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Crossing the Finish Line: Ending the Civilian Use of Highly Enriched Uranium

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One of the seminal achievements of the nuclear security summits (NSS) initiated by President Barack Obama has been to win global support for longstanding US efforts to phase out highly enriched uranium (HEU) in civilian use.[1] For nearly four decades, the United States has sought to secure and minimize the worldwide use of this material of choice for would-be nuclear terrorists. However, HEU has continued to power some civilian nuclear research facilities, to fuel some Russian icebreakers, and to be used in the production of a key medical isotope for medical diagnosis.

The NSS process has reinforced an emerging international norm on HEU minimization in ways both rhetorical and concrete. Summit communiqués have called for minimizing and eliminating the use of HEU where technically and economically feasible. Perhaps more importantly, countries have lined up to give "house gifts" (individual state commitments) and "gift baskets" (multistate commitments) in which they have pledged (and in some cases fulfilled these pledges already) to convert research reactors and medical isotope-production facilities away from the use of HEU and to ship fresh and spent HEU to their country of origin—the United States or Russia.

However, as the final NSS approaches in 2016, the world still lacks a comprehensive multilateral strategy to minimize and ultimately eliminate HEU from the civilian sector. At the same time, US budget pressures and the difficulty of some of the technical tasks that lie ahead risk slowing progress. In order to maintain momentum toward the goal of eliminating civilian HEU, the 2016 NSS will need to take a number of steps, such as endorsing a political framework that includes the following elements:

- An explicit commitment in the NSS communiqué to *end* civilian HEU use, when technically and economically feasible, not merely to *minimize* it.

- A gift basket or a joint statement drafted by the NSS troika of hosts (the United States, South Korea, and the Netherlands) that provides a road map for ending civilian HEU use within a clear time period. This road map should include a requirement that all civilian facilities housing HEU, including in the nuclear-weapons states, eventually be placed under International Atomic Energy Agency (IAEA) safeguards. The countries housing these facilities should pay the expenses of IAEA inspections.

- A continued commitment to the conversion or shutdown of all HEU-employing civilian reactors, with particular attention to critical assemblies, pulsed reactors, and fast reactors.

- A firm commitment that future research facilities, civilian naval reactors, and fast reactors will not use HEU, as there is no technical necessity to do so.

- A US-Russian bilateral commitment that any exports of HEU will be tied to a pledge from the recipient to demonstrated actions to convert its facility away from HEU use. Given concerns among some in the industry about potential future shortages of 19.75 percent low-enriched uranium (LEU), a guaranteed LEU supply contract could be an incentive for taking this step.

- A commitment to improve the security of HEU spent fuel wherever it exists in the nuclear fuel cycle, to ensure that the planned end of a US takeback program for HEU and some LEU waste does not leave spent HEU at vulnerable sites, and to determine appropriate disposition pathways for new forms of LEU fuels and targets in order to facilitate conversion.[2]

- A commitment at the 2016 NSS to end exports of the vital HEU-based isotope molybdenum-99 (Mo-99) unless the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) says there is insufficient global non-HEU production capacity available. Summit members should enact a similar pledge to ban the use of HEU-based Mo-99 if the OECD-NEA and relevant national authorities certify that a sufficient supply of non-HEU-based Mo-99 exists at that time.

- Continued attempts to convince Belarus and South Africa to reduce the risk created by their HEU stockpiles, including through a compromise blend-down to HEU with a lower enrichment level.

- An agreement in the long term among the Non-Proliferation Treaty (NPT) nuclear-weapon states (China, France, Russia, the United Kingdom, and the United States) to end production of HEU for civilian purposes and a commitment that any future HEU use in this sector would come from material that was manufactured for use in nuclear weapons.

Background

HEU represents a highly attractive target for terrorists. HEU can be used to create the simplest nuclear explosive device, a so-called gun-type weapon.[3] Using a gun-type design, such a device would explosively collide one subcritical piece of HEU with another in order to form the supercritical mass required for a nuclear detonation. This process is well publicized, and there is consensus among experts that the creation of an improvised nuclear device based on this design is within the technical reach of a financially and organizationally strong terrorist group.[4]

