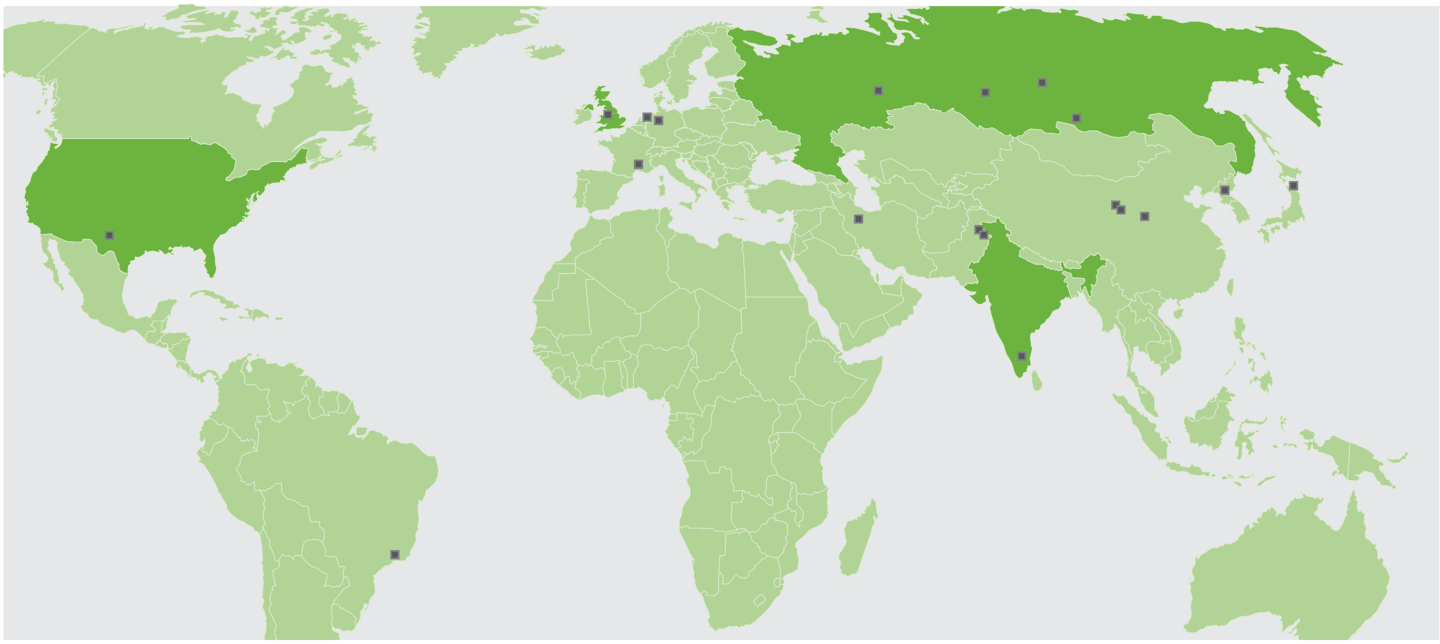

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Banning the Production of Highly Enriched Uranium

Frank von Hippel

Research Report No. 15
International Panel on Fissile Materials

Banning the Production of Highly Enriched Uranium

Frank von Hippel

On the cover: The map shows the states that use highly enriched uranium fuel for naval propulsion reactors and the locations of uranium enrichment plants.

Table of Contents

Tables

Figures

About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from sixteen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical bases for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons, and ensuring that terrorists do not acquire nuclear weapons.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon and naval fuel stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium fuel is used in about one hundred research reactors. The total amount used for this purpose alone is sufficient to make hundreds of Hiroshima-type bombs, a design potentially within the capabilities of terrorist groups.

The Panel is co-chaired by Alexander Glaser and Zia Mian of Princeton University and Tatsujiro Suzuki of Nagasaki University. Its 30 members include nuclear experts from Brazil, China, France, Germany, India, Iran, Japan, South Korea, Mexico, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom, and the United States. Short biographies of the panel members can be found on the IPFM website, www.fissilematerials.org.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. The reports are available on the IPFM website and through the IPFM blog, www.fissilematerials.org/blog.

Princeton University's Program on Science and Global Security provides administrative and research support for the IPFM. IPFM is supported by grants to Princeton University from the John D. and Catherine T. MacArthur Foundation of Chicago and the Carnegie Corporation of New York.

Overview

The earliest proposal for a nuclear weapon envisaged a fission chain reaction in uranium that had been highly enriched in the rare isotope uranium-235. The nuclear weapon used by the United States on August 6, 1945 to destroy the Japanese city of Hiroshima contained about 60 kilograms of uranium enriched to about 80 percent uranium-235. It was a simple gun-type assembly in which one piece of uranium metal was fired at another to make a supercritical mass and generate a nuclear explosion. There is no debate that today a terrorist group could potentially produce such a gun-type assembly weapon if it had access to a sufficient amount of highly enriched uranium.

For the purposes of safeguarding against nuclear proliferation, uranium containing 20 percent or more uranium-235 is considered weapon useable by the International Atomic Energy Agency (IAEA) and is formally defined as Highly Enriched Uranium (HEU); uranium of lower enrichment is defined as Low Enriched Uranium (LEU). The HEU actually used in modern nuclear weapons and in some nuclear reactors as fuel is mostly more than 90 percent uranium-235 and often is called "weapon grade." Uranium enriched up to about 5 percent in uranium-235 is used as fuel in the most common type of nuclear power reactors. Since natural uranium contains only 0.7 percent uranium-235, making HEU or LEU requires uranium enrichment technology able to separate this uranium-235 from the much more abundant uranium-238 isotope. Gas centrifuge technology for uranium enrichment is in use in 13 countries.

The global stockpile of HEU at the end of 2014 was about 1370 tons*, sufficient for more than 20,000 simple first-generation Hiroshima type weapons, or more than four times as many modern nuclear weapons. More than 99 percent of this material was held by the nuclear weapon states, mostly by Russia and the United States, with the United Kingdom, France and China possessing most of the rest. Pakistan, India, Israel and possibly North Korea hold smaller stockpiles – although still very significant in terms of weapon equivalents. About 5 tons of HEU (90 percent equivalent) is in non-weapon states, but most of this material was imported from the weapon states – primarily the United States and Russia. Among the non-weapon states, only South Africa produced its own HEU before 1991, when it had a nuclear-weapon program. In non-weapon states, HEU is under IAEA safeguards.

HEU is used in nuclear weapons but also has several non-weapon uses, all of which involve nuclear reactors. Ranked in order of the quantities of total HEU used annually, the reactor uses of HEU are:

- Fuel for naval and icebreaker propulsion reactors,
- Fuel for tritium-production and breeder reactors,
- Fuel for research reactors, and
- Neutron "targets" for medical radioisotope production in reactors.

---

* All tons are metric tons.

Since the late 1970s, there has been concern about the proliferation risk associated with the widespread use of HEU to fuel civilian research reactors. Since the attacks on the United States in September 2001, there also has been increased concern about the relative ease with which terrorists could make an "improvised nuclear device" if they gained access to several tens of kilograms of HEU.

In April 2010, leaders from 47 nations participated in the first Nuclear Security Summit, held in Washington DC with a view to increasing security of HEU and plutonium stocks and minimizing the use of HEU where feasible. At the subsequent Nuclear Security Summits – 2012 in South Korea and 2014 in the Netherlands – countries reported on their progress in reducing HEU use.

Despite the Nuclear Security Summits and other efforts to minimize HEU use, as of late 2015, there were over 150 nuclear-powered submarines and ships – more than half belonging to the United States, that use HEU as fuel in their propulsion reactors. There also were about 100 research reactors, half of them in Russia, and two tritium production reactors and a breeder reactor, also in Russia, fueled with HEU. Finally, HEU neutron "targets" were being used for medical radioisotope production in several countries. Altogether, the equivalent of about 7 tons of weapon-grade HEU are used for these purposes annually, sufficient for about 100 first-generation gun-type nuclear weapons.

Given the broad consensus on the security benefits of minimizing HEU use, it is natural to ask whether it would be possible to phase out all non-weapon uses of HEU, and, if so, is there enough HEU in the existing global stockpile to supply non-weapon requirements during the transition period. As is explained in this report, it would be feasible to end HEU production immediately.

An earlier IPFM report, *Plutonium Separation in Nuclear Power Programs* makes the case that there is no economic or waste-management justification for continuing the separation of plutonium for non-weapon purposes.

Ending HEU production

The long sought after Fissile Material (Cutoff) Treaty or FM(C)T would ban the production of HEU and plutonium for weapons. All five permanent members of the United Nations Security Council (the P5: China, France, Russia, the United Kingdom and the United States) are believed to have ended their production before or soon after the end of the Cold War. Only Pakistan, and possibly India and North Korea, are producing HEU for weapons today because they are still increasing the sizes of their nuclear-weapon stockpiles.

For countries with constant or declining nuclear-weapon stockpiles, there is no need to make new HEU for weapons. Material recovered from retired weapons can be recycled to make replacement warheads if desired. An FM(C)T would make the production halts for weapons in the P5 countries verifiable and irreversible and would end the buildups of weapon stocks in other nuclear-armed states.

A broader HEU production ban would prompt users of HEU for nuclear fuel and targets to make plans for a shift to LEU fuel or to alternative technologies that do not involve fission. A growing taboo on all HEU use also would help to accelerate a phase-out of its non-consumptive uses in critical assemblies and in pulsed reactors.

Russia and the United States have huge stocks of HEU recovered from excess Cold War warheads with which they could supply their own non-weapon needs and those of most other countries for many decades. Russia is producing some HEU for reactor fuel use, but this is a purely discretionary use of its excess enrichment capacity that could easily be ended if Russia's government deemed it politically important to join in a production ban.

Therefore, apart from the challenge of persuading India, Pakistan and North Korea to end their nuclear-weapon buildups, a ban on the production of HEU for any purpose could be accommodated relatively easily for many decades.

Phasing out non-weapon uses of HEU

It should take at most a few decades to implement a policy to transition all current non-weapon uses of HEU to LEU fuels or non-fission alternatives that would pose a much reduced risk of fueling nuclear proliferation or of nuclear terrorism.

Naval reactor fuel

The transition from HEU that would take longest to complete would be for nuclear naval propulsion in the United States, Russia, UK and India. France has already transitioned its nuclear submarines and nuclear aircraft carrier, and Russia is transitioning its nuclear-powered icebreakers to LEU fuel. It is believed that China always has used LEU fuel in its nuclear submarines.

The United States navy fuels its propulsion reactors with weapon-grade HEU (enriched to over 90 percent uranium-235). In 2014, however, the U.S. National Security Administration's Office of Naval Reactors suggested for the first time that it might be possible over 20 to 25 years to develop LEU fuel for United States naval propulsion reactors. The task is challenging because the United States has moved to lifetime cores in its nuclear submarines. Congress has asked for a plan for the necessary research and development. If the United States moved to LEU, so could the United Kingdom with which the United States shares propulsion-reactor design information.

Conversion to LEU fuel would be easier for Russia. Many of its later-generation naval reactors use HEU enriched to less than 50 percent uranium-235 and its propulsion reactors are refueled every ten years or so. India, the only other state that uses HEU for naval fuel, has received assistance from Russia in the design of its naval reactors and presumably could shift to LEU fuel if Russia did.

Establishment of a new norm that all naval propulsion reactors be fueled by LEU would help reduce a vulnerability of the nonproliferation regime. Brazil is the first non-weapon state that has started a serious program to develop a nuclear submarine. At this time, it is using LEU fuel in its land-based prototype reactor but it has made clear that it feels free to switch to HEU fuel if that would result in higher performance. In 2013, officials in Iran suggested they might one day begin to produce HEU for future nuclear submarines. Given concerns about access of international inspectors to sensitive military technology, it would be difficult to verify the non-diversion of HEU from a naval fuel cycle to weapons production.

Isotope-production and breeder reactors

Russia has two radioisotope-production reactors that are fueled with HEU. During the Cold War, they were used primarily to produce tritium, a heavy isotope of hydrogen with a 12-year half-life that is used in the triggers of nuclear explosives to produce a burst of fusion neutrons to “boost” the power of the fission reactions. Given Russia’s much reduced post-Cold War nuclear arsenal, these reactors today mostly produce radioisotopes for civilian purposes. Russia plans to replace them with a single reactor by 2023. Whether this reactor will be HEU or LEU-fueled has not been disclosed but there is no technical reason why it could not be LEU-fueled. The United States and France already have made this transition.

Russia also has fueled its prototype BN-600 breeder reactor with HEU since it began operating in 1980. If commercialized, breeder reactors would be fueled with plutonium but, until recently, Russia did not have a plutonium fuel production facility. The plan is to continue to fuel the BN-600 with HEU until it retires in 2020 or 2025. The first core of Russia’s new BN-800 reactor contains some HEU fuel but the plan is to transition it to 100 percent plutonium fuel. Russia also has provided initial HEU fuel for China’s Experimental Fast (breeder) Reactor but China plans to transition this reactor to plutonium fuel.

Research reactors

Since 1978, about 65 HEU-fueled research reactors have been converted to LEU and about 150 have been retired. Of the approximately 100 remaining HEU-fueled research reactors, about half are in Russia. Worldwide, about 60 of these 100 reactors are critical assemblies or pulsed reactors, all but a few of which could be retired with the rest consolidated into one or two high-security sites per country as the United States has done.

Of the approximately 40 research reactors that operate at power, 10 are low-powered reactors with lifetime cores that can be converted to LEU. Of the 27 high-powered reactors, about half could be converted to LEU. Conversion of the other half is waiting on new higher uranium-density fuel to be certified. The development of the new fuel has been delayed by more than a decade. Most of these high-power research reactors are around 50 years old, however, and it is possible that the reactors awaiting the new fuel for conversion will be retired before they can be converted. Future research reactors can be designed with LEU cores.

Medical radioisotope targets

The fission of uranium-235 in HEU "targets" in a nuclear reactor is used for industrial medical radioisotope production in a handful of countries. This industry is already transitioning to LEU targets. The transition could be virtually complete within the next few years.

In summary, although there are challenges in a few cases, it appears that there are paths forward to phasing out virtually all non-weapon use of HEU during the next few decades. During the transition, the large Russian and United States stockpiles of excess HEU could be used to meet the worldwide requirements for HEU for non-weapon purposes. It is feasible therefore to consider going beyond the proposed Fissile Material (Cutoff) Treaty ban on HEU production for weapons to establish a ban on the production of HEU for any purpose.

HEU production and stocks

In March 1940, in a memorandum to the British government, physicists Otto Frisch and Rudolf Peierls at the University of Birmingham proposed that a mass of nearly pure uranium-235 might be able to sustain an explosive nuclear fission chain and serve as the basis of a "super-bomb."[1] They also observed that "effective methods for the separation of isotopes have been developed recently" that could produce such highly enriched uranium. The major challenge for the British and later the United States nuclear weapons program during World War II – and for similar programs since then interested in making such a bomb – was to produce HEU from natural uranium, which contains less than one percent uranium-235.

Figure 1 shows the history of the global HEU stockpile. During the Cold War, the United States and Soviet Union produced together about 2,300 tons of HEU – mostly for weapons. The United Kingdom, France and China also produced HEU, but on a much smaller scale – less than a combined 100 tons. Some HEU was used as fuel in reactors and in nuclear-weapon tests.

HEU currently is being produced only by India, Pakistan, Russia and probably North Korea. Russia's HEU production is for non-weapon purposes. India's HEU production is at least in part for nuclear submarine fuel. Pakistan's and any in North Korea's would be for nuclear weapons.[2]

South Africa produced HEU as part of its nuclear weapons program, but since it signed the nuclear Non-Proliferation Treaty as a non-weapon state in 1991, the peaceful use of that material has been subject to International Atomic Energy Agency (IAEA) monitoring. No other non-weapon state has produced HEU.

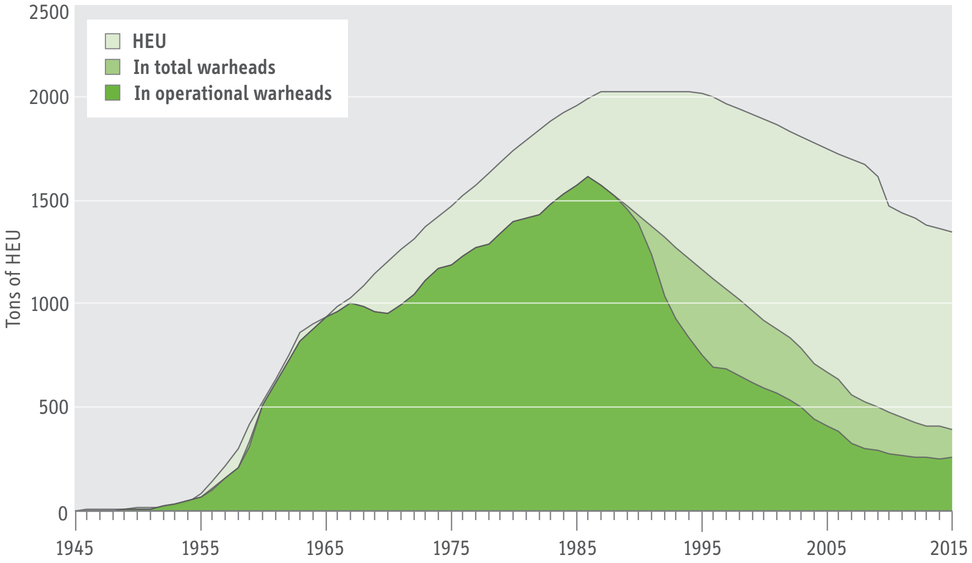

Figure 1. History of the global HEU stockpile. The figure shows estimates of the portion of the HEU stockpile in operational warheads and in warheads in the dismantlement queue.[3]

With the end of the Cold War, France, Russia, the United Kingdom and the United States announced that they had ended production of HEU for weapons and called for a global ban on the production of additional fissile materials for weapons – a Fissile Material (Cutoff) Treaty.

