Consolidation: Thwarting Nuclear Theft

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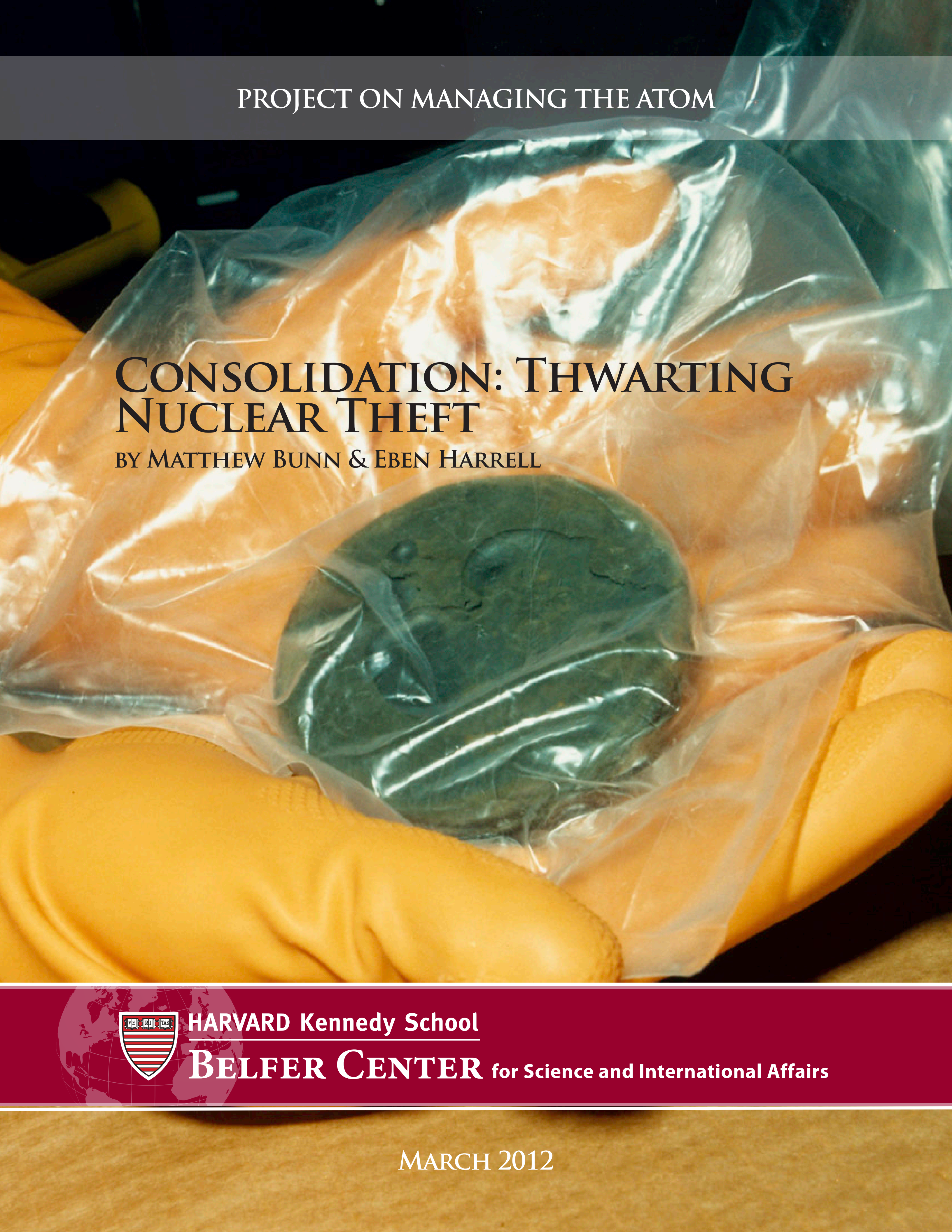

PROJECT ON MANAGING THE ATOM

CONSOLIDATION: THWARTING NUCLEAR THEFT

BY MATTHEW BUNN & EBEN HARRELL

HARVARD Kennedy School
BELFER CENTER for Science and International Affairs

MARCH 2012

About the Authors

Matthew Bunn is an Associate Professor of Public Policy at Harvard University's John F. Kennedy School of Government. Before coming to Harvard, Bunn served as an adviser to the White House Office of Science and Technology Policy, as a study director at the National Academy of Sciences, and as editor of *Arms Control Today*. He is the author or co-author of some 20 books or major technical reports, and over a hundred articles in publications ranging from *Science* to *The Washington Post.* He is an elected Fellow of the American Association for the Advancement of Science; a recipient of the American Physical Society's Joseph A. Burton Forum Award for "outstanding contributions in helping to formulate policies to decrease the risks of theft of nuclear weapons and nuclear materials"; and the recipient of the Hans A. Bethe Award from the Federation of American Scientists for "science in service to a more secure world."

Eben Harrell is a Research Associate at the Project on Managing the Atom in the Belfer Center for Science and International Affairs at Harvard Kennedy School. Harrell worked for four years in the London bureau of *TIME* magazine prior to joining HKS. He has also written for *The Economist* and *Sports Illustrated* and worked on the staff of *The Scotsman* newspaper in Edinburgh and *The Aspen Times* in Colorado.

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Project on Managing the Atom
Belfer Center for Science and International Affairs
Harvard Kennedy School
79 JFK Street; Mailbox 134
Cambridge, MA 02138
Phone: 617-495-4219
E-mail: atom@harvard.edu
Website: http://managingtheatom.org

Cover Image: A plutonium "button" in the hands of a technician, Photo Courtesy of U.S. Department of Energy

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EXECUTIVE SUMMARY

At the first nuclear security summit in April 2010, the assembled leaders agreed on the goal of securing all vulnerable nuclear material worldwide within four years, including consolidating plutonium and highly enriched uranium (HEU) to fewer locations and minimizing the use of HEU "where technically and economically feasible." Reducing the number of buildings and sites where nuclear weapons and weapons-usable nuclear material exist is a key element of preventing nuclear theft and nuclear terrorism, as the only way to completely eliminate the risk that nuclear material will be stolen from a particular location is to remove the material itself. States can achieve more effective nuclear security at lower cost if they have fewer places with nuclear weapons or weapons-usable nuclear material to protect.

The fundamental goal must be to reduce the number of sites and transports as far and as quickly as possible, and provide highly effective security for those that remain. Over time, the civil use of HEU should be phased out, and HEU should be eliminated from all civil sites. This paper outlines the efforts the international community is already making to meet these objectives, and recommends a range of next steps.

Today, nuclear weapons or their essential ingredients exist in hundreds of buildings and bunkers in dozens of countries, with widely varying levels of security. Fortunately, an array of national and international efforts to move nuclear weapons and weapons-usable nuclear material to fewer locations have been underway for years, and have made major progress. Since the end of the Cold War, nuclear weapons have been removed from many countries and scores of nuclear weapon sites have been eliminated. Twenty countries have eliminated all the weapons-usable nuclear material on their soil—six of them since President Obama called for a four-year effort to secure nuclear materials in April 2009. All weapons-usable nuclear material has been removed from dozens of other sites around the world. Some 180 research reactors that once used HEU fuel have either shut down or converted to using low-enriched uranium that cannot be used in a nuclear bomb. The world is more secure as a result.

But there is much more to be done. There are stocks of material and types of facilities that are not yet targeted for consolidation, and a range of political, bureaucratic, technical, and financial barriers to be overcome. There are potentially effective policy tools that have not yet been fully utilized. This paper (a) discusses how to set priorities among different stocks to be consolidated; (b) describes the scope and progress of existing consolidation efforts; and (c) suggests steps to complement and extend the existing programs. Our discussion of the next steps for consolidation will fall into two categories: covering additional stocks and facilities that are not yet effectively addressed, and using additional policy approaches to strengthen the effort. On the next page, table ES-1 summarizes our recommendations.

Table ES-1: Summary of Recommendations

ISSUE	RECOMMENDATION
Vision and goals	The United States and other governments should outline a clear vision for consolidation that includes removing all materials from the most vulnerable sites. The goal for the next few years should be to reduce the number of countries with weapons-usable nuclear material by ~50%; reduce the number of buildings and bunkers with nuclear weapons or weapons-usable material by 30-50%; and phase out civilian use of HEU entirely.
Prioritization	Consolidation efforts must be prioritized to focus on those stocks that offer the most risk reduction per unit of money or political capital invested. The highest-risk sites have some combination of the following factors: they contain enough material for a bomb, in forms that can readily be processed for use in a bomb; they have comparatively weak security measures in place; and they are in locations where adversary threats are high. Sites where there are few political, technical or economic barriers to consolidation should also be prioritized.
	Expanded Coverage of Materials and Facilities
U.S.-origin HEU	The United States should work in partnership with each of the states where U.S.-origin HEU exists to develop a specific plan and timetable for the elimination of this material. The United States should be willing to provide technical assistance and incentives for action where necessary. The United States should continue to work with these countries to complete and maintain an up-to-date database of the locations of all U.S.-origin HEU and separated plutonium.
Russian HEU research reactors	Russia should develop a strategic plan for minimizing its civilian use of HEU, converting many of its reactors at research institutes to use low enriched uranium (LEU) fuel and closing unneeded facilities, including many of its pulse reactors and critical assemblies. As Russia's HEU-fueled research reactors are managed by several different institutions, Russia should pull together an interagency effort that is able to make authoritative decisions. It should ship all unneeded HEU to sites where it can be down-blended or reprocessed. The United States should offer technical assistance for feasibility studies and conversion of HEU reactors to LEU fuel in Russia, and offer other incentives for consolidation. Russia and the United States should agree to use the Mayak Fissile Material Storage Facility as a site to send any separated plutonium or HEU whose risk of theft would be reduced by doing so.
Critical assemblies and pulse reactors	Countries with HEU or plutonium-fueled critical assemblies or pulse reactors should convert them or shut them down, as few such facilities are still needed. The International Atomic Energy Agency (IAEA) should convene a workshop to determine which critical assemblies, if any, are still required and still need to use HEU or plutonium fuel. In a limited number of cases, where reactors are very likely to continue to operate and cannot readily be converted to LEU, the United States should consider helping facilities to convert to a lower level of enrichment of HEU that would pose lower risks.

ISSUE	**RECOMMENDATION**
Not-yet-covered reactors	The United States and Russia should examine options for using LEU in the next generation of naval reactors, and Russia should accelerate the transition to LEU fuel for its HEU-powered nuclear icebreaker fleet. The United States should work to ensure that countries take the full spectrum of security costs and risks into account before building new HEU or plutonium-fueled reactors.
Avoiding the spread of HEU or plutonium production	The United States should work with other countries to engage North Korea and Iran, putting together packages of incentives and disincentives that convince these governments that it is in their national interests not to have nuclear weapons or capabilities to manufacture them rapidly. The United States and other interested countries should continue to pursue multiple means to limit the spread of enrichment and reprocessing plants, the key facilities that can produce weapons-usable nuclear material.
Civilian plutonium	Countries should work together to reduce the accumulation of civilian stocks of separated plutonium. To that end, the United States should reiterate its 1990s position that it does not encourage reprocessing and does not itself reprocess for either nuclear energy or nuclear weapons. Countries that do reprocess should minimize sites and transports containing separated plutonium as much as practicable (for example by co-locating reprocessing and fuel fabrication facilities).
Military plutonium and HEU	The United States and Russia should agree to develop strategic consolidation plans for the HEU and separated plutonium in their nuclear weapons complexes. The United States should complete its ongoing consolidation, and Russia should seek to consolidate these materials to four or five of its closed cities and cut the number of buildings housing these materials by 50% or more.
Nuclear weapons	The United States and Russia should develop strategic plans to consolidate their nuclear weapons storage to the minimum practical number of sites. The two countries should launch a joint initiative in which thousands of nuclear weapons on each side would be consolidated in secure storage open to monitoring by the other side, and committed to eventual verified dismantlement. As part of such an initiative, the United States should remove its tactical nuclear weapons from Europe. The United States and Russia should work with other states with nuclear weapons to convince them not to expand their number of storage sites, and to consolidate where possible.
	Use of Additional Policy Tools and Incentives
Effective nuclear security rules	Countries should put in place effective nuclear security rules, with appropriate grading for different materials, providing effective protection for HEU and plutonium sites. Doing so will create a financial incentive to remove these materials wherever possible to reduce security costs.
Incentives for shutdown	The United States and other interested countries should offer a range of incentives to convince operators or agencies that oversee facilities to shut facilities that are no longer needed. These shutdown efforts should be institutionally separated from conversion efforts so that managers of reactors with HEU do not suspect officials who assist in conversion to LEU to be ultimately interested in shutting down the reactor.

Issue	**Recommendation**
Broader targeted incentives for consolidation	The United States and other interested countries should offer a broad range of incentives, targeted to the concerns of individual facilities and the agencies that oversee them, to gain agreement on removing nuclear weapons, separated plutonium, or HEU from particular sites. The United States and Russia should work together to convince Belarus to return to its commitment to eliminate its dangerous HEU stockpile. South Africa should reaffirm its nonproliferation leadership by deciding to eliminate the hundreds of kilograms of HEU left over from its former weapons program (and the smaller stocks of HEU in irradiated fuel and targets from the Pelindaba reactor). Similarly, Japan should close or convert its Fast Critical Assembly, which also has hundreds of kilograms of weapon-grade HEU.
Incentives for non-HEU isotope production	The international community, having agreed on the goal of minimizing the civil use of HEU, should send the message to producers of medical isotopes that they will give preference to purchasing isotopes made without HEU. The United States is the largest market for medical isotopes and should either prohibit imports of medical isotopes made with HEU once sufficient non-HEU supplies are available, or impose a substantial user fee on all isotopes made from HEU (with the funds used to help producers convert to non-HEU production). The United States should also make clear that it will end exports of HEU for isotope production by a date certain, unless further exports are needed to fulfill medical needs. European governments should eliminate the regulatory hurdles restricting import of medical isotopes made without HEU. Canada should work to convince Russia to shift to non-HEU production for its isotope contract with Canadian firms. Medical societies should educate their members about the value of purchasing isotopes made without HEU. The National Nuclear Security Adminstration (NNSA) should consider increasing the cap on Global Threat Reduction Initiative (GTRI) support for domestic firms developing non-HEU production approaches from $25 to $50 million.
A broad offer to buy HEU	The United States should offer to buy HEU from any country willing to sell, and willing to commit not to produce or acquire more, offering something in the range of $25,000 per kilogram for weapon-grade material and less for less-enriched or irradiated HEU. The material should then be moved to secure, centralized facilities in the United States.
Strengthening the consolidation norm	The United States and other interested countries should seek to strengthen the global norm of nuclear weapons and materials consolidation, through the nuclear security summit process, the next Non-Proliferation Treaty Review Conference, and other international fora. Next steps should include agreements to declare stockpiles of HEU and separated plutonium, to convert any facilities that can be converted, to shut any facilities that are unneeded, and to eliminate any HEU that facilities no longer need. Parties to nuclear weapon-free zones should eliminate their HEU and separated plutonium and declare their zones free of weapons-usable material as well.

ISSUE	**RECOMMENDATION**
	Funding the Effort
Providing adequate funding	Despite current budget pressures, the United States and other donor states should provide sufficient funds so that efforts to consolidate nuclear weapons and weapons-usable materials are not slowed by lack of resources. Countries participating in the Global Partnership Against the Spread of Weapons and Materials of Mass Destruction should focus some of their funding on helping states consolidate nuclear materials at fewer locations. Russia should set aside funds for shipping Russian-origin HEU back to Russia and processing it there, and for conversions, decommissioning, and shipment and processing of HEU within Russia. France, which fabricates much of the world's research reactor fuel, should contribute to the cost of providing LEU fuel for converting reactors, and South Korea should do the same as it begins producing high-density LEU research reactor fuel. Canada should continue to fund U.S. NNSA efforts, and fund nuclear security improvements in Russia. The United Kingdom should also support global consolidation efforts through direct donations to the IAEA research reactor division or GTRI, or by paying for the removal of any remaining HEU that it once transferred to foreign countries. China should continue to assist in the conversion of HEU-fueled mini neutron source reactors that it sent to foreign countries, and also increase its dedicated financial support for the IAEA research reactor division's consolidation efforts.
Reducing excess stockpiles	The United States and Russia should agree to reduce their nuclear weapons stockpiles to something in the range of 1,000 weapons each, and to place all plutonium and HEU beyond the stocks needed to support these low, agreed warhead stockpiles (and modest stocks for other military missions, such as naval fuel) in secure, monitored storage pending disposition. They should then seek to accelerate the disposition of both HEU and plutonium, while maintaining high standards of security and accounting throughout the process. The countries with substantial stockpiles of separated civilian plutonium should work to reduce these stockpiles over time, ultimately reducing current stocks by 90 percent or more. The international community should redouble efforts to negotiate a fissile cutoff treaty, developing the text outside the Conference on Disarmament if necessary. States with nuclear weapons should open their reprocessing and enrichment facilities to IAEA safeguards and provide resources to the IAEA for safeguards implementation, allowing the existing production moratoria to begin to be verified pending negotiation of a verification regime for the fissile cutoff.

INTRODUCTION

At the first nuclear security summit in Washington, D.C. in April 2010, the assembled leaders agreed on the goal of securing all vulnerable nuclear material worldwide within four years. As part of that effort, the leaders agreed to "secure, account for, and consolidate" highly enriched uranium (HEU) and separated plutonium (the essential ingredients of nuclear weapons), to "encourage the conversion of reactors" from using HEU to using low-enriched uranium (LEU) that cannot fuel a nuclear bomb, and to encourage "the minimization of use" of HEU "where technically and economically feasible."[1] Several countries announced plans at the summit to eliminate all the weapons-usable material on their soil—and it is likely that more countries will make such announcements at the Seoul nuclear security summit in March 2012.[2] As described in more detail below, the international community is already making significant progress toward the goal of consolidating nuclear weapons and materials. Twenty countries have eliminated all the weapons-usable nuclear material on their soil, with six of those having completed the effort since President Obama first called for a four-year effort to secure nuclear material around the world in April 2009. More countries may soon join this group: Ukraine and Mexico, for example, both pledged at the 2010 nuclear security summit to eliminate all the weapons-usable nuclear material on their soil by the 2012 Nuclear Security Summit.

Why is consolidating nuclear materials at fewer locations important? Strengthening nuclear security can only reduce the risk that nuclear material will be stolen from a particular building; it can never

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[1] Office of the White House, "Communiqué of the Washington Nuclear Security Summit," (Washington, D.C.: The White House, 13 April, 2010), http://www.whitehouse.gov/the-press-office/communiqu-washington-nuclear-security-summit (accessed 23 February 2012). The principle of minimizing the use of HEU and plutonium is broadly accepted. UN Security Council Resolution 1887, unanimously adopted in September 2009, called on all states to "minimize to the greatest extent that is technically and economically feasible the civilian use of highly enriched uranium for civilian purposes, including by working to convert research reactors and radioisotope production processes to the use of low enriched uranium fuels and targets." The 2010 Nonproliferation Treaty review conference final document encouraged states to minimize HEU in civilian stocks, again "where technically and economically feasible." United Nations Security Council, "Resolution 1887," S/Res/1887 (New York: United Nations, 24 September 2009), http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N09/523/74/PDF/N0952374.pdf?OpenElement (accessed 23 February 2012) and *2010 Review Conference of the Parties to the Treaty on the Non Proliferation of Nuclear Weapons, Final Document, Volume 1, Part 1,* NPT/CONF.2010/50 (Vol. I)* (New York: United Nations, May 2010), http://www.un.org/ga/search/view_doc.asp?symbol=NPT/CONF.2010/50 (VOL.I) (accessed 20 February 2012). In 2007, the participants in the Global Initiative to Combat Nuclear Terrorism went further, including civil use of plutonium in what was to be minimized, saying that one of their "key priorities" was "minimizing the civil use of HEU and plutonium." See "Global Initiative to Combat Nuclear Terrorism: Joint Statement," (Washington, D.C.: U.S. Department of State, 12 June 2007), http://2001-2009.state.gov/r/pa/prs/ps/2007/jun/86331.htm (accessed on 20 January 2012). This paper focuses not only on consolidating civil material, but on consolidating military material and weapons as well.

[2] Many officials and policy analysts have contributed to consolidating nuclear weapons and materials around the world, especially to minimizing the use of HEU. For selections of this literature, see for example, the presentations at the Second International Symposium on HEU Minimization, Vienna, 23-25 January 2012, available at http://www.nti.org/about/projects/heu-minimization/event/2nd-international-symposium-heu-minimization (accessed 22 February 2012); the papers in "The Global Elimination of Civilian Use of Highly Enriched Uranium," special section of *Nonproliferation Review,* Vol. 15, No. 2 (July 2008); the papers produced by Alan J. Kuperman and his students, whose work is available at http://www.heuphaseout.org/ (accessed 22 February 2012); Alexander Glaser and Frank N. von Hippel, "Global Cleanout: Reducing the Threat of HEU-Fueled Nuclear Terrorism," *Arms Control Today,* January/February 2006, http://www.armscontrol.org/act/2006_01-02/JANFEB-HEUFeature (accessed 23 February 2012); and Miles Pomper, "The 2012 Seoul Nuclear Security Summit and HEU Minimization" (Washington, D.C.: U.S.-Korea Institute at the Johns Hopkins School of Advanced International Studies, January 2012), http://uskoreainstitute.org/wp-content/uploads/2012/01/USKI_NSS2012_Pomper.pdf (accessed 22 February 2012).

eliminate it. The only way to reduce that risk to zero is to remove the material entirely, so that there is no weapons-usable material left to steal. Every site where nuclear weapons or highly enriched uranium (HEU) or plutonium exist, and every transport of such items, is another chance for nuclear theft to occur—another group of insiders with access to the material, another chance for thieves to find a weak point in the inevitable variations in security measures from one operation to another. States can achieve more effective nuclear security at lower cost if they have fewer places with nuclear weapons or weapons-usable nuclear material to protect. Eliminating material from a site is an inherently sustainable security approach—once it is gone, no more time or money is needed to ensure that it will not be stolen. And efforts to consolidate material to fewer locations can play a key role in removing material entirely from some of the highest-risk sites.[3]

For all these reasons, consolidating nuclear weapons and materials to the minimum practical number of locations, and minimizing ongoing transports of these items, must be a fundamental part of improving nuclear security—during the four-year effort agreed to at the 2010 Nuclear Security Summit and beyond.[4] The fundamental goal must be to reduce the number of sites and transports as far and as quickly as possible, and provide highly effective security for those that remain. Over time, one key goal should be to end the civil use of HEU, and to eliminate HEU from civil sites. All countries with nuclear weapons, plutonium, or HEU must contribute to this consolidation effort. Each country that possesses such weapons or materials should examine each of its sites where these stocks exist, and each transport operation, to see whether it could be eliminated or converted to use less dangerous materials; each of these sites and transport operations represents an additional risk of nuclear theft, and should only continue to exist if its benefits outweigh its risks and costs. Countries could commit to undertake such a site-by-site review at or after the Seoul nuclear security summit, and announce consolidation steps resulting from the review at the next summit in 2014.

