WATCH THEM GO: SIMPLIFYING THE ELIMINATION OF FISSILE MATERIALS AND NUCLEAR WEAPONS

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NOTE

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TABLE OF CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

AWE	UK Atomic Weapons Establishment
CEA	French Atomic and Alternative Energy Commission (Commissariat à l'Energie Atomique et aux Energies Alternatives)
FMCT	Fissile Material Cut-Off Treaty
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
IPNDV	International Partnership for Nuclear Disarmament Verification
LEU	low-enriched uranium
MOX	mixed-oxide (fuel)
NPT	Non-Proliferation Treaty
PMDA	US–Russian Plutonium Management and Disposition Agreement
START	Strategic Arms Reduction Treaty

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SUMMARY

Nuclear disarmament is a complex undertaking that includes many interrelated elements, from creating political conditions for disarmament and designing legal and institutional structures to support the process, to the actual reductions of nuclear arsenals, elimination of delivery systems and dismantlement of nuclear warheads. It is also well understood that any process that aims to achieve reductions of nuclear arsenals in a comprehensive and irreversible manner has to include measures that ensure that fissile materials that are released in the course of nuclear disarmament are no longer available for weapons.

After the end of the Cold War, the international community has seen significant reductions of the number of nuclear weapons and of the global stock of fissile materials produced for nuclear weapons. The total nuclear weapon stockpile has been reduced from its peak of more than 70,000 weapons, reached in the 1980s, to less than 14,000 weapons today.[1] A significant fraction of fissile materials recovered from these weapons has been eliminated as well. However, military stockpiles of the nine nuclear-armed States still include an estimated 9,330 nuclear weapons, most of them in the Russian Federation and the United States.[2] These weapons contain approximately a fifth of about 1,170 tonnes of highly enriched uranium (HEU) and about 214 tonnes of separated plutonium that are still technically available for weapon purposes. This means that there are enough fissile materials in military programmes to produce more than 40,000 additional nuclear weapons. Even though it might be difficult to imagine circumstances in which all of this material would be used that way, the existence of large stocks of weapon-grade HEU and plutonium that are not covered by an obligation not to use it in weapons presents a serious challenge for the future nuclear disarmament efforts.

One way to address this challenge is to place this material, often referred to as 'excess material', under international safeguards. Indeed, the action plan adopted by the 2010 Non-Proliferation Treaty (NPT) Review Conference explicitly called on nuclear weapon States to declare all fissile material designated as no longer required for military purposes and to place this material under International Atomic Energy Agency (IAEA) or other relevant international verification.[3] This approach has also been discussed in the context of a Fissile Material Cut-off Treaty (FMCT), where it was suggested that the excess material could be "transferred to the civilian or non-proscribed military domain".[4]

While the main challenge of addressing the issue of excess materials is undoubtedly political, there are practical and technical dimensions of the problem as well. Disposition of weapon-origin fissile materials is a complex undertaking that could be associated with a considerable expense and increased nuclear security risks. In addition, most of the material that has been declared excess or could be declared as such in the future is still in weapons, weapon components or in a form that retains classified attributes. The need to protect sensitive information about weapons and weapon-related materials can add another level of complexity to the task of moving excess material to the civilian domain. This complexity in itself does not have to be an obstacle for practical steps towards nuclear disarmament, whether it is designation of additional material as excess for military purposes or dismantlement of nuclear weapons. However, the perceived complexity of disarmament verification arrangements definitely narrows the space for political initiatives in this area.

It is possible, however, to design an arrangement that would substantially simplify the process of dealing with excess military materials or dismantled weapons by eliminating the need to have access to classified

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[1] Hans M. Kristensen and Matt Korda, "Status of World Nuclear Forces", Federation of American Scientists, July 2019, https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/.

[2] Warheads in the 'military stockpile' are defined as warheads in the custody of the military and earmarked for use by military forces. An additional 4,560 warheads are estimated to be awaiting dismantlement; ibid.

[3] 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, document NPT/CONF.2010/50 (Vol. I), 2010, action 16, http://www.un.org/ga/search/view_doc.asp?symbol=NPT/CONF.2010/50%20(VOL.I).

[4] General Assembly, UN document A/70/81, 7 May 2015, para. 25.

information about weapons or materials. The arrangement, described in this report, will be referred to as 'contain and dispose'. It assumes that when the excess materials or weapons designated for elimination are placed in a storage facility, no measurements are taken of the materials or individual items. Instead, the host State declares the total amount of fissile materials contained in the facility. Once the material is placed in containment, it cannot be removed from there except when it is sent to disposition or transferred to the civilian domain. At that point the material would not have any sensitive attributes, so the amount of material leaving the containment facility can be accurately measured. At the end of the process, the amount of material removed from the facility should match the amount in the initial declaration. Arranged this way, the verification procedures would never require access to classified material or items (such as weapons or weapon components) or to the processes of weapon dismantlement or conversion of material into unclassified forms.

The contain and dispose arrangement would allow nuclear-armed States to place the fissile materials that they declare excess to their military needs under a verification regime that would ensure that the materials are not returned to the weapons programme. It could also be used in scenarios in which nuclear-armed States agree to dismantle their nuclear weapons under international verification. Since the verification procedures are designed to never deal with classified or proliferation-sensitive information, non-nuclear weapon States could participate in the verification process without restrictions.

Importantly, the contain and dispose approach would not require significant adjustments of the existing fissile material disposition plans and in most cases would not impose an additional financial or logistical burden on the implementing States. The verification procedures would not be particularly intrusive since they are largely limited to monitoring of the perimeter of the containment facilities and conducting measurements on fissile materials in unclassified forms. Moreover, implementation of perimeter monitoring would provide an important additional benefit as it could help the participating States to establish a point of contact for improving their nuclear security practices.

The proposed arrangement could be implemented in a variety of ways. It could be applied to the existing excess fissile material elimination programmes in the Russian Federation and the United States or expanded to include additional material in these programmes. It could be implemented by any State voluntarily or as part of a bilateral or multilateral agreement. It should be possible to implement this arrangement on a small scale and subsequently expand it to a larger programme. Any of these steps would demonstrate the commitment of nuclear-armed States to disarmament and help strengthen the nuclear non-proliferation regime.

The report is arranged as follows. The first section describes the challenges of securing and eliminating the existing stocks of weapon-origin fissile materials. The next section describes the key elements of the proposed approach to excess material and weapon dismantlement. The following two sections outline how the arrangement would be practically implemented and briefly describe its nuclear security benefits. Appendix A contains information about fissile material inventories of nuclear-armed States and their nuclear security arrangements. Appendices B and C describe past excess material declarations and excess material elimination programmes respectively. Appendix D provides an illustration of the non-nuclear template arrangement.

THE CHALLENGE OF ELIMINATING FISSILE MATERIALS AND WEAPONS

As of 2019, the global stock of nuclear-usable materials is estimated to include 1,200 tonnes of HEU and about 530 tonnes of separated plutonium.[5] Most of this material was produced during the Cold War and while some material has been produced and used in civilian applications, a significant fraction of the existing stock was produced by military programmes.

There has been some progress in limiting the production of fissile materials and reducing the existing stocks. Four of the nine nuclear-armed States—France, the Russian Federation, the United Kingdom and the United States—joined a moratorium on the production of fissile materials for weapons. China is believed to have ended production for weapon purposes as well.[6] A very large amount of weapon-related material produced during the Cold War has been eliminated or disposed of. The Russian Federation and the United States converted more than 650 tonnes of HEU into low-enriched uranium (LEU) that was used to fuel civilian power reactors. About 240 tonnes of weapon-usable material is covered by various commitments not to use it in weapons.[7] More than half of the separated plutonium—about 300 tonnes—is the material produced by civilian programmes that is unlikely to be used for military purposes.

Despite early progress in eliminating excess fissile materials, the process has considerably slowed down in recent years. No material has been declared excess to military purposes since 2005. One of the key excess material disposition programmes, the US–Russian agreement that committed each State to eliminate 34 tonnes of plutonium, came to an end amid disagreements about the future of the programme and the deterioration of the relations between the two States. Production of fissile materials for weapons continues in the Democratic People's Republic of Korea, India, Israel, and Pakistan.

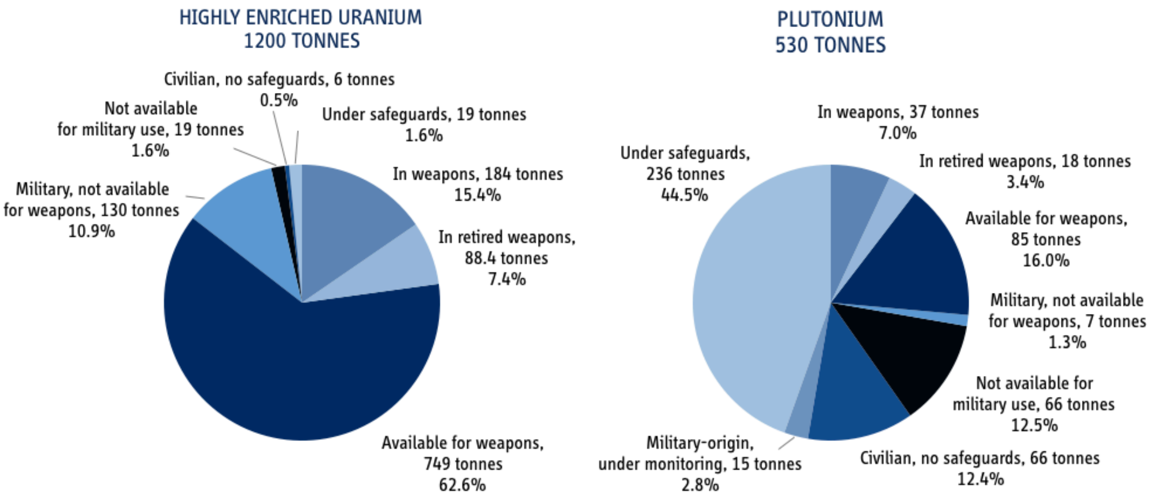

Figure 1. Global inventory of weapon-usable fissile materials by category

5 'Fissile material' is a material that can be used to manufacture a nuclear explosive device. The two most relevant materials are highly enriched uranium (HEU), which contains more than 20 per cent of the isotope uranium-235, and plutonium. This estimate does not include irradiated material. See appendix A for details. With irradiated material taken into account, the global inventory was estimated to include 1,340 tonnes of HEU and 520 tonnes of separated plutonium as of the end of 2017; Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

6 International Panel on Fissile Materials, "Global Fissile Material Report 2015", 2015, http://ipfmlibrary.org/ipfm15.pdf; Zhang Hui, "China's Fissile Material Production and Stockpile", International Panel on Fissile Materials, January 2018, http://fissilematerials.org/library/rr17.pdf.

7 This includes about 88 tonnes of plutonium declared excess by the Russian Federation and the United States and approximately 150 tonnes of HEU was produced or reserved for use in naval reactors. See appendix B for details.

Production of weapon-usable materials for civilian and non-weapon military programmes continues as well.

From the point of view of availability for weapons, the existing stocks of weapon-usable fissile materials can be divided into several categories, as shown on Figure 1 (national data are presented in Table 1). As can be seen from the figure, about 15 per cent of all HEU and 7 per cent of all separated plutonium are already in nuclear weapons that are part of military stockpile.[8] These weapons are in the custody of the

	Total stock	In weapons	In retired weapons	Available for weapons	Military, not available for weapons	Not available for military use	Civilian, no safeguards	Military-origin, under monitoring	Under safeguards
HIGHLY ENRICHED URANIUM									
Russian Federation	646	90	40	510			6		
United States	463	76	48	195	125	19			
United Kingdom	20	3.6	0.4	15	0.7				0.4
France	29	6		20					3.7
China	14	5.2		8.8					
India	4.4	0			4.4				
Pakistan	3.6	3.6		0					
Israel	0.3			0.3					
DPRK	0.5			0.5					
Non-weapon States	15								15
TOTAL	1200	184	88	749	130	19	6	0	19
PLUTONIUM									
Russian Federation	189	18	8	62		25	61	15	
United States	87.8	15	10	13.4		41.4	5		3
United Kingdom	119.2	0.72	0.08	2.4					116
France	73	1.2		4.8					67
China	2.9	1		1.9			0.0409		
India	7.87	0.57			6.9				0.4
Pakistan	0.31	0.31							
Israel	0.92	0.5		0.42					
DPRK	0.04			0.04					
Non-weapon States	49.6								49.6
TOTAL	531	37	18	85	7	66	66	15	236

Table 1. National stocks of unirradiated HEU and separatedplutonium by category (see appendix A for details)

[8] If one excludes the 300 tonnes of separated plutonium produced by civilian programmes, the fraction of plutonium contained in weapons is about 16 per cent.

military. The next category is the material in weapons that have been retired from the military arsenal and are awaiting dismantlement. This material retains all classified attributes and, once recovered during dismantlement, would be available for the use in new weapons. The last category of material available for weapons use is the material that is not in assembled weapons, but that is not covered by any obligations not to use it for weapon purposes. The HEU in this category accounts for more than 60 per cent of global stocks of that material; the share of plutonium—about 16 per cent—is smaller, but the amount of plutonium in this category is more than double that contained in weapons in military arsenals. Some material in this category is stored in weapon components, which means that it retains classified attributes just as the material in assembled weapons. The material that is stored in bulk form may retain some classified attributes, such as isotopic composition, as well.

Fissile materials in all other categories are not available for weapon purposes, although the extent of obligations attached to the material varies. A substantial amount of plutonium produced by civilian programmes—about 236 tonnes—is currently under IAEA and/or Euratom safeguards, which are administered with the specific purpose of preventing the use of the safeguarded material for military purposes. In addition, about 15 tonnes of plutonium that the Russian Federation produced at its defence production facilities is under monitoring in accordance with the terms of a US–Russian agreement. These arrangements provide the strongest guarantee against returning the material to the weapons domain.

Another category is unsafeguarded civilian material, which includes about 66 tonnes of separated plutonium as well as about 6 tonnes of HEU that will not be used for weapons purposes. With this material, the restriction on its use for weapons is largely a practical choice. As long as States have sufficient amount of unrestricted material, they are highly unlikely to use their civilian stock for weapons. Also, civilian material does not have sensitive attributes, so placing it under safeguards or monitoring would not present any difficulties.

Two other categories—material not available for military uses and military material not available for weapons—are covered almost exclusively by political commitments. The first category includes, for example, weapon-origin plutonium that was declared excess. The military material not available for weapons is mostly the HEU that was produced or reserved for use in military naval reactors. Although there is no reason to expect that any State that owns materials in these categories would not honour its political commitments, it should be noted that there is no mechanism in place that would verify that these materials are not used for military or weapon purposes. Also, unlike civilian material, the material in these categories would normally retain its classified attributes, so placing it under safeguards or monitoring would present a challenge.[9]

In total, about 1,000 tonnes of HEU and about 140 tonnes of plutonium are either in weapons or not covered by a political obligation not to use this material for weapon purposes. Additionally, about 150 tonnes of HEU and 73 tonnes of plutonium are covered by political obligations not to use it in weapons but have not been submitted to monitoring that would confirm that it cannot be returned to weapon use. This suggests that there is enough fissile material in the military domain to produce more than 40,000 nuclear weapons in addition to the 9,330 that are estimated to be in military arsenals today.

The existence of the large amount of material that can be used to produce nuclear weapons presents a serious challenge to efforts to advance nuclear disarmament. The importance of eliminating the existing stocks of weapon-usable fissile materials or placing them under safeguards has been emphasized during the NPT Review process. The action plan adopted by the 2010 NPT Review Conference explicitly called on nuclear-weapon States to declare all fissile material designated as no longer required for military purposes and to place this material under IAEA or other relevant international verification.[10] The issue of existing stocks of fissile materials and their availability for weapons use is also one of the most

[9] Indeed, some of the material in these categories may still be in weapons that are awaiting dismantlement or in weapon components.

[10] 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, document NPT/CONF.2010/50 (Vol. I), 2010, action 16.

contentious issues that emerged during the discussions of an FMCT. Many States support measures that would require nuclear-armed States to make a commitment to transfer "to the civilian or non-proscribed military domain" the materials that are no longer required for weapon purposes.[11]

While the main obstacle on the way to addressing the issue of excess materials is the lack of political commitment, the practical challenges should not be underestimated. First of all, a fissile material disposition programme can be a technically challenging task with considerable cost. For example, the cost of various options that the United States considered for its programme to dispose of 34 tonnes of excess plutonium ranged from $16 billion to $58 billion. It was estimated that the disposition of all 34 tonnes of the material would be completed in 2046–2060, depending on the option.[12] In the case of HEU, a disposition programme can, in fact, be commercially beneficial since the uranium could be easily used in fuel for power reactors. However, the rate of disposition is limited by the capacity of the existing facilities that convert the material into usable form. Construction of new facilities might be possible in principle, but it would entail a considerable additional expense.[13]

Another potential bottleneck in the process is the rate of dismantlement of weapons that can be practically achieved without sacrificing the safety of the process. During the 1990s, the United States and the Russian Federation demonstrated that they can dismantle as many as 1,300–1,500 warheads a year and probably considerably more. However, the nuclear complexes of both States have been downsized since then, slowing the dismantlement rate. Nevertheless, it is still at the level of 200–300 warheads a year in the United States and as high as 500 warheads a year in the Russian Federation.[14]

There is also a problem of 'demand' for the disposition material—the capacity of the civilian sector or disposition facilities to accept the material. For example, in the US–Russian Plutonium Management and Disposition Agreement (PMDA) and in the US–Russian HEU–LEU agreement the material disposition rate and, accordingly, the rate at which the material becomes available for monitoring were chosen to match the consumption of plutonium or HEU covered by the programmes.

It might be possible to overcome the limits imposed by the rate at which the material can be disposed of or used in civilian applications by creating an interim step of the process, in which fissile materials would be converted to a form suitable for long-term safeguarded storage. This approach, however, does not fully address an important limiting factor—the capacity of conversion facilities. Also, conversion is usually designed to be part of a larger material disposition programme as the specific process employed would depend on the choice of the disposition path for the material. Conversion of weapon-origin material into a form suitable for monitoring or safeguards, but that may require further conversion before it is sent to disposition, would add an extra step to the disposition programme, increasing its complexity and cost.[15]

[11] General Assembly, UN document A/70/81, 7 May 2015, para. 25.

[12] US Department of Energy, "Report of the Plutonium Disposition Working Group: Analysis of Surplus Weapon-Grade Plutonium Disposition Options", April 2014, pp. 27–28, http://nnsa.energy.gov/sites/default/files/nnsa/04-14-inlinefiles/SurplusPuDispositionOptions.pdf.

[13] For example, doubling down the HEU disposition rate in the US–Russian HEU–LEU programme was estimated to require up to $1.6 billion of investment and as long as 8–10 years to implement; Laura Holgate, "Accelerating the Blend-down of Russian Highly Enriched Uranium", Presentation at the 46th Annual Meeting of the Institute of Nuclear Materials Management, 2005.

[14] US Department of Defense, "Stockpile Numbers. End of Fiscal Years 1962–2017", 2018, http://open.defense.gov/Portals/23/Documents/frddwg/2017_Tables_UNCLASS.pdf. The Russian Federation is believed to remanufacture about 200 weapons annually, so the net dismantlement rate is about 300 weapons a year; International Panel on Fissile Materials, "Global Fissile Material Report 2011: Nuclear Weapon and Fissile Material Stockpiles and Production", 2011, p. 5, http://ipfmlibrary.org/gfmr11.pdf.

[15] It should be noted that the Russian Federation included this step in its plutonium disposition programme. As it was expected that the plutonium placed in the Mayak Fissile Material Storage Facility would be subject to monitoring, the Russian Federation converted the plutonium to be emplaced there into 2 kg metal spheres.

There is a nuclear security aspect of the issue as well. Any additional operation with fissile materials, especially if it involves transfer of materials between different facilities, inevitably increases the risk of an accident or loss.[16] Even though this risk can be justified in some circumstances, it is rarely warranted in those cases when a large amount of material has already been placed in secure storage as would be the case with disposition of weapon-origin fissile materials.

Given the difficulties of creating a disposition process that would absorb large quantities of weapon-origin fissile materials, it can be expected that future disposition programmes would probably follow the approach that the United States and the Russian Federation have adopted. This means that the material declared excess would be stored in its initial form, almost certainly with classified attributes intact, and would be converted to unclassified form and made available for monitoring and verification at the rate determined by the ability of the disposition programme to accept that material. In the HEU–LEU deal it was the rate the United States was ready to accept uranium for its power reactors without disrupting the market. In the PMDA agreement it was the capacity of power reactors to burn plutonium. In the current US plutonium disposition programme it would be the capacity of the geologic repository to process the material. The implementation of all these programmes is in the order of 20–25 years. During this period the material designated for disposition would be technically available for use in nuclear weapons, even if it is covered by a political obligation not to use the material for weapon purposes.

