Silent Dangers

Assessing the Threat of Nuclear Submarines

Prepared for the Outrider Foundation

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We would like to dedicate this work to all nuclear submariners serving today, and to the families of those who have been lost. The men and women of the "Silent Service" do not expect — but certainly deserve — recognition for their crucial role in maintaining global security.

Foreword

This report is the result of collaboration between the La Follette School of Public Affairs at the University of Wisconsin–Madison, and the Outrider Foundation, represented by former U.S. Ambassador Tom Loftus and Dr. Tara Drozdenko. The objective of our program is to provide La Follette School graduate students the opportunity to improve their policy analysis skills while providing the client the first comprehensive catalog and accompanying risk assessment of nuclear submarine accidents across several world locations and nations from 1958 to the present day.

The La Follette School offers a two-year graduate program leading to a Master of International Public Affairs (MIPA) degree. Students study policy analysis and public management, and they can choose to pursue a concentration in a policy focus area. They spend the first year and a half of the program taking courses in which they develop the expertise needed to analyze public policies. The authors of this report all are in the final semester of their degree program and are enrolled in Public Affairs 860, Workshop in International Public Affairs. Although acquiring a set of policy analysis skills is important, there is no substitute for actually doing policy analysis as a means of experiential learning. Public Affairs 860 gives graduate students that opportunity.

This year, workshop students in the MIPA program were divided into three teams. The other teams performed analyses of a rural health care facility in Haiti and the development of a child deprivation index for the United States similar to those in other rich nations.

The Outrider Foundation is interested in the risks facing society from nuclear weapons. As you will learn from this report, nuclear submarines are both unique and effective due to their secretive nature and global presence; their prevalence poses risks to the environment and to geopolitical security.

My students compiled the first comprehensive catalog and accompanying risk assessment of roughly 500 nuclear submarine accidents for 226 individual submarines from six countries from 1958 to the present day. For each data point, the team gathered information on submarine class and owner-country, as well as the personnel and armaments on board each vessel at the time of each case. The team also estimated the cost of each failure to the environment and geopolitical security and provided interactive visualizations, locational mapping, and other analyses of these incidents. The report recommends steps by which policymakers of nuclear-armed states can best mitigate the risks arising from the irresponsible use of nuclear submarines.

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Executive Summary

Submarines armed with nuclear ballistic missiles are employed as a component of nuclear deterrence due to their secretive nature and global reach. Furthermore, the majority of submarines today are powered by nuclear reactors. Their prevalence poses a threat to the environment and geopolitical security. This report for the Outrider Foundation prepares a comprehensive catalog and accompanying threat assessment of nuclear submarine failures from 1958 to the present day. It also provides recommendations for policymakers of nuclear-armed states about how to best mitigate the threats resulting from the irresponsible use of nuclear submarines.

We collected nearly 500 data points on 226 individual submarines from six countries, relying on open source academic articles, source books, reports from watchdog groups, and news media. For each data point, we gathered information on submarine class and owner-country, as well as the complement — the number of sailors and officers — on board each submarine at the time of each case. We recorded the armaments — the type and number of weapons — on board each submarine. In addition, we developed a Class Faultiness Index to determine whether any classes were more subject to failures, given their service periods and class strength.

Differentiating between acute and chronic costs, this report utilizes two scales to estimate the effect of each failure on the environment and geopolitical security. With the advice of experts in international relations, our team developed a scale to measure the geopolitical security effect. To analyze our data, we produced numerous regression models. In addition, we prepared interactive visualizations using Tableau and Google Earth. In total, this report contains three products:

- **Catalog**: a comprehensive dataset tracking nuclear submarine accidents since 1958, including measures such as complements and armaments, home port, and builder.
- **Visualizations**: interactive representations of our catalog to increase its accessibility to non-academic audiences.
- **Report**: an assessment of environmental and geopolitical security threats associated with nuclear submarine usage.

We recommend the establishment of an international forum of the nuclear submarine states, with four key objectives: (1) the collection of quality data on nuclear submarine failures, (2) the sharing of best practices in submarine safety, (3) multilateral efforts to reclaim lost nuclear submarines, and (4) normative codes of conduct to curb the irresponsible use of nuclear submarines.

Abbreviations

ASTOR — A nuclear-armed torpedo for anti-submarine warfare
EEZ — Exclusive Economic Zone
FR — French Republic
GeoSec — Geopolitical Security Scale
IAEA — International Atomic Energy Agency
IN — India
INES — International Nuclear and Radiological Event Scale
NGO — Non-Governmental Organization
PRC — People's Republic of China
RF — Russian Federation
SIGINT — Signals intelligence
SSBN — Nuclear ballistic missile submarine
SSGN — Nuclear guided (cruise) missile submarine
SSN — Nuclear attack submarine
SUBROC — Submarine Rocket, a nuclear-armed standoff weapon with a 40 to 48 km range
SUBSAFE — US program to improve submarine safety after the loss of the *Thresher*
UK — United Kingdom
UN — United Nations
US — United States
USSR — Union of Soviet Socialist Republics

Introduction

Summary of Results

We developed the first catalog of nuclear submarine failures with roughly 500 data points on 226 individual submarines from six countries. This data indicates that newer submarine classes experienced a greater volume and seriousness of failures early in their service lives. Generally, we found that collisions had a greater impact on geopolitical security, while equipment failures, as well as cases related to fire and water, had the greatest impact on the environment. We found that submarine failures generally produced two kinds of costs: chronic and acute. We also saw a marked reduction in the number of failures after the end of the Cold War. We found six countries with current nuclear submarine programs, but we anticipate a potential for proliferation in the number of countries with programs in the future.

Terminology

In this report, we use US Naval terminology when categorizing nuclear submarines. These terms are generalizable to all nuclear submarines. According to Ronald O'Rourke of the Congressional Research Service, modern nuclear submarines fit into three basic types: nuclear-powered attack submarines (SSNs), nuclear-powered cruise missile submarines (SSGNs), and nuclear-powered ballistic missile submarines (SSBNs) (O'Rourke 2018). SSNs and SSGNs are nuclear-powered but do not carry nuclear weapons. SSBNs are nuclear-powered and armed with submarine-launched ballistic missiles (SLBMs) containing nuclear warheads, intended to remain hidden from detection and deter nuclear attack.

While the US currently deploys submarine-launched nuclear weapons on only its 14 *Ohio* class SSBNs, both SSNs and SSGNs are nuclear-capable and have been deployed with nuclear weapons in the past. US SSGNs are converted *Ohio* class SSBNs, which previously carried nuclear SLBMs ("Guided Missile Submarines-SSGN" 2015). The Soviet Union operated — and the Russian Federation now operates — SSGNs that originally carried nuclear-armed cruise missiles but are now limited to those with conventional warheads by arms control treaties. However, unlike US SSGNs, these submarines were designed as platforms for cruise missiles, not converted SSBNs ("SSGN Oscar II Class (Project 949.A) (Kursk)" 2019). During the Cold War, all nuclear SSNs carried tactical nuclear weapons (Kristenson 2016). The two US tactical nuclear weapons described below are representative of those used by other nuclear submarine states.

ASTOR: In the late 1950s, the US began development of a nuclear-armed torpedo known as the Mark 45 or ASTOR. This was a response to fears that nuclear submarines' speed and greater diving capabilities would make them too difficult to destroy with conventional torpedoes, as the larger explosion of a nuclear weapon meant that hitting the enemy submarine was not necessary to destroy it. ASTOR was deployed in 1963 but discontinued in 1976, when advances in conventional torpedoes made nuclear torpedoes unnecessary ("Torpedoes of the United States of America: Post World War II" 2008).

SUBROC: The UUM-44 SUBROC was a nuclear-armed standoff weapon, designed to allow one submarine to destroy another at much greater range than is possible with a torpedo, thereby limiting the risk of a counterattack. After launch from a standard torpedo tube, SUBROC fired its rocket booster, bursting out of the water and travelling 40 to 48 km (25 to 30 mi), before returning to the water and detonating its thermonuclear warhead. As with ASTOR, the power of the nuclear warhead meant that a SUBROC could destroy submarines in the general area of the explosion. Development began in the late 1950s, and SUBROC was first deployed on the *USS Permit* (SSN 594) in 1965. It was used on *Thresher/Permit*, *Sturgeon*, and *Los Angeles* class submarines until 1989 (Parsch 2002). For more information on submarine types, see Appendix I: Nuclear Submarine Data.