For reducing the danger of nuclear theft, reducing the number of sites is more important than reducing the sheer quantity of nuclear weapons or weapons-usable materials. (Reducing the huge stocks of nuclear weapons and materials that now exist is important for achieving deep nuclear arms reductions, however—and can contribute to reducing nuclear theft risks if appropriately managed.[5]) Since even a single terrorist nuclear bomb would pose a terrifying threat, a site where 10 nuclear weapons are stored poses nearly the same risk of nuclear theft as a site where 1,000 nuclear weapons are stored, and a site where 100 tons of plutonium are stored does not pose a dramatically larger risk than a site where a single ton of plutonium is stored. Terrorists will get their nuclear material wher-

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[3] Note that while consolidation is occurring, transports will usually be required; it is only after the material has been moved to secure, consolidated locations that the pace of transports can be reduced. But the very short-term increase in risk from a transport, combined with the long-term risk reduction from eliminating a site that once had weapons-usable nuclear materials, will lead to significantly lower integrated risk over time—*if* the transport and the destination site are both well-secured. All transports of nuclear weapons, HEU, and plutonium should be effectively secured, and *ongoing* transportation that does not contribute to long-term security improvements should be minimized.

[4] For broader recommendations, see Matthew Bunn, *Securing the Bomb 2010: Securing All Nuclear Materials in Four Years* (Cambridge, Mass. And Washington, D.C.: Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School and Nuclear Threat Initiative, April 2010), http://www.nti.org/analysis/reports/securing-bomb-2010/ (accessed 5 March 2012) and William Tobey, "Planning for Success at the 2012 Seoul Nuclear Security Summit" (Muscatine, Iowa: Stanley Foundation, June 2011), http://www.stanleyfoundation.org/resources.cfm?id=459 (accessed 20 February 2012).

[5] See discussion in Matthew Bunn, "Securing Nuclear Stockpiles Worldwide," in George P. Shultz, Steven P. Andreasen, Sidney D. Drell, and James E. Goodby, eds., *Reykjavik Revisited: Steps Toward a World Free of Nuclear Weapons* (Stanford, Calif.: Hoover Institution Press, 2008), pp. 243-277.

ever they conclude it is easiest to get—not from the facilities that have the most of it. Nevertheless, dismantling nuclear weapons and converting materials to forms that can no longer be used in nuclear weapons can be important elements of consolidation. (See "Reducing Excess Stockpiles," p. 35.)

Scope of the Problem and a Vision for the Future

How large is the problem? How many buildings and bunkers are there where nuclear weapons, HEU, or separated plutonium exist? Specific numbers are hard to come by in the unclassified literature. Today, HEU or plutonium separated from spent fuel exists in hundreds of buildings—not thousands—in some 32 countries.[6] Nine of those countries possess nuclear weapons, which are located in hundreds of bunkers at more than a hundred sites—including, in the case of U.S. nuclear weapons, sites on the territories of five non-nuclear-weapon states in Europe.[7] While many of the countries where these materials exist have only a single facility where HEU or separated plutonium are located (such as an HEU-fueled research reactor), others may have dozens of buildings and bunkers where nuclear weapons or weapons-usable fissile materials are stored or processed (or, in the case of Russia, hundreds of such locations).

HEU and plutonium are used for both military and civil purposes, and exist in a wide variety of forms—fabricated fuel elements and weapon components, metal plates and ingots, oxides, solutions, scrap, wastes, and more. The military stockpiles are larger, but are generally heavily guarded, while the smaller civil stockpiles often have more modest security measures in place, particularly at small facilities such as research reactors.[8] Well over 100 research and training reactors still use HEU as their fuel, consuming over 700 kilograms of HEU every year.[9] Dozens more naval reactors, particularly in the navies of the United States and Russia, use nearly three tons of HEU every year. The number of sites processing or using separated plutonium is measured in dozens, but the quantities involved are large, with over 10 tons separated from spent fuel every year. Scores or hundreds of transports of nuclear weapons, HEU, or plutonium from one place to another occur every year.

We believe the number of sites where these dangerous stocks are stored and handled can and should be drastically reduced, without compromising the military and civil missions for which they are used. With sufficient international consensus and political will, it might be possible, within a very few years, to:

- Remove nuclear material entirely from the world's most vulnerable sites.

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[6] For a useful summary, see Nuclear Threat Initiative, *NTI Nuclear Materials Security Index, Building a Framework for Assurance, Accountability, and Action (*Washington D.C.: Nuclear Threat Initiative, January 2012), http://www.ntiindex.org/ (accessed 20 February 2012), p. 14.

[7] Robert S. Norris and Hans M. Kristensen, "Nuclear Notebook: Worldwide Deployments of Nuclear Weapons, 2009," *Bulletin of the Atomic Scientists*, November/December 2009, http://bos.sagepub.com/content/65/6/86.full (accessed 27 February 2012). This estimate (a) does not include sites where nuclear weapons are located temporarily (such as locations at naval bases where weapons might be stored pending being loaded onto a submarine, or locations where weapons might be stored while being transferred from one rail line to another); and (b) counts sites that may have a dozen or more weapon storage bunkers, or hundreds of missile silos, as one site. If these counting rules were changed, the number would be far larger.

[8] For a recent overview of world fissile material stockpiles, see International Panel on Fissile Materials, *Global Fissile Material Report 2011: Nuclear Weapons and Fissile Material Stockpiles and Production* (Princeton, N.J.: Program on Science and Global Security, Princeton University, 2011); http://www.ipfmlibrary.org/gfmr11.pdf.

[9] Ole Reistad's Untitled Presentation at the 2nd International Symposium on HEU Minimization (Vienna, Austria: January 2012), https://www.nti.org/media/pdfs/Reistad_-_HEU_Symposium__Vienna_23_jan_2012.pdf?_=1328045837 (accessed 23 February 2012).

- Reduce the number of countries where weapons-usable materials exist by as much as 50%.
- Reduce the number of locations where nuclear weapons and weapons-usable nuclear materials exist by 30-50%.
- Provide highly effective security and accounting at all of the remaining sites.

The vision, in short, is of a world in which sites with nuclear weapons and weapons-usable nuclear material are rare, and where they do exist, are well-secured. Over the longer term, one key goal of the consolidation effort should be to phase out the civil use of HEU. Over time, these consolidated stockpiles should also be dramatically reduced.

Fortunately, the United States and other countries have been investing for years in an array of programs with consolidation as their objective, and these efforts have made major progress. Twenty countries have eliminated all the weapons-usable nuclear material on their soil. Nuclear weapons once deployed in countries all over the world now exist only in the nine states that possess them and four more in Europe, eliminating scores of nuclear weapon storage locations. All weapons-usable nuclear material has been removed from scores of other sites around the world. Dozens of research reactors have converted from using HEU fuel to using low-enriched uranium that cannot be used in a nuclear bomb, or have shut down and eliminated their HEU. The world is more secure as a result. In a very real sense, the removed material represents bombs that will never go off.[10]

But there is more to be done. There are stocks of material and types of facilities that are not yet targeted for consolidation or have resisted consolidation efforts. There are potentially effective policy tools that have not yet been utilized. This paper will (a) discuss how to set priorities among different stocks to be consolidated; (b) describe the progress and scope of existing consolidation efforts; and (c) suggest steps to complement and extend the existing programs, falling into two categories: covering additional stocks and facilities that are not yet effectively addressed, and using additional policy approaches to strengthen the effort. Because we are writing within the United States, and the United States has played the leading role in financing and leading consolidation efforts to date,[11] many of our recommendations are directed to U.S. policymakers—but consolidation is an effort that all states with nuclear weapons, HEU, or separated plutonium on their soil should take part in.

SETTING CONSOLIDATION PRIORITIES

Consolidation efforts must be prioritized to focus on those stocks that offer the most risk reduction per unit of money or political capital invested. Security improvement efforts should be similarly

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[10] See Anthony Wier and Matthew Bunn, "Bombs That Won't Go Off," *Washington Post,* November 19, 2006.

[11] Most U.S.-supported consolidation efforts have been financed by the National Nuclear Security Administration (NNSA), part of the U.S. Department of Energy (DOE). The program putting the most resources into consolidation specifically is the U.S. Global Threat Reduction Initiative (GTRI), which was launched in 2004 to unite and expand several earlier efforts focused on converting research reactors and repatriating irradiated HEU fuels. The International Materials Protection and Cooperation program (more commonly known as Materials Protection, Control, and Accounting, or MPC&A) has also supported the Materials Consolidation and Conversion (MCC) effort within Russia, and has also supported a number of nuclear institutions in the former Soviet Union that are working to reduce the number of buildings on their sites where HEU or separated plutonium are stored and processed. A number of other NNSA programs and other agencies of the U.S. government also contribute to these efforts. Many other countries are making important contributions, as is the International Atomic Energy Agency.

prioritized, based on the principle of "graded safeguards," in which those materials that would be easiest to make into a nuclear bomb require the highest level of security. Clearly a site with less than a kilogram of HEU, or where there seems little chance of convincing the operator to cooperate, does not deserve the same focus as a site where there is a real opportunity to remove hundreds of kilograms or tons of weapon-grade HEU metal. Consolidation efforts should focus on stocks with the following characteristics.[12]

Enough material for a bomb, or a substantial step toward a bomb. Making a simple "gun-type" bomb, the easiest for terrorists to build, requires at least 50 kilograms of HEU enriched to 90% U-235 (and somewhat more material if it is less enriched, or if the design of the weapon is crude). An "implosion-type" bomb would be more challenging for terrorists to make—but still plausible, especially if they had knowledgeable help. Such a bomb is more efficient, requiring less material. The implosion bomb that destroyed the Japanese city of Nagasaki used roughly 6 kilograms of plutonium; a similar bomb using HEU would require roughly three times as much material.[13] Modern designs and explosives could make it possible to make do with less, and there is also the possibility that terrorists could get material from several sources, adding up in the end to being enough for a bomb. Hence, the Convention on Physical Protection of Nuclear Materials and IAEA recommendations specify that any stock of material that contains 5 kilograms or more of U-235 in HEU, or 2 kilograms or more of plutonium, should be considered "Category I," requiring the highest level of security.[14] In short, consolidation efforts should focus first on sites with enough high-quality HEU for a gun-type bomb; then on sites with enough HEU or separated plutonium for an implosion-type bomb; and then on sites with smaller Category I stocks. Stocks with less material than Category I should receive significantly lower priority.

Material in forms that would not pose large obstacles to use in a bomb. Some materials would be easier for adversaries to steal and make a bomb from than others. The isotopic content, physical form, chemical form, and radiation level emitted by the material all affect how hard it would be to steal and use in a nuclear bomb. In particular, while HEU does not have to be "weapon-grade" (enriched to 90% or more U-235) to be used to make a bomb, it is easier and requires less material to make a bomb from more enriched material. HEU enriched to less than 40% U-235 should receive significantly lower priority than HEU at much higher enrichments. Unfortunately, both "weapon-grade" and "reactor-grade" plutonium can be used to make nuclear explosives, and official assessments in the United States and elsewhere have concluded that any state or group that could make a bomb from weapon-grade material would likely also be able to make a bomb from reactor-grade material.[15]

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[12] The largest U.S.-funded consolidation effort, the Global Threat Reduction Initiative (GTRI), already has a risk-based prioritization approach based on somewhat similar factors—the category of the material at a site, a rough judgment about security at a site, and an estimate of the level of adversary threat at that location. The approach described here would use similar criteria in somewhat more depth, while also encouraging GTRI to focus its efforts even more intently on high risk facilities. The *NTI Nuclear Material Security Index* provides ratings of countries based on publicly confirmable indicators of nuclear security, threat level, and quantity of materials and sites, offering another perspective on priorities.

[13] Matthew Bunn and Anthony Wier, "Terrorist Nuclear Weapon Construction: How Difficult?," *Annals of the American Academy of Political and Social Science*, Vol. 607 (September 2006).

[14] International Atomic Energy Agency, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities*, INFCIRC/225/Rev.5 (Vienna: IAEA, 2011); http://www-pub.iaea.org/MTCD/publications/PDF/Pub1481_web.pdf.

[15] A terrorist bomb made from reactor-grade plutonium, however, would likely have a lower explosive yield than one made from weapon-grade plutonium, because the many neutrons present in reactor-grade plutonium would be

Nevertheless, sites with weapon-grade plutonium should receive modestly higher priority than sites with reactor-grade material.

Similarly, nuclear material that could readily be converted into forms usable in nuclear weapons—such as high-concentration HEU or plutonium metal or oxides—deserves higher priority than material requiring more chemical processing. If HEU or plutonium are mixed with other materials so that they are only a few percent by weight, thieves would have to steal a much larger amount of material to get enough for a bomb, and would then have to chemically process the stolen material to get the plutonium or HEU out of it. Unfortunately, however, while this separation would take time and add steps to the adversaries' effort, any group capable of accomplishing the difficult job of making a nuclear bomb from HEU or plutonium metal is likely also to be able to accomplish the simpler job of separating plutonium from uranium in fresh uranium-plutonium mixed oxide (MOX) fuel, or uranium from aluminum in typical research reactor fuel.

The physical form of material also matters: high-concentration HEU or plutonium in bulk form (such as powders) may be easier for insiders to steal without detection, and should thus receive urgent attention. Large, countable items with only low concentrations of material (so that adversaries would have to steal hundreds of kilograms or tons of material to get enough HEU or plutonium for a bomb) are likely to be less attractive targets for theft.

Radioactivity levels should also factor into prioritization decisions. Fresh plutonium and uranium that has not been used in reactors, while radioactive, are not radioactive enough to be hard to steal or easy to detect. Once material has been irradiated in a reactor, though, it becomes much more radioactive. Spent fuel from nuclear power reactors poses little risk of nuclear theft because it is in the form of massive, intensely radioactive fuel assemblies, and the plutonium it contains is only 1% by weight. The radiation is so intense that an adversary standing a meter away from a spent fuel assembly would be disabled by acute radiation sickness while a theft was still in progress.

Spent fuel from research reactors is a very different thing, in most cases. Research reactor fuel assemblies tend to be small and portable, and they typically generate much less power during their lifetime, resulting in many fewer fission products and much less intense radioactivity. Fairly quickly after research reactor fuel is discharged from a reactor, it is no longer radioactive enough to disable thieves in the course of a theft. Moreover, "spent" research reactor fuel often remains quite highly enriched: material that was 90% U-235 when it was loaded into a reactor is still likely to be more than 80% enriched when discharged—and the Hiroshima bomb was approximately 80% enriched.[16] Spent HEU targets from production of medical isotopes are often still about 90% enriched. In an age of suicidal terrorists, it is time to abandon the old notion that material emitting enough radiation to

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almost certain to start the nuclear chain reaction prematurely. Designs from sophisticated nuclear weapon states can overcome that problem. For a detailed unclassified statement, see U.S. Department of Energy, Office of Arms Control and Nonproliferation, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, DOE/NN-0007 (Washington, D.C.: DOE, 1997); http://www.osti.gov/bridge/servlets/purl/425259-CXr7Qn/webviewable/425259.pdf, pp. 37-39.

[16] Research reactors often use their fuel until about half of the U-235 atoms have been split. One might think this would mean that 90% enriched material would now be 45% enriched, but it does not work that way. If nine out of ten of the uranium atoms are U-235 (with the other being U-238), and half the U-235 atoms are split, that means that there will be 4.5 U-235 atoms left, on average, and still only one atom of U-238, so that the material is still over 80% U-235. The picture is very different, however, if the material started as, for example, 36% enriched HEU (the level now used in many Russian-supplied research reactors). If half the U-235 atoms in that material are fissioned, the resulting material will be only barely over the 20% U-235 threshold defining highly enriched uranium.

cause a dose of 1 gray (100 rad) per hour at one meter is "self-protecting" against theft; it would take 10-100 times that level of radiation to disable thieves during the course of a theft.[17] It is important to understand, also, that the chemical processing required to separate uranium from irradiated research reactor fuel is essentially identical to the processing required to separate uranium from fresh fuel. In short, for research reactor fuel that started off very highly enriched, the reduction in priority for the irradiated fuel should in most cases be modest.

Sites with modest security measures in place, or conditions that make it difficult to prevent theft. Clearly, removing weapons-usable material from sites where only modest security measures are in place to protect it should be a higher priority than removing it from sites where extensive security measures are in place. Almost all HEU-fueled research reactors have been upgraded to meet IAEA physical protection recommendations, but as these recommendations are very general and open to interpretation, many of these facilities—some of which are on university campuses—have only modest security measures in place. Some, for example, have no armed guards on-site, and may have security measures that would offer little time between when the first alarm sounded and when adversaries might gain access to the nuclear material. Many military-purpose facilities, by contrast, have extensive security measures in place. Facilities that process large quantities of weapons-usable material, in bulk form—such as fuel or weapons component fabrication facilities and reprocessing plants—pose a particular concern, as bulk processing is the stage when it is easiest for insiders to steal material without anyone noticing; almost all of the known thefts of HEU and plutonium have been of bulk material, such as powders, and were committed without anyone knowing the material was missing until it was seized.

Sites in areas where the adversary threat is especially high. While terrorist groups such as al Qaeda have demonstrated some degree of global reach, there is no doubt that there are some countries where terrorists and thieves can put together large and capable conspiracies more easily than they can in other countries. A nuclear security system that could reduce the risk of theft to a low level in Canada, for example, might not be sufficient to keep the risk low in Pakistan. Stocks in countries facing particularly severe adversary threats should have higher priority in consolidation efforts than stocks in other countries.

Stocks posing real opportunities. All of these factors—material quantity, material quality, security effectiveness, and adversary capabilities—relate to the risk of nuclear material theft. But in setting priorities, consolidation efforts and security upgrade efforts must consider both risk and opportu-

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[17] Unfortunately, the idea that nuclear material emitting 1 Gray/hr at one meter can be subject to much less protection is still written into national regulations (including U.S. Nuclear Regulatory Commission rules in 10 Code of Federal Regulations Part 73) and international conventions (such as the Convention on Physical Protection of Nuclear Material). The most recent revision of the IAEA physical protection recommendations, however, urges states to consider not reducing protection for material at this level of radioactivity. See International Atomic Energy Agency, Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities, INFCIRC/225/Rev.5 (Vienna: IAEA, 2011), http://www-pub.iaea.org/MTCD/publications/PDF/Pub1481_web.pdf (accessed 24 February 2012). A Los Alamos study concluded that thieves stealing HEU research reactor fuel emitting 1 Gray/hr with their bare hands might get only mild radiation doses. See J.J. Koelling and E.W. Barts, Special Nuclear Material Self-Protection Criteria Investigation: Phases I and Ii, Vol. LA-9213-MS, NUREG/CR-2492 (Washington, D.C.: U.S. Nuclear Regulatory Commission, 1982), http://www.sciencemadness.org/lanl1_a/lib-www/la-pubs/00307470.pdf (accessed 24 February 2012). An Oak Ridge study concluded that radiation doses would have to be as much as 100 times higher to be immediately disabling. See C.W. Coates, B.L. Broadhead, A.M. Krichinsky, R.W. Leggett, M.B. Emmett, and J.B. Hines, "Radiation Effects on Personnel Performance Capability and a Summary of Dose Levels for Spent Research Reactor Fuels," ORNL/TM-2005/261 (Oak Ridge, Tenn.: Oak Ridge National Laboratory, December 2005).

nity: some stocks may be judged to pose a high risk but little opportunity for reducing it, and hence may not deserve high priority. There is no sense wasting effort beating against brick walls. At the same time, there may be stocks that pose only medium-level risks, but whose owners are eager to get rid of them, and the opportunity these stocks represent may lead them to rise somewhat on the priority list.

Though we do not list specific facilities as high-risk here (to avoid providing suggestions to potential adversaries), several types of material and facilities appear to represent high priorities when we weigh all these factors together:

- Critical assemblies and pulse reactors. (See: "Types of Research Reactors and Their Uses," p. 10.) These facilities often have large quantities of weapon-grade HEU metal, and sometimes modest security. They represent a potential opportunity, because many of them have few remaining missions and could be shut down. For each of these reactor types, some two-thirds of the reactors are in Russia.
- Nuclear weapon sites in Russia and Pakistan. These obviously represent very high-quality items that some terrorists would love to get (though they generally have built-in safeguards to prevent unauthorized use). They represent an opportunity because all of their military missions could be performed with a much smaller number of storage sites. Pakistan's nuclear weapons pose an even higher risk, given the huge potential capabilities of adversaries there, but less opportunity to reduce the risk through consolidation, since they are already stored at a modest number of sites, and that is likely to be maintained.
- Bulk processing facilities. These facilities appear to have been the source of nearly all of the thefts of plutonium and HEU that have occurred to date, and therefore pose a major risk. Opportunities to limit the number of facilities involved in bulk processing appear to be limited, however (though some countries might be convinced not to establish new large-scale plutonium processing facilities or to consolidate some existing operations).
- Military and civil HEU and plutonium storage and handling in Russia. Russia has the world's largest number of buildings with HEU or plutonium. Russia could serve its own interests, save money, and improve nuclear security by consolidating these stockpiles. So far, Russia has not been willing to focus on consolidation, but this may change.
- Transports with nuclear weapons or Category I quantities of nuclear material. Transportation is the moment in the life-cycle of these items when they are most vulnerable to overt, violent attack, since they are outside the multiple layers of protection that can be installed at fixed sites. There may be opportunities to reduce transportation risks by co-locating certain operations (so that nuclear materials do not have to be shipped back and forth multiple times, as they are today in Russia for the HEU downblending as part of arms control measures, for example), or by broadening the trend of carrying less than a Category I quantity in each shipment, reducing the risk if the materials in a shipment were seized by adversaries.
- High-power HEU-fueled reactors. Reactors that generate several megawatts of thermal power require substantial amounts of fresh HEU every year, leading to a demand for bulk processing of HEU for fuel fabrication, shipment of HEU, and large-scale storage of

HEU. In the case of high-power civil research reactors, many also have relatively modest security measures in place (though their fuel is typically transported and stored before loading in amounts less than a Category I quantity). High-power civilian HEU-fueled reactors represent an opportunity because new fuels that will make it possible for nearly all of these reactors to convert to LEU are slated to become available within a few years—but each case poses unique difficulties (as we discuss later). High-power reactors for naval ships and civilian icebreakers use far more HEU, nearly three tons a year in total, but the chances of convincing the U.S. and Russian nuclear navies to shift to LEU in the near term are very small.

