THE CATEGORISATION OF NUCLEAR MATERIAL IN THE CONTEXT OF INTEGRATED SAFEGUARDS

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1. INTRODUCTION

As part of the re-examination of basic safeguards parameters, to consider their appropriateness or otherwise under Integrated Safeguards, an important area for attention is nuclear material categorisation. This is a major determinant of inspection effort and evaluation of safeguards performance. Under Integrated Safeguards, achieving credible assurance of the absence of undeclared nuclear material and nuclear activities, particularly those related to enrichment and reprocessing, in a State as a whole, would permit reductions in the current level of routine safeguards verification effort, particularly on less sensitive nuclear material. In this context matters to consider might include whether current nuclear material categorisation affects the scope for optimisation of verification effort, or whether it inhibits introduction of more rigorous verification (where and if this is desirable).

In addition to the three basic nuclear material categories – uranium, plutonium and thorium – the IAEA characterises nuclear material for various purposes according to criteria that can be grouped under the following headings: degree of processing (*source material* and *special fissionable material*), strategic value (*direct-use material* and *indirect-use material*), isotopic composition and radiation level (irradiated and unirradiated).

INFCIRC/153 states that the IAEA, in order to ensure optimum cost-effectiveness, should make use of "concentration of verification procedures on ... nuclear material from which nuclear weapons or other nuclear explosive devices could readily be made…" Thus, the objective of refining the nuclear material categories should be, to ensure that the Secretariat has the authority to require more rigorous safeguards standards on nuclear material of a form and composition that represents a significant proliferation risk (looking at risk here purely in terms of the characteristics of the material, without taking into account the State evaluation), while at the same time having the flexibility to require less rigorous standards where the risk is lower. Judgments of relative risk should also be reflected in evaluation of safeguards performance.

In this paper we discuss weapons-grade materials as opposed to materials typical of the civil nuclear fuel cycle, current IAEA definitions of material categories and whether those need to be revised under integrated safeguards.

2. WEAPONS-GRADE MATERIALS

Nuclear weapons are manufactured from either weapons-grade uranium or weapons-grade plutonium:

- Theoretically, a nuclear device can be constructed using HEU with U-235 fraction ranging from as low as 10% to 100%. The higher the U-235 composition, the lower the total mass of HEU needed. Thus, the term **weapons-grade uranium (WGU)** usually refers to pure uranium metal at very high enrichment levels, produced in enrichment plants designed and operated for this purpose (though the IAEA high enriched uranium (HEU) category starts at 20% U-235, WGU comprises 93% or more U-235). Although it is theoretically possible to construct a nuclear device using lower assay HEU, such a device would be more difficult to design and fabricate, with generally lower yield and less predictability than one constructed of WGU.

- **Weapons-grade plutonium (WGPu)** is pure plutonium metal that contains no more than 7% of the isotope Pu-240. It is produced in heavy water- or graphite-moderated production reactors (fuelled with natural or slightly enriched uranium, designed and operated to produce low burn-up plutonium) and separated from spent fuel or irradiation targets in reprocessing plants or plutonium extraction plants. Production reactors are on-load refuelled to allow for short fuel irradiation times[1]. Within *weapons-grade* there is the sub-category of **super-grade plutonium (SGPu)**, containing no more than 3% Pu-240. Another way to produce WGPu is through irradiation of U-238 by fast neutrons. Such are the conditions in the (natural or depleted uranium) blanket of a Liquid Metal Fast Breeder Reactor (LMFBR). The composition of plutonium produced in the blanket of a LMFBR (about 3-4% Pu-240) places it in the WGPu category. WGPu can inadvertently be produced in power reactors. In the early 1970s, this happened, for example, in the US when leaking fuel rods caused the utility operating the Dresden-2 reactor to discharge the entire initial core containing a few hundred kg of plutonium with 89-95% Pu-239[2].

3. MATERIALS IN CIVIL PROGRAMS

The weapons-grade materials described above are very different to those normally produced in civil programs, for example:

- **Low enriched uranium (LEU)** typically used in light water reactors is in the range of 3-5% U-235. A State seeking to utilise LEU as a source material for weapons would require a technological chain including chemical, enrichment and metallurgical processes. The requirement for such processes would increase the time frame for weapons development and production by 1.5–3 times compared with use of HEU as the source material. Increased cost for development and production from purchase and installation of required chemical, enrichment and metallurgical equipment would exceed the cost for HEU by a factor 3–15.

