PLUTONIUM MANAGEMENT OPTIONS: LIABILITY OR RESOURCE

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Since plutonium accounts for 40-50% of the power produced by uranium fuels, spent fuel contains only residual plutonium. Management of this plutonium is one of the aspects influencing the choice of a fuel cycle back-end option: reprocessing, direct disposal or wait-and-see.

Different grades and qualities of plutonium exist depending from their specific generation conditions; all are valuable fissile material. Safeguard authorities watch the inventories of civil plutonium, but access to those data is restricted. Independent evaluations have led to an estimated current inventory of 220 t plutonium in total (spent fuel, separated civil plutonium and military plutonium). If used as MOX fuel, it would be sufficient to feed all the PWRs and BWRs worldwide during 7 years or to deploy a FBR park corresponding to 150% of today's installed nuclear capacity worldwide, which could then be exploited for centuries with the current stockpile of depleted and spent uranium.

The energy potential of plutonium deteriorates with storage time of spent fuel and of separated plutonium, due to the decay of ^{241}Pu, the best fissile isotope, into americium, a neutron absorber. The loss of fissile value of plutonium is more pronounced for usage in LWRs than in FBR. However, keeping the current plutonium inventory for an expected future deployment of FBRs is counterproductive.

Recycling plutonium reduce the required volume for final disposal in an underground repository and the cost of final disposal.

However, the benefits of utilizing an energy resource and of reducing final disposal liabilities are not the only aspects that determine the choice of a back-end policy

KEYWORDS : Plutonium, Nuclear Fuel, Fuel Cycle, Back-end, MOX, Americium, Curium

1. INTRODUCTION

Political guidelines or legal obligations rather than economic or sustainability considerations result in utilities selecting a back-end option for the fuel cycle. In 2005, the IAEA organized a Technical Meeting devoted to "Fissile Materials Management Strategies for Sustainable Nuclear Energy", the proceedings of which have recently been published [1]. One of the three sessions was devoted to the back-end fuel cycle options. A Key Issue Paper [2] considered all aspects and a series of topical paper highlighted particular facets or presented alternative views. This article will provide some additional insights on plutonium management.

Worldwide roughly 10 000 tHM spent fuel (SNF) are discharged yearly from nuclear power plants (NPPs). While some 15% of it is being reprocessed, a once-through cycle is currently the official selection for a majority of the spent fuel tonnage, either because the residual fissile content is too low to justify recuperation or because of political decisions in a few large countries. When the choice is free, a wait-and-see policy is universally applied. Implementation of the two latter policies requires interim, perhaps long-term, storage, leaving opportunities to change the back-end policy in the future.

Since the fissile material in spent fuel is a resource that will be required sooner or later in a perspective of sustainability of the nuclear option, the question is when to recuperate this fissile material and for which reactor type. Timeliness of reprocessing and of reuse of the recuperated plutonium and uranium must take into consideration aging characteristics, economics and policy selection criteria. This paper will be devoted to the plutonium aspects.

2. BACK-END OPTIONS

Out of the three options for management of spent nuclear fuel (reprocessing, direct disposal and wait-and-see), the wait-and-see option is today the most common management strategy that simply focuses on the long-term storage of spent fuel.

A few examples can illustrate the rationale for choosing a strategy and its evolution over time.

2.1 Reprocessing and Recycle ("Closed Fuel Cycle")

During the early years of nuclear power, the reprocessing and recycle option was chosen primarily for two reasons.

The first and major reason was the energy value of the residual uranium and plutonium separated from the wastes during reprocessing. This energy value could be multiplied many times if recycled in fast reactors (FBRs). During the early years of nuclear power development, the USA, the UK, France (with contribution from Italy), Russia, Japan and Germany (with contribution from Belgium and the Netherlands) conducted R&D and demonstration programs devoted to the goal of recycle in fast reactors. Japan, Russia, China and India are all still domestically pursuing the development of fast reactor systems to benefit from the energy independence conferred by reprocessing and recycle.