History

These case studies are useful for understanding the kinds of nuclear submarine failures that have occurred historically.

Thresher

The *USS Thresher* (SSN 593) was the first nuclear submarine to be lost with all hands when it sank on April 10, 1963 (Ølgaard 1996; Bierly, Gallagher and Spender 2014). *Thresher* was engaged in a deep dive as part of post-overhaul trials off Cape Cod, Massachusetts. A seawater pipe failed, flooding the engine room and shutting down the nuclear reactor. The technology used to join pipes in the *Thresher* commonly failed in saltwater systems and had not undergone the most advanced quality control methods, which were not mandatory for this part of the submarine. This flooding would not have been severe at lesser depths, leading to the conclusion that “submarine design, construction and, operational capabilities had come ‘too far, too fast’” (Ainscough 2013). During the trials, *Thresher* was communicating with the support ship *USS Skylark* using an underwater telephone. The quality of this type of transmission decreases at greater depths, leading to “considerable disagreement over the exact communication” received from the *Thresher* during its final minutes (Ainscough 2013). While the flooding by itself was not fatal, a major design flaw in the emergency ballast tanks — where frozen moisture from the high-pressure air blocked the pipe — prevented the vessel from surfacing. The backup battery, which would have helped bring the *Thresher* to the surface, also failed. *Thresher’s* final transmission appears to include the phrase “exceeding test depth” (Ainscough 2013). The scenario presented here is the most widely accepted, but despite thorough investigation, scholars lack definitive evidence for why *Thresher* was lost (Ainscough 2013). Sinking past its test depth, the *Thresher* imploded at around 1,500m (4,921 ft) before resting on the bottom in 2,600m (8,530 ft) of water. All 129 sailors, officers, and shipyard personnel aboard the *Thresher* perished.

SUBSAFE

In response to the loss of the *USS Thresher*, the US Navy implemented the SUBSAFE program to “provide maximum reasonable assurance of watertight integrity and recovery capability” for the American submarine fleet (House Science Committee 2003). Specifically, the program “requires submarines to adhere to strict maintenance schedules and pass materiel condition assessments before they are allowed to submerge” (GAO 2018). For example, the silver-brazing used to join saltwater pipes on *Thresher* was replaced with more reliable welded joints (Ainscough 2013). While no certain cause for the *Thresher’s* sinking has been established, the record of the SUBSAFE program demonstrates some of the lessons learned by the US Navy. Since the program's inception, no SUBSAFE-certified submarine has been lost — the *USS Scorpion*, lost in 1968, was not certified.

Scorpion

The morning of May 27, 1968, the families of the crew aboard the *USS Scorpion* were waiting at Naval Station Norfolk for the SSN to return from the Mediterranean Sea (Offley 2018). In fact, the *Scorpion* had been lost five days before, southwest of the Azores. The wreck rests on the bottom in 3,600m (11,811 ft) of water. Like the *Thresher*, the resulting Naval Court of Inquiry was unable arrive at a conclusive cause for the sinking of the *Scorpion*. Whereas there is a commonly accepted theory about the loss of the *Thresher*, there are several competing theories in this case. Recent theories have focused on a torpedo erroneously arming itself and exploding, either inside the tube or as a result of homing in on the *Scorpion* after the crew jettisoned it (Ølgaard 1996). Because there are many suspicious circumstances and a further report by the Navy remains classified, we list the cause as unknown.

Kursk

The sinking of the Russian submarine K-141 *Kursk* with the loss of all 118 sailors on August 12, 2000, is the most recent example of the sinking of an operational nuclear submarine. The *Kursk*, an Oscar II (*Antey*) class nuclear-powered cruise missile submarine (SSGN), was participating in the Russian Northern Fleet's largest exercise since the dissolution of the Soviet Union (Barany 2004). During this exercise, the rest of the fleet lost contact with the *Kursk*, which was eventually found on the bottom at a depth of 108 meters. While the Russian Navy — almost reflexively — initially blamed a collision with a NATO submarine, the official investigation determined that the *Kursk* was destroyed by two explosions in the torpedo room. The explosion of a practice torpedo set off the other torpedoes a little over two minutes later, killing most of the crew and causing the *Kursk* to sink. In total, 23 crew members survived the first two explosions but perished from lack of oxygen by the time rescuers entered the *Kursk* nine days later (Barany 2004). The wreck of the *Kursk* was raised in 2001 by a Dutch firm. This operation was extremely difficult technically, despite the depth being much less than that of other lost submarines (Chalmers 2002).

Operation Holystone

Operation Holystone was a longstanding US intelligence gathering program that used nuclear submarines to infiltrate the territorial waters of the Soviet Union and other Cold War adversaries over 90-day missions (Kraska, 2015). These missions included the photographing of Soviet vessels and installations, collection of signals intelligence (SIGINT), and even the tapping of Soviet communication cables on the ocean floor. The US submarines carrying out these operations were nuclear-armed and crewed by seasoned officers and sailors (Shackleford, 2014). They operated on a "'wartime posture,'" (Shackleford, 2014) alert and ready for an engagement with Soviet forces, in order to collect intelligence considered vital to avoiding war. These missions resulted in two Cold War-era collisions; *USS Gato* (SSN 615) with *K-19*, a Soviet SSBN, and *USS Pintado* (SSN 672) with a still unidentified Yankee I (*Navaga*) class SSBN (Kraska, 2015). Other collisions between the US and USSR/RF may be connected to Operation Holystone as well. The 1992 collision of *USS Baton Rouge* (SSN 689) and *Kostroma*, a Russian

Sierra I (*Barrakuda*) SSN and the 1993 collision of the *USS Grayling* (SSN 646) and *Novomoskovsk*, a Russian Delta IV (*Delfin*) class SSBN, both in similar circumstances to the Cold War collisions, are strong evidence that submarine intelligence operations continued after the fall of the Soviet Union. While no later incidents of this type are recorded in our catalog, it is likely that this type of operation continues, at least in periods of high tension. The Soviets — and, later on, the Russians — used submarines for similar missions against the US and its allies beginning shortly after WWII (Kraska, 2015). A collision between the *USS James Madison* (SSBN 627) and an unknown Victor I or II (*Yorsch* or *Syomga*) SSN in 1974 near the entrance to the Holy Loch base used by US SSBNs may also be attributed to a Soviet mission similar to Operation Holystone. Other countries may engage in similar missions as well. For example, Chinese nuclear submarines were detected in Japanese waters and North Korean diesel-electric submarines were detected in South Korean waters, raising the prospect that these countries were conducting similar missions, albeit not necessarily with nuclear weapons.

Literature Review

In preparing this report, we reviewed a variety of literature on the impact of nuclear power — as well as nuclear weapons — on the environment and geopolitical security.

Environmental Literature

The environmental community generally opposes the use of nuclear energy and protests the use of nuclear submarines. The Sierra Club remains "unequivocally opposed to nuclear energy," and Greenpeace has called for the UK to withdraw all of its nuclear submarines due to severe risk to crew and marine life (Drew 1994). Despite significant opposition from the environmental community, the empirical dangers are not clear.

The criteria for determining the environmental impact of nuclear submarines can be measured by the impact on the fishing industry and the threat to the marine environment. Nuclear submarine failures may cause harm to fisheries and those who depend on fish as a significant part of their diet. This consequence is more direct and immediate. The threat to the marine environment results from abandoned, nuclear submarine reactors that will eventually rust through and cause damage to marine ecology. Such a threat represents the chronic impact of nuclear submarines on the environment. The current, empirical danger that nuclear submarines pose to the fishing industry is low, while the potential threat to the whole marine environment is vast.

Impact on Fishing Industry: The European Commission mandated a study on the threat that sunken nuclear submarines pose to the fishing industry. The research focused on leakage of radioactive material from the wreck of K-159 in the Barents Sea. The Barents Sea is a major site for European fishing, but is also home to sunken Soviet-era submarines. The large amounts of caesium-137 (137Cs) leaking from K-159 could increase levels of radioactivity in cod populations by 100 times. However, this level would still be below 'safe' standards set by the Norwegian government (Heldal 2013).

