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DU COMBUSTIBLE NUCLÉAIRE AUX DÉCHETS : RECHERCHES ACTUELLES

FROM NUCLEAR FUELS TO WASTE: CURRENT RESEARCH

Proliferation aspects of plutonium recycling

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Abstract Plutonium recycling offers benefits in an energy perspective of sustainable development, and, moreover it contributes to non-proliferation. Prior to recycling, reactor-grade plutonium from light-water reactors does not lend itself easily to the assembly of explosive nuclear devices; thereafter, practically not at all. Control systems for material security and non-proliferation should identify and adopt several categories of plutonium covering various isotopic mixtures associated with different fuel types, in order to better reflect the risks and to better focus their controls. The author proposes the adoption of three categories of plutonium. ***To cite this article: B. Pellaud, C. R. Physique 3 (2002) 1067–1079.***

proliferation / security / plutonium / recycling / MOX / explosive device / nuclear reactor

Prolifération et recyclage du plutonium

Résumé Le recyclage du plutonium ouvre des perspectives prometteuses compatibles avec un développement énergétique durable, et il peut de plus contribuer à la non-prolifération. Avant recyclage, le plutonium de la filière des réacteurs à eau légère se prête mal à la fabrication d'engins explosifs nucléaires ; après, quasiment plus. Les organismes de contrôles des matières nucléaires devraient identifier et adopter plusieurs catégories de plutonium tenant compte des différentes compositions isotopiques, afin de mieux refléter les vrais risques et mieux cibler leurs inspections. L'auteur propose l'adoption de trois catégories de plutonium. ***Pour citer cet article : B. Pellaud, C. R. Physique 3 (2002) 1067–1079.***

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1. Introduction

The chemical reprocessing of nuclear spent fuel leads to the separation of plutonium, an element that can in turn deliver much energy when re-inserted in nuclear power plants. The recycling of plutonium makes

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sense in terms of energy resources. Nonetheless, some people are concerned about related proliferation risks and they would prefer banning plutonium recycling altogether.

How serious are the proliferation risks of plutonium holdings, whether separated or still in spent fuel? Should the concern be the same for all mixtures of plutonium coming out of different reactor types and for different degrees of nuclear burnup? Should there be different categories of plutonium for control purposes, as is the case for enriched uranium? This paper reviews the issue of plutonium utilisation in nuclear weapons and explosive devices in the context of an effective and efficient control of nuclear materials by regional and international organisations.

2. Plutonium, a resource and a step towards sustainable development

The recycling of plutonium is a mature technology with an outstanding technical, safety and environmental record, and this for all its stages: the reprocessing of spent fuel, the fabrication of plutonium-bearing fuel elements and their use in nuclear reactors. However, the cost of natural uranium can affect the recycling of plutonium by rendering it economically unattractive in comparison with other options, such as indefinite storage of spent fuel at the surface, or even geological disposal.

In spite of transitory economic bottlenecks caused by low uranium prices, the recycling technology should be preserved as a technical and industrial option to allow for the future use of the large energy reserves embedded in spent fuel in the form of plutonium. Reprocessing and mixed-oxide fuel fabrication are needed technologies, if sustainable development is to remain a reality in the use of nuclear energy.

Besides economical considerations, several countries are opposed to plutonium recycling for non-proliferation reasons. This stance goes back to the decision of President Carter in April 1977 to abandon reprocessing in order to set an international example of good non-proliferation behaviour [1]. This same view was later restated in an official announcement of the American government: "*The Clinton's Administration policy announced in September 1993 reaffirms the link between non-proliferation goals and concerns vis-à-vis civil plutonium reprocessing and its use in nuclear power, as emphasized by the United States in the late 1970s*". "*. . . the United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes.*"

A reversal of the official American position is possibly underway. The energy plan announced by President Bush [2] in May 2001 leaves open the recycling option in the context of future energy needs: "*The United States should also consider technologies (in collaboration with international partners with highly developed fuel cycles and a record of close cooperation) to develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant*". "*In doing so, the United States will continue to discourage the accumulation of separated plutonium, worldwide*." More to the point, the Bush Administration announced in early 2002 that American weapon-origin plutonium would be converted to mixed-oxide fuel for use in nuclear power plants. This decision was possibly influenced by the interim findings of a Panel of the 'Committee on International Security and Arms Control' of the US National Academy of Sciences [3], which concluded that irradiating the plutonium in MOX (mixed oxides of uranium and plutonium) in a once-through nuclear reactor fuel cycle would meet its 'spent-fuel standard' for resistance to theft and proliferation better than the alternative. This selection could close the door to the alternative of matrix immobilisation and underground burial [4].

