used for deicing of ships. High-velocity water and steam provide some thermal energy for melting ice, but the primary use of high-velocity water or steam is to cut large ice accretions into smaller pieces for easy mechanical removal.

Steam can also be used to melt smaller ice accretions. Rand et al. (1989) indicate that water and steam lances can be effective on ships, but moving equipment on deck can be cumbersome unless the lances are hooked to an integral piping system. They also indicate that simply flooding surfaces with seawater that is warmer than freezing can add sufficient energy to ice to allow its removal. This is analogous to the thermally limited accretion zone on icing ships described by Ryerson (2008).

Operating Environment: High-velocity water and steam can be used to clear snow or ice in any temperatures. However, operators must prevent freezing of condensate in steam lines and in lines feeding high-pressure water systems. In addition, water from melt, or excess water from high-pressure water cutting systems, can freeze if allowed to pool. Steam lances were used to create water wells at Camp Century, Greenland in the 1960s (Science News Letter 1960). These systems can be used on surfaces of any orientation, though there is danger of forcing steam or water into sensitive electronics or breaking windows and other delicate surfaces from mechanical or thermal shock.

Engineering Concept: CRREL (Hanamoto 1977) summarizes 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^{-1} (Hanamoto 1977). Experiments were conducted with jet patterns and showed that a coherent jet produces the best results; commercial cleaning jets are not optimal. Experimenters found that temperature, wind direction, and wind speed were critical to success. High winds allowed water spray to blow back and refreeze onto the surface, and low temperatures slowed cutting. Cutting ice floating in water is slower than cutting dry ice because the water dissipates the spray jet energy. Low temperatures also hindered operations, with temperatures during experiments between -18°C and -29°C. Furthermore, low temperatures and a narrow kerf cut (0.5 to 1.0 cm) often allowed water to refreeze in the cut. In recent experiments in Japan, Takahashi et al. (2004) found that lower pressure (14 MPa) also cut ice at a 0.5-m standoff distance, but that performance improved if the ice was accreted onto a flexible rubber surface rather than steel or concrete. They also experimented with the effects of nozzle angle to the ice surface and cutting efficiency. Overall, water pressure cutting of ice is viewed as a viable method of removing large masses of ice from lock walls. Use of high water pressure ice removal methods on ships or offshore platforms is unknown.

Bojun and Si (1990) describe experiments using a steam lance to cut ice. A small boiler with a superheater 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 $m^3 min^{-1}$. Energy use calculations indicate that the ice was not melted, but was eroded by the steam jet. Energy use by cutting was only about 10% of that necessary to melt the same volume of ice. In addition, Howorka (1965) describes drilling 20-mm-diameter holes 8-m deep in glaciers using steam generated from a small boiler fired by butane lighter fuel cartridges.

TRL: 6. The technologies have been tested in relevant environments and are demonstrated as capable. They are not, however, COTS products dedicated to deicing.

Deicing or Anti-icing: Deicing.

Current Advantages and Disadvantages: Water jets can cut deeply into dry ice, but not deeply into ice floating in water because the water quickly disperses the energy of the jet. Water cutting of ice also produces a kerf of only 0.5- to 1-cm wide, which quickly freezes back. The reaction force of high-velocity water jet nozzles is often too great to be handheld, especially if the operator is on a slippery surface. In addition, the high pressure could damage delicate materials, such as glass and composites, harm personnel, and remove paint. 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. However, steam may potentially be very efficient in energy consumption.

Current Acquisition Cost: Unknown. Items must be fabricated, or commercial items adapted to deicing.

Operational Cost: Energy required to operate pumps and heaters.

Maintenance Requirements: Unknown.

Potential Marine Application and Safety Enhancement: High-velocity water jets and steam lances can be used wherever operators have access. These techniques can be used to deice superstructure icing below the main deck if access is available, and on decks, railings, bulkheads, helicopter landing pads, stairs, walkways and work areas, piping, and valves. High-velocity jets may not be safe to use on safety equipment such as fire equipment, sensors, antennas, and life rafts and boats—especially if the latter are of composite construction.

Marine TRL: 6. These technologies have been tested in freshwater ice environments and are demonstrated capable. Steam lances have also been tested on ships at sea. They are not, however, COTS products dedicated to deicing.

Marine Advantages and Disadvantages: In addition to above, these devices may be difficult to manage on slippery, crowded decks, narrow walkways, and close quarters. These technologies are closely related to manual methods because they must be operated by personnel in the icing environment.

Marine Technology Transfer Requirements: Develop designs applicable to offshore platform and shipboard operation. Determine if use onboard modern platforms and supply boats could cause damage to components intolerant of high-velocity water and steam.

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AirPlus! Forced Air Deicing System

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Figure 52. Air Force Global AirPlus! system. (Lower) Larger nozzle blows air or air and deicing fluid mist. (Upper) Smaller nozzle sprays deicing fluid at low velocity (Ryerson Image).

Intended or Actual Application: The Air Force has used high-pressure air from turbine engines 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 low-pressure air system used by the Air Force (Figure 52). Equipped with a boom-mounted cab and blower and 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 deicing mode because hazardous and costly glycol deicing 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 an adjoining nozzle (Figure 52) (Wyderski et al. 2003). Figure 53 shows snow being removed from helicopter surfaces during an experiment in the Eglin Air Force Base McKinley Climatic Chamber.

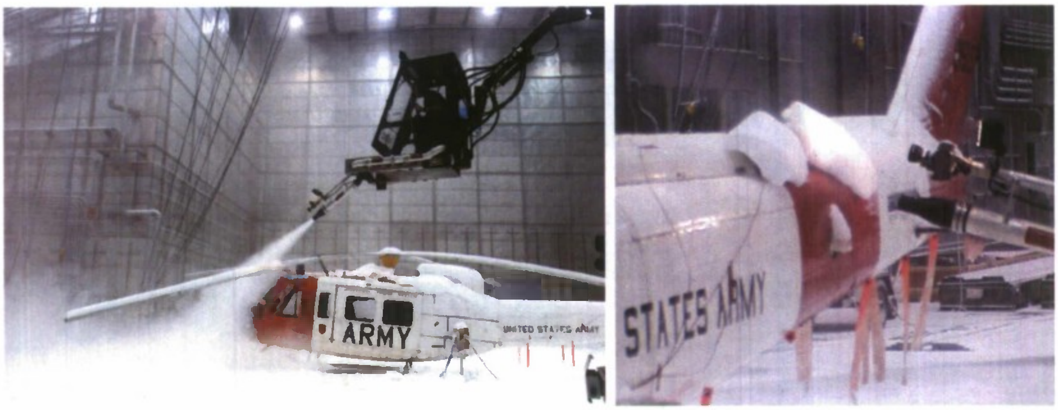

Figure 53. AirPlus! sprays air and deicing fluid mist on helicopter blades (left). Large pieces of 10-cm-thick snow are removed from fuselage by air alone (right) (Ryerson Images).

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 in any temperature, but may be compromised by high winds. Warm 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. Sound volume requires hearing protection that is incorporated into the required communication headsets. Although the system is truck mounted, it may be possible to place it on a smaller moving platform such as a boom-mounted open bucket.

Engineering Concept: A high-velocity air mode operating at a velocity of 313 m s^{-1} and a pressure of 53.7 kg m^{-2} removes loose snow and ice. Air alone is the preferred deicing mode because less glycol deicing fluid is 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. Recently, Global has developed a Tri-Barrel nozzle system to increase the fluid delivery options available to the operator. The operator now has the ability to use:

- AirPlus! – Air only
- AirPlus! + Fluid Injection – Hot Type 1 deicing fluid is injected into the air stream @ 6 gal/min (23 L min^{-1})
- AirPlus! + Fluid Injection + Low Flow – Hot Type 1 deicing fluid is injected into the air stream @ 6 gal/min (23 L min^{-1}) and Hot Type 1 @ 20 gal/min (76 L min^{-1}) is sprayed over the air stream
- AirPlus! + High Flow – Hot Type 1 deicing fluid @ 60 gal/min (227 L min^{-1}) sprayed over the air stream.

- Low Flow – Hot Type 1 @ 20 gal/min (76 L min^{-1})
- High Flow – Hot Type 1 @ 40 gal/min (151 L min^{-1})
- Anti-icing – Cold Type IV @ 25 gal/min (95 L min^{-1})

Several airlines have incorporated the AirPlus! system into their deicing and anti-icing procedures. One major cargo airline has demonstrated a 40% reduction in Type IV usage by applying Type IV over air. All Global AirPlus! deicers are delivered with this capability disabled, but require only slight modification to enable this option.

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 to move the air. The blower, located under the enclosed cab, 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 deicing 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 deicing fluid (25 L min^{-1}) 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 and Koenig 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 protection. 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 sec^{-1}. The forced air deicing system presented no significant hazards from ice and snow projectiles.

TRL: 8–9. Global AirPlus! is a COTS product.

Deicing or Anti-icing: Deicing and anti-icing.

Current Advantages and Disadvantages: The system is truck mounted. Two types of anti-collision systems are offered that prevent the operator from getting within 1.2 m of the surface being deiced. Hearing protection is necessary for all personnel working near the system. The system reduces deicing fluid use, especially in snow clearing conditions where fluid use is typically very high. The nozzle must be located within about 2 m of the surface to be effective. Use of fluid injection for frost is effective up to 10 m. Use of AirPlus! with low flow is effective up to 7 m. All of these ranges depend on type of contamination, wind speed, and angle of nozzle to surface being deiced.

Current Acquisition Cost: Unknown.

Operational Cost: Cost of fuel for truck and deicing or anti-icing fluid used. The AirPlus! system dramatically reduces the overall cost of deicing by reducing the amount of fluid used.

Maintenance Requirements: The current system requires an annual oil change, and checks of belt tension and mounting bolt torque.

Potential Marine Application and Safety Enhancement: The system could deice large areas of an offshore platform if it could be transported easily without a truck. It may be more challenging to use on a supply boat. It may deice bulkheads, decks, and helicopter landing pads. If capable in superstructure ice and sufficiently transportable, it may be able to deice areas under the main deck. The biggest issue will be supplying the required hydraulic power to run the system. The system normally uses a six-cylinder Deutz engine that produces 188 hp.

Marine TRL: 4–5. Basic elements of the AirPlus! System could be reengineered for use on an offshore platform. 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. The system is currently too large and is not readily transported on a platform. A system could be developed that uses a combination of heated glycol and seawater to deice along with the AirPlus! system.

Marine Technology Transfer Requirements: The system must be tested for its ability 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 transporting the system on a platform must be investigated because truck transport is not viable.

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11 Infrared

Infrared deicing, or anti-icing, is effectively the use of heat to melt ice or to prevent ice from forming. However, rather than requiring a heating element to be placed directly on the surface to be protected, infrared energy is typically transmitted through the atmosphere from an emitter; it is absorbed by the ice to cause melting, or by a surface that is warmed to prevent ice. Infrared radiation is a portion of the electromagnetic spectrum, and spans wavelengths from about 0.75 μm to over 1000 μm. Most of the infrared energy in the technologies described here is radiated in the midwave to longwave infrared spectra—with wavelengths between about 3 and 15 μm. Shorter wavelengths are emitted by hotter emitters, and hotter emitters radiate energy with greater intensity. However, the ability of the receiving surface to absorb energy is also important. Whereas ice is a strong absorber in wavelengths longer than about 3 μm, other materials often are not. For example, polished aluminum only absorbs about 10% of the infrared energy striking its surface, depending upon the wavelength, whereas oil-based paints absorb over about 90%. Other considerations include the method of heating the emitter sufficiently to emit infrared energy. In this summary, gas-fueled and electrically heated emitters are presented.

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Schaefer Ventilation HotZone Heaters

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Intended or Actual Application: The HotZone technology consists of a gas or electric infrared source with the energy focused by a unique reflective lens. The lens makes spot heating, or heating from a distance a unique capability of the product. Applications include heating ice hockey arenas for spectators and warming driving range users, stored steel (so it stays warmer than the dew point to prevent rusting), restaurant diners, freight sorting areas, and outdoor patios.

Intended or Actual Operating Environment: Building interiors and outdoor work areas, especially high air exchange areas where convective heating is ineffective, are the primary environments where HotZone heaters are applied. However, they have been used to keep diners warm on patios of the upper decks of moving ships. They should operate effectively in any temperature condition. They have been used experimentally by ERDC/CRREL to melt ice (Gulley and Davila 2007).

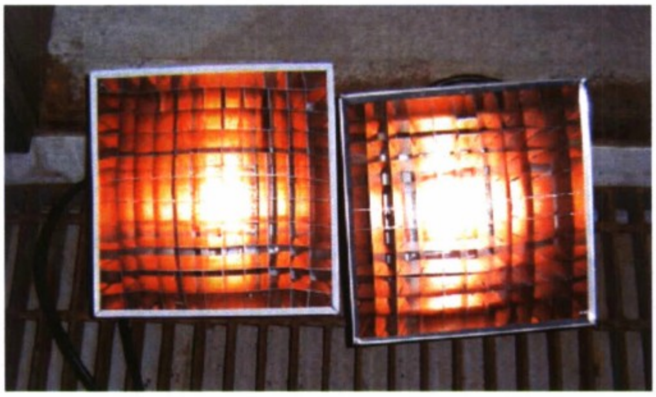

Figure 54. Two operating Schaefer HotZone heaters with lens (Ryerson).

Engineering Concept: Electric resistance heating provided by nichrome wire potted in an aluminum oxide fiber matrix, or gas burning on the surface of a porous refractory tile, provide the energy for heating the emitter to the temperature necessary for the proper emission wavelength. Radiant energy is emitted through a unique aluminum egg crate lens (IRLens) (also called "lobster eye" [Figure 54]) that directs the infrared energy and concentrates it where needed, delivering three to five times as much infrared energy to a location compared to a similar unfocused infrared heater (Gulley and Davila 2007).

The electric unit operates at a variety of voltages and wattages, from 1500 W to 5 kW. The electric element heater reaches about 800°C, and 90%–95% of the electrical energy input is converted to infrared energy. The nichrome wire is bare and is electrically live (Figure 55).

The non-catalytic gas-fired unit produces a flame on the surface of a perforated ceramic tile. Fuel and air are mixed within the ceramic tile with burning occurring on the surface. The gas unit burns natural gas or propane, operates at 800°C–900°C, and radiates at 65%–70% efficiency. The system is controlled by an electric ignition system that directly sparks to ignite the main burner with a 24- or 120-V current; there is no pilot light. The control is fail-safe; if ignition does not occur after a prescribed time the gas is shut off. The control uses a single-stage combination gas control, an ignition control, and a single-stage thermostat.

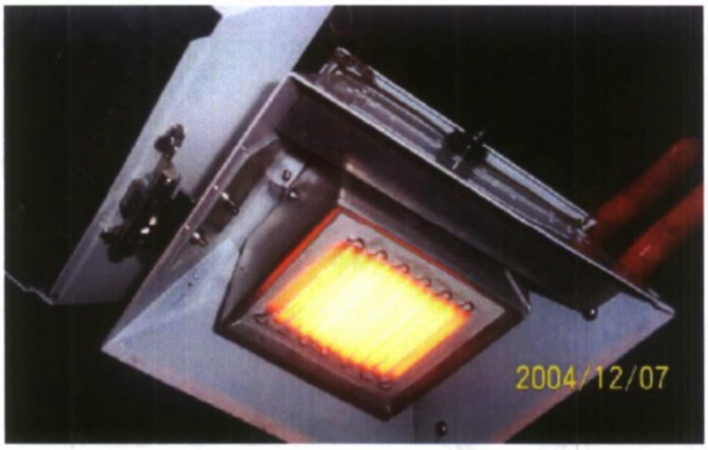

Figure 55. Schaefer HotZone electric heater operating without lens (Ryerson).

CRREL conducted a series of 12 experiments using a sample 500-W HotZone electric heater to evaluate the capabilities of this unit with regard to ice melt rate with and without the lens, over bare aluminum or gray painted substrates, and at three distances from the ice surface: 0.3 m, 0.46 m, and 0.6 m (Gulley and Davilla 2007). All ice thicknesses were nominally 7.6 mm, and the heater was operated consistently at the same power for each experiment. Ice was created on a 20-cm square aluminum plate. Ice melt time increased with distance of the emitter from the ice. Overall, ice melting with the lens was about 2.8 times faster at a 61-cm heater/ice distance, 4.0 times faster at a 45.7-cm heater/ice distance, and 5.6 times faster at a 30.5-cm heater/ice distance.

TRL: 8–9.

Deicing or Anti-icing: The company has no formal information about use of the units for deicing or anti-icing because they are COTS units and are not necessarily redesigned for specific applications. However, the lens system can be tailored to specific heating geometries, from aisle shapes to heating preferentially in a circle. The Air Force has installed three of the largest heaters in 10-m-diameter fiberglass radomes to keep the radome snow and ice-free. CRREL (Gulley and Davila 2007) has experimented with the use of the heaters for deicing with ice over bare aluminum (uncoated) and painted aluminum (coated). Figure 56 shows that the lens decreased ice melt time significantly.

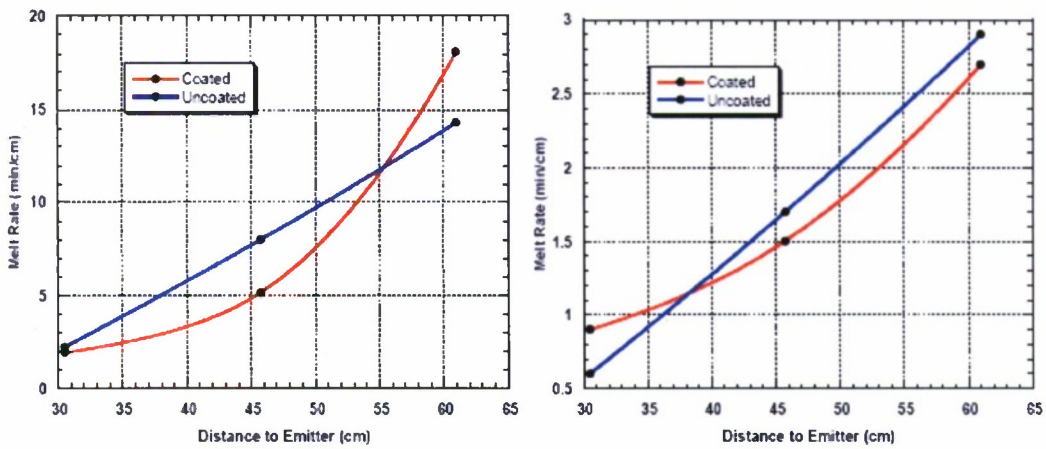

Figure 56. Melt time versus heater distance from ice without lens (left) and with lens (right) for coated and uncoated substrates. Ice melt rate is about five times more rapid when using lens (Gulley and Davila 2007).

Current Advantages and Disadvantages: The system is lightweight but also easily damaged if struck. System is corrosion resistant. Heating wires of infrared emitter are electrically live. The system focuses infrared energy to create an effectively higher watt density. Saltwater can cause emitter corrosion, but it is cosmetic only and does not affect performance. The natural gas and propane units' IR conversion efficiency is greatly affected by wind speed over the surface of the ceramic tile, and Schaefer does not recommend the use of gas HotZone heaters in unprotected environments.

Acquisition Cost: Retail prices for COTS electric units range from about $350 for a 1500-W unit to $550 for a 5000-W unit. Gas models range from about $950 for 10,000-W gas- and propane-fired units to $1550 for the larger 30,000-W units. Schaefer can also design an IRLens to fit almost any brand of natural gas or propane high-intensity heater and will sell lenses separately. Lenses are priced on a project-by-project basis.

Operational Cost: Cost to operate electrical units depends on wattage and cost of electricity per watt. The power rating of the gas units refers to their input energy; operating costs can be calculated using input energy costs.

Maintenance Requirements: Electrical radiant heating elements have an expected life of 2000 to 3000 hr. Gas units have an expected lifetime of 10–15 years. The only maintenance necessary is to check the system for damage and functionality and to occasionally blow dirt off the lens to maintain reflective efficiency.

Potential Marine Application and Safety Enhancement: Infrared technology could protect walkways, stairs, antennas, cranes and windlasses, valves, firefighting and rescue equipment, and air intakes. The technology is useful for all forms of ice, and is most applicable for anti-icing and deicing complex objects where an in situ deicing system is not applicable. It is also applicable where human and vehicular traffic may damage an in situ system. The units can be operated outdoors in wet environments, and electric units can even be submerged in water, removed, and immediately started. However, the system has not been systematically tested in a saltwater environment. Units have been used to heat upper decks of car ferries between Seattle and Vancouver and therefore are exposed to potentially salty air, and perhaps light spray conditions. They have also been used at beach houses where spray occasionally strikes heaters. Only aluminum, copper, and gold are effective infrared reflectors, therefore the reflective lens assembly is fabricated of aluminum. Corrosion of the aluminum reflector in a saline marine environment will cause a loss of about 15% efficiency.

Marine TRL: 5–6.

Marine Advantages and Disadvantages: Infrared sources are remotely positioned from locations requiring heat, and the HotZone IRLens allows greater distance between source and target. The hot electrical heating element could be an ignition source, and open flames in the gas unit could be an ignition source. Units have operated safely in near-shore beach environments and aboard ships. In addition, wetting may not cause thermal shock breakage of electrical heaters because the heater wires are embedded in a porous ceramic matrix. The lens protects the heating elements from wind cooling to some extent, however, wind can blow out the gas heater unless a wind box is installed as an accessory. Application under the main deck of a platform is unlikely unless measures are taken to make units more robust from wave impact.

Marine Technology Transfer Requirements: Improve electrical protection. Lens can be tailored to provide heat patterns required for the specific application. Reengineering could prevent heating elements from being ignition points. System is constructed of lightweight stainless steel and aluminum and may be damaged; the system may need to be more robust for the offshore environment.

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Trimac Industrial Systems LLC—Ice-Cat

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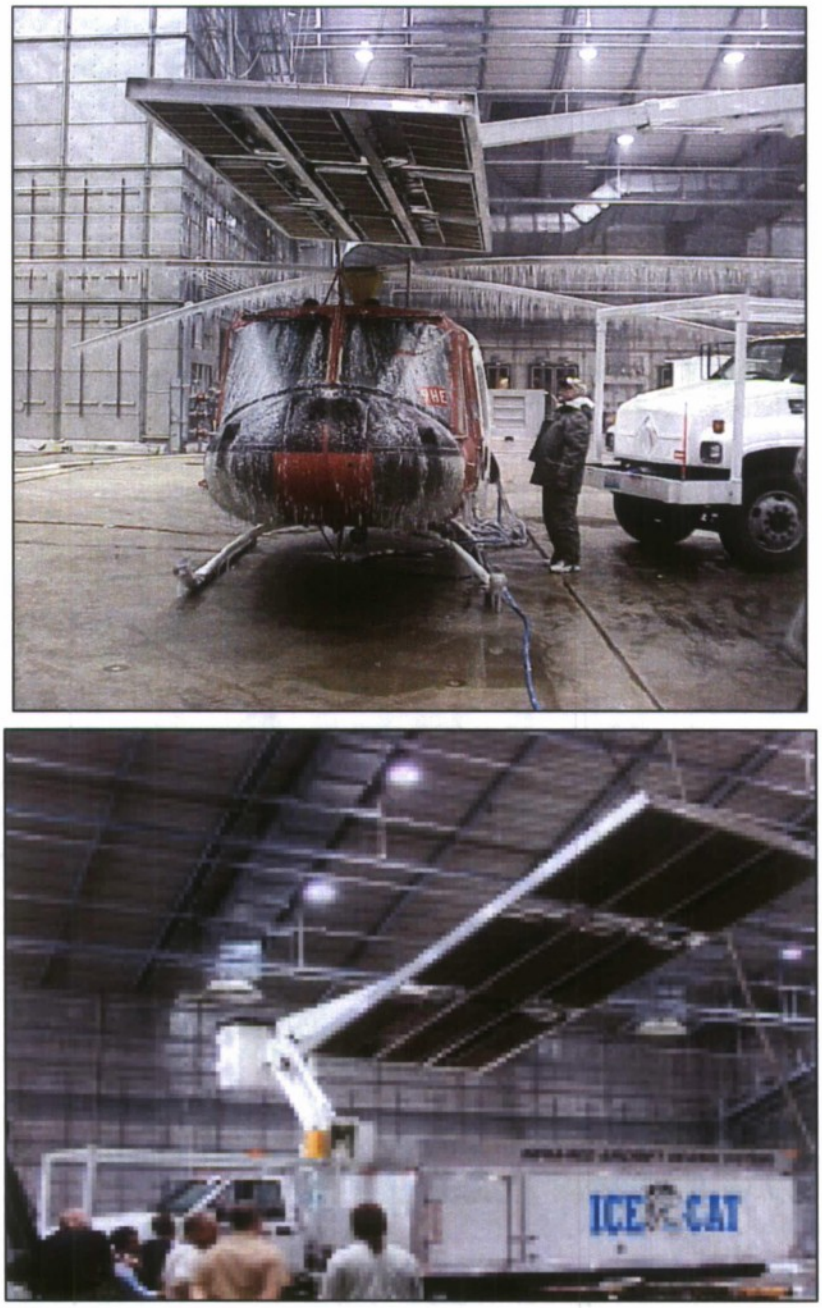

Figure 57. Ice-Cat heater over helicopter (top) and complete Ice-Cat heater, boom, and truck system (bottom) (both Ryerson).

Intended or Actual Application: The technology has been used for a wide variety of heating uses, including demonstrations of deicing of aircraft and many applications requiring curing, drying, dehydrating, powder coating oil pipeline pipe, and thermoforming. Ice-Cat and Gas-Cat are mature COTS gas-powered infrared heating technologies offered by Trimac;

electric systems are also marketed by the company for higher temperatures. The aircraft deicing system is called Ice-Cat (Figure 57), and it is powered by a Gas-Cat system.

Operating Environment: Systems are largely used in factory environments. However, the Ice-Cat is a portable, truck-mounted emitter with two degrees of motion on a gantry arm. It can operate in a wide variety of temperature regimes because the catalytic device that converts gas to heat is electrically heated to start the reaction. The system has been demonstrated to operate successfully in freezing precipitation. However, as with most infrared heaters, in the wavelengths emitted the gas system is slower at melting snow than ice.

Engineering Concept: The Gas-Cat uses a gas-fueled catalytic emitter panel, although electrically powered systems are also available. A chemical reaction produces heat within the proprietary platinum pad of the heater and the fuel, which can be natural gas, propane, or butane. Electronic controllers regulate system gas pressure and temperature. The platinum catalyst pad must be preheated, and the system typically operates at about 400°C emitting strongest in the mid-to-long infrared wavelengths, from 3–16 μm wavelengths. Heater by-products are water vapor and carbon dioxide; exhaust is minimal, reducing the amount of makeup air that must be heated. The system is flameless and can be specified for use in an explosion-proof environment meeting Factory Mutual and Canadian Standards Association insurance standards for use in Class 1, Division 2 environments. The basic components of the Gas-Cat gas infrared heater are: "(1) a gas-tight stainless steel pan, (2) a fuel dispersion tube that evenly distributes the fuel within the pan, (3) a dispersion screen, (4) an insulation pad, (5) a low-watt density heating element, (6) the catalyst pad, (7) a screen and (8) a welded trim piece" (Trimac 2008) (Figure 58).

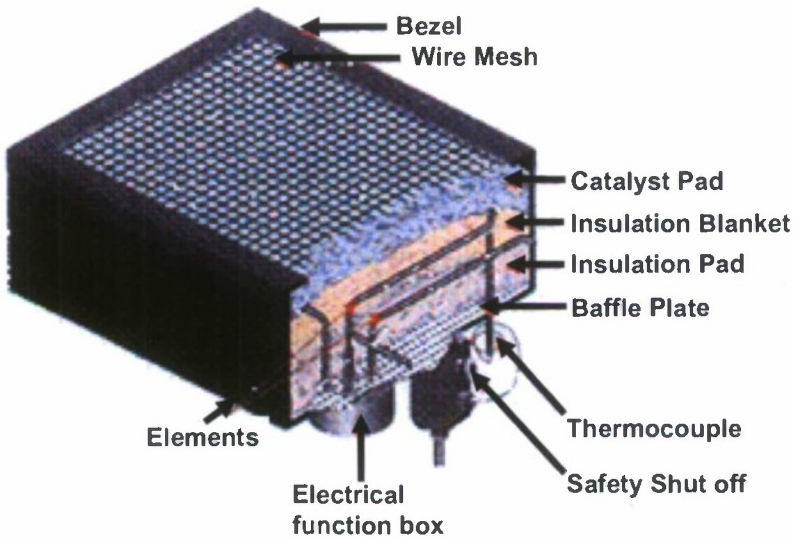

Figure 58. Components of Gas-Cat catalytic heater. Infrared energy is emitted from the top of the unit as viewed (courtesy Trimac Industrial Systems LLC).

The Gas-Cat catalyst can operate at temperatures of 120°C to 550°C. When the electric heating element warms the catalyst pad to 120°C (the temperature that will self-sustain the chemical reaction with the fuel gas), a safety shut-off valve allows natural gas or LP fuel to be introduced to the heated surface of the catalyst pads. When the catalytic process stabilizes, the electric heating element is turned off and stays off unless wind cools the system below 120°C, which then causes the electric preheaters to come on again.

The Ice-Cat system has a unique capability allowing the infrared heater 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. The controller then regulates fuel delivery to the panel as necessary to maintain a not-to-exceed temperature for the surfaces being heated.

Electric infrared heaters also manufactured by Trimac provide high temperature and more rapid heating from a cold start than do the gas heaters. Because of the higher temperatures the electric heaters also operate at shorter wavelengths. The electric heater elements are sealed behind a glass panel.

