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FM(C)T Meeting Series

Addressing Disparities in a Non-Discriminatory Fissile Material Treaty

UNIDIR RESOURCES

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Acknowledgements

Support for this project was received from The MacArthur Foundation and the Government of Germany.

About the Authors

Pavel Podvig is a Senior Research Fellow at the United Nations Institute for Disarmament Research (UNIDIR) and a researcher at Princeton's Program on Science and Global Security. Podvig also directs his own research project, Russian Nuclear Forces (RussianForces.org). His current research focuses on the Russian strategic forces and nuclear-weapons complex as well as technical and political aspects of nuclear non-proliferation, disarmament, missile defence, and the US–Russian arms control process. Podvig is a member of the International Panel on Fissile Materials. He holds a physics degree from the Moscow Institute of Physics and Technology and PhD in political science from the Moscow Institute of World Economy and International Relations.

Thomas E. Shea is an Adjunct Senior Fellow with the Federation of American Scientists (FAS). Before joining the FAS, Dr Shea had a distinguished career at the International Atomic Energy Agency where he helped to establish the basic IAEA safeguards implementation parameters and defined safeguards approaches for many complex nuclear facilities. Dr Shea was the head of the IAEA FMCT Working Group and also served as the head of the IAEA Trilateral Initiative Office and the Tripartite Project regarding safeguards at centrifuge enrichment plants equipped with Russian centrifuges.

Vitaly Fedchenko is a Senior Researcher with the European Security Programme at the Stockholm International Peace Research Institute (SIPRI). He works on nuclear security, arms control, and non-proliferation. Dr Fedchenko is the author or co-author of several publications on international non-proliferation and disarmament assistance, the international nuclear fuel cycle, and Russian nuclear exports. Most recently, he was the editor of *The New Nuclear Forensics*, published in 2014 by Oxford University Press.

Dealing with Disparities in a Non-Discriminatory Fissile Material (Cut-off) Treaty

Pavel Podvig

Introduction

The mandate to negotiate a treaty banning the production of fissile material for weapons and other explosive devices, contained in the Shannon report to the Conference on Disarmament, calls for a treaty that would be "non-discriminatory, multilateral and internationally and effectively verifiable."[1] A United Nations Group of Governmental Experts that worked in Geneva in 2014–2015 agreed that this mandate remains the basis for future negotiations, emphasizing that achieving a non-discriminatory treaty would require that the treaty obligations are applied equally to all its States parties.[2]

Equal application of obligations to all parties has long been considered one of the most valuable elements of the future treaty on fissile materials, commonly referred to as the Fissile Material (Cut-off) Treaty or FM(C)T. In practice, however, the treaty would inevitably have to deal with the fact that some States possess large stocks of unsafeguarded fissile materials and will retain nuclear weapons and weapon-usable materials for some time even if the treaty imposes obligations to reduce or eliminate those stocks.

The existence of unsafeguarded stocks will present a number of challenges that the future negotiations will have to address. First, the treaty's verification objectives—that is, what counts as a "significant quantity" of nuclear material and the timeliness of detection—might need to be adjusted to reflect the fact that nuclear-armed States already have

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1 Conference on Disarmament (hereafter CD), "Report of Ambassador Gerald E. Shannon of Canada on Consultations on the Most Appropriate Arrangement to Negotiate a Treaty Banning the Production of Fissile Material for Nuclear Weapons or Other Nuclear Explosive Devices", CD/1299, 24 March 1995.

2 United Nations General Assembly (hereafter UNGA), "Group of Governmental Experts to Make Recommendations on Possible Aspects That Could Contribute to but Not Negotiate a Treaty Banning the Production of Fissile Material for Nuclear Weapons or Other Nuclear Explosive Devices", A/70/81, 7 May 2015), paras 9, 10.

access to substantial quantities of materials. Second, nuclear-armed States are likely to demand that any verification activities on their territories must reliably protect sensitive information and hardware. Finally, there are questions about the applicability of certain verification techniques in States that have a history of significant production of fissile materials for weapons.

This paper provides a brief overview of existing approaches to verification of production of fissile material in States with unsafeguarded stocks. The aim is to pinpoint practical options that should be considered in the FM(C)T negotiations.

Existing stocks and treaty verification objectives

Since the central obligation of the FM(C)T is to ban the production of fissile materials for weapons, the verification system established by the treaty should provide sufficient guarantees that any fissile material that is produced after the treaty enters into force is not used for weapon purposes. In order to do so, the verification system should be able to detect undeclared production or diversion of fissile materials and to deter potential violations of the treaty. For this system to be effective, it should set specific objectives to guide the design of verification arrangements. These objectives will eventually determine the choice of tools and procedures to be applied at facilities that produce or handle fissile materials.

Since all non-nuclear-weapon States parties to the Nuclear Non-Proliferation Treaty (NPT) have agreed to comprehensive safeguards administered by the International Atomic Energy Agency (IAEA), there is considerable support for the idea of extending the IAEA comprehensive safeguards to all FM(C)T parties.[3] This approach would ensure that the future treaty is non-discriminatory in its nature and take advantage of existing verification tools and techniques developed by the IAEA. In practice, however, an extension of IAEA safeguards to a nuclear-armed State would have to account for its existing fissile material stock.

The IAEA safeguard system does, in fact, allow for a possibility that a State has unsafeguarded material. The early IAEA safeguards were project-oriented and applied only to materials and facilities supplied by the Agency or by member States or voluntarily submitted to safeguards by States.[4] The goal of the safeguard system was to ensure that safeguarded material and facilities were not used to further any military purpose.[5] This model did not exclude, however, the possibility that a State had materials *outside of the*

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[3] Ibid., para. 45.

[4] Safeguards would also apply to material produced at safeguarded facilities. International Atomic Energy Agency (hereafter IAEA), "INFCIRC/26. The Agency's Safeguards", 30 March 1961), art. I.1, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1961/infcirc26.pdf; IAEA, "INFCIRC/66/Rev.2. The Agency's Safeguards System (1965, as Provisionally Extended in 1966 and 1968)", 16 September 1968), art. II, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1965/infcirc66r2.pdf.

[5] IAEA, "International Atomic Energy Agency Statute (as Amended up to 23 February 1989)", 1989, arts III.5, XI.F.4.

safeguards that could be used for weapons or other military purposes. Accordingly, the first safeguard agreements did not contain specific safeguard objectives in terms of quantities or detection time.

For the purposes of the NPT the Agency developed a model comprehensive safeguards agreement, known as INFCIRC/153, that was used as a model for more robust safeguards in non-nuclear-weapon States. As specified in the agreement, the safeguards objective is to assure

the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.[6]

The question of what constitutes "timely detection" and "significant quantities" of nuclear material was left to the IAEA to determine. The Agency adopted an approach that sets the safeguards objectives on the basis of the time that would be required to manufacture a single nuclear explosive device from diverted material.

"Significant quantities", as defined by the Agency, represent "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded." Specific values for unirradiated direct-use material they are set at 8 kg for plutonium and 25 kg of uranium-235 in highly-enriched uranium.[7] These values were adopted by the Agency in 1977 at a recommendation of the Standing Advisory Group on Safeguards Implementation and have been used by the IAEA since then.[8] A number of experts have argued that these significant quantities do not accurately represent the actual amounts of material that would be required to build a nuclear weapon and that the Agency should adopt a much lower threshold for detecting diversion of fissile material.[9]

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[6] IAEA, "The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, INFCIRC/153 (Corrected)", 1972, art. 28.

[7] The significant quantity for uranium-233 is 8 kg. IAEA, *IAEA Safeguards Glossary*, 2002, paras 3.14.

[8] Marvin M. Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?", *Nuclear Control Institute*, August 1990, http://www.nci.org/k-m/mmsgrds.htm. The origins of these values are not entirely clear. The expert group appears to have based its recommendation on a 1967 UN report, which used the results of a study done in Sweden. The study concluded that some twenty-five kilograms of weapons-grade uranium or some eight kilograms of 95 per cent plutonium-239 would be required for the production of one nuclear warhead with a yield in the twenty kiloton range. See Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons", Natural Resources Defense Council, 13 April 1995, https://www.nrdc.org/nuclear/fissionw/fissionweapons.pdf; UN, "Effect of the Possible Use of Nuclear Weapons and on the Security and Economic Implications for States of the Acquisition and Further Development of These Weapons. A/6858", 10 October 1967, Annex IV, 2, 3, https://disarmament-library.un.org/UNODA/Library.nsf/3cec7176d3cb46e2852578b700660183/8725a4d5e25a2ae08525793700515b93/$FILE/A-6858.pdf.

[9] One proposal suggested adopting the following significant quantities: 1 kg for plutonium and uranium-233 and 3 kg of uranium-235 in HEU. See Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons".

These proposals have not been supported by the Agency, partly because they might require a significantly more complex safeguard arrangements than those that exist today.

Another component of the safeguard objective is the "timeliness" of detection of potential diversion. The IAEA defines the safeguard timeliness goal as the time required to convert the material into components of a nuclear weapon that is otherwise tested and ready. The conversion time depends on the physical form of the material. For unirradiated direct-use material in metal form, the conversion time can be a matter of days.[10]

It is important to note that the significant quantity values that are used by the IAEA relate to the potential acquisition of a *first* nuclear explosive by a non-nuclear-weapon State. There are additional factors that have to be taken into account if the safeguards are to be applied to facilities and materials in States that have (or have had) nuclear-weapon programmes.

First, most modern nuclear weapons require smaller amounts of fissile materials than older weapons, probably on the order of 3–4 kg of plutonium and less than 25 kg of HEU.[11] Nuclear-weapon States also have the expertise that would allow them to build an explosive device with a significantly smaller amount of material, if necessary. This means that if the goal of a verification arrangement really is to prevent diversion of the amount of fissile material required to build one nuclear weapon, smaller values for significant quantities than those currently used by the IAEA should be adopted.

Table 1. Estimated amounts of unsafeguarded fissile materials in nuclear-armed States

State	HEU, metric tons	Separated plutonium, metric tons
Russian Federation	680	180
United States	599	85.6
France	26	7
United Kingdom	19.8	3.2
People's Republic of China	18	1.8
India	3.2	5.7
Pakistan	3.1	0.2
Israel	0.3	0.9
Democratic People's Republic of Korea	0	0.03

Source: International Panel on Fissile Materials, fissilematerials.org.

[10] *IAEA Safeguards Glossary*, para. 3.13.

[11] International Panel on Fissile Materials (hereafter IPFM), "Global Fissile Material Report 2010: Balancing the Books: Production and Stocks", 2010, p. 148, http://ipfmlibrary.org/gfmr10.pdf.

Second, as shown in Table 1, nuclear-armed States already have large amounts of unsafeguarded fissile materials in their possession. As long as these States maintain their nuclear arsenals, diversion of one IAEA significant-quantity unit would have virtually no impact on their military capability.

The safeguard objectives that are applied to activities in non-nuclear-weapon States may not be suitable for verification arrangements in nuclear-armed States.

A uniform standard

Existing approaches to verification take for granted that the same objectives should apply to safeguarded materials and facilities in nuclear- and non-nuclear-weapon States alike. All NPT nuclear-weapon States have signed Voluntary Offer Agreements with the IAEA, which includes a mechanism for submitting fissile materials or facilities to Agency safeguards on a voluntary basis. These agreements specify that the objective of the safeguards procedures is "the timely detection of withdrawal from civil activities […] of significant quantities of nuclear material."[12]

In those nuclear-armed States that are not parties to the NPT, civilian materials and facilities can be covered by project-specific safeguards. The corresponding safeguards agreement, INFCIRC/66, does not contain a reference to safeguards objectives. It does, however, require the State to reach an agreement with the Agency on the definition of significant changes in the quantity of safeguarded material at a safeguarded facility. An INFCIRC/66 safeguard agreement also specifies the maximum frequency of IAEA inspections.[13]

From a technical standpoint, it is certainly possible to apply the same safeguard standards at all production facilities, regardless of whether they are located in nuclear- or non-nuclear-weapon States. On the surface, this approach might be the most direct way in which to treat all States in a non-discriminatory manner. There are, however, a number of practical challenges that should be considered.

First, even if the treaty verification system can provide assurances of timely detection of diversion of a significant quantity of fissile material at an individual production facility, it is more difficult to reach a broader conclusion about the absence of diversion of material at the State level. In the current IAEA practice, such a conclusion relies on the application of safeguards to *all* chains in the nuclear fuel cycle, which is the case in States that have an Additional Protocol in place. It is likely that the ability of the future FM(C)T verification system to provide assurances of non-diversion will depend on whether the system is focused exclusively on production facilities or whether it covers other parts of the fuel cycle as well.

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[12] Article 28 of the Voluntary Offer Agreements between the IAEA and the United Kingdom (INFCIRC/263), the United States (INFCIRC/288), France (INFCIRC/290), the Soviet Union/Russia (INFICR/327), and China (INFCIRC/369). See also *IAEA Safeguards Glossary*, para. 1.21.

[13] "INFCIRC/66/Rev.2", paras 43, 57; *IAEA Safeguards Glossary*, para. 11.16.