The civil use of plutonium in many European countries over several decades has firmly demonstrated the soundness of the technology, and has paved the way towards more efficient nuclear fuel cycles with a better utilisation of the uranium resources of the earth [5]. The proponents of plutonium recycling value the universal non-proliferation objectives, and they are convinced that recycling can satisfy these objectives.

3. Plutonium mixtures and material security

Plutonium has a positive record in the civilian applications of nuclear energy in laboratories and industry. Under proper conditions, plutonium is safe to handle. Its use is not associated with environmental pollution.

Remaining toxic for long periods, it does however require long-term safe disposal; but, more important for many people, plutonium is widely perceived as a proliferation threat.

Plutonium is indeed a material of interest for the making of nuclear devices by States or by terrorist groups. Today, the security of nuclear materials must remain a high priority at all levels, whether national, regional or international. Several new factors need, however, to be taken into account to design control systems that focus on the essentials and that make use of the financial resources most efficiently and effectively. First, there are very large inventories of civilian spent fuel in storage. The unseparated plutonium contained in high-burnup fuel can hardly be considered of 'direct use' any longer. A greater concern: a non-negligible fraction of that civilian spent fuel contains low burnup, high quality plutonium (in terms of weapon use) that would deserve more attention from the control organisations. Second, there are increasing inventories of separated plutonium. As implied by President Bush, the problem today is not reprocessing as such; it is the accumulation of separated plutonium resulting there from. In terms of perceived proliferation risks, the Achilles' heel of reprocessing is the still insufficient recycling of plutonium in power plants in the form of MOX fuel.

These new factors call for a closer look at the proliferation risks associated with plutonium and with different plutonium mixtures from different origins. Traditionally, the suitability of a plutonium mixture for explosive devices is determined by its Pu-240 contents, a most undesirable isotope because of its numerous spontaneous neutrons, its high radiation and heat production (see Table 1).

These definitions have been widely used by scientists [6, p. 19] and by weapon designers [7]. What is the usability of the various plutonium grades for the making of explosive nuclear devices? A review of available sources – and taking into account physics and engineering factors – leads to the broad assessment shown in the last column of Table 1, an assessment based on explanations spelled out in the coming sections.

3.1. Weapon-grade

The standard material is easy to use, with high yields, low radiation levels and low heat generation. The super-grade is even better.

3.2. Fuel-grade

Up to the 1970s, the definition of 'reactor-grade' started at 7% in Pu-240, and thus included what was later called 'fuel-grade category'. At that time, nobody saw any interest in fuel-grade for serious weapons use due to the higher radiation and heat levels. Everything beyond weapon-grade was labelled by default 'reactor-grade'. The confusion between the two definitions of what constitutes reactor-grade is frequently maintained – intentionally or not – by those people who want to emphasise the risk of reactor-origin plutonium.

An old American test is sometimes mentioned as proof that reactor-grade plutonium is a suitable explosive material. In 1977, then again in 1994, the United States Department of Energy (US-DOE) announced that the US had in 1962 exploded a device using 'reactor-grade plutonium' supplied by the

Table 1. Plutonium mixtures for explosive devices

Grades	Pu-240 concentration	Usability
Super-grade (SG)	<3%	Best quality
Weapon-grade (WG)	3–7%	Standard material
Fuel-grade (FG)	7–18%	Practically usable
Reactor-grade (RG)	18–30%	Conceivably usable
MOX-grade	>30%	Practically unusable

United Kingdom. A lively private debate ensued between the two governments [6, p. 61], since there are no records of reactor-grade plutonium as now defined being produced at the British Calder Hall and Chapelcross nuclear plants before 1962 (the fuel burnup was too low). The DOE announcement was misleading:[2] in reality, this was 'fuel-grade' plutonium containing a small proportion of Pu-240, presumably around 12% [8].

Fuel-grade plutonium does not qualify for a 'weapon programme', by the very definition of the word 'weapon', that is, a tool easy to handle and to store, and with a predictable impact. However, in combination with an adequate implosion technology, fuel-grade plutonium becomes a suitable material for a potential proliferator to make a powerful 'nuclear explosive device', even if the yield would be somewhat unpredictable.

