Mitigating the Threat of Nuclear-Weapon Proliferation via Nuclear-Submarine Programs

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ABSTRACT
Brazil is building a nuclear-powered attack submarine, South Korea has in the past asserted its need for nuclear-powered attack submarines to deal with the threat of North Korean nuclear-armed submarine-launched ballistic missiles, and Iran has asserted more vaguely its need for naval nuclear propulsion. All three countries are non-weapon-state parties to the Nuclear Nonproliferation Treaty (NPT). Their interest in naval reactors brings with it two challenges to the NPT: (1) The safeguards “loophole” under which a country can withdraw nuclear materials from IAEA safeguards indefinitely for allowed “non-peaceful activities”; and (2) A justification for the acquisition of national uranium-enrichment facilities because the international suppliers of enrichment services have peaceful-use requirements. In fact, Brazil’s acquisition of enrichment was driven by its navy. It is argued, however, that nuclear-powered attack submarines have advantages over modern conventional attack submarines primarily in their ability to transit great distances at high speed whereas only a few countries have foreign military commitments requiring such capabilities. For defense of nearby waters against foreign navies, attack submarines are merely one component of a complex system of anti-submarine aircraft and surface vessels and underwater sensor networks. Conventional attack submarines are no less effective and much less costly than nuclear-powered attack submarines in this role.

Introduction
The “submarine loophole” in IAEA safeguards is as old as the Nuclear Nonproliferation Treaty (NPT) safeguards regime. Under the NPT, non-nuclear-weapon-state parties forgo the right to make nuclear explosive devices, and all nuclear materials in “peaceful nuclear activities” must be placed under International Atomic Energy Agency (IAEA) safeguards. But states are allowed to use nuclear materials for nonexplosive military purposes outside safeguards. The loophole was inserted into INFCIRC/153 (IAEA 1972), the basic safeguards agreement between the IAEA and non-nuclear-weapon states, in 1972 at the behest of Italy and the Netherlands. At the time, Italy was interested in building a nuclear-powered naval transport and the Netherlands was interested in nuclear-powered attack submarines (Fischer

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Perhaps because of costs, neither country built a nuclear-powered ship or submarine. In any case, the result of their interest was INFCIRC/153, paragraph 14, “Non-Application of Safeguards to Nuclear Material to Be Used in Non-Peaceful Activities”, which allows a non-nuclear-weapon state to remove nuclear materials from IAEA monitoring (“safeguards”) for any military purpose other than the “production of nuclear weapons or other nuclear explosive devices”. No non-nuclear-weapon state has yet invoked paragraph 14, but a number have expressed interest in acquiring submarines powered by nuclear reactors.

The official US interpretation of paragraph 14 when it was negotiated was that it provides for the narrowest possible circumstances under which safeguards would not be applied with respect to activities and materials employed in ‘non-proscribed military uses.’ While the [International Atomic Energy] Agency has no right to approve such uses, or to request classified information concerning them, states may exercise this discretion only after entering into arrangements with the Agency which delimit the exemption insofar as possible. Of particular significance, activities, such as enrichment or reprocessing, which simply produce or process nuclear materials employed in non-proscribed military uses are not themselves military non-proscribed uses, and must be safeguarded. (International Energy Associates Limited 1984, 134)

The first non-weapon state that is building a nuclear submarine is Brazil. Brazil is a special case, however, because, in 1991, in partnership with Argentina, it negotiated a slightly different safeguards agreement, the “Quadripartite Agreement” between the two countries, the IAEA and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC). Article 13 of this agreement, INFCIRC/435 (IAEA 1994) contains a sentence that does not appear in paragraph 14 of INFCIRC/153:  

2Jeffrey M. Kaplow cites sources to the effect that the United Kingdom was also concerned that, if the treaty banned the transfer of naval propulsion technology, that might become a barrier to such transfers from the United States to the United Kingdom (Kaplow 2017).

3The Agreement [between the state and the IAEA] should provide that if the State intends to exercise its discretion to use nuclear material which is required to be safeguarded thereunder in a nuclear activity which does not require the application of safeguards under the Agreement, the following procedures will apply:

(a) The State shall inform the Agency of the activity, making it clear:

(i) that the use of the nuclear material in a non-proscribed military activity will not be in conflict with an undertaking the State may have given and in respect of which Agency safeguards apply, that the nuclear material will be used only in a peaceful nuclear activity; and

(ii) that during the period of non-application of safeguards the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices.