TRL: Current commercial TRL for the Gas-Cat and electric infrared heaters is 8–9. The Ice-Cat TRL is 7.

Deicing or Anti-icing: Ice-Cat is currently a deicing system using infrared heat only. An upgrade may include high-velocity air blow-off of snow and an ability to apply an anti-icing fluid after deicing. The infrared system alone could also be used to anti-ice at a low emitter temperature of about 120°C. The Gas-Cat stationary units could also be used for anti-icing or for deicing.

Current Advantages and Disadvantages: The system is COTS and is well-tested in industrial environments. Its characteristics are well-known to the manufacturer. It is well-accepted in the marketplace. The Ice-Cat system has been demonstrated for aircraft deicing. Although somewhat slower to deice than chemicals, it is more acceptable environmentally and may be applicable to helicopters and smaller airport operations. The Ice-Cat has a thermal feedback control, preventing it from exceeding preset temperatures. The Gas-Cat technology can work in explosive environments and corrosion should be minimal because of stainless steel construction.

Current Acquisition Cost: As an example, a 0.6- by 1.2-m Gas-Cat panel with 15,000-W output costs about $2000.

Operational Cost: Operation requires gas and electricity to preheat the catalytic pad.

Maintenance Requirements: Periodically the system should be run at high temperature for 30–45 min to burn off dirt that may be in the system and then brushed off. When used at pipeline pumping stations, time between maintenance and pad replacements is 3–10 years.

Potential Marine Application and Safety Enhancement: Infrared technology could protect walkways, stairs, cranes and windlasses, valves, firefighting and rescue equipment, and air intakes. Gas-Cat units are currently used on a seagoing corporate yacht for improving comfort on deck and for keeping windlasses and a helicopter deck ice-free. The system would be most effectively used above the main deck of a platform to avoid green water mechanical impact, and to prevent water from cooling the catalytic panel and stopping the chemical reaction. The system could use natural gas from wells on the platform.

Marine TRL: 4.

Marine Advantages and Disadvantages: The system could be damaged by waves and operation could be diminished by large quantities of spray. Contact with the heater could cause burns. Wind can cause cooling of the emitter surface.

Marine Technology Transfer Requirements: The system could be covered with an infrared-transparent material to isolate the catalytic device from water; air and gas could be brought in separately and the exhaust taken away in plenums.

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Radiant Aviation

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Intended or Actual Application: Radiant Aviation has developed a gas-fired system with heaters mounted in the ceiling of a tension membrane structure for deicing aircraft before flight (Figure 59). The heaters are located in the ceiling of the tension membrane structure to place them above the aircraft and to keep snow off the heaters. The "drive-through" structure is paved with asphalt to allow heating of the asphalt with the suspended heaters as the aircraft is heated to allow re-radiation to the bottom of the aircraft to melt runoff water that may refreeze on the bottom of wings and the fuselage. The system is in commercial operation at Newark and JFK airports, and has been in operation in Buffalo, NY (Ryerson et al. 1999). The JFK system is large enough to deice an Air Force C-17.

Operating Environment: The system melts ice, frost, and snow from aircraft surfaces. The infrared system operates in any environment, though strong winds through the structure can slightly cool the heaters and the surfaces being heated. Although re-radiation from the asphalt pavement reduces refreeze, anti-icing fluid is occasionally sprayed on the aircraft after deicing as a precaution. Deicing is rapid for ice and frost, and slower if considerable snow lies on aircraft surfaces.

Engineering Concept: A Radiant Aviation facility consists of an array of energy process units (EPUs), or infrared emitters, mounted on the ceiling of the tension membrane structure. The tension membrane structure is made of steel or aluminum tubing trusses and covered with fiberglass PVC fabric. The EPUs are non-catalytic gas-fired systems that burn a natural gas-air mixture inside a burner tube (or primary heat exchanger) that reaches about 1200°C. The burner tube is encased within a larger-diameter tube (or secondary heat exchanger) that collects exhaust from the burner combustion. The larger-diameter tube receives energy from the inner tube through convection and radiation. It, in turn, reaches a temperature of about 1000°C and radiates to the aircraft and pavement below with the help of reflectors above the tube. The emitter wavelength is tailored to produce maximum absorption by ice and snow at about 3–6 μm. Wavelength can be controlled by changing the relationship of the primary to secondary heat exchangers. Fuel can be natural gas or propane; if natural gas is burned right at oil wells, moisture must be removed. Burners are 1.5-m-long tubes with a natural gas nozzle and fan to provide air at one end in banks of four. Each burner tube provides about 13,500 W (or nearly 60,000 W/bank), and a fan supplies air to each burner and purges the burner tube of gas before start. A 24-V (DC) source powers the fan, valves, and starter circuit that is, in turn, controlled by an easily used graphical user-interface-based computer system.

Development has also started on a portable system. It is electrically heated but is not yet COTS.

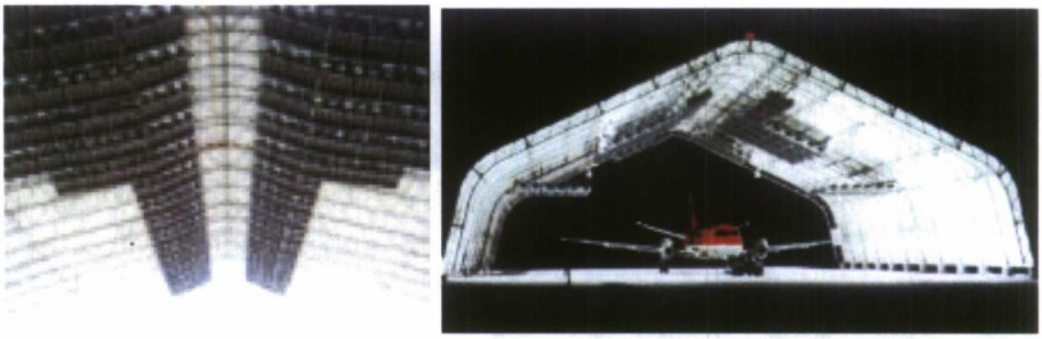

Figure 59. Radiant Aviation EPUs on ceiling of tension membrane structure (left) (Gulley and Davila, 2007). Turboprop aircraft being deiced (right) (courtesy Radiant Aviation).

Intended or Actual Application: The Radiant Aviation system was developed to deice aircraft before flight. However, airports often use the system as a maintenance facility in cold weather because of the comfort provided by the infrared heaters. The facilities can be constructed to accommodate the largest commercial or military aircraft.

TRL: TRL is 5 for the experimental portable electrical heater system, and the TRL is 8–9 for the gas heater system. The gas-heated system is COTS, except for the need to tailor the size and heater configuration for the type of aircraft that will be deiced.

Deicing or Anti-icing: Deicing.

Current Advantages and Disadvantages: The gas-fired system is COTS and it is effective at deicing aircraft. However, it is somewhat slower at deicing snow. It is rated for use near aircraft and aviation fuels; however, it is sensitive to wind, which causes cooling of the secondary heat exchangers.

Current Acquisition Cost: One bank of four 5-ft burners costs about $2000 for a 200,000 BTU gas rating. Construction cost of an 85.4- by 85.4-m facility large enough to accommodate a Boeing 747 is about $11 million (2008 dollars).

Operational Cost: The Radiant Aviation facility at the Newark airport costs $215 per hour to operate at full power (RAS 2006). The Newark facility is approximately 61-m square.

Maintenance Requirements: Maintenance involves periodic checks of gas pressure and blower operation for each burner tube.

Potential Marine Application and Safety Enhancement: The system would probably be used more for anti-icing than for deicing on an offshore platform. It would need to be operated in locations that had no potential for flammable gas concentration. As an infrared system, it would be useful for protecting walkways and stairs.

Marine TRL: TRL for the developing electric system is 3–4, and for the mature gas system the TRL is 6–7.

Marine Advantages and Disadvantages: The system is a proven COTS technology for aircraft deicing. The system is inexpensive to operate and can burn natural gas from a well with some pretreatment of the gas. The steel cabinets can rust, and the open-flame system is a possible ignition source, corrosion of components could be a factor, and the effects of sea spray on possible component-level thermal shock need to be investigated.

Marine Technology Transfer Needs: Metal components are steel and should be enamelized, coated with ceramic, or coated with a refractory material. Burners need to be fully ventilated unless a chimney is used to vent exhaust. EPUs may need to be ruggedized with fully enclosed covers to prevent thermal shock if exposed to large spray fluxes.

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Intended or Actual Application: The Vacca system is not a dedicated infrared heater, but is a variable output heater that can serve as an infrared emitter. It is not a COTS device; the developer tailors the device to the intended application. Heat output is variable, and varies with the type of fuel used. Applications anticipated or in progress with established vendors include home heating systems, rations heaters for soldiers, greenhouse heaters, heated soldier vests, and embedded runway deicing and anti-icing systems. The latter plan would use airport waste to create methanol that would be oxidized catalytically by the device to create heat. The technology is also anticipated to be useful for deicing any large area exposed to icing or snow, and for heating oil and natural gas pipelines because the device does not use a flame for heating and is therefore designed not to be an ignition source.

Operating Environment: The Vacca heater can be exposed to weather and to water if encapsulated to keep the oxidizing process dry. For example, the developer indicates that a wet diving suit has been designed to use the technology. The system can operate automatically and start and stop unattended in remote locations, triggered by temperature.

Engineering Concept: The Vacca heater is a scalable flameless membrane catalytic heater system (Figure 60) designed primarily for non-electric self-starting and passive self-regulation, although it is fully amenable to electronic regulation. The technology is an outgrowth of work with electric fuel cells. It can operate from a few degrees above ambient temperature to 800°C. The system is self-starting below 0°C, but depending upon the fuel used may need preheating. Methanol, ethanol, hydrogen, and natural gas are all usable as fuels, but the latter requires preheating and also operates at the highest temperature. The system can be engineered to operate to a closely set temperature or range of temperatures and/or to a specified power output.

In a demonstration (Gulley and Davila 2007) a 7.6- by 7.6- by 2.5-cm heater was able to reach a sustained temperature estimated to be about 70°C within 4–5 min after being started. There are no moving parts except for a valve that opens and closes to allow fuel into the catalyst. The developer claims that larger units have been built that can produce up to 2 kW of power, and the range of possible sizes is 100 W to 100 kW thermal energy output. Maintenance is claimed to be minimal except for a recommendation to run the unit hot periodically to keep it clean. Output from the system with methanol fuel are heat, water, and carbon dioxide. In the event that there is carbon monoxide in the operating unit's environment, it is capable of oxidizing it to carbon dioxide.

Figure 60. Vacca membrane methanol-powered heater (top) (Gulley and Davila 2007) and products in process of commercialization with other companies (bottom) (courtesy Vacca Inc.).

TRL: The catalytic device is TRL 6 and needs packaging for specific application. Vacca claims its military food heater is TRL 7 (Vacca, personal communication, 2009).

Deicing or Anti-icing: The Vacca system is not currently used for deicing or anti-icing. An airport planned to use the device for runway deicing by placing the heaters alongside the runway and transferring heat to the pavement using heat exchangers across the runway. The system is being applied to deicing a large horizontal surface in northern snowy climates.

Current Advantages and Disadvantages: The system requires significant engineering for each application "first"; it is not a COTS system. The technology cannot operate if wet.

Current Acquisition Cost: The system in its simplest operable form costs about $.01 per W to manufacture in large quantities.

Operational Cost: Operating cost is estimated by the developer at about $0.04 per kW·hour.

Maintenance Requirements: No maintenance except for need to occasionally operate at high temperatures. Vacca claims (Vacca, personal communication, 2008) a mean time between failure of about 200 years.

Potential Marine Application and Safety Enhancement: The Vacca technology has a potential marine application for heating surfaces directly, with heat exchangers, or through infrared heating. Walkways, stairs, antennas, and areas where heat exchangers run from the heater to the location of heat need can be accommodated. The system should be used primarily where combustible gases could not collect, unless packaged in a verifiable explosion-proof design. The technology would need to be encapsulated if operating in a wet location. It may be possible to use gas from a well drilled by the offshore platform as fuel, but this would need to be explored for tolerance of variability in gas quality, moisture content, and contaminants. Some contaminants, such as hydrogen, aid operation of the device when methane is the main fuel component.

Marine TRL: Because the technology must be engineered specifically for each application, the marine TRL is 4 or 5. The fundamental technology is mature, but it must be packaged for each specific application.

Marine Advantages and Disadvantages: The catalytic device could be used as a relatively low-temperature heat source for locations where thermal conduction is adequate, where heat exchangers could carry heat from the heater to the surface requiring protection, or it could possibly be used as a source of infrared energy. Each marine application would require engineering by the company. The system may possibly use gas available on an offshore platform. The system can recycle CO_2 in flu gases (note: system for this is available now) rendering the system operation CO_2 neutral. The technology is self-starting and controllable within narrow thermal operating ranges. The technology will not function if it is wet. It is not clear how the system responds in failure mode—whether it shuts down or runs away and overheats. However, a glut of fuel may cause heat production to shut down by blockage of access to the catalyst by air. Fuel deprivation, as expected, causes a drop in temperature. The heater starts in temperatures as cold as -40°C and is self-regulating so does not require external regulation controls except to start and stop fuel flow, although it is fully amenable to being instrumented for servo control.

Marine Technology Transfer Requirements: Failure-mode safety needs to be further demonstrated for the catalytic device. The use of gas from wells onboard offshore platforms needs to be explored. The system must be kept dry to prevent the catalytic reaction from extinguishing. The ability of the technology to accept industrial abuse, and the potential for gas leaks and frozen exhaust components when operating at cooler temperatures, should be investigated. The capability of the system as an infrared emitter should be investigated, and the capability of encapsulation techniques explored.

12 Manual Deicing Methods

Manual deicing is currently the principal way to deice marine structures. This involves using tools to crush and break ice, scrape ice from surfaces, and lift and push ice overboard. Manual deicing is an innovative process in that technologies are not commercially available for this specific use. Manual deicing uses tools that, in large part, are manufactured and sold for other purposes. Although effective, manual icing is slow, dangerous, and occasionally damaging to the structure. However, even if other methods are used to deice marine structures, manual deicing will probably always be required for those situations where other technologies are not effective.

Ice scrapers and breakers

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Hillerich & Bradsby Co.
800 W Main St.
Louisville, KY 40202
Telephone: 502-585-5226; 800-282-2287
E-mail: customer.service@slugger.com

Intended or Actual Application: Manual methods are occasionally the only option for removing ice from platforms or supply boats. Sometimes no other systems are available onboard for deicing or anti-icing, systems that are onboard are overwhelmed, or certain areas are not protected for mechanical, operational, or economic reasons. Manual methods require crew to use tools to loosen ice from surfaces, especially ice that is mechanically locked around objects, and move it overboard. This requires that crews be organized to remove ice whenever it is safe to work on deck. It also requires that ice be removed before it becomes dangerously thick, or accumulates asymmetrically on the platform or boat. It also requires that ice be removed in a planned manner so as not to create instability by removing too much ice in one area, and too little in another. This is especially true on supply boats.

Figure 61. Capt. A. D. Colburn (right) wielding an ice mallet to keep the deck of the Research Vessel *Knorr* clear of ice during a research cruise in February 1997 to the Labrador Sea (courtesy George Tupper, *Oceanus* magazine, Woods Hole Oceanographic Institution).

Figure 62. Crushing ice on deck with a wooden baseball bat on the Coast Guard cutter *Midgett*, Bering Sea, 1990 (from Ryerson).

Figure 63. "Icing is a serious concern when ships sail in winter conditions as it can affect ship's stability. In order to prevent building up of ice, all available personnel take part in chipping ice on the upper decks while the ship proceeds at slow speeds. This is a picture taken on the Grand Banks of Newfoundland, showing crew members chipping ice out on the forecastle including the Commanding Officer, Cdr Couturier." Frigate HMS *Fredrickton*, Canadian Navy (courtesy Petty Officer Randell/Lietenant M. Tremblay and the Canadian Department of National Defence, http://www.navy.forces.gc.ca/fredericton/0/0-s_eng.asp).

Operating Environment: Manual deicing techniques are typically used for removing superstructure ice caused by saline spray, and techniques have been largely developed around the physical properties of that ice (Ryerson and Gow 2000). However, superstructure ice hardens with time and if temperature decreases, enhancing brine drainage, it approaches freshwater ice in its mechanical properties. Manual deicing methods are also commonly used on Mt. Washington, New Hampshire, for example, to deice unheated antennas and to remove ice that has bridged thermal anti-icing systems. The primary ice types on Mt. Washington are rime ice and clear ice.

Engineering Concept: Two tasks are necessary for manual deicing: loosening ice from surfaces and moving the ice overboard. Ice is loosened by breaking it into small pieces by crushing or cutting. A variety of tools are available for loosening ice, including large wooden or "dead-blow" mallets (Figure 61), wooden baseball bats (Figure 62), ice chisels, and spud bars (Guest 2008; Zadra and Pyle 1990). However, iron or steel cutting surfaces will damage paint and material under the ice, and possibly cut electrical cables or other utilities unless used with great care. Generally, straight-bottom shovels, scoops, and snow shovels are used to remove loosened ice from decks (Figure 63). Guest (2008) suggests that steel-bladed ice scrapers and straight-bottom shovels can be used to remove thin ice from decks; spades, hoes, and picks can be used to remove thicker ice, and brooms and snow shovels can be used to remove snow. He indicates that care must be used with these tools to prevent damage to the ship. It is prudent to stock up with extra tools before encountering icing because tools frequently break, and some are lost overboard.

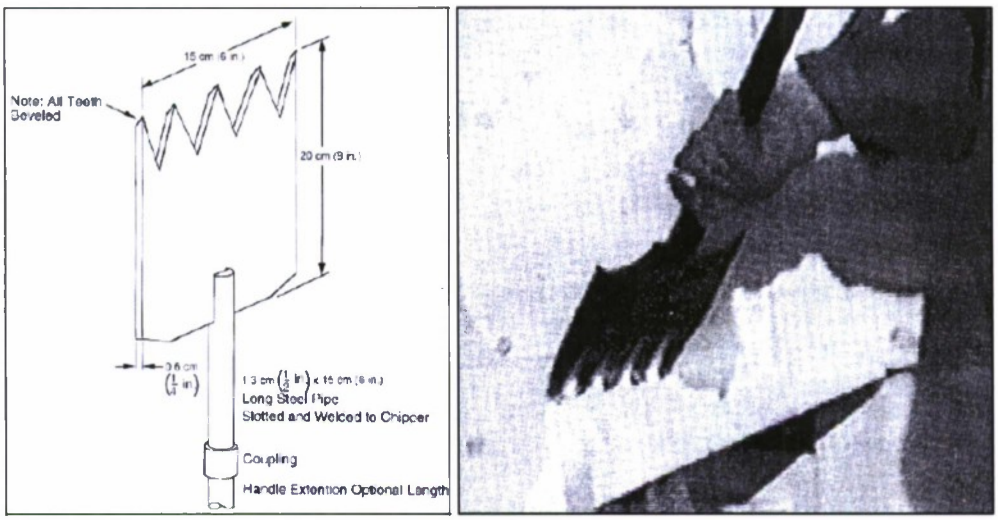

Figure 64. Army Corps of Engineers (2006) ice chipper (left), and five-point chisel (right) used successfully on the Coast Guard cutter *Midgett* (right from Ryerson).

Zadra and Pyle (1990) report on the effectiveness of various tools for removing ice from the Coast Guard cutter *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.

Tools taken aboard the *Midgett* were selected as a result of prior evaluations by Rand et al. (1989) 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; these tools were taken aboard the Coast Guard cutter *Midgett*. The shipboard experiments found that the spud bar and ice chisel effectively broke the ice into pieces that could be easily pushed overboard. However, the tools were too heavy, and when dropped against the deck they damaged the nonskid. The most effective tool was the five-point chisel. Its long tines and the chisel head width allowed it to break and rapidly remove ice (Figure 64). However, it still required about 20 min to remove 10 cm of ice from a 2-m^2 area (Zadra and Pyle 1990; Ryerson, personal observation, 1990). In addition, it was lightweight and did not damage nonskid. Importantly, the tool was the only method useful for removing ice from the 5-inch gun turret, which had a composite housing that would have been damaged by mallet and baseball bat impacts. The five-point chisel was the favorite tool of the crew and Deck Chief.

The U.S. Navy recommends in its *Cold Weather Handbook for Surface Ships* (U.S. Navy 1989) that the following equipment be stocked on cruiser-class ships for deicing: 48 wooden baseball bats, 30 fiber brooms, 30 wire brooms, two steam lances when a steam source is available, 12 nylon mallets, 12 rawhide mallets with a 7-cm nominal face diameter with a 12-cm-long head, 12 wooden mallets with a 15-cm nominal face diameter and a 20-cm-long head, two portable hair dryers and two heat guns, 455 kg of sharp sand, 24 steel grain scoop shovels, 24 snow shovels, and studded ice footgear. The 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.

The Army Corps of Engineers (2006), in reference to removing ice from dam sluiceways and lock walls, reports that two hand tools that can be reliably used to remove ice from concrete or steel are the pike pole and an ice chipper. Both tools are widely used by lock personnel. Figure 64 (left) shows the ice chipper that has been refined over many years by its users. As shown, it is similar to the five-point chisel (Figure 64 [right]) used aboard the Coast Guard Cutter *Midgett*.

TRL: 6–7. These products have been tested and are regularly used in the marine environment. However, specific commercial models that perform best, such as baseball bat brands or specific mallet models, are unknown. The five-point chisel must be fabricated because it is not commercially available. Testing would indicate whether a shingle removal shovel would be a commercial substitute for the five-point chisel, and, if so, which design because many variants or sold.

Deicing or Anti-icing: Deicing.

Current Advantages and Disadvantages: Mechanical methods require that crew members operate on slippery decks or other dangerous locations in often severe weather. Mechanical deicing is labor intensive and removes crew from other duties. It often causes damage to components of the vessel or structure. It is inexpensive with regard to equipment, but expensive with regard to personnel. Deicing may need to occur multiple times during a storm to prevent large accumulations.

Current Acquisition Cost: Cost of tools is typically $50 to $150 per item, but multiples of each should be purchased to replace those broken and lost.

Operational Cost: Cost of labor and broken tools.

Maintenance Requirements: Repair and replacement of tools and sick time for injured personnel. Repair of damaged paint and ship or platform components.

Potential Marine Application and Safety Enhancement: Manual methods allow areas safely reached by personnel to be deiced. However, heavy weather, rolling vessels, large waves, and strong spray may prevent crew from deicing. In addition, portions of offshore structures, especially platforms, may be inaccessible to personnel, especially under portions of the main deck and on support structures where large ice accumulations may occur.

TRL: See above (these tools and techniques are used in the marine environment).

Marine Advantages and Disadvantages: Manual methods require working often in severe weather and dangerous conditions with regard to footing. Many areas of offshore platforms where large ice accumulations may occur are not easily reached. Falling ice may be a hazard from cables, cranes, and antennas. Rates of ice accumulation may require crew to perform multiple deicing missions. Some objects cannot be easily deiced manually because they are delicate (such as sensors, lighting, and antennas) or because they are inaccessible. Crew members are not available for production or rest activities when deicing. Deicing is exhausting work in cold and wet conditions, risking crew member health, hypothermia, and loss overboard, which may be fatal.

Marine Technology Transfer Requirements: Experiment with more effective and commercially available tools.

13 Piezoelectric

Piezoelectric actuators move when an electric current is applied to them. When attached to a surface, the actuators can deform the surface, and move it at high frequencies depending upon the signal they receive. Surface deformation and vibration can peel brittle ice from surfaces, and shear it loose through acceleration of the surface. Piezoelectric actuators are being applied to move surfaces to overcome the adhesion strength of ice.

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Intended or Actual Application: FBS Inc. and the Pennsylvania State University, via a contract from the Army Aviation Applied Technology Directorate (AATD), have shown that by introducing sufficient ultrasonic shear stresses to a host structure/ice interface, instantaneous ice delamination is possible. A focus of the work is composite helicopter blades where it is necessary to exceed the bond strength of ice and simultaneously not to exceed the internal bond strength of the composite blade structure. The technology places piezoelectric actuators on metal or composite structures such as airfoils, and floods the airfoil with ultrasonic energy from one or multiple actuator locations. Using this approach, large area deicing has been demonstrated using only 50–100 W of power (<0.23 W/cm^2) supplied to the ultrasonic actuator. This concept was demonstrated on airfoil sections subjected to realistic impinging ice conditions in Goodrich's icing/wind tunnel. Phase II work efforts are focusing on optimizing ultrasonic actuator design and testing the concept on rotating rotor blade sections in Penn State's Adverse Environmental Rotor Test Stand (AERTS). The goal of the technology development is to reduce the energy required to deice aircraft.

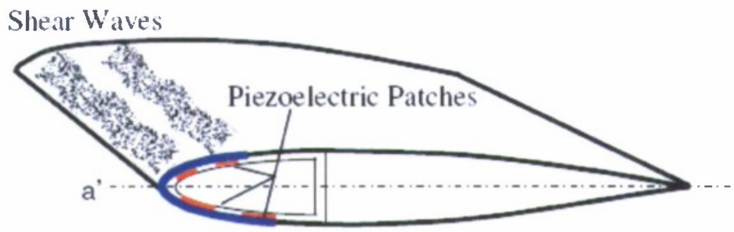

Figure 65. Schematic of piezelectric anti-icing system on airfoil (courtesy FBS Inc.).

Figure 66. Ice bonded to plate (left) with actuator location indicated on back of plate. Instant of ice debonding and falling upon activating actuator (right) (Palacios et al. 2008) (courtesy FBS Inc.).

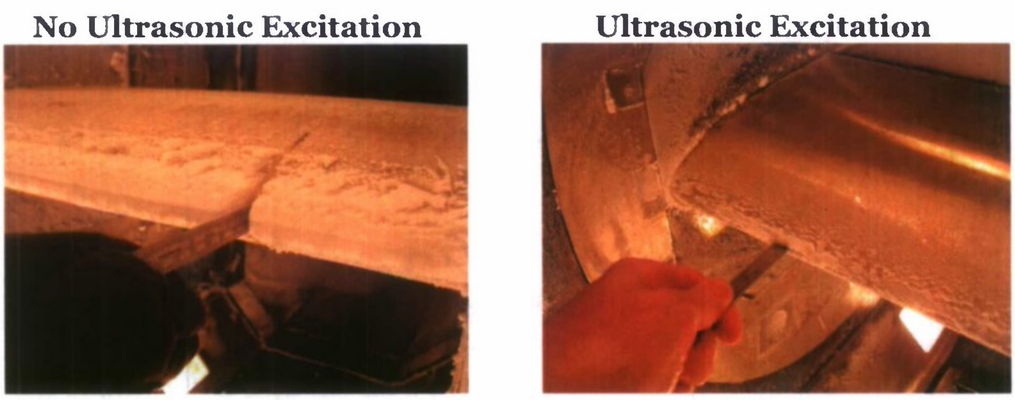

Figure 67. (Left) An airfoil specimen exposed to realistic impinging ice conditions in Goodrich Corporation wind/ice tunnel. Ice forms on the leading edge with no ice protection. (Right) The same airfoil exposed to the same icing conditions but with the ultrasonic ice protection system turned on. Note only a thin film of ice is formed on the leading edge. The actuators are embedded inside of the leading edge (not shown) (both images courtesy FBS Inc.).

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 to locations on the airfoil 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 internal to the composite airfoil structure sufficient to debond the materials. FBS used finite element models 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. Model and experimental results agreed within 5% (Palacios et al. 2008).

The technology operates by gluing or embedding one or more small actuators to the surface or in the surface requiring ice protection (Figures 65 and 66). In one experiment, one actuator was affixed to each end of a 61-cm-long sheet metal airfoil section. Ice 0.5-mm thick was grown in the middle of the airfoil. Energizing of the actuators in the 20- to 30-kHz range caused the ice patch to be removed. Average actuator power was 80 W applied for 0.1 sec. Actuators can be placed on the inside or outside of the airfoil skin. In addition, experiments suggest that some anti-icing effects are possible if the system is operated continuously as supercooled water is contacting the surface (Figure 67). Freezing is delayed during this process, and ice that does form is cracked and delaminated. Frequency tuning and placement of actuators can be used to optimize the location and magnitude of shear forces between ice and the substrate. Ideally, actuators could be placed at one or a few locations on an airfoil and dynamic frequency tuning can be used to deice specific locations on airfoils. FBS also indicates that the deicing actuators can be used to initially detect ice location using techniques similar to those used in ultrasonic non-destructive testing.

TRL: 4. The system has been taken through proof-of-concept in laboratory tests.

Deicing or Anti-icing: Deicing and, potentially, anti-icing.

Current Advantages and Disadvantages: The technology has the capability of deicing areas much larger than the actuator area through actuator placement and frequency tuning. 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 offshore platform surfaces to protect large areas, rather than covering the entire surface to be protected as is necessary with many other technologies. The technology is at an early stage of development. However, additional development has been funded allowing the technology to reach TRL 6 or 7 within a few years. Electrical isolation, electromagnetic interference and radio frequency interference (EMI-RFI) characteristics, and longevity of actuators are currently unknown.

Current Acquisition Cost: Unknown—too early in development.

Operational Cost: Modeling indicates about 9 W m^{-2} (Palacios et al. 2008).

Maintenance Requirements: Unknown—too early in development.

Potential Marine Application and Safety Enhancement: The capability of the technology on flat and curved surfaces of metal free to vibrate, at metal thicknesses to 9 mm, has been demonstrated. This may accommodate some surfaces of offshore platforms and supply boats. 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 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, the helicopter landing pad, 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. If effective on large-diameter thick-walled steel tubes, such as legs and other under-deck support structures, perhaps with sufficiently powerful actuators the technology could keep areas deiced into the wave wash area.

