Viewpoint

Ending the Production of Highly Enriched Uranium for Naval Reactors

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In December 1993, the U.N. General Assembly adopted, without dissent, a resolution calling for the negotiation of a fissile material production cut-off treaty (FMCT). In this resolution, the FMCT was described as a "non-discriminatory, multilateral and international and effectively verifiable treaty banning the production of fissile material (highly enriched uranium or plutonium) for nuclear weapons or other nuclear explosive devices."[2] The 2000 Review Conference of the parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) called for the completion of negotiations on the FMCT within five years.[3] The FMCT would serve as a key building block in the nuclear weapons nonproliferation and disarmament regime by putting a cap on the stocks of fissile material available for nuclear weapons. These stocks could then be reduced by verified, irreversible disposition.

However, the FMCT, as currently envisioned, has a potential loophole because it would permit the continued production of weapon-usable fissile material for use in military reactors. It would therefore leave open a potential diversion route whereby countries could produce or acquire weapon-usable fissile material and remove it from international safeguards under the pretext that it was to be used in military reactor fuel. However, they could then use some or all of it to make nuclear weapons. Investigations by the International Atomic Energy Agency (IAEA) to verify the declared use of the material could easily be thwarted by claims of military secrecy concerning the design of reactor fuel and reactor operations. Brazil may have planned such a subterfuge during the 1980s when its navy developed the capability to produce highly enriched uranium (HEU), nominally for submarine reactors, but probably for a nuclear weapon option as well.[4]

Currently, the United States and the United Kingdom use "weapon-grade" uranium containing more than 93 percent uranium-235 (U-235) to fuel their naval reactors, and Russia uses HEU containing more than the 20 percent U-235, defined by international agreement to be the threshold for direct weapons-usability.[5] France has fueled some of its submarines with HEU but has decided to shift to low-enriched uranium (LEU) containing less than 20 percent U-235. China reportedly uses LEU fuel. In the past, both the United States and the Soviet Union built HEU-fueled nuclear reactors for other military purposes.[6]

In this essay, we propose that the ban in the FMCT be extended to the production of weapon-usable fissile material for *any* military use, including naval reactors. Those countries currently using HEU in military reactors could fuel their reactors during a several-decades-long transition period with HEU recovered from excess nuclear warheads. Follow-on generations of nuclear-powered submarines and ships could be designed to use LEU. Any countries joining the nuclear navy "club" would design their propulsion reactors to use LEU—as India and Brazil currently plan to do.[7] There appears to be no significant interest in other types of military nuclear reactors today. However, if military interest were to revive, LEU fuel could be used in land-based reactors just as in naval reactors. Our hope would be that orbiting military reactors could be banned.[8]

An additional reason to shift naval reactors from HEU to LEU would be to reduce the danger of theft of HEU fuel. Theft has been a serious issue since 1993, when reports began of thefts of small quantities of Russian submarine fuel containing HEU.[9] For a nation or terrorist group interested in a nuclear weapon "option," it is far easier to produce a reliable nuclear weapon from HEU than from plutonium.[10]

THE NPT LOOPHOLE

There is already a military reactor loophole in the NPT. Article III.1 provides that:

> Each non-nuclear weapon state party to the Treaty undertakes to accept safeguards, as set forth in an agreement to be negotiated and concluded with the International Atomic Energy Agency…for the exclusive purpose of verification of the fulfillment of its obligations assumed under this Treaty with a view to

> preventing diversion…from peaceful uses to nuclear weapons or other explosive devices.

By omission, the NPT therefore allows withdrawal of fissile material from international safeguards for use in military reactor fuel. The historical reason was an interest in naval nuclear propulsion among some non-nuclear weapon states at the time the NPT was negotiated.[11] This loophole has been a concern within the nonproliferation community,[12] and various approaches to dealing with it have been proposed.[13]

The IAEA, which has the task of verifying that non-weapon state parties to the NPT are not diverting fissile materials to weapons use, has already anticipated the possibility that a country might request the withdrawal of some of its fissile materials from under international safeguards. Its model safeguards agreement for non-weapons states contains a section titled "Non-application of safeguards to nuclear material to be used in non-peaceful activities." The only explicit requirement on a state withdrawing fissile materials from international safeguards is that it undertake the political commitment:

> [t]hat 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 [and that] safeguards…shall again apply as soon as the nuclear material is reintroduced into a peaceful nuclear activity. [14]

The IAEA seems to have conceded any leverage in negotiations over verification of non-weapon use by agreeing in the same section to be barred from acquiring any "classified knowledge of the military activity or related to the use of the nuclear material therein."

Most countries that operate nuclear navies do not plan to *ever* reintroduce into peaceful nuclear activity the fissile material remaining in spent naval reactor fuel. U.S., British, and French spent naval reactor fuel is being stored pending the availability of final disposal in a geological repository. It will therefore remain indefinitely in a military form whose design is considered highly classified. Currently, Russia is reprocessing spent naval reactor fuel in order to recycle the recovered uranium in power reactor fuel. However, it may well discontinue doing so.

Thus the NPT appears to allow any non-nuclear weapon state to launch a military nuclear reactor pro-

gram and fuel it with weapon-usable uranium removed from under international safeguards, while blocking any effective international effort to verify that no material has been diverted to weapons use. The FMCT, as currently conceived, would propagate the same problem to the weapons states as well (see Figure 1).[15]

It would not be possible to close completely the NPT loophole by preventing its duplication in the FMCT. Countries could still shift fissile material produced before the FMCT came into force from safeguarded civil uses to unsafeguarded military uses. Existing civilian stocks of HEU are small (about 20 tons[16]) in comparison with military stocks, however, and could be reduced further as HEU-fueled research reactors are either converted to LEU or shut down. Although hundreds of tons of excess military HEU are being transferred by Russia and the United States to civilian use, virtually all of this HEU is being blended down to LEU for use in power-reactor fuel.

The United States has an explicit policy "to seek to minimize the civil use of highly enriched uranium" and to "eliminate where possible the accumulation of highly enriched uranium or plutonium."[17] However, to our knowledge, the only time that the possibility of shifting naval reactors to LEU has been raised officially within

the U.S. government was in 1994 when the Congress requested a study of the feasibility of converting U.S. naval reactors to LEU fuel.[18] The resulting report by the Office of Naval Nuclear Propulsion (ONNP) flatly rejected LEU: "The use of LEU for cores in the US nuclear powered warships offers no technical advantage to the Navy, provides no significant nonproliferation advantage, and is detrimental from environmental and cost perspectives."[19]

Nevertheless, because of the availability of a huge supply of HEU from weapons made excess by the end of the Cold War, the U.S. government has not produced HEU for naval reactor fuel or any other purpose since 1991 and has no plans to do so in the foreseeable future.[20] Russia is in a similar situation.[21] The United Kingdom is as well because it depends upon the United States for its HEU supply.[22]

Therefore, if the United States, United Kingdom, and Russia decided to join the other nations already using LEU fuel in their naval reactors in a formal commitment not to produce HEU for military reactors, their large stocks of excess HEU would allow them to make a several-decades-long transition to LEU fuel. In the longer term, if disarmament reduces military stockpiles of fissile materials to much lower levels, an FMCT ban on
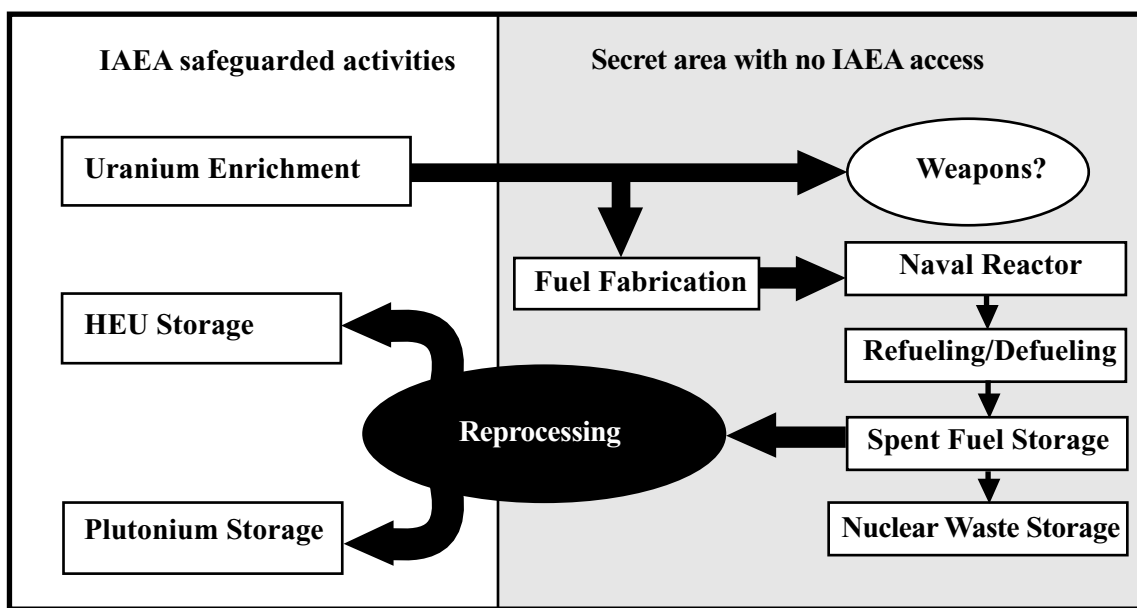

IAEA safeguarded activities

Secret area with no IAEA access

Uranium Enrichment

Weapons?