One way to ensure that the excess material cannot be returned to the military domain as it awaits disposition would be placing the material under safeguards while it is still in classified form or retains classified attributes. A version of this approach was adopted by the Trilateral Initiative, a joint project implemented by the IAEA, the Russian Federation, and the United States between 1996 and 2002. The Trilateral Initiative specifically sought to develop a procedure that would allow the IAEA to accept safeguards materials released from defence programmes.[17] The technical approach developed by the Trilateral Initiative allowed the determination of weapon-grade quality of the material placed under safeguards and confirmation that the mass of material accepted for safeguards exceeded a certain threshold. Since the programme assumed that the material placed under safeguards would retain classified attributes, it adopted a procedure for protecting sensitive information. Attribute measurements were combined with an information barrier, which masked the information collected during the measurement and presents the result as a 'pass/fail' output.

The issue of protecting sensitive information has been extensively studied as part of the efforts to develop approaches to verified nuclear disarmament. It becomes especially important in the disarmament scenarios where the items to be submitted to inspection are nuclear weapons that are entering a dismantlement process. Developing technologies to support verified dismantlement of nuclear weapons has been a subject of extensive research.[18] The approach to nuclear disarmament verification based on the dismantlement of weapons became the focus of a number of prominent international cooperative projects, such as the UK–Norway Initiative, the International Partnership for

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[16] For example, the US–Russian HEU–LEU programme involved transfers of large amounts of weapon-grade material among several facilities; Pavel Podvig, *Consolidating Fissile Materials in Russia's Nuclear Complex*, International Panel on Fissile Materials, 2009, p. 25.

[17] Thomas E. Shea, "Weapon-Origin Fissile Material: The Trilateral Initiative", in *Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty*, International Panel on Fissile Materials, 2008, http://ipfmlibrary.org/gfmr08.pdf. See appendix C for a more detailed discussion of the programme.

[18] For an overview of these efforts, see Nicholas Zarimpas (ed.), Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions, 2003; National Academy of Sciences, Monitoring Nuclear Weapons and Nuclear-Explosive Materials, 2005; Anatoly Dyakov, "Nuclear Warheads and Weapons-Grade Materials", in Alexei Arbatov, Vladimir Dvorkin, and Natalia Bubnova (eds), Nuclear Reset: Arms Reductions and Nonproliferation, Carnegie Moscow Center, 2012, http://armscontrol.ru/pubs/en/Diakov-NucWarheads.pdf; Jie Yan and Alexander Glaser, "Nuclear Warhead Verification: A Review of Attribute and Template Systems", Science & Global Security, vol. 23, no. 3, 2015, pp. 157–170.

Nuclear Disarmament Verification (IPNDV) and the QUAD Partnership.[19] For the most part, these projects include a version of the approach based on attribute measurements protected by an information barrier to confirm that the object that enters the dismantlement process is indeed a nuclear weapon.

The key advantage offered by the approach based on measurements of attributes, such as mass or isotopic composition of the material, is that the measurement can provide a confirmation that the amount of material that has been placed in storage exceeds a certain agreed limit and of its weapon-related nature. This approach, however, has several limitations that call into question its applicability for international verification.

First, and most importantly, the information barrier has to be trusted by the parties that are involved in the inspection. The host party might be concerned that the information barrier system records and transmits raw measurement data that are supposed to be protected. The inspecting party would be concerned that the system is equipped with a hidden switch that produces a false output when activated, for example, by indicating the presence of fissile material in an empty container. This issue can be partially addressed by various measures, but to date no State has been willing to expose a classified item to an information barrier system that was not built under its full control. The PMDA explicitly rejected the use of information barriers.[20]

Another serious challenge facing a system that would be designed to place fissile materials in classified forms under safeguards is the difficulty of using the attribute measurement method in the case of HEU. Plutonium is a fairly strong source of neutron and gamma radiation that can be used to measure a range of attributes of plutonium-containing objects. Uranium, on the other hand, is a relatively weak radiation source, which makes it virtually impossible to use passive measurements to measure attributes of HEU-containing items.[21] Systems that use active interrogation techniques to measure the presence and mass of uranium have been developed, but they have not yet been integrated with an information barrier.[22] Designing a trusted information barrier in this case is likely to be significantly more difficult than in the case of passive measurements used to detect plutonium.

Finally, even if an attribute measurement system with a trusted information barrier system is developed, practical application of this technology to the task of confirming the amount of fissile material placed under safeguards could leave a significant uncertainty about the amount of safeguarded material. By design, the method would only be able to confirm that that amount exceeds a certain agreed limit.[23] The actual amount of the material placed under safeguards could be larger, perhaps considerably so. However, if the owner wanted to take credit for the full amount of the material placed under safeguards,

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19 "United Kingdom–Norway Initiative", http://ukni.info/; International Partnership for Nuclear Disarmament Verification, "Phase I Summary Report: Creating the Verification Building Blocks for Future Nuclear Disarmament", November 2017, https://www.ipndv.org/wp-content/uploads/2017/12/IPNDV-Phase-I-Summary-Report_Final.pdf; Lars van Dassen, "The 'QUAD' Nuclear Verification Partnership and the LETTERPRESS Exercise, October 2017", presentation at Wilton Park, January 2018.

20 "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation (as Amended by 2010 Protocol)", 13 April 2010, annex on monitoring and inspections, Section II, para. 15, http://ipfmlibrary.org/PMDA2010.pdf.

21 Oleg Bukharin, "Russian and US Technology Development in Support of Nuclear Warhead and Material Transparency Initiatives", in Nicholas Zarimpas (ed.), *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, 2003, pp. 168–71.

22 Dan Archer, "Third Generation Attribute Measurement System", *Proceedings of the Institute of Nuclear Materials Management Annual Meeting*, 2012, p. 4; Jie Yan and Alexander Glaser, "Nuclear Warhead Verification: A Review of Attribute and Template Systems", *Science & Global Security*, vol. 23, no. 3, 2015, pp. 157–170.

23 For example, in the AVNG system that was developed as a result of the work that was initiated by the Trilateral Initiative, it was designed to confirm that the amount of plutonium in a container exceeds 2 kg; Sergey Kondratov et al., "AVNG System Demonstration", *Proceedings of the 51 St Annual Meeting of the Institute of Nuclear Material Management*, 2010, https://www.nti.org/media/pdfs/LA-UR-10-02620_AVNG_System_Demonstration.pdf.

it would be difficult to verify that claim. For example, containers used to emplace material in the Mayak Fissile Material Storage Facility in the Russian Federation can hold two 2 kg plutonium spheres.[24] If the attribute measurement system can only certify that the amount of plutonium in the container exceeds 2 kg, about half of the material emplaced in storage would be unaccounted for. This may not be a problem in a cooperative environment, but it could raise concerns in some scenarios.

The programmes that explored practical verification arrangements significantly advanced the understanding of the expert community of the challenges of verifying nuclear disarmament and developed technical approaches to some stages of the process. At the same time, these approaches demonstrated that a disarmament verification process that handles nuclear weapons or fissile materials in classified forms would be a complex undertaking that would create a significant burden in future disarmament arrangements. In addition, some of the verification problems, especially those related to protecting sensitive information, probably do not have satisfactory technical solutions. Even though relevant technologies exist, it has not yet been demonstrated that a system can be built that all participants of the verification process would trust.

24 Richard T. Kouzes, "A Dictionary for Transparency", Pacific Northwest National Laboratory, 2001), p. 9, https://www.pnl.gov/main/publications/external/technical_reports/PNNL-13723.pdf; "Хранилище делящихся материалов в Челябинске-65", http://nuclearno.ru/text.asp?2531.

THE 'CONTAIN AND DISPOSE' ARRANGEMENT

In light of the limitations of the approaches based on handling weapons and materials in classified forms, this section presents an alternative arrangement, which does not require access to classified or otherwise sensitive information about fissile materials or weapons. This arrangement, referred to as 'contain and dispose', instead relies on placing the excess material or weapons designated for elimination in a containment facility, from which the material could only be removed for disposition. The amount of material in the facility will be declared, but the correctness of the declaration will be verified at the time when the material enters the disposition process.[25]

EXCESS FISSILE MATERIALS

The verification arrangement for excess material would work as follows. After the material is designated for disposal it is placed 'as is' in a certain enclosed containment area. The host State then makes a declaration that specifies the exact amount of material placed there and accepts an obligation not to use that material for weapon purposes. No measurements of material attributes are taken at the time it is placed in storage, so there is no need to implement measures to protect its classified attributes. In addition to storage, the containment area will include conversion facilities to prepare the material for disposition. The conversion removes classified attributes of the material, so the material that is leaving the containment area for disposition can be accurately measured and accounted for. The record of the amount of material remaining in the containment the area is updated accordingly. Once the records show that all material included in the initial declaration has been removed, the containment area is inspected to verify that no material remains there, to confirm the correctness of the initial declaration. Designed this way, the material disposition arrangements never require access to any classified or otherwise sensitive information about the material.

For this arrangement to work, it must include measures to ensure that no fissile material enters or leaves the storage area once the initial placement is completed and the declaration of the amount of material in storage has been made. The only permitted removals would be those that send the material to disposition. This requires establishing control over the perimeter of the containment area and developing appropriate verification procedures.

Figure 2 shows the general outline of the contain and dispose scheme for excess material. The storage facility and the material conversion facility, which do not have to be co-located, together constitute a single containment area. Transfers between these two facilities are not subject to inspections as long as measures are taken to ensure that a transport leaving one site arrives to the other and is not diverted or tampered with while in transit. The chain of custody technology required for that has been the subject of intensive research and has been successfully used in the course of the implementation of the US–

[25] This approach is based on the concept of deferred verification, which was developed to support verified declarations of fissile material stocks in the context of FMCT and the broader process of nuclear disarmament. Pavel Podvig and Joseph Rodgers, *Deferred Verification: Verifiable Declarations of Fissile Material Stocks*, UNIDIR, 2017, http://www.unidir.ch/files/publications/pdfs/deferred-verification-verifiable-declarations-of-fissile-material-stocks-en-694.pdf. The pilot projects considered in that report would be similar to the containment facilities in the contain and dispose arrangement. Important elements of this arrangement were also explored as part of the "monitored transfer zone" concept in Tamara Patton and Alexander Glaser, "Deferred Verification: The Role of New Verification Technologies and Approaches", *The Nonproliferation Review*, vol. 26, no. 3–4, 2019, https://doi.org/10.1080/10736700.2019.1629072. Approaches to warhead dismantlement based on perimeter monitoring were considered in the 1997 study performed by US Department of Energy. The options considered in the study, however, assumed that nuclear warheads and components entering or leaving the perimeter would be subject to radiation measurements. US Department of Energy, Office of Arms Control and Nonproliferation, "Transparency and Verification Options: An Initial Analysis of Approaches for Monitoring Warhead Dismantlement", 19 May 1997, https://fas.org/sgp/othergov/doe/dis/transparency.pdf

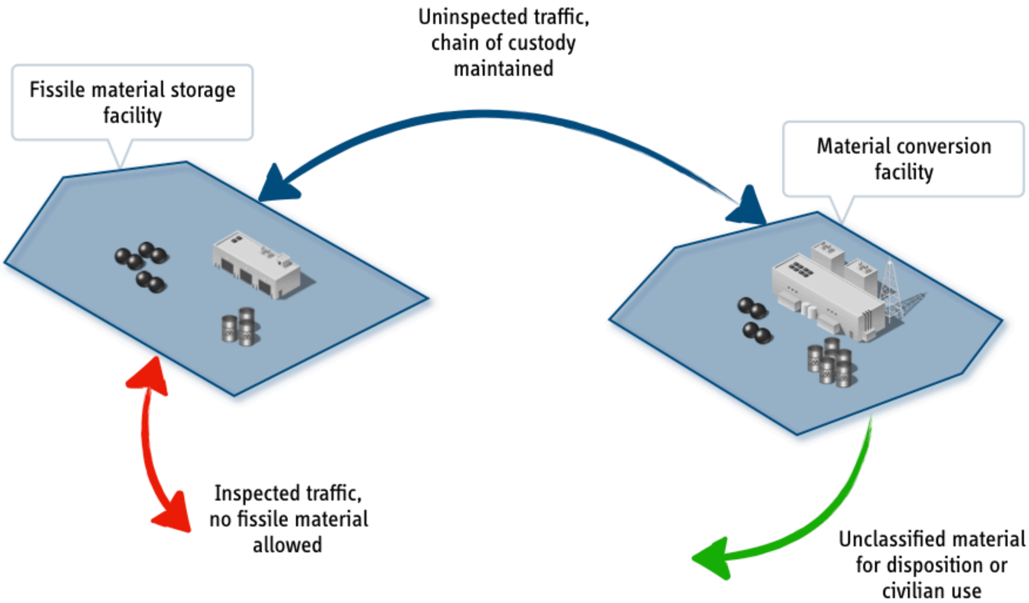

Figure 2. Outline of the contain and dispose arrangement for disposal of excess fissile materials

Russian HEU–LEU deal, which involved transfers of about 500 tonnes of HEU in different forms between facilities hundreds of kilometres apart.[26]

The perimeter control is established once the material placed in storage and the amount of material is declared. That information could still be potentially sensitive. For example, if the storage contains a known number of nuclear warheads, the mass of the material would reveal the average amount of material in a warhead. This information is often considered classified. The host may also want to protect information about the isotopic composition of the material declared excess. To protect classified information, the host could place in storage a certain amount of 'blend stock'—the material that would be used in the conversion process—to mask sensitive attributes. The amount of blend stock that can be added to the storage would have to be limited, so it would not constitute more than about 10-15 per cent of the material in storage.[27] This should not present any practical problems, especially since the actual mass of the added material need not to be revealed.

Once the perimeter is closed, there would be two types of traffic in and out of the storage area. First, transports that go to the conversion facility are tagged and sealed, but otherwise are not subjected to any examination. All other transports would be inspected to ensure that they do not carry fissile materials. Similar measures are implemented at the conversion facility, the only difference being that the host is allowed to remove fissile material that has been prepared for final disposal or for use in civilian applications. This material would not have any classified attributes and it will be available for detailed measurements in order to update the record of the amount of material that remains in storage. The material that leaves the conversion facility this way is then placed under safeguards, such as the ones administered by the IAEA, to ensure that it cannot be used for any military purpose.

[26] The actual mass of material that was transferred was considerably larger as at different points of the process the disposition HEU was converted to oxide and hexafluoride (and later to LEU). See appendix C for details. For a collection of resources, see International Partnership for Nuclear Disarmament, "Chain of Custody, Tags, Seals & Tamper-Indicating Enclosures", 2019, https://www.ipndv.org/resource_cat/chain-custody-tags-seals-tamper-indicating-enclosures/.

[27] This is the approach that was adopted in the US–Russian Plutonium Management and Disposition Agreement. The mass of blend stock material was not to exceed 12 per cent of the 34 tonnes of disposition plutonium.

NUCLEAR WEAPONS

The monitored perimeter arrangement could be adapted to the scenario in which excess fissile materials are released from nuclear weapons that are being eliminated under a formal disarmament agreement. In this case, the storage area would contain nuclear weapons that are removed from their launchers. In addition, the perimeter of the containment area would have to be extended to encompass a weapon dismantlement facility (Figure 3).

The process of eliminating the weapons and the materials they contain would begin with removing the agreed number of weapons from their deployment sites and placing them in a storage facility. Once this is done, the parties establish the perimeter around the storage site, the weapon dismantlement and material conversion facilities, which together constitute the containment area. In the process of closing the perimeter the host is allowed to add a certain amount of fissile materials, not to exceed about 10-15 per cent of the total mass, to the containment area in order to protect sensitive information about weapons. The actual amount or the composition of the blend stock material need not be disclosed. Once the perimeter is closed, the host declares the exact amount of fissile materials, plutonium and HEU, that has been placed in storage (which includes the amount of material in weapons plus the blend stock).

Dismantlement of nuclear weapons is carried out inside the containment area without monitoring. The materials extracted from weapons are then prepared for release into the open segment at the material conversion facility. At that point, the material would be accurately accounted for, so at the end of the weapons elimination process the amount of fissile material removed from the perimeter should match

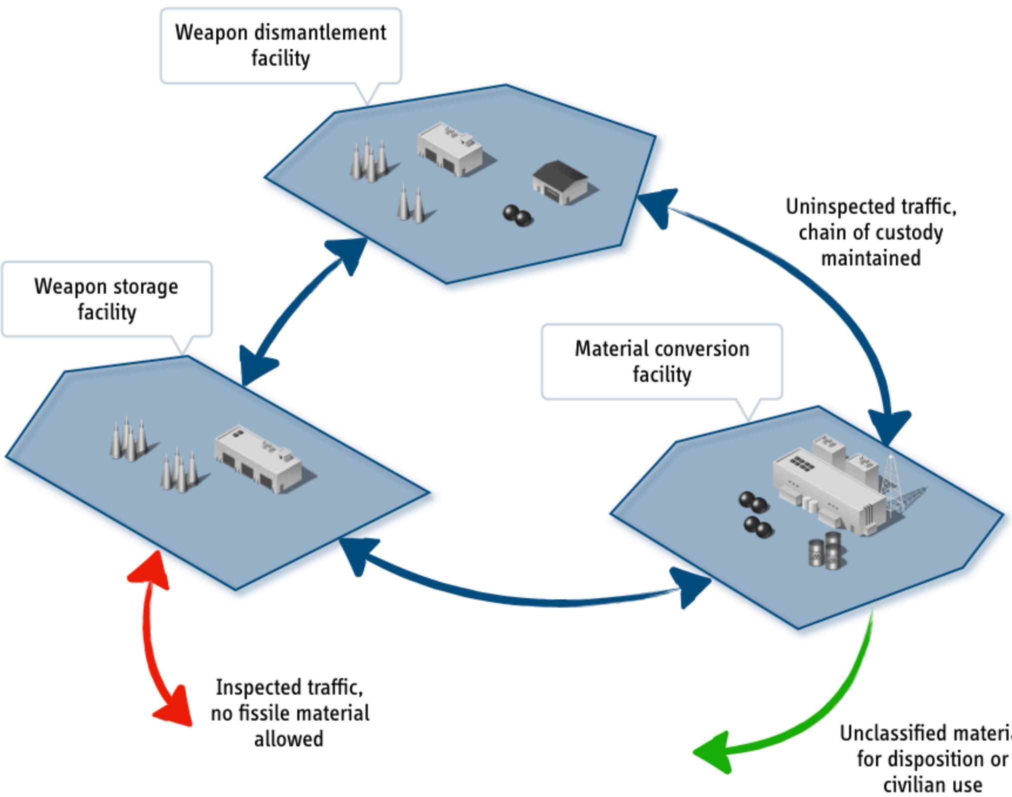

Figure 3. Outline of the contain and dispose arrangement for nuclear warhead dismantlement

the initial declaration. The inspecting party would then conduct an inspection to confirm that no materials remain in the containment area.

Because it does not require monitoring of the actual dismantlement process, the contain and dispose approach offers a significant advantage over a number of nuclear weapon dismantlement schemes. Furthermore, it does not involve measurements of nuclear weapons or other items or materials containing classified information. This stands in contrast with most arrangements considered so far, which assume that inspectors will have some access to weapons and materials and, in most cases, to the dismantlement process.[28] This point is illustrated on Figure 4, which shows the key steps in the weapon dismantlement as identified by the IPNDV and the scope of various projects that explored various elements of the process. The diagram shows that in the contain and dispose arrangement all of the dismantlement activity takes place in the containment area and therefore need not be monitored. This would greatly simplify the disarmament verification arrangements.

The key vulnerability of the contain and dispose approach is that it does not include a procedure that would confirm that the items being placed in storage are nuclear warheads or indeed whether these items contain any fissile material at all. This means that the host party could substitute 'fake warheads' for the real ones. This vulnerability, however, is common to all weapons dismantlement arrangements and none of the existing disarmament verification projects attempted to address it (steps 1–3 in Figure 4). Although a number of ways to address this problem have been suggested, none appears to offer a solution that would resist a determined evasion effort.[29] For example, if all warheads are replaced with objects containing only a small amount of fissile material, the substitution would be impossible to detect with either attribute measurements (assuming that the amount is sufficient to pass the information barrier) or by the template method (since all of the objects would be identical). The contain and dispose arrangement, in fact, may provide a more reliable way to counter the threat of substitution, since it requires the host party to verifiably demonstrate that the declared amount of fissile materials has been eliminated.

One of the most challenging elements of the contain and dispose arrangement for warheads dismantlement is related to the need to establish a perimeter around a weapon dismantlement facility. This might be especially difficult in those cases when the facility is also involved in assembly or warhead refurbishment work. However, an analysis of potential monitored dismantlement arrangements performed by the US Department of Energy suggested that it would be possible to separate a portion of the dismantlement facilities at the Pantex Plant and the Y-12 Complex for these purposes.[30] Indeed, the analysis concluded that, if appropriate measures are taken, it would be possible to allow inspectors to monitor the actual dismantlement process. This indicates that it should also be possible to make the necessary perimeter control arrangements.