- **Reactor-grade plutonium (RGPu)** is produced in power reactors and contains 19% or more of the isotope Pu-240. In general, plutonium derived from current commercial light- and heavy-water reactors contains around 50-65% Pu-239, the remainder being largely Pu-240 and heavier isotopes of plutonium. As there are many types of power reactors, and differences in fuel composition, coolant and moderator system and burn-up level, plutonium commonly called RGPu can have various isotopic compositions, as illustrated in Table 1. For the current generation of fuel, 60,000 MWd/t is seen as the limit, but DOE documents indicate that the Department hopes to develop an advanced LWR fuel capable of reaching burn-ups of 100,000 MWd/t with enrichment levels of 5% U-235[3]. A technological chain for the attempted utilisation of RGPu in weapons is relatively lengthy in comparison with the one for weapons-grade plutonium (WGPu). This plus the need for more sophisticated implosion-type initiating systems lengthen the time frame to 3–10 times longer than with utilisation of HEU as a source material. In light of the relatively complex reprocessing and/or chemical cascades plus developing, producing, and sustaining Pu-based nuclear weapons, the cost exceeds the corresponding cost for HEU, ranging from a factor of 8 (for chemical conversion from MOX fuel containing WGPu or RGPu) to a factor of 60 (direct reprocessing of spent fuel).

- **Fuel-grade plutonium (FGPu)** contains more than 7%, but less than 19%, of the isotope Pu-240. FGPu is produced in some nuclear reactors that have a spent fuel burn-up lower than that resulting in reactor-grade plutonium, but higher than that resulting in WGPu. For example, FGPu is often produced in tritium production reactors. FGPu can also be produced in power reactors, in initial core loads and in damaged fuel discharged after one year's irradiation.
- **MOX-grade plutonium (MGPu)**, which contains about 30% or more Pu-240. MGPu arises from the recycle of plutonium in irradiated MOX-fuel, which was fabricated from RGPu. Mixed oxide (MOX) fuel consists of a mixture of the oxides of uranium and plutonium that is used for recycling of reprocessed spent fuel (after the separation of waste) into thermal nuclear reactors (thermal recycling) and as a fuel for fast reactors. MOX is considered by the IAEA as *special fissionable material* and as a *direct-use material*.

Table 1.

Typical Isotopic Compositions of Spent Fuel at Discharge from Power Reactors[4]

Reactor type	Fuel burn-up GWd/t	Isotopic composition, %			
		Pu-239	Pu-240	Pu-241	Pu-242
GCR	3.6	77.9	18.1	3.5	0.5
PHWR	7.5	66.4	26.9	5.1	1.5
AGR	18.0	53.7	30.8	9.9	5.0
RBMK	20.0	50.2	33.7	10.2	5.4
BWR	27.5	59.8	23.7	10.6	3.3
PWR	33.0	56.0	24.1	12.8	5.4

4. CURRENT IAEA DEFINITIONS OF MATERIAL CATEGORIES

As already mentioned, in addition to the three basic nuclear material categories – uranium, plutonium and thorium – the IAEA characterises nuclear material for various purposes according to criteria which can be grouped under the following headings: the degree of processing required or undertaken, strategic value (suitability for weapons use), isotopic composition and radiation level.

Degree of processing Here there are two categories of nuclear material – *source material* and *special fissionable material*:

- Source material is natural uranium; uranium depleted in the isotope 235; thorium; any of the foregoing in the form of metal, alloy, chemical compound, or concentrate; any other material containing one or more of the foregoing in such concentration as the Board of Governors (BOG) shall from time to time determine; and such other material as the BOG shall from time to time determine[5]. Under INFCIRC/153-type safeguards, the term *source material* is interpreted as not applying to ore or ore residue[6], in particular to yellow cake, a concentrate consisting essentially of U_3O_8[7].
- Special fissionable material is Pu-239, U-233, uranium enriched in the isotopes 235 or 233, any material containing one or more of the foregoing and such other fissionable material as the BOG shall from time to time determine[8].