Fuel Fabrication

Naval Reactor

HEU Storage

Refueling/Defueling

Reprocessing

Spent Fuel Storage

Plutonium Storage

Nuclear Waste Storage

Figure 1: IAEA Safeguards on Naval Fuel Cycles under Current Draft of the FMCT

HEU production for any military purpose would become an invaluable barrier to clandestine nuclear weapon production by nuclear weapon states as well as proliferant states.

NAVAL REACTOR FUEL ENRICHMENT AND CONSUMPTION

The world's nuclear fleet currently contains about 170 submarines and ships, including six icebreakers and an Arctic transport operated by Russia. This is about half the size of the nuclear-powered fleet deployed at the end of the Cold War (see Figure 2 and Table 1).

All nuclear submarines, except those built by Russia, are powered by single reactors; most Russian submarines have two reactors. The United States, Russia, and France also have nuclear-powered surface ships in their fleets, most of which are powered by two reactors each. Although, in the past, both the United States and Soviet Union experimented with liquid-metal-cooled reactors, all naval reactors in use today are of the pressurized-

water reactor (PWR) type. Publicly reported enrichments of naval reactor fuel vary from weapon-grade (93 percent U-235 and above) for the United States[23] and Britain, to five percent U-235 for China (see Table 2).

The United States

All U.S. submarines are nuclear-powered. Nine out of its 12 aircraft carriers are nuclear-powered and two additional nuclear-powered aircraft carriers are under construction. The United States has abandoned nuclear power for other surface ships.[24] There has been a steady increase in core lifetime, from the original core of the first U.S. nuclear-powered submarine, the *Nautilus*, which lasted for about two years, to the cores for the new Virginia-class attack submarines, which are designed to last for the submarine's entire 33-year design life.[25] Current cores in the Nimitz-class aircraft carrier, Los Angeles-class attack submarine, and Ohio-class ballistic missile submarine last an average of about 20 years. Efforts are continuing to develop lifetime cores for new aircraft carriers (50 years) and the next-generation ballistic missile submarine (40 years).[26]

Figure 2: Evolution of the World's Nuclear Submarine Fleets
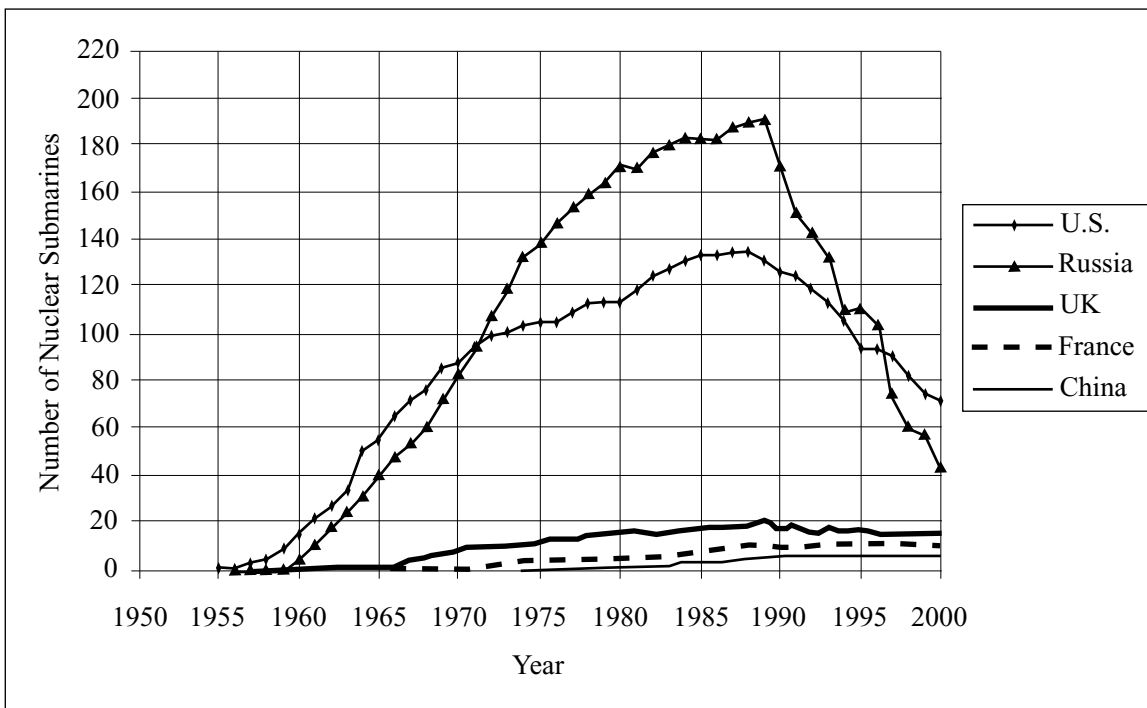
Sources: Oleg Bukharin and Joshua Handler, "Russian Nuclear-powered Submarine Decommissioning," *Science & Global Security* 5 (1995), p. 248; BAE Systems, *Evolution of the United States Navy Submarine Forces, 1900-2000,* December 1, 1999; *Jane's Fighting Ships 1996-1997* (London: Jane's Yearbooks, 1997); A.D. Baker III, *The Naval Institute Guide to Combat Fleets of the World 2000-2001* (Annapolis, MD: Naval Institute Press, 2000), pp. 918-925.

Table 1: World Nuclear-Powered Vessels, 2000

Countries	Attack and cruise missile submarines (SSN & SSGN)		Ballistic missile submarines (SSBN)		Surface vessels	
United States	Class	Number + under construction	Class	Number + under construction	Class	Number
	Virginia	0+4			**Aircraft Carriers**	
	Seawolf	2+1	Ohio	18	CVN-77	0+0
	Los Angeles	51			Nimitz	8+1
	Sturgeon	2			Enterprise	1
	Total	**55+5**		**18**		**9+1**
Russia	Severodvinsk	0+1	Borey	0+1	**Missile Cruisers**	
	Akula-I	7+1	Delta-IV	7	Kirov	3
	Akula-II	1+2	Delta-III	5	**Ice breakers** (not military)	
	Sierra-II	2	Typhoon	4	Taimyr	2
	Sierra-I	1			Sevmorput (Arctic transport)	1
	Victor-III	8			Arktika	4+1
	Oscar SSGN	9+2				
	Total	**28+6**		**16+1**		**10+1**
United Kingdom	Astute	0+1	Vanguard	4		
	Trafalgar	7				
	Swiftsure	5				
	Total	**12+1**		**4+0**		
France	Rubis	6	Triomphant	2+1	**Aircraft carrier**	
			Redoutable	2	Charles de Gaulle	0+1
	Total	**6**		**4+1**		
China	Project 093	0+1	Project 094	0+1		
	Han	5	Xia	1		
	Total	**5+1**		**1+1**		
Global Totals		**106+13**		**43+3**		**19+3**

Table 2: Key Characteristics of Commissioned Nuclear-Powered Submarines and Ships (2000)