The *Komsomolets* (K-278), a Soviet nuclear submarine that sank in the Norwegian Sea in 1989, is another vessel that has been studied for its effects on fisheries. The Norwegian Defence Research Establishment and the European Commission studied the potential effects of hazardous

137Cs leaking from *Komsomolets*. If 100 percent of the total amount of radioactive waste leaked from the submarine, cod populations would become 100 times more radioactive for two years, an increase of 0.002 Bq/Kg in the arctic fish. Cod average 1 to 10 Bq/Kg 137Cs (Hoibraten et al 1997). Such an increase in toxic levels would still be safe for consumption, even for people who depend on arctic fish for 100 percent of their diet. Although contaminated fish are considered safe for human consumption, neither study could determine what the greater ecological effects would be for the marine environment.

Threat to Marine Environment: Research by Norwegian environmental Non-Governmental Organizations (NGOs) illustrate the detrimental possibilities that nuclear submarines create. According to a joint Russian-Norwegian report from 2012, there are 17,000 containers of nuclear waste, 19 Soviet nuclear submarines, and 14 nuclear reactors that have been left at the bottom of the Kara Sea (Digges 2014; Digges 2017). Thomas Nilsen, editor at the *Barents Observer* and member of a Norwegian watchdog group, describes — referring to the severity of the radiation release — the sitting submarines as "an arctic underwater Chernobyl, played out in slow motion" (Bodner 2014). Once the casings of the submarines are rusted through, incredibly hot nuclear fuel will escape the reactors and emit massive levels of radiation into the environment. Dr. Nils Bohmer, managing director of the Bellona Foundation, a prominent Norwegian environmental NGO, claims that "counted in radioactivity, one single reactor compartment [of a nuclear submarine] with spent fuel inside contains much more radioactivity than all the thousands of containers combined" (Bodner 2014).

Geopolitical Security Literature

Experts on geopolitical security see submarines as unique, and even essential, nuclear deterrents. However, the nuclear submarine's place in the United States' nuclear triad — aircraft, missiles (ICBMs), and SSBNs — is subject to ongoing debate.

Col. Robert Spalding, a fellow at the Council on Foreign Relations, has stated that the US nuclear apparatus must be "survivable, affordable, flexible, visible, available, credible and provide stability" and that "submarines alone are not enough" (Spalding 2013). ICBMs are the cheapest leg of the triad. Bombers are multi-purpose, and they cannot be meaningfully scrapped. Having three legs is a hedge against one leg becoming obsolete. Submarines are not visible, and they cannot project power the same way as bombers.

Former Secretary of Defense William Perry, who served under President Bill Clinton, has written extensively on the dangers of nuclear-armed submarines. In one opinion piece, Secretary Perry advocated for an aggressive policy shift to "support strategic re-engagement with Russia and walk back from this perilous precipice" (Perry 2019). Secretary Perry is considered an expert on foreign policy and founded the William J. Perry Project, a nonprofit organization aimed at educating the public on the threats of nuclear weapons (Perry Project 2019). Perry suggests that the continued use of nuclear weapons for deterrence purposes is dangerous and an eventual nuclear blunder or nuclear terrorist attack is a great threat. Such a failure, he warns, is especially "likely when there is no sustained, meaningful dialogue between Washington and Moscow" (Perry 2019). He has advocated for increased communication and engagement from the two parties on a new approach of cooperation, transparency, and security to limit the risks of nuclear conflict. Leadership from the two countries that possess more than 90 percent of the world's nuclear weapons — the United States and Russian Federation — would inspire other countries to take further responsibility with such technology. Secretary Perry, along with George Schultz, Secretary of State under President Reagan, and Sam Nunn, former Chairman of the Armed Services Committee, made a joint statement recommending the US "reduce reliance on nuclear weapons … prevent their use and ultimately end them as a threat to the world" (Perry 2016).

By contrast, Secretary of Energy Rick Perry promotes the Trump administration's decision to budget more funding for the National Nuclear Security Administration (NNSA), as he claims that it is "abundantly clear" that NNSA needs increased financing (Sonne 2018). The 2018 spending bill allocates $10.6 billion to weapons activities within NNSA (an increase from $9.2 billion in 2017 and $8.85 billion in 2016). According Secretary Perry's Congressional Testimony, the US Department of Energy budget already allocates $1.5 billion to directly support the Navy's nuclear-powered fleet and continuation of the *Columbia* class submarine program (Perry 2017). The US has a massive advantage in deployment ability through its submarine fleet (a single *Ohio* class sub can carry up to 192 warheads, whereas Russia can deploy about 100). Bombers and ICBMs are more vulnerable than submarines.

In its 2018 report to parliament, the United Kingdom Ministry of Defense reported that its key objectives were cooperation with France, the US, and NATO (United Kingdom 2018). Eric Schmitt writes in the *New York Times* that Russian submarine assets have fallen significantly below Cold War levels (Schmitt 2016). However, recent Russian nuclear submarine activity has risen. Dr. Michael Paul, writing for SWP Berlin, notes that China likely possesses a credible nuclear deterrent but that its submarine program has faced issues with deployment, coordination, and technology (Paul 2018).

Some scholars have suggested that certain "difficulties of controlling escalation of conflict at sea" may exist (Ball 1985); however, we were unable to find a model that satisfactorily determines the risk posed by nuclear submarines to geopolitical security and the environment. We endeavor in this report to establish a framework that addresses both issues.

Criteria

We relied on two dimensions — the environment and geopolitical security — to evaluate our catalog, differentiating between acute and chronic costs. Acute costs are sudden and realized in the short run. Chronic costs accumulate over time and have a long-lasting impact. Because chronic costs might take years — or even decades — to materialize, they are not necessarily visible in observable data. We used two seven-point scales to measure the geopolitical security and environmental costs of each failure in nuclear submarines. These failures — or cases — may have resulted from a variety of causes, including human error or mechanical failure. Once mapped onto this scale, the data points were then categorized into four distinct categories: incidents, accidents, events, and catastrophes.

Environmental Scale

The International Atomic Energy Agency (IAEA) has developed a seven-point International Nuclear and Radiological Event Scale (INES) to communicate "the safety significance of events at nuclear installations" (IAEA 2014). We use the INES — or environmental scale — to measure the magnitude of acute environmental cost for in each nuclear submarine failure in our catalog. This is also the method that Reistad, Hustveit, & Roudak (2008) use. See Figure I for a graphical overview of this scale.

We assess the sinking of the *USS Thresher* as a 1 on the environmental scale because, while the original sinking did not release radiation and was not related to a nuclear power failure, radiation may be released into the environment as the reactor casing deteriorates.

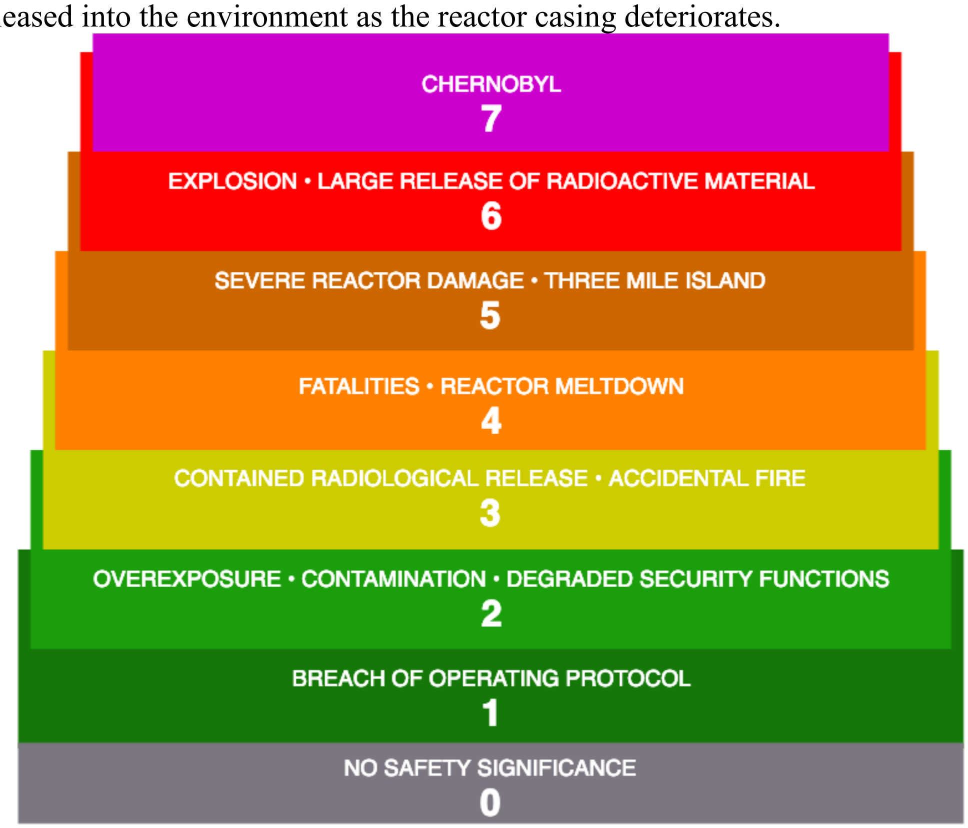

Figure I: International Nuclear and Radiological Event Scale (INES).

