Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR-2015/11 **July 2015**

Survivability, Structures, and Materials Department
Technical Report

An Analysis of U.S. Navy Arctic and Ice Operations With Regard to Ship Hull Coating Systems

by

David M. Stamper and Elizabeth G. Haslbeck

Approved for public release; distribution unlimited.

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CONTENTS

FIGURES

TABLES

ADMINISTRATIVE INFORMATION

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ABSTRACT

The U.S. Navy has given significant consideration to future operational capability in the Arctic. The impact of these operations on corrosion and biofouling has not, however, been emphasized in those considerations. Hull coating systems commonly applied directly to ship hulls for the control of corrosion and biofouling (typically consisting of antifouling (AF) coatings applied over anticorrosive (AC) primer coats) will become damaged from encounters with sea ice. Technical challenges requiring investment are related to the coatings themselves and include assessments of durability as a function of ice exposure. Additional questions center on biofouling mitigation and/or mitigation of non-indigenous marine pests include querying the interactions among, for example, organism transport mechanism, water quality, coating type, coating damage, coating ablation or polishing rate, biocide type, leached layer/diffusion path, biocide release rate, and biofouling species.

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EXECUTIVE SUMMARY

This report is primarily intended to explore the ramifications of increasing Arctic operations by the U.S. Navy with regard to ship biofouling and corrosion control coating systems. The report identifies technical and knowledge gaps. Recommendations for future investments are outlined.

The United States Executive Branch, motivated by changes in the climate in the Arctic, has given significant consideration to national and homeland security concerns as well as to local, regional, and global environmental issues associated with increasing ship operations in this region. Likewise, the U.S. Navy has given significant consideration to future operational capability in the Arctic. The impact of these operations on corrosion and biofouling has not, however, been emphasized in those considerations.

U.S. Navy ship hulls are designed to operate in open water free of ice that may pose structural risk or a risk of damage to critical steerage, propulsion, and navigation systems. Hulls lack any reinforced ice belt, are equivalent to IMO Category C vessels, and therefore proactively avoid encounters with ice. Hull coating systems commonly applied directly to ship hulls for the control of corrosion and biofouling (typically consisting of antifouling (AF) coatings applied over anticorrosive (AC) primer coats) will become damaged from encounters with sea ice[1]*. Ice-resistant AC coatings have been developed and are often used on commercial vessels that routinely ply ice-covered waters. A changeover to ice-resistant AC coatings by the Navy fleet, however, is not currently warranted given our understanding of near-term Arctic operations. Until Navy hulls and other below-waterline systems are modified to meet the requirements for routine encounters with damaging ice, the risk of coating damage will be largely mitigated by the fact that vessels will avoid sea ice as a matter of course.*

A subset of the U.S. Navy fleet (submarines and surface ships) is known to have encountered ice. An attempt was made to relate coating ice exposure to coating damage for those ships. The data used to explore the extent of coating damage from ice exposure were primarily taken from diver hull inspection reports. No relationship was found. This may be because the data were not taken with this specific goal in mind. If and when the time comes to qualify and validate the performance of ice-resistant coatings full-scale, improved methods and processes for data collection, tracking, and analysis will be required.

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[1] Exposure to ice of elastomeric systems for acoustic damping is not specifically addressed in this report. That said, AC paint systems are applied below, and AF systems on top of, acoustic damping elastomers that are installed on a subset of the Navy submarine fleet. The intentional use of ice-resistant AC coatings outside the acoustic treatment to minimize ice damage is unlikely to be effective. An alternative approach would likely be required. Exposure of these elastomeric systems to ice is not specifically addressed in this report.

Ice-resistant AC coatings are likely to improve corrosion control for vessel hulls exposed to ice. However, these paints do not provide protection against biofouling. AF coatings, even if applied over the ice-resistant AC materials, are not designed to withstand impact with ice, and are thus unlikely to survive operations where exposure to ice is likely to occur. Ice-resistant biofouling control coatings are not currently under development. This presents risks to the Navy with respect to operational capability, fuel efficiency, and maintenance as well as to the transport of nonindigenous species. When vessels homeported in the U.S. are intermittently tasked with operations in the Arctic, the effective mitigation of biofouling will require a dedicated investment in either improved coatings or maintenance regimen or both.

Technical challenges related to coatings themselves include assessments of durability as a function of ice exposure. Technical challenges for biofouling mitigation and/or mitigation of non-indigenous marine pests in the Arctic include querying the interactions among, for example, organism transport mechanism, water quality, coating type, coating damage, coating ablation or polishing rate, biocide type, leached layer/diffusion path, biocide release rate, and biofouling species.

INTRODUCTION

The Arctic Region

The Arctic is geographically defined as the area within the Arctic Circle, or north of 66° 34’ N latitude, nominally where the sun remains above the horizon for more than 24 hours on the June solstice. The Arctic is also climatologically defined by the 10°C isotherm (the warmest average temperature), which corresponds roughly with the Arctic Circle, but also extends to include the Bering and Labrador Seas. The 10°C isotherm also corresponds to an area of extensive ice cover for much of the year (Figure 1).

The Arctic is warming, opening up the area for shipping, tourism, and increased exploitation of natural resources. Because of this warming, the annual mean Arctic sea ice extent decreased over the period 1979 to 2012, with a rate that was very likely in the range of 3.5-4.1% per decade [Pachauri et al., 2014]. The extent of Arctic sea ice has decreased in every season and in every successive decade since 1979, but most rapidly in the summer season. The Arctic region (land and water) will continue to warm more rapidly than the global mean. The National Oceanic and Atmospheric Administration (NOAA) reports that the Arctic is warming twice as fast as the global average warming, and the period from 2007-2014 had the lowest ice cover in the last 35 years [Jeffries et al., 2014]. The Intergovernmental Panel on Climate Change (IPCC) models project that a nearly sea ice-free Arctic Ocean in the month of September is likely before mid-century [Pachauri et al., 2014].

Motivated by the changes in the Arctic, the United States Executive Branch has recently clarified policy in the “National Strategy for the Arctic Region” [POTUS, 2014] to:

- Meet national security and homeland security needs relevant to the Arctic region
- Protect the Arctic
- Ensure that natural resource management and economic development in the region are environmentally sustainable
- Strengthen institutions for cooperation among the eight Arctic nations in the Arctic Council (the United States, Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, and Sweden)
- Involve the Arctic's indigenous communities in decisions that affect them
- Enhance scientific monitoring and research into local, regional, and global environmental issues

In support of the above national policy goals, the U.S. Navy focuses on U.S. national security aspects. According to the “U.S. Navy Arctic Roadmap 2014-2030” [CNO, 2014], the strategic goals for the Navy are:

- Ensure United States Arctic sovereignty and provide homeland defense
- Provide ready naval forces to respond to crises and contingencies
- Preserve freedom of the seas
- Promote partnerships within the United States Government and with international allies and partners

Although the Navy has operated in the Arctic for decades, a future of decreasing Arctic ice compels the Navy to refine doctrine, procedures, tactics, techniques, and equipment in order to expand Arctic operations. Increased Arctic missions will require expanded capabilities, particularly with regard to cooperating with other Arctic-stakeholder agencies, such as the U.S. and Canada Coast Guards, U.S. Air Force and Army, private shipping and industry, and foreign militaries [CNO, 2014].

