

the flagship has performed well on supporting innovation, “the commercial conversion hasn’t been as big a success as one would expect.” And dependence on the subsidies the flagship has provided to industry could result in products that don’t sell, he says.

### A tipping point

Regardless of how its performance is judged, the Graphene Flagship isn’t expected to be extended beyond its 10-year term. “What happens after the flagship ends is that many of our activities will continue with the support of Horizon Europe,” says Chalmers’s Kinaret, referring to the EU’s €95.5 billion wide-ranging R&D program that runs through 2027. “And some will have reached the level of maturity that they no longer require support of the European taxpayer.”

Rather than duplicating the flagship, Barkan says, the US should drive demand by easing regulatory requirements that currently need approval from the Environmental Protection Agency for each new application of graphene. The US could also boost the growth of such products as graphene-embedded concrete by establishing low-carbon-emission requirements for road-building materials.

Forecasts for graphene demand vary widely, but there is little doubt that the market will rapidly expand. Still, graphene is being held back by a lack of application-oriented standards and uniform quality metrics. Part of the flagship program has been devoted to developing such standards, but adoption requires approval from multiple national and international standards bodies, a process that can take years. “The problem is, industry doesn’t have years to wait,” says Barkan, whose organization also works to accelerate the adoption of standards.

“Graphene is approaching a tipping point,” says Baker, who expects growth to occur in “fast and slow lane” applications. The fast category comprises such uses as rubber, plastics, and carbon fiber, where alterations to the manufacturing process aren’t necessary and government approval isn’t required. Water-purification membranes and biomedical applications will move more slowly, he explains, because of the need for regulatory approval and certification processes.

David Kramer

## Submarines afford a view from below the Arctic

Civilian–military cooperation builds understanding of the ocean, Earth, and climate change and benefits national security.

Arctic scientists and the US Navy are breathing new life into a 27-year-old partnership, the Submarine Arctic Science Program (SCICEX). Its heyday was in the 1990s, when the navy hosted dedicated science cruises. Since then it has continued in a more hands-off and less scientifically productive mode: Although scientists receive submarine data from the navy, they are no longer able to embark, install their own specialized instruments, or determine expedition routes.

Those limitations will remain under a new memorandum of agreement that’s in the works, says the University of Alaska Fairbanks’s Jackie Richter-Menge, chair of the SCICEX science advisory committee. Still, she and other scientists anticipate new opportunities; in particular, they hope for quicker declassification of data collected by the navy’s nuclear submarines.

### Security and science

SCICEX was the brainchild in the early 1980s of George Newton, a former navy captain who was a member, and later chair, of the US Arctic Research Commission, a government advisory body. (See the interview with current chair David Kennedy at PHYSICS TODAY online, 7 May 2021.) When the Cold War ended, says Newton, “we had built a submarine force that was in excess of the military’s need in a peacetime environment.”

Arctic submarine expeditions would both advance science and allow the navy to train sailors and maintain military capability in the harsh environment, Newton reasoned. “I started pushing the idea of the navy and scientists collaborating.” The former Soviet Union also had an excess of submarines, he says. “They began offering submarines for lease to scientists. That served as a bit of a motivator for SCICEX.”

By 2000, following a handful of collaborative expeditions, the partnership



**THE USS HAWKBILL** surfaced at the North Pole in 1999, during the Submarine Arctic Science Program’s last dedicated science expedition. The *Sturgeon*-class attack submarine sailed from Honolulu, Hawaii, to Portsmouth, UK, in 67 days.

morphed. The navy had decommissioned most of its submarines that were suitable for Arctic missions, Newton says, and there were no longer enough of them for dedicated science cruises.

For the past two decades, the navy has tied collection of Arctic submarine data for scientists to the partly classified ice exercises (ICEX) it has set up at ice camps every year or two since the 1960s. It invites mainly navy scientists to do research at those ice camps.

“I want to reinvestigate the partnership,” says Howard Reese, director of the navy’s Arctic Submarine Laboratory in

San Diego, California, and the liaison to both ICES science and SCICEX. "To really understand what's going on in the Arctic, scientists need to look from above and below."

Global warming has made surface passage across the Arctic easier, and for security purposes, the navy monitors activity in the area. It also has a long history of funding and running basic research in the Arctic. Submarine data help determine what's going on in terms of ice melt and climate change, says Reese. (See the articles by Peter Worcester and Megan Ballard, *PHYSICS TODAY*, December 2020, page 44, and by Martin Jeffries, James Overland, and Don Perovich, October 2013, page 35.)

Identifying patterns of freshwater runoff, temperatures, and sound velocity aid with national security, Reese says. For example, understanding physical features and the acoustic environment helps the navy to hide its submarines from potential adversaries and to listen for others' ships and submarines. And the navy needs to know where the ice is thin enough to surface a submarine. "We need to understand the environment to be able to operate effectively in the Arctic. Working with scientists is mutually beneficial," he says.