Geopolitical Security Scale

In the case of the INES, we found an existing framework for evaluating our data from an environmental perspective. However, no analogous scale for measuring the impact on geopolitical security exists. Therefore, we developed a seven-point Geopolitical Security (GeoSec) scale to evaluate the impact that each case had on geopolitical security. The GeoSec scale measures the material costs of an encounter (material index) and how it was perceived, which depends on the location of the case (geographical index) and the parties involved (contextual index). For more details on how we assigned values using this scale, see Appendix II: Expanded Geopolitical Security Scale.

After a qualitative review of each case, we assigned a value from one to seven using the following equation:

$$0.5* + 0.5*[*(weight) + *(1-weight)]$$

Where:
: The **material** index
: The **contextual** index
: The **geographical** index
weight: Based on geopolitical relationship between the countries (dyads) involved in each case

We borrowed the concept of a seven-point scale to evaluate the cost to geopolitical security for each of our data points. Using symmetrical scales makes comparison of the costs of cases simpler. This is the first attempt in scholarship to build a geopolitical security scale for nuclear submarines. We acknowledge its limitations and hope that it will serve as a baseline for future efforts. Because of the uncertainties surrounding the loss of the *USS Scorpion*, we are not assigning that case a value on the GeoSec scale. Figure II is a graphical overview of this scale.

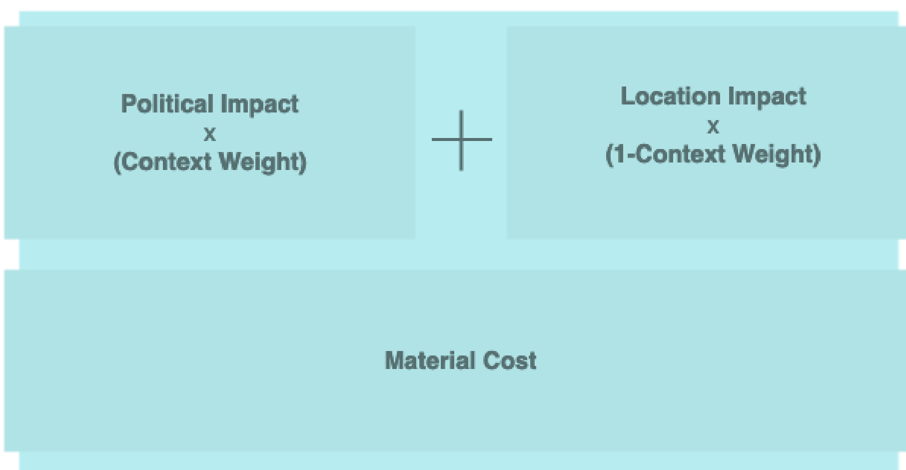

Figure II: Geopolitical Security Scale.

For instance, to evaluate the geopolitical security cost of the loss of the *USS Thresher*, we assigned numeric values to the material costs, geopolitical impact, political context, and sensitivity of the case's location. The material cost is a five — this case involved the sinking of an SSN where all those on board were lost. The political context is a two — the malfunction was significant, raising questions about the competence of the US Navy to operate nuclear submarines safely. Since a US submarine was the only vessel involved, the political weight is a one. The *Thresher* sank in domestic waters, so the location sensitivity is one. When placing these values into our GeoSec equation, we get 3.5 as the rating. The severity of the sinking raises the final value, but the lack of geopolitical threat mitigates how it is perceived.

Typology

Based on our review of the INES, we developed a scale to measure the impact on the environment and geopolitical security, dividing our catalog into four typologies based on the severity of the cost. These are:

Incidents: cases that moderately impact the environment and geopolitical security
Accidents: cases that significantly impact the environment but not geopolitical security
Events: cases that significantly impact geopolitical security but not the environment
Catastrophes: cases that significantly impact the environment and geopolitical security

A score from 0 to 3.4 designates a *moderate* cost and 3.5 to 7 designates a *significant* cost. In addition, we categorized the most severe catastrophes (level 6 or above on both scales) as Doomsday scenarios. With a rating of (3.5, 1) the sinking of the *Thresher* is considered an event. See Figure III for a graphical overview of this typology.

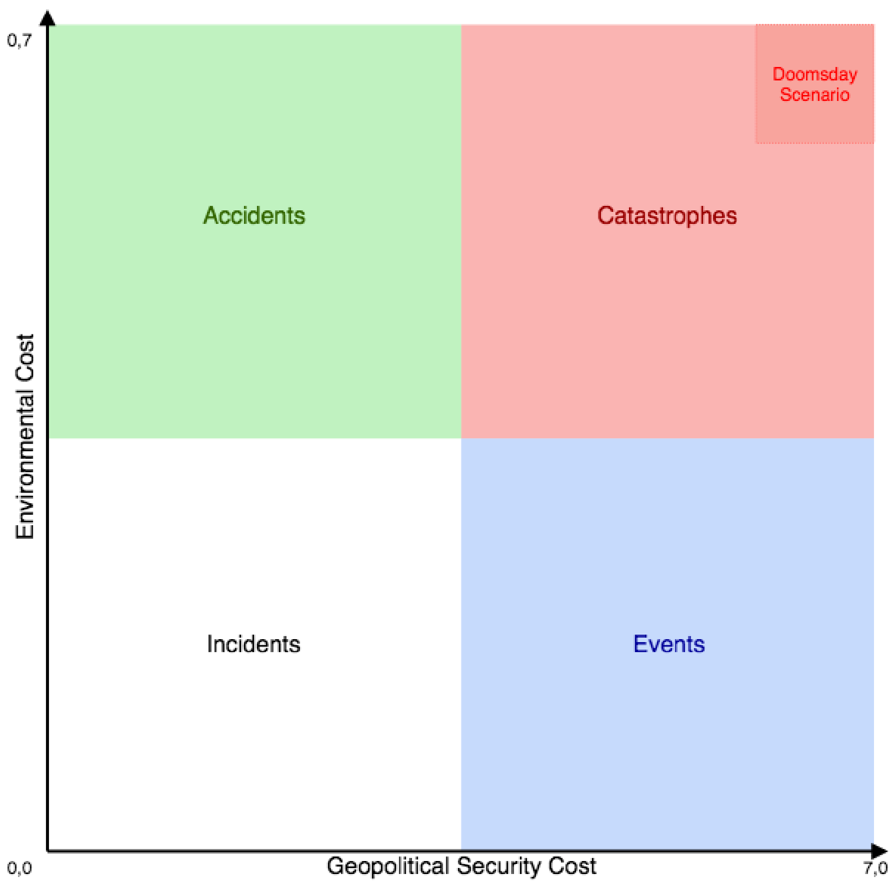

Figure III: Typology of Environmental and Geopolitical Security Costs.

Scope & Methodology

In this section, we outline the sources used in the process of building our catalog. A substantial number of cases were drawn from a single dataset covering the Cold War period, and several other cases were collected from academic articles and other scattered sources. In analyzing these cases, we relied partly on established international standards of evaluation, and partly on scales of our own formulation that were reached after extensive consultation with various experts.

Scope

We determined the **cause** of each known case when possible using 13 accident types.

