A Quarterly Magazine from ABS

Winter 2015

Surveyor

ABS

The Broad Scope of ARCTIC SEARCH & RESCUE

In this photo from July 2014, the US Coast Guard rescues the crew of a 36-foot sailboat that became trapped in ice as it tried to travel from Vancouver to eastern Canada using the Northwest Passage.

The vast, hostile emptiness of the Arctic makes search and rescue (SAR) a particularly challenging endeavor. With great distances to cover, awful seas to fight and deadly temperatures to contend with, Arctic SAR requires rapid response, a high level of skilled preparedness and, occasionally, a readiness for combined operations between the safety agencies of more than one nation.

The need for a far-reaching, effective maritime safety net increases with each new industrial incursion into the Arctic. To this end, the US and Canadian Coast Guards have cooperated on numerous Arctic operations over the past decade and worked with Russian forces in more than a dozen combined-operations exercises designed to improve their mutual capabilities for conducting integrated search and rescue operations in this difficult environment. ❖

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COVER:

An ABS scientist aboard a Polar research vessel contemplates the endless, harsh immensity of the Arctic. Today, companies in the maritime and energy sectors are considering long-term activities in the High North, and have begun engaging with classification societies and academic institutions in a growing number of research and development projects directed towards understanding, and dealing with, this exceptionally harsh and challenging environment.

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Using Science to Conquer the Arctic

How researchers help industry tackle the challenges of doing business safely and responsibly in the far north.

Organized collaboration between academia and industry has a long and fruitful history dating to the dawn of the Industrial Age. Since the founding of Britain's Royal Institution in 1798, numerous fora have appeared around the world in which those who create knowledge and those who commercialize it can join forces and, sometimes, develop ideas into goods and services of long-lasting benefit.

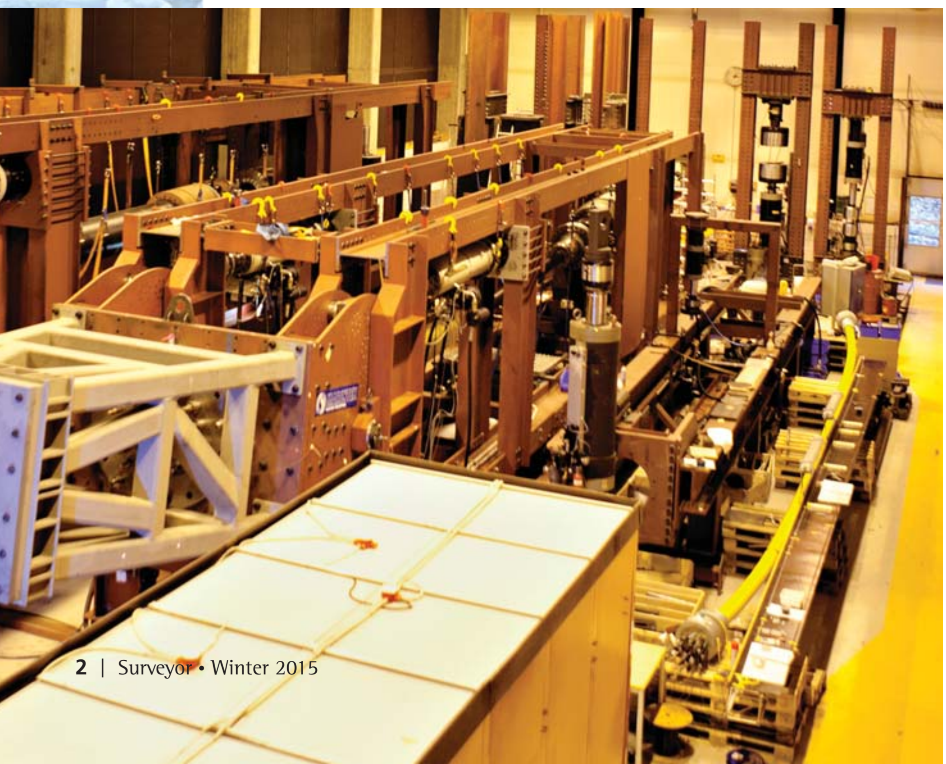
In the maritime world, one prominent organization at the academia-industry interface is Norway's Marine Technology Research Institute (Marintek), a contract research company headquartered in Trondheim, co-located with the Norwegian University of Science and Technology (NTNU in the Norwegian acronym). Although not part of the university, Marintek is located in the Marine Technology Center on campus and has a symbiotic relationship with the school: on the Center's first floor are lecture halls for students; the second floor holds offices of the professors from NTNU's Department of Marine Technology, who with their students work with Marintek on its various projects; and the third floor holds the offices of Marintek, which operates the university's big model basins and test facilities.

Marintek traces its origins to the 1939 completion of Norway's first towing tank – which was built on the campus of the institute that became the NTNU and is still in use – and the organization subsequently founded to operate the test facility. This organization changed names several times, lastly in 1984 when it became Marintek and was made a subsidiary company of Norway's Foundation for Scientific and Industrial Research (SINTEF). Marintek's primary shareholders today are SINTEF (56 percent) and the Norwegian Shipowners' Association (26 percent).

Established by the university in 1950, SINTEF is Scandinavia's largest independent research organization. With the NTNU and University of Oslo as its main academic partners, it annually performs about 9,000 research projects for some 3,000 customers and had a turnover in 2013 of NOK 3 billion (about $450 million), more than 90 percent of which was won in open competition.

As part of SINTEF, Marintek performs bilateral contract research in addition to taking part in joint industry projects, and devotes much time to participation in the research and technology development efforts sponsored by the Research Council of Norway (RCN), a government agency that identifies and funds research activities and recommends

The Marine Structures laboratory at Marintek.



national technological priorities. Two of the RCN's main funding schemes are the so-called Center of Excellence (CoE) and Center for Research-Based Innovation (CRI), terms that refer not to physical structures but to time-limited strategic research programs. For example, the Center for Autonomous Marine Operations and Systems at NTNU is a CoE, while the Center for Sustainable Arctic Marine and Coastal Technology (SAMCoT) is a CRI. Another funding scheme is the Knowledge-building Project for Industry (KPN in Norwegian), which focuses on bringing about specific, practical developments while also providing scholarships for PhD and post-doctoral students. One KPN currently underway has as its goal the development of a dynamic-positioning control technology specifically for use in ice-infested Arctic waters.

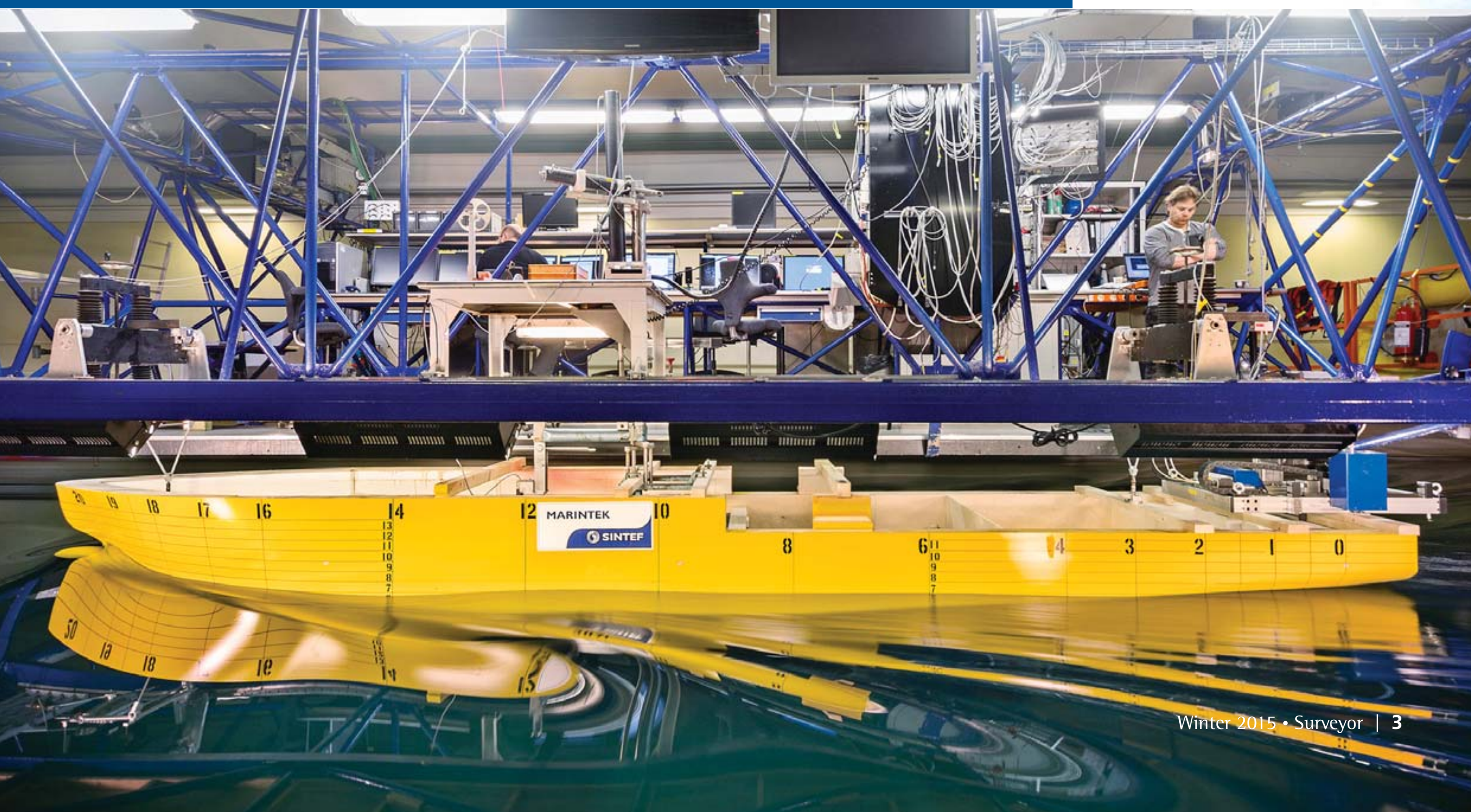
On the Road to Arctic DP

Dynamic positioning (DP) control systems were developed to counter three environmental forces that take a vessel off station: wind, wave and current. Many systems accomplish this through a combination of feedback and 'feed-forward' technologies. The feedback part, typically proportional-integral-derivative (PID) controllers, use data from global positioning system (GPS) satellites to note changes in the vessel's motion and heading and then direct its thrusters to bring it back on station. In so-called feed-forward control, the onboard computer takes measurements of wind speed and direction, calculates the forces they are likely to generate on the vessel and then orders the thrusters to compensate for the wind load directly, such that they counter any offsetting force in the moment of its occurrence and keep the vessel on station.