- HEU targets for medical isotope production. Roughly 50 kilograms of HEU are used each year for this purpose, a relatively modest amount. But after use, the material remains weapon-grade (if it started as weapon-grade), and not highly radioactive, building up in large quantities over time. There is a real opportunity to end this use and get rid of the accumulated stocks, because alternatives are available that make it possible to make medical isotopes without HEU for reasonable cost. So while this should not be the top priority, it is worth pursuing.

EXISTING CONSOLIDATION EFFORTS

Existing programs have made substantial progress in consolidating stockpiles of HEU, plutonium and assembled nuclear weapons to fewer locations.[18] The U.S. Global Threat Reduction Initiative (GTRI), established in 2004, has helped to remove all the weapons-usable nuclear material from dozens of sites around the world, and to convert research reactors so they no longer need HEU fuel.[19] The Material Consolidation and Conversion (MCC) program has helped consolidate some HEU within Russia.[20] National and cooperative efforts at the end of the Cold War and the years immediately following greatly reduced the number of sites where nuclear weapons are stored. Participation in such consolidation efforts is entirely voluntary; some states are enthusiastic participants, while others have largely declined to participate. Hence, while officials managing U.S. or international programs can set goals and outline what they hope to accomplish, success is ultimately dependent on whether the states which possess these stocks and facilities decide that it is in their interest to take action to consolidate or eliminate them. Below, we summarize the progress and planned scope of these efforts.

Converting or Shutting Down HEU-Fueled Reactors

During the 1950s-1970s, hundreds of research reactors opened in dozens of countries that used HEU as their fuel, or, in a few cases, as targets for producing medical isotopes. Many of these facilities have comparatively small stockpiles of weapons-usable nuclear material, often in forms that would require some chemical processing to be used in a bomb. But a modest number have substan-

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[18] For a useful overview, see "Past and Current Civilian HEU Reduction Efforts," Nuclear Threat Initiative http://www.nti.org/analysis/articles/past-and-current-civilian-heu-reduction-efforts/ (accessed 24 February, 2012)

[19] GTRI consolidated several pre-existing programs, making it possible to eliminate gaps, seize synergies, and accelerate the overall effort.

[20] MCC is part of the larger effort known as Material Protection, Control and Accounting (MPC&A), or more formally as the International Nuclear Material Protection and Cooperation program.

TYPES OF RESEARCH REACTORS AND THEIR USES

There are many different types of research reactors, used for a wide variety of purposes. All told, as of late 2011, there were roughly 230 research reactors operating in the world.[1] Of these, over 120 facilities, representing just over half of the total, were using HEU fuel, HEU targets for isotope production, or both.[2]

Most research reactors are *steady-state* reactors, operating at a steady power level for hours, days, or weeks at a time. These reactors are used for scientific experiments in fields ranging from neutron physics to medicine to archaeology (where the neutron-activation products produced in ancient materials can help, for example, match particular stones or gems to the mines they came from). They are also used to test new nuclear fuels or reactor materials, to train people in operating nuclear reactors, to irradiate materials for commercial purposes (to enhance the color of gemstones, for example), to produce medical isotopes, and more.

Another large class of research reactors are known as *critical assemblies.* These reactors are designed to be just barely critical, producing only a few fissions, usually at power levels of less than 0.5 kilowatts (10,000 times less, for example, than a typical steady-state research reactor).[3] These are used to measure the fission and absorption cross sections and other nuclear properties of various materials, and to model the cores of possible future reactors. In general, if the reactors to be modeled are planned to use LEU, LEU-fueled facilities can be used to model them and HEU or plutonium are not needed. HEU-fueled critical assemblies often have tens or hundreds of kilograms of weapon-grade HEU, or even tons in a few cases—and the material is often metal form, readily usable in nuclear weapons. Because only a few fissions take place in a critical assembly, their fuel is virtually no more radioactive than fresh, unirradiated nuclear material, so there is no radioactive barrier to stealing and processing it.

Pulse reactors are designed to create short but extremely intense bursts of neutrons—primarily to test what effects neutrons from a nuclear blast might have on various pieces of equipment. A few might also be used to test pulses that could occur in a severe reactor accident. Like critical assemblies, pulse reactors often use large quantities of weapon-grade HEU, often in metal form, and have so few fissions that there is no radioactive barrier to theft.

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[1] Total operational reactor figure from International Atomic Energy Agency, "Research Reactor Database," http://nucleus.iaea.org/rrdb (accessed 2 January 2012).

[2] Data provided by Strykaar Hustveit, December 2011.

[3] A few facilities are *subcritical assemblies,* where the nuclear chain reaction dies out rather than being sustained within the assembly.

tial stockpiles, in some cases in the form of weapon-grade HEU metal. Security for research reactor sites, some of which are on university campuses, is often minimal.

Fortunately, many of these facilities are being eliminated or converted to LEU fuel. Between 1978, when the United States established the Reduced Enrichment for Research and Test Reactors (RERTR) program and the fall of 2011, roughly two-thirds of the world's HEU-research reactors—over 180 total facilities—have been either converted to LEU fuels or shut down entirely.[21] Of those,

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[21] Since 1978, some 62 HEU-fueled reactors have converted to LEU and approximately 125 have shut down without converting. Figures updated from Ole Reistad and Styrkaar 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 8 March 2012). We are grateful to Strykaar Hustveit and Frank von Hippel for data on these topics.

76 either converted with help from the GTRI and RERTR programs, or were targets for conversion but shut down before conversion occurred.[22] Approximately 125 research or training reactors still use HEU fuel or targets—the majority of them in Russia—and GTRI hopes to assist in the conversion or shut-down of all but a couple of dozen of these by 2025.[23] As of early 2012, over 30 HEU-fueled reactors still exist that can convert with LEU fuels that are already available; GTRI estimates that new, higher-density LEU fuels now being developed would allow some 26 additional reactors to convert. These new fuels are based on mixtures of uranium and molybdenum, and are expected to become commercially available in the latter half of this decade.[24]

In addition, South Africa, one of the four major producers of medical isotopes, has begun producing isotopes from LEU rather than HEU targets; several small producers are also producing such isotopes without HEU, and the other major producers are exploring conversion options. Several options are under development for non-HEU production within the United States (which is the world's largest market for medical isotopes, but for many years has been entirely dependent on foreign supply).

Nevertheless, there remain more than 20 HEU-fueled reactors not covered by GTRI's current plans (almost entirely in the military sector), and a significant number of reactors that *are* covered will be difficult to convert, either technically (because it is difficult to achieve the reactor's mission with LEU, as is often the case with fast-neutron research reactors, for example), politically (because the reactor operator or the institution overseeing the reactor has no incentive to convert, as might be the case if the reactor has all the fuel it needs for the remainder of its life and the operator does not want to get a new license for, and pay for, new fuel), or both. Moreover, Russia is opening a new high-power civilian research reactor using HEU fuel and expanding its production of medical isotopes using reactors with HEU for both fuel and targets; it could potentially undercut LEU-based isotope suppliers on price. Thus, while the efforts to convert research reactors are making major progress, there is much that remains to be done.

In addition, there are a large number of other HEU-fueled reactors that are designed for purposes other than research. Russia uses significant quantities of HEU to fuel reactors in its nuclear-powered icebreakers. While the next-generation icebreakers are expected to use LEU, the existing fleet may continue to operate for some time. Both the U.S. and Russian nuclear navies use HEU fueled reactors—representing the largest annual use of HEU—and there are no plans to convert these reactors to LEU. Some fast-neutron reactors use HEU, and China has just started a new fast-neutron breeder reactor that uses hundreds of kilograms of 64% enriched HEU.

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[22] Data provided by NNSA, September 2011.

[23] Recent estimates suggest that there are 113 research reactors still using HEU fuel, eight more naval training reactors using HEU, and four reactors using LEU fuel but HEU targets, for a total in the range of 125. There are some uncertainties in these estimates, as new information about certain facilities' status regularly becomes available. In addition, there are 11 icebreaker reactors in Russia. As of the fall of 2011, GTRI planned to help with the conversion or shut down of 113 research reactors and 11 icebreaker reactors beyond the 76 already converted or shut down, for a total of 200. By their count, this left 29 HEU-fueled research or icebreaker reactors outside GTRI's plans. But a number of the reactors on GTRI's list either are not operating, are not research or operator reactors, or are not using HEU. Data provided by NNSA, September 2011, supplemented with data provided by Strykaar Hustveit of the Norwegian Radiation Protection Authority.

[24] Recent funding shortfalls have imposed roughly a three-year delay in the availability of these high-density fuels, which has extended GTRI's target for converting the reactors it hopes to convert 2022 to 2025. Data provided by NNSA, March 2012.

WHY IS CONSOLIDATION HARD?

There are important technical, economic, political, and organizational obstacles to consolidation that policies to foster consolidation must address.

The technical issues vary depending on the type of material or facility under consideration. When the issue is simply storing nuclear weapons or weapons-usable nuclear material in fewer places, few technical issues arise. But when the focus is on facilities that are actually operating with weapons-usable material, the issues are sometimes more complex. Many steady-state research reactors, for example, will have slightly lower neutron fluxes after conversion from HEU to LEU. Some isotope production facilities will have to cope with more total uranium waste using LEU (which requires nearly five times as much total uranium to have the same amount of U-235) than using HEU—and some facilities or processes have been designed specifically for using HEU. Some reactor types—such as critical assemblies modeling fast-neutron reactors—may simply be difficult or impossible to operate with only LEU (though they can typically be converted to material with enrichments in the range of 20-35%, far less attractive for weapons use than the 90% material many of them now use). Many of these technical issues can be addressed through technical fixes—either with technologies that already exist, or with additional research and development. In the end, there are likely to be only a few uses for HEU for which technically viable alternatives cannot be found—and in most cases, those uses of HEU may no longer be needed.

There are also genuine costs involved in consolidation. Transporting nuclear weapons and materials and providing adequate storage space at a smaller number of sites costs money. Managing irradiated HEU removed from a research reactor costs money, as does decommissioning facilities that are no longer needed. In some cases, the high-density LEU fuels to which reactors might be converted will cost more than the HEU fuels they have used in the past; indeed, for reactors with life-time cores (such as critical assemblies and pulse reactors), conversion means buying new fuel when they would not otherwise have to buy any fuel at all. In a small number of cases, reactors using LEU may have to refuel more often, so they have to purchase more total fuel, and spend more time out of operation for refueling. But as noted in the text, if a country's nuclear security rules require highly effective security for facilities with HEU or separated plutonium, the savings in security costs from eliminating these materials will more than compensate for the costs of consolidation. Moreover, the United States and other interested countries are willing, in many cases, to cover part of the costs of consolidation in the interest of reducing the risk of nuclear theft and terrorism.

A wide variety of political issues can also stand in the way of consolidation—and these and the organizational obstacles may often be the most difficult to resolve. For some countries or facilities, their HEU is seen as a source of prestige, not to be given up lightly. In other cases, countries come to realize the importance that others (especially the United States) attach to their HEU, and use it as a source of leverage. Belarus, for example, pulled back on its pledge to eliminate its HEU stock when the United States imposed sanctions over charges of election-rigging;[1] Moammar Qaddafi's Libya briefly delayed allowing a cooperative effort to remove its HEU over pique as to how Libya in general and Qaddafi in particular had been treated by the United States since the 2003 agreement to eliminate Libya's weapons of mass destruction programs.[2] Some countries, particularly South Africa,

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[1] See, for example, Miles Pomper, "Bringing Belarus Back to the Table," *WMD Junction,* 20 September 2011, http://cns.miis.edu/wmdjunction/110920_belarus.htm (accessed 5 March 2012).

[2] David Leigh, "Diplomatic Cables: Gaddafi Risked Nuclear Disaster After UN Slight," *The Guardian Newspa-*

WHY IS CONSOLIDATION HARD? (CONT.)

see consolidation of HEU as linked to broader disarmament concerns—why should they give up one small stock of HEU when countries like the United States and Russia still have hundreds of tons of this material, including the material in thousands of nuclear bombs? When they have already fulfilled their obligations as non-nuclear-weapon states under the NPT, why should they go still further than the treaty requires by eliminating their HEU when the nuclear weapon states have not (in their view) fulfilled their obligation to negotiate in good faith toward nuclear disarmament?[3]

Moreover, it is often the case that different actors in a country's decision-making structure have different views and interests, making it essential that foreigners attempting to influence a decision on consolidating a particular stock understand this interplay of forces and what offers might be most likely to lead to the desired outcome. In the case of decision-making about eliminating the HEU at Sosny in Belarus, for example, the site operators, the Academy of Sciences that oversaw the site, and the national political leaders each had somewhat different concerns, and developing an approach that got everyone on board—at least briefly—took time and sensitivity to the domestic factors in play. Rebuilding agreement in the future is likely to be difficult again—and is likely to be driven more by high-level political actors than by the needs of the site.

Organizational factors may also pose critical obstacles to consolidation. The manager of a research reactor or a nuclear weapon storage site is very likely to oppose shutting the site down. Staff at the site are likely to be concerned about their jobs and pay. Sites may be under the supervision of national officials—but those officials may have many other issues they want to address with the site, making eliminating a particular stock of HEU a low priority. In some countries—including, by some reports, in Russia—staff may receive higher pay if they are working with "dangerous" materials such as HEU and separated plutonium, so that consolidation may actually lead to reduced salaries, creating a strong incentive for staff to find reasons to maintain the HEU or plutonium at their sites. Some sites may be concerned that without HEU or plutonium, they will no longer be as competitive with other sites or essential as they were before. At one site in Russia, for example, even though the site employs some 10,000 people, only a few of whom work at its main research reactor, staff at the site are concerned that if that facility is closed, "it will be the end" for the site.[4] Whether such perceptions make sense technically or not, they shape the reality that consolidation efforts must cope with, and must be addressed.

Given all these intersecting obstacles, efforts to convince countries and facilities to agree to convert or shut down research reactors or reduce the number of other locations where nuclear weapons, HEU, and plutonium exist should go beyond technical cooperation programs like the Global Threat Reduction Initiative. Interested countries such as the United States should assign broad teams that include technical experts, local embassy officials, and political officers to work together to find ways to move consolidation forward in particular countries, drawing on a broad toolbox of possible incentives.

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per, 3 December 2010, http://www.guardian.co.uk/world/2010/dec/03/wikileaks-cables-libya-enriched-uranium (accessed 2 February 2 2012).

[3] William Potter, "Nuclear Terrorism and the Global Politics of Civilian HEU Elimination," *The Nonproliferation Review,* Vol. 15, No. 2, (July 2008), pp 135-158.

[4] Interview with site employee, July 2011. The employee specifically reported that this was also the view of the site director.

Removing Civil HEU

Once reactors have been converted to LEU or shut down and no longer need their HEU, the HEU can be removed and consolidated at secure locations or blended down to LEU fuel that can be used in civilian power plants. (In addition, there are some locations where there is unneeded HEU not associated with a research reactor, or HEU that is beyond what a reactor needs even though it is still operating with HEU.) Here, too, GTRI and other efforts have made significant progress—but there are gaps that should be addressed.

By the end of 2011, 20 countries had eliminated all the weapons-usable nuclear material on their soil.[25] (See Table 1, below.) As long as they do not reintroduce such material, none of these countries will ever again have to worry about having potential ingredients of nuclear weapons on their soil.

Since 1996 (when the U.S. take-back-offer for HEU fuel was renewed), U.S. programs have contributed to removing all the weapons-usable material from over 50 total sites outside the United States

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[25] Data provided by NNSA, December 2011. Taiwan is counted here as a country, since it currently has its own government separate from that of the rest of China. Iraq and Georgia, where nuclear material was removed by other programs, are added here to have a more complete accounting. Sweden, which is on NNSA's list, is not listed here because it still possess a few kilograms of separated plutonium, and therefore, while cleared of HEU, has not been cleared of weapons-usable material. Spain, which is included here, possesses significant stocks of plutonium separated from spent fuel, but as far as is publicly known these are located in foreign countries, not in Spain.

Table 1: Countries That Have Eliminated All Their Weapons-Usable Nuclear Material

Country	Year
Iraq	1992
Colombia	1996
Spain	1997
Denmark	1998
Georgia	1998
Philippines	1999
Thailand	1999
Slovenia	1999
Brazil	1999
Greece	2005
South Korea	2007
Latvia	2008
Bulgaria	2008
Portugal	2008
Romania	2009
Libya	2009
Taiwan	2009
Chile	2010
Serbia	2010
Turkey	2010

and Russia—representing more than 50 locations from which weapons-usable nuclear material can now never be stolen.[26] A large number of additional sites, particularly in the United States (and to a lesser degree in Russia) have eliminated all their weapons-usable nuclear material without any help from U.S.-funded nonproliferation programs.

All told, GTRI had helped remove 3,125 kilograms of HEU by February 2012. It plans to remove 2,225 more by the end of 2019, for a total of 5,350 kilograms to be consolidated.[27] The total removed by February 2012 includes:

- 1,623 kilograms of Russian-origin HEU returned to Russia, 67% of 2,438 planned;
- 1,250 kilograms of U.S.-origin HEU eligible for take-back returned to the United States, 69% of 1,822 kilograms planned; and
- 252 kilograms of "gap" HEU—consisting of material that is not U.S. or Russian origin, or is U.S. origin but not in the categories previously announced as eligible for take-back to the United States –23% of 1,090 kilograms planned.[28]

GTRI's removal plans do not cover all the world's HEU, or even all of the civil HEU outside the countries where it originated. (See "Plans for Different Categories of HEU," p. 14.)

Consolidating Civilian Plutonium Stocks

Today, ongoing programs to reprocess plutonium from spent fuel, which have far outpaced the use of the resulting plutonium as part of new uranium-plutonium mixed oxide (MOX) fuel, have led to the buildup of over 250 tons of separated plutonium in civilian stocks—more than in all the world's nuclear weapons programs combined. Over 95% of this civilian separated plutonium is located in Russia, Britain, France, or Japan, the countries that operate large civilian reprocessing plants; in these countries, it is primarily located in thousands of small canisters in large vaults at the reprocessing facilities. Reactors in Japan and several countries in Europe, particularly France, are using MOX fuel. In December 2011, the UK announced that it would use its huge stock of civilian separated plutonium as MOX fuel, though whether sufficient reactors will be available to accomplish this in a timely way remains uncertain.[29] India has recently built a new plutonium breeder reactor and has plans for more, along with additional reprocessing plants. China, similarly, has recently started a pilot-scale civilian plutonium reprocessing plant and the China Experimental Fast Reactor, fueled with HEU

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[26] Data provided by NNSA, January 2010, updated with removals during 2010-2011, and adding removals outside the United States and Russia that were assisted by U.S. programs but are not included in GTRI's data, such as the removal of HEU from Georgia in 1998 and Serbia in 2002. (The 2002 Serbian removal removed all fresh HEU from the site and all HEU from at least one of the facilities at the site, but irradiated HEU remained at the site until it was removed in late 2010.) The 1994 removal of HEU from Kazakhstan removed all HEU from the Ulba facility, though additional HEU was brought there later for downblending to LEU. The site is not believed to have any HEU at present.

[27] Data provided by NNSA, February 2012.

[28] Data provided by NNSA, December 2011. The figures for Russian-origin HEU do not include the material removed before GTRI was established, including the HEU removed from Iraq by the United Nations in 1992; the nearly 600 kilograms of HEU airlifted from Kazakhstan to the United States in Project Sapphire in 1994; the HEU shipped from Georgia to Great Britain in Operation Auburn Endeavor in 1998; or the HEU shipped from Serbia to Russia in Project Vinca in 2002.

[29] U.K. Department of Energy and Climate Change, *Management of the UK's Plutonium Stocks: A consultation response on the long-term management of UK-owned separated civil plutonium,* (London, December 1, 2011), http://www.decc.gov.uk/assets/decc/Consultations/plutonium-stocks/3694-govt-resp-mgmt-of-uk-plutonium-stocks.pdf (accessed 7 March 2012).

PLANS FOR DIFFERENT CATEGORIES OF HEU

U.S. nonproliferation programs such as GTRI currently plan to work in partnership with countries around the world to remove substantial quantities of HEU. But there is other HEU that is not covered in current plans. To understand what stocks are covered and what stocks are not, it helps to divide the world's HEU into several categories.

First, some 98% of the world's HEU is in military stocks, primarily in the United States and Russia; GTRI is only intended to address civilian stocks, though the United States is consolidating its own military stocks, and Russia has made some modest reductions in the number of buildings and stocks where its stocks reside.

Second, GTRI effectively divides the civil HEU stocks (most of which where supplied by the United States and Russia or its predecessor the Soviet Union) into several categories:

- U.S.-supplied HEU eligible to participate in the U.S. take-back offer (some 5.2 tons as of 1996, when the take-back offer was renewed);[1]
- Russian-supplied HEU (some 2.4 tons);
- U.S.-supplied HEU not eligible for the take-back offer, and HEU supplied by other countries (covered in part by GTRI's "gap" program, amounting to something in the range of 12-13 tons);[2]
- HEU within the United States (some 20 tons as of 2011); and
- HEU within Russia (also estimated at roughly 20 tons as of 2011).[3]

GTRI has different plans for each of these categories of civil HEU.

Eligible U.S.-origin HEU. GTRI is only planning to take back about a third of the eligible U.S.-origin HEU (because the remainder is held by countries who are not choosing to take advantage of the take-back offer, either because the HEU is still in use, they do not wish to pay the cost, or they have other disposition plans they consider preferable).