In 1993, the United Nations General Assembly adopted by consensus a resolution in support of:[4]

> "a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices."

At the end of the Cold War, Russia and the United States had stocks of HEU far in excess of their foreseeable needs. As of the end of 2014, they had down-blended a combined 663 tons of HEU to make low-enriched uranium (LEU) for use in power-reactor fuel; 517 tons of this HEU was Russian and 146 tons belonged to the United States.[5] Table 1 shows estimated HEU stockpiles available for military purposes as of the end of 2014, i.e., not including stocks reserved for civilian purposes and HEU in spent reactor fuel.

Of the remaining global stockpile of about 1370 tons of HEU, about 300 tons are in approximately ten thousand operational warheads and associated working stocks.[6] Since HEU can be recycled efficiently from old into new weapons, unless the weapon stockpiles grow again, little additional HEU will be needed for weapons.

Country	HEU production	Total HEU produced (tons)	Military HEU stocks, 2015 (tons)
United States	1945 – 1992	752	395
Soviet Union/Russia	1949 –	1350 – 1600	530 – 770
UK	1954 – 1962	9 – 13	~12
France	1967 – 1996	30 – 40	~26
China	1964 – 1987	17 – 25	~18
Israel	?	Small	~0.3?
Pakistan	1982 – continuing	2 – 4	~3
India	Early 1990s – continuing	2 – 4	~3
North Korea	Since late 2000s ?	?	?
Total		**2300 ± 140 tons**	**1100 ± 120 tons**

Table 1. HEU production and military stocks of the nuclear-armed states.[7]

France, the UK and the United States have decommissioned the gaseous-diffusion plants (GDPs) in which they produced their HEU and today only have commercial gas-centrifuge enrichment plants licensed to produce uranium enriched to less than six percent. The plants in the United Kingdom and United States are owned by the multinational, Urenco. Russia switched over to centrifuge enrichment while it was still producing HEU for weapons. China has shifted mostly to gas centrifuge enrichment but may still be operating one of its GDPs to enrich uranium for military reactor fuel.[8]

Given its huge stock of excess Cold War HEU, Russia's continuing production of HEU for non-weapon purposes requires explanation. This production became public in 2012 when Russia's nuclear fuel company, TVEL, announced plans to produce HEU for icebreaker, breeder and research reactor fuel.[9] One possible explanation is that, in the absence of sufficient orders for LEU, TVEL may simply prefer to use its excess enrichment capacity to satisfy its orders for HEU fuel rather than tapping into the national stockpile.[10]

It has long been recognized that HEU is of special concern because, while there is debate as to whether or not it would be possible for terrorists to master the implosion design required for a plutonium-based nuclear explosive, there is no debate that a terrorist group could potentially produce the gun-assembly design that is adequate for an HEU bomb.

The United States Atomic Energy Commission Advisory Panel on Safeguarding Special Nuclear Material reported in 1967 that there was a need for "minimum physical protection standards" and "safeguards programs should also be designed in recognition of the problem of terrorist or criminal groups clandestinely acquiring nuclear weapons or materials useful therein."[11]

Indeed, Luis Alvarez, who participated in the United States wartime nuclear bomb project, famously warned:[12]

> "With modern weapons-grade uranium, the background neutron rate is so low that terrorists, if they had such material, would have a good chance of setting off a high-yield explosion simply by dropping one half of the material onto the other half. Most people seem unaware that if separated U-235 is at hand it's a trivial job to set off a nuclear explosion, whereas if only plutonium is available, making it explode is the most difficult technical job I know."

Responding to the increased fears of nuclear terrorism after the attacks of September 2001, the Nuclear Security Summits in 2010, 2012 and 2014 sought to establish a principle of increasing the security of HEU and separated plutonium and minimizing the use of HEU. The 2010 Summit Communiqué declared that the leaders from 47 countries gathered in Washington DC:[13]

> "Recognize that highly enriched uranium and separated plutonium require special precautions and agree to promote measures to secure, account for, and consolidate these materials, as appropriate; and encourage the conversion of reactors from highly enriched to low enriched uranium fuel and minimization of use of highly enriched uranium, where technically and economically feasible."

Non-weapon uses of HEU

HEU is used to fuel naval-propulsion, isotope-production, breeder and research reactors, and in neutron targets for medical radioisotope production. The quantities consumed annually for each of these purposes are estimated below. Table 2 summarizes the results.

Requirements	Estimated annual HEU use
Naval-reactor fuel	4 tons/year
Isotope-production reactor fuel	1 ton/year (until 2023)
Breeder-reactor fuel	1 ton/year (weapon-grade equivalent) until 2020 or 2025
Research reactor fuel	0.7 tons/year
Medical isotope production targets	0.04–0.05 tons/year
Total	**~ 7 tons/year**

Table 2. Estimated annual HEU requirements for non-weapon uses.

Naval and icebreaker propulsion

Naval propulsion accounts for the largest number of HEU-fueled reactors worldwide and the largest annual use of HEU as fuel. Six nuclear-weapon states have nuclear-powered naval vessels and Brazil, a non-weapon state, has a development program underway (Table 3). Four of these seven: the United States, Russia, the United Kingdom and India fuel their propulsion reactors with HEU.

All currently operating naval nuclear reactors are pressurized water reactors. Most nuclear-powered vessels are submarines. Nuclear-powered aircraft carriers are central elements of the United States Navy, however, and Russia has civilian nuclear-powered icebreakers. The United States, Germany and Japan each built a single civilian nuclear cargo ship but found they were not economically competitive.[14]

Country	Nuclear ships/submarines	Fuel enrichment
	HEU fueled	
United States	10 aircraft carriers, 73 submarines[15]	93.5% weapon-grade HEU[16]
United Kingdom	11 submarines[17]	93.5% weapon-grade HEU (supplied by United States)[18]
Russia	42 submarines, 7 research-submarines, 2 cruisers, 6 icebreakers[19]	21–90+% HEU[20]
India	2 submarines (1 leased from Russia)[21]	21–45% HEU[22]
	LEU fueled	
China	9 submarines[23]	5% LEU[24]
France	1 aircraft carrier,[25] 10 submarines[26]	LEU (new submarine will be 6%)[27]
Brazil	Submarine under development	Less than 20% LEU[28]
Total	**11 aircraft carriers, 153 submarines, 2 cruisers and 6 icebreakers**	

Table 3. Naval nuclear propulsion programs as of 2015.

It is easy to understand the attractions of HEU as a naval fuel, especially for submarines. Most of the energy released from uranium fuel in a pressurized water reactor is from the fission of uranium-235. Weapon-grade HEU contains more than 90 percent uranium-235 and therefore is the most concentrated form of uranium-235 available. This makes it possible to reduce the volume of the fuel required to achieve criticality, which makes smaller cores feasible. Also, for a given core size and power, more uranium-235 in the core makes possible longer periods between refuelings.

The first naval propulsion reactor was built for the United States submarine *Nautilus*, commissioned in 1954. Its core reportedly was fueled with 18–20 percent enriched LEU.[29] The United States Navy quickly moved on to weapon-grade (greater than 90 percent uranium-235) fuel, however. Ultimately, increases in the uranium density of the fuel made possible lifetime cores in the new *Virginia*-class attack submarines (33-year design life) and the planned new United States ballistic-missile submarines (42-year design life).[30] The United States *Ford*-class nuclear-powered aircraft carriers, scheduled for delivery starting in 2016, will still be refueled at the midpoints of their 50-year lives.

Figure 2. USS Abraham Lincoln, a *Nimitz*-class United States aircraft carrier. Each of the ten United States *Nimitz*- class aircraft carriers is powered by two nuclear reactors fueled with weapon-grade uranium. *Source: U.S. Department of Defense.*[31]

The United Kingdom, too, fuels its nuclear submarines with weapon-grade HEU, which, since 1958, has been provided by the United States.[32]

Most of Russia's propulsion reactors use uranium that is less than weapon-grade but still HEU (i.e., enriched to 20 percent or more uranium-235) and therefore weapon-usable. India's submarine-propulsion reactor appears to have a similar design – perhaps because of Russian design assistance.[33]

France fuels its naval propulsion reactors with LEU and China is believed to do so as well.

Brazil is the first non-weapon state to launch a serious nuclear-submarine program. This has revived concerns about a "loophole" in the IAEA's Comprehensive Safeguards Agreement with non-weapon states. Under paragraph 14, a country can withdraw from safeguards material for use in non-proscribed "non-peaceful activities."[34] This loophole was originally introduced by Italy and the Netherlands, which were interested at the time in developing nuclear-powered ships and submarines respectively and were concerned that international inspectors not get access to classified naval design information.[35] It would be a particularly serious problem if the fuel were HEU and therefore directly weapon-useable. Brazil does not yet have nuclear submarines and its land-based prototype reactor is fueled with LEU but it has not foreclosed a future choice of HEU if that would be required to "optimize" the performance of a nuclear submarine.[36]

In 2013, during the confrontation over Iran's nuclear program, the then head of Iran's Atomic Energy Organization suggested that Iran might require uranium enriched to 45-56 percent uranium-235 for a nuclear submarine program.[37] This probably was a threat of further escalation at a time when Iran already was making 19.75 percent enriched uranium to fuel the Teheran Research Reactor. But it shows the vulnerability of the international nonproliferation regime to the non-proscribed, non-peaceful activities loophole in the Nonproliferation Treaty. A ban on the production of HEU for any purpose would close this loophole – at least for the potential diversion of this "direct use" nuclear material, which, without further enrichment, could be used to make a nuclear explosive.

According to current projections, the 152 tons of excess weapon-grade uranium that the United States committed for naval reactor fuel in 2005 will satisfy that need through 2064.[38] On this basis, the expected average rate of consumption of United States HEU for naval reactors would be about 2.5 tons per year. This presumably includes the United Kingdom's naval fuel requirements.

A projection for Russia's HEU use for the next ten years estimates an average of 1.6 tons of 90 percent HEU equivalent per year.[39] This includes the requirements for a nuclear submarine rented to India. India plans to build a fleet of up to five ballistic-missile submarines. For the next decade or so, however, India's consumption will be less than 0.1 tons per year of 90 percent HEU equivalent.[40]

In total then, the projected rate of use of HEU for naval reactors during the next decade is about 4 tons per year (90 percent enriched equivalent).

Tritium – production and breeder reactors

The second largest annual non-weapon use of HEU is in reactors that are used to produce tritium for nuclear weapons in Russia and in breeder reactors in Russia and China.

Tritium is used to "boost" the fission chain reaction in nuclear weapons with a burst of fusion neutrons. It is made mostly by neutron absorption in targets of lithium-6.[41] Tritium decays at a rate of 6 percent per year. Therefore, unless a warhead stockpile is reduced at a faster rate, the tritium in warheads must be replenished by new production.

The Russian and United States nuclear warhead stocks declined steeply at the end of the Cold War but have plateaued since and their production of tritium has resumed.

Most tritium is produced by neutron absorption in lithium-6 in a reactor core. It also is produced in heavy-water-moderated reactors by neutron capture on the deuterium.

Russia operates two HEU-fueled 1000-megawatt thermal (MWt) reactors at the Mayak Production Association in the Urals to produce tritium for weapons and radioisotopes for industry. These reactors, which are much higher power than research reactors, are estimated to use together about 1.1 tons of HEU fuel per year.[42] Given that Russia's nuclear-warhead stockpile has declined by almost a factor of ten since the two reactors were built around 1980, they must mostly be producing radioisotopes for other purposes today.[43]

In 2015, Mayak announced that a single new dual-purpose, electric power and isotope-production reactor will replace the two reactors by 2023.[44] No indication was given, however, as to whether the new reactor will be fueled by HEU or LEU.

During the Cold War, the United States used the HEU-fueled production reactors at its Savannah River Site to produce tritium for weapons until the last of those reactors was shut down in 1989. Currently, the United States produces tritium using a single LEU-fueled power reactor.[45] Since the United States and Russia have comparable numbers of nuclear weapons, it seems reasonable that Russia also could use an LEU-fueled power reactor to meet its tritium needs.

The United Kingdom produced tritium in its natural-uranium-fueled Chapelcross reactors until they were shut down in 2004.[46] Between 1960 and 1979, the United Kingdom also obtained tritium from the United States.[47] In the absence of a domestic source,[48] this arrangement may have been renewed.

France had two 190 MWt HEU-fueled tritium-production reactors that were shut down in 2009.[49] It appears likely that, in the future, France will produce its tritium using the new LEU-fueled naval prototype reactor, RES, currently under construction.[50]

China and India could obtain tritium from the moderator of their heavy-water reactors.[51] Israel probably produces its tritium in its Dimona production reactor.[52] On 6 January 2016, North Korea claimed to have tested a thermonuclear weapon. This seems doubtful but it is possible that it was a boosted fission explosion.

In the past, due to a lack of plutonium-fuel-fabrication capacity, Russia has fueled its prototype plutonium-breeder reactors with HEU. The BN-600 ahas been fueled with an estimated 3.7 tons of 21–26 percent enriched HEU fuel per year since it began operating in 1980 – equivalent in uranium-235 content to about 1 ton of weapon-grade HEU per year.[53] This HEU consumption will continue until the BN-600 is retired, currently projected for 2020 or 2025.[54] Russia plans to use plutonium fuel in its new BN-800 demonstration breeder reactor, as does India in its new Prototype Fast Breeder Reactor and China for future reloads of its Experimental Fast Reactor.

Research reactors

The value of HEU as a research-reactor fuel lies in the fact that it allows for small cores. This is beneficial to high-performance research reactors whose mission is to provide intense sources of neutrons for research and radioisotope production. For a given power, a smaller core produces a higher neutron flux (neutrons per second per square centimeter) in and around the core (Figure 3).

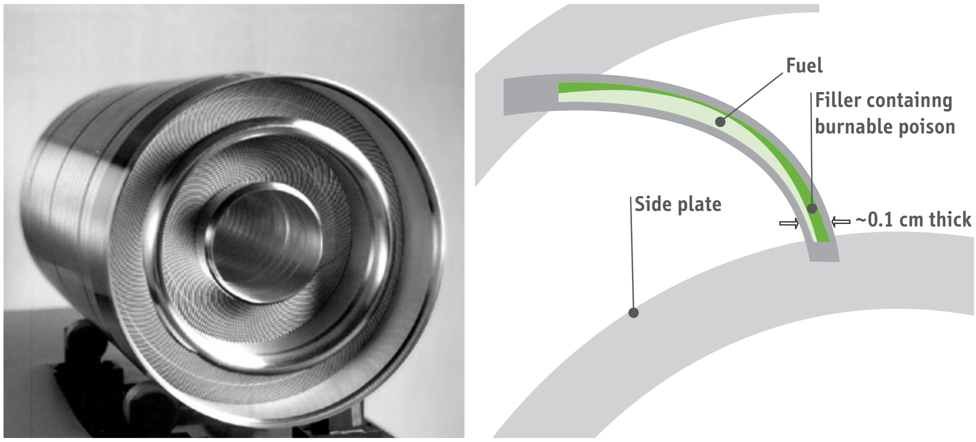

Figure 3. Core of the High Flux Isotope Reactor, Oak Ridge National Laboratory. The core is about 0.6 meters long and 0.4 meters in diameter, about the same size as an automobile engine but generates 85 megawatts of heat, hundreds of times more than an automobile engine at peak output. The empty space in the center is for samples requiring the highest intensity neutron flux. Cooling water flows between 171 curved fuel plates in the inner element and 369 in the outer element. The inset shows the complex cross-section of one of the plates, which contains both uranium and a neutron absorber to reduce the rate of heat production near the edges. *Source: BWXT and U.S. National Academy of Sciences.*[55]

Russia and the United States account for about 97 percent of historical HEU production.[56] During the 1950s and 1960s and, to a lesser extent thereafter, they each provided HEU-fueled research reactors to their own nuclear research institutes and universities, their allies, and also to other countries. Today, Russia and the United States still account for virtually all of the HEU supplied for research reactor fuel worldwide.[57] Figure 4 shows that United States exports of HEU for research and test reactor fuel, and targets for radioisotope production averaged more than one ton (tens of weapon-equivalents) per year during 1965–80. About half of this HEU was weapon-grade. Average United States exports of HEU since 2000 have fallen to about 0.05 tons or about two weapon equivalents per year.