More importantly, the experience of safeguarding existing fissile material production facilities suggests that in some cases it would be extremely difficult to achieve the safeguard objective with the timeliness goal and significant quantities values currently used by the IAEA. This is, for example, the case with large spent fuel reprocessing plants, where even a small error in measurement of the material throughput could lead to an uncertainty that corresponds to many significant quantities of plutonium.[14] Other facilities that handle bulk material, such as plutonium in a solution during chemical reprocessing, may be difficult to deal with as well. The historical record shows that a number of facilities of this kind safeguarded by the IAEA (in Japan) and Euratom (in France and the United Kingdom) had encountered problems with accounting for the material and in most cases it took considerable time to discover the problem and resolve it.[15]

Some of the verification challenges associated with bulk processing facilities such as reprocessing plants can probably be resolved by developing better verification technology and instituting additional organizational measures, such as short-notice random inspections.[16] But the effectiveness of these measures has yet to be demonstrated in practice and they may incur considerable costs. Also, these measures may not be fully effective at reprocessing plants that were designed and built without safeguard requirements in mind. In these cases, the uncertainty in plutonium measurements would often be higher than that required to achieve the IAEA safeguard objectives.[17] In another example, the safeguard procedures that were developed for the uranium enrichment plants that Russia supplied to China appear to have involved "some modifications/interpretations of the existing IAEA Safeguards Criteria" to take into account specific features of the Russian-designed centrifuge facilities.[18] These examples suggest that there may be a limit to what new verification technologies and organizational measures, such as additional inspections, could achieve.

Other problems with applying strict safeguards objectives in nuclear-armed States might be even more difficult to address. There is evidence that suggests that even though the formal safeguards procedures are identical, practical application of safeguards in nuclear-armed States may not be as rigorous as that in NPT non-nuclear-weapon States. The extent to which this factor presents a significant problem is difficult to assess. On the one hand, the IAEA has successfully implemented item-specific INFCIRC/66 safeguards in nuclear-armed States, certifying that all safeguarded material remains in peaceful use.[19] At the

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[14] Marvin M. Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?".

[15] Alan J. Kuperman, David Sokolow, and Edwin S. Lyman, "Can the IAEA Safeguard Fuel-Cycle Facilities? The Historical Record", in *Nuclear Weapons Materials Gone Missing: What Does History Teach?*, Henry D. Sokolski (ed.), Carlisle, PA: Strategic Studies Institute and US Army War College Press, 2014), http://npolicy.org/books/2014muf/Kuperman%20Chapter%205.pdf.

[16] Shirley Johnson, "The Safeguards at Reprocessing Plants under a Fissile Material (Cutoff) Treaty", IPFM, 2009, http://fissilematerials.org/library/rr06.pdf.

[17] Ibid., p. 10.

[18] A. Panasyuk et al., "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges", in *IAEA Symposium on International Safeguards*, 2001, http://www-pub.iaea.org/MTCD/publications/PDF/ss-2001/PDF%20files/Session%208/Paper%208-02.pdf.

[19] IAEA, "IAEA Annual Report 2015", 2016, p. 12, https://www.iaea.org/sites/default/files/gc60-9.pdf. The States where the Agency applies INFCIRC/66 safeguards are India, Israel, and Pakistan. India also has an

same time, the experience of applying Euratom safeguards to facilities in France and the United Kingdom indicates that the inspectors may not have the power to question the actions of operators, even in the cases when they suspect a loss of safeguarded fissile material.[20] For example, at the UK THORP reprocessing plant in 2005, a loss of material containing about 160 kg of plutonium went undetected for about eight months.[21] On balance, even though today there is not enough data to judge whether this kind of incident could be a serious problem, it is something that the future verification arrangements should take into account.

Overall, the analysis of existing IAEA safeguard practices shows that these practices can accommodate a variety of different approaches. Even though the Agency is formally committed to using the same safeguard objectives at all safeguarded facilities, in practice it has some flexibility in modifying these objectives when necessary. A similar approach could be taken in the FM(C)T as well. In this case, quantity and timeliness detection goals could be specified for each facility that is submitted to verification. This approach would be compatible with the established practice of IAEA item-specific INFCIRC/66 safeguards and safeguards administered by Euratom. For example, the latter specifies that the frequency of taking physical inventory and specific safeguard procedures should be determined for each facility individually.[22]

In this approach, the modifications of safeguard objectives are likely to be relatively small, since they would be determined primarily by technical factors and design features of individual production facilities. In this case, the decisions about verification goals would be left to the FM(C)T implementation body, which could use its technical expertise to determine the appropriate verification objective for each fissile material production and handling facility.

Tailored verification objectives

Even though it would be possible for the FM(C)T verification system to achieve verification goals that are comparable to the existing IAEA safeguards objectives at individual facilities, achieving these goals on a State level might be considerably more difficult. It may require a significant degree of control over all elements of the nuclear fuel cycle, implementation of

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additional safeguard agreement with the IAEA, INFCIRC/754, applied to its civilian facilities. This agreement generally follows the INFCIRC/66/Rev.2 agreement.

[20] Alan J. Kuperman, David Sokolow, and Edwin S. Lyman, "Can the IAEA Safeguard Fuel-Cycle Facilities? The Historical Record."

[21] BNFL, "Board of Inquiry Report. Fractured Pipe With Loss of Primary Containment in the THORP Feed Clarification Cell", 26 May 2005, http://rsearch.hitechsvc.com/sesa/Analysis/ll/BNFL_THORP_BOI-070705.pdf; Health and Safety Executive, "Report of the Investigation into the Leak of Dissolver Product Liquor at the Thermal Oxide Reprocessing Plant (THORP), Sellafield, Notified to HSE on 20 April 2005", 2007, http://www.onr.org.uk/periodic-safety-review/thorpreport.pdf.

[22] European Union, "COMMISSION REGULATION (Euratom) No 302/2005 of 8 February 2005 on the Application of Euratom Safeguards", 28 February 2005, Art. 6, https://publications.europa.eu/en/publication-detail/-/publication/48e4f5fc-d06b-4069-ab40-8c47a3e6a1bb/language-en.

rather intrusive measures directed at detection of undeclared production, and tight controls over fissile material produced for non-proscribed military purposes. The resulting verification system might become too complex and expensive.

During deliberations in the Group of Governmental Experts, most participants supported the idea that the verification system should aim at achieving a balance between effectiveness and resource efficiency. At the same time, most participants underscored that effectiveness concerns should take precedence over concerns about cost.[23] It is possible, however, that practical implementation of verification arrangements in States with large stocks of unsafeguarded fissile material would be adjusted in response to the cost considerations, leading to de facto unequal application of verification standards. In this situation, it may be preferable to adopt an approach that would explicitly acknowledge the disparity in the size of unsafeguarded stocks.

Such a differentiated approach may require accepting a definition of verification objectives that is somewhat different to the one used by the IAEA for the purposes of comprehensive safeguards. One option is to use the approach to verification that has typically been used for arms control agreements that do not have a clear enforcement mechanism, such as US–Soviet and US–Russian arms control agreements. With this approach, a treaty would be considered effectively verifiable if significant violations that could affect the security of parties to the treaty are detected in time to allow them to respond and offset any threat that the violation may create.[24]

This approach to verification is largely compatible with the IAEA safeguards objectives in non-nuclear-weapon States, since it can be argued that in that case an acquisition of material for a single nuclear weapon would constitute a significant violation of the treaty. In a nuclear-armed State, however, the quantity of diverted material would have to be considerably larger than one weapon's worth before the diversion could undermine security of the treaty parties. The detection time could also be longer, as it would not be determined by the time required to manufacture a single nuclear weapon. If this standard is accepted, the verification system could be significantly simplified and adjusted to the circumstances of each inspected State. Specific verification objectives to be applied in a State could be determined by the FM(C)T implementation body that would consider all relevant technical factors, such as the size of unsafeguarded stock or technical capability of verification tools and methods applied at individual fissile material production facilities or at the State level.

There are, however, a number of challenges associated with a verification arrangement that relaxes the safeguard objectives for nuclear-armed States. First, it would probably require all nuclear-armed States to make declarations of their fissile material stocks. If these declarations are to serve as a basis for determining verification objectives, they would have to be verifiable or at least sufficiently detailed to allow for an independent

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[23] "GGE Report", para 47.

[24] Amy F. Woolf, *Monitoring and Verification in Arms Control,* Congressional Research Service, 2011, pp. 1, 7, https://www.fas.org/sgp/crs/nuke/R41201.pdf.

validation. This may prove to be a serious obstacle to implementing this approach, as few nuclear-armed States are prepared to share information about their stocks.[25]

More importantly, a verification approach that explicitly takes into account existing stocks of unsafeguarded material will be seen as undermining the non-discriminatory nature of the treaty, as it is often assumed that the verification standard in nuclear-armed States should not be different from the one that is currently used in the IAEA comprehensive safeguards. Having a different set of verification objectives for nuclear and non-nuclear-armed States would perpetuate the disparity that exists in the NPT today, and would probably not be supported by non-nuclear-weapon States in the negotiations.[26]

One way to address the non-discrimination issue would be for the FM(C)T to adopt a single set of verification objectives that would be suitable for all nuclear-armed States and would be applied uniformly to all parties to the treaty. In non-nuclear-weapon States, however, these objectives would be met automatically as a result of application of stronger IAEA comprehensive safeguards. This arrangement would create a formally non-discriminatory FM(C)T, but it would maintain a two-tier verification system. The treaty should also include a mechanism for adjusting its verification standard as the stocks of unsafeguarded fissile materials are eliminated or submitted to safeguards. The adjustment could also reflect advances in verification technologies. Eventually, the two standards are expected to converge.

A tailored approach to verification objectives in the FM(C)T is likely to meet opposition from many non-nuclear-weapon States. However, an open acknowledgment of the existing disparities and subsequent development of a mechanism that would address them might produce a stronger treaty and a more effective and efficient verification system.

Protection of sensitive information

To function properly, the FM(C)T verification system would have to be given access to a broad range of information about activities and facilities involved in the nuclear fuel cycle. Some of this information can be sensitive from the point of view of national security, non-proliferation, or on commercial grounds. The treaty would therefore have to include measures that would protect such information in a way that does not undermine the credibility of the treaty.[27] Practical implementation of these measures may take different forms, depending on the specific provisions of the treaty, its scope, and the verification objectives included in the treaty.

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[25] On verifiable declarations, see Anatoly S. Diakov et al., "FM(C)T Meeting Series—Verifiable Declarations of Fissile Material Stocks: Challenges and Solutions", UNIDIR, February 2017, http://unidir.org/files/publications/pdfs/fm-c-t-meeting-series-verifiable-declarations-of-fissile-material-stocks-challenges-and-solutions-en-671.pdf.

[26] In particular, there is support to the idea that "the non-discrimination principle should also aim to rectify perceived inequities under the Treaty on the Non-Proliferation of Nuclear Weapons with regard to safeguards obligations." "GGE Report", para 10.

[27] Ibid., para. 10, 53.

The problem would be relatively easy to solve if the treaty adopts a focused approach to verification, which assumes that the verification activities will be concentrated at fissile material production facilities.[28] In this case, as far as proliferation-sensitive or proprietary information is concerned, the FM(C)T could use the procedures developed by the IAEA. The IAEA, after all, has experience dealing with these issues at various production facilities. The safeguard procedures developed by the Agency for uranium enrichment and reprocessing plants normally take into account any potential sensitivities related to information collected during monitoring and inspections. One area that has not yet been covered by this process is the production of fissile material for non-proscribed military purposes. It is possible that some characteristics of this material, such as its isotopic composition, may be considered sensitive national security information. However, even though the material itself may be subject to special verification arrangements after it is produced, the FM(C)T is not expected to make an exemption for the production process.[29]

Should the FM(C)T adopt a comprehensive approach to verification, the verification activities would cover most, if not all, of the nuclear fuel cycle.[30] In this case, it is possible that nuclear-armed States would seek to exempt some of their facilities from verification on national security grounds. Even though the exemption would not apply to fissile material production facilities, it might be applied to former material production and handling sites, complicating the task of the treaty verification system.

The current IAEA practice provides some indication of how the national security exemption may be handled in the FM(C)T. A comprehensive verification system would probably include measures that are similar to those of the IAEA Additional Protocol. The Protocol requires States to inform the Agency about a broad range of nuclear cycle activities and includes provisions for a number of verification procedures, such as environmental sampling. In nuclear-weapon States, the Protocol amends Voluntary Offer Agreements with the IAEA that are already limited in scope and do not cover any non-civilian facilities. Also, with the exception of the Additional Protocol signed by the United States, the reporting and verification measures in the Additional Protocols signed by nuclear-weapon states apply only to the activity that is carried out in the interest of non-nuclear-weapon States (such as production of material for a non-nuclear-weapon State).[31]

The US Additional Protocol is the most comprehensive of the nuclear-armed States' safeguard agreements. Committing the United States to provide information about its

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[28] Ibid., para. 49.

[29] It should be noted that IAEA comprehensive safeguards agreement allows for non-application of safeguards to fissile material that is used for non-weapon military purposes. However, this does not apply to facilities that are producing that material. "INFCIRC/153", art. 14.