Russian-supplied HEU. By contrast, GTRI hopes to help ship 100% of the Russian or Soviet-supplied HEU outside of Russia back to Russia for reprocessing (and recovery as LEU) or blending down to LEU by mixing with less enriched uranium (except for the tons of uranium in irradiated BN-350 fuel, which has been moved to a secure storage site within Kazakhstan).

"Gap" HEU and plutonium. GTRI's "gap" program is intended to deal with material that other efforts do not, including (a) HEU that does not come from the United States or Russia; (b) U.S. origin HEU that is not in the categories specified in the U.S. take-back offer; and (c) some small stocks of separated plutonium. GTRI hopes to address roughly one ton of material (of which less than 100 kilograms is separated plutonium, discussed below, rather than HEU). This represents less than 10% of the total of civil HEU around the

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[1] See, for example, discussion in U.S. Department of Energy, Office of the Inspector General, *Audit Report: Recovery of Highly Enriched Uranium Provided to Foreign Countries*, DOE/IG-0638 (Washington, D.C.: DOE, February 2004). The United States offered to take back HEU that was in fuel for TRIGA (Training, Research, Isotopes, General Atomics) reactors or aluminium-based fuels for Materials Test Reactor (MTR) reactors, because the United States had both of these types of reactors and already had to develop disposition pathways for these fuel types. Most of the HEU the United States had exported, however, was in other fuel forms.

[2] The amount of HEU the United States exported that was not eligible for the take-back offer is officially estimated at 12.3 tons. See DOE-IG, *Recovery of Highly Enriched Uranium Provided to Foreign Countries.* Some portion of that material has been reprocessed and no longer exists as HEU. But there is also a modest amount of material in civilian stocks that other countries such as Britain, France, and South Africa produced for themselves or provided to other countries.

[3] IPFM, Global Fissile Material Report 2011, p. 9.

PLANS FOR DIFFERENT CATEGORIES OF HEU (CONT.)

world in this category. GTRI believes that the remainder is primarily located in countries that are providing adequate security for the material, and will ultimately put it on a path to use or disposal without U.S. help. (Most of the U.S.-origin material not eligible for the take-back program is in France and Germany.)

Research reactor HEU in the United States. Within the United States, just under 20 HEU-fueled research or training reactors remain (counting both civilian and defense reactors), compared to many dozens decades ago.[4] Of these, all but four are within the Department of Energy or Department of Defense complexes, where security requirements are high.[5] The NRC only licenses two private facilities to possess Category I quantities of unirradiated HEU, both of which are fuel fabrication facilities—Nuclear Fuel Services (NFS) in Erwin, Tennessee, and BWXT in Lynchburg, Virginia. Moreover, nearly all of the HEU from the facilities no longer using HEU has been removed, as DOE has long offered the service of accepting the HEU spent fuel from domestic reactors.

Within the DOE complex, a major consolidation effort has been underway, driven in part by the high costs of meeting post-9/11 security requirements; dozens of buildings have been cleared of weapons-usable material, as have some major sites (such as Sandia National Laboratory, with Lawrence Livermore National Laboratory planned to follow). Under current plans, however, it appears that some U.S. HEU for research reactors will continue to exist (alongside huge stocks for weapons and naval fuel).[6]

Research reactor HEU in Russia. In Russia, consolidation of civilian HEU has barely begun, and no comprehensive plan has been developed. The Material Consolidation and Conversion (MCC) effort had paid to blend down some 13.5 tons of HEU by late 2011.[7] This material is thought to be from civilian facilities, but its exact origins are not clear, and it does not appear to have led to the removal of all HEU from any substantial number of facilities. Only one civilian site (the Krylov Shipbuilding Institute) is known to have eliminated all its HEU; several other reactors once fueled with HEU have shut down over the years, and some of these are being decommissioned.[8] The United States and Russia are discussing a possible cost-shared program to convert reactors and ship HEU that is no longer needed to secure sites for reprocessing or blending to LEU, but as of early 2012, this effort had not yet begun.

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[4] Data provided by Strykaar Hustveit, December 2011, updated from Reistad and Hustveit, "Appendix Ii: Operational, Shut Down, and Converted HEU-Fueled Research Reactors."

[5] The four remaining HEU-fueled reactors regulated by the NRC are at MIT, the University of Missouri, the National Institute of Standards and Technology, and a GE facility in California. The first three are slated to convert to LEU as soon as high-density fuels become available, and studies of the feasibility of converting the fourth are underway. See Jordi Roglans, "Types, Purposes, and Conversion Potential of U.S.-Origin Research Reactors," (paper presented at the Russian-American Symposium on the Conversion of Research Reactors to Low Enriched Fuel, Moscow, Russia, 8-10 June 2011).

[6] There appear to be no plans, for example, to eliminate the HEU that was used in the COMET, FLATTOP, GODIVA, PLANET, and TACS critical assemblies or the SPR-III pulse reactor (all now located at the Device Assembly Facility in Nevada), or to convert the U.S. Army's research reactor or the U.S. Navy's training reactors. Moreover, the HEU has not been removed from the Transient Reactor Test (TREAT) facility, which has not operated since 1994, and DOE is now considering returning the facility to use. On TREAT, see Roglans, "Types, Purposes, and Conversion Potential of U.S.-Origin Research Reactors."

[7] U.S. Department of Energy, FY 2013 Congressional Budget Request: National Nuclear Security Administration, DOE/CF-0071, Vol. 1 (Washington D.C.: DOE, February 2012), pp. 421-422,http://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/FY%202012%20NNSA%20Congressional%20Budget%20Submission_0.pdf (accessed 2 February 2012).

[8] For a discussion of consolidating weapons-usable nuclear material in Russia, see Pavel Podvig, *Consolidating Fissile Materials in Russia's Nuclear Complex,* Research Report No. 7 (Princeton, N.J.: International Panel on Fissile Materials, May 2009), http://fissilematerials.org/library/rr07.pdf (accessed 30 January 2010).

and designed to breed plutonium. In addition, small quantities of plutonium used for research exist at facilities in more than a dozen countries. The U.S. program for disposition of excess weapons plutonium will add a new MOX fabrication facility to the sites with material of concern, along with reactors that will have fresh plutonium-bearing MOX fuel stored on-site at least some of the time, in preparation for loading it into the reactors.

Currently, GTRI has a small-scale program to remove a few small stocks of unneeded plutonium, amounting to less than 100 kilograms in total. The United States is also seeking to limit the spread of reprocessing and enrichment plants to additional countries, though it is not actively seeking to convince countries such as India and China not to build large new civilian reprocessing plants, or to convince Japan that there is no need to operate its Rokkasho reprocessing facility given the likely scale-down of nuclear power following the Fukushima disaster. No current plan is in place to address the far larger stocks of separated plutonium building up in the civilian sector.

Consolidating Military HEU and Putonium Stockpiles

Military HEU or plutonium stockpiles exist in nine countries: the five nuclear weapon states under the nuclear Nonproliferation Treaty (NPT)—the United States, Russia, the United Kingdom, France, and China—and the four countries outside the NPT (India, Pakistan, Israel, and North Korea). Except for the United States and Russia, these countries generally have military nuclear complexes limited to a handful of facilities.

Within the United States, a major consolidation is underway within the Department of Energy's nuclear weapons complex, driven in substantial part by the huge costs of meeting post-9/11 security requirements for HEU and separated plutonium. All weapons-usable material has been removed from dozens of buildings and several sites, saving hundreds of millions of dollars a year in safety and security costs. The Rocky Flats plutonium weapons component fabrication plant has been entirely closed, cleaned up, and turned into a park. DOE has removed all weapons-usable material from Sandia National Laboratory and 90 percent of the material from Lawrence Livermore National Laboratory, with the rest of Livermore's inventory to be removed this year.[30] Hundreds of kilograms of weapon-grade HEU for critical assemblies were moved from the vulnerable Technical Area 18 site at Los Alamos National Laboratory to the highly secure Device Assembly Facility (DAF) in Nevada, along with tens of kilograms of weapon-grade material for another critical assembly from Livermore, and the material for a pulse reactor from Sandia. In the future, NNSA hopes to limit its plutonium and HEU operations to just a few buildings at five sites.[31] Processing of HEU within the DOE complex is to take place only at the Y-12 plant at Oak Ridge, and processing of plutonium only at Los Alamos and Savannah River. At the Department of Defense, the Army is down to one HEU-fueled

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[30] "NNSA Ships Additional Special Nuclear Material from LLNL," NNSA/DOE press release (Washington D.C., 31 August 2011), http://nnsa.energy.gov/mediaroom/pressreleases/materiallnl83111 (accessed 24 February 2012). This release indicates that consolidation to five NNSA sites will be completed during 2012; as Livermore is not one of those sites, this implies that Livermore's inventory will be removed during 2012.

[31] U.S. NNSA, "NNSA Ships Additional Special Nuclear Material from LLNL." The five remaining facilities are expected to be the Pantex nuclear weapons assembly/disassembly facility near Amarillo, Texas; the Y-12 HEU storage and processing site near Oak Ridge, Tennessee; the Los Alamos National Laboratory, where plutonium operations are to be located; the Savannah River Site, which includes plutonium storage and processing; and the Device Assembly Facility (DAF) at the Nevada National Security Site, a highly secure facility where hundreds of kilograms of weapon-grade HEU has been moved from other sites. In addition, a small number of DOE sites not controlled by NNSA, such as the Idaho National Laboratory, will also continue to have Category I and II quantities of HEU or separated plutonium.

reactor, the Navy has only a few training reactors beyond the reactors on the ships and submarines, and the Air Force has none.

Russia, by contrast, has been much more reluctant to consolidate—though inevitably, the collapse of the Soviet Union led to some significant reductions in what had been a gargantuan nuclear weapons complex. Russia has closed two of its four nuclear weapons assembly/disassembly facilities. With help from NNSA, Russia has shut down all three of its plutonium production reactors—which continued to operate because they provided heat and power to tens of thousands of people in Siberia. This represents a major step forward, ending a substantial accumulation of plutonium every year, major bulk-processing of plutonium at the reprocessing plants serving these reactors, and the use of some 600 kilograms a year of weapon-grade HEU in thousands of small, easy-to-carry fuel elements in these reactors' cores.[32] Weapons component manufacturing has been phased out at one of the two facilities that used to perform that function. Several of the remaining sites have significantly reduced the number of buildings where weapons-usable nuclear material is stored. Storage of unirradiated HEU fuel for the Russian navy has been reduced to only a few secure facilities.[33]

Nevertheless, there are still thought to be more than 200 buildings in Russia where HEU or separated plutonium is stored or handled. This is far larger than the comparable figure for any other country and far more than Russia plausibly needs.

China has a modest nuclear complex located at a modest number of sites. It has not been producing additional plutonium or HEU for many years, and appears to have no current plans to either expand or shrink the number of defense facilities handling HEU and plutonium. India's stockpile of weapons-usable materials is still growing, but it is not yet clear if the number of facilities where these materials are located will increase. Pakistan is rapidly increasing its nuclear stockpile, with two plutonium production reactors now in operation and two more under construction, and continued uranium enrichment as well; this increase, coupled with Pakistan's concerns over its stockpile's vulnerability to Indian attack or U.S. seizure, may lead Pakistan to increase the number of locations where nuclear weapons and materials exist. France, Britain, Israel, and North Korea are each believed to have their military nuclear materials at a very small number of locations, leaving little room for further consolidation.

Consolidating Nuclear Weapons Sites

At the peak of the Cold War, U.S. nuclear weapons were stationed in dozens of countries around the world, and Soviet nuclear weapons were distributed throughout the Soviet Union and Eastern Europe.[34]

In the waning years of the Cold War and after the collapse of the Soviet Union, there was a dramatic reduction in the numbers of locations where U.S. and Russian nuclear weapons were stored. All Russian nuclear weapons were returned to Russia. All U.S. nuclear weapons but a couple of hundred air-delivered bombs in Europe were returned to the United States. Thousands of U.S. and Russian tactical nuclear weapons were destroyed, and the remainder were largely consolidated in central storage facilities.

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[32] Each of these reactors used approximately 200 kilograms of 90% enriched HEU per year. See Oleg Bukharin, "Securing Russia's HEU Stocks," *Science & Global Security,* Vol. 7 (1998), pp. 311-331.

[33] Podvig*, Consolidating Fissile Materials in Russia's Nuclear Complex.*

[34] William M. Arkin and Richard W. Fieldhouse, *Nuclear Battlefields: Global Links in the Arms Race* (Cambridge, Ma.: Ballinger, 1985)

Table 2: Summary of Consolidation Progress

CATEGORY	ASSESSMENT
Russia	Some progress, major obstacles. Nuclear weapon sites reduced during 1980s-1990s pullbacks—but nuclear weapons continue to be stored at dozens of sites, with no apparent movement toward further consolidation. Russia has the world's largest number of HEU-fueled research reactors, and has only agreed to feasibility studies for conversion of six of them. The Russian Navy has greatly reduced its sites with HEU, and at least one facility has given up all its HEU as part of the DOE Materials Consolidation and Conversion initiative. Russia has closed down nuclear weapons work at several sites, and some of the remaining sites have moved nuclear material into a smaller number of buildings. But potential bomb material still exists in over 200 buildings, and the Russian government's view is that Russia's material is secure and accounted for, and consolidation is therefore not a priority.
Developing states with large programs (Pakistan, India, China)	Limited progress—but these countries have small nuclear stockpiles at small numbers of sites, so less consolidation is needed. China has joined the reactor conversion effort and has converted two research reactors and shut down two more. India has converted one HEU-fueled research reactor to LEU without U.S. help. Growing nuclear arsenals may be stored at larger number of sites in the future, particularly in Pakistan, which has the world's fastest-growing nuclear arsenal. China and India are both pursuing civilian plutonium programs that may eventually lead to widespread use of plutonium fuels.
Developing and transition states with small programs	Substantial progress. GTRI has accelerated the pace of converting HEU-fueled research reactors to LEU and of shipping Soviet-supplied HEU back to secure sites in Russia. Twenty countries have eliminated all the weapons-usable nuclear material on their soil. Of the countries in this category with enough high-quality HEU for a gun-type bomb on their soil (Belarus, South Africa, and Ukraine), Ukraine has agreed to eliminate all HEU on its soil (and may finish doing so in time for the 2012 Seoul nuclear security summit); Belarus has eliminated a portion of its HEU, committed to eliminate the rest, but then reneged on that commitment; South Africa has converted its research reactor to use LEU fuel and is in the process of converting its isotope production to use LEU targets but has not yet committed to eliminate its large remaining HEU stockpile.
Developed countries	Some progress, but a great deal more to be done. GTRI has accelerated the pace of converting HEU-fueled research reactors to LEU, and GTRI's "gap materials" effort—covering nuclear material not addressed in previous HEU removal programs—has brought tens of kilograms of fresh HEU back to the United States from countries such as Canada, Belgium, and the Netherlands. Only a small portion of HEU in these countries is currently targeted for removal, however, and some facilities have little interest in giving up the use of HEU. No programs are in place to minimize the locations where plutonium fuels are used.
United States	Substantial progress, though issues remain. U.S. nuclear weapons are now stored at a modest number of sites, though tactical bombs remain at several sites in Europe. All HEU-fueled research reactors that can convert with existing fuels have now done so, and only four HEU-fueled reactors outside the Department of Energy and Department of Defense complexes remain, waiting for higher-density fuels that should become available within a few years. DOE is substantially consolidating the sites and buildings with potential bomb material, though not as quickly or comprehensively as some experts have recommended. The planned MOX program for plutonium disposition would add a small number of reactors to sites with material of concern.

Since the mid-1990s, however, only modest further consolidation of nuclear weapon storage facilities has occurred; a few strategic storage sites have closed as strategic arms reductions have proceeded. Russia in particular still has an estimated 48 permanent storage locations for nuclear weapons, and dozens more temporary locations. The United States reportedly continues to maintain nuclear weapons in five countries in Europe.[35] No program is currently in place focused on consolidating nuclear weapons to fewer locations.

Of course, one reason to have nuclear weapons in more locations rather than fewer is to make it more difficult to attack them in a disarming nuclear first strike. But that is really only a key consideration for nuclear weapons associated with deployed launchers, such as those on long-range ballistic missiles and used by bombers. For stored nuclear weapons, more security can be achieved at lower cost by reducing the number of locations, with no reduction in the survivability of the deployed force (particularly since the number of storage locations in the United States and Russia is already far smaller than would be needed to provide any significant protection against destruction in a nuclear strike).

Summary of Current Consolidation Progress

In short, current consolidation programs are making major progress—but the global stocks of nuclear weapons, HEU, and separated plutonium are still spread at a far larger number of sites, buildings, and bunkers than they need to be. Table 2 (see p. 20) summarizes the current status of consolidation efforts in different countries and categories of countries.

EXPANDING THE MATERIALS AND FACILITIES COVERED BY CONSOLIDATION EFFORTS

The consolidation efforts underway so far are making progress and deserve strong support. They should also be expanded, however, both to consolidate a broader set of materials and facilities (the subject of this section) and to use a wider range of policy tools for doing so (the topic of the next section).

There are four categories of stockpiles that should be consolidated: (1) civil HEU; (2) civil plutonium; (3) military HEU and plutonium; and (4) nuclear weapons themselves. Current consolidation efforts focus almost exclusively on civil HEU, but even there, there is more to be done, and this paper will address civil HEU first, followed by the other categories.

Dealing With U.S.-Origin HEU Not Yet Eligible for Takeback

Currently, the U.S. government has no plan to deal with most of the HEU the United States exported. When all current U.S. return programs are completed, roughly 12 tons of U.S.-origin of HEU—enough for hundreds of nuclear bombs—will remain in foreign countries.[36] A large fraction (though not all) of this material is in Western Europe, predominantly France and Germany.

The U.S. government believes these countries are providing adequate security for this material and will ultimately carry out an appropriate disposition of it.[37] Nevertheless, this huge amount of mate-

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[35] Kristensen and Norris, *Bulletin of the Atomic Scientists*

[36] NNSA is completing an estimate of the full scope of U.S. HEU in foreign countries. Personal communication with NNSA official, November 2011.

[37] National Nuclear Security Administration, Office of Global Threat Reduction, *Strategic Plan* (Washington, D.C., U.S. Department of Energy, January 2007), p 8, http://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/

RUSSIAN APPROACHES AND U.S.-RUSSIAN RELATIONS

Russia's official view is that all Russian nuclear weapons and weapons-usable nuclear materials are secure and accounted for, and pose no risk of being stolen. Hence, while Russia is willing to endorse the principles of upgrading security for nuclear stockpiles and consolidating them to fewer locations, it sees no need for significant action within Russia.[1]

Russia now has roughly half of all the world's HEU-fueled research reactors, and has taken few significant actions to reshape this giant fleet. In 2005, when President Bush and President Putin agreed on a sweeping nuclear security initiative at their summit in Bratislava, Russia insisted on inserting "in third countries" where it referred to converting research reactors to use LEU—exempting Russia and the United States (where most of the world's HEU-fueled research reactors are) from the joint effort.

Russia has:

- Not converted any of its HEU-fueled research reactors to run on LEU.
- Shut only a handful of its HEU-fueled research reactors.
- Not provided funding to remove irradiated HEU (or unneeded fresh HEU) from its research reactor sites.

For many years, Russia refused to negotiate an agreement concerning cooperation on consolidating and blending down small stocks of HEU (for the Material Consolidation and Conversion program).

Russia did finally agree to do feasibility studies on converting six reactors to LEU. In January of 2012, it agreed to feasibility studies for two more. But it has made no commitment to convert those reactors—or any others.

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[1] Aleksie Danichev, "No 'Loose Nukes' in Russia—Memorandum," *RIA Novosti*, 13 March 2010, http://en.rian.ru/world/20100413/158566656.html (accessed 25 February 2012).

rial—all of which originated in the United States—represents a major gap in the world's efforts to minimize the use of HEU in civilian applications.

Recommendation: The U.S. government should work with each of the countries where this material exists to try to convince them to eliminate these stocks as rapidly as possible—converting or shutting down the research reactors that are still using these materials, and carrying out disposition of the HEU. Disposition could include blending the material to LEU, reprocessing it and recovering it as LEU, or preparing it for permanent disposal and emplacing it in disposal sites.

Recommendation: The United States does not have a complete database of all U.S.-origin HEU and plutonium in foreign countries, although NNSA is currently working to compile one.[38] This project should be completed as soon as possible, and the database should be regularly updated.

Recommendation: The United States should work in partnership with each of the states where

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GTRI_strategicplan_2007.pdf (accessed 24 February 2012).

[38] See U.S. Congress, Government Accountability Office, "U.S. Agencies Have Limited Ability to Account for, Monitor, and Evaluate the Security of U.S. Nuclear Material Overseas," GAO-11-920 (Washington, D.C.: GAO, 2007), http://gao.gov/products/GAO-11-920 (accessed 4 March 2012).

RUSSIAN APPROACHES AND U.S.-RUSSIAN RELATIONS (CONT.)

Russia and the United States have cooperated in developing new fuels to convert Russian-designed reactors in other countries, and to return Russian-origin HEU to Russia. But Russia has insisted that the United States pay 100% of the cost of these efforts—even charging a price for reprocessing the returned HEU, thus helping its facilities to make a good profit.

By the beginning of 2012, U.S.-Russian relations were souring. The Russian government has opposed U.S.-European missile defense plans, accused the United States of fomenting domestic opposition (and accused its domestic opponents of being tools of U.S. interests), and has even warned darkly that a failed space probe may have been disabled by powerful U.S. radars. The U.S. government, at the same time, sees an increasingly authoritarian Russia that is increasingly resisting U.S. policies in Iran, the Middle East, and elsewhere.

Cooperation to secure and dismantle nuclear stockpiles has been a pillar of the U.S.-Russian relationship throughout the ups and downs of the two decades since the collapse of the Soviet Union. Nevertheless, these souring relations may cast a shadow on cooperation to minimize HEU stockpiles.