- We classify **Collision** as an instance when a submarine collides with either another submarine or a ship. Our data show 112 collisions occurring between 1958 and 2019, making them the most frequent cause in the dataset of cases.
- **Equipment failure** is a mechanical malfunction or material failure leading to a case occurring. There have been 42 equipment failure cases.
- **Explosion** refers to nine cases of armaments exploding or explosions originating in various parts of the submarine.
- Our dataset shows 60 **Fires** occurring aboard submarines.
- **Fishing nets** are a common cause in the seas around the British isles and Japan, with 10 and three cases respectively.
- **Flooding** refers to the 17 cases where flooding was the leading threat to submariners' lives.
- **Grounding** is a situation where a submarine runs aground on the seabed. This case cause is frequent near ports.
- **Human error** is a situation where a mechanical failure or damage to the submarine occurs as a result of human error.
- **Propulsion accidents** were the most common failure amongst Soviet submarines. These accidents refer to malfunctions in the nuclear reactor or any connected systems.
- **Refueling accident** occurs during the process of removing and replacing nuclear fuel rods. These accidents release a large amount of radiation.
- **War scare** refers to a command and control failure that significantly increases the short-term likelihood of a major war.
- **Weather conditions** involve high winds or storm conditions impacting a submarine's operations.
- **Miscellaneous** refers to all other failures not included in the definitions above.

We also grouped failure types in five broad categories to simplify the analysis and achieve more robust regression results. The first group is **Confrontation**, which included Collisions and War scares. The second — and most numerous — category is **Equipment**, a combination of Equipment failures and Propulsion accidents. The next category is **Fire and Water,** comprising Explosions, Fires, and Floodings. **Human**-caused cases included Groundings, Human errors, and Refueling accidents; and the **Other** category encompasses the remaining case causes: Fishing nets, Miscellaneous, Weather Conditions, and Unknown.

We then recorded the **submarine class** and **owner-country**. Whenever referring to submarines from the Soviet Union, we used the demonym *Soviet* to distinguish between cases that occurred before and after 1991.

We recorded the **complement** — the number of sailors and officers — on board each submarine at the time of each case. We recorded the **armaments** — the type and number of weapons — on board each submarine. These values were initially assigned based on the class of the submarine but occasionally underwent modification according to information our team found for specific submarines.

In addition to the date of the case, we recorded the date the submarine was laid down, its launch date, commission date, and decommission date. From this we derived the age (in years) of the submarine from its launch date until the recorded case.

When sufficient information was available, we determined the latitude and longitude of the submarine's home base and the location of the case. From this we derived the distance between the submarine and its home base at the time of each case. We recorded the builder for each submarine to measure whether certain builders were tied to certain accident types.

To measure whether certain submarine classes were more likely to experience failure, we developed a Class Reliability Index by dividing the number of cases each class experienced by (1) the number of years the class was in service and (2) the number of submarines in that class. This index sought to normalize classes and determine whether any classes saw high number of cases because it was in service over a long period or a large number of units were built. More information on the process used to calculate this statistic is in the Methodology section below. Full results are available as Figure VI in Appendix I: Nuclear Submarine Data.

Sources

Of the 483 unique cases in our catalog, we derived 210 from the scholarship of Arkin & Handler (1989), a study that aggregated global submarine data from 1945 to 1988. We derived an additional 191 cases from the scholarship of Reistad, Hustveit, & Roudak (2008), a study that aggregated data on Russian nuclear submarines from 1959 to 2007. We utilized working translations of Yuri Apalkov's 2012 Russian-language research on Soviet era submarines for further data on the Soviet and Russian cases from Reistad, Hustveit and Roudak.

Numerous other resources supplemented our catalog. The scholarship of Ølgaard (1996), the scholarship of Ølgaard & Reistad (2006), and the website of the Federation of American Scientists (FAS) provided important, information on individual cases derived from the earlier studies, allowing for a more-detailed analysis of environmental and geopolitical security costs. Additional information was derived from David Ross's 2017 book *The World's Greatest Submarines*.

We attach numerous caveats to this catalog. First, due to security precautions taken by countries with nuclear submarines, it is difficult to certify that we have captured a complete or representative sample of all cases in our catalog. Our research was largely limited to English-language sources, hampering our ability to find French, Soviet and Russian, Indian, and Chinese cases. In addition, at various points of the data collection process key data were unavailable, requiring us to extrapolate based on other factors, such as submarine class. The lengthy declassification process and secrecy of nuclear submarine states meant that sensitive cases were sometimes unavailable in open source data at the time of data collection. In each of these cases, we did our best to rigorously adhere to academic standards in data collection.

Methodology

After building our catalog, we assigned values to each case based on the environmental and GeoSec scales. We did this by reviewing summaries from the data sources listed above. We took steps to ensure that each data point matched with a case from the sources. We assigned these values with a minimum of two team members checking to corroborate the decision. After assigning values, we used STATA to conduct the following analysis.

In estimating the number of nuclear weapons on board each submarine at the time of each case, we determined that (1) all SSBNs would have a fully nuclear armament of SLBMs, (2) nearly all SSNs after 1965 would have a tactical nuclear armament of SUBROCs until these weapons were decommissioned in 1989, and (3) SSNs before 1965 were unlikely to have any nuclear armaments. While these policies primarily applied to US submarines, we received guidance from retired US Navy personnel with knowledge on the subject that other countries generally adhered to the same policies as those outlined above.

To determine the relative reliability of different classes of nuclear submarines, and accounting for differences in number constructed and length of service, we developed a Class Reliability Index — also addressed in the Scope section above — whose value indicates the rate of failure for each submarine class. This index takes the number of cases for a given class and divides it by the number of submarines of that class that were launched. This quotient is further divided by the time, in years, between the launching of the first submarine in that class until the final one is decommissioned. For classes still in service, we selected an end date of April 18, 2019. Finding that experimental and other small classes were outliers at both ends of the distribution, we also present a version of this index that excludes all classes with less than three submarines launched. The higher the value in our Index, the less reliable was the nuclear submarine class.

Analysis

We found that earlier classes of submarines — such as the Soviet November (*Kit*) class — were more prone to failure. This finding is corroborated by other scholarship (Reistad, Hustveit, & Roudak 2008). Our Class Reliability Index, however, indicates that the high number of cases involving November (*Kit*) and Echo II (*Project 675*) class submarines are partly driven by the large number that were built. They receive Reliability values of 0.0705248 and 0.0564135 respectively. However, the contemporary Hotel I (*Project 658*), of which only eight submarines were built, receives a 0.2231718, the highest value for any class. In the case of the US, this trend is less pronounced, likely because the *Thresher* disaster prompted the development and implementation of the SUBSAFE program, mitigating the frequency and severity of failures in American nuclear submarines. Non-experimental US classes average 0.043635755 on our Class Faultiness Index. We hypothesize that this trend results from increasing expertise in submarine and reactor design and construction. The United States, Russian Federation, United Kingdom, and France all have decommissioned their early nuclear submarines, which may have contributed to the decline of failures after 1990. It is worth noting that this finding may result from inconsistent reporting of cases.

We also found that the vast majority of cases are located in or close to submarine bases or key straits through which many ships of all types travel regularly. These are the Straits of Gibraltar, Hormuz, Tsushima, and Juan de Fuca, each close to a submarine base. For a graphical illustration, see Figure IV. A likely explanation for this observation is that there are simply more submarines and other ships moving through the constrained waters of straits and bases, increasing the number of potential failures in that location. The most common cause — collisions — is especially likely in these high traffic areas, particularly if submarines, naval surface vessels, and civilian vessels all are operating there. The waters near the Virginia Capes — home to key US installations Naval Station Norfolk and Newport News Shipbuilding as well as a high volume of civilian shipping, including both fishing and cargo vessels — display numerous collisions. US, UK and USSR submarines all experienced collisions in the 15 km (10 mi) wide Straits of Gibraltar, the principal entrance to the Mediterranean Sea. US submarines have been involved in five collisions around the Straits of Hormuz, the entrance to the Persian Gulf. Another common failure, groundings, also are likely in these areas because of shallow waters and limited space for maneuvering.