The second reason was the technical availability of the option. Reprocessing had already reached a considerable level of maturity by the time of increased civil use of nuclear power and had reached an industrial stage of deployment in some countries. Indeed, for certain early fuel designs, such as the metallic Magnox fuel in the UK and the GCR fuel in France, reprocessing was the only technically viable option for managing the spent fuel. Other countries such as Belgium, Switzerland, Japan, the Netherlands and Italy for example had chosen in the past to contract for reprocessing their spent fuel arisings, taking into account availability of reprocessing services offered on the international market and economies of scale compared to building indigenous capabilities.

Some countries are developing, as potential options, alternatives to the standard technology, for instance the DUPIC (Direct Use of PWR In CANDU) concept in Korea and the electro-refining of spent fuel and vipac re-fabrication in Russia.

The justifications of the close cycle option have been reconsidered, as the development of FBRs had been slower than expected (e.g. Japan and Russia) or even abandoned (Germany, France, the UK and the USA). Recycling the plutonium in LWRs, a solution that has replaced their use in FBRs, has been implemented on a demonstration scale in India, Italy, Japan, the Netherlands, Sweden and the USA and, on a commercial scale, in Belgium, Switzerland, Germany and France.

The cycle time is longer than anticipated in the early days of nuclear power, when the discharge burnups were low. It is now typically 19-20 years:

- minimum 4 but more commonly 10 or more years between spent fuel discharge and reprocessing,
- minimum 2 but more commonly 4 years between availability of separated plutonium and delivery of the MOX fuel,
- 1 to 2 years (sometimes much more) before loading in the reactor,
- 4 up to 10 years residence time in the core.

Adding to this, due to the higher decay heat, spent MOX fuel must cool down twice longer in the spent fuel storage pool of the reactor than spent uranium fuel before it can be transferred to a (dry or wet) interim storage facility. So the closed cycle option can only be considered in a context of confidence in at least mid-term continuation of nuclear generation.

Since, at the current natural uranium price levels, recycling plutonium into LWR MOX fuel is less economic than utilizing enriched uranium from yellow cake (sometimes called "enriched natural uranium", ENU, to differentiate it from "enriched reprocessed uranium", ERU), almost all countries have presently abandoned the reprocessing option for either the once-through option or the wait-and-see option.

Only France and Japan are actively pursuing the closed cycle and LWR MOX option, for two reasons:

- They program a long-term policy of nuclear power generation, which implies that FBRs will become necessary in some future. The back-end (reprocessing and MOX fabrication) infrastructure and expertise must be available. Running these activities industrially and continuously improving the technologies is the best preparation for the future.
- It reduces volume and cost of the underground final repository for radioactive waste (see Section 5).
- The fuel cycle cost penalty is not prohibitive.

The UK provides commercial reprocessing services, partially in THORP for fulfillment of contracts with foreign utilities, which take back their plutonium, and partially in B205 for managing the spent fuel of the British Magnox plants. The British separated plutonium is stored with no defined end-use.

In Russia, industrial reprocessing is limited to the VVER-400 spent fuel, with utilization of the reprocessed uranium (RepU) to manufacture RBMK fuel and storage of the plutonium for future use in FBRs.

2.2 Once-through Cycle ("Open Fuel Cycle")

The once-through option is adopted as a strategy for the management of the spent fuel for a number of disparate reasons. These reasons have included, in particular, faith in abundance (or adequacy) of natural uranium resources and therefore no interest in longer term recycling, questions of economics, concerns about proliferation issues associated with reprocessing, political decision to phase out nuclear generation as whole and/or near-term availability of a large size underground repository .

A number of countries have switched from the reprocessing recycle option wholly to the once-through option; examples such as the USA, Germany and Sweden

are at the forefront of this trend. The USA is however revisiting this option [3].

Worth mentioning is that all the final disposal facilities are now designed for "retrievability" or even "reversibility". Therefore, in principle, the fissile material could always be recuperated in the future. However, the cost would be prohibitive in all reasonable perspectives of evolution of the natural uranium prices.

2.3 Wait-and-see Option

An increasing number of countries and individual utilities have currently adopted this option, which is simply long-term storage with no commitment to either direct disposal or reprocessing of spent fuel. The reasons why utilities or countries are committing to this strategy are diverse and several: economics, the long timescales involved in securing appropriate final disposal facilities, uncertainties about the future energy requirements and/or simply a lack of political guidance in overall national strategy.