Figure 4 also shows that Soviet and Russian exports outside the former Soviet Union (fSU) have averaged about 0.1 ton per year – one tenth of United States exports at their peak. As of the end of 2011, all the Soviet and Russian-provided HEU-fueled research reactors outside the fSU either had been converted or shut down and Russia's exports to those countries had ended. Starting in 1998, however, Russia has exported HEU to France and Germany, and to China to provide startup fuel for its experimental breeder reactor.

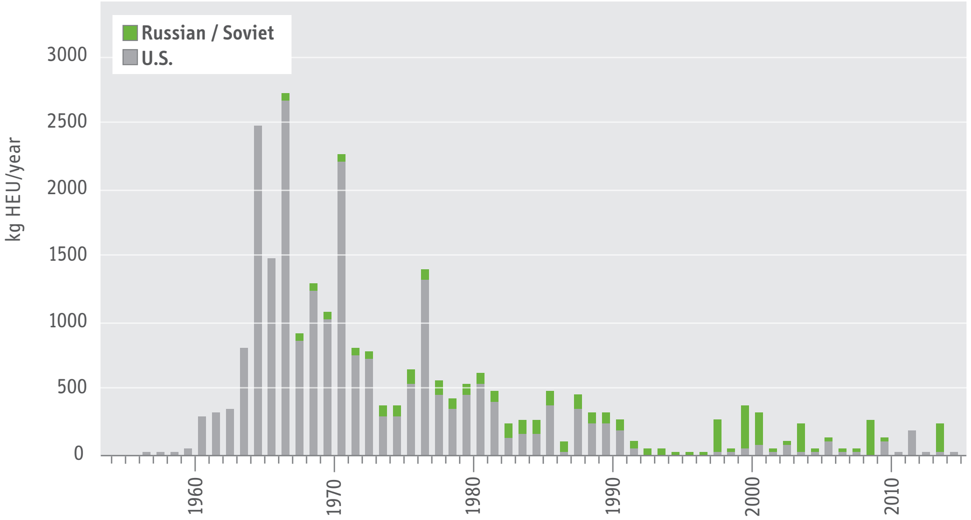

Figure 4. History of U.S. and Soviet/Russian HEU exports for civilian purposes.

The reduction in United States HEU exports is in part due to the decline in the global population of research reactors[58] and to Russia's supplying HEU for West European reactors previously supplied exclusively by the United States. It is also due in significant part to United States-led efforts to convert HEU-fueled research reactors to LEU fuel.

High-powered HEU-fueled reactors in the United States and Russia and Europe account for the remaining demand for HEU research reactor fuel.

Table 4 provides an overview of the remaining global population of HEU-fueled research reactors as of late 2015. A list of the reactors by country may be found on the website of the International Panel on Fissile Materials.

	High-power reactors (>30 kWt)	Low-power reactors (≤30 kWt)	Critical and subcritical assemblies	Pulsed reactors	Total
Russia	14	0	25 (3)	14 (10)	53 (13)
China		2	1		3 (0)
EU	4	2(1)	4	2(2)	12 (3)
USA	6	0	6 (5)	3(2)	15 (7)
Others	3	8	4	1	16 (0)
Total	**27**	**12 (1)**	**40 (8)**	**20 (14)**	**99 (23)**

Table 4. HEU-fueled research reactors by region and type, 2015. The number of military reactors in each category is shown in parentheses.[59]

Only the high-power research reactors use a significant amount of HEU.[60] Most reactors require about 2.8 grams of 90 percent enriched HEU per megawatt-day (MWt-day) of operation. For some reactors, the requirement is known to be higher; i.e., the "burnup" of the HEU fuel is less. This yields an estimate that the world's HEU-fueled research reactors require about 0.7 tons of HEU per year.[61]

Research reactors	Power (MWt)	Estimated HEU use	Initial criticality
Operating			
ATR, Idaho Falls, Idaho, U.S.	250	253 kg/year	1967
BOR-60, Dimitrovgrad, Russia	60	36 kg/year	1969
BR-2, Mol, Belgium	100	39 kg/year	1961
FRM II, Munich, Germany	20	33 kg/year	2004
HFIR, Oak Ridge, Tennessee, U.S.	85	66 kg/year	1965
MIR.M1, Dimitrovgrad, Russia	100	62 kg/year	1966
HFR, Grenoble, France	58	36 kg/year	1971
SM-3, Dimitrovgrad, Russia	100	70 kg/year	1961
Total		**595 kg/year**	
Not yet operating			
PIK, Saint Petersburg, Russia[62]	100		2012
Jules Horowitz, Saint-Paul-lès-Durance, France	100		2020?

Table 5. High-power reactors accounting for most of research reactor HEU use. All but one of the operating reactors are about 50 years old.

In 2015, about 90 percent of HEU use by research reactors was accounted for by 8 high-power research reactors that each require more than 30 kg of HEU in fuel per year: there are two such reactors in the United States, three in Europe and three in Russia. Two new high-powered reactors, one in France and one in Russia are expected to become operational soon (Table 5).

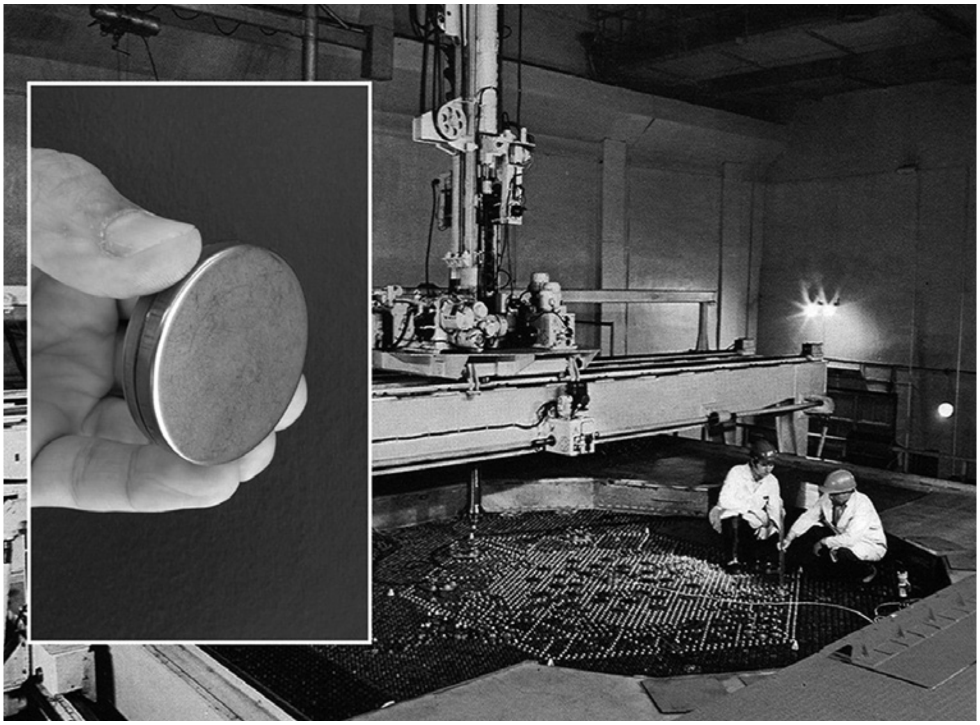

Figure 5. Russian critical assembly at Obninsk. Used for mocking up the core of a large breeder reactor, this assembly contains tens of thousands of lightly irradiated aluminum-clad disks of highly enriched and depleted uranium and plutonium metal and oxide. The total inventory as of 2013 was reported to include about nine tons of 36% and 90% enriched HEU. *Source: Institute of Physics and Power Engineering, inset: Alexander Glaser.* [63]

Table 4 shows that approximately 60 of the remaining 100 HEU-fueled reactors are critical assemblies (40) and pulsed reactors (20) – mostly in Russia. Such reactors fission so little uranium-235 that they do not require refueling. They contain barely irradiated HEU, however, which could be quickly converted to weapons use and is therefore of great security concern (Figure 5).

Targets for medical radioisotope production

HEU also is used in the production of radioisotopes for medicine. By far the most important of these radioisotopes is molybdenum-99 (Mo-99, 66-hour half-life), a fission product whose decay product, technicium-99m (Tc-99m, 6-hour half-life) is attached to biochemical tracers for gamma-ray imaging of organ functions.[64] Mo-99 is produced in uranium “targets” introduced into or next to research reactor cores. After about a week, Mo-99 production starts to be significantly offset by the decay rate of the accumulated inventory in the targets.[65] The targets are then withdrawn and the Mo-99 extracted and distributed to Tc-99m users as quickly as possible.

Since the fissions that produce Mo-99 occur dominantly in uranium-235, HEU targets have been preferred to minimize the amount of uranium from which the Mo-99 must be chemically separated. As of 2007, 95 to 98 percent of Mo-99 production worldwide was in HEU targets and the use of HEU for this purpose was estimated at 40 to 50 kg per year.[66] That is a reasonable estimate for 2015 as well.[67]

Most of the worldwide Mo-99 production is concentrated in a few places, Chalk River, Canada; Mol, Belgium; Petten, the Netherlands; Pelindaba, South Africa; and Sydney in Australia. The Chalk River facility is to close down in 2018. With government encouragement, a number of organizations are preparing to produce Mo-99 in the United States, which accounts for about half of global demand. With increasing demand for nuclear medical diagnostic applications in developing countries, production is likely to commence in other countries as well.

Converting away from HEU

Efforts to shift the non-weapon uses of HEU to LEU or to substitute technologies not involving fission are underway and are at various stages of development. Table 6 provides a summary.

HEU use	Stage of transition
Naval propulsion reactor fuel	France and China use LEU fuel New Russian nuclear icebreakers to use LEU fuel R&D on LEU fuel being considered in the U.S.
Isotope production reactors	Conversion feasible but no public information on intent
Breeder reactor fuel	New reactors will use plutonium fuel
Research reactor fuel	Many reactors have converted or shut down. Development of high-density LEU fuel needed by some high-power research reactors has been delayed
Radioisotope production targets	Transition underway

Table 6. Status of transition from HEU to LEU.

The status and prospects of these conversion efforts, and the specific challenges they face, are discussed below.

Naval and icebreaker propulsion

The countries that have developed or are developing nuclear-powered submarines have made different choices about the enrichment level of their naval fuel. France and probably also China are using LEU fuel in all their naval-propulsion reactors. There is therefore no question that it can be done. The United States, United Kingdom, Russia and India, however, use HEU fuel.

Until recently, the United States nuclear navy has been resistant to considering LEU fuel.[68] As is discussed below, space for at least a discussion of this topic has finally opened up. If the United States switched, the United Kingdom, which depends upon the United States for both naval nuclear technology and HEU, would be likely to switch as well. Given that both countries have moved to lifetime cores for their submarines, any LEU fuel that is developed would be used in new submarines. Aircraft carriers could be converted, however, at their mid-life refueling.

There is no indication that Russia has thought about using LEU in its nuclear submarines – as distinct from its new nuclear icebreakers, which are being designed to use LEU fuel. If Russia shifted, India, which may be as dependent on Russia for its naval reactor technology as the United Kingdom is on the United States, might also switch.

United States

As noted in the previous section, according to current United States Navy projections, the 152 tons of excess weapons uranium that was committed for naval reactor fuel in 2005 will be sufficient for projected Navy needs through 2064. This presumably includes the requirements of the United Kingdom's nuclear submarines, which have been fueled in large part with United States HEU since the United Kingdom stopped producing HEU in 1962.[69] More excess United States weapons HEU could be committed to naval fuel if necessary, since the number of operational United States warheads has declined from 8360 at the end of September 2005, the year the last United States declaration of excess was made, to 4717 at the end of September 2014.[70] As of the end of 2014, the amount of weapon-grade HEU still available for weapons in the United States was about 250 tons.[71]

In January 2014, after being asked by the House and Senate Armed Services Committees to provide an update on its views concerning the feasibility of shifting to LEU fuel, the National Nuclear Security Administration's Office of Naval Reactors (ONR) responded that:[72]

> "recent work has shown that the potential exists to develop an advanced fuel system that could increase uranium loading beyond what is practical today while meeting the rigorous performance requirements for naval reactors. Success is not assured, but an advanced fuel system might enable either a higher energy naval core using HEU fuel, or allow using LEU fuel with less impact on reactor lifetime, size, and ship costs."

With regard to the timeline and cost for the development of the new fuel, the report stated:[73]

> "The investment to develop a fuel technology and determine its viability is estimated to be up to $2 billion over at least 10 to 15 years. At least another ten years beyond that would be needed to deploy a nuclear reactor with this fuel."

Two billion dollars to develop and test the LEU fuel over 10 to 15 years would average $0.13 to $0.2 billion per year.

One reason for ONR's new receptivity to the idea of LEU fuel may be that it needs a project to fill in until a new reactor design is required. It currently has two ongoing projects: design of the propulsion reactor for the new class of ballistic missile submarines that are to replace the *Ohio*-class and refurbishing and refueling its land-based *Ohio* prototype S8G reactor at the Knolls Atomic Power Laboratory in upstate New York. In the absence of a new project, ONR's R&D budget is projected to peak in fiscal year 2019 and then to decline as these two programs wind down.[74]

In fact, in its 2014 report to Congress, ONR stated that significant parts of its naval-fuel-development capabilities could be lost without a new project:[75]

> "Essential staff and facilities needed to develop an advanced fuel system are in place and include unique resources such as the Advanced Test Reactor and other facilities within the Knolls Atomic

> Power Laboratory and the Bettis Atomic Power Laboratory. These capabilities are currently being sustained by ongoing new design work and design project funding. Once ongoing new ship design work is complete, it will not be practical to sustain all of the Program's unique technology capabilities or develop an advanced fuel system without other sources of funding. If these essential capabilities are lost, then development of an advanced fuel system will become impractical."

The next new-design United States propulsion reactor probably will be for the replacement to the *Virginia*-class attack submarine. The first submarine in that class, *Virginia*, was commissioned in 2004. Given its 33-year design life, it will have to be replaced in 2037. In the absence of significant new improvements being proposed, however, it is possible that the same reactor could be used for the replacement submarines.

We have been told that, while the new LEU fuel would have a significantly higher uranium density than the current HEU fuel used by United States propulsion reactors, if it were only 20 percent enriched, the amount of fission energy that could be extracted from it per cubic centimeter would be less. In that case, LEU-fueled lifetime reactor cores for submarines would either have to be larger than today or the submarines would require mid-life refueling – something that the navy is reluctant to consider at this point.

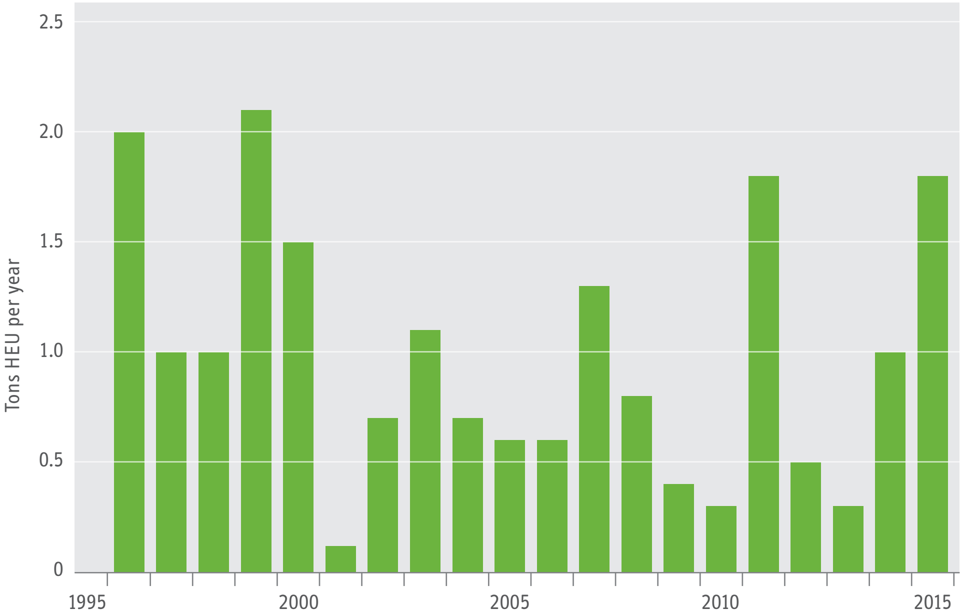

Figure 6. Quantities of HEU in U.S. spent naval fuel sent to Idaho for storage. The spent fuel is stored at the Naval Reactors Expended Core Facility in Idaho. All the peaks except that in 1999 – 2000 occur two years after the year of completion of an aircraft carrier refueling. Taking the difference between the averages of the peaks and the other years during 2005 – 15, when the effect of the mass post-Cold-War retirement of United States attack submarines would have abated, gives an estimate that United States aircraft carriers collectively accounted for about one third of the total HEU in the spent fuel during this period. *Source: Annual letters from the U.S. Navy to the Governor of Idaho, courtesy of Beatrice Brailsford of the Snake River Alliance, Idaho.*[78]

We also have been told, however, that conversion of the existing large reactors of the United States aircraft carriers to LEU might be feasible without increasing their refueling frequency.[76] The reactors on the new *Ford*-class aircraft carriers will have to be refueled at mid-life in any case. The first ship in this class, the *Gerald Ford*, is to be commissioned in March 2016 and would begin its mid-life overhaul and refueling 23 years later, in 2039.[77]

Converting United States aircraft carriers to LEU would significantly reduce the United States nuclear fleet's use of HEU. Each United States aircraft carrier has two reactors that are much more powerful than submarine propulsion reactors.[79] Figure 5 shows the pattern of fuel discharges by the United States nuclear fleet over 20 years. All but one of the peaks (1999 – 2000) occurred two years after an aircraft carrier defueling.[80] Assuming that the peaks above the average during 2005 – 15 represent the amount discharged by the aircraft carrier reactors, they collectively discharged about 50 percent as much HEU as the four times more numerous nuclear submarine reactors during this period.[81]

Congress responded to ONR's 2014 report in its appropriations for the fiscal year 2016 federal budget by designating:[82]

> "$5,000,000 to start a technical program to develop and qualify a low-enriched uranium (LEU) fuel system for naval reactor cores [and] to provide to the Committees on Appropriations of both Houses of Congress, not later than March 31, 2016, a report that describes the key goals and milestones, timeline, and annual budget requirements to develop a LEU fuel system for naval reactor cores."