[30] "GGE Report", para. 50.

[31] See INFICRC/369/Add.1 (China), INFIRC/290/Add.1 (France), INFCIRC/327/Add.1 (Russia), INFCIRC/263/Add.1 (United Kingdom), and INFCIRC/288/Add.1 (United States). For an analysis of the provisions of these additional protocols, see Eva Uribe et al., "A Comparison of the Additional Protocols of the Five Nuclear Weapon States and the Ensuing Safeguards Benefits to International Nonproliferation Efforts", Los Alamos National Laboratory, 2009, http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-09-04012. India also signed an Additional Protocol, INFCIRC/754/Add.6, that amends its Safeguards Agreement with the IAEA.

national nuclear cycle activities, the US Protocol comes closer to the Additional Protocol non-nuclear-weapon States have concluded with the IAEA than those of the other nuclear-armed States. However, the United States reserved the right to exclude the instances where application of the Protocol "would result in access by the Agency to activities with direct national security significance to the United States or to locations or information associated with such activities."[32] Although the scope of this exclusion is difficult to assess, it is known to cover sites that were involved in the production of fissile materials in the past as well as some current facilities that can produce fissile materials.[33] Some of the excluded facilities, such as reprocessing plants, would be explicitly covered by the FM(C)T verification activities. Others, however, may remain exempt from routine verification on national security grounds.

The situation would be similar in other nuclear-armed States, as they would probably request a national security exemption for some of their past or current nuclear activities. Some of these activities may be relevant for maintenance of their nuclear weapon arsenal.[34] States might also request an exemption based on proliferation-sensitivity of past fissile material production activities.[35]

Even if the treaty would make provisions for excluding some facilities or locations from verification on national security or non-proliferation grounds, States would still have the responsibility to provide credible assurances of compliance with the treaty provisions.[36] Specific measures that can be applied in this case would have to be considered in the overall design of the FM(C)T verification arrangements and may become an essential condition for building an effective verification system.

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[32] IAEA, "INFCIRC/288/Add.1. Protocol Additional to the Agreement between the United States of America and the International Atomic Energy Agency for the Application of Safeguards in the United States of America", 9 March 2009), art. 1.b.

[33] US Government Printing Office, "The List of Sites, Locations, Facilities, and Activities Declared to the International Atomic Energy Agency", 2009, http://permanent.access.gpo.gov/lps113004/US-Rept-IAEA_2009.pdf.

[34] For example, in its 2006 proposal, the United States suggested that "activities involving fissile material produced prior to entry into force" should not be considered production and therefore would not be covered by the FM(C)T. United States Department of State, "Texts of the Draft Mandate for Negotiations and the Draft Treaty", 18 May 2006, art. II.3, http://2001-2009.state.gov/t/isn/rls/other/66902.htm. One example of such activity is a clean-up of weapon plutonium to remove the americium that accumulates in the material with time. CD, "Working Paper Submitted by Australia: Suggestions for the Substance of the Fissile Material Cut-Off Treaty", CD/1895, 14 September 2010, para. 23.

[35] For example, the United Kingdom withheld information about its early plutonium production from public release arguing that "technical information about the early years of the defence nuclear programmes of the Nuclear Weapon States is likely to be of particular value to any aspiring proliferator seeking to build a low-level, unsophisticated nuclear capability." United Kingdom Ministry of Defence, "The United Kingdom's Defence Nuclear Weapons Programme", *The National Archives*, 3 September 2003, http://webarchive.nationalarchives.gov.uk/20060130214247/http:/www.mod.uk/publications/nuclear_weapons/accounting.htm.

[36] "GGE Report", para. 53.

Past production of weapon materials

Another issue that the FM(C)T verification system must consider is the degree to which past fissile material production activities may affect the efforts to detect undeclared production facilities. All nuclear-armed States have a history of producing fissile materials for weapons, and in some cases this activity created a substantial environmental footprint that could mask future activities. This is especially relevant for such verification techniques as environmental sampling. It is known that some experts questioned the value of environmental sampling in detecting undeclared activity in States that had been operating unsafeguarded facilities on a significant scale.[37] Unlike the issue of a national security exemption, this is largely a technical question of the ability of the verification system to detect signs of an undeclared activity against a background created by past production activities.

As with all verification arrangements, the technical capability to detect undeclared activity must be measured against the broader verification objectives adopted by the treaty. At the same time, the technical limits of verification measures as well as their cost-effectiveness should be clearly understood if the treaty is to build a robust verification system. Environmental detection of undeclared fissile material production activity is a very difficult technical task in most circumstances.[38] This task would be further complicated by the presence of traces of past material production.

It should be noted that the IAEA has experience conducting safeguards activities, including local and wide area environmental sampling, in States that had produced fissile material for weapons in the past. One of these States is South Africa, which produced highly-enriched uranium for its nuclear-weapons programme before that programme was terminated. Another is Canada, which produced and separated weapon-grade plutonium in the early days of its nuclear programme.[39] Both States signed the Additional Protocol, allowing the IAEA to conduct a broad range of verification activities. The Agency eventually drew what is known as a broader conclusion that all material in these countries remains in peaceful activities. This process, however, was rather difficult as it required the IAEA to analyse a large amount of information about past fissile material production.[40] It is not known whether the verification tools such as environmental sampling were essential in these two cases, but it is important that the IAEA has experience with practical application of Additional Protocol tools in States with a history of fissile material production for weapons.

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[37] Ibid., para. 60.

[38] R. Scott Kemp, "Environmental Detection of Clandestine Nuclear Weapon Programs", *Annual Review of Earth and Planetary Sciences*, vol. 44, no. 1, 2016, pp. 17–35.

[39] South Africa produced about 800 kg of highly-enriched uranium. Canada separated about 17 kg of plutonium in 1949–1954 and then produced about 250 kg of weapon-grade plutonium in spent fuel for the United States in 1959–1964. See Institute for Science and International Security, "Nuclear Weapon Programs: South Africa", n.d., http://isis-online.org/country-pages/southafrica and "Nuclear Weapon Programs: Canada", n.d., http://isis-online.org/country-pages/canada.

[40] For example, the documentation submitted by Canada as part of its Additional Protocol reporting was said to contain about 300,000 pages. Interview with a former IAEA official, 12 August 2014.

Whether this experience would be applicable in States with more substantial past production is not entirely clear. From 2001 to 2005 the IAEA conducted wide area environmental sampling field trials around large-scale reprocessing and uranium enrichment plants in the United Kingdom and around a small-scale reprocessing facility in the Russian Federation.[41] To get a better understanding of the capability of the sampling technique, the IAEA should continue these tests and report its findings to the international expert community. Further research in this area could also help address the question of the extent to which past production activities would interfere with various verification procedures.

If inspectors have direct access to a facility that was involved in production of weapon materials in the past, but has been converted to civilian use, separating the signatures from new and old production can be done with techniques that use concentration of radioactive decay products to determine the time that has elapsed since production or last reprocessing of the material. These techniques are available for plutonium as well as for highly enriched uranium, although in the case of HEU they may not produce a reliable result for particles that are a few years old.[42] This would not be a problem for those enrichment plants that stopped producing HEU, as the accuracy of the method improves as the time since last production increases. However, the use of age-dating techniques would be more difficult at those uranium enrichment plants that continue production of HEU.

To summarize, the history of production of military fissile materials should not present an unsurmountable problem for the FM(C)T verification system. At the same time, further research is warranted to answer the questions raised by some States about the possibility of past production affecting the effectiveness of the verification arrangements.

Conclusions

The presence of large amounts of unsafeguarded fissile materials will certainly present a challenge for the FM(C)T and for the verification system that it will create. However, there are a range of options that would allow the treaty to address this problem in ways that would be generally compatible with the principle of non-discrimination.

Regarding verification objectives at individual production facilities, there are no technical reasons why the FM(C)T cannot adopt the significant quantity and timeliness of detection standards that currently guide application of IAEA safeguards in non-nuclear-weapon States. The FM(C)T can build upon the IAEA's and Euratom's experience of safeguarding large reprocessing and enrichment plants. It might be technically possible to adopt the current IAEA standards for verifying non-diversion of fissile material at the State level. This

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[41] J.W.A. Tushingham, "UK Safeguards Support Programme. Report on Activities and Progress During the Period 1 April 2012 to 31 March 2013", Department of Energy and Climate Change, August 2013, p. 5, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255025/srdp_pr33_2013_annual_report.pdf.

[42] IPFM, "Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty", October 2008, p. 49, http://ipfmlibrary.org/gfmr08.pdf.

approach, however, is likely to require building a comprehensive verification system that would cover all elements of the nuclear fuel cycle and therefore would be associated with considerable cost.

A different approach to defining the verification objectives in the FM(C)T would explicitly take into account the presence of unsafeguarded materials in the inspected State and adjust the values for significant quantities and timeliness accordingly. This could make the verification system considerably less complex without compromising its effectiveness. Although it may not be fully non-discriminatory, this approach could provide a viable option for the FM(C)T, especially if the treaty includes a transparent mechanism for adjusting the verification objectives.

Another potential verification challenge is that nuclear-armed States will most likely demand to have certain facilities and activities exempted from verification on national security or proliferation-sensitivity grounds. This challenge might be more difficult to resolve by purely technical means. It should be noted, however, that if the exemption does not apply to fissile material production facilities, which is expected to be the case in the FM(C)T, the treaty could allow some flexibility in this area. Development of verification technologies that provide non-intrusive access to sensitive facilities and managed access procedures could probably provide sufficient assurances of non-diversion of fissile materials.

The question of applicability of some verification techniques in States that have a history of substantial production of fissile materials for weapons would probably have to be addressed in the overall design of the verification system. The detection of undeclared fissile material production activity is an extremely difficult task and no single verification tool is likely to provide a definitive proof of non-compliance. At this point it is difficult to say if some specific technologies, such as environmental sampling, would be suitable for the purposes of the FM(C)T. Further research in this area seems necessary. In any event, since the treaty verification arrangements would rely on a range of different technologies, success or failure of any one of them would not necessarily affect the overall effectiveness of the verification system.

Dealing with Classified Materials in the Fissile Material Treaty

Thomas E. Shea

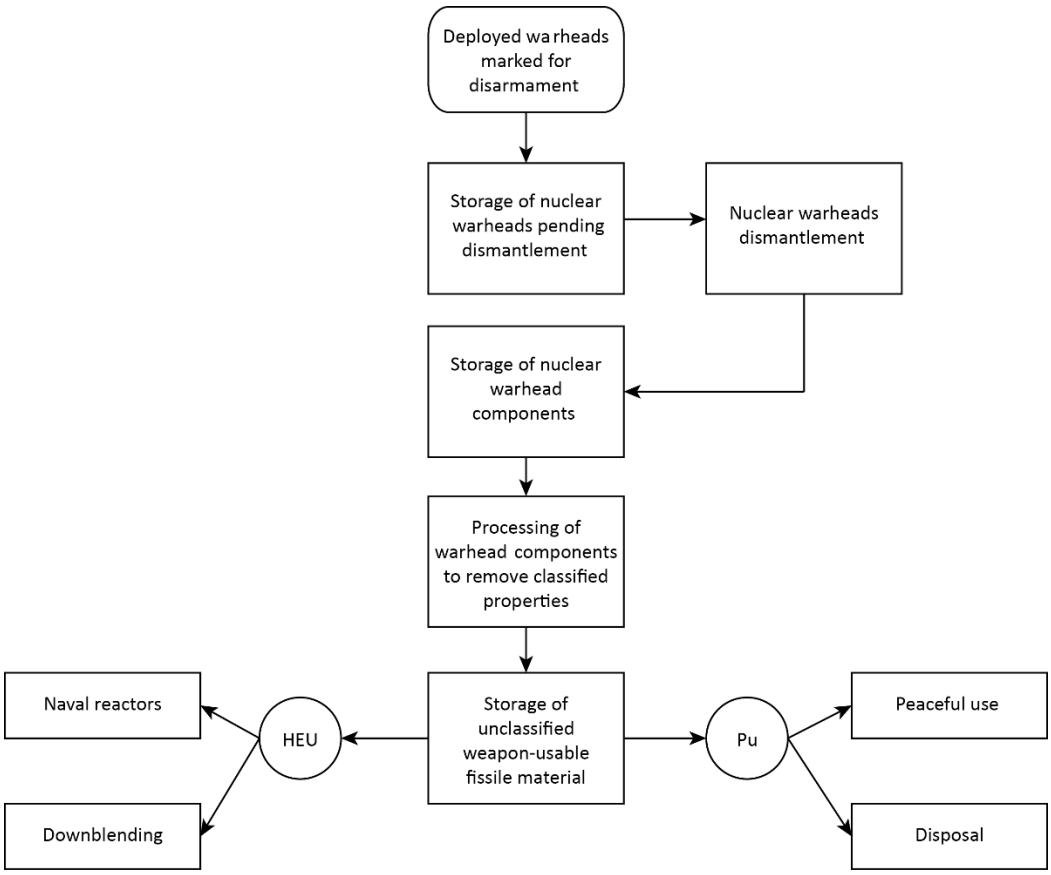
Introduction

The Shannon Mandate is now 22 years old. Yet, negotiations on a fissile material treaty are no nearer today than they were when Ambassador Shannon secured consensus on the FM(C)T negotiations in 1995. With Geneva diplomatic assignments generally lasting three years, seven generations of diplomats have cycled through, but the topics of discussion and the arguments offered have remained the same, the stalemate securely in hand. The principal reason for this absence of progress is that the nine nuclear-armed States do not seem to be interested in starting a formal negotiation process that would have to be then brought to a meaningful conclusion. Attempting to mollify these concerns, the scope of suggested fissile material treaties has sometimes been minimized to the extent that if implemented, the rump treaty would have little if any impact on the process of disarmament.