Country	Reactor type and model[a]	Thermal power, shaft horsepower (shp) per reactor[b]	Fuel enrichment (percent U-235)	Reactors per vessel	Vessel type and name of first in class[c]	Displacement (tons)[d]	Years built
United States	PWR/S6G	130 MW, 35,000 shp	97.3%	1	SSN-688 Los Angeles	6,927	1985-1996
	PWR/S8G	220 MW, 60,000 shp	97.3%	1	SSBN-726~743 Ohio	18,750	1974-1997
	PWR/S9G	40,000 shp		1	SSN-774 Virginia	7,700	1998-
	PWR/S6W	220 MW, 57,000 shp	97.3%	1	SSN-21 Seawolf	9,137	1989-
	PWR/A2W	120 MW, 35,000 shp	97.3%	8	CVN-65 Enterprise	93,970 full	1958-1961
	PWR/A4W	140,000 shp	97.3%	2	CVN-68~77 Nimitz	91,487-102,000	1968-
	PWR/A5W	140,000 shp	97.3%	2	CVN-78, CVNX		being built
Russia	PWR/VM-4, OK-300	75 MW, 31,000 shp	21%	2	SSN-Victor III	6,300	1978-1986
	PWR/VM-4-2, OK-700A	90 MW, 30,000 shp	21%	2	SSBN-Delta III SSBN-Delta IV	13,250 13,500	1975-1981 1981-1992
	PWR/OK-650a	190 MW, 47,5000 shp	21%-45%	1	SSN-Sierra-1	8,100	1982-1987
	PWR/VM-5, OK-650W	190 MW, 50,000 shp	21%-45%	2	SSBN-Typhoon	26,500	1978-1989
	PWR/VM-5, OK-650B	190 MW, 50,000 shp	21%-45%	2 1 1 2	SSGN-Oscar I/II SSN-Akula SSN-Sierra-II SSBN-Borey	17,000/18,300 9,100 9,100 17,000	1977-1994 1982-1994 1989-1993 being built
	PWR/OK-650KPM	200 MW		1	SSN/SSGN-Severodvinsk	11,800	1993-
	PWR/KN-3	150 MW	55%~90%	2	CGN-Kirov cruiser	24,300 full	1974-1995
	PWR/KLT-40	135 MW	Up to 90%	2	Arktika icebreaker	23,460 full	1972-1997
	PWR/KLT-40	135 MW	Up to 90%	1 1	Sevmorput auxiliary ship Taimyr icebreaker	 23,500 full	-1988 1987-1989
United Kingdom	PWR//PWR-1	70 MW, 15,000 shp	97.3%	1	SSN-Trafalgar	5,208	1978-1991
	PWR//PWR-2	130 MW, 27,500 shp	97.3%	1	SSBN-Vanguard	15,900	1986-1999
France	PWR/SNLE	16,000 shp	Up to 90%	1	SSBN-Le L'Indomptable	8,920	1969-1984
	PWR/SNLE-NG /K-15	150 MW, 41,500 shp	Up to 90%	1 2	SSBN-Le Triomphant CVN-Charles de Gaulle	14,335 40,550 full	1986-2007 1994-1999
	PWR/SNA72	48 MW, 9,500 shp	7%	1	SSN-Le Rubis	2,670	1976-1973
China	PWR	58 MW	3%~5%	1	SSBN-Xia	6,500	1978-1987
	PWR	58 MW	3%~5%	1	SSN-Han	5,550	1967-1990
India	PWR	about 190 MW	20%				planned

a. PWR = pressurized water reactor; b. 1 shaft horsepower = 0.746 kilowatts; c. SSBN= nuclear-powered ballistic-missile submarine; SSGN= nuclear-powered cruise-missile submarine SSN= nuclear-powered attack submarine; CGN= nuclear-powered cruiser; CVN= nuclear-powered aircraft carrier; d. long ton = 1,016 kilograms, submerged displacement for submarines.

Sources: Thomas Nilsen, Igor Kudrik and Aleksandr Nikitin, *Nuclear-powered vessels, The Russian Northern Fleet,* Bellona Foundation, <http://www.bellona.no/e/russia/nfl>; *Jane's Fighting Ships 1997-1998;* A.D. Baker III, *The Naval Institute Guide to Combat Fleets of the World 2000-2001* (Annapolis, MD: Naval Institute Press, 2000); Viking Olver Eriksen, *Sunken Nuclear Submarines: A Threat to the Environment?* (Oslo: Norwegian University Press, 1990); USA Military Analysis network website, <http://www.fas.org/man/dod-101/sys/ship/eng/index.html>; Albright, Berkhout and Walker, *Plutonium and Highly Enriched Uranium 1996;* Mark Gorwitz, *The Indian SSN Project: An Open Literature Analysis,* December 1996, <http://www.fas.org/nuke/guide/india/sub/ssn/part01.htm>; BAE Systems, *Evolution of the United States Navy Submarine Forces, 1900 to 2000,* December 1, 1999.

During the 1980s, the U.S. Navy ordered four to five metric tons of U-235 in HEU per year.[27] However, the size of the US nuclear submarine fleet has declined from 139 in 1990 to 73 (18 ballistic missile submarines and 55 attack submarines) in 2000 and the number of naval propulsion reactors has decreased to 97. Given that improved uranium efficiency is likely to have contributed to the greater longevity of the new reactors, the annual requirement for American nuclear submarines today is probably very roughly two tons U-235.[28] For a nominal core life of 20 years, this would imply an average of five cores per year containing about 400 kilograms (kg) of U-235 each.

A number of authors estimate that the total stockpile of U-235 in U.S. HEU at the end of the Cold War was approximately 600 tons.[29] This total has since been reduced by 174 tons of HEU (almost all lower than weapon-grade) being declared excess to military needs. However, much of the weapon-grade uranium recovered from excess nuclear weapons is being placed in a reserve for future naval reactor use.[30] As a result, the United States has enough HEU stockpiled to fuel its nuclear ships at the current rate for "many decades."[31]

Russia

Most of Russia's nuclear submarines, four of its six nuclear-powered icebreakers, and its three nuclear-powered cruisers each have two reactors (see Table 2). The fuel used in Russia's first two generations of naval reactors was 21-percent enriched but some of the fuel in third-generation reactors is as much as 45-percent enriched. The enrichment of icebreaker fuel is up to 90 percent. The amount of U-235 in each reactor core has increased from 50 kg in the first generation to 70 kg in the second generation, to 115 kg in the third generation as the power of the reactors increased.[32] The reactors require refueling every seven to 10 years.[33]

The Soviet Union had about 197 nuclear submarines in 1990. Russia inherited this large fleet but did not need and could not support so many nuclear vessels. As a result, by 2000, Russia had reduced its nuclear fleet to about 44 operational nuclear submarines (19 attack submarines, 16 ballistic missile submarines, and nine cruise missile submarines), three missile cruisers, six icebreakers, and one Arctic transport with a total of about 91 reactors (see Table 1). The missile cruisers are likely to be reduced soon, and the number of nuclear submarines

is expected to decline still further.[34] Assuming an average core life of eight years and an initial charge of about 115 kg U-235, the average annual requirement of U-235 of the Russian nuclear fleet would be about 1.3 tons. This is less than the estimate for the U.S. Navy, but, except for the icebreakers, Russia's nuclear ships spend relatively little time at sea.

Very roughly, Russia has 1,000 tons of weapon-grade HEU in its stockpile.[35] Although 500 tons are committed for blend-down to LEU and sale to the United States, Russia's remaining excess is likely to remain sufficient to meet its naval reactor requirements for many decades.

United Kingdom

British submarines are fueled with weapon-grade uranium.[36] The refueling interval for the new Vanguard-class ballistic missile submarine is anticipated to be eight to nine years.[37] The reactor core for the new generation Astute-class attack submarine is designed to last the 25 to 30 year design-life of the submarines.[38]

According to current plans, Britain is expected to deploy fewer than its current 16 nuclear submarines in 2010. We assume that British nuclear submarines use about half as much U-235 per year as U.S. submarines because of their smaller size, lower power, and the shorter distances traveled. The fuel requirements of the British nuclear fleet would then be about 0.16 tons of U-235 per year. Britain has declared its total stockpile of HEU as 21.9 tons.[39] As with the United States and Russia, post-Cold War downsizing of the U.K. nuclear stockpile has made a significant fraction of this HEU available for naval reactor fuel. In case of need, Britain could also continue to buy HEU from the much larger U.S. stockpile.

France

Different classes and generations of French submarines use different fuel enrichments. The first three of France's first-generation (1970s) Redoutable-class ballistic missile submarines were reportedly fueled by LEU. However, the fourth and fifth ballistic missile submarines in this series were shifted to HEU. France's first generation of attack submarines, the Rubis class, and a second generation of ballistic missile submarines, the Triomphante class, returned to LEU fuel (see below). In the wake of France's decision to end the production

of HEU, its intention appears to be to stay with LEU enriched to less than 10 percent.[40]

Based on its current plans, in 2015 France is expected to have the same number of nuclear-powered submarines as it has in January 2001: four ballistic-missile submarines and six attack submarines—plus one nuclear-powered aircraft carrier.[41]

CHINA

Chinese naval reactors reportedly use LEU fuel enriched to five percent.[42] In 2010, China is expected to deploy one or two ballistic missile nuclear submarines and five or six nuclear-powered attack submarines.[43]

HEU VS. LEU IN NAVAL REACTOR FUEL

The details of naval reactor design are closely held military secrets. However, France has published diagrams of the internal layout of the LEU-fueled Rubis-class attack submarine[44] and of the prototype of the reactor that powers it (see Figure 3a). The Norwegian government has also made public some basic data it received about the HEU-fueled reactor of a compact Russian icebreaker. Finally, a considerable amount of experience has been accumulated in converting compact research reactors from HEU to LEU.