3.3. Reactor-grade

More than 2000 nuclear explosions have been carried out worldwide since 1945; none is known to have used reactor-grade plutonium (>18% Pu-240), none with Pu from light-water reactors (LWR). Reactor-grade Pu can be used in principle to make a crude explosive device; the practical difficulties are nevertheless considerable, as pointed out below. One should, incidentally, specify the type of reactor when applying this definition: gas-cooled and heavy water reactors operate at different burnups, and produce different mixtures of plutonium falling frequently in the fuel-grade category.

3.4. MOX-grade

This is plutonium resulting from the use in a LWR of MOX fuel manufactured from LWR reactor-grade plutonium. In other words, this is the plutonium coming out of Pu recycling. MOX-grade plutonium contains so much Pu-240, and in addition so much Pu-238 (some 2% or more), that its handling becomes extremely difficult in terms of radiation and heat levels. The French scientist and engineer Robert Dautray – former High-Commissioner of the French Atomic Energy Authority (Commissariat à l'énergie atomique), and a key figure of the French nuclear weapon programme – writes the following about MOX fuel [5, p. 127]: "*MOX brings a further benefit: this plutonium is not suitable for making weapons. One could thus bury MOX, if one so wishes, after cooling. Furthermore, the security of the repository is then simplified*". As noted above, the Panel of the 'Committee on International Security and Arms Control' of the US National Academy of Sciences has also reached a positive conclusion as to the resistance to theft and proliferation of MOX-grade plutonium.

4. Usability of reactor-origin plutonium: isotopic factors

Plutonium quality plays a central role in the making of nuclear weapons and of nuclear explosive devices. While not practical for a weapons arsenal, the usability of fuel-grade plutonium for explosive devices is demonstrated and thus undisputed. On the other hand, several experts seem to acknowledge the de facto unusability of MOX plutonium. Therefore, the issue is really about reactor-grade plutonium containing between 18 and 30% of Pu-240: is this Pu mixture 'easily usable' as some claim, or only 'conceivably, theoretically usable'?

The most frequent isotopes in spent fuel are, in order, 239, 240 and 241. Pu-238 is the least frequent, but the most undesirable when its concentration begins to weigh in, above a burnup of about 30 $\mathrm{MWd \cdot kg^{-1}}$. The respective fundamental characteristics are summarised in Table 2 [9].

Of main concern for the making of an explosive device are the very high figures for Pu-238 and Pu-240 of the spontaneous fission neutrons and of the decay heat (and implicitly of the radiation levels). Spontaneous neutrons can lead to a pre-initiation of the chain reaction, while heat and radiation complicate the manufacturing and the handling of the device. Pu-238 is so undesirable that some authors see too many difficulties beyond a 2% fraction of the total plutonium. Pu-241 also creates serious problems in handling

Table 2. Characteristics of plutonium isotopes

Isotope	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Half-life (years)	87.7	24 100	6560	14.4	376 000
Bare critical mass (kg)	10	10	40	10	100
Spontaneous neutrons ($kg^{-1}\cdot sec^{-1}$)	2 600 000	22	910 000	49	1 700 000
Decay heat ($watt\cdot kg^{-1}$)	560	1.9	6.8	4.2	0.1

Table 3. Plutonium isotopic composition of spent fuel at discharge

Isotopic contents in % of total Pu	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Burnup – irradiated LWR uranium oxide:					
20 MWd/kg heavy metals (Siemens)	0.7	70	18	10	1.6
33 MWd/kg heavy metals (Mark)	1.3	60	24	9	5
33 MWd/kg heavy metals (Siemens)	1.2	58	23	14	4
50 MWd/kg heavy metals (Siemens)	2.7	47	26	15	9
60 MWd/kg heavy metals (Siemens)	3.5	44	27	15	11
Burnup – irradiated LWR mixed oxide:					
33 MWd/kg heavy metals (Mark)	1.9	40	32	18	8

Table 4. Plutonium grades and usability parameters

Device made with grade	Weapon	Reactor[a]	MOX[b]
Spontaneous neutrons (kg/sec)	66 000	360 000	570 000
Plutonium mass (kg)	3	8	>20?
Decay heat (watt/kg)	2.5	11	13.7
Heat from device (watt)	8	100	>300?

[a] Assumptions: from pressurised water reactors (PWR) spent fuel with a burnup of 33 $MWd\cdot kg^{-1}$ stored 10 years prior to reprocessing.

[b] Assumptions: from PWR-MOX spent fuel produced from the same reactor-grade plutonium.

because it decays to americium-241, which is very radioactive. Pu-242 does not help either, with its high critical mass and high rate of spontaneous neutrons.