Negotiated nuclear arms reductions between the United States and the Russian Federation have thus far focused exclusively on delivery systems, rather than nuclear warheads. Controls on fissile material offer a complementary venue for progress on nuclear disarmament. A comprehensive fissile material treaty regime could address both nuclear disarmament and the prevention of re-armament. Figure 1 illustrates the disarmament steps that could be incorporated in a comprehensive fissile material treaty. The full treaty should also address measures to prevent re-armament, discussed later in this report.

The nuclear-armed States would likely oppose a comprehensive fissile material treaty—perhaps more vehemently than the limited scope proposals. But a more comprehensive fissile material treaty might command a strong consensus among non-nuclear-weapon States and hence define more clearly what the majority sees as an essential platform.

Figure 1. The disarmament process beginning with unclassified forms of fissile material and upstream eventually to include mounted warheads.



Such a treaty regime would be complex and would require patience, good will, and focused research and development. It would best be implemented in stages, beginning with a small number of States and expanding up and down the Figure 1 ladder and laterally to eventually include all nine nuclear-armed States.

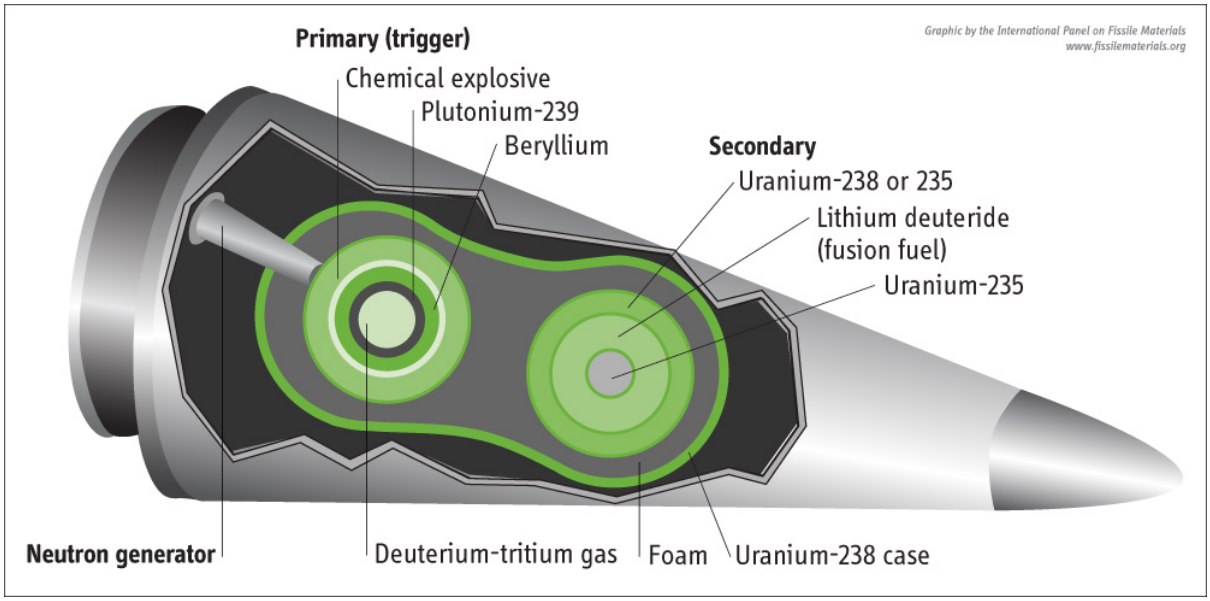
A comprehensive fissile material treaty could begin with securing weapon-usable fissile material stocks that have no classified properties and the production complex used to produce plutonium and highly enriched uranium for use in nuclear weapons. These obligations could be met by the IAEA today, using proven methods and highly skilled inspectors. Verification could be based on 1 per cent of the fissile material under IAEA verification in a State subject to this comprehensive fissile material treaty, in which the full inventory is under continuous surveillance and electronic seal monitoring, and confirmed on a monthly basis by on-site inspection measures.

Verification of fissile material with classified properties

Moving upstream would require that verification methods for classified forms of fissile material be adopted. Moving up to include weapon components, such as plutonium pits, would allow the treaty to include weapon components in storage and awaiting processing to remove classified shape, mass, alloying, and isotopic information. That alone could accelerate progress by more than 10 years. Accepting warhead components into a monitoring regime would require that the verification authority confirm that the objects stored are in fact warhead components, and when processed to remove classified properties, that the feed objects are as declared, that the processing integrity is assured, and that the amounts of plutonium and/or HEU recovered are measured using the best methods the IAEA has available.

Including weapon components would require that each nuclear-armed State and the verification authority responsible for controlling nuclear warhead components agree on the methods and procedures to be used.

Figure 2. What a modern nuclear warhead might look like



Source: From IPFM, http://fissilematerials.org/library/graphics/design_of_a_modern_thermonucle.html. Drawing adapted from "Final Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the Peoples Republic of China", 3 January 1999, also known as the Cox Report.

Moving up the ladder shown in Figure 1 to include complete warheads would increase the sensitivity of the information involved and would require the host (nuclear-armed State) to agree to additional operational steps necessary for such

verification. The same verification methods used on components could likely be adapted to verify warheads, with appropriate modifications.

This step could also accelerate progress toward verified disarmament by over ten years. Accepting warheads into a monitoring regime would require that the verification include stored warheads awaiting disarmament and the highly sensitive dismantlement process itself.

Moving up from stored warheads awaiting dismantlement to warheads mounted on weapon delivery systems marked for disarmament would further increase the sensitivity of the steps, bringing the verification into the military deployment arena. It would enable the comprehensive fissile material treaty to engage at the earliest point when a nuclear-armed State agrees to cut its deployed forces by a specified amount. Verification of this step would involve visual examination and the application of chain of custody techniques that would allow the inspectors to follow the de-mating of the warheads and their transfer to designated storage sites either on military bases, or returning to the weapon manufacturing complex.

Nuclear disarmament could proceed with no verification of fissile material with classified characteristics. The reasons for including such steps would be to augment the assurance that each nuclear-armed State gains by participating in verifying progress in another nuclear-armed State.

Decision factors affecting the selection of verification methods for classified forms of fissile material

Five factors will be critical in the selection of verification methods and procedures that could be used in relation to classified forms of fissile material for nuclear disarmament.

Information security vs authenticity

The most fundamental and absolute requirement for verification methods for classified forms of fissile material is the security/authenticity conundrum:

- No State possessing nuclear weapons shall accept any verification method or procedures that could allow unauthorized access to nuclear weapon design or manufacturing secrets.
- At the same time, the verification methods must be based on sound scientific principles and the procedures for their use must be carried out in such a manner as to provide authentic results.

During the Trilateral Initiative, Russian participants noted that if the IAEA wanted to use verification equipment that the IAEA would bring to Russia, every piece of

equipment must first be submitted to Russian security officials for examination.[1] Each examination could take as long as 18 months, and at the end, if the equipment was found to be unacceptable, the IAEA would be so informed, but not told why. Moreover, the equipment would likely not be returned to the IAEA. If, on the other hand, an item of equipment was found to be acceptable to the Russian security officials, then the IAEA would be allowed to use it under specified arrangements. But the IAEA could not re-examine the equipment, as that would void the Russian approval. And as the IAEA could not conclude that the equipment had not been modified, it could no longer assure its authenticity.

The way forward found under the Trilateral Initiative was as follows:

1. Russian, US, and IAEA technical experts would jointly develop design specifications for the equipment, including detailed hardware drawings.
2. All computations would be performed using processors that would be built for this purpose alone, only have the capability to perform the specified operations, and not be programmable for any other purpose.
3. Prototype systems would be designed and tested by the three parties to confirm that the equipment meets all requirements.
4. Upon production of the equipment for actual use, the IAEA, the Russian Federation, and the United States would:
    - agree on the numbers of each piece of equipment and essential components to be manufactured, taking into account a sustainability plan to maintain operational functionality over an agreed interval;
    - jointly monitor all stages of producing all verification equipment at all stages of its manufacture, and conduct joint acceptance tests;
    - select, at random, components, materials, and full systems for testing, independently, by the IAEA and the host state;
    - transport equipment approved for use to the facility where it would be used;
    - secure all equipment and replacement modules in a secure installation at the facility, maintaining the equipment in operational standby mode;
    - install, test, and commission initial equipment sets at the facility by the IAEA and host state officials; and
    - test, replace, and remove from the facility equipment and replacement modules selected by and for IAEA examination at a designated IAEA location.

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[1] T.E. Shea and L. Rockwood, "Nuclear Disarmament: The Legacy of the Trilateral Initiative", Deep Cuts Working Paper, no. 4, March 2015, http://deepcuts.org/images/PDF/DeepCuts_WP4_Shea_Rockwood_UK.pdf. In a subsequent effort, Shea and Rockwood proposed an extension of the Trilateral Initiative to include all nuclear-armed States and all classified forms of fissile material associated with nuclear weapons. T.E. Shea and L. Rockwood, "IAEA Verification of Fissile Material in Support of Nuclear Disarmament", Belfer Center, May 2015, http://belfercenter.ksg.harvard.edu/files/iaeaverification.pdf.

Broadening the scope from a “trilateral” undertaking to a more inclusive endeavour will make decisions more difficult. Nuclear disarmament will require cooperation by each nuclear-armed State and the designated verification authority.

In the disarmament phases of such a treaty, each nuclear-armed State will be seeking credit for the steps it takes; the verification authority must be able to verify that the steps taken and the materials presented are bona fide. In the complementary phase of such a treaty, the verification authority will be charged with providing assurance that each nuclear-armed State is not attempting to circumvent the restrictions it accepts by acquiring fissile material that it could use to rebuild its arsenal.

Disarmament value

Eventually, depending on its adversarial relations with other nuclear-armed States, a State will demand increased assurance that further steps on its part are not undermining its national security. It may be enough, however, to begin the process of accepting objects for monitored storage based on information that is less complete that it might later require. In the following list, nine steps are identified. The first three formed the basis of the Trilateral Initiative involving the Russian Federation, the United States, and the IAEA.

1. Does the object contain plutonium and/or highly enriched uranium?
2. Is the isotopic composition of the plutonium and/or HEU in the object typical of that found in nuclear weapons?
3. Does the mass of plutonium and/or HEU within the object exceed a minimum level set for such objects at the facility where the verification activities are taking place?
4. Other physical attributes:
    a. Is the geometry of the Pu and/or HEU components consistent with those of nuclear weapons?
    b. Are the dimensions, weight, conductivity, and moment of inertia the same for all items of a given population?
5. If an object presented for verification does not contain a warhead or warhead components, does the measurement allow the measurement of the exact mass of plutonium and/or HEU and the isotopic composition of both?
6. If exact measurements of the mass or plutonium and/or HEU are not permitted, does the measurement allow for placing the results in bins: e.g., for plutonium, ≤ 1kg; 1–2 kg; etc.?
7. Does the measurement allow estimates to be made of the total amount of plutonium and/or HEU under monitoring and verification?
8. Does the measurement allow confirmation that the object contains a nuclear warhead, a “physics package”, warhead components, or other fissile materials associated with nuclear weapons?
9. Does the verification allow the specific model identity of a nuclear warhead, “physics package”, or pits and/or secondaries to be confirmed?

Ideally, all nine steps could be included, and along the way, classification requirements could be modified to permit the inclusion of additional disarmament-related information. It will be useful to consider starting with minimal requirements for monitored storage while continuing research and development to enhance the disarmament value of the verification methods applied. Verification pursuant to the Trilateral Initiative would have been limited to items 1–3 above.

Susceptibility to cheating

The vulnerability of any method or combination of methods proposed must be tested by the State and the verification authority taking into account the provisions of the first factor, security vs authenticity.

Practicality

Verification methods that impose great costs, safety risks, or disruptions to normal operating practices should be avoided wherever possible.

Affordability

The costs of verification equipment and the support costs associated with their use shall be as low as possible, consistent with the need to provide the authenticity, accuracy, and efficiency necessary to carry out the designated verification mission.

Candidate verification methods for classified forms of fissile material

Including the Trilateral Initiative and recent work, there are now four candidate methods for verifying classified forms of fissile material. These are identified in Table 1. Hopefully more will follow, principally from universities and laboratories in States not possessing nuclear weapons. None of the current methods is suitable for immediate use; all would need careful scrutiny and adversarial testing by the nuclear-armed States in their secure locations, and in an international centre for nuclear disarmament research and development, to enable all States to have a role in this critical determination.

