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A Comprehensive Approach to Elimination of Highly-Enriched-Uranium From All Nuclear-Reactor Fuel Cycles

Frank von Hippel

> "I would be prepared to submit to the Congress of the United States, and with every expectation of approval, [a] plan that would . . . encourage world-wide investigation into the most effective peacetime uses of fissionable material . . . with the certainty that the investigators had all the material needed for the conducting of all experiments that were appropriate."
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> –President Dwight D. Eisenhower at the United Nations, Dec. 8, 1953,

Over a period of about a decade after President Eisenhower's "Atoms for Peace" speech, the U.S. and Soviet Union exported research reactors to about 40 countries. By the mid-1970s, most of these reactors were fueled with weapon-useable highly-enriched uranium (HEU), and most of those with weapon-grade uranium. In 1978, because of heightened concern about nuclear proliferation, both countries launched programs to develop low-enriched uranium (LEU) replacement fuel containing less than 20 percent ^{235}U for foreign research reactors that they were supplying with HEU fuel.

By the time the Soviet Union collapsed, most of the Soviet-supplied research reactors outside the USSR had been converted to 36% enriched uranium but the program then stalled because of lack of funding. By the end of 2003, the U.S. program had converted 31 reactors to LEU, including 11 within the U.S. If the development of very high density LEU fuel is successful, it appears that conversion of virtually all remaining research

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reactors with steady powers greater than 1 megawatt (MWt, thermal) could be completed by approximately 2012. It is also technically straightforward to convert to LEU the HEU targets used in the production of the fission product ^{99}Mo, whose decay product ^{99}Tc is widely used in medical procedures. However, there are political obstacles to ending the use of HEU in research and medical-isotope-production reactors. The big ^{99}Mo producers are resisting conversion, and Russia has not yet committed to convert its own research reactors. Furthermore, large classes of reactors fueled with HEU including critical facilities, pulsed reactors, icebreaker propulsion reactors and naval reactors, have not yet been targeted for conversion.

Most HEU-fueled reactors do not need to be converted, however. About a hundred underutilized HEU-fueled reactors should be shut down instead, and they and about another hundred already shutdown HEU-fueled reactors must be decommissioned. The fresh and spent HEU fuel at these reactor sites, as well as at the sites of reactors being converted, must be recovered and blended down to LEU. In 1996, the U.S. resumed taking back spent U.S.-supplied HEU fuel from foreign reactors. Recovery of fresh HEU fuel from foreign reactors supplied by the former Soviet Union began in 2002 with U.S. financial assistance, but return to Russia of spent exported Soviet and Russian HEU fuel is stalled.

All these slow-moving programs must be consolidated and broadened into a comprehensive high-priority effort to eliminate HEU from all nuclear fuel cycles, including those of icebreaker, tritium-production and naval-propulsion reactors. Recently, there have been signs of increasing political support within the U.S. for a more comprehensive effort to help eliminate HEU from civilian nuclear fuel cycles worldwide. This article provides a preliminary map of the territory that would be covered by such a program.

INTRODUCTION

In a little more than a decade following President Eisenhower's 1953 "Atoms for Peace" speech, the nuclear-weapon states (primarily the U.S. and Soviet Union) exported research reactors to approximately 40 countries. Although the reactors first exported were fueled with non-weapon-useable low-enriched uranium (LEU, $<$20 percent ^{235}U) fuel, desire for higher neutron fluxes and longer fuel life, in combination with a loosening of export restrictions, resulted in a shift to high-enriched fuel ($\geq$20% ^{235}U)—usually weapon-grade uranium (WgU) containing 90 percent or more ^{235}U.[1]

The U.S. and Soviet Union built even more HEU-fueled research reactors domestically than they exported. The U.S. Department of Energy has identified 161 operating research reactors designed to use HEU fuel.[2] Those in China and the U.K. and some in France are fueled with domestically produced HEU, and those countries each provided a small amount of HEU to fuel research reactors that they have exported. Russia and the U.S. have been the dominant suppliers, however. The five original nuclear-weapon states (the U.S., Russia, U.K., France, and China) also have other types of reactors fueled with HEU: naval and Russian icebreaker propulsion reactors, plutonium and tritium production reactors, and in the past—and potentially the future—space-power reactors. Many of these reactors have higher power ratings than most research reactors and therefore require a larger flow of HEU fuel. In addition, HEU is used as the target material for production of the fission product ^{99}Mo, whose radioactive decay product, ^{99}Tc, is widely used in medicine.

HEU AND THE DANGER OF NUCLEAR TERRORISM

HEU, unlike plutonium, can be used to make simple nuclear explosives, such as the one the U.S. used on Hiroshima. That weapon contained about 50 kg of ^{235}U in uranium with an average enrichment of about 80%.[3] The neutron-production rate in 60 kg of metallic weapon-grade (93% U-235) uranium, from both spontaneous fission and (α,n) reactions on oxygen, is about 10^2 per second. This relatively low rate makes it possible to use the simple but relatively slow (about 10^{-4} second from initial criticality to full supercriticality) gun-type assembly for the highly-enriched uranium weapon used in the Hiroshima bomb with low probability of pre-initiating the neutron chain reaction. In contrast, the neutron emission rate in 6 kg of even super-grade (2% Pu-240) plutonium is about 10^5 per second,[4] resulting in the requirement of a much more rapid (10^{-5} sec) implosion-type assembly for the plutonium weapon that was tested at Trinity and then used over Nagasaki.[5]

Although there are arguments about the likelihood of a terrorist group acquiring the capability to make an implosion design, there is little argument that it is much easier to design and produce a gun-type weapon that could be expected to work without testing. According to Hans Bethe, "The theory of the [gun-type] fission bomb was well taken care of by Serber [then an Assistant Professor of physics] and two of his young people" during a Berkeley summer study in 1942 before the bomb-design group was assembled in Los Alamos in 1943.[6]

South Africa designed and produced a WgU-based gun-type weapon over a period of several years in the 1970s and a safer, more reliable design during the 1980s. In the early 1980s, the program employed about "100 people, of which only about 40 were directly involved in the weapons program and only about 20 actually built the devices."[7]

Stocks of HEU fuel at reactors and in their nuclear fuel cycles are of special concern as potential targets for theft because they are often not so well protected as fissile material at weapons-production facilities. In November 2001, after the Al Qaeda attacks on the World Trade Center and the Pentagon, the IAEA warned of the possibility of nuclear terrorism, reporting that it had collected information on 18 cases in which small amounts of HEU or plutonium had been stolen since 1993.[8] The IAEA considers the details confidential but a number of thefts from HEU-reactor fuel cycles in Russia were reported in the press in the period after the breakup of the Soviet Union and before government secrecy was reimposed. In 1992, for example, a worker at the Luch Scientific Production Association, a nuclear-fuel manufacturing facility in Podolsk, outside Moscow, carried out of the plant amounts of weapon-grade uranium smaller than the measurement error of the facility's material accounting and control system tens of times over a period of several months. By the time he was caught as a result of an unrelated investigation, he had accumulated 1.5 kg.[9] In November 1993, submarine nuclear fuel containing 4.5 kilograms of HEU was stolen in the middle of the night from a fuel storage facility at the Sevmorput nuclear shipyard near Murmansk.[10]

According to "sources in the Russian special services," the group of 50 heavily armed Chechen terrorists that took 700 hostages in a Moscow theater in October 2002 had considered seizing a research reactor in the nearby Kurchatov Institute of Atomic Energy so as to be able to threaten to blow it up and contaminate Moscow with radioactivity.[11] They could equally well have stolen HEU fuel from one of those reactors.

Eliminating the terrorist risk stemming from the use of HEU as a nuclear-reactor fuel has three main dimensions:

1. Collecting and disposing of both unused fresh HEU fuel and spent HEU fuel and target material from the reactors,
2. Converting operating HEU-fueled reactors to non-weapon-usable low-enriched uranium, and
3. Shutting down and decommissioning the huge number of HEU-fueled reactors that are no longer needed.

Of course, it is also critically important to ensure that HEU is made as secure as possible for as long as it continues to be present.

Below, each of the above dimensions is discussed in turn.