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[28] Theodore B. Taylor, "Verified Elimination of Nuclear Warheads", *Science & Global Security*, vol. 1, no. 1–2, 1989, pp. 1–26; Steve Fetter et al., "Detecting Nuclear Warheads", *Science & Global Security*, vol. 1, no. 3–4, 1990, pp. 225–253; Sidney Drell, Chairman, JASON programme, MITRE Corporation, "Verification of Dismantlement of Nuclear Warheads and Controls on Nuclear Materials", January 1993, https://fas.org/irp/agency/dod/jason/dismantle.pdf; US Department of Energy, Office of Arms Control and Nonproliferation, "Transparency and Verification Options: An Initial Analysis of Approaches for Monitoring Warhead Dismantlement", 19 May 1997, https://fas.org/sgp/othergov/doe/dis/transparency.pdf; Nicholas Zarimpas (ed.), *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, 2003; National Academy of Sciences, *Monitoring Nuclear Weapons and Nuclear-Explosive Materials*, 2005; International Partnership for Nuclear Disarmament Verification, "Phase I Summary Report: Creating the Verification Building Blocks for Future Nuclear Disarmament", November 2017; Lars van Dassen, "The 'QUAD' Nuclear Verification Partnership and the LETTERPRESS Exercise, October 2017", presentation at Wilton Park, January 2018.

[29] For detailed discussion see Taylor, "Verified Elimination of Nuclear Warheads", pp. 15–18.

[30] "Transparency and Verification Options: An Initial Analysis of Approaches for Monitoring Warhead Dismantlement", *op. cit.*, p. 46.

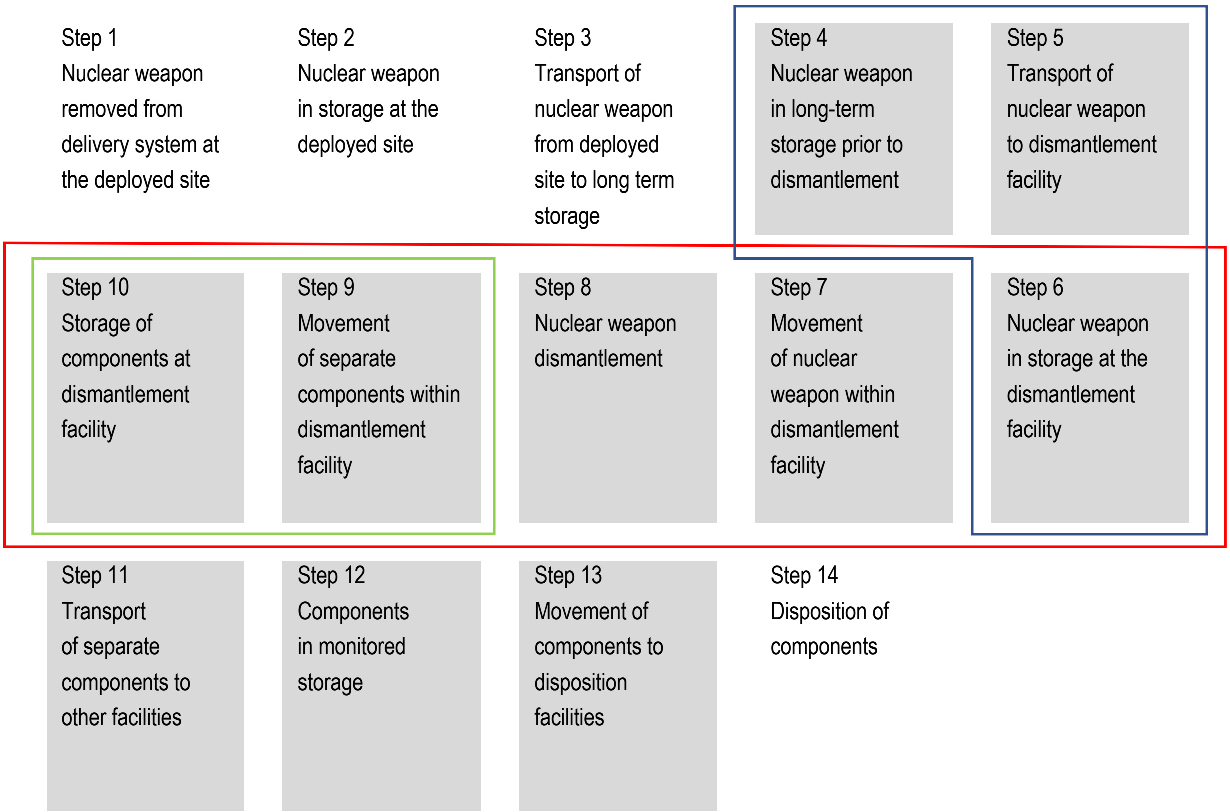

Figure 4. Key steps in the weapon dismantlement process and the scope of various disarmament verification projects[31] (Red line shows the steps included in the IPNDV Basic Dismantlement Scenario, blue is the scope of the LETTERPRESS exercise of the QUAD Partnership, and green that of the NuDiVe exercise. The UK–Norway Initiative explored steps 4 to 12 at different stages of the project. Shaded cells are the dismantlement steps that would be carried out inside the containment area and which therefore would not require access under the contain and dispose arrangement.)

PERIMETER CONTROL

One important element of the verification arrangements in the contain and dispose approach is the procedure that confirms no items containing nuclear materials are entering or leaving the containment area.

The simplest solution would be to prohibit all transfers in and out of the area, the only exception being the material that is removed for disposition or civilian use. This material would be accounted for and placed under safeguards. In practice, however, it is likely that since the facilities in the containment area will operate for a considerable period of time, a certain amount of traffic to support their operations is unavoidable. A procedure that would verify the non-nuclear nature of items brought in or removed from the containment area would thus need to be developed. Moreover, this procedure should be designed in a way that protects classified or otherwise sensitive attributes of the inspected items. For example, if the containment area includes a weapon dismantlement facility, the host might want to

[31] Adapted from International Partnership for Nuclear Disarmament Verification, "Phase I Summary Report: Creating the Verification Building Blocks for Future Nuclear Disarmament", November 2017, p. 10, https://www.ipndv.org/wp-content/uploads/2017/12/IPNDV-Phase-I-Summary-Report_Final.pdf.

protect information about non-nuclear weapon components that are released in the course of the dismantlement process.[32]

In some circumstances, verifying the non-nuclear nature of an object is a relatively simple task. For example, in the Strategic Arms Reduction Treaty (START) and New START the United States and the Russian Federation developed an agreed procedure that uses radiation measurements to confirm the non-nuclear nature of objects that can be deployed on strategic launchers. This procedure, however, makes a number of implicit assumptions, namely that a nuclear weapon contains a certain amount of plutonium. It also assumes that the inspected party does not shield the inspected object to interfere with the measurement.[33] These assumptions cannot always be made in the case of inspecting items leaving the containment area. For example, an object that leaves the storage can contain a small amount of plutonium, it could contain HEU, and the material could be heavily shielded.

In most cases, a more intrusive inspection could help address the issue. For example, if a container could be opened, a closer visual examination combined with radiation measurements could establish the absence of fissile material and shielding. A more aggressive active interrogation of containers could lower the detection threshold even in the presence of shielding. However, there are limits to this approach, especially in those cases when the objects crossing the perimeter contain classified items. In this case, a detailed visual inspection might not be an option. There are also practical limits to the intensity of active sources that can be used to examine the item, or the time available for measurements. Some of these issues have been explored as part of the effort to screen cargo coming into the United States. While researchers suggested a number of approaches, it is understood that detecting properly shielded HEU in incoming cargo still presents a serious challenge.

One way to deal with these limits would be to take advantage of the fact that the host and the inspecting party could agree on some details of the inspecting procedure. The host specifies the type of objects that would cross the perimeter. These could be, for example, storage and transport containers containing some materials or items that would be removed or added to the facility. The design of the arrangement requires these items to be non-nuclear. Once these objects are identified, the host presents a reference object for each of the types of the containers that would be moved in or out of the containment area. The inspecting party then has an opportunity to thoroughly examine each reference object to confirm its non-nuclear nature and to see what kind of materials it contains. Then the inspecting party performs radiation measurements on the reference object using one of the agreed methods. The signature obtained during these measurements becomes a "non-nuclear template"—any inspected object whose signature matches the template is considered non-nuclear.[34]

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32 It should be possible to keep the non-nuclear components extracted during the weapon dismantlement process inside the containment area. However, unless the host disposes of the non-nuclear components in a manner that removes all their sensitive attributes (for example, by shredding them), protection of information about non-nuclear items may still be an issue.

33 For an analysis of the radiation measurement procedure, see Alexander Glaser, "Ceci N'est Pas Une Bombe. Toward a Verifiable Definition of a Nuclear Weapon", presentation at the 58th Annual Meeting of the Institute of Nuclear Material Management, July 2017. To prevent the use of shielding, the treaties explicitly prohibit placing inspected objects in a container. "Protocol to the Treaty Between the United States of America and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms", April 8, 2010, annex on inspection activities, Part Five, Section VI, article 16(l).

34 One way to illustrate the non-nuclear template concept is to consider an example of geometric shapes. In this example, the host would declare that the only shapes that are crossing the perimeter are triangles (which represent non-nuclear items) and provides a reference triangle to the inspectors. The inspectors examine the reference triangle and develop a procedure that confirms that an inspected object has a triangular shape. The triangular shape becomes the template, so any triangular object is allowed to pass the perimeter. It is important that this procedure does not require disclosure of any information about prohibited (nuclear) items, which could be squares or circles. A properly designed procedure would also not require knowledge of the actual parameters of the triangles presented for an inspection, which means that the sensitive information about non-nuclear items would be protected as well.

This procedure, described in more detail in appendix D, does not rely on the knowledge of attributes of nuclear weapons or fissile materials to be stored in the containment area. Moreover, the use of a reference object allows classified or sensitive non-nuclear information to be protected. This means that it could be used in a range of other scenarios, such as verifying the absence of nuclear weapons at a storage facility that may contain conventional weapons.[35]

[35] Nuclear disarmament scenarios that would require verification of the absence of nuclear weapons are considered in Pavel Podvig, Ryan Snyder, and Wilfred Wan, "Evidence of Absence: Verifying the Removal of Nuclear Weapons", UNIDIR, 2018, http://www.unidir.org/files/publications/pdfs/evidence-of-absence-verifying-the-removal-of-nuclear-weapons-en-722.pdf.

POTENTIAL PRACTICAL IMPLEMENTATION

Any disposition arrangement should start with a State designating a certain amount of material as excess for military purposes and making a commitment to eliminate that material or use it in civilian applications. As detailed in appendix B, three States have made these commitments so far—the United States, the Russian Federation, and the United Kingdom. The United Kingdom has already transferred all its excess material under safeguards, and the Russian Federation has completed elimination of its HEU that it declared excess to military purposes. The United States has almost completed eliminating the HEU that was covered by an obligation not to use it in military applications. The remaining excess HEU is the material reserved for use in naval reactors and in tritium production. The plutonium stocks in the Russian Federation and the United States today constitute the largest category of excess fissile materials—about 40 tonnes of material in each side.

In addition to the material already declared excess, about 840 tonnes of HEU and more than 100 tonnes of plutonium are not in weapons stockpiles. This material is de facto excess for weapon requirements and could conceivably be declared excess. Declaring additional excess material could be done in variety of ways. It could be a unilateral voluntary political commitment, potentially reciprocated by other States. It could also be a result of a formal bilateral or multilateral agreement that would specify conditions of future use of the material. It is also possible that future nuclear disarmament agreements include an obligation to eliminate fissile materials extracted from the eliminated weapons.

In the excess material declarations made so far, the commitment to dispose of a certain amount of material did not necessarily identify the actual material covered by that declaration. This is the approach that was taken by the United States and the Russian Federation in their excess HEU elimination programme. Most of the excess uranium remained part of the HEU inventory until the moment it entered the disposition process. With some exceptions, it was not placed in a separate storage facility. The situation is different with plutonium. As described in appendix B, in the Russian Federation virtually all excess plutonium is stored separately from the rest of the plutonium stock at two facilities—the Fissile Material Storage Facility in Ozersk and a storage facility in Zheleznogorsk. In the United States, approximately a third of the excess plutonium is stored at the K-Area Material Storage site in Savannah River and the rest is in storage at the Pantex Plant facility in weapon components, along with other plutonium.

The nature of the plutonium storage arrangements of the United States and the Russian Federation indicates it is possible to designate storage facilities that would only hold the fissile materials declared excess and to establish a monitored perimeter around them. Part of the K-Area Material Storage is already under IAEA safeguards. In addition to this, a perimeter could be established around the areas that store plutonium designated for disposition. In the Russian Federation, the storage in Zheleznogorsk is already under monitoring. Establishing a perimeter around the Fissile Material Storage Facility in Ozersk would not present any challenges as it is a stand-alone building, separated from the rest of the Ozersk storage and production facilities. The conversion facility would be located in Zheleznogorsk, where the material will be used to manufacture nuclear fuel.

In the United States, the weapon components that contain excess plutonium are stored at the Pantex Plant, in structures known as ‘magazines’ or ‘igloos’. The main storage area has about 70 structures, each capable of holding several hundred plutonium pits.[36] The amount of plutonium in a magazine is probably on the order of 1–2 tonnes. It should therefore be possible to establish a monitored perimeter around the magazines that store plutonium declared excess. The conversion facility would be located at the Savannah River Site, which will prepare plutonium for disposal.

[36] This area is known as Zone 4 West. Additional storage facilities are located in Zone 12, which is the weapons assembly and disassembly area. US Department of Energy, Office of Arms Control and Nonproliferation, “Transparency and Verification Options: An Initial Analysis of Approaches for Monitoring Warhead Dismantlement”, 19 May 1997, p. 37; Union of Concerned Scientists, “The UCS Nuclear Weapons Complex Map”, https://www.ucsusa.org/nuclear-weapons/us-nuclear-weapons-policy/nuclear-weapons-complex-map.html.

The United States and the Russian Federation, in fact, have most of the infrastructure required to implement the contain and dispose arrangement for their excess plutonium. Should they declare additional amounts of plutonium as excess, they could make corresponding arrangements for that material as well. The Russian Federation could place that material in one of its other storage facilities; in the case of Pantex, a perimeter could be established around the magazines that store the additional material.

It is difficult to say whether similar arrangements could be easily implemented in other nuclear-armed States. It is possible that in most cases fissile materials are consolidated in a single storage facility and additional facilities that would be suitable for the contain and dispose arrangements may not be available. Also, separating excess material from the rest of the stock may not be advisable from the nuclear security point of view. However, the US experience with the K-Area Material Storage suggests that it is possible to designate a containment area within a facility with restricted access. It is therefore likely that the key elements of the contain and dispose approach can be used in all nuclear-armed States.

It is also worth noting that perimeter arrangements at a storage site might not require constant physical access to the material and can be done with the help of remote monitoring. In most cases, there will be no incoming traffic and the volume of outgoing traffic would be fairly low, and the items removed from storage would go to conversion and subsequent disposition. Most of the activities related to inspecting the items that are crossing the perimeter would be concentrated at the conversion facility, which is likely to be less sensitive.

NUCLEAR SECURITY ASPECTS

Even though the primary purpose of the proposed contain and dispose arrangement is to provide a mechanism for nuclear disarmament verification, the arrangement could have important nuclear security benefits as well. Physical protection of nuclear materials is the area that requires constant attention as the failure to protect weapon-usable materials could have extremely serious consequences.[37] And yet, today there is no agreed set of rules and regulations that would govern security of fissile materials or a governing body that would ensure rigorous application of the recommendations developed by the international community or enable exchange of nuclear security best practices.[38]

The challenge is particularly serious when it comes to fissile materials in military programmes as there is virtually no accountability regarding the security practices applied to them.[39] Understandably, nuclear-armed States regard everything related to fissile materials in their military programmes as matters of high national security sensitivity and are reluctant to share information about them. It is often assumed that the special status of military materials automatically provides them with a stronger protection. In fact, the opposite might be the case. The experience of complex organizations that deal with various aspects of safety and security strongly suggests that, without independent oversight, it is extremely difficult to build and maintain a strong system of that kind. It is also vital to establish a mechanism that would allow the organization to learn from mistakes and the best practices, whether its own or those of similar organizations. These are exactly the elements that a closed system overseeing security of military materials tends to lack.

Figure 5 illustrates the magnitude of the problem. Only about 15 per cent of the global fissile material inventory (1.5 per cent of HEU and about 45 per cent of plutonium) is currently under safeguards and an additional 5 per cent (approximately) could be considered the material under civilian control. Even though international safeguards do not regulate physical protection, it is at least conceivable that the States that own this material would be relatively open about the nuclear security arrangements applied to them. Indeed, some progress in this area has been made in recent years. The Nuclear Security Summit process brought attention to the issue. It led to important commitments by individual States and groups of States, such as the Joint Statement on Strengthening Nuclear Security Implementation (INFCIRC/869). The process also helped secure entry into force of the 2005 Amendment to the Convention on the Physical Protection of Nuclear Material. Although these are important achievements, the degree of openness and cooperation on nuclear security matters regarding civilian materials remains limited.[40]

The lack of openness is an even more serious problem when it comes to materials outside of civilian control. One possible way to address this issue and overcome the closed nature of the nuclear security arrangements applied to the defence-related fissile materials is to focus on the materials that are

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[37] For a detailed treatment of the issue, see Matthew Bunn, Nickolas Roth, and William H. Tobey, *Revitalizing Nuclear Security in an Era of Uncertainty,* Project on Managing the Atom, Belfer Center for Science and International Affairs, 2019, https://www.belfercenter.org/sites/default/files/2019-01/RevitalizingNuclearSecurity.pdf.

[38] This section is partially drawn from Pavel Podvig, "Discussion Paper: Managing Risks of Fissile Materials", Nuclear Threat Initiative, January 2019, https://www.nti.org/documents/2391/Discussion_Paper-Managing_Risks_O7Bbcdc.pdf.

[39] International Institute for Strategic Studies, James Martin Center for Nonproliferation Studies, and Vienna Center for Disarmament and Non-Proliferation, "Improving the Security of All Nuclear Materials: Legal, Political, and Institutional Options to Advance International Oversight", September 2016, http://vcdnp.org/wp-content/uploads/2016/09/IISS-CNS-VCDNP-report_Final.pdf; Pavel Podvig, *Global Nuclear Security. Building Greater Accountability and Cooperation*, UNIDIR, 2011, http://www.unidir.org/files/publications/pdfs/global-nuclear-security-building-greater-accountability-and-cooperation-383.pdf.

[40] Matthew Bunn, Nickolas Roth, and William H. Tobey, *Revitalizing Nuclear Security in an Era of Uncertainty,* Project on Managing the Atom, Belfer Center for Science and International Affairs, 2019, https://www.belfercenter.org/sites/default/files/2019-01/RevitalizingNuclearSecurity.pdf.

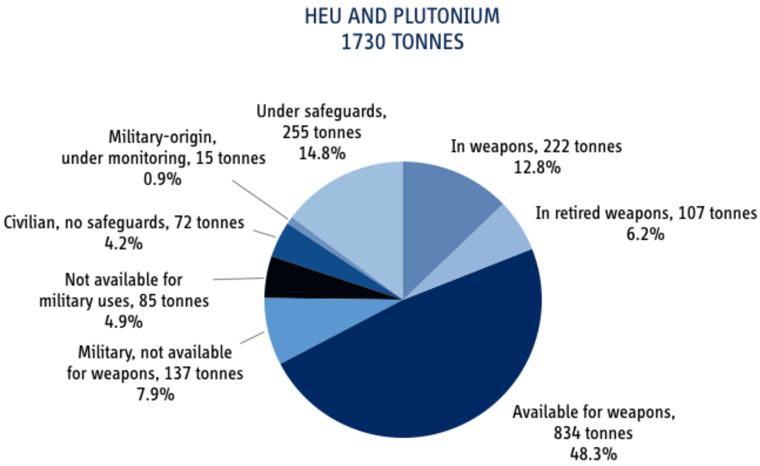

Figure 5. Weapon-usable materials by category

declared excess to weapon or military purposes and that are designated for disposition or use in the civilian programmes.

This is where the contain and dispose arrangement described in this report could provide a way to approach the issues of physical protection. Continuous presence of inspectors or monitoring equipment on the site would require close cooperation between the host State and the inspecting parties. At the same time, the fact that the inspectors would not be expected to have access to the activities inside the facility should make it easier to establish that presence.

It should be noted that the United States and the Russian Federation have valuable experience with perimeter monitoring arrangements. The Intermediate Range Nuclear Forces treaty, signed in 1987, established continuous perimeter monitoring at missile production facilities in Votkinsk in the Russian Federation and in Magna, Utah, in the Unites States.[41] The START treaty, signed in 1991, also included provisions for portal monitoring, under which the United States continued to monitor the facility in Votkinsk until 2009.[42] Also, as part of the Cooperative Threat Reduction Program the United States provided the Russian Federation with assistance that strengthened nuclear security at the military sites.[43] Although these programmes did not include the presence of US inspectors, they did involve significant technical assistance with establishing secure perimeters at nuclear weapon storage facilities managed by the 12th Main Directorate of the Russian Ministry of Defence. This suggests that in the right political circumstances nuclear security professionals can establish good working contacts.

It is, of course, highly unlikely that any State would be willing to share the details of its security arrangements—even those applied to excess materials. However, this is not necessary. The verification procedures of types required to implement the contain and dispose arrangement could provide a point of contact between the parties. The constant contacts on verification issues would allow the parties to share nuclear security expertise. Even if these interactions are limited and largely informal, they would provide a valuable channel of communication that does not exist today and that would help strengthen nuclear security of all involved parties.