(b) The Agency and the State shall make an arrangement so that, only while the nuclear material is in such an activity, the safeguards provided for in the Agreement will not be applied. The arrangement shall identify, to the extent possible, the period or circumstances during which safeguards will not be applied. In any event, the safeguards provided for in the Agreement shall again apply as soon as the nuclear material is reintroduced into a peaceful nuclear activity. The Agency shall be kept informed of the total quantity and composition of such unsafeguarded nuclear material in the State and of any exports of such material; and

(c) Each arrangement shall be made in agreement with the Agency. The Agency’s agreement shall be given as promptly as possible; it shall only relate to the temporal and procedural provisions, reporting arrangements, etc., but shall not involve any approval or classified knowledge of the military activity or relate to the use of the nuclear material therein (IAEA 1972)."
The State Party and the Agency shall make an arrangement so that, these special procedures shall apply only while the nuclear material is used for nuclear propulsion or in the operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity as agreed between the State Party and the [International Atomic Energy] Agency.

This language suggests that the IAEA and Brazil could agree on nonintrusive verification arrangements (“special procedures”) while the fissile material is not subject to standard IAEA safeguards. If this language does indeed give the IAEA additional leverage in the negotiation of verification arrangements with Brazil, an agreement with Brazil on such procedures could be a valuable precedent for verification arrangements on submarine nuclear fuel cycles with other countries.

Academics have put forward proposals for how to verify nonintrusively that the enriched uranium Brazil removes from safeguards is not diverted to make a nuclear explosive. The basic idea is as follows:

1. The enriched uranium would remain under IAEA safeguards until it is introduced into the fuel fabrication process.
2. Thereafter, if the design of the fuel is considered sensitive, IAEA inspectors would use containment-and-surveillance techniques to verify that no material leaves the fuel fabrication facility or associated storage facilities without the IAEA’s knowledge. The inspectors would check the interiors of these facilities after production campaigns to verify that no undeclared enriched uranium remains.
3. Until the fuel was loaded into a submarine’s reactor, inspectors would monitor the fuel from outside a container that would conceal its design details.
4. After the submarine fueling was complete, the inspectors would seal the pressure vessel containing the reactor core and the submarine’s refueling hatch in a manner that would reveal if they had been opened before the next inspection.
5. When spent fuel is discharged from the reactor, inspectors would be present and place it under safeguards, with the fuel again inside a sealed container if necessary.
6. Ultimately, the spent fuel would be deposited into an IAEA-safeguarded geological repository or would be reprocessed. If it were reprocessed, some sort of containment and surveillance of the process would be required until after the fuel was dissolved and the additional elements of regular IAEA safeguards (that is, in addition to containment and surveillance) could be reimposed on the recovered uranium and plutonium (Philippe 2014; Diniz Costa 2017).

Even assuming perfect seals, the interval between the refuelings of nuclear submarines is typically on the order of a decade or more, which is much longer than the weeks or months (depending on the enrichment level) within which the IAEA would consider the detection of diversion to be timely (IAEA 2002, 22). Confidence in the verification system would therefore depend on a diversion analysis that concluded that after the submarine’s reactor compartment is closed up and its reactor is powered up,

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4A decade for France, Russia and probably China. The United States and the United Kingdom are moving to lifetime cores – that is, 30–40 years – for their submarines. Recently, Russia’s lead design bureau for submarine propulsion reactors has announced that it is working on a lifetime core (RT News 2018).
clandestine diversion and recovery of the enriched uranium in the fuel would be either detectable or implausible. It could, for example, be argued that fuel could not be extracted from a submarine except at a known facility with the necessary capabilities and that activities at the small number of possible sites could be monitored by satellites. It also could be argued that, after a submarine reactor has been powered up for a significant length of time, its fuel will be radioactive and recovery of its enriched uranium would require a reprocessing plant. Clandestine arrangements could be improvised, however, and these issues can be debated.