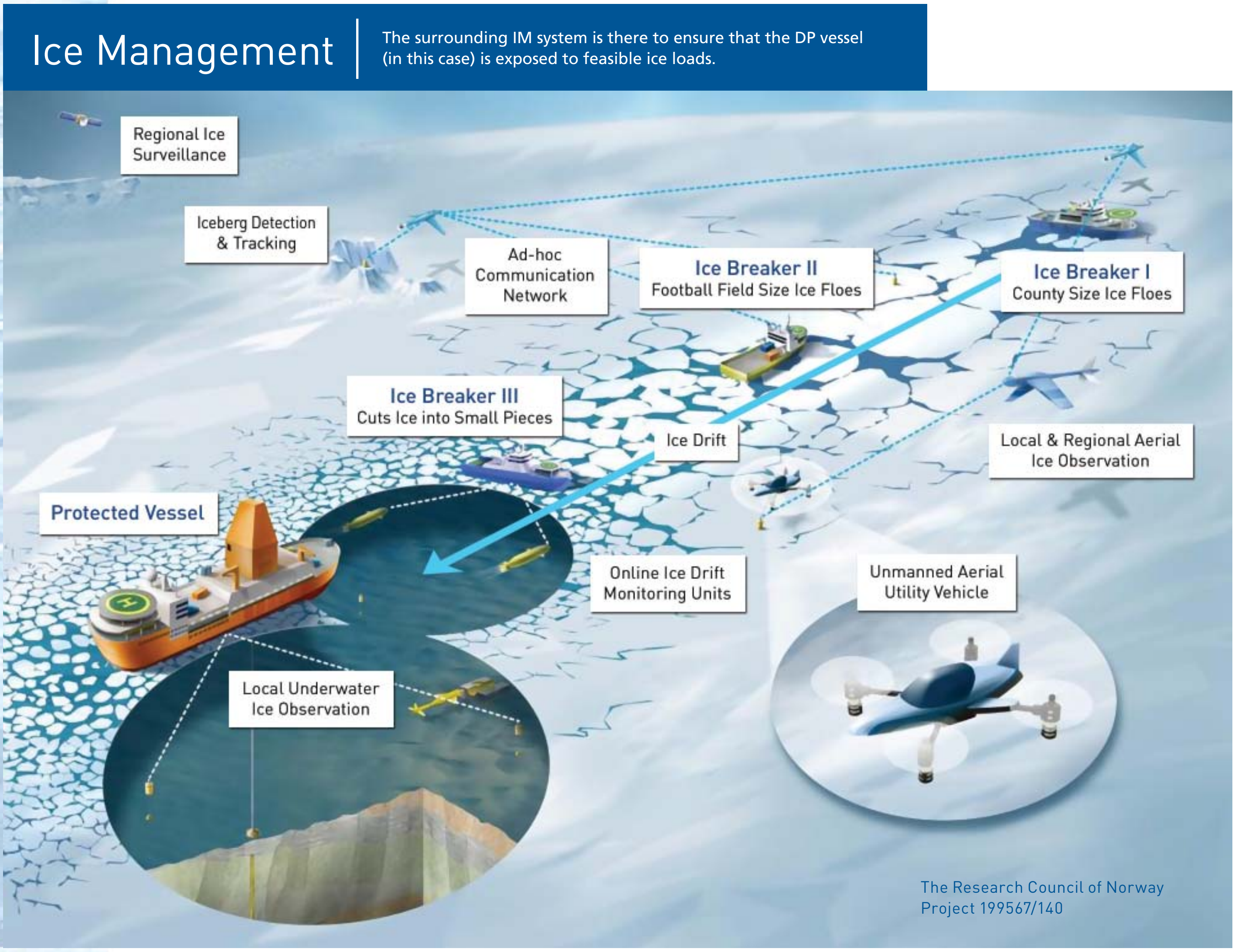
These well-established control strategies are severely challenged by ice-infested Arctic environments – so much so that new technologies need to be developed to bring DP safely into the High North, according to Dr. Roger Skjetne, a Professor of Marine Control Engineering at NTNU whose current research projects with Marintek include Arctic DP, ice surveillance and development of power management systems.

"Traditional DP systems are not designed for positioning in ice. Ice forces are very different from wind, wave and current forces," Skjetne says. "They are not constant like ocean currents, for example. They can vary rapidly, and the variations can be very large; they can stay at extreme levels for some time and then drop to almost nothing; an analogy would be to wind gusts. Different from wind gusts, however, is the lack of measurable ice parameters from which we can estimate the corresponding forces and moments on the vessel – we don't have a 'wind sensor' for ice loads," he explains.

Dr. Roger Skjetne, Professor, Marine Control Engineering, NTNU



The large towing tank at NTNU operated by Marintek.



An ice management scenario developed by NTNU and Marintek researchers.

Vessels trying to keep station in 'managed' ice – ice that is broken and manipulated by icebreakers – contend with a unique problem. Ice floes, under the influence of wind and current and their own momentum, collide with each other in an unending series of destructive knock-on effects as the broken-up masses float along. This creates a large number of potentially destructive, quickly changing ice encounter scenarios that challenge researchers to develop not only new DP control systems, but also new vessel designs to go with them.

"This project addresses effective station-keeping, effective ship design, effective ice management, and a DP control system that is able to compensate for ice forces," Skjetne says. "In developing new DP control algorithms, one question to answer is how the DP system should understand ice forces. If we want to develop a reactive control strategy, we need feedback and feed-forward control algorithms better suited to the task than the current PID controllers. If, instead, we want a proactive strategy, we need to find something we can continuously measure that will enable us to apply an ice characteristics model that gives some prediction of ice behavior and forces. Then, if the DP system 'knows' in advance the forces coming in, say, over the next ten seconds, it could build up thrust and prepare to compensate for them," he explains. "This leads to another question, which is whether ice management information data can be fed into the DP control system such that some sort of coordination between the ice management vessels and the DP vessel becomes possible."

The Arctic DP project and SAMCoT have a number of studies running under various work packages in their ice operation investigations. For example, several PhD students are working on developing the parameters needed for good ice modeling, such as drift speed, direction, thickness and concentration. One research topic involves using drones to take digital images of ice fields, which are run through a computer program that identifies each individual floe and produces floe size statistics or models to support decision-making by ice managers. Another study has a PhD student developing numerical simulations of vessels floating in broken ice. In SAMCoT this topic is taken further, with the aim of developing a numerical simulator of structures in ice.

One important effort involves developing 'capability plots' for ice operation – the analyses of a DP vessel's actual stationkeeping performance and capability most likely to be attained during operation under given environmental conditions.

"For open-water DP capability plots, there are well-established equations that map wind speed and current; wind speed into wind-generated waves and wave forces; and wind forces and current forces – if I input a certain wind and current speed and direction, I get a resulting wind force, wave force and current force. I can then allocate those forces to my thruster system and see if it can compensate for them," Skjetne says. "The problem with ice is that, while equations for ice forces exist, they are far too uncertain. To get around this, numerical simulation tools are now emerging so that, instead of calculating these forces exactly through an equation, we can take a certain condition – say, ice thickness or speed – and simulate it for enough time to generate a data series, against which we can evaluate the thruster," he explains. "This raises the question of which force to use – average force, maximum force or some kind of 'significant' force? That's a research topic in itself," he adds.

Strategies for Understanding the Ice World

The large number of unknowns in the ice environment has given rise to many projects aimed at developing computer programs that can reliably simulate the movement, properties and forces of Arctic ice, and its interactions with itself and with man-made structures. Successful development of such programs depends on good collection and analysis of data on the natural environment, says Dr. Sören Ehlers, a Professor with the NTNU's Department of Marine Technology whose projects with Marintek include various aspects of Arctic vessel structural design.

Regarding sea ice, Ehlers says observation systems need to monitor such characteristics as movement, size and structure of the ice floes, and provide reliable data on such properties as ice concentration, ice geometry and drift speed; this data can then be used to provide reliable assessments of threats they pose and the effects of ice management with icebreakers.

"Regarding icebergs, of first importance is the need to detect and track them," Ehlers says. "Even though they are big, that's not always so easy to do. After that, we need simulation programs that are able to forecast drift scenarios and provide information that can aid the difficult task of iceberg handling – essentially towing them so that they don't drift into a field development."

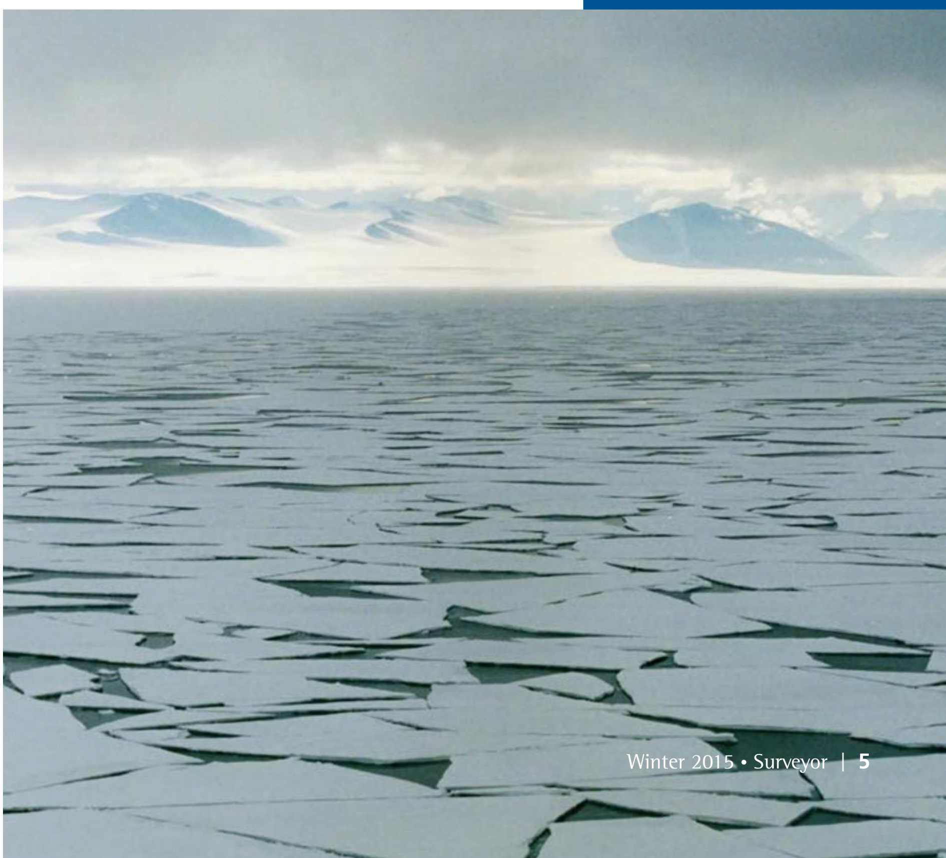
Among Arctic researchers, iceberg forecasting is a topic of great interest as well as a target of simulation development. The SAMCoT CRI focuses quite a lot of effort on creating iceberg drift models and on developing ideas for how to handle icebergs, whether in open water or frozen into sea ice.

"In open water operations, you can design a ship or structure for the 10,000-year wave, but the Arctic is different," Ehlers adds. "It is very difficult to simulate the forces you can expect just from level ice; the forces from disintegrated ice floes are even more difficult to simulate," he says. "Then, regarding an iceberg, it could be surrounded by freshwater ice or frozen into solid seawater ice, for example, which is a system with very different mechanical properties; and you could have it all in combination, which is extremely challenging to simulate."

Although no computer program currently in existence can provide that level of prediction, several are in encouraging stages of development, he says.

Once good data becomes regularly available – and, ideally, can be streamed in real time into numerical simulation tools – it can be input to sophisticated decision support tools that will

Dr. Sören Ehlers, Professor, Department of Marine Technology, NTNU



In the Arctic, prompt emergency response will be crucial in order to save lives and protect the environment.

make Arctic operations safer. For this reason, Marintek is engaged in projects directed at developing a wide variety of observation and measurement strategies, ranging from airborne drones collecting data from above to autonomous underwater vehicles (AUVs) gathering information from under the ice. The idea is not to eliminate all but the best measurement system, but to develop a field of systems that cover each other's weaknesses and together contribute to increasing the robustness of the technological support systems of Arctic advancement. For example, when heavy fogs or storm systems render drone-based equipment useless, an AUV-based underwater system could shoulder the better part of the data burden.

"The reason why we work on so many different strategies is because they are redundant and complementary – if the 'most intelligent' prediction system fails, you can still rely on accelerometers, instrumentation and other measurement methods," Skjetne says.

Safety & Communications, Critical Concerns

Rapidly changing, extreme weather conditions stretching over vast, empty distances make the Arctic a very dangerous place to industrialize. Although much public attention to Polar research has so far focused on progress in vessel design and operation, a large body of work has grown around solving the communications challenge at the top of the world.

Large areas of the Arctic are expected to be ice-free in summer within 15 years. This will bring a larger number of users to these areas and, consequently, an increased demand for communications capacity. It will also bring a higher probability of accidents. Reliable means of sharing situational awareness between commercial vessels and safety authorities will be crucial to safe operation in the harsh remoteness of far northern seas.

Between the needs of normal operations and the exigencies of occasional emergencies, demand for bandwidth in the Arctic is predicted to grow significantly over the next few years as oil and gas development, shipping services and industrial activities in the high latitudes increase. One estimate by the European Space Agency (ESA) predicts that from Europe alone the overall bandwidth demand in latitudes above 75°N will increase from about 500 megabytes per second in 2015 to more than a gigabyte per second in 2020.

The challenge to all this is that, in the high latitudes, high-frequency radio signals start degrading due to magnetic and solar phenomena and broadband (apart from the occasional fiber-optic link to civilization) and GPS signals degrade and disappear due to poor satellite geometry – the angle between satellite and receiver. The most widely used maritime communications systems use geostationary earth orbit (GEO) satellites, like INMARSAT, which orbit the earth at the equator. Unfortunately for the High North, signals from these satellites, which have a theoretical range of up to 81.3 degrees north, actually become unstable for various reasons beginning at 70 degrees.