Reduced Arctic ice cover has the Arctic Council and other stakeholders considering increased resource exploitation and, in particular, shipping. Shipping via the Northern Sea Route, the northern coast of Eurasia (mostly Russia) between the Norwegian Sea and the Chukchi Sea (Figure 1), is expected to expand from only two weeks of open water and 41-53 vessels yearly from 2011-2014 [average 45; NSRIO, 2015] to six weeks of open water and 450 vessels in 2025. In this context, open water does not mean ice-free, but rather ice cover at <10% where an icebreaker is not necessary for passage. The Northwest Passage, along the northern coast of North America (mostly Canada) from the Labrador Sea to the Chukchi Sea (Figure 1), is currently open only sporadically, but is expected to have five weeks of open water by 2030 [CNO, 2014]. The Transpolar Route is expected to be open for approximately six weeks by 2030. Unlike the Northern Sea Route and the Northwest Passage, the Transpolar Route largely avoids territorial waters by traversing the Arctic Ocean via the North Pole (Figure 1). All three routes also have seasons of several weeks before and after open-water, when passage may be possible by Polar Class vessels (described below), or with the assistance of icebreakers.

In the near-term (through 2020), the Navy is not anticipating much economic exploitation in the Arctic given the still-harsh conditions for most of the year. The Navy presence in the near-term will be primarily through undersea and air assets, with surface ships limited to operating in open water. Beyond 2020 and from 2030 and beyond, exploitation of Arctic petroleum and fisheries resources is anticipated to increase [CNO, 2014]. Additionally, from 2020-2030 shipping is expected to account for up to 2% of global traffic, primarily via the Northern Sea Route. With this growth, and through that period, the Navy anticipates increasingly complex exercises, as well as actual search and rescue or freedom of navigation operations, with the goal of increasingly-sustainable Arctic operations into the long term. The U.S. Navy Arctic Roadmap does specify (p. 17) that the Navy will be forward deployed for these mid- and long-term roles, but does not specify where this will be or what ship classes will be involved [CNO, 2014]. The

Navy currently has no forward-operating fleet presence in the Arctic, and Naval Forces Alaska is currently under U.S. Coast Guard command.


Scale 1:39,000,000
Azimuthal Equal-Area Projection
500 Kilometers
500 Miles

The Arctic region is often defined as that area where the average temperature for the warmest month is below 10°C.

Figure 1. The Arctic region. The red line is the 10°C isotherm – the warmest average temperature of the region. The Arctic Circle is also shown as the dotted line at 66° 34’ N latitude [en.wikipedia.org/wiki/Arctic_Circle].

Arctic Operations

Vessels operating in the Arctic must be designed and/or operated in order to mitigate the risks imposed by the severe environment. Vessels can face many varieties of sea ice (see Appendix A, Ice Definitions) impinging on the hull which can cause direct damage to underwater structures and systems. Vessels may also experience the accumulation of ice on topside surfaces from precipitation or sea-spray. Finally, sub-zero (°C) temperatures can freeze sea chest inlets and tanks adjacent to the hull, thus affecting other systems regardless of location (waterline or topside).

Recognizing these issues, the Polar Code of the International Maritime Organization [IMO, 2015] requires vessels intending to operate in the defined waters of the Arctic (and Antarctic) to apply for a Polar Ship Certificate in one of three categories.

- Category A vessels are designed for operation in polar waters at least in medium first-year ice, ranging from Polar Class 1 (year round, all ice conditions) down to Polar Class 7 (summer-autumn in thin, first year ice). Polar Class 1-7 certifications have extensive requirements, at different levels, for vessel construction, materials, environmental protection, operating procedures, and specialized equipment and training.

- Category B vessels are those not included in Category A, but designed for operations in thin, first-year ice which may include old ice inclusions. Category B vessels have less-stringent construction and constrained operating procedures.

- Category C vessels are designed to operate in open water or ice that poses no structural risk. Currently U.S. Navy ships, although not under the jurisdiction of the IMO, lack any reinforced ice belt (Figure 2), and would likely be equivalent to IMO Category C.

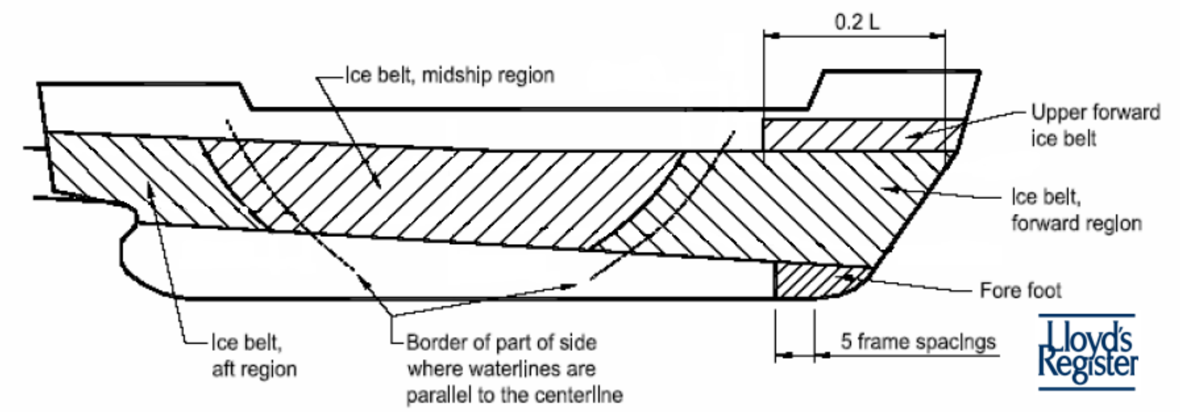

Figure 2. Depiction of the hull reinforcement necessary for Polar Class certification, according to Lloyd's Register [Hasholt, 2011].