COLLECTING AND DISPOSING OF EXCESS FRESH HEU FUEL AND SPENT HEU FUEL

Few research-reactor cores contain the 50 kg ^{235}U in highly-enriched uranium (HEU) required to make a gun-type—or even the 15–25 kg required to make a first-generation—implosion weapon.[12] According to the September 2000 edition of the IAEA's *Nuclear Research Reactors in the World*, only nine countries (including three nonweapon states) had HEU-fueled research reactors containing more than 10 kg of ^{235}U in their cores. HEU-fueled research reactors that do have large core inventories are mostly experimental fast-neutron breeder reactors, critical mockups of breeder-reactor cores, or pulsed reactors used in weapons programs (discussed below).[13]

Nevertheless, even HEU-fueled research reactors with relatively small core inventories can have large on-site inventories of HEU in fresh and spent fuel. The U.S. Department of Energy (DOE) has identified 128 "research reactors and associated facilities possessing 20 kilograms or more HEU on site."[14] Several cores of fresh fuel can be stored on site—especially for reactors requiring frequent refuelings. A 10-MWt reactor operating at 80% average capacity with 35% ^{235}U "burnup" (consumption by both fission and nonfission capture) before fuel discharge will require makeup fuel containing 10 kg ^{235}U per year.[15] Since the cores of these reactors typically contain between 1 and 10 kg of ^{235}U, they are refueled relatively frequently. Germany's new 20 MWt FRM-2 reactor, for example, contains only 8 kg of WgU in its core and is to be refueled five times per year.[16] There are 20 research reactors in 11 countries fueled with weapon-grade uranium that have thermal powers greater than 10 megawatts (MWt).[17]

Fresh HEU. Russia has an especially large amount of excess fresh HEU at its nuclear reactor facilities and in their fuel cycles. In 1999, therefore, the U.S. Department of Energy's Materials Protection, Control and Accounting (MPC&A) program launched a Materials Consolidation and Conversion Initiative (MCC) with the objective of clearing as many Russian facilities and buildings as possible of HEU. The recovered HEU is blended down to 19% enrichment at the Luch Production Association in Podolsk and the Research Institute of Atomic Reactors in Dmitrovgrad. The blend-down facilities are paid per kilogram of HEU blended down and retain ownership of the resulting 19% enriched uranium. Facilities that give up their HEU share in the U.S. payment. As of mid 2004, five tons of reactor HEU had been blended down and HEU was being blended down at a rate of about two tons per year.[18]

DOE is interested in funding an increase in the MCC program blend-down rate to five tons per year. The rate is limited in part by the difficult negotiations involved in getting facilities to agree to separate themselves from their HEU, the presence of which brings higher salaries, longer vacations and earlier retirement. The program is also hampered by the lack of an umbrella government-to-government agreement that would allow Russia's Federal Atomic Energy Agency (formerly MINATOM) to provide the U.S. with official information about where the HEU is coming from.[19]

The U.S., Russia and the IAEA also have launched a joint program to return to Russia both fresh and spent HEU fuel from 16 countries to which the Soviet Union and Russia have supplied HEU fuel. [20] As of the end of June 2004, fresh

HEU fuel containing a total of approximately 70 kg of 80% and 25 kg of 36% enriched HEU had been returned from four countries: Serbia (August 2002), Romania (Sept. 2003), Bulgaria (December 2003), and Libya (March 2004).[21] In an earlier operation (1998), the U.S. airlifted to the U.K. 3.5 kg of 90% enriched fresh fuel and 0.8 kg of spent fuel from a shutdown research reactor in the country of Georgia.[22]

Spent HEU fuel. Spent HEU fuel typically still contains more than 50 percent of its original content of HEU. It can accumulate for decades in the cooling ponds of research reactors. The proliferation risk grows with time as its fission-product radioactivity dies down and the spent fuel becomes easier to handle.

From 1957 through 1992, the U.S. exported 26 metric tons of HEU for research-reactor fuel—mostly to Euratom, Canada, and Japan. Some was returned as spent fuel. As of January 1993, however, the U.S. Nuclear Regulatory Commission estimated that 17.5 tons of U.S.-origin HEU remained abroad in 51 countries.[23] In 1996, as part of a policy to encourage their conversion to LEU fuel, the U.S. agreed to take back certain types of spent fuel discharged from foreign research reactors fueled by U.S. HEU. About 5.2 tons of HEU exported by the U.S. to 33 countries are covered by this offer. As of Oct. 2003, spent fuel originally containing about 1.1 tons HEU had been returned. In February 2004, the Inspector General of the U.S. Department of Energy estimated that only about half of the 5.2 tons covered by the take-back offer would be returned by 2009.[24] However, it appears that most of the remainder is to be reprocessed and down-blended in France or sent to a geological repository in Canada.[25] Of the remaining 12.3 tons of HEU not covered by the take-back program, approximately 9.5 tons were originally shipped to France and Germany but tons were reshipped to and from other countries.[26]

According to a Russian report published in 2002, 28,500 spent-fuel assemblies were stored at 24 Russian research reactors.[27] Assuming that this spent fuel is mostly weapon-grade uranium, it would contain tons of WgU.[28] An additional 13,000 Russian-origin spent HEU-fuel assemblies were stored at East and West-European research reactors.[29]

Except for the spent Russian-origin HEU research reactor fuel retrieved from Iraq after the 1991 Gulf War, no HEU spent fuel has been shipped back to Russia from 20 Soviet-designed research reactors outside Russia since 1988.[30] The objective of the new U.S.-Russian-IAEA collaborative agreement is to repatriate to Russia spent as well as fresh HEU fuel. However, the return of spent-HEU fuel to Russia has been delayed by problems in obtaining the necessary environmental approvals within Russia.

Russia also has huge quantities of stored spent HEU nuclear-submarine fuel. The U.S., Norway, Germany and Japan have been assisting Russia in defueling and dismantling its excess nuclear submarines and increasing its capacity to transport spent HEU fuel from its Northern and Pacific naval fleets and its Arctic nuclear-powered icebreakers to the Mayak reprocessing facility in the Urals.[31] There the fuel is reprocessed and the HEU either recycled into new naval fuel or diluted to LEU for recycle in power reactors.[32] As of 2000, there were an estimated 32,000 spent-fuel elements on submarines awaiting dismantlement and an additional 32,000 in storage ships and in storage on the Kola Peninsula.[33] This spent fuel contains tens of tons of ^{235}U.[34]

CONVERTING RESEARCH REACTORS TO LEU FUEL

Research and Isotope-Production Reactors Requiring Regular Shipments of U.S.-Supplied HEU

India's use of plutonium separated from the spent fuel of a Canada/U.S.-provided research-reactor to make a "peaceful" nuclear explosion in 1974 spotlighted the proliferation vulnerabilities of the Atoms for Peace Program. This helped stimulate the launch of the U.S. Reduced Enrichment Research and Test Reactor (RERTR) program in 1978. The Department of Energy's Argonne National Laboratory outside Chicago manages this program. Its original mission was to develop substitute low-enriched fuel and targets for the foreign reactors that the U.S. was supplying with HEU. However, the program is now international. For example, in addition to the U.S., Argentina, Canada, China, France, and Indonesia currently produce LEU fuels for export as well as domestic use and Brazil, Chile, and South Korea are developing an export capability. Argentina and China supplied LEU fuels to convert HEU-fueled reactors in Iran and Pakistan respectively.

In 1992, after significant progress had been made in the development of LEU fuels, the "Schumer amendment" (named after then Representative Charles Schumer) required foreign reactors supplied with HEU fuel by the U.S. to commit to convert to LEU as quickly as possible:

> "The [Nuclear Regulatory] Commission may issue a license for the export of highly enriched uranium to be used as a fuel or target in a nuclear research or test reactor only if, in addition to any other requirement of this Act, the Commission determines that: (1) There is no alternative nuclear reactor fuel or target enriched in the isotope 235 to a lesser percent than the proposed export, that can be used in the reactor; (2) The proposed recipient of that uranium has provided assurances that, whenever an alternative nuclear reactor fuel or target can be used in that reactor, it will use that alternative in lieu of highly enriched uranium; and (3) The

United States Government is actively developing an alternative nuclear reactor fuel or target that can be used in that reactor."[35]

Recently, however, Russia, which does not yet apply Schumer-amendment-type conditions to its HEU exports, has become an alternate source of HEU for the last few HEU-fueled West European reactors.[36] Also, although LEU targets have been developed for ^{99}Mo production and three of the smaller producers are converting to LEU targets, in 2003, Nordion, a major Canadian medical isotope producer joined by a U.S. company producing ^{99}Mo in the Netherlands backed an almost-successful effort to create a conditional exemption for HEU targets used in foreign medical isotope-production reactors.[37] The 2.7-day halflife fission product molybdenum-99 decays to 6-hour halflife technicium-99m, which emits a 0.14 MeV decay gamma ray used for medical imaging.

In 1986, the U.S. Nuclear Regulatory Commission (NRC) promulgated the requirement that NRC-licensed reactors in the U.S. (i.e., excluding DOE and DOD owned reactors) must convert to LEU fuel if the U.S. Government pays the conversion costs.[38] Eleven U.S. university reactors have been converted under this program at costs ranging from \$0.4 to \$1.6 million per reactor. Eight other (six university-, one company- and one DOE-owned) U.S. reactors for which replacement fuel is available have not yet been converted because Department of Energy funds have not been made available for the purpose. All of these reactors have powers of about 1 MWt or less and therefore long-lived cores.[39]

There are also 13 foreign reactors fueled with U.S.-origin HEU that do not have plans to convert to LEU. All are also low-power reactors with lifetime cores. U.S. policy currently is not to pay the costs of converting foreign reactors fueled with U.S. HEU.[40]

The fuel conversion approach pursued by the U.S. RERTR program has been to try to develop LEU fuels that have the same geometry and will last as long in reactor cores as the HEU fuel. For WgU fueled reactors, this means that more than five times as much uranium must be squeezed into the same-sized fuel plates: somewhat more ^{235}U than in the HEU fuel to maintain criticality and fuel life, plus four grams of ^{238}U per gram of ^{235}U to dilute the ^{235}U down below 20 percent enrichment.[41] This is theoretically possible because HEU fuels generally have densities of 0.5–1.7 grams of uranium per cubic centimeter (gmU/cc)[42] while metallic uranium has a density of almost 19 grams/cc. Metallic uranium is not used as a fuel, however, because it swells too rapidly as gaseous fission products accumulate within it.