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41 Joseph P. Harahan, *On-Site Inspections Under the INF Treaty*, US Department of Defense, 1993, Chapter 5, http://www.dtra.mil/Portals/61/Documents/History/On-Site%20Inspections%20INF%20Treaty-opt.pdf.

42 Another site that was subject to US inspection was the missile production plant in Pavlohrad, Ukraine. The United States discontinued monitoring of that site in 1995. The Soviet Union and then the Russian Federation had the right to conduct monitoring operations at the Thiokol plant in Promontory, Utah, but never exercised that right. Federation of American Scientists, "Strategic Arms Reduction Treaty (START I)", https://fas.org/nuke/control/start1/.

43 Joseph P. Harahan, With Courage and Persistence. Eliminating and Securing Weapons of Mass Destruction with the Nunn-Lugar Cooperative Threat Reduction Programs, Defense Threat Reduction Agency, 2014, Chapter 9, https://www.dtra.mil/Portals/61/Documents/History/With%20Courage%20and%20Persistence%20CTR.pdf.

CONCLUSION

The arrangement described in this report could allow nuclear-armed States to implement practical steps towards nuclear disarmament by placing fissile materials that are no longer required for military purposes under verification that ensures that these materials cannot be used for nuclear weapons. The key element of the proposed scheme is that it avoids dealing with classified information about fissile materials or nuclear weapons. This is accomplished by establishing perimeter control around the material storage facility and declaring the quantity of fissile materials that are contained there. The accuracy of the declaration is verified at the point when the material is converted to an unclassified form to be sent to disposition or use in civilian applications. The arrangement could also be used to organize dismantlement of nuclear weapons in a way that does not require access to the dismantlement process or to weapons and their components.

This approach, if implemented, could also provide an opportunity to strengthen nuclear security of materials in defence programmes. The verification measures that would be required to implement the scheme would require close interactions between the host and the inspecting body enabling exchange of expertise related to nuclear security arrangements.

While implementation of these measures will not be possible without a renewed commitment to nuclear disarmament on the part of nuclear-armed States, this arrangement could provide space for that commitment to emerge by providing an approach to nuclear disarmament and nuclear security that could address some of the technical issues that are currently seen as a serious barrier on the way towards elimination of nuclear weapons.

APPENDIX A. FISSILE MATERIAL INVENTORIES

The global stock of weapon-usable fissile materials is estimated to include about 530 tonnes of separated plutonium and 1,200 tonnes of unirradiated HEU.[44] This estimate accounts for fissile materials that can be classified as 'unirradiated direct-use material'. The IAEA defines direct use material as "material that can be used for the manufacture of nuclear explosive devices without transmutation or further enrichment". Unirradiated material is defined as material that "does not contain substantial amounts of fission products".[45]

Most of this material—485 tonnes of plutonium and almost all HEU—is owned by the nine nuclear-armed States. This appendix provides a brief overview of national stocks of weapon-usable fissile materials in nuclear-armed States and the nuclear security arrangements that are applied to these materials.

In considering national stocks, it is possible to distinguish several categories of materials according to their availability for use in nuclear weapons or other military purposes and the degree of monitoring or safeguards applied to these materials.

The category 'material in weapons' includes plutonium and HEU that is in 'weapons in nuclear stockpile', which include 'active' weapons that are operationally deployed as well as those in reserve and can be deployed in a short period of time. These warheads are fully assembled, and have they limited life components (such as tritium bottles) installed. The 'nuclear stockpile' category also includes 'inactive' warheads that are maintained in a lower degree of readiness and may require some work, such as installation of limited life components or other components before they can be deployed for operational use. The 'material in retired weapons' category covers plutonium and HEU in assembled warheads that

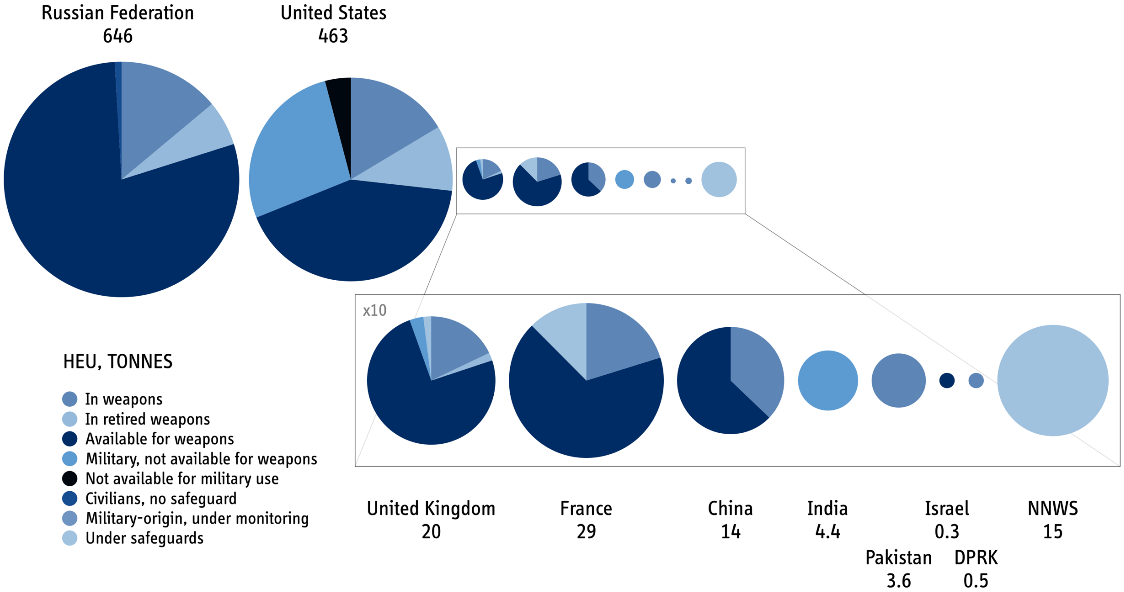

Figure 6. Global inventory of unirradiated highly enriched uranium by country and category (NNWS indicates non-nuclear-weapon States.)

[44] This means that the estimate does not include such categories of material as HEU in operating naval reactors (estimated to be 60 tonnes) or the material in spent fuel (about 70 tonnes of HEU and 8 tonnes of plutonium).

[45] International Atomic Energy Agency, *IAEA Safeguards Glossary*, 2002, § 4.25. See also a discussion in Pavel Podvig, "Fissile Material (Cut-off) Treaty: Definitions, Verification, and Scope", UNIDIR, 2016, pp. 6–8, http://unidir.org/files/publications/pdfs/fmct-definitions-verification-and-scope-en-655.pdf.

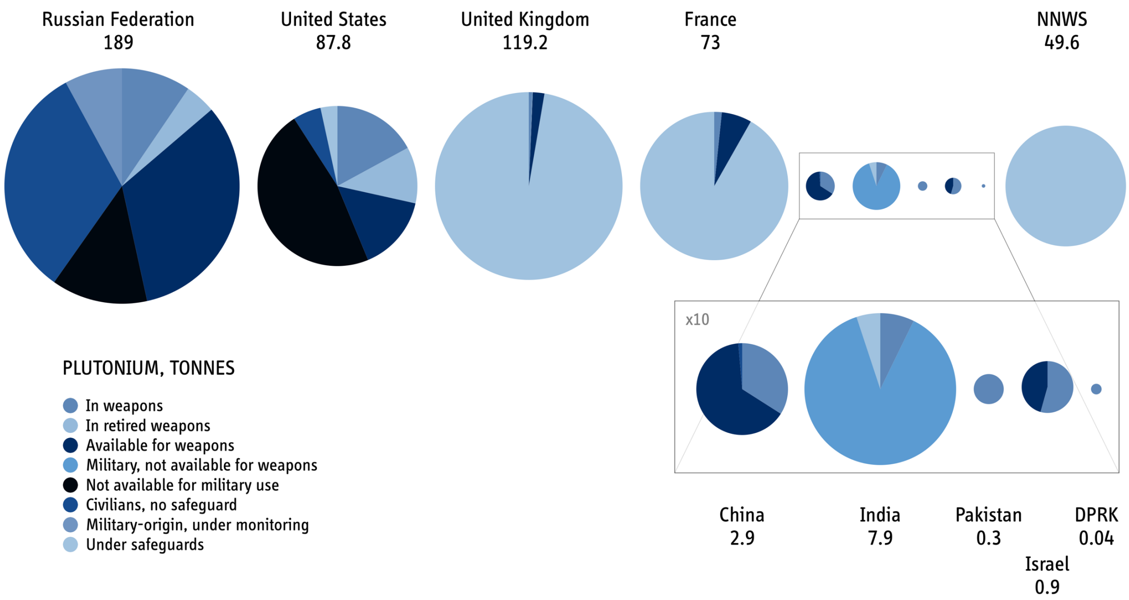

Figure 7. Global inventory of separated plutonium by country and category (NNWS indicates non-nuclear-weapon States.)

are awaiting dismantlement and will not be returned to operation.[46] Other material available for weapons could be stored in weapon components or in some other form.

To estimate the amount of fissile material in nuclear weapons, it was assumed that a modern US or Russian medium-yield thermonuclear weapon is estimated to contain 3–4 kg of plutonium and 15–25 kg of weapon-grade HEU.[47] For the purposes of this analysis, we will assume that advanced nuclear warheads on average contain 4 kg of Pu and 20 kg of HEU.[48] Different assumptions were made for States with small nuclear arsenals, as their material is almost entirely in weapons.

The category of materials that cannot be used for weapons includes HEU that is covered by corresponding political obligations. This material can be used for fuel of naval reactors or in production of tritium. There is also a separate category of material (plutonium as well as HEU) that cannot be used for any military purpose.

Some States have civilian fissile materials that are not explicitly covered by an obligation not to use them in military applications, but that are unlikely to be used for that purpose, even though it has not been placed under safeguards. This category mostly includes separated civilian plutonium in the Russian Federation and HEU that is used in research reactors. The Russian Federation also has about 15 tonnes of weapon-grade plutonium that has been placed under monitoring. This material is in its own category. Finally, a substantial amount of civilian fissile material is under safeguards administered by the IAEA or Euratom.

[46] This classification follows the definitions used in the United States. US Government, "Fact Sheet: Transparency in the U.S. Nuclear Weapons Stockpile", 29 April 2014, http://ipfmlibrary.org/usg14.pdf; US Department of Defense, Office of the Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs, *The Nuclear Matters Handbook. Expanded Edition*, 2011, p. 37, http://www.acq.osd.mil/ncbdp/nm/nm_book_5_11/docs/NMHB2011.pdf.

[47] International Panel on Fissile Materials, "Global Fissile Material Report 2013: Increasing Transparency of Nuclear Warhead and Fissile Material Stocks as a Step toward Disarmament", 2013, p. 94, http://ipfmlibrary.org/gfmr13.pdf.

[48] This is in line with the US Department of Energy estimate that assumes that a nuclear weapon contains about 25 kg of fissile material (HEU and plutonium). US Department of Energy, "Department of Energy FY 2016 Congressional Budget Request", February 2015, p. 565, http://www.energy.gov/sites/prod/files/2015/02/f19/FY2016BudgetVolume1%20_1.pdf.

THE RUSSIAN FEDERATION

The Russian Federation is believed to possess the largest share of the global stock of weapon-usable fissile materials. Estimates of the size of the Russian inventory are characterized by rather large uncertainty as the Russian Federation never release information about its fissile material holdings. As of 2019, the Russian Federation was estimated to have 189 ± 8 tonnes of separated plutonium and 670 ± 120 tonnes of HEU.

PLUTONIUM

Of the total stock of 189 tonnes of plutonium, 128 ± 8 tonnes is the material that was produced for military purposes and that is currently outside of civilian control.[49] The remaining 61 tonnes belong to the Russian civilian plutonium separation programme.[50] It is considered civilian material, even though it is not covered by an obligation not to use it for military purposes. This plutonium has been separated from spent fuel of power reactors at a dedicated civilian reprocessing facility; it is handled separately from materials in the military stock. In addition, its isotopic composition makes its use in the Russian weapon programme extremely unlikely. The Russian Federation annually provides the IAEA with a report on its civilian plutonium holdings as part of its INFCIRC/549 submission.

About 40 tonnes of the estimated 128 tonnes of weapon-grade plutonium produced by the military programme cannot be used for military purposes. This material includes about 15 tonnes of weapon-grade plutonium that was separated after September 1997 and the 34 tonnes of weapon-origin plutonium that is covered by the PMDA.

This leaves the Russian Federation with about 88 tonnes of weapon-grade plutonium available for weapons. Only a relatively small fraction of this plutonium is actually contained in nuclear weapons. As of 2019, the Russian Federation was estimated to have 4,490 weapons in its nuclear stockpile, with an additional 2,000 retired weapons awaiting dismantlement.[51] This means that weapons in the nuclear stockpile contain about 26 tonnes of plutonium—18 tonnes in active stockpile and about 8 tonnes in weapons in the dismantlement queue.

This estimate suggests that the Russian Federation could declare as much as 62 tonnes of weapon-grade plutonium as excess to its military requirements in addition to the 40 tonnes already covered by an obligation not to use it in weapons. However, the Russian government has not indicated that it intends to do so.

Civilian plutonium is stored at a dedicated storage facility next to the RT-1 civilian reprocessing plant. Some material can also be located at the mixed-oxide (MOX) fuel fabrication facility in Zheleznogorsk that produces fuel for the BN-800 power reactor.

HEU

Russia's stock of highly-enriched uranium is estimated to be 670 ± 120 tonnes of 90 per cent HEU equivalent. The actual amount of HEU is larger as some of this material is HEU with enrichment of less than 90 per cent. For the purposes of this section HEU is understood as 90 per cent HEU equivalent. The

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49 Anatoli Diakov, "The History of Plutonium Production in Russia", *Science & Global Security*, vol. 19, no. 1, 2011, pp. 28–45.

50 In its most recent INFCIRC/549 submission to the IAEA, the Russian Federation reported having 59 tonnes of separated civilian plutonium as of 31 December 2017. International Panel on Fissile Materials, "2017 Civilian Plutonium Declarations Submitted to IAEA", 19 September 2018, http://fissilematerials.org/blog/2018/09/civilian_plutonium_infcir.html. The amount used here is an estimate based on the historical separation rate. Some of this material is weapon-grade plutonium separated from the fuel irradiated in fast neutron reactors.

51 Hans M. Kristensen and Matt Korda, "Russian Nuclear Forces, 2019", *Bulletin of the Atomic Scientists*, vol. 75, no. 2, 2019, pp. 73–84, https://doi.org/10.1080/00963402.2019.1580891.

amount of HEU is known with very high uncertainty, largely because of the difficulty of reconstructing the history of HEU production.[52]

Virtually all HEU in the Russian Federation has been produced as part of the military programme. The material, however, is used in a range of civilian applications, such as research facilities, transport reactors or power reactors. It has been estimated that various research facilities contain about 6 tonnes of HEU. About 25 tonnes of HEU is believed to be in use in the naval fuel cycle, primarily in the cores of operational naval reactors.[53] This means that about 640 tonnes of HEU is either in nuclear weapons or available for weapon purposes.

Assuming that in 2019 the Russian Federation had 4,490 weapons in its nuclear stockpile and 2,000 retired weapons, one can estimate that about 130 tonnes of HEU is in assembled weapons—approximately 90 tonnes in the active stockpile and about 40 tonnes in weapons that are awaiting dismantlement. The remaining 510 tonnes are stored as weapon components or bulk material at the Rosatom sites.

FISSILE MATERIALS IN WEAPONS AND STORAGE

Plutonium and HEU that remain in the military programme are stored in a number of large storage facilities that are located in five Rosatom 'closed cities' – Sarov, Snezhinsk, Ozersk, Seversk, and Zheleznogorsk.[54] All material storage facilities are managed by the Rosatom State Corporation.

Information about facilities in Seversk provides some details about the storage arrangements in the closed cities. Seversk apparently has two old facilities for storing fissile materials and weapon components with a reported capacity for about 23,000 containers.[55] A facility that stores weapon components, which is probably different from these two, was established on the territory of one of the reactor sites.[56] Yet another storage facility was used for the plutonium separated after 1997 before it was moved to Zheleznogorsk. The total amount of material that was stored in Seversk at some point appears to be on the order of 80–100 tonnes.[57]

The weapon-grade plutonium that cannot be used for nuclear weapons is stored at two separate facilities. The post-1997 plutonium is currently stored at a facility in Zheleznogorsk as oxide.[58] The weapon-origin plutonium metal is stored in the Fissile Material Storage Facility in Ozersk.[59]

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[52] Pavel Podvig, "History of Highly Enriched Uranium Production in Russia", *Science & Global Security*, vol. 19, no. 1, 2011, pp. 46–67. At the time, the amount of HEU was estimated to be 679 tonnes. The current estimate takes into account the consumption of HEU since 2010. Anatoli Diakov, "HEU in Russia: An update", presentation at the Annual Meeting of the International Panel on Fissile Materials, Princeton, 6 May 2019.

[53] Pavel Podvig (ed.), *The Use of Highly-Enriched Uranium as Fuel in Russia*, International Panel on Fissile Materials, 2017, pp. 2 and 8, http://fissilematerials.org/library/rr16.pdf.

[54] Pavel Podvig, *Consolidating Fissile Materials in Russia's Nuclear Complex*, International Panel on Fissile Materials, 2009, p. 2.

[55] V. M. Kondakov, "Siberian Chemical Combine", in A. M. Petrosyants (ed.), *Ядерная индустрия России* [Russia's Nuclear Industry], 2000.

[56] I. V. Goloskokov and A. P. Yarygin, "Integrated Protection of Nuclear Materials at Major Industrial Nuclear Weapons Enterprise", Proceedings of the 2nd International Conference on Material Protection, Control & Accounting, May 22–26 2000, Obninsk, Russian Federation.

[57] In 2003, the US Department of Energy reported that it concluded contracts with Minatom to secure 80 tonnes of weapon-usable fissile material at Tomsk-7 (Seversk). US Government Accountability Office, "Additional Russian Cooperation Needed to Facilitate U.S. Efforts to Improve Security at Russian Sites", March 2003, pp. 81 and 90. In recent years the Russian Federation undertook a number of steps designed to move defense-related activities out of Seversk. It is possible that as part of this programme all defense-related material was removed from Seversk.

[58] International Panel on Fissile Materials, "Russia Removed Weapon-Grade Plutonium from Seversk", 17 April 2015, http://fissilematerials.org/blog/2015/04/russia_removed_weapon-gra.html.

[59] The facility is capable of storing 50 tonnes of plutonium and 200 tonnes of HEU. Joseph P. Harahan, With Courage and Persistence. Eliminating and Securing Weapons of Mass Destruction with the Nunn-Lugar Cooperative Threat Reduction Programs, Defense Threat Reduction Agency, 2014, pp. 280 and 282.

All Russian nuclear weapons (with the exception of those that are operationally deployed) are managed by the 12th Main Directorate of the Ministry of Defence (12 GUMO). The Russian Federation is believed to have 12 national-level storage facilities and more than 30 base-level storage sites that can service weapons associated with military units that deploy them.[60]

The weapons that are awaiting dismantlement are most likely stored at two national-level facilities, Lesnoy-4 and Trekhgorny-1. These storage sites are located near the two assembly and disassembly plants, the Electrochemical Instrument Combine in Lesnoy and the Instrument Building Plant in Trekhgorny respectively.[61]

Security at the Rosatom facilities that handle weapon-usable materials is provided by a combination of the Internal Troops of the Ministry of the Interior, who are responsible for protecting the perimeter and outer areas, and the Rosatom protective force, Atomokhrana, which is responsible for inner areas of the facility.[62] Protection of the nuclear weapon storage sites and that of nuclear weapons at all stages of storage and transportation (excluding operational deployment) is provided by the 12th Main Directorate.[63]

UNITED STATES

The United States has the second largest stock of weapon-usable fissile materials. It is the only State that has published a detailed account of the history of its fissile material production and periodically provides information about changes in its fissile material holdings. As of 2019, US fissile material stock includes 79.8 tonnes of separated plutonium and 571 tonnes of HEU.

PLUTONIUM

According to the most recent update of the plutonium inventory, published by the US Department of Energy in 2012, the United States had 95.4 tonnes of separated plutonium as of 30 September 2009.[64] This number should be adjusted to take into account the 0.1 tonnes of plutonium disposed in a geological depository since 2009, the 0.1 tonnes lost to decay, and the addition of 0.4 tonnes of plutonium transferred from abroad. Of the resulting 95.6 tonnes, 7.8 tonnes of material is reported to be in irradiated reactor fuel.[65] This means that the amount of separated unirradiated plutonium in US stocks is 87.8 tonnes.

The United States does not reprocess fuel from civilian power reactors, so virtually all US plutonium has been produced as part of the military programme. Most of the material is therefore weapon-grade plutonium, although of the 95.4 tonnes available in 2009 12.7 tonnes were reported as fuel grade (from 7 to 19 per cent Pu-240) and 1.4 tonnes as reactor grade (19 per cent Pu-240 and higher).[66]

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60 Pavel Podvig and Javier Serrat, "Lock Them Up: Zero-Deployed Non-Strategic Nuclear Weapons in Europe", UNIDIR, 2017, pp. 31–40, http://unidir.org/files/publications/pdfs/lock-them-up-zero-deployed-non-strategic-nuclear-weapons-in-europe-en-675.pdf.

