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by Heri Sulistiyono

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Risk-based Winterization for Vessels Operations in Arctic Environments

Ming Yang [a], Faisal I Khan [a], Leonard Lye [a], Heri Sulistiyono [a], John Dolny [b], Dan Oldford [b]

[a] Faculty of Engineering and Applied Science, Memorial University of Newfoundland,
St John's, NL, Canada, A1B 3X5
[b]. Harsh Environment Technology Center, American Bureau of Shipping,
St. John's, NL, Canada, A1B3X5

Abstract

As the oil and gas industry has an increasing interest in the hydrocarbon exploration and development in the Arctic region, it becomes important to design exploration and production facilities that suit the cold and harsh operating conditions. In addition to well-established minimum class requirements for hull strengthening, winterization should be considered as a priority measure early in the design spiral for vessels operating in the Arctic environments. The development of winterization strategies is a challenging task, which requires a robust decision support approach.

This paper proposes a risk-based approach for the selection of winterization technologies and determination of winterization levels or requirements on a case-by-case basis. Temperature data are collected from climatology stations located in the Arctic regions. Loading scenarios are defined by statistical analysis of the temperature data to obtain probabilistic distributions for the loadings. Risk values are calculated under different loading scenarios. Based on the risk values, appropriate winterization strategies can be determined. A case study is used to demonstrate how the proposed approach can be applied to the identification of heating requirements for gangways.

Keywords: *Winterization, Vessel Operations, Risk, Arctic Environments*

1. Introduction

The increasing demand for oil and gas worldwide has generated increasing interest in the exploration and development of hydrocarbon basins in the Arctic region. However environmental conditions of the Arctic, such as low visibility, extreme cold weather, and ice impose greater difficulties for navigational, developmental, and operational activities than other regions. Therefore, it is necessary to adapt conventional vessels, installation designs, and their operations in the harsh cold environments for safe operations. One such adaptation is called winterization. Winterization is traditionally related to issues that include de-icing, ice effects mitigation, heat tracing, protection of operating condition, piping arrangement and prevention of ice accretion. Developing a winterization scheme, which includes the level of winterization, the selection of appropriate technologies, implementation and monitoring of performance, is a challenging task. This is because uncertain engineering and environmental outcomes can vary with the technologies used and operating conditions. Moreover, risk and safety become even more critical in the Arctic regions with limited available infrastructures. Therefore, a robust approach needs to be developed to support the decision-making process of winterization.

In a harsh cold environment, many systems will be operated at or close to their design limits. To improve their workability, winterization methods are required. Vessel winterization has been an increasingly important subject of research for many years. The American Bureau of Shipping (ABS) has provided guidance for vessels operating in low temperature environments (ABS, 2010, Legland et al., 2006). Winterization requirements for hull construction, machinery equipment, and operational parts have also been developed and provided in other sources such as:

(1) RMRS's (Russian Classification Society) Requirements for Ship Equipment to Ensure Long-Term Operation at Low Temperature;
(2) DNV (Norwegian Classification Society) Ice Class Rules- Sections 6 and 7, Winterization and Design Ambient Temperature (DAT);
(3) ISO 19906: Petroleum and natural gas industries - Arctic offshore structures (International Arctic Offshore Structures Standard); and
(4) IMO Guidelines for Ships Operating in Polar Waters.

These published works are mainly focused on establishing requirements for winterization associated with Arctic shipping. However, less work has been reported on the development of an approach to advise on which winterization technologies should be applied to operations in the Arctic, and to inform as to what extent these technologies can be relied on. A risk-based approach is an attractive option to provide the capability to evaluate winterization strategies and manage risks within tolerable ranges by the completion of winterization. Some risk-based methods have been developed for evaluation and selection of Arctic production facilities, and strategies for escape, evacuation, and rescue (Gao et al., 2010; Yuan and Marsden, 2010). ABS (2000) has provided general guidance notes on risk assessment applications for the marine and offshore oil and gas industries in addition to Guidance Notes on Review and Approval of Novel Concepts (ABS, 2003). These guidelines offer general methodologies for classification of novel designs to which traditional class rules may not be directly applicable.. However, to date there is little work discussing risk-based approaches specific to winterization.

This paper aims to develop a risk-based decision support framework for the evaluation and selection of winterization technologies and requirements for vessels operating in Arctic environments. The paper is structured as follows. Section 2 will review winterization methods for structures and systems of vessels. Section 3 will review approaches on how the extent or level of winterization can be determined. The proposed risk-based winterization approach will be presented in Section 4. Section 5 will demonstrate the application of the proposed approach to the identification of heating requirements for gangways. Finally, Section 6 will provide conclusions and some recommendations for future work.

2. Review of Winterization Methods

Table 1 summarizes the winterization methods available for vessels operating in low temperature environments. In the following sections, each winterization method will be discussed.

2.1 Insulation

Thermal insulation should be applied to exposed structural boundaries, such as decks, bulkheads, pipes, tanks, pressure vessels, and other process equipment on ships operating in low temperature environments. Among all the above items, the shell boundaries and decks of ships are critical paths of heat flow (Hart et al., 2008). The standard thermal insulation material for exposed structures is referred to as “hull board” or “navy board”.

All raw materials or mixtures used for manufacturing the insulation layers should meet the following three criteria (Karrer, 1998):

(1) Resistance to low temperatures;
(2) Non-combustible; and
(3) Contains no solvent.

Since insulation alone can only prolong the time required to freeze and cannot prevent freezing of vessel systems (e.g., pipes handling aqueous solution), heating is usually implemented combined with insulation.

2.2 Heat Tracing

To winterize vessels, heat tracing systems are often installed in areas including combustion air system, tank vents, safety-related piping, overboard discharges, valves, piping and pressure/vacuum preventing system, door coamings, water spray deluge systems, walkways, stairwells, hand rails, and emergency escape routes (ABS, 2010). There are two types of heat tracing methods typically used, electric and steam heat tracing. In addition to heat tracing, heating coils are required to be installed in ballast water and fresh water tanks.