To make matters worse, because HEU is only weakly radioactive, it is relatively safe to handle and hard to detect. Even HEU waste is less radioactive than one might hope from a security-oriented standpoint. In a matter of months, HEU waste quickly loses its "self-protection," in that it will not give an incapacitating radiation dose to a would-be thief. Of particular concern is HEU waste from the isotope-production process.[5] It is only lightly irradiated and often very highly enriched. Moreover, the ultimate disposition pathways for some HEU waste are unclear amid changes in US take-back and disposition programs and technical changes to replacement LEU fuels and targets.[6]

Despite these dangers, HEU continues to be widely employed in civilian research facilities and naval propulsion reactors, and in the production of a medical isotope used in cancer and other medical diagnostics. An estimated 54 tons of HEU are in civilian use worldwide, spread across 29 countries.[7] Both superpowers started shipping HEU throughout the world in the 1960s as part of the US "Atoms for Peace" program and a similar Soviet initiative. India's "peaceful nuclear explosion" in 1974 raised concerns about the potential misuse of exported HEU and led the international community to reconsider additional transfers. By 1978, Washington and Moscow had launched fledgling efforts to reduce HEU use overseas (and in the US case, also domestically).[8] In the United States, these efforts were further bolstered by the 1992 Schumer Amendment to that year's Energy Policy Act. This measure restricted US HEU exports to reactor operators who could not use LEU fuel or targets and had committed to transition from HEU once a low-enriched substitute became available, and to cases where the United States was in the process of developing such a substitute.

These HEU minimization initiatives were revitalized in the aftermath of the September 2001 terrorist attacks in the United States, which drove home the threat of nuclear terrorism. Subsequently, the George W. Bush administration consolidated a number of existing programs into the Global Threat Reduction Initiative and, with the support of Congress, boosted funding for these efforts and expanded their scope to take in additional types of facilities and materials.

The Bush administration also fostered bilateral cooperation with Russia, whose partnership was and remains critical. Presidents Bush and Vladimir Putin reached an agreement in 2005 whereby both countries pledged to provide LEU stocks for any US- or Russian-designed research reactor operating with HEU. Spent or remaining fresh HEU would then be repatriated to its country of origin. In practice, this has largely meant that the US National Nuclear Security Administration has paid Russia to help ship back HEU to Russia from countries such as Belarus, Poland, Serbia, and Ukraine.

In his speech in Prague in April 2009, President Obama announced "a new international effort to secure all vulnerable nuclear material around the world within four years."[9] Obama said the United States "will set new standards, expand our cooperation with Russia, pursue new partnerships to lock down these sensitive materials."[10] These efforts have had considerable success. The US-origin take-back program has so far removed 1,264 kg of HEU, while the Russian-origin take-back program had by early 2013 removed 1,781.5 kg of HEU.[11] As a result, 28 countries have been cleared of HEU.[12] The most concrete outgrowth of this effort is the NSS process, which, as detailed below, has helped clear some longstanding political roadblocks that were in the way of HEU removals. The Obama administration has also led a push to reinvigorate efforts to end HEU in medical isotope production (detailed below). In other aspects, it has continued the policy begun by the Bush administration.

In June 2012, the Obama administration made clear its explicit goal of eliminating HEU in civil use: "The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes."[13] While Obama's 2009 Prague speech emphasized securing all vulnerable materials, this less-noted statement acknowledges that the best way to secure such material is to eliminate it, particularly given the diminishing need for civil HEU.

Growing International Support for Civilian HEU Minimization

In recent years, these largely unilateral US initiatives have fostered and helped support an international consensus on the need to *minimize* (but not *eliminate*) the civilian use of HEU. The issue has been taken up in the NPT review conferences and perhaps most significantly at the UN Security Council summit held in September 2009, chaired by President Obama. Resolution 1887, which was unanimously adopted at that meeting, called on states to "manage responsibly and minimize to the greatest extent that is technically and economically feasible the 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."[14]

The NSS process permitted the United States to channel this broader support into new commitments. The summits have consistently endorsed civilian HEU minimization. For instance, at the 2014 NSS, the final communiqué encouraged "states to continue to minimize the use of HEU through the conversion of reactor fuel from HEU to LEU, where technically and economically feasible, and in this regard welcome cooperation on technologies facilitating such conversion."[15] As detailed below, the summits also produced important communiqué language and joint commitments (gift baskets) to convert from using HEU in medical isotope production and cooperate on new non-HEU fuel development.