Nuclear-Submarine Programs as Justifications for National Enrichment Programs

A second proliferation issue associated with nuclear-submarine programs is that they provide excuses for acquiring national enrichment plants – or, for a country that already has an enrichment plant, an excuse to produce highly enriched uranium (HEU, uranium enriched to 20% or more U-235). Brazil’s enrichment program, which was launched while the country was ruled by a military junta (1964–85), is still controlled by Brazil’s navy. Brazil has two enrichment plants: one that produces uranium enriched up to 20% uranium-235 for a prototype naval reactor and for research reactors, and a “commercial” plant that enriches uranium up to about 4% for Brazil’s power reactors. As of the end of 2016, although it had been three decades since Brazil mastered centrifuge technology, Brazil’s civilian enrichment plant had only enough capacity to produce about 40% of the annual enrichment requirements for its first power reactor, the 34-year-old, 600-megawatt electric (MWe) Angra-1 (INB 2016, 11). This is not a significant amount of civilian capacity, but it is a proliferation concern because, if reconfigured to produce weapon-grade (90%-enriched) uranium, it could produce enough material for a nuclear bomb in about a month. Recall that the Obama administration’s requirement for the Iran nuclear deal was that Iran’s enrichment capacity and stock of potential low-enriched uranium (LEU) feed be reduced to the point where it would take Iran at least a year to produce enough HEU for a bomb.

To prevent use of the submarine loophole to acquire HEU for a nuclear weapon, the IAEA would have to determine whether a country was truly pursuing a naval nuclear program or not. In 1978, in response to a question from Australia, IAEA Director General Sigvard Eklund stated that, if any member state invoked paragraph 14 of INFCIRC/153, the IAEA’s agreement with that state on the arrangements for removal of enriched uranium from safeguards would have to be submitted to the IAEA Board of Governors (Hibbs 2017). This would give concerned countries represented on the board an opportunity to ask pointed questions about the proposed program even if the IAEA Secretariat had not.

This paper discusses the following subjects:

(1) Historical and current interest among non-nuclear-weapon states in acquiring nuclear-powered attack submarines;

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5Assuming an annual consumption of 20 tons of 4% enriched uranium per gigawatt electric capacity.
6For 90% enriched uranium containing 25 kilograms (kg) of U-235 assuming 4.3% enriched feed and 0.4% U-235 depleted uranium.
(2) That the missions for submarines sought by countries such as Brazil and South Korea could be accomplished more cost-effectively with advanced conventional attack submarines; and

(3) The options for obtaining the necessary enriched uranium fuel if countries insist on nuclear submarines.

Interest among Non-Nuclear-Armed States in Acquiring Nuclear Submarines

Since INFCIRC/153 was introduced in 1972, five countries without nuclear weapons have with various degrees of seriousness considered acquiring nuclear-powered attack submarines. In approximate historical order, they are Brazil, Canada, Iran, Australia, and South Korea.

Brazil\(^7\)

Brazil’s navy has been interested in nuclear submarines since the end of World War II and made its first attempt to acquire gas centrifuges for uranium enrichment from Germany in 1954. In 1975, after the United States indicated that it did not have enough enrichment capacity to provide fuel for Brazil’s first nuclear reactor, which Westinghouse, a US company had supplied with fuel guarantees, Brazil signed a contract with Germany for power reactors, an enrichment plant, and a reprocessing plant.

The Netherlands, which is a partner with German utilities and the United Kingdom in controlling Urenco, a uranium enrichment combine, vetoed the transfer of centrifuge technology to Brazil, which the United States also opposed. Germany therefore delivered instead jet nozzle enrichment technology that was not subject to the Urenco agreement. Brazil’s navy found that technology impractical, however. Around 1978, therefore, it launched an indigenous centrifuge enrichment program based in part on detailed design information on the first Soviet gas centrifuges that had been published by the US Atomic Energy Commission in 1960 (Kemp 2017). This program succeeded in 1985 and, by 1988, Brazil was producing uranium enriched up to the internationally agreed threshold for weapon usability, 20% (Glaser 2006).

In 2008, Brazil signed a contract with France to build five submarines of French design in Brazil, with the fifth submarine to be powered by a Brazilian-designed reactor (Groizeleau 2017). A land-based prototype reactor, LABGENE, with a design power of 48 megawatts thermal, is currently under construction at Brazil’s Naval Technological Center in Iperó, Sao Paolo (Piovezan and Abe 2014; de Carvalho and de Oliveira Neto 2011).

Canada

Canada explored buying nuclear-powered attack submarines in 1987. Both France and the United Kingdom offered to sell versions of their attack submarines. The project was abandoned, however, because of cost, opposition from the United States, and opposition from Canadian citizens concerned about nuclear accidents in the wake of the 1986 Chernobyl accident (Burns 1987; Weston 2011; Wikipedia 2018b).