2.2.1 Electric Heat Tracing

Electric heat tracing usually takes the form of an electrical heating element installed and operated in physical contact along the length of an object (e.g., a pipe). This system consists of a heat-producing conductor, a controller to sense the ambient air temperature and a relay to turn on the current. As the current goes through the cable, the resistance of the conductors causes the cable to generate heat.

The advantages of electric heat tracing are as follows:

(1) Ease of installation with lower costs: for most applications, electric heat tracing is usually easier and less expensive to install and operate;

(2) Good temperature control: with and without a control system, an electric heat tracing system (e.g., self-regulating heat trace) usually offers better and more accurate temperature control than a steam heat tracing system; and

(3) Energy efficiency: electric tracing system can accurately provide necessary energy for temperature maintenance or freezing protection, which avoids the waste of energy.

The disadvantages of electric heat tracing are as follows:

(1) Low heat output: electric heat tracing does not provide multiples of the required energy. Therefore, designers should consider safety factors in the heat loss calculation to handle problems such as damaged insulation; and

(2) Risk of overheat and burn out: electric heat tracing using series and parallel constant faces the risks of overheat and burn out when crossed. However, the introduction of self-regulating cables eliminates this problem.

2.2.2 Steam Heat Tracing

Steam heat tracing uses dry saturated steam as heating media for freeze protection and temperature maintenance. A standard steam heat tracing system consists of a tracer, steam supply lines to transport steam to the traced item, a steam trap to remove the condensate and hold back the steam, and a condensate return system. Steam heat tracing can be applied within a wide temperature range.

The main advantages of steam tracing are as follows:

(1) High reliability: there are very few of the possible problems that may lead to the failure of steam tracing system. For example, the failure of steam traps in an open position will not terminate the continuous flow of steam. Also, leaks will not result in heat tracing failures due to the high heat output of a steam tracer;

(2) Cost-effective operation: steam heat tracing may have an advantage over electric heat tracing in sites where steam is produced from process heat since steam can be considered of no cost; and

(3) High heat output: a steam heat tracing system can provide a large amount of heat to the traced item.

The main disadvantages of steam tracing are as follows:

(1) Energy inefficiency: a steam heat tracing system usually uses energy much larger than the actual requirement to maintain the traced item at the desired temperature;

(2) Poor temperature control: the traced pipe will reach an equilibrium temperature at some point between the steam and ambient temperatures. Although there are some temperature control systems available for steam heat tracing systems, they are

usually very costly to implement. Thus, it is more common to see steam heat tracing systems operating in the “free run” mode; and

(3) High installation and maintenance costs: the piping systems for steam supply and condensate return systems must be installed and insulated. Leaks and steam traps must be checked and replaced when necessary to minimize the energy loss. The installation and maintenance costs are rarely economically competitive to electric heat tracing.

2.3 Air Bubbler and Circulation System

Ballast water in tanks above the waterline may freeze starting from the top and sides of the tank in cold environments. The Canadian Coast Guard recommended circulating the ballast water to prevent from freezing on bulk carriers operating in cold regions (Armstrong. 1997). The circulation of ballast water can be achieved through an air bubbler and a circulation system. An air bubbler system is one of the anti-freezing equipment that is widely used for winterization of water ballast tanks of vessels operating in cold regions. A bubbler system uses low pressure and high volume air pumped through self-weighted hoses lying on the bottom of the tank. The air from holes in the hose can bring warmer water (typically between 0 and 4 °C) to the surface and also create some level of agitation on the surface. The bubbler system also generates a sufficient number of air nozzles distributed throughout the tank bottom. Thus, ice formation in the tank can be reduced.

Bubbler systems can help prevent ballast water from freezing and can be used in temperature as low as -30°C. Below this temperature, heating coils are required to be installed in accordance with the ABS Guide for Vessels Operating in Low Temperature Environments (2010). The advantage of the air bubbler system is its high durability and dependability; while the disadvantages are its performance is degraded and unstable below -30 ̊C and high initial cost.

2.4 Ice Repellent Coatings

The application of ice repellent coatings can lessen or mitigate the accumulation of ice and snow. Such coatings with anti-stick characteristics create hydrophobic surfaces that cause the water to bead up on the coatings and prevent the ice accumulation. Currently, epoxy or polyester matrix composites with glass and/or carbon fibres are used by most manufacturers. Nano-composite coatings are the focus of current research (Parent and Ilinca, 2011). The ice repellet coating should be considered being applied to externally exposed surfaces including decks, deckhouses, superstructures, deck machinery and etc. The application of coatings to most vessel surfaces can assist ice removal.

The advantages of using ice repellent coatings are:

(1) Low cost and easy maintenance; and
(2) User can control the timing of ice shedding events to avoid danger of ice falling from cranes, cables or other structures (Ryerson, 2011).

The disadvantages of applying ice repellent coatings are:

(1) Icing prevention on exposed structures by special coatings alone is not realistic;

(2) The properties and performance of coatings with regard to their ice-phobic capability can vary substantially when applied over different substrates; and
(3) The results of various test methods of the adhesion strength of ice to coatings are not comparable (Ryerson, 2009).

2.5 Deicing and Anti-Icing Chemicals

Deicing and anti-icing chemicals are applied to decks, stairways, and work platforms for ice control. There are various ice control chemicals including sodium chloride, calcium chloride, magnesium chloride, potassium chloride, calcium magnesium acetate, and sodium acetate. Among them, potassium acetate is recommended because of its low-temperature capacity and low corrosivity (Ryerson, 2011). Application of these chemicals is through wicking systems for decks or walkways and weeping systems for bulkheads (Ryerson, 2009). The advantages of chemical applications are low costs and easy implementation; while the disadvantages are leaving slippery residues after application, potential corrosion to vessel structures, and easy to be diluted and washed off by waves. In addition some deicing and anti-icing chemicals can be considered harmful substances and may become restricted for use in Polar waters.