But perhaps the most tangible accomplishments of the summits have been to push individual countries to move ahead with converting reactors from HEU and sending that material to the United States or Russia. One indication of the value of the summits in advancing HEU conversions and removals: the United States had been pressing to clear Ukraine of HEU for nearly two decades, but it was only the political leverage of the summit process that finally accomplished this goal in 2012. Similarly, the 2014 summit led to one of the largest promises to date: Japan's pledge to send all remaining HEU stored at its Fast Critical Assembly (FCA) site to the United States to be downblended and disposed of.[16] All told, in the 28 countries that have been cleared of HEU over the life of these efforts, nearly half of these removals (13 countries) took place since the summits were announced in 2009.

Remaining Political Obstacles

Still, the NSS process has had its setbacks. Further HEU stock minimization remains blocked by a few recalcitrant countries, and establishing broader legal principles on HEU management is proving to be difficult.

HEU Hoarders

An unlikely pairing—Belarus and South Africa—are both keeping HEU stockpiles for political purposes, albeit in support of very different causes.

In early December 2010, in part using the lure of potential participation in the 2012 NSS, US Secretary of State Hillary Clinton reached an agreement with Belarusian Foreign Minister Sergei Martynov for the return of all of Belarus's HEU to Russia. Later that month, following protests over election fraud, longtime Belarusian dictator Alexander Lukashenko arrested over 700 individuals, some of whom were severely beaten. As a result, the European Union and the United States imposed sanctions on the state.[17] In retaliation for further US sanctions in August 2011, Minsk froze the HEU-return process. The situation remains at an impasse, and there are significant uncertainties about Belarus's HEU stockpile; it is believed to have 80 to 280 kg left.[18]

South Africa, an NSS participant, maintains several hundred kilograms of HEU at the Pelindaba Nuclear Research Center. The exact amount is unknown; South Africa has stated it will not release a public figure on its HEU holdings nor the enrichment percentages of the HEU in the current stockpile.[19] South Africa has converted its SAFARI research reactor to use LEU fuel and is in the process of moving toward 100 percent LEU-isotope production. Despite the country's positive initiatives with regard to reactor-conversion efforts, HEU repatriation, and LEU-based-isotope production, South Africa continues to refuse to convert its HEU to LEU en masse.[20] It has used its HEU stockpile as leverage in support of the Non-Aligned Movement's position that global nuclear risk reduction should focus on nuclear weapons disarmament.[21]

Some compromise appears possible. For instance, South Africa could agree—as an intermediate step—to blend down any remaining weapons-grade HEU to a lower HEU level. South Africa's Democratic Alliance Party, currently the official opposition, publicly displayed its support for such an initiative in a letter to the IAEA.[22] The United States could further incentivize South Africa and respond to the latter's demand for disarmament by declaring as excess to weapons use an amount equivalent to that which South Africa downblends to LEU.[23]

HEU Guidelines and Code of Conduct

Attempts to use the NSS process to advance broader legal principles when it comes to HEU use have also hit roadblocks. At the 2012 summit, France circulated a non-paper calling for the creation of HEU management guidelines (modeled on existing plutonium guidelines) to provide greater transparency on states' HEU holdings and tougher standards for security, transportation, and international transfers. The guidelines would aim in part at raising the cost of storing the material, encouraging states that are making little use of stocks to eliminate or consolidate them.

The initiative met resistance from a number of quarters. Russia and Germany were concerned that the guidelines would shed poor light on their HEU holdings; some developing countries resisted drafting HEU guidelines as part of the summit process, saying such issues were best addressed within the IAEA rather than effectively being imposed on the agency from the outside.

Similarly, a proposal by some nongovernmental groups and Norway for a voluntary code of conduct on HEU minimization in which various stakeholders—operators, customers, governments—pledge to take steps to minimize and ultimately eliminate HEU gained little traction, although the nuclear industry summits (industry side meetings to the official summits) have joined the call for minimizing HEU. For example, the statement for the 2014 Nuclear Industry Summit not only supported the minimization principle but also called for greater industry cooperation on key technical challenges, such as the development of new high-density LEU fuel and the assurance of sufficient disposal options for spent research-reactor fuel.[24]

The HEU guidelines experience demonstrates that it is hard for NSS participants to draft language that seems to directly influence IAEA rules. On the other hand, a clear majority of NSS participants in 2014 pledged as part of a Strengthening Nuclear Security Implementation initiative to adhere to several important IAEA guidelines, such as the physical protection of nuclear materials (including but not limited to HEU).[25] This achievement indicates that an effective political strategy for the 2016 summit in regard to HEU minimization would further this initiative and advance those efforts that can be undertaken in the summit process without seeming to direct action in the IAEA. Therefore, one priority should be winning the adherence of remaining summit participants (particularly Russia and Pakistan) to this initiative.

