

PROJECT ON MANAGING THE ATOM

PREVENTING NUCLEAR TERRORISM

CONTINUOUS IMPROVEMENT
OR DANGEROUS DECLINE?

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The "Tunnel Vault" nuclear materials storage facility at Technical Area 41, Los Alamos National Laboratory, as seen in October, 1964. (Los Alamos Archive).

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level of operating organizations and individuals. WINS offers workshops, best practice guides, and now the WINS Academy, which provides training and certification for nuclear security managers and staff.¹¹⁹ WINS' membership continues to grow, and the importance of its work is increasingly recognized. The 35-nation nuclear security implementation initiative, for example, included a pledge to support or participate in the development of WINS' best practice guides.¹²⁰

Risk summary and trend: The risks of nuclear theft in these different countries vary widely, given varying nuclear security measures and different threat environments. Some countries still have nuclear security measures that are not likely to provide protection against the full spectrum of plausible adversary threats. Civilian HEU likely poses the highest risks, but the risks posed by civilian plutonium and military materials cannot be ignored. Overall, the average trend in these countries appears to be toward decreasing risk, as nuclear security measures continue to improve. Whether security improvements will continue to keep pace with evolving threats in the future remains uncertain, however.

Consolidating Nuclear Weapons and Weapons-Usable Materials

Consolidating nuclear weapons and weapons-usable material to fewer sites is a critical element of the effort to reduce the risk of theft. The only way to completely eliminate the risk of nuclear theft at a site is to eliminate the weapons-usable nuclear material from the site. And states can achieve more effective nuclear security at less cost by protecting fewer sites. Moreover, eliminating HEU or plutonium from a location is inherently sustainable: once weapons-usable nuclear material has been eliminated from a site, it stays gone.

Here, the measure of progress is clear: what fraction of the sites with nuclear weapons or weapons-usable nuclear materials in the world, or in a particular category of concern, have been eliminated?

Reductions in the size of nuclear stockpiles are much less important to the risk of nuclear theft than reductions in the number of locations. A building with 100 tons of weapons-usable nuclear material represents essentially the same risk of nuclear theft as a building with 10 tons—already more than thieves would likely be able to carry away. By contrast,

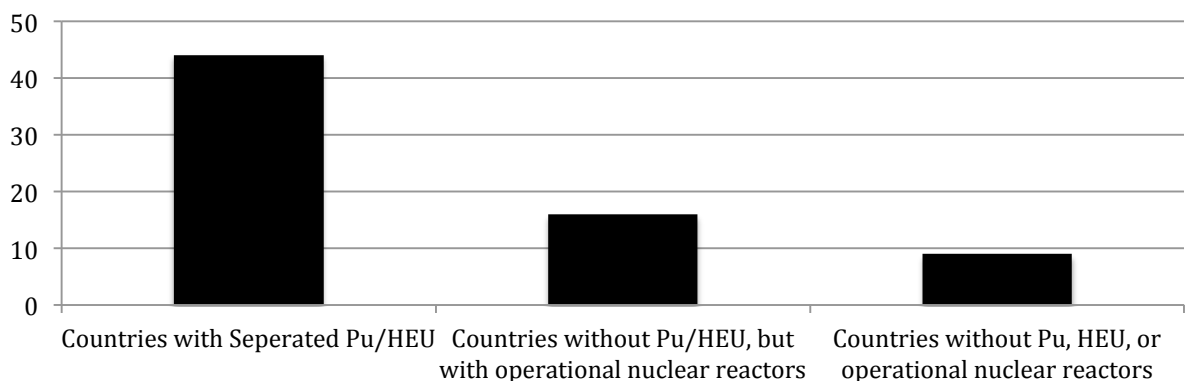
119 For information on WINS mission, goals, and services, visit <https://www.wins.org/>.

120 Dal, Herbach, and Luongo, "The Strengthening Nuclear Security Implementation Initiative."

eliminating a site means eliminating another chance for mistakes to create a vulnerability that might be exploited, and another group of insiders with access to potential nuclear bomb material. Hence, the number of sites with all weapons-usable nuclear material removed is a far better measure of progress than the quantity of HEU or plutonium removed.

Over the past 30 years, there has been considerable progress in reducing the number of places where nuclear weapons and the materials needed to make them can be found. At one time, U.S. and Soviet nuclear weapons were deployed in many countries around the world. Today, except for roughly 200 bombs at a few bases in Europe, all U.S. and Russian nuclear weapons are in the United States and Russia. In the United States, those weapons not on strategic delivery systems are stored at a very few storage facilities. In Russia, the number of storage facilities is far larger, but still significantly smaller than it was decades ago. Throughout the nuclear age, a total of 57 countries have possessed weapons-usable nuclear materials. That number has been cut by more than half. Even within countries that still have weapons-usable nuclear materials, the number of sites has been substantially reduced, particularly in the United States, where the costs of meeting post-9/11 security requirements have motivated many sites to eliminate these materials.

Figure 2: IPPAS Missions in Countries with/without Relevant Materials or Technology



Note: Based on data from the IAEA

Despite this significant progress, nuclear weapons are stored in more than a hundred sites in fourteen countries. The material needed to make nuclear weapons, HEU, and plutonium, is

located in hundreds of buildings spread across 27 countries.¹²¹ More than four-fifths of these materials, however, are in Russia and the United States, along with the largest number of locations where these materials reside. The number of nuclear weapons sites has stabilized in the United States and Russia and may be increasing in Pakistan and elsewhere; reductions in the U.S. and Russian nuclear weapons stockpiles have slowed; reductions in the global HEU stockpile have slowed dramatically with the end of the HEU Purchase Agreement; stocks of civilian separated plutonium continue to increase, while a few countries continue to produce military plutonium; and efforts to convert research reactors to LEU fuel and to remove unneeded HEU and LEU around the world appear to be slowing.

