Cold Regions Science and Technology 65 (2011) 97–110

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Ice protection of offshore platforms

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ARTICLE INFO

Article history:
Received 6 October 2009
Accepted 12 February 2010

Keywords:
Offshore platform
Atmospheric icing
Superstructure icing
Ice protection
Safety
Arctic

ABSTRACT

Climate change-induced reduction in the extent and duration of sea ice cover, as well as an increase in energy demands, has caused renewed interest in exploring and drilling for oil in Arctic waters. Superstructure icing from sea spray and atmospheric icing in the Arctic may impact offshore platform operations. Though icing has not caused the loss of an offshore platform, it can reduce safety, operational tempo, and productivity. Historically, many ice protection technologies were tested on offshore platforms with little success. However, new technologies and modern versions of old technologies used successfully in aviation, the electric power industry, and ground transportation systems, may be adapted to an offshore environment. This paper provides a framework for assessing the relative threat of ice accumulation types, such as superstructure ice, glaze, rime, frost, and snow, to the safety of platform functions. A review of ice protection strategies for functional platform areas is also provided.

Published by Elsevier B.V.

1. Introduction

Arctic oil exploration and production have increased because of a reduction in sea ice cover. The increased global demand for oil will result in a larger number of offshore structures built, used, and exposed to icing from atmospheric sources. Atmospheric icing is defined by the International Standards Organization (ISO) and the International Council on Large Electric Systems (CIGRE) as any process of ice or snow accumulation on objects exposed to the atmosphere (Farzaneh, 2008; Fikke et al., 2006). Atmospheric icing is further classified as types of ice, based upon methods of deposition and characteristics of deposits. These include glaze from precipitating freezing rain or freezing drizzle, snow, rime ice resulting from supercooled cloud or fog droplets, and hoar frost resulting from the deposition of water vapor directly as ice crystals. Sleet, a form of freezing precipitation, and superstructure ice resulting from sea spray, are traditionally not classified as atmospheric icing, but they are similar in formation processes. More complete descriptions of these ice types may be found in Farzaneh (2008); Fikke et al. (2006), Ryerson (2008), and SAE (2002). These types of icing can reduce offshore operations safety and operational tempo and are discussed in this paper. Though floating sea ice also degrades offshore platform operations and safety, floating sea ice types are not discussed in this paper and should not be confused with atmospheric ice types (AES, 1994).

Offshore platforms are complex with regard to the types of operations conducted onboard, and the type of and variability of icing problems. Selection of safety-enhancing ice protection technologies requires consideration of platform design, operations compromised, type, amount and frequency of ice formation, and applicability of ice protection technologies.

The creation of a comprehensive offshore platform icing safety plan is also benefitted by knowledge of the physics of ice accretion processes and methods for prediction of icing events. Because platforms are difficult to move on short notice, weather prediction is rarely useful for avoidance of icing events. Forecasting, however, can aid in tactical preparation of a platform prior to an icing event. Superstructure and atmospheric icing physics and modeling are not discussed in this article, but comprehensive reviews are available from Makkonen (1989) and Lozowski et al. (1986, 2000) for superstructure icing, and from Farzaneh (2008), Poots (1996), and Makkonen (1984) for glaze, rime, snow, and frost.

This paper presents an assessment of the threat of icing to structural and operational areas of platforms through the use of a cross-tabulation matrix. The matrix combines relative safety threats of six ice types and the relative importance of seventeen areas and operations of offshore platforms. Cross tabulations provide an indication of the importance of ice type versus location. Although not currently available, the addition of explicit ice frequency and magnitude information would add value. A table is also included to present the most successful technologies for protection of differing platform areas and operations.

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0165-232X/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.coldregions.2010.02.006

More quantitative approaches for assessing platform ice safety threats and appropriate location-specific ice protection technologies are not currently available. However, the approach presented here provides structure to the complexities of icing-related, platform area safety and choice of appropriate ice protection technologies.

2. Background

The icing environment and unique structures and operations of offshore oil exploration and production platforms make superstructure and atmospheric icing a threat to safety and operational tempo. In addition to observations about the effects of icing on platforms (Ryerson, 2008, 2009), icing as a safety threat is consistent with conceptual theories of accident causation. Using material from a wide variety of industrial accidents compiled by the insurance industry, Heinrich (1950) suggested that frequent minor unreported events caused by phenomena such as icing may lead to more serious accidents. This premise was known as the accident pyramid or triangle where many minor unreported incidents lead to fewer but more serious reportable accidents. If allowed to continue, fewer reportable accidents or injuries could lead to one or more fatal or catastrophic events. Following this logic, the apparently benign impact of small icing events that are of little threat may ultimately lead to major serious icing accidents. Though Heinrich's theory is controversial and often challenged, it has been widely accepted for over 70 years (Conklin, 2007). Many other theories, such as the confluence of multiple factors commonly used in assessment of aviation accidents, attempt to explain accident causation. Gunter (2008) reviewed theories of accident causation and concluded that the importance of ergonomics and stress is influenced, in part, by the physical environment. These theories of accident causation suggest the potential safety impact of icing in the marine industrial environment.

Superstructure icing from sea spray, and atmospheric icing from snow, glaze, rime, and frost were recognized hazards to offshore platforms in the 1980s (Jorgensen, 1982). Icing hazards identified 25 years ago still, in large part, exist today. Overall, little systematically-collected information about the impact of superstructure or atmospheric ice on offshore operations is available.

Neither atmospheric nor superstructure icing have caused the loss of any oil rigs (Oilrigdisasters, 2008). Although some major rig losses have occurred during winter storms, there is no indication that icing has contributed to these losses. The North Sea, with its reputation for severe, cold weather, has not created significant icing problems for platforms (Jorgensen, 1982), although ice loadings in the range of 225–450 MT have occurred on these rigs (Liljestrom and Lindgren, 1983; Liljestrom, 1985).

Icing is typically a nuisance rather than a significant threat, as suggested in a study (Brown and Mitten, 1988) of icing on rigs located off of the Canadian East Coast. This study found that icing events on drilling platforms are "quite frequent," but most accrete less than 18 MT of ice and have minimal impact on offshore operations. However, despite the infrequency of truly dangerous conditions in Canada, there are documented cases of significant icing impacts upon rig safety in locations such as Alaska (Nauman and Tyagi, 1985).

The specific hazards caused by offshore icing are a function of the type of icing, and how each icing type affects specific areas and functions of platforms. Icing is not a general problem; the types of ice that can be experienced offshore, where it forms, and its physical characteristics impact various activities and areas of platforms differently (Ryerson, 2009). Fig. 1 shows where different ice types may be expected to accumulate on an Arctic semisubmersible platform.

3. Icing safety assessment

A cross-tabular methodology was developed to assess the impact of ice by type on platform function (Table 1). Ice type was ranked by the expected hazard that ice types might inflict on platform safety. Platform function was ranked by the relative importance of each function to overall platform safety. For example, when compared to snow, frost as an icing type has little impact on a helicopter landing pad. However, the helicopter pad has a greater impact on platform safety than railings, for example, if each is iced. Justifications for each ice and platform function safety ranking are described below.

Fig. 1. Potential ice accretion areas, by ice type, on the Ocean Rig semisubmersible *Erik Raude* (from Paulin, 2008).