Although facing the same Arctic environment as IMO-regulated vessels, Navy ships have unique, specialized equipment and operational needs. An extensive description of the risks of waterline ice, topside icing, and temperature effects on Navy ships' systems can be found in "Assessment of Surface Ship Operations in Arctic Conditions" [Farley et al., 2012]. Additional aspects of Arctic conditions on ships and personnel were also enumerated in the "U.S. Navy Cold Weather Handbook for Surface Ships" [Surface Ship Survivability Office, 1988]. Although these two reports describe many systems and operational hazards ships face because of exposure to cold environments, both only briefly mention hull coatings. Farley et al., [2012] list and describe numerous issues Navy ships face in the Arctic environment. These issues are re-listed here in Table 1 in order to demonstrate that hull coatings are only one of many issues facing Navy ships and operators in the Arctic.

Table 1. Categories of issues and approaches to solutions for surface ship operations in Arctic conditions. [Farley et al., 2012]

1	Hull strengthening	20	Sea chest
2	Ice-designed propeller	21	Portable space heaters
3	Sonar dome hardening	22	Life rafts
4	Hangar door	23	Ventilation openings
5	Underwater appendages	24	Portable diesel engines
6	LPD 17 advanced enclosed mast and bulwarks	25	Electrical heating
7	Combat and communications systems	26	Hydraulic pump units ambient temperature
8	Fire fighting	27	Battery powered equipment
9	Underwater electromagnetics	28	Ice detection systems and sensors
10	Arctic tactics, training, and procedures	29	Topside ice monitoring
11	Non-skid coatings	30	Cold weather boat
12	Exposed rotating radars	31	Boat stern seal
13	Reverse osmosis unit enhancements	32	Boat human factors
14	Human factors	33	Davit and rigid hull inflatable boat covers
15	Strength of materials	34	Boat engine discharges
16	Lube oil heating	35	NAVAIR Moriah wind sensor system
17	Bridge window defogger	36	NAVAIR Vertical Landing Aid systems
18	Hull, machinery, and engineering tactics, training, and procedures	37	NAVAIR Recovery Assist, Securing, and Traversing System
19	Anchoring equipment protection	38	NAVAIR Tactical Air Navigation System

With regard to non-coating underwater systems, Farley et al. [2012] suggest a possibility of ice impact to the active sonar dome, although being maximum forward and deep may make this less likely, short of running into a sizeable growler or bergy bit (see Appendix A for ice terminology); an event ships' crews are motivated to avoid. On some vessel classes, amidships are several masker belts for acoustic signature reduction. Toward the stern, propellers, rudders, shafts, and struts are all subject to damage from ice. The Surface Ship Survivability Office [1988] indicates that propellers and steering gear are more susceptible to ice damage than is the hull, particularly when travelling at higher speed or in reverse, where ice can be drawn under the stern into the propellers. Not discussed by Farley et al. [2012] are the impressed current cathodic protection (ICCP) anodes for corrosion protection. On CG and DDG ship classes, the ICCP anodes are located on both sides of the ship, forward, amidships, and aft. The anodes, located on raised patches on the hull, together with the requisite reference electrodes, may be particularly susceptible to ice damage. No data relating exposure to ice and a properly functioning ICCP system were identified.

Avoiding damage to critical systems such as steering, propulsion, ICCP, and sonar motivate ships to avoid sea ice exposure. The U.S. National/Naval Ice Center produces both generalized and customized reports of ice cover and meteorological conditions for U.S. interests worldwide (Figure 3). Navy ships access such reports for cold-water missions where ice is anticipated.

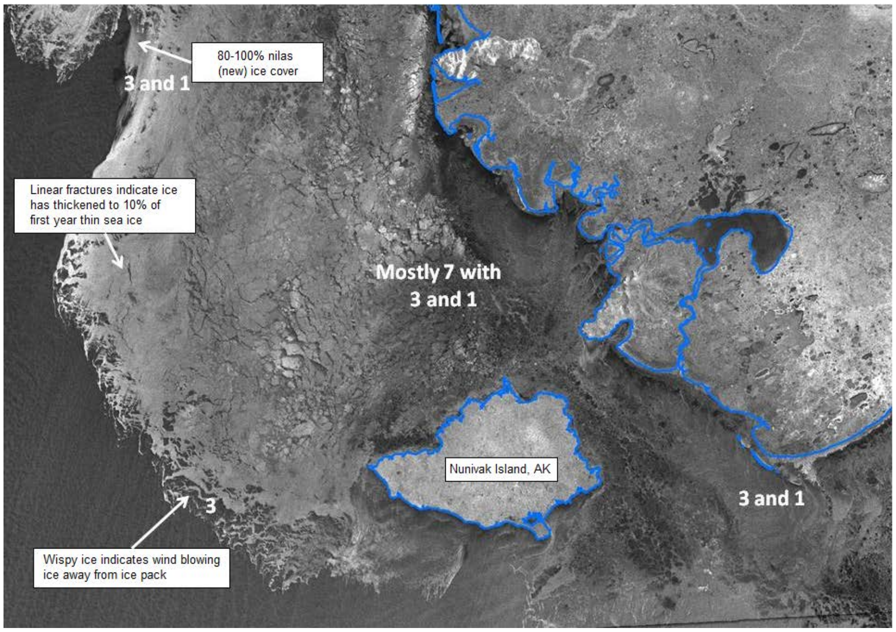

Figure 3. Example of U.S. National/Naval Ice Center (www.natice.noaa.gov) imagery, annotated with ice type and extent in the vicinity of Nunivak Island, AK in the eastern Bering Sea. Ice cover ranges from slush and nilas (1) to young ice (3), to multiyear ice (7). Courtesy of Tom Holden [Jan 2015].

Navy Hull Coatings

The Navy uses protective coatings to mitigate the negative effects of biofouling and corrosion. Commercial products that meet the requirements of a performance specification [MIL-PRF-24647E] are available for use in the fleet. For decades now the underwater hulls of most ships have been coated with a 5-coat copper ablative antifouling (AF) paint system consisting of two coats of epoxy AC of contrasting colors overcoated with three coats of AF (red, black, red). Type I, II, and IV AF coatings inhibit biofouling by releasing biocide(s) to inhibit settlement. Ablative coatings (Type I is non-copper-based and Type II is copper-based) are designed to slowly erode or otherwise wear away over time. This process helps to ensure sustained release of an effective dose of biocide. Within the last 5 years or so, ablatives have effectively replaced the obsolete Type IV “hard” copper-based coatings.

Although the biocides in ablative AF coatings are EPA approved, they are not entirely environmentally benign [Howell and Behrends, 2010; ten Hallers-Tjabbes and Walmsley, 2010]. Water and air quality requirements together with a desire to improve overall biofouling control efficacy have served as drivers for the development of alternative products. Two non-toxic fouling release (Type III) coatings [Webster and Chisolm, 2010] are qualified to MIL-PRF-24647E. These are typically applied as four-coat systems (two coats of AC primer, a tie coat to promote adhesion, and a topcoat). Fouling release (FR) coatings are designed to minimize the adhesion strength of biofouling organisms such that they slough off while the vessel is underway. They do not release biocides and do not ablate or polish away over time. Although two FR coating systems meet the requirements of the current performance specification, their use is limited given the lack of a compelling business case.