Remaining Technical Issues and New Political Commitments

Despite the considerable progress to date, significant minimization activities are still required in the field of reactor conversions, where work is planned to continue for several decades.[26] It is estimated that 119 HEU-fueled facilities of all types still remain in operation, of which 45 are research reactors proper and 62 are pulsed reactors and critical/subcritical assemblies.[27]

An enduring political and economic commitment is needed, given the technical challenges and economic costs of conversion. As one of us has previously noted:

"Converting reactors is a time consuming and technically demanding process akin to using a new kind of fuel in a car engine while seeking to maintain the car's performance and safety and not altering its basic dimensions or operating costs. The challenge is particularly difficult given that research reactors are even less standardized than power reactors. As a result, almost every conversion of a reactor requires a lengthy study to determine what changes can be made safely even before undertaking the conversion process, which can take years. A very few reactors are seen as particularly difficult to convert either because of their individual dimensions or their high performance levels."[28]

For the most difficult high-performance research reactors, which have typically relied on HEU to generate a sufficient flow of neutrons in small areas ("neutron flux"), change will come only with the manufacturing of increased-density LEU fuel, potentially supplemented with new technical tweaks.[29] These developments are important not only for the conversion of existing research reactors, but also for the nonuse of HEU in replacement research reactors in development today. For instance, the new European Jules Horowitz reactor will be forced to use HEU fuel until high-density fuel becomes available.[30]

Even in cases where the technical difficulties are manageable, complex logistics as well as economic and political issues impede progress. Beyond traditional financial, technical, and logistical assistance, new initiatives can help smooth HEU-to-LEU transition at educational research reactors, such as coalitions of research reactors or Internet-enabled reactor-sharing techniques.[31]

The lion's share of active HEU facilities remains in Russia (at least 59 of all types).[32] Russia has done little to convert its own reactors, although it has shut some down. The United States and Russia conducted feasibility studies for the conversion of six research reactors, and Russia has begun the conversion of one reactor. More recently, the two countries had been discussing the possibility of conducting an additional set of feasibility studies. It remains to be seen whether these cooperative projects will survive the current Ukrainian crisis.

Conversion of Other HEU Facilities

While the conversion of standard research reactors has made good progress, the two other types of research facilities—pulsed reactors and critical assemblies, which by far hold the most HEU—have largely been left out of this process.[33] Pulsed reactors provide huge bursts of neutrons (high neutron flux), which used to be required for nuclear physics research, in particular for nuclear weapons work.[34] Critical and subcritical assemblies are test beds where different core configurations and fuel types are tested before deployment.

Pulsed reactors are mostly located in Russia, where 16 known HEU-fueled pulsed reactors remain in operation.[35] Thanks to the large physics dataset already gathered throughout the world, as well as advances in computing, pulsed reactors are becoming increasingly unnecessary, especially for civilian use; this reality has been increasingly recognized in Russia.[36] Moreover, thanks to advances in reactor design, modern LEU-fueled replacement reactors have been estimated by a Russian scientific team from the Russian Federal Nuclear Center VNIIEF (the All-Russian Research Institute of Experimental Physics) as being able to match or surpass the performance of old HEU-fueled pulsed reactors.[37]

There are also approximately 40 critical and subcritical assemblies around the world, with Russia housing the majority of active ones.[38] As with pulsed reactors, there is a current debate over the continued necessity for critical assemblies, as opposed to using computer simulations based on benchmark experiments. A comprehensive approach is needed for diminishing HEU use in critical and subcritical assemblies and pulsed reactors, which would include decommissioning impossible-to-convert reactors, consolidating workloads toward reactors most likely to be convertible once higher-density fuels become available, and, if needed, deploying new LEU-powered replacement reactors for niche applications.[39]

Recent experience also indicates that as an important first step toward conversion, it would be valuable to investigate closely whether the work carried out at these facilities truly requires fissile materials. Apparently, one of the reasons Japan was able to move forward with removing HEU from the FCA is that Japanese and US officials concluded that facility scientists were no longer carrying out research on fast neutron reactors that previously required such materials. Similar conditions are said by government experts to pertain to some of the Russian facilities. Other policy recommendations include pushing for a commitment that any future critical assemblies will be HEU free, and that HEU at critical assemblies be put under IAEA safeguards at the owner's expense within a concrete time frame.