\(^7\)Unless otherwise indicated, the history summarized here is from de Sá (2015).
Iran

It is not clear that Iran’s interest in nuclear submarines is serious. Its government has publicly expressed interest in developing propulsion reactors on only two occasions – both after the United States escalated sanctions on Iran. It is therefore possible that these statements were simply signals that Iran too could escalate by producing HEU – nominally for a future propulsion reactor. Although China and France are believed to use LEU to fuel their nuclear submarines, the United States, the United Kingdom, Russia, and India have all set the unfortunate precedents of using HEU – weapon-grade in the cases of the US and UK (von Hippel 2016). In 2013, during the period of confrontation, before productive negotiations over Iran’s nuclear program began, the head of the Atomic Energy Organization of Iran (AEOI) suggested that Iran might require uranium enriched to 45–56% for a nuclear-submarine program (Reuters 2013). More recently, after the US Congress extended the Iran Sanctions Act in 2016, Iran’s president, Hassan Rouhani, ordered the head of the AEOI to come up with a plan for producing nuclear-powered ships and the fuel to propel them (AP 2016). Since Iran committed in the July 2015 nuclear deal – formally known as the Joint Comprehensive Plan of Action (JCPOA) – that its nuclear program would be “exclusively peaceful”, it must be assumed that the plan that President Rouhani called for would be implemented only if the deal collapsed or that it would be for a civilian ship, in which case the fuel would be under safeguards (Hibbs 2017).

Australia

In December 2016, Australia signed a $38 billion (AUD 50 billion) contract with France for 12 submarines that will be diesel-driven derivatives of France’s latest class of nuclear attack submarines, the Barracuda class (Ohff 2016). With the cost comparable to that of nuclear submarines, the obvious question was raised: Why not buy the nuclear version? This idea was rejected, however, in part because of the country’s lack of personnel and infrastructure to operate nuclear submarines (Scimia 2017).

South Korea

South Korea’s president, Moon Jae-in, has declared an interest in building or buying nuclear attack submarines. During US President Donald Trump’s November 2017 visit to Seoul, the two leaders reportedly discussed the possibility of South Korea purchasing a US nuclear attack submarine (Yeo 2017). Russia’s premier designer of naval propulsion reactors, OKBM Afrikantov, has made public the fact that, in 2017, it had discussions with the Korea Atomic Energy Research Institute on the possibility of providing the design of a new Russian icebreaker reactor as a “reference design” for a South Korean “maritime propulsion” reactor (Sputnik International 2018). The Russian icebreaker reactor, the RITM-200, was designed to use LEU fuel (IAEA 2016a, 180), but apparently will use HEU fuel (IPFM 2017).

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8 Russia and India are believed to use mostly 21–45% enriched uranium.
9 An email communication to the author from a South Korean government official on 9 August 2018 stated that the Moon administration was no longer actively pursuing the idea of a nuclear-powered attack submarine.
Nuclear versus Nonnuclear Submarines

Forty countries have attack submarines today, but only the five original nuclear-weapon states – China, France, Russia, the United Kingdom, and the United States – have nuclear-powered attack submarines.\(^{10}\)

There are two primary reasons: cost and mission.

**Cost**

Nuclear submarines usually cost several times more than conventional submarines. For example, in production at a rate of two per year, US *Virginia*-class attack submarines cost about $2.7 billion each (O’Rourke 2018, 3). For comparison, Germany’s Type 212 conventional submarines reportedly each cost about $0.4 billion (Roblin 2017) and France’s *Scorpène* about $0.6 billion in deals agreed to in 2005 and 2008, respectively (Defense Industry Daily 2014; Rahmat 2017). Nuclear submarines also can be quite costly to repair and decommission.

In part, the disparity in capital cost reflects the larger size of *Virginia* – about 8,000 tons displacement submerged (US Navy 2017) vs. 1,800 tons for the Type 212. Nuclear submarines generally have much larger displacements than conventional submarines, although France’s first nuclear attack submarine, *Rubis*, displaced only 2,600 tons (Wikipedia 2018c).

Two of the five countries with nuclear submarines also operate nonnuclear submarines, perhaps to save money. Only five of China’s 59 attack submarines (Office of the Secretary of Defense 2017, 24) and about half of Russia’s 41 attack submarines (D-Mitch 2018) are nuclear-powered.