United Kingdom

The United Kingdom depends upon the United States for naval nuclear technology. The 2014 amendment to the 1958 Agreement between the United Kingdom and the United States for Cooperation on the Uses of Atomic Energy for Mutual Defense Purposes gives a sense of the breadth of that dependence:[83]

> "The Government of the United States may authorize … transfer by sale to the … United Kingdom … submarine nuclear propulsion plants and parts thereof, including spare parts, replacement cores, and fuel elements … and … information as is necessary for the design, manufacture, and operation of submarine nuclear propulsion plants."

This recent amendment may have been necessary because of the mutual interest of the United States and United Kingdom nuclear navies in sharing the design of the new-generation United States reactors and their lifetime fuel so that the next class of United Kingdom ballistic missile submarines too can have lifetime cores.[84] Because of its dependence on the United States for naval reactor technology and fuel, if the United States shifted to LEU fuel, the United Kingdom probably would also do so.

France

Starting in the 1970s, France began to shift to LEU fuel in order to avoid incurring the high cost of refurbishing its enrichment plant once the HEU requirements of its weapons program were satisfied.[85] In the new *Suffern*-class attack submarines, the first of which is scheduled to enter into service in 2017, the level of enrichment will be 6 percent, the highest enrichment that France's George Besse II commercial enrichment plant is licensed to produce.[86] This is much lower than the 19.75 percent enrichment used to convert research reactors and that is being discussed for United States naval reactors.

The first French nuclear attack submarine *Rubis* (launched in 1979) was designed to use LEU fuel despite the fact that it was tiny by United States standards: 2600 tons submerged displacement vs. 6900 tons for the contemporary United States *Los Angeles* (1979).[87] A number of design innovations were undertaken to achieve its compact nuclear propulsion system. One was to put the steam generator inside the reactor pressure vessel. Another appears to have been to operate the control rods from the side rather than the top (Figure 7).

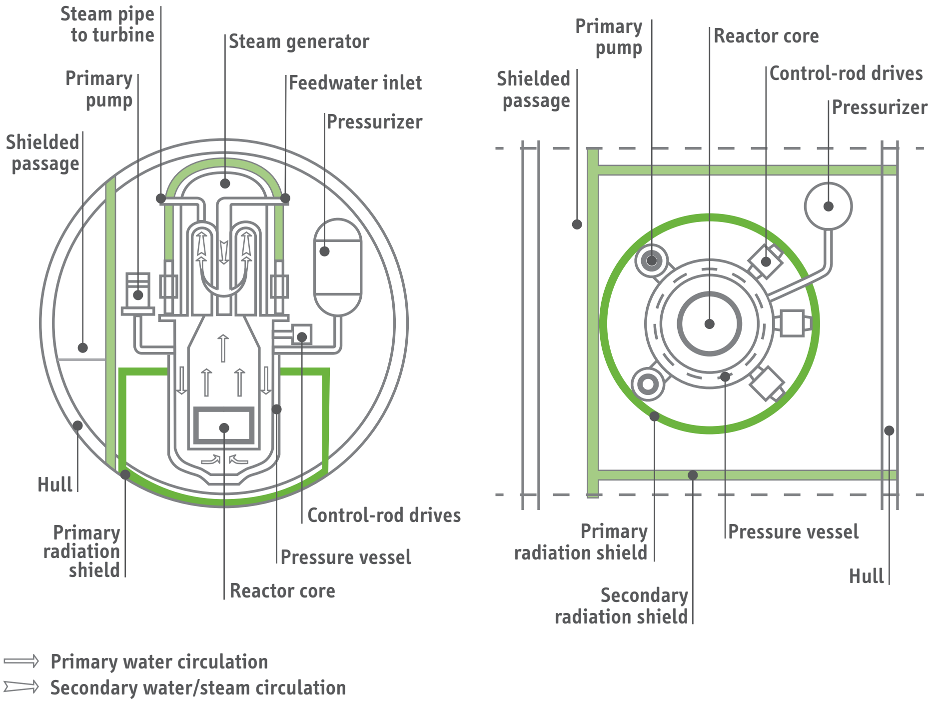

Figure 7. Naval propulsion reactor with integrated steam generator. In the vertical cross-section (left), it will be seen that the stream generator is inside the reactor pressure vessel. This arrangement, pioneered by France, is more compact than that used in United States nuclear submarines, where the steam generators are separate units connected to the pressure vessel with pipes. The thick enclosure around the lower part of the pressure vessel, which holds the core is the primary radiation shield. The thick barriers seen in the horizontal cross-section (right) at the front and back ends of the compartment and on the side, where there is a shielded passageway between the front and rear portions of the submarine, constitute the secondary radiation shield. Note also that the mechanisms for raising and lowering the control rods in the core are operated from the side rather than from above or below the reactor vessel, reducing the submarine diameter required. *Source: Adapted from Charles Fribourg.*[88]

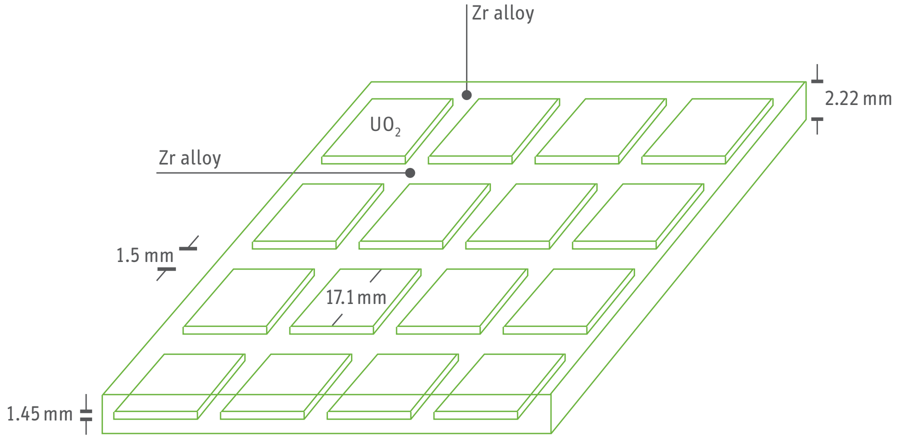

Figure 8. France's LEU "caramel" fuel. This high uranium density fuel was used to convert France's naval propulsion reactors to LEU. It is made of thin tablets of uranium oxide embedded in plates of zirconium alloy metal.[90]

France developed a high-density "caramel" fuel as part of its transition to LEU fuel. The fuel design was published because it also was used to convert France's *Osiris* research reactor to LEU. The uranium-containing fuel "meat" of the *Osiris* fuel was made of square tablets of UO_2, separated by strips of zircaloy (zirconium alloy) (Figure 8). The resulting average uranium density of the meat, including dividers, is 7 grams of uranium per cubic centimeter.[89]

The planned refueling frequency of France's next-generation *Suffern*-class attack submarines is ten years, matched with the timing of the required safety inspections of the nuclear reactor.[91] Theoretically, if the enrichment of the fuel were increased to 19.75 percent and the fuel "burn-up" per kilogram of uranium could be increased proportionately, it would be possible to achieve a lifetime core. The reported burn-up achieved with caramel fuel is only 50 MWt-days/kgU.[92] This is equivalent to the fission of 5 percent of the uranium and similar to the burn-up achieved in the 4 – 5 percent enriched UO_2 fuel pellets used in light water power reactors.

Fuel meat capable of higher burn-up would be required to realize the potential benefits of higher enrichment. The 19.75 percent enriched monolithic uranium metal alloy meat of the fuel being developed to convert high-performance research reactors to LEU fuel is designed to achieve a three times higher burn-up (see below).[93] This uranium alloy might not be suitable for naval fuel, however. Naval reactors have higher operating temperatures than research reactors, and their fuel must be mechanically more robust.[94]

Much of the reason for the 9-month refueling times of United States submarines is that their hulls are cut open and welded shut again after the new fuel is installed. This provides an additional incentive for developing lifetime cores. French nuclear submarines have refueling hatches, however. As a result it takes only about three months to completely remove the reactor core and its reactivity control system, carry out visual and ultrasound inspection of the pressure vessel and primary piping, and to load a fresh core.[95]

Russia

The challenge of developing LEU fuel for naval reactors may be significantly less for Russia than the United States.

Russia's third-generation submarine reactors, which dominate the current fleet, have zoned cores with enrichments ranging from 21 percent in the interior to 45 percent uranium-235 at the periphery.[96] Converting to LEU fuel enriched to less than 20 percent uranium-235 therefore would be a much smaller step than for United States and United Kingdom naval cores.

In addition, Russia's submarines are refueled about every ten years.[97] This too would make their cores much easier to convert to LEU fuel than the United States and United Kingdom lifetime cores.[98]

Finally, Russia has experience in developing LEU fuel for nuclear propulsion, including as replacement for HEU fuel. Rosatom has already designed the reactors of its new floating nuclear power plants and its new nuclear-powered icebreakers to use 19.75 percent enriched LEU fuel.[99]

In the case of the floating power plant, this choice may reflect Rosatom's interest in selling floating power plants to other countries.[100] There is a strong economic incentive, however, to maximize the refueling interval for both the floating nuclear power plant and the nuclear icebreakers. Economically, therefore, the shift to the new LEU fuel may have been made possible by the fact that it has about the same useable energy content per cubic centimeter as the 90-percent enriched fuel previously used.

The uranium density in the new fuel meat is about 6 grams/cc, twice that of the HEU fuel currently used in the icebreakers. The maximum burnup of 153 MWt-days/kgU is almost three times that of the French caramel fuel and of the fuel used in the current generation of Russian icebreaker reactors.[101] In this case, conversion to LEU fuel apparently involved no loss in fuel longevity.[102]

Tritium – production and breeder reactors

As noted earlier, Russia's two tritium-production reactors together use about a ton annually of HEU fuel and its breeder reactors use another ton (90 percent equivalent) per year. There has been little attention to phasing out this HEU use but it would appear to be straightforward.

With regard to Russia's HEU use for tritium and isotope production, the open question is whether or not the replacement production reactor planned for 2023 will be HEU or LEU-fueled.

It appears that Russia's use of HEU in its breeder reactors will continue until the BN-600 reactor is retired, which, in 2013, was projected for 2020 or 2025.[103]

Research reactors

The conversion of HEU-fueled research reactors to LEU fuel has attracted the greatest policy attention of any non-weapon use of HEU to date and there has been considerable progress. The remaining hard cases involve about half of the approximately 30 high-power research reactors that are still HEU-fueled and approximately sixty HEU-fueled critical assemblies and pulsed reactors (Table 4).

The United States Reduced Enrichment Research and Test Reactor (RERTR) program was launched in 1978, inspired in part by one of the few areas of agreement in the report of the contemporaneous International Fuel Cycle Evaluation:[104]

> "Although it may not be technically possible in some research reactors, decreasing the enrichment from 90% range as far as reasonable toward 20% would be a worthwhile improvement in proliferation resistance of research reactor fuels."

Development of high-density LEU fuel

The objective of the United States RERTR program has been to develop LEU fuels to replace existing HEU fuels. The Soviet Union launched a parallel program around 1980 with the initial objective of shifting the enrichment of its exported reactor fuels from 80 percent HEU to 36 percent HEU and then, in 1994, to 20 percent enriched LEU fuel.[105]

In the absence of offsetting design changes, there is a neutron intensity penalty of 5 to 10 percent associated with shifting to LEU because of neutron absorption by the greatly increased concentration of uranium-238 in the fuel.[106] This is a relatively minor penalty and can be more than offset with improved equipment in some important applications,[107] but it adds to the natural resistance of reactor operators to change.

In 1986, the United States Nuclear Regulatory Commission, which licenses all United States civilian reactors except those owned by the U.S. Department of Energy, mandated that HEU-fueled research reactors must convert to LEU as soon as suitable LEU fuel has been developed if federal funding to cover the expense of conversion is available. It also announced that it would not license any new HEU-fueled research reactors.[108]

In 1992, in the Schumer amendment to the Energy Policy Act, Congress extended the pressure to foreign research reactor operators who use fuel made with United States HEU. The Schumer amendment made it a requirement that the reactor operators commit to converting to LEU as soon as suitable LEU fuel became available.[109] Russia appears to have adopted the same condition for continuing to provide HEU to the countries it supplied.

After the terrorist attacks of 11 September 2001, the United States Government became more concerned about the possibility that terrorist organizations might acquire nuclear-weapon materials. In 2004, the RERTR program became part of the Department of Energy's Global Threat Reduction Initiative and its funding increased greatly. [110]

The goal for LEU fuel development has been, in effect, to dilute the uranium-235 in research reactor fuel to 19.75 percent enrichment by adding uranium-238 without increasing the volume of the fuel. This requires developing fuels with about five times higher uranium density than the HEU fuels they are replacing. In theory, this should be possible, since the pre-RERTR HEU fuel densities were less than 1.7 gramsU/cc,[111] while the density of uranium metal is 19 grams/cc. But pure uranium metal is not a suitable fuel.[112] The challenge therefore has been to find a high-density alloy or compound of uranium with properties suitable for a reactor fuel (Figure 8).

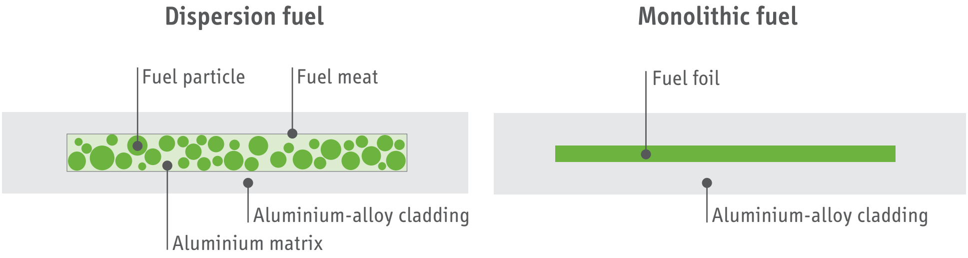

Figure 9. Research reactor fuel plates. The cross section on the left shows the typical meat of the fuel is particles of a uranium-containing material dispersed in aluminum surrounded by an aluminum cladding. In the highest-density LEU fuel currently under development, shown on the right, the meat is a thin foil of uranium-molybdenum alloy. *Source: U.S. National Academy of Sciences.*[113]

By 1989, a research-reactor fuel, whose meat was composed of a dispersion of U_3Si_2 particles in aluminum, had been developed with a density of 4.8 grams of uranium per cubic centimeter.[114] This has made it possible to convert many reactors. Specifically, by the end of 2014, approximately 65 HEU-fueled research reactors had been converted to LEU fuel.[115] In addition, about 150 HEU-fueled research reactors were retired during this period.[116] As a result of these conversions and retirements and a joint U.S.-Russian campaign to repatriate fresh and irradiated HEU fuel that they had exported, HEU was removed from 30 non-weapon states (Figure 10) and from many sites in the United States.