Finally, special types of experimental power reactors—fast breeder reactors—employed HEU in the past. New models are transitioning to a plutonium-uranium fuel mixture called MOX (mixed oxide fuel), and experimental efforts are under way to see if both can be replaced with LEU fuel. Therefore, there is no technical rationale for new HEU-fueled fast breeder reactors anywhere in the world, and this realization should be acknowledged at the political level.

Fuel Cycle Incentives

To foster continued conversion, governments, particularly the United States, need to ensure that reactor operators are confident they can count on having adequate supplies of replacement LEU fuel (enriched to 19.75 percent) as well as a means of disposing of their wastes (both LEU and HEU). US officials say they have the means to provide replacement LEU for the foreseeable future, but at the Nuclear Industry Summit and in other venues, industry officials have expressed concern and a desire for additional sources.[40] One option would be for the United States and Russia to offer a guaranteed LEU supply contract years in advance to reactors that pledge to convert from HEU with conditions akin to the Schumer Amendment. On the back end of the fuel cycle, a US program to remove HEU (and some LEU) waste is due to draw to a close in 2019, with any fuel needing to be irradiated by May 2016.[41] While alternative end-use pathways exist for some current fuels—albeit often at higher prices—new techniques will be needed to reprocess or otherwise manage the higher-density LEU fuels still in development. The United States and other governments should ensure that the potential end to the program does not prevent the removal of HEU or discourage conversion. If necessary, they should waive these deadlines. Indeed, perhaps the key sweetener for the FCA deal is said to have been the US willingness to extend for a decade the take-back deadline for HEU and LEU spent fuel from other Japanese facilities. Such incentives may provide valuable leverage with other hard cases.

Nuclear-Powered Icebreakers

Russia is the only country in the world that uses HEU for civilian naval propulsion. A subsidiary of Russia's state-owned nuclear giant Rosatom called Atomflot operates four HEU-powered icebreakers. Moreover, the lifetimes of Atomflot's icebreakers have been extended; they were supposed to be decommissioned by 2016, but this does not seem likely given that the first new icebreaker is due in 2017 if all goes well.[42] These future icebreakers are slated to use the RITM-2000 reactor for nuclear propulsion, which will use LEU.[43] The icebreaker fleet is not just an economic project: it is a part of the current Russian administration's assertive stance in the Arctic, and a switch to LEU is therefore likely to be gradual, as old HEU-fuel boats are replaced with new LEU-fueled ones. As part of the summit process, Russia should be encouraged to formalize this commitment not to build any new HEU-fueled civilian icebreakers.

Progress on Medical Isotope Production

Reactors are used to produce the vital isotope molybdenum-99 (Mo-99) by irradiating uranium "target" plates. Mo-99 decays into the even shorter-lived technetium-99m (99mTc), which is used as a tracer in more than 30 million medical procedures each year.[44] Historically, these reactors were powered with HEU and used HEU in the uranium targets. Production is heavily concentrated: eight reactors produce the vast majority of Mo-99 in the world.[45]

The United States has pushed for the conversion of both reactors and targets to LEU, primarily by using its control over HEU exports under the Schumer Amendment. Most of the major producers have converted their isotope-production reactors to LEU fuel in response.[46] Unfortunately, switching to LEU targets has faced far greater technical, economic, and political issues. Technical efforts have only been partially successful, and several reactor operators and some physicians have argued that conversion entails heavy economic costs and could lead to supply shortages with negative repercussions for public health.[47] In some cases, this argument was self-serving—for example, Canada's isotope producer Nordion lacked the capability to process anything other than HEU targets. And on the whole, experts have concluded that this line of argument is misplaced: a high-level intergovernmental group concluded in a series of reports that supply shortages over the last few years have resulted from the fact that older HEU-fueled reactors have had their capital costs effectively subsidized, making it difficult for new LEU-based competitors to enter the market and compete successfully. Rather than fretting about the relatively small cost of conversion as a factor on supply, they and a high-level group convened by the OECD-NEA stressed the importance of ending the subsidies for the older HEU-based reactors ("full cost recovery").[48]

A major breakthrough occurred when European host countries for several major isotope producers in Europe committed at the 2012 nuclear security summit to push their firms to convert to LEU in the next few years, assuming regulatory approvals.[49] The 2013 American Medical Isotopes Production Act also put additional pressure on foreign reactors to convert. The law provides support for the development of domestic non-HEU Mo-99 production and forces the phaseout of US HEU exports over a seven-year period, with a six-year delay option in case such a reduction would significantly disrupt Mo-99 supply.[50]