Submarine reactors must be compact, both because of the limited space available on submarines and because of weight constraints. The reactors and their associated coolant loop are surrounded by massive quantities of material to shield crew members from the penetrating neutron and gamma radiation emitted by the core and from the primary coolant (see Figure 3b).[45]

There is also an incentive to pack as much U-235 as possible into naval-reactor cores in order to maximize the time between refuelings. Refueling a nuclear submarine is costly and time consuming. For U.S. and Russian submarines, it involves cutting through the submarine hull and removing the core. France's Rubis-class submarines, however, have large hatches that reduce the time required for refueling from years to months.[46]

The cumulative amount of energy that can be extracted from a naval reactor core depends upon two factors:

• *Quantity of U-235 in the core.* The fission of one gram of U-235 releases about one Megawatt-day

(MWd) of thermal energy. The thermal energy is converted into mechanical energy using a steam turbine. The overall efficiency of conversion of thermal to mechanical energy is about 20 percent.[47]

• *Fractional Burn-up.* The "burn-up" of fuel is usually measured in terms of the cumulative number of MWd generated per kg of uranium originally in the fuel. Below, in order to compare HEU and LEU fuel, we will quote burn-up in terms of MWd per kg of U-235 originally in the fuel. If all the U-235 were completely fissioned and no other fissile material were generated and fissioned, the burnup would be 940 Megawatt-days per kilogram of U-235 fissioned [MWd/(kg-U-235)].[48]

Claims from the US Office of Naval Nuclear Propulsion (ONNP)

In his 1995 report to the U.S. Congress, the Director of the Office of Naval Nuclear Propulsion (ONNP) asserted that:

> [U.S.] Naval reactor cores have evolved in compactness to the point where the maximum amount of uranium is packed into the smallest volume, and the only way to make more volume available for uranium would be to remove cladding, structure or coolant. In other words, no more uranium could be packed into a modern long-lived core without degrading the structural integrity or cooling of the fuel elements.[49]

Assuming this constraint, he reported results for two alternative approaches for using 20-percent enriched uranium in nuclear-propulsion-reactor cores:

1. Keep the size of the cores fixed and replace the weapon-grade uranium with an equal amount of LEU. This would reduce the amount of U-235 in the cores by a factor of 4.7. According to the ONNP report, such a reduction would reduce the core life for the Virginia-class submarine from 33 to 7.5 years, and, for Trident-class submarines and Nimitz-class aircraft carriers equipped with 45-year cores, to 14 and 10.4 years respectively.

2. Increase the volume and hence the amount of uranium until the same core life can be achieved with LEU. The ONNP report states that the volume of the core would have to be increased by approximately a factor of three. This is less than the ratio of 4.7 between the amount of 20-percent LEU and weapon-
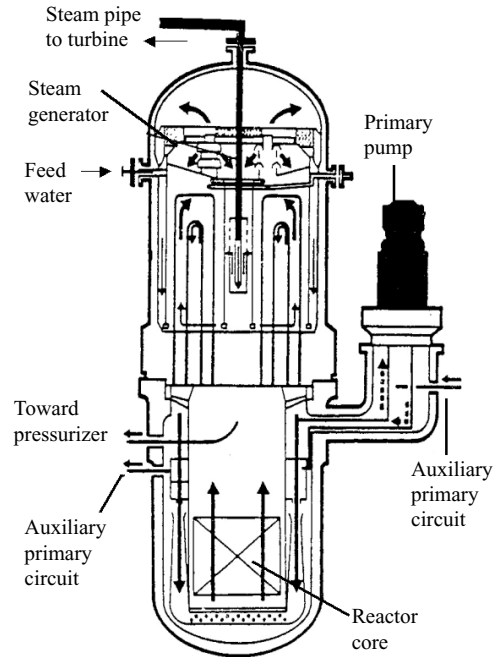
Figure 3a: Integrated Reactor and Steam Generator in France's Rubis Nuclear-Powered Submarine
Source: Adapted from Thomas Lynch, "Canadian Acquisition Program (CASAP), Nuclear Propulsion," *Wings Magazine* (April 1988), p. 64–68 (with permission from *Wings Magazine*.)
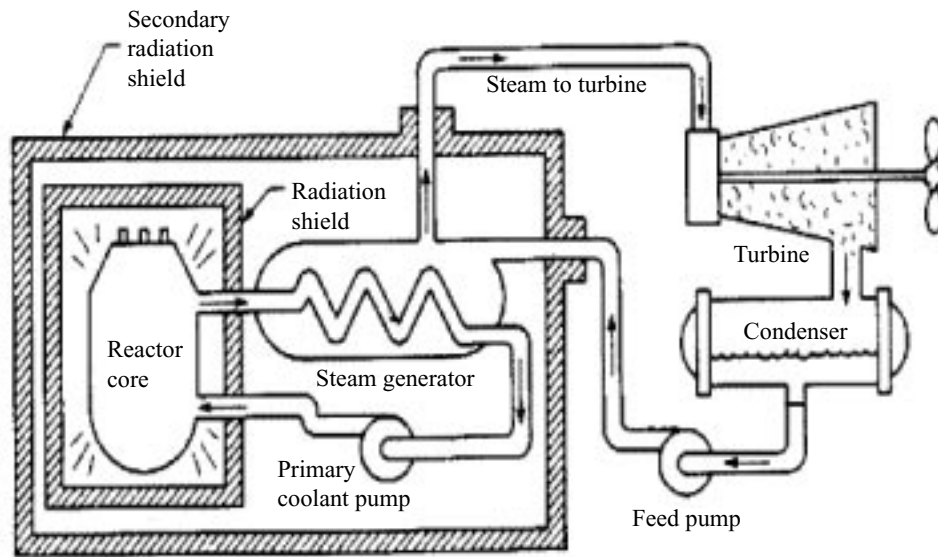

Figure 3b: Separate Reactor and Steam-Generator in U.S. Nuclear Submarines
Source: Director, Naval Nuclear Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, 1995, p. 5.

grade uranium containing 93 percent U-235 because some of the uranium-238 (U-238) added to the fuel would be converted by neutron absorption to fissile plutonium fuel. Also, the larger reactor would have the same power as the smaller reactor and therefore would not require proportionally more cooling.

Below, we will use the approximate relationship found in the ONNP analysis between core volume and core life.[50] However, it holds only if, as the ONNP assumed, the design of the fuel is not changed when shifting from weapon-grade uranium to LEU.

The ONNP report explained the compounding effect of a three-times larger core on the size of the vessel as follows:

> …the sizes and weights of the reactor vessel, pressurizer,[51] and other primary plant components must be increased to accommodate the larger core. This in turn increases the size and weight of the reactor compartment and the amount of shielding needed to protect the crew. Consequently, the ship's volume must be increased to add buoyancy to compensate for the increase in reactor compartment and shielding size and weight.[52]

In a design study for the new Virginia-class attack submarine, which has a submerged displacement of 7,700 tons, it was found that the ultimate result of a three-fold increase in core size would be an increase in the displacement of the submarine by 12 percent. Thus, assuming that the original core contained about 0.4 tons of weapon-grade uranium, the addition of about two tons of U-238 to dilute the U-235 down to LEU would, according to the ONNP report, have a compounding effect that would increase the weight of the submarine by 1,000 tons! The effects on the larger ballistic missile submarine and aircraft carrier were less dramatic.[53]

The principal reason for the large effect on the size of the attack submarine was apparently an increase in the diameter of the hull by about one meter (about three feet) to about 11.4 meters to accommodate the larger reactor.[54] However, the French have shown that it is possible, with an integrated design which places the steam generator inside the reactor pressure vessel (see Figure 3a), to build a 48-MWt nuclear power plant with a 10-year core life into the 7.6-meter-diameter hull of the 2,700-ton-displacement *Rubis* attack submarine. This not only makes the system more compact but it elimi-nates the need for the heavy shielding around the external steam generators shown for U.S. naval reactors in Figure 3b. It seems likely that, with a more creative approach, the U.S. Navy could manage to accommodate a larger core in the *Virginia* without significantly increasing its size.

The ONNP report was careful not to reveal the actual sizes of the cores of U.S. naval-propulsion reactors. However, two other sources suggest that they are remarkably small. The first is design calculations carried out in an MIT nuclear-engineering thesis in 1990. The second is information that has recently become available about the design of the compact core of a Russian nuclear-powered icebreaker.

Alternative Design Calculations

In 1990, Thomas Ippolito Jr. wrote a nuclear-engineering thesis in which he used public information about naval nuclear reactors and about different types of research-reactor fuel to develop notional designs for 50-MW HEU and LEU cores for the French Rubis-class attack submarine. He designed the cores to have lifetimes of 10 or 20 years if the reactor operated with a typical average output of one-sixth of full power.[55]

The fuel design Ippolito selected for the LEU-fueled reactor was the "caramel" fuel developed by France. The fuel is made of flat squares of uranium-dioxide (UO_2) ceramic imbedded in a zirconium-alloy grid.[56] This fuel "meat" is covered top and bottom with thin layers of zirconium alloy (see Figure 4). Caramel fuel is able to contain the pressure buildup from fission-product gases up to a fission fraction of at least six percent of the total uranium.[57] For 20-percent enriched uranium, this would correspond to the fission of 30 percent of the U-235.