2.6 Chemical Seals

Chemical seals need to be installed on instrumentations where process medium might freeze or is corrosive, viscous, and solidifying. Freezing media causes problems such as inaccurate measurements and pressure port blocking. The selection of the proper chemical seals should be based on: materials, process temperatures, process work pressures, and mounting type. Chemical seals can be easily applied on instrumentation and maintained at low cost and effort. However, it is not realistic to use chemical seals alone for the freezing prevention of instrumentation.

3. Determination of Winterization Level

The approaches by which the requirements for winterization methods are decided will be reviewed in this section. Traditionally, the design calculations for winterization methods are often taken from theoretical values and limited laboratory tests (Brazil et al., 2012). For example, the capability of heat tracing systems to function at the minimum anticipated temperature (MAT) is demonstrated by onboard testing and heat loss calculations. The MAT can be obtained from temperature data of the trading area. Determination of the winterization level through theoretical calculations could be very difficult because of the lack of knowledge of relating to the heat transfer and ice-removal forces.

The factors that may need to be considered in deciding the extent of winterization are ambient temperature, rate of snowfall, wind velocity, and humidity. These meteorological factors can be viewed as environmental loads to vessels that need winterization. In most guidelines for vessel winterization, the environmental load is assessed based on ambient temperature. However, various approaches are used for load assessment in these guidelines. The “ABS Guide for Vessels Operating in Low Temperature Environments (Low Temperature Guide)” specifies the design service temperature (DST) and the MAT. The DST is taken as the lowest mean daily average temperature in the area of operation for data taken over at least a 20-year period. The graphical definition of the DST is presented in Figure 1. Defining the MAT is self-explanatory however, in the absence of appropriate data, the MAT is determined as the DST minus 20 °C. The "RMRS's Requirements for Ship Equipment to Ensure Long-Term Operation at Low Temperature" specifies the design ambient temperature (DAT). The DAT is the minimum mean daily temperature during the five-year observation period in the most adverse cooling conditions of ship service. The "DNV Ice Class Rules" specifies two temperatures, t_1 (material design temperature) and t_2 (extreme design temperature) for ship classification. The material design temperature is the lowest mean daily average air temperature in the area of operation. This is equivalent to the DST in the ABS Low Temperature Guide; however no observational period is specified. The extreme design temperature is defined as material design temperature minus 20 °C. It is equivalent to the MAT. In DNV Ice Class Rules, different winterization levels are required for vessels operating in cold environments for shorter and longer periods.

When the winterization level is dependent on the DST and the MAT as load, it may lead to over winterization and add unnecessary costs because this minimum temperature may only occurs for a very short period or at a low frequency. Such load may not cause failures of systems and impair safety. Sulisityono et al., (2012) proposed a statistical-based approach for load assessment based on the intensity, duration and frequency of annual extreme low temperatures. Probability distributions of extreme low temperatures of various durations can be achieved through statistical analysis of long-term (20 years) temperature data. Moreover, in deciding the winterization level, structures and systems are grouped and assigned the minimum winterization level for the whole group based on the DST or the MAT. This means that some structures or systems may also be over winterized. A risk-based winterization approach will be proposed for the determination of winterization level on a case-by-case basis.

4. Risk-based Winterization Methodology

Figure 2 presents the risk-based winterization methodology. Major steps of the proposed methodology will be described in the following sections. A simple example will be used to illustrate these steps.

4.1 Step 1 Environmental Load Modeling

Once the system that needs to be winterized is determined, environmental load placed on this system is to be modeled. The load (L) is a random variable which can be described by a function of ambient temperature (T) and duration or time (t), i.e., f (T, t). In order to derive such a parameter, long-term temperature data must be collected from climatology stations located in the Arctic regions of interest. Loading scenarios should then be defined for the statistical analysis on the temperature data. The scenarios can be defined in two dimensions: (a) temperature range, and (b) consecutive hours of exposure. For example, "6 consecutive hours of temperature below -40 ˚C" can be used as a loading scenario.

For the risk-based analysis, operators may develop a set of loading scenarios, e.g., temperatures between -40 ˚C to -30 ˚C for 12, 24, 48, and/or 120 consecutive hours.

Operators may customize the temperature range and duration based on: (a) where the vessels will be operated; and (b) how long they will be operated in the region. For each scenario, statistical analysis will be conducted to obtain probabilistic distribution of load for the risk-based analysis presented in Sections 4.2 and 4.3. The process described in these two sections can be repeated until all the selected scenarios have been analyzed.

4.2 Step 2 Probabilistic Risk Assessment Before Winterization

To determine the demand for winterization, probabilistic risk assessment on the selected system exposed to the load is to be conducted. If the risk value exceeds the acceptable level, winterization methods must be applied. The risk is a function of the probability of the failure (PoF) i.e., probability of exceeding the acceptable condition, and severity of the consequence if the acceptable condition is exceeded.

4.2.1 Estimation of the PoF

The PoE of the system can be calculated using the limit state function:

$$g(x) = |\Delta T_{Actual}| - |\Delta T_{Limit}| \qquad \textbf{(1)}$$

Where (a) $|\Delta T_{Actual}| = |L - T_{op}|$ i.e., the difference between the load and operating envelope (T_{op}), T_{op} is defined as the temperature to be maintained for normal operation of a system; and (b) $|\Delta T_{Limit}|$ is defined as the maximum allowable temperature difference between the load and operating envelop of a system without winterization.

Let $f_L(L)$ and $f_{T_{op}}(T_{op})$ be the probability density functions (PDF) of L and T_{op}. The $f_L(L)$ can be obtained through statistical analysis of the temperature data. The $f_{T_{op}}(T_{op})$ can be derived from the ranges of T_{op} provided by industrial operators. Based on $f_L(L)$ and $f_{T_{op}}(T_{op})$, we can obtain the PDF of $|\Delta T_{Actual}|$. Let $f_{\Delta T_a}(\Delta T_a)$ be the PDF of $|\Delta T_{Actual}|$.