While radio links do exist in the Arctic, the advanced communications and decision support systems now common aboard modern ships demand more digital data capacity than radio can carry. This presents a challenge in maintaining situational awareness, for merchant ship navigation, for emergency services like search and rescue, and for the world's militaries.

In May 2014, the US Navy demonstrated for the first time that it is possible to transfer large megabyte data files over stable satellite connections in the Arctic. During its Ice Exercise 2014, the Navy employed the Mobile User Objective System (MUOS) of narrowband tactical satellite communications to provide nearly 150 hours of secure data

transmission. The permanent broadband systems needed by the world of commerce are still some time off, but nearing reality. Since 2007, Marintek has been involved in a series of projects attempting to help bring about that change.

"The current communication infrastructure in the Arctic is inadequate to support the operational requirements of the maritime and offshore oil and gas sectors. This will have a negative impact on safety, which the Norwegian authorities rightly insist should be at least as good as it is in the Norwegian Sea," says Dr. Tor Einar Berg, Principal Research Engineer with Marintek who also serves as an adjunct professor at NTNU. Among his main areas of interest are safety and, in particular, Arctic Search and Rescue (SAR).

"In the Arctic, prompt emergency response will be crucial in order to save lives and protect the environment. Parties onshore, aboard ships, in rescue aircrafts and possibly offshore structures need to coordinate their understanding of a critical situation and plan appropriate cooperative responses," Berg says.

"In terms of accident response and human safety, the first thing you need to know is that something has gone wrong; this means you need reliable, functional alarm systems that can withstand the Arctic environment," he says, noting that, while alarm systems do exist, the technology for transmitting their signals is unreliable. "There's also the question of how to find people in the darkness or dense summer fog up there, and quickly – survival time in Arctic waters is not very long," he adds.

With comparatively few ships traversing the high latitudes, knowing the closest source of emergency help is important. Oceangoing ships carry automatic identification system (AIS) technology, which can indicate if other ships are nearby. The problem, Berg says, is that the mandate to carry AIS equipment applies only to ships over a certain size; the Arctic has many smaller vessels, such as fishing boats, which could be enlisted in an SAR operation if they could be contacted. To this end, Marintek has been working with Norwegian telecommunications company Telenor and the Norwegian Space Center to bring a dedicated maritime communications system to the High North. After several delays, their Arctic Satellite Communications project hopes to launch its Thor 7 satellite sometime in 2015.

Meanwhile, the saga of Arctic industrialization is only beginning, and many chapters on safety and preparedness remain to be written. For example, Berg points out that many basic personnel issues for Arctic operations are only poorly addressed in the maritime industry. These range from a lack of proper work clothes and survival gear to insufficient education about life in the deep cold.

"Most ship crews come from tropical countries and have no idea about the realities of working in northern latitudes," he says. "Being outdoors in -20°C temperatures, perhaps without even sunlight, can take a severe toll on anyone, particularly on people unprepared for real cold. In addition, insufficient Arctic-specific training and poor preparedness have led to emergency towing operations going badly," he says, citing the losses of the *Selendang Ayu* in 2004 and the *Kulluk* drilling rig in 2012 as examples.

This means that, ultimately, the greatest obstacles in conquering the Arctic may not be technical in nature, but human – from mentalities on board to attitudes in the boardroom.

"The maritime industry definitely needs to run more EER – escape, evacuation and response – projects," Berg says. "Distance and weather will be the principal challenges for any industry establishing itself at these latitudes." ❖

Dr. Tor Einar Berg, Principal Research Engineer, Marintek

Demystifying the Dangers of Arctic Ice

A research program develops new knowledge about, and new technologies to deal with, collision between ice and steel structures.

Much of what the maritime industry knows about the behavior of ships and structures at sea comes from experience – often, bitter experience.

The sophisticated technologies and comprehensive regulatory regimes that today do so much to protect life, property and the environment at sea are, to a certain extent, dividends of disaster. Consider, for example, the International Maritime Organization's two most important Conventions: the legislative trail leading to the formation of the Safety of Life at Sea (SOLAS) Convention stems from the public outcry after the loss of the *Titanic* in 1912, and that of the Marine Pollution (MARPOL) Convention from the public outrage following the *Torrey Canyon* oil spill in 1967. In a similar vein, many modern design and analysis tools were developed to resolve technical problems troubling society – an example being ABS' revolutionary SafeHull system, which evolved during the industry's struggle to understand and resolve the problems of light-scantling, short-life ships and the causes of numerous bulk carrier incidents in the 1990s.

Today, with environmental awareness much on the public's mind, both the maritime industry and the society it serves acknowledge they can no longer afford to learn largely from errors, particularly regarding industrialization of the Polar regions – nor do they have to.

In various research and development projects around the world, cutting-edge analysis and simulation programs are now being developed to help designers produce ships that are better prepared than ever before for the rigors of Polar navigation. The leaders of one project in particular are even looking to extend their simulation program's predictive capabilities to the point where they can assist shipmasters' decision-making in live ice navigation scenarios and even help coordinate ice management efforts. When that project, a five-year initiative named STePS^2 (for Sustainable Technology for Polar Ships and Structures) run by the Department of Engineering and Applied Science at Memorial University in Newfoundland, Canada, recently concluded, it not only brought to light new knowledge about what happens when steel structures and Arctic ice collide, but also opened a door to the future through development of an altogether new numerical simulation technology.

"For concepts at the leading-edge of design, and for Arctic projects in particular, owners, regulators and the public are demanding to know much more than whether a design is 'safe'; they want to know what can go wrong and how bad things can become," says Dr. Claude Daley, Professor in the Ocean and Naval Architectural Engineering program at Memorial University, who led the STePS^2 project. "This means that one of the basic

design questions for Arctic vessel structures is changing, from predicting the limits of intact capacity to modeling reserve capacity," he says. "That's why, in this project, we focused not only on learning more about the nature of the ice loads on a ship's hull, but also on developing a better understanding of structural reserve capacity and what happens during progressive damage by ice. If you want to show the real outcome of an ice navigation scenario, you need a way of modeling all possible damage and showing its consequences. That's what we were able to develop in STePS^2."

Into the Unknown

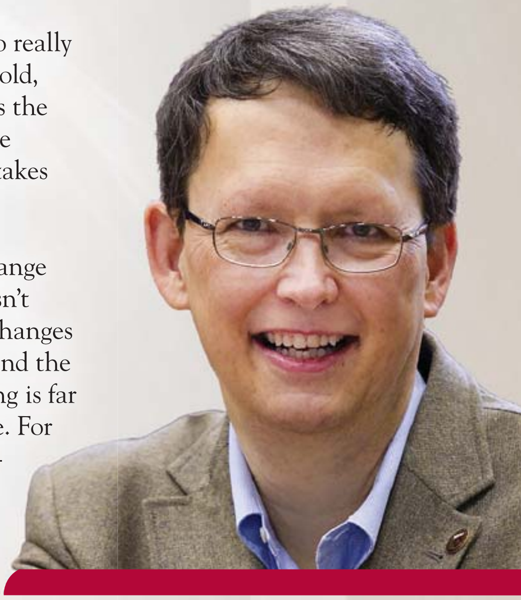
Daley ran the STePS^2 effort in cooperation with the ABS Harsh Environment Technology Center (HETC), a research coordinating organization headquartered at Memorial that brings the school's teachers and students into Polar-related investigative initiatives directed towards the maritime and oil and gas sectors. For Professor Daley, whose doctorate is in ice mechanics, this was the largest of the many research and development projects on vessel behavior in ice and ship-ice interactions that he has led over the past three decades. A constant team of 30-plus people were employed in the effort at all times, but more than one hundred different students gained experience by participating in the project through internships of at least four months throughout its five-year run; altogether, more than 50 doctoral theses and scientific papers were produced as a result of this work.

The big challenge for the researchers lay in exploring, analyzing and then reliably simulating the process of structural failure, because it took them into the relatively uncharted realm of nonlinear phenomena.

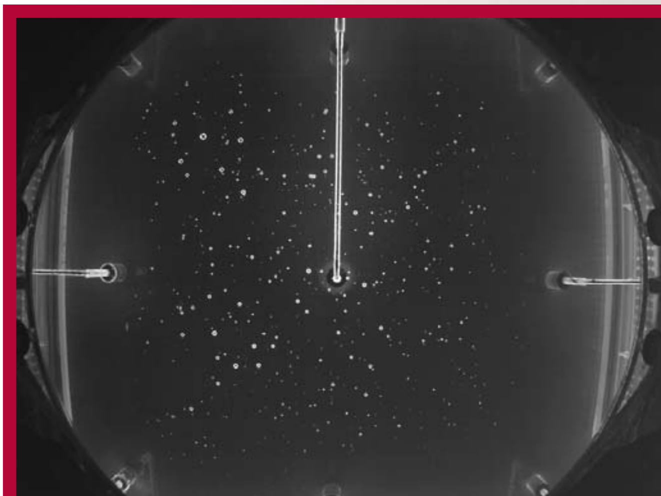
Typically, analysis of a structural design looks at the limits of intact behavior, taking it to the point where permanent deformation or damage sets in. Up to its intact limit, a structure behaves in a way that engineers characterize as 'elastic', meaning it returns to its original condition after impact. This is a linear phenomenon, progressing in a predictable, proportionate relationship to the loads applied. Once damaged, a structure can become much more sensitive to further loading and leaves the realm of linearity behind.

"As damage progresses, its consequences change," Daley says. "There are stages of damage that produce step changes in consequences – and not just small changes, but orders of magnitude when things go really wrong. Once you cross a certain threshold, things get very bad, very quickly. That's the fundamental nature of nonlinearity: the situation doesn't just change a bit, but takes a jump," he explains.

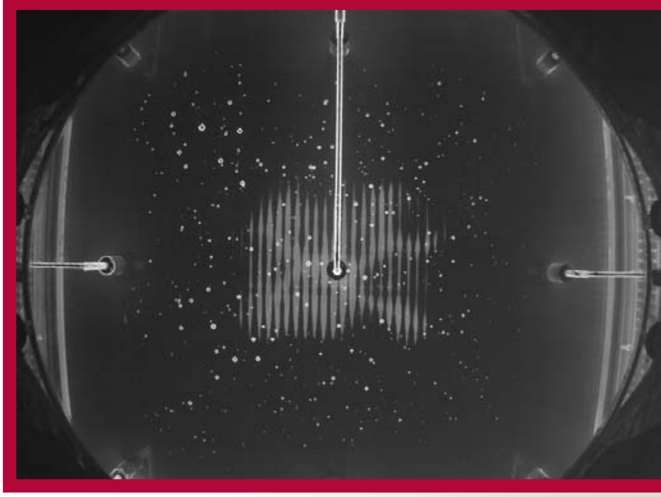
The Arctic ice loading scenario is a strange and complex phenomenon because it isn't only the damaged steel structure that changes nonlinearly, but also the ice structure and the nature of the load it imposes. Ice loading is far more than a force applied to a structure. For one, the load itself changes with time – as with the waxing and waning of the wind and wave forces that move the floe. The experimenters discovered that, at very low collision speeds (up to about 1 meter per second or roughly half a knot), the ice can actually become stronger as it attacks because its cracks have time to fuse, allowing the mass to 'heal itself'. At higher collision speeds loading also fluctuates, but for other reasons.



Dr. Claude Daley,
Professor,
Ocean & Naval Architectural Engineering Program,
Memorial University



Ice pressure distributions measured by the large, high-resolution pressure panel (developed by the Canadian National Research Council) before (above) and during double pendulum collision experiments.



The one-meter ice cone sample mounted in the STePS² large double pendulum apparatus for 'crash testing'.

The experimenters found that the pressure an ice load produces on a vessel, which occurs within the area of contact between ice and structure, changes with time because, as the ice breaks and changes shape, the area of contact changes. As contact area and average pressure change over time, they create a force that changes over time. Making matters worse, not only does the area of contact change, but also the 'texture' of the contact – as the ice breaks, its surface undergoes many changes in 'topography', producing an unending succession of peaks, valleys, ridges and plains that alter the amount and distribution of pressure within the contact area. This results in constantly changing zones of high and low pressure, called a pressure area effect. On top of it all, the scientists discovered an inertial effect that further complicates the situation: as broken ice piles up around a vessel it creates a 'confinement' that resists more ice being pushed away, which further increases the ice pressure on the hull.