3.1. Ice type

The following superstructure and atmospheric ice hazards are rated for overall threat to platform safety and operations. A rating of 10 is the highest threat. Ratings are indicated in Table 1 and in parentheses next to the description of the icing type.

3.1.1. Sea spray (superstructure) ice (10)

Most investigators, except for a few (Makkonen, 1984; Minsk, 1984), agree that sea-spray-created superstructure icing is typically the

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

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

Classification: 70–100 dark grey, 30–69 medium grey, 0–29 light grey.

greatest threat to offshore platform safety. Superstructure ice can reduce rig stability, damage rig structure due to changes in stress on structural components, cause slipping hazards, render deck cargo unavailable, disable winches, cranes, and antennas, and cover windows, rescue equipment, hatches, firefighting equipment, valves, and radomes. Superstructure icing can accumulate over 1000 MT of ice on a platform (Ryerson, 2008). Other areas that can be affected include air intakes, the moon pool, the cellar deck, and legs and deck bracing (Fig. 2).

3.1.2. Snow (8)

Snow can add considerable weight to a platform and contribute to instability of floating platforms; up to 136 MT has been reported at a depth of 0.3-m on decks (Liljestrom and Lindgren, 1983). Snow can cause personnel slipping hazards, 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 that is hazardous to personnel and material. In addition, snow often occurs during sea-spray icing and can enhance superstructure ice accumulation (Brown and Agnew, 1985; Brown and Roebber, 1985).

3.1.3. Glaze (7)

Glaze is a precipitation deposit from freezing rain or freezing drizzle, and primarily affects horizontal surfaces. However, wind and runoff can cause glaze accumulation on vertical surfaces, and lattice structures are especially susceptible to freezing rain accretion (Jorgensen, 1982). Glaze produces slipping hazards and can disable winches and cranes by locking cables in continuous hard ice. Glaze coats antennas and radomes, windows, hatches, rescue and firefighting equipment, and valves. Up to 270 MT of glaze ice has been reported on a Canadian platform (Liljestrom and Lindgren, 1983), with thicknesses to 3 cm reported (Brown and Mitten, 1988). Glaze ice is difficult to remove because of its high density and hardness, and layers less than 1-mm thick can cause dangerous decks and stairways.

3.1.4. Rime (6)

Rime ice results from super-cooled fog or cloud drops carried by the wind (Ryerson, 2008). Objects facing the wind—especially smaller-diameter objects such as railings, antennas, cables, and lattice structural shapes—will usually accumulate the largest rime ice thicknesses because of their higher droplet collection efficiency. These structures can partially fill in, causing increased surface area and wind loads. Ice later falling can be a personnel hazard. Wind blowing across a deck can also occasionally cause rime accumulation on small amplitude rough surfaces, such as nonskid, and produce slippery conditions. Wind blowing across stairs, especially if constructed as an open grid, can coat them with rime and cause falls. Fett et al. (1993) reported an accumulation of up to 10 cm on decks and 30 cm on railings in 12 h.

Fig. 2. Superstructure icing on the semisubmersible *Ocean Bounty* in Alaska (Courtesy U.S. Minerals Management Service).

3.1.5. 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 on windless clear nights on surfaces facing the sky (Ryerson and Claffey, 1995). On days when warm, moist air moves over surfaces that are cold soaked, frost forms on surfaces that are coldest and with no orientation preference (Ryerson, 2009). Frost forms on decks, railings, stairs, handles, and cables and presents a slipping hazard for personnel, even at a thickness of only 0.05 mm (Haavasoja et al., 2002).

3.1.6. Sleet (1)

Sleet, often referred to as ice pellets, forms when falling raindrops freeze before hitting surfaces. Sleet accumulates loosely on horizontal surfaces such as decks, stairs, hatches, and helicopter landing pads. Sleet is not technically considered a form of atmospheric icing, but it may produce a slipping hazard (Ryerson, 2009).

3.2. Platform functions and components

If disabled or hindered by ice accretions, components and functions of offshore platforms are rated for the magnitude of possible safety hazards. Ratings are based on the importance of functions or components. Threats to the safety of an entire rig are of greater importance than are threats to the entire crew, which are more important than threats to individuals. And, threats to individuals are more important than threats to work tempo. A rating of 10 signifies a high threat, and a rating of 1 indicates a least threatening condition. Ratings are indicated in parentheses next to the description of the platform function or component in Table 1.

3.2.1. Stability (10)

Rig stability can be threatened by large superstructure ice accretions. Large masses of ice can cause larger rolling moments and decrease the freeboard of floating platforms, as occurred on the *Ocean Bounty* in Cook Inlet, Alaska (Nauman and Tyagi, 1985) (Fig. 2). Superstructure icing builds on platform legs, bracing, blowout-preventer guidelines, mooring chains, marine risers, and flexible kill and choke lines in the splash zone 5 to 7 m above the sea (Baller, 1983). In moderate sea states, most ice accumulates on platform legs above the water line and may not seriously affect the rig center of gravity, although freeboard would be decreased (Nauman, 1984). Differential ice accretion may also cause heeling, because most ice typically accretes on the windward side. Loss of stability has a high hazard rating because destabilization of a rig could be catastrophic and could cause it to founder causing the loss of multiple lives and producing large oil and chemical spills.

3.2.2. Integrity (10)

Integrity refers to the potential for a rig to break up due to structural loads caused by ice on parts of the structure. Rig structural members are designed to accommodate oscillatory stresses due to wave action, and changes in drag, inertia, diameter, roughness, and flexural response caused by ice accretion could change the structure's design wave capability (Crowley, 1988). These stresses could cause fatigue in supports under the main deck and, potentially, loss of a rig. Similar to stability, break up is a significant hazard because it may cause total rig loss and sinking of the structure, loss of all personnel, and potential massive spills of oil and drilling chemicals.

3.2.3. Fire and rescue (9)

Ice encasement may cause loss of firefighting capability, fire and gas sensors, rescue equipment such as life rafts, and potentially cause loss of the platform should fire or explosion occur (Fig. 3). Iced safety

Fig. 3. Iced fire hose hydrant and hose on the U.S. Coast Guard Cutter *Midgett* in the Bering Sea (from video courtesy author).

system sensors are blinded, valves freeze shut, and crew cannot move rapidly on decks that are slippery and partially ice blocked. In addition, the ability to deploy escape pods via chutes or davits may be hindered by ice accumulation (Fig. 4).

3.2.4. Communications (8)

Loss of communications would be an unlikely cause of the loss of a platform but could risk crew members' lives if life-threatening events occurred that require rescue or assistance (Fig. 5). Whip and dipole communication antennas readily collect ice because of their small diameters and exposed locations. Water is trapped in the ice, especially if the ice is saline with brine pockets, which raises the dielectric constant and may block signals. Ice also may bridge insulators and short antennas. Loss of radio and radar prevents communication to potential rescuing boats and helicopters. Even though supply boats and helicopters may not be able to reach platforms during icing events due to heavy weather and high seas, ice can persist after weather improves and can keep communication equipment disabled after active ice accretion ceases.