Assume the actual temperature difference exceeding the limiting temperature difference is a failure state, i.e., g(x) > 0. The PoF is the probability that $|\Delta T_{Actual}| > |\Delta T_{Limit}|$. It can be expressed by the following equations:

Let $|\Delta T_{Limit}|$ be a constant k

$$\text{PoF} = \Pr(|\Delta T_{Actual}| > k) = \int_k^{\infty} f_{\Delta T_a}(\Delta T_a)\, d\Delta T_a \qquad \textbf{(2)}$$

In the above equation, k or $|\Delta T_{Limit}|$ may vary depending on vessel systems. Operators may develop values of $|\Delta T_{Limit}|$ for different systems based on criticality, system specifications, regulatory requirements, etc. For example, a smaller $|\Delta T_{Limit}|$ would to be assigned to safety-critical systems or systems dedicated to escape, evacuation, and response procedures.

For illustration purpose, suppose a pipeline on deck is the selected system that needs to be winterized. Assume that:

(a) Load: ambient temperature data follows a normal distribution with μ_1= -22.7 and σ_1= 1.1;

(b) T_{op} follows a normal distribution with μ_2= 10 and σ_2= 4

(c) $\left|\Delta T_{Limit}\right|$ = 25 °C =k

Since $\left|\Delta T_{Actual}\right| = \left|L - T_{op}\right|$, then $\left|\Delta T_{Actual}\right|$ may follow a normal distribution with $\mu = \left|-22.7 - 10\right|$ = 32.7 and $\sigma = [(1.1)^2 + (4)^2]^{0.5}$ = 4.14

$$\text{PoF} = \Pr(\left|\Delta T_{Actual}\right| > k) = \int_k^{\infty} f_{\Delta T_a}(\Delta T_a)\, d\Delta T_a = 1 - \Phi\left(\frac{k-\mu}{\sigma}\right) = 1 - \Phi\left(\frac{25-32.7}{4.1}\right) = 0.97$$

4.2.2 Consequence Assessment

Severity levels of consequences depend on the criticality of systems. Criticality can be determined based on experts' opinions. Table 2 presents the quantification scheme that can be used for consequence assessment. The severity values are subjectively assigned and have no physical meanings. The magnitude of financial loss can be changed from case to case as per an organization's criterion.

Following the previous example, failure of a pipeline on deck may affect the performance and lead to subsequent failure of the system. According to Table 2, it belongs to criticality: required for good operation. Then the severity value of the consequence is 4.

4.2.3 Risk Estimation

Risk is defined as the product of probability of failure and consequence.

Risk (R) = PoF × Severity Value **(3)**

A risk matrix (Figure 3) is proposed to define the various risk levels as the product of PoF and severity categories. If the risk exceeds the acceptable level or is located in the very high, high, or medium areas in Figure 3, winterization methods must be applied to this system. Operators need to define the acceptable level and customize the risk matrix. This level may be decided based on the As Low As Reasonably Practicable (ALARP) criterion. Under this criterion, risk should be reduced to the lowest level as is practical (i.e., risk-reduction measures are required to the point where their costs far outweigh the benefits).

In the previous example, the risk can be obtained:

R = 0.97 × 4 = 3.88

The risk is considered very high according to the proposed risk matrix (Figure 3); therefore, winterization methods must be applied.

4.3 Step 3 Probabilistic Risk Assessment After Winterization

Probabilistic risk assessment on the selected system after winterization will be conducted to quantify the potential improvement or risk reduction rate. This approach provides a measure of relative risk for a system with and without winterization technologies applied.

4.3.1 Estimation of PoF

PoF of the system after winterization can be calculated using the following limit state function:

$g'(x) = |\Delta T_{Actual}| - E - |\Delta T_{Limit}|$ **(4)**

where (a) E is the winterization efficacy defined as the capacity of a method to produce freezing protection effect (i.e., the capacity to reduce the temperature difference between the load and operating envelop), E can either be a constant or represented probabilistically; (b) $|\Delta T_{Actual}|$ and $|\Delta T_{Limit}|$ are defined the same as in Equation 1.

Assume g'(x) >0 or $|\Delta T_{Actual}| - E > |\Delta T_{Limit}|$ is a failure state. PoF can be calculated using the following equations:

Let $|\Delta T_{Limit}|$ be a constant k

$$\text{PoF} = \Pr\,(|\Delta T_{Actual}| - E > k) = \int_k^{\infty} f_{\Delta T_a'}(\Delta T_a')\,d\Delta T_a' \qquad (\Delta T_a' = \Delta T_a - E) \qquad \textbf{(5)}$$

Following the previous example of the winterization of a pipe on deck, suppose two electric heat tracing methods are available:

(1) Heat tracing method #1 is able to provide Q = 12 watt; and

(2) Heat tracing method #2 is able to provide Q = 15 watt

Efficacy of winterization, i.e., E, in terms of temperature difference can be calculated through the following steps.

(a) Calculate the convective heat transfer coefficient using formulas proposed by MacAdams (1954):

$h_c = 4.3v + 6.2 \qquad v \leq 5 m/s$ **(6a)**

$h_c = 7.6v^{0.78} \qquad v > 5 m/s$ **(6b)**

where h_c is convective heat transfer coefficient ($W/m^2.K$), and v is the wind speed (m/s).

Wind effects on heat loss is considered by using the above convective heat transfer coefficient.

(b) Calculate the overall heat transfer coefficient by (Earle, 1983):

$$\frac{1}{U} = \frac{1}{h_{c1}} + \frac{1}{(k_1/x_1)} + \frac{1}{(k_2/x_2)} + \ldots \frac{1}{(k_n/x_n)} + \frac{1}{h_{c2}} \qquad \textbf{(7)}$$

where U is the overall heat transfer coefficient, h_{c1} and h_{c2} are the convective coefficients of surfaces 1 and 2, k_i is the conductivity factor of material i, and x_i is the thickness of material i (i=1, 2, …,n).

(c) Calculate E in terms of ΔT:

$$E = \Delta T = \frac{Q}{UA} \qquad \textbf{(8)}$$

where Q is the amount of heat that can be provided to compensate heat losses, A is the heat transfer area, and U is defined by Equation 7.