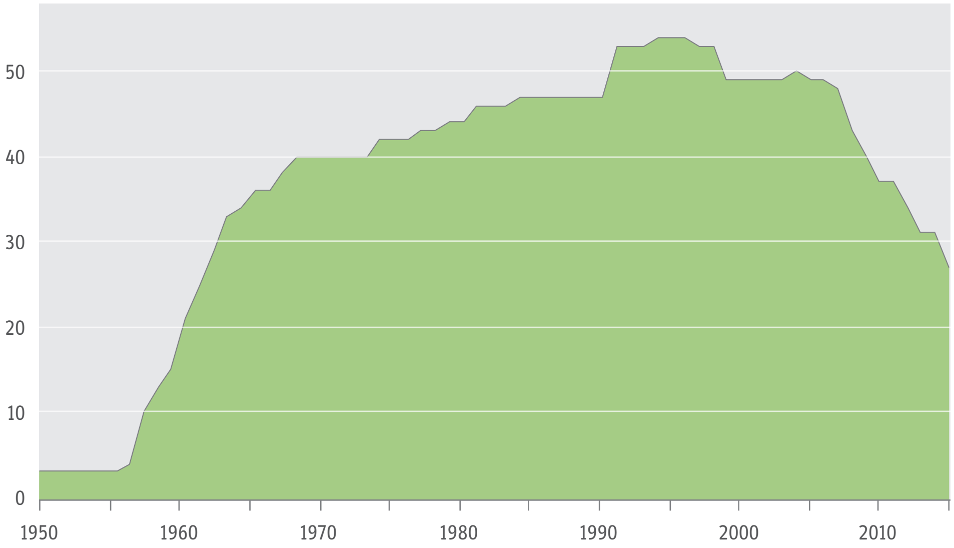

Figure 10. Number of countries with one kilogram or more HEU. The rise followed President Eisenhower's 1953 "Atoms for Peace" speech at the United Nations. The fall has been largely due to the U.S.-led efforts to convert reactors to LEU fuel and to repatriate fresh and spent HEU fuel to Russia and the United States. This effort started in 1978 but was given a much increased priority after the 11 September 2001 attacks on the United States. The sudden increase by six states in 1991 was due to the disintegration of the Soviet Union. As of the end of 2015, HEU had been cleaned out of thirty non-weapon states.[117]

As of the end of 2015, eight of the remaining 27 countries with one kilogram or more HEU (Argentina, Australia, India, Indonesia, Netherlands, Norway, Poland and South Africa) do not have HEU-fueled reactors.[118] This leaves 19 countries with about 100 HEU-fueled research reactors between them. Seven of these countries had only miniature low-power reactors produced by China and Canada with about one kilogram of HEU each in their long-lived cores. Replacement fuel has been developed and some of these reactors are being converted.[119]

There are an additional eleven HEU-fueled research reactors in six non-weapon states: Belarus (2), Belgium (2), Germany (1), Italy (1), Japan (3) and Kazakhstan (2). United States sanctions following the controversial reelection of President Lukashenko in 2010 derailed negotiations over the replacement of Belarus' HEU-fueled critical and subcritical facilities.[120] Efforts to convert Kazakhstan's reactors are underway.[121] The Belgian and German reactors require the development of higher-density fuels.[122] Studies are underway on the convertibility or replacement of the Japanese reactors.[123] The fuel of Italy's

Tapiro fast neutron source, like most of the pulsed reactors to be discussed below, is already made of maximum density uranium-molybdenum alloy.[124] It therefore would have to be replaced by an alternative neutron source.

The nine nuclear-weapon states collectively have about 80 HEU-fueled research reactors. Russia alone has about 50 (Table 7).

Country	Number of HEU fueled research reactors
Russia	52
United States	15
France	7
China	3 (2 miniature reactors being converted to LEU)
United Kingdom	1
Israel	1 (to be shutdown in 2018)[125]
Pakistan	1 miniature Chinese-designed reactor
North Korea	1

Table 7. HEU-fueled reactors in nuclear-weapon states.[126]

Some of the high-powered research reactors, including five in the United States and four in Europe, are awaiting advanced high-density LEU fuel.[127]

Funding for the development of higher density fuels was suspended in the United States from 1989 to 1995. The focus since that time has been on uranium metal alloyed with up to 10 percent by weight molybdenum (U-Mo) to stabilize its crystalline structure.[128]

The United States has focused its research and development effort on "monolithic" fuel with a uranium density of about 15.5 gramsU/cc while Russia, South Korea and Europe have focused on fuels with U-Mo particles dispersed in aluminum with a density up to 5.4, 8 and 8 gramsU/cc respectively.[129]

The tests of the radiation resistance of the U-Mo alloy were successful and, in 2007, the U.S. Department of Energy projected optimistically that:[130]

> "the [RERTR] program will, by 2010, complete development of new higher density LEU fuel and through FY 2012, complete the conversion from HEU to LEU fuel of a cumulative 95 of the 129 [HEU-fueled] civilian research reactors (the remaining 34 reactor conversions are planned for 2013 to 2018)."

When sample fuel elements were tested, however, irradiation caused weaknesses to develop at the interfaces between the U-Mo fuel meat and aluminum cladding of the monolithic fuel, and between the U-Mo particles and the aluminum matrix within which they were embedded in the dispersion fuel. Fabrication of the monolithic fuel also proved difficult. As of the end of 2015, the projected date for having monolithic fuel available for United States high-power reactors had slipped to around 2030.[131] The European fuel developers have not made such projections but their radiation tests for dispersion fuel currently extend through 2025.[132]

In view of this situation, a U.S. National Academy of Sciences study has proposed consideration of a strategy in which United States and European research reactors would be converted to lower HEU enrichments using the already licensed U_3Si_2 fuel and go to LEU when higher-density fuels become available.[133] This strategy has already been adopted for France's still-under-construction Jules Horowitz reactor, which was designed to use the U-Mo LEU dispersion fuel. Because of the delay in the availability of this fuel, the reactor is to start operating with 27 percent enriched U_3Si_2 fuel.[134]

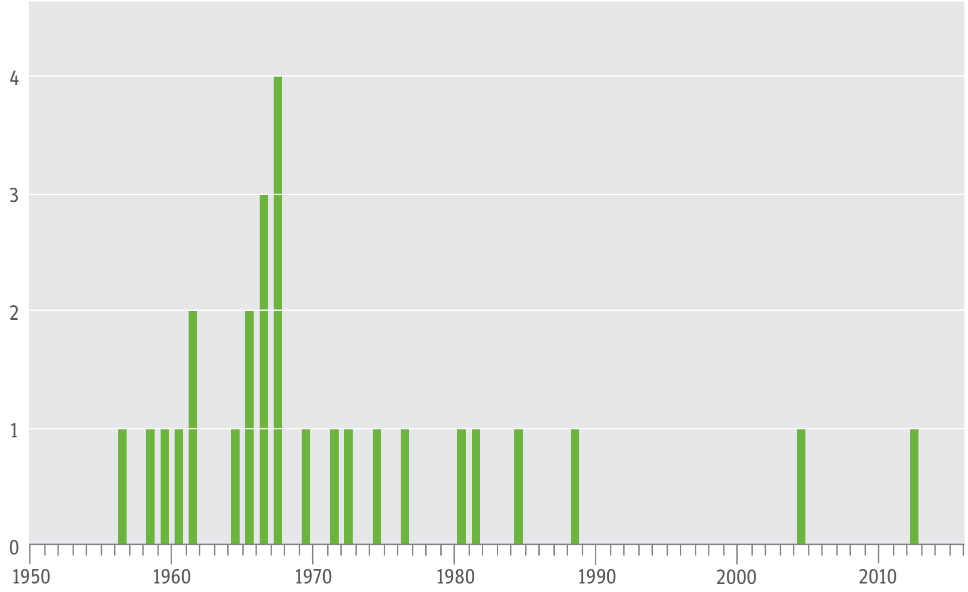

Figure 11. First criticality of high-power HEU-fueled research reactors. *Source: IAEA*.[135]

By 2030, however, most of the reactors to be converted with these fuels are likely to have retired or be close to retirement.[136] Figure 11 shows the dates of first criticalities of the 27 HEU-fueled high-power reactors that were operational in 2015 (fourteen in Russia, six in the United States, four in Europe and one each in Kazakhstan, Israel and North Korea). By 2030, only 10 of these reactors will be less than 60 years old.

Because of the norm that has developed against building HEU-fueled research reactors since 1978, it is worth accounting for the three that had their first criticalities after 1984:

- *Russia's OR-M Reactor.* Although the IAEA's Research Reactor Database (RRDB) shows the first criticality of the OR-M was in 1988, this was a modification of an old reactor on which construction began in 1950.
- *Germany's FRM II research reactor.* Construction on the FRM II began in 1996 and it went critical in 2004. Its designers caused a major scandal by designing a compact HEU core using higher-density fuel developed for converting research reactors to LEU.[137] The benefits to the users of going against the international norm are unclear. According the RRDB, the FRM II has only half the peak flux of France's high-powered High Flux Reactor, which had its first criticality in 1971.
- *Russia's PIK research reactor.* According to the RRDB, construction of Russia's PIK reactor started in 1976, 46 years before the reactor went critical in 2012. The apparent explanation of the long hiatus is that construction of the reactor was suspended after the 1986 Chernobyl accident. It was redesigned and construction resumed in 2007.

One reason for the low rate of construction of new high-power research reactors is that, in the United States, Europe and Japan, the research model in which every nuclear institute and research university has its own research reactor has largely been replaced. In the new model a few well-equipped national or international centers have high-power research reactors to which groups from many institutes can come to do their research.

A second reason is the rise of an alternative way of producing neutrons for research: proton-accelerator-driven spallation neutron sources in which intense beams of high-energy protons hit targets of heavy metal and "spall" neutrons off their nuclei.[138] These sources have the additional advantage for some types of experiments that the protons can be accumulated in a storage ring before being directed at the target, making possible intense pulses. The United States, after designing a new high-powered HEU-fueled research reactor to replace the Oak Ridge National Laboratory's aging High Flux Isotope Reactor (first criticality in 1965), decided in the 1990s to build a Spallation Neutron Source (SNS) instead as a collaborative project between six national nuclear laboratories.[139] The SNS came on line in 2007. A spallation neutron source has been built in Japan. China and Europe (in Sweden) both have such sources under construction.

Research-reactor fuel supply

In 2005, the United States set aside 20 tons of HEU from excess Cold War warheads for use to fuel research reactors until they can be converted – and space-based reactors if interest in them revives.[140] As of the end of September 2014, about 3 tons had been used for both United States (2.3 tons) and United States-supplied foreign research reactors (0.6 tons).[141]

The United States has allocated an additional 23 tons of its excess Cold War HEU to be blended down to 19.75 percent to fuel research reactors. As of 2012, it was supplying annually about 1.5 tons of 19.75 percent LEU for U.S. and foreign research reactors.[142] That amount could be produced by blending 0.26 tons of 90 percent enriched uranium down with 5 percent enriched uranium or by blending 0.32 tons with natural uranium. In the future, if HEU for blend-down runs low, one portion of one enrichment plant could satisfy the global demand for 19.75 percent uranium.[143]

Russia has much more excess HEU than the United States (see Table 1) and is also supplying both HEU fuel for reactors that are not yet converted and 19.75 percent LEU for foreign reactors that have converted.

As the numbers in Tables 4 and 7 suggest, Russia has not given a high priority to converting its own HEU-fueled research reactors or shutting down those that are underutilized. As a result, as of 2015, about half the HEU-fueled research reactors remaining in the world were in Russia.

In 2010, the United States government persuaded Russia to allow a joint conversion feasibility assessment for six Russian HEU-fueled civilian research reactors. One solution reactor was converted to LEU as a result.[144] Due to the deteriorating Russian-U.S. political relationship after Russia's incursions into Ukraine, the joint project was terminated in 2014 before other conversions could be undertaken.[145] The United States participants concluded, however, that the other five Russian reactors that had been analyzed could be converted with the tube-type U-Mo dispersion fuel with a 5.4 gramsU/cc meat density that Russia had in advanced development.[146] Of the seven other Russian high-powered research reactors, it was judged that two (IVV-2M and WWR-M) could be converted with pin-type fuel using the same dispersion fuel meat. Four pressurized higher-temperature research reactors (SM3, RPT-6, RBT-10 and PIK) would require the development of a new type of fuel.[147] The BOR-60 sodium-cooled fast-neutron materials testing reactor, is expected to be shut down in 2020.

Critical assemblies and pulsed reactors

Critical assemblies are mostly mockups used to check criticality calculations for nuclear-weapon components or reactor cores. When the reactors that they model are retired and converted to LEU, the critical assemblies too can be shut down or converted. Increasingly, however, they can be shut down in any case because high-resolution computer simulations have made them obsolete. An international database of the results of criticality experiments can be used to check or "benchmark" the accuracy of these computer simulations.[148]

Today, the United States has six HEU-fueled critical assemblies. One is a mockup of the core of the Advanced Test Reactor at the Idaho National Laboratory used to check the effect on its criticality of different arrangements of materials to be irradiated, and the other five have been moved from Los Alamos National Laboratory to the high-security Device Assembly Facility at the former Nevada Test Site (now the Nevada National Security Site) to be used for training weapons designers and safeguards experts.[149]

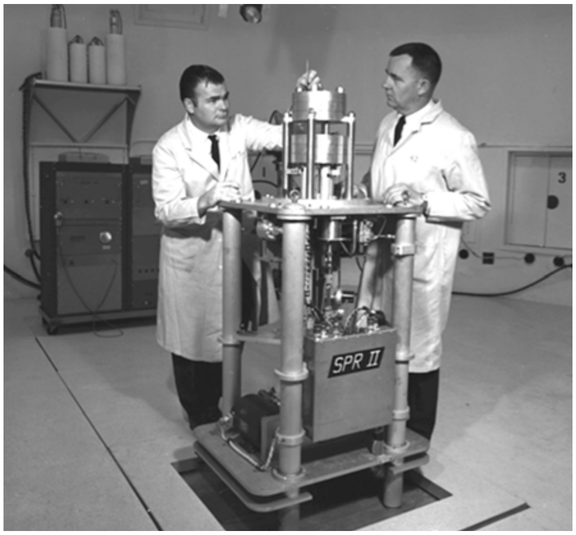

Figure 12. Sandia Pulsed Reactor II. The two metal cylinders at the top constituted the core. Samples were irradiated in an axial hole in the center. The reactor was made critical with control rods and then shut itself down as a result of increased neutron leakage out of the metal due to the thermal expansion caused by the release of fission energy. The control rods then would be positioned to assure that the core remained subcritical when it cooled. *Source: Sandia National Laboratory.*[150]

The core of a pulsed reactor is typically a cylinder of uranium-molybdenum alloy with an axial hole in which samples are subject to intense bursts of fission neutrons (Figure 12). The primary purpose of military pulsed reactors (two thirds of pulsed reactors) has been to test the radiation "hardness" of electronics subjected to a nearby nuclear explosion. As of 2015, the United States had three remaining pulsed reactors:

- The U.S. Army's Fast Burst Reactor, which is to be replaced by an accelerator-driven pulsed neutron source in order to save "security costs of several million dollars annually." [151]
- The multi-purpose Annular Core Research Reactor at the Sandia National Laboratory in Albuquerque, whose core at the bottom of a tank of water contains 15 kilograms of 35 percent enriched HEU.[152]
- The Transient Reactor Test Facility (TREAT) at the Idaho National Laboratory is to be converted to LEU fuel.[153] TREAT is used to test the behavior of reactor fuel during high-power transients.

The focus within the United States on retiring or consolidating HEU-fueled critical and pulsed reactors has been in good part due to the costly security requirements that have been imposed on nuclear materials in United States government-owned facilities since the attacks of 11 September 2001.

Three major U.S. Department of Energy (DOE) sites have been cleaned out of HEU and plutonium (defined as containing less than 1 kg of uranium-235 in HEU and 0.5 kg of plutonium):[154]

- Sandia National Laboratory in New Mexico, where the fuel of the Sandia Pulsed Reactor, containing about 225 kg weapon-grade uranium in slightly irradiated uranium-molybdenum alloy, was removed to the Device Assembly Facility at the former Nevada Test Site;[155]

- Hanford, Washington, one of the nation's two former military plutonium-production sites, whose remaining stock of separated plutonium was transferred for disposal to the Savannah River Site in South Carolina, DOE's other former military plutonium-production site;[156]
- Lawrence Livermore National Laboratory in California, a nuclear-weapon laboratory, whose special nuclear materials have been shipped to other sites.[157]

The National Nuclear Security Administration, which is responsible within DOE for the nuclear weapons laboratories, estimated that the cleanout of special nuclear material from Livermore's high-security "Superblock" alone would result in saving it security costs of $40 million per year.[158]

Other countries have not increased their security requirements for unirradiated HEU or plutonium to anywhere near the same degree. In 2014, concerned that Japan does not arm the guards at its nuclear facilities, the United States obtained an agreement to ship to the United States approximately 300 kg of unirradiated HEU and 330 kg of unirradiated plutonium from Japan's Fast Critical Assembly.[159]

Medical radioisotope production

Although the annual use of HEU for producing medical radioisotopes (mostly Mo-99) is a relatively small 40 to 50 kilograms per year, only about 3 percent of the uranium-235 in the targets is fissioned. The remainder accumulates in waste from which HEU could easily be recovered.[160]

The United States accounts for about half the global market for Mo-99 – with tens of millions of procedures per year.[161] It is not currently a Mo-99 producer, however. As of 2009, most of the global supply of Mo-99 came from the irradiation of HEU targets at five research reactors in Canada, Europe and South Africa.[162]

As of 2009, the HEU used for Mo-99 production targets in four of these five reactors was supplied by the United States. The exception was South Africa, which has its own stock of HEU from its former nuclear weapons program.

Two smaller suppliers use LEU targets: Argentina since 2002,[163] and Australia, which plans to become a significant supplier.[164] Other regional suppliers will most likely arise in the future with the increasing global demand for medical radioisotopes.