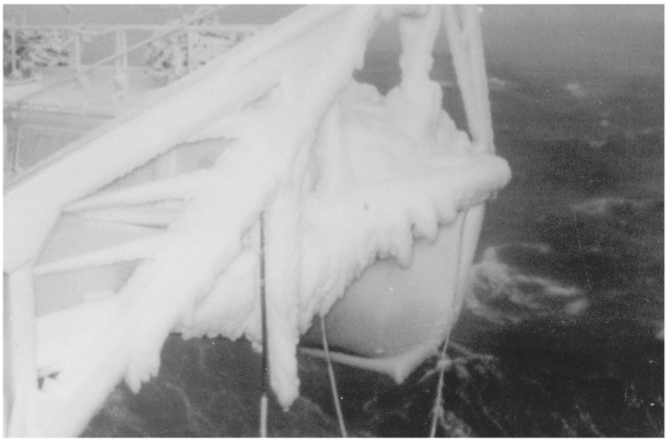

Fig. 4. Ice covering lifeboat, davits, and cables on semisubmersible *Ocean Bounty* (Courtesy U.S. Minerals Management Service).

Fig. 5. Superstructure ice covering communications and radar antennas and bridge windows (courtesy Kevin F. Plowman, U.S. Coast Guard).

3.2.5. Helicopter landing pad (8)

Loss of use of the helicopter landing pad due to icing prevents rapid evacuation of injured or endangered crew members and supply of critical safety or medical items. In addition, slippery conditions on landing pads, which have no safety railings, could cause personnel to fall, sliding of the helicopter on the pad, and difficulty tying down the helicopter.

3.2.6. Air vents (8)

Ventilation is critical on rigs because of the danger of toxic or explosive gas concentrations. Blockage of air intakes can increase the danger of stagnating explosive or poisonous gases in living areas or in locations with ignition sources. In addition, operating machinery often requires ventilation for combustion, exhaust, and cooling. Loss of ventilation could cause failure of critical services and possibly death of one or more crew members. Loss of power due to machinery shutdown could cause loss of the platform in extreme circumstances. Carstens (1983) observed ice-blocked vents on a semisubmersible platform in the Gulf of Alaska (see extreme right of Fig. 6).

3.2.7. Flare boom (7)

Flare booms are exposed to icing more than many other platform structural elements, because they extend over the water. As a result, they are exposed to atmospheric and sea-spray icing. Ice and snow loads on burner booms must be considered when designing the capacity of the boom (Fagan, 2004). In addition, flare booms are typically lattice structures, which present a large surface area for ice and snow accretion. Because flare booms burn off explosive gases, ice and snow damage to the boom structure, or blockage of the burner nozzles, 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.

3.2.8. Handles, valves (6)

Iced handles and valves may not turn or may be difficult to operate. Frozen valve handles could prevent the operation of critical components affecting the safety of the rig or personnel (Fig. 3).

3.2.9. Windows (5)

Ice-covered windows cause loss of visibility for crane operators and other personnel working within enclosed control stations (Fig. 5). Although loss of visibility can be dangerous, it most likely will cause

Fig. 6. Iced air vent on right, and ice littering deck of semisubmersible platform *Ocean Bounty* (Courtesy U.S. Minerals Management Service).

non-lethal accidents and injuries. However, a crane or similar accident could possibly threaten the platform and entire crew if a resulting explosion or fire occurred.

3.2.10. Cranes (4)

Cranes are among the highest structures on a platform, often extending over 100 m above the sea surface. Open lattice framework booms on cranes are potential areas for rime and glaze icing, and for hazardous ice fall from refreezing of melt water in structural crotches. Collection efficiency of the small structural elements is high, and surface areas are large. Iced crane components could also jam the windlass and cause cables to jump pulleys or jam in guides. Though not potentially life threatening, loss of a crane due to ice could cause injuries or loss of operational tempo. Falling of a crane derrick could possibly cause a catastrophic chain of events.

3.2.11. Winches and windlasses (4)

Ice-jammed winches can cause erratic operation of cranes and other lifting or dragging operations, and endanger personnel.

3.2.12. Stairs (4)

Iced stairs are a fall hazard for personnel, because they are slippery and can become irregular in shape, causing loss of footing. Decks, stairs, and catwalks may be constructed of bar grating, may be a solid, painted steel surface, or may be covered with nonskid material. Open grids allow water to drain, but eventually ice may bridge between the grate bars. Nonskid coatings ice up readily and are difficult to deice.

3.2.13. Decks (3)

Horizontal surfaces and materials on these surfaces are susceptible to precipitation icing from snow, freezing drizzle, and freezing rain. Frost may form under appropriate conditions, and sea spray, if lofted to the main deck, may also freeze on horizontal surfaces. Deck icing is most severe if scuppers freeze and do not allow water to drain. According to Jorgensen (1982), sea spray was observed on rig decks in the North Sea when waves exceed a 10-m height. Iced decks, though less dangerous than stairs, are a fall hazard (Fig. 6).

3.2.14. Railings (3)

Iced railings are a personnel hazard because they become slippery, increase in diameter, become irregular in shape and difficult to grasp. Railings also can accumulate glaze or significant quantities of rime or superstructure ice because of their small radii elements and exposed locations (Fig. 7).

3.2.15. Hatches (2)

Iced hatches can be difficult to open or remove because they increase in weight, become difficult to grasp and lift, and the ice can act as an adhesive that holds hatch covers to the deck. Although iced hatches are an inconvenience that impedes work and a potential cause of accidents and injuries, they are unlikely to be a significant hazard.

3.2.16. Cellar deck (1)

Icing of the cellar deck primarily reduces operational tempo. Ice will accrete on many small-diameter objects such as piping, and become a hazard for personnel movement and operation of equipment. In addition, frozen walkways, valves, and sensors could cause fire, explosion, and personnel hazards.

3.2.17. Moon pool (1)

The moon pool is an open area near the center of a platform where drilling pipe and other apparatus extend to the ocean floor. Icing of the moon pool can affect the operation of valves, risers and slip joints and is an active work area during drilling. The moon pool is susceptible to icing from wave splash and funneling of winds under the platform (Baller, 1983). Excessive ice accretion should be avoided on slip joints, especially if the platform is a floater and heaves in heavy seas during icing events. Icing of the moon pool reduces operational tempo. However, a failure that cannot be contained in the moon pool area could possibly cause a catastrophic chain of events.

3.3. Ice type versus platform function

Table 1 provides numerical combined safety impacts of ice type versus platform function or component. The numerical ratings are

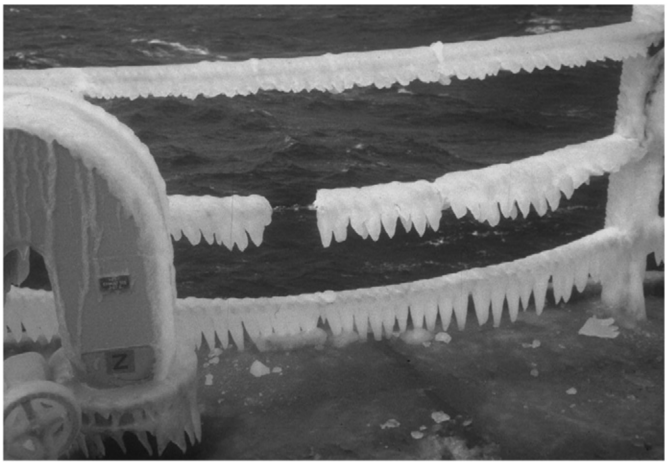

Fig. 7. Superstructure ice icicles on cable life lines of U.S. Coast Guard Cutter *Midgett* (courtesy author).

products of the ice type hazard rating and the platform component or function safety rating. Scores range from 100 for the most severe icing-related safety hazards to 1 for the least severe rating. Discussions of some of the combined ratings follow.