## From seafloor to surface ice

Among the main quantities that scientists measure in the Arctic Ocean are seafloor topography; extent, thickness, and roughness of sea ice; and temperature, depth, conductivity, and nutrients. Some quantities can be measured via satellites, icebreaking ships, autonomous underwater vehicles, or instruments on the ice or in the water. But others are better—or only—accessible from a submarine.

Long-term changes in the thickness and roughness of sea ice are best studied from data collected with upward-looking sonar on submarines, says Richter-Menge. Satellites have done a good job of measuring sea-ice area since the 1980s, she says, but only recently have technological advances made it possible for them to infer thickness. Satellite estimates rely on models that take into account the properties of the sea ice and snow, she notes. "Contemporaneous submarine measurements offer the best tool for validating this new technology." Without submarine data, she says, "we wouldn't have appreciated the

extensive thinning of the ice over the past few decades."

Geophysicist Margo Edwards, director of the University of Hawaii's Applied Research Laboratory, was the first woman to deploy on an operational navy submarine under ice. She remembers her second day out with SCICEX in 1999: "We were doing a survey of the Chukchi seafloor and we saw evidence of scouring—a sheet of ice had pushed around the terrain many thousands of years ago. It was exciting."

At that time, the SCICEX submarine was outfitted with an interferometric sonar device that provided topographical data of the seafloor in unprecedented extent and detail—at least an order of magnitude better resolution and more precise positioning than from standard surface single-beam echo sounders. The terrain data provide clues about the history of the planet and climate cycles, says Martin Jakobsson, a geophysicist at Stockholm University. He incorporates data from SCICEX into the Seabed 2030 Project, which aims to map Earth's entire ocean floor by the end of this decade. Many people use the project's data to model ocean circulation, study the seafloor, and more, he says.

Knowing the seafloor topography is necessary for navigating safely and laying pipes and cables, says Larry Mayer, director of the Center for Coastal and Ocean Mapping at the University of New Hampshire and a member of the SCICEX science advisory committee. It is important for defining countries' rights to resources, studying plate tectonics, predicting tsunamis, and locating shipwrecks to study maritime heritage, he continues. And the seabed topography influences ocean circulation. For climate models, "seafloor roughness is important in terms of generating turbulence that impacts the distribution of heat."

So far only about 20% of the global seafloor has been mapped to current standards. "Literally more of the Moon and Mars have been mapped, and at better resolution," says Mayer.

Bernard Coakley, a geophysicist at the University of Alaska Fairbanks, sailed on a pre-SCICEX test cruise in 1993 and then on later SCICEX expeditions. He and colleagues measured gravity anomalies in the Gakkel Ridge that "were difficult to explain unless it had a very thin crust." In 2001, subsequent dredging of the

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ridge, located between Greenland and Siberia, confirmed their gravity findings, he says.

Because of a history of irregular sampling and poor navigation, says Coakley, many Arctic geologic features “were mispositioned by 100 kilometers laterally and they might be 1500 meters shallower than had been thought.” With submarines, he says, features of the water and seafloor can be sampled more systematically. Now that more is known about the Arctic, he says, “we can ask significant questions, like How did this feature form? and How do sets of faults on a ridge relate to each other?”

## Ice camps

In the reconfigured SCICEX of the past two decades, scientists obtain some of the submarine data that are collected in conjunction with an ICEX ice camp. They also conduct experiments from the ice. The camps typically take place over six or seven weeks in late winter.

MIT emeritus professor Arthur Baggeroer and colleagues have studied a layer of warm water about 70 meters deep that enters the Arctic from the Pacific Ocean through the Bering Strait. Known as the Beaufort Lens, the warm water creates a barrier to sound penetration. The speed of sound is higher in the layer than in the surrounding, colder layers, so the layer acts as a refractive waveguide.

Discovered by Russian scientists, the layer “ensures the transarctic propagation of low-frequency sound,” as described by Aleksandr Grigor’evich Litvak in *Herald of the Russian Academy of Sciences* (volume 85, page 239, 2015). Says Baggeroer, who spearheaded classified research on the water layer at ICEX, “I recognized the significance of the Beaufort Lens in the western Arctic for anti-submarine warfare.”

Henrik Schmidt is director of MIT’s Laboratory for Autonomous Marine Sensing Systems. At the 2016 ICEX camp he studied how the acoustic environment had changed. “We were lucky to study the same location that had been looked at in 1994. We compared directly the characteristics of ambient noise. There was a dramatic change.” In 1994 the ice was 4 meters thick. Large ice floes would grind when blown by the wind, he says. In 2016, the ice buildup was 1 meter thick, and there was no more grinding. “If the wind blew, the noise was from ice cracking.”

The biggest obstacle in working with ICEX, Schmidt says, is that “science is not the highest priority.” Jon Collis, an underwater acoustician at MIT’s Lincoln Laboratory, has taken part in the three most recent ICEX events. The navy plans to do tactical exercises during the 2022 ICEX, he says, “but they can’t do that all the time, so it leaves a lot of time for science.” Even so, competition is stiff for access to an ice hole, he says. “We negotiated and will work nights.” His team plans to deploy sensors at various depths to measure salinity, temperature, and sound velocity and to use hydrophones to listen to the ice sheet breaking.