Bulk Processing Facilities

Nearly all of the confirmed thefts of plutonium and HEU are material in bulk form such as powders, which appear to have been stolen from bulk-processing facilities. Given the uncertainties in measurement, in a bulk-processing facility handling tons of plutonium or HEU each year, it is very difficult for accounting systems to confirm that a few kilograms have not gone missing.

Hence, bulk processing facilities should be a top priority for efforts to reduce the number of locations with nuclear weapons or weapons-usable nuclear material. Unfortunately, no programs targeted on reducing the number of bulk-processing facilities exist, though the United States and other countries have long sought to limit the spread of plutonium reprocessing (one form of bulk processing) and uranium enrichment to additional countries.

Despite the lack of programs focused on them, a number of bulk-processing facilities have shut down or reduced operations in recent years. With the end of the Cold War, both the United States and Russia shut down military plutonium production, closing reprocessing facilities, while also consolidating and reducing the throughput of facilities for fabricating plutonium and HEU weapons components. In Japan, the Rokkasho Reprocessing Plant has still not opened, and the pilot-scale Tokai reprocessing plant has shut down. In the U.K., the Thermal Oxide Reprocessing Plant (THORP) at Sellafield has never performed

¹²¹ The *NTI Nuclear Security Index* lists 24 remaining countries with a kilogram or more of HEU or separated plutonium. Since then, all the plutonium has been removed from Switzerland. In addition, however, Ghana, Syria, and Nigeria have just under a kilogram of this material in the cores of Slowpoke or Miniature Neutron Source Reactors (MNSRs), and Indonesia has just three kilograms of irradiated HEU from past nuclear activities. See U.S. National Nuclear Security Administration, National Nuclear Security Administration, “United States Collaborates with Switzerland to Remove Last Remaining Separated Plutonium” (Washington, D.C.: NNSA, March 4, 2016), <http://nnsa.energy.gov/mediaroom/pressreleases/united-states-collaborates-switzerland-remove-last-remaining-separated> (accessed Mar 15, 2016); GAO, *DOE Made Progress*, 2015, pp. 17–18.

well, and is slated to shut down in a few years, when it finishes its existing contracts. The plutonium-uranium mixed oxide (MOX) fuel fabrication plant at Mol, in Belgium, closed years ago, as did the MOX plant at Caderache, in France, and the Sellafield MOX Plant in the United Kingdom. A new MOX plant under construction in the United States will likely never be completed, due to escalating costs, but a new MOX plant is still under construction in Japan. As noted earlier, however, new reprocessing plants have been completed or are under construction in both Pakistan and India; China is considering construction of commercial-scale reprocessing plants; Russia opened a new MOX plant in 2015 to implement its obligations under the U.S.-Russian Plutonium Management and Disposition Agreement (PMDA) and continues to plan to build a new reprocessing plant in the future.¹²²

Civilian HEU

Since 1978, the United States has been working to convert research reactors so they no longer use HEU, and then eliminate the HEU they no longer need. Since 1991, 30 countries have eliminated all of their weapons-usable nuclear material.¹²³ More than half—17 countries—eliminated all of their weapons-usable nuclear material during the Obama administration, 13 during the four-year effort, three more during 2015, and one so far in 2016.¹²⁴ Today, 27 countries still have weapons-usable nuclear material on their soil. Nine of these countries are states with nuclear weapons. For many of the others, the only weapons-usable nuclear material on their soil is civilian HEU at one or a small number of research reactor facilities.

From 1996 through the end of 2015, the United States supported more than 200 removals from more than 40 countries, totaling over four tons of weapons-usable nuclear

122 For a discussion of the Chinese plans, see Hui Zhang, *Rethinking Chinese Policy on Commercial Reprocessing* (Cambridge, MA: Project on Managing the Atom, Harvard Kennedy School, March 2012), http://belfercenter.ksg.harvard.edu/files/ChinaReprocessing_hzhang.pdf (accessed February 19, 2016). See also *Global Fissile Material Report 2015: Nuclear Weapon and Fissile Material Stockpiles and Production* (Princeton, N.J.: International Panel of Fissile Materials, 2015), <http://fissilematerials.org/library/gfmr15.pdf> (accessed February 9, 2016), pp. 17–18, 33.

123 The 30 countries are Brazil, Bulgaria, Colombia, Denmark, Greece, Iraq, Latvia, Philippines, Portugal, Slovenia, South Korea, Spain, Thailand, Austria, Chile, Czech Republic, Hungary, Libya, Mexico, Romania, Serbia, Sweden, Switzerland, Taiwan, Turkey, Ukraine, Vietnam, Uzbekistan, Georgia, and Jamaica. See “NNSA Achievements: 2015 by the Numbers,” <http://nnsa.energy.gov/content/2015-year-review> (accessed February 19, 2016); and National Nuclear Security Administration, “United States Collaborates with Switzerland to Remove Last Remaining Separated Plutonium.” In some of these countries, a few grams or tens of grams of material remain for research purposes, but these amounts are far too small to be a significant part of the material needed for a nuclear bomb.

124 The 13 countries that eliminated their weapons-usable nuclear material during the four-year effort are Austria, Chile, Czech Republic, Hungary, Libya, Mexico, Romania, Serbia, Sweden, Taiwan, Turkey, Ukraine, and Vietnam. Twelve of those countries eliminated their HEU during that period. Sweden, which had eliminated its HEU in 2002, eliminated its plutonium stocks. The three countries that eliminated their nuclear material during 2015 are Uzbekistan, Georgia, and Jamaica. The combined amount of HEU in all three of these countries was less than 10 kg, and none of it was fresh fuel. See GAO, *DOE Made Progress*, 2015. Switzerland eliminated its plutonium in 2016.

material.¹²⁵ Early on, removals concentrated on U.S.-origin HEU, but in recent years, they have included Russian-origin HEU, small amounts of plutonium, and small amounts of material that originated in other countries as well. Since 2009, only 85 kilograms of repatriated nuclear material has been of U.S. origin (see Figure 3.)