Sea-spray-icing and platform stability and integrity have the highest combined safety rating. Superstructure ice is most likely to add weight that may cause the platform to heel, which will compromise seaworthiness and cause platform structural components to fail. Because the entire platform could be lost, causing loss of an entire crew and creating oil spills, the safety hazard rating is 100.

Snow and the flare boom have a combined safety rating of 56 because the flare boom could be damaged by snow or impaired by blockage of the burner by snow and ice created by snow. Though an impaired flare boom could endanger the entire platform and possibly cause a fire or explosion, it is unlikely to result in loss of the platform or the entire crew. In addition, snow is judged less likely to cause catastrophic failure than sea-spray ice. However, snow may cause greater safety threats to the flare boom than rime, for example, because snow may accumulate in larger masses in the burner, absorb spray, and increase weight.

Glaze ice and decks have a combined safety rating of 21 because glaze is a hazard to footing, but it is unlikely to cause loss of life or injure more than a few individuals. This safety hazard is easily minimized with the use of chemicals or a friction enhancer such as sand. In addition, a fall on a glaze-covered deck is less likely to occur or cause injury than a fall on stairs, with a combined rating of 28, because the fall could be of a considerable distance, and head injuries are more likely to occur.

Frost and the helicopter landing pad have a combined safety rating of 32 because frost creates slippery conditions that might cause the helicopter or personnel to slide. However, frost is usually not thick, is often short lived, and is relatively easily removed.

Some cross tabulations in Table 1 would have little to no effect on safety, and this is demonstrated by low scores even though they are non-zero in magnitude. For example, frost has a rating of 20 on windows because, even though it reduces visibility, it is easily melted or scraped away. Sleet is a loose material that will primarily affect personnel when it is underfoot. Though sleet has non-zero values for stability, integrity, communications, air vents, handles and valves, windows, the cellar deck and the moon pool, it is unlikely that sleet would have any effect on the functioning of these areas. The same may be said for frost versus stability and integrity.

The above explanations indicate that there are generally several factors that cause the combination of ice type and certain platform components or functions to present a greater or lesser safety hazard. The safety ratings in Table 1 are a result of the author's knowledge of ice, offshore platform components and functions, and information regarding the impact of ice on platforms (Ryerson, 2008). Ideally, Table 1 should be verified by cold regions-offshore platform operators with operational experience during icing. In addition, a more deterministically-derived Table 1 matrix could be created by using platform superstructure and atmospheric ice accretion models coupled with reliable, current meteorological and climatological information input. Adaptation of a model such as RIGICE may be possible (Forest et al., 2005).

4. Ice protection

A wide variety of technologies are available for deicing, anti-icing, and detecting ice on offshore structures (Ryerson, 2009). Many of these technologies are currently applied in aviation, highway, and electric power transmission operations. Consequently, a number of these technologies were developed with different requirements than those needed for an offshore environment. Some technologies may be more adaptable to marine applications than others. This summary reviews the principal characteristics of each technology type, and provides suggestions about how the technologies may be best applied to offshore platforms.

4.1. Technology matrix

Platform functions and components are paired with ice protection technologies in Table 2. This pairing considers the platform function that requires ice protection. For example, technologies that would not survive foot traffic would not be paired with deck and stair applications. Technologies that might impair radio frequency signals would not be paired with communications equipment. Ice type was considered secondarily, because some technologies may be more applicable to certain ice types.

Unknown factors, such as icing severity and frequency, and the specifics of technology products make the process of matching operational needs and technologies subjective. The table and summaries should be considered only as guidance. The experience of offshore operators with specific technologies, if available, would add utility.

4.2. Ice protection technologies

4.2.1. Chemicals and chemical application

Chemicals are widely used in highway and aviation snow and ice control. At least fourteen common deicing and anti-icing chemicals are available, as well as a variety of application methods for solid and liquid chemicals. Application methods include: trucks for broadcasting solid materials or liquids on highways and runways; fixed and truck-mounted boom spray systems for deicing aircraft; Fixed Anti-Icing Spray Technology (FAST) for bridges; weeping systems for aircraft wings; and wicking systems for walkways and decks (Ryerson, 2009). Most of these methods could be adapted to offshore operations by scaling and re-engineering these technologies. Application can be as simple as using garden sprayers for liquids, as is occasionally used for deicing helicopters (Peck et al., 2002), to hand broadcasting solid chemicals or using lawn-fertilizer type spreaders. These latter methods may be most suited for decks, stairways, and some work areas of platforms. Application of chemicals below the main decks of platforms in superstructure icing areas, the cellar deck and moon pool areas, and lattice structures such as flare booms and derricks, may require dedicated and fixed FAST-type spray systems.

Until recently, chlorides were the most common ice control chemicals used on pavements (Viadero, 2005). Sodium chloride is inexpensive, corrosive, operates slowly, and is relatively ineffective at low temperatures (Greenawalt, 2008). Calcium chloride is less corrosive than sodium chloride, is effective to lower temperatures, and is exothermic, allowing it to melt through ice and snow relatively rapidly.

Table 2
Platform functional areas versus potential ice protection technology solutions.

	1[a]	2	3	4	5	6	7	8	9	10	11
Stability	X	X	X	X	X	X		X		0	
Integrity	X	X	X	X	X	X		X		0	
Fire and rescue		X	X		X	X	X	0			0
Communications		X	X		X		X	0	0	0	
Helicopter pad	X				X	X		X			0
Air vents		X	X	0	X		0	X	0		
Flare boom	X	X	X					0		0	0
Handles, valves		0			X	X	X	X			0
Windows	X	0			X			X			
Cranes	X	X	X			0		0		0	0
Winches	X	X	0		0	X	X	X			0
Stairs	X		X		X	X	X	X	0		
Decks	X		X		0	X	X	X	0		
Railings		0	0	0	0	X		X		0	0
Hatches		X		X	X	X		X	0		0
Cellar deck		X	X	0	X	X	X	0			
Moon pool		X	X	0	X	X	X	0			

X indicates a stronger match than does a 0. Empty cell indicates no match.
1. Chemicals; 2. Coatings; 3. Design; 4. Expulsive; 5. Heat; 6. High-Volume Fluids; 7. Infrared; 8. Manual; 9. Piezoelectric; 10. Boots; 11. Covers.

[a] Technology key.

However, it leaves a slippery residue that could be hazardous to workers and is corrosive (Peeples, 1998). Magnesium chloride has characteristics similar to calcium chloride, including leaving a slippery residue, and being corrosive and hygroscopic (Ryerson, 2009). Though the hygroscopicity of calcium chloride and magnesium chloride hastens ice and snow melt, it promotes clumping in storage which may be of concern in the humid marine environment. Potassium chloride is intended to be used with other chemicals to increase effectiveness—alone it is a relatively ineffective and expensive deicer (Peeples, 1998).