An effort to boost US demand for non-HEU-based Mo-99 was also rolled out by the White House in 2013.This led to the Centers for Medicare and Medicaid Services providing a greater reimbursement for some non-HEU-based 99mTc than its HEU-produced counterpart and to a January 2014 announcement from the Veterans Administration encouraging its facilities to purchase the LEU variety of the isotope. Despite some technical and administrative glitches, this carrot-and-stick approach generally seems to be working, with sales of LEU-based 99mTc growing slowly but steadily, two new US firms poised to enter the market, and Russia—which once appeared ready to expand HEU-based production—announcing positive steps toward using LEU targets only a few months ago.[51] Ideally, this transition should be completed and codified by the 2016 summit. Should this not be possible for technical reasons, states should ensure it takes place as soon as possible after the summit.[52]

Restoring the Norm on Ending New HEU Production for Civilian Use

Until recently, an informal moratorium was in place on the production of new HEU for civilian reactors, with existing HEU facilities relying on existing stocks or former military material. Russia restarted civilian HEU production in 2012 by launching a centrifuge cascade at the Electrochemical Plant Production Association facility in Zelenogorsk. The initial official justification for the decision was that domestic "new projects, in particular on the icebreaker fleet," would require HEU—a troubling statement given the norm against using HEU in new projects.[53] In the end, it appears almost certain that HEU production was restarted for export to Europe, at least for the Jules Horowitz reactor.[54] Assuming this is the case, diplomatic efforts should seek to persuade Russia to supply this HEU only in return for a Schumer Amendment-like pledge to convert to LEU. In return, Russia or the United States could offer a guaranteed supply of 19.75 percent LEU.

In the long term, an agreement among the five NPT nuclear-weapon states to end production of HEU for civilian purposes and that any HEU used in this sector once stockpiles were extinguished would come from former weapons HEU would be highly desirable. These states had previously agreed (China informally so) on a moratorium on HEU production for weapons purposes, and all had stopped HEU production for civilian purposes. To be sure, China does not declare any of its HEU as civilian, and Russia's general stockpile is clouded in secrecy; it would take serious diplomatic effort to persuade both to publicly employ a "civilian-military" classification with some measure of transparency.[55]

Some of the above initiatives could be included in a joint statement for the 2016 summit that should be drafted by the NSS troika of hosts.

This gift basket would provide a road map for ending civilian HEU use within a clear time period and dovetail with a broad commitment to elimination in the 2016 summit. One aspect of this road map should be a requirement that all civilian facilities housing HEU, including in the weapons states, eventually be placed under IAEA safeguards in order to provide some additional assurance against diversion to state and nonstate actors. Governments hosting the material would pay the expenses of IAEA inspections.

In addition, some summit members may want to further another approach for cementing progress: the creation of "HEU free zones." Doing so would be an easy way to register support for HEU elimination in regions, such as Latin America, that have essentially been cleared of such materials. In other cases, such as in Eastern Europe, the creation of such zones might be a means of encouraging recalcitrant actors (Belarus in this case) to part with their HEU. Such zones could stand alone or be tied to existing institutions, such as nuclear-weapon-free zones.

Conclusion

The efforts of the United States and other countries to minimize HEU use have been quite successful, but their scope has been too limited and too often hampered by a lack of multilateral support. With the end of the high-level summit process likely approaching in 2016, time is running out to set a clear objective that can muster sustained engagement from the full international community. That goal needs to be the elimination of this material from civil use, which is technically possible given sufficient political support. The United States, the Netherlands, and South Korea should take full advantage of the summit mechanisms—while they have them—to build this support.

Endnotes

[1] "HEU" is a catchall term for uranium that has undergone industrial processes to increase the concentration of the fissile U-235 isotope well above its natural level of less than 1 percent of uranium ore. By definition, HEU has been "enriched" to the point where the concentration of U-235 (the isotope that can cause a chain reaction) is at least 20 percent of the available isotopes. It includes concentrations of as much as 90 percent—the level states often employ in nuclear weapons ("weapon-grade").