Some countries, such as Belgium and Switzerland, have switched from the reprocessing and recycle option to the wait-and see option.

Many countries are following dual strategies, for instance all countries that are committed to a reprocessing and recycle strategy are also applying a wait-and-see strategy to a proportion of their spent fuel arisings. For example in the UK, not all AGR fuel has been reprocessed and no decision has yet been made on the management option for Sizewell-B PWR fuel. In France, not all spent fuel arisings are being reprocessed, spent MOX fuel and some spent uranium fuel is currently being stored.

3. PLUTONIUM CONTROL AND ACCOUNTANCY

The irradiation of uranium generates plutonium naturally. It was discovered in the products of the Oklo natural reactor in Gabon, which was active almost two billion years ago in a uranium-rich geological formation. Therefore, plutonium is an intrinsic by-product of uranium-fuelled nuclear reactors but is partially consumed in the reactor itself. At present, plutonium fissions produce over 40% of the energy generated in a nuclear power plant and, with the current trend to increase discharge burnup of nuclear fuel, this will rise to over 50%. The discharged fuel contains only the remaining plutonium.

Most of the plutonium is created when the ^{238}U isotope in nuclear fuel absorbs a neutron released by the fission process. At first, it produces ^{239}U, which rapidly (half-life 24 min) ejects an electron to decay into ^{239}Np. This isotope also quite soon (half-life 2.3 d) looses an electron, resulting in ^{239}Pu, a fissile isotope. Some of this ^{239}Pu disappears by fission, releasing energy. However, not all the ^{239}Pu undergoes fission. Some impacting neutrons are absorbed producing ^{240}Pu. This is a fissile isotope in fast reactors, but almost exclusively a neutron absorber in thermal reactors, but at the same time a fertile ingredient. The neutron absorption results in ^{241}Pu, an even better fissionable material than ^{239}Pu, which, however, progressively (half-life 14.4yr) decays into ^{241}Am, a strong neutron absorber and the main contributor to gamma activity of plutonium. Beside the depletion by fission and radioactive decay, some ^{241}Pu absorbs impacting neutrons resulting in ^{242}Pu, approximately as strong a neutron absorber as ^{241}Am.

Two other plutonium isotopes, ^{236}Pu and ^{238}Pu, are produced as a result of decay chains from ^{237}U, formed by neutron absorption in successively ^{235}U and ^{236}U. Only ^{238}Pu is in percent quantities. It is a neutron absorber. ^{236}Pu is in ppm quantities, but it is a high-energy gamma emitter.

3.1 Proliferation Concerns

The quality of plutonium depends very much on its isotopic composition, as regards both to its potential use as a fissionable material and to its intrinsic radiological self-protection. The origin of the spent nuclear fuel (PWR, BWR, AGR, Magnox, gas-cooled production reactor), the discharge burnup, the storage time before reprocessing, the storage time after reprocessing and many other secondary factors affect the isotopic composition of each plutonium batch. Table 1 provides examples of the variety of isotopic compositions.

In principle, any of such plutonium types can be adequate

Table 1. Typical Isotopic Composition of Plutonium (rounded w/o)

Type	WPu	Civil Pu ("RPu")						
NPP	GCR	Magnox	AGR	PWR	PWR	BWR	PWR	PWR
SNF	U	U	UOX	UOX	UOX	UOX	MOX	MOX
GWd/tU	~ 0.8	5-6	18-24	33	55	30	33	60
Pu 238	0.0	0.3	0.6	1.6	3.3	2.8	2.7	5.5
Pu 239	94	69	54	60	50	55	42	34
Pu 240	5.5	25	31	24	27	23	28	30
Pu 241 + Am	0.5	4.2	10	9	10	14	18	19
Pu 242	0.02	1.1	5	5.3	9	5	8	12

to make an explosive device [5,6]. Consequently, for safeguards purposes, whether or not it is intended for civil uses is the sole criterion to differentiate civil plutonium from military plutonium (often referred to as "defense plutonium"). Only plutonium with a high content in ^{239}Pu can efficiently be used for weapon purposes [7,8]. However, in 1977, then again in 1994, the Department of Energy (DOE) announced that the US had exploded in 1962 a nuclear "device" made from "reactor grade plutonium". Based on information released in [9], this plutonium was certainly low burnup Magnox plutonium supplied by the UK. Indeed only Calder Hall and Chapelcross produced Pu and the ^{240}Pu content was around 12%. The DOE now calls it fuel grade plutonium.