61 Pavel Podvig, *Consolidating Fissile Materials in Russia's Nuclear Complex*, International Panel on Fissile Materials, 2009, p. 15.

62 Dmitry Kovchegin, "Nuclear Security Aspects of HEU Minimization", in Pavel Podvig (ed.), *The Use of Highly-Enriched Uranium as Fuel in Russia*, International Panel on Fissile Materials, 2017, pp. 80–81, http://fissilematerials.org/library/rr16.pdf.

63 Pavel Podvig and Javier Serrat, "Lock Them Up: Zero-Deployed Non-Strategic Nuclear Weapons in Europe", UNIDIR, 2017, pp. 17–18, http://unidir.org/files/publications/pdfs/lock-them-up-zero-deployed-non-strategic-nuclear-weapons-in-europe-en-675.pdf.

64 US Department of Energy, "The United States Plutonium Balance, 1944 - 2009. An Update of Plutonium: The First 50 Years, DOE/DP-0137, February 1996", June 2012, p. 9, http://fissilematerials.org/library/doe12.pdf.

65 International Atomic Energy Agency, "INFCIRC/549/Add.6/20. Communication Received from the United States of America Concerning Its Policies Regarding the Management of Plutonium", October 12, 2017, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1998/infcirc549a6-20.pdf.

66 "The United States Plutonium Balance, 1944 - 2009", *op. cit.*, p. 9.

It is possible to classify some of the plutonium as civilian, understood here as the plutonium that is either already placed under safeguards or that does not have classified attributes that would prevent access to the material. This category would include the "nearly 3 metric tons" of weapons plutonium that have been placed under IAEA safeguards at the Savannah River Site.[67] It also includes the 4.6 tonnes of plutonium in unirradiated fuel of ZPPR and FFTF reactors and the 0.4 tonnes of plutonium that the United States brought from abroad in 2016. This makes for 8 tonnes of plutonium that can be considered civilian.

In its annual reports on the status of plutonium management to the IAEA, the United States declares the total of 49.4 tonnes of unirradiated separated plutonium that is part of the plutonium stock declared excess to military needs.[68] Of this amount, 8 tonnes are accounted for as civilian material in the previous paragraph. The remaining 41.4 tonnes of excess plutonium is mostly the military material in weapon components or other military material.

The amount of plutonium that is currently in weapons or can be used in weapons is estimated to be 38.4 tonnes. The United States is estimated to have 3,800 weapons in its stockpile and another 2,385 weapons in the dismantlement queue.[69] This means that about 25 tonnes of plutonium is in assembled nuclear weapons—about 15 tonnes in the stockpile and almost 10 tonnes in retired weapons.

HEU

The United States published a detailed account of the history of HEU production up until 1996 and provided several updates on the status of its HEU stocks. According to the most recent statement, in September 2013, the US HEU inventory was 585.6 tonnes, of which 499.4 tonnes was reserved for future use in military and non-military applications. Of the remaining 86.2 tonnes, 44.6 tonnes was in spent fuel and 41.6 tonnes was available for disposition by down-blending. As of the end of 2017, an additional 14.6 tonnes of HEU have been blended down.[70] A further 4 tonnes are expected to be down-blended by the end of 2019, when the United States plans to stop disposition of the surplus HEU, covered by an obligation not to use it for military purposes.[71] Instead, the United States will begin down-blend 20 tonnes of HEU not covered by this obligation to produce LEU for fuel for power reactors that produce tritium for the weapons programme.[72] Some other HEU in the US inventory is reserved for specific programmes or covered by political obligations. For example, in the 2005 excess declaration, 20 tonnes of HEU was reserved for use in research reactors and 152 tonnes for naval reactors. Since then, consumption has reduced the size of these reserves to about 16 and 105 tonnes respectively.

Taking all these developments into account, the size of the US inventory of HEU outside of spent fuel can be estimated to be 503 tonnes in 2019. This includes 23 tonnes earmarked for down-blending and 480 tonnes reserved for future use. The latter category includes about 16 tonnes that are available for use in HEU reactor fuel and about 105 tonnes in the naval reserve.[73] About 40 tonnes of HEU is probably

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67 US Department of State, "U.S.-IAEA Safeguards Agreement", 2019, http://www.state.gov/t/isn/5209.htm.

68 "INFCIRC/549/Add.6/20", *op. cit.*

69 Hans M. Kristensen and Matt Korda, "United States Nuclear Forces, 2019", *Bulletin of the Atomic Scientists*, vol. 75, no. 3, 2019, pp. 122–134.

70 Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

71 US Department of Energy, "Department of Energy FY 2020 Congressional Budget Request", March 2019, p. 461, https://www.energy.gov/sites/prod/files/2019/03/f61/doe-fy2020-budget-volume-1_0.pdf.

72 International Panel on Fissile Materials, "United States to Down-Blend HEU for Tritium Production", 1 October 2018, http://fissilematerials.org/blog/2018/10/united_states_to_down-ble.html.

73 For consumption, see Frank von Hippel, *Banning the Production of Highly Enriched Uranium*, International Panel on Fissile Materials, 2016, p. 16, http://fissilematerials.org/library/rr15.pdf; US Department of Energy, "Tritium and Enriched Uranium Management Plan Through 2060. Report to Congress", October 2015, p. 6, http://fissilematerials.org/library/doe15b.pdf.

in the cores of operational naval reactors and therefore not available for weapons purposes.[74] This leaves about 319 tonnes of HEU that is used or can be used in weapons. Assuming that in 2019 the United States had 3,800 weapons in its nuclear stockpile and 2,385 retired weapons, one can estimate that about 124 tonnes of HEU is in assembled weapons—approximately 76 tonnes in the active stockpile and about 48 tonnes in weapons that are awaiting dismantlement. The rest of the weapon-usable material—approximately 195 tonnes of HEU—is most likely the weapon-grade material that is stored in weapon components or similar forms.

FISSILE MATERIALS IN WEAPONS AND STORAGE

Weapons that constitute the US nuclear stockpile are in the custody of the Department of Defense. Active stockpile weapons are either deployed or stored at operational military bases ready to be deployed. A number of bases have a role of central storage sites as they store inactive and retired weapons as well. The Kirtland Underground Munitions Maintenance and Storage Complex, the Strategic Weapons Facility Pacific, and the Strategic Weapons Facility Atlantic store active and inactive stockpile warheads as well as retired warheads that are awaiting dismantlement.[75]

Retired weapons that are entering the dismantlement process are transferred to the Pantex Plant of the Department of Energy—the primary site for dismantlement and assembly of nuclear weapons. Pantex has storage facilities that can store a relatively small number of nuclear weapons while they are awaiting disassembly or refurbishment.[76] It also has the capacity to store plutonium components of disassembled weapons—pits. The Pantex Plant was reported to be authorized to store 20,000 pits and about 14,000 pits were reported to be there as of 2010.[77] In total, it is estimated that about 40 tonnes of US plutonium are stored as pits at the Pantex plant.[78]

Another large plutonium storage site is the Savannah River Site in South Carolina. It includes the K-Area Material Storage facility that is currently used to store about 12 tonnes of plutonium.[79] About 3 tonnes of plutonium there is currently under IAEA safeguards.[80] Most of the remaining plutonium—reportedly between 6 and 7 tonnes—is the PMDA-obligated material.

HEU weapon components released during weapon disassembly is sent to the Y-12 National Security Complex of the Department of Energy. The complex is the site of the Highly Enriched Uranium Material Facility, which stores most of the US HEU stocks. Y-12 also has the facilities for the processing of HEU, manufacturing, and disassembly of HEU components. About 280 tonnes of HEU are stored as HEU components at the Y-12 National Security Complex.[81]

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74 Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors", *The Nonproliferation Review*, vol. 8, no. 1, 2001, p. 92, https://doi.org/10.1080/10736700108436841.

75 Hans M. Kristensen and Matt Korda, "United States Nuclear Forces, 2019", *Bulletin of the Atomic Scientists*, vol. 75, no. 3, 2019, pp. 122–134.

76 Ibid.

77 Union of Concerned Scientists, "Pantex Plant. Fact Sheet", https://www.ucsusa.org/sites/default/files/legacy/assets/documents/nwgs/nuclear-weapons-complex/pantex-fact-sheet.pdf.

78 This estimate is based on the data in International Panel on Fissile Materials, "Global Fissile Material Report 2011: Nuclear Weapon and Fissile Material Stockpiles and Production", 2011, p. 9, http://ipfmlibrary.org/gfmr11.pdf.

79 Colin Demarest, "DOE Discloses Amount of Surplus Plutonium at SRS; Future Disposition Explained", *Aiken Standard*, 17 May 2019, https://www.aikenstandard.com/news/doe-discloses-amount-of-surplus-plutonium-at-srs-future-disposition/article_69e43a30-78a2-11e9-90e5-4fac2c3a5f26.html.

80 Allen Gunter, "K Area Overview/Update", US Department of Energy, Office of Environmental Management, 28 July 2015, https://cab.srs.gov/library/meetings/2015/fb/RevisedAllenGunterFinalCABKAreaOverview_%20PresentationRev1%206-2-15.pdf.

81 This estimate is based on US Department of Energy, "Highly Enriched Uranium Inventory: Amounts of Highly Enriched Uranium in the United States", January 2006, p. 3, http://ipfmlibrary.org/doe06f.pdf.

A number of other facilities of the US nuclear complex manage smaller amounts of plutonium and HEU. Among those are the Los Alamos National Laboratory, Sandia National Laboratories, the Idaho National Laboratory, and the Nevada National Security Site.

Security of nuclear weapons while they are in the custody of the Department of Defense is provided by the dedicated Security Force units of the respective armed services. Air transport of nuclear weapons as cargo is carried out by the Prime Nuclear Airlift Force, the mission currently provided by the 4th Airlift Squadron at McChord Air Force Base.[82] Some nuclear weapons, such as cruise missiles and bombs, are normally transported by the aircraft these weapons are assigned to.[83] Ground transportation of nuclear weapons is normally handled by the Office of Secure Transportation of the Department of Energy.[84]

Nuclear facilities owned by the US Department of Energy are normally operated by commercial or non-profit contractors. For example, the Pantex Plant and the Y-12 National Security Complex, the sites that store most of the US fissile materials, are operated by Consolidated Nuclear Security, LLC, which is, in turn, a consortium of other companies that provide management services.[85] The contractors are responsible for all aspects of facility operation, including physical protection.

Transportation of government-owned special nuclear materials, nuclear weapons in the custody of the Department of Energy (and ground transportation of Department of Defense nuclear weapons) is managed by the Office of Secure Transportation of the National Nuclear Security Administration.[86] The Office of Secure Transportation is responsible for all aspects of the transport, including security.

UNITED KINGDOM

The United Kingdom is estimated to own about 120 tonnes of separated plutonium, most of which is in the civilian programme, and about 22 tonnes of HEU.

PLUTONIUM

Most of the plutonium stock is civilian material, separated from fuel of power reactors. According to the annual report submitted to the IAEA, as of the end of 2017 the United Kingdom owned 113.1 tonnes of civilian plutonium.[87] In addition, it held about 21 tonnes of the material owned by Japan. By 2019, the amount of civilian plutonium owned by the United Kingdom is estimated to have increased to about 116 tonnes. All that material is currently under safeguards.

Based on the official account of the UK defence fissile material production programme, the amount of plutonium in the defence programme is estimated to be 3.2 tonnes.[88] Most of this material is outside of assembled weapons. Since 2015, the UK operational stockpile consists of 120 nuclear warheads.[89] In addition, about 60 warheads appear to be kept in reserve and further 15–20 are awaiting

[82] Tyler Hemstreet, "PNAF Airmen ... Perfect ... Always!", *Team McChord*, 25 September2009, https://www.mcchord.af.mil/News/Article-Display/Article/248032/pnaf-airmen-perfect-always/.

[83] Hans M. Kristensen, "Flying Nuclear Bombs", Federation of American Scientists, 5 September 2007, https://fas.org/blogs/security/2007/09/flying_nuclear_bombs/.

[84] US Department of Defense, "DoD Transportation of U.S. Nuclear Weapons. Instruction Number 4540.05", 31 August 2018), p. 16, https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/454005p.pdf?ver=2019-02-26-144428-793.

[85] Consolidated Nuclear Security, "About | Consolidated Nuclear Security, LLC", https://www.cns-llc.us/about.

[86] US Department of Energy, National Nuclear Security Administration, "Office of Secure Transportation", 2019, https://www.energy.gov/nnsa/office-secure-transportation.

[87] UK Office for Nuclear Regulation, "Annual Figures for Holdings of Civil Unirradiated Plutonium as at 31 December 2017", June 2019, http://www.onr.org.uk/safeguards/civilplut17.htm.

[88] International Panel on Fissile Materials, "Global Fissile Material Report 2010: Balancing the Books: Production and Stocks", 2010, p. 77, http://ipfmlibrary.org/gfmr10.pdf.

[89] UK House of Commons, "House of Commons Hansard Ministerial Statements for 20 Jan 2015. The Secretary of State for Defence (Michael Fallon) on Nuclear Deterrent", 20 January 2015, http://www.publications.parliament.uk/pa/cm201415/cmhansrd/cm150120/wmstext/150120m0001.htm.

dismantlement.[90] This means that the amount of plutonium in the active arsenal is about 720 kg, and about 80 kg is in assembled weapons in the dismantlement queue. The remaining 2.4 tonnes of plutonium, stored as components or in some other form, is available for weapons.

HEU

The UK stock of HEU includes military as well as civilian material. On the military side, the United Kingdom declared that in 2002 it had 21.86 tonnes of HEU.[91] It appears that that amount did not include the material in naval spent fuel. About 2.2 tonnes of HEU was estimated to be in the cores of submarine reactors.[92] The naval reactors must have consumed some HEU after 2002, but it is likely that the United Kingdom also received HEU for its naval reactors from the United States.[93] Therefore, this estimate assumes that the amount of HEU outside of reactor cores and spent fuel has not changed in a significant way. This amount is estimated to be about 19 tonnes. About 4 tonnes of HEU is in assembled warheads—3.6 tonnes in the active arsenal and reserve and 0.4 tonnes in warheads awaiting dismantlement. The remainder of 15 tonnes, stored as components or in other forms, is potentially available for weapons purposes.

In its INFCIRC/549 submission to the IAEA the United Kingdom reported that as of the end of 2017 it had 1,103 kg of unirradiated civilian HEU. Since then it transferred about 700 kg of that material to the United States, so the amount of unirradiated civilian HEU in 2019 is estimated to be 0.4 tonnes.[94] This material is currently under Euratom safeguards.

FISSILE MATERIALS IN WEAPONS AND STORAGE

Nuclear warheads that are part of the arsenal are either deployed on the delivery systems, Trident II submarine-launched ballistic missiles, or stored at the Coulport Royal Navy Ammunition Depot, located near the Clyde naval base in Faslane, Scotland.[95] When not deployed, warheads are in the custody of the Atomic Weapons Establishment (AWE) that operates under a contact with the Ministry of Defence's Defence Nuclear Organization. AWE is also responsible for management of military fissile materials.

The Coulport depot is managed jointly by the ABL Alliance—a partnership of AWE, Babcock and Lockheed Martin UK.[96] The warheads stored there are periodically transported to the AWE Burghfield site for refurbishment or dismantlement. Road convoys that transport warheads are managed by the

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90 The United Kingdom plans to reduce its total stockpile to "no more than 180" warheads by the mid-2020s from 225 warheads in 2010. This estimate assumes a rate of dismantlement of about three warheads a year. UK Ministry of Defence, "Request for Information under the Freedom of Information (FOI) Act", 25 July 2013, http://robedwards.typepad.com/files/mod-foi-response-on-dismantling-nuclear-weapons.pdf.

91 UK Ministry of Defence, "Historical Accounting for UK Defence Highly Enriched Uranium. A Report by the Ministry of Defence on the Role of Historical Accounting for Highly Enriched Uranium for the United Kingdom's Defence Nuclear Programmes", March 2006, http://fissilematerials.org/library/mod06.pdf.

92 International Panel on Fissile Materials, "Global Fissile Material Report 2010: Balancing the Books: Production and Stocks", 2010, p. 75, http://ipfmlibrary.org/gfmr10.pdf.

93 Nick Ritchie, "The UK Naval Nuclear Propulsion Programme and Highly Enriched Uranium", Federation of American Scientists, February 2015, https://fas.org/wp-content/uploads/2015/03/2015-FAS-UK-NNPP-HEU-final2.pdf.

94 International Panel on Fissile Materials, "Transfer of HEU from the United Kingdom to the United States Is Completed", 9 May 2019, http://fissilematerials.org/blog/2019/05/transfer_of_heu_from_the_.html.

95 Hans M. Kristensen and Robert S. Norris, "Worldwide Deployments of Nuclear Weapons, 2017", *Bulletin of the Atomic Scientists*, vol. 73, no. 5, 2017, pp. 289–297, https://doi.org/10.1080/00963402.2017.1363995; Tamara Patton, Pavel Podvig, and Phillip Schell, "A New START Model for Transparency in Nuclear Disarmament. Individual Country Reports", UNIDIR, 2013, p. 40, http://unidir.org/files/publications/pdfs/a-new-start-model-for-transparency-in-nuclear-disarmament-individual-country-reports-en-415.pdf.

96 AWE, "Our Locations – AWE", https://www.awe.co.uk/about-us/our-locations/.

Truck Cargo Heavy Duty division of AWE.[97] Physical protection of the transports is provided by armed Ministry of Defence police.

AWE Burghfield is the only UK weapons assembly and disassembly facility. It may have a limited weapons and components storage capacity associated with these operations. The main site that stores military materials and manufactures weapon components is AWE Aldermaston.[98] Some military material could be present at defence-related research facilities. Physical protection of these sites is the responsibility of the Ministry of Defence police that works together with AWE.[99]

Civilian plutonium and most of the remaining civilian HEU are stored at the Sellafield site that is managed by the UK Nuclear Decommissioning Authority.[100] Protection of civilian sites and nuclear materials is provided by the Civil Nuclear Constabulary.[101]

FRANCE

The stock of fissile materials owned by France is estimated to include 75 tonnes of separated plutonium, most of which is civilian material, and about 30 tonnes of HEU, military as well as civilian.

PLUTONIUM

France is one of the few States that have a large-scale civilian plutonium separation programme. As of 2018, the amount of separated civilian plutonium owned by France was estimated to be about 67 tonnes.[102] In addition, France stores about 15.5 tonnes of plutonium that belongs to Japan. All this material is under Euratom and IAEA safeguards.

France's military plutonium stock is estimated to be 6 ± 1 tonnes.[103] Only a small fraction of this material is in weapons. In 2008, France announced that it will reduce its "operational arsenal" to no more than 300 warheads and that this number includes all its warheads.[104] It can be therefore estimated that the amount of plutonium in assembled warheads is about 1.2 tonnes. About 4.8 tonnes is the material that is available for weapon purposes.

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97 Nuclear Information Service, "AWE: Britain's Nuclear Weapons Factory Past, Present, and Possibilities for the Future", June 2016, p. 14, http://nuclearinfo.org/sites/default/files/AWE%20-%20Britain%27s%20Nuclear%20Weapons%20Factory_0.pdf.

98 UK Parliamentary Office of Science and Technology, "Assessing the Risk of Terrorist Attacks on Nuclear Facilities", July 2004, p. 11, http://www.parliament.uk/documents/post/postpr222.pdf.

99 "Assessing the Risk of Terrorist Attacks on Nuclear Facilities", *op. cit.*, p. 19; "AWE: Britain's Nuclear Weapons Factory Past, Present, and Possibilities for the Future", *op. cit.*, p. 38; International Institute for Strategic Studies, James Martin Center for Nonproliferation Studies, and Vienna Center for Disarmament and Non-Proliferation, "Improving the Security of All Nuclear Materials: Legal, Political, and Institutional Options to Advance International Oversight", September 2016, p. 24, http://vcdnp.org/wp-content/uploads/2016/09/IISS-CNS-VCDNP-report_Final.pdf;

100 UK Parliamentary Office of Science and Technology, "Managing the UK Plutonium Stockpile", September 2016, http://researchbriefings.files.parliament.uk/documents/POST-PN-0531/POST-PN-0531.pdf.

101 United Kingdom, "Civil Nuclear Constabulary", https://www.gov.uk/government/organisations/civil-nuclear-constabulary.

102 France reported having 65.4 tonnes of civilian plutonium at the end of 2017. This estimate assumes that accumulation of plutonium continued at the rate demonstrated in the past. International Atomic Energy Agency, "INFCIRC/549/Add.5/22. Communication Received from France Concerning Its Policies Regarding the Management of Plutonium", 3 June 2019, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1998/infcirc549a5-22.pdf.

103 Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

104 "Presentation of SSBM 'Le Terrible'—Speech by M. Nicolas Sarkozy, President of the Republic", 21 March 2008, http://carnegieendowment.org/2008/03/24/presentation-of-le-terrible-in-cherbourg/ynb. This probably means that no nuclear warheads are considered to be in the dismantlement queue.

HEU

The HEU stock in France includes civilian as well as military material. In its report to the IAEA France declared that as of the end of 2017 it had 5,190 kg of HEU, 3,654 kg of which was unirradiated material.[105] All of this material is under Euratom safeguards.