For illustration purposes, the materials and dimensions of the pipe and insulation are assumed and presented in Table 3. Assume wind speed = 15m/s, then $h_c = 7.6v^{0.78} = 62.8$ (W)/(m^2)(°C). The overall heat transfer coefficient can be calculated:

$$U = \frac{1}{\frac{1}{h_c} + \frac{x_{steel}}{k_{steel}} + \frac{x_{fiberglass}}{k_{fiberglass}}} = 1.6 \text{ (W)/(m}^2\text{)(°C)}$$

$$A = A_{lm} = 2\pi L\left[\frac{r_{outer} - r_{inner}}{\ln(\frac{r_{outer}}{r_{inner}})}\right] \qquad \text{(U.S. Department of Energy, 1992)}$$

where A_{lm} is the log mean cross sectional area, L is the length of the pipe, r_{outer} and r_{inner} are the outer and inner radii of the object.

For one meter of pipe, $A = 2\pi \times 1 \times \left[\frac{0.0825 - 0.051}{\ln(\frac{0.0825}{0.051})}\right] = 0.41 \text{ m}^2$

Then E of heat tracing method #1: $E = \Delta T = \frac{Q}{UA} = 19\ ^\circ C$

Similarly E of heat-tracing method #2 is $23\ ^\circ C$.

Assume the load remains the same, then:

For heat tracing method #1: $PoF = 1 - \Phi(\frac{k - (\mu - E)}{\sigma}) = 1 - \Phi(\frac{25 - (32.7 - 19)}{4.1}) = 0.004$

For heat tracing method #2: $PoF = 0.0001$

4.3.2 Consequence Assessment

The same quantification scheme is used for consequence assessment of systems' failures. In the above example, the same severity value (i.e. 4) is used in risk assessments before and after winterization.

4.3.3 Risk Estimation

$$Risk'(R') = PoF' \times \text{Severity Value} \qquad \textbf{(9)}$$

where PoF' is the probability of failure after winterization.

If the risk still exceeds the acceptable level or is located in the medium, high or very high areas in Figure 3, winterization methods or strategies need to be redesigned.

Risk reduction rate is defined as $RR = \frac{R - R'}{R}$. This rate can be used as an important criterion for the selection of winterization methods.

In the previous example, the risks after winterizations are calculated as follows:

For heat tracing method #1: $R'_1 = 0.004 \times 4 = 0.016$ (medium according to Figure 3)
$RR_1 = 0.995$

For heat tracing method #2: $R'_2 = 0.0001 \times 4 = 0.0004$ (low)
$RR_2 = 0.999$

Therefore, heat tracing method #2 is preferred and the pipeline after winterization is considered safe under the loading scenario. However, if a consequence value of 0-2 was used in this example, both methods would be low risk and therefore the most efficient solution would have been the lower heat output option.

5. Case Study: Determination of Heating Requirements for Gangways

In Section 3, a simple example is used to illustrate the risk-based winterization method. In this section, we will demonstrate how the proposed method can be applied to the development of surface heating requirements for gangways.

Historically, it has been accepted that heating requirements for gangways, open deck areas, stairways should not be less than 300 w/m^2 (ABS, 2010). Extensive testing has been done to estimate heating requirements for anti-icing under various conditions. The results indicate that heat loads reported for anti-icing systems for surfaces vary significantly. Through the proposed method, the opportunities to estimate the heat requirements more accurately will be established.

The minimum heating requirements can be achieved by setting risks after winterization equal to the acceptable level. Through a reverse of the process presented in the previous example to calculate the risk after winterization, the heating requirement can be obtained.

Temperature data for 22 years were collected at the Barrow Station in Alaska. Considering the worst-case scenarios, the lowest annual average temperature over durations of 6, 12, 24, 36, 48, 72, 96, 120, 144, and 168 hours were analyzed. Normal distributions could not be rejected at 5% level for all durations. As an example, Figure 4 gives the normal probability plot of the lowest average temperature over durations of 24 hours. Table 4 summarizes the parameters of these distributions. They were used as environmental loadings in the risk analysis. Table 5 gives other information needed for the calculation. Finally, the heating requirements for different loading scenarios were obtained. Figure 5 presents the results. Figure 5(a) shows that the heating requirement decreases with the increasing of the durations or the decreasing of the means of the loading distributions. Figure 5(b) shows that all of the achieved heating requirements are above two times greater than the standard requirement (i.e., 300w/m^2). It indicates that this gangway might be under winterized if the standard requirement was applied. Moreover, Figure 5(c) shows that the heating requirements for different scenarios consistently increase when a smaller $\Delta T_{\lim it}$ is used.

6. Conclusions

Winterization aims to adapt vessels for cold and harsh operating conditions. A number of factors, such as changing environmental conditions, facility performance, workability, and remoteness may have considerable influence on the selection of winterization solutions. A risk-based method is proposed for the selection, evaluation, and development of winterization strategies under varying weather conditions. The proposed method provides the capability to control risks below tolerable levels by winterization. Moreover, it is also able to predict the heating requirements for various structures and systems on vessels. The validation of the proposed method is through its application to the identification of the heating requirements for gangways. The analysis of the results of the case study indicates that the proposed method is capable of determining winterization levels on a case-by-case basis.

Further validation on other vessel systems is required and work in this direction is in progress. As mentioned in the case study, the change of $\Delta T_{\lim it}$ has an influence on the results of the proposed approach. Therefore, future work will be needed to develop a method to accurately estimate $\Delta T_{\lim it}$.

Disclaimer

The views expressed herein are those of the authors and are not to be construed as official views of ABS.