Through linear regression analysis of the GeoSec Scale and the INES on our data, we made the following findings:

1. Collisions and human errors were associated with higher values on the GeoSec scale
2. Northern European Waters and the Asia-Pacific region were associated with higher values on the GeoSec scale
3. Equipment failures, largely attributable to the Soviet Union, were associated with higher values on the INES

Although we did not find a high correlation between Northern European Waters and the INES, we do note that the Barents Sea region, having been a dumping ground for more than a dozen nuclear submarine reactors, is potentially exposed to high environmental costs in the future. We also note that due to the limitations of our data, the regressions ran on around 290 cases of the nearly 500 in our catalog. The regression on the INES explained around 32 percent of the variation in the data, whereas the regression on the GeoSec Scale explained around 41 percent. The complete regression table can be found in Appendix I: Nuclear Submarine Data.

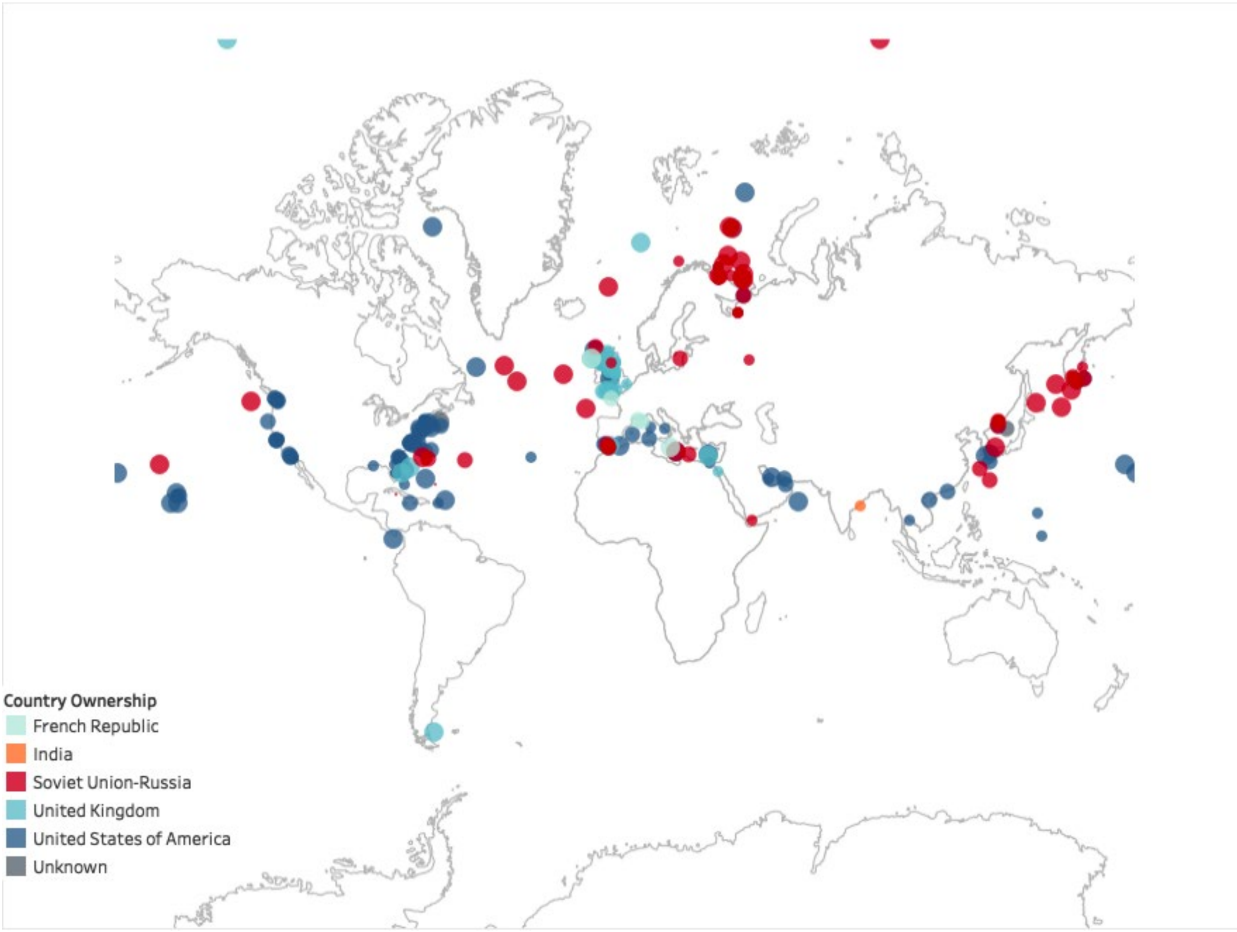

Figure IV: Map of Nuclear Submarine Failures by Country, 1958 - Present

Clusters of cases on the high seas are much rarer than those in straits and bases. Some apparent clusters — particularly in the Mediterranean and Barents Seas — result from inadequate location data. When a case was described as taking place in a general area, for example the Barents Sea, our method was to select a central location in that area and locate the case there, labelling it as having a precision of three (within 1000 nm). In our Google Earth file, this has the unintended side-effect of making it appear as if there is a cluster of cases in the middle of these seas.

However, our data does provide evidence of one cluster of cases in international waters. It is located northwest of Scotland, and south-southwest of the Faroe Islands, just outside the UK's Exclusive Economic Zone (EEZ), which extends 200 nm from the shore. This is the area where the 2009 collision of the SSBNs *HMS Vanguard* (S28) and *Le Triomphant* (S616) occurred. A report on the incident included the assessment from nuclear engineer John Large that, "navies often [use] the same 'nesting grounds.' 'Both navies want quiet areas, deep areas, roughly the same distance from their home ports. So you find these station grounds have got quite a few submarines, not only French and Royal Navy but also from Russia and the United States'" (BBC, 2009). Our data provides further evidence for this explanation, as all but one of the cases in this cluster are for missile submarines (SSBNs or SSGNs) and belong to the four navies mentioned by Large. The relatively small number of cases in our catalog means there is insufficient evidence to identify or confirm other SSBN patrol areas. Similarly, the number of cases provides insufficient degrees of freedom for a convincing statistical analysis of the frequency of cases occurring in any location.

A major limitation of our analysis is missing data — particularly location and cause — which prevented GeoSec and INES scoring of many of the Soviet/Russian cases from Reistadt, Hustveit & Roudak (2008). In their dataset the only information included was the submarines' sailnumber, class, an indication of whether the case was a propulsion accident or all other causes, a three-point scale denoting the severity of the case, and if radiation had been released. For the small number of cases where we were able to find a description in another source, we assess the geopolitical and environmental impact. Future research should seek to find the information necessary to score all cases in the catalog, including further engagement with Russian language sources. This would provide a more complete picture of the costs that resulted from Soviet nuclear submarine operations. We expect that researchers who read Russian would be able to find additional Soviet and Russian cases, particularly minor failures like groundings, that are not reported in English language sources.

Recommendations

Earlier in our report, we drew a distinction between the acute and chronic costs associated with nuclear submarine failures. We measured geopolitical security and environmental cost in our scales above and found substantial acute costs for both. However, chronic environmental costs — that is, the costs that might be incurred over time as a result of these failures — are increased by the high frequency of known groundings, collisions, fires, and propulsion accidents. In comparison, acute GeoSec costs are compounded primarily from collisions, but these cases will not necessarily have a substantial long-term impact. As a result, the GeoSec long-term effects are disparate and hard to measure. Therefore, our recommendations seek to mitigate (1) the chronic environmental costs and (2) acute GeoSec costs of nuclear submarine failures. We also seek to address the lack of quality data on nuclear submarine failures through our recommendations.

International Forum

We recommend the establishment of a multilateral forum to share best practices and build norms around the safe use of nuclear submarines and for states to decrease the likelihood of nuclear weapons-induced conflict and avoid environmental disaster from their irresponsible use. Participants in this forum should include government officials from nuclear submarine states and other states often impacted by submarine failures, NGOs, and subject-matter experts.

An important reason for establishing a multilateral forum is our finding that each country's early classes of nuclear submarine are more likely to be involved in failures. While the established nuclear submarine forces (US, RF, UK, and FR) have decommissioned their early classes, emerging nuclear submarine states are now deploying their early nuclear submarines. Sharing best practices with these and other states that develop nuclear submarines in the future may prevent them from repeating this trend.