**Mission**

As the name suggests, the principal mission of attack submarines is to attack other countries’ ships and submarines. For most countries, the mission is local – to defend a country’s home waters against foreign navies. For this purpose, a modern conventional submarine is adequate. Unlike the World War II diesel submarines, which were powered by batteries with very limited range when completely submerged without access to air,\(^{11}\) modern conventional submarines operating at depth are powered by fuel cells that consume liquid hydrogen and oxygen stored outside the pressure hull (van Biert et al. 2016). This makes it possible for modern conventional submarines to spend weeks on a patrol of thousands of kilometers without putting up a snorkel tube to take in air.\(^{12}\)

Under license from Germany, South Korea built nine Type 214 (KSS-2) attack submarines similar to the Type 212 shown in Figure 1 (Jeong 2018). South Korea’s interest in nuclear submarines reportedly stems from a desire to track future North Korean ballistic-missile submarines at all times (Gady 2017). But the larger number of modern conventional submarines that South Korea already has in its fleet could do as well or better.

\(^{10}\)At the end of 2017, India announced that it would build six nuclear-powered attack submarines (Business Standard 2017).

\(^{11}\)The Barbel-class submarines, the last conventional submarines built for the US Navy (1956–59) could spend 102 h (about four days) submerged while traveling at 5.6 kilometers (km) per hour for a total distance of about 600 km (Wikipedia 2018a).

\(^{12}\)A German 212-type submarine traveled 2800 km in two weeks without either surfacing or snorkeling, an average speed of about 8 km/hr (Thomas 2008).
One article, by Sukjoon Yoon, a retired captain of a South Korean destroyer, cites a study by the Korea Institute for Maritime Strategy that recommended that South Korea’s next attack submarines be nuclear-powered and capable of long-endurance underwater operations (preferably 50 percent longer than [North Korea’s] Sinp’o/Gorae-class [ballistic-missile submarines]), high speed, and improved maneuverability at various depths in the complex underwater spaces around the Korea Peninsula (Yoon 2017).

However, the Type 214’s fuel cells already give it the desired superiority over the North Korean battery-powered submarines for long-endurance, air-independent underwater operations. Also, smaller nonnuclear submarines can be more maneuverable than large nuclear submarines. On the other hand, nuclear submarines have a higher speed than conventional submarines and, as Yoon states, “can both chase enemy submarines and elude torpedo attacks on themselves”. But he also acknowledges that “only an ASW [anti-submarine-warfare]-oriented naval task force will be able to conduct effective ASW operations in the complicated underwater environment around the Korea Peninsula, in which sound distortion is commonplace”. An ASW task force would include surface ships, fixed-wing aircraft able to drop sonar sensors and to detect snorkel tubes with radar, and helicopters, as well as attack submarines.

The primary missions of US nuclear-powered attack submarines are to protect US carrier strike forces from hostile submarines and to hunt Russian and Chinese ballistic-missile submarines in their deployment areas in the Arctic Ocean and off the Asian coast of the Pacific Ocean. These tasks require traveling long distances at sustained high speeds submerged, either accompanying an aircraft carrier task force or moving to distant areas where Russian or Chinese ballistic-missile submarines are deployed, missions for which nuclear submarines are uniquely suited. France and the United States are also expanding their submarine forces and will continue to play a role in the region.

Figure 1. Cutaway of German 212A-class submarine. A diesel generates electric power for propulsion and internal use when the submarine is traveling on the surface or snorkeling. Otherwise, fuel cells use stored hydrogen and oxygen to make electrical power and water (Naval Technology n.d.).

F. VON HIPPEL
Kingdom, unlike the United States, no longer have far-flung military commitments. Each does have a single aircraft carrier, however, and the United Kingdom is planning for a second one. An additional task for the French and UK nuclear attack submarines is to assure that hostile attack submarines do not trail the sometimes single ballistic-missile submarine that each has at sea as its nuclear deterrent. A mission for Russian and Chinese nuclear attack submarines would be to attack US carrier battle groups and keep foreign nuclear attack submarines from loitering in the “bastion” areas at sea where they deploy their ballistic-missile submarines.

In short, nuclear attack submarines are superior for travel to distant deployment areas, not for tracking a neighbor’s diesel submarine in nearby waters.

**Fuel for Nuclear Submarines**

A key question a country interested in acquiring a nuclear-powered submarine must consider is where to obtain the enriched uranium for the reactor fuel? Four of the six nuclear-armed states that currently have nuclear submarines have domestic uranium mines and national uranium enrichment capabilities. Each of the other two (the United Kingdom and the United States) lacks a national enrichment facility but has access to so much excess weapon-grade uranium from the downsizing of the US Cold War nuclear weapon stockpile that it will not need to make more HEU for about another 40 years. Among the non-nuclear-weapon states currently interested in acquiring nuclear submarines, Brazil and Iran both have uranium mines and enrichment programs. This leaves South Korea, which has neither.