Marine TRL: 4

Marine Advantages and Disadvantages: Anticipated advantages in the marine environment include the potential for deicing large areas without requiring deicing hardware to cover large areas and the potential ability to protect support areas below the main deck down to the waterline. Electrical systems would require isolation in the wet, saline environment. Ability to debond soft saline ice from substrates would require demonstration. It may be possible to protect some areas of lattice structures.

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 deicing. Assessment of technology capabilities on complex surfaces such as corners, braced metal surfaces, and lattice structures will be necessary for offshore platform and supply boat applications. Assessment of the technology capability in saline ice is needed, as is the EMI/RFI signature of the system.

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Intended or Actual Application: Creare has developed and has provided proof-of-concept for using piezoelectric actuators to remove ice from aircraft airfoils and from ships, especially ship communications equipment (Figure 68). The work was conducted in projects funded by NASA Glenn Research Center and by the Federal Aviation Administration. Piezoelectric actuators are bonded to the areas to be protected. The system breaks the ice adhesive bond with the substrate when actuated, allowing the ice to fall, or to be carried away by air flow. The system is intended to allow removal of smaller quantities of ice than inflatable boots, for example, so there are fewer aerodynamics effects of ice accumulation when applied to aircraft. In addition, the technology will allow ice to be removed with 5%

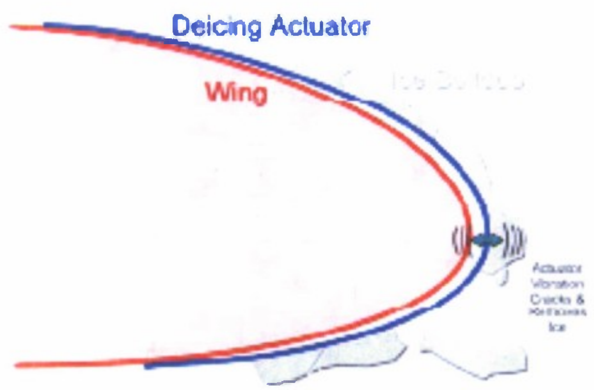

Figure 68. Movement of actuator and resulting ice debonding on an airfoil (from Pilvelait 2002) (courtesy Creare Inc.).

to 10% of the energy used by traditional electrothermal systems; it is readily available when needed, unlike jet engine bleed air, which is least available when icing is most probable.

Operating Environment: The system was initially tested in temperatures ranging from -20°C to +20°C, and with ice thicknesses up to 3 mm. A mature prototype would be required to operate in the same conditions to which the aircraft is exposed. Ice with an adhesion strength of at least 60,000 Joule/m^3 can be removed by the actuators. The system can also be designed to operate in the saline marine environment aboard ships.

Engineering Concept: The Creare system uses a thin, electrically activated piezoelectric activator attached to the surface to be protected to break the ice-substrate adhesive bond and cause it to be ejected from the surface. The actuator is a multilayer structure consisting of a thin piezoelectric ceramic sheet attached to the back of a thin, metal substrate upon which ice forms. This mass-spring system is about 0.5-mm thick and is curved to conform to airfoil leading edges. The system is driven by a controller that causes the piezoelectric actuator to expand when electrically excited and to contract when power is removed. When driven at the system resonant frequency, the amplitude of movement is sufficient to break

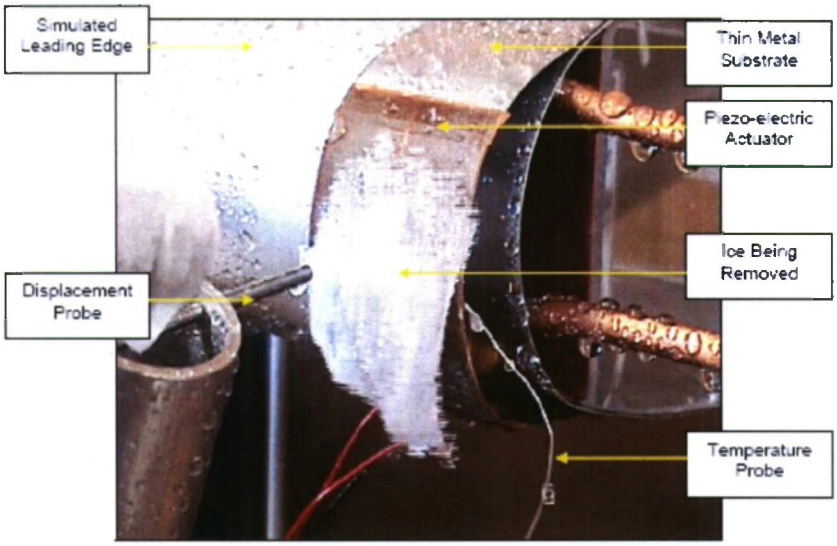

Figure 69. Moment of ice debonding and falling from surface when actuator is energized (from Pilvelait 2002) (courtesy Creare Inc.).

ice from the surface (Figure 69). When ice accretes on the surface, displacement is small because movement is constrained by the stiffness of the ice and its adhesion strength. However, when amplitude is small, applied forces are high and are adequate to crack and expel ice. The system applies high stresses and strains to remove ice, operates at high efficiency, and even recovers some of the energy used when the system relaxes. The system consumes less than 0.02 W/cm^2, compared to 1.6 to 3.2 W/cm^2 required by traditional electrothermal systems. The system is lightweight, weighing approximately 1.5 kg/m^2, and readily conforms to surfaces. Initial testing in the Phase I proof-of-concept development operated the system for over 200 hr without failure. At the expected rate of ice accumulation on aircraft, the system would need to be actuated for 1 sec every 30 sec.

TRL: 3–4.

Deicing or Anti-icing: The system is principally a deicing system, but may be able to deice sufficiently thin ice layers to be considered nearly an anti-icing system.

Current Acquisition Cost: Unknown—too early in development.

Operational Cost: Less than 0.02 W/cm^2

Maintenance Requirements: Unknown—too early in development.

Current Advantages and Disadvantages: The demonstrated system has low power requirements, removes ice with a smaller ice accumulation than do pneumatic boots, and is expected to be inexpensive to apply to surfaces because it is thin and has low mass. The system is currently a laboratory system with several demonstrations in an icing wind tunnel.

Potential Marine Application and Safety Enhancement: The technology should be applicable in all locations where expulsive systems would operate because the technologies are similar. Piezoelectric technologies would be effective in the superstructure ice accretion zones underneath the main deck of a platform. It could be wrapped around large-diameter platform legs, and be applied to railings, hatch covers, and bulkheads. The system will form ice debris after firing, therefore it should be used only where safety and operations would not be compromised by ice debris.

Marine TRL: 3–4.

Marine Advantages and Disadvantages: The technology has the potential to be applied easily to bulkheads, under-deck support structures such as legs and braces, potentially even in the wave wash area, and on tight radii objects such as railings. The developer proposes its use on communication antennas. The capability of the technology on young saline ice accretions that are softer and less brittle than freshwater ice accretions needs to be investigated. In addition, the adhesion strength of saline ice needs to be investigated, though it is likely lower than that of freshwater ice. The technology may not be practical to use where ice debris could litter work areas, clog machinery, or endanger personnel. Furthermore, potential electromagnetic and radio frequency interference effects need to be investigated.

Marine Technology Transfer Requirements: The Creare piezoelectric technology has had demonstrated proof-of-concept, and has been successfully demonstrated in an icing wind tunnel. However, it has not been developed beyond a TRL of about 3–4 and requires investment to complete actuator development, develop a dynamic controller, and test and evaluate performance in a variety of environments including freshwater versus saline ice. In addition, its EMI-RFI characteristics, mean time between failure, and methods to keep electrical components isolated in a wet, saline, heavy industrial environment should be investigated.

14 Pneumatic Systems

Pneumatic boots have been a mainstay of aircraft deicing technology for decades. Boots have been used experimentally at sea, in navigation locks, and to protect antennas and cables.

Deicing boots

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Sensors and Integrated Systems
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http://www.goodrich.com

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Fenwick, WV 26202-4000
Telephone: 304-846-6636; 800-767-6899
E-mail: info@iceshield.com
http://www.iceshield.com/default.asp

AirSuppliers
4200 North Main St., Suite 220
Fort Worth, TX 76161
Telephone: 800-888-0431
E-mail: orders@airsuppliers.com
http://www.airsuppliers.com

Intended or Actual Application: Pneumatic deicers were invented by Goodrich in the 1930s and became the first practical means of removing ice from the critical control surfaces of aircraft in flight. The first commercial application was for protection of the wings and empennage of the Northrop Alpha mail plane. Pneumatic deicers are still used today for aircraft (albeit much improved in life and efficiency) where sufficient electrical power or bleed air is not available to thermally protect critical surfaces. Cost and weight are also important factors because this is normally the lowest cost / lowest weight means of providing in-flight ice protection. Pneumatic deicers 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 and replaced much like a boot or overshoe. The deicer consists of layers of elastomeric materials and rubber-coated nylon fabric that are cured together with heat and steam, much like an automobile tire. The rubber-coated fabric layers are stitched (sewn) together to form internal tubes that are inflated to 124 kPa. Approximate air volume requirements are 0.158 cubic meters per square meter of coverage. When deflated a vacuum source can also be applied to quickly remove the air and precisely flatten the deicer to the surface of the structure being protected. The deicers remove ice by expanding and breaking the ice layer that has formed over the surface. On aircraft the high-speed air stream quickly removes the ice pieces. The surface of the deicer can also be treated with a very low ice adhesion coating called ICEX, aiding in more complete ice removal. Although the primary use of boots is on aircraft, boots have been successfully tried on antennas (Ackley et al. 1977), cables (Govoni and Franklin 1992), on the tugboat *Keokuck* (Kenney 1976), and on lock walls (Hanamoto 1977) (Figures 70 and 71).

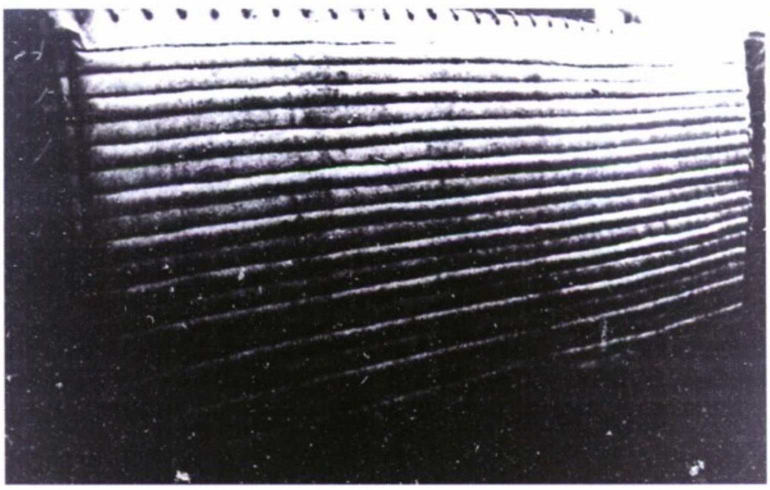


Figure 70. Urethane-coated Dacron fabric air-pulsed tube assembly on the tugboat *Keokuk* (Kenney 1976). The inflatable tubes are oriented lengthwise. This was the most successful deicing system tested in the *Keokuk* experiments.

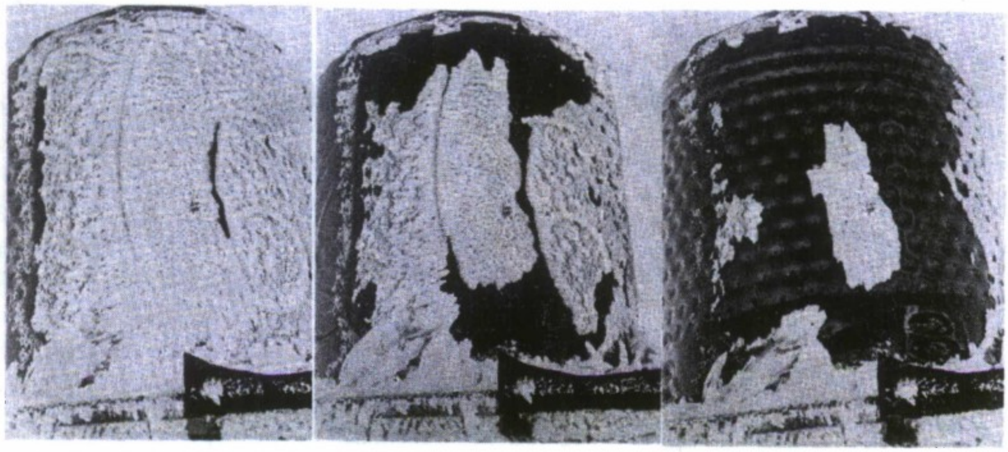
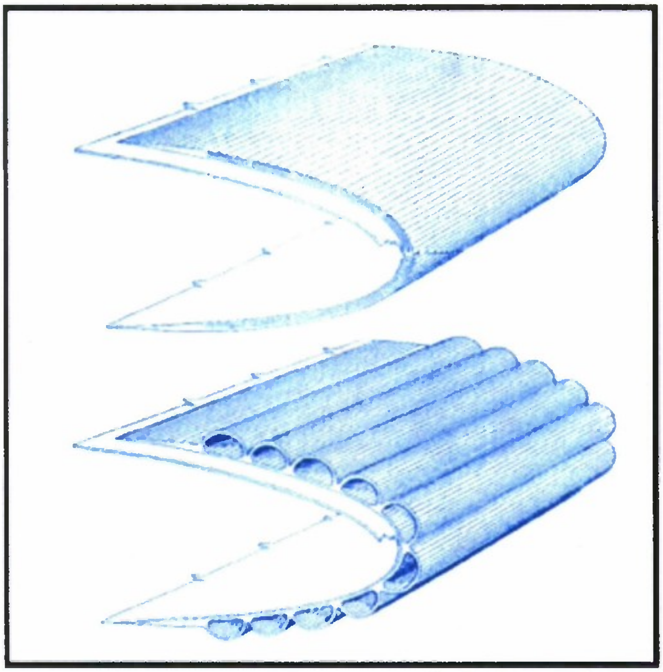


Figure 71. Inflatable boot system protecting TACAN aviation antenna. Ackley et al. (1977) found this system worked successfully even in the harsh icing conditions of Mt. Washington, New Hampshire.

Operating Environment: Boots are a deicing technology. Because boots operate by distorting the shape of the surface to be protected and peeling the ice and boot apart, ice has to form before the boots can execute their function. Boots cannot be inflated below -40°C because the rubber is normally brittle at this point. This is likely acceptable for atmospheric ice, but may limit application for removal of frost or sea spray ice at temperatures below -40°C. A low-watt density heater could be integrated into the boot at manufacture to slightly warm it for the lower temperature applications.

Considerable attention has been given to several operating characteristics of boots—some of which are most important in aviation applications. 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 but not peel off and be carried away. If too much ice is allowed to accumulate, degraded flight qualities may occur due to drag from ice roughness and change in airfoil shape. Current FAA guidance is to activate "modern" deicing boots (defined below) 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).



Goodrich pneumatic boots

Figure 72. Spanwise configuration of traditional Goodrich pneumatic aircraft deicing boots in deflated condition (top) and inflated condition (bottom) (courtesy Goodrich Corporation).

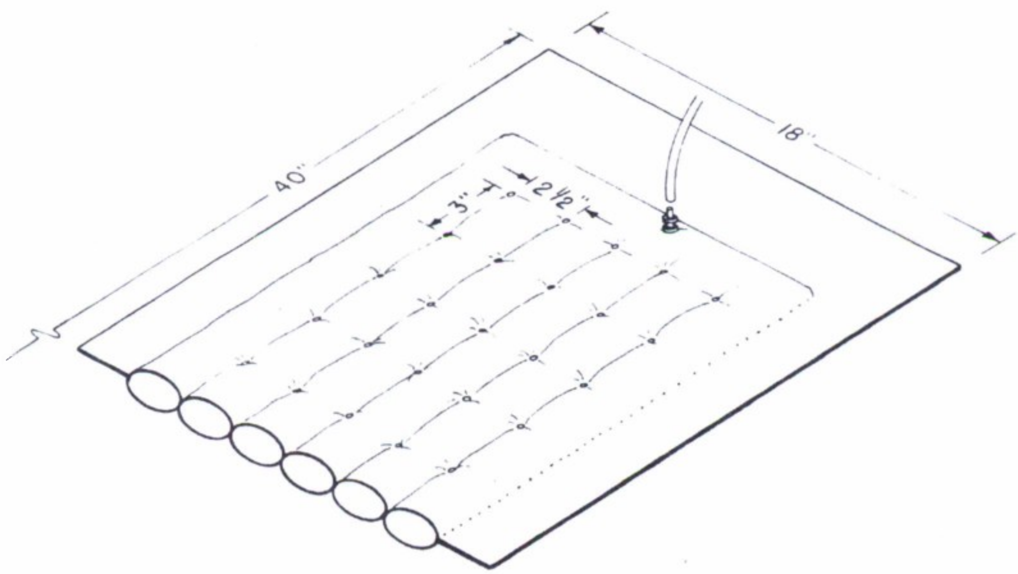


Figure 73. Cross section of TACAN boot tested by Ackley et al. (1977).

Engineering Concept: Aircraft deicing boots are generally constructed of neoprene synthetic rubber, Estane, or other flexible material, reinforced with fabric, forming parallel tubes that typically run spanwise along the leading edge of airfoils to 10% or 15% of chord (Figure 72). However, chordwise tubes usually cause less aerodynamic drag when inflated because air is flowing along the tubes rather than across the tubes. The thickness of pneumatic boots when not inflated is typically less than 2 mm (FAA 1993). They are reasonable in cost, are lightweight, require little power, and are easily retrofitted. Materials are typically fluid resistant with built-in protection against ozone, weathering, oxidation, and erosion. Older traditional pneumatic boot systems generally have long, uninterrupted, large-diameter tubes operated at low pressures by engine-driven low-pressure pneumatic pumps. The low pressure and long tubes cause long inflation and deflation cycles and dwell times (dwell time is the time that the boot is fully expanded after completion of the inflation cycle until the beginning of the deflation cycle). Modern pneumatic boot systems have short, segmented, small-diameter tubes inflated at relatively high pressures (125–160 kPa) by bleed air from turbine engines. Boots can be inflated and deflated in as little as 2 sec. Boot tubes are manifolded together for simultaneous inflation and deflation. Deflation is usually assisted with a vacuum pump to draw the boot flush with the airfoil surface to minimize aerodynamic disturbance. Maximum surface movement is typically 9.5 mm, and minimum removable ice thickness is as little as 1.5 mm (FAA 1993).

Pneumatic boots have been experimentally tested to remove ice from ships, antennas, cables, and lock walls. Ackley et al. (1977) designed a pneumatic boot system to remove snow and ice from TACAN antennas (Figure 71). They designed a boot with a cross section as shown in Figure 73. 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 sec, and deflation times were about 60 sec. 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 a Rosemount ice detector.

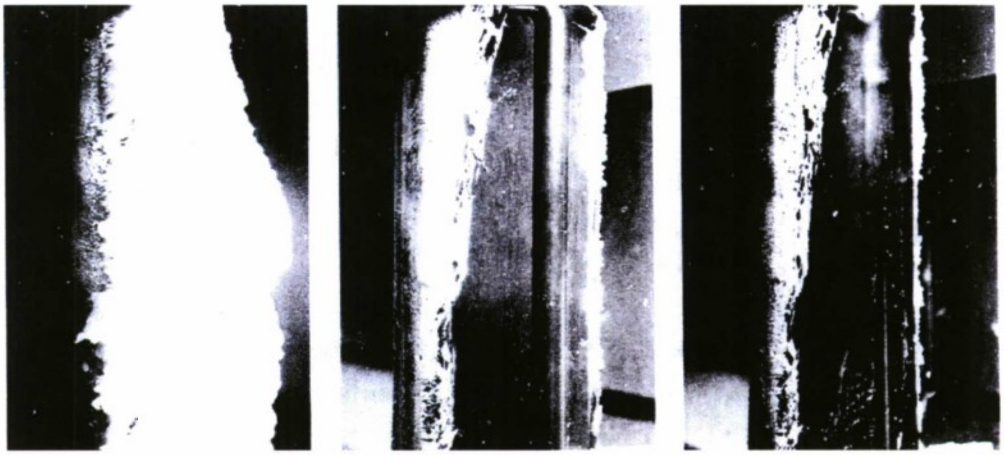


Figure 74. Stallabrass iced pneumatic mast device (left), deicer inflated (center), and after deflation (right). Temperature was -22 °C, ice thickness was up to 7.6 cm, and pneumatic system air pressure was 103 kPa (Stallabrass 1970).

Kenney (1976) and Stallabrass (1970) tested inflatable boots for shipboard use, and Stallabrass indicated that marine uses of inflatable boots could include masts and stays, bridge fronts, radar antennas, and life raft stowages. Stallabrass tested pneumatic deicers applied to a mast and to a bulkhead in an icing tunnel and on an outdoor test stand. All tests were done with freshwater rather than saline water. According to Stallabrass (1970), this made the tests potentially more severe than might be experienced with less strong saline ice. A pneumatic deicing system was laced to a 0.3-m-diameter by 1.4-m-long pole to represent a mast. One to three inflations were generally necessary to remove all ice (Figure 74). The bulkhead system was tested on a 0.9- by 1.2-m panel. Requiring up to three cycles to remove ice, especially when ice thickness was 10 cm, the bulkhead pneumatic deicer was considered successful (Figure 75). Stallabrass concluded that the inflatable boots would be effective at sea, especially when assisted by the buffeting of a ship but cost, susceptibility to damage when placed in work areas, and the need to remove ice from decks after falling from the mast or bulkhead were negatives.

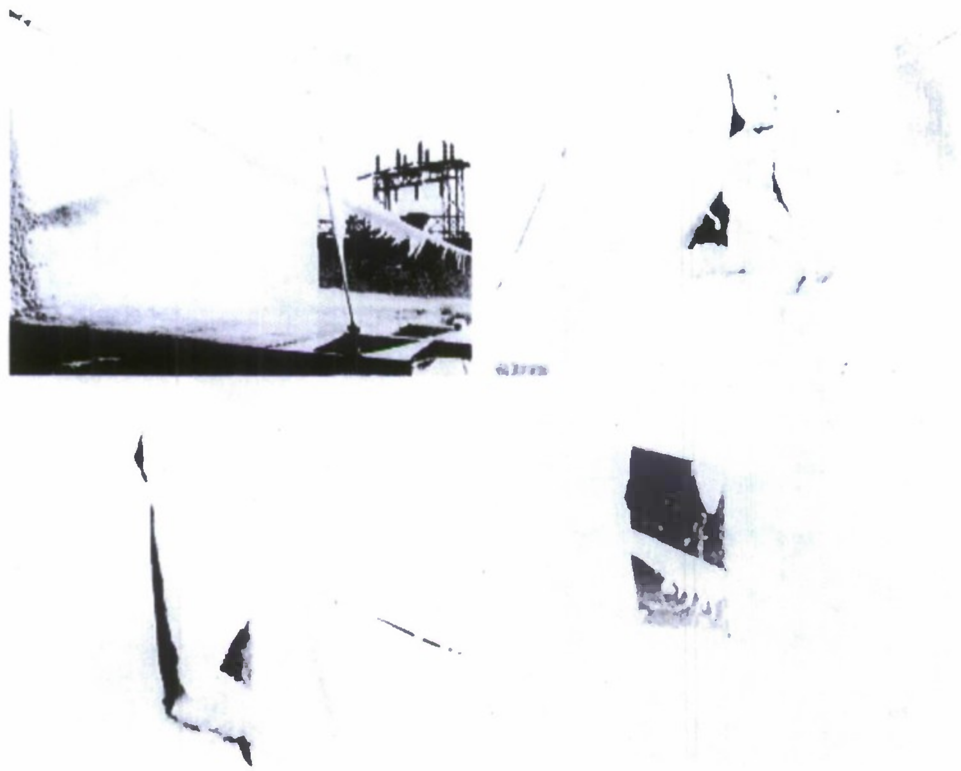


Figure 75. Stallabrass (1970) bulkhead deicing. Top left shows panel before deicing, top right and bottom left show loosening of 10-cm ice thickness after two inflations, and the bottom right image shows most ice removed after three inflations. Diagonal ice in bottom right image is a foreground iced cable.

Kenney (1976) tested his panels on the tug *Keokuk* and conducted sea trials in Maine, thus accumulating saline superstructure ice on the panels. Two panels, with inflatable tubes made of Dacron fabric and neoprene, were tested with up to 25 mm of accumulated ice. Pressurizing the panels to 34 to 55 kPa was sufficient to remove all of the ice. Kenney (1976) concluded that the air/vacuum pulsed panels were effective, and even more successful in areas with an icephobic coating. In addition, they are lightweight and easily stowed, require less power than thermal systems, require no special skills to install or operate, and have the potential to cover large areas.

Ackley et al. (1977) also developed and tested several pneumatic designs to remove anchor, or collar, ice from lock walls. Anchor ice can reach thicknesses of 0.6 m or more (Hanamoto 1977). The most successful design, ultimately tested on a lock wall, embedded a 10-cm-diameter fire hose in cast rubber and protected the assembly with a flexible metal cover to reduce potential damage from ships moving through the lock (Figure 76). The system was designed to peel off thick ice, greater than about 42-mm thick. Air pressure of 0.55 MPa was used to inflate the system. Ice of about 30-cm thickness was removed with two to four inflation cycles. Although successful, the authors indicated that the cost was high and that durability needed full evaluation.

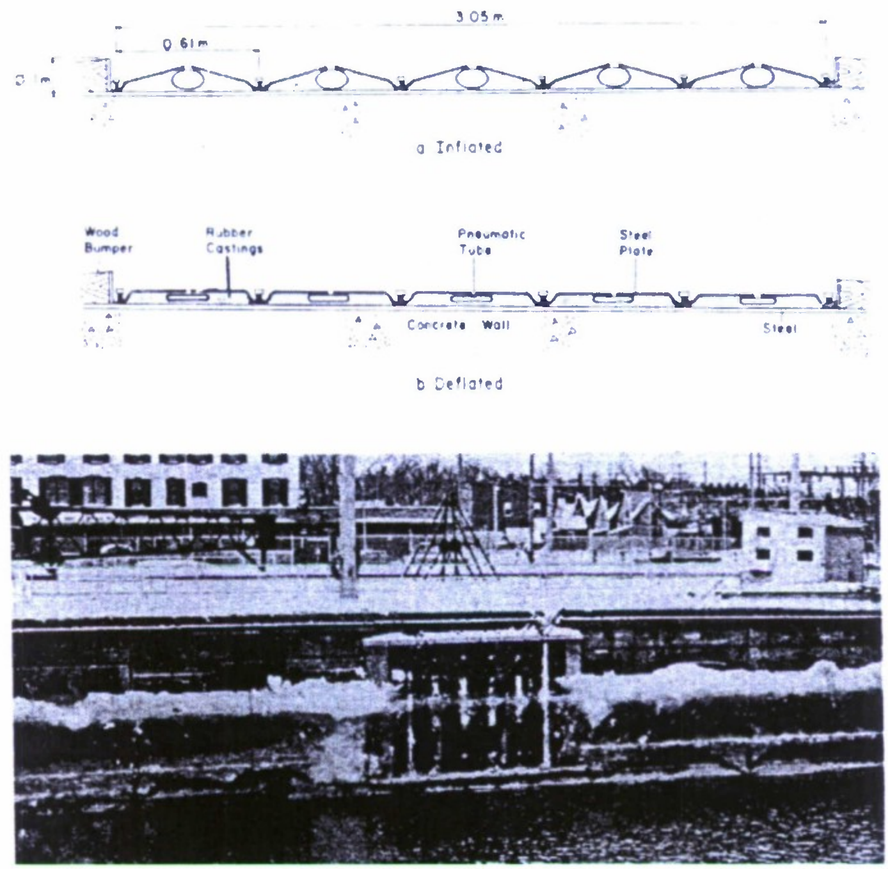


Figure 76. Cross-section diagrams of lock wall device inflated and deflated (top and middle). Bottom image shows system at Sault Sainte-Marie, Michigan after inflation removed ice (Hanamoto 1977).

TRL: 8–9 for aircraft deicing boots.

Deicing or Anti-icing: Deicing.

Current Acquisition Cost: Estimate $200 to $3000 per square meter for the marine environment depending on number of deicers, size, and whether cost of inflation equipment and controllers is included. Aircraft boots are typically more expensive because of certification costs (Burnside 2008).

Operational Cost: Unknown.

Maintenance Requirements: Aircraft boots require periodic maintenance to check for deterioration of boot material, holes, and delamination from wings. Cleaning the surface with soap and water periodically is good practice. Pinholes that occur in boots installed on airfoils are primarily due to static buildup and discharge through the layers. The static is associated with high wind speeds with rain impingement on airfoils. Thin rubber/fabric patches are available, from Goodrich for example, with pressure-sensitive adhesive that can be used to repair small holes. Rubber ages with exposure to sunlight, ozone, and other contaminants after a number of years. Fluids are available (Agemaster, for example) that apply protective chemicals to the surface ply. Coatings, such as ICEX, are also available that reduce ice adhesion when applied to the surface of boots. But, as with any surface treatment, they can wear off and must be reapplied.

Current Advantages and Disadvantages: Boots are a well-understood technology from decades of use. They require a compressed air and, perhaps, vacuum source. Boots do not produce meltwater to run off and refreeze elsewhere.

Potential Marine Application and Safety Enhancement: Boots could be used to protect large flat or simple curved areas (concave or convex) such as bulkheads and support structures underneath the main deck. They can protect antennas, masts, and guy wires. They could be used on 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 can remove considerable ice thicknesses. If designed similarly to lock wall deicers, they may function successfully in the wave wash area.