Three acetate chemicals, calcium magnesium acetate (CMA), potassium acetate, and sodium acetate, have recently become more acceptable than chlorides because of their lower corrosion rates. CMA has become a favored deicing chemical; however it is expensive, relatively slow acting at low temperatures, and has a relatively high biological oxygen demand (BOD), which damages surface waters. It can be applied as a solid or a liquid (Fischel, 2001). Potassium acetate is a low corrosion chemical that operates well at low temperatures (Greenawalt, 2008). Its corrosion rate is so low that it can be used on runways and helipads (AFCESA, 1995). However, aircraft need to be washed after exposure because of suspected damage to brakes and to cadmium. Potassium acetate is also expensive and has a higher BOD than CMA (Fischel, 2001). 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, it causes destructive alkali–silica reactions in concrete, a possible concern for platforms incorporating concrete in the structure. As with the other acetates, it is low overall in corrosivity, and it is expensive (Switzenbaum et al., 1999; Rangaraju et al., 2006).

Two glycol-based chemicals have been available to deice and anti-ice aircraft before flight. Common at one time, ethylene glycol is currently rarely used for deicing or anti-icing because of toxicity. Though still commonly used as an engine coolant, usage of ethylene glycol anti-freeze is inappropriate for deicing, because the corrosion inhibitor and fire suppression additives in coolant are different than for deicing fluid. Propylene glycol is used in all current aircraft deicing and anti-icing fluids. Except for additives, it is non-toxic, minimally corrosive, and is effective at moderately low temperatures. However, propylene glycol has a high BOD, can cause eutrophication in surface waters, and has caused sickness of aircraft occupants when it accidentally entered vents (a potential problem for platform personnel). Glycols are also slippery on decks and walkways (EPA, 2000; AEA, 2008).

Sodium formate and urea are two deicing chemicals that are not chemically related to other deicing substances. Sodium formate is approved for roadways and runways, has low corrosivity and BOD, low toxicity, is expensive, and functions at low temperatures (Air Force, 2005). It is available only as a solid but is highly soluble in water. It does, however, damage zinc-coated galvanized steel (Reeves et al., 2005). Urea is available as a liquid or a solid and is used on runways because of its low corrosivity. It does not rapidly deice at low temperatures, however, and has a high BOD and high aquatic toxicity. As urea decomposes it releases ammonia gas, a potential hazard in unventilated areas of offshore platforms (Switzenbaum et al., 1999).

A relatively recent class of new deicing chemicals is based on sugars from agricultural by products of sugar beets, corn, and alcohol. As a class, these chemicals have minimal corrosivity, function at low temperatures, have somewhat higher viscosities than other deicing chemicals, and provide a residual effect between storms. All of these liquid chemicals are relatively expensive, but they are rapidly becoming accepted for highway use (Hartley and Wood, 2005; Sdoutz, 2006; Glacial Technologies, 2008; Road Solutions, 2008).

Platforms have a variety of surfaces that may benefit from chemical deicing treatment. The most notable are decks, stairs, and helicopter landing pads. One significant problem of chemicals in the offshore environment is the potential for dilution and wash off by waves and heavy spray. This may be a significant problem under the main deck of platforms. Permanent spray application systems similar to FAST 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 helipad, decks, and stairs (Johnson, 2001; Ryerson, 2009). Wicking systems could be placed on decks and stairs, and weeping systems could be placed on bulkheads and allowed to drip over windows (Stallabrass, 1970; Innovative Dynamics Inc., 2007). Potassium acetate may be applicable to platforms because of its low-temperature capability, low corrosivity, and utility on helicopter pads. Propylene glycol is also a candidate fluid, because it is available as a deicer or anti-icer and is safe for aircraft. Use of agricultural sugar-based chemicals may be an advantage because of their acceptable performance and low corrosion potential.

4.2.2. Coatings

Coatings are intended to reduce the adhesion strength of ice to substrates and are often considered an ideal solution to icing, because they are passive. Adhesion strengths of less than 10 kPa have been measured between ice and coatings, but ice adhesion strengths have not been reached that are sufficiently low to prevent ice formation.

Some coatings are ablative, and a layer of coating material is removed with the ice because the cohesive strength within the coating is lower than the adhesive strength of the coating with the ice (Ferrick et al., 2008). In addition to ablative coatings, coatings that cause ice to release at the ice–coating interface are available, as are coatings that release melting point depressants, and coatings that expand and contract to break ice away (Ryerson, 2009). Most coatings are somewhat hydrophobic, with low surface energy holding liquid water drops to the surface. The greater the sphericity of the drop, the larger its contact angle with the surface; thus the surface is more hydrophobic. Farzaneh (2008) indicates that an increase in hydrophobicity should yield a decrease in ice adhesion strength. If drops freeze on a superhydrophobic surface as spheres, they may then roll off if the surface is tilted, vibration occurs, or air moves over the surface with sufficient velocity. Nanotechnology has made some progress in creating superhydrophobic surfaces (Ryerson, 2008; Kulinich et al., 2009; Kannapardy et al., 2010).

Coatings can also increase the efficiency and effectiveness of active technologies. When used with an active approach, users can control the timing of ice shedding events—especially important if there is danger of ice falling from cranes, cables, or other overhead structures.

In most cases, the following limitations apply to coatings. The properties and performance of coatings vary widely with regard to their hydrophobic versus icephobic capability, and for any given coating hydrophobic and icephobic capabilities can vary substantially when applied over different substrates. In addition, methods of applying them to surfaces vary widely from simply applying with common painting tools to requiring curing in an autoclave. Often, hydrophobicity and icephobicity both decrease with time, coatings have a finite lifetime from months to a few years, and contamination of the surface after application can decrease icephobic qualities.

Methods of testing the adhesion strength of ice to coatings vary widely, and many of the different test method results are not comparable. In addition, standardized tests have not been applied to testing the longevity, application characteristics, and resistance to contamination of coatings. Therefore, only relatively crude and incomplete guidelines are presently available regarding their performance.

The application of coatings to most platform surfaces will assist with ice removal. Coating of supports, piping, and cables under the main deck, in high sea-spray areas where significant superstructure icing can occur, may facilitate ice removal by wave impact and other structure vibration. The coating of fire and rescue equipment may allow ice to be removed without damaging sensitive sensors, valves, and composite structures. Coatings may prevent antenna damage during deicing. Lattice structures such as cranes and the flare boom may benefit from icephobic coatings and may allow ice to be removed soon after accretion occurs, thus reducing melt, refreeze and later hazardous ice fall. Coatings should be investigated before application to decks, stairs, work areas, and helicopter landing pads; when wet they may be sufficiently slippery that they create their own safety hazard.

4.2.3. Design

Structural 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 platform operations.

In general, icing is most effectively reduced by decreasing the magnitude and height of spray generated by wave and swell impacts with the structure, decreasing the surface area upon which ice can form, and reducing the number of small-diameter objects that increase ice collection efficiency and the capability of ice to mechanically lock to the structure. Therefore, reduced surface area at the waterline and flare of the platform structure with height above the water, similar to a flared ship bow, may reduce spray and deflect it away (Ryerson, 2009). Large-diameter tubular support legs with enclosed, flat bottom main decks may reduce ice accretion and encourage self-shedding. Greater distances between the main deck and the waterline may reduce spray liquid water content and drop size on the main deck and work areas. Jack-up platforms can reduce potential ice accretion on the lattice legs by enclosing the legs in large tubular jackets that reduce surface area and reduce mechanical locking (Paulin, 2008; Ryerson, 2009). Enclosing walkways, decks, stairs, the derrick, and moon pool areas, and antennas in radomes are viable ice reducing design strategies.