For weapon-grade fuel, a much higher percentage of uranium fission must be achieved if there is to be any benefit from the high enrichment. Ippolito therefore assumed a design in which small UO_2 spheres with diameters of about 0.1 millimeters are imbedded in a solid zirconium matrix. Such ceramic-metal or "cermet" fuel, containing 21-percent UO_2 by volume, has been shown to be able to contain fission gases up to a 70-percent uranium fission fraction.[58]

Using these fuels, Ippolito determined the minimum core sizes for refueling intervals of 20 years that could be achieved with 20-percent enriched caramel fuel and 97.3-percent enriched cermet fuel. He found the volume

of the LEU core was 1.7 to 2.5 times larger than that of the weapon-grade uranium core. This factor is less than estimated in the ONNP report in part because the ONNP assumed that the same fuel design would be used for LEU as for weapon-grade uranium fuels. Ippolito, in contrast, followed the French approach and used a different type of fuel with a higher uranium density for the LEU core.[59] For a cylindrical core geometry, Ippolito found that the height and diameter of the LEU core were only 1.08 and 0.88 meters respectively.

There is as yet no public information available about the power of the reactor in the *Virginia*. But the reactor in the slightly smaller (6,900-ton displacement) *Los Angeles* submarine has a power of 130 MWt—2.6 times larger than the Rubis-class core modeled by Ippolito. We therefore scale up the volume of his reactor by a factor of 2.6 to give the 130 MWt power output and then scale up the volume by an additional factor of $(1.65)^{0.75}$ to get from his core life of 20 years to a core life of 33 years. The result is a core with height and diameter of 1.7 and 1.4 meters respectively—still small in comparison with the reactor compartment of the *Los Angeles*, which has an outside diameter of 10 meters, a length of 13 meters, and a weight of 1,680 tons.[60]

A Russian Ice-Breaker Core

Confirmation of the likely small size of submarine cores is provided by information about the core of the Russian ice-breaker-class container ship *Sevmorput*, which was built during 1984-88. The *Sevmorput* is based, along with six other nuclear-powered icebreakers, in Murmansk, Russia, not far from the Norwegian border.[61] In 1990, prior to a visit by the *Sevmorput* to the Norwegian port of Tromsø, the Norwegian government was supplied with a safety report that states that the ship has a single KLT-40 reactor with a thermal power of 135 MWt, about the same as the reactor on a U.S. Los Angeles-class attack submarine. The height and diameter of the *Sevmorput* core were given as 1.0 and 1.2 meters respectively. The mass of contained U-235 was given at 150.7 kg. Additional information about the core design was provided.[62]

On the basis of this information and a private communication that the fuel "meat" was made up of a uranium-zirconium alloy with a uranium density of 4.5 grams per cubic centimeter (g-U/cc), a group of Norwegian reactor experts developed a notional core design

containing about 11,600 thin fuel rods with a radius of 0.29 cm, each containing 12.9 grams of U-235. The fuel cladding was assumed to be 0.06 centimeters (cm) of zirconium alloy, making the radius of the fuel "meat" 0.23 cm. It was assumed that the fuel rods were in the form of hollow cylinders. For uranium enriched to 90 percent, the inside radius of the hollow cylinder was found to be 0.21 cm. [63]

This design contains enough unused volume inside the fuel rods to make it possible to increase the uranium loading of the fuel by up to a factor of 5.8. This is more than the factor of 4.5 required to reduce the enrichment of the uranium from 90 percent to 20 percent while holding the amount of U-235 in each fuel element constant. This design would make it feasible to maintain the core life with LEU fuel.[64] Indeed, a 1994 Russian proposal to use a KLT-40 reactor to power desalination and barge-mounted nuclear power plants for use in remote areas assumed 8.5- to 10-percent enriched fuel.[65] However, a recent critique of a project to actually build such a power plant for the Siberian Arctic port of Pevec states that the fuel would have an enrichment of 60 percent.[66] Recent discussions also confirmed that Russian reactor designers are still interested in converting a future version of this floating power plant to LEU fuel.[67]

The typical operating life of the *Sevmorput* reactor between refuelings was given in the safety report as about 1.14 full power years.[68] It is not clear whether this is determined by the fuel life or scheduling convenience. The model developed by the Norwegian experts has sufficient reactivity to operate for 1.9 years at full power. For a submarine reactor operating at an average of one-sixth of full power, the corresponding refueling interval would be about seven or 11 years.

These refueling intervals are considerably shorter than the 33 years projected for the reactor core of the U.S. *Virginia*. Scaling up the volume by a factor of $3^{0.75}$ or $4.7^{0.75}$ to achieve such a lifetime would give cores with heights of 1.3 or 1.5 meters and diameters of 1.6 or 1.8 meters. These volumes are up to 50 percent larger than those calculated by Ippolito.[69] This difference may result in part from the lower uranium density in the *Sevmorput* fuel meat: 4.5 versus 8.7 grams per cubic centimeter (gm/cc) in the caramel fuel assumed by Ippolito. Nevertheless, once again these scaled-up cores are quite small in comparison to the size of the *Los Angeles* reactor compartment. Thus the claims of the Office of Na-

Figure 4: In the High Uranium-Density LEU "Caramel" Fuel Used in French Nuclear Submarines, Platelets of UO2 Are Embedded in Zirconium Alloy
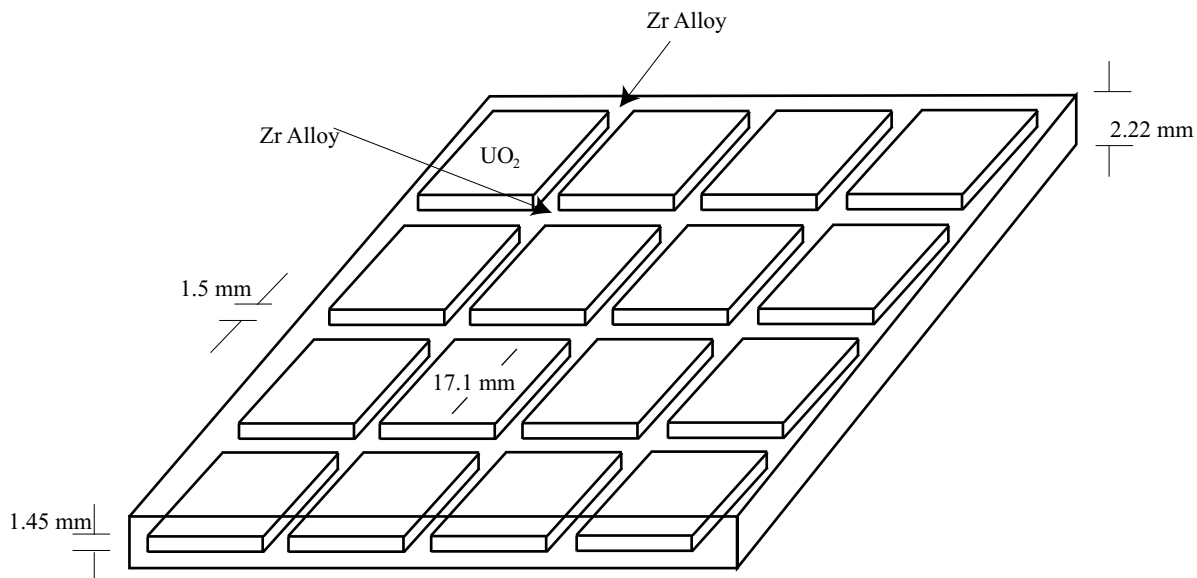
ADVANCED NON-NUCLEAR PROPULSION FOR SUBMARINES

Nuclear propulsion is being abandoned for surface ships other than for U.S. and French aircraft carriers and Russian icebreakers. For aircraft carriers, a detailed Greenpeace study,[70] subsequently confirmed by a U.S. General Accounting Office study,[71] showed that nuclear-powered aircraft carriers are more costly and have no measurable performance superiority over their oil-powered counterparts in actual operations.

In contrast, the advantages of nuclear propulsion for submarines seem obvious. They can travel for months at high speed without surfacing. However, few countries need such a capability. As a result, some countries have decided against nuclear submarines because of the high costs and safety and environmental concerns. For their needs—primarily anti-submarine and anti-ship missions in coastal seas—diesel-electric submarines are adequate.