Table 1. Candidate methods for verifying classified forms of fissile material

#	Title	Description	Remarks
1	Attribute measurements with Information barriers.[2]	Uses sensitive measurement instruments to answer unclassified questions.[3] For example, for plutonium: a. Is Pu present in the object presented? Yes or No? b. Is the isotopic composition typical for weapon material? Is the ratio of Pu-240 to Pu-239 less than 0.1? Yes or No? c. Is the amount of plutonium contained in an object more than a threshold established at a given facility? Yes or No?	Advantages: a. Method could in principle be used on all classified fissile material. b. A prototype was built and tested. c. In the Trilateral Initiative, Russia and the US agreed that this method could be used. The IAEA agreed in principle. d. Disadvantages: e. Method provides only 1–3 nuclear disarmament information; f. Requires extraordinary methods to prevent disclosure of classified information to inspectors; g. Requires extraordinary methods to assure authentic verification.

[2] T. Shea and L. Rockwood, "Deep Cuts Working Paper #4: The Trilateral Initiative", Deep Cuts Commission, March 2015, http://deepcuts.org/publications. The Trilateral Initiative agreed on a system for "attribute verification by neutron and gamma ray assay using information barriers", or AVNG. The AVNG system combines a high-resolution gamma ray detector (HPGe = high purity germanium solid state detector) plus a neutron multiplicity detector. Originally the neutron multiplicity detector was to be equipped with over 100 helium-3 (He-3) neutron detector tubes, but a global shortage in He-3 required that an alternative be used (plastic scintillator detectors doped with neutron capture material). After the Trilateral Initiative was concluded, American and Russian experts continued work on the AVNG system under a bilateral cooperative programme and eventually succeeded in building a prototype system that was tested by Russian security officials.

[3] S. Razinkov, A. Livke, S. Kondratov, J.Thron, M. Bulatov, M. Leplyavkina, D. Sivachev, S. Tsybryaev, A. V'yushin, D. W. MacArthur, "The Design and Implementation of the AVNG", Abstract #302, Proceedings of the 51st Annual Meeting of the Institute of Nuclear Materials Management, Baltimore, MD, July 2010.

#	Title	Description	Remarks
2	A zero-knowledge protocol for nuclear warhead verification using neutron interrogation.[4]	"A new approach to nuclear warhead verification that incorporates a zero-knowledge protocol, which is designed in such a way that sensitive information is never measured and so does not need to be hidden. We interrogate submitted items with energetic neutrons, making, in effect, differential measurements of both neutron transmission and emission. Calculations for scenarios in which material is diverted from a test object show that a high degree of discrimination can be achieved while revealing zero information."	"The proposed technique suggests a way to perform comparisons or computations on confidential data without measuring the data in the first place." The system requires an appropriate neutron source and detection system.
3	Physical cryptographic verification of nuclear warheads using nuclear resonance fluorescence.[5]	"We introduce a tomographic method that simultaneously resolves both the geometric and isotopic makeup of an object. We also introduce a method of protecting information using a provably secure cryptographic hash that does not rely on electronics or software. These techniques, when combined with a suitable protocol, constitute an interactive proof system that could reject hoax items and clear authentic warheads with excellent sensitivity in reasonably short measurement times."	"We present a mechanism in the form of an interactive proof system that can validate the structure and composition of an object, such as a nuclear warhead, to arbitrary precision without revealing either its structure or composition." The system requires an appropriate source of high-energy photons, e.g. an electron linear accelerator, plus a gamma ray spectrometer.

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

[5] R. Scott Kemp et al., "Physical Cryptographic Verification of Nuclear Warheads", *Proceedings of the National Academy of Sciences*, vol. 113, no. 31, 2016, pp. 8618–23.

#	Title	Description	Remarks
4	Cosmogenic muon verification method with physical encryption.[6]	Muons stop in matter displacing atomic electrons that cascade down to the atomic ground state, emitting characteristic gamma rays with energies in the 2-10 MeV range. All of the gamma rays are emitted instantaneously allowing a very tight trigger window. These gamma rays would escape from the object being verified. Measuring their spectrum provides a means to infer the elements present. Isotope shifts (which can also be measured) will be large here, since the muon is so close to the nucleus and this should identify specific isotopes. If holes are drilled in the top and bottom detectors at random locations, detection of some of the muons will be blocked according to the locations and trajectories of the holes, thereby encrypting the physical details of the shape and composition of the object being verified.	The muons would come from cosmic radiation (and thus are free). This technique should be background-free. The gamma rays could be detected either with common scintillator detectors or high resolution HPGe gamma ray detectors. The overall system would be cheap (relatively) and rather portable. Two methods would protect classified information: Physically encrypted aperture masks; and Low counting statistics, by limiting the measurement time of each object.

A combination of two or more methods may prove to be necessary and efficient. This activity could be carried out during the initial phase of implementation, concentrating on unclassified forms of weapon-origin fissile material and weapon-usable fissile material.

[6] P. Huber, Virginia Tech, private communication.

Verification planning parameters

Verification methods and performance requirements for a comprehensive fissile material treaty should reflect progress in relation to nuclear disarmament, anticipating that in the final stages of disarmament, the requirements for disarmament should converge with those for non-proliferation.

Under the Trilateral Initiative, if an item presented for monitored storage failed the acceptance test, the only action that the IAEA could have taken was to reject the item and not accept it for monitored storage. Under non-proliferation safeguards, if an item fails a test, more intensive tests are required, involving, where appropriate, the use of highly accurate laboratory measurements with no restrictions.

The IAEA has adopted parameters for the terms included in the safeguards objective (INFCIRC/153, §28) related to proliferation, which is based on the acquisition of the first nuclear weapon by a non-nuclear-weapon State. The parameter "significant quantity" is significant in that regard, and the values adopted relate to corresponding assumptions that the State does not possess a tested design, and hence is likely to be inefficient, and that its process losses are likely to be substantial. As a State gains experience and its modelling becomes more refined, the significant quantity values should no longer be understood in terms of a number of weapons that could be made.

In a disarmament process, each nuclear-armed State would begin the process with an inventory of deployed nuclear weapons, which the State itself will obviously know. It will declare its inventory at some point in the process, perhaps truthfully, perhaps not. Estimates of its arsenal will be made and be updated over time by its nuclear adversaries, and by experts who specialize in such assessments.

No two arsenals are identical. They normally include more than one nuclear-weapon system, often more than one warhead model, and sometimes more than one model warhead component (i.e., pit and/or secondary). The composition of each arsenal will be changed from time to time as necessary to maintain its functionality.

The amount of Pu and/or HEU in an arsenal will be different from model to model, and within a model may vary if a warhead allows for variable yields.

Verification planning in relation to nuclear disarmament could begin with the estimated total arsenal inventories for each of the nine nuclear-armed States, revising these initial estimates as better estimates are made, and as arms reductions decrease the number of deployed weapons in each nuclear-armed State. Corresponding to the IAEA "significant quantity" values, for each State, it could be assumed that if it managed to increase its arsenal by some percentage, e.g. 10 per cent, then that State would pose a significantly greater risk to its nuclear adversaries, who then might wish to take countermeasures. For stored warheads and warhead components submitted for monitoring, the sample parameters could then be set assuming that each container would hold a complete warhead or the necessary

makings. Such an arrangement would provide for a natural convergence with non-proliferation safeguards—when the arsenal has been reduced to a total of ten (or fewer) deployed weapons, the significant number for verification planning would be one.

For other classified forms of fissile material that are not specifically related to a nuclear warhead, the number of containers to be used as the verification goal could be set at 1 per cent of the total submitted for verification.

Under this concept, 100 per cent of all items would be verified upon being presented for acceptance into the monitoring and control system, using one or a combination of methods to be approved for such use. Periodically thereafter, the verification authority would re-verify the monitored inventory to maintain confidence in the status of monitoring. The frequency and methods to be used could be determined in relation to each facility. This would involve a choice of containment and surveillance measures, access arrangements, containers, the use of in situ sealing, and motion monitoring. The choice would take into account the essential character of the monitored objects and the relative ease with which they could be used to increase the number of deployed nuclear weapons in that State.

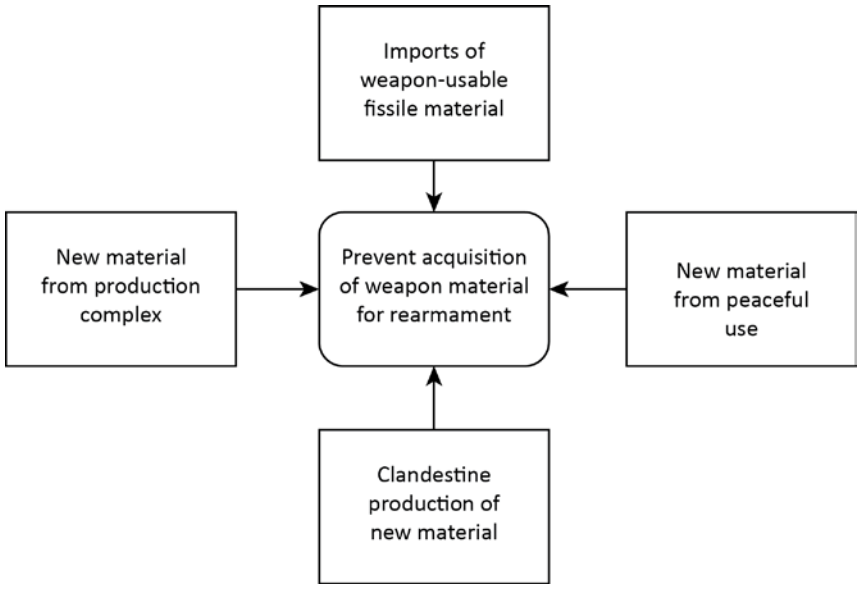
Preventing re-armament

In addition to managing the fissile materials recovered through disarmament as shown in Figure 1 (including the disposition actions and the use of HEU in naval reactors as shown at the bottom of the figure), a comprehensive fissile material treaty should prevent re-armament through any plausible means. It will be necessary and appropriate to phase these measures in gradually, and to tighten the verification requirements as the process of disarmament goes forward. The steps involved are shown in Figure 3.

All of these actions are implemented by the IAEA under the current safeguards agreements in all non-nuclear-weapon States Parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) under comprehensive safeguards agreements concluded pursuant to IAEA publication INFCIRC/153 and augmented, for many states, by an Additional Protocol concluded pursuant to INFCIRC/540.[7] And while IAEA non-proliferation safeguards research and development needs are met chiefly through voluntary Member State support programmes in approximately 20 States, the existing methods are fully capable. The verification methods already exist for these activities and are used routinely.

[7] See, for example, T.E. Shea, "Assuring Effective IAEA Verification of the Iran–P5+1 Agreement", Search for Common Ground and Princeton University, July 2015, https://www.sfcg.org/wp-content/uploads/2015/07/Shea_Paper_Final-3.pdf.

Figure 3. The actions necessary to prevent a nuclear-armed State from acquiring fissile material that could enable the State to manufacture replacement weapons during or after the dismantlement of its existing arsenal



The verification requirements of a comprehensive fissile material treaty should include these same measures as a means to diminish and eventually eliminate the discrimination that now exists in favour of the nuclear-armed States.

Also, in detecting non-compliance with safeguards agreements, the IAEA employs methods that complement the traditional nuclear material accountancy arrangements, making it possible for the IAEA to question a State over picograms of nuclear material with suspicious properties, or over satellite imagery showing actions that are not connected with the peaceful use of nuclear energy. Moreover, the provisions of Article VIII.A of the IAEA Statute encourage States to provide "such information as would, in the judgment of the member, be helpful to the Agency." In the case of the questions about possible military dimensions to Iran's nuclear program, the IAEA Director General informed the Board of Governors that more than 10 Member States had provided such information.

Under non-proliferation safeguards, populations of items are verified using a random sampling plan to detect gross defects (e.g. empty items), partial defects (some of the contents removed), or bias defects (a diversion is concealed by spreading it over hundreds or possibly thousands of items).

As progress is made towards the elimination of nuclear weapons, the verification goals in relation to preventing re-armament should be intensified, ultimately converging with those used in non-nuclear-weapon States. For example, the verification goal could be set equal to (10 per cent of the number of remaining

weapons in an arsenal) x 1 significant quantities (using the IAEA values of 8 kg Pu, or 25 kg 235U in HEU).

When a State has 10 or fewer nuclear weapons remaining in its arsenal, the verification provisions deterring re-armament should expand to include all nuclear material using the same verification requirements as for non-nuclear-weapon States.

Conclusions

Twenty-two years after agreement on the Shannon Mandate, States possessing nuclear arms continue to block meaningful negotiations on a Fissile Material Cut-Off Treaty. There is no evident change of will on the horizon. In the meantime, the non-nuclear-weapon States Parties to the NPT grow increasing frustrated at the lack of progress. With the 50th anniversary of the NPT's entry into force coming up in 2020, the NPT Review Conference marking that anniversary is likely to be very contentious.

A fissile material treaty limited to stopping the operation of the production complexes in the nine nuclear-armed States would be a useful step, but it would not provide significant progress toward establishing the framework for, or progress toward, the elimination of existing arsenals and the measures necessary to prevent re-armament.