Altogether, the STePS² experimenters were faced with deconstructing and quantifying two nonlinear systems that had never before been thoroughly analyzed: a progressively changing damaged marine structure and a progressively changing damaging force.

"To know what happens in a nonlinear system, you have to check every single situation and load combination; this makes the analysis much harder, because you have to understand the full loading process and the full structural response process in order to be able to tell the interested party what will happen in a particular damage scenario," Daley says. "To do this, we need tools for modeling complex damage scenarios – specifically, simulation-based design and assessment tools that will help designers fully understand any situation that may occur to a structure. We want to be able to follow the path of damage, determine the reserve strength of the structure and give the client a sense of the consequences. This is particularly important for operations in the Arctic, where no one wants to be learning from errors," he says.

"That's why we focused on understanding the process of structural damage to a deep level, following Arctic ice loads and structural response as far along the spectrum of damage behavior as we could reasonably get. We wanted to be able to give meaningful advice and opinions on the important questions," he adds.

Using small- and full-scale physical research in the laboratory to verify its developments in numerical research, the STePS² team reached its goal.

"Ultimately, we developed an understanding of ice structure and ship-ice interaction, and believe we can model them better than has ever been done before," Daley says. "We believe we understand the important issues in these scenarios as well as how to model the vessel situation and how to advise people to model it."

Experiment & Simulation

The physical part of the STePS² project called for development of specialized test gear. In one setup, a huge hydraulic ram simulated the slow, relentless crushing force of an ice floe. In another, a double pendulum impact simulator, which measures 4 x 5 x 8 meters, duplicated high-speed collisions between ice and ice-class ship hull panels in full scale – a world first.

The experimenters re-created side shell panels for a 10,000-dwt vessel designed to Baltic 1-A Super ice class specifications, equivalent to a PC-6 rating on the Polar scale. Although that represents the low end of displacement and ice class in the world fleet, the structures provided the levels of size and strength needed for the experiments to deliver meaningful results.

The ice samples were squat cones with a base diameter of one meter. They were pressed into side shell structures at a rate of 1 mm per second using the ram, and swung into side shell panels at simulated speeds of up to ten knots using the pendulum.

In the pendulum tests, the side shell was represented by rigid panels held in a frame mounted on one of the pendulums, while an ice cone was mounted on the other pendulum. These could be swung at each other simultaneously or individually to simulate collisions at various velocities. Meanwhile, the hydraulic ram experiments used a full-scale ‘grillage’ (a grid structure) consisting of side shell plates supported by five stiffeners across and four stringers (longitudinal beams) top-to-bottom. The ice load was applied to the center in order to simulate real-life effects on an ice-class side shell and accurately test its structural reserve capacity.

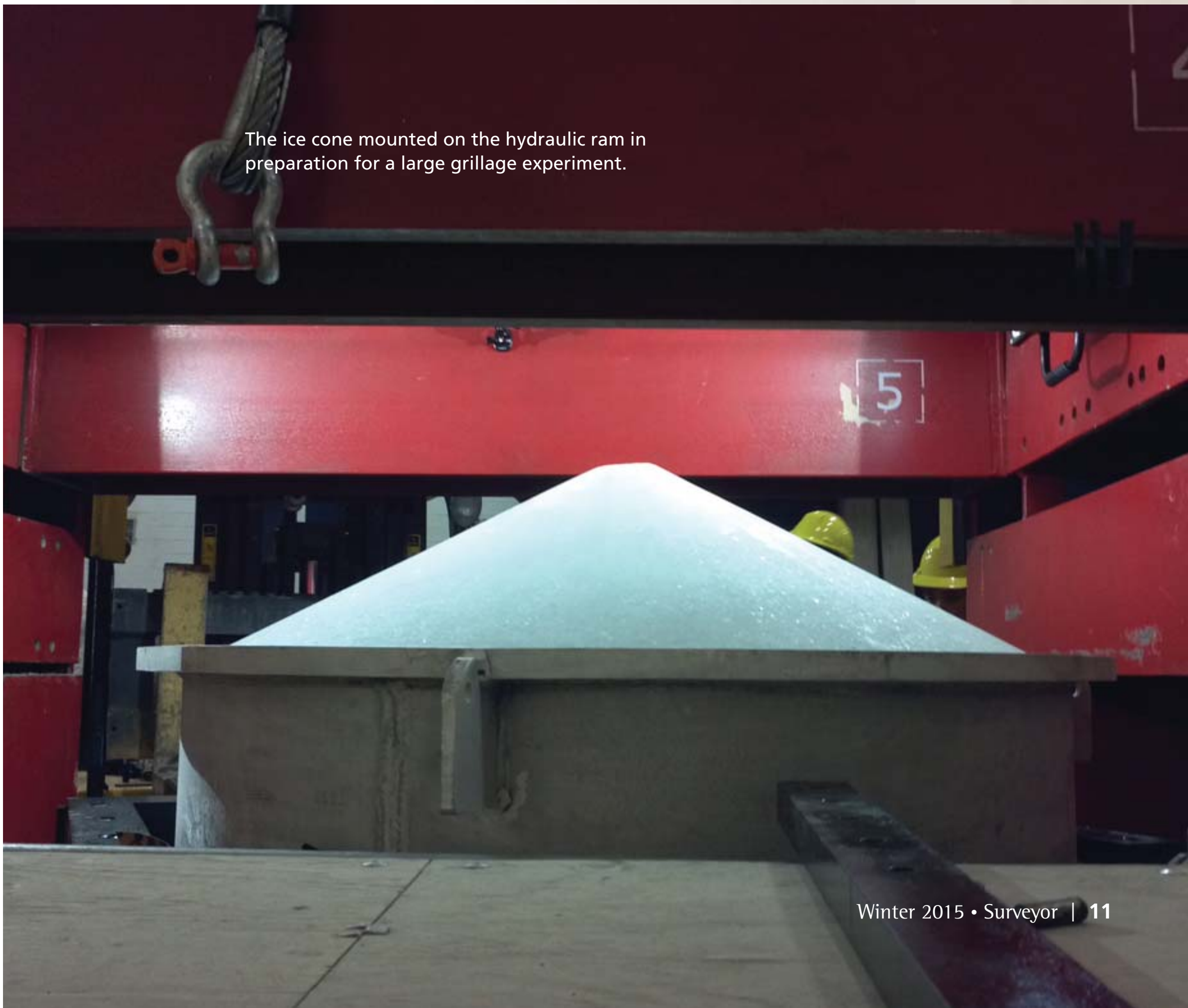
These physical experiments brought to light important new knowledge. One valuable result of the collision tests was an improved understanding of the nature of the interactions between steel structures and ice. Before these tests, Daley believed that the greatest need in Arctic vessel design was to devise new ways of laying out structure so as to prevent fracture. The experimental results somewhat contradicted this, demonstrating that, while room for improvements remain, current designs have remarkable ductility and resistance to fracturing. The tests also suggested that a collision-resistant steel structure might possibly be made from lighter material, although this bears further investigation.

The hydraulic ram tests also brought in some startling results, with the side shell structures displaying a reserve ten times greater than the design load. In fact, the only consequence of 660,000 pounds pressure on the samples was a 12-inch dent, with no holing or tearing. Only the stroke limitations of the ram prevented the experimenters from going further to find the point at which their panel would tear – which Daley estimates could be upwards of one million pounds force.

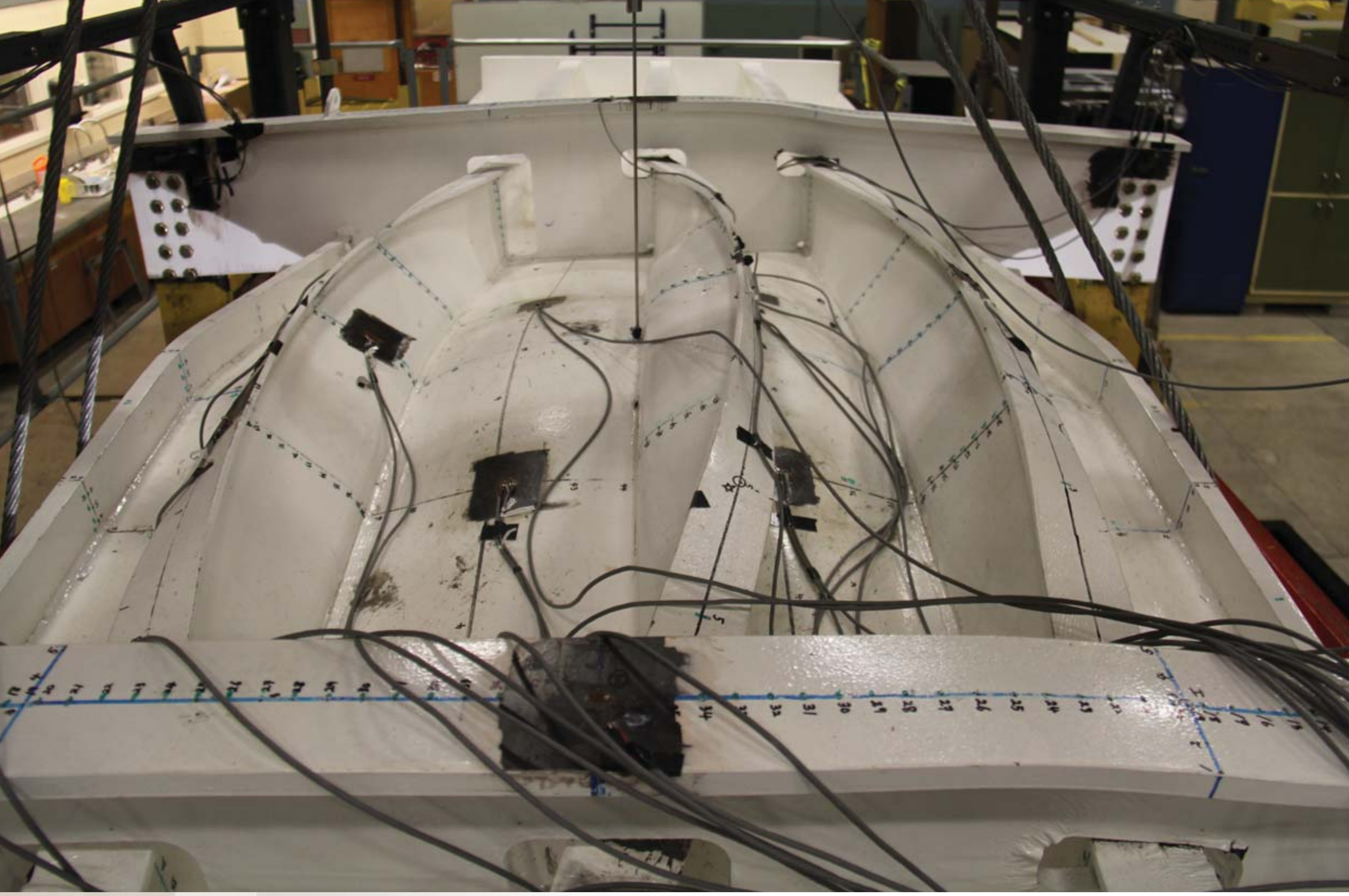
For the experimenters, the main value of the physical test information was to validate their developing high-performance numerical modeling programs. These models were based on a dynamic finite-element modeling program named LS-DYNA, which was first developed by Livermore Labs in the 1950s to model the internal scenario of an exploding nuclear bomb and soon found widespread peacetime use in modeling fast-moving phenomena – for example, it became the tool of choice for modeling automobile collisions.

One fascinating result of their modeling was the discovery of the effects on hull damage produced by moving loads.

“If ice causes a dent and then moves along the hull, it creates a ‘moving dent’ that weakens the structure substantially,” Daley says. “A normal dent goes straight in at one spot, and the undented structure restrains it from growing. If the load moves at the same time it is creating a dent, it produces a ‘damage shadow’ – a trail of damage on one side of the dent that reduces the structure’s total ability



The ice cone mounted on the hydraulic ram in preparation for a large grillage experiment.



A large grillage section representing an ice-class ship's side shell structure, showing deformation during hydraulic ram tests due to ice pressures of 660,000 pounds.

to restrain its growth; damage happens more easily under a moving load than under a static load," he explains.