The time has come for a change of approach. Even at the height of the Cold War, the United States and the Soviet Union worked closely together to build the nonproliferation regime and stop the spread of nuclear weapons. As one of the founders of the global nonproliferation effort, co-chair of the Global Initiative to Combat Nuclear Terrorism, and one of the world's leading nuclear powers, Russia needs to return to its historic leadership role, taking the lead in drastically reducing the huge numbers of buildings and bunkers in Russia where nuclear weapons and their essential ingredients continue to exist, and in helping other countries around the world to do the same. The United States, at the same time, should work to address Russian concerns and put U.S.-Russian nuclear cooperation back on a firm foundation. Both countries can save money, improve security, and demonstrate global leadership at the same time by reducing the number of places where nuclear weapons, HEU, and separated plutonium continue to exist.

U.S.-origin HEU exists to develop a specific plan and timetable for the elimination of this material. The U.S. should be willing to help, and to provide technical assistance and incentives for these countries to act, where necessary. Such a plan—and implementation of a portion of it—would be an outstanding element of a country's commitment to the next nuclear security summit in 2014.

Addressing HEU-Fueled Research Reactors in Russia

GTRI hopes to help convert or shut down a large number of HEU-fueled research reactors and icebreaker reactors in Russia, but doing so may be difficult. To date, Russia has shown little interest in a large-scale effort to shrink its fleet of some 60 research and training reactors using HEU fuel or targets—now representing not only the world's largest, but almost half of all the research and training reactors using HEU in the world.[39] As recently as 5 March 2012, Russia's Foreign Ministry argued that Russia does not need to consolidate its nuclear weapons and weapons-usable nuclear material because all of its stocks are well guarded.[40] Russia has shut down a modest number of HEU-fueled

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[39] Data provided by Strykaar Hustveit, December 2011. For an overview, see Podvig, *Consolidating Fissile Materials in Russia's Nuclear Complex.*

[40] "American NGO "Initiative to reduce the nuclear threat," Ministry of Foreign Affairs of the Russian Federation

research reactors and critical assemblies in recent years, and has agreed to joint feasibility studies on converting some of its reactors. But despite summit statements agreeing on the importance of minimizing the use of HEU, Russia has been highly reluctant to go further. Indeed, in the otherwise far-reaching 2005 Bratislava nuclear security initiative agreed to by then-U.S. President George W. Bush and then-Russian President Vladimir Putin, Russia insisted on inserting the phrase "in third countries" in the reference to converting HEU-fueled research reactors to LEU, focusing the effort only on facilities beyond Russia's borders; it has taken years to get Russia to accept more recent summit language on the importance of minimizing the use of HEU in general, without the focus on third countries. Feasibility studies for converting six of Russia's reactors were slated for completion in December 2011; two of the studies were completed and concluded that conversion was feasible, two more are expected to be completed in the first half of 2012, and the remaining two may take longer.[41] In January 2012, Russia agreed to undertake studies of the feasibility of converting two more reactors, making a total of eight.[42]

Russia's dominance of HEU-fueled critical assemblies and pulse reactors is even greater than its dominance of HEU-fueled research reactors overall. Critical assemblies and pulse reactors often have hundreds of kilograms or even tons of weapons-grade HEU; because very little fission takes place in these facilities (because their power is so low or their pulses are so brief), their fuel is essentially "fresh" even when it has been in use for decades, posing no radioactive barrier to theft or processing; and their fuel lasts indefinitely, giving facilities little incentive to convert to new, less-enriched fuel. Russia has some two-thirds of the world's total in each of these categories, roughly 27 HEU-fueled critical assemblies and 15 HEU-fueled pulse reactors.[43] Some of these facilities have massive amounts of nuclear material: several tons of weapon-grade HEU metal in the case of the BFS critical assembly at the Institute of Physics and Power Engineering, some 833 kilograms of weapon-grade HEU for the BIGR pulse reactor in Sarov.[44]

There is no plausible justification for more than a few of these facilities to continue to operate. The United States, by comparison, used to have three pulse reactors (a type used to simulate the effects of the pulse of neutrons from a nuclear bomb), and now has only one in operation. The United States now has HEU-fueled critical assemblies at only 2 sites—the Device Assembly Facility in Nevada, a highly secure facility built to assemble nuclear weapons for testing (where 5 assemblies are located), and one at the Idaho National Engineering Laboratory.[45] Similarly, the entire European Union houses only five HEU-fueled critical assemblies, and one, the Masurca fast neutron reactor at Cadarache in France, operates with 30% enriched fuel.[46] As discussed below, with the trend toward the

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press release, 5 March 2012, http://www.mid.ru/BDOMP/brp_4.nsf/sps/E45786803A088032442579B80059EE27 (accessed on 6 March 2012).

[41] Personal communication with Argonne National Laboratory expert, January 2012.

[42] Data provided by NNSA, March 2012.

[43] Data provided by Strykaar Hustveit, December 2011. There is some uncertainty in these figures, as new information about various facilities becomes available over time, and changes in facility status occur over time as well.

[44] Paul Osborne, "Conversion and Decommission: Critical Assemblies and Pulsed Reactors in Russia," (Austin: NPPP Policy Research Project, University of Texas at Austin, 2011), http://www.heuphaseout.org/wp-content/uploads/2011/04/Osborne.pdf (accessed 24 February 2012).

[45] Four of these critical assemblies, Comet, Flattop, Godiva, and Planet, where moved from Technical Area 18 at Los Alamos National Laboratory because that site was judged to be too vulnerable to protect the weapon-grade HEU at reasonable cost. The other, the Training Assembly for Criticality Safety (TACS), was moved from Livermore National Laboratory for similar reasons.

[46] Osborne, "Conversion and Decommission: Critical Assemblies and Pulsed Reactors in Russia," p. 6.

use of LEU in most future power reactor designs, the increasing sophistication of computer simulations for evaluating future reactor cores, and the large numbers of measurements already taken in critical assemblies, the need for HEU-fueled critical assemblies is far smaller than it once was. Even for the period when some are still needed, it is likely the research required for the whole world could be done with half a dozen or fewer. Indeed, just as work in high-energy physics has shifted to a small number of widely shared, high-capability facilities, research reactors should move in a similar direction—toward a modest number of widely shared facilities around the globe fueled with LEU.

At the same time, a large quantity of HEU exists at Russian research reactor facilities that is already unneeded, even before any further conversions or shutdowns take place—and of course, if additional facilities convert to LEU or shut down, there will be more HEU that is no longer required.

Recommendation: Russia should undertake a strategic review of its research reactor needs in the context of its nuclear power development plans, and how the research it needs to do can be done at minimum cost and risk. (Indeed, in the 1990s, what was then Russia's Ministry of Atomic Energy agreed that such a study was needed and agreed to undertake it—but it was never done.) It should examine each location where civilian HEU is located and ask whether the continuing benefits of using HEU at that location outweigh the costs and risks. An impartial review would inevitably conclude that all, or all but a few, of the pulse reactors and critical assemblies could be shut down or converted to LEU—along with most of Russia's other HEU-fueled research reactors. As Russia's HEU-fueled research reactors are managed by several different institutions, Russia should pull together an interagency effort that is able to make authoritative decisions.

Recommendation: Given Russia's presidential-level commitment to minimizing the civil use of HEU, it should convert the six facilities where feasibility studies are complete or nearing completion as rapidly as practicable, study the feasibility of converting its remaining HEU-fueled reactors,and convert those that can feasibly be converted. The United States should continue to offer to work with Russia to carry out these feasibility studies and conversions. In particular, Russia and the United States should go beyond conversion of steady-state reactors to begin pursuing conversion of critical assemblies and pulse reactors. For example, they should pursue the proposal made by Russian scientists from Sarov in 2005 to convert all six of the pulse reactors at Sarov (which collectively use almost two tons of HEU).[47] It should also pursue the proposal for converting or shutting down many of the HEU-fueled reactors at the Kurchatov Institute that Kurchatov and the Argonne National Laboratory made jointly in 2002.[48] In a limited number of cases, where reactors are very likely to continue to operate and cannot readily be converted to LEU, the United States should consider the balance of benefits, costs, and risks in helping facilities to convert to a much lower level of enrichment that would pose greater obstacles to terrorists wishing to construct an improvised nuclear device. For example, it appears that the BFS fast critical assembly at the Institute of Power Engineering (which uses tons of 90% enriched HEU in small portable disks, along with 36% enriched HEU in similar disks) could accomplish all its current missions using the 36% enriched disks, eliminating the 90%

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[47] V.P. Dubinin, A.M. Voinov, M.A. Voinov and V.F. Kolesov, "Goals and Objectives of ISTC Project 3128 'Using Low-Enriched Urnaium in VNIEFF Pulsed Nuclear Reactors," (paper presented at the 27th International Meeting on Reduced Enrichment for Research and Test Reactors, Boston, Mass., 6-10 November, 2005),http://www.rertr.anl.gov/RERTR27/Abstracts/S12-9_Dubinin.html (accessed 2 February, 2012).

[48] N. N. Ponomarev-Stepnoi and S.K. Bhattacharyya, "Russian Research Center Kurchatov Institute/Argonne National Laboratory Project on conversion of the RRCKI to a secure, safe and clean nuclear research center within the boundaries of the City of Moscow," unpublished, April 2002.

enriched disks, without any need for new fuel development, leaving the remaining material much less attractive for use in a nuclear bomb.[49]

Recommendation: Russia should ship all the HEU at civilian sites that is no longer needed to appropriate facilities for blending to LEU or reprocessing; the central government should provide the funds needed for this purpose, without requiring facilities to fund the effort out of their own resources. In particular, Russia should ensure that all HEU is removed from the research reactors that have closed in recent years. A much slimmed-down fleet of HEU-fueled research reactors and a greatly reduced stock of civilian HEU would save Russia money, improve Russian security, and demonstrate Russian leadership in preventing nuclear terrorism. A commitment to take these steps would be an outstanding element of Russia's national commitment for the next nuclear security summit.

In addition to research reactors, Russia has a number of other HEU-fueled reactors, some of which could potentially be converted or shut down. First, Russia has 11 HEU-fueled reactors on nuclear-powered icebreakers. Russia's new barge-mounted floating reactor, a modified KLT-40 reactor, based on the icebreaker reactors, uses LEU fuel, and it seems clear that with some effort, all of Russia's icebreaker reactors could be converted to LEU. Russia also has two isotope production reactors, *Lyudmila* and *Ruslan*, which use HEU fuel. These reactors could potentially be converted with fuels similar to the LEU fuel designs once considered for converting Russia's plutonium production reactors. And, like the United States, Russia uses HEU fuel for its nuclear navy—though the fuels it uses are typically not as highly enriched as U.S. fuels. These reactors, too, might someday be converted, though further study would be needed.[50]

Recommendation: It is in the U.S. national security interest for all plutonium and HEU in Russia (or in other countries) to have the most secure possible storage. The United States spent over $300 million helping Russia build the highly secure Mayak Fissile Material Storage Facility, only a small portion of which is full. Because this began as an arms-reduction project, the United States has taken the position that only plutonium from nuclear weapons should be stored there. The United States should change this approach, focusing not only on disarmament but on reducing the risk of nuclear theft. The United States and Russia should agree to use this facility as a site to send any separated plutonium or HEU whose risk of theft would be reduced by doing so. The United States and Russia could cooperate to demarcate a portion of the facility that was for material from dismantled weapons, and other portions that were open to a broader range of materials.

Recommendation: The United States and other interested countries should engage Russia at the highest levels to encourage Russia to take these actions. The MCC program can help finance the cost of removing and blending down fresh HEU from research reactors that no longer need it, and under the aegis of the GTRI program, the United States could, if necessary to convince Russia to move quickly, finance part of the cost of shipping irradiated HEU to Mayak and reprocessing it (an approach the two countries have been discussing). As discussed later in this paper, a variety of other incentives could be provided, targeted to the interests of particular facilities or of the federal agencies overseeing these facilities. Ultimately, however, this material is Russia's to manage, and in the long run Russia should bear the costs of doing so.

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[49] Frank Von Hippel, "Future Needs for HEU-Fueled Critical Assemblies," (paper presented at the 27th International Meeting on Reduced Enrichment for Research and Test Reactors, Boston, Mass., 6-10 November, 2005).

[50] Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review,* Spring 2001.

Coping With Other HEU-Fueled Pulse Reactors and Critical Assemblies

While Russia has some two-thirds of the world's pulse reactors and critical assemblies, these dangerous reactor types exist in other countries as well. Outside of Russia, there are an estimated 14 critical or subcritical assemblies and seven pulse reactors.[51] GTRI hopes to help with conversion or shut-down of many of these facilities, but in many cases this is likely to be difficult—in some cases because facilities would have difficulty operating with LEU fuel (especially in the case of fast-neutron facilities), in others because the operators or their governments may be reluctant to close or convert these facilities. More than half of the 29 reactors GTRI currently lists as "out of scope," or too difficult to attempt to convert (either politically or technically) are critical assemblies or pulse reactors.[52]

An IAEA consultation in 2005 found that the need for critical assemblies was diminishing; with the many nuclear cross-section measurements already taken in critical assemblies in years past, fewer were needed in the future (particularly if there were a greater effort to pool this data internationally).[53] Substantial pooling efforts are already underway, and could be expanded: the International Criticality Safety Benchmark Evaluation Project has dedicated itself to compiling data from around 3,800 critical configurations and distributing the evaluations to 60 countries.[54]

The IAEA consultation also concluded that with the measurements already taken, some evaluations of future reactor cores could be performed with computer simulations without requiring critical facilities.[55] For example, some 38 research reactors have thus far been converted from HEU to LEU by GTRI and its predecessor programs without the aid of critical assemblies,[56] using computer simulations and previously published data instead. Only a few critical facilities around the world are now needed to do "benchmark" experiments to check computer codes when new experiments are required.[57] Such experiments could be done in facilities whose use is widely shared internationally. Moreover, among currently proposed future reactors, only fast reactors would use HEU or plutonium in their cores, and current fast reactor proposals are dominated by the use of plutonium, suggesting that there is minimal remaining need for HEU-fueled critical assemblies for modeling future reactor cores. Indeed, many critical assemblies have already been converted to LEU fuel as the larger reactors they were intended to model converted. One U.S. reactor design expert has proposed that with global data-sharing, only a handful of critical assemblies fueled with HEU or plutonium would be needed worldwide.[58]

Recommendation: The IAEA consultation recommended that the IAEA or others convene workshops of reactor physics and design experts to work out what HEU or plutonium-fueled critical

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[51] Data provided by Strykaar Hustveit, December 2011.

[52] Data provided by NNSA, October 2011.

[53] Frank von Hippel, "Future Needs for HEU-Fueled Critical Assemblies," in *Proceedings of the 27 International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR),* Boston, MA, 6-10 November 2005 (Argonne, Ill.: Argonne National Laboratory, 2005), http://www.rertr.anl.gov/RERTR27/PDF/S9-3_vonHippel.pdf (accessed 27 February 2012).

[54] For a concise argument about data sharing from critical facilities see McFarlane, Harold, "Is It Time to Consider Global Sharing of Integral Physical Data?," Journal of Nuclear Science and Technology, Vol. 44, No. 3, pp. 518-521 (2007).

[55] von Hippel, "Future Needs for HEU-Fueled Critical Assemblies."

[56] von Hippel, "Future Needs for HEU-Fueled Critical Assemblies."

[57] HEU in critical facilities may still be needed to mock up new breeder reactors, naval propulsion systems, and other fast critical facilities that have high concentrations of fissile materials in their core, but only a few facilities are needed for such work.

[58] See Harold F. McFarlane, "Is it Time to Consider Global Sharing of Integral Physics Data?"

assemblies are still needed. This should be done without delay. The United States should offer to finance such workshops if necessary.

Recommendation: Each country operating HEU or plutonium-fueled critical assemblies should examine whether each facility continues to have a mission substantial enough to justify the costs and risks of continuing to operate it, and whether it could convert to non-weapons-usable fuels. They should then shut down or convert all reactors for which the costs and risks of continuing to use HEU or plutonium fuel outweigh the continuing benefits of doing so. Even if an HEU-fueled critical assembly is still considered to be needed, they could typically be converted to a much lower enrichment level, in the range of 25-35% U235, which would make their fuel far less attractive for potential terrorist nuclear bombs than the 90% enriched material that is now often used.

There is likely only one critical assembly in a non-nuclear-weapon state that has enough weapon-grade HEU for a gun-type bomb: the Fast Critical Assembly at the Tokai facility in Japan. Japan also has two other HEU-fueled critical assemblies, though with smaller amounts of material or less-enriched material. The other HEU-fueled critical or subcritical facilities in non-nuclear-weapon states are in Belarus and Kazakhstan, both of which, if all goes well, should be converted to LEU within the next few years.

Recommendation: Japan should either close the Fast Critical Assembly, convert it to LEU, or, at a minimum, convert it to use HEU in the 20-35% range. (That level of enrichment would be adequate for the missions the facility performs, and would make its fuel much less attractive for use in nuclear weapons.) Japan should announce a decision to take one of these steps as part of its national commitment for the next nuclear security summit. The United States and the United Kingdom, the countries which supplied Japan's HEU, should work in coordination to convince Japan to take this step and to blend down the Fast Critical Assembly's HEU in Japan or send it elsewhere for that purpose.

Pulse reactors pose similar issues, often having large quantities of high-quality HEU, virtually no burnup of this material (and hence virtually no radioactive barrier to theft), and little incentive to convert, since they never need new fuel. There are an estimated seven pulse reactors outside Russia. With all the tests of the effects of neutron pulses on different types of equipment that have been done over the years, and the modern capabilities of computer simulation, pulse reactors are much less needed today than they once were. The principal U.S. pulse reactor, the SPR-III at Sandia, has been closed and its nuclear material moved to the Device Assembly Facility at Nevada (where it could be used again someday, in principle). Other countries should consider taking similar steps. For those countries that believe they may still need pulse reactors—which can also be used for some nuclear accident simulations, in some cases—it may be possible to convert pulse reactors to LEU, as Russian scientists proposed to do in the case of the BIGR pulse reactor at Sarov.[59]

Recommendation: Each country operating pulse reactors should assess whether the benefits of continuing to operate these reactors continue to justify their costs and risks—and if not, these facilities should be shut down, or new facilities constructed using LEU. The United States should consider shutting down its last pulse reactor (or establishing a comparable LEU-fueled capability if needed), and encouraging Britain, France, and others to do the same. Kazakhstan and Uzbekistan should convert or shut down their IGR and Photon reactors, the latter of which Uzbek officials say may soon be decommissioned and its HEU fuel returned to Russia.[60]

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[59] Dubinin et al., "Goals and Objectives of ISTC Project 3128."

[60] Umar Salikhbaev, "HEU Minimization at Institute of Nuclear Physics, Uzbekistan," (paper presented at the Second

Addressing the HEU Reactors Still Not Covered By GTRI

GTRI estimates that there are still 29 HEU-fueled research reactors that it does not plan to help convert or shut down. The majority of these facilities are critical assemblies or pulse reactors in Russia, and the remainder are critical assemblies and pulse reactors in other countries; all these reactors would be addressed if the recommendations above were implemented.

There are, however, a substantial number of HEU-fueled reactors that are so far beyond GTRI's planning they do not make it onto the official lists. The largest global users of HEU every year are U.S. and Russian naval reactors (see "The Challenge of HEU Naval Fuel," p. 32), and there is little prospect for their conversion. Similarly, there is one commercial and one experimental fast-neutron reactors that use HEU fuel today—though in the future, power reactors of this type are expected to use plutonium as their fuel. These include the BN-600 commercial reactor in Russia (which uses medium-enriched material in the 22-27% enrichment range), along with the BOR-60 experimental reactor in Russia and a new fast neutron research reactor being planned; the recently opened China Experimental Fast Reactor (CEFR), which uses 64% enriched material; and the experimental Joyo reactor in Japan.[61] Most other fast reactors use plutonium fuel. A large commercial fast reactor, the BN-800, is under construction in Russia, and is slated to use plutonium fuel. Most of these reactors have troubled operating histories, and might shut down (as the world's other fast reactors have done in the past). Moreover, fast reactors to date have been uneconomic, and this is unlikely to change for decades to come. The United States should encourage countries to consider the full costs and risks before embarking on fast reactor programs. In any case, future fast reactors, to the extent they are built in the near term, are likely to be plutonium-fueled rather then HEU-fueled, though it is not clear that offers any significant proliferation advantage compared to the use of HEU in the 20-30% range, which itself would be difficult to use to make a nuclear bomb.

Avoiding the Spread of Weapons-Usable Material Production

The broad range of steps needed to reduce the danger of nuclear proliferation are beyond the scope of this paper. But one element that is clearly related to consolidation is to ensure that new states do not begin producing plutonium or HEU, creating new potential sources for nuclear theft. This includes addressing the nuclear programs of North Korea and Iran, and limiting the spread of enrichment and reprocessing facilities—the key technologies that make it possible to produce weapons-usable nuclear material.

Recommendation: The United States should work with other countries to engage North Korea and Iran, putting together packages of incentives and disincentives that convince these governments that it is in *their* national interests not to have nuclear weapons or capabilities to manufacture them rapidly.

Recommendation: The United States and other interested countries should continue to pursue multiple means to limit the spread of enrichment and reprocessing plants.[62] (See below for a discus-

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International Symposium on HEU Minimization, Vienna, 23-25 January 2012), http://www.nti.org/media/pdfs/Salikhbaev_-_HEU_Symposium_-_Vienna_23_jan_2012.pdf?_=1328045876 (accessed 2 February 2012).

[61] Thomas B. Cochran, Harold A. Feiveson, Walt Patterson, Gennadi Pshakin, M.V. Ramana, Mycle Schneider, Tatsujiro Suzuki and Frank von Hippel, *Fast Breeder Reactor Programs: History and Status* (Princeton, N.J.: IPFM, February 2010), http://fissilematerials.org/library/rr08.pdf (accessed 24 February 2012).

[62] For a recent discussion of some of the policy approaches being pursued, see Fred McGoldrick, *Limiting Transfers of Enrichment and Reprocessing Technology: Issues, Constraints, Options*. (Cambridge, Mass.: Project on Managing the

sion of plutonium reprocessing facilities in particular.) They should continue working to establish an International Framework for Nuclear Energy Cooperation that would provide assured supplies of fresh nuclear fuel and cooperative management of spent nuclear fuel, reducing incentives for states to build their own enrichment and reprocessing facilities (and heightening attention to the possible ulterior motives of those who nevertheless choose to do so). The United States and other interested countries should also explore options for international ownership, management, and staffing of fuel cycle facilities, seeking approaches that could reduce the proliferation and terrorism threats these facilities pose.