Because we estimate that countries improve their submarine safety practices over time, as they build expertise and institutional frameworks for quality control, the existence of gaps in our catalog pose a significant problem, especially for countries with relatively-new nuclear submarine programs, like the Republic of India and People's Republic of China.

This international forum would have four key objectives: (1) the collection of quality data on nuclear submarine failures, (2) the sharing of best practices in submarine safety, (3) multilateral efforts to reclaim lost nuclear submarines, and (4) normative codes of conduct to curb the irresponsible use of nuclear submarines. Each of these objectives — addressed in detail below — would lead to improvements in the Environmental and GeoSec threat from nuclear submarine failures.

Data Collection Agency

This is the first current, comprehensive, publicly available catalog of nuclear submarine failures. For this reason, we recommend that the nuclear submarine states contribute to the organization of a professional agency, placed under the administration of the international forum, to collect and maintain records on nuclear submarine failures and inform future research.

This organization should work with established NGOs like the Bellona Foundation, as well as national governments and global institutions like the United Nations and the International Atomic Energy Agency, and collect open source data to publish in an annual report. In addition, this organization should prepare periodic threat assessments that provide an overview of broad trends and descriptions of new submarine classes, as nuclear submarine states continue to modernize their fleets.

For each nuclear submarine failure this organization tracks, it should endeavor to collect at least the following dimensions:

1. Owner country
2. Submarine class and sailnumber
3. Cause of failure
4. Armaments
5. Complement
6. Location of failure
7. Age of submarine

This component of the forum should take on a professional, bureaucratic structure to ensure the preparation of consistent, high-quality data for researchers and policymakers.

Best Practice Sharing

Our catalog clearly indicates that some nuclear submarine states have a better safety record than others, as is clear from the Class Reliability Index (See Appendix I). Additionally, the same index indicates that first-generation classes pose a greater likelihood of failure. However, a clear policy for mitigating these threats exists. After the loss of the *Thresher*, the United States' SUBSAFE program prioritized safety and resilience in nuclear submarines through improved design, regular maintenance, and strict quality control, with impressive results for US submarines reliability. The US also has a better record in terms of nuclear reactor safety. Sharing the general methods and practices behind these successes could improve the safety records of the other nuclear submarine states. This would be in the interest of all parties because safer submarines would diminish the environmental and geopolitical threat to all. Some aspects of SUBSAFE are classified, so the US is highly unlikely to disclose them. However, the aspects that could be shared without compromising US security are probably sufficient for improving safety standards for all nuclear submarine states. Further, sharing expertise gained from operational experience could help reduce the threat of failures resulting from inexperience. This is a step to building the confidence for further cooperation on larger issues.

Multilateral Reclamation Initiatives

We recommend an initiative to reclaim all nuclear reactors that have been abandoned at the bottom of the sea. There are 19 rusting, Soviet nuclear submarines and 14 nuclear reactors (that have been removed from vessels) sitting at the bottom of the Kara Sea. Experts predict that the casings around the nuclear reactors will start to fail and expose highly enriched uranium to the water sometime between 2020 and 2030. Alexander Shestakov, head of the World Wildlife Fund's Global Arctic Program, warns that the "changing ocean currents, resulting from Arctic thaws propelled by global warming, could end up carrying Soviet radioactive waste far beyond the [region]" (Bodner 2014). This recommendation seeks to address the chronic environmental cost we estimated from the catalog.

The Russian government successfully raised the *Kursk* nuclear submarine from the Barents Sea floor in 2001 (Oliver 2001). The operation lasted 15 hours and cost $80 million (McMahon 2001). A Dutch-led international consortium managed the project and, although the operation was difficult, it was executed smoothly. The Russian government stated that the *Kursk* "must be raised to avoid any danger to the environment from its nuclear reactors." This effort may be easier than lifting other fallen, nuclear submarines. The *Kursk* was positioned in shallow waters, lying just 108 meters below the surface, and 140 kilometers off the coast of Russia. Although this was an incredibly technical process, feasible due to the shallow depth of the submarine, improved technology may make it possible to recover lost submarines and nuclear reactors at deeper depths. Experts at SMIT, one of the companies responsible for recovering the *Kursk*, believe such missions are technologically possible. SMIT successfully recovered the Japanese vessel *Ehime Maru* from a depth of 610 meters in 2001 (Politi 2018). Considering how much technology has improved since 2001, SMIT does not see a barrier to reaching an additional 300 or more meters beneath the surface. Though the technology does not prohibit reclamation efforts, each expeditions would be costly.

Stewart Little, who manages the Submarine Rescue Consultancy and worked with submarines for more than 30 years in the British Royal Navy, recognizes that the missions would be feasible, but estimates the lifting of a submarine lost at deep depths beneath the surface would cost about $100 million (Politi 2018). This would make a multilateral reclamation initiative, that lifts all 19 nuclear submarines and 14 dumped nuclear reactors in the Kara Sea, a roughly $3.3 billion effort. Further, acknowledging the high costs and length of time that each raising requires, older wrecks should be prioritized, because they would leak sooner.

Although this seems like an expensive endeavor, the cost of *not* implementing such a policy is greater. As time passes, it will be more difficult to successfully raise the nuclear submarines without damaging their reactors in the process. Further, as the Bellona Foundation advocates, if the reactors are not raised soon, the casing will begin to rust through, and the downwind effects will become apparent in human and marine ecosystems.

Normative Codes of Conduct

As described above, collisions are one of the principal failures in our catalog, and they produce some of the highest values on our GeoSec scale when they occur between states whose relations are in a state of high tension. Therefore, we recommend the establishment of a Normative Code of Conduct among all nuclear submarine states to reduce the risk and severity of this type of case in the future. This would include agreement on shared standards for operations in tense situations, such as an unexpected encounter, and would set up navy-navy communications protocols to facilitate learning from failures.

There are past examples of both bilateral and multilateral codes of conduct. The 1972 Incidents at Sea agreement was one of the bilateral accords between the US and USSR that stemmed from the May 1972 Moscow summit (Lynn-Jones 1985). It may have resulted in fewer naval encounters between the member states. The agreement was nonbinding and was ignored in 1984, when the Soviet Victor I *K-314* collided with the *USS Kitty Hawk*, an aircraft carrier participating in the joint training exercise Team Spirit with the South Korean military (NHHC 2011). Lynn Jones (1985) suggests this collision was an aberration and this agreement was a major success in mitigating tensions in situations that risked turning the Cold War hot. Other limitations are that the agreement did not address Holystone-type missions and included only the United States and Soviet Union.

Another precedent, the Code for Unplanned Encounters at Sea, which stemmed from the 2014 Western Pacific Naval Symposium, is a multilateral effort to improve naval safety in the Pacific Ocean through communication. It includes more than 20 signatory countries, including the United States and People's Republic of China. While the code is non-binding, it seeks to reduce the number of "unplanned encounters" when vessels meet "casually or unexpectedly." (Rajagopalan 2014).

The form of Code of Conduct that we recommend would be an improvement over these previous efforts. By involving all nuclear submarine states, this version avoids the problem the 1972 agreement faced. This is particularly important as new nuclear submarine states are emerging and expanding their forces. Conversely, it is less inclusive than the broader 2014 code, meaning that it can be targeted specifically to nuclear submarine states and the issues that nuclear submarine operations present. Limiting the number of stakeholders to only those that are directly relevant will also make it easier to achieve agreement on common standards. Similarly, as a military-military rather than a political document, we expect the Code of Conduct to be focused on practical issues. While nuclear submarine states are unlikely to agree to prohibit tension-raising submarine intelligence-gathering missions, as they are a unique source of intelligence like SIGINT, this code could nevertheless curb the most dangerous practices.

As Arkin & Handler (1989) note, US submarines involved in Operation Holystone were armed with either nuclear-tipped ASTOR or SUBROC torpedoes. Because these operations necessarily involve high political tension and occur in sensitive locations, increasing the severity of how states perceive these cases, conducting them in the least provocative way possible is important in preventing tensions from escalating to armed conflict. As such, we recommend that nuclear submarine-operating states agree on best practices for these missions, especially to not use nuclear-armed submarines. This should be part of the Code of Conduct, although, given the sensitive nature of these operations, it would likely be a secret protocol. Our analysis is that nuclear weapons do not ease the completion of these missions, they only — unnecessarily — increase the severity of any case that occurs in the course of them.