"For ships traveling in the Arctic, just about all the loads are moving, and the ship is moving too, but none of the assessment strategies that existed prior to STePS^2 took this movement into account," he adds. "It is significant new knowledge that you can lose half your overload capacity due to that movement, which no one noticed until we analyzed it. That means you need tools in the finite-element setting that don't just model load growth, but also model load movement at the same time."

After 'quite a bit of head-scratching', as Daley puts it, the STePS^2 team did develop a means of doing this. Then, at a certain point in their investigations, their accumulating experience made them realize that, to have a realistic understanding of a vessel's Arctic experience, they needed to be able to model ice interaction scenarios in the context of actual navigation.

"Once we understood all these motion-related effects, we realized that we also needed to know how the vessel would actually be navigated. For example, the speed at which a ship strikes one ice floe affects the speed at which it rebounds into the next floe," Daley says. "This meant that we had to develop the capability to model the preconditions of collision and then the whole sequence of collisions for every helm decision throughout an ice navigation scenario so that we could see the whole picture, not just in snapshots of single events, but in long stretches of time."

Design by Simulation

The investigators realized the answer to the problem of live navigation simulation lay in an analytical tool Daley had developed several years earlier while working with ABS engineers on analyzing a novel icebreaking LNG carrier design. That tool, named DDePS (for Direct Design of Polar Ships), is, basically, a spreadsheet containing many mathematical models describing collisions between steel structures and Arctic ice. These formulas would provide a number of ready-made solutions for collision scenarios, once it was determined when they could be applied. The next step was to develop a simulation program that could use them.

This led the STePS^2 team to enlist the help of a computer science professor, with whom they achieved a revolutionary new development known as GEM simulation technology. GEM stands for 'GPU-based event mechanics', and the GPU (graphic processing unit) currently employed by the GEM system has

3,000 calculation cores and can run tens of thousands of calculations simultaneously. This gives the researchers the ability to perform parallel processing of the movement of thousands of pieces of ice of different sizes, strengths and speeds, while also simulating a ship trying to move safely among them. Making use of the DDePS-based pool of event formulas, the high-speed GPU is able to perform event simulations in 'hyper-real-time' – up to 200 times real-life speeds.

The DDePS equations take multiple inputs – such as ice velocities, shapes, angles, and masses and vessel speed and heading – and create multiple outputs; the GEM simulator runs a series of equations, calculating results that show whether a structure is damaged and what the consequences are. This opens the door to a true design revolution: design by simulation.

"In design by simulation, you're not just trying to capture a single design scenario; you're trying to look at the future life of the structure," Daley explains. "This allows designers to explore a staggering number of options during design development. In effect, it is trial-and-error operation on the computer that provides a realistic future history of the vessel," he adds.

"The GEM system can invoke the right equation for the right scenario so quickly that it can actually simulate ships traveling in pack ice. The value of that – and this is where we really hope to go with it – is in one day being able to provide these simulation tools not only to designers and engineers, but also to the operator on the bridge of a ship," Daley says. "The idea is that rapid, accurate simulations can help operators figure out how to approach the ice navigation problem in front of them and make decisions about the use of their field resources – how many icebreakers to deploy and how, for example."

Already, a basic laptop can be used to model more than three hours of navigation in less than one minute, taking a ship through 1,000-plus ice floes in a 1 x 1-km area. This gives Daley high expectations for the kinds of things that can be done once the technology is ready for installation on a shipboard workstation.

Altogether, Daley sees a great future for the fruits of the STePS² project. "In research, you usually find one answer and two more questions, and the work we've done is no different," he says. "For example, one question involves hydrodynamics; we don't understand very well the influence of water on the contact process. Another involves fracture; we understand structural reserve through the plastic deformation range, but not into the fracture range – which is extremely important for the Arctic, considering the consequences for personal safety and the environment," he says. "There are many areas for a follow-up project to explore."

"In the future, we'll be able to put tools on the bridges of ships and offshore structures that let operators confidently model the coming hours, days, weeks, months and years of their projects," Daley concludes. "The people who work in the Polar regions will really benefit from simulations that let them fully understand the likely consequences of their decisions and, thereby, improve their operation and their own safety – and we can help them get there." ❖

Building an Arctic Knowledge Bank

An online library of Arctic maritime research serves as a catalyst for cooperation on shipping in the High North.

In July 2014, a shipping line made the news by announcing that in 2018 it plans to bring liquefied natural gas from Russia to Japan on history's first regularly scheduled commercial shipping service through the Northeast Passage, the ice-infested sea route connecting Asia to Europe over the top of Russia. This significant advance in Arctic shipping is the latest step in a revolutionary journey that began four years ago in a round-table project organized by a young not-for-profit information service named the Center for High North Logistics (CHNL).

Founded in 2008 by Norwegian shipowner Felix Tschudi, the CHNL is based in Kirkenes, Norway, a town on the Russian border about 400 km (250 miles) north of the Arctic Circle. It was established with matching funds from Norway's Ministry of Foreign Affairs, which, like Mr. Tschudi, believes the Northern Sea Route (NSR) – Russia's designation for that very long part of the Northeast Passage (NEP) that runs through the Russian Exclusive Economic Zone – and, ultimately, the whole NEP, can be intelligently commercialized so as to benefit a number of industrial sectors.

The CHNL began as a five-year research project focused on gathering knowledge about logistics solutions for Arctic shipping. This is reflected in the Center's first work product, *Shipping in Arctic Waters*, a broad study that in the course of some 300 pages summarizes wide-ranging issues relating to the Northeast Passage, the Northwest Passage and the Trans-Polar Passage. Soon after the Center's work commenced, Tschudi realized it held the potential to develop something much bigger: an online digital library devoted to the maritime Arctic.

"As we began our work, we found that there is a huge body of research and quite a lot of knowledge about Arctic shipping out there, particularly from Russian sources, but that much of it existed on paper alone and very little of it had been collected, translated and made accessible – and therefore had very few users," Tschudi says. "We realized that the best contribution we could make would be to help organize that knowledge and make it available to the public."

To that end, the CHNL has spent the past five years developing a free searchable online database named ARCTIS (for Arctic Resources and Transportation Information System), the goal of which, Tschudi says, is "to connect knowledge about the High North with those who need it."

One of the steps in building ARCTIS was to make widely available digital versions of the 167 reports generated by the International Northern Sea Route Program (INSROP), a research effort that ran from 1993 to 1996. By 2008, the project's reports, which did not then

exist in digital form, were becoming scarce. The same is true of the vast body of Russian research into the NSR and the Arctic, which the CHNL has spent a great deal of time locating, translating and digitizing.

The ARCTIS library is not limited to saving the disappearing intellectual patrimony of the past, but also includes current research that exists elsewhere in digital form, such as the far-reaching work of the Arctic Marine Shipping Assessment (AMSA). An international research effort sponsored by the Arctic Council, the AMSA project ran from 2006 to 2008 and brought 185 Arctic experts together in a series of 13 workshops covering a broad range of topics related to the Arctic, including: scenarios of future navigation; indigenous marine use; marine incidents; environmental impact of industrial operations; studies of marine infrastructure and technology; and the future of the Northern Sea Route and adjacent seas.

Today ARCTIS contains hundreds of documents organized into eight main topics with about 50 sub-topics or themes: Transportation Research; Arctic Energy and Mineral Resources; Marine Transport and Logistics; Arctic Sea Routes; People, Industries and Institutions; Maps and Charts; Arctic Sea Ice and Climatology; and Arctic Policies and Governance. Before going online, all information is verified by subject matter experts under the direction of a 'theme editor'. Although developed in a rigorous, scholarly atmosphere, the ARCTIS project aims to be far more than an academic exercise, says Tschudi, who describes it as "a bridge between knowledge sources and business communities."

The Great Experiment

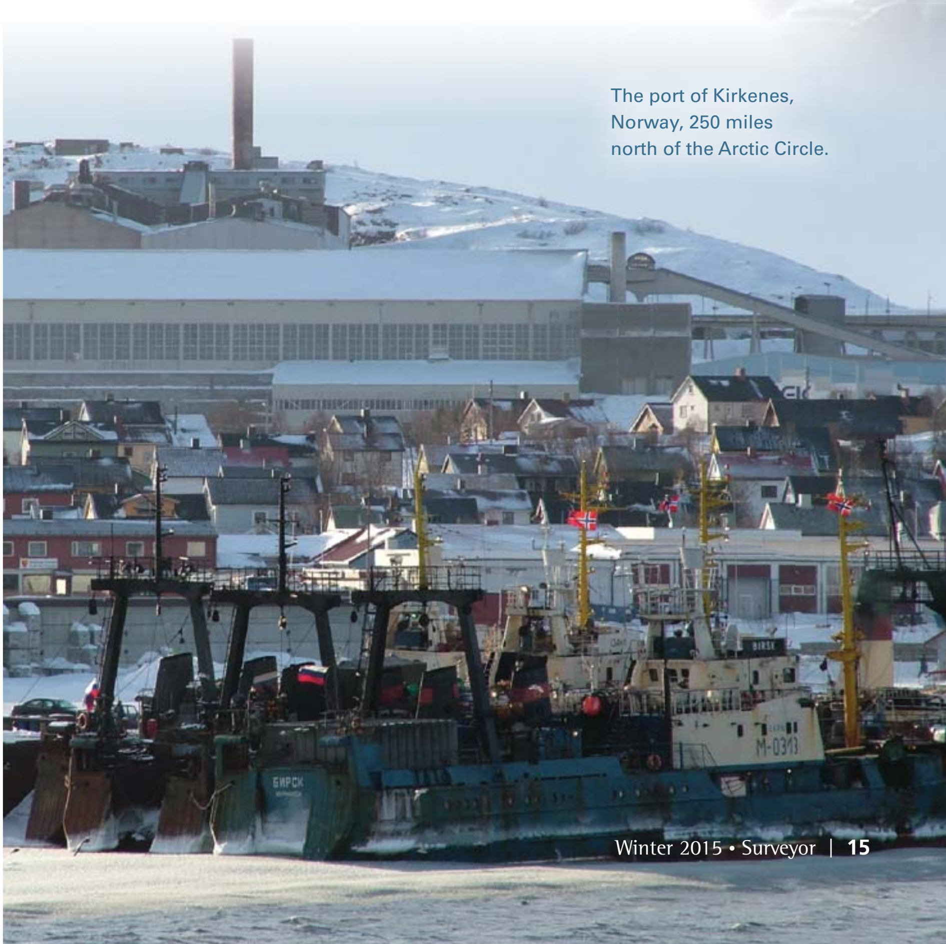
There's no better demonstration of an idea's worth than when it helps spark real, positive change – as in the 2010 effort when the CHNL helped open the door on the future of Polar navigation.

Not long after the fall of the Soviet Union, Tschudi saw opportunity in the newly freed Russian State and set up a shop in Kirkenes, building a variety of cross-border businesses ranging from bread baking to oil product transshipment. The big opportunity came in 2006 when the company was able to purchase the closed-down Sydvaranger iron mine from the Kirkenes municipality. Tschudi's original intent was to develop its included port facility for industrial use, but, at the seller's request, looked into whether the century-old mine had any remaining commercial potential. He discovered that it could still produce a marketable iron ore concentrate and, with the help of Australian investors, began exporting concentrate to China in 2009.

Meanwhile, ice conditions in the Arctic had begun changing noticeably. As the 2000s progressed, the maritime community revived age-old curiosities, speculation and hopes about one day using Polar seaways to shorten shipping times between the Atlantic and Pacific Oceans. Spurred by this change in intellectual climate, Tschudi – whose ore concentrate shipments to China were all scheduled to transit the Suez Canal – decided that the Northeast Passage was worth investigation. It was exactly the kind of project the CHNL had been created to assist.