Approximately 1.6 tons, or 40 percent, of this material was removed or disposed of during the four-year effort, from 2009 through the end of 2013, an average of more than 300 kilograms of material per year.¹²⁶ Removals have slowed since then. In 2014, the United States helped to remove 135 kilograms of weapons-usable nuclear material, which included material taken from Belgium and Italy in the run-up to the nuclear security summit in April of that year.¹²⁷ In 2015, the United States helped to remove or eliminate 141 kilograms of HEU. This included the removal of 36 kilograms of HEU from the Institute of Nuclear Physics (INP) in Almaty, Kazakhstan, and of two kg of HEU from a breeder reactor in Georgia.¹²⁸

In FY 2016, the National Nuclear Security Administration (NNSA) expects the amount of nuclear material removed to increase again. The United States plans to assist in the removal of an additional 723 kilograms of nuclear material by the end of the year, including complete cleanout of four additional countries: Switzerland, Poland, Indonesia, and Argentina.¹²⁹ There are also plans to ship a small amount of Georgian HEU being stored in

125 This figure includes only removals of HEU or plutonium supported by U.S. programs. NNSA often includes in its totals 1,240 kilograms of HEU the U.K. blended down and 112 kilograms of HEU Japan blended down without U.S. support. See GAO, *DOE Made Progress*, p. 14. All but a small amount of this material was HEU.

126 GAO, *DOE Made Progress*, 2015. Additionally, in 2013, the United States verified that the United Kingdom had downblended 1,240 kg of HEU and Japan had downblended 112 kg of HEU, but it is unclear when that took place or what part the United States played in it. Our estimate in *Advancing Nuclear Security* took into account the downblending of the British material, but we were unaware of the Japanese material.

127 See “Belgium Highly Enriched Uranium and Plutonium Removals,” *National Nuclear Security Administration Fact Sheet*, March 24, 2014, <http://nnsa.energy.gov/mediaroom/factsheets/belgiumremovals> and “Fact Sheet: Italy Highly Enriched Uranium and Plutonium Removals” March 24, 2014), <https://www.whitehouse.gov/the-press-office/2014/03/24/fact-sheet-italy-highly-enriched-uranium-and-plutonium-removals> (accessed February 19, 2016).

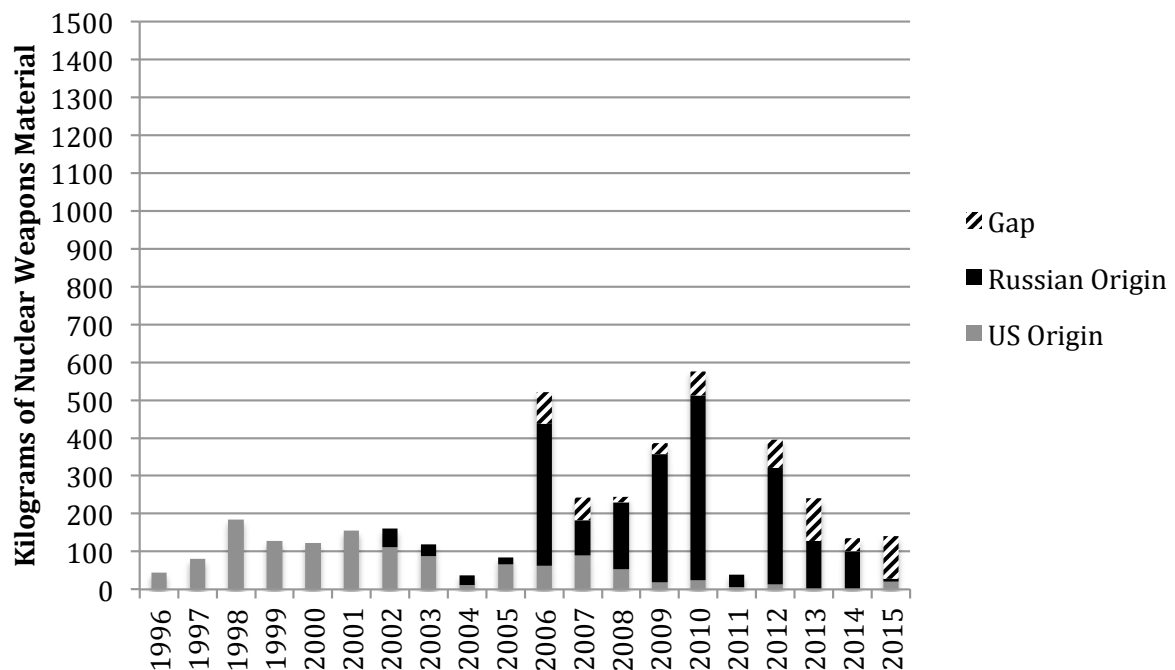
128 World Nuclear News, “Georgia ships Breeder-1 HEU to Russia,” *WNN Regulation and Safety News*, December 23, 2015, <http://www.world-nuclear-news.org/RS-Georgia-ships-Breeder-1-HEU-to-Russia-23121501.html> (accessed February 10, 2016); and “U.S., Kazakhstan Cooperate to Eliminate Highly Enriched Uranium,” *National Nuclear Security Administration Press Release*, January 7, 2015, <http://nnsa.energy.gov/mediaroom/pressreleases/kazakhstan> (accessed February 10, 2016). Until the announcement by the IAEA that this material had been removed most of the world had been under the impression that all HEU had been removed from Georgia in 1998 as part of Operation Auburn Endeavor. See the White House, Office of the Press Secretary, “Operation Auburn Endeavor,” (Washington, D.C.: The White House, April 24, 1998), <http://fas.org/nuke/control/ctr/news/980424-wh.htm> (accessed February 19, 2016).