Strategic value This is a relative measure of the usefulness of a nuclear material to a potential diverter for producing nuclear explosives. There are two categories:

- Direct-use material – nuclear material that can be used for the manufacture of nuclear explosives components without transmutation or further enrichment, such as plutonium containing less than 80% Pu-238[9], HEU and U-233. Chemical compounds, mixtures of direct-use materials (eg MOX), and plutonium contained in spent nuclear fuel also fall into this category. Unirradiated direct-use material would require less processing time and effort than irradiated direct-use material (contained in spent fuel).
- Indirect-use material – all nuclear material except direct-use material, eg natural uranium, or LEU which must be further enriched to be converted into HEU or inserted into a reactor to produce Pu-239 which can be separated in a reprocessing plant, or thorium.

Isotopic composition It is obvious that isotopic composition is closely related to strategic value, and isotopics were taken into account in the categorisation into *direct-use* and *indirect-use* material (eg plutonium with or without a certain proportion of Pu-238, HEU as distinct from DNLEU). The isotopic composition of the material controls the relative difficulty of manufacturing a nuclear explosive with material of a specific isotopic composition or altering its isotopic composition to produce weapons-grade or weapons-useable material. Attributes that are important for determining the useability of material for weapons applications include:

- critical mass, ie the minimum amount of material needed to achieve criticality; in principle a small critical mass represents a lower barrier to proliferation than a large critical mass;
- spontaneous neutron generation that complicates the design, yield and reliability of a device; for plutonium – this is strongly dependent on the concentration of Pu-240 and Pu-242 isotopes;
- heat generation rate – heating produced by nuclear decay of the material complicates device design; for plutonium, this is strongly dependent on the concentration of Pu-238;
- radiation – the radiation released by the material itself interferes with the handling, processing and design of a nuclear device; for plutonium, this is dependent on the concentration of Pu-240 and 242; for U-233 this is dependent on U-232;
- degree of isotopic enrichment – natural and low-enriched uranium cannot be used directly in a weapon, but they can be converted to weapons-useable material by enrichment or re-enrichment; thus, the isotopic barrier to proliferation is higher for uranium enriched to low levels of U-235 or U-233, and lower for uranium enriched to very high levels.

In the case of uranium, the IAEA distinguishes between four categories based on isotopic composition:

- natural uranium – uranium as it normally occurs in nature, having an atomic weight of approximately 238 and containing minute quantities of U-234, 0.7% U-235 and 99.3% U-238;
- depleted uranium – uranium in which the abundance of the isotope U-235 is less than that occurring in natural uranium, eg uranium in spent fuel from natural uranium fuelled reactors and tails from uranium enrichment processes;
- low enriched uranium (LEU) – uranium enriched to less than 20% U-235;
- high enriched uranium (HEU) – uranium enriched to 20% U-235 or more. HEU is defined as a *special fissionable material* and a *direct-use material*.

The following table illustrates the relative "distance" between different isotopic categories of uranium in terms of the required separation work.

Table 2.

Separation Work (SWU) Required to Produce Uranium of Different Enrichment Levels (% U-235) and the Amount of Product (kg)

Feed Material – 5,640 kg of Natural Uranium

Enrichment (% U-235)	2.235	3.6	19.9	40.0	60.0	93.0
SWU	2,500	3,180	4,510	4,760	4,870	5,000
Amount of product (kg)	1,198	703	118	58	39	25

In the case of plutonium, to date the isotopic composition of plutonium has not been a major issue for safeguards, because most plutonium under safeguards is of a similar composition, ie what is termed "reactor-grade" (>19% Pu-240). Effectively the IAEA recognises two categories:

- plutonium containing 80% or more of the isotope Pu-238, which is exempted from safeguards; and
- all other plutonium, which is treated alike for safeguards purposes.

Thus the IAEA applies similar safeguards measures to all plutonium, regardless of isotopic composition, apart from an exemption for plutonium containing 80% or more of the isotope Pu-238[10]. This is a policy position intended to reflect that all isotopes of plutonium are fissionable by fast neutrons, and that theoretically a nuclear explosive device, albeit perhaps of unpredictable yield, could be constructed using any grade of plutonium. For IAEA safeguards purposes all plutonium, even including that still in spent fuel, is defined as "direct-use" material, ie material that can be used for the manufacture of nuclear explosives.

While the above statement reflects the common understanding of IAEA practice, there is however an interesting qualification to the formal position that all plutonium (other than Pu-238) is treated alike. In the context of substitution of unsafeguarded nuclear material for safeguarded nuclear material, the IAEA recognises that the isotopic composition of plutonium is relevant for safeguards purposes – INFCIRC/66 paragraph 26(d) provides that nuclear material substituted for safeguarded material must have at least the same proportion of fissionable (ie here meaning fissile) isotopes.