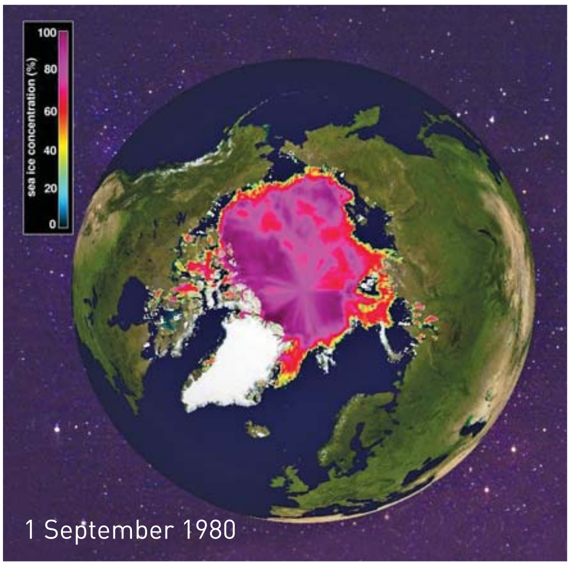
"We didn't know whether a Polar transit would be economically feasible, or even if the Russians would support our use of the Northern Sea Route," Tschudi recalls. "So, through the CHNL, we organized a workshop in Kirkenes to make a case study for Arctic shipping, using as the test case a cargo of iron ore concentrate going from Kirkenes to China."

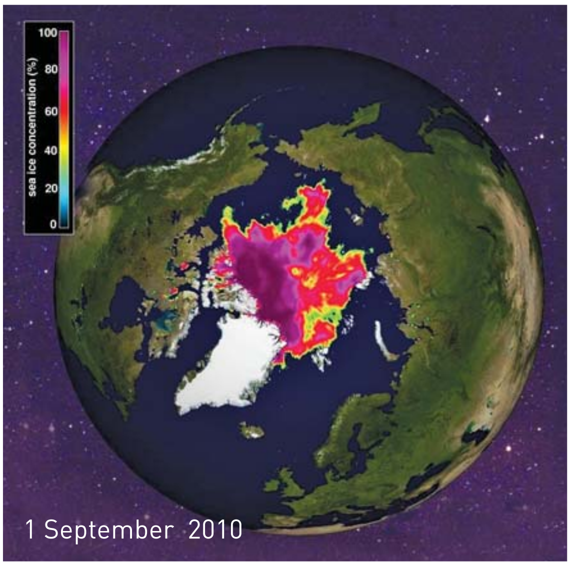
Felix Tschudi, CHNL



The port of Kirkenes, Norway, 250 miles north of the Arctic Circle.

Changing Arctic Summer Ice





Map provided by 'The Crysosphere Today' from the University of Illinois shows the change in summer Arctic ice that made an NSR transit feasible in 2010.

The CHNL gathered 27 stakeholders around the table, from a wide range of interests including shipowners, insurers, lawyers, brokers and, most importantly, Russian authorities, including the heads of Atomflot, the nuclear icebreaking fleet, and Norilsk Nickel, arguably the world's most experienced Arctic shipping company.

"Everyone was curious and skeptical, including us," Tschudi says. "During the case study, we made real voyage calculations and found that it was largely Russian tariffs that made the Suez route cheaper at the time. Then we got a clear message from the General Director of Atomflot that 'we want to be competitive with Suez; we want to be pragmatic.' Everyone was surprised that the workshop ended on a hopeful note," he says. "When the workshop was organized, we didn't know whether it was even possible, but we approached it saying 'let's see if it can be done'. And, although it began in an air of skepticism, it ended in an air of belief – so it really achieved something," he adds with satisfaction.

Armed with the results of the case study, Tschudi joined forces with a Danish shipowner on an effort they called NSR Project 2010, the goal of which was to get one of his iron ore concentrate cargoes through the Northeast Passage to China in the 2010 season. Through what he calls a "strong Nordic-Russian partnership" the plan succeeded. In September, shepherded through the NSR by Atomflot, 41,000 tons of concentrate left Kirkenes and reached its destination in China. Compared with a panamax taking the Suez route, the Polar shortcut shaved ten days off the trip – cutting voyage time by one-third – and made a 43,000-dwt ship economically superior to its much larger competitor.

That said, the following year freight rates had fallen so far that only a 75,000-dwt panamax might have made the economics of using the NSR work out. For Tschudi, the real milestone of the project was that, for the first time since World War II, a non-Russian cargo on a non-Russian ship going between non-Russian ports was permitted to transit the NSR – the ice, as it was, had been broken.

A Future of Many Parts

Since NSR Project 2010, transits of the NSR increased from four in 2010 to 71 in 2013, but dropped to 39 in 2014 due to harsh ice conditions, the introduction of a new tariff system and low freight markets. Those numbers vary depending on who you ask, as the definition of 'transit' is still somewhat flexible, but however you count it, Tschudi says what's important is not the number of vessels making the trip, but the variety.

"The NSR is becoming a flexible trade route, and many different kinds of ships are using it," he says. "Two LNG carriers have already traveled from Norway to Japan through the NSR, and more will come. Several refrigerated vessels have transited the NSR taking frozen fish from east to west; one seismic vessel stationed north of Hammerfest took a summer job in New Zealand and, because it had the appropriate ice class, used the NSR and saved eight to ten days over the Panama Canal – for a vessel with a day rate of $250,000, that represents significant savings. The economic benefits are even more attractive in offshore oil and gas, for example in repositioning a mobile offshore drilling unit," he adds, citing the possibility of large savings over traditional routes by using the NEP to take a rig between the Atlantic and Pacific basins.

"Most of world trade occurs in the southern regions, so the NSR will never replace the Suez Canal," Tschudi observes. "That said, for cargoes going from ports in the northern part of the North Atlantic to Japan, Korea or China, a savings of more than 50 percent of voyage time might be achieved using the NSR."

To aid the practical and administrative side of project development, the CHNL established a subsidiary in Murmansk, Russia named the Northern Sea Route Information Office (NSRIO), which focuses specifically on NSR navigation issues and Russian regulations, providing practical assistance

with administrative issues and such port information as locations, available infrastructure and fees.

Looking far forward, Tschudi hopes to see the CHNL and ARCTIS grow in scope to cover all other Arctic ports, eventually becoming the total Arctic Logistics Information Office that he originally envisioned. His more immediate concern is that the Center's original five-year funding period has run its course. He has begun seeking support to help the project continue. He hopes to attract new business partners and more scientific partners, particularly research institutes and universities.

"There is a lot of duplication of effort in academia; why not join together and do different projects in one place?," he proposes, citing academic cooperation as a natural extension of the Center's proven ability to bring diverse parties together on projects of common interest.

To date, the CHNL has established close cooperation with a number of international institutions in efforts ranging from conferences and workshops to academic research. These include: in South Korea, the Institute of Arctic Logistics at Youngsan University and the Korean Maritime Institute; in Japan, the Ocean Policy Research Foundation and Weathernews Inc; and in the United States, the University of Alaska, Fairbanks and the Institute of the North in Anchorage.

"The rules in the Arctic are not entirely set yet, so to do business there you really need to build bridges between authorities and industry," Tschudi says. "The CHNL tries to build those bridges. Our first workshop was one very interesting way to do that. It was a study, which academics understand, and also a case study, which the business community understands, and thereby made for meaningful dialog between both sides. We hope to organize that sort of session again."

Possible future topics include addressing insurance issues for Arctic operations and aiding the oil and gas future of the Arctic by, for example helping businesses develop logistics chains for platform support.

Altogether, he sees a long future for the CHNL in helping advance not only commercial interests, but also the public interest by providing information that helps interested parties make the right, responsible decisions to move their projects forward, he says.

"I believe the CHNL can serve as a catalyst for cooperation in helping new initiatives and projects get started: organizing workshops, holding conferences and seminars; running case studies where many stakeholders get together around a common interest; and, in general, providing information that helps interested parties make the right decisions," Tschudi says. "There is a lot of knowledge out there that can be harnessed to serve the purposes of business." ❖

Arctic Maritime Research

- Center for High North Logistics
  www.chnl.no
- Arctic Resources & Transportation Information System
  www.arctis-search.com
- Northern Sea Route Information Office
  www.arctic.lio.com

Museum with a Mission

The Fram Museum in Oslo, Norway, goes a step beyond the typical museum in that it not only enshrines a historically important ship and honors great achievements in Polar exploration, but also uses its historic patrimony for educational outreach and environmental advocacy on behalf of the Polar regions.

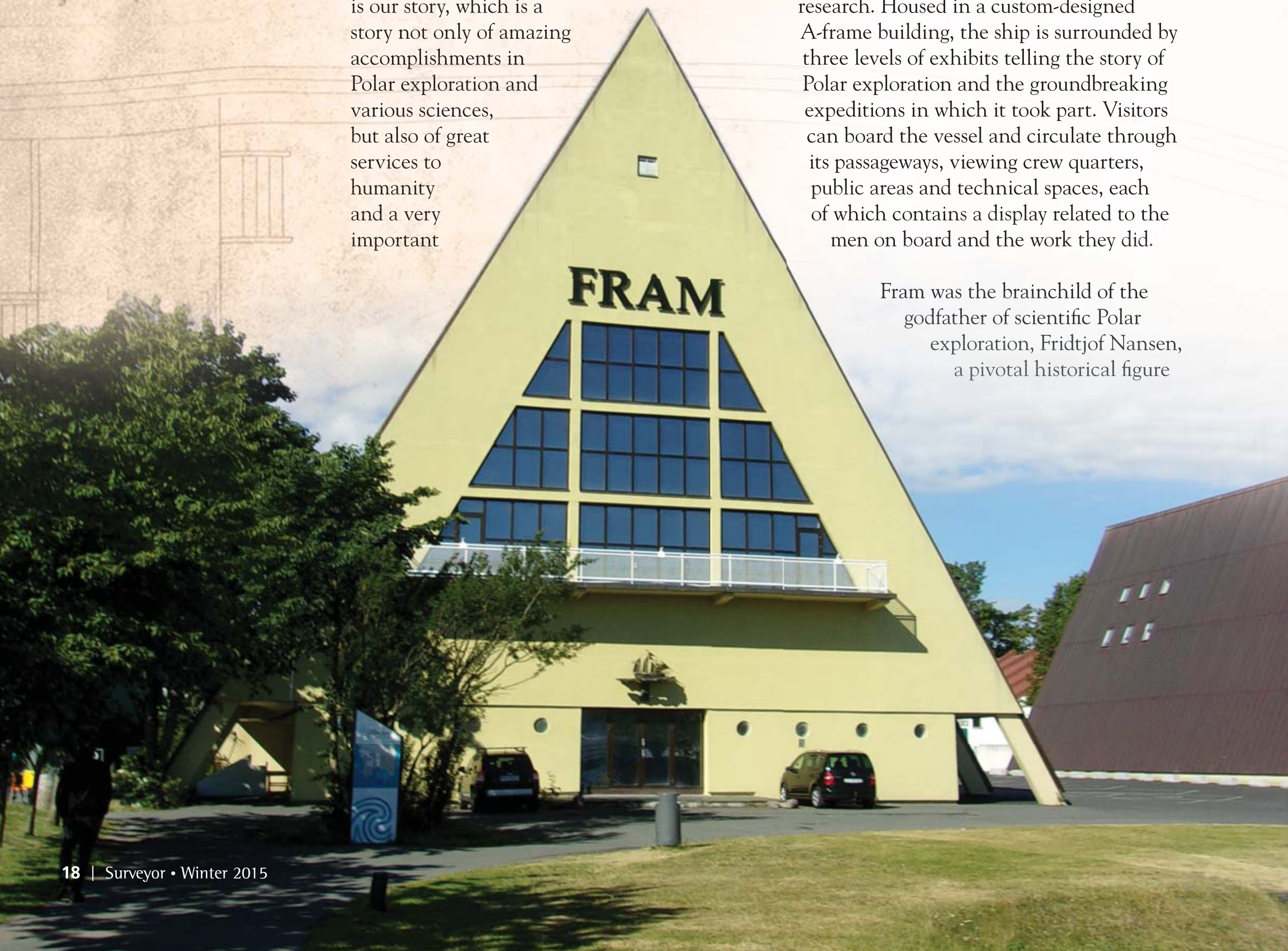
The museum, which opened in 1936, honors all Polar exploration but focuses most of its attention on the work of famed Norwegian explorers Fridtjof Nansen, Otto Sverdrup and Roald Amundsen.

"Our goal is to tell the stories of the past and to bring awareness to the Polar issues of the future," says Geir O. Kløver, Director of the Fram Museum. "We try to both entertain and interest people in our section of history. Wherever you go in the world, you find historical museums telling their piece of world history; this museum is our story, which is a story not only of amazing accomplishments in Polar exploration and various sciences, but also of great services to humanity and a very important part of how Norway became an independent nation," he says.