Now, Table 3 provides some indicative figures as to the isotopic composition of discharged LWR fuel, in relation to the achieved combustion burnup [10,9].

Table 4 shows some relevant technical values for an explosive device made of various grades of plutonium (from [9], except for the values with a question mark in the last column).

Table 4 warrants some comments. The reactor-grade used in this table corresponds to a burnup of only 33 $MWd\cdot kg^{-1}$. Today's LWR burnups go beyond 50 $MWd\cdot kg^{-1}$; as a result, the device characteristics would worsen dramatically, with much more than a 100-watt heat release, a figure that some authors see as a practical limit for proper assembly. According to J. Carson Mark, the values of the column 'Reactor' would lead to an equilibrium temperature of 190 °C in the device, assuming a 10 cm layer of chemical high explosives (HE) around the core. He adds that "*the breakdown rate of many types of HE begins to become significant above about* 100 °C", but that "*a thermal bridge with a total cross-section at the*

surface of the core of only one square cm could halve the temperature increase induced by the reactor-grade plutonium". Then, the physicist Carson Mark brushes aside all practical engineering difficulties to conclude rather unexpectedly "*The difficulties of developing an effective design of the most straightforward type are not appreciably greater with reactor-grade plutonium than those that have to be met for the use of weapons-grade plutonium*". The omission in Mark's paper of serious reservations as to the constructive difficulties is almost as interesting as the inclusion of the lengthy physical recapitulation about fizzle yields.

As to MOX-grade, the values of Table 4 for the critical mass and for total heat release come from a simple first-order estimate; they do nevertheless illustrate the 'unusability' view of Robert Dautray quoted above, a view further substantiated by Fig. 1. Indeed, the recycling of plutonium eliminates – for all practical purposes – the proliferation risks associated with plutonium. The plutonium contained in, or separated from, MOX spent fuel incorporates so much undesirable isotopes (Pu-238 and Pu-240) that the material becomes useless for a weapon and even for an explosive device. This makes a strong case for the recycling of plutonium in MOX form.

5. Usability of reactor-origin plutonium: technology factors

The availability of suitable nuclear materials – in particular, of plutonium with the proper isotopic composition – is a prerequisite to bring a nuclear device to explosion. In addition, the availability of a series of technological skills is just as important, e.g. in chemical explosives, electronic devices, mechanical tools, etc. There are here differences between the potential proliferators of concern, say, a State acting clandestinely under international controls, or a sub-national group acting without the knowledge of the host country. A State can more easily make undetected use of national technological resources than a sub-national group.

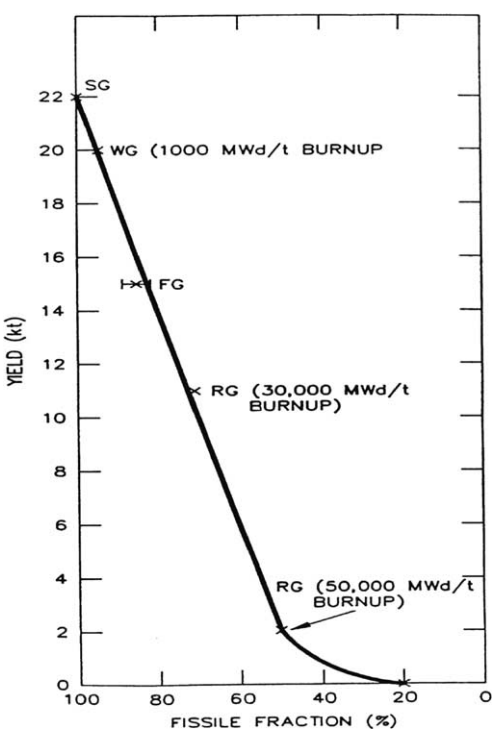

Figure 1. Calculated yield curve.

Fig. 1 shows the calculated average explosive yield [11] of a nuclear device as a function of the 'fissile' fraction, that is, the two valuable isotopes of a uranium or plutonium mixture, U-235 and Pu-239. This curve assumes the availability of the required technology, unhampered by technical constraints such as heat and radiation levels. In a sense, this curve represents an upper bound of what can be achieved with a given grade of material (and a corresponding tamper).