129 U.S. Department of Energy, *FY 2017 Congressional Budget Request: National Nuclear Security Administration*, Vol. 1, DOE/CF-0119 (Washington, D.C.: DOE, February 2016), http://energy.gov/sites/prod/files/2015/02/f19/FY2016BudgetVolume1_1.pdf (accessed May 2, 2014), p. 479. Supplemented with data supplied by NNSA, March 2015 and March 2016.

the United Kingdom to the United States.¹³⁰ Between FY 2017 and FY 2021, NNSA plans to remove or confirm the disposition of 745 kilograms of additional HEU or plutonium, an average of nearly 150 kilograms of material a year.¹³¹ This is a significantly reduced rate compared to what was planned in 2015.

Most of the 2016 material is expected to be the 215 kilograms of HEU and 331 kilograms of plutonium from Japan's Fast Critical Assembly (FCA), which Japan pledged to eliminate at the 2014 nuclear security summit.¹³² This will eliminate one of the few places in non-nuclear weapon states with enough weapon-grade HEU metal for a simple gun-type nuclear bomb, representing a major step forward for consolidation efforts.¹³³

Figure 3: **Removals of U.S. Origin, Russian Origin, and Gap Nuclear Weapons Materials**



Note: This chart is based on data provided by the National Nuclear Security Administration. It does not include 1352.3 kilograms of Japanese and British HEU that were confirmed in 2013 to have been downblended. This downblending likely took place much earlier, without the support of the United States.

130 This is the small amount of irradiated material included in the HEU removed in Operation Auburn Endeavor, which is being removed from Dounreay as part of the decommissioning of that facility.

131 DOE, *FY 2017 Congressional Budget Request: NNSA*, p. 479.

132 Matthew Bunn, "Eliminating Potential Bomb Material from Japan's Fast Critical Assembly," *Nuclear Security Matters Blog*, March 24, 2014, <http://nuclearsecuritymatters.belfercenter.org/blog/eliminating-potential-bomb-material-japan%E2%80%99s-fast-critical-assembly> (accessed February 10, 2016).

133 Bunn, "Eliminating Potential Bomb Material from Japan."

Unfortunately, although the goal should be to eliminate all civil HEU, the planned removals would leave large quantities of civil HEU still in the world. For example, over 13 tons of U.S.-origin civil HEU existed in foreign countries as of 2013, and more than 10 tons of that material would not be covered in NNSA's current removal plans.¹³⁴ If U.S.-Russian cooperation on consolidation and HEU reactor conversion remains suspended, and Russia continues not to prioritize such efforts, large quantities of civil HEU are likely to remain in Russia, as well.

In the case of research reactors using HEU fuel, the reactors must convert to other fuel or shut down before all the HEU can be removed from the site. Hence, reactor conversion and shutdown are also major parts of the effort to consolidate nuclear material to fewer locations.

From 1978, when U.S.-sponsored reactor conversion programs began, through 2015, 65 reactors converted from HEU fuel to LEU fuel, and well over 100 HEU-fueled reactors have closed; together, the conversions and shutdowns represent something in the range of 60 percent of what was once the world's total of HEU-fueled research reactors. Still, more than 125 reactors around the world (not counting an additional several dozen naval propulsion reactors) continue to use HEU for their fuel or for targets for isotope production.¹³⁵ Of these, roughly 90 are civilian reactors of various types, which would have to be addressed if the goal of eliminating the civil use of HEU were to be achieved.¹³⁶

Table 2 shows the number of reactors that converted to LEU fuel or shut down in the years before the 2004 founding of GTRI; from 2004-2008, before the four-year nuclear security effort began; and from 2009-2015. From 2004 to 2008, 17 HEU reactors or medical isotope production facilities were converted and six shut down. From 2009-2015, only 13 facilities that use HEU were converted and 20 shut down. From FY 2016 through FY 2020, NNSA plans to convert or confirm the shutdown of 18 research reactors, representing some 14

134 The United States only plans to remove a cumulative total of 6,800 kilograms of nuclear material by 2021. By 2013, the United States had already helped remove approximately 2,965 kilograms of nuclear material. This means only an additional three tons of nuclear material will be removed from 2014 through 2021. See DOE, *FY 2017 Congressional Budget Request: NNSA*, p. 473.

135 This includes the 118 land-based reactors identified by the International Panel on Fissile Materials (except for two that are actually plutonium-fueled rather than HEU-fueled), and nine reactors for nuclear-powered icebreakers in Russia. See International Panel on Fissile Materials, "Facilities: Research and Isotope Production Reactors" (Princeton, N.J.: IPFM, 2015), http://fissilematerials.org/facilities/research_and_isotope_production_reactors.html (accessed May 3, 2015).

136 This includes 74 civilian research reactors using or planning to use HEU fuel; six reactors using HEU for targets for isotope production; two civilian power reactors (the BN-600 and BN-800 reactors in Russia); and the nine icebreaker reactors. For a list of the 74 civilian HEU-fueled research reactors, along with lists of military-purpose and icebreaker reactors, see U.S. National Academies of Sciences, Engineering, and Medicine, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors* (Washington, D.C.: National Academies Press, January, 2016), pp. 31–33, 186–187.

percent of the remaining HEU-fueled reactors.¹³⁷ If that pace remained constant after FY2020, it would take a quarter-century to convert the remaining civilian HEU-fueled reactors.