Most current research-reactor fuels are made by dispersing uranium-containing particles in an aluminum matrix. That composite material then comprises the fuel "meat" and is covered in aluminum cladding. Thus far, the

RERTR program has developed higher-density uranium fuels in a step-by-step progression by increasing the uranium density of the particulate material. That progression was interrupted around 1990 in both the U.S. and Soviet Union due to funding limitations. By that time, the U.S. RERTR program had developed U_3Si_2 dispersion fuels with fuel meat densities up to 4.8 gmU/cc and it had become possible to convert most U.S.-supplied foreign research reactors and research reactors at U.S. universities. By 1995, 20 of 38 foreign HEU-fueled research reactors with powers $\geq$1 MWt that had been consuming 70% of 350 kg ^{235}U in U.S. HEU annually shipped abroad by the U.S., were in various stages of conversion.[43]

In 1996, the U.S. RERTR program received funding from DOE to resume the development of higher-density fuels. The most important result thus far has been the confirmation that the swelling of irradiated metallic uranium fuel can be reduced if the uranium is alloyed with 6–10 percent molybdenum, which stabilizes it in the radiation-resistant gamma phase.[44] This "U-Mo" alloy has initially been used in the traditional form of small particles dispersed in aluminum to create fuel meat with intermediate density up to 8 gmU/cc. Until recently, the plan had been to use these fuels both to convert an additional set of reactors and to replace the U_3Si_2-Al fuels that had been used to convert many reactors to LEU.[45]

Prior to 2004, the RERTR program hoped to have the U-Mo dispersion fuel commercially available "around the end of 2006."[46] However, in early 2004, French, Russian and U.S. researchers all made public test results that showed internal cracking and swelling of the fuel above 30–40 percent ^{235}U burnup. The problem does not appear to be with the U-Mo particles themselves but rather in the interaction layer formed between them and the surrounding aluminum matrix. The result is that the commercialization of these fuels has slipped until at least 2010.[47] Given this slippage, the U.S. Department of Energy plans to extend the deadline of the U.S. spent-fuel take-back offer, which was not to apply to spent fuel discharged after May 13, 2006.[48]

Four or five U.S., three West European reactors, and an as-yet undetermined number of Russian reactors will require monolithic U-Mo fuel, in which the fuel is solid U-Mo with a density of about 15.6 gmU/cc to convert to LEU.[49] With this fuel, only the German FRM-2, which was designed to use WgU in medium-density fuel developed by the RERTR program to replace HEU fuel, still could not be converted to LEU without changes in fuel geometry.[50] With the success of the U-Mo dispersion fuel in question, the monolithic fuel also has become a backup for the reactors that were to be converted to the intermediate density U-Mo dispersion fuel. The current RERTR program goal is to commercialize the monolithic fuel by approximately 2012.[51] DOE plans to spend approximately

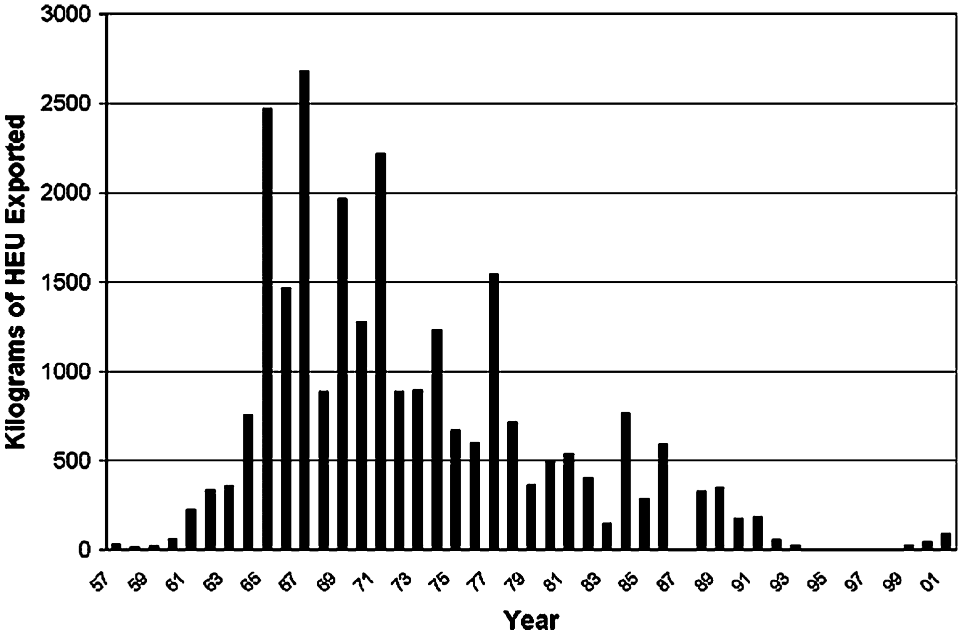

Figure 1: U.S. Exports of HEU, 1957–2000. ("Civilian Highly Enriched Uranium and the Fissile Material Convention" by Alan J. Kuperman, *Nuclear Power & the Spread of Nuclear Weapons*, Paul L. Leventhal, ed. (Brassey's Inc., 2002), p. 249. Notes on the original figure; "Sources: 1993 Nuclear Regulatory Commission report to Congress pursuant to the Energy Policy Act of 1992, subsequent NRC export data, submissions to Nordlon Inc. to NRC, and data provided by Transnuclear Inc. personal communications to author, January 16, 2002. Note: Does not include 1994 export to France of surplus Fort St. Vrain HEU fuel, because this material was required to be blended down LEU as a condition of its export.")

$26 million on this fuel-development effort from fiscal years 2004 through 2012. An additional $26 million is to be spent on core-conversion analyses of reactors currently fueled with U.S. HEU, and $5 million on assisting medical-isotope producers to convert to LEU targets.[52]

Figure 1 shows the decline of U.S. HEU exports since the heyday of the Atoms for Peace program. By the end of 2003, the U.S. RERTR program had converted worldwide 20 foreign and 11 U.S. research reactors. Seven more research reactors outside the U.S. had been "partially converted." Together, these reactors would otherwise have consumed about 250 kg of HEU per year.

The largest part of the job remains to be done, however. The world's remaining fleet of HEU-fueled research reactors still requires an estimated 830 kg of HEU per year (about 250 kg in U.S. reactors, 370 kg in Soviet-designed reactors and most of the remaining 200 kg in six high-powered West European reactors that are today largely fueled with Russian and previously exported U.S. HEU). Reactors that use HEU targets to produce ^{99}Mo consume an estimated additional 85 kg/yr.[53]

Soviet-Designed HEU-Fueled Research Reactors

By the time Soviet Union's RERTR program ran out of funds, just before the collapse of the USSR in 1991, it had developed fuels dense enough to convert almost all the foreign research reactors that it supplied from 80% to 36% enriched fuel. In 1996, Argonne received a grant of $1.5 million from the State Department's Nonproliferation and Disarmament Fund to support Russian nuclear institutes to develop low-enriched fuel for Soviet-designed foreign reactors. In fiscal year 2004, the U.S. DOE took over responsibility for funding this program and currently projects spending $18 million through fiscal year 2012 on the conversion of Soviet-designed research reactors.[54]

Replacement LEU fuel has been developed that could be used to convert seven Soviet-designed, non-Russian reactors in Bulgaria, Germany, Libya (2), Ukraine, and Vietnam. Twenty-one other Soviet-designed, HEU-fueled research reactors in the Czech Republic (2), Kazakhstan (2), North Korea, Poland, Russia (14), and Uzbekistan require the development of higher-density fuel before they can be converted.[55] Seven of these 28 reactors are zero-power critical assemblies that do not consume the fuel in their cores. However, in the case of these reactors, unlike that of foreign reactors containing U.S. HEU, the U.S. is willing to purchase replacement LEU cores if the operators are willing to allow the HEU cores to be removed.[56]

The fuel assemblies of most Soviet/Russian-designed research reactors are made of nested circular, square or hexagonal tubes with outside diameters of up to 7 cm.[57] Water flows between the tubes as well as inside the innermost one and outside the assembly. The RERTR program is developing pin-type as well as tube-type replacement LEU fuel.[58]

Russia has not yet adopted a Schumer-amendment-type policy that would require foreign reactors that it supplies with HEU fuel to take LEU fuel as soon as it is available. However, the U.S. has conditioned its financing of Russia's spent fuel take-back program on the reactors committing to convert to LEU fuel.