Marine TRL: 6. Goodrich has made specialty boots to evaluate experimentally on marine vessels, but not for commercial production.

Marine Advantages and Disadvantages: Boots cannot be used on walkways, or easily used on complex surfaces. They can be coated with icephobic materials to improve ice release. They are not a source of ignition for volatile gases. They provide no electrical hazard in a wet, saline environment. They can remove large ice thicknesses.

Marine Technology Transfer Requirements: Evaluate robustness over long periods and in wave wash areas. Perform more extensive testing in marine conditions aboard supply boats and platforms.

15 Vibration and Covers

Although appealing as a direct way of removing ice from surfaces, low-frequency, low-technology vibration has not proven to be reliable for deicing. However, the U.S. Navy recommends that objects that must be protected from water or ice at sea be covered by tarps, though even the vibration of tarps in wind is not sufficient to keep them deiced. Beating of tarps during manual deicing, which causes flexing, does facilitate ice removal.

Protective covers

Fetter Manufacturing Inc.
921 South 7th St.
Louisville, KY 40203
E-mail: info@e-tarps.com

Intended or Actual Application: Vibration has been explored by several researchers as a method of either anti-icing, but more commonly deicing. Ryerson (2008) reviewed several of the most notable experiments, most of which failed to reduce icing problems. Most low-technology vibration methods generally shake a surface at a relatively high amplitude and low frequency to remove ice. However, unless the surface is accelerated sufficiently to exceed the adhesive shear strength of ice with the substrate, ice remains on the surface. In addition, many of the surfaces vibrated have been stiff structures, thus relying solely upon acceleration due to the vibration amplitude and frequency, and not deformation. Kenney (1976), for example, vibrated a plywood-fiberglass panel sandwich on the tugboat *Keokuk* as one of several experiments to find solutions to icing on ships. The system failed to anti-ice or to deice. Mulherin (personal communication, 2008) experimented with vibration of two systems, a shaker attached to a stiff beam and a flexible 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 ice—especially when the tower's resonant frequency was reached and the tower flexed. Unfortunately, the flexing that allowed most ice removal also broke welds and destroyed the tower's structural integrity. Makkonen (1984) reports that attempts were made to use flapping and flexible materials at sea to reduce icing, but with little success. Jorgensen (1982) recommends the use of tarps that vibrate because of ship motion, and reports that tarps have been successful for deicing when provided with the low ice adhesion coatings.

Operating Environment: The experiments described above suggest that an important component of a vibration approach is flexing of the surface being vibrated. In that regard, the U.S. Navy encourages the use of protective covers onboard ships transiting cold regions (U.S. Navy 1989). Protective covers are typically constructed of a lightweight, strong, waterproof, fire-retardant, and flexible material such as duck cloth, sail cloth, or polyurethane. The U.S. Navy (1989) recommends that ship boats, davits, capstans and windlasses, and all outdoor command, control, and communication stations be covered.

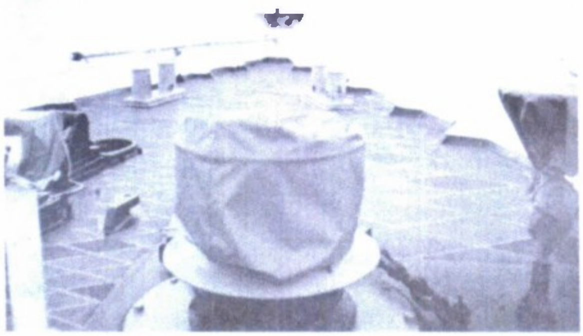


Figure 77. Hypalon cover placed loosely over capstan assisted ice removal (Zadra and Pyle 1990).

Figure 78. Hypalon cover placed tightly over vent hindered ice removal (Zadra and Pyle 1990).

Engineering Concept: 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 Coast Guard cutter *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. Hypalon is a trademark name for DuPont's chlorosulfonated polyethylene (CSPE) synthetic rubber (CSM). CSPE is noted for its resistance to chemicals, temperature extremes, and ultraviolet light. It is a common material for making inflatable boats and roofing. The Hypalon covers remained flexible in the -1°C to -2°C temperatures and remained tear resistant. Deicing ease was a function of how tightly the Hypalon was attached to protected hardware. Hypalon that was loosely attached was easily deiced because the material could be easily bent and deformed (Figure 77). Material that was tightly wrapped around objects was as difficult to deice as objects that were not covered (Figure 78). Therefore, loosely attached protective covers that are easily deformed are easily deiced.

TRL: 5–6. Protective covers have been tested in a relevant environment.

Deicing or Anti-icing: Primarily deicing, with potential minor anti-icing when loosely installed.

Current Acquisition Cost: Unknown.

Operational Cost: Only costs are for installation and removal.

Maintenance Requirements: Repair or replace damaged tarps.

Current Advantages and Disadvantages: Tarps loosely tied to encourage anti-icing and more effective deicing may be carried away in the wind. Items covered with tarps are often unavailable for use until uncovered. Tarps are relatively inexpensive ice protection for items requiring little use during storms. Tarps must be placed before storms or they are ineffective. Tarps are difficult to install in high winds and may be hazardous.

Potential Marine Application and Safety Enhancement: Tarps can be used to protect relatively small objects from ice. Tarps can temporarily cover helicopter landing pads when not in use. Tarps can cover safety equipment but should not render it inaccessible. Tarps can cover walkways if personnel can move about under the tarp. There are no apparent applications of tarps under the main deck in heavy superstructure icing.

Marine TRL: 3–4.

Marine Advantages and Disadvantages: Tarps require time to install, remove, and repair. Tarps require storage space. Tarps are relatively inexpensive to purchase and repair. Time for tarp placement and removal can be wasted if anticipated icing does not occur.

Marine Technology Transfer Requirements: Determine ideal tarp weights and materials for use. Develop tie-down procedures.

16 Windows

Windows are a special icing problem. They are delicate, and their transparency must be preserved. Heat and deicing fluids have been the traditional methods of deicing windows in the automotive and aviation environments. Low ice adhesion transparent coatings are available for reducing ice adhesion strength.

Heat

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Lebanon, NH 03766
Telephone: 603-448-9206; 888-448-9206
E-mail: contact@iceengineering.com

Planned Products LLC
5560 Boulder Hills
Longmont, CO 80503
Telephone: 303.682.0274
http://www.frostfighter.com/index.htm

Astronics (window heat controls)
9845 Willows Rd. N.E
Redmond, WA 98052-2540
Telephone: 425-881-1700
http://www.astronics.com/

Intended or Actual Application: Heating is the traditional method to defog and deice windows—especially in automobiles and aircraft. Heat can be delivered to the window through direct electrical heating using a high-resistance conductor, or through blowing hot air or spraying hot liquid onto the window surface. All three systems are used in automobiles and aircraft. Systems are usually integrated into vehicles by the Original Equipment Manufacturer (OEM), for example, General Motors, Ford, or Cessna. However, some of the technologies are available as accessories, or are only available after-market.

Operating Environment: Most systems built into automobiles and aircraft are defogging systems with some deicing capability. Aircraft windshield heaters are installed to defog, deice, and keep the windshield flexible enough to withstand a bird strike without shattering. Automobile windshields can cope with frost, snow, and light-to-moderate freezing rain conditions. Aircraft windshields are designed to cope with FAA FAR25 Appendix C in-cloud icing conditions.

Engineering Concept: Automobile windshields are generally heated from behind by blowing warm air from vents in the dashboard that direct air upward over the window surface from an engine coolant heat exchanger. Turbine and jet aircraft often use engine bleed air to heat windows and operate at much higher temperatures than automobile systems. Hot air is slow and inefficient because air has a low heat capacity; heat is exchanged twice, once from the engine coolant heat exchanger to air, and then from air to the glass where it is conducted through to the ice on the outside. If only defogging the inside of the glass, then heat is transferred directly to the water on the back of the glass, and temperature is raised enough to evaporate the water and clear the fog.

Electric window heating systems are more rapid and efficient than are forced air systems. Electric systems typically heat the glass directly from a resistant electrical circuit embedded within the glass, such as windshields of Fords equipped with very thin wires embedded in the front windscreen glass for the *Quickclear* or *Instaclear* system and some aircraft. Circuits are also adhesively applied to the inside of the window as found nearly universally in modern automobile rear windows (Figure 79). The electrically conductive lines are composed of a silver-ceramic material that when fired on glass becomes bonded to the glass and is highly resistant to abrasion.

Figure 79. General layout of rear window electrical grids (top) and a photograph of the right side of a rear window showing the thin heater circuit and the wide bus feeding current to the heaters. (top image courtesy Prof. Kevin Sullivan at http://www.autoshop101.com; bottom image courtesy Stephen Foskett at http://www.miata.net).

Cessna provides an electrical windshield heater manufactured for them by Pittsburg Plate Glass (PPG) for external application to Cessna 300 and 400 series aircraft (Figure 80). The Hot Strip system is a 15-cm-wide by about 60-cm-long plexiglass window overlay that allows visibility in icing conditions.

Petrenko at al. (2003) have developed a high-frequency pulse method that provides a low-voltage, high-amperage current through a thin transparent high-resistance conductor on the glass surface (Ryerson 2008). The sharp electrical pulse rapidly heats the conductor and a thin layer of ice, sufficient to release the ice from the surface. The rapid pulse reduces heat loss to the substrate 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.

Figure 80. Cessna/PPG Hot Strip window deicer oriented vertically on aircraft windshield (image provided by RAM Aircraft, LP).

TRL: TRL varies from 9 for OEM and COTS automobile and aircraft forced air and resistance heating products to 5 for the pulse heating technique.

Deicing or Anti-icing: Deicing and anti-icing.

Current Advantages and Disadvantages: Forced air systems are effective, robust technologies, but are slow and inefficient. Electrical resistance technologies are fast and relatively energy efficient. However, current can be high and cause fire hazards, with several documented aircraft incidents (Anon 2003). The pulse heating method is not COTS, and a robust window surface conductor is not yet available. It requires high amperage at low voltage similar to resistance welding, but the technique is rapid.

Current Acquisition Cost: Cessna/PPG Hot Strip approximately $800; after-market automobile rear window defroster about $50. Others unknown.

Operational Cost: Function of amount of thermal and electrical energy required.

Maintenance Requirements: High-amperage electrical components require periodic inspection for arcing at connections.

Potential Marine Application and Safety Enhancement: Systems could be applied to supply boat bridge windows, platform crane operator windows, operations office windows, and other critical work areas.

TRL: 4 (for pulse method) to 7 (for other methods because they would require reengineering to be tailored to marine applications).

Marine Advantages and Disadvantages: Most of these systems would require reengineering for the marine environment. Forced air systems would provide supplemental heat to work area and structure interiors and are easily adapted to marine applications. High-amperage electrical systems may be electrical hazards and high maintenance in marine environments. The pulse method may not be robust, and high amperage may be high maintenance and an electrical hazard. High temperatures of resistance-heated windows may cause breakage if struck with large water volumes, for example, on a ship bridge.

Marine Technology Transfer Requirements: Evaluate capability of each technology in marine environment with spray and saline conditions. Develop more robust pulse deicing method for marine environment with lower amperage and improved conductive transparent coatings.

****

Fluids

Ice Free
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Contact: Phillip Tubert
Telephone: 877-777-9372 (Ext. 713)
E-mail: phillip.tubert@worldsourceinc.net

Microheat Inc.
38755 Hills Tech Dr.
Farmington Hills, MI 48331
Telephone: 248-489-2400
Fax: 248-489-5797

CAV Aerospace Inc.
2734 Arnold Court
Salina, KS 67401
Telephone: 888-865-5511; 785-493-0946
E-mail: tkssales@weepingwings.com
http://www.weepingwings.com

Intended or Actual Application: Fluids and fluid delivery systems are available or have been developed to improve window deicing. These technologies have been developed for automobile and aircraft windshield deicing in flight or preflight. Ice Free is a glycol-based anti-icing fluid that has evolved from aircraft deicing fluids. It is intended to be applied before an icing event to reduce ice adhesion to windshields. CAV Aerospace produces the TKS weeping wing aircraft deicing and anti-icing system that includes a sprayer for deicing the aircraft windshield. Microheat developed the Hot Shot to preheat windshield deicer fluid to remove ice and snow, and insects during the summer.

Operating Environment: All three fluid technologies operate in ice and snow. However, the lower temperature limit of Ice Free is only about -7°C. Hot Shot has no stated minimum temperature, and the TKS deicing/anti-icing fluid has a minimum temperature of -60°C. Ice Free is an anti-icing fluid that has deicing capabilities. Hot Shot is a deicing system, and TKS is a general ice protection system.

Engineering Concept: The TKS system was described in the chemicals discussion. The TKS 406B Kilfrost fluid used in the system contains a mixture of glycol and alcohol as freezing point depressants. Ice Free was initially developed as a more environmentally acceptable deicing fluid by NASA Ames. It has a lower percentage of Propylene glycol than most aircraft deicing fluids, hence its relatively high minimum working temperature. Windows could also be deiced with fluids using the Stallabrass (1970) weeping approach, where a manifold placed above the window could weep deicing fluid down the window to reduce or prevent ice accumulation.

TRL: 8–9.

Deicing or Anti-icing: Deicing and anti-icing.

Current Acquisition Cost: $140 to $200 for Hot Shot. TKS available only as system for specific aircraft. Ice Free price unknown.

Operational Cost: Cost of fluids.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: Fluids are easily applied and are generally effective. Snow typically requires large volumes of fluids. Fluids require replenishing. Systems are relatively inexpensive and technology is generally robust.

Potential Marine Application and Safety Enhancement: Fluids can be applied to bridge windows of supply vessels. Platform windows such as at control areas and on cranes could be deiced and anti-iced with fluids. A weeping system manifold could be placed over windows to reduce ice accretion.

Marine TRL: 4–5. These technologies have not been applied in the marine environment.

Marine Advantages and Disadvantages: Fluids could accumulate on decks and deice decks, but also create slippery conditions. High winds may cause sprays to be ineffective, and heavy sea spray may dilute fluids. Fluid technology is well-understood and relatively robust. Fluids and systems are COTS, but redesign may be necessary for marine applications.

Marine Technology Transfer Requirements: Investigate practicality of spray systems in marine environment with wind and sea spray. Develop manifolded weeping system for window application. Determine effectiveness of fluid systems with saline spray ice. Assess system application to lattice structures and irregular shapes such as windlasses.

****

Coatings

SOPUS Products
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ePaint Company
25 Research Rd.
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E-mail: mike@epaint.com
http://www.epaint.net

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KISS Polymers LLC
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Tampa, FL 33688-4087
Telephone: 813-962-2703
E-mail: info@kisspolymers.com
http://www.kisspolymers.com/index.htm

Intended or Actual Application: Icephobic/hydrophobic coatings have a potential for reducing icing problems on windows. Coatings available or under development from the vendors listed above are claimed to be transparent and potentially usable on windows. SILC was developed specifically for use at cryogenic temperatures on Space Shuttle fuel tank components. WC-1-ICE was developed by the U.S. Navy for use on most locations on ships. KISS Polymers applications are broad and include the marine environment.

Operating Environment: Of the five vendors listed, three products were evaluated for shear strength: SILC by NASA, and WC-1-ICE of 21st Century Coatings and KISS-COTE by the Army Corps of Engineers (2006). Tests of the coatings were made in a variety of conditions and on differing substrates. In addition, formal shear tests of coatings have not been conducted recently by CRREL on glass substrates. Tests by NASA on external shuttle fuel tank components at temperatures of -12°C to -7°C showed that the SILC coating had an 80% reduction in shear strength when compared to shear strength on the same uncoated materials. In addition, SILC performed well for at least five ice and snow cycles when used casually on automobile windshields. SILC has not been formally evaluated in the marine environment. KISS-COTE 1063 also performed well in CRREL tests over aluminum substrates, with an average shear strength of 388 kPa (Army Corps of Engineers 2006). KISS-COTE was developed, in part, for improving the speed performance of boats. However, formal performance of the material on glass in marine environments is unknown. Rain-X is reported to have icephobic properties by the manufacturer and by informal reviewers/users. Formal tests on glass in marine conditions have not been located. ePaint was developed through Navy and Air Force funding for use, in part, in the marine environment. However, performance in the marine environment is not known. The NanoSonic coating has not yet been tested in the marine environment under realistic conditions. However, it is intended to be used to alleviate superstructure icing problems.

Engineering Concept: Rain-X is a silicone-based material that increases the hydrophobicity of windows. It is sold specifically to reduce wetting of windows and allow droplets to be carried off windows by airflow over the window. Rain-X is also marketed to reduce ice adhesion—a property claimed by some users. Rain-X is not known to be specifically icephobic. SILC is a mixture of 60% Rain-X and 40% PTFE powder. The PTFE forms a lubricious coating that is icephobic. The material is sacrificial, as is Rain-X, and must be periodically renewed. Shear appears to occur within the SILC material when ice is removed rather than at the ice-SILC interface. ePaint is developing a hydrophobic material with an embedded phase change component. The hydrophobic material encourages icephobicity, and the phase change material causes differential expansion and contraction within the coating, which encouraged shear of ice from the coating surface, therefore reducing ice shear strength. Recent tests by ePaint have shown shear strengths of 28.85 ± 11.8 kPa (M. Goodwin, personal communication, 2 January 2009). NanoSonic is developing a coating that is sufficiently hydrophobic so that droplets roll off the surface before or after freezing. Therefore, testing has demonstrated that the material is effectively icephobic and possesses this capability in the saline marine environment. It is anticipated that the material will have a 3-year lifespan before requiring renewal. KISS-COTE is a silicone-based polymer (poly(dimethyl siloxane)) that bonds to nearly any material and is highly hydrophobic and icephobic. It is a smooth-feeling, slippery, dry, non-toxic, waterproof, non-stick coating that is applied at room temperature by spraying or rubbing onto surfaces with a clean cloth.

TRL: Rain-X and KISS-COTE are COTs and are TRL 8–9. NanoSonic's coating is TRL 4. ePaint has performed testing in the marine environment and is at TRL 7+. SILC is at TRL 5.

Deicing or Anti-icing: Assists active deicing or anti-icing technology.

Current Advantages and Disadvantages: These coatings assist active systems by reducing ice adhesion strength on glass. This keeps glass areas clean of ice more often and reduces active system energy usage. Rain-X is the only of the five materials with known frequent use on windows.

Current Acquisition Cost: See discussion under "Coatings."

Operational Cost: Unknown.

Maintenance Requirements: Depends upon recoating requirements—months to years depending upon product.

Potential Marine Application: These products can be applied to any windows to assist active deicing or anti-icing technologies.

Marine TRL: Rain-X, TRL 5; SILC, TRL 4; ePaint, TRL 7+; NanoSonic, TRL 4; and KISS-COTE, TRL 7.

Marine Advantages and Disadvantages: The ePaint, NanoSonic, and KISS-COTE products are intended for or evolved from marine applications. Sacrificial coatings have a relative short lifetime. The effect of these materials on window optical quality is unknown. Rain-X, for example, is reported to reduce window optical quality as it wears away. Some coatings will require periodic renewal.

Marine Technology Transfer Requirements: Evaluate effects of coating on window optical quality immediately and over time. Evaluate difficulty of applying material over windows. Evaluate compatibility of material with active technologies such as heat and fluids for active system influence on deterioration in icephobic qualities or optical quality.

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17 Cables

Like windows, cables are a special challenge to deice or anti-ice. They are thin and therefore accumulate ice relatively efficiently. Ice often mechanically wraps around cables. Cables are often either located where they cannot be reached easily for manual deicing, or they operate through sheaves and on windlasses, such as on cranes. However, there are methods to deice cables. Excellent reviews for electric power transmission cable deicing are provided by Laforte et al. (1998) and Farzaneh et al. (2008).

Pneumatic boots

Figure 81. Icicles hanging from lifeline on U.S. Coast Guard cutter *Midgett* in the Bering Sea, March 1990 (Ryerson).

Intended or Actual Application: Structures with guy wires, such as communication towers or safety railings on marine structures and ships, are susceptible to coating with ice. Accumulation of ice by wind-driven drops on one side of a cable causes increased weight on the upwind side. Because cables are generally weak in torsion, the heavy ice-laden side rotates down due to gravity and more ice then accumulates on the freshly exposed side of the cable. Occasionally, cables may completely rotate through this process, enveloping the cable in a spiral of ice (Kuroiwa 1965). Slow freezing of drizzle and rain also cause cables to become enveloped in ice. Freezing was sufficiently slow on the Coast Guard cutter *Midgett* in a March 1990 superstructure icing event so that the resulting accretion created icicles (Figures 81 and 82) (Ryerson and Gow 2000).

Operating Environment: Govoni and Franklin (1992) tested a pneumatic cable deicing concept at the summit of Mt. Washington, New Hampshire. The cable boot was 14-m long and encased a 1-cm-diameter guy wire on a 9.5-m-high tower. The pneumatic boot was controlled by an ice detector that cycled the boot when 90 g of ice formed on the ice detector. During icing conditions the boot inflated every 9 to 60 min with inflation times of 15 to 30 sec. Govoni and Franklin (1992) concluded that a cycling frequency of 15 min for a duration of 15 sec could keep the cable boot ice-free in the most severe conditions. The boot was least successful with soft rime, which is also the least threatening of ice. The boot was most successful shedding hard rime and glaze (Figures 83 and 84). During the tests, cloud liquid water contents ranged from 0.1 to 0.8 g m^{-3}.

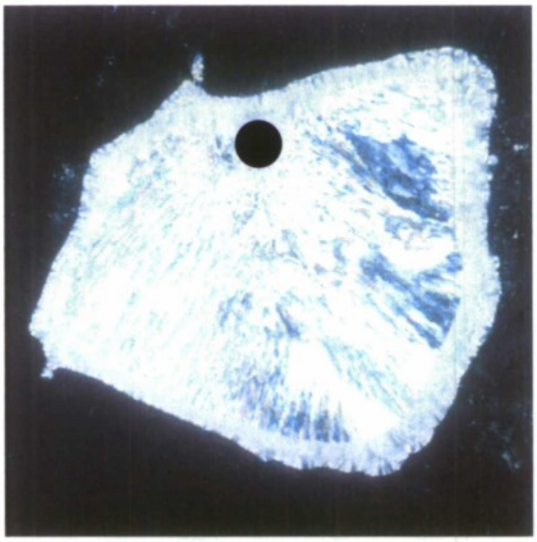

Figure 82. Vertical section of icicle taken from gap on lifeline ice in Figure 81. The section is photographed between crossed polarizers to show crystal structure. Note the small, round ice crystals near the lifeline, and the elongated crystals radiating away from it. The outermost layer around the sample is an artifact of mounting the sample on a glass slide (Ryerson and Gow 2000).

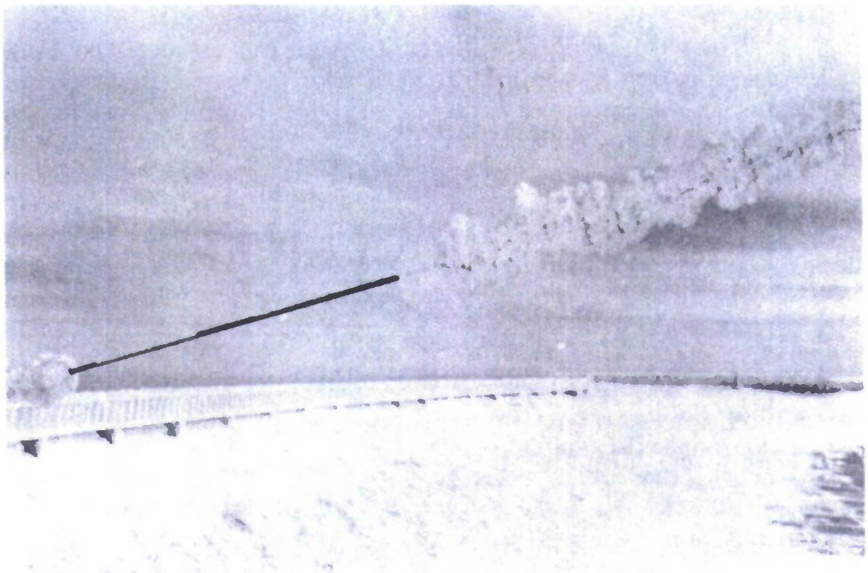

Figure 83. Dark line shows ice-free deicing boot. Hard rime covers the guy wire above and below the boot (Govoni and Franklin 1992).

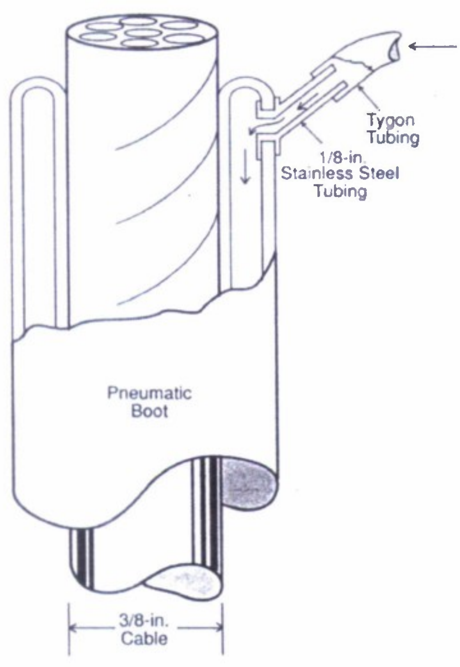

Figure 84. Cross section of inflatable cable deicing boot (Govoni and Franklin 1992).

Engineering Concept: A cross section of the Govoni and Franklin (1992) deicing boot is depicted in Figure 84. The boot was constructed to slip over the 1-cm-diameter stranded cable. The prototype boot was attached to the cable at each end with hose clamps and silicone sealant. The 14-m cable was inflated with dry nitrogen at a pressure of 172 kPa per inflation cycle.

TRL: 6.

Deicing or Anti-icing: Deicing. High winds also moved the boot and provided some anti-icing capability without inflating the boot.

Current Acquisition Cost: Unknown.

Operational Cost: Cost of providing dry gas for inflation.

Maintenance Requirements: Replenish gas. Periodic checks for leaks.

Current Advantages and Disadvantages: The boot deiced successfully in most icing conditions, but required removal of cable for installation. The boot cannot be used on wires that heat because they are energized, or on cables that operate through guides and sheaves. Some anti-ice capability is possible without inflation.

Potential Marine Application and Safety Enhancement: The cable boots could be used on guy wires on supply boat masts or platforms. They may also be adaptable to pipes.

Marine TRL: 4–5. The cable boot has not been applied in the marine environment.

Marine Advantages and Disadvantages: The technology is not proven in saline superstructure ice. The system's ability to withstand severe spray under the main deck is unknown. The system may be damaged in a heavy work environment.

Marine Technology Transfer Requirements: Redesign boot for installation without removal of cable. Redesign boot for installation over pipes. Evaluate boot for capability in superstructure sea spray ice conditions.

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Expulsive

Déglaçage Industriel DGI Inc.
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Intended or Actual Application: Laforte et al. (1995) have designed an expulsive system that can be installed on nearly any cable. The system consists of a pair of wires that are wound around and encircle the cable protecting all sides (Allaire and LaForte 2001, 2003). In addition, 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 Baelt suspension bridge at Korsor connecting East and West Denmark (Figure 85). Atmospheric ice, rime, and glaze formed on bridge cables (Figure 86). When sun warmed the ice during the day, heavy pieces of the ice fell onto the roadway forcing the bridge to close, occasionally for periods of two hours. Therefore, a cable expulsive system has been placed experimentally on the upper 100 m of two vertical hangars next to a tower (Figure 87) (Laursen 2004; Laursen and Zweig 2007).

Figure 85. Great Baelt suspension bridge connecting East and West Denmark. Atmospheric in-cloud icing occurs about 150 m above the ocean surface. The towers are 203-m high (image courtesy E. Laursen).

Figure 86. In-cloud icing of cable structure at a tower top (both images courtesy E. Laursen).

Operating Environment: TheDéglaçage Industriel DGI electroexpulsive system was developed for deicing electrical transmission line cables. Electrical transmission lines ice due to rime and also glaze from freezing rain and freezing drizzle. Conditions verifying the capability of the system on the Great Baelt Bridge have not occurred because no icing has yet been observed on the main cable structure since the system was installed in 2003. The DGI developer claims the system "looks very promising as a solution in marine icing problems" (Laforte et al. 1995; Allaire and LaForte 2001, 2003).

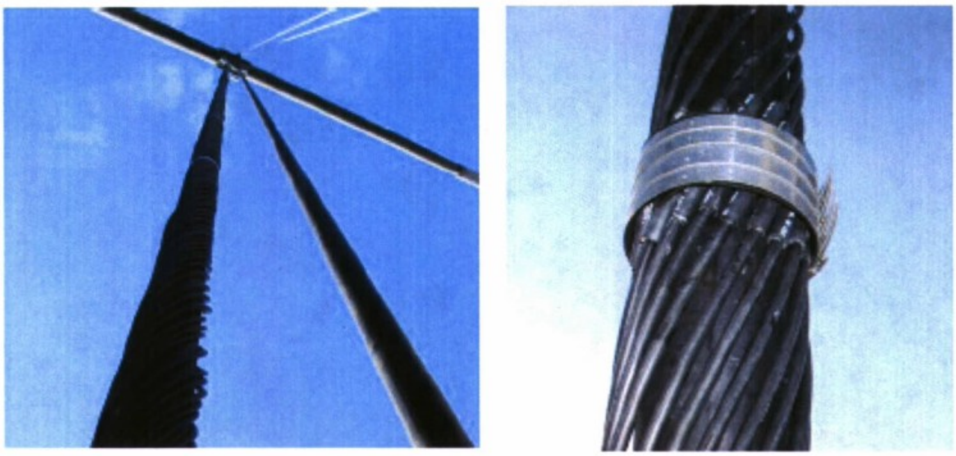

Figure 87. DGI electroexpulsive cables located on upper 100 m of vertical hangar (left cable in left image). Closeup of connections between DGI cables (right image) (both images courtesy E. Laursen).