New Initiatives to Consolidate Civilian Plutonium Stocks

To date, consolidation efforts have focused primarily on civilian HEU, though as noted earlier, GTRI hopes to address a small amount (less than 100 kilograms) of separated plutonium as well. Broader initiatives to address the continuing buildup of separated plutonium are needed. Though there has been no resolution of the long-standing debates over whether reprocessing and recycling plutonium from spent fuel or direct disposal of spent fuel is the best approach to the back end of the nuclear fuel cycle, it should be possible over time to reach agreement on limiting the number of sites where plutonium separated from fission products is processed, stored, and used.

Recommendation: The United States should formally reiterate its 1990s-era position that it does not reprocess plutonium from spent fuel for either weapons or energy, and does not encourage others to do so (though it will not interfere in the fuel cycle decisions of allies already pursuing a plutonium fuel cycle).[63] It should actively work with countries to exchange information concerning the costs and risks of plutonium reprocessing, and to promote alternatives, such as dry cask storage of spent fuel and cooperation in assessing long-term uranium resources. It should support development of options for safe, secure, and cost-effective international storage sites for power reactor spent fuel. And as the Blue-Ribbon Commission has proposed, the United States should be prepared to bring small amounts of spent nuclear fuel from foreign power reactors to the United States when doing so would serve U.S. national security interests.[64]

Recommendation: The United States should work with countries that are using separated plutonium in their civilian programs to convince them to consolidate these operations at the minimum practicable number of sites. For example, in the future, reprocessing and fuel fabrication facilities should be integrated, so there is no need for long-distance transport of plutonium until it has been turned into fabricated fuel—and use of plutonium fuel might be done at only a few well-guarded sites (possibly with several reactors at a site). Transport of separated plutonium should be minimized, and when it does occur, should be under heavy guard and in forms that would be as difficult to steal and process to make a bomb as possible. As with HEU, the United States should work

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Atom, Harvard University, May 2011), http://belfercenter.ksg.harvard.edu/files/MTA-NSG-report-color.pdf (accessed 24 February 2012).

[63] Specifically, the United States stated that "the United States does not encourage the civil use of plutonium, and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes," though the United States would "maintain its existing commitments" with respect to the use of civilian plutonium in Western Europe and Japan. See The White House, "Fact Sheet: Nonproliferation and Export Control Policy," (Washington D.C, September 27, 1993), http://www.fas.org/spp/starwars/offdocs/w930927.htm (accessed 7 March 2012).

[64] Blue Ribbon Commission on America's Nuclear Future, "Report to the Secretary of Energy," (Washington D.C: Blue Ribbon Commission, January 2012), http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf (accessed February 2, 2012).

to ensure that all sites using separated plutonium have highly effective security and accounting measures in place, which will create incentives to consolidate material to reduce security costs (see discussion later in this paper).

Recommendation: The United States should work with other countries to gain commitments to limit the continued accumulation of separated plutonium. In general, plutonium should only be separated from spent fuel when it is needed for fabrication of new fuel. In particular, the United States should again take up the nearly-completed Clinton-era effort to reach agreement with Russia on a 20-year moratorium on further plutonium separation in the two countries.

Consolidating Military Nuclear Materials

There is much still to be done to consolidate military HEU and plutonium to a smaller number of sites, particularly in Russia and the United States. Both countries could save money and improve security through further consolidation.

Some sites are taking advantage of this opportunity for savings, efficiency improvements, and security improvements. At the Machine-Building Plant in Elektrostal (Russian acronym MSZ, also known as Elemash), for example, Russia's largest nuclear fuel manufacturer, Rosatom chief Sergei Kirienko visited in 2008 and complained (probably with some exaggeration) that the floor space was 100 times that of Western facilities with comparable capacity, and the staff was 10 times as large, increasing costs.[65] By 2011, the plant was implementing a plan for consolidating all of its HEU operations in a single building, with an advanced real-time computerized accounting and control system for all the nuclear material.[66]

Recommendation: The United States and Russia should work together to develop long-term plans for the future of their military nuclear complexes. (Initial discussions on this topic took place in the 1990s.) Doing this in concert would increase transparency, confidence, and the exchange of best practices. In particular, the United States should encourage Russia to reduce the number of buildings in Russia with weapons-usable material by 50% or more over the next decade. It may be possible for Russia's military to consolidate its HEU and plutonium outside of nuclear weapons to facilities in four or five closed nuclear cities.[67] The United States should provide briefings on its own consolidation experience, including the huge savings in security and safety costs that have resulted, the various obstacles that had to be overcome, and how those obstacles were addressed. Recent visits of Russian security experts to Los Alamos and U.S. security experts to Sarov have begun to exchange some of this information. The joint commission on nuclear energy and nuclear security, co-chaired by Rosatom chief Sergei Kirienko and Deputy Secretary of Energy Daniel Poneman, would be an ideal forum to address this large-scale issue for the future of their nuclear complexes.

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[65] Galya I. Balatsky, William R. Severe, and Nathaniel H Young, *Rosatom's Money Woes: The Effect of the Financial Crisis on Russia's Nuclear Goals and Nonproliferation Implications*, LA-UR 09-01530 (Los Alamos, N.M.: Los Alamos National Laboratory, 2009).

[66] Arguably the planned HEU area should be considered two connected buildings—but it will be far smaller and far better controlled than the areas for HEU processing have been in the past. Elektrostal was the site of several nuclear material thefts in the 1990s. For a description of the new system, see Viktor G. Bozin and Vladimir A. Mosolov, "Materials Controls and Physical Protection Systems for the Consolidated Production Building at the OAO 'MSZ' Site in Elektrostal, Russia," in *Proceedings of the 52nd Annual Meeting of the Institute for Nuclear Materials Management*, Desert Springs, Calif., 17-21 July 2011 (Northbrook, Ill.: INMM, 2011).

[67] See Podvig, *Consolidating Fissile Materials in Russia's Nuclear Complex*, p. 26.

THE CHALLENGE OF HEU NAVAL FUEL

The largest stockpile of non-weapons HEU in the world is for naval propulsion reactors for submarines, aircraft carriers and icebreakers, which together consume roughly three tons of HEU a year.[1] The U.S has designated 128 tons of HEU for future naval use, and Russia presumably has a similar stockpile—enough for thousands of weapons. These massive stockpiles are not only a potential targets for theft, they also pose complications for future arms control negotiations.[2]

The United States and Russia have by far the world's largest nuclear navies, and they and Britain and India appear to be the only countries that use HEU to fuel these vessels. U.S. nuclear ships and submarines are fueled with weapon-grade HEU, while Russia's typically use enrichments in the range of 40%.[3] Unfortunately, neither navy is interested in pursuing conversion to LEU, and neither government seems interested in overruling its nuclear navy on this point.

The U.S. Office of Naval Reactors has argued that converting to LEU would require either larger reactor cores or more frequent refueling, to compensate for the lower density of U-235 atoms in LEU fuel. Their analysis estimated that more frequent refueling would involve $1.8 billion a year in additional maintenance costs, and that larger cores would mean $4.7 billion in one-time construction costs and an increase of $1.1 billion annually in construction costs.[4] Some commentators have questioned this report and asked for an independent peer review of its conclusions.[5]

Similarly, the Russian Navy has no plans to convert its existing naval reactors. As one analyst put it, "they are using a proven design with a proven fuel cycle and any deviations from this could bring economic cost and introduce uncertainty with regard to reliability and performance."[6] If anything,

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[1] Ole Reistad, untitled paper presented at the Second International Symposium on HEU Minimization, Vienna, Austria, 23-25 January 2012, https://www.nti.org/media/pdfs/Reistad_-_HEU_Symposium_-_Vienna_23_jan_2012.pdf?_=1328045837 (accessed 2 February 2012). The U.S. and UK fuel their naval reactors with weapons-grade HEU. Russia fuels its reactors with medium-enriched but still weapons-usable HEU.

[2] If Russia and the U.S. reduce their weapons stockpiles to 1000 warheads each, for example, they will both have more weapons-usable HEU in naval reserve than they have in their weapons (228 tons combined versus 150 tons combined), which could give each side a 'break out' capacity if they chose to divert their naval HEU into their weapons programs See Frank von Hippel "Minimizing the Use of HEU as a Reactor Fuel," paper presented at the Harvard-Peking University Workshop on Nuclear Security, Beijing, 13 October, 2011.

[3] Ma and von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors."

[4] Refueling is also costly and time consuming. For U.S. and Russian submarines, it requires cutting through the hull of a submarine and removing the core.

[5] See, for example, von Hippel, "Minimizing the Use of HEU as a Reactor Fuel."

[6] Yaroslav Primachenko, "Prospects for HEU to LEU Conversion of Russian Military Nuclear Sea Vessels,"

Recommendation: The United States should complete the planned consolidation of HEU and separated plutonium in its nuclear complex, and seek ways to further reduce the number of buildings where these materials exist.[68]

Next Steps to Consolidate Nuclear Weapons Sites

There are still estimated to be 111 permanent storage sites for nuclear weapons, in fourteen coun-

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[68] Project On Government Oversight, "U.S. Nuclear Weapons Complex: How the Country Can Profit and Become More Secure by Getting Rid of Its Surplus Weapons-Grade Uranium," (Washington D.C.: Project On Government Oversight, 14 September 2010), http://pogoarchives.org/m/nss/downblending/report-20100914.pdf (accessed 24 February 2012).

THE CHALLENGE OF HEU NAVAL FUEL (CONT.)

it appears that Russia is considering increasing future enrichments to allow refueling to occur only when the vessel needs regular maintenance.[7]

There are some suggestions, however, that the use of LEU rather than HEU would be possible for both navies. All nuclear-powered French naval vessels are currently LEU-powered and the new class of French submarines represents a substantial improvement over the current class, suggesting that it is possible to produce high-performing, LEU-powered naval vessels.[8] Chinese nuclear vessels are apparently also LEU-fueled, and Brazil plans to use LEU fuel for its planned nuclear submarine.[9] The next generation of Russian nuclear-powered icebreakers will use LEU, and Russia's planned floating nuclear barges, using a reactor based on Russia's icebreaker reactors, are also slated to use LEU fuel.

Given the current resistance of the U.S. and Russian navies and the enormous institutional momentum these programs have, converting these reactors to LEU is at best a long-term proposition. In the future, however, if nuclear weapons stocks are reduced to hundreds rather than thousands, stocks of HEU sufficient to make thousands of nuclear weapons may pose a major obstacle to reductions, and will have to be addressed somehow.

Recommendation: As an early step, the U.S. government should engage with the Russian government on conversion of its icebreaker reactors, as GTRI already plans to do. The United States could offer technical cooperation and cost-sharing for feasibility studies and new fuel designs.

Recommendation: The U.S. government should seek to engage the Russian government on possible future approaches to fueling naval vessels without HEU, in the context of very deep arms reductions. This might initially proceed on the basis of lab-to-lab or Track II cooperative studies. Such studies should also include development of means to verify that HEU set aside for naval use is not used for weapons.

Recommendation: The U.S. government should finance an independent study—possibly by the National Academy of Sciences—of possibilities for LEU fueling of U.S. naval vessels, and their feasibility and costs.

(Austin: NPPP Policy Research Project, University of Texas at Austin, 2011), http://www.heuphaseout.org/wp-content/uploads/2011/04/Primachenko.pdf (accessed 3 February 2012).

[7] Primachenko "Prospects for HEU to LEU Conversion of Russian Military Nuclear Sea Vessels," p. 11.

[8] Rebecca Ward, "Prospects for Conversion of U.S. Naval Propulsion Reactors" (Austin: NPPP Policy Research Project, University of Texas at Austin, 2011http://www.heuphaseout.org/wp-content/uploads/2011/04/Ward.pdf (accessed 3 February 2012) p. 2.

[9] Ward, "Prospects for Conversion of U.S. Naval Propulsion Reactors."

tries.[69] (This does not include individual missile silos or submarines where nuclear-armed missiles are deployed.) In addition, there are scores of temporary storage locations (such as rail transfer points where they might be stored during a shift of trains, or loading areas where they might be stored before being loaded onto a submarine), particularly in Russia. In particular, U.S. threat reduction programs have helped upgrade security at 41 geographically separate permanent nuclear weapon storage facilities and 56 temporary facilities, for a total of 97 weapon storage facilities in Russia; these represent a very large fraction, but not all, of the weapon storage facilities that exist.[70]

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[69] See Robert S. Norris and Hans M. Kristensen "Nuclear Notebook: Worldwide Deployments of Nuclear Weapons, 2009."

[70] See Matthew Bunn, *Securing the Bomb 2008* (Cambridge, Mass.: Project on Managing the Atom, Harvard Universi-

Two decades after the collapse of the Soviet Union, there is no plausible military need for such a vast number of storage sites for nuclear weapons. It is time for policy initiatives to reduce these numbers drastically.

Recommendation: The United States and Russia, in particular, should work together to consolidate warheads at a much smaller number of locations.[71] Each country should develop a strategic plan for achieving its military objectives at lowest cost and risk with the smallest practicable number of nuclear weapon storage facilities. If existing storage facilities at a small number of sites do not have sufficient capacity to receive warheads from other sites,[72] simple but highly secure bunkers for large numbers of warheads, such as those at the U.S. Pantex facility, could be built in one to two years. The two countries should exchange information on former nuclear weapon storage facilities that have been closed, and the United States should provide briefings on how much money it has saved on security by closing many of its former nuclear weapon storage facilities.

Recommendation: In particular, the United States and Russia should launch a major nuclear warhead consolidation, security, and reductions initiative, as described in the box on "Reducing Excess Stockpiles."

Recommendation: As part of such an initiative, the United States and its NATO allies should agree to remove the nearly 200 U.S. B-61 tactical nuclear bombs now deployed in Europe. These weapons have no military utility,[73] pose unnecessary security risks, are unpopular among the populations of the countries where they are stored, and have become potent symbols among non-nuclear-weapon states of what they see as U.S. unwillingness to pursue disarmament in good faith as required under the NPT. Their deterrence function for NATO countries can be covered by U.S. long-range forces.[74] If agreement cannot rapidly be reached on a complete withdrawal, these weapons should be consolidated at a single highly secure site in Europe.

Recommendation: While the consolidation challenge is not as severe elsewhere, the United States and Russia should also work with other states with nuclear weapons to encourage them not to

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ty, and Nuclear Threat Initiative, November 2008), http://www.nti.org/securingthebomb (accessed 13 February 2012), pp. 93-94; U.S. Congress, Government Accountability Office, *Nuclear Nonproliferation: Progress Made in Improving Security at Russian Nuclear Sites, but the Long-Term Sustainability of U.S.-Funded Upgrades is Uncertain,* GAO-07-404 (Washington, D.C.: February 2007), pp. 17-19.

[71] For similar recommendations, see Harold P. Smith, Jr., "Consolidating Threat Reduction," *Arms Control Today* Vol. 33, No. 9 (November, 2003); http://www.armscontrol.org/act/2003_11/Smith.asp, p. 19; Gunnar Arbman and Charles T. Thornton, *Russia's Tactical Nuclear Weapons: Part Ii: Technical Issues and Policy Recommendations*, Vol. FOI-R-1588-SE (Stockholm: Swedish Defense Research Agency, 2005); http://www.foi.se/upload/pdf/FOI-RussiasTactical-NuclearWeapons.pdf.

[72] For a discussion of storage capacity constraints as of the late 1990s, see Joshua Handler, *Russian Nuclear Warhead Dismantlement Rates and Storage Site Capacity: Implications for the Implementation of START II and De-Alerting Initiatives*, AC-99-01 (Princeton, N.J.: Center for Energy and Environmental Studies, Princeton University, 1999).

[73] For a discussion of the lack of military utility for B-61s deployed in Europe, see Karl-Heinz Kamp and Robertus C.N. Remkes, "Options for NATO Nuclear Sharing Arrangements," in Steve Andreasen and Isabelle Williams (eds), *Reducing Nuclear Risks in Europe: A Framework for Action (*Washington DC: Nuclear Threat Initiative, 2011), http://www.nuclearsecurityproject.org/publications/reducing-nuclear-risks-in-europe-a-framework-for-action (accessed 1 March 2012).

[74] As former U.S. Senator Sam Nunn points out, NATO's tactical nuclear weapons are only one ingredient of "an extremely difficult menu of security issues" between NATO and Russia that also includes U.S. missile defence and the balance of conventional forces in Europe. For a ten-point plan about how tactical weapons can be addressed as part of a wider dialogue on Euro-Atlantic security, see Sam Nunn, "Away from a World of Peril," *Survival,* Vol. 54, No.1 (February-March 2012), pp. 234-244, http://www.nti.org/media/pdfs/Away_from_a_World_of_Peril.pdf (accessed 1 March 2012). Nunn argues that NATO's nuclear weapons should be consolidated to the United States in five years (p. 242).

expand their numbers of nuclear weapon sites, and to consolidate where possible. In particular, the United States should seek to convince Pakistan, which has the fastest-growing nuclear arsenal in the world (coupled with some of the greatest terrorist threats in the world) not to expand the number of sites where its warheads are located, and to provide maximum practicable security for all of its weapons sites and transports. Easing tensions between Pakistan and both the United States and India, to reduce Pakistani concerns over the potential vulnerability of its weapons to seizure or attack, is likely to be important to convincing Pakistan not to expand its number of weapon sites. China, Pakistan's main nuclear-weapon-state ally, should send the same message about the importance of consolidation.

ADDITIONAL POLICY TOOLS AND INCENTIVES FOR CONSOLIDATION

The approaches that GTRI and other consolidation programs have used have proved their value, and should continue to be used. In essence, since the passage of Schumer amendment in 1992 and the restart of the U.S. research reactor fuel take-back program in 1996, U.S. policy has been that the United States (a) will not export HEU for new reactor fuel unless the receiving facility cannot convert to LEU with existing fuels and is committed to converting once new fuels become available;[75] and (b) will take back U.S.-origin fuel from the most important types of U.S.-supplied research reactors only if the reactor already uses LEU or is committed to convert to LEU as soon as appropriate fuels become available. The United States has also been willing, in many cases, to pay for part of the cost of conversion to LEU. These approaches have been effective, particularly in the case of reactors that regularly need new supplies of fuel and regularly discharge spent fuel that has to be managed. But these and other current approaches should be complemented with additional policy tools, to make it possible to expand the scope of consolidation efforts around the world and accelerate their progress.

Effective Nuclear Security Rules and the Cost of Security

The cost of providing effective security can provide a strong incentive for removing nuclear weapons, plutonium, and HEU from as many sites as possible. But for this incentive to be effective, there must be regulations requiring intensive security measures for these materials—and those requirements must be structured so that once a site has eliminated its weapons-usable nuclear material, it no longer requires such expensive security measures.

Hence, the United States and other interested countries should focus heavily on convincing all countries with HEU or separated plutonium on their soil to put in place effective nuclear security regulations—which will have the double benefit of helping to ensure that operators provide effective security wherever HEU and separated plutonium continue to exist, and giving them a strong economic incentive to remove these materials from as many sites as possible.

In the United States, for example, the requirements to provide protection against a particular design basis threat (DBT) imposed in the late 1970s drove a dramatic reduction in the number of facilities using HEU and plutonium. As noted earlier, a further large-scale reduction is now underway, driven by the costs of meeting post-9/11 security requirements.

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[75] When the Schumer amendment was passed in 1992, this policy also applied to export of HEU for targets for medical isotope production. In 2005, however, in response to lobbying from producers using HEU, Congress modified the law to permit continued exports of HEU for isotope production to those countries where the largest suppliers were located. Legislation is now being debated that would end further U.S. HEU exports for this purpose after a date certain, unless sufficient supplies of medical isotopes produced without HEU were not available.

REDUCING EXCESS STOCKPILES

As of early-2011, over 19,000 assembled nuclear weapons continued to exist in the world, along with nearly 500 tons of separated plutonium and probably over 1,400 tons of HEU.[1] These stocks are far larger than plausibly required for any current military or civilian mission.

The United States, Russia, and other nuclear weapon states should join in an effort to radically reduce the size, roles, and readiness of their nuclear weapon stockpiles, verifiably dismantling many thousands of nuclear weapons and placing the fissile material they contain in secure, monitored storage until it can be safely and securely destroyed. These steps would lay an essential foundation for the eventual prohibition of nuclear weapons. Very deep reductions in nuclear stockpiles, if properly managed, would reduce the risks of nuclear theft—and could greatly improve the chances of gaining international support for other nonproliferation steps that could also reduce the long-term dangers of nuclear theft.

Recommendation: President Obama should launch a joint initiative with Russia to reduce total U.S. and Russian stockpiles of nuclear weapons to something in the range of 1,000 weapons each, and to place all plutonium and HEU beyond the stocks needed to support these low, agreed warhead stockpiles (and modest stocks for other military missions, such as naval fuel) in secure, monitored storage pending disposition.

Recommendation: In particular, the United States and Russia should launch another round of reciprocal initiatives, comparable to the Presidential Nuclear Initiatives of 1991-1992, in which they would each agree to: (a) take several thousand warheads—including, but not limited to, all tactical warheads not equipped with modern, difficult-to-bypass electronic locks—and place them in secure, centralized storage; (b) allow visits to those storage sites by the other side to confirm the presence and the security of these warheads; (c) commit that these warheads will be verifiably dismantled as soon as procedures have been agreed by both sides to do so without compromising sensitive information; and (d) commit that the nuclear materials from these warheads will similarly be placed in secure, monitored storage after dismantlement.

Recommendation: The United States should accelerate the blend-down of the stocks of HEU it has already designated as excess to its military needs, and should expand the total amount of HEU declared excess as arms reductions proceed. Russia should seize the opportunity to gain billions of dollars in revenue and support its strategic initiatives in nuclear energy by blending down hundreds of tons of additional Russian HEU, beyond the 500 tons being blended under the U.S.-Russian HEU Purchase Agreement, which expires in 2013.[2] Ultimately, the United States and Russia should agree that all HEU not needed to support a small, agreed nuclear weapon stockpile and reduced naval use should be blended to LEU. Pending disposition, both the United States and Russia should consolidate their excess HEU at one or two sites; blending efforts should also be consolidated at one or two locations, with the minimum transportation necessary to the effort. All of this blending of HEU should be done with very stringent security and accounting arrangements in place, to ensure that these measures intended to reduce proliferation and terrorism risks do not contribute to them.[3]

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[1] International Panel on Fissile Materials, *Global Fissile Material Report 2011: Nuclear Weapons and Fissile Material Stockpiles and Production*. Both the nuclear weapon figure and the HEU figure are highly uncertain, with the largest uncertainties relating to Russia's stockpiles, which Russia has never publicly declared.