DOE Secretary Abraham and Minatom Minister Rumyantsev agreed in September 2002 to "work on accelerated development of LEU fuel for both Soviet-designed and United States-designed research reactors."[59] However, Minatom's successor, the Federal Atomic Energy Agency, had as of September 2004, still not committed to support the conversion of reactors inside Russia.

In good part this hesitation reflects concerns that the performance of the replacement fuel will be inferior to that of HEU fuel.[60] The ^{238}U in LEU fuel absorbs some of the neutrons from ^{235}U fissions. This reduces the thermal neutron flux. The effect is typically only on the order of 3–10 percent, however.[61] For most experiments, a small flux loss should be tolerable. Reassuring Russian reactor operators in this regard should be a high priority.

Russia also has four high-power research reactors for which the types of fuels currently under development are unlikely to be suitable.[62] If LEU fuel is developed for the KLT-40 icebreaker reactor (see below) it might be used to convert these reactors—or vice versa.

China, although it does not yet participate formally in the international RERTR effort, has designed its new 60 MWt China Advanced Research Reactor (CARR) to use LEU uranium-silicide fuel and is doing feasibility studies on converting its 125 MWt HFETR and the 5 MWt MJTR to LEU fuel.[63]

Critical Assemblies and Pulsed Reactors

Even if the RERTR program completes its task, as currently defined, it will have addressed only a part of the universe of HEU-fueled research reactors. According to the U.S. DOE's count, beyond the 105 HEU-fueled research reactors that the RERTR program would convert if funding were available (including at least 23 that do not currently plan to convert[64]) there are an additional 56 research reactors that

> [f]or a variety of reasons, DOE has excluded from its reactor conversion program . . . [Some] are used for military or other purposes, such as space propulsion that require HEU. Others are located in countries such as China that have so far not cooperated with the United States on converting their reactors to LEU. Finally, the time and costs associated with developing LEU fuel for some of the reactors may exceed their expected lifetimes and usefulness.[65]

These are mostly "zero-power" critical assemblies and fast-burst reactors.[66] Both classes of reactors have lifetime cores because they do not in their lifetimes fission a significant fraction of their inventories of ^{235}U.

The RERTR program thus far has ignored most such reactors because it has, in effect, been focusing primarily on ending shipments of HEU fuel to research reactors. The U.S. and Russia also have the greatest leverage for affecting conversion of research reactors that require refueling because they can refuse to supply HEU fuel or repatriate spent HEU fuel from reactor operators who do not agree to convert when acceptable replacement LEU fuel has been developed.

There is, however, a huge amount of HEU in the cores of research reactors that do not require refueling and are not currently targeted by the RERTR program. Furthermore, this fuel is vulnerable to diversion because its low contamination with fission products—and therefore very low radioactivity—makes it particularly easy to remove and process.

The BFS1 and BFS2 critical assemblies in the Institute for Physics and Power Engineering in Obninsk, Russia, are extreme examples of the security threat posed by critical assemblies. The BFS facility which houses these critical assemblies contains 8.7 tons of 36% and 90% enriched uranium and 0.8 tons of plutonium—mostly in the form of about 90,000 disks 4.7-cm in diameter and ranging in thickness from 0.06 to 0.56 cm.[67] The corresponding example for pulsed reactors is the BIGR pulsed reactor at the Institute of Experimental Physics (VNIIEF) in Sarov, Russia, whose core contains 833 kg of 90% enriched uranium. Conversion of such facilities would require the purchase of new fuels that otherwise would not have been purchased.

It should be possible—and preferable—however, to decommission most critical facilities. Most of the criticality "bench-mark" experiments needed by the computer codes used to model reactor-core behavior have been done.[68] Argonne National Laboratory's ZPPR fast critical facility, for example, the U.S. counterpart of Russia's BFS facility, was shut down in 1997.[69]

VNIIEF has requested funding to do a study on the feasibility of converting its BIGR and another VNIIEF pulsed reactor to LEU.[70] If the results are encouraging, studies could be launched of the feasibility of converting pulsed reactors at the other Russian, U.S., U.K. and Chinese nuclear-weapon laboratories that have such reactors.

Tritium-Production, Icebreaker, Floating Power Plant, Naval and Space Reactors

Even the full universe of research reactors—including the critical facilities and pulsed power reactors that are not currently targeted for conversion—is still only a part of a still larger universe of HEU-fueled reactors. Indeed, the HEU consumption of tritium-production, icebreaker, naval and reactors is much larger than that of research reactors.

Tritium-Production Reactors. The U.S. dual-purpose plutonium and tritium production reactors at the Department of Energy's Savannah River site were fueled with HEU prior to their shutdown in 1989.[71] With the end of the Cold War, U.S. plutonium production was terminated. In the future, any replacement tritium will be produced in LEU-fueled power reactors.

Russia reportedly still operates two HEU-fueled 1000-MWt reactors at the Mayak facility to produce tritium and other isotopes. These reactors have been estimated to consume up to 1.5 tons of weapon-grade uranium per year—more than the world's fleet of research reactors.[72] Converting them would therefore be highly worthwhile.

Russia also continues to operate three plutonium-production reactors because they provide byproduct heat and electricity to regional populations. The primary fuel of these reactors is natural uranium but they also use some weapon-grade uranium fuel to shape the power in the reactor cores.[73] The U.S. has committed to build replacement coal-burning plants but the costs have escalated to-reactor-production the point where the future of the project is in question.[74]

Icebreaker Reactors. Russia operates 11 HEU-fueled reactors on seven nuclear-powered icebreakers that, in the average year, collectively load HEU fuel containing about 0.4 tons of ^{235}U. Russia's nuclear-reactor-production complex is adapting the KLT-40 icebreaker propulsion reactor for a floating power plant. The lead nuclear-fuel development institute, the Bochvar Institute, has requested U.S. funding to develop LEU fuel for both the floating nuclear-power plant and icebreaker reactors.[75] A first stage in the fuel development process, supported by the multinational International Science and Technology Center in Moscow, was completed in 1997[76] but follow-on funding has not been made available.

Naval Reactors. If the Russian Navy were so inclined, fuel developed for Russia's icebreakers might also be adapted to convert Russian naval-propulsion reactors. The HEU fuel in the fuel cycle of these reactors has been a major proliferation concern.[77] France is shifting its naval-propulsion reactors from HEU to LEU fuel for economic reasons. China is most likely using near-LEU fuel in its submarine-propulsion reactors.[78] India is developing a submarine-propulsion reactor that is reportedly fueled with 30–45 percent enriched uranium.[79] Brazil's Navy stated in 2000 that, as of that time, it was committed to use LEU for Brazil's nuclear-submarine program.[80]

Converting U.S. and U.K. naval reactors to LEU would be more difficult. French and Russian reactors are refueled every 5 to 10 years. The U.S. and U.K., in an effort to avoid refueling shutdowns, are moving to reactor cores designed to last the lifetime of the ship—up to 45 years. In a 1995 report to Congress, the Department of Energy's Office of Naval Nuclear Propulsion asserted that the density of the uranium in its naval-reactor fuel could not be increased and that, therefore, if the core lifetimes were to be preserved, conversion to LEU would require three times larger and proportionately more costly cores.[81] There has been no independent peer review of this conclusion. Since naval-reactor fuel designs are classified, such peer review would have to be done on a classified basis.

For next-generation nuclear ships, reactor design as well as the fuel design could be changed.[82] If it proved necessary, new ships could also be designed to accommodate larger cores. The tradeoffs between large cores and refueling at 15- or 20-year intervals could also be reviewed. Although it would require a significant commitment by senior government officials to persuade the U.S. Navy to consider such alternatives seriously, the issue is well worth pursuing. The flow of weapon-grade uranium through naval-reactor fuel cycles brings with it very serious proliferation and nuclear-terrorism risks and is already complicating nuclear arms control.[83]

Space Reactors. In the past, the Soviet Union and U.S. both placed low-powered HEU-fueled reactors in earth orbit. The vast majority were launched by the Soviet Union to power space radars to track U.S. Navy task forces. During the Reagan Administration, there was interest in developing reactors to power antiballistic-missile beam weapons—inspiring the label "Star Wars." [84] Recently, NASA has launched an effort to develop a reactor to power missions to the outer planets—and perhaps also to shorten the flight time for humans to Mars.[85] All space reactors have been designed to be fueled with weapon-grade uranium. Only one cursory study has been done of the weight penalty if LEU were used instead. For fast-neutron reactors, which require uranium fuel enriched to near 20 percent, the weight-increase factor was found to be large.[86] Weight is a major factor in the cost of a space mission. However, a detailed study of LEU alternatives should be required before HEU fuel is permitted.