Engineering Concept: Farzaneh et al. (2008) explain the DGI technology in a thorough review of transmission line deicing technologies. It comprises 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. To operate successfully, the actuator wires must be tightly wrapped around the cable. 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 deice a 260-m cable (Farzaneh et al. 2008). The expulsive system consumes about 0.01 times the power of conventional thermal methods and does not cause interference with telecommunications.

TRL: 5–6. System is being tested in a relevant environment, the Great Baelt Bridge, but results of tests are not yet available.

Deicing or Anti-icing: Deicing.

Current Acquisition Cost: Company no longer in operation.

Operational Cost: Cost of electricity. Developer claims system uses 1% of the power of thermal deicing systems.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: System must be installed on cables. Systems cannot be used on cables that operate through sheaves or wind on windlasses. The system causes no telecommunication system interference. The system is not yet proven to be effective except in limited testing. The system has the potential to completely deice cables.

Potential Marine Application and Safety Enhancement: The DGI system could be used to deice supply boat rigging and cabling on a platform such as railings. It does not appear to be usable on crane and windlass cables.

Marine TRL: 4–5. The technology has not been applied in the marine environment, though the developer claims that it would be effective.

Marine Advantages and Disadvantages: The system is electrical and will require appropriate wiring for safety, and periodic inspection. It could be used on smaller-diameter cables and piping under the main deck in heavy superstructure icing areas without frequent attention. It is unclear how effective it is with fresh, soft sea spray ice. It is potentially usable on safety railing cable. It is probably not usable on cables used for lifting or pulling, and those used in sheaves and windlasses.

Marine Technology Transfer Requirements: Evaluate system capability in all forms of icing. Determine system capability in heavy spray areas under platform main deck. Determine applicability on supply boat rigging where damage is possible.

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Coatings

Intended or Actual Application: Coatings on cables have applied principally to electrical transmission lines, where most of the research on cables and icing has been accomplished. Icing of lines on ships such as rigging for fishing trawlers is a secondary, but significant potential application. Icing of catenary and overhead wires for delivering power to electric railway vehicles has also been an occasional application.

Operating Environment: Cables are used in nearly any environment and experience a broad range of temperatures and rime ice, glaze ice, and frost conditions. In addition, on marine structures cables can accumulate large masses of saline ice. Examples include the rigging of boats and ships, and potentially cabling of cranes, railings, and cables in the cellar deck of platforms.

Engineering Concept: Baum et al. (1988) described experimentation 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), in a review of transmission line deicing technologies, found no coatings acceptable. 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) conclude 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 deicing and anti-icing technologies, also find no currently available coatings adequate to keep ice from forming on cables. However, they indicate that there is promise in new superhydrophobic materials because there is a positive relationship between hydrophobicity and icephobicity. In addition, drops may be able to roll off surfaces before freezing. They also indicate that two promising icephobic materials are self-assembled monolayers and diamond-like carbon.

TRL: 1–5. Several superhydrophobic materials are near market-ready and others are in concept.

Deicing or Anti-icing: Deicing—with a goal of anti-icing.

Current Acquisition Cost: Varies.

Operational Cost: None.

Maintenance Requirements: Most coatings require periodic renewal.

Current Advantages and Disadvantages: Many coatings reduce ice adhesion strength, but none are sufficiently low in strength so as to prevent ice accretion, or to self-shed without assistance. Ice often mechanically locks around cables rendering coatings less effective. Coatings require periodic renewal over a period of months to a few years. Coatings may not be able to overcome mechanical locking of ice to cable strands.

Potential Marine Application and Safety Enhancement: Coatings can be applied to lifelines, guys, rigging, and cables used on cranes and windlasses.

Marine TRL:1–6. These technologies have not been applied in the marine environment.

Marine Advantages and Disadvantages: Some coatings are developed as anti-fowling materials for the marine environment and are therefore designed to survive marine conditions. Coatings are often difficult to apply in the marine environment. Coatings may cause slippery conditions if applied to safety rail cables. Coatings will not release ice that is attached mechanically by wrapping around cables.

Marine Technology Transfer Requirements: Evaluate effectiveness of cable coatings in superstructure icing conditions. Evaluate coating durability. Evaluate ease of applying coatings. Evaluate compatibility of coatings with active deicing systems used on cables, such as expulsive, mechanical, and electrical systems.

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Heat

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Intended or Actual Application: Various technologies have been developed to deice or anti-ice cables through heating. Most technologies function only on energized electric transmission lines where current flowing through the line is used directly, or in modified form, to heat the cable. However, many cables are not energized, such as ground wires atop high-voltage transmission lines, chairlift cables, gondola cables, guy wires, ship rigging, and cables on cranes and winches used for hoisting. Other technologies, such as induction (Petrenko and Sullivan 2007), may be used to heat normally unenergized lines.

Operating Environment: The most common icing threats to cables are caused by glaze from freezing rain or freezing drizzle, rime, and wet snow. Ice increases weight on cables causing them to sag and, in the case of conductors, touch other cables or reduce ground clearances to dangerous levels. Ice wraps around cables and, if inclined like guy wires, can slide down the wire and strike anchors with sufficient force to break them loose and cause tower failures. Ice changes the shape of cables and can cause aerodynamic effects such as galloping that tears cables loose from insulators. Ice can also freeze pulleys and guides through which cables run, such as on chairlifts, gondolas, and cranes, which may cause the cable to jump the guides, wear grooves in the pulleys, or wear cable wires. All of these effects can occur over the wide range of thermal, wind, and moisture conditions that create glaze, rime, and wet snow.

Engineering Concept: Many approaches, all electrically powered, have been used, or proven in concept, for heating and anti-icing or deicing cables. Several of these methods are reviewed by Farzaneh et al. (2008). The most common and oldest method is Joule heating. 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. Farzaneh et al. (2008) explain several additional three-phase and contact load transfer methods that involve more intimate knowledge of how AC electrical transmission lines operate. Joule heating methods are used worldwide and are well-accepted as transmission line deicing methods.

Several innovative methods to heat lines have been conceived and patented at Dartmouth College by Petrenko and colleagues. To date, none of these concepts have been applied to commercial transmission lines, but tests are being planned. One concept is a variation of the pulse electrothermal method (Petrenko et al. 2003). In this case, the cable is coated with a dielectric material, which is coated on the outside with a conductive material (Farzaneh et al. 2008; Petrenko and Sullivan 2005). A rapid, high-current pulse is sent through the external conductor to melt a thin layer of ice causing adhesive strength to decrease and the ice to fall. This requires modification of the cable to add the dielectric and conductive coatings. In addition, ice mechanically wrapped around the cable will not release using this technique.

Another method deices energized and non-energized lines. A cable requiring deicing is paralleled by a second cable up to 3 m away, carrying a high frequency AC current operating at 60 to 100 kHz (Petrenko and Sullivan 2007). The high-frequency current in the energized line induces a high-frequency capacitive current in the parallel unenergized line. A portion of the induced current flows through the ice capacitively and resistively, with the resistive portion of the current inducing Joule heating that melts the ice. The inventors suggest that this technology could be used on bridge and ship cables for deicing.

A variation of the high-frequency approach has been applied by Sullivan et al. (2003) for deicing long sections of transmission line by exciting cables with high-frequency power operating between 20 and 150 kHz. The technique uses an ice dielectric and skin effect to create up to 80 W m^{-1} of heating in the line. No modification of the line is necessary except for providing the source of high-frequency power, and the addition of traps at either end of the line segment being heated. However, the authors do express concerns about the creation of EMI that will disrupt communications systems and cause corona (Petrenko and Sullivan 2007).

Petrenko and colleagues have also recently revealed a variable resistance cable deicing technique. No technical details of the invention have been released. However, a press release (Lamm 2009) indicates that it involves minor cable modifications when the line is renewed, and a control system. Installation would increase the cost of replacement cables by about 10%. Testing of the technology is planned in China, and also in Russia in 2009.

TRL: 5–9. Joule techniques are applied operationally worldwide. The new methods have been tested in laboratories.

Deicing or Anti-icing: Deicing and anti-icing—depending upon the approach.

Current Acquisition Cost: Unknown.

Operational Cost: Cost of the power to operate the system.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: All technologies require energized lines, a coating that is energized, or a parallel line that is energized. High frequencies may cause EMI. Cable modification would be required to use any of the technologies on ship rigging or on hoisting cables. The systems could cause a potential electrical hazard, especially in a saline environment where arc-over of insulators contaminated with salt could occur.

Potential Marine Application and Safety Enhancement: The technologies are potentially applicable to lifelines, crane hoisting cables, and ship rigging. Cable modification for hoisting cables may be difficult. Lifelines would require isolation before being energized, and salt in ice may cause current leakage to areas where current flow is not desired. Several technologies may be applied to ship rigging, but arc-over of insulators may be a problem.

Marine TRL: 4–5. No record of testing or use of these technologies in the marine environment could be located.

Marine Advantages and Disadvantages: Use of these technologies for hoisting and in the marine environment would present challenges, and may cause new safety concerns. EMI may disrupt communications. If usable, the technologies could make cable deicing fast and efficient.

Marine Technology Transfer Requirements: Evaluate technologies in saline marine environment. Evaluate how to apply technologies to hoisting cables, lifelines, and ship rigging.

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Mechanical

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https://www.bchydro.com/contact/index.jsp?pg=

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http://www.protura.no/startpage.html

Intended or Actual Application: Mechanical deicing systems are applied to electrical transmission lines, ship rigging, and electric railway overhead wires. Mechanical methods can refer to manual methods or automated systems that vibrate or mechanically shock cables.

Operating Environment: Mechanical systems are often applied manually; therefore the cable must be within reach of personnel or they can be activated remotely. Mechanical systems can be applied to electrical transmission lines from the ground or from helicopters, to ship rigging, and to electric railway overhead wires. Remote mechanical methods include expulsive (covered separately), roving ice cutters, and systems that mechanically 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.

Engineering Concept: Mechanical methods can take several forms. Expulsive is a mechanical method described separately. Shock waves, vibration, and twisting of cables all are mechanical. Govoni and Ackley (1986) do hypothesize that natural cable twisting did cause some ice shedding of cables on Mount Washington, New Hampshire. However, Laforte et al. (1998) suggest that cable twisting methods weaken cables and are difficult to apply. Allaire and Laforte (2003) have designed a system that slowly twists cables about their longitudinal axis, and then suddenly releases them. A manual version of the method has been successfully demonstrated on cables, 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, Figure 6.2). Although effective, it may be difficult to reach cables for applying such an apparatus. Two systems have been developed to 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 (Deicer 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, Figure 6.4). Blank cartridges fire a piston into the cable, causing a shock wave strong enough to remove ice without damaging the cable. 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, Figure 6.6). The system successfully removes ice accretions. It is easily installed on cables and is powered from an external source.

TRL: 5–8. Devices are developed as prototypes and tested in relevant environments, or they are commercially available.

Deicing or Anti-icing: Deicing.

Current Acquisition Cost: Unknown.

Operational Cost: Unknown.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: Mechanical methods are often difficult to apply because they must be either permanently installed, or the cable must be accessible for emplacement 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.

Potential Marine Application and Safety Enhancement: Mechanical methods can be used to deice most cables, guys, and lifelines. Short cable lengths on lifelines may make mechanical methods difficult to apply. Automated mechanical methods may be applicable in superstructure icing areas under main decks if operated frequently enough for ice not to become too thick.

Marine TRL: 4–5. These technologies have not been applied in the marine environment.

Marine Advantages and Disadvantages: Mechanical methods may be difficult to apply to cables on cranes due to height. Cables under the main deck also may not be readily accessible. Mechanical methods generally are developed for hard, brittle freshwater ice. Fresh superstructure ice is relatively soft.

Marine Technology Transfer Requirements: Evaluate mechanical systems in saline marine environment. Evaluate systems with softer saline superstructure ice.

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18 Ice Detection

Automation of ice protection requires detection of ice to know when to activate deicing and anti-icing technologies. Many methods of ice detection are available, and excellent reviews are provided by Fikke et al. (2006) for electrical transmission line applications, by Jackson and Goldberg (2007) and the SAE (2004) for aviation applications, and by Homola et al. (2006) for application to wind turbines. The marine environment has other requirements, and an overview of potential technology solutions follow.

Ice Hawk

Goodrich Corporation
Sensors and Integrated Systems
14300 Judicial Rd.
Burnsville, MN 55306
Telephone: 952-892-4300
http://www.goodrich.com

Figure 88. Ice Hawk imager mounted in pod atop Twin Otter fuselage (image courtesy NASA Glenn Research Center).

Intended or Actual Application: The Goodrich Ice Hawk images the location of ice and snow on surfaces. The system was originally developed to detect the presence of ice and snow on aircraft surfaces to determine whether they required deicing and, more importantly, to determine whether they were completely ice-free. The Ice Hawk was used by Ryerson et al. (1999) to show the location of ice-free areas on helicopters after using a variety of deicing technologies. NASA Glenn Research Center mounted the Ice Hawk on a pylon about 1 m above the main wing of a Twin Otter aircraft and mapped in-flight ice formation on the wing (Figure 88). It was also evaluated by the U.S. Air Force during deicing 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) (Figure 89).

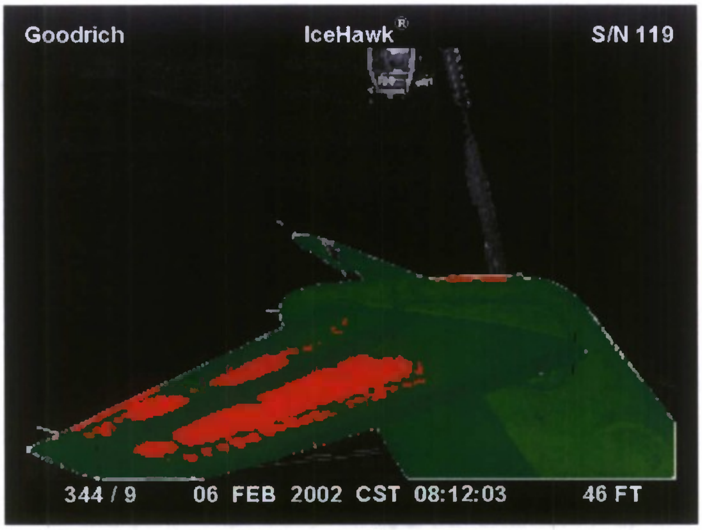

Figure 89. Ice Hawk image of ice (red areas) on DC9 horizontal stabilizer (Bender et al. 2006) (courtesy Goodrich Corporation).

Operating Environment: The Ice Hawk is intended for the airport operating environment. CRREL used the system at temperatures near 0°C when using infrared, hot air, and hot water deicing technologies (Ryerson et al. 1999). Air Force tests were conducted within the Eglin Air Force Base McKinley Climatic Chamber in dense water fog, which may have affected ice detection accuracy (Wyderski et al. 2003). Goodrich specifications indicate an imaging range of 2.4 to 22.8 m, and the area viewed from a distance of 22.8 m is 9.1 by 13.7 m. These viewing ranges and areas can be easily changed for other applications.

Engineering Concept: The IceHawk detects ice by analyzing the polarization of laser light reflected from surfaces (Figures 90 and 91). 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; this is detected and pixels are mapped

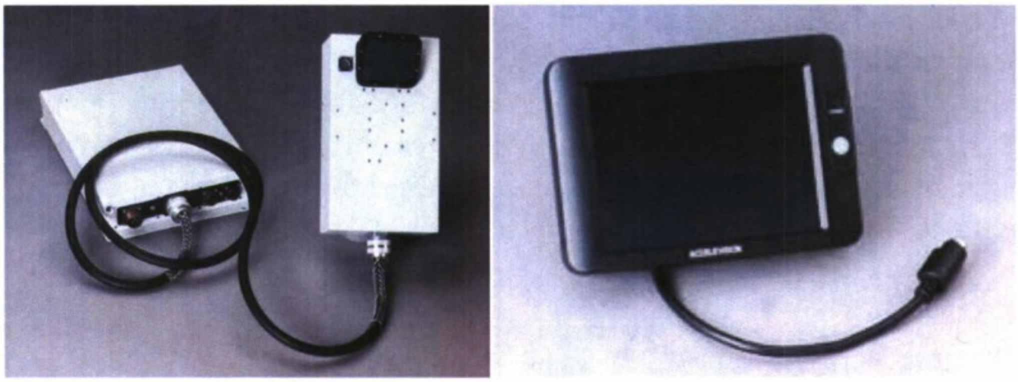

Figure 90. (Left to right) Ice Hawk electronics module, sensor module, and display (courtesy Goodrich Corporation).

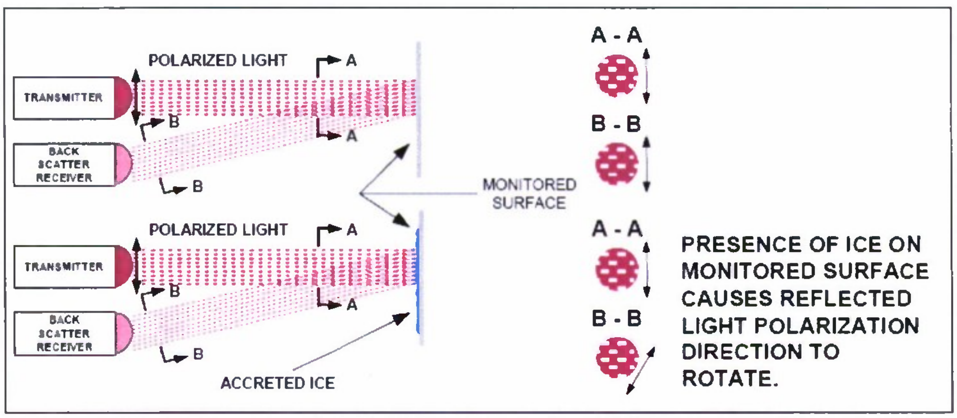

Figure 91. Rotation of polarized light emitted by sensor shows presence of ice or snow (courtesy Goodrich Corporation).

as ice. The current Ice Hawk model 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 thicknesses. Additionally, the Ice Hawk has the ability to "see through" materials such as deicing fluid and anti-icing fluid, hydraulic fluid, and fuel to detect frozen contaminant buildup underneath. The emitter is eye-safe.

TRL: 9. COTS.

Deicing or Anti-icing: Ice detection.

Current Acquisition Cost: Goodrich is not currently manufacturing the Ice Hawk, but the company still owns the technology and is currently developing other variants of optical ice detection systems for use on the ground or in flight for a variety of applications.

Operational Cost: Minor.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: The Ice Hawk provides a visual indication of the presence of ice, but currently does not activate deicing systems automatically; this capability is planned. The imaging capability provides information about the spatial distribution of ice or snow. The system could provide information about the distribution of ice thinner than 0.5 mm. It does not measure and display ice thickness. The system operates without external light sources on most materials.

Potential Marine Application and Safety Enhancement: Ice Hawk could provide information about dangerous thin-ice formation on work areas, and ice on helicopter landing pads, walkways, and stairs. It could provide an indication of incipient superstructure icing under the main deck.

Marine TRL: 7. System has not been evaluated in marine environment.

Marine Advantages and Disadvantages: The Ice Hawk can indicate the presence of thin ice dangerous to personnel and helicopters. The system can cover a large area. Range of detection can be tuned for specific applications. The system may require protection of optics from salt spray. The system may detect ice on complex lattice structures, such as the flare boom if it could be viewed within the detection range specifications. The system may be less accurate in obscuring optical conditions such as fog, precipitation, and spray. The system may be difficult to use in the heavy spray environment of a supply boat.

Marine Technology Transfer Requirements: Evaluate Ice Hawk in marine conditions on a platform and, potentially, on a supply boat. Evaluate ability to detect thin saline ice. Determine effectiveness in deteriorated infrared transmission weather conditions.

****

Ice Camera

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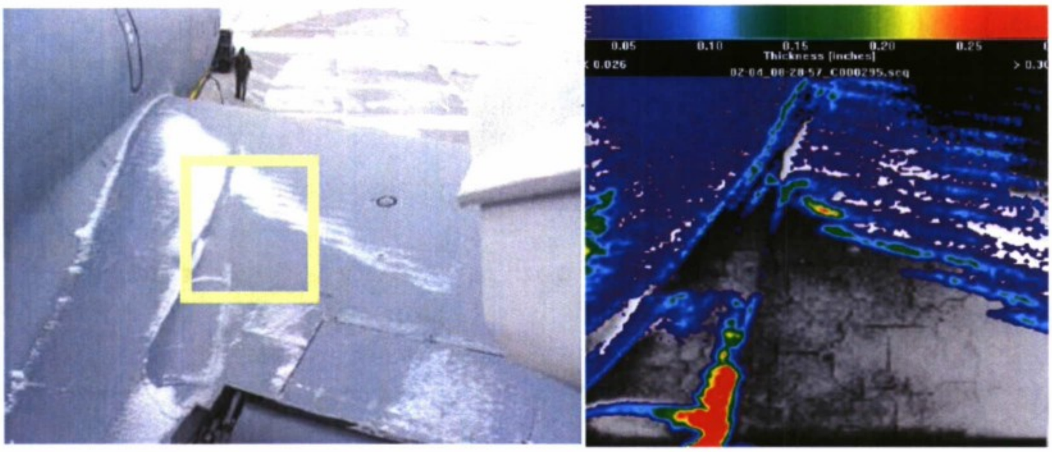

Figure 92. Snow and ice on wing root (left) and Ice Camera image of snow and ice greater than 0.5-mm thick (right). The degree of contamination is color-coded such that blue represents thin ice and red represents thick ice (images courtesy MDA Space Missions).

Intended or Actual Application: The MDA Ice Camera maps the location of ice on surfaces and its thickness. Intended users are aircraft preflight deicing operators. Pilots must know that the aircraft is completely free of ice before takeoff, and tactile methods are often faulty (Bender et al. 2006). Highway and runway deicing interests wish to know when "black ice" and other thin accumulations are causing deterioration of traction. The NASA spaceflight program has conducted extensive experiments with the Ice Camera to determine its ability to detect ice, frost, and ice balls of various diameters on the exterior Sprayed On Foam Insulation (SOFI) of the Space Shuttle external fuel tank. The system is intended to replace visual, tactile, or other mechanical indications of the presence of ice on surfaces.

Operating Environment: The Ice Camera is intended to be used in "a wide range of winter weather conditions and it must detect ice in the presence of water, deicing and anti-icing fluids" while minimally impacting airline operations (Gregoris et al. 2004). It must withstand weather exposure in remote locations viewing roadway surfaces. It also must be sufficiently portable and must be explosion proof to be moved through the NASA Space Shuttle launch gantry system. The system has not been fully engineered to operate in all of these environments. The intensity of the computed signal corresponds to the thickness of ice or water. The system detects less than 0.5 mm of ice on any surface and beneath water or deicing and anti-icing fluids. It can distinguish between ice, slush, and water. It indicates ice thicknesses of 0.5–12 mm at ranges of 3–28 m, but ranges to 80+ m have been achieved. Image update rate is 1–2 Hz. The system has all-weather capability and operates in all-natural lighting conditions (Gregoris 2006).

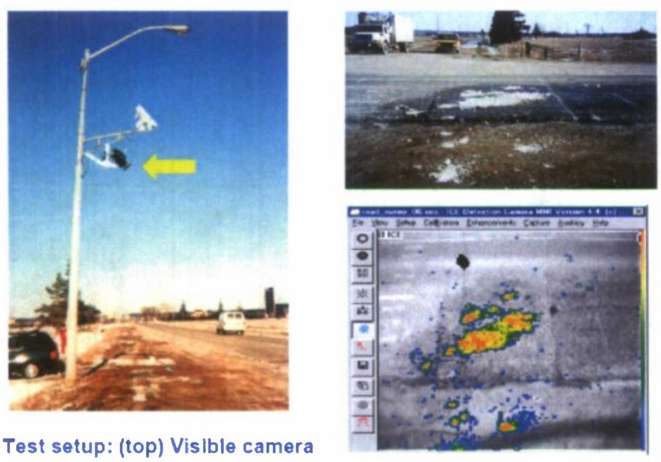

Figure 93. Ice camera (yellow arrow) and visible imaging camera viewing road surface (left). Visible and Ice Camera images of snow on pavement (right top and bottom, respectively) (Images courtesy MDA Space Missions).

Engineering Concept: The Ice Camera system uses a patented technique that measures near infrared wavelengths to detect ice, water, and fluids. In operation, a low-power (<100 W) Xenon strobe emits short-wave infrared energy. A focal plane array sensor and optical filters collect energy reflected from the surface of interest at several wavelength bands in the 1.1- to 1.4-µm region. The intensities of each wavelength band are used to calculate the spectral contrast (Figure 94). Wavelength shifts occur as the infrared energy passes through the ice, and the reflected spectral contrast indicates the material at the surface (Figures 92 and 93) (Meitzler et al. 2007). For water- and glycol-based deicing 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. The camera generates digital video of the surface under inspection and displays it in grayscale, which is color enhanced where ice exists to represent thickness (Figures 92 and 93). The proof-of-concept system used to inspect the Space Shuttle External Tank weighs about 100 kg including the camera and illuminator, cart, explosion proof enclosures, a battery, a gaseous nitrogen purge system and bottle, and an operator display and data recording system (Meitzler et al. 2007) (Figure 95). The purge system is required for operation in hazardous areas. The Ice Camera used for aircraft inspection weighs <14 kg. A production system for aircraft inspection that will meet SAE AS5681 is currently in the design phase.

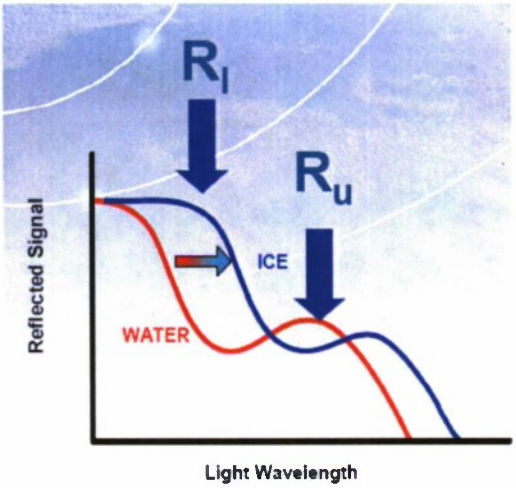

Figure 94. The ratio of ice to water reflectance indicates the presence of ice. Thickness is correlated with wavelength contrast intensity (courtesy MDA Space Missions).

TRL: 7. Basic components are integrated and tested in a simulated operational environment.

Deicing or Anti-icing: Ice and water/glycol detection.

Current Acquisition Cost: Unknown.

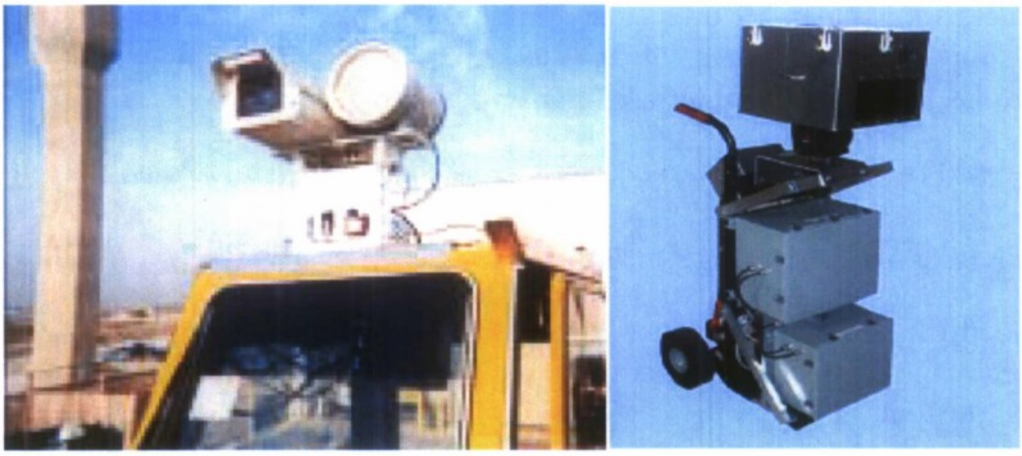

Figure 95. All-weather sensor head for aircraft inspection (left), and portable system used for Space Shuttle experiments (right) (images courtesy MDA Space Missions).

Operational Cost: Cost of electricity.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: System provides ice or water location and thickness on almost any surface. It detects ice through water and deicing fluids. Range of clear ice thicknesses detected are 0.2 mm to approximately 75 mm. Ice thickness to 25 mm has been measured. The system can be used to estimate the ice and water content of slush. Operational range is a camera design parameter with typical ranges 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. System is not influenced by ambient light.

Marine TRL:5.

Marine Advantages and Disadvantages: The Ice Camera can indicate the presence of ice at locations dangerous to personnel and helicopters. The system may require protection of optics from salt spray. The capability of the system in partially obscured conditions is unknown; the system may not be practical in the heavy spray environment of a supply boat. The range of ice thicknesses displayed may show incipient icing on decks, stairs, work areas, and helicopter landing pads.

Marine Technology Transfer Requirements: Evaluate Ice Camera in sea spray superstructure icing conditions on a platform, and possibly on a supply boat. Evaluate ability to detect thin saline ice. Determine effectiveness in deteriorated infrared transmission conditions.