In recent years, there have been significant setbacks in the effort to convert HEU-fueled research reactors. First, there are technical barriers: developing high-density fuels to convert high-performance research reactors is taking far longer than expected because of early test failures and problems ramping up fabrication of the new fuel. As a result of these hurdles, NNSA has pushed back its deadline of converting 200 reactors from 2020—the goal it set for itself in 2010—to 2035, although there is significant uncertainty even in that estimate.¹³⁸ This long timeline for conversion has caused some to begin debating the question of whether to convert existing reactors or build new ones. (Different LEU fuels being developed in Europe, Russia, and South Korea will probably be available sooner, but do not offer a high enough density to convert the highest-performance reactors.)

The conversion effort is also facing political problems. Roughly half of the remaining operational HEU reactors in the world are in Russia, and Russia has suspended cooperative work on reactor conversions there. In 2010, the United States and Russia agreed to study conversion of six Russian HEU-fueled reactors to LEU, but only one—the Argus reactor at the Kurchatov Institute in Moscow—actually converted before cooperation was suspended.¹³⁹ Russian experts have made clear that neither converting reactors to LEU within Russia nor shutting down HEU-fueled reactors are priorities, though Russia continues to develop high-density fuels that could be used for future conversions.¹⁴⁰ Russian reactors, in short, are not likely to convert in substantial numbers unless Russia changes its approach. In addition, Russia appears to be prepared to export HEU fuel (as it did for the China Experimental Fast Reactor), which could undermine the influence the United States has wielded from being the only available source of HEU fuel for most countries.

At the same time, the United States is planning to restart the HEU-fueled Transient Reactor Test Facility at the Idaho National Laboratory for studies of severe accidents at nuclear reactors. This will be the first time the United States has added an HEU-fueled reactor to its fleet in many years, though DOE hopes to convert the facility to LEU after the initial startup with HEU.¹⁴¹

137 U.S. Department of Energy, *FY 2016 Congressional Budget Request: NNSA*.

138 U.S. Department of Energy, *FY 2016 Congressional Budget Request: NNSA*, p. 565.

139 International Panel on Fissile Materials, “Russia completed conversion of Argus research reactor,” *IPFM Blog*, November 30, 2014, http://fissilematerials.org/blog/2014/11/russia_completed_conversion.html (accessed February 10, 2016).

140 Interview with Rosatom expert, October 2015. See also Khlopkov, “Russia’s Nuclear Security Policy.”

141 Pavel Podvig, “United States Prepares to Restart TREAT Reactor,” *International Panel on Fissile Materials*, October 7, 2014, http://fissilematerials.org/blog/2014/10/united_states_prepares_to.html (accessed February 10, 2016). For the plan to start with HEU and then convert to LEU, see Alfred Sattleberger and John W. Herczeg, “Status of NEAC Fuel Cycle Subcommittee Recommendations,” *U.S. Department of Energy*, December 11, 2015, [http://www.energy.gov/sites/prod/files/2016/01/f28/NEACRecommendationsStatus-NE-5\(FINAL\).pdf](http://www.energy.gov/sites/prod/files/2016/01/f28/NEACRecommendationsStatus-NE-5(FINAL).pdf) (accessed February 10, 2016).

One area where there has been steady progress throughout the Obama administration is in reducing the use of HEU for producing medical isotopes, principally molybdenum-99 (Mo-99, sometimes referred to as “moly-99”). Until recently, all of the largest producers made their Mo-99 from HEU, using over 40 kg of weapons-grade HEU every year (as the production process involves only brief irradiation, nearly all of the HEU used ends up in “waste” that is still very highly enriched and not very radioactive). South Africa, with extensive U.S. support, became the first of the large producers to produce Mo-99 from LEU; Belgium and the Netherlands have both committed to converting and are both in the process of doing so, though with some delays; Canada, the last of the large producers, plans to shut down its production in 2018; and NNSA has supported companies that are expected to begin producing Mo-99 within the United States without HEU in the next few years. Within a few years, it should be possible to meet all of global demand for medical isotopes without HEU.¹⁴² At the same time, Rosatom intends to expand its isotope production, still using HEU fuel and targets; while Russia is considering converting to LEU, there are concerns that expanded Russian production using HEU could undercut producers that have converted away from HEU.¹⁴³

Table 2: Total Worldwide GTRI Conversion and Shutdown Reactors

Years	1978–2003	2004–2008	2009–2015
Converted	35	17	13
Shutdown	90	6	20

Note: Data from Ole Reistad and Stykkaar Hustveit, “Appendix II: Operational, Shut Down, and Converted HEU-Fueled Research Reactors,” *Nonproliferation Review*, Vol. 15, No. 2 (July 2008), http://cns.miis.edu/npr/pdfs/152_reistad_appendix2.pdf (accessed May 21, 2015) and information provided by NNSA officials, January 2016. The number of reactors converted from 1978–2003 are adapted from NNSA data. NNSA counts a reactor as converted when conversion begins, and this table attempts to count reactors as converted when they are no longer using HEU fuel; at a minimum, this affects one research reactor in Mexico and one in Austria whose first use of LEU fuel was before 2003 but whose conversions were completed in 2012, and one in Vietnam whose conversion began in 2007 but was completed in 2011. Additionally, the chart counts a research reactor in Switzerland and one at Georgia Tech as shut down rather than converted because both were reportedly shut down before operating without HEU.

142 Anton Khlopkov and Miles Pomper, with Valeriya Chekina, “Ending HEU Use in Medical Isotope Production: Options for U.S.-Russian Cooperation,” *Nuclear Threat Initiative Media*, February 14, 2014, http://www.nti.org/media/pdfs/Ending_HEU_Use_in_Medical_Isotope_Production.pdf?_=1393952246 (accessed February 10, 2016); and *World Nuclear News*, “U.S. firms target revival in domestic Mo-99 production,” *WNN Corporate News*, May 1, 2015, <http://www.world-nuclear-news.org/C-US-firms-target-revival-in-domestic-Mo-99-production-01051501.html> (accessed February 10, 2016).