Radiation Level Here there are two categories, irradiated and unirradiated. The radiation hazard associated with the material must be taken into account at each step in the civil nuclear fuel cycle and in any process to produce a weapons-useable material. The radiation hazard is the radiation field associated with the material and the internal dose potential to humans. There are many attributes one might select to describe the effectiveness of the radiological barriers to proliferation, among them: the specific dose rates at one meter unshielded or the contact time required to accumulate the mean lethal dose. Radiation can also complicate chemical processing. Other possible attributes could categorise the materials by the degree of remote handling required: unlimited hands-on handling acceptable, limited hands-on access acceptable, remote manipulation required, shielded facilities required.

Currently the IAEA does not apply a numerical value for the irradiation level of spent fuel – the definition in the current Safeguards Criteria refers only to direct-use material containing "substantial amounts of fission products". It is our understanding that the IAEA is currently reconsidering its definition of the irradiated fuel in light of integrated safeguards. The main issue is – could the radiation level of spent fuel decay over time to a point where its "self-protection" was lost? Because the handling of spent fuel having a low radiation level could require less shielding, and might not require sophisticated handling equipment, in principle at least such fuel could be more easily diverted and reprocessed. Should the intensity of safeguards be increased to reflect that such fuel may be of greater proliferation attractiveness? It is particularly pertinent to examine this issue in the context of the change in the spent fuel timeliness goal under integrated safeguards from 3 months to 12 months (discussed below).

5. CATEGORISATION AND CURRENT IAEA CRITERIA

It should be noted that a major impact of nuclear material categorisation on inspection effort appears to be through the concept of timeliness, and in fact categorisation and timeliness are closely related. Thus, under the currently applied Safeguards Criteria certain nuclear material categorisations are major determinants of inspection effort and evaluation of safeguards performance. The present timeliness goals, including their changes for integrated safeguards purposes, are summarised as follows.

Table 3.

Timeliness Goals under Classical and Integrated Safeguards

	Classical Safeguards	Integrated Safeguards
unirradiated direct-use material (Pu, HEU, U-233)	one month	one month
irradiated direct-use material (Pu, HEU, U-233)	three months	one year
indirect-use material (DNLEU)	one year	one year

Under integrated safeguards a revised concept of timeliness could allow the Agency to apply timeliness goals in a less rigid manner, both in the setting and implementation of inspection frequency and in the evaluation of goal attainment. In applying timeliness goals, eg in establishing inspection frequency (which could be set above or below the current timeliness goals) it would be appropriate to reflect, inter alia:

- the confidence which the IAEA is able to derive of the absence of undeclared nuclear material and activities, and the likely time frame in which these would be detected;
- considerations of practicality and cost-effectiveness.

Under this approach, *the question arises whether some further development of nuclear material categories is required, or even desirable*. We believe it would be important to avoid a new scheme of categorisation leading to excessive rigidity, negating the flexibility and judgment that the new approach to timeliness is intended to establish. *Under a flexible approach to timeliness, to some extent the categorisation of nuclear material can be probably sidestepped*, being taken into account by the Secretariat in an informal way without the necessity to establish a formal scheme. As against that, at the least it would seem desirable to establish guidelines to assist the Secretariat in the judgmental process, and to engender transparency in this process.

In any further development of the nuclear material categories, it is assumed *there will be a continuing requirement for many of the existing categories*, either for practical reasons or because they are established under the IAEA Statute, treaties and other legal instruments. These would probably include the degree of processing, strategic value and radiation level. However, some refinement of some of the categories might be desirable.

For some of the nuclear material categories, there would seem to be limited scope or purpose in refining the existing categories. This would apply to the degree of processing category, ie there seems no reason to create any categories additional to *source material, special fissile material* and *fertile* material. This would probably also apply to the category of radiation level – apart from establishing a suitable definition, the distinction between unirradiated and irradiated would seem sufficient, without the need for additional categories, eg specifying degrees of irradiation.

Thus the principal scope for possible refinement appears to be in the area of strategic value/isotopic composition. Possibilities here might include:

- ❑ for enriched uranium:
    - · whether there is a case for an intermediate category, between the existing LEU category and the category of HEU (the starting point of which would be raised to take account of the new intermediate category); or
    - · whether there is a case for a different value for the end of LEU and the start of HEU;
- ❑ for plutonium, whether there is a case for new categories, eg:
    - · high fissile plutonium (low Pu-240 plutonium, weapons grade, possibly extending into fuel grade – recognising the particular proliferation risk posed by such material because of its greater attractiveness for nuclear weapons use);
    - · normal reactor grade plutonium;
    - · high burn-up plutonium, such as in recycled MOX (recognising its relative unattractiveness for weapons use).