****

Goodrich (Rosemount) Icing Rate Detector

Goodrich Corporation
Sensors and Integrated Systems
14300 Judicial Rd.
Burnsville, MN 55306
Telephone: 952-892-4300
http://www.goodrich.com

Intended or Actual Application: The Goodrich (Rosemount) icing sensor technology is probably the most widely used and analyzed detection technology. Rosemount ice detectors sample the icing environment at the probe location, and the user must determine how representative the measurements are to other locations. The icing sensor operates by accumulating ice on a vibrating probe that decreases in frequency as ice mass accumulates. The fundamental technology has evolved into a suite of detectors that operate in many environments. Detectors are designed for use on aircraft to correlate to ice accumulation on airfoil and engine inlet surfaces. They are also designed to detect freezing rain glaze ice accumulation (Ryerson and Ramsay 2007), or rime ice (Claffey et al. 1995) near the ground (Figure 96). Rosemount ice detectors have also been used experimentally on ships and on oil platforms, and have been used operationally on communication towers, wind turbines, ground turbines, and marine vessel engine intakes (Ryerson and Longo 1992; Minsk 1985).

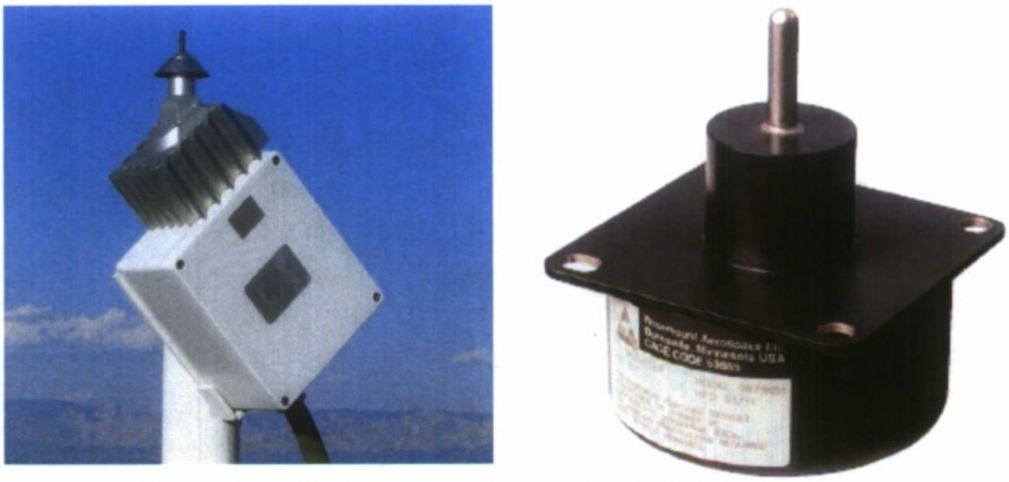

Figure 96. The model 872E3 icing sensor measures the intensity and duration of freezing rain ice storms (left) (Ryerson). The model 871LH1 is a freezing rain sensor that may also be usable in marine icing conditions (right) (courtesy Goodrich Corporation).

Operating Environment: Goodrich Rosemount icing sensors are used in a wide variety of environments. Aircraft-mounted icing sensors experience FAA FAR25 Appendix C icing conditions; they must survive cruise speeds of over 300 m sec^{-1} and temperatures found at cruise altitudes. Aircraft ice detectors are mounted such that they sample essentially the same (or similar) air stream as the wing and engine inlet. Thus, the ice accretion on the ice detector probe can be correlated to these surfaces. Sensors are also located near ground level to measure rime ice or freezing rain. The 872C3 sensor, similar in appearance to the 872E3 in Figure 96, is used by the U.S. National Weather Service's Automated Surface Observing System (ASOS) at over 600 locations in the United States to measure glaze ice accretion onset and, in the future, perhaps icing amount (Ryerson and Ramsay 2007). Other models are designed for use on communications towers to trigger ice protection technologies for antennas and radomes.

Engineering Concept: The Goodrich Rosemount icing detector senses ice mass on a 25-mm-long by 6-mm-diameter cylindrical probe (usually oriented vertically in non-aircraft applications) that vibrates axially at a nominal 40 kHz when ice-free due to magnetostriction (Figure 97) (Jackson and Goldberg 2007). When rime, glaze, or frost accumulates on the probe, the mass and stiffness of the ice causes 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 probe heater is activated for a period of typically 5–7 sec. Ice melts and runs from the probe and vaporizes. Following a deicing cycle, the probe typically cools below freezing (and resumes the reporting of ice accretion) in a few seconds on aircraft-mounted units, to less than 5 or 6 min on ground-based units. Infrequently (e.g., with ambient temperature very near freezing, very 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). Cooling rate (like the ice accretion time) is a function of airspeed/airflow, ambient temperature, and liquid water content. 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).

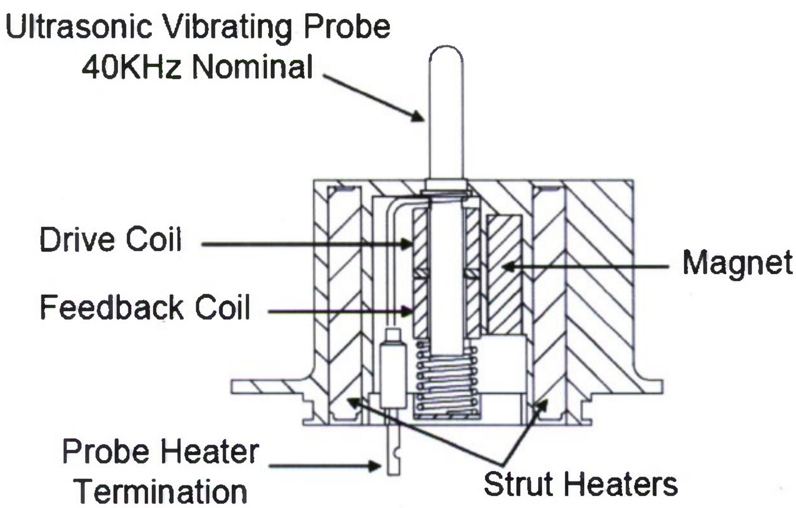

Figure 97. Cross section of Goodrich magnetostrictive ice detector strut and probe assembly (courtesy Goodrich Corporation).

TRL: 9. Goodrich icing sensors have been COTS products since the 1960s.

Deicing or Anti-icing: Icing rate detection.

Current Advantages and Disadvantages: Goodrich Rosemount icing sensors indicate when icing is occurring and its rate. Algorithms may be used to compute ice accumulation on structures (Ryerson and Ramsay 2007). However, relationships between the probe and other objects are only correlative and depend upon their relative exposure and shape, and the detector calibration. The probes do not indicate how much ice is on objects after icing ceases and melts or other ice removal begins. The instruments are easily installed and operated. However, they are also damaged if struck, which affects their response to ice accretion.

Current Acquisition Cost: Unknown.

Operational Cost: The unit in sensing mode is less than 5–10 W. Heater power is dependent on the model chosen; 50 W is for the probe heater only and 250–350 W will include a strut heater.

Maintenance Requirements: No routine maintenance is required.

Potential Marine Application and Safety Enhancement: Goodrich Rosemount detectors can provide an indication of icing rate for the environment within which they are placed. Goodrich ice detectors could be placed over decks to determine potential icing of work areas or walkways. The instruments could be used on helicopter landing pad areas, flare booms, and perhaps under the main deck in sea spray icing.

Marine TRL: 7.

Marine Advantages and Disadvantages: The probes can become overwhelmed in heavy icing, such as may occur in superstructure icing, if probe heaters cannot keep the probe deiced. The probe strut can be damaged if struck, such as in heavy industrial environments, and cause a shift in calibration. They detect all types of ice readily and are used in many operational environments. They rarely give false alarms.

Marine Technology Transfer Requirements: Measure probe capability in saline superstructure icing conditions.

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Microwave Aircraft Icing Detection System (MAIDS)

ITT, Intelligence and Information Warfare
85 Northwest Blvd.
Nashua, NH 03063
Contact: Philip J. Joseph, PhD
Telephone: 603-459-2236
http://www.iiw.itt.com

Intended or Actual Application: Dedicated Electronics (now ITT) developed the Microwave Aircraft Icing Detection System (MAIDS) to detect ice on aircraft surfaces with enough sensitivity to provide a warning before the ice accretes to a dangerous thickness. The detector development was funded under a Small Business Innovation Research (SBIR) program by the NASA Glenn Research Center. The detector is flush and conformal with the wing surface so that ice forms on the detector in the same manner as on the wing if the detector is also similar to the wing thermally and with regard to materials that effect ice adhesion (Figure 98).

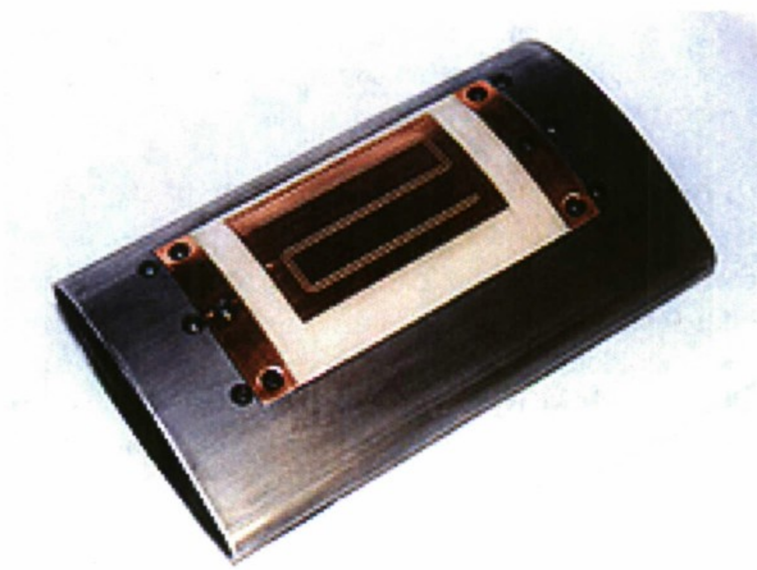

Figure 98. ITT conformal microwave ice detector (courtesy Intelligence and Information Warfare).

Operating Environment: MAIDS can measure incipient icing from 0.025-mm to about 6-mm thickness. It can also distinguish among (1) ice, (2) water (or deicing fluid), and (3) a mixture of ice and water (or deicing fluid). Sensors are sufficiently rugged so as to withstand rain erosion. The system is low in complexity and, therefore, is robust with regard to capability in harsh conditions.

Engineering Concept: MAIDS provides a continuous-wave microwave signal. The output is split onto a sensor path and a reference path. The sensor path is a microwave transmission line that is either a ground-plane coplanar-waveguide (CPW) or slot-line (SL). Either type is mounted flush with the airfoil surface at the desired ice-detection location. With the exception of the sensory portion of the transmission line, all circuitry is enclosed. The sensor- and reference-path outputs are processed through an inphase/quadrature (I/Q) detector, then through an analog-to-digital (A/D) converter. The data processing subsystem computes the magnitude and phase of the sensor signal relative to those of the reference signal, and uses the sensor signal obtained when the sensor is bare to normalize the response of the system when water and/or ice are present. The normalized magnitude and phase response of the system serve as an indication of the thickness of ice and or water (Figure 99). Output is sent to a cockpit display.

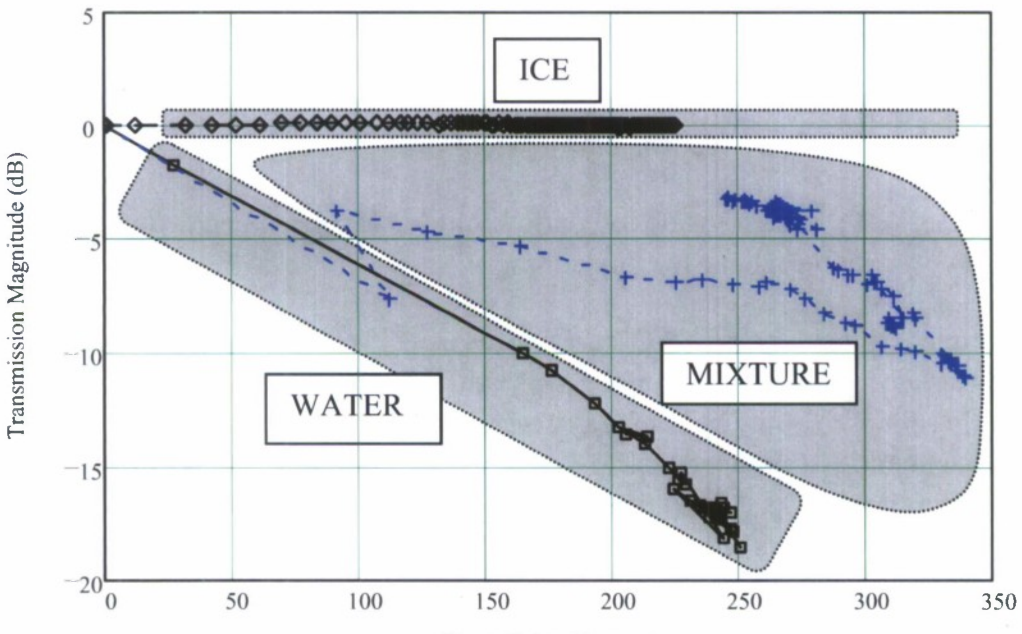

Figure 99. Three distinct regions of transmission magnitude versus phase make it possible to distinguish among ice, water, and mixtures on the detector surface. The thickness of ice is indicated by the amount of phase shift (courtesy Intelligence and Information Warfare).

TRL: 5. The system has been tested in several icing wind tunnels.

Deicing or Anti-icing: Ice detection.

Current Acquisition Cost: Unknown. Inquiries concerning rights for commercial use should be addressed to NASA Glenn Research Center, Commercial Technology Office, Mail Stop 4–8, 21000 Brookpark Rd., Cleveland, OH 44135. Refer to LEW-17135.

Operational Cost: Minimal.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: MAIDS detects thin ice layers that are a hazard to aviation and to traction in walkways, runways, and roads. The system is robust and conformal to the ice accretion surface. The system can distinguish ice from water and deicing fluids. The system can indicate ice thickness.

Potential Marine Application and Safety Enhancement: If the system can operate in saline ice, it could be used on many surfaces, including walkways, decks, helicopter landing pads, and bulkheads. It may also be an ideal sensor for areas under platform main decks where superstructure icing forms. It has the potential to reduce accidents for personnel and perhaps protect the entire platform.

Marine TRL: 4. There is no indication that MAIDS has been evaluated in a simulated or actual marine environment.

Marine Advantages and Disadvantages: The system is conformal and therefore less easily damaged than other detectors. It may be sufficiently robust to apply in sea spray areas under platform main decks, and on bulkheads of supply boats. It is not known if the system functions in saline environments, or requires additional calibration. It is not known if the system interferes with communication and control electronics.

Marine Technology Transfer Requirements: Evaluate capability in saline marine environments. Determine if system interferes with communication and electronic control devices. Determine if microwaves are a hazard to humans when placed in work areas.

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SMARTboot

Goodrich Corporation
Sensors and Integrated Systems
1555 Corporate Woods Parkway
Uniontown, OH 44685-8799
Telephone: 330-374-3040
http://www.goodrich.com

Intended or Actual Application: SMARTboot is an aircraft ice detection and protection system combining inflatable pneumatic boots and a wide-area flush-mounted ice detection system. The system detects and measures ice accretion, indicates when to activate boots, confirms deicing boot inflation, detects residual ice, and verifies ice removal. The system removes ambiguity about the amount of ice that has accumulated on the airfoil and when to activate a pneumatic boot system. 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. SMARTboot was certified as an advisory system. A panel light indicated to the pilot when it was time to activate (inflate) the deicers.

Operating Environment: SMARTboot is an in-flight ice detection system paired with a pneumatic deicing boot. It is certified for flight in FAA FAR25 Appendix C conditions and is designed to detect the icing conditions defined by the temperatures, drop diameters, liquid water contents, and duration of exposure in the FAR. The system is designed for the leading edge of a fixed-wing aircraft, especially on tail surfaces, such as the Piper Malibu/Mirage. Although the SMARTboot ice detector was originally designed as a wide-area sensor for pneumatic deicers, very thin sensor patches (1.0-mm thick) have been successfully developed for sensing ice buildup on other surfaces. One application uses patches applied to non-deiced surfaces of a UAV to warn the remote pilot operators when ice is forming. It may be adapted to many other surfaces.

Engineering Concept: The SMARTboot ice detector is embedded within the flexible material of the deicing boot (Napert 1998; Pruzan et al. 1993). However, as stated by Rauckhorst (1996), it can be removed from the boot and attached anywhere on the aircraft as an ice detector. The detector consists of conductive strips built into the surface of the boot (Figure 100). The conductive strips are strands of graphite embedded into conductive rubber. When ice forms on the surface, one of the electrodes (the driver or positive electrode) sends a signal to the receiving electrode and the impedance is measured between the electrodes. The impedance provides the thickness of the ice. When a predetermined ice thickness is reached, the boots are inflated. The sensor covers a 232-cm^2 area, and a typical installation weighs less than 5 kg.

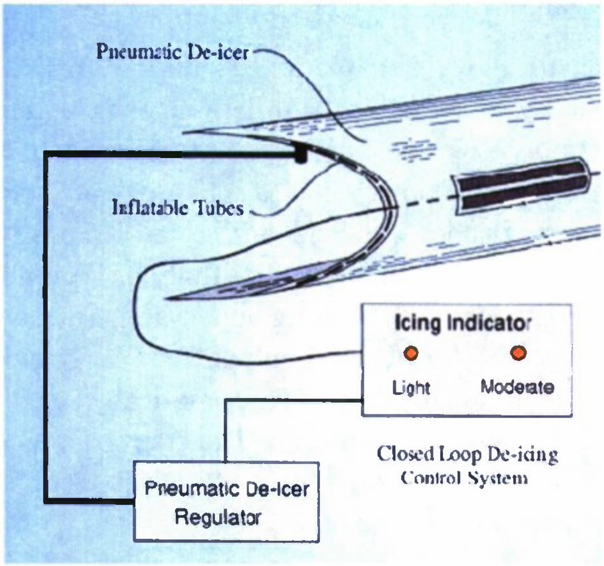

Figure 100. SMARTboot system with icing rate enunciator and boot inflation controls (courtesy Goodrich Corporation).

TRL: 8. Product that can be configured to various aircraft.

Deicing or Anti-icing: Ice detection.

Current Acquisition Cost: Contact Goodrich Corporation for assistance: Goodrich Corporation, Sensors and Integrated Systems, 1555 Corporate Woods Parkway, Uniontown, OH 44685-8799. Telephone: 330-374-3040; http://www.goodrich.com

Operational Cost: 1 amp at 28 V (DC).

Maintenance Requirements: The electrical sensing system requires periodic testing by checking continuity of the ice thickness sensors to confirm there are no intermittent shorts (Napert 1998).

Current Advantages and Disadvantages: Detectors are easily placed anywhere on a surface without the boots. Placing the detector on the boot allows pilot to know the amount of ice on the boot at the sensor location. The detector and boot combination allows potential automatic boot activation.

Potential Marine Application and Safety Enhancement: The SMARTboot detector could be placed at multiple locations, inexpensively and easily, on a marine structure if the impedance-based technology is compatible with the saline marine environment. The detector and boot combination could be placed on bulkheads and in locations under the main deck where superstructure icing dominates, and anywhere that conventional boots are applicable. The detector alone could be placed on flare booms, cranes, and nearly any location requiring monitoring for incipient icing. The detectors could not be used on walkways, in work areas, and locations where physical damage could occur.

Marine TRL: 5. The technology requires evaluation in a saline marine environment.

Marine Advantages and Disadvantages: Because impedance is the method of ice thickness measurement, the system may require recalibration for saline icing conditions. The bare conducting surface could be damaged easily in work areas and locations where abrasion or bridging of conductors could occur. Residual salt on the detector surface could cause false indications of ice.

Marine Technology Transfer Requirements: The SMARTboot detector needs thorough testing in marine saline conditions because it is based upon impedance. Recalibration or reengineering may be necessary. The effects of residual salt requires evaluation.

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TAMDAR

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Morrisville, NC 27560
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http://www.airdat.com

Intended or Actual Application: Tropospheric Airborne Meteorological Data Reporting (TAMDAR) 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.

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 (Figure 101). 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 direction to operate with maximum accuracy. Daniels et al. (2004) provide a thorough review of instrumentation performance.

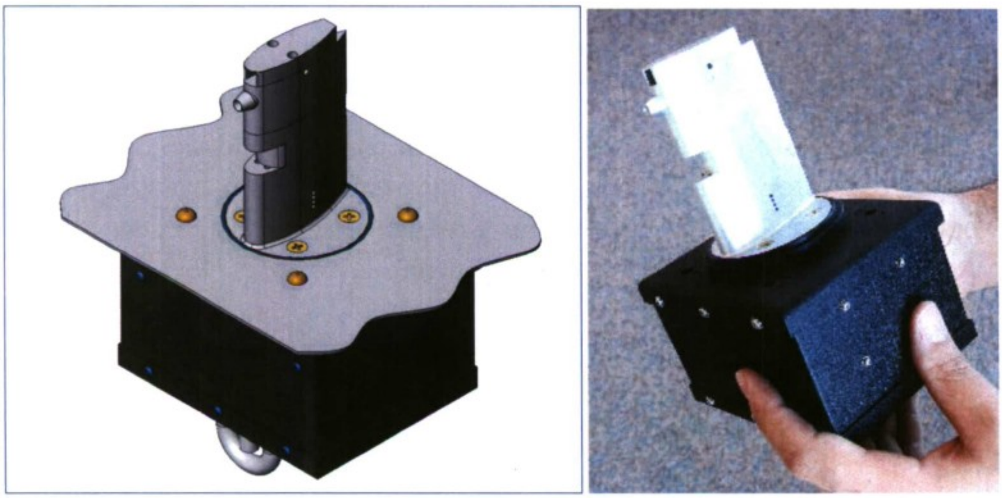

Figure 101. Rendering of TAMDAR sensor head (left) and image of actual sensor head (right) (images courtesy AirDat LLC).

TRL: 9. TAMDAR has been certified for several transport aircraft models.

Deicing 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 is 10 W with deicing heaters powered off, and 280 W with heaters powered on.

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: The TAMDAR sensor head could be mounted on a supply boat or offshore platform. However, orientation into the wind would be required. It could provide icing rates at a number of locations on the platform 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.

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 using artificial aspiration, for example. The system provides multiple weather variables. The sensor head 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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Vaisala

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Telephone: 800-408-9457 (toll-free)
E-mail: icena.customer.support@vaisala.com
http://www.vaisala.com/weather/applications/traffic

Intended or Actual Application: Vaisala markets several sensor systems to detect icing on pavements for road weather advisory systems. In situ sensors are available that are embedded in the pavement, and remote sensing systems are available that detect road conditions from a sensor scanning the pavement from a tower or other remote structure.

Operating Environment: The Vaisala systems operate along roads, runways, and bridges in all conditions of temperature, wind, and precipitation. 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. In situ sensors (DRS511/DRS511B) can indicate the presence of "black ice," provide an optical measurement of ice thickness, provide pavement and ground temperature, and measure conductance and polarization of the surface. The remote sensors (DSC111 and DST111) provide optical detection of ice, snow, or frost, and provide an assessment of pavement friction (Haavasoja 2006).

Engineering Concept: The in situ DRS511 sensor (Figure 102) detects roadway surface conditions by making six measurements. These include optical detection, surface conductivity, electrochemical polarizability, surface capacitance for black ice (black ice has no capacitance and because it is ice frozen without many air bubbles, it is transparent and takes the color of the material on which it lies, making it difficult to detect), surface temperature, and ground temperature at a depth of 6 cm. Actual values reported are surface temperature and ground temperature at a 6-cm depth (-40°C to 60°C), 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^{-1}) 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 & Runway Surface Analyzer (ROSA) to report all of the conditions listed.

The ROSA and DRS511 system can also estimate road surface 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).

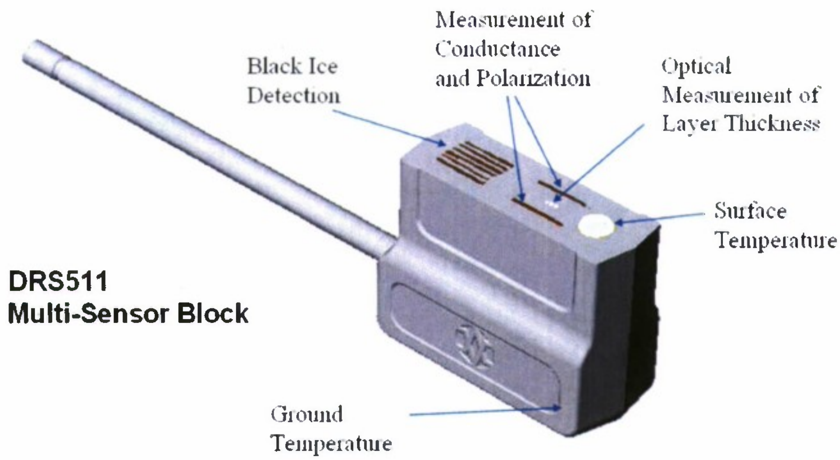

Figure 102. DRS511 sensors (top) and sensor systems buried in pavement (bottom) (images courtesy Vaisala Inc.).

The DCS111 Remote Road Surface Condition Sensor and DST111 Remote Road Surface Temperature Sensors together provide road surface conditions and friction estimates using their suite of measurements (Figures 103 and 104). 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 m². Energy reflected back from the road surface differentiates between 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 of 2 mm, and snow water equivalent to 1 mm, all with a 0.01-mm resolution. The system operates in fog and falling snow unimpaired. In addition, the DST111 directly measures air temperature and humidity, and measures road temperature remotely using a passive infrared sensor over a road surface area of about 0.8 m^2. Agreement of DSC111, DST111, and DRS511 with independent measurements is typically over 90%. Systems are currently in use in Canada, the United States including Alaska, Finland, Sweden, Germany, and the United Kingdom.

Figure 103. DSC111 remote road condition sensor (left) and DST111 remote road temperature sensor (right) (images courtesy Vaisala Inc.).

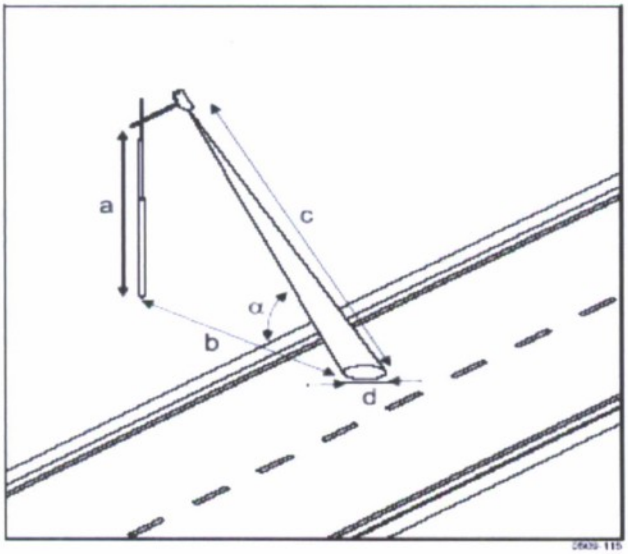

Figure 104. DSC111 and DST111 are mounted on a pole alongside the area sensed. For proper functioning, distance c must be between 1.8 and 15 m, and angle α must be between 30° and 85° (images courtesy Vaisala Inc.).

TRL: 8–9. COTS products.

Deicing or Anti-icing: Ice detection.

Current Acquisition Cost: Unknown.

Operational Cost: Electricity usage for these units varies; DSC111 and DST111 are about 4–7 W each.

Maintenance Requirements: Occasional lens cleaning.

Current Advantages and Disadvantages: The instruments provide indications of state of the roadway surface for multiple variables at a single location. The remote instruments cannot be operated in a pan-tilt mode because of calibration considerations. The systems are not degraded by poor visibility. The technologies provide friction estimates—useful for predicting conditions that users of pavement will experience. DRS511 also indicates chemical freezing point depression—useful for indicating when surface treatment renewal is required.

Potential Marine Application and Safety Enhancement: The systems would be useful for showing conditions of work areas, walkways, stairs, and decks. The sensors may work on vertical surfaces with modification. The in situ instrument would be useful on helicopter landing pads. The systems are useful for indicating incipient icing and the ongoing conditions of surfaces with anti-icing and deicing technologies.

Marine TRL: 6–7. The systems have not been reported as tested in the marine environment.

Marine Advantages and Disadvantages: The systems can operate on bridges, so they may operate on marine structures. The ability of the remote sensors to withstand heavy spray is unclear. The systems would report conditions when decks and work areas are becoming dangerously slippery. The in situ DRS511 may have applications in many locations, including under the main deck in superstructure icing areas.

Marine Technology Transfer Requirements: Evaluate all three sensor systems in marine environment conditions. Evaluate systems on surfaces that are not horizontal. Assess capability of systems for predicting slippery decks for personnel.

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Visidyne

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Intended or Actual Application: With funding from NASA and the U.S. Army, Visidyne developed the first non-contact sensing system for detecting the accumulation of ice on rotorcraft blades in flight (Visidyne n.d.). The system is intended for use on helicopters where placement of in situ sensors on blades is difficult. The technology was originally developed and patented by Massachusetts Institute of Technology (Dershowitz and Hansman 1991; Hansman and Dershowitz 1994).

Operating Environment: The system is designed for helicopters operating in icing conditions. Although this generally refers to operation in FAA FAR25 Appendix C icing conditions, most helicopters operate at altitudes below 3000 m, and icing conditions at lower altitudes are somewhat different than FAR25 Appendix C (Masters 1983).