In general, two types, called "grades", of plutonium are commonly considered:

- WPu (weapons-grade plutonium). The French authorities have defined it, in particular for licensing purposes, as containing less than 17% ^{240}Pu, a cut-off generally adopted throughout the world.
- RPu (reactor-grade plutonium), which is plutonium with a higher than 17% content in ^{240}Pu.

However, based on their experience, the US DOE and Department of Defense (DoD) are identifying three plutonium grades:

- Weapons grade, containing less than 7% ^{240}Pu. Although not declared as such, it is the only material practically adequate to fabricate a nuclear weapon.
- Fuel grade, containing from 7% to less than 19% ^{240}Pu. It is good enough to fabricate an explosive device, but is unattractive for weapons use.
- Power reactor grade, containing 19% or more ^{240}Pu. Although not recognized as such, it is inadequate for fabricating an explosive device. Indeed, computer calculations have demonstrated that it could theoretically be shaped into an explosive configuration (however not a weapon), but only with the help of heavy and sophisticated technologies. It is therefore inappropriate as a substitute to WPu

A further definition of weapons grade plutonium exits for implementation of the "Agreement between the Government of the United States of America and the Government of the Russian Federation concerning the management and disposition of plutonium designated as no longer required for defense purposes and related cooperation", signed September 2000 and known as the "Plutonium Management and Disposition Agreement". In that context, weapons grade plutonium means "plutonium with an isotopic ratio of plutonium 240 to plutonium 239 of no more that 0.10".

3.2 Plutonium Inventories

As plutonium undergoes radioactive decay (Table 2), it is impossible to keep a true plutonium inventory over the time frames of interest. The inventory should indeed be continuously corrected for the ^{241}Pu decay into americium, which is impracticable. Such correction occurs only whenever reprocessing separates the plutonium present in stored spent fuel, while the then present americium goes currently to high-level waste (HLW). Indeed, at the reprocessing plant, the material balance of each individual spent fuel batch and each separated plutonium batch takes into account the plutonium disappeared by decay into americium and, at that moment, the true plutonium quantity is properly recorded in the in/out files.

The decay, referred to as "plutonium aging", affects differently the various types of plutonium. Table 3 illustrates the loss of plutonium after 10, 20, 30 and 40 years storage of either spent fuel or separated plutonium (therein included

Table 2. Radioactive Decay of the Plutonium Isotopes

Isotope	Half-life (yr)
Pu-236	2.85
Pu-238	87.7
Pu-239	24 100
Pu-240	6 540
Pu-241	14.4
Am-241	432
Pu-242	37 600

Table 3. Loss of Plutonium Quantity Due to Aging (%)

Type	WPu	Civil Pu ("RPu")						
NPP	GCR	Magnox	AGR	PWR	PWR	BWR	PWR	PWR
SNF	U	U	UOX	UOX	UOX	UOX	MOX	MOX
GWd/tU	~ 0.8	5-6	18-24	33	55	30	33	60
10 yr	0.19	1.6	3.8	3.4	3.8	5.3	6.8	7.2
20 yr	0.31	2.6	6.2	5.5	6.2	8.6	11	12
40 yr	0.43	3.6	8.5	7.7	8.5	12	15	16

fabricated MOX fuel) for the plutonium types defined in Table 1. The loss of fissile value of plutonium is larger than this, as will be outlined in Section 4.

Global inventory assessments do not take these corrections into account. Therefore, what is called "plutonium inventory" is really a (plutonium + americium) inventory. In comparing the data before and after reprocessing (or before and after separated plutonium has been purified by stripping off the americium), it gives the impression that some plutonium has been lost or diverted. Of course, the safeguards agencies (IAEA, EURATOM and the national agencies) take the elimination of americium in to account.