[2] These issues were discussed in several papers delivered at the European Research Reactor Conference in Ljubljana, Slovenia, March 30–April 3, 2014: C. Messick and J. Galan, *Global Threat Reduction Initiative's Nuclear Material Removal Program: 2014 Update, http://www.euronuclear.org/meetings/rrfm2014/transactions/RRFM2014-transactions.pdf;* S. Tozser et al., *Available Reprocessing and Recycling Services for Research Reactor Spent Nuclear Fuel (Introduction of a New IAEA Report)*; C. Eysseric et al., *Status of Sillicide Fuels Treatment at La Hague Plant.*

[3] How much HEU would be needed would depend on the enrichment level of the HEU, the design and makeup of the weapon, and the expertise of the bomb builders. Without a reflector and at normal density, a sphere of pure U-235 would be just critical at 50 kilograms, i.e., just on the verge of a chain reaction. Therefore, weapon-grade HEU (90 percent) would be critical at roughly 56 kilograms without any compression or collision. A 1998 study by Los Alamos National Laboratory concluded that roughly 20 kilograms of 94-percent enriched HEU would be one critical mass if a four-inch reflector of natural uranium was used. Joseph L. Sapir, Russell Kidman, and R. W. Brewer, "235U (94%) Spheres Surrounded by Natural-Uranium Reflectors," *http://lib-www.lanl.gov/la-pubs/00418688.pdf*. States, which can use implosion technology to increase the density of the HEU, can use much less material. As a rule of thumb for safeguards, the IAEA estimates a "significant quantity of HEU" (that is the material that a state actor would need for a first nuclear weapon) as 25 kilograms of U-235. For useful discussions see Annette Schaper, *Highly Enriched Uranium: A Dangerous Substance That Should Be Eliminated*, Report No. 124, Peace Research Institute Frankfurt, 2013, 3–6, *http://www.hsfk.de/fileadmin/downloads/prif124.pdf*, and Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing Out Highly Enriched Uranium* (Abingdon, UK: Routledge, 2013), 4–5.

[4] Charles D. Ferguson, William C. Potter, *The Four Faces of Nuclear Terrorism* (New York: Routledge, 2005), 134.

[5] C. Hansell and F. Dalnoki-Veress, "Examining Self-Protection Requirements: Methods to Improve the Security of HEU Materials," presentation at the International Symposium on Nuclear Security, Vienna, April 2, 2009, 5–10, *http://www-pub.iaea.org/mtcd/meetings/PDFplus/2009/cn166/CN166_Presentations/Session%208/072%20hansell_Dalnokiveress.pdf*.

[6] Messick and Galan, *Global Threat Reduction*, 273.

[7] Schaper, *Highly Enriched Uranium,* 7. For more detailed estimates, also see *Civilian HEU: Who Has What,* Nuclear Threat Initiative, January 2014, *http://www.nti.org/media/pdfs/heu_who_has_what_1.pdf?_=1355442796*.

[8] Anya Loukianova and Cristina Hansell, "Leveraging U.S. Policy for a Global Commitment to HEU Elimination," in *The Global Politics of Combating Nuclear Terrorism: A Supply-Side Approach*, eds. William C. Potter and Cristina Hansell (Abingdon, UK: Routledge, 2010), 33–34.

[9] President Barack Obama, "Remarks by President Barack Obama, Hradcany Square," speech, Prague, Czech Republic, April 5, 2009, *http://www.whitehouse.gov/the_press_office/Remarks-By-President-Barack-Obama-In-Prague-As-Delivered*.

[10] Ibid.

[11] Messick and Galan, *Global Threat Reduction,* 269; S. Tozser and P. Adelfang, *The IAEA Activities in Supporting Long Term Interim Storage and Take-Back Programmes of RRSNF,* paper presented at the European Research Reactor Conference, Saint Petersburg, Russia, April 21–25, 2013, 166–168, *http://www.euronuclear.org/meetings/rrfm2013/transactions/RRFM2013-transactions.pdf*.

[12] *Civilian HEU: Who Has What.*

[13] White House, "Fact Sheet: Encouraging Reliable Supplies of Molybdenum-99 Produced Without Highly Enriched Uranium," June 7, 2012, *http://www.whitehouse.gov/the-press-office/2012/06/07/fact-sheet-encouraging-reliable-supplies-molybdenum-99-produced-without-*.

[14] United Nations Security Council, Resolution 1887 (2009), September 24, 2009, S/RES/1887 (2009), para. 25, p. 5, *http://www.un.org/News/Press/docs/2009/sc9746.doc.htm*.

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