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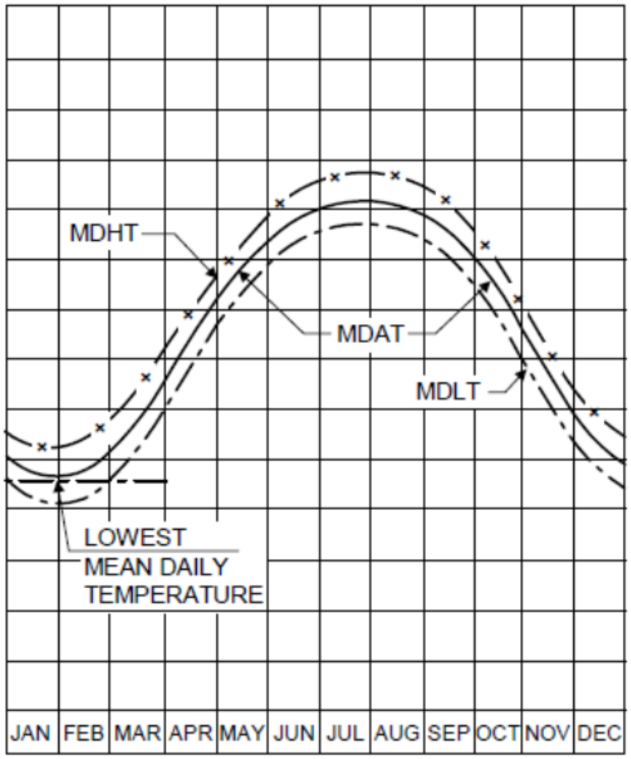


MDHT: Mean Daily High Temperature

MDAT: Mean Daily Average Temperature

MDLT: Mean Daily Low Temperature

LMDT: Lowest Mean Daily Temperature - (Design Service Temperature)

Figure 1 Graphical representation of the DST (ABS, 2010)

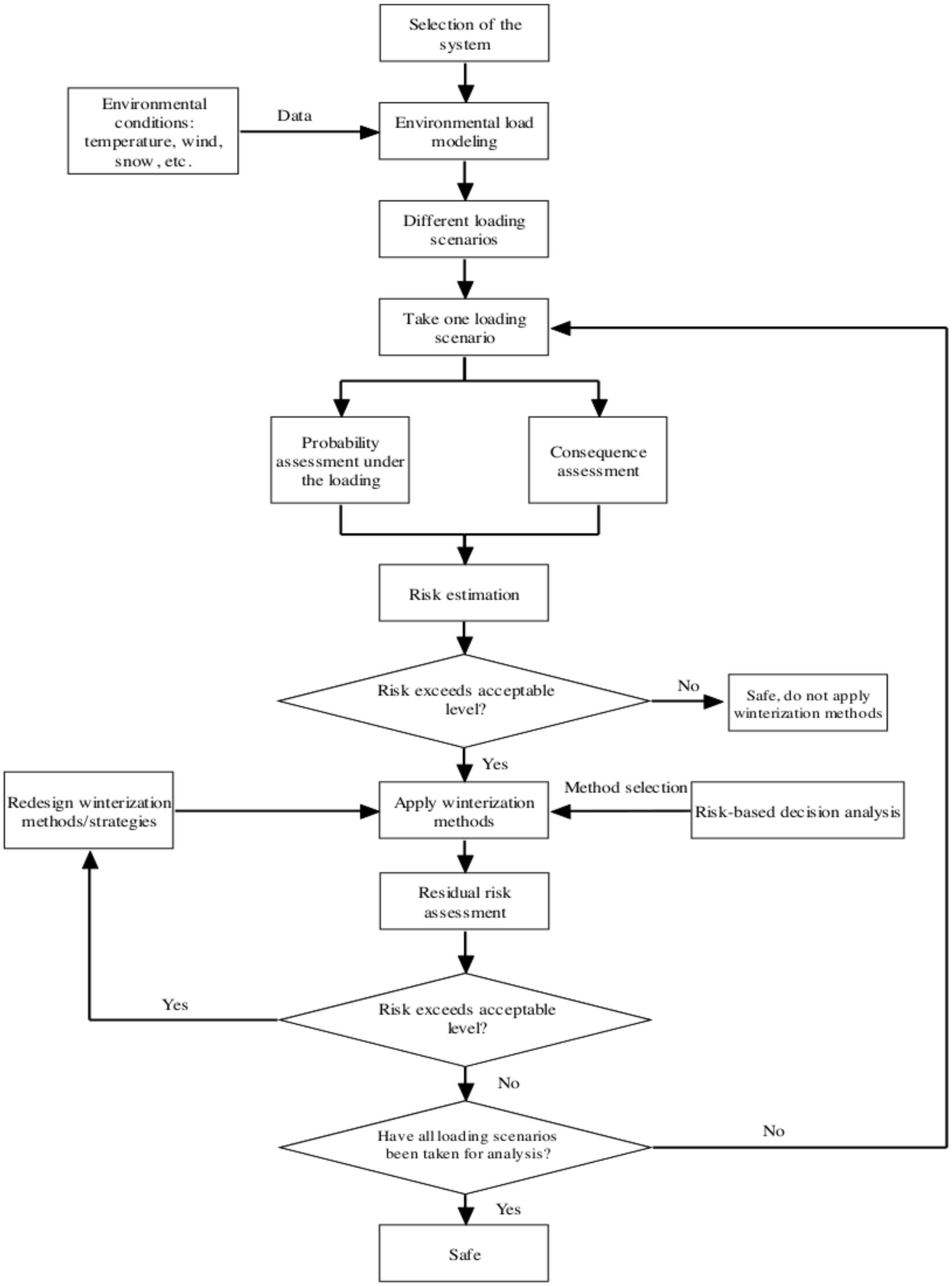
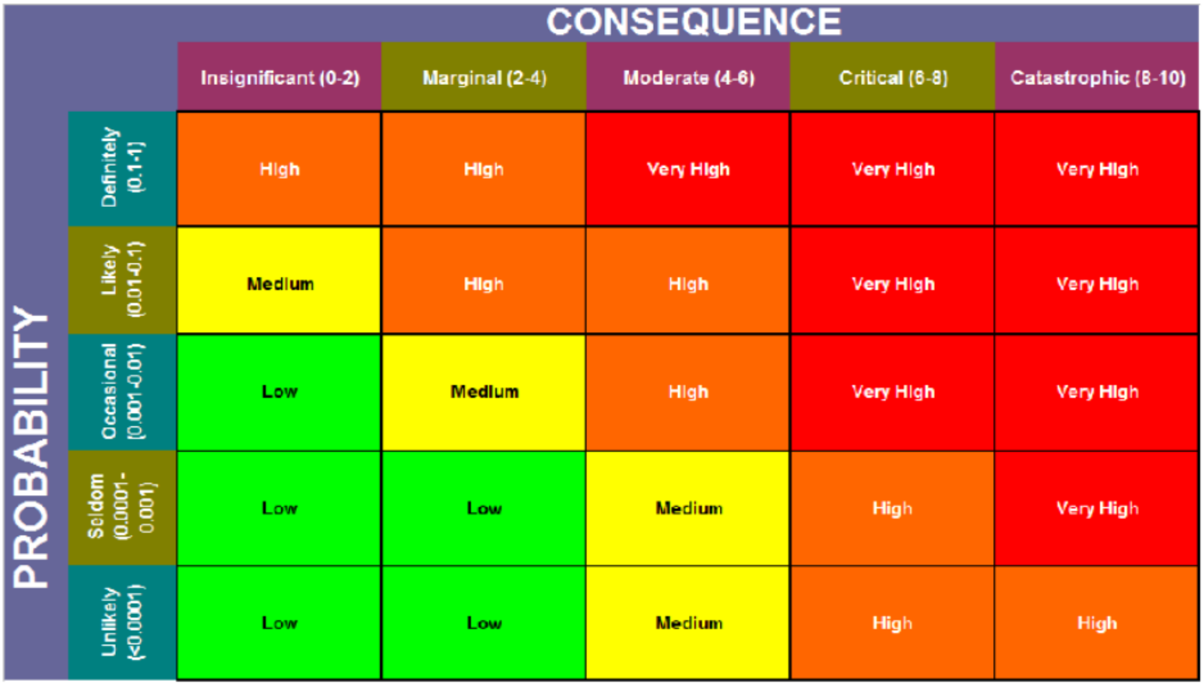