3.3 Publication of Plutonium Inventories

Materials under international **safeguards** by the IAEA and EURATOM being well documented, the docketed figures are the most reliable data of holdings of separated plutonium and plutonium present in the spent fuel. Since the safeguards database is confidential, various organizations, on behalf of governments or pressure groups, tried to evaluate the plutonium holdings from diverse and often incoherent information sources. At the end of the 1980s, the need for some official release of plutonium inventories became obvious to improve trust and confidence. The IAEA held several meetings during 1992-1993 to discuss issues related to the accumulation of separated plutonium in civil programs.

During this timeframe, Belgium, China, Germany, France, Japan, Switzerland, the UK, Russia and the US formed a Working Group independent of the IAEA to discuss plutonium management issues. While the IAEA has facilitated these meetings by providing the Secretariat, this work has been voluntary, involving only countries that had committed to greater transparency in the management of their plutonium holdings. In March 1998, this Working Group published the "International Guidelines for the Management of Plutonium" **INFCIRC/549** [9]. These guidelines set out an internationally accepted framework for disclosing commercial plutonium inventories. Not being a safeguards accountancy record, the figures are rounded to the closest 100 kg plutonium, to provide for readability.

Within their commitment under the Guidelines, each of those nine Member States makes available, in a letter to the Secretariat, an annual statement of its national holdings, as of December of the year, of

- civil unirradiated plutonium, i.e. what is generally but inadequately (since it includes plutonium tied up in fresh MOX fuel) designated by "separated plutonium" and
- plutonium contained in spent civil reactor fuel.

The letter also mentions changes in their plutonium and fuel cycle policy since their last statement. For the information of all Member States, the IAEA publishes each of those communications in an addendum, INFCIRC/549/Add.x/y, where x is

1 for Japan
2 for Germany
3 for Belgium
4 for Switzerland
5 for France
6 for the United States of America
7 for China
8 for the United Kingdom
9 for the Russian Federation

and y is the ordinal sequence of the addenda.

Table 4. INFCIRC Reporting Format for Separated Plutonium

INFCIRC/549 Annex B		
ANNUAL FIGURES FOR HOLDINGS OF CIVIL UNIRRADIATED PLUTONIUM National Totals	as of 31 Dec. 199.. (Previous year's figures in brackets) Rounded to 100 kg plutonium with quantities less than 50 kg reported as such	
1. Unirradiated separated plutonium in product stores at reprocessing plants.	_____	(_____)
2. Unirradiated separated plutonium in the course of manufacture or fabrication and plutonium contained in unirradiated semi-fabricated or unfinished products at fuel or other fabricating plants or elsewhere.	_____	(_____)
3. Plutonium contained in unirradiated MOX fuel or other fabricated products at reactor sites or elsewhere.	_____	(_____)
4. Unirradiated separated plutonium held elsewhere.	_____	(_____)
Note:		
(i) Plutonium included in lines 1-4 above belonging to foreign bodies.	_____	(_____)
(ii) Plutonium in any of the forms in lines 1-4 above held in locations in other countries and therefore not included above.	_____	(_____)
(iii) Plutonium included in lines 1-4 above which is in international shipment prior to its arrival in the recipient State.	_____	(_____)

The format of presentation of the information is specified in INCIRC/549 Annex B for the holdings of civil unirradiated plutonium (Table 4) and in INCIRC/549 Annex C for the estimated amounts of plutonium contained in spent civil reactor fuel. The latter contains only three items: plutonium contained in spent fuel respectively "at civil reactor sites", "at reprocessing plants" and "held elsewhere". For both data sheets, the "holdings" include all the plutonium holdings present in the country, irrespective as to whether the title belongs to an organization within the Member State or to a foreign organization. Therefore, it does not represent the plutonium holdings for which the Member State has the responsibility to care for, in particular by defining an end-use policy. For obvious reasons, the data under items (i), (ii) and (iii) are often not disclosed. Even when disclosed, it gives no details as to which quantity belongs to which foreign country or is held in which foreign country. As a result, it provides the quantity of plutonium holdings in each of those nine Member States and the total for those nine countries, but no indication about the quantity each country has to manage.