The military HEU stock is believed to include 26 ± 6 tonnes of the material.[106] The warheads in the operational arsenal would contain about 6 tonnes of HEU. This means that about 20 tonnes of the material is available for weapons.

FISSILE MATERIALS IN WEAPONS AND STORAGE

All activities related to weapons and fissile materials are managed by the Atomic and Alternative Energy Commission (Commissariat à l'Energie Atomique et aux Energies Alternatives, or CEA), which has the responsibility for weapons at all times, technically even when they are in the custody of the military.[107] CEA is also responsible for the civilian fissile materials.

France deploys its nuclear warheads on submarine-launched ballistic missile (SLBMs) and fighter-bombers based on land and aircraft carriers. The non-deployed SLBM warheads are stored and serviced at the facility in Saint-Jean, located near the Île Longue submarine base. The air-delivered weapons are stored at the air bases at Istres and Saint-Dizier.[108] The facility at Île Longue appears to be a CEA-managed site that in addition to storage has some capability to dismantle SLBM warheads. A similar dismantlement facility for air-delivered weapons is located at the 'special military centre' at the Valduc Research Centre. Disassembly of nuclear components is done at the nuclear weapon production facilities of the Valduc Research Centre.[109] Military fissile materials are probably also stored at Valduc.

Nuclear security arrangements at the CEA centres appear to be the responsibility of the centre directors who coordinate all security activities according to a protocol developed by the specific site. Physical protection of the defence-related centres, such as Valduc, is provided by a combination of CEA Local Security Units (Formations locales de sécurité) and specialized Gendarmerie Protection Squads (Pelotons spécialisé de protection de la Gendarmerie).[110] The Squads also provide physical protection at the civilian nuclear installations, such as nuclear power plants.

CHINA

China's stock of fissile materials is estimated to include 2.9 ± 0.6 tonnes of separated plutonium and 14 ± 6 tonnes of HEU.[111] Virtually all of this material has been produced as part of the military programme. The exception is a small amount of separated civilian plutonium—in its report to the IAEA China

[105] "INFCIRC/549/Add.5/22. Communication Received from France Concerning Its Policies Regarding the Management of Plutonium", 3 June 2019. Some of that material is held in France on behalf of other European States. For example, as much as about 600 kg of HEU is the material for fuel of a German research reactor.

[106] In addition to the high uncertainty of that estimate, it is also possible that the stock is significantly lower (as low as 6 tonnes). Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

[107] French National Assembly, "Rapport d'information déposé en application de l'article 145 du Règlement par la Commission de la défense nationale et des forces armées sur la fin de vie des équipements militaires et présenté par M. Michel Grall, Député", 16 March 2009, p. 19, http://www.assemblee-nationale.fr/13/rap-info/i3251.asp.

[108] Hans M. Kristensen and Robert S. Norris, "Worldwide Deployments of Nuclear Weapons, 2017", *Bulletin of the Atomic Scientists*, vol. 73, no. 5, 2017, pp. 289–297.

[109] "Rapport d'information", *op. cit.*, pp. 11–12.

[110] French National Assembly, "Question N°1420 - Assemblée Nationale", 5 December 2017, http://questions.assemblee-nationale.fr/q15/15-1420QE.htm.

[111] Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

declared that as of the end of 2016 it had separated 40.9 kg of plutonium from spent fuel of civilian nuclear reactors.[112]

Estimates of China's nuclear arsenal suggest that it has about 260 nuclear warheads, most of them in the operational stockpile.[113] This means that about 1 tonne of plutonium and about 5.2 tonnes of HEU are in assembled weapons.

The nuclear warhead storage and handling facilities are believed to be managed by the People's Liberation Army Rocket Force. The central storage facility, Base 22, may have the capability to perform the final integration and assembly of warheads. Nuclear components are produced at the facilities of the Chinese Academy of Engineering Physics (CAEP). Two facilities in the Sichuan province have been identified as weapon manufacturing and storage sites—in the Pingtongzhen area and the Zitong area.[114]

Security of the warhead storage sites is most likely provided by the military. Physical protection of nuclear facilities is the responsibility of China's Ministry for Public Security, which probably handles physical protection of the CAEP sites as well as security of materials during transport. CAEP also has nuclear security role and it most likely has local security units that are involved in physical protection of its facilities.[115]

INDIA

India's stock of fissile materials is estimated to include 7.9 ± 3.7 tonnes of separated plutonium and 4.4 ± 1.5 tonnes of HEU.[116] This material belongs to separate categories only one of which is directly weapon-related. India is believed to have produced about 0.57 ± 1.5 tonnes of plutonium for use in its weapons programme. About 6.9 tonnes is plutonium separated from spent fuel of unsafeguarded power reactors. This material is unlikely to be directly used in weapons, but it could be used in fuel of future fast neutron reactors to produce weapon-grade material. India also has 0.4 tonnes of plutonium under IAEA safeguards. The HEU in India's inventory is also not a weapon material. It is produced for use in fuel for naval reactors and is believed to have enrichment between 30–45 per cent of uranium-235.

India's arsenal is estimated to include 130–140 nuclear weapons.[117] All plutonium is therefore likely to be used in assembled weapons.

The military and civilian parts of India's nuclear programme are managed by the Department of Atomic Energy. Plutonium is probably stored at the Bhabha Atomic Research Centre, which is the main fissile material production site. Some material could also be stored at the Chandigharh Plant, a nuclear weapon

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[112] International Atomic Energy Agency, "INFCIRC/549/Add.7/16. Communication Received from China Concerning Its Policies Regarding the Management of Plutonium", 18 October 2017, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1998/infcirc549a7-16.pdf.

[113] Hans M. Kristensen and Robert S. Norris, "Chinese Nuclear Forces, 2016", *Bulletin of the Atomic Scientists*, vol. 72, no. 4, 2016, pp. 205–211, https://doi.org/10.1080/00963402.2016.1194054.

[114] Mark A. Stokes, *China's Nuclear Warhead Storage and Handling System*, Project 2049 Institute, 2010, http://project2049.net/documents/chinas_nuclear_warhead_storage_and_handling_system.pdf; Hans M. Kristensen and Robert S. Norris, "Worldwide Deployments of Nuclear Weapons, 2017", *Bulletin of the Atomic Scientists*, vol. 73, no. 5, 2017, pp. 289–297.

[115] Zhang Hui, "China: Evolving Attitudes on Nuclear Affairs", in Mike Mochizuki and Deepa M. Ollapally (eds), *Nuclear Debates in Asia: The Role of Geopolitics and Domestic Processes*, 2016, p. 44; Zhang Hui, *China's Nuclear Security*, Belfer Center for Science and International Affairs, Project on Managing the Atom, 2016, https://www.belfercenter.org/sites/default/files/legacy/files/Chinas%20Nuclear%20Security-Web.pdf.

[116] Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

[117] Hans M. Kristensen and Matt Korda, "Indian Nuclear Forces, 2018", *Bulletin of the Atomic Scientists*, vol. 74, no. 6, 2018), pp. 361–366, https://doi.org/10.1080/00963402.2018.1533162.

assembly facility in Punjab.[118] HEU is probably located at the Rattehalli Rare Materials Plant uranium enrichment facility near Mysore and at the Indira Gandhi Centre for Atomic Research in Kalpakkam that develops naval reactors. Security of the facilities of the nuclear weapons complex is provided by the Central Industrial Security Force of the Ministry of Home Affairs and the Department of Atomic Energy security force.[119]

PAKISTAN

Pakistan's stockpile of weapons-grade material is estimated to include 3.6 ± 0.4 tonnes of HEU and 0.31 ± 0.1 tonnes of separated plutonium.[120] Most of the HEU is believed to be in approximately 140–150 nuclear weapons that are located at a number of military bases across the country.[121]

The material that is not in weapons is reserved for weapons use.[122] The key organization that oversees nuclear security in Pakistan is the Strategic Plans Division, which also manages other aspects of Pakistan's nuclear programme. Security of the few civilian nuclear installations is regulated by the Nuclear Regulatory Authority. The United States may have provided Pakistan with some assistance in improving nuclear security at its sites.[123]

ISRAEL

Israel has an official policy of not confirming or denying possession of nuclear weapons. It is believed to have produced 0.92 ± 0.13 tonnes of weapon-grade plutonium. It also may have obtained 0.3 tonnes of HEU from the United States in or before 1965.[124] Israel's arsenal is estimated to include about 80 nuclear weapons, which are assumed to contain about half of the plutonium stock.[125] Extra plutonium and HEU could be stored as material available for weapons, probably at the Negev Nuclear Research Centre in Dimona, which is the plutonium production site, and at the Soreq Nuclear Research Centre that carries out weapon-related research and production.[126] Israel's nuclear facilities appear to have their own security units that probably act in coordination with the military or the troops of the Interior Ministry.

DEMOCRATIC PEOPLE'S REPUBLIC OF KOREA

Information about the Democratic People's Republic of Korea's stock of nuclear materials is scarce. It is believed to have produced about 60 kg of plutonium, some of which was spent in nuclear tests. The

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[118] International Panel on Fissile Materials, "Global Fissile Material Report 2009: A Path to Nuclear Disarmament. Fourth Annual Report of the International Panel on Fissile Materials", 2009, p. 133, http://ipfmlibrary.org/gfmr09.pdf.

[119] Bhabha Atomic Research Centre, "Press Release on the Security Related Concerns Expressed in the Media", 3 April 2012, http://barc.gov.in/press/2012/security.pdf.

[120] Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

[121] Hans M. Kristensen, Robert S. Norris, and Julia Diamond, "Pakistani Nuclear Forces, 2018", *Bulletin of the Atomic Scientists*, vol. 74, no. 5, 2018, pp. 348–358, https://doi.org/10.1080/00963402.2018.1507796.

[122] International Panel on Fissile Materials, "Pakistan Outlines Scope for FM(C)T Intended to Establish Parity with India", 11 August 2014, http://fissilematerials.org/blog/2014/08/pakistan_outlines_scope_for_fmct.html.

[123] Matthew Bunn, Nickolas Roth, and William H. Tobey, *Revitalizing Nuclear Security in an Era of Uncertainty*, Belfer Center for Science and International Affairs, 2019, pp. 95 and 97.

[124] Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019, pp. 288–294.

[125] Hans M. Kristensen and Matt Korda, "Status of World Nuclear Forces", Federation of American Scientists, July 2019, https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/.

[126] International Panel on Fissile Materials, "Global Fissile Material Report 2009: A Path to Nuclear Disarmament. Fourth Annual Report of the International Panel on Fissile Materials", 2009, p. 134, http://ipfmlibrary.org/gfmr09.pdf.

current plutonium stock may include about 40 kg of the material.[127] DPRK also operates uranium enrichment facilities and may have produced about 500 kg of HEU as of 2018.[128] Security of nuclear facilities is probably provided by dedicated military units.

[127] Moritz Kütt, Zia Mian, and Pavel Podvig, "Global Stocks and Production of Fissile Materials, 2018", in *SIPRI Yearbook 2019: Armaments, Disarmament and International Security*, SIPRI, 2019.

[128] Siegfried Hecker, Robert Carlin and Elliot Serbin, "A Comprehensive History of North Korea's Nuclear Program: 2018 Update", Center for International Security and Cooperation, Stanford University, 11 February 2019, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/2018colorchartnarrative_2.11.19_fin.pdf.

APPENDIX B. EXCESS AND DISARMAMENT MATERIAL

Beginning in the 1990s, the United States and the Russian Federation have eliminated about 680 tonnes of HEU, most of which was produced as part of their military programmes. In addition to that, they declared more than 100 tonnes of separated plutonium as excess to their defence needs and committed to eliminate most of this material. The only other State that declared part of its defence-related fissile material excess was the United Kingdom, which transferred this material to its civilian stock.

This appendix provides an overview of the key material elimination programmes and the transparency measures that were implemented or developed to provide transparency and accountability in the process.

THE RUSSIAN FEDERATION

The Russian Federation formally announced its commitment to eliminate "up to" 50 tonnes of plutonium and 500 tonnes of HEU in 1997.[129] However, the commitment to eliminate the HEU was made earlier. In 1993, the United States and the Russian Federation reached an agreement under which the Russian Federation committed to convert 500 tonnes of its weapon-origin HEU into LEU that would be then sold to the United States for use in power reactors.[130] This agreement initiated the largest excess material elimination programme, sometimes referred to as "Megatons to Megawatts". The agreement included measures that ensured that the eliminated material came from weapons. After the programme completed in 2013, the Russian government indicated that it was not interested in expanding it beyond the original 500 tonnes.

In addition to the weapon-origin HEU declared excess, the Russian Federation eliminated by down-blending about 17 tonnes of civilian HEU as part of the Material Conversion and Consolidation programme.[131] The programme was carried with US assistance, but the LEU that it produced remained in the Russian Federation. The programme was terminated in 2014.[132]

The Russian Federation's pledge to eliminate up to 50 tonnes of plutonium was made in response to the earlier commitment made by the United States. However, the PMDA that resulted from these reciprocal commitments covered only 34 tonnes of the material on each side. The Russian Federation insisted on full reciprocity and the United States could not identify a sufficient amount of weapon-quality material to include in the agreement. On the Russian side, the excess material included 25 tonnes of weapon-quality plutonium metal and 9 tonnes of plutonium oxide.

The 9 tonnes of plutonium oxide in the PMDA come from the stock of plutonium that was separated after September 1997, when the United States and the Russian Federation signed an agreement on shutdown of plutonium production reactors.[133] In the agreement, the Russian Federation committed never to use that plutonium for weapon purposes. In practice, this agreement covers about 15 tonnes of weapon-grade plutonium that is currently stored at a facility in Zheleznogorsk, where it is periodically

[129] "Message from the President of the Russian Federation to the Forty-First Session of the General Conference of the International Atomic Energy Agency", 26 September 1997, quoted in Matthew Bunn, "The Next Wave: Urgently Needed New Steps to Control Warheads and Fissile Material", April 2000, p. 60, http://belfercenter.ksg.harvard.edu/files/fullnextwave.pdf.

[130] See section in appendix C that describes the programme.

[131] International Panel on Fissile Materials, "U.S. Assistance in Securing Fissile Materials in Russia", 5 February 2010, http://fissilematerials.org/blog/2010/02/us_assistance_in_securing.html.

[132] Pavel Podvig, "Reactor Use of Highly Enriched Uranium in Russia", in Pavel Podvig (ed.), *The Use of Highly-Enriched Uranium as Fuel in Russia*, International Panel on Fissile Materials, 2017, p. 11, http://fissilematerials.org/library/rr16.pdf.

[133] "Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning Cooperation Regarding Plutonium Production Reactors", 23 September 1997, Article V, http://ipfmlibrary.org/gov97.pdf.

inspected by the United States. The inspections establish the mass of plutonium in containers, its weapon-grade nature, and confirm its age.[134]

While the plutonium production reactor agreement remains in force, the PMDA has been effectively terminated. In 2016 the Russian Federation suspended implementation of the agreement but pledged not to use the material covered by that agreement for any military purpose.[135]

Since the excess HEU elimination programme has been completed, the approximately 40 tonnes of weapon-grade plutonium remain the only weapon material that is awaiting disposition. The Russian Federation originally planned to use the 34 tonnes of PMDA material in fuel for its fast neutron reactors. However, after it suspended implementation of the agreement it uses its civilian plutonium stock for that purpose. The PMDA material is likely to remain in storage for an unspecified period of time. The Russian Federation also has not made a decision to dispose of the post-1997 plutonium. In the long run, all plutonium is likely to be used in fuel for power reactors.

UNITED STATES

HEU

The first US declaration of excess fissile materials was made in March 1995. The United States made a commitment to withdraw more than 200 tonnes of fissile materials from its nuclear stockpile and not to use that material for nuclear weapons. This amount included 174.3 tonnes of HEU.[136] That amount was later increased to 175 tonnes, of which 22 tonnes was contained in spent fuel and later disposed of as waste. The remaining 153 tonnes were made available for down-blending. The use of this material was restricted to non-military applications.[137]

In the second excess HEU declaration, made in 2005, the United States removed an additional 200 tonnes of HEU from the nuclear weapons stockpile.[138] Initially, 160 tonnes of this material was reserved for naval fuel, but that amount was later reduced to 152 tonnes.[139] With that correction, 28 tonnes of the material was made available for down-blending and subsequent use in power and research reactors. The remaining 20 tonnes was reserved for space missions and HEU fuel for research reactors.

The amount of HEU that is potentially available for down-blending appears to be larger than that identified in the two excess declarations. In 2008, the Department of Energy set a goal of completing disposition of 217 tonnes of surplus HEU by 2050.[140] By 2016, however, this goal was changed to down-blending of 186 tonnes of surplus HEU by 2030.[141] In addition to the 181 tonnes designated for down-

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[134] Anatoly Dyakov, "Nuclear Warheads and Weapons-Grade Materials", in Alexei Arbatov, Vladimir Dvorkin, and Natalia Bubnova (eds), *Nuclear Reset: Arms Reductions and Nonproliferation*, Carnegie Moscow Center, 2012, pp. 250–51, http://armscontrol.ru/pubs/en/Diakov-NucWarheads.pdf.

[135] International Panel on Fissile Materials, "Russia Suspends Implementation of Plutonium Disposition Agreement", 3 October 2016, http://fissilematerials.org/blog/2016/10/russia_suspends_implement.html.

[136] US Department of Energy, "Department of Energy Declassifies Location and Forms of Weapon-Grade Plutonium and Highly Enriched Uranium Inventory Excess to National Security Needs", 1995, https://www.osti.gov/opennet/forms?formurl=document/fs020696/factshe.html.

[137] US Department of Energy, "Tritium and Enriched Uranium Management Plan Through 2060. Report to Congress", October 2015, p. 6, http://fissilematerials.org/library/doe15b.pdf.

[138] US Department of Energy, "Remarks Prepared for Energy Secretary Sam Bodman. 2005 Carnegie International Nonproliferation Conference", 2005, https://www.energy.gov/articles/2005-carnegie-international-nonproliferation-conference.

[139] US Department of Energy, "Tritium and Enriched Uranium Management Plan Through 2060. Report to Congress", October 2015, p. 6, http://fissilematerials.org/library/doe15b.pdf.

[140] US National Nuclear Security Administration, "Department of Energy FY 2009 Congressional Budget Request", February 2008, p. 519, https://www.energy.gov/sites/prod/files/FY09Volume1.pdf.

[141] US Department of Energy, "Department of Energy FY 2017 Congressional Budget Request", February 2016, p. 479, http://energy.gov/sites/prod/files/2016/02/f29/FY2017BudgetVolume%201_0.pdf.

blending in the surplus declarations, this amount appears to include material received from other sources, such as transfer of HEU from foreign research reactors.[142]

In recent years the Department of Energy made a decision to change the nature of the HEU down-blending programme at the end of 2019, after completing disposition of 162 tonnes of HEU. The down-blending activities will continue, but the resulting LEU will be used in fuel for power reactors that produce tritium for the US nuclear weapons programme.[143]

The numbers indicate that the United States has largely completed its surplus HEU disposition programme. In addition to the 20 tonnes of the material that will be used in tritium production, the surplus stock appears to include about 3–4 tonnes of HEU still available for down-blending, and the estimated 16 tonnes of HEU from the reserve that was set aside in 2005 for space missions and HEU fuel for research reactors.[144] In total, this is about 40 tonnes of surplus material.

The surplus HEU described above includes material in various forms. A significant portion of this HEU appears to be part of the national security stock stored at the Y-12 Complex.[145] Accordingly, it might be difficult to transfer this material into a separate storage facility. At the same time, the Y-12 Complex has experience with these operations. In 1994, the United States placed 10 tonnes of weapon-grade HEU under IAEA safeguards at a Y-12 site that was "isolated from the rest of the plant operations".[146] That material, however, was withdrawn from the safeguards some time before 2010 and the facility where it was stored was decommissioned.[147]

A significant amount of HEU that could be identified as excess to weapon purposes in the future—estimated to be about 48 tonnes—is contained in nuclear weapons that are awaiting dismantlement.

PLUTONIUM

In its 1994 surplus material declaration, the United States declared 38.2 tonnes of weapon-grade plutonium as excess to weapon purposes.[148] With the addition of the plutonium with higher Pu-240 content, the total amount of the material that was considered excess at the time was 52.5 tonnes.[149] In 2007, the United States made a commitment to eliminate an additional 9 tonnes of weapon-grade plutonium, bringing the total amount of the material that was declared excess to 61.5 tonnes.[150]

In its annual INFCIRC/549 submissions to the IAEA the United States has provided some details about the categories of its excess material. Only 49.4 tonnes of the material declared excess is separated

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[142] "Tritium and Enriched Uranium Management Plan", *op. cit.*, p. 6.

[143] US Department of Energy, "Department of Energy FY 2020 Congressional Budget Request", March 2019, p. 490, https://www.energy.gov/sites/prod/files/2019/03/f61/doe-fy2020-budget-volume-1_0.pdf.

[144] This assumes that US research reactors consume about 320 kg of HEU annually. Frank von Hippel, *Banning the Production of Highly Enriched Uranium*, International Panel on Fissile Materials, 2016, p. 16, http://fissilematerials.org/library/rr15.pdf.