Various authors have attempted to assess the role of technological factors on the yield. Johan Swahn [12] has considered three levels of technological know-how applied to the making of an explosive device; he uses as a yardstick the compression velocity induced by the chemical explosion on which the nuclear yield depends: "*First, we have the terrorist group or the sub-State ethnic group, perhaps with the support from a State, at level 1. These can possibly achieve a compression velocity of* 500 m/sec. *Second, at level 2, we have the level of know-how that the United Sates achieved during the Second World War during the Manhattan Project, with compression velocities of about* 1000 m/sec. *The general technological level is higher nowadays, and one can today count most of the world's States, with perhaps a few exceptions in the developing world, in this category. Finally, we have level 3 at which the nuclear weapon States, but also many other industrialised States, are. The technological know-how in these States would allow the construction of a device with a compression velocity of over* 2000 m/sec." Quoting a former study of the Swedish National Defence Research Institute [13], Swahn concluded: "1. *Reactor-grade plutonium* (20–30% Pu-240) *is at compression velocities of about* 500 m/sec*, only useful for devices of at most a kiloton yield. The function will remain uncertain.* 2. *Reactor-grade plutonium can at very high compression velocities* (2000 m/sec) *be used in* 1 kT *devices with a good reliability and in* 10 kT *devices with limited reliability"*. Later American sources [14] match these values.

High compression velocity – the most critical technology factor – cannot be achieved without extensive testing of high explosives. An advanced State could do so clandestinely; a sub-national group could not, without the complicity of the hosting State.

Accordingly, with a mastery of implosion technology, LWR Pu can be used 'in principle' to make a crude explosive device [5, p. XXXI]. Nevertheless, many obstacles stand in the way besides the availability of the nuclear material and the required implosion technology. Altogether, according to Alexander DeVolpi [15], [3] there are some ten difficulties facing a new proliferator attempting to manufacture an explosive device with reactor-grade plutonium:

- larger critical mass;
- larger size and weight;
- longer neutron lifetime;
- smaller explosive yield;
- unpredictable yield;
- pre-initiation more likely;
- risk of metallic phase changes;
- high surface doses and temperatures;
- chemical explosive testing required;
- forced cooling of device required.

All those are major obstacles. A would-be proliferator would rather choose a less visible and less complicated technical process, for example, uranium enrichment, as done by South Africa and Iraq.

Is then the mere possession of separated reactor-grade plutonium a substantial proliferation risk? The French nuclear scientist Robert Dautray has the following to say [5, p. 152]: "*We know of no scientific reference in the US, the United Kingdom and France – not stamped 'defence secret' – that bears out rigorously and quantitatively the above assertion (to possess separated plutonium). Yet, all assertions from expert reports say '…as well-known from the open scientific literature…', with references to each other. Such assertions ought to be qualified with accurate reservations – never spelled out – and backed up by experimental or theoretical references always absent from such reports*".

Alexander DeVolpi had said earlier [15]: *"A shibboleth of some current policy analysis is that all Pu is 'weapons usable'. This is a deceptive oversimplification that could result in delaying effective steps to defuse the caliber of Weapon-Grade Pu. Moreover, by creating an aura of futility, that portrayal provides a rationale to stall further arms reductions"*.

6. New environment

New categories of plutonium are needed to handle properly what are really different materials in terms of security and verification criteria. The non-proliferation and security control systems, e.g. the International Atomic Energy Agency (IAEA) and the Euratom Inspectorate, have lumped all plutonium isotopes together and applied common control parameters to the lump regardless of the grade. This was acceptable at the time (in the late 1950s) in view of the small quantities of plutonium-bearing materials in non-nuclear weapon States. Yet, the quality and the isotopic mixture of plutonium play an essential role in defining the degree of risk of misuse. New factors now call for a revision of verification goals and criteria, such as:

6.1. Strong differentiation between plutonium grades

Even though all Pu isotopes are fissionable for the fast neutrons of an explosive device, all isotopes other than Pu-239 have a strong negative impact on the feasibility and on the yield of a device. The concentration of the useful isotope Pu-239 – and those of the most undesirable, Pu-238 and Pu-240 – must be taken into consideration in a well-defined control system. On the one hand, low-burnup fuel contains fuel-grade plutonium that deserves more attention than has been the case so far. On the other hand, very high burnup fuel and MOX spent fuel contain plutonium of practically no proliferation concern.

6.2. More and more high-burnup LWR fuel

Some 1500 tonnes of plutonium have accumulated worldwide, about 250 tonnes of which are in the military sector. In 2000, under all its safeguards agreements in non-nuclear weapon States, the IAEA had to control 726 tonnes of Pu, separated and unseparated. The cost of verification in the world and in Europe of high burnup spent fuel is growing beyond reason. Controls of such spent fuel in future direct geological depositories would be expensive and even more senseless; less stringent controls could apply to these materials without incurring proliferation risks.