It is important to note the definition of "civil plutonium" under these guidelines. The countries have agreed to include all plutonium designated for peaceful nuclear use. Although no military plutonium is included, if a Nuclear Weapons State (NWS), as is the case with Russia and the US, determines that a given quantity of military plutonium is now surplus to its defense requirements (officially designated as "no longer required for defense purposes"), this material is included in the communicated inventory. The US has applies this principle as soon as such plutonium has been designated. Russia and China have indicated that they will only apply the guidelines to plutonium physically transferred to peaceful use. The US has removed data from its inventory list whenever plutonium has been buried in the Waste Isolation Pilot Plant (WIPP).

INFCIRC/549 instruction is to submit, for IAEA publication, the previous year's data by May of following year. However, it appears that this is more an objective than hard and fast deadline. Being official figures, cautiously checked, the result is that publication of the data as of 31 December of a year occurs between July of the next year and April (even sometimes November) of the year thereafter.

The figures from INFCIRC/549 reflecting the situation as of 31 December 2001 and 2006 (if available, otherwise, in parenthesis, the 2005 data) are given respectively in Tables 5 and 6 for separated plutonium and in Tables 7 and 8 for plutonium contained in spent civil reactor fuel.

Table 5. Unirradiated Plutonium Holdings (t Pu) as of 31 December 2001

Item	JP	DE	BE	CH	FR	US	CN	GB	RU	Total
1	0.8	0.0	0.0	0.0	51.1	0.0	0.0	79.9	34.0	**165.8**
2	2.9	0.3	1.9	0.0	14.1	pm	0.0	0.8	0.0	**20.0**
3	1.5	9.0	1.0	0.06	9.9	4.6	0.0	1.7	0.2	**28.5**
4	0.4	1.6	pm	pm	5.4	40.4	0.0	0.0	1.0	**48.8**
Total	**5.6**	**10.9**	**2.9**	**pm**	**80.5**	**45.0**	**0.0**	**82.4**	**35.2**	**263.1**
(i)	0.0	/	/	pm	33.5	0.0	/	17.1	0.0	/
(ii)	32.4	/	1.0	0.0	pm	0.0	/	0.9	pm	/
(iii)	0.0	0.0	0.0	0.0	0.0	0.0	/	0.0	/	/

/ stands for the undisclosed figures
pm stands for quantities less than 0.05 t

Table 6. Unirradiated Plutonium Holdings (t Pu) as of 31 December 2006

Item	JP	DE	BE	CH	FR	US	CN	GB	RU	Total
1	1.6	0.0	0.0	0.0	48.6	0.0	0.0	102.9	41.1	**194.2**
2	3.5	0.0	0.3	0.0	12.7	pm	0.0	1.2	0.0	**17.7**
3	1.2	10.4	0.3	0.7	19.6	4.6	0.0	1.9	0.3	**39.0**
4	0.4	0.0	pm	pm	1.2	40.3	0.0	1.0	1.0	**43.9**
Total	**6.7**	**10.4**	**0.6**	**0.7**	**82.1**	**44.9**	**0.0**	**106.9**	**42.4**	**294.8**
(i)	0.0	/	/	0.7	29.7	0.0	0.0	26.5	0.3	/
(ii)	25.3	/	0.0	0.0	pm	0.0	0.0	0.9	0.6	/
(iii)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	/	/

Table 7. Plutonium (t Pu) in Spent Civil Reactor Fuel as of 31 December 2001

Country	Reactor sites	Reprocessing plants	Elsewhere	Total
JP	86	4	pm	**90**
DE	41	0	5	**47**
BE	20	0	0	**20**
CH	8	0	0	**8**
FR	89	83	0.5	**173**
US	363	0	12	**375**
CN	/	/	/	**/**
GB	6	35	pm	**41**
RU	54	3	24	**81**
Total	**667**	**125**	**42**	**834**