4.2.4. Expulsive

Expulsive systems are designed primarily to deice. However, if activated with sufficient frequency, some expulsive systems can effectively anti-ice. Expulsive systems operate by accelerating the iced substrate and accumulated ice with sufficient velocity so that the moving ice overcomes its adhesion strength to the substrate when the substrate reaches its limit of motion. Therefore, the inertia of the ice overcomes its adhesion strength with the substrate and detaches from the substrate to be carried away by wind or gravity. Systems vary from placing electromagnetic coils under a flexible metal skin, to gluing a thin flexible sandwich of conductors and dielectric materials to the protected surface (Embry et al., 1990; Al-Khalil, 2007; Innovative Dynamics Inc., 2007; Ryerson, 2009). Though all systems readily remove hard, brittle freshwater ice, their ability to remove softer saline superstructure ice has not been widely documented. Expulsive systems are mechanical and are energy efficient when compared to traditional thermal systems, because they do not use energy to supply latent heat for melting ice. They also have the capability of removing large masses of ice, such as from lock walls (Fig. 8).

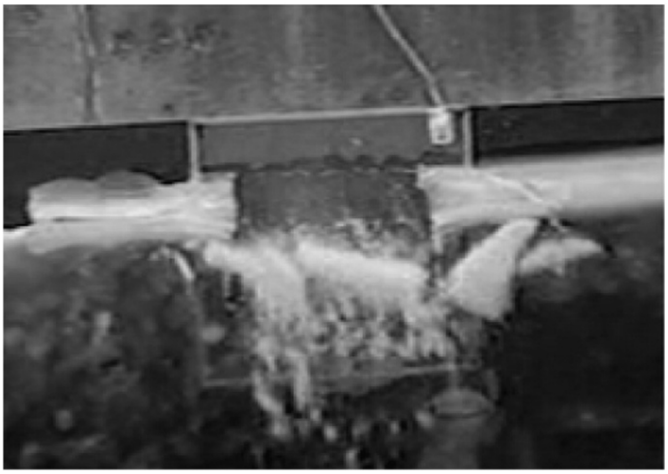

Fig. 8. A nominal 1-m square expulsive system on a Mississippi River lock wall removing collar ice with a single pulse (courtesy N. Mulherin, CRREL).

Expulsive systems may be applied with greatest advantage on platforms in areas inaccessible to personnel during severe weather. For example, expulsive systems could effectively deice supports under the main deck, the cellar deck, the moon pool area, and exterior bulkheads. They may also be applied to vents if louver geometry is adaptable. Hatches and railings are also potential applications. Expulsive systems may be able to survive impacts and wave wash areas near the waterline since they can operate successfully in navigation locks. Because expulsive systems mechanically accelerate ice away from the icing surface, their placement should be carefully planned to prevent ice debris from striking personnel. In addition, ice falling from deicing of bulkheads may litter decks—as can occur with several other deicing technologies.

4.2.5. Heat

Heat for deicing can be provided in many ways, from moist hot air that delivers much of its heat as latent energy, to dry hot air, to new electrothermal systems that deliver heat with greater efficiency than traditional electrothermal systems (Ryerson, 2009). Several technologies deliver hot air to iced surfaces and melt the ice from the air–ice interface to the ice–substrate interface (Curry, 1998; Ryerson et al., 1999). This process requires that personnel maneuver a nozzle to deliver heat to the iced surface, directing hot air to melt the ice. Hot 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.

Electrothermal systems operate either as anti-icing systems that continually maintain a surface temperature that is warmer than freezing, or they heat intermittently so that accumulated ice melts and slides away—a more energy efficient process. Typically, heating wires are buried several millimeters inside the surface being protected, requiring that heat be conducted through the surface materials and into the ice. Therefore, thermal rise is relatively slow, and energy is wasted heating the substrate before the ice is heated. To improve energy efficiency, several new electrothermal systems place heaters directly on the icing surface. In addition, the heater is warmed more rapidly and to higher temperatures than traditional electrothermal systems when deicing is desired. In this manner less heat is lost to substrate materials and more heat enters the ice at the ice–heater interface (Petrenko et al., 2003). The heating melts only a thin layer of ice sufficiently to reduce ice adhesion strength and this allows the ice to slide off the surface. These new “pulse” heater technologies are 20% to 50% more efficient than traditional electrothermal systems (EGC Enterprises, 2008; Eric and Hans, 2009).

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 masses of ice to be rapidly and efficiently removed from the platform if they prove to be sufficiently robust for the marine environment.

Hot air deicing systems can be applied to platforms, especially in areas where personnel can maneuver hoses and nozzles to deice decks, safety equipment, bulkheads, windows, antennas, and railings. Temperature sensitivity of materials must be considered, as must the location of heat sources. However, other than placing systems onboard to deliver the warm air, little infrastructure change is necessary.

4.2.6. High-velocity fluids

High-velocity fluids, air, water and steam, have proven of value for removing snow and ice from structures. Steam lances have been used to remove ice from ships and to open frozen pipes and drains (Rand et al., 1989). Water and steam jets have been demonstrated to cut nearly 1-m ice thicknesses from surfaces (Hanamoto, 1977). Most demonstrations have occurred on concrete surfaces that are not easily damaged by high-velocity spray. However, use of similar systems on offshore platforms would require care that paint is not removed from surfaces, and that heat sensitive and soft materials (e.g., composites and plastics) and brittle materials (e.g., glass) are not damaged or destroyed.

Some airports use high-volume, low-pressure air systems to remove snow from aircraft (Wyderski et al., 2003) (Fig. 9). Ice is difficult to remove by air alone even though velocities approach 300 m/s. However, injection of 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 (Dawson, 2000; Ryerson and Koenig, 2003). These systems may be particularly effective for removing large masses of relatively soft, new superstructure ice.

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 requires powerful systems that are difficult for personnel to handle unassisted. Whereas most ice protection technologies are effective for removing millimeters to many centimeters of ice, they may fail when required to remove a meter or more of ice, which is mechanically attached to multiple structural components. High-velocity water, steam, or deicing fluid may provide viable solutions to these thick ice situations, with the caution that damage to some platform components is possible without careful handling.

4.2.7. Infrared

Infrared energy is a remote method of delivering heat to an object from an electrically or gas-fired emitter (RAS, 2006; Ryerson et al., 1999; Ryerson, 2009). Infrared emitters can deice or anti-ice where conventional, in situ deicing systems might be damaged. Infrared deicing, or anti-icing, is 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 transmitted through the atmosphere from an emitter. Infrared energy is absorbed by the ice to cause melting, or warms a surface to prevent icing. Most infrared energy in the technologies used for ice protection is radiated in wavelengths between about 3 μm 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 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 90%. Objects that need to be warm and subject to anti-icing, should be coated with material with high absorption in infrared wavelengths. Objects within the emitter field of view that should be kept cooler can be covered with a coating that has less infrared absorption. Some systems have lenses for focusing infrared energy, making the heaters more effective at greater distances (Gulley and Davila, 2007).