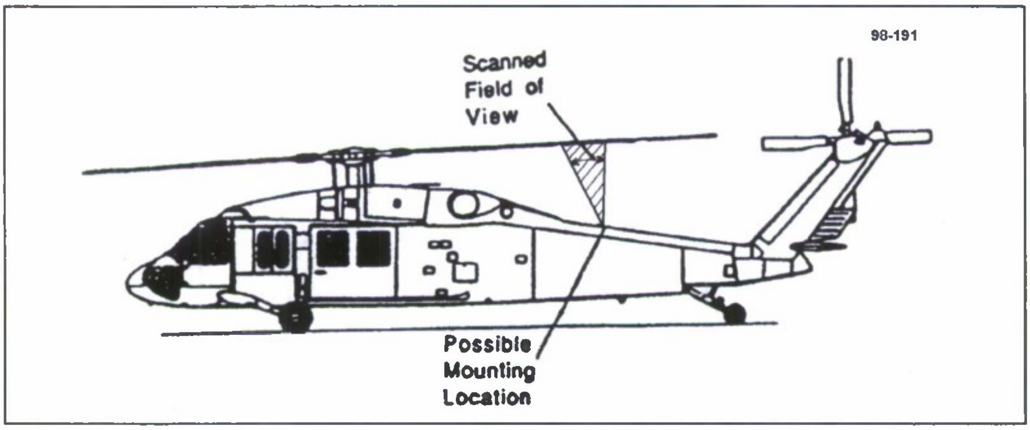

Figure 105. Sensor application to helicopter (courtesy Visidyne Inc.).

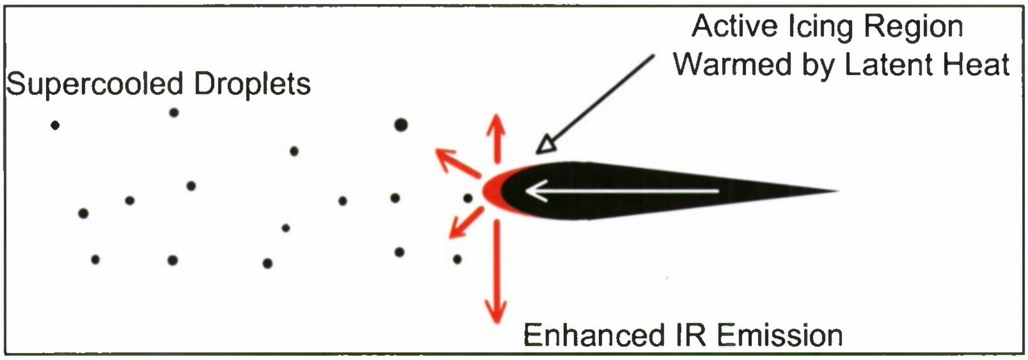

Figure 106. Representation of latent heat release during icing (courtesy Visidyne Inc.).

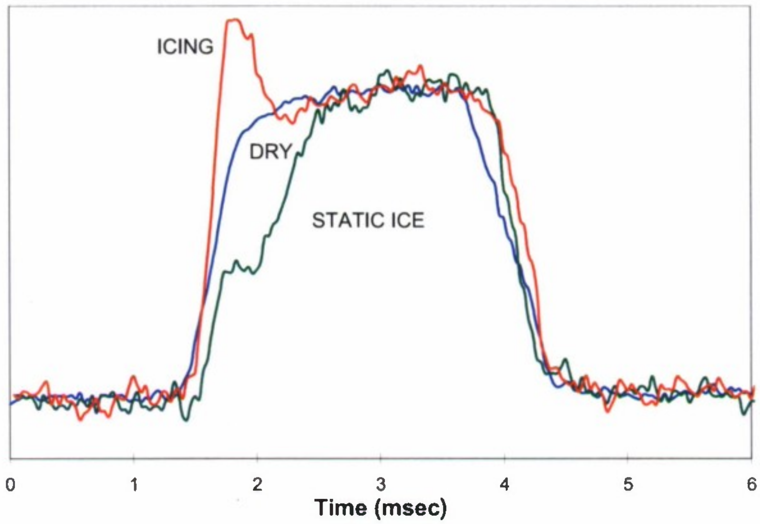

Figure 107. Differing thermal response of blade leading edge when dry, when actively icing, and after ice has accreted. Vertical axis is unscaled, but increasing in temperature with height above horizontal axis (courtesy Visidyne Inc.).

Engineering Concept: Visidyne demonstrated a prototype sensor that detected ice accretion on rotor blade leading edges by measuring the characteristic temperature profile resulting from the latent heat released as supercooled water freezes. The system was field tested 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 (Figure 105). When ice accreted, the region where the freezing occurred became warmer than the surrounding surface due to the release of latent heat of fusion (Figures 106 and 107). 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 edge of each blade to determine whether icing was occurring. Neither Visidyne (n.d.) from their field trials, nor Hansman and Dershowitz (1994) from laboratory experiments, provided examples of temperatures recorded during their experiments. In general, though, all temperatures will be relative to air temperature, position on the rotor blade due to aerodynamic heating, rate of ice accumulation, and whether the accumulation was wet-growth clear ice (above the Ludlam limit) or dry-growth rime ice (below the Ludlam limit).

TRL: 6. Demonstration of a prototype in a simulated operational environment.

Deicing or Anti-icing: Icing detection.

Current Acquisition Cost: Unknown.

Operational Cost: Minimal.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: The sensor system indicates that icing is occurring. However, it would require modeling and testing to assess the absolute values of icing from the relative temperatures sensed. It is not clear how effectively the system shows ice on the leading edge after it is no longer accumulating. Its greatest value appears to provide a binary indication that ice is accumulating, or that it is not accumulating.

Potential Marine Application and Safety Enhancement: The technology may be applicable to areas of a platform or a supply boat that are not readily accessible to human observers. It may be applicable in superstructure icing locations on supply boats and below the main deck of platforms. It would not be useful for detecting snow or sleet accumulation, and probably not frost formation because of the small latent heat quantities released when it forms. The technology may be applicable to helicopters servicing offshore platforms.

Marine TRL:4. No marine testing has occurred.

Marine Advantages and Disadvantages: The system may not be effective in a heavy spray environment due to water flowing over the ice surface. The optics could become covered with spray or salt, causing obscuration. It is not clear that the system indicates the presence of ice after it has stopped accumulating. It could be used to activate an ice protection system. The system may be useful, as proposed, on helicopters.

Marine Technology Transfer Requirements: Determine system capability in marine environment. Further assess utility as a helicopter blade ice detector because in-flight icing of helicopters serving offshore facilities is a documented hazard.

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Pole-Ice

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Intended or Actual Application: The Valley Group provides real-time electrical transmission line thermal rating technology that increases line capacity and reliability. Pole-Ice was developed to represent ice accumulation on electrical transmission lines. The instrument was tailored to represent cable ice load. Pole-Ice provides a continuous measure of ice load on a rod analogous to a horizontal electrical transmission line ground wire (Figures 108 and 109).

Operating Environment: Pole-Ice was intended to operate at stations along electrical transmission lines. Therefore, the instrument was designed to measure and survive icing conditions caused by freezing rain and rime ice. Seven Pole-Ice instruments were installed along an electrical transmission line that crossed the Appalachian Mountains in western Virginia to provide a measure of ice accretion on that line. Furthermore, one unit is in use at the National Weather Service AWOS in Troutdale, OR, and another was tested in New Zealand (Seppa 1996).

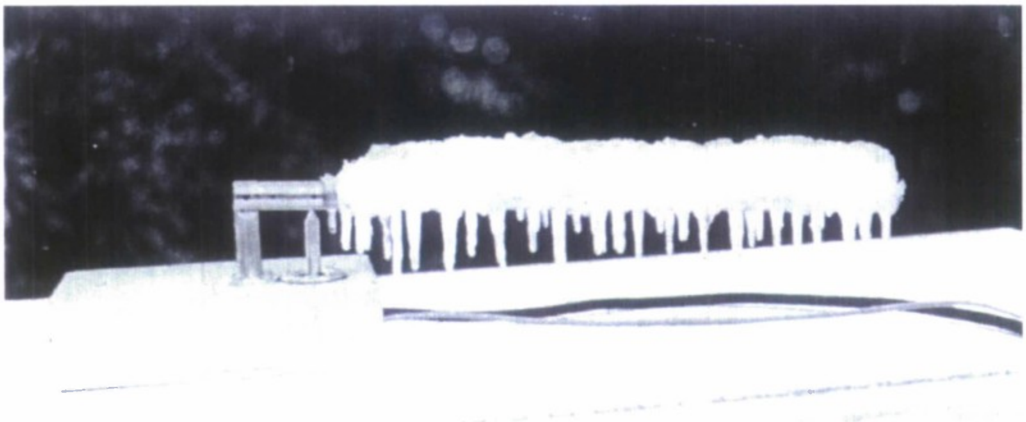

Figure 108. Pole-Ice with ice accretion (courtesy The Valley Group).

Engineering Concept: Pole-Ice consisted of a 19-mm-diameter aluminum cylinder representing the diameter of a transmission line. The cylinder was attached to a pivot at one end, and rested on a knife edge on a load cell (Figures 108 and 110). As ice accumulated, the rod increased in weight and increased the precision load cell signal (Figure 109). Rod length could be increased for more sensitivity at lower ice loads, but the instrument would then have lower overall capacity. Cylinder diameter could also be changed to assess the effect of collector diameter on ice load (Seppa 1996).

TRL: 7. Pole-Ice at one time was a COTS product. It is no longer available or supported by the Valley Group.

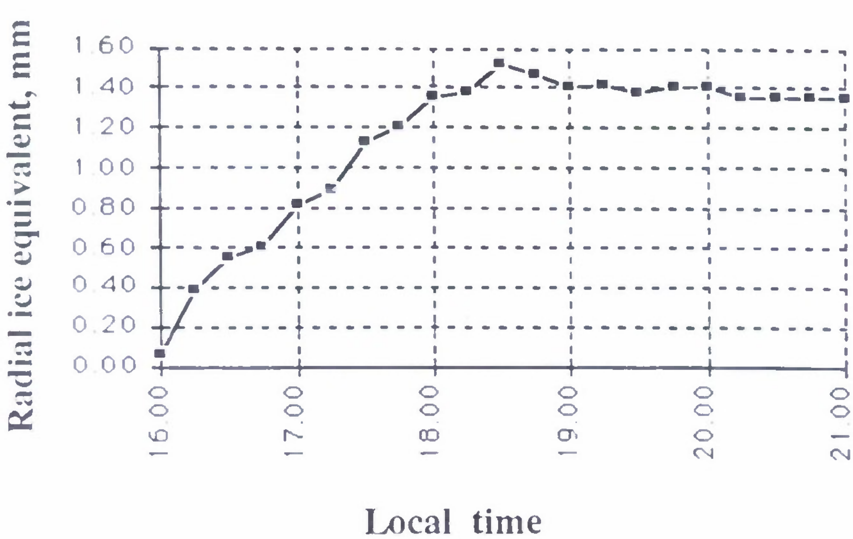

Figure 109. Freezing rain event of 14 December 1995 showing change of ice load with time during storm (courtesy The Valley Group).

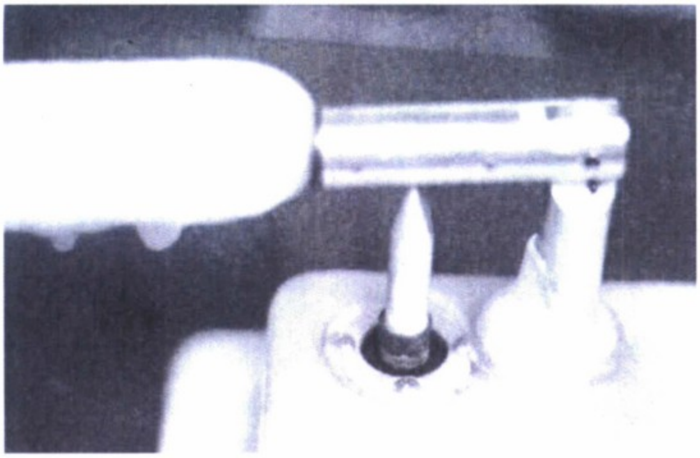

Figure 110. Heaters within Pole-Ice keep the hinge and load cell ice-free. A thermal insulator visible on the rod at the ice edge prevents the outer rod area from warming (courtesy The Valley Group).

Deicing or Anti-icing: Ice load measurement.

Current Acquisition Cost: No longer available and no longer supported by The Valley Group.

Operational Cost: Minimal. Heater and data logging electrical costs.

Maintenance Requirements: Unknown.

Current Advantages and Disadvantages: Pole-Ice provides a continuous measure of ice load on the exposed rod. Unlike ice detectors that periodically deice, Pole-Ice indicates icing rate from the ice load time-series. The system has no method of deicing the rod, therefore ice load decrease is a function only of natural deicing conditions such as melt or sublimation. However, this is one of the few instruments that can measure the entire natural time history of ice accumulations.

Potential Marine Application and Safety Enhancement: Pole-Ice, or a derivative, could be used to assess icing rates above the main deck of a platform. Pole-Ice may best represent icing of cables and wires—its ability to represent icing of decks and bulkheads is unknown. However, it could serve as an analog for other surfaces.

Marine TRL: 4–5. Pole-Ice is not known to have been evaluated in a marine environment.

Marine Advantages and Disadvantages: Motion of a supply boat may cause the ice accumulation rod to bounce and cause measurement noise. The instrument may not be sufficiently robust for heavy spray environments, such as in areas of high superstructure icing. The capability of Pole-Ice in snow and superstructure icing conditions is unknown. Pole-Ice may not represent icing of flat surfaces such as decks and bulkheads accurately without calibration.

Marine Technology Transfer Requirements: Conduct study of Pole-Ice capability in marine conditions, including its ability to represent superstructure icing conditions. Determine ability to represent cable, bulkhead, and deck ice accretion. Determine Pole-Ice capability in snow and rime ice conditions.

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19 Technology Summary and Application

The summaries presented, and the brief reviews by Ryerson (2008), suggest that a wide variety of technologies may be available for deicing, anti-icing, and detecting ice on offshore structures. Most of these technologies are currently used in aviation, highway, and electric power transmission applications. However, they have been developed with different requirements, in many cases, than are needed by the offshore environment.

This summary is organized from two perspectives. The first perspective is from a technology viewpoint, providing a summary of the principal characteristics of each technology group. The second perspective is from that of the offshore problem. That is, given an icing problem, as summarized in Table 1 for offshore platforms and in Table 2 for supply boats, suggestions are made about which technologies may have the greatest probability of providing useful solutions. This summary provides an overview of the characteristics of technologies versus potential applications.

Technology application matrices

Impacts of icing on platform and supply boat locations and operations versus potential anti-icing or deicing technology solutions are paired in Tables 8 and 9. These tables show the technologies that may be most readily applied to reducing the impact of icing at the location, or for the operation, listed for platforms and supply boats. The need for, and success of, any technology solution is a function of the icing impacts experienced by the offshore operation as demonstrated in Tables 1 and 2, specifics of the offshore operation, and the ability to adapt technologies to the requirements. Unknowns make the process of matching operational needs and technologies imperfect and somewhat subjective. The tables and following summaries should, therefore, be taken as guidance rather than absolute recommendations. Experience of operators with specific technologies may be the most useful guidance.

Table 8. Platform icing safety impact versus potential technology solution matrix.

	1*	2	3	4	5	6	7	8	9	10	11
Stability	X	X	X	X	X	X		X	x	X	
Integrity	X	x	X	X	X	X		X	x	X	
Fire and rescue		x	X		X	x	X	X			x
Communications		X	X		X		X	x		X	x
Helicopter pad	X	x	x		X	X		X	x		X
Air intakes		X	X	x	X	x	X	X			
Flare boom	X	X	X			X	x		x	x	x
Handles, valves		x	x		x	x	X	X			X
Windows	X	X			X	X		X	x		
Cranes	X	X	X			X	x		x	x	x
Winches	X	X	x		x	X	X	X			x
Stairs	X		X		X	X	X	X	x		
Decks	X		X		x	X	X	X	x		
Railings		x	x	X	X	X		X	x	x	x
Hatches		X		X	X	X		X	x		x
Cellar deck		X	X	x	X	X	x	x			
Moon pool		X	X	x	X	X	X	x			

Bold uppercase **X** suggests a stronger match than does an unbolded lowercase x.

*Technology key
1. Chemicals and Chemical Distribution
2. Coatings
3. Design
4. Expulsive
5. Heat
6. High-Volume Water, Air, Steam
7. Infrared
8. Manual
9. Piezoelectric
10. Pneumatic Boots
11. Vibration and Covers

Table 10 summarizes the range and average of current and marine TRLs for technologies summarized within each technology category. The TRLs were subjectively determined, using Graettinger et al. (2002) for guidance, from information available from vendors, technical papers, and discussions with developers and suppliers. Therefore, they should be considered rough guidance regarding the state of development of the technology for the intended purpose, and especially for the offshore marine environment.

Table 9. Supply boat icing safety impact versus potential technology solution matrix.

	1*	2	3	4	5	6	7	8	9	10	11
Seaworthiness	x	**X**	**X**	**X**	**X**	**X**		**X**	x	**X**	x
Fire and life rafts		**X**	**X**		**X**	x	x	**X**			x
Communications		**X**	**X**		**X**		**X**	x		**X**	x
Ventilation		**X**	**X**	x	**X**		**X**	x			
Windows	x	**X**			**X**	**X**		**X**	x		
Ladders	x				**X**	**X**	x	**X**	x		
Decks and railings	**X**		**X**	x	**X**	**X**	x	**X**	x	x	x
Hatches		**X**		**X**	**X**	**X**		**X**	x		x
*See Table 8 for technology key.											
Bold uppercase **X** suggests a stronger match than does an unbolded lowercase x.											

Several rough conclusions can be drawn from Table 10. TRLs of near 8 or higher indicate that a product is near or is commercially available. Differences of two to three points between current and marine TRLs usually indicate that the product has not been evaluated in a marine environment. For example, infrared emitters are generally at a high level of development and most of the infrared technologies reviewed were readily available to purchase, but, in some cases, with engineering for specific situations. The 5–9 range of current infrared TRLs with an average of 8 for four reviewed technologies supports this observation. The four-point lower infrared TRL for the marine environment indicates that there is little documentation or indication by developers that infrared emitters have been tested in an actual, or high-fidelity simulated, marine environment. Boots, as another example, are readily available commercially for aircraft, as they have been for approximately 70 years. Boots have also been tested in the marine environment and have shown some success. However, commercial boots designed for specific use in the marine environment could not be located; they would require custom design and construction.

Table 10 suggests that even manual deicing methods, the traditional method of deicing marine structures, were not rated as TRL 8 or higher because equipment used in the marine environment, such as mallets, were not designed specifically for deicing. Manual items designed for deicing have only been tested and are not commercially available.

Table 10. Technology TRL summary.

	TRL Range	TRL Average	Marine TRL Range	Marine TRL Average
Chemicals and Chemical Distribution	6-9	8	5-7	6
Coatings	2-9	6	1-8	5
Design	6-7	7	5-6	6
Expulsive	5-8	7	4-5	5
Heat	6-9	7	4-7	5
High-Volume Water, Air, Steam	6-9	7	4-6	5
Infrared	5-9	7	3-7	5
Manual	6-7	7	6-7	7
Piezoelectric	3-4	4	3-4	4
Boots	8-9	9	6	6
Vibration and Covers	5-6	6	3-4	4
Windows	4-9	7	4-7	5
Cables	1-9	6	1-5	4
Ice Detection	5-9	8	4-7	5

Chemicals and chemical distribution

Summary: Chemicals are the most widely used ice control technology, and because of the volume of material used and their effects on the environment and infrastructure, it is believed that more dollars are spent on chemicals than any other ice protection technology. In the chemical category, three application technologies and 14 chemicals are described. The three described application methods—weeping wings, anti-icing mats, and FAST—all require liquid chemicals and are certainly not the only methods of applying chemicals. Common techniques, such as spraying from a dedicated apparatus like aircraft deicing trucks, or spraying liquids or broadcasting solid chemicals from a highway maintenance truck, were not presented in the chemical descriptions. However, they are all viable methods that could be adapted to offshore operations by scaling and adapting the technologies. The choice of liquid or solid chemicals will also determine application method. Application could be as simple as using garden sprayers for liquids, as is occasionally used for deicing small aircraft such as helicopters (Peck et al. 2002), to hand broadcasting solid chemicals or using lawn-fertilizer-type spreaders. The manual methods may be most suited for decks, stairways, and some work areas of platforms and supply boats. However, chemicals may not be appropriate for application to open grid walkways and stairs unless the chemical is a thick liquid, such as a Type IV glycol-based anti-icing fluid that may adhere to an open grid—though waste would probably still be large and slipperiness could be a concern. Application of chemicals below the main decks of platforms in superstructure icing areas, to the cellar deck and moon pool areas, and to lattice structures such as flare booms and derricks, may require dedicated spray systems where personnel cannot safely reach.

A wide variety of chemicals are available for deicing, and many have become common in highway and runway ice control. Until recently, the chlorides were generally the most common ice control chemicals in use. Sodium chloride is inexpensive, but very corrosive, operates slowly, and is relatively ineffective at low temperatures. Calcium chloride is somewhat less corrosive than sodium chloride, is effective to lower temperatures, and is exothermic allowing it to melt through ice and snow relatively rapidly. However, it leaves a slippery residue that could be hazardous to workers, and it is still aggressively corrosive. Magnesium chloride has similar characteristics to calcium chloride including leaving a slippery residue, being aggressively corrosive, and being hygroscopic. Though the hygroscopicity of calcium chloride and magnesium chloride hastens melting of ice and snow, it also allows clumping in storage, which may be a concern in the humid marine environment. Potassium chloride is intended to be used with other chemicals to increase their effectiveness—alone it is a relatively ineffective and expensive deicer.

The three acetate chemicals common to deicing and anti-icing have become more acceptable than chlorides because of their lower, but not negligible, corrosion rates. Calcium magnesium acetate (CMA) has become a favored deicing chemical, however, it is expensive, relatively slow at low temperatures, and has a relatively high BOD. It can be applied as a solid or a liquid. Potassium acetate is also a low-corrosion chemical that operates well at low temperatures. Its corrosion rate is so low that it is used on runways. However, aircraft need to be washed after exposure because of suspected damage to aircraft brakes and to cadmium. It is also expensive and has a higher BOD than CMA. Sodium acetate is available as a liquid or solid, is effective at low temperature in ice or deep snow, and is approved for use on runways. However, it is also recommended that aircraft be washed after exposure to sodium acetate. In addition, the acetates cause destructive alkali-silica reactions in concrete. As with the other acetates, it is low overall in corrosivity and it is expensive.

Two glycol-based chemicals have historically been available to deice and anti-ice aircraft before flight. Glycol-based fluids are also used in flight in weeping wing systems. Although common at one time, ethylene glycol is rarely used for deicing or anti-icing today because of its toxicity. Although still commonly used as a piston engine coolant, it is inappropriate to use ethylene glycol anti-freeze for deicing because the corrosion inhibitor and fire suppression additives in coolant are different than necessary for deicing fluid. Propylene glycol is the primary chemical used in all current aircraft deicing and anti-icing fluids. It is non-toxic except for additives, minimally corrosive, and is effective at moderately low temperatures. However, it has a high BOD and can cause eutrophication problems in surface waters. In addition, it has caused sickness of aircraft passengers and crew when it has accidentally entered vents. Glycols are also slippery and can cause hazards on decks and walkways.

Sodium formate and urea are two deicing chemicals that are not related to the others chemically. Sodium formate is approved for roadways and runways, has low corrosivity and BOD, low toxicity, is expensive, and functions at low temperatures. It is available only as a solid, but is highly soluble in water. It does, however, damage zinc-coated galvanized steel. Urea is available as a liquid or a solid, and has been used on runways because of its low corrosivity, though rarely on highways. It is not effective at low temperatures, however, and has a high BOD and high aquatic toxicity. A danger, however, is that as urea decomposes it releases ammonia gas, a potential hazard in unventilated locations.

A relatively recent class of new deicing chemicals is based on sugars; sugar beets, corn, and alcohol. As a class, these agriculturally based chemicals have almost no corrosivity, function at low temperatures, have somewhat higher viscosities than other deicing chemicals, and provide a residual effect that can last between storms. As a class, most of the agriculturally-based chemicals are typically mixed with traditional deicing chemicals. All of these chemicals are relatively expensive, but they are rapidly becoming accepted for highway use. They are all available as liquids.

Applications to platforms: Platforms have a variety of surfaces to which chemicals can be applied to deice or anti-ice. One significant problem of chemicals in the offshore environment is the potential of dilution and wash-off by waves and heavy spray. This is a potentially significant problem under the main deck of platforms where spray and wave wash may be heavy in severe storms. Permanent spray application systems could be placed under the main deck to protect support structures and piping, on cranes and the flare boom to deice the lattice structures, and possibly the helicopter landing pad, decks, and stairs. Wicking systems could be placed on decks and stairs, and weeping systems could be placed on bulkheads and allowed to drip over windows. Among the acetates, potassium acetate may be applicable to platforms because of its low-temperature capability and low corrosivity. In addition, it could be used on the helicopter landing pad. Propylene glycol is also a candidate fluid because it is available as a deicer or anti-icer and is safe for aircraft. It is slippery, however, and could be hazardous on decks, walkways, and helicopter landing pads. The bio-based chemicals also bear consideration because of their acceptable performance and low corrosion potential.

Applications to supply boats: Application of chemicals to supply boats is more difficult than to platforms because of the extreme spray environments that can occur over most of the vessel. Weeping systems could gradually apply deicing chemicals to windows and decks. Spray systems could be installed that would provide deice capability after an icing event, though the effectiveness of such systems would require demonstration. Wicking systems may be effective on decks. Acetates and bio-based fluids may be most applicable to supply boats. The higher viscosity of the bio-based chemicals may allow them to remain effective for a longer period than other chemicals before being diluted.

Coatings

Summary: Coatings are intended to reduce adhesion strength of ice to substrates, and are often considered a potential panacea with regard to solving the icing hazard. If the adhesion strength of ice to substrates is sufficiently low, then the weight of any drop of water that freezes on a vertical or overhead surface should be sufficient to detach it. Although adhesion strengths of 40 kPa and lower have been measured on coatings, adhesion strengths have not been reached that are sufficiently low so as to prevent ice formation. And, once ice forms on a surface, it can mechanically lock to surface geometry or surface irregularities making the cohesive strength of ice as important as its adhesive strength with the substrate. Only the super-hydrophobic coatings have a possible near-term opportunity to prevent icing—but that remains to be proven definitively.

Some coatings are ablative, where a layer of coating material is removed with the ice; that is, the cohesive strength within the coating is lower than the adhesive strength of the coating with the ice. In addition to ablative coatings, coatings that create shear at the ice-coating surface are available, as are coatings that release melting point depressants. Most coatings are somewhat hydrophobic (versus icephobic), with low surface energy holding the drop to the surface. The greater the sphericity of the drop, and thus the larger its contact angle with the surface, the more hydrophobic the surface is. If drops freeze on a surface as near spheres without adhering, they may then roll off if the surface is tilted, vibration occurs, or air moves over the surface with sufficient velocity to roll the drops. Nanotechnology has made some progress in creating superhydrophobic surfaces. Farzaneh et al. (2008) suggest that development of an icephobic coating upon which ice cannot accumulate, or where ice could be sheared off by its own weight, may be achievable within 10 years.

Current coatings can significantly reduce the adhesion strength of ice to substrates, but have not been demonstrated to reliably prevent the formation of ice in an operational environment. Therefore, though a passive coating approach alone is ideal, coatings are most effective when used with an active deicing or anti-icing technology. Coatings can increase the efficiency and the effectiveness of active technologies. In addition, when used with an active approach, users have control over when ice shedding occurs—especially important if there is danger of ice falling on personnel or equipment from cranes, cables, or other overhead structures.

In most cases, the following limitations apply to coatings. The properties of coatings and their performance varies widely with regard to their hydrophobic versus icephobic capability, their ability to tolerate heat or other active deicing technology characteristics, and their capability over various substrates (which can vary substantially). In addition, coating hydrophobicity or icephobicity generally decreases with time, coatings have a finite lifetime from months to several years, and contamination of the surface after application can decrease icephobic qualities.

Applications to platforms: There is ample opportunity to apply coatings to offshore platforms. The application of coatings to most surfaces will assist the removal of ice. Platform supports, piping, and cables under the main deck in high sea spray areas where significant superstructure icing can occur may, if coated, may allow ice to be removed by wave impact and other structure vibration. Fire and rescue equipment such as escape pods, if coated, may allow ice to be removed without damaging sensitive equipment, valves, and composite structures. Coatings on antennas would assist the removal of ice and may prevent antenna damage. Lattice structures such as cranes and the flare boom may benefit from icephobic coatings. Mechanical locking of ice to the lattice is a significant problem on these structures. However, if ice can be removed soon after accretion, it may prevent melt and accumulation and refreeze of water in structural joint areas that later fall as hazardous ice balls. Coatings should be investigated before application to decks, stairs, work areas, and helicopter landing pads; when wet they may be sufficiently slippery for personnel so that they create their own safety hazard.

Applications to supply boats: Application of coatings to supply boats has similar opportunities and limitations as applications to platforms. Coatings can be applied to cables, hatches, hull surfaces, antennas, ventilation louvers, antennas, and life rafts. Some coatings can be applied to windows and maintain optical clarity. The wave impact, vibration, and relative wind on a supply boat may make coatings more effective than on platforms because the boat dynamics may mimic an active, impact-based deicing system.

Design

Summary: Design is perhaps the most significant tool for reducing icing hazards on offshore platforms and supply boats. However, design for ice prevention may hinder the efficiency of other functions and, therefore, icing is not likely to dominate the design process. Elements of design that will reduce ice as a safety hazard should be considered in any arctic offshore structure design.