/ stands for the undisclosed figures
pm stands for quantities less than 0.5 t

Table 8. Plutonium (t Pu) in Spent Civil Reactor Fuel as of 31 December 2006

Country	Reactor sites	Reprocessing plants	Elsewhere	Total
JP	108	18	pm	**126**
DE	67	0	8	**75**
BE	28	0	0	**28**
CH	9	0	2	**11**
FR	95	111	7	**212**
US	459	0	12	**471**
CN	/	/	/	**/**
GB	6	28	pm	**34**
RU	63	4	37	**104**
Total	**835**	**161**	**66**	**1061**

Over these 5 years, the inventory of unirradiated plutonium has increased by 13%. It is mainly due to the UK and Russia that have no possibility for currently utilizing their separated plutonium. The UK has to continue reprocessing of their Magnox fuel, for technical reasons, but the plutonium stockpile will stabilize in the future, since the schedule for the last Magnox NPP to cease operation is 2010. As indicated in Section 2.1, Russia keeps its plutonium for feeding FBRs. The current unit BN-600 can only accommodate a few MOX fuel assemblies. The new unit BN-800, designed for operation with almost a full MOX core, could start up in 2012, if funding granted under the recent financial program [10] is allocated. However, under the agreements undersigned between the Russian Federation and the US, Russia should utilize first and exhaust the military plutonium designated as no longer required for defense purposes before starting to use their stockpile of reactor-grade plutonium. Consequently, this stockpile will continue to grow at least until 2025.

The quantities itemized under "plutonium contained in spent fuel at reprocessing plants" do not necessarily represent spent fuel to be reprocessed in a short or medium term. The storage ponds of the THORP facility serve as away-from-reactor (AFR) storage facility for AGR spent fuel, which is under a "wait-and-see" regime. The La Hague storage pools serve as AFR storage facility for the spent fuel that EDF does not consider for reprocessing in the medium term, namely the spent MOX fuel, the spent ERU fuel and part of the ENU fuel.

The 27% increase over 5 years of plutonium inventory in spent fuel (as compared to 13% for separated plutonium) reflects the effect of policy switches in several countries from the closed cycle to the wait-and-see option and even the open cycle option for Germany.

The largest inventory of plutonium (separated + in spent fuel) is in the US, representing 38% of the total for the eight countries that have declared their holdings. The next largest is in France (22%).

The INFCIRC/549 database is not comprehensive, as

the nine participant countries represent only 70-75% of the nuclear electricity supplied yearly and the database deals only with civil (and demilitarized) plutonium. Since 1992, various organizations (e.g. BNIF, FEX, IAEA, ISIS and SIPRI) have attempted to broaden the evaluation to separated civil plutonium worldwide and to military plutonium and have made projections as to how these holding will evolve in the future. These attempts have been deceiving. For instance, the holdings of separated civil plutonium predicted for 2010 varied from 0 to 280 t Pu (with a median at 100 t Pu) for the seventeen recorded predictions made in the 1990s and from 165 to 330 t Pu (with a median at 270 t Pu) for the nine recorded predictions made in the 2000s. One of the most detailed assessments is from **ISIS** (The Institute for Science and International Security). Table 9 summarizes their last update [11] providing plutonium inventories as of 31 December 2003.

Table 9. Evaluation of Worldwide Inventories as of 31 December 2003

Type	Status	t Pu
RPu	in spent fuel	1325-1340
	separated	238
	sub-total	**1563-1578**
WPu	in excess	102
	military	155
	sub-total	**257**
Total		**1820-1835**

According to this evaluation, the largest inventory of plutonium (civil + military) is in the US, representing 27% of the world total. The next largest is in Russia (15%), followed by France (13%) and Japan (8%).

The bases for all such evaluation are published data complemented by "guestimates" resulting from assumed similarities and best judgments. The Nuclear Fuel Cycle Simulation System **NFCSS** (formerly known as **VISTA**) [12] developed by the IAEA can provide for high precision data on the actinide inventories, including the isotopic composition of each actinide. The inputs are amongst others:

- the reactor characteristics: type of reactor (PWR, BWR, VVER, PHWR, RBMK, AGR, Magnox or, more recently incorporated, FBR), power and annual load factors
- the fuel characteristics: average discharge burnup, ratio MOX (or ERU) fuel / total fuel loaded
- the reprocessing characteristics: quantity of spent fuel reprocessed, years after reactor discharge, whether UOX fuel only or MOX fuel also.