Infrared energy usage requires care, because it can overheat materials such as composites. Emitters operate near 1000 K, and unless designed appropriately could be an ignition source if explosive gases were to concentrate nearby. In addition, emitters could be thermally or mechanically damaged by heavy sea spray if not sited carefully.

Infrared systems may be useful on platforms for anti-icing fire and rescue equipment, communication antennas, vent openings, valves and handles, irregular surfaces such as winches and windlasses, and stairs and walkways (Fig. 10).

4.2.8. Manual deicing

Manual deicing methods, using wooden baseball bats and mallets, and shovels are the traditional way of deicing marine structures (Fig. 11). Many vessels may have been saved using mechanical deicing

Fig. 9. High-velocity air deicing system with fluid injection removing 10-cm thick wet snow from wing section in experiment at Eglin Air Force Base McKinley Climatic Center (courtesy author).

Fig. 10. Infrared anti-icing system protecting front entrance of CRREL (courtesy author).

Fig. 11. Manual deicing of superstructure ice with wooden baseball bat on forecastle deck of U.S. Coast Guard Cutter *Midgett* (from video courtesy author).

methods. However, many may have been lost, because manual deicing was the only option. If decks are inaccessible due to heavy weather, manual deicing is slow or cannot occur. Mechanical deicing also requires a large number of personnel with considerable stamina, exposure to potentially severe weather, and a risk of personnel going overboard. Though manual deicing is cost effective with regard to equipment, it is costly to personnel. Objects on the platform can be damaged or broken from being struck by mallets and bats. Regardless, manual methods will likely always be required for those locations on platforms not fully protected by alternative deicing or anti-icing technologies. In addition, manual methods are an important backup deicing technique if other methods fail.

Manual deicing methods are only effective on areas of platforms accessible by personnel. Areas where personnel may have no access in severe weather include potentially large areas underneath the main deck, the moon pool area, the flare boom, and cranes. Windows and antennas must be deiced with care, as should composite structures and fire and gas sensing systems that could be damaged. Devices such as scrapers may be more appropriate for composite structures and windows.

4.2.9. Piezoelectric actuators

Piezoelectric actuators deice by distorting and/or accelerating surfaces sufficiently that the adhesion strength of ice is overcome (Palacios et al., 2008; Ryerson, 2009). Transducers are placed on the back of flexible surfaces. Activated transducers elongate in one or more axes, which causes a reaction in the substrate material. Piezoelectric systems are currently in early development, and if prototypes become available, may be applied in limited areas to protect specific items on platforms. Ultimately, high power actuators may be used to protect large areas if these areas are structurally uniform. As with expulsive systems, piezo actuators may cause falling ice particles to accumulate on decks and other surfaces located below objects being deiced. Piezoelectric actuators may protect bulkheads, decks, and hatch covers and other areas constructed of relatively thin and flexible materials.

4.2.10. Pneumatic boots

Pneumatic boots are used successfully for deicing aircraft wing leading edges. 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 its surface and peeling off and breaking the brittle ice. Gravity or airflow carries the loosened ice away. Boots have been tested on ships, lock walls, and radomes, in addition to aircraft (Kenney, 1976; Ackley et al., 1977; Hanamoto, 1977; Govoni and Franklin, 1992). All tested applications of the technology show promise. Though ice is not always fully removed after one or two boot inflations, most ice is removed with additional attempts. Boot performance can be enhanced by application of icephobic coatings to the boot surface. Though boots can be punctured, they are relatively inexpensive, robust, simple to build and operate, and easily installed. Boots have been tested at the waterline of lock walls to remove collar ice (Hanamoto, 1977). Since they survived that environment, they may survive the harsh spray and wave-washed environment under the main deck of a platform.

Pneumatic boots may 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. Small boots could protect pipes and safety railings.

4.2.11. Covers

The use of flexible covers has yielded mixed results (Zadra and Pyle, 1990). Flexible covers have not been known to deice themselves in the wind. However, in a manual deicing process, 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. Covering objects with tarps reduces the functionality of the object, and a decision must be made as to what hinders the use of objects more significantly—a tarp or ice.

Covering 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, if practical (based on location), would reduce the surface area that accumulates ice and may make ice removal more effective.

4.2.12. Windows

Windows are a special deicing challenge because of their optical and mechanical requirements. The most effective and current methods for keeping windows deiced are heat, chemicals, and coatings. Window heating is a well-established technology matured by the automobile and aircraft industries. 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, such as pulse deicing, promise to be more efficient by heating the ice–heater interface rather than heating the glass (Petrenko et al., 2003). 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 concept could be used on windows. This method would allow deicing fluid to drip down the glass surface from an overhead manifold (Stallabrass, 1970). Several hydrophobic/icephobic coating developers and marketers also provide optically clear coatings that promise to reduce ice adhesion (Ryerson, 2009). As with most coatings, effectiveness and longevity vary. These coatings do not prevent ice formation, but they can make ice removal easier.

Heat, fluids, and coatings are easily adapted to platform windows. More coatings, however, will become available as this technology matures. Weeping technology will require engineering and fabrication for platform applications. Because platform windows are generally located well above the ocean surface, sea spray is less likely to remove chemicals rapidly.

4.2.13. Cables

Cable icing is a traditional and costly problem for the electric power industry, especially for high voltage long-distance transmission lines. Cable icing is also a problem for communication tower guy wires, ski lift and gondola operators, cable stay bridges and electric railway catenary (Laursen, 2004; Daniel, 2005). Cables on offshore platforms are typically not electrical conductors, and thus the common Joule heating method used on electric transmission lines is unavailable.

Relatively short platform cables (for example, life lines) (Fig. 7), may be deiced by using pneumatic boots. Although this technology is not commercially available, it has been demonstrated on Mt. Washington, New Hampshire, and application would not be difficult (Govoni and Franklin, 1992). However, boots are not viable for windlass cables where abrasion and crushing would destroy them. Expulsive cable deicing methods have also been developed for electrical transmission lines and are currently being tested on a suspension bridge (Laforte et al., 1995; Laursen, 2004). The technology is easily applied and would be suitable for some platform rigging and cables, but not for windlasses where the technology would be damaged.

Coatings can be applied to cables to assist ice removal. Though mechanical locking of ice to cables is a common problem, coatings may allow cables to clear off ice more completely (Laforte et al., 1998). Mechanical methods, including 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 vibrating devices that develop significant amplitude to remove ice, have also been tested successfully (Farzaneh, 2008). The robotic and mechanical shock methods may be most useful for cables used on cranes and windlasses, because the deicing devices are only temporarily attached to the cable. However, when cables are located at significant heights, attaching systems to cables, especially in icing conditions, may be difficult or impossible. Coatings combined with mechanical techniques may be most effective.

Fig. 12. Ice covered and ice free areas viewed with ice imaging system on helicopter blade in upper image. Lower image taken simultaneously shows difficulty of seeing deiced area without ice imaging system (courtesy author).