[2] Matthew Bunn, "Expanded and Accelerated HEU Downblending: Designing Options to Serve the Interests of All Parties," in *Proceedings of the Institute for Nuclear Materials Management 49th Annual Meeting,* Nashville, Tenn., 14-17 July 2008 (Deerfield, IL: INMM, 2008).

[3] For a discussion of HEU disposition, see Matthew Bunn and Anatoli Diakov, "Disposition of Excess Highly

REDUCING EXCESS STOCKPILES (CONT.)

Recommendation: Similarly, the United States and Russia should work together to expand and accelerate their efforts to reduce their stockpiles of excess weapons plutonium, transforming them into forms that pose little more security risk than the large stockpiles of plutonium in spent fuel from commercial reactors ("the spent fuel standard"). Ultimately, both countries should declare all of their separated plutonium other than the amount needed to support low, agreed nuclear weapon stocks to be excess to their military needs and subject to disposition. As with HEU, excess plutonium stocks should be consolidated at one or two facilities, bulk processing for disposition should be consolidated at one or two facilities (ideally co-located with the storage facilities), transportation should be minimized, and stringent security and accounting procedures should be maintained throughout.[4]

Recommendation: The United States should work with Russia, France, the United Kingdom, Japan, and other countries with excess stockpiles of civilian plutonium to explore options for reducing these stockpiles. In some cases, it may be possible to use this material in reactor fuel; in other cases, it may make more sense to dispose of it as waste. Commercial deals in which one country uses the plutonium generated by another may be useful in reducing these stockpiles, if managed with effective security arrangements. For example, France may be able to use some of the plutonium on its soil that belongs to its foreign customers in French reactors, limiting the number of countries using plutonium fuel and the transports of this fuel. Ultimately, countries should reduce current stocks by 90% or more, to the levels that may genuinely be needed for "working stocks" as long as facilities managing separated plutonium continue to operate, and they should agree not to build large stocks up again. Over the long term, the United States should seek to build consensus that it is no longer acceptable to store tens of tons of separated plutonium for years at a time in the civilian fuel cycle.

Recommendation: In addition to reducing existing stockpiles, stopping the buildup of additional stockpiles is also important. On the civilian side, no new HEU is being produced; steps to reduce the huge ongoing accumulation of separated plutonium were discussed above. On the military side, President Obama should more aggressively seek new ways to overcome the obstacles to negotiating a verified fissile material cutoff treaty, including negotiating the text outside the Conference on Disarmament process if necessary—while also seeking to end all production of HEU for any purpose, and to phase out civilian separation of weapons-usable plutonium. As an initial step, President Obama should ensure that all U.S. reprocessing and enrichment facilities, old and new, are on the list of U.S. facilities eligible for IAEA safeguards, and offer to provide the funds necessary for the IAEA to implement safeguards at these facilities, while encouraging other states with nuclear weapons to do the same. By that means, the existing production moratoria could come under an increasing degree of verification step-by-step, using existing agreements and arrangements, pending development of a verification regime specific to the fissile cutoff.

Enriched Uranium," in *Global Fissile Materials Report 2007* (Princeton, NJ: International Panel on Fissile Materials, October 2007), pp. 24-32. A briefer update is included in International Panel on Fissile Materials, *Global Fissile Material Report 2010: Balancing the Books: Production and Stocks* (Princeton, N.J.: Program on Science and Global Security, Princeton University, 2010); http://www.fissilematerials.org/ipfm/site_down/gfmr10.pdf.

[4] For a discussion of plutonium disposition (now somewhat outdated), see Matthew Bunn and Anatoli Diakov, "Disposition of Excess Plutonium," in *Global Fissile Materials Report 2007* (Princeton, NJ: International Panel on Fissile Materials, October 2007), pp. 33-42. A briefer summary is available in International Panel on Fissile Materials, *Global Fissile Material Report 2010: Balancing the Books: Production and Stocks*. International Panel of Fissile Materials, *Global Fissile Material Report 2007* (Princeton, N.J.: IPFM, 2007), pp. 33-42.

With respect to research reactors, U.S. expert Harold McFarlane put the goal of consolidation as "more money to research, less to security." He summed up the situation well:[76]

> In the United States at least, it costs far more to secure the fissile material than it does to operate a critical facility for a year, including all the measurement and analysis… Although the situation is unique in every country, if comparable security upgrades are not being made for other facilities, the international community has reason to question the adequacy of safeguards measures.

In some countries, however, nuclear security rules are not stringent enough to provide strong incentives for consolidation. In Japan in 2006, for example, one of the authors (Bunn) visited an LEU-fueled reactor that also had more than eight kilograms of separated plutonium on-site. They had received the plutonium years before, but had never had funding to do the experiments with it. In the United States, the extra cost of security for maintaining that plutonium would have amounted to millions of dollars per year, but in Japan it was so low it was not worth bothering to move the material to a large plutonium storage facility elsewhere on the Tokai nuclear site.

In other countries, the difference in security rules between weapons-usable nuclear materials and other materials is not large enough to create much incentive for consolidation. Russia is one example. A manager of the Krylov Shipbuilding Institute, asked by one of the authors (Bunn) how much his site would save on security from eliminating its HEU, replied "zero"—because under Russian rules, the site would need the same security to continue to operate with LEU.[77] U.S. experts have been discussing a more graded approach to nuclear security regulations with Russian experts for years. New regulations approved in recent years represent some improvement, but there is much more to be done.

A related issue in Russia is that the cost of security does not fall entirely on the operator of a site, reducing the operator's incentive to consolidate. For example, in many cases the Ministry of the Interior largely pays the costs of providing troops to guard nuclear facilities. Whether the sites pay for security themselves or a central agency pays the costs, a single entity ought to pay the full costs of security, so that those costs are clear, and the full benefit of reducing those costs by eliminating stocks of HEU or plutonium is obvious.

Recommendation: The U.S. government should greatly increase its focus on working to convince other countries to put in place nuclear security regulations that will ensure that any remaining HEU and plutonium sites are well-protected against both outsiders and insiders (with appropriate grading, so that the costs of guarding LEU are far lower), thereby creating a security cost incentive for operators to get rid of as many HEU and plutonium sites as possible. At the same time, the U.S. government should work with Russia to convince Russia to consolidate the full cost of nuclear security for each facility in a single set of hands, making those costs clear.

Providing Incentives for Appropriate Shutdowns

Many of the world's research reactors have few remaining missions. Only a few reactors with unique capabilities are fully utilized and have enough money to operate almost continuously. The rest

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[76] McFarlane, "Is it Time to Consider Global Sharing of Integral Physics Data?" By "safeguards" in this context, McFarlane means "security"—in the United States, security and accounting measures for nuclear material have long been referred to as "domestic safeguards," even though their purpose is dramatically different from the purpose of "international safeguards."

[77] Interview, July 2007.

struggle along on a variety of subsidies, used only part of the time. Many find they can no longer continue, and shut down.

Providing targeted incentives to encourage shutdowns of little-used HEU-fueled reactors should be added as a complementary policy tool to conversion. The IAEA, with support from the Nuclear Threat Initiative (NTI), is helping research reactors establish coalitions to share information, improve their strategic planning, allow other research or isotope reactors to step in when one facility has an unexpected outage, and more.[78] These coalitions could make it possible for scientists from reactors that can no longer afford to keep operating to make use of other facilities in their region. But these coalitions are not currently structured to provide positive incentives for underutilized reactors to shut down. How should such incentives be provided? In some cases, the best route will be through national governments, which may be growing tired of the drain on the budget imposed by subsidizing these reactors and may be more willing to negotiate over these reactors' fate than the operators themselves. Incentives packages might include funding research at a site that does not require the research reactor, funding research as a user group at another facility in the region, or helping with shutdown and decommissioning. In some cases, it may make sense to provide guaranteed employment for the staff of a facility to be shut down for a specified period, to ease the transition to work that does not require the use of the research reactor.

Adding shutdown as a complementary policy tool to conversion of reactor has several advantages. First, there are no technical barriers to shutdown—it can be pursued immediately, without waiting for new fuels to be developed, and there are no obstacles in reactor design, materials processing, or licensing. There are still more than two dozen HEU-fueled reactors that GTRI considers too difficult to convert, and some of the facilities GTRI *does* hope to convert face major conversion challenges—but shutdown would be technically feasible for all of them. Whether shutdown made sense overall would have to be decided case by case, depending on the balance of the benefits, costs, and risks of continued operation.

Second, in many cases, shutdown is likely to be cheaper and quicker than conversion (even taking into account the cost of related incentives). There is no need to buy new fuel, and the facility's operating costs will be greatly reduced once it shuts down. Of course, once facilities shut down, they ultimately need to think about the costs of removing the nuclear material and decommissioning the facility—but U.S. and other nonproliferation programs are likely to be willing to cover much or all the cost of removing HEU in low-income countries, and the decommissioning costs will ultimately have to be incurred in any case. Moreover, many facilities are shut for a substantial period before any costs of decommissioning are incurred, which might be attractive in the current austere economic climate.

Even in the absence of any targeted incentives, nearly twice as many HEU-fueled reactors have shut down since conversion efforts began as have converted, as noted earlier, showing the potential power of the shutdown tool in HEU minimization efforts. Indeed, IAEA experts have estimated that of the roughly 260 reactors still operating in the world (both HEU-fueled and otherwise), only 30-40 are likely to be needed in the long term—suggesting that more than 80% of the world's research reactors may be appropriate targets for either near-term or medium-term closure.[79] Ultimately, research reac-

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[78] See, for example, Ira N. Goldman, Pablo Adelfang, Arnaud Atger, Kevin Alldred, and Nigel Mote, "Developing Research Reactor Coalitions and Centres of Excellence," paper presented at "Research Reactor Fuel Management 2007," Lyon, France, 12 March, 2007), http://www.igorr.com/home/liblocal/docs/Proceeding/Meeting%2011/Goldman.pdf (accessed 24 February 2012).

[79] International Atomic Energy Agency, "New Life for Research Reactors? Bright Future but Far Fewer Projected" (Vienna: IAEA, 8 March, 2004); http://www.iaea.org/NewsCenter/Features/ResearchReactors/reactors20040308.html.

tors should go in the direction that particle accelerators went long ago—toward broad international sharing of a few high-capability machines.

Recommendation: The United States and other interested countries should explicitly add efforts to encourage unneeded facilities to shut down to their toolbox of HEU minimization approaches. They should offer a range of incentives targeted to the concerns of particular facilities or agencies charged with making these decisions to help convince them to shut little-used facilities and eliminate their HEU.

Recommendation: Such shut-down efforts should be institutionally separated from conversion efforts, so that the trust necessary to convince operators to convert is not undermined by the operators believing the real agenda of the conversion experts is to shut them down. The best approach might be for the United States and other interested countries, in cooperation with the IAEA, to launch a "Sound Nuclear Science Initiative," focused on ensuring that the world gets the highest-quality research, training, and isotope production out of the smallest number of safe and secure reactors at the lowest cost. Such an initiative should have staff and funding that is separate from GTRI, though of course shutdown and conversion efforts should be closely coordinated.

Incentives Targeted to the Needs of Each Site or Institution

Governments, agencies, and operators will only agree to remove the nuclear weapons, plutonium, or HEU from a site when they believe it is in their interest to do so. An array of incentives must thus be targeted to the concerns of the particular decision-makers involved.

The history of successful HEU-removal efforts such as Project Sapphire in 1994, which removed 581 kg of HEU from Kazakhstan and Project Vinca in 2002, which removed 48 kilograms of HEU from Serbia, makes clear that incentives targeted to the needs of a particular country or facility can be essential to success—and that the needed incentives are likely to be different in each particular case, suggesting the need for flexible and creative approaches.[80]

Already, in a few high-priority cases, the GTRI program, in concert with several other agencies of the U.S. government, has offered some substantial incentives, ranging from help to establish a new accelerator facility for the Kharkiv Institute of Physics and Technology in Ukraine to assistance with a subcritical assembly for the Sosny Joint Institute for Power and Nuclear Research in Belarus. These have had important successes: they were critical to Ukraine's agreement to eliminate all of the HEU on its soil (the most dangerous of which was the HEU at the Kharkiv institute), and to Belarus' commitment to eliminate all of its HEU. Unfortunately, while Ukraine is moving forward on its commitment, Belarus announced that it would not eliminate its HEU after the United States sanctioned the country over charges of election fraud. As of early 2012, some discussions were continuing and U.S. officials still hoped to get the initiative back on track.

But there is a need to consider incentives more broadly, in a broad range of situations. For steady-

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[80] In the case of Project Sapphire, the United States promised help for the facility itself, and tens of millions of dollars in cooperative threat reduction assistance for other projects. In the case of Project Vinca, authorities there would only allow the HEU to be removed if they received funding to deal with their spent fuel and nuclear waste problems—and since no U.S. government agency was well set up to provide funding for managing another country's nuclear waste, the private Nuclear Threat Initiative (NTI) stepped in. See, for example, Philipp C. Bleek, *Global Cleanout: An Emerging Approach to the Civil Nuclear Material Threat* (Cambridge, Mass.: Project on Managing the Atom, Harvard University, 2004); http://belfercenter.ksg.harvard.edu/files/bleekglobalcleanout.pdf (accessed 30 March 2012)

state reactors concerned about the potential reduction in neutron flux resulting from converting to LEU, the United States or other countries promoting conversion might couple conversion assistance with help installing a modern neutron guide that could actually increase neutron flux at the experiment locations ten-fold, as Princeton's Alexander Glaser has suggested.[81] In other cases, it may be that agreeing to cooperate on another high-profile technical initiative can overcome the prestige concerns in giving up a stock of HEU. As noted earlier, incentives to help convince little-used reactors to shut down might include funding for other research not requiring the reactor, funding for the scientists at that site to travel to other reactors and use them, help with decommissioning the facility, or help with a new technical piece of equipment that can take the institute in a different direction.

It may in some cases be necessary to offer incentives not only for developing countries or transition countries, but for wealthy developed countries as well. These are, after all, the countries where a large fraction of the HEU and separated plutonium outside the United States and Russia exist. The fact that these countries have the funds to deal with consolidating their stocks on their own does not mean that they will choose to do so in the absence of incentives.

Of course, many important incentives will not be financial but diplomatic. A visit from the President or from another high-level official, agreement to support a cherished government initiative, communications that make clear that relations with the United States will be better if the country agrees to the consolidation initiative—all of these and more can be important parts of reaching agreement to remove a particular dangerous stock of nuclear material. But they require that all branches and departments within the U.S. government make international fissile material consolidation a priority, and be willing to put forward resources to support that goal.

Recommendation: International efforts to consolidate nuclear material should include a broad range of incentives, targeted to the concerns of individual facilities and the agencies that oversee them, to gain agreement on removing nuclear weapons, separated plutonium, or HEU from particular sites. The Obama administration and Congress should work together to ensure that relevant U.S. programs have (a) sufficiently broad authority to cover a range of potential incentives, and (b) sufficient funding for the incentives that may be needed. As recommended in the box on the obstacles to consolidation, U.S. consolidation efforts should include teams that include technical experts, officials from the U.S. embassy in the country, and other political officials, to pull together all the elements that may be necessary to achieve success.

Recommendation: Belarus should return to its commitment to eliminate the HEU on its soil, in cooperation with other countries. The United States and other interested countries should continue to work to convince Belarus to fulfill this commitment. Russia is Belarus' closest ally, energy supplier, and nuclear technology supplier, and should expand its effort to to convince Belarus to allow this HEU to be removed and replaced with LEU. Russia, the United States, and other interested countries should offer both positive and negative incentives for progress.

Recommendation: Given its presidential-level commitment to minimizing HEU and its global leadership role in nonproliferation, South Africa should decide to eliminate the hundreds of kilograms of HEU left over from its former weapons program (and the smaller stocks of HEU in irradiated fuel and targets from the Pelindaba reactor). South Africa has the largest stock of weapons-grade HEU in

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[81] Alexander Glaser, "Performance Gain with Low-Enriched Fuel and Optimized Use of Neutrons," (paper presented at the "29th International Meeting on Reduced Enrichment for Research and Test Reactors," Prague, 23-27 September 2007), http://www.rertr.anl.gov/RERTR29/PDF/5-4_Glaser.pdf (accessed 2 February 2012).

MAKING MEDICAL ISOTOPES

Medical isotopes have traditionally been produced by irradiating uranium targets—usually HEU targets—in research reactors. This generates a number of fission products, including Mo-99, and the targets are then chemically processed to separate the Mo-99 from the rest of the material. Mo-99 decays (with a half-life of 2.75 days) to technetium-99m (Tc-99m), which is used in medical imaging in some 30 million diagnostic procedures every year (14 million of which are performed in the United States).[1] The other largest market is in Europe. Because of Mo-99's short half-life, the targets are only irradiated briefly—so when HEU is used, the leftover material after production is still HEU, often weapon-grade, and only lightly irradiated. Globally, some 40-50 kilograms of HEU are used for medical isotope production every year.[2]

However, Mo-99 can be produced using LEU fuel and targets in reactors. A study by a committee of the National Academy of Sciences concluded that there are "no technical reasons that adequate quantities [of medical isotopes] cannot be produced from LEU targets in the future."[3]The process is more expensive for the reactor operator—with an increased cost of anywhere from 10 to 30 percent—and also results in increased waste (since there is more unused U-238 in LEU). But the effect on the price of the pharmaceutical once it reaches the health care provider is very small: a committee of the U.S. National Academy of Sciences has estimated that the increased costs of producing Mo-99 would represent less than 1%of the total cost of the delivered pharmaceutical, which itself is a small part of the medical procedure in which it is used.[4]

The medical isotope market is a commercial market, but heavily influenced by government policies, regulations, and subsidies. The market is dominated by four major producers: MDS Nordion (Canada), Covidien (Netherlands), Institut National des Radioéléments (Belgium), and the Nuclear Energy Corporation of South Africa (NECSA). Until recently, all of these producers used HEU targets, and resisted conversion to LEU, citing concerns about the cost of handling increased waste and disruption of production.[5] South Africa decided to convert

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[1] The most authoritative available overview of the isotope issue is National Research Council of the National Academy of Sciences. *Medical Isotope Production Without Highly Enriched Uranium.* Frank von Hippel and Laura Kahn, "Feasibility of Eliminating the Use of Highly Enriched Uranium in the Production of Medical Radioisotopes." *Science and Global Security* 14.2-3 (2006) pp.151-162.and Alan J. Kuperman, "Bomb-grade bazaar." Bulletin of the Atomic Scientists 62.2 (2006) pp. 44-50.

[2] National Academy of Sciences, *Medical Isotope Production Without Highly Enriched Uranium*, p. 11.

[3] National Academy of Sciences, *Medical Isotope Production Without Highly Enriched Uranium,* p. 2.

[4] Miles Pomper, "The 2012 Seoul Nuclear Security Summit and HEU Minimization," p. 14.

[5] However, all but one of the five reactors used for large-scale Mo-99 production have converted to LEU fuel, and the BR-2 in Belgium is in the process of being converted See: G.F. Vandergrift et al., "GTRI Progress in Technology Development for Conversion of Mo-99 Production to Low Enriched Uranium" (paper present-

any developing non-nuclear-weapon state, and the material, stored at the Pelindaba nuclear site, is of particular concern following the November 2007 attack on the site by two groups of armed men.[82] Since then, South Africa has taken major positive steps, converting its research reactor to run on LEU

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[82] For a description of this event, see Bunn, *Securing the Bomb 2008*, pp. 3-4 (with sources cited therein),

MAKING MEDICAL ISOTOPES (CONT.)

to LEU targets in 2009, and is now producing much of its medical isotopes with LEU (though the slow pace of European country-by-country regulatory decisions to permit the use of isotopes produced by this different process has delayed complete conversion). Mo-99 has not been produced in the United States for many years, but NNSA has entered into cost-sharing arrangements with four groups seeking to establish non-HEU production in the United States. Russia is now entering the isotope market in a major way, including through a contract to supply isotopes through Canada's MDS Nordion, and plans to use both HEU fuel and HEU targets; Russia's production—which may be state-subsidized—could potentially make planned non-HEU production uncompetitive.[6]

The reactors that the major suppliers use to produce medical isotopes are old, and will soon need to be replaced. Shut-downs of Canada's National Research Universal (NRU) reactor in 2007 and 2009, combined with the suspension of Canada's plans to build new isotope production reactors and disruptions at European facilities, created a major shortage of medical isotopes and global concerns over the adequacy and reliability of supply. Hence, policymakers in the United States and elsewhere have been pursuing two key objectives: ensuring a reliable future supply of medical isotopes, and doing so without HEU.

To achieve these objectives, the U.S. government has been pursuing three main pathways: (1) Helping U.S. groups to establish new production methods that do not use HEU, expanding supply and making the United States less dependent on imports; (2) helping smaller foreign producers begin supplying non-HEU medical isotopes; and (3) helping those major producers willing to do so to convert from HEU to non-HEU production.

In principle, the Canadian, Belgian, and Dutch suppliers have in the past committed to converting when appropriate targets become available, but translating these words into practice has not been easy. Canada plans to cease isotope production in the aging NRU reactor in 2016, and is unlikely to be willing to undergo the expense of converting its process to LEU in the short time before then; new medical-isotope production reactors known as MAPLE, were cancelled by the Canadian government

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ed at RERTR 2011: International Annual Meeting on Reduced Enrichment for Research and Test Reactors, Santiago, Chile, 23-27 October 2011), and F. Charrolais et al., "Leonidas U(Mo) Dispersion Fuel Qualification Program: Progress and Perspectives," (paper presented at the same meeting).