**Uranium Suppliers**

The need to acquire natural uranium is not a major barrier to a country interested in fueling a few nuclear-powered attack submarines. Fueling a single nuclear submarine would require mining less than 10 metric tons of natural uranium per year. A 10-year core would require less than 100 tons. Figure 2 shows that there are 11 countries that each accounted for more than 1% of global production of natural uranium in 2014. One percent was about 560 tons per year. Virtually any country has sufficient low-grade uranium ores to produce much more than 10 tons per year (Deffeyes and MacGregor 1980).

**IAEA Reporting Requirements**

Paragraph 34 of INFCIRC/153, which virtually all non-nuclear-weapon states have signed, requires the following:

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13 The United Kingdom receives both naval reactor technology and highly enriched uranium for fueling its naval reactors under the Agreement between the Government of the United Kingdom of Great Britain and Northern Ireland and the Government of the United States of America for Co-operation on the Uses of Atomic Energy for Mutual Defence Purposes of 1958. The text of the agreement, as amended through 1994, may be found at [http://www.reformation.org/text-of-1958-us-uk-mutual-defense-agreement.html](http://www.reformation.org/text-of-1958-us-uk-mutual-defense-agreement.html). The most recent amendment and 10-year renewal, which was in 2014, can be found at [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/396347/TS_2.2015_Cm_8996_Web.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/396347/TS_2.2015_Cm_8996_Web.pdf).

14 A reactor with a capacity of 150 MW thermal (MWt) operating at an average of 25% power would fission about 14 kg of U-235. If one assumes 50% of the U-235 in the fuel is fissioned, that would increase the annual U-235 requirements to about 30 kg. On the assumption that 60% of the 0.7% of U-235 in natural uranium ends up in the naval reactor fuel, about 7.5 metric tons of natural uranium would be required annually.
(a) When any material containing uranium or thorium which has not reached the stage of the nuclear fuel cycle described in subparagraph (c) below is directly or indirectly exported to a non-nuclear-weapon State, the State shall inform the Agency of its quantity, composition and destination, unless the material is exported for specifically non-nuclear purposes;

(b) When any material containing uranium or thorium which has not reached the stage of the nuclear fuel cycle described in sub-paragraph (c) below is imported, the State shall inform the Agency of its quantity and composition, unless the material is imported for specifically non-nuclear purposes; and

(c) When any nuclear material of a composition and purity suitable for fuel fabrication or for being isotopically enriched leaves the plant or the process stage in which it has been produced, or when such nuclear material, or any other nuclear material produced at a later stage in the nuclear fuel cycle, is imported into the State, the nuclear material shall become subject to the other safeguards procedures specified in [this] Agreement.

As illustrated by Iran’s imports prior to the JCPOA, however, some suppliers in Africa have ignored these requirements (Hibbs 2013; Barnes 2013). Israel reportedly simply hijacked a shipment of 200 tons of natural uranium to meet its early needs for fueling its plutonium production reactor (Davenport, Eddy, and Gillman 1978).

**Bilateral Obligations**

In addition to the IAEA’s notification requirement, many uranium exporters have bilateral peaceful-use agreements with importers that prohibit the use of their uranium for any military purpose. Australia, Canada (Canadian Nuclear Safety Comission 2017) and the United States, which together accounted for 28% of the uranium mined in
2014, require countries importing their uranium to track it and report its location to the supplier until it is placed under IAEA safeguards.¹⁵

**Enrichment Suppliers**

In contrast to the many potential suppliers of natural uranium, only three countries (China, France, Russia) plus a multinational, Urenco, dominate the enrichment market (Figure 3). In addition, there are three countries – Brazil, Iran, and Japan – with enrichment capacities too small to produce enough enriched uranium to fuel a single 1000-MWe-class nuclear power reactor (about 0.1 million separative work units [SWUs] per year) but big enough to produce enough fuel for a submarine reactor or to be a significant nuclear-weapon proliferation concern (Japan Nuclear Fuel Limited 2018).¹⁶

Brazil’s 2016 enrichment capacity of 0.02 million SWU (MSWU) could produce about 500 kg of 20% enriched uranium per year, enough to fuel a few nuclear submarines.¹⁸ Iran’s capacity of 0.005 MSWU is four to five times lower than its

![Figure 3](image)

**Figure 3.** Global enrichment capacity, 2015 (based on information from World Nuclear Association 2017).¹⁷

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¹⁵ Australia describes its bilateral administrative agreements (AAs) with 36 countries as follows: “The AAs are drafted in accordance with IAEA safeguards and to avoid duplication, the AAs use the IAEA’s accounting system, but include set procedures by which material included under the corresponding agreement can be identified (country of origin may be traced) . . . Once [Australian obligated nuclear material] has been converted into a usable form, it becomes subject to IAEA safeguards and [IAEA] inspection activities become responsible for ensuring that nuclear material is used for peaceful purposes” (Joint Standing Committee on Treaties 2006, 51–53).