DECOMMISSIONING EXCESS RESEARCH-REACTOR CAPACITY

Before discussing the possibility of conversion, the first question that should be asked is whether a research reactor should be decommissioned instead? According the IAEA, there are 275 operating research reactors worldwide.[87] The official responsible for the IAEA's research-reactor program recently estimated that perhaps only 30–40 research reactors will be required in the future.[88] An earlier IAEA report put it this way:

> The worldwide demand for nuclear science education, training, research, technology development, and reactor services has decreased, and no longer requires the large number of research reactors currently in operation. Consequently, many facilities are challenged to find users for their services, or to permanently shut

> down and eventually decommission. Only reactors with special attributes (such as a high neutron flux, a cold [neutron] source, in-core loops to simulate power reactor conditions) or with commercial customers (such as radioisotope production or silicon doping) are adequately utilized.[89]

Between 1996 and 2000, forty-seven research reactors were shut down, while only 12 were commissioned. This trend can be expected to continue, since most of the world's research reactors are over 30 years old, only seven are under construction and only another eight are planned. The IAEA suggests that the research-reactor community would be best served if smaller countries focused on sharing "'regional centers of excellence' where a single reactor can serve a number of neighboring countries."[90] The same idea of regional research reactors could be implemented within large countries such as Russia and the U.S.

The IAEA has noted further, with regard to the world's already shut down but not decommissioned research reactors, that

> It is a serious concern that many of the shut down, but not decommissioned reactors still have fuel, both fresh and spent, at the sites. An extended delay between final shutdown and decommissioning will affect both cost and safety at the time of decommissioning, mainly due to the loss of experienced staff (already ageing at the time of shut down) necessary to participate in decommissioning activities.[91]

In 2000, the IAEA's International Nuclear Safety Advisory Group urged "proper decommissioning" of over 200 shutdown research reactors.[92]

Unfortunately, budgeting considerations sometimes work against shutting down and decommissioning reactors. Although it will save funds in the long run to decommission a reactor, it can be less costly on an annual basis to continue to operate it or maintain it in a safe shutdown state. Decommissioning research reactors can cost millions to tens of millions of dollars, while operating one typically costs less than a few million dollars a year.[93]

It can also be difficult for nuclear institutes with shutdown research reactors to obtain funding for new missions. This situation can be mitigated for a few years if the maintenance and operating staff participates in the cleanup process.[94] For the research staff, there is also the possibility of becoming a "user group" at another research reactor. Such arrangements are quite common in the U.S. and Western Europe but apparently not in Russia.[95] Probably the easiest HEU-fueled research reactors in Russia to shutdown would be at institutes with multiple research reactors whose staffs can be combined to work at the institute's one or two most capable research reactors.

Table 1: Current programs to eliminate HEU fuel use and collect spent HEU fuel.

	LEU fuel development	**Conversion**	**Decommissioning**
Research reactors			
– Unpressurized	Yes (RERTR)	Yes (not in Russia)	Mostly no
– Pressurized	No	No	No
– Critical facilities	No (a few exceptions)	No	Yes (MCC)
– Pulsed reactors	No	No	No
Icebreaker reactors	No	No	No
Tritium prod. reactors	No	No	No
Naval reactors	by France	by France	Yes

CONCLUSION

Table 1 summarizes what is and is not being done to eliminate the use of HEU fuel.

All the existing efforts would benefit from increased budgets. But high-level political support and attention are also essential to broaden the effort and to remove or overcome the bureaucratic obstacles to its progress.

Recently, there have been some manifestations of high-level interest within the U.S. Government in eliminating the use of HEU in civilian nuclear reactors. In May 2004, the Senate added to the Defense Authorization Act for fiscal year 2005 an amendment authorizing accelerated efforts on what is often described as a "global cleanout" of civilian weapon-useable fissile materials and of radiological materials that could be used to make so-called "dirty bombs." Two of the listed elements of the comprehensive program outlined were

- "The development of alternative fuels and irradiation targets based on low-enriched uranium to convert research or other reactors fueled by highly-enriched uranium . . . as well as the conversion of reactors and irradiation targets employing highly-enriched uranium . . .
- "The provision of assistance in the closure and decommissioning of sites identified as presenting risks of proliferation of proliferation-attractive fissile materials . . . "[96]

In submitting the amendment, Senator Domenici gave

> As one example of a potential concern beyond the research reactors, the Russian ice breakers are powered with nuclear reactors using highly enriched uranium. I hope we can help to convert those reactors in the course of this program.[97]

The amendment included no additional funding for these programs, however.

A week later, DOE Secretary Spencer Abraham, in Vienna, Austria, announced a "new initiative, the Global Threat Reduction Initiative (GTRI)" in which he appeared to expand somewhat the objectives of some of the existing DOE programs:

- "Repatriate all Russian-origin fresh HEU fuel by the end of next year [2005, and] complete the repatriation of all Russian-origin spent fuel by 2010 . . .
- "Complete the repatriation of all U.S.-origin research reactor spent fuel under our existing program from locations around the world within a decade . . . [All U.S. origin fuel is not covered under the existing program.]
- "Work to convert the cores of civilian research reactors that use HEU to use low enriched uranium fuel instead. We will do this not just in the United States—where we are scheduled to complete core conversion by 2013—but throughout the entire world . . . " [All civilian research reactors are not covered under the existing program.][98]

Abraham stated that the U.S. "plans to dedicate more than $450 million to this effort which should be more than sufficient to complete the U.S. Foreign Research Reactor Spent Fuel Return, the Russian Research Reactor Fuel Return efforts and to also fund the conversion of all targeted U.S. and Russian supplied research reactor cores under the Reduced Enrichment for Test Research and Test Reactors (RERTR) program." He also announced that "we will establish a single organization within the Department of Energy's National Nuclear Security Administration to focus exclusively on these efforts."

Thus, although there is not yet a new plan, there appears to be a new openness to examine the possibility of broadening the existing programs. When the DOE was asked how much new funding it required for the new initiative in fiscal year 2005, however, its answer was a disappointing $5 million and the House of Representatives refused even that in the absence of a program plan.[99] Hopefully, when the DOE has developed a program plan, it will return to Congress with a proposal to reprogram significant funding from lower-priority programs to support the GTRI.

A significant effort is still required to develop and put into place a comprehensive U.S. program to help eliminate HEU in civilian nuclear fuel cycles. Beyond that, further effort will be required to get a commitment by the Russian Government to implement such a program inside Russia. Finally, a much greater effort still will be required to launch comprehensive programs to eliminate HEU from naval reactor fuel cycles.

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NOTES AND REFERENCES

1. *DOE needs to take action to further reduce the use of weapons-usable uranium in civilian research reactors,* U.S. Government Accountability Office, GAO-04-807, July 2004, p. 10. Figure 1 of this report is a world map showing the countries included in the Reduced Enrichment Research and Test Reactor program and the number of RERTR-program-targeted, HEU-fueled reactors originally in each (39 of 105 have already been fully or partially converted). Many HEU-fueled reactors are not currently targeted. China and India, both of which have HEU-fueled reactors, do not currently participate in the program.

2. Ibid., p. 7. A list of most of the world's research reactors may be found in *Nuclear Research Reactors in the World* (IAEA, 2000), Table 9, which lists 135 HEU-fueled reactors. One ambiguity is that minimum and maximum enrichments are listed. The responsible IAEA official believes that reactor operators generally interpret "minimum enrichment" to mean "the minimum enrichment of fresh fuel that they ever used in the reactor" (Iain Ritchie, private communication, June 9, 2004). Removing reactors with minimum enrichments of 20% or less would reduce the number of HEU-fueled reactors to about 117. Additional data on the original enrichments of research reactors covered by the U.S. spent-fuel take-back agreement can be found in "Foreign Research Reactors in the EIS: Aluminum-based and Triga spent nuclear fuel containing enriched uranium of United States origin" by James Matos, June 3, 1996, ⟨http://www.td.anl.gov/Programs/RERTR/FRRSNF/EISREACT.html.⟩

3. Robert Serber, *The Los Alamos primer: The first lectures on how to build an atomic bomb* (University of California Press, 1992), pp. xv, 22.

4. *Reversing the Arms Race: How to Achieve and Verify Deep Reductions in the Nuclear Arsenals,* Frank von Hippel and Roald Z. Sagdeev, eds., (Gordon and Breach Science Publishers, 1990), Table 11.2. It was assumed that uranium and plutonium metal contain 0.2 percent oxygen by weight.

5. "Explosive properties of reactor-grade plutonium" by J. Carson Mark, *Science & Global Security 4* (1993), p. 111.

6. Richard Rhodes, *The making of the atomic bomb* (Simon & Schuster Touchstone, 1986), p. 417.

7. David Albright, "South Africa and the Affordable Bomb," *Bulletin of the Atomic Scientists,* July/August (1994), p. 37.

8. "Calculating the new global nuclear terrorism threat," IAEA Press Release, Nov. 1, 2001.

9. Matthew Bunn and Anthony Wier, *Securing the bomb: An agenda for action* (Harvard University, Managing the Atom Poject, 2004) pp. 13, 16.

10. The enrichment of this fuel was at the bottom of the 21–45% range used in currently operating Russian submarines, Oleg Bukharin and William Potter, "'Potatoes were guarded better," *Bulletin of the Atomic Scientists*, May/June (1995), p. 46.