143 Khlopkov, Pomper, Chekina, “Ending HEU Use: U.S.-Russian Options.”

Civilian Plutonium

Global stocks of civilian separated plutonium are immense, amounting to over 270 tons, more than all the plutonium in all the world's military stockpiles combined, and continue to grow every year as reprocessing of plutonium continues to outpace its use as fuel. Few current efforts are targeted either on minimizing these huge stocks or reducing the number of locations where they are stored and handled.

Unlike HEU, most civilian plutonium is at reprocessing plants or fuel fabrication facilities, not at small research facilities. Current minimization efforts are focused on addressing the few small stocks of plutonium at research facilities and other locations where its owners have concluded it is no longer needed. These efforts are small: only one percent of the nuclear material the United States has helped to remove or confirm disposition of since 1996 has been plutonium.

Nevertheless, the United States has helped eliminate plutonium from several locations around the world. In March 2016, the United States helped remove 20 kg of plutonium from Switzerland.¹⁴⁴ As noted above, if all goes as planned, 2016 will also see the biggest plutonium removal yet, of some 331 kg of plutonium from the FCA in Japan. Nevertheless, these plutonium removals are addressing only a very small part of the overall problem of civilian separated plutonium around the world.

Military Stockpiles

Some 85 percent of the world's weapons-usable nuclear material is in military programs, rather than in civilian use. Some of the world's largest military stockpiles exist in countries with track records of corruption, theft, and political instability.

Russia and the United States have by far the largest military nuclear complexes, making consolidation a particular issue for those two countries. Both have consolidated their nuclear weapons complexes in the last two decades. In the United States in particular, a variety of factors, including a push to consolidate nuclear material at fewer locations, led to the closure and decommissioning of the Rocky Flats plutonium facility; an end to plutonium reprocessing, except for some modest processing for cleanup purposes that continues at Savannah River; the elimination of Category I and II weapons-usable nuclear

¹⁴⁴ U.S. National Nuclear Security Administration, "United States Collaborates with Switzerland to Remove Last Remaining Separated Plutonium."

material from the Sandia and Livermore national laboratories, and from Technical Area 55 at Los Alamos National Laboratory; and the clean-out of dozens of buildings that once held weapons-usable nuclear material at other sites. The number of buildings with weapons-usable nuclear material has been reduced to a fraction of what it was at the peak of the Cold War.

In Russia, as noted above, four nuclear weapons assembly and disassembly plants have been reduced to two, the last plutonium production reactors and their associated reprocessing plants have closed, and fabrication of plutonium and HEU weapons components has been consolidated at a single site. But overall, Russia still has much farther to go, with much larger number of nuclear weapon storage facilities than any other country; some 200 buildings with weapons-usable nuclear material; and something in the range of two-thirds of all the world's HEU-fueled pulse reactors and critical assemblies. For its own interests, Russia could get the military support and research operations it needs for less cost and risk with a smaller number of facilities.

Few initiatives are under way to consolidate nuclear weapons or military stocks of weapons-usable nuclear material. There have been, however, major initiatives to reduce the size of these stockpiles. In 2013, the United States and Russia completed the 20-year-long HEU Purchase Agreement, which eliminated 500 tons of Russian HEU. The HEU Purchase Agreement was a seminal achievement for nuclear security, eliminating thousands of bombs' worth of nuclear material, providing revenue and employment to stabilize key Russian nuclear facilities at a critical time, and introducing innovative transparency measures.¹⁴⁵ Unfortunately, Russia declined U.S. suggestions for a follow-on effort to blend more HEU.¹⁴⁶

By contrast, U.S.-Russian plutonium disposition programs have made only modest progress. As noted earlier, the U.S. MOX plant appears likely to be abandoned, among skyrocketing costs.¹⁴⁷ It appears that the favored alternative is to store plutonium at the Waste Isolation Pilot Plant (WIPP) in New Mexico.¹⁴⁸ There are, however, significant tech-

145 "The 1993 United States-Russian Federation Highly Enriched Uranium Purchase Agreement: Overview, Implementation and Results," *NNSA Office of Nonproliferation and Arms Control*, <http://www.state.gov/documents/organization/242396.pdf> (accessed January 16, 2016).

146 For suggestions on approaches Russia could take to use its remaining excess to make billions of dollars while supporting its nuclear energy growth and export objectives, see Matthew Bunn, "Expanded and Accelerated HEU Downblending: Designing Options to Serve the Interests of All Parties," (presented at the 49th Annual Meeting of the Institute for Nuclear Materials Management, Nashville, TN, July 17, 2008), <http://belfercenter.hks.harvard.edu/files/inmm-expanded-blend-down-incentives.pdf> (accessed March 6, 2016).

147 Kingston Reif, "Cost Estimate for MOX Plant Jumps," *Arms Control Today*, June 2015, https://www.armscontrol.org/ACT/2015_06/News-Briefs/Cost-Estimate-for-MOX-Plant-Jumps (accessed January 15, 2016).

148 Derrek Asberry, "White House hopefuls tackle MOX, eminent domain," *Aiken Standard*, February 17, 2016, <http://www.aikenstandard.com/article/20160217/AIK0101/160219533> (accessed February 19, 2016).

nical, safety, and legal issues that need to be addressed before the WIPP alternative could be implemented.¹⁴⁹ Russia has completed its MOX plant and brought the BN-800 online, but the fate of the U.S.-Russian plutonium disposition agreement and whether the BN-800 will run on former weapons plutonium or reactor plutonium remain uncertain.¹⁵⁰

Strengthening Security Culture and Combating Complacency

As discussed below, strong security cultures, in which all security-relevant staff take the issue seriously and are always looking for vulnerabilities to be fixed and ways to make improvements—are essential to nuclear security excellence. The foundation of a strong security culture is belief in the threat—never “forgetting to be afraid.”¹⁵¹

Initiatives such as the nuclear security summits and GICNT have done a great deal to build international consensus that the threat of nuclear terrorism is real, and that nuclear security is a critical element of efforts to address the threat. Nevertheless, in many quarters, complacency remains.