Navy fast attack submarines utilize related coating systems but in a slightly different configuration than surface ships [NAVSEA Submarine Maintenance Engineering, 2006]. Two coats of AC (yellow, then black) on the outer hull are covered with an acoustic damping hull treatment material. The AC coating would, therefore, normally be protected from ice damage by the acoustic hull treatment. A black, flexible epoxy tie-coat [MIL-PRF-24631/1C, Formula 187] is applied between the AF and the hull acoustic treatment. From the waterline to the keel, Virginia and Seawolf Class submarines are coated with two coats of black AF on top of the epoxy tie-coat. Los Angeles Class submarines are coated with two to four (usually two) coats of black AF above main beam to the waterline, while two coats of red or black AF are used below max beam. No publically-released reports of Ohio Class ballistic missile submarines operating in the presence of ice were found, and these submarines will not be discussed further in this publication.

Coating systems in use by Navy surface ships and submarines are reasonably well-performing overall. The Navy has put into place engineering control practices (maintenance inspections, cathodic protection systems, and hull and propeller cleaning events) to mitigate the impact of corrosion and extensive biofouling accumulation, especially as paint systems age. Although rare, catastrophic failure of hull coating systems can become a liability (drag/operational capability), such as when the USS America (CV-66) was prevented from launching aircraft in 1984 because of biofouling that increased hull drag and reduced hull speed [Lewis, 1998]. Similarly, and also rare, increased corrosion from damaged AC coatings and/or a poorly or improperly functioning cathodic protection system can result in significant pitting and/or loss in plate thickness, therefore making this a longer-term liability.

ANALYSIS OF NAVY HULL COATINGS AND ICE EXPOSURE

For surface ships, the most likely coating systems to be impacted by ice are the underwater AC/AF coating system [MIL-PRF-24647E] near the bow and along the veritical sides; the flat bottom and stern are much less likely to experience this type of damage. For submarines, the most likely coating systems to be impacted by ice are the topside and nonskid systems [MIL-C-24667; NST, 2015]; damage to the underwater hull coating system (AC and AF together) by exposure to ice would be limited to the area from max beam up to nominally the waterline. Additionally, because of the way submarines interact with ice, the impact on the underwater hull coating system could be minimal, or at least different from that experienced by surface ships, especially due to the lack of forward movement as they surface through ice. On fast attack submarines, damage to the AC paint is buffered by the presence of acoustic damping tile.

Ablative and fouling release hull coatings are not formulated to withstand abrasion, and it is widely recognized that they are unlikely to hold up to encounters with ice [M. Dust, personal communication, 2015]. Because assessments of coating system performance (physical and biofouling control) are a routine part of ship and submarine maintenance inspections, an inspection report database [Seaward Marine Services, Inc., SeaDoc database] was queried for known (publicly-released) Navy vessel encounters with ice. Reports as far back as 2003 were reviewed.

Maintenance inspections are primarily conducted by commercial divers and in accordance with standard processes such as the Naval Ships' Technical Manual (NSTM), Chapter 081 [NSTM, 2002]. The data characterizing coating physical performance on both surface ship and submarines are typically broken out by major hull area (bow, vertical sides, flat bottom, etc.) and are limited to areas below the waterline. Areas that are subject to damage by operations in the presence of ice are not always well-accounted for in established protocols. For example, for surface ships, divers do not routinely report on the condition of the boottop, yet this area may become damaged by ice. In addition, for submarines routine diver maintenance inspections do not includes assessments of topsidea areas; an assessment of the impact of ice on these areas was not possible for this report.

Surface Ship Inspections

Although there have been more recent examples of Arctic operations, only one instance of operations in the Arctic by a surface ship could be identified where the vessel clearly encountered sea ice - USS Normandy (CG 60) in June 2007 (Figure 4). The hull inspection carried out after these operations indicated no coating damage and likely reflects on the attention paid by vessel operators to avoid ice impact. In contrast with USS Normandy, documentation indicates SA Agulhas, an ice-strengthened South African research and supply vessel, passed directly through sea ice that scoured away ~30% of the self-polishing AF coating (Interspeed 340) [Lee and Chown, 2009]. Scoured areas were rapidly colonized by organisms, including *Ciona intestinalis* (Figure 5), an invasive biofouling organism also found in the Northern Hemisphere [Patanasatienkul *et al.*, 2014]. The type and condition of the AC coating was not reported for this vessel. Similar AF coating loss could be expected for Navy surface ships if they did not avoid exposure to sea ice.

Figure 4. USS Normandy (CG 60) navigates an open pack ice (Appendix A) north of Iceland (June, 2007). U.S. Navy photo by LTJG Ryan Birkelbach. Notice the six or seven lookouts at the bow, and the two people on lookout watch in the foreground.

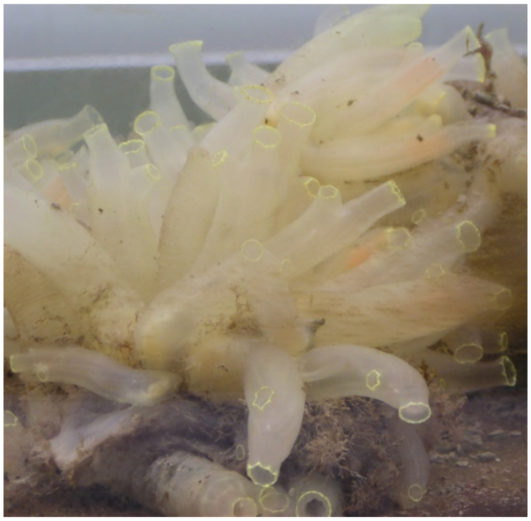

Figure 5. *Ciona intestinalis*, an invasive tunicate that is commonly found among hull fouling organisms. Photo from en.wikipedia.org/wiki/Ciona_intestinalis.

Submarine Inspections

Although the surface Navy avoids direct sea ice exposure, many submarine exercises in the Arctic are designed to encounter ice (Figure 6). In fact, the majority of the Navy Arctic operations we identified have involved submarines. During these operations submarines tend to surface slowly with zero forward motion [Hopper, 2014]. Since 2003 at least 18 U.S. Navy submarines were found to have encountered ice (Table 2; publicly-released reports only). Some vessels encountered ice more than once (noted with the use of "<u>underline</u>"). Coating damage was reported on a subset of these (noted with the use of "**bold"**), but the damage frequently could not be connected to ice exposure. Few encounters with ice corresponded with documented coating damage. There was no evidence of coating damage for more than half of the events, even when submarines surfaced through ice more than two feet thick.