Figure 2 Risk-based approach for winterization



		CONSEQUENCE				
		Insignificant (0-2)	Marginal (2-4)	Moderate (4-6)	Critical (6-8)	Catastrophic (8-10)
PROBABILITY	Definitely (0.1-1)	High	High	Very High	Very High	Very High
	Likely (0.01-0.1)	Medium	High	High	Very High	Very High
	Occasional (0.001-0.01)	Low	Medium	High	Very High	Very High
	Seldom (0.0001-0.001)	Low	Low	Medium	High	Very High
	Unlikely (<0.0001)	Low	Low	Medium	High	High

Figure 3 Risk matrix

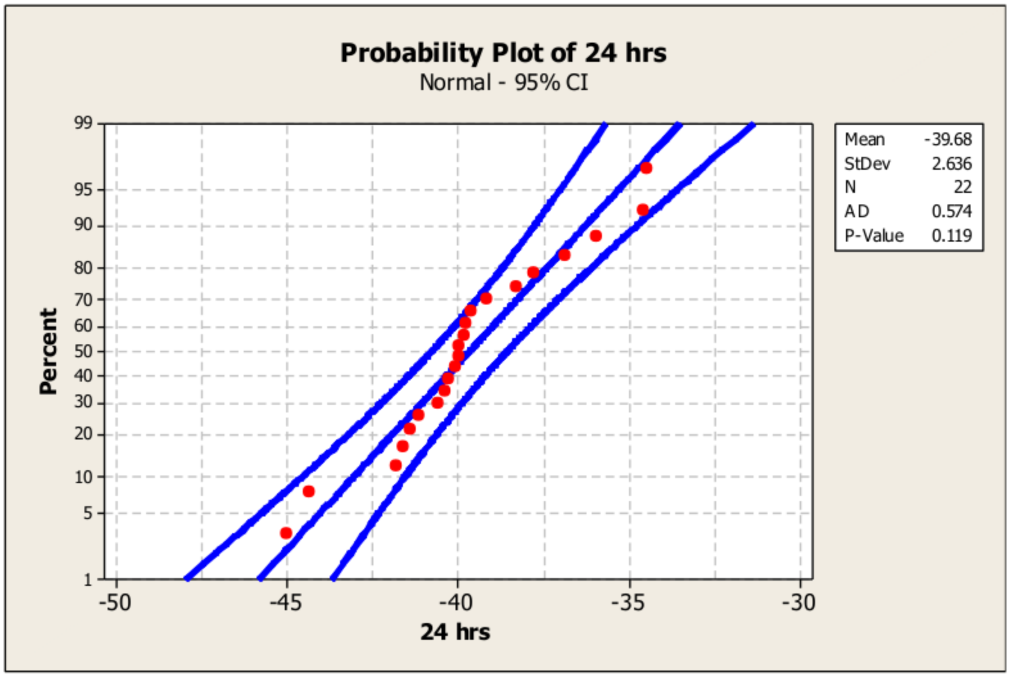


Figure 4 Normal probability plot of the extreme temperature data over 24 hours

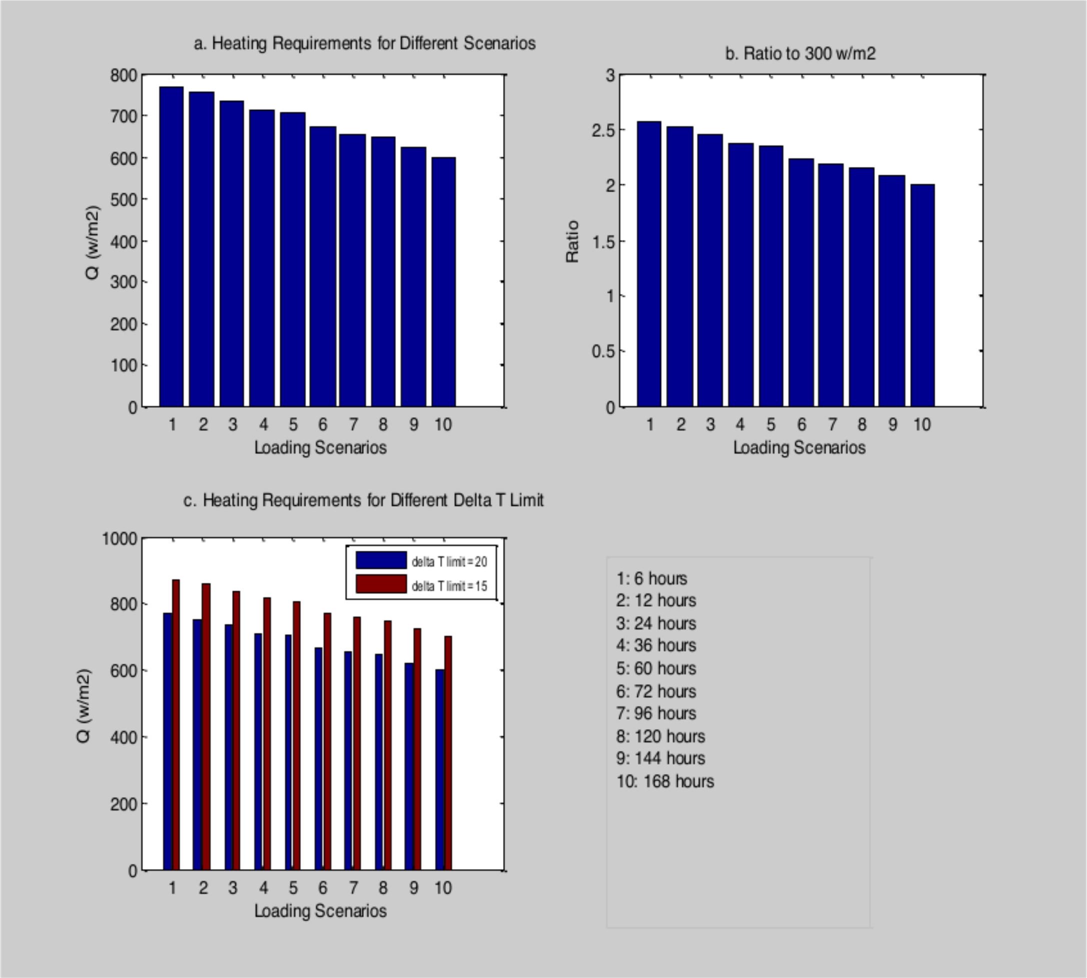


Figure 5 Heating requirements for gangways for different durations

Table 1 Winterization methods for vessel structures or systems

Structures/systems	Items	Potential Winterization Methods
Hull construction and equipment	Tanks	Heat tracing, air bubbler system, insulation, heating coils
	Deckhouses	Heat tracing, insulation, ice repellent coatings, deicing or anti-icing chemical application
	Superstructures	Heating tracing, insulation, ice repellent coatings, deicing or anti-icing chemical application
	Anchoring arrangements	Heating tracing, insulation
Vessel system and machinery	Prime mover	Heat tracing, self draining piping
	Combustion air systems	Heat tracing, insulation
	Anchor windlass	Heat tracing, ice repellent coatings
	Cargo handling equipment	Heat tracing, ice repellent coatings, insulation
	Piping systems	Heat tracing, insulation, self-draining piping
	Electric systems	Heat tracing, insulation
	Fire safety systems	Heat tracing, insulation, deicing or anti-icing chemical application, chemical seals
Safety systems	Navigational equipment	Heat tracing, insulation
	Launching stations and arrangements	Heat tracing, insulation, deicing or anti-icing chemical application
	Lifeboats	Insulation, ice-repellent coatings
Pressure relief system	Pressure relief valves	Heat tracing
	Emergency vapor depressurizing equipment	Heat tracing, insulation
Process equipment	Process vessels	Heat tracing, insulation, chemical seals
	Process heat exchangers	
	Process electric heaters	
	Compressors	
	Pumps	
	Atmospheric storage tanks	