Chemical proliferation barrier In any refinement of material categories, other factors to be taken into account might include: the physical or chemical form of the material (whether metallic or in a chemical compound), whether in a mixture, eg with material of a different category (as is the case with MOX). The chemical proliferation barrier refers to the extent and difficulty of chemical processing required to separate fissionable material from accompanying diluents and contaminants. Attributes of the chemical barrier generally relate to the degree of technical difficulty needed to refine materials into the appropriate form, be they metals or compounds. Other possible attributes include the existence of admixtures (such as those incorporated to frustrate chemical separation or denaturing), and the number of separate processing steps needed to obtain materials of sufficient purity for weapons applications. The chemical barrier effectiveness of some of the more common materials involved in the nuclear fuel cycle can be classified in the following order: pure metals; compounds (including oxides, nitrides, etc.); mixed compounds (in particular MOX fuel, and including diluents and burnable poisons; spent fuel and vitrified wastes, including fission products (highest proliferation barrier).

Material in advanced nuclear energy generating systems A further matter to address in the future is whether the current nuclear material categorisations are appropriate for the kinds of materials that may be produced through the introduction of new nuclear power generation concepts.

6. CONCLUSIONS

The concepts of material categorisation and timeliness are closely related. A new concept of timeliness under Integrated Safeguards would allow the Agency to apply timeliness goals in a less rigid manner, both in the setting and implementation of inspection frequency and in the evaluation of goal attainment. Under this approach, the question arises whether some further development of nuclear material categories is required, or desirable. However, it would be important to avoid a new scheme of categorisation leading to excessive rigidity. Under a flexible approach to timeliness, to some extent the different characteristics of nuclear material can be probably be taken into account by the Secretariat in an informal way without the necessity to alter formal material categorisations. As against that, it would seem desirable to establish guidelines to assist the Secretariat in the judgmental process, and to bring transparency to this process.

For some of the nuclear material categories, there would seem to be limited scope or purpose in refining the existing categories. This would apply to the degree of processing category, ie there seems no reason to create any categories additional to source material, special fissile material and fertile material. This would also apply to the category of radiation level – apart from establishing a suitable definition, the distinction between unirradiated and irradiated would seem sufficient, without the need for additional categories, eg specifying degrees of irradiation. Thus the principal scope for refinement appears to be in the area of strategic value and isotopic composition. Some possibilities are discussed in the paper.

While there is understandable caution about changes to safeguards parameters relating to *direct-use material,* it should be recognised that the direct-use material category covers a broad range of materials which do not all have the same proliferation sensitivity. Although the Secretariat uses the term *direct-use material* to include MOX, this is strictly speaking not a "direct-use material" since it could not be used in a nuclear explosive without further, non-trivial, processing to separate the contained plutonium. It might be reasonable to recognise that the different characteristics of materials within the *direct-use* category could justify differing approaches, rather than applying the category in a simplistic manner.

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1. See eg "Plutonium: The First 50 Years. United States Plutonium Production, Acquisition, and Utilisation from 1944 to 1994," DOE (1996). Prior to the 1970's, there were only two terms in use (by DOE) to define plutonium grades: *weapons-grade* (≤7% Pu-240) and *reactor-grade* (>7% Pu-240). In the early 1970's, the term *fuel-grade* (>7 - <19% Pu-240) came into use, which shifted the starting point of the reactor-grade definition (≥19% Pu-240).

2. WOHLSTETTER, A., "Spreading the Bomb Without Quite Breaking the Rules", Foreign Policy, vol. 25 (Winter 1976/1977) 88-96, 145-179.

3. HURIO, E., "DOE Program Aimed at Stretching Fuel Burnup to 100,000 MWd/MT," Nuclear Fuel, February 24, 1997, 3.

4. Compiled from a number of sources.

5. IAEA Statute, Article XX.3.

6. INFCIRC/153, paragraph 112.

7. IAEA Safeguards Glossary, Item 32.

8. IAEA Statute, Article XX.1.

9. INFCIRC/153, paragraph 36 (c).

10. INFCIRC/153, paragraph 36 (c).