In the end, only seven submarines were found to have been exposed to ice over nine events where there was also reported coating damage (Table 2, vessels 3, 4, 5, 6, 8, 15, and 16). Of these, evidence consistent with coating damage as a function of ice exposure is clear for only vessels 3 and 15. For these two vessels an inspection prior to the ice exposure indicated excellent coating condition, but within months of ice exposure a follow-on inspection indicated evidence of coating damage that was clearly consistent with exposure to ice. In only one case (vessel 8) did the damage seem to extend beyond the AF coating into the tie-coat and down to the acoustic hull treatment, but this damage was also recorded prior to Arctic operations.

Table 2. Publicly-released U.S. Navy submarine ice-events from 2003-2014, combined with coating damage reports from the Seaward Marine Services, Inc. SeaDoc records. Vessels experiencing ice more than once are underlined. Vessels with coating damage are in bold. Confusing notes in the records are marked (?). Several Virginia Class submarines events are not listed, but are discussed in the text.

#	Vessel Name	Arctic Date (ref)	Report Dates	Coatings Condition (WL = waterline, MB = max. beam)
1	SSN 22 Connecticut	4/03 (1)	none 9/04	AF 99%, tie >99%; AF in good condition
2	SSN 718 Honolulu	10/03 (1)	8/03 2/04	AF 99%, tie 99%; AF in excellent condition AF 99%, tie 99%; AF in excellent condition
3	**SSN 767 Hampton**	**4/04 (1)**	**3/03 6/04**	**AF 98%, tie 99%; AF overall good condition AF 90%, tie 99%; AF worn from WL to MB**
4	**SSN 757 Alexandria**	**7/04 (2)**	**4/04 1/05**	**AF 70%; tie 99%; AF primarily worn from WL to MB AF 60%; tie 99%; AF primarily worn above MB**
5	**SSN 723 Oklahoma City**	**8/04 (2)**	**7/04 12/04**	**AF 65%; tie 99%; AF fair to poor condition, growth tenacious AF 80% (?); tie 99%; AF in fair condition**
6	**SSN 691 Memphis**	**9/05 (2)**	**1/05 12/05**	**AF 95%; tie 99%; AF good condition, missing WL to MB (?) AF 99%; tie 99%; AF good condition, missing WL to MB (?)**
7	SSN 766 Charlotte	11/05 (1)	9/05 1/06 1/08	AF 90%, tie 99%; AF overall good condition Interim cleaning but no data on coating condition. Visibility 1 ft. AF 100%, tie 100%; AF in excellent condition
8	**SSN 716 Salt Lake City**	**11/05 (1)**	**5/05 None**	**AF 75%, tie 75% Decommissioned directly after Arctic ops.**
9	SSN 763 Santa Fe	7/06 (2)	5/06 5/08	AF 99%, tie 99%; AF in excellent condition AF 100%, tie 100%; AF in excellent condition
10	SSN 21 Seawolf	8/06 (2)	7/06 5/07	AF 99%, tie 99%; AF in overall good condition AF 98%, tie 99%; AF in overall good condition
11	SSN 764 Boise	11/06 (2)	10/06 8/07	AF 99%, tie 99%; AF in good condition AF >94%, tie >98%; AF in good condition
12	SSN 22 Connecticut	7/06 (2)	9/04 7/07	AF 99%, tie 99%; AF in good condition AF 99%, tie 99%; AF in good condition
13	**SSN 757 Alexandria**	**3/07 (1)**	**3/06 2/07 5/08**	**AF 50%, tie 99%; AF in fair condition, missing WL to MB AF 50%, tie 99%; AF missing WL to MB AF 95% (?), tie 99%; AF is mostly missing WL to MB (?)**
15	**SSN 719 Providence**	**7/08 (1)**	**2/08 1/09**	**AF 98%, tie 99%; AF 1% localized abrasions WL to MB AF 70%, tie 99%; AF 10% localized abrasions WL to MB**
16	**SSN 760 Annapolis**	**3/09 (1)**	**8/07 9/10**	**80% AF, tie 95%; AF missing WL to MB 90% (?) AF, tie 98%; AF missing WL to MB, scattered AF missing along bottom**
17	SSN 725 Helena	3/09 (2)	2/09 12/11	AF 95%, tie 98%; AF in good condition AF 99%, tie >99%; AF in good condition
18	SSN 22 Connecticut	3/11 (1)	6/09 10/11	AF 99%, tie 99%; AF in good condition AF 99%, tie 99%; AF in good condition
19	**SSN 767 Hampton**	**3/14 (4)**	**4/12 1/14 8/14**	**Dry dock and Painting AF 99%, tie 99%; AF in good condition AF 80%, tie 99%; AF overall good condition**

1. Arctic Submarine Laboratory, 2011a.
2. Arctic Submarine Laboratory, 2011b.
3. DVIDS, 2007.
4. America's Navy, 2014.

Figure 6. Representative images of submarine Arctic operations. A) USS Hampton (SSN 767) surfaced at the North Pole, taking part in ICEX 04 (April, 2004). U.S. Navy photo by Chief Journalist Kevin Elliott. B) USS Alexandria (SSN 757) surfaced through two feet of ice during ICEX-07 (March, 2007). U.S. Navy photo by Chief Mass Communication Specialist Shawn P. Eklund. C) USS Providence (SSN 719) breaks through the ice at the North Pole in the Arctic Ocean (July, 2008). U.S. Navy photo by Yeoman 1st Class J. Thompson. D) USS Annapolis (SSN 760) rests in the Arctic Ocean after surfacing through three feet of ice during ICEX 09 (March, 2009). U.S. Navy photo by Petty Officer 1st Class Tiffini M. Jones.

The fact that damage was observed on few vessels known to have encountered ice is likely a function of local conditions, the actual number of ice encounters for each vessel[2] and the care with which the submarines surface through the ice. Moreover, some ice damage may have been overlooked because the inspection data collection technique is tied to below-waterline maintenance inspection priorities that are not specifically designed to detect coating damage attributable to ice, or damage to topside coatings. Two of the more common inconsistencies include reporting of better coating condition following ice exposure than prior to ice exposure, and inconsistent reporting of the location of coating damage.

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[2] For any listed ice exposure event, a vessel may have surfaced and submerged through the ice several times (Hopper, 2014), but such details are not publicly-available.

In addition to the 19 ice encounters in Table 2, three Virginia-Class submarines have experienced Arctic conditions. These submarines are limited to surfacing through no more than six inches of ice [Hopper, 2014] and reports of Arctic operations are consistent with this limitation. The ice encounters described for these submarines (below) would not be expected to cause any damage to the AF coating.