Progress in combating complacency and strengthening security culture is extraordinarily hard to assess. But that is no excuse for not focusing on the issue, given its crucial importance to nuclear security success. Indicators that could be used to assess progress in these areas include:

- The fraction of the world’s locations with nuclear weapons, separated plutonium, or HEU that are managed by organizations with targeted programs in place to strengthen their security culture, and assess their progress in doing so.
- The degree of improvement such programs are achieving in attitudes and behavior of staff, as measured in surveys and self-assessments.
- The degree to which national policymakers involved in nuclear security decisions express belief in the threat and the need for action to improve nuclear security—and the degree to which they back that up by allocating resources and approving stringent nuclear security requirements.

149 Oak Ridge National Laboratory, *Final Report of the Plutonium Disposition Red Team* (Oak Ridge, TN: Oak Ridge National Laboratory, August 13, 2015), <http://www.ucsusa.org/sites/default/files/attach/2015/08/final-pu-disposition-red-team-report.pdf> (accessed March 6, 2016).

150 “Russia Launches Commercial MOX Fuel Fabrication Facility,” *International Panel on Fissile Materials*, September 28, 2015, http://fissilematerials.org/blog/2015/09/russia_launches_commercia.html (accessed January 16, 2016).

151 James Reason, *Managing the Risks of Organizational Accidents* (Aldershot, U.K.: Ashgate, 1997), p. 195.

4. Broaden Nuclear Consolidation Efforts

The United States and other interested countries should make it a priority to reduce the number of locations where nuclear weapons and their essential ingredients exist around the world as much as possible. As detailed earlier in this report, existing consolidation programs have made considerable progress; half of all the countries that once had weapons-usable nuclear materials on their soil have eliminated it. These programs deserve strong support. But the consolidation effort should be broadened and expanded.²¹⁸ They should include not only civil HEU but civil plutonium and military stocks as well. Key steps are listed below.

A Comprehensive Approach

Each state with nuclear weapons, HEU, or separated plutonium should undertake a review of every site where these materials exist, eliminating any site whose continued benefits are outweighed by its costs and risks. This review should include the costs of ensuring effective security against a broad range of potential adversary threats if the material remains in place. The material at sites to be closed should then be consolidated at other locations.

Countries should ensure that operators have strong incentives to eliminate HEU or separated plutonium stocks where feasible, to help overcome facility operators' natural resistance to change.²¹⁹ Regulators should ensure that regulations appropriately require substantially more stringent security measures when HEU or separated plutonium is present (as IAEA recommendations suggest), so that operators can save money on security costs by eliminating this material.²²⁰ States should eliminate any institutional incentives that may exist for operators to maintain HEU or separated plutonium (such as increased research funding for facilities using these materials, for example). The U.S. government and other interested governments should continue and expand their use of substantial

218 For more detailed analysis and recommendations, see Bunn and Harrell, *Consolidation: Thwarting Nuclear Theft*.

219 For more on eliminating the use of HEU, see Frank von Hippel, *Banning the Production of Highly Enriched Uranium* (Princeton, N.J.: International Panel of Fissile Materials, 2016), <http://fissilematerials.org/library/rr15.pdf> (accessed March 18, 2016).

220 In the United States, the high costs of meeting post-9/11 security requirements for plutonium and HEU have driven a major consolidation of nuclear materials in the DOE complex, with all Category I and Category II material eliminated from Livermore and Sandia National Laboratories, HEU removed from TA-55 at Los Alamos to the highly secure Device Assembly Facility in Nevada, and substantial reduction in the number of buildings with weapons-usable material elsewhere. But in a recent survey of nuclear security experts in 18 countries with plutonium or HEU, experts from nine countries reported that the nuclear security rules and procedures in their countries either created no significant incentive to consolidate these stocks or gave sites incentives to maintain the stocks they had. See Bunn and Harrell, *Threat Perceptions and Drivers of Change*, p. 31.

packages of incentives, shaped for the needs in each case, to convince countries to eliminate civilian sites with dangerous stocks of high-quality HEU or separated plutonium. Donors, for example, could offer financial support for work at other research reactors and help with decommissioning if an HEU-fueled research reactor shut down, or, if a high-flux research reactor agreed to convert to LEU fuel, donors could offer improved neutron guides that would allow the reactor to achieve a better flux of neutrons for their experiments than ever before.²²¹

The U.S. government should have a blanket policy that wherever plutonium or HEU exists in the world, it will either take it back to be secured in the United States, help arrange its disposition elsewhere, or work to ensure that it has sustainable security that will protect it from the full range of plausible threats while it stays in place.

Bulk Processing Facilities

As large facilities that process weapons-usable nuclear material in bulk pose the greatest dangers of insider nuclear theft, the United States and other interested countries should work to ensure that:

- The number of such bulk-processing facilities does not increase;
- New states have incentives not to build such facilities;
- The overall scale of bulk processing worldwide decreases rather than increases;
- These facilities process material in forms as difficult to make into nuclear weapons as practicable; and
- Each of these facilities implements the highest standards of security, accounting, and control for the nuclear material it handles.

²²¹ See 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. 141–54.