Another aspect of the museum's mission is to raise public awareness of the Polar regions and, in particular, such important issues as the lingering widespread effects of industrial pollution and environmental mismanagement. One recent example of this activity is the museum's 'Explore the Arctic – past, present and future' exhibit that recently traveled to three cities in China, introducing that industrializing populace to concepts of Polar conservation and environmental responsibility. "We try to educate people about current issues related to the Polar regions, to give them a broader understanding of the impact that their actions have," Kløver says.

The centerpiece of the museum is the Polar research vessel *Fram*, regarded as history's first ship built specifically for scientific research. Housed in a custom-designed A-frame building, the ship is surrounded by three levels of exhibits telling the story of Polar exploration and the groundbreaking expeditions in which it took part. Visitors can board the vessel and circulate through its passageways, viewing crew quarters, public areas and technical spaces, each of which contains a display related to the men on board and the work they did.

Fram was the brainchild of the godfather of scientific Polar exploration, Fridtjof Nansen, a pivotal historical figure



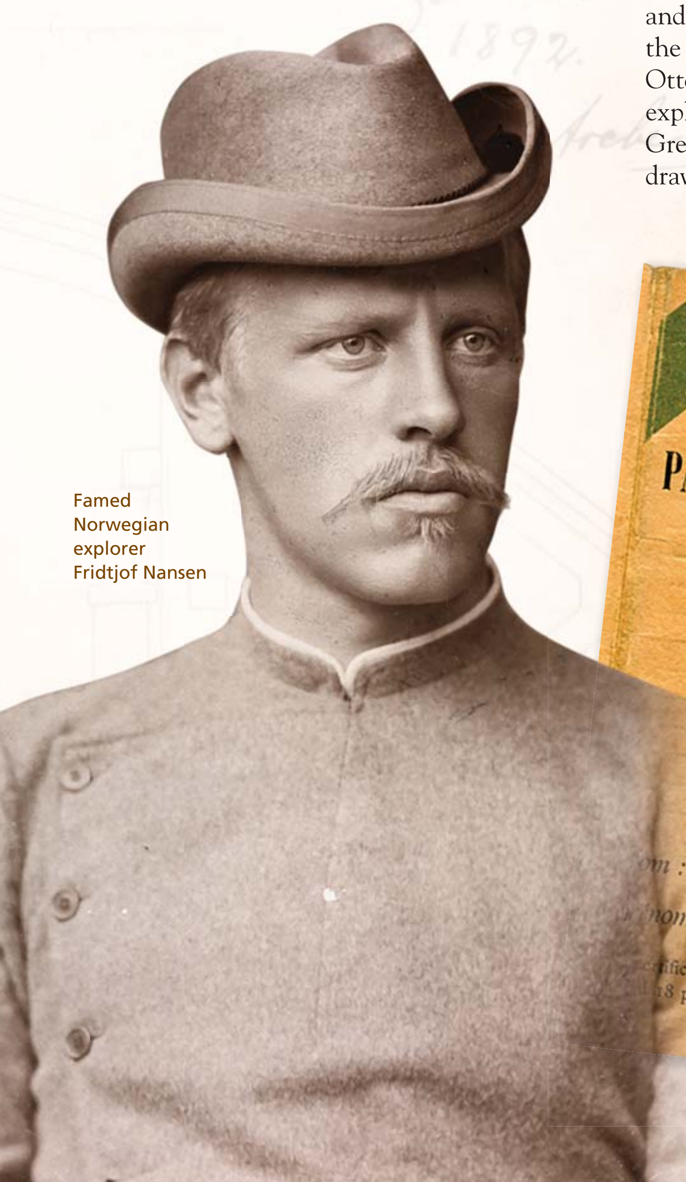
not only in Polar exploration, but also in oceanography, neurology, Norwegian history and humanitarianism. The name of his ship means ‘forward’ in Norwegian, a word that, perhaps more than any other, describes Nansen himself – always moving forward into new territory.

Born in 1861, Nansen was a champion athlete in his youth. In college he studied zoology, and his investigations into the central nervous system of marine creatures led him to contribute new theories to the then-developing science of neurology, earning him a doctorate. Shortly after submitting his doctoral thesis, the 27-year-old led the team that made the first crossing of Greenland’s icecap on foot, a feat that some of the world’s leading explorers had failed at. Nansen reasoned that previous efforts had failed due to their plan, which was to go from Greenland’s populated west coast to its harsh, unpopulated east, and then return – the round-trip was necessary because the east coast rarely saw a ship; he believed the answer was to start from the east, making a one-way journey towards civilization in which, because there was no safe base behind, the only hope would be to go forward. After a harrowing adventure, all six men made it across and, when they returned to Norway after wintering with local inhabitants, were welcomed as national heroes.

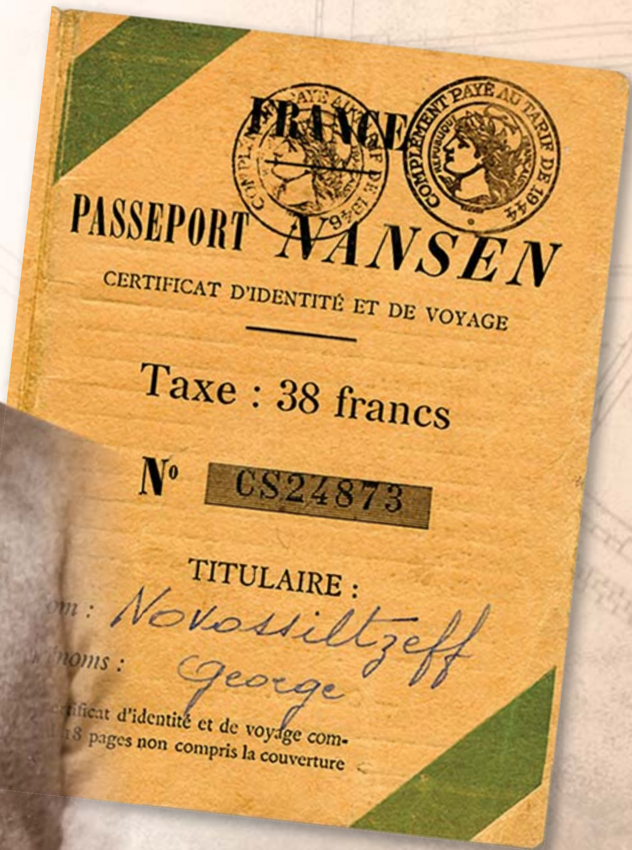
A year after his return, Nansen made the daring proposal that would forever change Polar exploration: a unique drifting voyage to prove the then-controversial theory that a cross-Polar Ocean current existed. The theory, developed by Norwegian meteorologist Henrik Mohn, was based on the discovery on Greenland’s coast of wreckage from the steamer *Jeannette*, an American ship that had been destroyed by ice some six years earlier on the opposite side of the Arctic Ocean. Nansen reasoned that a suitably strong ship, specially designed to withstand the crushing pressures of being frozen into the ice, would likewise drift to Greenland, possibly passing near the North Pole. Much of the world scoffed, including seasoned Polar explorers, but the Norwegian people and its government believed and funded the adventure.

Nansen brought in leading naval architect and shipbuilder Colin Archer to help bring the idea to life. Working with Nansen and Otto Sverdrup, a former sea captain and fellow explorer who had accompanied Nansen across Greenland, Archer brought *Fram* from the drawing board to the sea.

Geir O. Kløver, Director, Fram Museum



Famed Norwegian explorer Fridtjof Nansen



The unique vessel had probably the strongest wooden hull ever built: three layers of oak, pine and greenheart (one of the hardest woods available on the open market), reinforced with iron straps and supported by massive ribs of naturally-formed oak that were bolted together in pairs for extra strength and laid just 5 cm apart. Other innovations included a wind generator to power the ship's electric lights and a rudder and propeller that could be retracted to prevent damage from the ice.

Archer discussed the ship's novel design with *Popular Science* magazine in 1900, noting that, "In order to utilize this principle, it was decided to depart entirely from the usual deep-bilged form of section and to adopt a shape which would afford the ice no point of attack normal to the ship's side, but would, as the horizontal pressure increased, force the attacking floes to divide under the ship's bottom, lifting her as described above... Plane or concave surfaces were avoided as much as possible by giving her round and full lines. This, while increasing the power to resist pressure from outside, also had the advantage of making it easy for the ice to glide along the bottom in any direction."

The Polar research ship FRAM lodged in drifting Arctic ice in 1894. The windmill mounted amidships provided electricity.

The resulting vessel was nearly oval in shape, with a 39-meter length, 11-meter beam and a 5-meter draft. While the rounded hull was perfect for surviving in ice, it gave the ship a tendency to roll very uncomfortably in the open sea. "A ship that is built with exclusive regard to its suitability for Nansen's objective must differ essentially from any known vessel," Archer said.

In 1893, *Fram* entered the Arctic pack ice near where *Jeannette* had been crushed, and spent much of the next three years drifting in its ice prison. The explorers kept busy with a rigorous program of scientific measurement, testing and observation of nature; the tremendous amount of data they generated required several decades to be fully analyzed and published.

Although neither the vessel nor the explorers reached the North Pole, the expedition made major geographical and scientific discoveries, such that the president of Britain's Royal Geographical Society declared that Nansen had resolved "the whole problem of Arctic geography" because he proved the North Pole was located not on land, but on shifting pack ice. The expedition also provided the first detailed oceanographic information from the area – for example, that the Arctic Ocean is not a shallow body of water, but has sections that are 4,000 meters (about two miles) deep and a rugged sea floor in spots.

Nansen experimented continuously and produced a number of inventions ranging from scientific equipment to cooking apparatus that helped revolutionize Arctic travel. These include the Nansen Sledge, which had broad runners based on ski designs; the Nansen Cooker, which had better heat efficiency than the standard spirit stoves then in use; and the layer principle for cold-weather clothing, which replaced traditional, heavy single garments with multiple layers of lightweight materials. The device he invented for sampling water, called the Nansen Bottle, remained a standard piece of scientific equipment through the 1980s and, in a modified form, can still be seen in use today (although an electronic device is more commonly employed).

On his return in 1896, Nansen retired from exploration and became the guru of Polar science, and a generation of explorers came to seek his advice. He then moved forward yet again, becoming a statesman whose efforts were critical to the establishment of Norway as an independent nation in 1905 and to the installation of its King. During the last decade of his life he led humanitarian efforts to help refugees, particularly those displaced after the Russian Revolution and the Armenian Genocide, for which he was awarded a Nobel Prize. Those efforts led to creation of the Nansen Passport by the League of Nations, which gave some 450,000 stateless people an identity under which to immigrate to any welcoming nation – history's only internationally valid passport issued in the name of a private citizen. Its legacy is today's 'alien's passports' issued to refugees by the United Nations.

After Nansen, *Fram* was employed on two subsequent Polar expeditions, under Otto Sverdrup to the archipelago west of Greenland (now Canada's Nunavut region) from 1898 to 1902, and under Roald Amundsen to Antarctica for his South Pole expedition of 1910 to 1912. A fourth expedition back to the Arctic was forestalled by World War I, and when hostilities ended the vessel was found to have deteriorated beyond the point of recovery. Amundsen built a new exploration vessel named *Maud*, and the *Fram* was left to the tender mercies of nature.

A preservation effort during the late 1920s led by Otto Sverdrup eventually saved *Fram* from destruction. With the critical help of shipowner Lars Christensen, *Fram*, then almost a wreck, was towed to a shipyard and restored under Sverdrup's supervision. Sverdrup died in 1930, just six months after his friend Nansen, but Christensen oversaw the next six years of fundraising that – without any support from the government – ultimately brought the heroic old ship to its present resting place, a small piece of land fronting Oslo harbor that had been privately donated to the preservationists.

FRAM in its museum setting, surrounded by exhibits related to Polar exploration.

The main museum building, raised around *Fram* after she was winched ashore, was supplemented by a second structure in 2013 built to house *Gjøa*, the vessel which, captained by Amundsen, became the first vessel to make it through the Northwest Passage in 1906. Besides *Fram* and *Gjøa*, the museum offers a large collection of the scientific equipment used by the explorers as well as the artifacts they gathered, and conducts an ongoing effort to locate objects from the expeditions.