6.3. More and more low-burnup civilian spent fuel

A growing inventory of low-burnup spent fuel is now under IAEA safeguards [17]. For LWR spent fuel, there are close to 100 kg of weapon-grade plutonium and about 5000 kg of fuel-grade plutonium, 'easily' accessible through chemical processing; yet these sensitive nuclear materials are under 'normal' safeguards criteria only. Additional large quantities of weapon-grade and fuel-grade plutonium are contained in spent fuel from gas-cooled and heavy water reactors. When low-burnup spent fuels are disposed of directly in geological formations, they do become – after fission product decay – authentic 'bomb plutonium mines'. For such materials, reprocessing (in a mix with high-burnup fuel) should really be mandatory. John Carlson and his colleagues at the 'Australian Safeguards and Non-Proliferation Office' [17] have tried for many years to draw the attention of the world safeguards community on the problem of low-burnup fuel. They have also pointed out the 'weapon-grade' quality of the plutonium produced in the blankets of fast breeder reactors (2–4% Pu-240), with such material available in several countries. Be it low-burnup spent fuel or blanket materials, more stringent controls than the current ones should apply to these materials.

6.4. Weapons-origin Pu coming into the civilian cycle

If this will ever happen, the supplying countries will probably make the material available under lease only. They will also require very stringent controls, much more stringent than the current international controls.

7. Needed: categories of plutonium for controls

For all these reasons, all organisations dealing with nuclear material security should initiate an in-depth review of plutonium, with the objective of categorising it in a suitable manner.

A pertinent proposal to that effect was made in the 1996 report published by the Canberra Commission, a group of eminent personalities brought together by the Government of Australia.[4] The report contains interesting ideas about the use of civilian and demilitarised fissile materials. Noting that a proper balance must be struck between the legitimate civilian use of such materials and the objectives of nuclear non-proliferation and disarmament, the Commission states that striking such a balance might be feasible: "*One possibility may be to draw a distinction between plutonium of different isotopic grades and to use this distinction both for safeguards purposes and for a proscription on the separation of plutonium of an isotopic composition which makes it attractive for weapons use*"… "*It is an unfortunate consequence of the current practice of not differentiating between plutonium grades for safeguards purposes that special attention is not directed to plutonium having the isotopic characteristics of greatest proliferation concern*"… "*Therefore, there would be merit in investigating various categories of plutonium in terms of applicable safeguards measures and resulting verification costs*".

In line with the advice of the Canberra Commission, this paper takes the position that nuclear materials control systems should be designed with due consideration for the types of materials to be verified and for realistic risk assessments. Taking into account the technical factors related to the use of various kinds of plutonium for the fabrication of a nuclear explosive device, a categorisation of plutonium is being proposed here – see Table 5.

7.1. High-grade

This definition of high-grade Pu is conservative and prudent: it includes of course the weapon-grade (<7%), but also almost all the intermediate category 'fuel-grade' (7–18%). This material comes:

(1) from dismantled weapons, before and after one MOX cycle,
(2) from breeder reactor blankets, and
(3) from various types of power reactors, also from LWR in case of abnormally short exposure in reactor.

The threshold value of 17% corresponds to the safety/criticality limit in large modern reprocessing plants; this is thus a convenient way of segregating materials for verification purposes. The high-grade category deserves all the attention of the control organisations; actually, it deserves more attention than in the past. Therefore, the timeliness of such separated plutonium should be reduced from the current one month to two weeks (this should also be the case for highly-enriched uranium). The timeliness of unseparated Pu could stay at the current value to reflect the time required for chemical separation from spent fuel.

7.2. Low-grade

This material, the bulk of materials to be verified, corresponds primarily to medium-high burnup LWR fuel. In view of the difficulties associated with the use of such plutonium, the key verification parameters

Table 5. Verification criteria versus plutonium grades

Category	Pu-240 fraction	Significant quantity	Timeliness (separated)	Timeliness (unseparated)
High-grade	<17%	8 kg	Two weeks	One month
Low-grade	17–30%	16 kg	Three months	One year
Depleted grade	>30%	–	One year	–

The 'significant quantity' is the approximate quantity of nuclear materials needed to manufacture a first nuclear device, taking into account losses in conversion and in manufacturing. 'Timeliness' is a component of inspection goals related to the conversion time, that is the time required to convert a given nuclear material into metallic components for an explosive device.