- USS Texas (SSN 775) – March 2009 – Moored to the ice [Cole, 2009]. A post-Arctic operations inspection report was obtained and there was no coating damage reported.

- USS New Hampshire (SSN 778) – March 2011 – surfaced through slush [ASL, 2011a].

- USS New Mexico (SSN 779) – March 2014 – surfaced in open water [Hopper, 2014].

Ice Resistant Coatings

Standard epoxy polyamide AC coatings are installed primarily as a barrier to corrosion and also serve as a tie coat to promote good adhesion of the topcoats. Most epoxy polyamide coatings are somewhat durable but are not designed to be resistant to the abrasive or impact forces of ice. Lloyd’s Register recognizes several AC coatings for use on vessels that experience sea ice [Table 3; Lloyd’s Register, 2014]. Most contain glass flake to enhance their abrasion and impact resistance, characteristics which can be quantified using standard durability tests such as ASTM D4060-14 and ASTM D2794-93. ASTM D4060-14, Abrasion Resistance of Organic Coatings by the Taber Abraser, quantifies coating weight loss per abrasive cycles required to wear through the coating, normalized to coating thickness. ASTM D2794-93 (or ISO 6272-93), Impact Resistance, quantifies the force of a falling indenter punch sufficient to cause coating penetration or cracking.

The recognized ice-resistant AC coatings afford extra hull protection from both direct ice abrasion and the corrosion that would result from loss of AC integrity. Ice-resistant AC coatings are so durable that they are actually factored into a ships’ polar certification. A relationship between ice-resistant paint thickness (coating-dependent) and plate thickness has been established: 500 µm of paint can be equivalent to as much as one mm of steel in the ice belt [Figure 2, Hasholt, 2011].

Although resistant to ice, ice-certified AC coatings lack a mechanism to resist or mitigate the deleterious effects of biofouling. Typically, biofouling is mitigated on these durable ice-resistant coatings by underwater hull cleaning. In some cases a process has been identified for overcoating ice-resistant coatings with an AF coating such as an ablative or self-polishing system. Hempel, Jotun, and International Paint manufacture AC coatings (Table 3) that can be overcoated with AF, especially when applied with an appropriate tie-coat [Futrell, 2015; Hayman, 2015; Mangano, 2015].

Although ice-resistant AC coatings are available, given the attention the surface Navy pays toward avoiding ice contact, changing to using these coatings is not currently warranted. In the hypothetical situation where Navy ships will be called on for increased operations in the Arctic, however, the use of a certified ice-resistant AC coating should be strongly considered. Under scenarios where those vessels would operate in both the Arctic and in the temperate waters of the U.S., over-coating the durable ice-resistant with a biofouling control coating is possible and would be advisable. If required today, the most suitable coating system would likely be a copper ablative or a copper-free ablative formulation (Type I or Type II). These paints are likely to offer some level of biofouling protection as long as a proportion of the topcoat is left behind. By contrast, fouling-release coatings (Type III) are notably fragile and the ability of a fouling release coating to slough biofouling is negatively impacted by physical damage [Holm *et al*. 2011].

Table 3. Lloyd's Register recognized AC coatings for use on vessels exposed to sea ice.

Product Name	Manufacturer	Certificate Expiration	Coating Thickness	% Solids (wt./vol.)	Description
Permax 1000 HB (1)	Chugoku Marine Paints Chugoku-Samhwa Paints	4/2019	300-350 µm	82±2	Vinyl-ester resin with glass flake
Permax 3000 S (1)	Chugoku Marine Paints Chugoku-Samhwa Paints	4/2019	300-500 µm	92±2	Epoxy/polyamide with glass flake
Permax 3000 SW (1)	Chugoku Marine Paints Chugoku-Samhwa Paints Chugoku Paints B.V.	4/2019	300-500 µm	92±2	Epoxy/polyamide with glass flake
Hempadur Multi - Strength 35870 (2)	Hempel Manufacturing Sp. z.o.o.	11/2017	350-500 µm	87±2	Amine-adduct cured epoxy with glass flake
Intershield 163 / Inerta 160 (3)	International Paint Ltd.	7/2015	500 µm	95±2	Epoxy
Marathon IQ (4)	Jotun Paints Ltd.	9/2014	500 µm	98±2	Amine-cured epoxy
Marathon (5)	Jotun Paints Ltd.		250-500 µm		Amine-cured epoxy with glass flake
Sigmashield 460 (6)	PPG Coatings Co., Ltd.	8/2014	250-400 µm	81±2	Polyamine-adduct epoxy with glass flake
Sigmashield 1200 (6)	PPG Coatings Co., Ltd. PPG Coatings SPRL/BVBA	4/2016	400-500 µm	100	Free amine phenolic epoxy
Ecospeed (7)	Subsea Industries NV	9/2016	2X 500 µm	63 vol/vol (estimate)	Vinyl-ester resin with glass platelets

Biofouling and Invasive Species in the Arctic

Keeping hulls clean of biofouling not only saves fuel [Schultz *et al.*, 2011], but inhibits the transfer of nonindigenous species (NIS). Hull fouling is one of several important vectors for NIS. For example, Gollasch [2002] found that of 186 vessels coming from outside the North Sea, 96% of those vessels' hulls supported at least one NIS. In non-Arctic regions research has shown that, when unchecked, NIS transport has the potential to result in environmental and economic harm [Lewis and Coutts, 2010]. Minimizing the introductions of non-native species is recognized as an important component of protecting the Arctic environment (U.S. National Strategy for the Arctic Region [POTUS, 2014]).

The resistance of native communities to invasion by non-native species is not well understood and is difficult to predict [Miller, 2014]. Environmental factors such as water temperature, salinity, wave energy, and insolation are important predictive factors in whether an introduced species is able to become invasive, but increased water temperature is the most obvious effect of Arctic warming. As the Arctic warms and melts, the ability of North Atlantic and North Pacific and Arctic species to mix may be impacted. Arctic species' distributions have already been observed as contracting [Kordas *et al.*, 2011], and the biological systems associated with Arctic sea ice, in particular, are subject to very high risks with additional warming [Pachauri *et al.*, 2014]. Additionally, a warming Arctic will tend to disrupt food chains, since warming increases the metabolic rate of organisms and decreases the relative energy supply available at each trophic level [Kordas *et al.*, 2011]. Life cycle timing can also be disrupted by warming [Kordas *et al.*, 2011]. Warming simultaneously improves the environmental conditions for lower-latitude invasive species and disrupts the native communities. Pelagic species are generally expected to migrate northward with a warming climate, whereas locally cold and stratified bottom-water is anticipated to restrict benthic species distributions in the Bering, Chuckchi, and Beaufort Seas [Sigler *et al.*, 2011]. Although anticipated to change as the Earth continues to warm, the scale of biogeographic range has already been observed, with 75% of 129 coastal marine species shifting distributions poleward [Kordas *et al.*, 2011]. Because of these and other factors, Miller and Ruiz [2014] predict a new wave of invasions across the Arctic and near-Arctic.