"In terms of our mission, it is most important to ensure the relics of the past are safe, for people to see and experience," Museum Director Kløver says. "That said, we can't be an educational institution alone; we are part of the entertainment industry, so to speak, and must tell our stories in a way that is relevant to modern people. Showing the relevance of the past to the present and to the future is a very important part of what we do today."

Interactive exhibits include a cold simulator, where visitors can get a taste of the harsh, gnawing cold that filled the daily life of the explorers and enjoy the somewhat unsettling experience on standing on the deck of a vessel being crushed by ice. Another simulation exhibit allows visitors to appreciate the physical demands of Polar exploration by trying to pull a laden sled. A less demanding part of the exhibit provides a pleasing simulation of the Northern Lights phenomenon, ideal for families not wishing to spend a few house mortgage payments venturing up north for a look at the real thing.

The museum is now looking to raise 10 million Kronor (roughly $1.26 million) to restore *Gjøa*. Curiously, although the Fram Museum honors three of Norway's greatest citizens, it receives no government support and survives primarily on admissions and earnings from its bookshop.

Nonetheless, the museum has successfully told its inspiring stories to more than ten million people during its near 80-year history, attracting over 290,000 visitors in 2014, and is able to bring its message of Polar advocacy around the world. The Fram Museum shares its part of Oslo harbor with the Viking Ship Museum, the Kon-Tiki Museum (highlighting the work of famed explorer and scientist Thor Heyerdahl), the Cultural Museum and Maritime Museum, together making one of Oslo's most popular touristic destinations. ❖

The Weirdest Weapon of

War calls into national service both bold warriors and bold dreamers, who in the pursuit of victory mutually inflame each other's powers and sometimes produce astounding feats that capture the imagination of all succeeding generations – and, sometimes, astounding fails that prove equally fascinating.

So it was with a daring World War II plan that emerged from Britain's Combined Operations Command, an office whose remit was to coordinate multi-agency harassment of the enemy and foster development of new technologies and equipment for the war effort. The Command drew out the genius in some wild ideas, including the bouncing bomb, the artificial harbors that anchored the D-Day invasion and the undersea pipeline, which was invented to support the Allied advance in Europe. Of all its unorthodox concepts that produced a prototype, one takes first place for audacious oddity.

Geoffrey Pyke

The project was code-named Habakkuk, for the Biblical prophet who foretold deliverance from oppressors saying, "Regard and wonder marvelously, for I will work a work in your days which you will not believe, though it be told to you." No better name for this fantastic effort could have been selected.

Project Habakkuk proposed to support the invasion of Europe and defeat the U-Boat menace in the North Atlantic by building an aircraft carrier 2,000 feet long by 300 feet across, with a freeboard of 50 feet, a draft of 200 feet and a displacement of some two million tons. This super-ship, which would have dwarfed any vessel before or since, would have had hangar capacity for 200 fighters or 100 bombers and the workshops to support them. It was to have a service speed of seven knots, a fuel capacity of 5,000 tons and a radius of action of 7,000 miles. Its complement would include some 400 officers and a crew of 3,200.

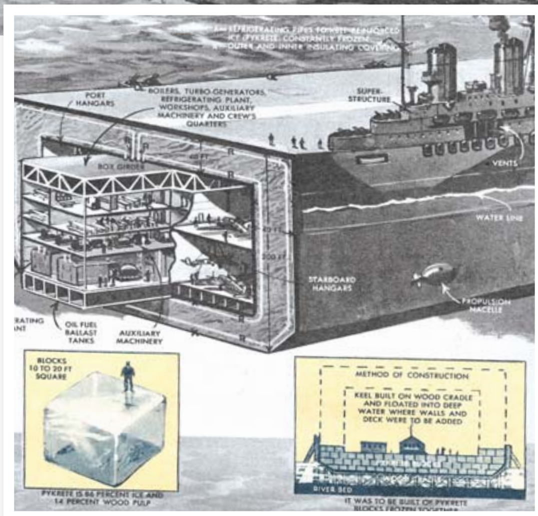
That said, the oddest aspect of this vision is not the vessel's immensity, but that the whole structure was to be made of ice.

The plan originated with an interesting character named Geoffrey Pyke, an Englishman who the *Times* of London, in its 1948 obituary, called a fearless innovator and "one of the most original if unrecognized figures of the present century." Like the natural scientists of previous generations, Pyke applied his considerable imagination and energies to many areas, but did not achieve lasting success. As a young war correspondent during World War I, he entered Germany on a false passport and after six days of snooping was arrested as a spy, but made a daring prison break in which he and a fellow captive walked 80 miles to cross the Dutch border. He did not continue in that career, but in the 1920s made and lost a fortune in the commodities markets, spending all his money developing an experimental school based on then-novel concepts of fostering the individual development of the child (following pioneer Maria Montessori); although highly praised, the school closed following his bankruptcy. He later became an ardent early opponent of the Nazi movement and founded an organization that developed novel technologies to aid the Spanish Civil War. During World War II, he turned his mind to weaponry and devised a light armored car driven by screw-threaded cylinders to take soldiers rapidly over Norway's snows. The design was not manufactured, but did win the respect of Lord Louis Mountbatten, then Chief of the Combined Operations Command – which, in 1942, enabled Pyke to sell him the concept he called Habakkuk.

Pyke was not the first to conceive an ice aerodrome, but, coming amid desperation over steel shortages, U-Boat domination of the Atlantic and insufficient ranges of land-based aircraft, he was the most timely. He reasoned that a ship with a thick ice hull, kept solid by inboard refrigeration, would resist torpedoes and bombs like an iceberg, and that any damage could be repaired with seawater. The plan captivated the dynamic imagination of Winston Churchill, who enthusiastically endorsed it in a 'most secret' memo, writing that "the advantages of a floating island or islands, even as refueling depots for aircraft, are so dazzling that they do not at the moment need to be discussed."

Grudgingly approved by the Admiralty, project development was handed to Canada's National Research Council, which brought several of the country's leading universities into the effort. A 60 x 30-foot prototype of the ice ship was built on Patricia Lake in Alberta (with labor provided by a camp of conscientious objectors), and impressively survived the summer. Still, the shaky structural properties of normal ice proved unsuitable for a ship's hull, putting the project's future in doubt.

World War II



The development trail then led to research performed at Brooklyn Polytechnic Institute by Herman Mark, an important pioneer in polymer chemistry and founder of the first facility for polymer research in the United States. Mark reasoned that, just as polymers could be reinforced by the addition of fibers, so could ice be strengthened. He found that wood pulp stabilized the mechanical properties of ice and made it behave like construction material, then passed his work to friend and former student Max Perutz, who happened to be an amateur glaciologist. Today Perutz is known as a father of molecular biology, but decades before he won the Nobel Prize in Chemistry he picked up his former professor's strange product and perfected it.

The new material, a frozen mix of water with 14 percent wood pulp, seemed almost magical. Highly resistant to melting, it was hard as concrete yet could easily be cut and machined or turned on a lathe. Its crush resistance was more than 3,000 pounds per square inch, it was practically bulletproof and if cracked it could be repaired with water. It was given the name Pykrete (for Pyke and concrete) in honor of the man whose imaginative spark led to its creation.

Addressing Britain's Institute of Structural Engineers in 1951, Lord Mountbatten recalled how he sold Pykrete to the Allied leadership. He had a sample of it wheeled into a meeting along with a block of normal ice and an axe. He asked the strongest man in the room – a US General – to break each block with the axe. The General easily broke the ice, but shouted in pain as he hacked away at the impervious Pykrete. Mountbatten then drew his pistol and with one shot destroyed the remaining ice, but his next bullet merely ricocheted off the Pykrete and nearly struck the Chief of the Royal Air Force. Everyone left the meeting duly impressed with the possibilities of a Pykrete aircraft carrier.

Despite its allure, Project Habakkuk ended up a victim of timing, economics and practicality. While it was still in development, the Atlantic war turned in the Allies' favor and realistic estimates of Habakkuk's building costs (involving $70 million and 8,000 laborers) indicated that scarce resources were better spent elsewhere. Abandoned in late 1943, the prototype sunk into Lake Patricia. Its wood and metal parts were discovered in the 1970s and in 1988 the project was memorialized by the Archaeological Society of Alberta with a lakeside plaque.

Interest in Pykrete periodically resurfaces, and over the years it has been proposed for structural use in Arctic piers and other cold-weather projects. Its first large-scale application came in 2013, when the Eindhoven University of Technology used it to build the world's largest ice dome. Perhaps, as industrial activity in the Polar regions proceeds, productive use will be found for this strange material that has vainly called to the imagination of technology visionaries for seven decades. ❖

VIEWPOINT

The Right Regulation for Polar Waters

Captain John W. Mauger, Chief, Office of Design and Engineering Standards, US Coast Guard and the US Head of Delegation to IMO for the Polar Code

The International Maritime Organization (IMO) adopted the safety provisions for the Polar Code in November 2014, and in May 2015 is expected to adopt the environmental provisions. This will bring the full Code into effect on 1 January 2017. The Code includes mandatory requirements for certification, risk assessment, operational plans and procedures, ice-strengthening, low temperature equipment, additional navigation and safety equipment, and specialized crew training. If the draft environmental provisions are adopted, it will also include additional restrictions on ship discharges to protect the environment and coastal communities. This set of regulations is the culmination of over a decade of work at IMO, but in several respects marks the beginning of the work rather than the end.

The Polar Seas are vast and diverse, but their shipping activity is limited to niche markets due to sparse populations, harsh conditions and the maritime industry's need for voyage predictability. Although recent attention has focused on receding ice and projected growth in Arctic shipping, traffic is still seasonal and limited to a few hundred transits per year. These factors drove the Polar Code toward a risk-based approach, which includes a combination of goals, functional requirements and prescriptive regulations throughout the safety portion of the Code. Based on the planned operating conditions, the prescriptive regulations have escalating measures which range from no additional requirements to stricter standards for ice-strengthening, low temperature performance, life-saving, navigation equipment, and training.

Critics argue that this approach lacks sufficient detail to ensure the safety of the highest-risk operations. While uniform ice-strengthening standards, detailed specifications for low-temperature safety equipment and standardized guidance for vessel operations in ice will improve the Code, these can be developed and incorporated into the existing framework as our knowledge of the risks and mitigation measures associated with Polar shipping evolve over time. The beauty of the Code's framework is that it is designed to absorb such evolution.

In June 2013, I attended IMO's symposium on the Future of Ship Safety, in which maritime industry leaders, including owners, shipyards and labor, discussed their thoughts on how IMO regulations should evolve to serve industry and public needs. As these leaders noted the dynamic growth of their segments over the past 40 years and forecast an even more dynamic industry going forward, it became readily apparent that the regulatory framework put in place during the 1960s, modified in 1974 and amended over time has served both industry and the public well.

I reflected on those discussions as we finalized our work on the Polar Code. The Code is based on a framework for safe shipping regulations that has been proven over the course of immense changes in the industry during the last four decades. We can expect that, over time, we will need to add additional detailed requirements to this framework, similar to the way SOLAS evolved. In some cases the Polar Code requirements themselves will drive this evolution, while in others it will be driven by public or industry demands – either way, as interest in Polar shipping continues the Code will evolve, any changes are likely to be additions to rather than replacements of the present regulatory framework.

Like other specialized Codes invoked by SOLAS and MARPOL, the Polar Code will be implemented and enforced using existing flag and port State policies. In many cases, this responsibility will be delegated to classification societies, whose surveyors, scientists and engineers will play key roles in further understanding its risks and developing detailed technical requirements to address those risks. The US and other delegations relied heavily on these experts during development of the Code.

Looking back, I am impressed by the expertise, professionalism and concern exhibited by all parties during development of the Code. Everyone understood the significance of our work for protecting the mariners, the environment and the Arctic peoples and their communities. All participants can take great satisfaction that their good work has produced a durable document that embodies the right regulation for responsible use of the world's Polar regions. ❖

"We all have a 'Land of Beyond' to seek in our life – what more can we ask? Our part is to find the trail that leads to it. A long trail, a hard trail, maybe; but the call comes to us, and we have to go. Rooted deep in the nature of every one of us is the spirit of adventure, the call of the wild, vibrating under all our actions, making life deeper and higher and nobler."

– Polar explorer Fridtjof Nansen (1861-1930)
From his 1925 address as Rector of St. Andrew's University, Scotland

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