Diesel-electric submarines operate on battery power while submerged and on diesel power for propulsion and battery recharging while snorkeling or on the surface. The United States and Britain are the only countries that do not have such submarines. Forty-two other countries do.[72] Britain, China, Germany, France, the Netherlands, Russia, and Sweden export diesel submarines.[73]

Diesel submarines can operate at high speed on battery power—but only for a few hours. They can operate at low speed on battery power for several days. Under these circumstances, they are quieter than nuclear submarines. They can travel thousands of miles to a deployment area on the surface or snorkeling.[74]

During the past decade, new types of "air-independent propulsion" (AIP) submarines have been developed to provide greater underwater endurance at low speed. This involves storing liquid oxygen in the submarine and using it to burn fuel in a closed-cycle diesel, turbine, or Stirling engine, or to react with hydrogen in a fuel cell. Reportedly, AIP can extend underwater operations at low speed to more than two weeks.[75] At a speed of five knots, such a submarine could travel 2,400 miles in 20 days without snorkeling.

val Nuclear Propulsion about the large displacement increases that would be necessary if LEU were used instead of weapon-grade uranium in future U.S. attack submarines appear questionable.

Most countries should find adequate for their attack submarines the triple combination of diesel power for higher-speed, long-distance surface or snorkel travel; battery power for short high speed underwater spurts; and the new generation of AIP for prolonged, slow, stealthy cruises. As for the strategic deterrent mission, before the development of nuclear-powered ballistic missile submarines, the Soviet Union used diesel submarines as missile-launch platforms. Beginning in 1956, variants of the Golf-class submarine were equipped with two and then three nuclear-armed ballistic missiles each.[76]

China still uses a Golf-class submarine as a test platform for underwater launches of ballistic missiles. This submarine launched the 1,700-km-range JL-1 ballistic missile in 1982 and is expected to be the test platform for the successor missile JL-2, a variant of the new 8,000-km-range DF-31 intercontinental ballistic missile.[77]

It is possible that, in a future era of small arsenals and long-range ballistic missiles, countries could shift their submarine-launched ballistic missiles to AIP submarines. In the early 1980s, the United States considered such a basing option for the 10-warhead MX missile. Because of its long range, the MX could reach Soviet targets from U.S. coastal waters. According to one proposal, a small (3,300-ton submerged) diesel submarine could carry four 100-ton MX missiles in steel capsules strapped into hollows on its upper deck. The launch of a MX missile would have been accomplished by releasing one of these capsules, which would rise to the surface to float vertically with one end out of the water. That end of the capsule would then be blown off and the MX launched out of the canister. The submarines were estimated to cost perhaps one-fifth as much and have crews one-fourth as large as the 19,000-ton-displacement Trident submarines, which carry 24 submarine-launched ballistic missiles each.[78]

If this solution were viable for the MX, it would certainly be viable for the smaller U.S. and Russian submarine-launched ballistic missiles, which also have long enough ranges to reach the other country from their home coastal waters. The missiles on British and French submarines also have enough range to reach Russia from European coastal waters. With the deployment of the JL-2 missile, China could reach the United States from near-coastal waters.[79]

CONCLUSIONS

The FMCT could close the door to new HEU production for any military purpose. This would make it possible to begin closing the naval reactor loophole in the NPT. Since HEU use in civilian land-based reactors is being phased out,[80] it is likely that the production of HEU would end worldwide. Thus, the IAEA could verify FMCT compliance at declared enrichment plants simply by confirming that they were not producing HEU.

During the transition to LEU fuel—or to non-nuclear submarines and ships—U.S., Russian and British naval reactors designed to use HEU could be fueled from excess nuclear weapons. In the longer term, future naval reactors could be fueled with LEU without significantly increasing the size of nuclear submarines, reducing their power, or giving up the goal of lifetime cores. If, on the other hand, the FMCT is adopted as currently conceived and permits the production of HEU for naval reactor fuel, verification would become virtually impossible in nations using HEU for such purposes. In that case, IAEA inspectors would be forbidden by military secrecy to verify the use of the HEU.

In the meantime, the fraction of ships and submarines that are nuclear-powered is likely to continue to decrease. Nuclear-powered ships are costly and require a huge dedicated support infrastructure. As the current situation in Russia shows, when a country loses the ability to support the technology, serious environmental problems can result. For countries that do not send their fleets across oceans, nuclear propulsion is unnecessary. Non-nuclear propulsion is improving and is adequate for most missions—even for submarines carrying ballistic missiles, if the missiles have a long enough range to allow the submarines to be kept in home waters.

[1] The authors would like to thank Oleg Bukharin, Harold Feiveson, Morten Bremer Maerli, Joshua Handler, Zia Mian, and James Clay Moltz for their very helpful suggestions.

[2] U.N. General Assembly consensus resolution 48/75L, December 16, 1993, <http://www.acronym.org.uk/fmctdesc.htm>.

[3] 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, April 14-May 19, 2000, New York, <http://www.basicint.org/nuclear/revcon2000/FinalDocAdvance.htm#Article VI>.

[4] Rodney W. Jones and Mark G. McDonough, *Tracking Nuclear Proliferation 1998* (Washington, D.C.: Carnegie Endowment for International Peace, 1998), pp. 231-232.

[5] *IAEA Safeguards Glossary* (Vienna: IAEA, 1987), p. 12.

[6] Steven Aftergood, "Background on Space Nuclear Power," *Science & Glo-*

bal Security 1 (1989), p. 93; Stephen I. Schwartz, ed., *Atomic Audit: The Costs and Consequences of U.S. Nuclear Weapons Since 1940* (Washington, D.C.: Brookings Institution Press, 1998), pp. 123-126. Reactors, which derive their energy from a fission chain reaction, are not to be confused with radioisotope thermal generators (RTGs), which derive their heat from the decay of radioisotopes such as plutonium-238.

[7] Andrew Koch, "Nuclear-powered submarines: India's trump card," *Jane's Intelligence Review* (June 1998), p. 29, states: "The reactor will burn plate-type 20 percent enriched uranium fuel." Admiral Pinheiro da Silva, director of the Brazilian Navy's Aramar Research Center, where the first module of an industrial-scale gas-centrifuge uranium enrichment plant has been built, stated that "because of a political decision" the enrichment of uranium will be limited to 20 percent (Jones and McDonough, *Tracking Nuclear Proliferation 1998*, p. 234, note 13).

[8] J. Primack, N. Abrams, S. Aftergood, D. Hafemeister, D. Hirsch, R. Mozley, O. Prilutsky, S. Rodionov, and R. Sagdeev, "Space Reactor Arms Control," *Science & Global Security* 1 (1989), pp. 59-82.

[9] Rensselaer Lee, "Recent Trends in Nuclear Smuggling," in Phil Williams, ed., *Russian Organized Crime: The New Threat?* (London: Frank Cass, 1996), p. 109, lists six cases of arrests for the theft of fresh HEU naval fuel from the storage facilities of Russia's Northern Fleet during the period 1993-1996. The United States and Russia have since mounted a joint program to upgrade the security of the storage facilities.

[10] HEU can be used in a "gun-type" design in which one subcritical piece of HEU is fired into another to create a super-critical mass. Because of the presence of neutrons created by spontaneous fissions, such a slow method of assembly of plutonium would be interrupted and reversed by a premature chain reaction before a significant nuclear yield could occur. Plutonium is therefore imploded to a supercritical density by a much more complicated arrangement of high explosive. The Hiroshima bomb was a gun-type design, as were the seven nuclear warheads built by South Africa, each of which contained 55 kg of weapon-grade uranium (David Albright, "South Africa and the affordable bomb," *Bulletin of the Atomic Scientists* 52 [July/August 1994], p. 37).

[11] Italy and Holland, in particular, were interested in building nuclear-powered naval ships, David Fischer, *History of the International Atomic Energy Agency, the First Forty Years* (Vienna: IAEA, 1997), pp. 272-273.

[12] Marie-France Desjardins and Tariq Rauf, "Opening Pandora's Box? Nuclear-Powered Submarines and the Spread of Nuclear Weapons," Aurora Papers 8 (Ottawa: The Canadian Centre For Arms Control And Disarmament, 1988); and Marvin Miller, "Nuclear Submarines and their Implications for Weapons Proliferation," in Paul Leventhal and Sharon Tanzer, eds., *Averting a Latin American Nuclear Arms Race* (MacMillan/Nuclear Control Institute, 1992), p. 153.

[13] Morten Bremer Maerli, in "Deep Seas and Deep-Seated Secrets: Naval Nuclear Fuel Stockpiles and The Need for Transparency," *Disarmament Diplomacy*, No. 49 (August 2000), p. 14, argues that this problem and the problem of very large HEU stocks held in reserve for naval nuclear fuel should be dealt with by transparency measures. James Clay Moltz, in "Closing the NPT Loophole on Exports of Naval Propulsion Reactors," *Nonproliferation Review* 6 (Fall 1998), p. 108, argues for agreements not to export naval nuclear reactors or HEU submarine fuel.