As for the current mode of SCICEX, without scientists on board the submarines, says Mayer, of the Center for Coastal and Ocean Mapping, “we have very little control of when instruments are on or off. We would, of course, rather use our own dedicated systems.” Still, he says, the data that scientists obtain “are

a lot better than nothing. Every sounding is useful.” Scientists often can’t afford submarines or Arctic camps on their own, so they’re dependent on the navy for much of their Arctic access.

“The general perspective of the navy is that [hosting scientists] is a nice thing to do,” says Val Schmidt, who was a junior naval officer aboard the 1998 and 1999 SCICEX cruises. “It’s not the navy’s primary mission, and they see it as a bit of a hassle having to accommodate the scientists.” For his part, though, he says he had an “insatiable curiosity” and constantly “pestered” the scientists. After he left the navy he got a master’s degree in ocean engineering and now leads the marine robotics program at the Center for Coastal and Ocean Mapping.

## Partnering with the military

Military–civilian scientific partnerships to explore the oceans with submarines go back at least to the 1920s, says Sam



**JOAN GARDNER** (left) and Rick Hagen of the US Naval Research Laboratory analyze ice-core samples at the navy ice camp in March 2016. (Courtesy of the Arctic Submarine Laboratory.)



**SCIENTISTS FROM MIT** lower a sound array through a hole in the ice at the navy ice camp in March 2018. (Courtesy of the Arctic Submarine Laboratory.)

Robinson, a historian of ocean science at the University of Cambridge. At that time, Dutch geodesist and geophysicist Felix Andries Vening Meinesz took his instruments aboard Royal Netherlands Navy submarines in order to measure gravity anomalies. His goal was to establish the shape of Earth and the geoid, the shape Earth would take if winds and tides were absent.

For more than three decades starting in 1971, Peter Wadhams of the University of Cambridge sailed with UK Royal Navy submarines to study sea-ice thickness. Large ice blocks pile up to form deep ridges that protrude to depths of 40 meters or more. "That's important for navigation and for drilling rigs," says Wadhams. The distribution and size of the ridges follow a simple exponential law, he says. "You get fantastic insight into the role of ice and ice mechanics in climate."

Wadhams's *in situ* explorations came to an abrupt halt in 2007 after a canister containing potassium chlorate that was part of the backup oxygen system exploded and killed two sailors. He now works with unmanned underwater vehicles. They are not as good as submarines, he says. "They are short range, and you

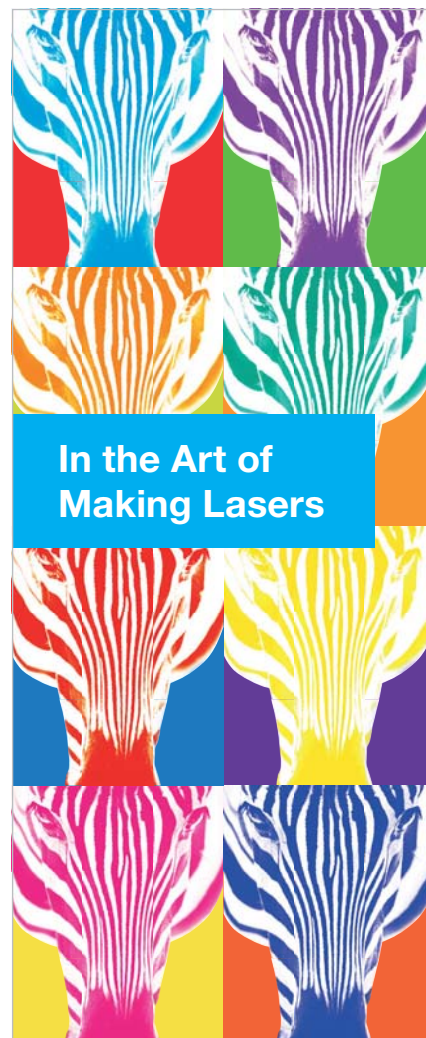
can't collect data from across the entire Arctic basin."

A sticking point in all the military-civilian collaborations is that the data are classified. Even scientists who have security clearance and can access the data can't easily publish them in the open literature. The US Navy wants to keep the location and speed of its submarines under wraps: That's to prevent potential adversaries from identifying the acoustic signal of a given submarine by sifting through past recordings.

To that end, data released by the navy is "fuzzied up," says SCICEX science advisory committee chair Richter-Menge. More problematic is that, because the data are manually reviewed, it can take months or even years for the navy to release them to scientists. "The value of these data can depend on who's in charge," she says.

The navy has been "sporadic" about releasing data, says Reese, the Arctic Submarine Laboratory director. Algorithms are being developed to extract data that can safely be handed to civilian scientists. "If we get these data released, more scientists will be enthused and get involved," he says. "I hope we have a new agreement in a matter of months, not years."

**Toni Feder** 



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