Process piping system	Thermal relief valves	Heat tracing, chemical seals
	Block valves	
Safety system	Fire and gas detection	Heat tracing, insulation, deicing anti-icing chemical application, chemical seals
	Emergency shutdown station	

Table 2 Quantification scheme for severity levels of consequences

Criticality/Importance Class	**Description**	**Financial Loss ($)**	**Injury/ Fatality**	**Severity Value**
Critical	Failure causes system to stop functioning	>$1 Million	One or more fatality	8 – 10
Important for good operation	Failure causes impaired performance and adverse consequences	>$0.5Million	Permanent injury or fatality	6 – 8
Required for good operation	Failure may affect the performance and lead to subsequent failure of the system	>$0.2Million	Serious injury requiring weeks to recover	4-6
Part of the good operation	Failure may not affect the performance immediately but prolonged failure may lead to failure of the system	>$10,000	Injury requiring rest and recovery	2-4
Optional for operation	Failure may not affect the performance of the system	<$10,000	First Aid	0-2

Table 3 Materials and dimensions of the pipe and insulation

	Material	**k factor (W/m.K)**	**Outer diameter (inch)**	**Inner diameter (inch)**	**Thickness (inch)**
4 inch pipe	Steel	43	4.5	4.0	0.25
Insulation	Fiberglass	0.04	6.5	4.5	1

Table 4 The probability distributions for environmental loadings

Duration (hours)	Distribution Type	Mean	Standard Deviation
6	Normal	-41.54	2.58
12	Normal	-40.90	2.54
24	Normal	-39.68	2.64
36	Normal	-38.68	2.61
48	Normal	-37.96	2.68
72	Normal	-36.89	2.53
96	Normal	-36.05	2.60
120	Normal	-35.45	2.56
144	Normal	-34.71	2.49
168	Normal	-34.16	2.38

Table 5 Data for heating requirements calculation

T_{op} follows a normal distribution with $\mu = 5$ and $\sigma = 1$
$\left\|\Delta T_{Limit}\right\|$ =k = 20 °C
Wind speed = 10 m/s
Thickness of gangway = 3mm, conductivity factor of steel = 43 W/m.K
The acceptable level of risk is 0.001 and severity value is 2, then the acceptable level of PoF is 0.0005.

Risk-based Winterization for Vessels Operations in Arctic Environments

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