Table 6. Verification classes

Verification class	Materials coming from:
High-grade separated	Weapon-origin, low-burnup origin
High-grade unseparated	Blankets, low-burnup spent fuel
Low-grade separated	Fresh mixed oxide fuel made with LWR Pu
Low-grade unseparated	High-burnup LWR spent fuel
Depleted grade	Separated or not, irradiated MOX and very high burnup fuel

should be adjusted: the significant quantity doubled with respect to weapon-usable material, the timeliness for separated material increased from one month to three months, and the timeliness for unseparated Pu (spent fuel) raised to one year – a step that the IAEA plans anyhow to adopt under integrated safeguards for the current single Pu category.

7.3. Depleted grade

This covers mostly Pu in irradiated LWR MOX, but also Pu from spent fuel with higher burnup, say above 50 MWd/kg. In this category, it is not only the Pu-240 content that is relevant, but also the Pu-238 whose fraction can exceed several percentage points in high burnup fuel. As noted by Alexander DeVolpi [15]: "*Yet, even without recycle, higher burnup can further degrade Pu*". A Pu-238 threshold of 2% (in an AND/OR criterion) could here be added to the definition. The concept of 'significant quantity' is here irrelevant. As to controls, an occasional verification of separated material (an unlikely situation) would be sufficient.

7.4. The use of these categories

In so proposing three categories of plutonium, one can draw a limited analogy with the three broad categories of uranium: 'highly enriched (HEU)' ($>$20% U-235), 'low-enriched (LEU)' (0.71–20% U-235) and the 'depleted-natural' ($\leqslant$0.71%) range. To account for the not very attractive uranium recovered from reprocessing plants, it would, incidentally, be sensible to group in a single category all uranium below say, 1.5% U-235. One recalls that the concern about LEU is not its usability as such, but the 'distance' that separate it in terms of separation work units (SWU) from the full HEU level. At the typical research reactor enrichment of 20%, the distance is a good 0.9 of the full distance (5000 SWU required for one significant quantity of 93% HEU); at a typical LWR enrichment of 3.5%, it is still 0.63; and at 1.2% (a value on the high side for uranium out of reprocessing), the distance is down to 0.26.

The security measures applied to nuclear materials by Euratom in the European Union and the safeguards controls of the IAEA in the world should therefore distinguish between five different forms of plutonium – Table 6.

In conclusion, the adoption of several categories of plutonium – as for uranium – would lead to a better perception of the link between plutonium recycling and proliferation. This would allow for a more effective and more efficient control of nuclear materials, from both the security and safeguards viewpoints. This would strengthen the case of plutonium as component of a sustainable development of nuclear energy. Last, but not least, it would pave the way to further nuclear disarmament initiatives.

8. Postscript

This paper does not question the theoretical feasibility of exploding plutonium of various categories. The emphasis lies on the practical obstacles standing in the way and on a realistic assessment of the technical difficulties to be encountered. The objective is here the determination of optimum criteria for international

controls of nuclear materials. Optimising means using the available resources effectively and efficiently, with more stringent controls on materials of real concern, and less stringent on materials of little concern.

Since the rejection of reprocessing by the Carter Administration in 1977, American officials have repeatedly argued against reprocessing and Pu recycle elsewhere in the world, leaning on the questionable claim that all plutonium is 'weapon-usable', under the impression of the alleged 'reactor-grade' nuclear test of 1962. In international forums, these officials have therefore refused to contemplate a categorisation of Pu and any other re-assessment of the relevant verification criteria. Behind a veil of secrecy, the opinion of weapon designers is short-handedly invoked to definitively validate positions. While recognising the need for confidentiality, the independent observer gains too often the impression of a lack of technical objectivity. To develop a more balanced technical opinion on the matter, there is a need to look – as done in this paper – beyond the physics, at the interface between physics and engineering, to gain a better understanding of the real difficulties for a proliferator of using less than good quality plutonium.

In fact, physics alone is not a reliable guide to conceive an optimum nuclear material control system. Other technical, economical and even political factors must be taken into consideration to achieve the best results. The following related issues in the fields of non-proliferation and disarmament illustrate the need to 'balance things out':

8.1. The americium bomb

In the late 1990s, the IAEA discussed potential controls over stocks of neptunium and americium, two transuranium materials that accumulate in some non-nuclear weapons countries and that are usable for explosive purposes – to different degrees. Some national representatives insisted unreasonably for identical controls on both materials, even though americium is almost as unusable as Pu-238 in terms of radiation and heat. The justification was simply that skilled weapon designers 'have said they could do it'. Common sense prevailed at the end, with enough other parties keen on seeing the IAEA concentrate its new efforts on neptunium, the material of real concern.