Civil HEU

Countries using HEU for nonmilitary purposes should join together in agreeing on the goal of eliminating the civil use of HEU, and a target date for doing so.²²² While continuing to push to convert research reactors fueled with HEU to LEU, the United States and other interested governments should also offer incentives to shut down unneeded HEU-fueled reactors and to eliminate their dangerous nuclear material. (Most of the world's research reactors are underutilized, and many of the facilities with high-quality HEU would be quite difficult to convert to LEU.)²²³ Shutting down reactors will frequently be cheaper than converting them, and unlike conversion, there are no technical barriers to shutdown. The United States, working with other countries (perhaps through the IAEA) should establish a program to offer incentives for unneeded HEU-fueled facilities to shut down, including assistance with decommissioning costs, funding for scientists to share time at other research reactors in their region, and more.²²⁴

The United States and other interested governments, working in collaboration with the IAEA, should help countries convert research reactors to particle accelerators wherever practical, accomplishing similar research and isotope production with reduced proliferation risk, as well as reduced fuel supply and waste management challenges.²²⁵ The United States should offer to buy HEU from anyone willing to sell (and willing to promise not to make or get more).

Russia and the United States should each prepare a plan for achieving the science, training, and isotope production they need at minimum cost and risk, with minimum use of HEU or plutonium—plans for “Neutrons for America” and “Neutrons for Russia.” This is important because Russia now has roughly two-thirds of the world's HEU-fueled critical assemblies, and two-thirds of the world's HEU-fueled pulse reactors (both of which often

222 For other recommendations on coping with civil HEU, see, for example, Andrew J. Bieniawski and Miles A. Pomper, *A Roadmap to Minimize and Eliminate Highly Enriched Uranium* (Washington, D.C.: Nuclear Threat Initiative, James Martin Center for Nonproliferation Studies, and Fissile Material Working Group, May 2015); Fissile Materials Working Group, *The Results We Need in 2016*; and Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing Out Highly Enriched Uranium* (New York: Routledge, 2013).

223 There are over 240 research reactors in the world (roughly half of them still fueled with HEU), and IAEA experts have estimated that the world only needs 30–40 such reactors for the long term. International Atomic Energy Agency, “New Life for Research Reactors? Bright Future but Far Fewer Projected” (Vienna: IAEA, March 8, 2004).

224 Bunn and Harrell, *Consolidation: Thwarting Nuclear Theft*, pp. 38–40.

225 Israel, for example, is replacing its Soreq research reactor with a particle accelerator, and expects to be able to accomplish even better scientific research than before. For a brief discussion of the potential role of accelerators as an alternative to many research reactors, see David Nusbaum, “Smashing Atoms for Peace: Using Linear Accelerators to Produce Medical Isotopes Without Highly Enriched Uranium” (Cambridge, MA: Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, October, 2013), <http://belfercenter.ksg.harvard.edu/publication/23513/> (accessed January 21, 2016).

have hundreds of kilograms or even tons of high-quality HEU), while the United States has several aging high-performance research reactors that cannot be converted to LEU with existing fuels. Neither country has a long-term plan for their research reactor fleets. If Russia and the United States are able to renew nuclear security cooperation, they should discuss the specifics of these plans, and ways they might work together (for example sharing certain facilities where scientific objectives overlap).

Finally, in cases where an HEU-fueled reactor is still needed, and it is projected to take many years before conversion can occur, states should: provide stringent security measures for the HEU; and consider converting 30-45 percent enriched HEU as an interim step to reduce risk until full conversion can be accomplished, as a recent National Academy of Sciences panel has recommended.²²⁶

Civil Plutonium

The United States and other countries should undertake new efforts to consolidate civilian separated plutonium and limit the buildup of ever-larger stockpiles. In particular, they should seek to get countries to commit to:

- Eliminate any unneeded sites with separated plutonium (as Switzerland and Sweden, among others, have done in recent years);
- Avoid expanding the number of plutonium reprocessing facilities, and the number of places where separated plutonium is stored and used;
- Reprocess no more plutonium than they use each year, so that stocks remain stable or decline, rather than increasing;
- Handle plutonium as much as possible in forms mixed with other materials, requiring chemical separation before they could be used in a bomb; and
- Maintain high standards of security and accounting throughout all storage, transport, processing, and use of separated plutonium.

226 National Academies of Sciences, Engineering, and Medicine, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors*.

Military Stocks

At the same time, the United States, Russia, and other interested countries should expand cooperative efforts to consolidate military stocks of nuclear weapons, separated plutonium, and HEU. Russia and the United States, in particular, as the countries whose nuclear stockpiles are dispersed at the largest number of buildings and bunkers with nuclear weapons or weapons-usable material, should each develop a national-level plan for accomplishing their military and civilian nuclear objectives with the smallest practicable number of locations with nuclear weapons or weapons-usable material.²²⁷

Recommendations for the Next U.S. President

The next U.S. president should:

- Launch a comprehensive consolidation effort, covering bulk-processing facilities, civil HEU, civil plutonium, and military stocks, as described above.
- Make consolidation a major priority of the U.S. nuclear security program.
- Work with Congress to ensure that efforts to consolidate nuclear weapons and weapons-usable nuclear materials are not slowed by lack of funds.

5. Develop Approaches to Confirm That Effective Nuclear Security Is in Place

Insecure nuclear material anywhere is a threat to everyone, everywhere—and all countries have a national security interest in seeing that all countries with nuclear weapons or weapons-usable nuclear materials protect them effectively. Today, however, few mechanisms are in place to give countries confidence that such effective protection really is in place.

The United States and other interested states should establish an experts group to work out approaches to providing assurances that would build real confidence without unduly compromising sensitive information. For example, states could:

²²⁷ The United States has already gone much farther in consolidating its stocks than Russia, but may have more to do. In the 1990s, Russia's Ministry of Atomic Energy committed to developing a consolidation plan for civilian nuclear material, but this was never accomplished.