The extent to which ports are developed in the Arctic is also a factor in the propagation of invasive species. Ports represent favorable habitat to many invasive species and port activities tend to disrupt native communities, making it easier for invasive species to become established. The opportunity afforded by ships coming and going increases the number and timing of possible introductions, making it more likely over time that invasive species do become established and eventually serve as another source for further invasions [Miller, 2014].

The following resources/efforts are available/underway to document the changes [Bluhm *et al.*, 2011]:

Arctic Register of Marine Species	www.marinespecies.org/arms
Ocean Biogeographic Information System	www.iobis.org
Arctic Ocean Diversity Project	www.arcodiv.org
Marine Barcode of Life Initiative	www.marinebarcoding.org
Arctic Biodiversity Assessment	www.caff.is/aba

SUMMARY AND RECOMMENDATIONS

Assessment of Science and Technology Gaps

The protective marine coating systems currently used on the underwater hulls of U.S. Navy surface ships and submarines are not designed to withstand exposure to the abrasive and impact forces associated with exposure to ice. Exposure to significant ice impact and abrasion increases the risk of corrosion when coating damage exposes bare metal. This condition can be further exacerbated when ice also damages the cathodic protection system (zinc anodes or impressed current cathodic protection system). Ice also abrades and damages the AF coating system which is critical to controlling biofouling. The added roughness from uncontrolled biofouling negatively impacts both ship fuel efficiency and operational capability/readiness, and encrustations of biofouling also increase the potential to spread nonindigenous species.

Today, infrequent and careful Navy vessel operations in the Arctic translate to low risk of ice damage to these coating systems. Surface fleet vessels proactively and effectively avoid impact with ice especially since their hulls and other underwater systems are not designed (strengthened) to withstand such impacts. Submarine operations in the Arctic, even when deliberately contacting ice, infrequently result in AF coating damage, while the AC coating is normally protected by the acoustic hull treatment. For these reasons, there is no immediate need to develop and/or implement more durable AC coating solutions or to explore improvements in biofouling protection, at least in support of the Arctic operations in the near-term.

As the Navy expands Arctic operations approaching and during the 2020-2030 timeframe, the process by which coating performance metrics are collected should be improved. For vessels that operate in the Arctic, more attention should be paid to metrics that are associated with possible ice damage. This includes establishing a relationship between opportunity for physical damage as a function of operations (timing, frequency, duration, and severity of ice exposure) and actual coating system damage. Such an investment would establish baseline physical performance of legacy underwater AC and AF coatings of surface ships and of topside and AF coating systems for submarines that operate in the Arctic.

If it is found that the AC coating system of surface ships is damaged along with the AF coating, the most likely solution for the U.S. Navy would be the use of an AC coating on Lloyd's Register of recognized coatings for use on vessels exposed to sea ice (Table 3). A combination of panel and full scale testing to validate performance would be required in order to establish performance requirements and establishing a process for material qualification. The process improvements with which metrics are collected and related to ice exposure (see above) would be applied in order to accurately measure improvements over the baseline systems. Finally, an assessment of adhesion between the AC and AF topcoats would be required.

An assessment of the baseline biofouling control performance of legacy AF coatings installed on ships that operate in the Arctic is also required. The focus would be on: 1) accounting for the impact of water quality on parameters such as biocide release rate and polishing/ablation rate on coating performance, 2) characterizing biofouling opportunity in terms of organism type, availability, and response to legacy hull coating systems, 3) characterizing operational profile of the vessels (operational tempo and speed-time profile), and 4) evaluating physical performance of biofouling control systems as a function of timing, frequency, duration, and severity of ice exposure. If the performance of legacy biofouling control systems is found to be inadequate then mitigation of fouling risk will mostly like come in the form of in-water hull cleaning. A decision matrix would be developed as a function of coating type, risk, and opportunity.

In order to meet our national security objectives in the Arctic Region over the longer term (beyond 2030), the Navy may need surface ships that are specifically designed to encounter ice. The baseline characterizations of current AF and AC coatings would serve to inform the decisions regarding the coatings systems that would be part of such new ship designs.

REFERENCES

America’s Navy. 2014. Navy Commences Participation in ICEX 2014 (NNS140319-17) Available at www.navy.mil/submit/display.asp?story_id=79747 Accessed 2/2015.

Arctic Submarine Laboratory. 2011a. Submarines Under Ice. Available at www.csp.navy.mil/asl/Submarines.htm. Accessed 2/2015.

Arctic Submarine Laboratory. 2011b. Historical Timeline. Available at www.csp.navy.mil/asl/Timeline.htm. Accessed 2/2015.

Bluhm, B.A., A.V. Gebruk, R. Gradinger, R.R. Hopcroft, F. Huettmann, K.N. Kosobokova, B.I. Sirenko, and J.M. Weslawski. 2011. Arctic marine biodiversity: An update of species richness and examples of biodiversity change. Oceanography 24:2323-248.

Chief of Naval Operations. 2014. U.S. Navy Arctic Roadmap from 2014-2030. Available at www.navy.mil/docs/USN_arctic_roadmap.pdf Accessed 1/2015.

Cole, W. 2009. USS Texas pays icy visit to Arctic. Honolulu Advisor 11/8/09. Available at the.honoluluadvertiser.com/article/2009/Nov/08/ln/hawaii911080383.html. Accessed 2/15.

Dust, M., 2015. USCG coatings subject matter expert, Personal communication.

DVIDS, Defense Video & Imagery Distribution System. 2007. USS Normandy Cruises Through Arctic Circle. Available at www.dvidshub.net/image/49935/uss-normandy-cruises-through-arctic-circle#.VNTJpnYo7ow. Accessed 1/2014.

Farley. S.M., T.T. Hendricks, R.M. George. 2012. Assessment of surface ship operations in arctic conditions. NSWCCD-70-TR-2012/015.

Fernandez, L. 2014. Bioeconomic strategies to address potential marine invasive species in the Arctic. *In* Nordic Council of Ministers “Marine Invasive Species in the Arctic”. Copenhagen. Aug 2014.

Futrell, B. 2015. Hempel Manufacturing Sp. representative. Personal communication.

Gollasch, S. 2002. The importance of ship hull fouling as a vector of species introductions into the North Sea. Biofouling 18: 105-121.