¹⁶ Argentina operated its Pilcaniyeu gaseous-diffusion enrichment plant, which has a reported capacity of 0.02 million SWU/yr, from 1983 to 1989. In 2015, it announced implausible plans with no timetable to upgrade it to a capacity of 3 million SWU/yr. In 2017, based on its production of 4.3% enriched uranium, Brazil produced about 0.025 million SWU at its commercial enrichment plant (INB 2018, 27). Iran is limited by the Joint Comprehensive Plan of Action till 2025 to operating 5060 IR-1 centrifuges (about 0.005 million SWU capacity); Japan’s capacity is about 0.075 million SWU/yr.

¹⁷ The figure includes Brazil, India, Iran, and Japan in “other” with a total capacity of 0.045 million SWU/yr. That calculation assumed the following capacities: Argentina (although its plant is not currently operating) 0.02; Brazil, 0.02; Iran, 0.005 and Japan 0.075 million SWU.

¹⁸ Assuming 50% fission of the U-235, this much fuel per year could produce an average of 140 MWt. This is approximately the peak output of an attack submarine reactor, but the average output may only be 20% as large.
capacity prior to the JCPOA but is expected to increase to more than 0.1 MSWU by around 2030 as that deal expires (AEOI 2014).\textsuperscript{19}

Thus, South Korea is the only non-nuclear-weapon state currently interested in naval reactors that does not have an enrichment plant. It therefore would have to either build its own enrichment plant or buy enrichment services.

**Building an Enrichment Plant**

The NPT does not explicitly prohibit a country from acquiring an enrichment plant. That is, in fact, one of the most important weaknesses of the nonproliferation regime. South Korea is technically advanced and, if it were not concerned about the plant’s economic competitiveness, could, within a few years, build enrichment capacity sufficient to support at least a few submarines. The United States is South Korea’s main security and nuclear energy partner, however, and South Korea therefore is sensitive to US views on the matter.

Since at least the 1992 Joint Declaration of the Denuclearization of the Korean Peninsula, the United States has opposed South Korea building either an enrichment or reprocessing plant because that would undermine the objective of eliminating such facilities in North Korea. The renewal of the US agreement for peaceful nuclear cooperation with South Korea, which was scheduled to expire in 2014, was delayed by more than a year because of the need to resolve disagreements over South Korea’s interest in enrichment and reprocessing (Choe 2011). Ultimately, the United States did not agree to South Korea acquiring either type of facility but left open the possibility for the future. The agreement therefore says:

> Any facility designed or used primarily for uranium enrichment, reprocessing of nuclear fuel, heavy water production, or fabrication of nuclear fuel containing plutonium, and any part or group of parts essential to the operation of such a facility may be transferred under this Agreement if provided for by an amendment to this Agreement, or may be transferred under a separate agreement between the Parties. (South Korean-US Nuclear Agreement 2015)

A provision later in the agreement specifies that, if South Korea enriches uranium under the agreement, it must keep the enrichment level below 20%. The United States cannot control what South Korea might do with uranium and technology provided by other countries but, once again, South Korea would be attentive to the views of its principal military ally.

The Trump administration’s views may be different from its predecessors’ on the desirability of South Korea acquiring an enrichment plant, and South Korea has a new president whose views also may be different from those of his predecessor. A revised agreement for nuclear cooperation would, however, take some time to negotiate and also would have to be submitted to Congress, which could disapprove all or part of it within 90 days of continuous session (Nuclear Nonproliferation Act of 1978 1978).