Since 1986, the United States RERTR program at Argonne National Laboratory has been developing LEU target designs (Figure 13) and promoting the use of these targets to Mo-99 producers and helping them adapt their Mo-99 recovery processes to LEU.[165] In 2012, Congress passed the American Medical Isotopes Production Act (MIPA), which included additional incentives and harnessed the market power of the United States as a consumer of half of the global Mo-99 supply to put pressure on the producers to convert.[166] Pressure also was exerted on the European producers in negotiations over shipments of additional United States HEU for their targets.[167]

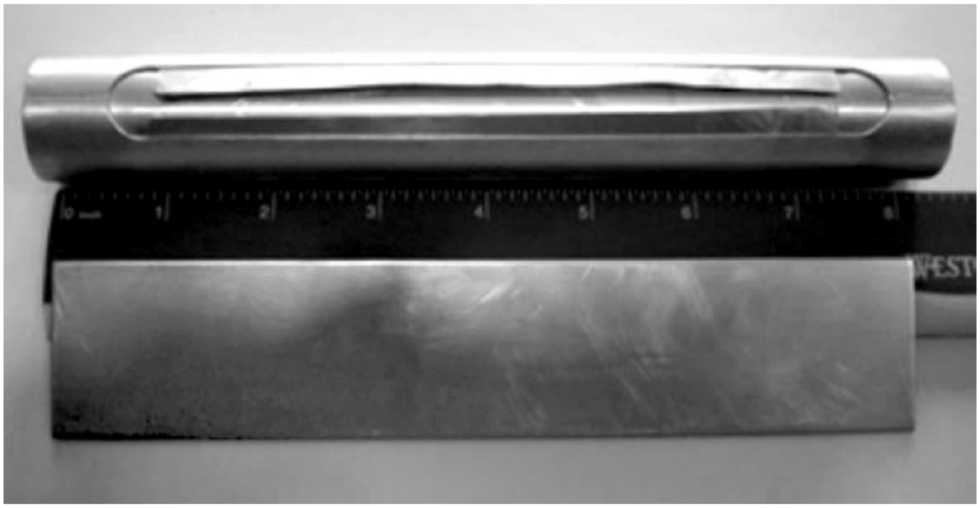

Figure 13. LEU (top) and HEU (bottom) targets for Molybdenum-99 production. These targets would produce the same amount of Mo-99 under the same irradiation conditions. Part of the outer aluminum layer of the LEU target (top) has been removed to show the nickel-coated LEU foil wrapped around an inner aluminum tube. Both targets contain about 5 grams of uranium-235. The LEU enrichment is 19.75 percent. *Source: IAEA*.[168]

In part at least because of this new pressure, the major producers finally appear to be moving forward on conversion to LEU targets:[169]

- South Africa announced in 2014 that it was “the first country in the world to successfully implement commercial scale LEU-based Mo-99 and I-131 production”;[170]
- In 2015, Mallinckrodt, which supplies 60 percent of the global Mo-99 market (75 percent of the United States market) projected that it would complete conversion to LEU targets in 2017;[171]
- The operators of Belgium’s BR-2 reactor expect to begin industrial-scale production of Mo-99 from LEU targets in 2016–17.[172]

In Russia, a number of nuclear institutes are producing Mo-99 for the domestic market and are also beginning to make small export deliveries, starting with Iran. Russia has its own HEU supply but likely would be responsive to market incentives to shift to LEU targets – for exports at least.[173]

It therefore appears that the shift away from HEU to LEU targets could be completed within a few more years if there is continued pressure to do so.

Conclusion

There is broad international support for a Fissile Material (Cutoff) Treaty which would ban the production of HEU and plutonium for nuclear weapons. Such a treaty would, however, leave open the possible production of HEU for non-weapon purposes such as nuclear reactor fuel or radioactive isotope production. Such production of HEU carries proliferation risks, since states may seek to divert for weapons the HEU that has been produced or stockpiled for non-weapon purposes. HEU stocks also pose a risk of theft for the purposes of nuclear terrorism, since a simple HEU-based gun-type weapon of the kind used on Hiroshima is within the reach of non-state groups. Reducing these risks from HEU requires a ban on the production of HEU for any purpose.

A road away from HEU-fueled nuclear reactors and the use of HEU targets for medical isotope production is open. It is only necessary for governments to decide to take it.

The most difficult challenge is to design naval propulsion reactors to use LEU fuel. France has done it already and it appears that China has always used LEU fuel. Russia is designing its new nuclear-powered icebreakers to use LEU fuel and this experience could help it convert its other nuclear vessels.

The United States has been the most reluctant to consider changing from HEU to LEU naval fuel, and has made the technical challenge of doing so the most difficult by using dense HEU fuel to achieve lifetime cores for its nuclear submarines. The United Kingdom has followed the United States down the same path. Recently, however, the Department of Energy's Office of Naval Reactors has reported to Congress, albeit with great ambivalence, that it may be possible to develop an even denser fuel that could make it feasible to shift to LEU naval fuel if that were desired. Congress has expressed a tentative interest in the possibility.

Russia can end its use of HEU-fueled reactors to produce tritium. It is building a new reactor to replace them. It has only to decide to design it to use LEU fuel, as has been done in other countries. Russia also plans to retire its HEU-fueled BN-600 breeder reactor within the next decade.

The effort to end the use of HEU fuel in research reactors has been underway for decades. There are about one hundred HEU-fueled reactors left – mostly more than 50 years old. Some of these reactors can be converted to LEU and most of those that cannot are obsolete and can be retired.

The transition to LEU targets for the production of medical radioisotopes is well underway and is likely to be virtually complete within the next few years.

In the meantime, even at current rates of use, there remains enough HEU from excess Cold War nuclear warheads to satisfy non-weapon needs of HEU for a period on the order of a century.

There is therefore no further need to produce HEU and an international agreement can be pursued to ban its production for any purpose.

Endnotes

[1] O.R. Frisch and R. Peierls, "On the Construction of a 'Super-bomb' based on a Nuclear Chain Reaction in Uranium," March 1940.

[2] There are reports that Pakistan is interested in nuclear submarines, "Pakistani Navy to Develop Nuclear-Powered Submarines: Reports," *Defense News*, 11 February 2012. Pakistan's near-term focus, however, appears to be on the possibility of deploying nuclear-armed cruise missiles on non-nuclear submarines, David Tweed, "Xi's Submarine Sale Raises Indian Ocean Nuclear Clash Risk," *Bloomberg News*, 16 April 2015.

[3] For fissile materials, IPFM, *Global Fissile Material Reports 2010* and *2015* and Hui Zhang, "China's uranium enrichment complex," *Science & Global Security* Vol. 23 (2015), pp. 171–190. For warheads, Hans Kristensen and Robert Norris, "Global Weapons Inventories, 1945–2013," *Bulletin of the Atomic Scientists*, 2013, assuming an average of 25 kg of HEU in each U.S. and Soviet/Russian warhead, based on declarations of historical stocks of U.S. HEU and warheads and estimates of the corresponding Soviet/Russian stocks. Numbers of warheads in dismantlement queues based on annual estimates published in the *Bulletin of the Atomic Scientists* by Kristensen and Norris for Russia and the United States.

[4] United Nations General Assembly Resolution 48/75L, 1993, www.ipfmlibrary.org/unga4875.pdf.

[5] Five hundred tons of Soviet/Russian 90-percent-enriched uranium from weapons "Megatons to Megawatts," http://www.centrusenergy.com/russian-contracts/megatons-megawatts; about 17 tons from Russian research institutes, U.S. Department of Energy, *FY 2014 Congressional Budget Request*, Vol 1, p. DN-98; *FY 2015, Congressional Budget Request*, p. 513; and 146 tons of U.S. excess HEU with 62 more tons of U.S. HEU designated for future blend-down, U.S. Department of Energy, *FY 2014 Congressional Budget Request,* Vol 1, p.565.

[6] Not including an estimated 3700 Russian and 2500 U.S. warheads awaiting dismantlement, Hans M. Kristensen and Robert S. Norris, "Worldwide deployments of nuclear weapons, 2014," *Bulletin of the Atomic Scientists*, 2014.

[7] The United States has declared its total HEU production and stocks. All other values are estimates published in *IPFM Global Fissile Material Reports 2010* and *2015*. Not shown here are about 150 tons of HEU in irradiated naval propulsion reactor fuel, 26 tons in or reserved for research reactor fuel and about 62 tons remaining from the 209 tons that the U.S. committed to be blended down to low-enriched uranium. An HEU stockpile of 0.1–0.5 tons has been suggested for North Korea, David Albright, "North Korean Plutonium and Weapon-Grade Uranium Inventories," Institute for Science and International Security, 7 October 2015.

[8] Hui Zhang, "China's uranium enrichment complex," *op. cit*.

[9] Pavel Podvig, "Russia is set to produce new highly-enriched uranium," 1 June 2012, http://fissilematerials.org/blog/2012/06/russia_to_resume_producti.html.

[10] Thomas Meade and Eileen Supko, "Enrichment excess is here to stay," *Nuclear Engineering*, 13 October 2015.

[11] *Report to the Atomic Energy Commission by the Ad Hoc Advisory Panel on Safeguarding Special Nuclear Material*, 10 March, 1967, p. 4. Reprinted in *Nuclear Safeguards*: *A Reader*, Report by the Congressional Research Service for the United Sates Congress House of Representatives Committee on Science and Technology, December 1983, http://njlaw.rutgers.edu/collections/gdoc/hearings/8/84602067/84602067_2.pdf.

[12] Luis W. Alvarez, *Alvarez: Adventures of a Physicist* (Basic Books, 1987) p. 125. The relevance of background neutron rate is due to the possibility that a spontaneous fission of a uranium or plutonium nucleus could set off a premature chain reaction in the fissile material. A chain reaction while the material was barely supercritical would build up slowly enough so that the pressures developed would disassemble the device before much energy was released. The spontaneous fission rate of plutonium-240, which is present in low single percentages in weapon-grade plutonium, is about a million fissions per second per kilogram vs. about 10 and 0.3 per second per kilogram for U-238 and U-235 respectively.

[13] Communiqué of the 2010 Nuclear Security Summit, Washington DC, 13 April 2010, http://www.state.gov/documents/organization/237037.pdf.

[14] The U.S. nuclear ship, *Savannah*, was launched in 1959; the German nuclear ship, *Otto Hahn*, in 1968, and Japan's *Mutsu* in 1970.

[15] There are also two land-based prototype reactors and two dock-side retired submarines used to train reactor operators. U.S. aircraft carriers are each propelled by two nuclear reactors, Ronald O'Rourke, *Navy Virginia (SSN-774) Class Attack Submarine Procurement: Background and Issues for Congress; Navy Ohio Replacement (SSBN[X]) Ballistic Missile Submarine Program: Background and Issues for Congress;* and *Navy Ford (CVN-78) Class Aircraft Carrier Program: Background and Issues for Congress*, Congressional Research Service, 23 September 2015.

[16] *Global Fissile Material Report 2010*, Table 2.2.

[17] "UK Royal Navy, Submarine Service," http://www.royalnavy.mod.uk/our-organisation/the-fighting-arms/submarine-service.

[18] *Global Fissile Material Report 2010*, Table 5.2.

[19] This includes 12 ballistic-missile submarines. The research submarines are for deep ocean exploration, Eugene Miasnikov, "Russian/Soviet naval reactor programs," in *The Use of Highly-Enriched Uranium as Fuel in Russia*, IPFM, forthcoming. Delta III and Delta IV-class ballistic missile submarines, Oscar II-class cruise-missile submarines, nuclear cruisers, and three of the six icebreakers are powered by twin reactors.

[20] *Global Fissile Material Report 2010*, Table 4.2.

[21] "India Submarine Capabilities," Nuclear Threat Initiative, 30 September 2015.

[22] Thirty to forty-five percent enriched for the Indian submarine, *Global Fissile Material Report 2010*, Table 9.2.

[23] Including four ballistic-missile submarines, *Military and Security Developments Involving the People's Republic of China 2015*, Annual Report to Congress, U.S. Department of Defense, 2015, pp. 8, 9.

[24] *China Today: Nuclear Industry*, China Social Science Press, Beijing, 198, p. 239, cited by Hui Zhang in *Global Fissile Material Report 2010*, endnote 508.

[25] France's *Charles de Gaulle* aircraft carrier is powered by two reactors.

[26] "France Submarine Capabilities," 28 September 2015, http://www.nti.org/analysis/articles/france-submarine-capabilities/.

[27] "France's Future SSNs: The Barracuda Class," *Defense Industry Daily*, 21 December 2011. The first submarine in this class will be the *Suffren*.

[28] Leonam Guimaraes, former Nuclear Propulsion Program Coordinator at Brazilian Navy Technological Center at Sao Paulo, personal communication, 29 July 2011.

[29] Norman Friedman, *Submarine Design and Development*, Annapolis, Md.: Naval Institute Press, 1984, p. 134.

[30] Stew Magnuson, "Nuclear Power Plants on New Submarines May Last 40-Plus Years," *National Defense*, February 2015.

[31] The aircraft carrier, *USS Abraham Lincoln* (CVN-72) underway at high speed, 1993, Collections, Best of the U.S. Navy Set 1, Image DN-ST-95-01174.

[32] Prior to 1996, the U.S. transferred HEU containing about 16 tons of uranium-235 to other countries for military purposes – almost all to the UK for naval-reactor fuel, *Global Fissile Material Report 2010,* Table 2.2.

[33] It has been reported that, starting in 1991, the Russian submarine-design bureau Rubin cooperated with India's Defense Research and Development Organization in developing the reactor for India's first nuclear submarine, *Asian Age*, 25 May 1996, p. 1.

[34] *The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons*, IAEA, INFCIRC/153, corrected, Paragraph 14, "Non-Application of Safeguards to Nuclear Material to be Used in Non-Peaceful Activities".

[35] David Fischer, *History of the International Atomic Energy Agency*: *The First Forty Years*, IAEA, 1997, pp. 272–3.

[36] Andrea de Sá, interview with Orpet Peixoto, a Brazilian official at the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials, in "Brazil's Nuclear Submarine Program: A Historical Perspective," *Nonproliferation Revie*w, Vol. 22, No. 1, 2016, pp. 3–25.

[37] "Iran may need highly enriched uranium in future, official says," *Reuters*, 16 April 2013.

[38] *Interagency review needed to update U.S. position on enriched uranium that can be used for tritium production,* (U.S. Government Accountability Office, 2014, footnote 10.

[39] Eugene Miasnikov, "Russian/Soviet naval reactor programs," *op. cit.*

[40] This assumes that the reactor cores have lifetimes on the order of ten years. The core of India's prototype submarine reactor reportedly contained about 70 kg of U-235 in 30–45% enriched HEU, *Global Fissile Material Report 2010*. India has declared an interest in building one or two nuclear-powered aircraft carriers and six nuclear-powered attack submarines in addition to three or four ballistic missile submarines, "The Indian Navy's design bureau is favourably considering nuclear propulsion for the second, and possibly a third indigenous aircraft carrier," *The Economic Times*, 14 December 2015.

[41] At the high temperatures inside a fission explosion, the thermonuclear reaction, tritium plus deuterium → helium-4 plus a neutron becomes possible. Tritium is produced via the reaction, neutron + lithium-6 → helium-4 plus tritium.

[42] Based on the fact that, as of 2002, Mayak had reprocessed about 20 tons of spent HEU fuel from these two reactors and that together they had operated for 36 reactor years by that time, Pavel Podvig, "History of Highly Enriched Uranium Production in Russia," *op. cit.* p. 65. The source of the 20-ton number is Vladimir Korotkevich, Evgeny Kudryavtsev, "Tekhnologia i Bezopasnost obrashcheniya s obluchennym yadernym toplivom v Rossiiskoi Federatsii "("Technology and Safety of Handling of Irradiated Nuclear Fuel in the Russian Federation") *Bulletenpo atomnoy energii*, *TsNIIAtominform*, No. 12, (2002) p. 26. During the period 2004–2016, only one of the tritium production reactors has been operating at one time. LF-2/Lyudmila was undergoing modernization in 2004–2011. *Ruslan* has been down for modernization since 2011 but is expected to come back online in 2016.

[43] A HEU-fueled production reactor can produce about 10 grams of tritium per GWt-day. This estimate is based on the estimate of about 1 kg of plutonium per GWt-day, *Global Fissile Material Report 2010*, Fig. 8.7 multiplied by the ratio of the atomic weight of tritium (3) to plutonium-239.

[44] "Mayak Combine starts design of a new research reactor," 2 October 2015, http://www.atomic-energy.ru/news/2015/10/02/60198.

[45] Four U.S. power reactors are licensed to produce tritium but, as of the end of 2015, only one had been used, *Draft Supplemental Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor* (U.S. National Nuclear Security Administration, 2014). In 1999, the Department of Energy indicated that 3400 Tritium-producing Burnable Absorber [lithium-6] Rods (TBARs) in one reactor would be sufficient to meet a requirement of 3 kg of tritium per year, *Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor* (DOE/EIS-0288, 1999) p. S–24. In 2014, this requirement was revised down to 2500 TBARs, Draft Supplemental *Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor* (DOE/EIS-0288-S1, 1999) pp. 2–5. That would scale the tritium production down to about 2.2 kg/yr. Assuming that the only tritium loss is to decay, the U.S. tritium stockpile would be about 40 kg or roughly 8 grams for each of the 4717 operational warheads that the U.S. declared as of the end of September 2014, *2015 Report of the United States of America Pursuant to Actions 5, 20, 21 of the 2010 Nuclear Non-Proliferation Treaty Review Conference Final Document, April 27*, 2015, p. 7.