[14] International Atomic Energy Agency, *The Structure and Content Of Agreements Between The Agency And States Required In Connection With The Treaty On The Non-Proliferation Of Nuclear Weapons*, INFCIRC/153 (Corrected), June 1972, paragraph 14.

[15] See also the longer discussion of this problem in Desjardins and Rauf, "Opening Pandora's Box."

[16] David Albright, Frans Berkhout, and William Walker, *Plutonium And Highly Enriched Uranium 1996: World Inventories, Capabilities And Policies* (Oxford: Oxford University Press/Stockholm International Peace Research Institute, 1997), p. 253.

[17] White House Press Release, "Nonproliferation and Export Control Policy," September 27, 1993.

[18] U.S. House of Representatives, *Conference Report on the National Defense Authorization Act for Fiscal Year 1995*, 103rd Cong., 2nd session, Report 103-701, August 12, 1994, p. 745. The House approved an amendment

(sec. 1042) to the National Defense Authorization Act for Fiscal Year 1995 that directed "the Secretary of Energy and the Secretary of Defense to study the costs, advantages and disadvantages of using low-enriched uranium to fuel naval reactors." The Office of Naval Propulsion is a joint office of the Departments of Energy and Defense. However, the Senate agreed only on the condition that the Secretary of the Navy alone be responsible for the study.

[19] Director, Naval Nuclear Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion,* 1995, p. 1.

[20] Albright, Berkhout, and Walker, *Plutonium And Highly Enriched Uranium 1996*, p. 81.

[21] Three out of Russia's four uranium enrichment facilities are now licensed to enrich uranium only up to five percent. The fourth, at Novouralsk (formerly Sverdlovsk-44), is licensed to produce HEU enriched only up to 30 percent (T.B. Cochran, R.S. Norris, and O.A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin* [Boulder: Westview, 1995], p. 187).

[22] Albright, Berkhout, and Walker, *Plutonium And Highly Enriched Uranium 1996,* pp. 118-119. France declared in 1996 that it had sufficient HEU for its future needs and that it would dismantle its HEU production plant (ibid., p. 121). And China, although it has not made any official declaration, and is thereby keeping its future options open, reportedly suspended HEU production for weapons in 1987 (ibid., p. 126).

[23] In the past, the U.S. Navy had its HEU specially enriched to 97.3 percent. Since the end of U.S. HEU production, however, it is shifting to 93-percent enriched uranium extracted from surplus nuclear warheads.

[24] A.D. Baker III, *The Naval Institute Guide to Combat Fleets of the World 2000-2001* (Annapolis, MD: Naval Institute Press, 2000), pp. 918-925.

[25] Director, Naval Nuclear Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, p. 3.

[26] Department of Energy, *FY1999 Congressional Budget Request, Other Defense Activities, Naval Reactors: Reactor Technology and Analysis*,<http://www.fas.org/man/dod-101/sys/ship/eng/navalr.pdf>.

[27] Thomas Cochran, William Arkin, Robert Norris, and Milton Hoenig, *U.S. Nuclear Warhead Production* (Cambridge: Ballinger, 1987), p. 71.

[28] Not all of this U-235 is consumed. Some of it is discharged in the spent nuclear fuel.

[29] Frank von Hippel, David H. Albright, and Barbara G. Levi, *Quantities of Fissile Material in U.S. and Soviet Nuclear Weapons Arsenals* (Princeton: Princeton University, Center for Energy and Environmental Studies Report #168, 1986); Cochran, Arkin, Norris, and Hoenig, *U.S. Nuclear Warhead Production*, p. 191; and Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium 1996*, p. 91.

[30] Albright, Berkhout and Walker, *Plutonium And Highly Enriched Uranium 1996*, p. 93.

[31] Director, Naval Nuclear Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, p.28.

[32] Nilsen, Kudrik and Nikitin, *The Russian Northern Fleet, Nuclear-Powered Vessels*, Section 2.3.7: "Russian Submarine Fuel," Bellona Foundation, <http://www.bellano.no/e/russia/nfl>.

[33] Oleg Bukharin and William Potter, "Potatoes Were Guarded Better," *Bulletin of Atomic Scientists* 51 (May/June, 1995), p. 46.

[34] *Jane's Fighting Ships, 1999-2000* (London: Jane's Yearbooks, 2000).

[35] Albright, Berkhout and Walker, *Plutonium and Highly Enriched Uranium 1996*, p. 80.

[36] Ibid, p. 119.

[37] Viking Olver Eriksen, *Sunken Nuclear Submarines, A Threat to the Environment?* (Oslo: Norwegian University Press, 1990), p. 77.

[38] *Jane's Navy International*, April 1997, p. 8.

[39] U.K. Ministry of Defense, *Strategic Defense Review*, July 1998, <http://www.mod.uk/polic/sdr.htm>. Enrichment not specified.

[40] M.B. Davis," Nuclear France: materials and sites," <http://www.francenuc.org/en_chn/fabricationu_dle.htm>; Y. Girard, Technicatome, Saclay, "The Implications of the Acquisition of Nuclear-Powered Submarines by Non-Nuclear Weapons States," unpublished transcript of a talk at a conference at MIT on March 27-28,1989.

[41] Baker, *The Naval Institute Guide to Combat Fleets of the World 2000-2001*, p. 187.

[42] Albright, Berkhout, and Walker, *Plutonium And Highly Enriched Uranium 1996*, p. 129, note 114.

[43] Baker, *The Naval Institute Guide to Combat Fleets of the World 2000-2001*.

[44] Charles Fribourg, "La propulsion nucléaire navale," *RGN* No. 2 (1999), p. 32.

[45] The coolant is a source of gamma rays primarily because of neutron transmutation of oxygen in the water, n + O-16 --> p + N-16. The N-16 decays with a seven-second half-life back to O-16, emitting a very high energy (6.1 Million electron-Volt) gamma ray about 70 percent of the time.

[46] The Rubis fuel is reportedly shuffled and replaced at intervals of five and 10 years respectively (Marvin Miller, MIT, private communication, November 2000). The length of time required for refueling of the Rubis is reportedly only five months and is to be reduced further to three months (Davis, "Nuclear France: materials and sites," <http://www.francenuc.org/en_chn/reactors_res_e.htm>). Engineered refueling overhauls of U.S. submarines in Portsmouth Naval Shipyard take about two years (Richard Fabrizio, "Shipyard Reinvents Itself for Future," *Portsmouth Herald*, June 11, 2000, <http://www.seacoastonline.com/news/6_11b.htm>).

[47] For example, the heat output of the reactor on a Los Angeles-class submarine is 130 Megawatts (MW) and the power delivered to its propeller is 26,000 MW (35,000 shaft horsepower). Eriksen, *Sunken Nuclear Submarines, A Threat to the Environment?,* Table 15.

[48] Samuel Glasstone and Alexander Sesonske, *Nuclear Reactor Engineering,* Vol. 1 (New York: Chapman and Hall, 1994), p. 18.

[49] Director, Naval Nuclear Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, p. 8.

[50] We have used a relationship between core volume V and core lifetime T as V is in proportion to $T^{0.75}$. According to this relationship, if T is increased by a factor of 4.3, V increases by a factor of three.

[51] The "pressurizer" keeps the pressure of the reactor coolant above the pressure at which it would boil.

[52] Director, Naval Nuclear Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, p. 10.

[53] However, concern was expressed that the aircraft carrier core might become "so large that its being able to meet all the functional requirements on naval reactors is not necessarily assured" (ibid., pp. 11-12). The concern may relate to the complexity of controlling power distributions in large reactor cores.

[54] The *Virginia's* length and outside diameter are 115 and 10.4 meters respectively (*Jane's Fighting Ships 1997-1998*, p. 795).

[55] This would correspond, for example, to the submarine spending two-thirds of its time at sea and, while at sea, the reactor operating at an average of one-quarter of its maximum output. Because the power required to push a submarine through the water increases as the third power of its speed, one-quarter power would correspond to a speed of about 16 knots for a submarine capable of 25 knots. (A knot is a speed of one nautical mile [1.852 kilometers] per hour.)

[56] Each piece of UO2 is a square ceramic wafer 1.71 centimeters (cm) on a side and 0.145 cm thick. The zirconium-alloy ribs that separate the wafers are 0.15 cm thick. The uranium density in the UO2 is 10.3 grams per cubic centimeter (gm-U/cc). The zirconium grid reduces the average density of the fuel "meat" to 8.7 gm/cc. The combination of UO2 and zirconium alloy has been adopted for water-cooled power reactors because it can withstand high neutron irradiation, is very resistant to corrosion, and is stable to high temperatures. Zirconium begins to react with water at 1,200 degrees centigrade and melts at 1,850 degrees. Its absorption of neutrons is small.