11. Vladimir Bogdanov, "Terrorist Had Pass Giving Access to Warheads, 'Nuclear Special Forces' Operating in Russia" *Rossiyskaya Gazeta*, Nov. 01, 2002 (World News Connection, FBIS translated excerpt).

12. The core of an implosion weapon would have to be subcritical before implosion. With a 5.1 cm beryllium or tungsten-carbide reflector, the solid-sphere critical mass of 93.5% enriched uranium is about 20 kg ^{235}U, *Critical Dimensions of Systems Containing* ^{235}U*,* ^{239}Pu*, and* ^{233}U*,* (Los Alamos National Laboratory, 1986), Table 28.

13. The countries with such facilities are China, France, India, Russia, U.K., U.S., and Italy (fast neutron source used for medical research), Japan (mockups of fast-neutron cores), and Romania (a high-power Triga reactor that is being converted to LEU), *Nuclear Research Reactors in the World* (IAEA, 2000).

14. *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) p. 28.

15. Approximately one megawatt-day of fission energy is released per gram of fission. In 0.8×365 days, therefore, there will be about 0.29 kg of fission. For each gram of ^{235}U fissioned, about 0.2 grams of ^{235}U will be converted to ^{236}U by nonfission neutron capture. Therefore, (0.29 kg) $\times 1.2 = 0.35$ kg of ^{235}U will be destroyed per megawatt of capacity per year.

16. "The conversion of research reactors to low-enriched fuel and the case of the FRM-II," Alexander Glaser, *Science & Global Security 10* (2002), p. 61. This refueling rate, 2 kg WgU per MWt-year, is twice the average for reactors supplied with U.S. HEU, *Plutonium and Highly Enriched Uranium 1996,* by David Albright, Frans Berkhout and William Walker (Oxford University Press, 1997), Appendix D.

17. US: ATR (250 MWt), HFIR (85 MWt), NBSR (20 MWt), MURR (10 MWt), MITR-2 (5–10 MWt); Russia: MIR–M1 (100 MWt), SM-3 (100 MWt), WWR-M (18 MWt), IVV-2M (15 MWt), RBT-10/2 (10 MWt); France: HRF (58 MWt), ORPHEE (14 MWt); Germany: FRM-II (20 MWt), FRJ-2 (23 MWt); Australia: HIFAR (10 MWt); Belgium: BR-2 (100 MWt); China: HFETR (125 MWt); Kazakhstan: EWG-1 (60 MWt); Netherlands: HFR (45 MWt); South Africa: SAFARI (20 MWt), *Nuclear Research Reactors of the World*.

18. This program should not be confused with the U.S.-Russian "Megatons to Megawatts" program under which the U.S. Enrichment Corporation is currently buying 30 metric tons of weapon-grade uranium per year recovered from excess former

Soviet *weapons* after the HEU has been blended down to 4 to 5 percent enrichment. This LEU is resold to U.S. and other utilities for use in power-reactor fuel, ⟨http://www.usec.com/v2001_02/HTML/megatons.asp⟩.

19. Private communication, Tom Wander, manager of the MCC program, June 10, 2004.

20. Belarus, Bulgaria, China, the Czech Republic, Egypt, Germany, Hungary, Kazakhstan, Latvia, Libya, Poland, Romania, Serbia, Ukraine, Uzbekistan, and Vietnam, T. Dedik, I. Bolshinsky, and A. Krass, "Russian research reactor fuel return program starts shipping fuel to Russia," presentation at the 2003 International Conference on Reduced Enrichment Research and Test Reactors, Chicago, Ill (hereafter 2003 International RERTR Meeting). Papers given at the annual International RERTR Meetings from 1995 on may be found at ⟨http://www.td.anl.gov/Programs/RERTR/RERTR.html⟩.

21. In August 2002, prior to the formal launch of the tripartite initiative, and with $5 million for decommissioning supplied by the private Nuclear Threat Initiative, 48 kg of fresh 80% enriched fuel were shipped from the "Vinca" research reactor outside Belgrade to Dimotrovgrad for downblending. The Vinca reactor had been shut down since 1984. The movement of the HEU to Belgrade's airport was guarded by 1200 Yugoslav troops, Joby Warrick, "Risky Stash of Uranium Secured, U.S., Russia Remove Weapons-Grade Nuclear Material from Yugoslavia" *Washington Post*, August 23, 2002, p. A01. In September 2003, 14 kg of fresh HEU (approximately one-third 80% enriched and the remainder 36% enriched) were removed from the Institute for Nuclear Research in Pitesti, Romania to Novosibirsk for downblending, "IAEA, U.S., Russia assist Romania to remove fresh HEU research reactor fuel," IAEA, *World Atom,* Sept. 22, 2003 (information on the fuel enrichment from IAEA). In December 2003, 17 kg of 36% enriched uranium were removed from a shutdown research reactor in Sofia, Bulgaria, "U.S.-Russian Team Removes Uranium From Bulgarian Reactor," (AP) New York Times, December 25, p. A-6, "Removal of High-Enriched Uranium: IAEA, USA, Russia Assist Bulgaria in Removal of HEU Fuel," IAEA Staff Report, 24 December 2003. In March 2004, 16 kg. of 80% enriched HEU in fresh fuel was shipped from an operating Libyan research reactor to Dimitrovgrad, "Libya sends Tajura HEU to Russia, prepares to convert reactor to LEU Nuclear Fuel," *Nuclear Fuel,* March 15, 2004, p. 4.

22. The 8 MWt reactor had been shut down in 1986, after the accident at Chernobyl. Before the Soviet Union collapsed at the end of 1991, some of its remaining fresh fuel had been shipped to a sister reactor in Uzbekistan and most of its spent fuel had been shipped to Russia, Michael R. Gordon, "U.S. and Britain relocate a cache of nuclear fuel," *New York Times,* April 20, 1998, A1, T.A. Shelton, J.M. Viebrock, A.W. Riedy, S.D. Moses, and H.M. Bird, "US - led effort to remove HEU/LEU fresh and spent fuel from the Republic of Georgia to Dounreay, Scotland" 1998 International RERTR Meeting.

23. *U.S. Nuclear Regulatory Commission's Report to Congress on the Disposition of Highly Enriched Uranium Previously Exported from the United States* (USNRC, 1993); *Plutonium and Highly Enriched Uranium 1996*, p. 239; and "Foreign Research Reactors in the EIS," *ops. cit.*

24. *Recovery of highly-enriched uranium provided to foreign countries*, U.S. Department of Energy, Office of Inspector General, Office of Audit Services, DOE/IG-0638, Feb. 2004, p. 2.

25. Belgium and France have opted to send spent HEU fuel that originally contained a total of about 2000 kg of HEU to a French site for reprocessing. This will result in the recovered uranium being blended down to LEU. HEU recovered from about 600 kg

of HEU used for target material for the production of ^{99}Mo is stored at Chalk River, Canada. Current plans are to dispose of this material in a future geological repository.

26. *Recovery of highly-enriched uranium provided to foreign countries*, op cit. p. 2. As of 1993, 4.4 tons of the U.S. HEU shipped to EURATOM countries had been retransferred to other countries within EURATOM (such transfers do not have to be reported to the U.S.) and 1.7 tons had been retransferred to non-EURATOM countries that had retransferred 0.55 tons of *their* U.S.-origin HEU to EURATOM countries, *U.S. NRC's Report to Congress on the disposition of highly enriched uranium previously exported from the U.S.*

27. Y. Kozlov, Y. Kosarev, N.S. Tikhonov, and S.D. Khromeev. "Management of research reactor spent nuclear fuel and economic aspects of its shipment" *Proceedings of the 5th International Conference on Radiation Safety: Spent Nuclear Fuel and Radioactive Waste Management, Sept. 24–27, 2002*, pp. 144–152, referenced in *End Points for spent nuclear fuel and high-level radioactive waste in Russia and the United States* (National Academy Press, 2003) p. 37.

28. Five types of Soviet designed HEU fuel assemblies used in research reactors outside Russia contain 37–44 (WWR-M2), 147–171 (IRT-2M), 300–342 (IRT-3M), 430 (MR-6), and 83–109 (WWR-TS) grams of ^{235}U each, James Matos, "Accelerating the design and testing of LEU fuel assemblies for conversion of Russian-designed research reactors outside Russia," 2003 International RERTR Meeting.

29. Pablo Adelfang and Iain G. Ritchie, "Overview of the status of research reactors worldwide," 2003 International RERTR meeting.

30. Iain Ritchie, IAEA, private communication, Sept. 24, 2003.

31. "Russia received one more special train for spent nuclear fuel transportation," Bellona, Nov. 21, 2003; and "Japanese officials have confirmed Tokyo's intention to begin dismantlement work on 41 tactical and general-purpose submarines of the Pacific Fleet which have for several years remained afloat with their reactors still loaded with nuclear fuel, a Japanese government official said Wednesday," Charles Digges, Bellona, January 7, 2003, at ⟨http://www.bellona.no⟩.