[6] Chad Westmacott, "HEU Minimization Challenges: The Supply of Medical Isotope 99-Molybdenum/99m-Technetium" (paper presented at the Second International Symposium on HEU Minimization, Vienna, January 24, 2012), https://www.nti.org/media/pdfs/Westmacott_-_HEU_Symposium_-_Vienna_24_jan_2012.pdf?_=1328045999 (accessed February 3, 2012).

and beginning the process of converting Mo-99 production to LEU before any of the other major producers were willing to do so, as well as undertaking major security upgrades at the Pelindaba site. Since it will no longer use HEU for either fuel or targets, South Africa no longer has any need for the HEU at Pelindaba, which could be blended to LEU worth tens of millions of dollars. The United States and other interested countries should continue and expand their discussions with South Africa over the future of this material. Negotiations with South Africa—a leader of the Non-Aligned Movement—have a strong political dimension. As noted in the box on obstacles to consolidation, South Africa and other non-nuclear-weapon states question why, having already fulfilled their obligations under the NPT, they should have to go still further and eliminate their small HEU stockpiles when the nuclear weapon states are maintaining huge HEU stockpiles and failing (in this view) to meet their NPT obligation to negotiate in good faith toward nuclear disarmament. Interested countries should structure packages of incentives that help address South Africa's disarmament concerns, while also making available the substantial monetary value of South Africa's enriched uranium. South Africa could gain nuclear prestige by undertaking major non-HEU R&D projects, and by taking the leading role in turning the Pelindaba Nuclear Weapon Free Zone (NWFZ), covering all of Africa, into a zone also free of weapons-usable nuclear material (see discussion later in this paper).

Incentives for Isotope Production Without HEU

Medical isotope producers use approximately 50 kilograms of HEU a year for isotope production targets.[83] This material is only lightly irradiated when making isotopes, and after processing is stored at the processing sites, building up to hundreds of kilograms of weapon-grade HEU "waste" at some locations. Current efforts to provide adequate, stable supplies of medical isotopes produced without HEU should be continued. (See "Making Medical Isotopes," above) But it seems clear that additional incentives to motivate producers of medical isotopes to convert are needed. In particular, if Russia begins providing large quantities of isotopes made from HEU at low cost as is currently planned, it could undermine the economic prospects for producers hoping to establish or continue non-HEU production.

The United States has four key sources of leverage in this industry: (1) it is the largest market for medical isotopes; (2) it supplies most of the HEU used for medical isotope production; (3) its nonproliferation programs have funding available to help support non-HEU-based production; and (4) with other countries, it has helped foster a growing international consensus that the civil use of HEU should be phased out wherever practicable. The United States should take steps to expand its use of each of these four sources of leverage, and encourage other interested countries to do the same.

Recommendation: States throughout the international community, having agreed on the goal of minimizing the civil use of HEU, should send the message to producers that they will give preference to purchasing isotopes made without HEU. As the world's largest market for medical isotopes, the United States plays a special role. The U.S. Congress should pass legislation that would either (a) prohibit the import of medical isotopes produced with HEU after a specified date unless relevant authorities certified that adequate non-HEU supplies were not available; or (b) impose a user fee on all medical isotopes made using HEU, perhaps amounting to roughly 30-50 percent of the value of the isotopes. Such steps would create a powerful incentive for producers to convert from HEU.[84] They may be essential to avoid having non-HEU production undercut by HEU-based supplies, some of which may be state-subsidized. Because the isotopes represent a tiny fraction of the cost of the medical procedures that use them, such a fee would have little effect on patient costs or the availability of needed isotopes. The revenue could be used to assist producers willing to convert. This approach

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[83] National Research Council of the National Academy of Sciences, *Medical Isotope Production Without Highly Enriched Uranium* (Washington D.C.: National Academies Press, 2009). p. 11.

[84] The specific amount required to ensure that non-HEU supplies were economically competitive would have to be judged based on market conditions.

should be included in an amended version of the American Medical Isotopes Production Act, now being debated in Congress.

Recommendation: The United States should strengthen its efforts to use the leverage provided by its role as the main supplier of HEU for isotope production to convince suppliers to convert. NNSA should continue its effort to get Belgian and Dutch companies that produce isotopes to commit to specific conversion plans in return for a last shipment of HEU. The U.S. Congress should pass the American Medical Isotopes Production Act (with an amendment as noted above), which would (a) authorize matching funds (and government responsibility for radioactive wastes from isotope production) to help the private sector establish non-HEU medical isotope production in the United States and (b) prohibit U.S. exports of HEU for medical isotope production beginning seven years after enactment, unless the Secretary of Energy certifies that non-HEU supplies are not sufficient to meet U.S. needs.[85] The importance of such action was highlighted by General Electric's recent announcement that it was suspending, for financial reasons, its efforts to develop a novel, non-HEU production method of isotopes.[86]

Recommendation: The United States should continue and expand its support for producers willing to convert to non-HEU production and for isotope production without HEU in the United States. A $25 million grant to cover part of the costs of conversion proved influential in South Africa's decision to convert.[87] NNSA is exploring similar cooperation with other major producers. NNSA should also explore possibilities for such cooperation with Russia. Similarly, given the competition coming from subsidized HEU-based isotope production, NNSA should consider increasing the cap on GTRI support for any single domestic producer from $25 to $50 million. Domestic production of medical isotopes without HEU would eliminate the need for the United States—the world's largest market for medical isotopes—to import medical isotopes produced with HEU.

Recommendation: Interested countries, including the United States, should continue to work to strengthen the international consensus in favor of minimizing the civil use of HEU in general, and of phasing out HEU use for medical isotope production in particular. It should seek strong language on phasing out HEU use for isotope production at the next nuclear security summit, the Global Initiative to Combat Nuclear Terrorism, and in other contexts. It should seek to convince the governments of Canada, Belgium, the Netherlands, Russia, and smaller HEU-based suppliers (such as Poland) to

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[85] From 1992-2005, the Schumer Amendment prohibited U.S. exports of HEU for research reactor fuel or targets unless (a) no appropriate LEU fuel or target was available for the facility requesting it; (b) appropriate LEU fuels or targets were under development; and (c) the facility committed to convert when appropriate LEU fuel or targets became available. U.S. exports of HEU plunged to almost nothing, and in principle at least, the major producers of Mo-99 committed to convert to LEU when appropriate targets became available. But in 2005, after a fierce lobbying campaign largely sponsored by the isotope producers (especially MDS Nordion), the Burr Amendment lifted this restriction. The Medical Isotopes Act would create a more complete ban than the Schumer Amendment, beginning seven years after enactment.

[86] Matthew Wald, "Radioisotope Recipe Lacks One Ingredient: Cash," *The New York Times.* 6 February 2012, http://www.nytimes.com/2012/02/07/science/ge-ends-bid-to-create-a-supply-of-technetium-99m.html (accessed 24 February 2012).

[87] According to one account, South Africa's decision to convert to LEU targets was influenced in part by the American Medical Isotope Production Act, which caused South African officials to become concerned that the U.S. would soon institute a tariff on HEU-produced Mo-99. A $25 million grant from the NNSA to help the NECSA convert also helped influence the final decision. See Chloe Colby, "The Conversion of South Africa's Medical Isotope Production from HEU to LEU: Policy Implications for Global Conversion" (Austin: NPPP Policy Research Project, University of Texas at Austin, 2011), http://www.heuphaseout.org/wp-content/uploads/2011/04/Colby.pdf (accessed 26 February 2012).

commit to phasing out the use of HEU by a specified date—and ask these countries to include that promise in their national commitments for the next nuclear security summit.

Recommendation: Like the United States, European countries should use their substantial market power to encourage the switch to non-HEU production of medical isotopes, expressing a clear preference for purchasing isotopes made without the use of HEU. As the U.S.Food and Drug Administration has already done, European health regulatory bodies should fast-track the licensing of LEU-made isotopes. (The slow pace of this process is now the major obstacle to completing South Africa's phase-out of HEU use.)

Recommendation: Following up on the strong support the 17,000-member Society for Nuclear Medicine has offered for the American Medical Isotopes Production Act, medical societies and physicians groups should spread awareness among physicians and patients about the importance of demanding "safe and sustainable" (i.e. terrorist and proliferation-proof) rather than "cheap" supplies of Mo-99.[88] Groups such as the American Association of Medical Dosimetrists (AAMD), the American Public Health Association, and Physicians for Social Responsibility are already involved; international associations such as the European Association of Nuclear Medicine and the World Federation of Nuclear Medicine & Biology should join them in supporting non-HEU production and educating their members to purchase isotopes produced without HEU where possible, creating further incentives for producers to convert.

Recommendation: Canada should work with Russia to develop a plan to shift their production of medical isotopes away from the use of HEU.

Recommendation: Based on its nonproliferation leadership, its Presidential-level commitment to minimize the civil use of HEU, and the likelihood that major markets will enact preferences for non-HEU supplies, Russia should begin a rapid transition away from the use of HEU in its production of medical isotopes.

A Broad Offer to Buy HEU

The United States and other countries should create a broad incentive that encourages facilities with excess HEU to identify themselves and seek opportunities to eliminate it. Most civil HEU outside of the United States and Russia is located in high-income countries such as Germany, France, and Canada, to which the United States does not currently offer any incentives for consolidating their HEU.

Additional incentives may be needed in high-income countries and others to achieve the maximum practicable reduction in sites with HEU. One important incentive could be based on the inherent value of HEU. One metric ton of 90-percent enriched uranium could be blended with depleted uranium to create 20 tons of 4.7-percent enriched LEU for the commercial market, worth more than $40 million. Of course, the costs of securing, transporting, and processing the material to produce LEU must be substracted from this figure. Less enriched material is worth less, and irradiated material is a net liability since the costs of managing it outweigh its potential value.

Recommendation: The United States should make an open offer to purchase HEU from any country willing to give it up. The United States might offer $25,000 per kilogram for 90% enriched mate-

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[88] See, for example, "SNM Sends Letter to Senate Leadership regarding American Medical Isotopes Production Act," Society for Nuclear Medicine press release (July 22, 2010), http://interactive.snm.org/index.cfm?PageID=9905&Archive=1 (accessed 24 February 2012).

rial, for example—roughly the original price agreed to in the U.S.-Russian HEU Purchase Agreement—with any HEU purchased to be stored at a single secure site in the United States (such as the Y-12 facility) and eventually blended to LEU. The only condition would be that countries providing HEU should not be making or importing more. The program should be structured to focus on eliminating the modest stocks at small facilities, not on buying up the huge stocks of excess weapons HEU in the United States and Russia; indeed, it might include a bonus payment for facilities that eliminated 100 percent of their weapons-usable nuclear material. [89] Not all of the HEU purchased would need to physically come to the United States—some of it might be processed in facilities in Russia or France where fissile material already exists, for example. Lower per-kilogram payments could be offered for less enriched or irradiated material that poses lower proliferation threats. If this approach was extremely successful and countries agreed to give up 10 tons of HEU, the total cost of this extra incentive would be only $250 million (plus the costs of securing, transporting, and processing the material—likely to be higher than the purchase cost proposed here). In reality, the purchase cost would be substantially less, since much of the relevant HEU is in less-enriched or irradiated forms, and it is unlikely that a quantity as large as 10 tons of HEU would be addressed through such an effort. While some of the purchase cost might go to wealthy countries, the cost would be tiny by comparison to the security stakes—and the United States should work with other countries, such as France and Germany, to convince them to make a similar offer or contribute to the fund paying for the effort. Such an incentive would be particularly useful in convincing critical assemblies and pulse reactors, with their large quantities of high-quality HEU, to convert or shut down, as it would create financial incentives to eliminate their material and help defray the costs they might incur.

Strengthening Global Consolidation Norms

A global norm in favor of minimizing the civil use of HEU is emerging, through both statements of international bodies and conferences and the actual HEU-reduction actions of states. Additional action to strengthen these norms could help convince countries to convert or shut down HEU-fueled reactors and eliminate the HEU they once used.

The nuclear security summit, recent NPT Review Conferences, and the UN Security Council have all called for minimizing the civil use of HEU.[90] The nations participating in the Global Initiative to Combat Nuclear Terrorism have gone further, identifying "minimizing the use of highly enriched uranium *and plutonium* in civilian facilities and activities" (emphasis added) as one of their "key priorities."[91]

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[89] This would include, of course, arrangements to ensure that they were not producing or importing more HEU. The program would be intended to clear out small stocks of HEU from facilities around the world, not to address the huge excess stockpiles that will remain in Russia after the current 500-ton U.S.-Russian HEU purchase is complete; those stocks should be addressed in separate agreements designed for that purpose (see main text below). The program might offer smaller amounts for HEU in forms that would be more difficult for terrorists to make a bomb from, such as material that was only 20–50% enriched or irradiated material. The proposal here would be an addition to existing incentives. In developing and transition countries, GTRI already encourages reactors to convert to low-enriched uranium (LEU) fuel and send back their fresh and spent HEU fuel by providing new LEU fuel (valued at some $15,000 per kilogram) free of charge, and paying the costs of packaging, transport, and disposition. Many research reactors, however, already have enough HEU fuel for their projected reactor lifetimes, or for many years to come; for them, supply of LEU fuel offers little incentive to switch to LEU and ship away their HEU. Where needed, GTRI sometimes offers additional incentives in the form of technical assistance to improve reactor efficiency or to replace shut-down reactors as well as providing technical training.

[90] Miles Pomper." The 2012 Seoul Nuclear Security Summit and HEU Minimization," pp.7-8.

[91] U.S. Department of State, "The Global Initiative To Combat Nuclear Terrorism" (Washington, D.C.: U.S. Depart-

What could be done to strengthen this emerging norm? The consolidation initiative outlined in this paper, would help to strengthen the consolidation norm, and so build its own momentum. In addition, the U.S. and other interested countries must seek stronger assertions of the norm in international meetings and resolutions.

Recommendation: To solve a problem, it helps to know how big the problem is. Hence, all countries should agree to declare their stocks of HEU and separated plutonium. Such declarations could begin by adding guidelines for civilian HEU declarations to the already existing guidelines for civilian plutonium declarations, and then convincing the full set of countries that have HEU or plutonium on their soil to participate. Declarations of military stockpiles of plutonium and HEU may take longer, but should also be pursued, step-by-step. The participants in the nuclear security summit process should seek to reach agreement on declarations of at least civilian HEU by 2014; even if full agreement on declarations of military stocks of plutonium and HEU could not be reached, individual countries could be encouraged to make declarations of military stocks on their own, as the United States and Great Britain have done in the past.[92]

Recommmendation: The participants in the nuclear security summit process should endorse a code of conduct on the use of HEU, including commitments to convert any facilities that can be converted, shut any facilities that are unneeded, and eliminate any HEU that facilities no longer need. If sufficient progress cannot be made by Seoul, this code of conduct could be adopted and further strengthened at meetings of the Global Initiative, by the G-20, or at the next nuclear security summit in 2014.

Recommendation: The parties to the nuclear Nonproliferation Treaty should seek a strong statement on HEU minimization at the next NPT review conference, endorsing the role of minimizing HEU as a fundamental part of nuclear security, which supports all three pillars of the NPT—disarmament, nonproliferation, and peaceful use.[93]

Recommendation: The parties to existing Nuclear Weapons Free Zones (NWFZs) should seek to eliminate all the weapons-usable nuclear material in their zones, and then make political declarations that these are also zones free of weapons-usable nuclear material. If current plans are fulfilled, there will soon be no more HEU or separated plutonium in the Latin American zone established by the Treaty of Tlatelolco; the only HEU in the African zone established by the Treaty of Pelindaba is South Africa's stock and just under a kilogram each in Niger and Ghana (both in research reactors that may soon be converted); it may soon be possible to remove the last small amounts of HEU from the South Pacific and South-East Asian zones established by the Treaties of Roratonga and Bangkok; and if Kazakhstan - decides to eliminate all its HEU, it may also be possible to eliminate all HEU and separated plutonium from the Central Asian zone established by the Treaty of Semei. Should

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ment of State, 2009), http://www.state.gov/t/isn/c18406.htm (accessed 19 February 2009).

[92] See Pavel Podvig, "Challenges of HEU Minimization" (paper presented at the 2nd International Symposium on HEU Minimization, Vienna, Austria, 23 January 2012), https://www.nti.org/media/pdfs/Podvig_-_HEU_Symposium_-_Vienna_23_jan_2012.pdf?_=1328045733 (accessed 23 February 2012); and Mohamed ElBaradei and Jonas Gahr Støre, "How the world can combat Nuclear Terrorism," *IAEA BULLETIN*, 48/1, September 2006, http://www.iaea.org/Publications/Magazines/Bulletin/Bull481/pdfs/dg_address.pdf (accessed 24 February 2012), p. 15.

[93] Matthew Bunn, "Expected—or Hoped for—Outcomes of the Seoul Nuclear Security Summit," (paper presented at the 10th Annual RoK-UN Joint Conference on Disarmament and Nonproliferation, Jeju, Republic of Korea, 7 November 2011, http://belfercenter.ksg.harvard.edu/files/bunn-nuclearsecuritysummit-jeju-nov-2011.pdf (accessed 24 February 2012).

that occur, essentially all of the southern hemisphere would be in zones free of both nuclear weapons and weapons-usable nuclear material.

FUNDING THE EFFORT

Many of the steps recommended in this paper will cost money. But their costs are modest by comparison to their security benefits—and in many cases, the savings in security costs will more than compensate for the costs of consolidation.

The United States, like many other countries, is facing serious budget problems and has decided to reduce overall federal spending by hundreds of billions of dollars. But it should be remembered that the amounts spent on consolidation and other threat reduction efforts make up a tiny portion of federal spending. The security stakes in preventing terrorists from getting nuclear weapons are huge, yet all U.S. threat reduction programs combined amount to less than half of one percent of what the United States spends every year on defense. Given the security stakes, U.S. policymakers should not allow these efforts to be slowed by lack of funds.

The United States, which has been funding many of these efforts, should continue, and other states should join in offering funding, expertise, or in-kind contributions. Other countries that have produced and distributed nuclear material abroad—Russia, France, China and the United Kingdom—should also be willing to pay the costs to return HEU to their countries and store and eliminate it once there. The U.S. Congress should be commended for providing all but $8 million of the funding the Obama administration had requested for GTRI (a cut of less than 2%) despite cuts of hundreds of billions of dollars in the federal budget overall for fiscal year (FY) 2012. For FY 2013, however, the Obama administration has proposed a budget in which GTRI's efforts to remove nuclear and radiological materials from potentially vulnerable locations around the world would be cut by some $47 million compared to the FY 2012 appropriation (a 19% cut). Moreover, GTRI's projected budgets for FY 2013-FY2016 have been cut by more than half a billion dollars compared to previous plans.[94] Clearly, there has been no dramatic reduction in the number of HEU-fueled reactors to be converted or shut down, or the amount of HEU to be removed; this requested budget and set of projections, if left unchanged, seems certain to slow progress, and would certainly make it far more difficult to expand consolidation efforts to cover a broader set of materials and facilities and a broader range of incentives, as recommended in this paper.

Recommendation: The Obama administration and Congress should work together to find ways to provide sufficient funding for GTRI and other consolidation efforts so that no opportunity to consolidate nuclear weapons or materials is delayed by lack of funds. This should include sufficient funding for incentives to help convince sites and the agencies that oversee them to support consolidation.

Recommendation: Russia, as a global leader in nonproliferation, should set aside funds to pay for shipping Russian-origin HEU back to Russia and processing it there, rather than relying on the United States to pay the full costs as it does now. Russia should also set aside sufficient funds to ship all unneeded HEU within Russia, both fresh and irradiated, to appropriate facilities for processing.

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[94] U.S. Department of Energy, *FY 2013 Congressional Budget Request: National Nuclear Security Administration* (Washington, D.C.: DOE, February 2012), pp. 463-464 and U.S. Department of Energy, *FY 2012 Congressional Budget Request: National Nuclear Security Administration* (Washington, D.C.: DOE, February 2011), pp. 421-422.

Recommendation: France, which fabricates much of the world's LEU research reactor fuel, should cover a portion of the cost of fabricating the first LEU cores for reactors converting from HEU as one of its contributions to nonproliferation, rather than relying on the United States to pay the full cost. Similarly, as South Korea begins to fabricate high-density LEU research reactor fuels in the future, it should cover a portion of the cost as a contribution to nonproliferation.

Recommendation: Now that the participants in the G8 Global Partnership Against the Spread of Weapons and Materials of Mass Destruction have agreed to expand the partnership to a global focus, with security for nuclear materials a high priority, participating countries should focus some of their funding on helping states consolidate nuclear materials at fewer locations. Canada's pledge in 2010 to contribute $5 million to GTRI's reactor conversion fund was welcome, and Canada should continue to fund U.S. NNSA efforts.[95] The United Kingdom should also support global consolidation efforts through direct donations to the IAEA or to GTRI, or by paying for the removal of any remaining HEU that it once transferred to foreign countries. China should continue to assist in the conversion of HEU-fueled Miniature Neutron Source Reactors (MNSRs) that it sent to foreign countries, and also increase its dedicated financial support for the IAEA's consolidation efforts.

THE WAY FORWARD

Each building where nuclear weapons, HEU, or separated plutonium exists represents another chance for a security vulnerability to lead to catastrophe, with potential nuclear bomb material falling into the hands of terrorists or criminals. The world is making progress in reducing the number of locations where such a disaster could occur. But more needs to be done, and soon. Countries around the world could take simple and relatively inexpensive steps to consolidate highly enriched uranium and plutonium to a small number of heavily guarded locations. The vision of a world in which locations with nuclear weapons, HEU, and separated plutonium are few, and effectively secured wherever they continue to exist, can be achieved rapidly if countries are willing to work together toward that objective. An unjustified complacency is the biggest barrier to action; it is time for countries to summon the political will to act.

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[95] Office of the Prime Minister of Canada, "Canada's Global Partnership Program collaboration with the United States and Mexico," April 13, 2010, http://pm.gc.ca/eng/media.asp?id=3282 (accessed 6 March 2012).

About the Project on Managing the Atom

The Project on Managing the Atom (MTA) is the Harvard Kennedy School's principal research group on nuclear policy issues. Established in 1996, the purpose of the MTA project is to provide leadership in advancing policy-relevant ideas and analysis for reducing the risks from nuclear and radiological terrorism; stopping nuclear proliferation and reducing nuclear arsenals; lowering the barriers to safe, secure, and peaceful nuclear-energy use; and addressing the connections among these problems. Through its fellows program, the MTA project also helps to prepare the next generation of leaders for work on nuclear policy problems. The MTA project provides its research, analysis, and commentary to policy makers, scholars, journalists, and the public.