[46] Donald MacKenzie, "The tritium factor," *The Independent*, 14 April 1996.

[47] 6.7 kg of tritium, Ministry of Defence, "The United Kingdom's Defence Nuclear Weapons Programme: Plutonium and Aldermaston – An Historical Account, 2000," p. 9.

[48] The last UK government-owned reactor with sufficient power to produce tritium on the scale that the UK needs was the Shore Test Facility prototype naval reactor, used for testing submarine-reactor fuel, which shut down in 2015, "Submarine test reactor at Scottish site shut down," *BBC*, 24 July 2015.

[49] *Global Fissile Material Report 2010*, p. 87.

[50] Construction on RES began in 2007, IAEA, Research Reactor Database.

[51] In heavy-water reactors, some neutrons are captured on the deuterium in the heavy water to make tritium. China has 1.35 GWe of heavy-water reactor generating capacity; India has 4.5 GWe; and, Pakistan 0.09 GWe, IAEA, Power Reactor Information System, 12 December 2015. Operating at capacity factors typical for Canadian heavy-water reactors, they could produce annually about 180 grams of tritium per GWe of capacity, P. Gierszewski, *Tritium Supply for ITER from Ontario Hydro*, Canadian Fusion Fuel Technology Project, CFFTP G-9616, April 1996.

[52] *Global Fissile Material Report 2010*, pp. 113–115.

[53] Podvig, Pavel. "History of Highly Enriched Uranium Production in Russia." *Science & Global Security* Vol. 19 (2011) p. 62. Updated numbers are 1.5 tons of 21% and 2.2 tons of 26% HEU, Pavel Podvig, personal communication, 3 February 2016.

[54] O.A. Potapov, "Operating experience from the BN600 sodium fast reactor," International Conference on Fast Reactors and Related Fuel Cycles, Paris, 3–7 March 2013, slide 28.

[55] The characteristics of the HFIR core are from https://neutrons.ornl.gov/hfir/core-assembly. The cross-section is from *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors,* National Academy Press, *2016,* p. 83.

[56] *Global Fissile Material Report 2010*.

[57] The U.S. has not supplied additional HEU fuel for Israel's IRR-1 reactor since the reactor was originally provided by the U.S. in 1958, "Israel's Soreq nuclear reactor to shut down in 2018," *Israel Hayom*, 21 March 2012, http://www.israelhayom.com/site/newsletter_article.php?id=3600. Russia's last supply of HEU fuel for North Korea's IRT-DPRK, originally provided by the Soviet Union in 1963, was in 1973, Nuclear Threat Initiative, "IRT-2000 Nuclear Research Reactor," 25 June 2012, http://www.nti.org/facilities/767/.

[58] For the history of the global fleet of research reactors prior to 2002, see "Research reactors," background paper prepared for the IAEA's 2004 General Conference, https://www.iaea.org/About/Policy/GC/GC48/Documents/gc48inf-4_ftn1.pdf. For the current status of the world's research reactors, see the IAEA's Research Reactor Database.

[59] International Panel on Fissile Materials, http://fissilematerials.org/facilities/research_and_isotope_production_reactors.html.

[60] The HEU requirements of a research reactor can be estimated by multiplying its power in thermal megawatts (MWt) times the number of days it operates per year, as reported to the IAEA's Research Reactor Database, http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?rf=1. The estimate for the megawatt-days (MWt-days) is then multiplied by an estimate of the number of grams of HEU required per MWt-day.

[61] The 2.8 grams of HEU per megawatt-day is obtained as follows: one gram of U-235 fissioned plus 0.25 grams transmuted to U-236 multiplied by two because only about 50% of the U-235 in the HEU is "burned up" in this way and divided by 0.9 for the assumed enrichment of the HEU. For the FRM II, HFIR, MURR and RHF, it was assumed that the U-235 burnup was less: 20, 30, 25 and 40% respectively, James Matos, Argonne National Laboratory Reduced Enrichment Research and Test Reactor Program, personal communication, 30 November 2015. Diakov has estimated the U-235 consumption of Russian reactors using Russian sources and obtains different numbers for individual Russian reactors but about the same total, Anatoli Diakov, "Prospects for Conversion of HEU-Fueled Research Reactors in Russia," *Science & Global Security* Vol. 22 (2014) pp. 166–187. A new National Academy of Sciences study reports about half as much HEU use by the U.S. Advanced Test Reactor, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.*, Table 4.5.

[62] In 2015, the IAEA's Research Reactor Database showed the reactor as still not operational.

[63] BFS2 critical assembly at the Institute of Physics and Power Engineering, Obninsk. Image downloaded from the institute website circa 2005. Information on the inventory of the BSF facility from Igor P. Matveenko, Valery Ya. Poplavko and Gennady M. Pshakin, "Decreasing HEU Stocks and Use at the Institute of Physics and Power Engineering," *Science & Global Security* Vol. 21 (2013) pp. 197–209.

[64] Globally, about 80 percent of diagnostic procedures using radioisotopes involve Mo-99, *The Supply of Medical Radioisotopes: 2015 Medical Isotope Supply Review: 99Mo/99mTc Market Demand and Production Capacity Projection, 2015–2020*, OECD, 2015, p. 1.

[65] *Medical Isotope Production Without HEU*, National Academy Press, 2009, Sidebar 3.1, "Six-day Curies," p. 35.

[66] *Medical Isotope Production Without Highly Enriched Uranium, op. cit.* pp. 11, 16.

[67] The National Academy estimate for 2007 was premised on a weekly global demand of 12,000 six-day Curies of Mo-99, *Medical Isotope Production Without Highly Enriched Uranium, op. cit.*, p. 66. In 2015, the OECD estimated that, due to improved efficiencies, the global demand had decreased to 9000 6-day Curies per week, *The Supply of Medical Radioisotopes, op. cit.*, OECD, 2015.

[68] In a report responding to a question from Congress, in 1995, the then Director of Nuclear Propulsion concluded, "The use of LEU for cores in U.S. nuclear powered warships offers no technical advantage to the Navy, provides no significant non-proliferation advantage, and is detrimental from environmental and cost perspectives," *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, June 1995, p. 1, http://fissilematerials.org/library/onnp95.pdf.

[69] *Global Fissile Material Report 2010*, p. 74.

[70] "Transparency in the U.S. Nuclear Weapons Stockpile," U.S. Fact Sheet presented at the 2015 NPT Review Conference and *Report of the United States of America Pursuant to Actions 5, 20, 21 of the 2010 Nuclear Non-Proliferation Treaty Review Conference Final Document*, 27 April 2015, p. 7.

[71] *Global Fissile Material Report 2015*, Figure 4.

[72] Department of Energy Office of Naval Reactors, *Report [to Congress] on Low Enriched Uranium for Naval Reactor Cores*, January 2014, p. ii.

[73] *Report on Low Enriched Uranium for Naval Reactor Cores*, *op. cit.* 2014, p. 5.

[74] Budget projections in Department of Energy, *FY 2017 Congressional Budget Request,* p. 610.

[75] *Report on Low Enriched Uranium for Naval Reactor Cores, op. cit.* 2014, p. 5.

[76] Discussions with Congressional and Office of Naval Reactors staff, January 2016.

[77] Tamir Eshel, "Newest Aircraft Carrier USS Gerald R. Ford Launched," *Defense Update*, 9 November 2013.

[78] The number for 2015 is the Navy's projection. Because shipments to Idaho were halted during 1993–5, the 1996 delivery may include more than one year's discharges.

[79] *Virginia*-class submarines have 25,000 shaft-horsepower vs. 260,000 for U.S. *Enterprise* aircraft carrier, Norman Polmar, *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet*, 19th edition, Naval Institute Press, 2013, pp. 73, 118. This suggests that the aircraft carrier fraction may be greater than this simple estimate finds.

[80] The last years of the refueling outages of U.S. aircraft carriers during this period were: *Enterprise* (1994). *Nimitz* (2001), *Eisenhower* (2005), *Vinson* (2009) and *Roosevelt* (2013), *Enterprise*: http://www.uscarriers.net/cvn65history.htm, *Nimitz*: http://www.uscarriers.net/cvn68history.htm, *Eisenhower*: http://www.uscarriers.net/cvn69history.htm, *Vinson*: http://www.uscarriers.net/cvn70history.htm, *Roosevelt*: http://www.uscarriers.net/cvn71history.htm.

[81] For the eleven years 2005 – 2015 after the massive post-Cold War downsizing of the nuclear fleet was over, the average of the eight non-peak years was 0.56 tons and of the three peak years was 1.63 tons. Subtracting the average from the peaks results gives 3.2 tons from the aircraft carriers and 6.2 tons from the submarines during this period, or an average of 0.29 and 0.56 tons per year respectively.

[82] Explanatory statement, "Division D-Energy and Water Development and Related Agencies, Appropriations Act, 2016," http://docs.house.gov/meetings/RU/RU00/20151216/104298/HMTG-114-RU00-20151216-SD005.pdf, p. 39. Although this accompanying guidance is not in the Appropriations law itself, it conveys the intent of Congress and therefore is generally complied with by executive agencies. The Defense Authorization Act for FY2016 provided more specific instructions, requiring that the Deputy Administrator for Naval Reactors submit:

> "a conceptual plan for a program for research and development of an advanced naval nuclear fuel system based on low-enriched uranium to meet military requirements. Such plan shall include the following: (1) Timelines; (2) Costs (including an analysis of the cost of such research and development as compared to the cost of maintaining current naval nuclear reactor technology); (3) Milestones, including an identification of decision points in which the Deputy Administrator shall determine whether further research and development of a low-enriched uranium naval nuclear fuel system is warranted; (4) Identification of any benefits or risks for nuclear nonproliferation of such research and development and eventual deployment; (5) Identification of any military benefits or risks of such research and development and eventual deployment; (6) A discussion of potential security cost savings from using low-enriched uranium in future naval nuclear fuels, including for transporting and using low-enriched uranium fuel, and how such cost savings relate to the cost of fuel fabrication; [and] (7) The distinguishment between requirements for aircraft carriers from submarines…"

National Defense Authorization Act for Fiscal Year 2016 (H.R. 1735) Conference Report, pp. 1180 – 1182.

[83] "Amendment to 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 Cooperation on the Uses of Atomic Energy for Mutual Defense Purposes, Washington, 22 July 2014," Article 2.

[84] Nick Ritchie, "The UK Naval Nuclear Propulsion Programme and Highly Enriched Uranium," Federation of American Scientists, 2015.

[85] Y. Girard, Technicatome, presentation at an MIT workshop on nuclear submarines hosted by Marvin Miller, written version dated 26 October 1989.

[86] Areva, "Expanding the U.S. Nuclear Infrastructure by Building a New Uranium Enrichment Facility," presentation at pre-application meeting with the U.S. Nuclear Regulatory Commission, May 21, 2007, http://pbadupws.nrc.gov/docs/ML0716/ML071650116.pdf.

[87] Displacement of *Rubis* from http://www.militaryfactory.com/ships/detail.asp?ship_id=FS-Saphir-S602; for *Los Angeles* from http://www.navy.mil/navydata/fact_print.asp?cid=4100&tid=100&ct=4&page=1.

[88] Charles Fribourg, "Réacteurs nucléaires de propulsion navale" Techniques de L'ingénieur, no. BN3141, pp 1 – 17, 2002, http://www.techniques-ingenieur.fr/base-documentaire/energies-th4/typologie-des-reacteurs-nucleaires-42456210/reacteurs-nucleaires-de-propulsion-navale-bn3141/.

[89] Francois Cherruau, "The Caramel Fuel in OSIRIS: The Complete Conversion of a High Flux Research to a Low Enriched Fuel," *Proceedings of the international meeting on development, fabrication, and application of Reduced Enrichment fuels for Research and Test Reactors (RERTR)* 1983.

[90] Chunyan Ma and Frank Von Hippel, “Ending the Production of Highly Enriched Uranium for Naval Reactors,” *Nonproliferation Review,* Spring 2001, pp. 86–101.

[91] “Replacing the Rubis: The Barracuda Class SSN,” http://www.defenseindustrydaily.com/frances-future-ssns-the-barracuda-class-02902/.

[92] J. P. Schwartz “Uranium Dioxide Caramel Fuel,: An Alternative Fuel Cycle for Research and Test Reactors,” Commissariat à 1'Energie Atomique – France, International Conference on Nuclear Non-Proliferation and Safeguards, Atomic Industrial Forum, 22–25 October 1978, New York.

[93] The requirements for U.S. high-performance research reactor range up to $7x10^{21}$ fissions/cc or 2.6 MWt-days/cc, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors*, National Academy Press, 2016, Fig. 4.3. The density of uranium in monolithic U-Mo fuel is about 15.5 grams/cc. The burnup therefore would be up to 170 MWt-days/kgU. TRISO particles containing uranium particles within three layers (from the inside out, low-density pyrolitic carbon, silicon carbide, and high-density pyrolitic carbon) have achieved burnups of 190 MWt-days/kgU, “Advanced Gas Reactor Fuel Program's TRISO Particle Fuel Sets A New World Record For Irradiation Performance” (DOE Office of Nuclear Energy announcement, 16 November 2009. However, the average uranium density of a TRISO particle is only about 1 gram/cc, John D. Hunn, “AGR-2 Fuel Compacts Information Summary: Prepared for the NRC MELCOR Project,” Oak Ridge National Laboratory, ORNL/TM-2010/296, 2010.

[94] Some fission products, notably the isotopes of krypton and xenon, are gases. They tend to migrate in the fuel and accumulate as small bubbles of gas between crystals and between the fuel meat and cladding. A higher operating temperature means higher pressure in these bubbles.

[95] French law requires these inspections to happen at least once every 10 to 12 years. They are usually part of a major overhaul of the entire submarine, Charles Fribourg, Technical Director, Technicatome, “Navires à propulsion nucléaire,” [“Nuclear-propelled ships”] (2001) http://www.techniques-ingenieur.fr/base-documentaire/energies-th4/typologie-des-reacteurs-nucleaires-42456210/navires-a-propulsion-nucleaire-bn3140/.

[96] В. М. Кузнецов, “Энергетические блоки атомного подводного флота” [V. M. Kuznetsov, “Power plants of the nuclear submarine fleet”] pp. 31–32, cited in Eugene Miasnikov, “Russian/Soviet naval reactor programs,” *op. cit.*; and Thomas Nilsen, Igor Kudrik and Alexandr Nikitin, *The Russian Northern Fleet: Nuclear-powered vessels*, Bellona, 1996, http://spb.org.ru/bellona/ehome/russia/nfl/nfl2-1.htm, section 2.3.7.

[97] In 1992, Russia’s Navy needed to refuel about 20 nuclear vessels per year out of about 150 in operation, A.V. Yablokov et al, *Facts and problems related to radioactive waste disposal in seas adjacent to the territory of the Russian Federation*, Office of the President of the Russian Federation, 1993, English translation by Small World Publishers, Inc., quoted in *Analysis of Risks Associated with Nuclear Submarine Decommissioning, Dismantling and Disposal*, Ashot A. Sarkisov and Alain Tournyol du Clos, eds., Springer, 1999, p. 92.

[98] It has been suggested that 4th-generation Russian nuclear submarines might be designed with lifetime cores, V. Apalkov, *Submarines of the Soviet Navy*, 1945–1991, Volume 3. *The third and fourth generations of submarines*, Moscow: Morkniga, 2009, p. 102 but there has been no confirmatory evidence.

[99] G. V. Kulakov et al, “Particulars of the Behavior Under Irradiation of Dispersion Fuel Elements with the Uranium Dioxide + Aluminum Alloy Fuel Composition,” *Atomic Energy*, Vol. 117, No. 4, February 2015 (Russian Original Vol. 117, No. 4, October, 2014).

[100] "Russian atomic agency Rosatom says 15 countries, including China, Algeria, Indonesia, Malaysia and Argentina, have shown interest in hiring such power plants for their own projects." in "1st mass-produced floating nuclear plant to power Russian Arctic in 2016," 21 April 2015, https://www.rt.com/news/251709-russian-arctic-nuclear-powerplant/.

[101] "Particulars of the Behavior Under Irradiation of Dispersion Fuel Elements with the Uranium Dioxide + Aluminum Alloy Fuel Composition," *op. cit.* For a discussion of the 90%-enriched uranium-zirconium alloy fuel currently used in Russia's icebreakers, see Ole Reistad and Povl L. *Ølgaard, Russian Nuclear Power Plants for Marine Applications,* Norwegian Radiation Protection Authority, NKS-138, 2006, p. 23.