A comprehensive fissile material treaty incorporating the elements set out in this report could provide a critical step in enabling disarmament to begin in earnest. Two further steps, however, will be essential.

- First, there is a need for the international community to create an international centre for nuclear disarmament research and development. This would provide an arena for all States to contribute to meeting this universal need. Establishing a centre would be an important step toward extending the scope of verification to classified forms of fissile material.
- Second, the framework will probably require progress toward negotiating a treaty on nuclear disarmament, which would provide the legal framework for disarmament to proceed.

I believe that together, these steps can bring about the international relations necessary for disarmament to become an honest undertaking.

FM(C)T Verification in States with Significant Nuclear Material Production History: Possible Contributions from the Discipline of Nuclear Forensic Analysis

Vitaly Fedchenko

Introduction

The nuclear fuel cycle is a chain of nuclear facilities and activities involved in the production of nuclear materials and sometimes nuclear power, interconnected by streams of nuclear material. Nuclear material can be visualized as moving through this system or being stored in parts of it, most often changing its physical, chemical, elemental, or isotopic characteristics with every step of the fuel cycle. In other words, each use or even simple storage of nuclear material will leave a mark. Nuclear material will retain some information about its history, at least for some time. It may be possible in many cases to "read" this information from the materials and learn what happened to them and what they were like in the past. This can often be achieved because nuclear fuel cycle facilities use only a limited number of physical and chemical processes that can be applied to a limited number of existing nuclear material types, and researchers in most cases know, at least approximately, what those processes and materials are.

The discipline of nuclear forensic analysis, or nuclear forensics, examines nuclear and other radioactive materials for the purposes of various national and international security applications. The terms "nuclear forensic analysis" and "nuclear forensics" were probably first coined in the context of combating illicit trafficking of nuclear materials in the early 1990s. However, the discipline traces its origins to 1940s and was used under different names in several contexts, as shown in Table 1. Nuclear forensic analysis can be defined as the analysis of a sample of nuclear or other

radioactive material and any associated information for determining the history of the material for the purposes of national or international security applications.[1]

In a nutshell, nuclear forensic analysis works the following way: Once a sample of a nuclear (or other radioactive) material is obtained, a well-understood process can be applied to extract useful information from it. First, the material can be characterized, i.e. measured to determine the four kinds of material characteristics mentioned above (physical, chemical, elemental, and isotopic characteristics). This step will yield a raw data as a result—numbers or perhaps images—that has little meaning by itself. For example, a plutonium sample can be determined to comprise plutonium metal with additional 0.8 weight per cent gallium and an isotopic composition of Pu-239 isotope of 93 per cent and Pu-240 of 6 per cent. The second step is the interpretation of obtained data—the process of correlating the characteristics of the sample with information on known methods of material production, handling, and use. Nuclear forensics interpretation is aided by the concept of nuclear forensic signatures, which are essentially sets of material characteristics that enable a material in the sample to be identified.[2] In the example above, the characteristics could be seen as a "signature", revealing that the material in the sample is weapons-grade plutonium. This second step—normally requiring an experienced analyst's expertise—is expected to yield useful, meaningful information. At the third step that information can be combined with information from other available sources to reconstruct the history of a material in the sample or an event associated with it.

Table 1. Applications of nuclear forensic analysis for nuclear security and treaty verification

Framework	Typical sample form, content (and source)	Information to be inferred on the material's or item's history
Non-proliferation and disarmament		
NPT (environmental sampling for safeguards)	Particles (on swipes from material handling areas) Air, water, sediments, vegetation, soil, biota	Age, production process (consistency with declaration)

[1] For more information, see V. Fedchenko (ed.), *The New Nuclear Forensics: Analysis of Nuclear Materials for Security Purposes,* Oxford University Press, 2015, pp. 4–7. The International Atomic Energy Agency is using a narrower definition for the purposes of its nuclear security work, where "nuclear forensics" is "the examination of nuclear or other radioactive materials, or of evidence that is contaminated with radionuclides, in the context of legal proceedings under international or national law related to nuclear security". IAEA, *Nuclear Forensics in Support of Investigations: Implementing Guide*, IAEA Nuclear Security Series, 2015.

[2] For a strict definition see IAEA, Nuclear Forensics in Support of Investigations: Implementing Guide, 2015, p. 26.

Partial Test-Ban Treaty	Particles and gases (weapon debris)	Nuclear explosive origin of debris, their age and location, especially if leaked from an underground test
CTBT (IMS and on-site inspections)	Particles and gases in air (weapon debris)	Nuclear explosive origin of debris
Fissile Material (Cut-off) Treaty (if and when negotiated)	Noble gases (reactors, isotope production or reprocessing facilities) Bulk graphite samples (shut-down plutonium-producing reactors)	Origin and age of nuclear materials and fuel cycle effluents Reactor's lifetime plutonium output
Nuclear security		
Attribution in an illicit trafficking case	Nuclear or radioactive materials, items or bulk form (nuclear fuel cycle facilities)	Age, production process, manufacturer
Nuclear terrorism event attribution	Particles and gases (weapon debris) Particles (RDD) Human body and excretions (RDD and poisoning)	Design features of explosive device, material used, explosion yield, device and material origin
Nuclear intelligence		
Monitoring of foreign explosions	Particles and gases (weapon debris)	Explosive device's characteristics
Monitoring of foreign facilities and materials	Noble gases (reactors, isotope production or reprocessing facilities) Particles in man-made media (e.g. wine or clothing), in air, water, sediments, vegetation, soil, and biota	Nuclear material production
National weapons development programmes	Bulk material, particles, and gases (from weapon debris)	Explosion yield, device's efficiency, other performance characteristics

Source: V. Fedchenko, "Nuclear Material Analysis for Forensic and Other Security Purposes", Institute of Nuclear Materials Management, 53rd Annual Meeting of the Institute of Nuclear Materials Management, 10–14 July 2012, p. 4.

The verification system for the Fissile Material Cut-off Treaty, if and when negotiated, will be able to "stand on the shoulders of giants", i.e. employ multiple techniques and disciplines that have already been developed. Nuclear forensic analysis in its contemporary form can contribute to the FM(C)T verification system with techniques and methods that were first proposed in the 1940s as part of the national weapons-development programmes and efforts to monitor foreign nuclear facilities and nuclear-weapons tests. Then they were further developed and employed by governments for many years and later offered for verification of major international treaties, including the NPT (in the context of safeguards and for verification of the Iraqi nuclear programme) and the CTBT. Significant improvements of these techniques and methods have also been made in the context of combatting illicit trafficking starting in the 1990s.

This paper will review how existing applications of these methods could be applied to various aspects of the FM(C)T verification system. As has been discussed elsewhere, the most widely accepted model for verifying a future FM(C)T would impose clear requirements on the architecture of the verification system of the future treaty.[3] Specifically, the FM(C)T verification system is expected to have three distinct verification missions:

1. verification at declared production facilities, possibly including:
    a. verification of absence of undeclared material production and
    b. verification of historical material production;
2. downstream verification to ensure non-use of declared fissile material for weapons;
3. detection of undeclared production facilities.

In the first part of this paper, I describe how nuclear forensic methods could be relevant for each of these missions. In the second part, I discuss detection of undeclared facilities by nuclear forensic methods. In the third part, I focus on verification of absence of undeclared material production at declared facilities under various conditions. The fourth part will discuss methods of analysing historical production of fissile material. The fifth part offers brief conclusions.

Nuclear forensics and detection of undeclared facilities

The methods of nuclear forensic analysis rely on obtaining and analysing samples of nuclear or other radioactive material, looking for clues about the material's history. In case of detection of undeclared facilities, the verification system will examine the material to look for information about the facility of its origin. Since the location and

[3] P. Podvig, "Background document prepared for the meeting 'Fissile Material (Cut-off) Treaty: Elements of the Emerging Consensus'", *FM(C)T: Elements of the Emerging Consensus*, FM(C)T Meeting Series, UNIDIR, 2016, p. 7, http://unidir.org/files/publications/pdfs/fmct-series-final-report-meeting-1-en-667.pdf.

even existence of a target facility are not certain, the only way to look for such material is to conduct multiple sampling campaigns in the environment over the large territory. There are several methods of such "wide-area environmental sampling", some of which were in development and use by the 1940s and 1950s. These methods rely on obtaining nuclear or other radioactive material from a number of different matrices, usually ground water and air from the atmosphere.

Detection of undeclared facilities by analysing waterways

Detecting nuclear facilities by analysing waterways was first suggested by the Manhattan Project's scientific director, J. Robert Oppenheimer. In September 1943, Oppenheimer proposed to uncover operating nuclear reactors on German territory by investigating "the radioactivity of rivers some miles below any suspicious and secret plant". The idea was that any significant radioactivity would seep into the groundwater below the facility, ultimately finding its way to lakes or rivers where US intelligence operators could take samples. Using this technique, the German experimental reactor at Haigerloch was located about 100 kilometres north and upstream of Lake Constance (Bodensee) and the upper reaches of the Rhine River. Samples were also collected from the lower Rhine near the Dutch town of Nijmegen.[4] Although no radioactive traces originating from German facilities were found at that time, the technique was further developed and applied. In the 1948 the US Navy scientists have observed the effect of rain "scavenging" radioactivity from the atmosphere, which makes rainwater a carrier of information about nuclear activities. This method was shown the same year to be precise enough to register a nuclear explosion by analysing rainwater collected at a distance of 14,500 km from the explosion site. It has since been further developed and applied for long-range detection of nuclear tests.[5] These early cases are relevant for the future FM(C)T because they demonstrate the potential of the technique.

In the early 1990s, waterway analysis was applied in a manner even more directly related to FM(C)T verification. In 1991, a study conducted at the nuclear fuel reprocessing facility at Sellafield in the United Kingdom concluded that a small "emission-controlled" reprocessing facility producing 8 kg of plutonium per year is likely to release annually 12 milligrams of carbon-14 and 2 mg of strontium-90 split between air and water and 125 grams of iodine-129 and 15 grams of technetium-99 in off-site water.[6] Even though these emissions would then be dispersed over a large area in the environment, it is clear that ultra-sensitive methods (e.g. certain mass-spectrometry techniques and neutron activation analysis) will be able to reliably detect such effluents.

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4 V. Fedchenko (ed.), note 1, pp. 162–63.

5 V. Fedchenko (ed.), note 1, pp. 169, 171–74.

6 United States Congress, *Environmental Monitoring for Nuclear Safeguards*, OTA-BP-ISS-168, Office of Technology Assessment, September 1995, p. 17.

As part of its Programme 93+2, the IAEA asked the Savannah River National Laboratory of the US Department of Energy (DOE) to develop a programme to sample the waterways of Iraq to detect any radioactive effluent that might have been introduced by clandestine activities of the Iraqi government. The programme consisted of four components: (a) a geographical study to identify choke points and confluences of rivers to ensure an effective network of sampling locations; (b) a system of periodic sample collection, not real-time monitoring; (c) water concentration systems to reduce the volume of material to be shipped for analysis; and (d) sampling of sludge and vegetation as well as water.[7] In 1992, the IAEA conducted a survey at a total of 52 sites in Iraq that established "a radionuclide and stable isotope composition baseline in the major watershed regions of Iraq in order to detect changes resulting from aqueous effluents of nuclear related facilities".[8] Three kinds of samples were taken for this purpose: a 100-millilitre water sample, a sediment core, and a filtering column used to concentrate dissolved and particulate matter from a water sample of approximately 300 litres. The samples were analysed by widely available methods of high-sensitivity gamma spectrometry, alpha spectrometry, secondary ion mass spectrometry (SIMS), ultra-low background gas proportional counting for tritium, and inductively coupled plasma mass spectrometry (ICP-MS).[9]

Once the baseline was established, the IAEA concluded that its verification purposes could be satisfied by revisiting 15 chosen sampling sites twice a year. Regular sampling was conducted between 1993 and 1998 and then repeated in 2002. The sensitivity of this verification method was reportedly quite high. The system often detected quite minute traces, such as those emanating from permitted use of medical radioisotopes and fallout from the Chernobyl accident and nuclear weapons tests around the world. It was a clear demonstration that this method would be quite effective at detecting fission products associated with reactor operations or reprocessing—a finding clearly relevant for the FM(C)T verification. It may also have some utility in detecting undeclared facilities handling uranium with an isotopic composition uncommon in nature (but not natural uranium).[10]

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[7] A.L. Boni, "High sensitivity measurements of ultra-low amounts of radioactivity in the environment", in *50 Years of Excellence in Science and Engineering at the Savannah River Site: Proceedings of the Symposium*, Westinghouse Savanah River Company, 17 May 2000, p.278; A.L. Boni, "Environmental sampling in water for verification purposes", IAEA Scientific Forum, 22–24 September 1998, http://www.iaea.org/About/Policy/GC/GC42/SciProg/gc42-scifor-11.pdf.

[8] IAEA, "Report on the fourteenth IAEA on-site inspection in Iraq under Security Council Resolution 687 (1991)", 24 September 1992, annex to UN document S/24593, para. 11.