Hasholt, S. 2011. Rules for ice and cold operations. “Winterization of vessels. Lloyd’s Register. Available at www.skibstekniskselskab.dk/public/dokumenter/ Skibsteknisk/ Download%20materiale/2011/Arktisk%20Sejlads/Lloyds.pdf. Accessed 12/2014.

Hayman, F.P. 2015. Jotun Paints Ltd. representative. Personal communication.

Holm, E.R., J.R. Curran, A.P. Stephens, G.W. Swain, and E.G. Haslbeck. 2011. Effecit of repeated cleaning on condition and performance of a fouling-release coating. Final. NSWCCD-61-TR–2011/11 July 2011.

Hopper, R. 2014. ICEX 2014. Available at www.public.navy.mil/subfor/underseawarfaremagazine/Issues/Archives/issue_55/ICEX.html. Accessed 2/2015.

Howell, D. and B. Behrends. 2010. Consequences of antifouling coatings – the chemists perspective. *In* Biofouling, S. Dürr and J.C. Thomason (Eds.) John Wiley & Sons, West Sussex, UK.

IMO. 2015. Polar Code of the International Maritime Organization. Available at www.imo.org/MediaCentre/HotTopics/polar/Pages/default.aspx. Accessed 2/2015.

Jeffries, M.O., J. Richter-Minge, and J.E. Overland. 2014. Arctic Report Card, 2014. Available at www.arctic.noaa.gov/reportcard. Accessed 1/2015.

Kordas, R.L., C.D.G. Harley, and M. I. O'Connor. 2011. Community ecology in a warming world: The influence of temperature on interspecific interactions in marine systems. J. Exp. Mar. Biol. Ecol. 400: 218–226.

Lee, J.E., S.L. Chown. 2009. Temporal development of hull-fouling assemblages associated with an Antarctic supply vessel. Mar. Ecol. Prog. Ser. 386:97-105.

Lewis, J.A. and A.D.M. Coutts. 2010. Biofouling invasions. . *In* Biofouling, S. Dürr and J.C. Thomason (Eds.) John Wiley & Sons, West Sussex, UK.

Lloyd’s Register. 2014. Recognized abrasion resistant ice coatings, as of 5/11/2014. Available at www.cdlive.lr.org/information/Documents/Approvals/PaintsResinsReinforcements/paint18.pdf. Accessed 12/2014.

Mangano, J. 2015. International Paint LLC representative. Personal communication.

Miller, A.W. 2014. Melting sea ice, accelerated shipping, and Arctic invasions. *In* Nordic Council of Ministers “Marine Invasive Species in the Arctic”. Copenhagen. Aug 2014.

Miller, A.W., G.M. Ruiz. 2014. Arctic shipping and marine invaders. Nature Clim. Chg. 4:413–416.

Naval Ships’ Technical Manual Chapter 081, Waterborne Underwater Hull Cleaning of Navy Ships, S9086-CQ-STM-010/CH-081R4, Revision 4, April 2002.

NAVSEA Submarine Maintenance Engineering. 2006. Submarine Maintenance Standard. MS NO. 6310-081-015 REV G.

NSRIO, Northern Sea Route Information Office. 2015. Available at www.arctic-lio.com/. Accessed 2/2015.

NSTC, Naval Surface Treatment Center. 2015. Exterior Non-Skid. Available at www.nstcenter.biz/writeup.aspx?title=Exterior%20Non-Skid&page=NavyCommunityAppExtSubNon-Skid.html. Accessed 2/2015.

Pachauri, R.J., *et al.* 2014. The Synthesis Report of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Available at www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT_Corr2.pdf Accessed Jan 2015.

Patanasatienkul, T., C.W. Revie, J. Davidson, and J. Sanchez. 2014. Mathematical model describing the population dynamics of *Ciona intestinalis*, a biofouling tunicate on mussel farms in Prince Edward Island, Canada. Man. Biol. Invas. 5:39-54.

POTUS, Office of the President of the United States of America. 2014. National Strategy for the Arctic Region. Available at www.whitehouse.gov/sites/default/files/docs/nat_arctic_strategy.pdf. Accessed 1/2015.

Schultz, M.P., J.A. Bendick, E.R. Holm ER, and W.M. Hertel. 2011. Economic impact of biofouling on a naval surface ship. Biofouling 27:87-98.

Sigler, M.F., M. Renner, S.L. Danielson, L.B. Eisner, R.R. Lauth, K.J. Kuletz, E.A. Logerwell, and G.L. Hunt Jr. 2011. Fluxes, fins, and feathers: Relationships among the Bering, Chukchi, and Beaufort Seas in a time of climate change. Oceanography 24:250–265.

Surface Ship Survivability Office. 1988. U.S. Navy Cold Weather Handbook for Surface Ships. OPNAVP-03C-01-89.

ten Hallers-Tjabbes, C.C, and S. Walmsley. 2010. Consequences of antifouling coatings – an environmental perspective. In Biofouling, S. Dürr and J.C. Thomason (Eds.) John Wiley & Sons, West Sussex, UK.

Webster, D.C., and B.J. Chisholm.2010. New directioins in antifouling technology. In Biofouling, S. Dürr and J.C. Thomason (Eds.) John Wiley & Sons, West Sussex, UK.

APPENDIX A. ICE DEFINITIONS

Ice Definitions (modified from Surface Ship Survivability Office, 1988)

Bergy bits	*ice masses (not flat) about the size of a small house*
Close ice	*ice whose concentration is 70-80% coverage*
Compact pack ice	*essentially 100% coverage by ice pieces, but not yet frozen together*
Consolidated pack ice	*100% coverage by ice pieces that are frozen together*
Diffuse ice edge	*dispersed ice usually on the leeward side of pack ice*
Drift ice	*free-floating ice*
Fast ice	*ice that remains attached to the coastline*
Floe	*any relatively flat piece of ice >20 m across*
Frazil ice	*spicules or plates of ice suspended in water*
Grease ice	*frazil ice that has coagulated to form a slushy layer at the surface*
Growlers	*ice (not flat) smaller than bergy bits, around the size of a piano*
Iceberg	*a large mass (not flat) of floating ice typically spawned by a glacier, bigger than a bergy bit*
Ice cake	*flat ice 2-20 m across*
Multi-year ice	*ice that has survived at least two summers and is much harder than first year ice*
Nilas	*thin, elastic, and bendable crust of ice*
Old ice	*ice that has survived one summer*
Open pack ice	*ice coverage about 40-60%*
Pack ice	*any area of sea ice other than fast ice*
Pancake ice	*circular pieces of slushy ice from 1-9 ft diameter, typically with raised rims*
Polynya	*open water surrounded by more or less consolidated ice*
Shuga	*spongy whitish ice lumps formed from grease ice, a few centimeters across*
Very close ice	*pack ice at 90+% coverage*

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