[145] "Tritium and Enriched Uranium Management Plan", *op. cit.*, p. 17.

[146] J.M. Whitaker, "Lessons Learned in Implementing IAEA Safeguards on U.S. Excess Fissile Materials, Oak Ridge Y-12 Plant", US Department of Energy, 21 February 1997, https://doi.org/10.2172/629448.

[147] The United States suggested replacing the 10 tonnes of weapon-grade HEU with 15 tonnes of HEU with lower enrichment from the surplus stock. However, the IAEA declined to accept this substitution and the safeguards were terminated. "U.S. Highly Enriched Uranium (HEU) Disposition—Overview", 26 January 2005, http://pogoarchives.org/m/hsp/2005nuclear/appendixD.pdf; Interview with a former IAEA official, August 24, 2014.

[148] US Department of Energy, "Department of Energy Declassifies Location and Forms of Weapon-Grade Plutonium and Highly Enriched Uranium Inventory Excess to National Security Needs", 1995, https://www.osti.gov/opennet/forms?formurl=document/fs020696/factshe.html.

[149] US Department of Energy, "Plutonium: The First 50 Years. United States Plutonium Production, Acquisition, and Utilization from 1944 through 1994", February 1996, p. 17. It appears that 0.2 tonnes of non-weapon grade plutonium was reclassified as waste.

[150] US Department of Energy, "The United States Plutonium Balance, 1944 - 2009. An Update of Plutonium: The First 50 Years, DOE/DP-0137, February 1996", June 2012, p. 15, http://fissilematerials.org/library/doe12.pdf.

unirradiated plutonium; 7.8 tonnes of plutonium is contained in irradiated fuel, 4.5 tonnes were disposed of as waste, and 0.2 tonnes were lost to radioactive decay.[151]

A significant fraction of the unirradiated excess plutonium is still in weapon components that are stored at the Pantex Plant. In 2009, 23.4 tonnes of plutonium were reported in that category.[152] About 12 tonnes of the material is stored at the Savannah River Site.[153] This amount apparently includes the "nearly 3 metric tons" of weapons plutonium that is currently under IAEA safeguards and between 6–7 tonnes of the PMDA material.[154]

The United States has a number of ongoing plutonium disposition programmes that deal with some categories of its plutonium. Since 1999, one of these programmes deposited about 6 tonnes of plutonium in waste in an underground geologic repository at the Waste Isolation Pilot Plant in New Mexico.[155] In addition to that, in 2016 the United States made a decision to dispose of up to 6 tonnes of non-PMDA excess plutonium in WIPP, using the technology known as "dilute and dispose".[156] In an important step toward transparency of the disposition process, the United States offered the IAEA to monitor "the dilution and packaging" of that material. It is possible that the IAEA would also monitor the process of emplacing the containers underground.[157]

The United States has made a commitment to eliminate 34 tonnes of its excess plutonium as part of the PMDA, described separately. According to original plan, the plutonium would be used to manufacture MOX for power reactors. However, the construction of the MOX Fuel Fabrication Facility was terminated due to escalating cost and as of 2019 no decision has been made as to the disposition route for the 34 tonnes of the PMDA material. The dilute and dispose option will probably emerge as the most viable alternative.[158]

UNITED KINGDOM

The United Kingdom is the only other State that declared excess fissile material. In the 1998 Strategic Defence Review the UK government identified 4.4 tonnes of plutonium, including 0.3 tonnes of weapon-grade plutonium, as "no longer required for defence purposes".[159] The 4.1 tonnes of non-weapon grade plutonium included, in the surplus, was never part of the weapon programme as this material was stored

[151] International Atomic Energy Agency, "INFCIRC/549/Add.6/20. Communication Received from the United States of America Concerning Its Policies Regarding the Management of Plutonium", October 12, 2017.

[152] US Department of Energy, "The United States Plutonium Balance, 1944 - 2009. An Update of Plutonium: The First 50 Years, DOE/DP-0137, February 1996", June 2012, p. 14, http://fissilematerials.org/library/doe12.pdf.

[153] Colin Demarest, "DOE Discloses Amount of Surplus Plutonium at SRS; Future Disposition Explained", *Aiken Standard*, 17 May 2019.

[154] Allen Gunter, "K Area Overview/Update", US Department of Energy, Office of Environmental Management, 28 July 2015, https://cab.srs.gov/library/meetings/2015/fb/RevisedAllenGunterFinalCABKAreaOverview_%20PresentationRev1%206-2-15.pdf. Edwin Lyman, personal communication, 18 May 2019.

[155] Some of this material is excluded from material accounting and therefore is not included in the 4.5 tonnes of disposed plutonium reported to the IAEA. International Panel on Fissile Materials, "Disposition of Plutonium in Waste Isolation Pilot Plant (WIPP)", 24 September 2016, http://fissilematerials.org/blog/2016/09/disposition_of_plutonium_.html.

[156] Tom Clements, "United States to Dispose of 6 MT of Weapon-Grade Plutonium in the Waste Isolation Pilot Plant", International Panel on Fissile Materials, 6 January 2016, http://fissilematerials.org/blog/2016/01/united_states_to_dispose_.html.

[157] US Department of Energy, "United States Commits to IAEA Monitoring for the Verifiable Disposition of Six Metric Tons of Surplus Plutonium", 5 December 2016, https://www.energy.gov/articles/united-states-commits-iaea-monitoring-verifiable-disposition-six-metric-tons-surplus.

[158] International Panel on Fissile Materials, "United States to Discontinue Construction of MOX Fuel Fabrication Facility", 10 February 2016, http://fissilematerials.org/blog/2016/02/united_states_to_disconti.html.

[159] UK Ministry of Defence, "Strategic Defence Review", July 1998, para. 26, http://fissilematerials.org/library/mod98.pdf.

at the production facility at Sellafield. The United Kingdom placed all its surplus material under Euratom safeguards and made it available to IAEA inspections.

The surplus military material identified in 1998 also included a substantial amount of LEU. The HEU, however, was kept in the military stock to be used for the naval propulsion programme.[160]

[160] UK Ministry of Defence, "Strategic Defence Review", July 1998, para. 26, http://fissilematerials.org/library/mod98.pdf.

APPENDIX C. EXCESS AND DISARMAMENT MATERIAL DISPOSITION PROGRAMS

This appendix describes the programmes that were designed to eliminate fissile material that was declared excess to military purposes. The programmes in this category include the US–Russian HEU Purchase Agreement (HEU–LEU deal) and the Plutonium Management and Disposition Agreement (PMDA). Another relevant programme is the US–Russian–IAEA Trilateral Initiative that aimed at developing procedures that would allow the IAEA to accept military-origin fissile materials for safeguards.

US–RUSSIAN HEU PURCHASE AGREEMENT

In February 1993, the United States and the Russian Federation reached an agreement that was designed "to arrange the safe and prompt disposition for peaceful purposes of highly enriched uranium extracted from nuclear weapons".[161] According to the agreement, the Russian Federation was to convert about 500 tonnes of HEU extracted from nuclear weapons into LEU that would be purchased by the United States for use as fuel in commercial nuclear reactors. The schedule established by the agreement anticipated that the conversion would be completed in no later than 20 years. The agreement also included provisions that created a mechanism to ensure that the HEU was indeed coming from existing weapon stock and that the LEU was fabricated into fuel of commercial reactors.[162]

The work on transparency measures was finalized in 1996. These measures included permanent presence of US monitors at Russian facilities that were involved in conversion as well as presence of Russian monitors at US fuel manufacturing facilities. The US monitors were able to observe the process of converting uranium metal shavings into uranium oxide. Even though the mass of uranium metal was not measured, the procedure allowed to confirm that HEU is not a freshly produced metal, giving the United States sufficient confidence in knowing that it was HEU from the weapon-related stock.

At its peak, the programme processed about 30 tonnes of HEU annually, which required a high volume of shipments between the Russian facilities involved in the programme. The programme was deliberately structured in a way that maximize their involvement and allow them to benefit from participation in the programme. The HEU metal was shipped from weapon disassembly or material storage facilities to Ozersk and Seversk, which performed conversion of metal into oxide. These transfers were not monitored by the United States.

Once the HEU was converted into oxide, US monitors applied tags and seals to all containers that were used to transport the material in all forms. HEU oxide was transferred from Ozersk to Seversk and Zelenogorsk, HEU hexafluoride was shipped from Seversk to Zelenogorsk and Novouralsk. Transfers of HEU between various facilities in Seversk were probably monitored as well. The LEU produced by the programme was shipped, in the form of LEU hexafluoride, from Novouralsk, Seversk, and Zelenogorsk to the St. Petersburg port and from there to the destination in the United States. At that point the Russian monitors checked the arrival of the LEU hexafluoride containers.

The first shipment of LEU to the United States took place in 1995 and the programme was successfully completed in 2013 after down-blending 500 tonnes of HEU from the Russian Federation's weapon stock.[163] It is widely considered one of the key US–Russian disarmament achievements. It is also extremely important that the programme demonstrated the feasibility of implementing a very complex set of measures designed to monitor movements of large amounts of weapon-grade material and

[161] "The Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Disposition of Highly Enriched Uranium Extracted from Nuclear Weapons", 18 February 1993, http://ipfmlibrary.org/heuleu93.pdf.

[162] The discussion of transparency measures follows Oleg Bukharin, "Understanding Russia's Uranium Enrichment Complex", *Science & Global Security*, vol. 12, no. 3, 2004, pp. 193–214. See also US Department of Energy, "Megatons to Megawatts: Implementing HEU Transparency Measures", 1999, https://media.nti.org/pdfs/32_5.pdf.

[163] International Panel on Fissile Materials, "Last HEU-LEU Program Shipment to Leave Russia", 14 November 2013, http://fissilematerials.org/blog/2013/11/last_shipment_of_heu-leu_.html.

provide strong material control and accountancy measures. This experience was be invaluable for any future efforts to monitor nuclear disarmament processes.

US–RUSSIAN PLUTONIUM MANAGEMENT AND DISPOSITION AGREEMENT

After the United States made its first fissile material declaration in 1994, the Russian Federation reciprocated with a similar commitment and the two States began negotiating an agreement that would commit each party to irreversibly eliminate up to 50 tonnes of excess plutonium. In the negotiating process the amount of material covered by the agreement was reduced to 34 tonnes on each side, which included high-quality weapon-origin and weapon-grade material. The Plutonium Management and Disposition Agreement (PMDA) was signed in 2000 and then amended by a protocol in 2010.[164]

In its final form, PMDA committed the United States and the Russian Federation to eliminate the agreed amount of plutonium by irradiating the material in nuclear reactors. The United States chose to irradiate the PMDA plutonium to produce MOX fuel for light water reactors. The Russian Federation decided to irradiate the material in its BN-600 and BN-800 fast neutron reactors.[165] Both parties expected to complete the construction of fuel fabrication facilities and begin the irradiation activities in 2018. The agreement committed each party to achieve the disposition rate of no less than 1.3 tonnes of plutonium per year. With that rate, the disposition of the PMDA plutonium would be completed in 2045.

Important elements of the agreement include the transparency measures that the United States and the Russian Federation agreed to implement during the disposition process and the commitment to provide effective physical protection of the material and facilities, taking into account IAEA recommendations.[166]

The agreement specified that, of the 34 tonnes of PMDA-obligated plutonium, 25 tonnes will be in the form of "pits and clean metal", described as "plutonium in or from weapon components or weapon parts, and plutonium metal prepared for fabrication into weapon parts". The remaining 9 tonnes could be in the form of metal and oxide.[167] In practice, in the United States most of the 'pits and clean metal' would come from the weapon components that are currently stored at the Pantex Plant. Some of that material was to be shipped from the Los Alamos National Laboratory, which performs small-scale weapon disassembly activities. Substantial amount of plutonium, including the material in the 'pits and clean metal' category is stored at the Savannah River Site. It has been estimated as of 2019 that about 6–7 tonnes of the plutonium stored at Savannah River is PMDA-obligated material.[168] In the Russian Federation, the 25 tonnes of weapon-origin material are stored at the Fissile Material Storage Facility at

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[164] "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation (as Amended by 2010 Protocol)", 13 April 2010, Annex on Monitoring and Inspections, http://ipfmlibrary.org/PMDA2010.pdf.

[165] The agreement also envisaged the possibility of irradiating plutonium in a Gas Turbine Modular Helium Reactor or any other reactors if agreed, but neither party has chosen to pursue these options. "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium", Article III.

[166] "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium", Articles VII and VIII. The updated version of the IAEA physical protection guidelines, issued in 2011, would apply to the agreement. International Atomic Energy Agency, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5)*, 2011, p. 5, http://www-pub.iaea.org/MTCD/publications/PDF/Pub1481_web.pdf.

[167] "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium", Annex on Quantities, Forms, Locations, and Methods of Disposition.

[168] Edwin Lyman, personal communication, 18 May 2019.

the Mayak Plant in Ozersk.[169] At the early stages of the construction of this facility, it was expected that the United States would have access to the material stored there.[170] To protect the information about the shape of weapon components, the Russian Federation recast the material into 2 kg spheres before placing the plutonium in storage.[171] The 9 tonnes of plutonium in the oxide form would come from the post-1997 material currently stored at Zheleznogorsk.

The material in storage would be shipped to the corresponding conversion facilities. The United States planned to build a dedicated MOX Fuel Fabrication Facility that would produce MOX fuel for light-water reactors. In the Russian Federation, the main facility that would use the PMDA plutonium (as well as plutonium from the civilian stock) to manufacture fuel for fast neutron reactors was built at the Mining and Chemical Combine in Zheleznogorsk.[172]

The parties agreed to establish a monitoring and inspections system that would verify the disposition of plutonium. To protect information about isotopic composition of the material, the agreement allowed the parties to introduce a limited amount of non-weapon plutonium, called 'blend stock', into the disposition flow. The United States chose not to use blend stock in its disposition process. The Russian Federation had an option to use 4.08 tonnes of plutonium to mix it with the disposition material.[173] The mixture of disposition plutonium and the blend stock, referred to as 'conversion product' would be subject to monitoring and inspections once it has been received at the disposition facility.

The agreement specified that neither party would have access to any parameters that would be considered classified "because of their relationship to nuclear weapon design or manufacturing". Moreover, no material present at the disposition facilities was supposed to have classified properties. The use of information barriers during inspections was explicitly ruled out, even in those cases when the procedure could reveal information considered sensitive.[174]

It was expected that the IAEA would play an active role in establishing the monitoring and inspections system. In 2010, the United States and the Russian Federation requested the IAEA to establish verification measures with respect to their plutonium disposition programmes.[175] The agreement with the IAEA, however, was never completed.

Among the reasons the progress towards the PMDA implementation has slowed down was the uncertainty about the future of the US disposition programme. The construction of the MOX Fuel Fabrication Facility that was central to the US programme encountered technical problems and budget overruns. In addition, it was unclear if any of the US commercial reactors would be willing to accept the

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169 The facility is capable of storing 50 tonnes of plutonium and 200 tonnes of HEU. Joseph P. Harahan, With Courage and Persistence. Eliminating and Securing Weapons of Mass Destruction with the Nunn-Lugar Cooperative Threat Reduction Programs, Defense Threat Reduction Agency, 2014, pp. 280 and 282.

170 Anatoly Dyakov, "Nuclear Warheads and Weapons-Grade Materials", in Alexei Arbatov, Vladimir Dvorkin, and Natalia Bubnova (eds), *Nuclear Reset: Arms Reductions and Nonproliferation*, Carnegie Moscow Center, 2012, p. 250, http://armscontrol.ru/pubs/en/Diakov-NucWarheads.pdf.

171 Oleg Bukharin, Thomas B. Cochran, and Robert S. Norris, "New Perspectives on Russia's Ten Secret Cities", Natural Resources Defense Council, October 1999, p. 23, https://fas.org/nuke/norris/nuc_10019901a_208b.pdf.

172 International Panel on Fissile Materials, "Russia Launches Commercial MOX Fuel Fabrication Facility", 28 September 2015, http://fissilematerials.org/blog/2015/09/russia_launches_commercia.html.

173 The blend stock was expected to have higher content of Pu-240 and other isotopes. However, the total amount of Pu-240 in the 38.08 tonnes of conversion product was limited to 3,000 kg, and the amount of Pu-238 to 50 kg. "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium", Annex on Monitoring and Inspections, Section II.11.

174 For the Russian Federation, the terms 'classified' and 'sensitive' would be 'the information considered state secret' and 'konfidentsial'naya' accordingly. "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium", Annex on Monitoring and Inspections, Sections II.13-15.

175 International Panel on Fissile Materials, "United States and Russia Request Safeguards for Their Excess Plutonium", 16 September 2010, http://fissilematerials.org/blog/2010/09/united_states_and_russia.html.

MOX fuel.[176] In 2016, the United States decided to discontinue the construction of the facility and to explore an alternative option, known as 'dilute and dispose'.[177] The Russian Federation raised concerns about the change of plans and the uncertainty surrounding the US programme. In 2016, amid the overall deterioration of the US–Russian relationships, the Russian Federation suspended its participation in PMDA. At the same time, it confirmed that the plutonium that was to be eliminated under the programme will not be used "for the purposes of manufacturing nuclear weapons or other nuclear explosive devices, or for research, development, design, or tests that are related to such devices, or for any other military purposes".[178]

Even though a return to PMDA implementation is rather unlikely, the agreement has played an important role in creating a framework for future fissile material elimination efforts. The procedures that were developed for the plutonium disposition programmes could be used with minimal modifications in deferred verification arrangements. Among these procedures are the obligation to eliminate a fixed amount of fissile material, isolation of the disposition material in a separate storage facility (in the Russian Federation), the use of blend stock to mask classified information about weapon-origin material, and the implementation of verification arrangements at the point when the material enters the disposition process.

THE TRILATERAL INITIATIVE

In 1996, the United States, the Russian Federation and the IAEA launched a joint program, known as the Trilateral Initiative, to develop methods that would allow the Agency to monitor fissile materials in classified forms.[179] As the United States and the Russian Federation were declaring large amounts of weapon-origin fissile materials as excess to military purposes, the goal of the programme was to explore arrangements that would place these materials under international monitoring to preclude their future use in nuclear weapons. The key challenge that was facing the IAEA was to find ways to accept materials for safeguards while protecting classified information about nuclear weapons.

Most of the practical work was carried by the Trilateral Initiative Working Group that included experts from the parties. The group addressed a range of issues related to the task—from a legal framework and handling of sensitive information by the IAEA to development of verification criteria and specialized equipment that would be used during the inspections.

The technical work was focused on verifying plutonium in classified components. The method developed by the working group was based on defining a set of agreed attributes that were considered sufficient for the purposes of the Initiative. The group decided to focus on detecting the presence of plutonium and did not consider approaches that could be applied to HEU. The selected attributes were:

- The presence of plutonium;

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[176] International Panel on Fissile Materials, "U.S. Plutonium Disposition Program: Uncertainties of the MOX Route", 10 March 2011, http://fissilematerials.org/blog/2011/03/us_plutonium_disposition_.html.

[177] International Panel on Fissile Materials, "United States to Discontinue Construction of MOX Fuel Fabrication Facility", 10 February 2016, http://fissilematerials.org/blog/2016/02/united_states_to_disconti.html.

[178] International Panel on Fissile Materials, "Russia Suspends Implementation of Plutonium Disposition Agreement", 3 October 2016, http://fissilematerials.org/blog/2016/10/russia_suspends_implement.html.

[179] This section is based on the description of the Trilateral Initiative in Thomas E. Shea, "Weapon-Origin Fissile Material: The Trilateral Initiative", in *Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty*, International Panel on Fissile Materials, 2008, http://ipfmlibrary.org/gfmr08.pdf.; Thomas E. Shea and Laura Rockwood, "IAEA Verification of Fissile Material in Support of Nuclear Disarmament", Belfer Center, May 2015, http://belfercenter.ksg.harvard.edu/files/iaeaverification.pdf. A general approach to applying IAEA safeguards to excess fissile materials was considered in Thomas E. Shea, "On the Application of IAEA Safeguards to Plutonium and Highly Enriched Uranium from Military Inventories", *Science & Global Security*, vol. 3, no. 3–4, 1993, pp. 223–236.

- A weapon-grade nature of the plutonium, determined by isotopic ratio of Pu-240 to Pu-239 not exceeding 0.1;
- A mass of plutonium exceeding an agreed minimum.

The key challenge in the attribute approach is that radiation measurements reveal very detailed information about the inspected object or material and therefore their use to examine sensitive objects is considered inadmissible in the context of international inspections.[180] To overcome this problem, the attribute approach is usually combined with an information barrier, which processes the information obtained by the measurements in a way that hides sensitive data, but still allows confirmation of whether the inspected object possesses the selected attributes.