[9] V. Fedchenko (ed.), note 1, pp. 237–38.

[10] V. Fedchenko (ed.), note 1, pp. 238–39.

Detection of undeclared facilities by analysing samples of air

Detection of reactors and plutonium separation facilities by analysis of noble gases

Similar to the idea of verification of waterways, the suggestion to detect nuclear reactor operations by detection of radioactive noble gases in the atmosphere was also put forward by a Manhattan Project employee, Louis W. Alvarez, in the autumn of 1943. The idea put forward by him at that time was that the radioactive isotope xenon-133 would be easy to detect downwind of a facility, because it is generated at a high rate during fission and is produced by any reactor in significant quantities. Since it is a noble gas, it would be escaping a nuclear facility in detectable quantities instead of chemically reacting with other elements. At the same time, it would be relatively easy to separate it from other gases in the air due to significantly different boiling points. It would also be easy to detect because it does not exist in nature due to its short half-life (about 5 days), and because it produces distinctive gamma and beta radiation. The xenon-detection system was built by the summer of 1944, tested and deployed in Germany in the autumn of the same year. A few Douglas A-26 Invader aircraft made a number of flights over locations that were considered potentially related to the German nuclear programme. These locations were pinpointed by analysis of open source information, aerial photographs, and reports from British and US intelligence agencies. No xenon was found.[11] Alvarez suggested the use of xenon-133 in the autumn of 1943 because a different and better suited noble gas radioisotope—krypton-85—was only discovered later that year in Germany.[12] Krypton-85 has a longer half-life (almost 11 years), and so it does not decay to the same degree during the time it takes to escape a nuclear reactor or, especially, nuclear fuel being "cooled down" before processing at a plutonium separation facility.

Analysis of krypton-85 in the atmosphere has since been conducted quite extensively by the US and other governments for the purpose of locating unknown plutonium separation facilities and even for taking estimates of total plutonium production in the USSR.[13] It has been demonstrated that emissions from individual facilities are distinguishable at a distance of a few tens of kilometres.[14] However, due to the isotope's relatively long half-life, operations of plutonium separation and medical isotope production facilities have led to an accumulation of a quite significant krypton-85 background in the atmosphere. It has been shown that the "current absolute level of the worldwide Kr-85 background and the fluctuations in the Northern Hemisphere, especially in Europe and parts of Asia, makes detection of

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[11] V. Fedchenko (ed.), note 1, pp. 160–62.

[12] H.J. Born and W. Seelmann-Eggebert, "Uber Einige Neue Spaltprodukte bei der Bestrahlung des Urans mit schnellen Neutronen (Ru and Rh)", *Naturwissenschaften*, vol. 31, no. 36, 1943, p. 420.

[13] M.S. Goodman, Spying on the Nuclear Bear: Anglo-American Intelligence and the Soviet Bomb, Stanford University Press, 2007, pp. 180–86.

[14] P.R.J. Saey, "Ultra-low-level measurements of argon, krypton and radioxenon for treaty verification purposes", *ESARDA Bulletin*, no. 36, July 2007, p. 44.

clandestine facilities in these regions extremely difficult".[15] The possibility of applying this technique to wide-area detection of undeclared facilities for the purposes of FM(C)T verification will have to be quite scenario-dependent (e.g. in specific cases in the southern hemisphere). However, deployment of Kr-85 detectors in a specific area (identified by other means) could be a viable option to verify that no reprocessing is taking place.

Detection of uranium enrichment facilities by detection of particulate emissions

There is a consensus that a direct remote detection of uranium enrichment facilities, especially those using centrifuges, is difficult due to their low emissions into the environment. It has been suggested that attention should instead focus on uranium hexafluoride (UF6), which is necessary for any enrichment plant operating today and most enrichment plants in the foreseeable future. If the UF6 production and inventory is verified at all uranium conversion plants, and all imports are monitored, then undeclared enrichment activities would not be possible without producing the UF6 covertly. Published research suggests that remote detection of facilities producing UF6 through detection in the atmosphere of UF6 degradation products, namely UO2F2 aerosols, is possible in principle, but will be problematic at longer distances and if high-efficiency particulate air filters is installed at the clandestine facility.[16]

Nuclear forensics and verification of declared facilities

Depending on the specific design of the FM(C)T verification system one can expect that the verified State will declare in advance a number of pertinent facilities. If direct access to a certain facility is not possible, the nuclear forensic techniques developed for wide-area search for undeclared facilities can be applied. Detection equipment can be installed just outside the perimeter of the facility to collect samples of the air in search of krypton-85 (e.g. to verify that plutonium separation is not conducted at a certain facility) or, perhaps, in search of uranium microparticles in the vicinity of a uranium enrichment facility. If access to a declared facility is granted, and collection of samples there is permitted, nuclear forensic methods can be used in several ways.

Undeclared production at an inactive declared facility

If access to a declared facility is allowed, and production of weapons-grade Pu or HEU was declared as stopped there, nuclear forensics techniques can be reliably

[15] M. Shoeppner, A. Glaser, and M.E. Walker, "Detecting clandestine plutonium separation activities with krypton-85", Institute of Nuclear Materials Management, 56th Annual Meeting of the Institute of Nuclear Materials Management, 12–16 July 2015, p. 9.

[16] R.S. Kemp, "Environmental detection of clandestine nuclear weapon programs", *Annual Review of Earth and Planetary Sciences*, vol. 44, 2016, pp. 17–35.

applied to verify that the facility in question did in fact not produce any fissile material after a declared "cut-off date". Cut-off date verification is possible by determining the "age" of nuclear material, which is defined as "the time elapsed since its last separation or latest chemical purification".[17] This method is based on the fact that nuclear and other radioactive materials decay at known rates (i.e. have known half-lives). Decay products of the nuclear materials are continuously produced within the nuclear material due to the radioactive decay of the parent nuclides. A chemical separation removes these decay products (also known as "progenies" or "daughter isotopes") from the parent isotopes (the actual nuclear material in this case). The parent isotopes continue to decay. Therefore, the amount of decay products will be proportional to the time elapsed since the most recent chemical purification. This method is dependent on the assumption that the removal of daughter isotopes during the latest chemical transformation, purification, or reprocessing was reasonably complete. If the removal of progenies was not done well, however, this "age-dating" method will overestimate the age of the material. Determination of the material's age (or production date) is most often done on the basis of a set of parent-daughter and parent-granddaughter ratios, which allows researchers to spot inconsistencies and perceive if the removal of progenies was incomplete. For example, determination of plutonium age can be done on the basis of four ratios (238Pu : 234U, 239Pu : 235U, 240Pu : 236U, 241Pu : 241Am). If all of them indicate the same material age, it is certain that the separation was complete and age determination is correct.[18]

In most cases, sensitive mass-spectrometry techniques are used for determining the isotopic composition of uranium and plutonium for age-dating purposes.[19] It follows from the nature of the technique that it works best if a significant amount of material is available. It is also easier to determine the material's age if it comprises isotopes with shorter half-lives, as that provides more progeny isotopes for measurement. In other words, this method is easier applied to bulk samples than to individual micron-sized particles, and plutonium may be easier to age-date than uranium. Therefore, the worst-case scenario for this method is age-dating of individual microparticles of uranium. Depending on a scenario, such dating could be difficult or impossible for uranium particles smaller than a few micrometers and younger than 20–30 years.[20]

Age determination is a well-understood technique that has been used in international security applications since the 1940s. It is currently established in the

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[17] For detailed discussion of uranium and plutonium age determination, see K. Mayer, M. Wallenius, and Z. Varga, "Sample characteristics and nuclear forensic signatures", in V. Fedchenko (ed.), note 1, pp. 111–122.

[18] K. Mayer, M. Wallenius, and Z. Varga, note 17, p. 116.

[19] K. Mayer et al., "Inorganic mass spectrometry as a tool of destructive nuclear forensic analysis", in V. Fedchenko (ed.), note 1, pp. 47–73.

[20] IPFM, Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cut-off) Treaty, September 2008, pp. 48–49.

IAEA safeguards practice as part of the Agency's environmental sampling techniques.[21] For example, the US government used age determination to calculate the time (and, by extension, the location) of the first Soviet nuclear-weapon test in August 1949.[22] In an example more relevant to FM(C)T verification, the IAEA successfully used this technique to verify "an initial report on all nuclear material subject to safeguards" submitted by the Democratic People's Republic of Korea (DPRK) on 4 May 1992. The initial report contained a declaration that the DPRK had conducted a single experiment in March 1990 at the Radiochemical Laboratory in Yongbyon aimed at separating about 90 grams of plutonium from reportedly damaged spent fuel rods removed from the adjacent gas-graphite reactor. During an inspection visit to Yongbyon, the IAEA took swipe samples from inside and outside gloveboxes at the end of the reprocessing line, where freshly separated plutonium is converted from liquid form into oxide compound. The swipe samples were analysed to determine their elemental and isotopic composition, and then the plutonium isotopics data was used to calculate the age of various particles located on swipes. It was determined that the plutonium in the Yongbyon particles was separated in 1989, 1990, 1991, and possibly in early 1992, and not in a single March 1990 experiment as declared by the DPRK.[23]

Some members of the Group of Governmental Experts (GGE) established by the UN General Assembly to make recommendations concerning the possible elements of the future FM(C)T questioned the value of environmental sampling in detecting undeclared activity in States that were conducting significant unsafeguarded operations "due to false alarms potentially generated by past production".[24] This seems to suggest that in countries with large fuel cycles, the multi-year operation of multiple production facilities and active transportation of nuclear material between them may have created a situation where swipe-sampling would not work. For example, it may yield microparticles that would not be representative of the facility where the samples were taken from. In some cases, the presence of relatively fresh uranium particles may create significant uncertainty in analysing the samples. (As discussed above, nuclear forensic analysis of plutonium will likely be easier due to more isotopes available for construction and interpretation of signatures.)

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[21] Environmental sampling (ES) is one of the IAEA's safeguards measures, defined as "collection of samples from the environment with a view to analysing them for traces of materials that can reveal information about nuclear material handled or activities conducted". In most cases ES is done by swipe sampling, that is "the collection of environmental samples by swiping a surface with a piece of ultraclean medium (such as cloth) to remove from the surface traces of materials present". IAEA, *IAEA Safeguards Glossary: 2001 Edition*, International Nuclear Verification Series, no. 3, 2001, p. 72.

[22] V. Fedchenko (ed.), supra note 1, p. 171.

[23] V. Fedchenko (ed.), supra note 1, pp. 242–43.

[24] UNGA, "Group of Governmental Experts to make recommendations on possible aspects that could contribute to but not negotiate a treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices", A/70/81, 7 May 2015, para. 60.

Indeed, this has happened in the past. In 2008, the US government discovered "very few" enriched uranium particles on North Korean reactor documents and tried to determine their age. It was already known at that time that Pakistan had provided North Korea with "a sample centrifuge kit for uranium enrichment" in the early 1990s. If the uranium in the particles was older than the date of that transaction, then the existence of those particles on North Korean documents could be explained by cross-contamination from Pakistani equipment. Younger particles would have been a cause for concern that they would signify having originated in the DPRK itself and therefore be an indicator of a clandestine enrichment programme. One agency "was basing its analysis on a single particle that, through age-dating techniques, was believed to be about 3 1/2 years old".[25] Other agencies disagreed and called the particle an "outlier" that should be excluded from analysis in accordance with scientific practice.

It is indeed possible for unexpected microparticles to be found, especially at large nuclear facilities operating as parts of old and active fuel cycles. However, just as it happens in normal IAEA safeguards practice, unusual occurrences can be investigated at a working level without becoming a political issue. In the FM(C)T context, such investigations would be aided by a few factors. First, the FM(C)T would probably only be concerned with highly enriched uranium (HEU). Most States (except for India, Pakistan, North Korea) stopped HEU production 20 years ago or more. Their HEU particles will thus be easier to age-date. Second, FM(C)T verification will first establish a baseline of enrichment signatures existing at each plant, and then take regular swipe samples to check for consistency with the baseline. This is a standard practice (see e.g. the case of verification of Iraqi waterways) that will diminish the number of "unexpected" particles significantly. Third, apart from mass-spectrometry, particle morphology studies using scanning electron microscopy may help to determine if the particle is old (degraded) or new (e.g. spherical in shape). In general, one should agree with the conclusion of the GGE experts on this matter: "These issues are likely to be site-specific and will likely be resolved on a case-by-case basis".[26]

Undeclared production at an active declared facility

It is possible that the future FM(C)T will allow for controlled production of some fissile material for non-prescribed, non-weapons purposes, e.g. HEU for naval fuel and some weapons-grade plutonium separation in case of a breeder programme. This scenario raises the possibility of small-scale clandestine production of HEU or plutonium in an isolated part of a plant, masked by a permitted larger-scale fissile

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[25] G. Kessler, "White House Voices Concern on North Korea and Uranium", *Washington Post*, 8 January 2009, http://www.washingtonpost.com/wp-dyn/content/article/2009/01/07/AR2009010703530.html.

[26] UNGA, supra note 24, para 60.

material production at the same plant. The methods of nuclear forensic analysis can also be employed to help safeguard against such possibilities.