4.2.14. Ice detection

Four ice detection technologies; imaging, remote, conformal, and probe, are available for annunciating the presence of ice, automatically triggering ice protection technologies, and indicating whether ice has been completely removed. Ice imaging technology shows the extent, and in some cases the thickness of ice coverage to determine whether there is ice on surfaces before or after deicing (Wyderski et al., 2003; Gregoris et al., 2004) (Fig. 12). Studies have demonstrated that imagers are sufficiently accurate to replace tactile ice sensing, which has been the standard method of determining whether aircraft surfaces were iced (Bender et al., 2006). Imaging 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. Wide-area detection may be most useful for monitoring areas where thin ice accretions, not easily visually detected, 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 ice thickness and the presence of water or ice and snow (Haavasoja et al., 2002). These technologies would be useful for monitoring the safety of platform stairs, decks, and work areas.

Ice detectors embedded flush with a surface are conformal with regard to shape. Although most important in aviation to maintain undisturbed flow over airfoils, sensors embedded in a surface may more faithfully represent the amount of ice forming on that surface if they are also thermally similar to their surroundings (Napert, 1998; Haavasoja et al., 2002; Ryerson, 2009). Shape conformality may also reduce the chance of sensor damage since it does not protrude above the surrounding surface.

Probe ice detectors are the most common type of ice detector in aviation, weather, electrical transmission line, and wind turbine applications. Through many years of use, the characteristics of some of these sensors have become well understood (Tattelman, 1982; Baumgardner and Rodi, 1989; Ryerson, 1990; Ryerson et al., 1994; Claffey et al., 1995; Ryerson and Claffey, 1995; Ramsay, 1997; Fikke et al., 2006; Homola et al., 2006; Ryerson and Ramsay, 2007) (Fig. 13). Fikke et al. (2006) describe a variety of probe detectors, some with decades of use in the electric power industry, that measure accumulated ice weight. According to Jackson and Goldberg (2007), it is easier to correlate ice accretion on a structure with probe-style ice detectors than with other types of detectors. Probe sensors typically provide only an indication of the rate of icing and do not directly indicate how much ice actually resides on a surface. Icing rate at any one location is highly dependent upon local factors. Therefore, correlations between probe sensors and surfaces of interest are necessary, though these correlations may not remain accurate as conditions change within icing events (Ryerson and Ramsay, 2007).

Platforms could benefit from a variety of ice detection devices. Imaging and remote detectors, and some conformal detectors, may be

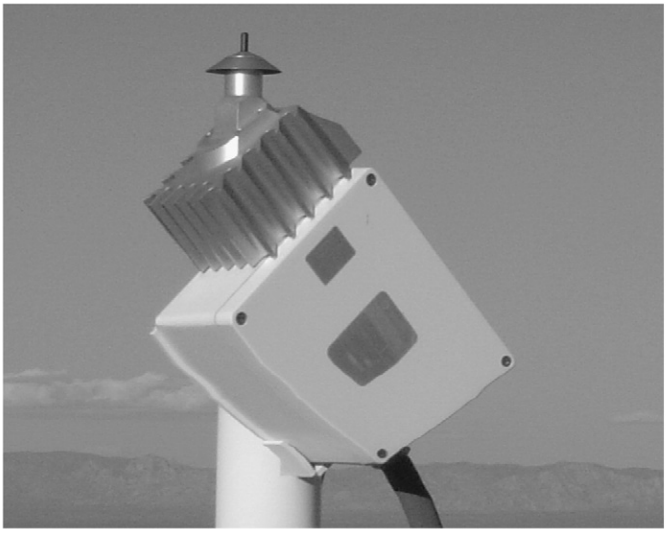

Fig. 13. Probe-style ice detector for measuring freezing rain and freezing drizzle (courtesy author).

useful for detecting the initial formation of ice on work areas. These detectors excel at determining the onset of icing and the beginning of hazardous conditions that can cause falls. Helicopter landing pads cannot be imaged or remotely sensed because the sensors must be mounted above the landing pad. However, conformal sensors that can tolerate traffic over their surfaces may be effective. Ice accretion on other platform surfaces such as below the main deck, ice formation on life lines and exterior bulkheads, and ice accretion on derricks, flare booms, and escape pods may be best detected with a combination of probe and conformal detectors. Probe detectors are best placed where they can represent icing conditions at multiple locations. A significant hazard to most probe ice detectors, and some conformal detectors, is the potential for damage during manual deicing. All detectors should be integrated into a data acquisition and hazard annunciation system. In addition, they should be evaluated for effectiveness in saline ice conditions and for their ability to survive in the marine environment. Fikke et al. (2006) and Homola et al. (2006) for wind turbines, and the SAE (2004) for aircraft, provide excellent summaries of an even wider variety of ice detector technologies and designs available worldwide.

5. Discussion and conclusions

Icing can be a safety hazard on offshore platforms. Actions necessary to improve safety must be considered with regard to the level of safety desired. Since no single technology can protect an entire offshore platform in all functional areas, the selection of areas to protect and the method of protecting them should be chosen with discretion. This requires an awareness of the types of icing that can affect offshore platforms, and of the importance of each functional area of a platform to safety.

In aviation and in electric transmission line operations, icing is typically considered from the perspective of preventing catastrophic loss by preventing crashes and preventing collapse of transmission towers. Protecting an offshore platform is more similar to highway ice protection. Highways are deiced most thoroughly where the greatest danger is perceived by highway departments, because it is not possible to completely clean all highways at all locations all of the time. And highway accidents during icing conditions, though more frequent than during non-icing conditions, are less frequently lethal (Vanderbilt, 2008).

A goal of platform ice protection may be to increase safety as much as possible with the least investment. This requires identification and protection of the critical safety-related areas on a platform since it is unlikely that all functional areas of platforms can be protected during all icing events. From this analysis, ice protection technologies can be selected that are compatible with the function of areas needing protection and the ice types that may most compromise the safety of those functional areas.

Table 1 suggests that the most important functions to protect are those which, if compromised, could cause catastrophic loss of the platform. And the ice type to protect against is that which is most likely to cause catastrophic loss—superstructure icing. The safety pyramid of Heinrich (1950), however, suggests that many small, less reportable events eventually lead to reportable accidents and, ultimately, to a catastrophic accident. Approaching safety from the Heinrich hypothesis, it may be more appropriate to prioritize the protection of decks, stairs and other areas where individuals can be injured more frequently with the anticipation that this may reduce the chances of a rare catastrophic event.

The best safety theory to follow cannot be provided in this paper, but the safety theory or philosophy selected may drive how to protect a platform. Ice protection strategy will likely also be driven by icing frequency and magnitude by ice type, and perhaps even requirements of insurance companies.

One goal of this paper is to provide a framework for identifying the most significant safety problems caused by icing on offshore platforms as related to platform functional area and ice type. The approach presented provides structure to a complex problem of how to identify where the greatest icing-related safety gains may be made on platforms. The framework is not dogma, for it lacks information that is unique to specific offshore operations and icing environments. And clearly there is some philosophical flexibility in selecting a safety strategy with regard to icing. The paper also presents information about potential ice protection technologies, new and old, and how they may be applied in the offshore environment. Though icing problems were identified on offshore platforms over 25 years ago, there have been few suggestions about how to systematically address the problem. Concepts presented in this paper are intended to provide at least a basis for thought and discussion, if not a plan for action.

Acknowledgments

Funding for this research was provided by U.S. Department of the Interior Minerals Management Service, Herndon, VA. The findings of this report are not to be construed as an official U.S. Department of the Army or U.S. Department of the Interior position unless so designated by other authorized documents.

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