The specific method chosen by the Trilateral Initiative working group relied on high-resolution gamma spectroscopy to establish the presence of plutonium and to determine the ratio of isotopes Pu-240 and Pu-239. Then, a neutron multiplicity counter was used to determine the mass of Pu-240. Since the results of these measurements, either separately or taken together, would be considered classified, they were processed by the information barrier that provided a simple 'pass–fail' output.[181] The concept developed by the working group was explored further by US and Russian experts, who manufactured a prototype of the measurement system after the Trilateral Initiative was concluded.[182]

Although the working group was successful in developing an agreed approach to measuring attributes of plutonium-containing objects, the discussions held by the group also demonstrated the challenges of a process that relies on an information barrier. The most challenging problem in this approach is that all parties have to trust the information barrier equipment to perform its function. Authentication of the equipment is a serious challenge and it is possible that the problem does not have a solution that would not depend on a degree of trust among the parties involved in the authentication and verification process.[183] There are measures that can be introduced to the process to increase confidence in the technology, such as joint design and testing of components and software, reliance on simple (or vintage) technology, but these may not fully address the challenge if the parties do not trust each other.[184]

In addition to addressing the technological challenge, the Trilateral Initiative developed a detailed legal framework that would allow implementation of the arrangement. In the end, however, the United States and the Russian Federation decided to end this work, even though they agreed that the Initiative had successfully achieved its goals. Indeed, the work on the Initiative demonstrated that it is possible to develop complex technical and legal arrangements that would be applied to monitoring and verification of fissile materials that are declared excess to military purposes.

In 2002, the working group issued its final report, which stated that the project "found no technical problem that would prevent the IAEA from undertaking a verification mission in relation to … fissile

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[180] Oleg Bukharin, "Russian and US Technology Development in Support of Nuclear Warhead and Material Transparency Initiatives", in Nicholas Zarimpas (ed.), *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, 2003, pp. 171–173.

[181] Thomas E. Shea, "Weapon-Origin Fissile Material: The Trilateral Initiative", in *Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty*, International Panel on Fissile Materials, 2008, pp. 67–68, http://ipfmlibrary.org/gfmr08.pdf.

[182] This system, AVNG, was demonstrated in Sarov to a joint US–Russian audience in 2009. Sergey Kondratov et al., "AVNG System Demonstration", *Proceedings of the 51 St Annual Meeting of the Institute of Nuclear Material Management*, 2010, https://www.nti.org/media/pdfs/LA-UR-10-02620_AVNG_System_Demonstration.pdf

[183] Keith Tolk, Jacob Benz, and Jennifer Tanner, "Authentication of Electronics for Arms Control", *INMM Just Trust Me 2019 Workshop*, 13 March 2019, https://www.inmm.org/INMM/media/PATRAM/5-Authentication-of-Electronics-for-Arms-Control.pptx.

[184] Keith Tolk, Jacob Benz, and Jennifer Tanner, *op. cit.*; Thomas E. Shea and Laura Rockwood, "IAEA Verification of Fissile Material in Support of Nuclear Disarmament", Belfer Center, May 2015, p. 10, http://belfercenter.ksg.harvard.edu/files/iaeaverification.pdf.

materials released from defence programmes".[185] However, the United States and the Russian Federation decided against signing a corresponding agreement with the IAEA and the programme was closed down.

[185] Thomas E. Shea, "Weapon-Origin Fissile Material: The Trilateral Initiative", in *Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty*, International Panel on Fissile Materials, 2008, pp. 65–66, http://ipfmlibrary.org/gfmr08.pdf.

APPENDIX D. VERIFYING THE NON-NUCLEAR NATURE OF AN OBJECT

The arrangement described in this report to a substantial extent relies on development of an arrangement that would verify the non-nuclear nature of objects presented for inspection. The key principle is that once a perimeter around a storage facility is established, no fissile materials, weapons, or weapon components should be allowed to leave or enter the site. There are other scenarios in which the ability to certify the non-nuclear nature of objects leaving and entering a monitored perimeter would be essential. For example, this arrangement could be used to verify the absence of nuclear weapons in storage at military bases.[186] It would also be instrumental in supporting verification of the naval fuel cycle under a ban on production of fissile materials for weapons—there, it would be essential to ensure that no fissile material is leaving a fuel fabrication facility.[187]

In a general form, a verification procedure designed to confirm the non-nuclear nature of an object should be able to establish the absence of nuclear materials in a container that can be used to store or transport weapons, weapon components or nuclear materials. It should be able to deal with situations when the container cannot be opened for a visual inspection as it may contain non-nuclear classified items, such as non-nuclear weapons or non-nuclear components of nuclear weapons. Neither can the procedure rely, explicitly or implicitly (as it is done in New START), on the absence of shielding or on the knowledge of specific weapon attributes, such as the mass, type or isotopic composition of fissile material, since these attributes would be considered classified as well.

These conditions are deliberately designed to be rather restrictive to cover a wide range of possible verification scenarios. Even under these conditions, however, it is possible to design a verification protocol that could confirm the non-nuclear nature of an object presented for an inspection and do so without revealing classified information about the inspected object. This protocol, described in this appendix, will be referred to as 'a non-nuclear template'. It takes advantage of the fact that any item presented for an inspection is expected to be non-nuclear and that the host and the inspecting party could agree on some details of the inspecting procedure beforehand.

The key principle of the non-nuclear template arrangement is that the host and the inspecting party reach an agreement on the type of inspected objects. These objects would essentially be the basic unit of inspection. In the case of a material storage facility these could be fissile material storage and transport containers. At a weapon storage or dismantlement facility these could be the containers that are used for transporting nuclear weapons or non-nuclear components of nuclear weapons. Ideally, the basic unit of inspection would be as large as a truck or a railcar, but at this point it is not clear if the non-nuclear template method could be successfully applied to the objects that large. This discussion will assume that the inspected item is an approximately cylindrical object or a box with linear dimensions of about one metre across and the length of up to several metres. This would be compatible with most containers that are used to transport nuclear materials and nuclear weapons.

Before the inspections begin, the host party presents to the inspectors a reference object that represents the item that the host will be submitting to inspection. The inspecting party will then be able to thoroughly examine the reference object to confirm that it does not contain any nuclear materials. After the examination, inspectors will record a signature of the reference object using an agreed technique. This signature becomes the non-nuclear template that it is then used to confirm the non-nuclear nature of the items that are crossing the perimeter. If the signature of an inspected item matches the recorded template, the item is considered non-nuclear.

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[186] Pavel Podvig, Ryan Snyder, and Wilfred Wan, "Evidence of Absence: Verifying the Removal of Nuclear Weapons", UNIDIR, 2018, http://www.unidir.org/files/publications/pdfs/evidence-of-absence-verifying-the-removal-of-nuclear-weapons-en-722.pdf.

[187] Pavel Podvig, "Fissile Material (Cut-off) Treaty: Elements of the Emerging Consensus", UNIDIR, 2016, http://www.unidir.org/files/publications/pdfs/fissile-material-cut-off-treaty-elements-of-the-emerging-consensus-en-650.pdf.

It is important to emphasize that the reference object does not have to be a replica of the real item that will be submitted for an inspection. All that is required is that it produces the signature identical or sufficiently similar to that of the real item. It is also important to note that the inspecting party will have full access to the reference object and will be able to conduct any measurements on it and determine what kind of materials were used to build it. This way, the presence of any shielding material would be detected, and the measurement process would be adjusted accordingly. For example, the presence of absorbent material may require increasing the measurement time. In some cases, the inspecting party may request the use of a different measurement technique, for example, choosing active interrogation instead of passive. The host would then provide a different reference object.

Since neither the reference object nor the inspected items are supposed to contain any nuclear materials, at no point of the process would the host party have to reveal information about fissile materials or nuclear weapons. The use of a reference object instead of the actual non-nuclear item should also be able to protect classified information about non-nuclear components. However, in some cases that may not be sufficient.

One point of concern is the measurement process when it is applied to the inspected item. If the measurement technique is sensitive enough, it could potentially reveal sensitive (non-nuclear) information about the item. This issue can be addressed in a number of different ways. One would be to degrade the resolution of the measurement system in a way that does not allow detailed information about the inspected object to be obtained.[188] A different approach would be to use a variation of the zero-knowledge protocol that ensures that sensitive data are never measured in the first place in the process of creating a template.[189] Adapting this protocol to the non-nuclear template arrangement may require additional research, but there appears to be no fundamental reason why this cannot be done.

Another concern is that the reference object itself can reveal sensitive information about the inspected item. Even though it would not have to be an exact replica, it would have to resemble the inspected item in some way. This might not be an issue for transport containers, but if this arrangement is applied to confirming the non-nuclear nature of a weapon in a container, the composition of the reference object may disclose classified details of its design, such as relative position and size of its components.[190] To conceal this information, the reference object could be assembled from small modules and submitted for examination in disassembled form.

Information about the reference object will allow the inspecting party to adjust the parameters of the measurement process in a way that would provide high confidence in the absence of nuclear materials in an inspected container. The following sections outline a possible design of the non-nuclear template protocol.

PLUTONIUM

In some scenarios, the verification protocol can assume that inspected objects contain a certain amount of plutonium. This would be the case if inspections are applied to plutonium or plutonium components placed in a monitored storage facility, such as the K-Area Material Storage site in the United States or the Fissile Material Storage Facility in the Russian Federation. If the verification arrangement is

[188] JASON programme, MITRE Corporation, "Verification Technology: Unclassified Version", October 1990, pp. 99–102, https://fas.org/irp/agency/dod/jason/verif.pdf.

[189] Alexander Glaser, Boaz Barak, and Robert J. Goldston, "A Zero-Knowledge Protocol for Nuclear Warhead Verification", *Nature*, vol. 510, no. 7506, 2014, pp. 497–502, https://doi.org/10.1038/nature13457.

[190] It is worth noting that it is often assumed that non-nuclear objects do not have classified attributes that need to be protected. See, for example, JASON programme, MITRE Corporation, "Verification Technology: Unclassified Version", October 1990, pp. 99–102, https://fas.org/irp/agency/dod/jason/verif.pdf. If that is indeed the case, the inspection protocol could be made significantly simpler. However, the use of a non-nuclear template allows handling situations where non-nuclear classified information is protected as well.

implemented to confirm the absence of nuclear weapons, parties could decide that they have sufficient confidence in the presence of plutonium.

Detection of plutonium is most readily done by detecting neutrons emitted by the spontaneous fission of the plutonium-240 isotope, which is likely present in a concentration of about 6–7 per cent in weapon-grade plutonium.[191] Each gram of plutonium-240 emits about 1,000 neutrons per second and detection of this radiation is relatively straightforward.[192] The procedure for verifying the non-nuclear nature of inspected objects included in START and New START agreements is based on measuring the neutron emission of Pu-240.[193] Apparently, in developing the procedure the parties made the assumption that a nuclear weapon would have to contain a certain amount of plutonium and that no significant measures could be taken to shield plutonium within the inspected object. With these assumptions, the procedures outlined in New START provide high confidence that a nuclear object can be identified if presented for an inspection.

In those cases when the inspected item is a shipping container with material rather than a weapon inside, one would not be able to make the assumption about the amount of material in a container.[194] However, even in this case, measurement of the neutron emissions by Pu-240 can provide high confidence in the absence of plutonium in a container. The presence of 100 grams of plutonium, if left unshielded, could be confirmed in 1–2 seconds if a neutron detector were placed 1 m away.[195]

The presence of neutron-absorbing shielding material would certainly affect the prospects for successful detection. However, fission neutrons would still escape from the container no matter how effective the absorbent is, especially since the procedure assumes inspected containers of a certain size. The question is whether it would be possible to confirm the absence of plutonium over a practical duration. It is also important that the procedure described here assumes that the inspecting side can examine the reference object in advance, so the presence of neutron-absorbing material will be known to the inspectors.

As a reference for assessing whether 100 grams of plutonium can be identified in a container that contains neutron-absorbing material, the dimensions of the DOT 9975 container used by the US Department of Energy to ship plutonium to different US sites that handle nuclear material will be considered. This container is a 35-gallon drum with a diameter of approximately 53 cm standing roughly 92 cm high.[196]

One of the most effective materials for absorbing neutrons is concrete, and there exists a range of attenuation factors for neutrons as they travel through different types. The upper limit of this

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[191] The United States classified plutonium as weapon-grade if it contained less than 7 per cent of Pu-240. US Department of Energy, "The United States Plutonium Balance, 1944 - 2009. An Update of Plutonium: The First 50 Years, DOE/DP-0137, February 1996", June 2012, p. 9, http://fissilematerials.org/library/doe12.pdf. Reactor-grade plutonium contains considerably higher concentrations of Pu-240 and therefore would be easier to detect. Some processes can produce plutonium with a concentration of Pu-240 as low as 1–2 per cent. However, it can be safely assumed that Pu-240 will always be present in a sample. See, for example, J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium", *Science & Global Security*, vol. 4, no. 1, 1993, pp. 111–128.

[192] Steve Fetter et al., "Detecting Nuclear Warheads", *Science & Global Security*, vol. 1, no. 3–4, 1990, pp. 228–230.

[193] Alexander Glaser, "Ceci N'est Pas Une Bombe. Toward a Verifiable Definition of a Nuclear Weapon", presentation at the 58th Annual Meeting of the Institute of Nuclear Material Management, July 2017.

[194] As a point of reference, the containers that are used to dispose plutonium in WIPP would contain about 380 grams of plutonium. Frank von Hippel and Edwin Lyman, "Could the U.S. Waste Isolation Pilot Plant Go Critical If More Plutonium Were Disposed in It?", International Panel on Fissile Materials, 6 January 2016, http://fissilematerials.org/blog/2016/01/could_the_us_waste_isolat.html.

[195] This result was calculated using only a single neutron detector with an acceptance diameter of 10 cm, a detector efficiency of 10 per cent, and background radiation of 50 counts per square metre every second.

[196] US Nuclear Regulatory Commission, "Certificate of Compliance for Radioactive Material Packages No. 9975", 21 October 2014), https://rampac.energy.gov/docs/default-source/certificates/1019975.pdf.

attenuation factor for the most common compositions appears to be about 0.12 cm^{-1},[197] which raises the question whether the non-nuclear nature of a DOT 9975 container could be verified if 100 grams of plutonium was placed inside and surrounded with this absorbent material.

Given its 53 cm radius, the thickest layer of concrete that could be placed between plutonium in a DOT 9975 container and a detector would be 26.5 cm. Rounding up, we assume that 30 cm is the maximum thickness that may surround plutonium as it exits a facility. If a detector is placed 1 m away from the container, 100 grams of plutonium could be detected through this layer of shielding in about 35 minutes.

This provides a useful baseline for verifying the presence of plutonium. If the reference object submitted by the host contains absorbent material, the presence of that material will be known, and the inspecting party could adjust the measurement time accordingly.

The gross neutron count over the period of time that is set based on the result of examination of the reference object would constitute one element of the non-nuclear template. To exclude a scenario in which neutron-absorbing material is not present in the reference object, but added to the item presented to inspection, the template would also have to include the measurement of the integral neutron absorption in the container.

HIGHLY ENRICHED URANIUM

Detecting the presence of highly enriched uranium (HEU) in a container presents a more complex challenge. Here, passive detection of neutrons is not practical due to the low rate at which they are emitted by spontaneous fission.[198] And with each fission producing roughly seven prompt gamma rays, passive detection of gamma rays is a bit more promising but not much. Detecting even a large quantity of HEU that may be found in a uranium-only weapon through a thin tungsten tamper would only be possible over an hour from less than a metre away.[199] Thus active interrogation of some sort is probably required.

Active interrogation uses an external source of radiation to actively interrogate a sample of nuclear material, thereby inducing fissions and producing a stronger signal than that emitted by spontaneous fission alone. Using a readily available external 14 MeV source that emits 10^{11} neutrons per second[200] would allow a flux of about 8×10^5 neutrons through each square centimetre per second one metre away. If these neutrons are able to reach HEU, they will cause fissions and emit ~4.4 neutrons for each of these events in the process.[201] In most situations, active interrogation will produce a signal yielding more neutrons, but this technique still comes with challenges.

First, while not a fissile isotope capable of sustaining a chain reaction, uranium-238 can also be fissioned by 14 MeV neutrons releasing over 4 prompt-fission neutrons per nucleus in the process. This suggests that the neutron-induced fission of uranium-238 could produce about the same gross neutron count

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[197] W.L. Bunch, "Attenuation Properties of High Density Portland Cement Concretes as a Function of Temperature", General Electric Co., 22 January 1958), p. 236, https://www.osti.gov/biblio/4331636; Fritz A.R. Schmidt, "The Attenuation Properties of Concrete for Shielding of Neutrons of Energy Less Than 15 MeV", Oak Ridge National Laboratory, August 1970, table 12, p. 62, https://inis.iaea.org/collection/NCLCollectionStore/_Public/02/004/2004075.pdf.

[198] Only 0.30 neutrons per second are emitted by one kilogram of uranium-235 from spontaneous fission. Uranium-238 has a higher spontaneous fission rate, but its concentration in weapon-grade HEU is normally less than 10 per cent. Steve Fetter et al., "Detecting Nuclear Warheads", *Science & Global Security*, vol. 1, no. 3–4, 1990, pp. 236.

[199] Steve Fetter et al., "Detecting Nuclear Warheads", *Science & Global Security*, vol. 1, no. 3–4, 1990, pp. 225–253.

[200] Peter A. Egelstaff and John M. Carpenter, "Miniature Neutron Sources: Thermal Neutron Sources and Their Uses in the Academic Field", in *Neutrons, X Rays, and Gamma Rays: Imaging Detectors, Material Characterization Techniques, and Applications*, vol. 1737, International Society for Optics and Photonics, 1993, pp. 330–343, https://doi.org/10.1117/12.138674.

[201] Steve Fetter and Robert Mozley, "Emission and Absorption of Radiation", *Science & Global Security*, vol. 1, no. 3–4, 1990, p. 275.

as uranium-235, which complicates identifying whether HEU, natural uranium, or depleted uranium is being removed from a storage facility. This may require that the verification protocol treats any item containing uranium, no matter the enrichment level, as a nuclear object. This should not present a problem if the protocol is used to examine containers with fissile materials leaving or entering monitored storage. It would, however, make it difficult to use neutron interrogation to confirm the absence of nuclear weapons since a non-nuclear weapon could legitimately contain depleted uranium.

Second, 14 MeV neutrons scatter, both elastically and inelastically, off surrounding materials and create a larger neutron background than normally exists. These scattered neutrons will also bleed into the energy range of prompt-fission neutrons (~2 MeV), thereby complicating whether the detected neutron counts are a unique identifier of fission.[202] This would create a serious challenge for detecting uranium if the container (and the reference object) contain significant amount of high-Z material, such as tungsten. While the existence of the reference object would help address the issue of scattered neutrons, estimates suggest that if the detection relies on gross neutron count to confirm the absence of fission neutrons, the detection threshold becomes rather high. In an extreme, although not entirely realistic, for a DOT 9975 container filled with tungsten it would take one hour to detect 7.5 kg of HEU located at the centre of the container.[203]

One way around this problem would be to use a source of neutrons with energies below those of prompt-fission neutrons. Then the detection of 2 MeV neutrons would be an indicator of fission and thus the presence of fissionable nuclear material in an object that is verifiably not non-nuclear. Another benefit of a low-energy neutron source is that uranium-238 will not undergo fission from interrogation by neutrons with energies below 1 MeV, which would permit identifying the presence of uranium-235 instead of only uranium. Low-energy neutron sources are not easy to produce and may require large amounts of moderating material to slow neutrons down to the desired energy. However, when verifying the non-nuclear nature of objects leaving storage facilities, equipment of considerable size is not likely to be a concern. If these neutron sources are able to be designed with enough intensity, the remaining challenge for non-nuclear verification would be identifying whether shielding capable of absorbing neutrons is added to a container that may be used for smuggling HEU. Yet, even without a readily available source of low-energy neutrons, it should be possible to develop a measurement protocol that would use simple, existing techniques. For example, it might be possible to exploit the difference in angular distribution between scattered and fission neutrons or combine the gross neutron count with detection of gamma rays produced during fission. In general, adding several measurement channels to the measurement would help build a reliable non-nuclear template.

Adding measurement channels and combining different detection techniques would also provide a guard against an attack that would substitute uranium for non-nuclear material of the reference object. For example, it might be possible to replace some tungsten by uranium in a way that would keep the gross neutron count unchanged. However, the substitution could be revealed by an alternative measurement, such as gamma-ray radiography. This would take advantage of the difference between neutron and gamma-ray properties of the materials.[204]

In general, designing a reliable non-nuclear template for items that should be checked for the absence of HEU presents a number of challenges, especially if one considers extreme evasion scenarios. However, in most practical cases the availability of the reference object should help design a protocol that would confirm the non-nuclear nature of an inspected item.

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[202] Steve Fetter et al., "Detecting Nuclear Warheads", *Science & Global Security*, vol. 1, no. 3–4, 1990, p. 248.

[203] This calculation was done assuming that the number of neutrons scattering from or emitted by the HEU must exceed four times the square root of the active background measured from the tungsten carbide. This would provide the same level of confidence in confirming the non-nuclear nature of an object as required by the New START treaty.

[204] Steve Fetter et al., "Detecting Nuclear Warheads", *Science & Global Security*, vol. 1, no. 3–4, 1990, pp. 241.

This study describes a new approach to nuclear disarmament verification that would allow nuclear armed states to verifiably dispose of fissile materials that are no longer required for military purposes or to dismantle and eliminate nuclear weapons. The key advantage of the proposed arrangement is that it does not require access to sensitive information about fissile materials or weapons, which greatly simplifies the disarmament verification process.

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