[102] A discussion of the motivations for Russia's design of the new icebreaker reactors to use LEU fuel may be found in Christine Egnatuk, "Russia: Icebreaker Ships and Floating Reactors," chapter 5 in *Nuclear Terrorism and Global Security: The challenge of phasing out highly enriched uranium*, Alan Kuperman, ed., Routledge, 2013.

[103] O.A. Potapov, "Operating experience from the BN600 sodium fast reactor," *op. cit.*, p. 20.

[104] *International Nuclear Fuel Cycle Evaluation*, Vol. 8, IAEA, 1980, p. 138.

[105] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors*, *op. cit.*, p. 99.

[106] See e.g. S.C. Mo and J.E. Matos, "Conversion Feasibility Studies for the Grenoble High Flux Reactor," *Proceedings of the 12th International Meeting on Reduced Enrichment for Research and Test Reactors*, *Berlin,* Federal Republic of Germany 10–13 September 1989, http://www.rertr.anl.gov/LEUCONVS/RHF89.pdf.

[107] Alexander Glaser and Uwe Filges, "Neutron-Use Optimization with Virtual Experiments to Facilitate Research-Reactor Conversion to Low-Enriched Fuel," *Science & Global Security*, Vol. 20, No. 2–3 (2012) pp. 141–154.

[108] U.S. Nuclear Regulatory Commission, "Limiting the Use of Highly Enriched Uranium in Domestically Licensed Research and Test Reactors," *Federal Register*, Vol. 51, No. 37, 25 February 1986, Rules and Regulations, http://www.rertr.anl.gov/REFDOCS/NRCRULE.html.

[109] "Schumer Amendment" to the Energy Policy Act of 1992," http://www.rertr.anl.gov/REFDOCS/EPACT92.html.

[110] In 2015, the Global Threat Reduction Initiative was relabeled the Materials Management and Minimization Program *Department of Energy FY 2016 Congressional Budget Request*, Vol. I, p. 551, footnote.

[111] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit* (2016) p. 65.

[112] See e.g. Brian R.T. Frost, *Nuclear Fuel Elements: Design, Fabrication and Performance,* Pergamon, 1982, pp. 18–20.

[113] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) p. 62.

[114] Reduced Enrichment Research and Test Reactor program, "Qualified LEU Fuels," www.rertr.anl.gov/QualFuel.html.

[115] As of the end of October 2004, 38 reactors, Armando Travelli, "Status and Progress of the RERTR Program in the Year 2004," presentation at the 2004 International Meeting on Reduced Enrichment for Research and Test Reactors, 7–12 November 2004, Vienna, Austria. During the period 2004–2014, an additional 27 HEU-fueled reactors were converted to LEU, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) Table 6.1.

[116] About 130 during 1978–2007, Ole Reistad and Styrkaar Hustveit, "HEU Fuel Cycle Inventories and Progress on Global Minimization," *The Nonproliferation Review*, Vol. 15, No. 2 (2008) pp. 265–287; and 19 during 2008–14, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) Table 6.1.

[117] Dates of acquisition of HEU-fueled reactors based primarily on when those reactors first began to operate, although some of the early reactors were first fueled with LEU. Dates for cleanout based primarily on U.S. National Security Administration press releases.

[118] India is a nuclear-weapon state. Norway never had an HEU-fueled reactor but received 4 kg of U.S. HEU as a result of a retransfer from Euratom, *U.S. Nuclear Regulatory Commission's Report to Congress on the Disposition of Highly Enriched Uranium Previously Exported from the United States,* January 1993.

[119] As of the end of 2015, Canada (2), China (2), Ghana, Iran, Nigeria, Pakistan and Syria, all had reactors in the less than 30 kilowatt (thermal) class with about 1 kg of HEU fuel. The reactors in China, Ghana and Nigeria are being converted, Jordi Roglans, "GTRI Reactor Conversion Program: Scope and Status," presentation to the National Academy of Sciences Committee on Status and Progress on Eliminating HEU Use in Fuel for Civilian Research and Test Reactors, 23 October 2014, slide 7. The remaining three reactors in this power class are in France, Italy and Japan and have larger inventories of HEU in their cores.

[120] For a history of efforts and discussions with regard to converting or replacing the Belarusian facilities, see *The Global Politics of Combating Nuclear Terrorism: A Supply-Side Approach*, William C. Potter and Cristina Hansell editors, Routledge, 2013, chapter 6.

[121] Jordi Roglans, "GTRI Reactor Conversion Program: Scope and Status," 23 October 2014, *op. cit.* slide 19.

[122] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) Table 4.4.

[123] Jordi Roglans, "GTRI Reactor Conversion Program Scope and Status," 23 October 2014, *op. cit.*, slide 17.

[124] M. Carta and M. Palomba "TRIGA RC-1 and TAPIRO ENEA Research Reactors," presentation at an IAEA Consultancy meeting on Development of a Research Reactor Catalogue, Vienna, June 10–12, 2013.

[125] "Israel's Soreq nuclear reactor to shut down in 2018," *Israel Hayom*, 21 March 2012.

[126] IPFM, "Research and isotope production reactors," http://fissilematerials.org/facilities/research_and_isotope_production_reactors.html.

[127] In the U.S.: Advanced Test Reactor at the Idaho National Lab, High Flux Isotope Reactor at the Oak Ridge Laboratory, Department of Commerce Neutron Beam Split-core Reactor and MIT and University of Missouri research reactors. In Europe: Belgium's BR-2 reactor; France's Jules Horowitz and RHF reactors (Orphée is expected to be shut down prior to conversion); and Germany's FRM2 reactor, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) p. 65.

[128] Brian R.T. Frost, *Nuclear Fuel Elements: Design, Fabrication and Performance, op. cit.* p. 21.

[129] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) pp. 69, 79, 80.

[130] U.S. Department of Energy, FY 2008 *Congressional Budget Request*, Vol. 1, p. 516.

[131] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) pp. 81, 87.

[132] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) p. 78.

[133] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) p. 91.

[134] Jules Horowitz Reactor, "General Description," http://www-cadarache.cea.fr/rjh/general-description.html.

[135] IAEA, Research Reactor Database.

[136] According to the OECD Nuclear Energy Agency, of the high-power reactors that produced the medical radioisotope Mo-99 for export in 2014, all but one were expected to retire by 2030 after operating an average of 60 years. *The Supply of Medical Radioisotopes: Medical Isotope Supply in the Future: Production Capacity and Demand Forecast for the 99Mo/99mTc Market, 2015–2020*, OECD Nuclear Energy Agency, 2014, Appendix I.

[137] See e.g. Nuclear Threat Initiative, “Civilian HEU: Germany”.

[138] Thomas E. Mason, Masatoshi Arai, and Kurt N. Clausen, “Next-Generation Neutron Sources,” *Materials Research Society (MRS) Bulletin*, December 2003, pp. 923–928.

[139] Different national laboratories with relevant expertise designed different parts of the facility. The Lawrence Berkeley Laboratory designed the proton ion source; Los Alamos National Laboratory and the Thomas Jefferson National Accelerator Facility the linear proton accelerator; Brookhaven National Laboratory the proton storage ring; the host laboratory, Oak Ridge National Laboratory (ORNL), the spallation target; and Argonne National Laboratory and ORNL jointly the experimental setups for using the resulting neutrons, http://www2.lbl.gov/Science-Articles/Archive/SNS-front-end.html.

[140] No space reactor has been launched since 1988. The U.S. launched one in 1965 and the Soviet Union about thirty-six between 1965 and 1988 to power space radars tracking U.S. ships at sea, Steve Aftergood, “Background on space nuclear power,” *Science & Global Security*, Vol. 1 (1989) pp. 93–107. Interest continues, however, for both military purposes and space travel.

[141] Parrish Staples, NNSA, “Uranium Supply and Demand,” presentation to the National Research Council Committee on “Current Status of and Progress toward Eliminating Highly Enriched Uranium Use in Fuel for Civilian Research and Test Reactors,” 21 May 2015.

[142] Gary Person et al, Y-12 National Security Complex “Progress Down-Blending Surplus Highly Enriched Uranium,” Annual Meeting of the Institute for Nuclear Materials Management, 15–19 July, 2012, Orlando, Florida.

[143] The total combined power of the world’s research reactors is about 2 GWt, IAEA, Research Reactor Database. If all used 19.75% enriched uranium and operated on average 60% of the time with 40% of the U-235 in their fuel being fissioned, they would require about 5 tons of uranium in their fuel annually, which would require about 225,000 separative work units (SWU) per year to produce. A typical commercial enrichment plant produces several million SWU per year.

[144] In a solution reactor, a soluble uranium salt (usually a sulfate or nitrate) is dissolved in a tank of water to a concentration that results in the solution going critical.

[145] Jordi Roglans, Argonne National Laboratory, “NNSA’s Russian Reactor Conversion Program: Historical Overview, Major Accomplishments, Current Status,” presentation to the National Academy of Sciences Committee on Status and Progress on Eliminating HEU Use in Fuel for Civilian Research and Test Reactors, 16 April 2015, slide 23.

[146] OR and IR-8 at the Kurchatov Institute; IRT-MEPHI at the Institute of Engineering Physics in Moscow, IRT-T at the Tomsk Polytechnic Institute and MIR.M1 at the Research Institute of Atomic Reactors in Dimitrovgrad.

[147] *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, op. cit.* (2016) p. 65; and Anatoli Diakov, "Prospects for conversion of Russia's HEU-fueled research reactors," *Science & Global Security*, Vol. 22 (2014), pp. 166–167 and in the forthcoming IPFM report *The Use of Highly-Enriched Uranium as Fuel in Russia*.

[148] *International Criticality Safety Benchmark Experiment Handbook ICSBEP-2015*, OECD Nuclear Energy Agency, NEA-1486, 2015.

[149] "National Criticality Experiments Research Center," Nevada National Security Site Fact Sheet, 2013.

[150] "Sun sets on Sandia Pulsed Reactor," Sandia National Laboratory, press release, 4 September 2007. The dimensions given for the core of the SPR III, a modified version of the same reactor are: outside diameter 29.72 cm, inside diameter 17.78 cm, height 31.9 cm, and containing 227 kg of fully enriched uranium in 10 weight percent molybdenum alloy, *Design and Initial Performance of the Sandia Pulsed Reactor-III,* Sandia National Laboratory, SAND-75-6236, 1976.

[151] Phoenix Nuclear Labs, "More neutrons, less risk: Fast Burst Reactor Replacement," undated, http://phoenixnuclearlabs.com/case-study/fast-burst-reactor-replacement/.

[152] "Annular Core Research Reactor," http://www.sandia.gov/research/facilities/annular_core_research_reactor.html. When the other HEU was cleaned out of Sandia, the ACRR was downgraded as a security concern and kept. The justification was not clear. See U.S. Department of Energy Inspector General Report, *Removal of Categories I and II Special Nuclear Material from Sandia National Laboratories-New Mexico*, DOE/IG-0833, January 2010.

[153] I.J. van Rooyen et al, "Performance and Fabrication Status of TREAT LEU Conversion Conceptual Design Concepts," Conference on Reduced Enrichment for Research and Test Reactors, Vienna International Center, October 12–16, 2014. In the existing HEU fuel, about 20 kg of weapon-grade HEU is mixed homogeneously with about 10 tons of graphite moderator, J. H. Handwerk and R. C. Lied, *Manufacture of the Graphite-Urania Fuel Matrix for TREAT*, Argonne National Laboratory, ANL-5963, 1960, Appendix A.

[154] U.S. Nuclear Regulatory Commission, "Appendix M to Part 110 – Categorization of Nuclear Material".

[155] "First Phase of Nuclear Material Consolidation Complete," National Nuclear Security Administration press release, 28 February 2008 and "Sun sets on Sandia Pulsed Reactor," *op. cit.*, 4 September 2007.

[156] "Special Nuclear Material Removed from Hanford's Plutonium Finishing Plant, U.S. Department of Energy press release, December 2009.

[157] "NNSA Ships Additional Special Nuclear Material from Lawrence Livermore National Laboratory as Part of De-inventory Project," National Nuclear Security Administration (NNSA) press release, 10 November 2010.

[158] "NNSA Completes Removal of All High Security Special Nuclear Material from LLNL [Lawrence Livermore National Laboratory]," NNSA press release, 21 September 2012.

[159] Douglas Birch, "Japan agrees to return some plutonium," Center for Public Integrity, 11 March 2014. See also Douglas Birch et al, "Japan could be building an irresistible terrorist target, experts say," Center for Public Integrity, 20 November 2015.

[160] *Medical Isotope Production Without Highly Enriched Uranium*, National Academy Press, 2009, pp. 11, 16, 29.

[161] An estimated 23 million procedures a year in 2005, *Medical Isotope Production Without Highly Enriched Uranium*, Table 3.3, p. 51.

[162] *Medical Isotope Production Without Highly Enriched Uranium*, p. 34. Canada, the largest supplier of Mo-99 to the United States, plans to shut down its production reactor in 2018. Shutdown of the NRU reactor has been postponed repeatedly, however, most recently from 31 October 2016 to 31 March 2018, "Reprieve for Canadian isotope reactor," World Nuclear News, 9 February 2015.

[163] "Production and Supply of Molybdenum-99," IAEA, 2010.

[164] "ANSTO's production of medical isotopes: Supplying Australia and the world," Australia Nuclear Science and Technology Organization, Fact Sheet, 2014.

[165] See e.g. J.L. Snelgrove *et al*, "Development and Processing of LEU Targets for Mo-99 Production– Overview of the [Argonne National Laboratory] Program," Presented at the 1995 International Meeting on Reduced Enrichment for Research and Test Reactors, September 18–21, 1994, Paris, France.

[166] National Defense Authorization Act for Fiscal Year 2013, Public Law 112–239, Title XXXI, Subtitle F, "American Medical Isotopes Production". The Act includes:
1) Cost sharing for the establishment of Mo-99 production in the United States not using HEU targets;
2) A lease system for LEU targets under which the DOE will take back the residual waste; and
3) Termination of HEU exports for targets within seven years unless there is still an insufficient supply of Mo-99 made without HEU.

[167] *Nuclear Terrorism and Global Security: The challenge of phasing out highly enriched uranium, op. cit.*, pp. 92–94.

[168] *Non-HEU Production Technologies for Molybdenum-99 and Technicium-99m*, IAEA, 2013, p. 8. The LEU target contains almost five times as much uranium as the HEU target. The HEU target is thicker because its uranium is dispersed in aluminum to a density of 1.7 gramsU/cc, less than one tenth the 19 gramsU/cc density of the uranium metal foil inside the LEU target.

[169] For additional information on the issues that have arisen re conversion in Belgium and the Netherlands, see Alexander Fay, "Belgium and the Netherlands," chapter 6 in *Nuclear Terrorism and Global Security, op. cit.*

[170] "NTP Radioisotopes: A Glowing Example of a South African Triumph!," press release, 30 May 2014. Gavin Ball, the leader of the effort complained, however, about "increased costs [and] decreased production capacity," "Experiences of HEU to LEU Mo-99 Production Conversion at NTP," IAEA Consultancy on Conversion Planning for Mo-99 production facilities for HEU to LEU, 24–27 August 2010, Vienna and G. Ball, "Reflections on Five Years of Conversion Experience," Mo-99 2015 Topical Meeting on Molybdenum-99 Technological Development, 31 August–3 September 2015, Boston, Massachusetts.

[171] Roy W. Brown, "Mallinckodt Progress towards Conversion to Low-Enriched Uranium (LEU) Production of Molybdenum-99 (Mo-99)," briefing to the National Academy Sciences Committee on the State of Mo-99 Production and Utilization and Progress toward Eliminating Use of Highly Enriched Uranium (HEU) May 11, 2015. Mallinckrodt processes Mo-99 targets from the Netherlands' HFR reactor, Poland's Maria reactor and Belgium's BR2 reactor.

[172] Bernard Ponsard, "Irradiation of LEU targets in the BR2 reactor for Mo-99 production," Mo-99 2015 Topical Meeting" 31 August–3 September 2015, Boston, Massachusetts, *op. cit*. The 15–20 percent reduction in Mo-99 produced per target is to be offset by an increase in the fraction of the year that the BR-2 irradiates Mo-99 production targets.

[173] Anton Khlopkov and Miles Pomper with Valeriya Chekina, "Ending HEU Use in Medical Isotope Production: Options for US – Russian Cooperation," Nuclear Threat Initiative, 2014.

About the author

Frank von Hippel, a Senior Research Physicist and Professor of Public and International Affairs emeritus in Princeton University's Program on Science and Global Security, has worked on fissile material policy issues for forty years. He co-founded the IPFM, Princeton's Program on Science and Global Security and the journal, *Science & Global Security*. During 1983–89, he partnered with Gorbachev's arms control advisor Evgenyi Velikhov to propose measures to end the nuclear arms race. During 1993–94, as Assistant Director for National Security in the White House Office of Science and Technology Policy, he helped launch U.S.-Russian cooperative nuclear security programs and led the inter-agency group on plutonium disposition.

A report published by
The International Panel on Fissile Materials (IPFM)
www.fissilematerials.org

Program on Science and Global Security
Princeton University
221 Nassau Street, 2nd Floor
Princeton, NJ 08542, USA

March 2016

Krænk Visuell