32. Oleg Bukharin, "Securing Russia's HEU stocks," *Science & Global Security* 7 (1998), p. 311.

33. "Mayak spent fuel storage moves to Kola. Minatom and the Industrial Group cancel the planned naval spent fuel storage at Mayak—regional storage sites at the Kola Peninsula are to be built instead by Thomas Nilsen," Bellona, March 20, 2000.

34. Since 1999, the Soviet Union has retired approximately 150 nuclear-powered ships, each of which typically powered by two reactors, each reactor containing on average about 100 kg of ^{235}U, Chunyan Ma and Frank von Hippel, "Ending the production of highly enriched uranium for naval reactors," Nonproliferation Review 8 (2001), p. 86.

35. H. R. 776, Comprehensive National Energy Policy Act, Sec. 903. Restrictions On Nuclear Exports: Amendment to Chapter 11 of the Atomic Energy Act of 1954 (42 U.S.C. 2151 et seq.) *Congressional Record* (October 5, 1992), p. H12103.

36. In 2001, Russia shipped about 400 kg of WgU to France to be fabricated into a 10-year supply of cores for Germany's new FRM-2 reactor. Two other shipments to France: one of 228 kg in 1998 and a second of undisclosed size in 2001 will fuel France's Orphee reactor for the remainder of its life and France's RHF reactor for three years. Four hundred kilograms of previously imported but unused U.S. WgU have been used by

European research reactor operators to tide themselves over until new supply arrangements could be made. The European Community has also taken an option with Russia for a lifetime supply of 600 kg of WgU to fuel its HFR reactor in Petten, the Netherlands, "Russia Supplants U.S. in Sales of HEU for European Reactors," *Nucleonics Week* (March 28, 2002), p. 4, correction, April 18, 2002.

37. R. Jeffrey Smith, "Measure Would Alter Nuclear Nonproliferation Policy, Energy Bill Provision Backed by Two Firms Would Ease Constraints on Exports of Bomb-Grade Uranium" *Washington Post* (October 4, 2003), p A02. The measure was part of an energy bill that failed to pass because of other controversial sections. See also the discussion of the concerns of the manufacturers about conversion costs in *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) pp. 5, 25–26.

38. "Limitations on the use of highly enriched uranium (HEU) in domestic non-power reactors," *Code of Federal Regulations*, part 50.64.

39. The GAO reports that "according to DOE officials, conversion for each [of these] reactor[s] is projected to cost between $5 million and $10 million . . . but could not provide documentation to support . . . [these high] estimates," *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) pp. 13–16, 31.

40. *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) pp. 16–18. The GAO mistakenly lists South Africa's 20-MWt Safari reactor as being fueled with U.S. HEU. South Africa produced its own HEU.

41. The ^{235}U loading has to be increased by 10–15 percent because the added ^{238}U depresses the reactivity by absorbing neutrons at the beginning of the fuel life. As the fuel burns up, however, neutron absorption in U-238 results in the production of fissile Pu-239, which replaces some of the ^{235}U that is being fissioned, slowing the decline in the fuel reactivity.

42. A. Travelli, "Status and progress of the RERTR program in the year 2003," 2003 International RERTR meeting.

43. A. Travelli, "The RERTR program: Status and progress," 1995 International RERTR Meeting.

44. G. L. Hofman et al., "Recent observations at the post-irradiation examination of low-enriched U-Mo miniplates irradiated to high burnup," 2003 International RERTR meeting. The fission gas bubbles were small, uniformly distributed and did not coalesce. The total volume increase of the fuel "meat" at 80% burnup was 6–10% for a beginning-of-life peak fuel temperature of 130°C.

45. The motivation for replacing the U_3Si_2-Al fuels is that France's reprocessing company, Cogema, has been reluctant to accept silicon-containing fuels for reprocessing, the preferred method in Western Europe for disposing of research-reactor spent fuel. Silica forms a gel after the fuel has been dissolved. However, the U.S. reprocessing plant at Savannah River has demonstrated that this gel can be removed by centrifugation of the solution. Cogema has recently reconsidered its position, "Cogema poised to offer more reprocessing of silicide fuel," *Nuclear Fuel* (March 29, 2004), p. 21.

46. "Status and progress of the RERTR program in the year 2003," op. cit.

47. "High-density test reactor fuel delayed until 2010," *Nuclear Fuel* (March 29, 2004), p. 1.

48. "Department Refocuses Threat Reduction Efforts to Return Nuclear Research Reactor Fuel," U.S. Department of Energy press release, April 14, 2004.

49. In the U.S.: Idaho National Lab Advanced Test Reactor (ATR, 250 MWt), National Institute of Standards and Technology (NBSR, 20 MWt), Oak Ridge (HFIR, 85 MWt), University of Missouri (MURR, 10 MWt), and MIT (MITR-II, 4.9 MWt); in France: (RHF-Grenoble, 58 MWt), (ORPHEE, 14 MWt); and Belgium: (BR-2, 100 MWt), private communications, Armando Travelli, RERTR Program, Argonne National Laboratory, Sept. 14 and Oct. 17, 2003.

50. The FRM-2 fuel is 3 gmU/cc U_3Si_2 fuel. Germany's Federal Ministry for Environment & Nuclear Safety (BMU) requires that the reactor be converted to uranium enriched to less than 50% by the end of 2010, "BMU License FRM-2 Start-Up but Requires Fuel Conversion," *Nucleonics Week* (April 24, 2003), p. 6.

51. "Status and progress of the RERTR program in the year 2003," op. cit.

52. *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) p. 37.

53. RERTR program estimates, private communication, June 10, 2004.

54. *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) p. 37.

55. *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) pp. 19–20, 21,22. The only Russian LEU fuel that is currently available is UO_2 dispersion fuel with a density of about 2.5 gmU/cc (Armando Travelli, private communication, July 31, 2004). The German reactor is a critical assembly with a lifetime core.

56. Recently, the U.S. committed to pay $4 million for LEU fuel for a Romanian Triga reactor in exchange for the return of fresh HEU fuel to Russia from another Romanian research reactor, *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) p. 18.

57. "Accelerating the design and testing of LEU fuel assemblies for conversion of Russian-designed research reactors outside Russia," op. cit.

58. Pin-type U-Mo dispersion fuel may be more robust against cracking than plate-type fuel because of the hoop stresses in the cladding compress the fuel meat, Armando Travelli, manager, RERTR program, private communication, July 31, 2004.

59. Joint Statement by Secretary Abraham and Minister Rumyantsev, September 16, 2002.

60. In November 2003, Rumyantsev, asked in an interview about the impact of reactor conversion on the science that could be done with a research reactor, responded, "It reduces scientific value of experiments. Getting something wholly new becomes virtually impossible," Alexander Yemelianenkov, "Russia and the United States will handle research reactors of Soviet vintage," *Rossiiskaya Gazeta* (November 19, 2003), pp. 1, 12 (World Press Service English-language summary).

61. See, for example, the calculation for a generic 30 MW research reactor in Alexander Glaser and Frank von Hippel, "On the importance of ending the use of HEU in the nuclear fuel cycle: An updated assessment," 2002 International RERTR Meeting.

62. Most research reactors operate below 100°C and have their cores in pools or unpressurized tanks. The U-Mo alloy on which the future of the RERTR program is based suffers from increasing radiation-induced swelling as its temperature and the pressure of the gaseous fission products trapped within it increase. Thus far, the fuel has been tested only up to a beginning-of-fuel-life peak temperature of 180°C at 50% burnup and 140°C for 80% burnup, "Recent observations at the post-irradiation examination of low-enriched U-Mo miniplates irradiated to high burnup," op. cit. Russia has two pressurized water research reactors designed to operate at water temperatures of about 280°C: the 100 MWt SM-3 reactor at the Dimitrovgrad Scientific Research Institute of Atomic Reactors, and the not-yet-operating 100 MWt PIK reactor at the St. Petersburg Nuclear Physics Institute. The 10 MWt RBT 10/2 and 2 MW RBT 2/6 at Dimotrovgrad are fueled with discharged SM-3 fuel.

63. Yuan Luzheng, CARR Chief Engineer, China Institute of Atomic Energy, private communication, July 23, 2004.

64. The eight U.S. reactors discussed above for which LEU fuel is available but whose conversion the DOE has not yet committed to fund; the 13 foreign reactors, also discussed above, that contain U.S. HEU in lifetime cores; the Soviet-designed German reactor that has a lifetime core; and South Africa's Safari reactor which is currently fueled with HEU produced from South Africa's former nuclear-weapons program. In addition, the GAO report lists three foreign reactors with U.S. HEU fuel that could be converted but either plan to shutdown (Israel) or have not yet decided whether to shutdown or convert (Japan and Portugal) *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) p. 16.

65. *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) p. 10.