8.2. The one kg plutonium bomb

Throughout the 1990s, American antinuclear scientists tried to convince the IAEA to change the standard significant quantity for Pu from 8 kg to the low figure of one kilogram. Again, the argument was that experienced American and Russian weapon designers 'have said they can do it'. After review, the IAEA ignored the call and kept the current figure, on the ground that its control mission is to detect the *first* device ever of a proliferator (and not the 10^{th} or the 100^{th}), and because miniaturisation cannot be achieved without prior testing of larger devices.

Robert Dautray has his own opinion on this matter: "*In this respect, the low mass values quoted by some scientific journals and by 'experts' (experts?, yes, but for what?) who sit as such in the world's highest-level scientific committees are questionable; these values suppose very specific matching conditions, difficult to fulfil, never explicitly stated, because not rigorously and quantitatively understood by these 'experts' (this is not a mere speculation of the author, but it reflects his personal experience)*" [5, p. 152].

8.3. Fissile Material Cut-off Treaty

Throughout the 1990s, the Conference on Disarmament in Geneva tried to conclude a 'Fissile Material Cut-off Treaty (FMCT)', a treaty that would forbid the production of nuclear materials for explosive purposes. Several States – in particular France and the United States under the Clinton Administration – made valuable contributions towards such a goal. The process is now stalled for a number of reasons, in particular the excessive demands (in the FMCT context) of other States for the full disclosure of existing stockpiles.

In last analysis, the future of the FMCT will largely depend on the practicability and the cost of verifying such a treaty. This in turn will depend on the number of installations to be inspected, a number that relates

directly to the types of plutonium to be considered. If all reactor-grade plutonium in spent fuel is deemed usable for weapon purposes, then hundreds of nuclear plants and the associated fuel stores will require inspection in the States not already controlled by the IAEA (that is the five declared weapon States, Israel, Pakistan and India). With such a heavy financial burden, a FMCT will never happen. Agreeing on plutonium categories is a necessary prerequisite for a viable and affordable FMCT. Those who oppose Pu categories under the Non-Proliferation Treaty – in particular those coming from the weapon establishment – should not give the impression that they do so in order to make a FMCT impossible from the onset, as hinted by Alexander DeVolpi in the above quotation ("*a rationale to stall further arms reductions*").

8.4. Conclusion

Whether for americium, or the one-kilogram bomb, or reactor-grade plutonium under the NPT or the FMCT, the design of an optimum control system demands a serious, honest and all-encompassing assessment of all relevant factors. In last analysis, this is a political balancing act between the perception and reality of risks, between economical constraints and the technical capabilities of the proliferator and those of the control agencies.

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[1] Bruno Pellaud is a former Deputy Director General of the International Atomic Energy Agency (IAEA) and head of the Department of Safeguards (1993–1999), now adviser to the European Commission on Euratom security matters and President of the Swiss Association for Atomic Energy (ASPEA/SVA).

[2] "*This was a prize example of misleading information being released from its formerly classified status for political purposes*" from [1].

[3] "*Over the years, Dr. DeVolpi and DOE security officials have clashed repeatedly over the contents of his publications, which officials say have sometimes revealed classified information. Following his publication of an encyclopaedia article on nuclear weapons a few years ago, DOE went so far as to seize his personal computer and seal his files, until the Secretary of Energy intervened and apologized*" [16].

[4] Canberra Commission on the Elimination of Nuclear Weapons, i.a. Nobel Peace Prize Joseph Rotblat, Ambassador Jayantha Dhanapala, Prime Minister Michel Rocard, Secretary of Defense Robert McNamara, Dr. Ronald McCoy (International Physicians for the Prevention of Nuclear War), Lee Butler (Commander in Chief of the US Strategic Air Command) [18].

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Discussion

Remarque de R. Dautray

En application de l’exposé de monsieur Pellaud, R. Dautray énonce les compositions isotopiques du Pu des UOX et MOX usés. Il les situe dans la classification de monsieur Pellaud et propose d’y ajouter d’autres caractéristiques pertinentes. Il précise également les plages des caractéristiques des couvertures des RNR (de tous types). Il analyse le sens profond de toutes ces limitations et leurs conséquences réelles en prenant les derniers exemples internationaux relevant du sujet traité par l’orateur et de la manière dont ils ont été traité par les pays concernés.