\textsuperscript{19}The primary justification for Iran’s enrichment program has been to supply the Bushehr power reactor. Assuming 27 metric tons per year of 3.5% enriched uranium to fuel the reactor, the enrichment work required to fuel the Bushehr I reactor is approximately 100,000 SWU/yr.
The Nuclear Suppliers Group (NSG) guidelines discourage the spread of national enrichment plants – especially if they could be used to produce highly enriched uranium:

If enrichment or reprocessing facilities, equipment or technology are to be transferred, suppliers should encourage recipients to accept, as an alternative to national plants, supplier involvement and/or other appropriate multinational participation in resulting facilities. Suppliers should also promote international (including IAEA) activities concerned with multinational regional fuel cycle centres …

For a transfer of an enrichment facility, or equipment or technology therefor, suppliers should seek a legally-binding undertaking from the recipient State that neither the transferred facility, nor any facility incorporating such equipment or based on such technology, will be modified or operated for the production of greater than 20% enriched uranium. Suppliers should seek to design and construct such an enrichment facility or equipment therefor so as to preclude, to the greatest extent practicable, the possibility of production of greater than 20% enriched uranium. (IAEA 2016b, 3, 4)

The guidelines also highlight the NSG requirement that exports not be used for military purposes, advising that suppliers

should consult with potential recipients to ensure that enrichment and reprocessing facilities, equipment and technology are intended for peaceful purposes only … (IAEA 2016b, 3).

Argentina, Brazil, China, France, Germany, Japan, Netherlands, Russia, the United Kingdom and the United States are all members of the NSG.

**Provision of Enriched Uranium**

With regard to the provision of enriched uranium, the Chinese, French, Russian, and US agreements for cooperation with South Korea on the peaceful uses of nuclear energy require that materials and technology transferred to South Korea be exclusively for peaceful use (South Korean-Chinese Nuclear Agreement 1995; French-South Korean Nuclear Agreement 1982; South Korean-Russian Nuclear Agreement 1999; South Korean-US Nuclear Agreement 2015). Reportedly, the same conditions have been applied by the Urenco countries (Carlson 2017).

**Conclusions**

The current nonproliferation regime allows countries to acquire or construct nuclear-powered submarines or ships for military purposes. However, it discourages other countries from providing enriched uranium for nonpeaceful activities. This leaves a country interested in adding nuclear-powered vessels to its navy with the option of mining its own uranium and building its own enrichment plant. This is, in fact, what Brazil, the first non-nuclear-armed state to embark on building a nuclear submarine, is doing. Iran, which has expressed an interest in building nuclear-powered vessels, already has uranium mines and an enrichment plant and could do the same.

South Korea, if it proceeds, would be the first country interested in acquiring a nuclear submarine that does not already have an enrichment capacity. It has expressed an interest
in acquiring such a capacity in the past, but the United States has discouraged that interest out of concern that it would make it more difficult to persuade North Korea to give up its enrichment program. US opposition to South Korea building an enrichment plant is also consistent with the policy of the Nuclear Suppliers Group to discourage the proliferation of national enrichment plants. Fortunately, from a nonproliferation perspective, the military case for South Korea acquiring nuclear-powered instead of advanced conventional submarines appears weak.

The acquisition of national enrichment plants by non-nuclear-weapon states to fuel naval reactors remains a challenge to the nonproliferation regime, however. If it becomes possible to end the production of enriched uranium for nuclear weapons in a Fissile Material Cutoff Treaty, the retention of national enrichment plants by the nuclear-weapon states to provide naval reactor fuel will become a major weakness to the nuclear-disarmament program as well.

In the case of the provision of enriched uranium for civilian purposes, the alternative to the proliferation of national enrichment plants has been for a few countries to become the suppliers of enrichment services to the rest of the 30 countries with nuclear power plants. This has worked because the economies of scale have made contracting for enrichment services less costly than national enrichment facilities for all but the countries with the largest reactor fleets. This arrangement could be made less discriminatory by turning the Chinese, French and Russian enrichment combines into multinationals, building on the model that Urenco has provided.

Could there be multinational arrangements for supplying enriched uranium for naval reactors? The United States already supplies the United Kingdom with enriched uranium for its nuclear submarines. France’s enrichment plant uses centrifuges made by a joint subsidiary with Urenco but produces fuel for France’s submarines as well as for its power reactors. If South Korea could not be persuaded to abandon its nuclear-submarine project, would it be better for the nonproliferation regime if South Korea’s principal security partner, the United States, supplied it with enriched uranium for its naval reactors than for South Korea to acquire its own enrichment plant? Would it make sense for Brazil to form a multinational enrichment partnership with Argentina that would supply enriched uranium both for their power plants and for Brazil’s nuclear submarines? The case for providing multinational enrichment services for naval propulsion programs is not obvious but perhaps it is worth considering as an option.

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