66. The exceptions include Sandia National Laboratory's 4 MWt annular core Triga research reactor; the two already-mentioned Chinese reactors; a 2-MWt reactor in Chile that operates so little that it is not expected to require refueling; an Indian 0.4 MWt reactor that is reportedly being converted by India; two space reactor prototypes at the former Soviet test site in Kazakhstan; and a small Russian fast-neutron reactor (BOR-60), information from Argonne National Laboratory. It also includes eight very low power (0.03 MWt) Chinese Miniature Neutron Source Reactors that each contain approximately 1 kg of 90-percent-enriched uranium in very long-lived cores. China has exported five of these reactors to Ghana, Iran, Nigeria, Pakistan, and Syria. Canada has exported a similarly low-power, low-core-inventory Slowpoke reactor to Jamaica. It has converted two of its own Slowpokes to LEU. The cost of the conversion of the Jamaican reactor has been estimated at $1.5 million, *DOE needs to take action to further reduce the use of weapons-usable uranium* (GAO, 2004) p. 17. The U.S. also has exported very low-power Argonaut reactors whose cores contain up to 5 kg of weapon-grade uranium to France, Japan, and the Netherlands and LEU-fueled variants to Austria, Brazil and France, *Nuclear Research Reactors in the World* (IAEA, 2000).

67. I.P. Matveyenko et al., "Physical inventory of nuclear materials on BFS facility," paper presented at the MPC&A-2000 conference, Obninsk, Russia, May 22–26, 2000.

68. See e.g. "Applicability of ZPR critical experiment data to criticality safety," presentation by R. Schaefer, S. Aumeier and H. McFarlane at the Experts' Meeting on Experimental Needs in Criticality Safety, Albuquerque, New Mexico, September 25–26, 1995, and private communication, Harold McFarlane, Argonne National Laboratory, June 10, 2004.

69. *Nuclear Research Reactors in the World, 2000*, op. cit.

70. "Use of low-enriched uranium in VNIIEF pulse nuclear reactors," research proposal from VNIIEF to the International Science and Technology Center, Moscow, 2004.

71. *Plutonium and highly-enriched uranium 1996: World inventories, capabilities and policies*, op. cit.

72. Oleg Bukharin, Securing Russia's HEU stocks," op. cit.

73. D.F. Newman, C.J. Gesh, E.F. Love, and S.L. Harms, *Summary of near-term options for Russian plutonium production reactors*, Pacific Northwest Laboratory, PNL-9982, 1994, p. 10.

74. *DOE's effort to close Russia's plutonium production reactors faces challenges, and final shutdown is uncertain,* Government Accountability Office, GAO-04-662, 2004.

75. A. Savchenko (Bochvar), "Development and validation of LEU core for nuclear icebreakers and floating nuclear power plant reactors (FNPP) to avoid the risk of nuclear material proliferation," April 24, 2003.

76. A. Vatulin, V. Lysenko and A. Savchenko, "Designing a new generation fuel element for different purpose water reactors," 1997 International RERTR Meeting.

77. "Potatoes were guarded better," op. cit. However, the security of Russia's naval nuclear fuel cycle has been significantly upgraded. See Morten Bremer Maerli, "U.S.-Russian naval security upgrades: Lessons learned and the way ahead," *Naval War College Review* (Autumn 2003), p. 20, ⟨http://www.nwc.navy.mil/press/Review/2003/Autumn/pdfs/art2-a03.pdf⟩.

78. China's submarine-propulsion reactor designs are likely based on those of early Russian naval reactors, which were fueled with 21 percent enriched HEU, Chunyan Ma and Frank von Hippel, "Ending the production of highly enriched uranium for naval reactors," op. cit.

79. Mark Hibbs, "India to equip centrifuge plant with improved rotor assemblies," *Nuclear Fuel* (Dec. 1, 1997), p. 7.

80. Mark Hibbs, "Brazil may enrich to HEU for submarine reactor fuel," *Nuclear Fuel* (July 24, 2000), p. 7.

81. *Report on the use of low enriched uranium in naval reactors* by the Director, Naval Nuclear Propulsion, 1995.

82. For a more detailed discussion of the technical issues, see Thomas D. Ippolito, *Effects of Variation of Uranium Enrichment on Nuclear Submarine Design*, Master of Science Thesis, MIT Department of Nuclear Engineering, May 1990. See also Marvin M. Miller, "Nuclear Submarines and their Implications for Weapons Proliferation," in *Averting a Latin American Nuclear Arms Race,* Paul L. Leventhal and Sharon Tanzer, eds., Macmillan, London (1992), p. 153.

83. The U.S. has proposed that a Fissile Material Production Cutoff Treaty (FMCT) that would ban future production of fissile for weapons use, not be subject to verification. The author has been told by a knowledgeable U.S. Government official that this policy decision was driven in good part by the U.S. Navy, which was concerned that the FMCT might interfere with its future supply of WgU fuel. Since the U.S. has stockpiled enough excess weapon-grade uranium to fuel its and U.K. nuclear-powered ships for about 100 years, this exemption would not be necessary if the U.S. and U.K.

were willing to develop LEU-fueled designs for their future nuclear ships during that period.

84. Steven Aftergood, "Background on space nuclear power," *Science & Global Security* 1 (1989), p. 93.

85. "Project Prometheus," NASA, ⟨http://spacescience.nasa.gov/missions/prometheus.htm⟩, July 28, 2004.

86. *Impact of the use of low or medium enriched uranium on the masses of space nuclear reactor power systems* (Department of Energy, Office of Nuclear Energy, 1994).

87. Iain Ritchie, IAEA, private communication, July 28, 2004. The IAEA database of research reactors in Russia is incomplete, however. It does not include, for example, research reactors and critical assemblies located at VNIIEF (Russia's Los Alamos).

88. "New life for research reactors? Bright future but far fewer projected," IAEA press release, March 8, 2004, ⟨http://www.iaea.org/NewsCenter/Features/ResearchReactors/reactors20040308.html⟩.

89. Pablo Adelfang and Iain G. Ritchie, "Overview of the status of research reactors worldwide," 2003 International RERTR Meeting. The Director General of the European Union's Joint Research Center similarly observed that Europe faces an oversupply of research capacity, "Enlarging EU faces oversupply of research and test reactors," *Nucleonics Week* (March 23, 2000), p. 13.

90. "New life for research reactors? Bright future but far fewer projected," op. cit.

91. "Overview of the status of research reactors worldwide," 2003, op. cit.

92. "Over 200 research reactors need decommissioning, ISAG told IAEA," *Nucleonics Week* (Sept. 28, 2000), p. 11.

93. Decommissioning costs cover a wide range, depending on activation and contamination levels, and the standards set for the cleanup. Denmark has committed $66 million to decommission its 10-MWt D-3 and two smaller research reactors and return the site to a "greenfield" standard. By comparison, the estimated cost of overseeing the spent fuel at the shutdown Danish reactors was $2.6 million/yr, "Danes Begin Decommissioning of Risø Laboratory Reactors," *Nucleonics Week*, (Aug. 29, 2002), p. 7. Decommissioning Germany's 58-MWt KNK reactor will cost $12 million, "Westinghouse gets KNK job," *Nucleonics Week* (April 12, 2001), p. 14. The shutdown of the UK's 0.3-MWt UTR-300 reactor will cost $3.2 million, "BNFL Gets Dismantling Contract For Scottish Research Reactor," *Nucleonics Week* (June 10, 1999), p. 15. In June 2004, U.S. agreed to help Latvia decommission a shutdown 5-MWe HEU-fueled research reactor at the Institute of Nuclear Physics in Salaspils. The total decommissioning cost estimated in 1999 was about $21 million, ⟨http://www.nti.org⟩. Operating costs also cover a wide range, depending upon the powers and missions of research reactors. Cornell University recently decided to shut down its 0.5 MWt Triga reactor, which cost an estimated $0.5 million/year to operate, "Cornell Board of Trustees Votes in Favor of Closing Reactor," *Nucleonics Week* (May 31, 2001), p. 3. The operating budget for MIT's 5-MWt reactor is about $2.9 million/yr and the 1999–2000 budget for the University of Michigan's 2-MWt reactor was about $1.7 million. Regulatory issues can also influence a shutdown decision. In 2001, the University of Michigan was considering shutting down its reactor in part because it was due for relicensing and renovation that would cost an estimated $5–10 million, "DOE reviewing task force advice on university research reactors," *Nucleonics Week* (May 17, 2001), p. 3.

94. "Martha Krebs, director of DOE's Office of Science . . . added there will probably be enough early shutdown work at the reactor over the next two years to warrant retaining its full staff, estimated at 90 workers. Fluids will have to be drained from the reactor and the fuel will have to be moved, she said," "Brookhaven Research Reactor To Permanently Close, DOE Says," *Nucleonics Week* (November 18, 1999), p. 15.

95. Private communication, Nikolai Arkhangelski, Department of Atomic Energy, Russian Atomic Energy Agency, October 6, 2003.

96. S.2400 as passed by the Senate on June 23, 2004, Section 3132, "Acceleration of removal or security of fissile materials, radiological materials and related equipment at vulnerable sites worldwide."

97. *Congressional Record*, May 19, 2004, S5772.

98. "Remarks prepared for Energy Secretary Spencer Abraham—International Atomic Energy Agency, Vienna, May 26, 2004.

99. *Congressional Record*, June 25, 2004, pp. H5118-19.