Conclusion

Nuclear submarines are secretive, widespread, and constitute a substantial threat to the environment, as well as geopolitical security. We hope that our unique contributions — the catalog of failures, the Geopolitical Security Scale, and the Class Reliability Index — will push forward scholarship on this subject and invite researchers to make further contributions. We recommend that policymakers — especially those in countries with nuclear submarine programs — consider our recommendations seriously and take steps to improve communication and coordination to mitigate the acute and chronic costs from nuclear submarine failures.

Appendix I: Nuclear Submarine Data

We have generated a number of tables for further analysis below, which were not included in the main body of the report due to space constraints. Figure V below provides the complete result of our regressions of the INES and GeoSec Scale. The variables used in Figure V are described in further detail in the main body of the report, under the Scope & Methodology.

We adopted the following process to generate the two dependent variables used in our analysis. After constructing the catalog of nuclear submarine failures, we employed our own geopolitical security equation (GeoSec), and the INES table to assess the cost of each data point. We thoroughly reviewed and assigned appropriate values to each case, considering the material cost, political context, and location. We often utilized multiple sources to discover relevant details about the failure, in order to accurately assess the costs. After each failure with available information had been assessed using the two scales, we used STATA to conduct the analysis.

Figure V: Complete Regression Results

	GeoSec	INES
Location		
Western European waters	0	0
	(.)	(.)
Northern European waters	0.415	0.38
	(-0.305)	(-0.279)
Atlantic Ocean	0.526	1.777***
	(-0.362)	(-0.49)
Artctic waters	-0.187	0.902
	(-0.286)	(-0.796)
American waters	-0.211	0.224
	(-0.179)	(-0.195)
Pacific Ocean	0.058	0.227
	(-0.3)	(-0.325)
East Asian waters	0.377	-0.077
	(-0.267)	(-0.26)
South Asian waters	0.43	0.168
	(-0.302)	(-0.293)
Middle Eastern waters	0.043	0.204
	(-0.338)	(-0.4)
Meditarreanean Sea	0.051	-0.075
	(-0.189)	(-0.217)
N	288	290
R2	0.407	0.322

	GeoSec	INES
Decades		
1950s	0	0
	(.)	(.)
1960s	0.229	0.722*
	(-0.21)	(-0.397)
1970s	0.467**	0.952**
	(-0.228)	(-0.403)
1980s	0.559**	1.072***
	(-0.232)	(-0.397)
1990s	0.637***	0.391
	(-0.236)	(-0.367)
2000s	0.515**	0.415
	(-0.242)	(-0.39)
2010s	0.515*	1.001**
	(-0.282)	(-0.403)
Nuclear Armaments (dummy)		
Nuclear armed	-0.137	0.026
	(-0.138)	(-0.18)

	GeoSec	INES
Country of ownership		
French Republic	0	0
	(.)	(.)
Soviet Union-Russian Federation	0.876**	-0.279
	(-0.402)	(-0.327)
United Kingdom	0.143	-0.919***
	(-0.327)	(-0.301)
United States of America	0.354	-0.953***
	(-0.329)	(-0.286)
Unknown & Other	0.117	-0.605
	(-0.438)	(-0.381)
Case cause		
Confrontation	0	0
	(.)	(.)
Equipment	-0.590***	0.643***
	(-0.133)	(-0.177)
Fire and Water	-0.443***	0.413**
	(-0.165)	(-0.199)
Other	-0.475***	-0.01
	(-0.147)	(-0.166)
Human	-0.801***	-0.119
	(-0.118)	(-0.137)

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The figure below provides a tabulation of the submarine classes in our catalog, based on their rank within our Class Reliability Index. As stated in the main body of our report, the higher the value on the Index, the less reliable the nuclear submarine class.

Figure VI: Class Reliability Index Results

Country	Class	Class Reliability Index
USSR-Russian Federation	Hotel I	0.2232
USSR-Russian Federation	Mike	0.1427
USSR-Russian Federation	Papa	0.1295
USSR-Russian Federation	Yankee II	0.0842
USSR-Russian Federation	Echo I	0.0826
USSR-Russian Federation	Charlie I	0.0826
USSR-Russian Federation	November	0.0705
USSR-Russian Federation	Echo II	0.0564
USSR-Russian Federation	Alfa	0.0476
USSR-Russian Federation	Sierra I	0.042
USSR-Russian Federation	Hotel II	0.0376
USSR-Russian Federation	Delta I	0.0219
USSR-Russian Federation	Typhoon	0.0216
USSR-Russian Federation	Victor I	0.021
USSR-Russian Federation	Charlie II	0.02
USSR-Russian Federation	Delta III	0.0066
USSR-Russian Federation	Victor III	0.0063
USSR-Russian Federation	Oscar II	0.005
USSR-Russian Federation	Akula I	0.004
USSR-Russian Federation	Golf II	0.003
United States	Triton	0.4671
United States	Nautilus	0.3609
United States	Virginia	0.1263
United States	Grayback	0.0782
United States	Skate	0.0716
United States	Tullibee	0.071
United States	Lafayette	0.0613

United States	Skipjack	0.0464
United States	Ethan Allen	0.0442
United States	Thresher/Permit	0.0419
United States	Narwhal	0.0314
United States	Seawolf	0.028
United States	George Washington	0.0234
United States	Sturgeon	0.0179
United States	Los Angeles	0.0161
United States	Benjamin Franklin	0.0155
United States	Ohio	0.0153
United Kingdom	Dreadnought	0.3059
United Kingdom	Valiant	0.1792
United Kingdom	Churchill	0.0942
United Kingdom	Resolution	0.0918
United Kingdom	Astute	0.0632
United Kingdom	Vanguard	0.0277
United Kingdom	Trafalgar	0.0227
United Kingdom	Swiftsure	0.0201
French Republic	Rubis	0.0126
French Republic	Triomphant	0.01
People's Republic of China	Jin	0.02
Republic of India	Arihant	0.0343

Appendix II: Expanded Geopolitical Security Scale

Below are the guidelines that we used when determining the values that each case received on our Geopolitical Security Scale.

Figure VII: Geopolitical Security Scale Criteria

What Happens

	Material Cost	
7	- Nuclear war - Nuclear attack *Hiroshima & Nagasaki*	-Command and Control Failure
6	Intentional sinking of an SSBN (all hands lost)	
5	-Sinking of an SSBN (or diesel-powered ballistic missile sub) (some lost) -Sinking of an SSN (all hands lost) *K-129*	-Command and Control Failure -Gross negligence
4	-Sinking of an SSN (some lost)	-Negligence -Fatal Manufacturing Defect *1983 sinking of Charlie class submarine off Kamchatka*
3	-Collision -Serious damage	
2	-Discovery -Minor Collision -serious competence incident -Grounding requiring repairs in port	-Accident/Incident leading to emergency surfacing -Medium operational error
1	-Threats/Signals -Grounding	-Small Operational Error *Opening Wrong Valve and Releasing Insignificant Amount of Radioactive Water*
	No geopolitical security significance (Below scale/Level 0)	

How it is viewed

	Political Impact	**Location**
7	-Conflict -DEFCON 1 *Able Archer & CMC*	-War zone -most sensitive areas
6	-Involving foreign military vessel + high tension	-Highly sensitive areas
5	-Involving foreign vessel + high tension -high tension and suspicious circumstances *K-129*	-sensitive areas
4	-Involving foreign military vessel [Reasonable doubt of accidental nature]	-Foreign territorial waters (12 naut mi)
3	-Involving foreign vessel -Reasonable doubt of accidental nature -high tension -Repeated sabotage	-Foreign Exclusive Economic Zone (200 naut mi)
2	-Reasonable doubt of accidental nature -domestic military vessel -sabotage -significant malfunction	-international waters
1	-low tension -existing reputation for safety -domestic vessel -very minor collision	-domestic waters
	No geopolitical security significance (Below scale/Level 0)	

0.5* + 0.5*[*(weight) + *(1-weight)]

: The material cost

: The political impact

: The location

weight: The weight on the political context, dyadically based

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