[57] M. Barnier and J.P. Beylot, "Osiris, a MTR adapted and well fitted to LEU utilization, qualification and development," in *Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors, October 24-27, 1983, Tokai, Japan* (Japan Atomic Energy Research Institute report JAERI-M84-073, 1984).

[58] Thomas Ippolito Jr., "Effects of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design," Ph.D. diss., MIT, 1990, p. 67.

[59] The French caramel design has a 4.35 times higher uranium density in the fuel meat than the cermet design that Ippolito used for his weapon-grade uranium reactor. This density increase is partially offset, however, by the

[60] higher strength of the cermet fuel, which allows the fission of a 2.5 times larger fraction of the originally contained U-235.

[60] U.S. Department of the Navy, *Final Environmental Impact Statement On The Disposal of Decommissioned, Defueled Cruiser, Ohio Class, and Los Angeles Class Naval Reactor Plants*, April 1996, p. 2-7.

[61] Nils Bøhmer, *Murmansk Shipping Company*, September 17, 2000, Bellona Foundation, <http://www.bellona.no/imaker?sub=1&id=12667>.

[62] The core has 241 fuel assemblies. The outer diameter of each fuel assembly is six centimeters (cm) and the outer diameters and spacing between the centers of the fuel rods in the assembly are respectively 0.58 and 0.7 cm (*Information of Safety of Icebreaker-Transport, Lighter/Containership with Nuclear Propulsion Plant Sevmorput*, Tables 3.1, 3.6 (The only identifying information given on the cover of this report is "approved by the Register of Shipping of the USSR").

[63] Morten Bremer Maerli, Sigurd Børrensen, Knut Gussgard, Steinar Høibråten, and Matylda M. Sobieska, *Criticality Considerations on Russian Ship Reactors and Spent Nuclear Fuel* (Oslo: Norwegian Radiation Protection Authority, 1998). The fuel meat reportedly contains 48.2 percent uranium and 51.8 percent zirconium by weight. A hexagonal close-packed array of fuel elements was assumed. This would provide space for 55 fuel rods per assembly. These analysts assumed that six spaces in each assembly would be occupied by rods containing gadolinium, a potent neutron absorber, to reduce the initial excess reactivity of the core. According to the safety report, 16 fuel assemblies contain spaces for control rods. The Norwegian analysts assumed 16 control rods in each of these assemblies. Then there would be 225 fuel assemblies with 49 fuel rods each and 16 with 39 fuel rods (if the assemblies containing the spaces for control rods did not contain gadolium rods) for a total of 11,649 fuel rods.

[64] At the beginning of core life, the presence of U-238 reduces the core reactivity because it absorbs neutrons. At the end of core life, this effect is more than offset by the reactivity added by the bred plutonium (calculations by Jungmin Kang, Frank von Hippel and Demetra Papadopoulos).

[65] Y.K. Panov, V.I. Polunichev, V.I. Vasyukov, A.A. Ardabyevsky, and L.M. Veksler, "How to avert the torment of Tantalus, or how to satisfy humanity's thirst for fresh water," *Atom Inform,* No. 5-6 (1994) (in Russian), pp. 13-16. Harnessed to a desalination plant, the reactor would have a heat output of 80 MWt and a core life of about 2.6 years at an average capacity factor of 80 percent.

[66] V.M. Kuznetsov, A.V. Yablokov, V.M. Desyatov, A.K. Nikitin, and I.V. Forofontov, *Floating Nuclear Power Plants in Russia: A Threat to the Arctic, World Ocean and Non-Proliferation Treaty* (Moscow: Nuclear and Radiation Safety Program, Socio-Ecological Union, Greenpeace, 2000). An earlier summary of the project had been done by V. Kovalenko, "Braving the Chill of the Market," *Nuclear Engineering International* (January 1993), p. 52-54. The article describes the KLT-40 design and discusses a possible application in a barge-mounted transportable power plant that would have an output of 70 megawatts electric from two KLT-40 reactors. A more recent presentation, announcing that long-lead-time components for a barge-mounted plant nuclear-powered electricity and heat plant to be located in the Siberian Arctic port of Pevec had been ordered, was made by K.B. Veshnyakov, A.I. Kiryushin, Yu. K. Panov, and V.I. Polunichev, "Floating nuclear heat and power station 'Pevec' with KLT-40S Type reactor plant for remote regions of Russia," International Workshop on Utilization of Nuclear Power in Oceans, Tokyo, Japan, February 21-24, 2000.

[67] One proposal is to use a fuel meat made from a mix of UO2 and zirconium. This could give a higher U density than the U/Zr alloy (Armando Travelli, Argonne National Laboratory, private communication, November 6, 2000).

[68] *Information of Safety of Icebreaker-Transport, Lighter/Containership with Nuclear Propulsion Plant Sevmorput,* Table 3.6. This corresponds to a burn-up of about 373 MWd/kg-U-235.

[69] The volume of the 33-year 130-MWt core scaled up from Ippolito's calculation is 2.5 m³. The volumes scaled from the *Sevmorput* core are 2.6 and 3.7 m³.

[70] Hans Kristensen, William Arkin, and Joshua Handler, *Aircraft Carriers: The Limits of Nuclear Power,* (Greenpeace, Neptune Paper No. 7, June 1994).

[71] U.S. Government Accounting Office, *Navy's Aircraft Carrier Program:*

Investment Strategy Options (Letter Report, 01/01/95, GAO/NSIAD-95-17), <http://www.fas.org/man/gao/gao9517.htm>; *Navy Aircraft Carriers: Cost-Effectiveness of Conventionally and Nuclear-Powered Aircraft Carriers*, GAO/NSIAD-98-1, August 1998, <http://www.gao.gov>.

[72] U.S. Office of Naval Intelligence, *Worldwide Submarine Proliferation in the Coming Decade* (circa 1994).

[73] Daniel Revelle and Lora Lumpe, "Third World Submarines," *Scientific American*, August 1994, p. 16-21.

[74] The improved Russian Kilo 636 attack submarine has a displacement of 3,126 tons submerged and about 5,500 shaft horsepower. Its top submerged speed is about 20 knots but it can only travel 100 miles (five hours) at this speed before its batteries are exhausted. It can travel for 400 miles (5.5 days), however, at a speed of three knots. Snorkeling, it can travel 7,500 miles at a speed of seven knots (Baker, *Combat Fleets of the World, 2000-2001*).

[75] "Sweden launches first production AIP submarine," *Jane's International Defense Review*, March 1995, p. 17. The submarine has a displacement of 1,500 tons submerged and is equipped with two 65 kilowatt electric (kWe) [75 kWe peak] Stirling engines. The "hotel load" (internal electric-power requirements of the submarine) are about 80 kWe. Richard Scott, "Boosting the staying power of the non-nuclear submarine," *Jane's International Defence Review*, November 1999, p. 41 describes: a variant of the German U-212 (displacement, 1,830 tons submerged) with a 300 kWe hydrogen fuel-cells capacity (with the hydrogen stored in a metal hydride powder) that can power it at a speed of up to eight knots; and systems powered by closed-cycle diesel engines and Rankine turbines (the last variant has been purchased by Pakistan). For systems involving combustion or reforming of fossil fuels with stored liquid oxygen, the CO_2 is chemically scrubbed out of the exhaust and mixed into the ocean water.

[76] Pavel Podvig, ed., *Russian Strategic Nuclear Weapons* (Boston: MIT Press, forthcoming).

[77] Bill Gertz, "U.S. Secrets Aboard Latest Chinese Missile to Be Able to Hit Anywhere in the U.S.," *Washington Times,* December 6, 1999, p. A1; and *Jane's Fighting Ships, 1997-98.*

[78] U.S. Congress, Office of Technology Assessment, *MX Missile Basing* (Washington, D.C.: Government Printing Office, 1981).

[79] Gertz, "U.S. Secrets Aboard Latest Chinese Missile," reports that "a special panel headed by Rep. Christopher Cox, California Republican, stated that the JL-2's 7,400-mile range allows it 'to be launched from the PRC's territorial waters and to strike targets throughout the United States.'" Other sources expect the range of the JL-2 to be about 8,000 km (5,000 miles) (see e.g., "Chinese Nuclear Forces, 2000," *Bulletin of the Atomic Scientists* 56, (November/December 2000), p. 78). The distance from Beijing to Seattle is 5,400 miles.

[80] Armando Travelli, "Progress of the RERTR Program in 2000," paper presented at the 2000 International Meeting on Reduced Enrichment for Research and Test Reactors, October 1-6, 2000, Las Vegas, Nevada, <http://www.td.anl.gov/Programs/RERTR/RERTR.html>.