In general, icing is most effectively reduced by decreasing the magnitude and height of spray generated by wave and swell impacts with the structure, by decreasing the surface area upon which ice can form, and by reducing the number of small-diameter objects that increase ice collection efficiency and increase the capability of ice to mechanically lock to the structure. Therefore, reduced surface area at the waterline and flare with height above the water, similar to a flared ship bow, may reduce spray and deflect spray around rather than over the structure. Large-diameter tubular support legs with an enclosed, flat bottom cellar deck with as few small-diameter hardware components as possible exposed to spray may reduce ice accretion and may encourage self-shedding. Greater distances between the main deck and the waterline should also reduce the liquid water content and median drop size of spray reaching the deck and work areas. Jack-up platforms can reduce potential ice accretion on the lattice legs by enclosing the legs in large flat or tubular jackets that reduce surface area, reduce mechanical locking, and encourage self-shedding if the surfaces are fabricated with smooth steel and welds.

Enclosing work areas, walkways, decks, stairs, the derrick, and moon pool areas reduces ice accretion where personnel work. Enclosing antennas in radomes and minimizing exposed cables and other small objects will reduce icing.

Applications to platforms: A platform that has large-diameter tubular legs with little piping, cabling, ladders, and open lattice walkways will accumulate less superstructure ice. Waves striking the structure will create spray, but a flared structure should deflect some spume and structure-created spray. Enclosing decks, walkways, work areas, and stairs will reduce icing and increase crew safety and comfort. Also, enclosure of crane and flare boom lattice structures will significantly reduce ice accretion, and the difficulty of removing ice from those structures.

Applications to supply boats: Icing is decreased on boats when freeboard is increased; large scuppers allow rapid water drainage from decks, the bow has sufficient flare to deflect a large portion of spray, and there is little rigging and few booms and masts to accumulate ice and raise the center of gravity. Antennas should be enclosed within radomes as possible. As with platforms, a clean, clutter-free design reduces ice accretion and decreases the difficulty of ice removal.

Expulsive

Summary: Expulsive systems primarily deice. However, if activated with sufficient frequency, some expulsive systems have the ability to effectively anti-ice. Expulsive systems operate by deforming the surface, and therefore pealing ice from the substrate, and by accelerating the surface sufficiently so that the moving ice overcomes its adhesion strength to the substrate when the substrate reaches its limit of motion and rapidly decelerates. Systems vary from placing electromagnetic coils under a flexible metal skin, to gluing a thin flexible expulsive sandwich of conductors and dielectric material to a substrate. All systems described effectively remove ice. Although the systems remove hard, brittle freshwater ice readily, their efficiency in removing soft saline superstructure ice is unknown. The systems are energy efficient when compared to traditional thermal systems, and have the capability of removing large masses of ice, such as from lock walls. If placed in locations where physical damage can occur, they may cease to function. Furthermore, their ability to survive wave wash areas near the waterline is unknown. However, expulsive systems do operate successfully in navigation locks near the water line, but less effectively when partially submerged. Expulsive systems are mechanical and accelerate ice away from the icing surface. Ice may fly with sufficient force to injure personnel, and falling ice could litter decks.

Applications to platforms: Expulsive systems may be applied with greatest advantage on platforms in areas inaccessible to personnel. For example, expulsive systems could effectively deice support legs under the main deck, in areas generally inaccessible to personnel in severe weather, in areas that need frequent deicing, and in areas where ice shards can fall without injuring personnel or material. Therefore, expulsive systems should not be used on bulkheads and locations where personnel could be struck by flying ice. They may be applied to vents if vent geometry is adaptable. In addition, there may be applications in the moon pool and cellar deck areas. Hatches and railings are also potential applications if access by personnel is limited when the systems are activated.

Applications to supply boats: Expulsive systems may be applicable to hull sides, masts, and bulkheads of supply boats where significant ice can accumulate. Expulsive technologies may also be applied to vent openings, depending upon geometry, and to hatch covers.

Heat

Summary: Heat for deicing can be delivered in many ways as the technologies reviewed demonstrate. These range from moist hot air that delivers much of its heat as latent energy, to dry hot air, to several electrothermal systems that promise to deliver heat with much greater efficiency than traditional electrothermal systems. Because methods of delivering heat vary widely, application on offshore platforms and supply boats will also differ considerably.

Two of the technologies deliver warm air to iced surfaces and melt the ice from the air-ice interface to the ice-substrate interface. This requires that personnel maneuver a nozzle or head to deliver heat to the ice surface allowing the warm air to melt the ice. Based upon aircraft ground deicing technologies, warm air deicing requires sufficient energy to melt the entire volume of ice residing on the surface unless the air velocity can also loosen the ice and remove it in pieces during melt. Although requiring considerable energy, this approach offers considerable flexibility for deicing different portions of a platform or a supply boat.

The other thermal technologies presented offer a more efficient variation of electrothermal inflight deicing technologies. Traditional electrothermal systems either operate as an anti-icing system and maintain a surface temperature that is warmer than freezing, or they heat an area of wing leading edge enough so that ice melts and eventually slides off of the airfoil. Because heating wires are traditionally buried several millimeters inside the wing leading edge structure, heat from the heater wires must be conducted through the wing leading edge material into the ice. Because of this, the thermal rise is relatively slow, allowing considerable heat to be conducted into the ice and into the substrate before it warms sufficiently to melt at the wing-ice interface. Several new electrothermal technologies summarized rely upon heaters placed on the icing surface. In this manner, ice accumulates on the heater itself. Because of this, when the heater is warmed little heat is lost to the wing material, and nearly all of the heat enters the ice at the ice-heater interface. In addition, temperature is raised so rapidly that only a thin layer of ice at the ice-heater interface melts, reduces the ice adhesion strength, and allows the ice to slide off of the surface. This allows the new heaters to be more efficient than traditional electrothermal systems. In addition, because they are not melting the entire volume of ice they expend less energy than systems that melt the entire volume of ice from the air-ice interface to the substrate-ice interface.

Applications to platforms: Hot air deicing systems can be applied to platforms, especially areas where personnel can maneuver, to deice decks, equipment, bulkheads, windows, antennas, and railings. Temperature sensitivity of materials must be considered, as must the location of warm air sources versus hoses that must be maneuvered to deliver the warm air. However, other than placing systems onboard to deliver the warm air, little infrastructure change is necessary. If it is possible to use a gantry to maneuver the air delivery nozzle, it may be possible to deice superstructure below the main deck as well as above. However, considerable engineering may be necessary to accomplish this.

The rapid-response electrothermal systems require that heater mats be attached and wired to the platform. These heater mats could be permanently or temporarily attached to bulkheads, support structures under the main deck, piping, air intakes, hatches, and perhaps elements of the moon pool and cellar deck areas. These systems may allow large volumes of ice to be rapidly and efficiently removed from the platform.

Applications to supply boats: Small portable hot air systems may be applicable for deicing complex supply boat structures such as windlasses, stairs, antennas, and railings. Rapid-response electrothermal systems could be applied to bulkheads and masts, and perhaps to hatch covers, though they may be susceptible to damage in these locations. It may also be possible to apply electrothermal mats to outside areas of the hull, especially well above the waterline.

High-velocity air, water, steam

Summary: High-velocity air, water, and steam have proven of value in removing snow and ice from structures. Steam lances have been used to remove ice from ships, and are often used to open frozen pipes and drains. Though high-velocity water or steam systems specifically engineered to remove ice and snow could not be located, commercial components and units have been adapted for removing ice from navigation lock walls in demonstrations. Water and steam jets can cut significant thicknesses of ice from surfaces. Most demonstrations have occurred on concrete surfaces that are not easily damaged by high-velocity spray. However, use of similar systems on offshore platforms and boats could require care that paint is not removed from surfaces, and that softer materials (e.g., composites and plastics) and brittle materials (e.g., glass) are not damaged or destroyed.

The U.S. Air Force and some airports use high-volume low-pressure air systems that are available from several manufacturers to remove snow from surfaces. Ice is less readily removed by air alone. However, injection of only small volumes of deicing fluid into the air stream, along with heat in the fluids, has been demonstrated to rapidly remove heavy wet snow and ice. These systems may be particularly effective for removing large masses of relatively soft, new superstructure ice from platforms and boats. However, some reengineering of existing systems would be necessary to provide the mobility needed to fully use the capability on a platform. Applications to supply boats may be even more challenging.

Applications to platforms: The utility of high-velocity systems on platforms is a balance between maneuverability and effectiveness. Removal of large volumes of snow or ice from platform components will require relatively powerful systems that are difficult for personnel to handle unassisted. In addition, maneuvering a system about on a platform, and especially lowering it to potentially heavily iced areas under the main deck, may require significant reengineering. Whereas most ice protection systems described in this report are effective for removing millimeters to many centimeters of ice, they may fail when required to remove a meter or more of ice that is mechanically attached to multiple structural components. High-velocity water, steam, or deicing fluid may provide viable solutions to these thick ice situations. Platform areas that could be deiced, or de-snowed, by high-velocity systems include support structures, decks, railings, stairs, the helicopter landing pad, and winches. The moon pool and cellar deck areas may also be reachable.

Applications to supply boats: Much like fishing trawlers, supply boats can accumulate large masses of ice because of the frequent traverses of spray clouds over the superstructure due to bow-wave interaction and relative wind over the vessel. For this reason, high-velocity steam, warm water, and possibly air with fluid injection may capably remove ice from supply boats. As with platforms, the size and power of high-velocity units may rapidly overcome the ability of personnel to handle them. A powerful system requires mechanical assist, and maneuvering a system on a supply boat may be difficult. Other than handheld nozzles, more powerful systems may not be practical for supply boat applications. Hull surfaces, life rafts, decks, railings, and hatches could all be deiced with high-pressure systems.

Infrared

Summary: Infrared energy is an attractive tool for deicing and anti-icing. Infrared energy is a remote method of delivering heat to an object. Infrared emitters can deice or anti-ice where conventional, in situ deicing systems might be damaged. For example, emitters can deice walkways or work areas. They can be designed to emit the amount of energy needed, and some systems have lenses for focusing infrared energy making the heaters more effective at greater distances. Most infrared systems emit at wavelengths of about 3 μm and longer. This means that the energy is absorbed at the ice surface, and the infrared energy is used to melt the ice. Most infrared energy does not penetrate the ice to the substrate and melt from the bottom, which would be more efficient if physics allowed it to be possible. Infrared energy intensity and wavelength can be controlled by emitter temperature. The amount of energy absorbed by an ice-covered surface can be controlled by the temperature and distance of the emitter, but also by controlling the absorptivity of the surface being irradiated. Objects that are desired to be warm, if used for anti-icing, should be coated with material with high absorption in the infrared wavelengths. Objects within the emitter field of view that should be kept cooler should have a surface that has less infrared absorption.

Infrared energy does require care in its use. It has the potential to overheat materials such as composites. Emitters also operate at high temperatures and, unless designed appropriately, could be a source of ignition if explosive gases were to concentrate near heaters. Finally, emitter design should be considered carefully when placed in locations frequented by heavy spray.

Applications to platforms: Infrared systems may be useful on platforms for anti-icing fire and rescue equipment, communication antennas, ventilation openings, valves and handles, irregular surfaces such as winches and windlasses, and stairs and deck walkway areas. Heaters could also be placed under the helicopter landing pad—heating it from below. Application of infrared energy may be challenging in heavy sea spray areas such as under the platform main deck, but emitters placed high under the cellar deck aimed at support structures may be possible.

Applications to supply boats: Supply boats are a challenging application for infrared energy because of the potentially large volumes of sea spray moving over the vessel that could strike emitters. As with platforms, infrared emitters could keep life rafts, antennas, ventilation duct openings, ladders, portions of decks, and possibly hatches deiced. However, more power may be required than is available on a supply boat. In addition, large relative winds over boats may cause sufficient cooling to make infrared systems less effective.

Manual deicing

Summary: Manual methods, using baseball bats, mallets, and shovels are the traditional method of deicing marine structures. It is likely that many vessels have been saved using these methods. However, it is also possible that many have been lost when this is the only option. If decks are inaccessible due to heavy weather, for example, deicing is slow or cannot occur. It also requires a large number of personnel, stamina, and exposure to potentially severe weather conditions, and has the risk of personnel going overboard. Objects on the platform or boat can be damaged or broken using manual methods. Manual deicing is cost-effective with regard to equipment, but costly with regard to personnel. However, it is likely that manual methods will always be required for those locations in the marine environment not fully protected by alternative deicing or anti-icing technologies. In addition, manual methods are an important backup if other methods fail.

Applications to platforms: Manual deicing methods can be effective on areas of platforms reachable by personnel. However, areas where personnel have no access cannot be deiced, including potentially large areas underneath the main deck, the moon pool area, the derrick, the flare boom, and cranes. Windows and antennas must be deiced with care, as should composite structures that may delaminate when impacted. Devices such as scrapers may be more appropriate for composite structures and windows.

Applications to supply boats: Manual methods are applicable on all areas of supply boats, except that windows, lighting, and antennas must be treated carefully. It may be difficult to reach higher masts and cabling for cranes, derricks, or rigging on supply boats.

Piezoelectric actuators

Summary: The use of piezoelectric actuators to deice involves distorting and/or accelerating surfaces sufficiently so that the adhesion strength of ice is overcome. This is accomplished by placing piezoelectric actuators on the back of flexible surfaces. When powered, the actuators elongate in one or more axes causing a reaction in the substrate material. The technology is currently in early development, and if prototypes become available, may be applied in limited areas to protect specific items on a platform or supply boat. Ultimately, with high-power actuators, large areas of structures may be protected if they are relatively uniform structurally. As with expulsive systems, falling particles of ice may require removal from decks and other surfaces located below the object being deiced.

Applications to platforms: Piezoelectric actuators may be able to protect stairs, decks, and hatch covers. Ultimately, it may be possible to protect large structural support elements under the main deck, but that must wait for development of more powerful actuators.

Applications to supply boats: Piezoelectric actuators could potentially protect decks, hatch covers, and windows on supply boats. However, the applications will likely require development of more powerful actuators than are currently available.

Pneumatic boots

Summary: Pneumatic boots have been used successfully for deicing aircraft wing leading edges for more than 70 years. Boots remove ice in a manner similar to several other technologies—ice accumulates on the boot surface, and when sufficient ice accumulates the boot is inflated, distorting the boot surface, and pealing off and breaking the brittle ice. At that time, either gravity or airflow over a wing carries the loosened ice away. Boots have been tried on ships, lock walls, and radomes in addition to aircraft. All tested applications of the technology show promise. Though ice often is not fully removed after one or even two boot inflations, most ice is eventually removed with additional attempts. And, boot performance can be improved by application of coatings that improve the boot surface icephobicity. Although boots can be damaged if placed in heavy work environments, they are overall relatively inexpensive, simple to build and operate, and easily installed. Boots have been proposed for placement at the waterline of offshore platform legs to reduce stresses caused by floating sea ice. If they survive that environment, they may well survive the harsh spray and wave-washed environment under the main deck area of a platform.

Applications to platforms: Pneumatic boots may potentially, with testing, be placed in the support structure areas of platforms to protect the legs, braces, and deck bottom from large ice accumulations. They may be wrapped around the lattice structure of cranes and flare booms to reduce ice accretion area and to remove ice. Boots can protect communication antennas. It may also be possible to use small boots to protect solid pipe safety railings.

Applications to supply boats: Pneumatic boots may be used to protect portions of the upper hull and communication antennas on supply boats. However, the upper hull area of a supply boat may be subject to abrasion when moored and cause damage to boots. As with platforms, it may also be possible to protect safety railings with boots.

Vibration and covers

Summary: Experiments with low-frequency high-amplitude vibration of solid structures to remove ice have generally not been successful. Vibration has worked only when the structure is somewhat flexible; ice was removed when it flexed most violently at the resonant frequency of the structure, which damaged the structure. Success has been mixed with the use of flexible covers. Flexible covers have not been observed to deice themselves in the wind. However, when manually deicing, objects covered loosely with tarps are more easily deiced than objects that are tightly bound with tarps. When ice forms on a loose tarp it conforms to the shape of the tarp. When loosely affixed, the tarp easily distorts when struck with a mallet or baseball bat, causing the brittle ice to peel loose and shatter. Tarps manufactured of material that is icephobic, or even hydrophobic, may be deiced even more easily when loosely attached to objects. Unfortunately, covering objects with tarps often reduces the functionality of the object. It must be decided which hinders operations more significantly—a tarp or ice.

Applications to platforms: Covering of fire and rescue equipment, hatch covers, railings, and winches with tarps may allow them to be more easily deiced. Wrapping tarps around the lattice structure of crane and flare booms reduces the surface area that will ice and may make ice removal easier. However, tarps wrapped around lattice structures may increase wind load significantly.

Applications to supply boats: Items such as winches, hatch covers, railings, and life rafts may be covered with tarps on supply boats.

Windows

Summary: Windows present a special deicing situation, requiring an analysis of deicing and anti-icing technologies that conform to the optical and mechanical needs of windows. Although piezoelectric methods have been suggested for deicing windows, these are new technologies that have not been tried with glass. The most promising technologies for keeping windows deiced are heat, chemicals, and coatings. Heat is a well-established technology matured principally by the automobile industry. However, air and electrically heated windows are also common in aircraft. Heat is delivered to glass either by blowing warm air over the window surface, or by energizing resistance heating elements embedded in the glass or affixed to the surface. Technologies in development that are a variation of the resistance heating technologies, such as pulse deicing, promise to be more efficient by heating the ice heater interface rather than heating the glass, similar to the rapid response thermal systems described earlier. Chemicals can be used to deice windows. In addition to the common window deicing fluids used in automobile windshield washers, a variation of the weeping wing concept could be used on windows, allowing deicing fluid to drip by gravity down the glass. Several hydrophobic/icephobic coating developers and marketers provide optically clear coatings that promise to reduce ice adhesion. Several are available commercially, and one is available in automobile parts supply stores. As with most coatings, effectiveness and longevity vary, and material applied to windows may not prevent ice, but it may make the ice easier to remove.

Applications to platforms: All three of the technologies described for window deicing—heat, fluids, and coatings—are easily adapted to platform windows. More coatings, however, will become available as the technologies mature; the weeping window technology will require engineering and fabrication for a platform application. Because platform windows are generally located well above the ocean surface, sea spray is less likely to remove chemical applications rapidly.

Applications to supply boats: Windows on supply boats are, arguably, more important to keep ice-free than those on platforms because they are used for navigation and maneuver. However, icing of supply boat windows is likely more severe than on platforms because of the higher relative wind often experienced by supply boats, and because they are exposed to larger volumes of water. For these reasons, heat loss from windows will be greater on supply boats, chemicals will wash off more rapidly, and coatings may not be as effective for as long. Therefore, larger volumes of chemicals, if used, may be necessary to protect boat windows, coatings may need more frequent reapplication, and heating will need to be greater.

Cables

Summary: Cables are not included in Tables 8 and 9 above. Cable icing has been a significant problem for the electric power industry, especially after the development of long distance transmission networks. Cable icing is also a problem for communication tower operators on guy wires, ski lift operators on lift cables, and catenary wires of bridges and electric railways. Cables on offshore platforms and supply boats are typically not electrical conductors. In many ways this simplifies deicing, although it does remove the possibility of Joule heating (where the wires are electrically overloaded to heat and melt ice).

There are several potential approaches to deicing cables. For limited cable lengths such as those found on platforms and boats, pneumatic cable deicing may be possible. Although this technology is not commercially available, it would not be difficult to apply and it was shown to be effective in test applications. However, the approach is not viable for hoisting cables and cables on winches where abrasion and stretching would destroy the boot. Expulsive cable deicing methods have been developed. They have been demonstrated to operate effectively on electrical transmission lines in tests, and are currently being tested on a suspension bridge to reduce falling ice hazards. The technology is relatively easily applied and would be suitable for some rigging and cables that, again, are not used for hoisting or winching. Running the expulsive-equipped cables through sheaves may destroy the system. Coatings can be applied to cables to assist ice removal. However, mechanical locking is a common problem with cable icing; coatings may not reduce the incidence of mechanical locking, though they may reduce the severity of the locking and allow cables to clear of ice sooner and more completely. A variety of mechanical methods are also available for clearing cables of ice. These include robotic ice cutters that travel the cable and remove ice, devices that apply a sharp mechanical shock to the cable causing ice to be shattered and removed, and twisting and vibrating devices that develop significant amplitude to remove ice. The mechanical methods—because several of them can be temporarily attached to cables for actuation—may be most useful for cables used on cranes and windlasses. However, when cables are located at significant heights above decks, attaching systems to cables, especially in icing conditions, may be challenging.

Applications to platforms: Most cables on platforms appear to be used by cranes. This limits the solutions to icephobic coatings, which may reduce ice adhesion, and certain mechanical methods. Coatings combined with mechanical techniques may be effective in most icing conditions. Cable railings can be deiced manually or with chemical, pneumatic or expulsive systems, and coatings could reduce ice adhesion.

Applications to supply boats: Supply boats typically have little rigging and cabling. However, cables used to stay masts could be kept deiced using pneumatic or expulsive technologies. Expulsive techniques could be supplemented with an icephobic coating. Cables used for hoisting, winching, or binding could use coatings and mechanical systems as described in the platform applications. Cable railings can be deiced manually or with chemical, pneumatic or expulsive systems, and the application of coatings could reduce ice adhesion.

Ice detection

Summary: The ice detection methods presented are broadly representative of technologies available; the devices described are not an exhaustive list of ice detectors available. Four fundamental types of detectors are described: wide-area, remote, in situ, and probe designs. Wide-area ice imaging technology shows the extent and, in some cases, the thickness of ice coverage. These are standoff (or remote sensing) technologies developed to determine whether there is ice on aircraft surfaces before or after deicing. Studies have demonstrated that wide-area sensing has the capability of substituting for tactile ice sensing, heretofore the standard method of determining whether aircraft surfaces were iced. Wide-area technologies may be applied to the marine environment, especially where incipient icing could cause slipping hazards on decks, stairs, work areas, and helicopter landing pads. However, imaging ice on the sides of outer areas of a platform or boat may be more difficult because of the standoff distances required and the range of the systems. Imaging ice coverage on the sea-facing surfaces of a platform may require a helicopter to obtain the proper view. However, helicopters may not be flyable or available during the time images are desired. Salt contamination of optics may be a concern if the system is permanently mounted. The range of ice thicknesses that can be displayed, when they are provided by the technology, may be important for assessing walkway and helicopter pad safety where slipperiness is important. However, ice thickness displays are less important where greater thicknesses of ice are expected to be a threat. Wide-area detection may be most useful for monitoring areas where small ice accretions are a safety threat, such as walkways, work areas, stairs, landing pads, and perhaps the moon pool area.

Non-imaging remote detection, currently used for road weather information systems and for activating roadway FAST systems, indicates minimal ice thickness and the presence of water or ice and snow. This would be useful for monitoring the safety of walkways, stairs, work areas, and landing pads. Because remote systems require specific standoff distances and monitor relatively small areas, their signals should serve as an index for conditions in similar areas of a platform or boat. A system that monitors a deck, for example, should be placed so that it represents as many deck areas as possible.

In situ ice detectors are embedded flush with the surface of a structure and are conformal with regard to shape. Although most important in the aviation environment, sensors embedded in a surface (if they are also thermally similar to their surroundings) can better represent the amount of ice forming on that surface because drop collection efficiency and wind flow over the sensor will more likely match that of its surroundings. Shape conformality may also reduce the chance of sensor damage since it does not protrude above the general surrounding surface. In situ sensors may be most useful in the marine environment where information about ice accretion on large surface areas is needed, such as platform support legs and exterior bulkhead areas. In addition, some in situ ice detectors are thin, flexible, and easily applied to many surfaces.

Probe ice detectors are the most common type of ice detector in aviation, weather, and electrical transmission line applications. In some cases, through many years of use, the characteristics of these sensors are well understood. According to Jackson and Goldberg (2007), it is easier to correlate ice accretion from probe-style ice detectors to ice accretion on other parts of a structure than with other types of detectors. As with most in situ sensors, probe sensors only provide an indication of the rate of icing and do not indicate how much ice actually resides on a surface. Ice thickness at any one location is highly dependent upon local factors. Therefore, correlations between probe sensors and surfaces of interest are necessary, correlations that are not necessarily accurate as conditions change from storm to storm (Ryerson and Ramsay 2007).

Applications to platforms: Platforms could benefit from a variety of ice detection devices. Wide-area or remote detectors, and some in situ RWIS detectors, may be most useful for detecting the initial formation of ice on areas where ice can be a personnel hazard due to slipping. These detectors excel at determining the onset of icing and the beginning of hazardous conditions that can cause falls on decks, stairs, and in work areas. Helicopter landing pads cannot be imaged by permanently located wide-area or remote detectors because imagers must be mounted above the landing pad. However, in situ sensors that can tolerate traffic over their surfaces may be effective. Ice accretion on other platform surfaces such as large ice masses that may form from superstructure icing below the main deck, ice formation on lifelines and exterior bulkheads, and ice accretion on derricks, flare booms, and escape pods may be best detected with a combination of probe and in situ detectors. Detectors would need to be located in areas experiencing representative icing conditions, but also in areas not susceptible to damage. A significant hazard to most probe ice detectors (and to some in situ detectors) is the potential for damage during manual deicing activities. In all cases, any detector chosen must be integrated into a data acquisition and hazard annunciation system. In addition, they must be evaluated for effectiveness in saline ice conditions and for their ability to survive the marine environment.

Applications to supply boats: Supply boats present, in many ways, a more severe icing environment than do platforms because of the higher spray volumes generated, potentially more frequent spraying, and higher speed relative winds. Wide-area ice detection may be challenging to apply to supply boats unless it is a handheld system or the optics are permanently located on the mast looking down on the vessel decks. In situ sensors could be placed on the deck or the bulkhead. However, either system must be sufficiently robust to survive abrasion and other abuses on decks and potentially on bulkheads. A significant hazard to most probe ice detectors (and to some in situ detectors) is the potential for damage during manual deicing activities. Ideally, ice detectors should be integrated into a data acquisition and hazard annunciation system. In addition, they must be evaluated for effectiveness in saline ice conditions and for their ability to survive the marine environment.

20 Conclusions

Many technologies are available for deicing, anti-icing, and detecting ice on components of the national infrastructure. This report contains a broad and representative sample of the variety of technologies available. Mature technologies that have been available for decades, and technologies and products in early stages of development are summarized to indicate what is available today and what is being developed and may be available in the near future. No attempt has been made to include all products available within each technology category. Technology adopters are encouraged to search more broadly for additional developers and suppliers.

Of technologies that are currently COTS, most have been tested and have been proven in service in the aviation, electric transmission, and highway maintenance environments; a few have been used in the marine environment. However, in nearly all cases, a technology selected for potential application on an offshore platform or supply boat will require testing in a simulated or actual offshore marine environment. This could be accomplished in national laboratories, in universities and commercial laboratories, or perhaps by the marine operator. The latter is important because the marine operational environment is unique, as are the aviation, electrical, and highway transport operational environments. Ice protection technologies must work seamlessly and, preferably, with little or no intrusion on the infrastructure and activities that define the marine operational environment. The offshore oil exploration and production environment is heavy industry with unique requirements. High temperatures could be a hazard in potentially explosive environments, and electrically operated technologies require additional consideration in saline and often unique grounding conditions. Ice protection technologies must be fail-safe because, as in aviation, catastrophic failure could potentially escalate to a more serious threat in an unforgiving environment. Therefore, assessment of the most appropriate ice protection technologies, and how to adapt them, is best accomplished by teaming operational and ice protection expertise to select optimal solutions for icing safety threats to specific operations.

The technology summaries in this report, and assessments of offshore icing threats by Ryerson (2008), indicate that no single technology can solve all of the icing safety problems on an offshore platform or supply boat. Specific needs typically require unique solutions. However, many capable technologies are available that can provide desired improvements in safety. In most cases these safety improvements will require partnered investment by technology developers, vendors, and by marine operators. The relatively high TRLs of most technologies indicate that the primary investment in invention and innovation has occurred, and only adaptation to marine operations is necessary. Although material in this report is drawn from a broad spectrum of technologies developed for a variety of operational environments, many of these technologies can effectively improve safety in the offshore marine icing environment with creativity, careful evaluation, and minor reengineering.

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14. ABSTRACT

Offshore oil exploration and production operators in high latitude regions recognize icing as a seasonal challenge. Icing is often accepted as an inconvenience, but that tolerance can rapidly become a safety hazard that requires solutions. This report evaluates the superstructure and atmospheric icing hazard on offshore platforms and supply boats with location and operation on the structure. It also explains the potential impact of icing on these locations and operations by icing type: sea spray, snow, glaze, rime, frost, and sleet. Fourteen ice protection technology categories are identified for anti-icing, deicing, and ice detection. These technologies include chemicals, icephobic coatings, structure design, expulsive techniques, heat, high-volume water, air and steam, infrared energy, manual deicing, piezoelectric methods, pneumatic boots, vibration and covers, and as separate categories windows, cables, and ice detection methods. Each technology category is described with regard to products available, current use, engineering design, technology readiness levels, capability at the current level of development for the marine environment, possible use in the marine environment to improve safety, and indications of development necessary to transfer the technology to offshore use. Examples of technology sources are also provided. Suggestions are made with regard to the application of technologies to solve icing safety threats on platforms and supply boats. Technology readiness levels are also summarized. The goal is to provide a technology resource for offshore oil and production operators with icing-related safety requirements.

15. SUBJECT TERMS

Anti-icing, Atmospheric icing, Deicing, Glaze, Ice, Ice protection, Marine ice protection systems, Offshore oil rigs and platforms, Rime, Safety, Sea spray icing, Snow, Superstructure ice protection, Superstructure icing, Supply boats

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