Clandestine production of HEU for weapons at a facility that enriches uranium for naval nuclear fuel would not be difficult to detect with swipe sampling methods unless the facility operator would try to enrich it to exactly the same level as "permitted" HEU. Production of HEU even with minimal difference in enrichment would very likely be detected by the same tried and tested environmental sampling methods that are being employed by the IAEA for the purposes of safeguards. This problem can be alleviated if the navies in question would not use weapons-grade HEU for fuel (which is the current practice in the US and UK fleets), but material enriched only to between 40 and 50 per cent (which is reportedly the current practice in the Russian and Indian Navies). If the navies in question switched to LEU, like vessels of the French and Chinese Navies, the problem would be eliminated entirely.[27]

Even in cases where an enrichment facility is permitted to produce weapons-grade HEU, three factors will make clandestine, "parallel" production difficult. First, the feed material for enrichment, UF6, will presumably be controlled using nuclear materials accountancy and control (NMAC) methods that have been routinely applied by facility operators and as an element of IAEA safeguards for decades. This means that the feed for a clandestine enrichment cascade must be produced at a clandestine plant or taken from some undeclared storage. Existence of such facilities introduces additional risks of detection by itself. Second, the clandestine UF6 will very likely have different elemental (e.g. rare earth elements) and isotopic signatures (e.g. stable isotope ratios) found in trace concentration levels (ppb to ppm) that are likely to be detected by nuclear forensic analysis methods.[28] Third, the clandestine cascade will have to have the size and shape of the "permitted" one, which is again problematic. Studies show that the HEU isotopic composition is dependent on both material and enrichment cascade configuration. For example, HEU from a single cascade will be distinguishable from similarly enriched HEU from a series of four cascades.[29]

A scenario in which a State uses declared separation of weapons-grade Pu (e.g. as part of the breeder programme) to mask a small undeclared production of Pu for weapons implies the existence of a separate, clandestinely operating plutonium production reactor, because all the fuel from declared reactors would presumably be

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[27] G.M. Moore, C.A. Banuelos, and T.T. Gray, "Replaced Highly Enriched Uranium in Naval Reactors", NTI Paper, March 2016, p. 1.

[28] Z. Varga et.al., "Propagation of Impurities at the Front-End of Fuel Cycle", IAEA International Conference on Nuclear Security: Commitment and Actions, 7 December 2016, https://conferences.iaea.org/indico/event/101/session/16/contribution/166.pdf.

[29] D. Fischer and M. Ryzhinsky, "Safeguards Environmental Sampling Signatures: Comparison of Two Enrichment Scenarios", Institute of Nuclear Materials Management, 46th Annual Meeting of the Institute of Nuclear Materials Management, 10–14 July 2005.

controlled by the usual NMAC methods. It was already discussed that reactor operations have a rather high chance of being detected by nuclear forensic analysis. Additionally, regular swipe sampling at such a "double" facility would be very likely to uncover clandestine separation activities, because isotopic composition of Pu (including in case of particle analysis) is much more informative than that of HEU. Methods for determination of reactor type, burnup, time since reprocessing, and time since reactor discharge by analysis of isotopic composition of plutonium are well understood and have in some cases been applied since the 1940s.[30]

Nuclear forensic analysis of historical production of fissile material

A large proportion of reactors built for production of military-grade plutonium use graphite as a moderator. This has been the case in China, the DPRK, France, the Soviet Union, the United Kingdom, and the United States. Once a graphite-moderated reactor is decommissioned, one technique of nuclear forensic analysis—the graphite isotope ratio method (GIRM)—can assist in determining how much plutonium that reactor produced in its lifetime. GIRM was developed jointly by Russian and US scientists in the framework of bilateral disarmament and non-proliferation initiatives. The key benefit of this method for FM(C)T verification is that it can estimate the graphite reactor's cumulative lifetime plutonium production even after its fuel was reprocessed or otherwise made unavailable for verification.[31]

The method relies on the fact that the reactor graphite is normally built into the reactor and stays there until the reactor is dismantled. Even highly purified reactor-grade graphite contains impurities at the level of a few parts per million. Those impurities will be subjected to irradiation by neutrons, and their isotopic composition will inevitably change by that irradiation. After the reactor has been shut down, a sufficient number of graphite samples can be obtained from various points in its core. The isotopic composition of the impurities can then be measured by mass spectrometry techniques and compared with the isotopic composition of impurities in the fresh unirradiated graphite. Once changes in the impurities have been determined, the total quantity of neutrons needed to cause such change (i.e. the fluence) can be calculated. The total amount of plutonium produced is proportional to the fluence. US–Russian studies have determined specific isotopic ratios appropriate for estimating lifetime plutonium production of various reactors.

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[30] K. Mayer, M. Wallenius, and Z. Varga, "Sample characteristics and nuclear forensic signatures", pp. 111-17; V. Fedchenko (ed.), supra note 1, pp. 172–73, 242–43.

[31] T. Wood et al., "Establishing confident accounting for Russian weapons plutonium", *Nonproliferation Review*, vol. 9, no. 2, 2002, pp. 126–37.

According to most studies, GIRM plutonium production estimates can be accurate to within a few per cent.[32]

GIRM and the idea behind it (analysis of cumulative changes in isotopic composition of impurities in reactor materials) have been applied on a number of occasions. One proposed application was a detailed description of how to apply GIRM to estimate the total amount of plutonium produced in the graphite reactor at Yongbyon.[33] Another proposal is to expand GIRM into a generic isotope ratio method applicable for other reactor types, including CANDU reactors, and some research reactors. More importantly for FM(C)T purposes, it was demonstrated that this generic method is also applicable to heavy-water moderated reactors of the type used for military plutonium production in India (CIRUS) and Pakistan (Khushab-I).[34]

One study also suggested that applying nuclear forensic analysis methods to the equipment from decommissioned gaseous diffusion plants, especially diffusion barriers, could provide useful information for verification of history of enriched uranium production at such plants.[35]

Concluding remarks

Nuclear forensic analysis has become a powerful verification tool, useful for many national and international security applications (see Table 1). It has the potential to contribute to the future FM(C)T verification system. From the point of view of treaty verification, it is, of course, not a silver bullet. As demonstrated by the IAEA safeguards experience and described above, nuclear forensic methods work best if used together with other verification techniques, such as nuclear materials accountancy.

Verification with nuclear forensic methods will likely be organized in a clear legal framework that defines the procedures for access to facilities or State territory for effective sampling, regulations pertaining to shipping and analysis of samples, processes for resolution of anomalies, and protection of sensitive information. The

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[32] P.G. Heasler et al., "Estimation procedures and error analysis for inferring the total plutonium (Pu) produced by a graphite-moderated reactor", *Reliability Engineering & System Safety*, vol. 91, nos 10–11, 2006, pp. 1406–13.

[33] J. Kang, "Nuclear archeology on the 5 MWe graphite reactor at Yongbyon", Institute of Nuclear Materials Management, 51st Annual Meeting of the Institute of Nuclear Materials Management 2010, vol. 2, 2011; J. Kang, "Using the graphite isotope ratio method to verify the DPRK's plutonium production declaration", *Science and Global Security*, vol. 19, no. 2, 2011, pp. 121–29.

[34] A. Gasner and A. Glaser, "Beyond GIRM: nuclear archaeology for heavy-water-moderated plutonium production reactors", 51st Annual Meeting of the Institute of Nuclear Materials Management 2010, vol. 2 2011.

[35] S. Philippe and A. Glaser, "Nuclear Archaeology for Gaseous Diffusion Enrichment Plants", *Science and Global Security*, vol. 22, no. 1, 2014, pp. 27–49.

latter issue was particularly noted by the Group of Governmental Experts (GGE).[36] It is true that nuclear forensic analysis of fissile materials, especially plutonium, can be quite informative. This can be addressed by, for example, defining specific permitted measurement techniques or designating trusted analytical laboratories, as already tried in the contexts of the CTBT verification and IAEA safeguards. At the same time, it would be useful to clarify what are the specific reasons why certain information concerning fissile material composition is deemed sensitive and why it can or cannot be used in the future FM(C)T verification. These questions have not been sufficiently explored in the open literature.

To conclude, nuclear forensic methods have proved their worth in several verification scenarios relevant to the future FM(C)T verification system. The FM(C)T verification system designers can certainly use those methods as part of a larger verification toolbox available to them. One should agree with the sense of the GGE that issues associated with these methods are certainly site- and scenario-specific, and are likely to be resolved on a case-by-case basis.

[36] UNGA, supra note 24, para 60.

Dealing with Disparities in a Non-Discriminatory Fissile Material (Cut-off) Treaty: Summary of the Discussion

Pavel Podvig

This part of the report presents a brief summary of the discussion that followed the presentation of the papers included in this volume at the third meeting of the UNIDIR FM(C)T Meeting Series, which took place in the Palais des Nations, Geneva on 29 November 2016. The discussion at the meeting focused on a number of issues that reflected the complexity of building a truly non-discriminatory regime. Most importantly, it was noted that formal equality in the treaty's provisions and obligations does not automatically translate into the actual equality of States under the treaty.

One reason is that the starting conditions of the Treaty's Parties will inevitably be very different. The treaty restraints will have different implications for different States. One example that was used to illustrate this point was the Comprehensive Nuclear Test-Ban Treaty: while the treaty imposes equal obligations not to test on all its parties, the States that have tested nuclear weapons in the past retain the knowledge they accumulated through their test programmes. Even though the fissile material treaty would be different in that the materials that were produced before entry into force can be used for production of nuclear weapons or can be eliminated, certain aspects of the situation are similar—it may be difficult to design a treaty that would correct for that inequality.

The discussion also reflected the fact that it is possible that the future treaty would attempt to correct the inequality that inheres from States' different starting conditions, for example, by imposing stronger obligations on States that produced military fissile material in the past. Also, to some extent, the inequality can be addressed by explicitly taking into account the fact that the FM(C)T is not a stand-alone instrument, but rather a part of a broader nuclear arms control, non-proliferation, and disarmament framework. It was noted that this could help create a fissile material control regime that is accepted as non-discriminatory and therefore is more stable in the long run.

Then the participants discussed the more specific issue of the safeguard standard that could be taken as a basis for the FM(C)T verification arrangements. Several participants commented on the fact that if the treaty verification system is to be based on the Comprehensive Safeguards Agreements (INFCIRC/153) and not the Additional Protocol, then the States that adopted the Additional Protocol would be in an unequal position. This situation can obviously be avoided if the Additional Protocol is accepted as the starting point, but the fact remains that the Additional Protocol is not universally accepted by States.

Regarding the Additional Protocol, it was emphasized during the discussion that the experience of applying its provisions in the United States demonstrates that there are no fundamental reasons why it cannot be taken as a basis for the FM(C)T verification arrangements. This solution, however, would have to address the issue of national security exemption, which allows nuclear-armed States to limit access to sensitive facilities and materials. The discussion showed that that the national security exemption may become an element of the treaty if it is designed in a way that does not constrain the capability of the verification system to detect diversion of fissile materials or discover undeclared production facilities.

The participants discussed different approaches to the issues of non-discrimination and the commencement of negotiations. Some participants suggested that it is important to focus on getting the negotiations underway. That way, negotiators could start to grapple with specific issues related to the equality of verification standards. This view was generally supported, although it was also noted that it is important to gain clarity on the issue of non-discrimination as the negotiations start, so the FM(C)T could make a meaningful contribution to international security.

As a solution to the non-discrimination conundrum, some participants proposed the establishment of a verification system that would avoid setting specific verification objectives. Instead, the verification system would be designed to provide the strongest assurances technically possible about non-diversion of material and the absence of undeclared production. The confidence in the conclusions would grow with advances in verification technologies. Another factor that could help increase confidence in the effectiveness of the FM(C)T verification system is a possible abandonment of some nuclear cycle technologies (this possibility was discussed at the first meeting of this series). The task of the verification system would be much easier if no State operates a reprocessing facility and there are no enrichment plants that are producing highly enriched uranium.

Finally, a portion of the discussion was devoted to the potential discrimination that may be created by organizational arrangements. It was noted that if the verification of former weapon-related facilities or materials is entrusted to a dedicated organization other than the IAEA, this organization might be dominated by the weapon States, since all verification activity it will conduct would be concentrated in these States. This may create a new level of inequality and undermine the treaty. It was suggested, however, that it might be possible to separate the (military)

verification activities provided for by the FM(C)T from the (civilian) IAEA safeguards. This arrangement might provide a way to gradually involve nuclear-armed States into the treaty regime through programmes like the Trilateral Initiative, thus extending the scope of the treaty to military materials.

UNIDIR

FM(C)T Meeting Series

Addressing Disparities in a Non-Discriminatory Fissile Material Treaty

The mandate to negotiate a treaty banning the production of fissile material for weapons and other explosive devices calls for a treaty that would be “non-discriminatory, multilateral and internationally and effectively verifiable.” The papers presented in this volume examine practical ways the future Fissile Material (Cut-off) Treaty could deal with the existing disparities in the size of fissile material stocks and the history of production of fissile materials for military purposes while still preserving the non-discriminatory nature of the treaty and building an effective and efficient verification system.