Tracking each reactor would result in precise worldwide data, provided the input data are available. However, dealing individually with each of the 560 reactors (in operation and shut down) would represent an enormous task, since it involves more than 14 000 reactor-years, over which reactor power (upgrades), discharge burnups (increasing), MOX loadings and other input parameters have varied. Therefore, calculations conducted on the reactor park in a country or the worldwide reactor park is the most common approach. It is the one utilized by the IAEA for the default dataset included in the program. The historical input data have been retrieved from reported data, such as the PRIS database [13], the Nuclear Industry Status Report [14] and IAEA conferences or publications. Whenever checked against the INFCIRC/549 data, the plutonium inventories were within one or a few percent margins.

The program is useful for generating prospective evaluations based on scenarios of how the input data might evolve in the future. This function was utilized [15] for the datasets illustrating [2]. A web based user interface enables interested people to use IAEA NFCSS software [16].

3.4 Energy Content

The 1820-1835 t total plutonium inventory (civil + military) mentioned in Table 9 has most likely reached 2200 t Pu by now (2008). It constitutes an important reservoir of fissile material if used as MOX fuel.

Utilized once-through in **PWR**s, this MOX fuel could substitute 320 000 t natural uranium, i.e. almost 5 years of the world reactor requirements, estimated at 64 200 tU/yr in 2006 [17]. Calculated otherwise, it would produce 14 600 TWh, i.e. 5.5 years of the nuclear electricity supplied in 2006 by the worldwide reactor park [18] or over 7 years of the electricity supplied in 2006 by all the PWRs (excluding the VVERs) and BWRs.

Utilized to fuel the first core of **FBR**s, this plutonium inventory is sufficient to deploy in total 530-620 GWe installed FBR capacity, i.e. much more than 370 GWe, the total capacity of nuclear power reactors connected to the grid on 31 December 2006 [18]. If run in a self-generating mode, such FBR reactor park could provide nuclear power for centuries. Indeed, the current inventory of depleted uranium (enrichment tails), reprocessed uranium and uranium in spent fuel is sufficient to feed such FBR park during over 500 years, without having to add natural uranium.

Those figures illustrate the high energy potential of the plutonium inventory. LWRs can efficiently use this resource, but the optimum utilization is in FBRs.

4. PLUTONIUM AGING

As mentioned in Section 3.2 and illustrated in Table 3, the plutonium inventory depends on the time elapsed since the spent fuel was discharged from the reactor. Its fissile value depends even more on the time elapsed since the spent fuel was discharged (and, for separated plutonium, since reprocessing). Indeed,

- ^{239}Pu and ^{241}Pu are fissile in LWRs and in FBRs. ^{241}Pu

is the best, but it decays into ^{241}Am, a neutron absorber in both reactor types.
- ^{238}Pu and ^{240}Pu are neutrons absorbers, but at the same time fertile materials producing respectively ^{239}Pu and ^{241}Pu. In FBRs, they are also weakly fissile.
- ^{242}Pu is an absorber in LWRs and very weakly fissile in FBRs.

To take into account the plutonium isotopic composition, a Pu equivalence formulation has been adopted by almost all the MOX fuel designers, however, there are differences in the methodologies used to derive the formula. Moreover, the formula to be applied depends on the reactor type, the fuel management, the reactor operation (effect of decaying ^{241}Pu), the nominal Pu isotopic composition, the nominal Pu content, etc [4].

4.1 Plutonium Recycling in LWRs

Taking as example [4] the plutonium from 55 GWd/tU spent PWR UOX fuel from Table 1, separated plutonium still containing its americium would lose 42% of its equivalence value (i.e. its technical value as fissile material) after 10 years storage of the plutonium and 66% after 30 years storage. Plutonium recently separated from this stored spent fuel would lose 27% of its equivalence value after 10 years storage of the spent fuel, 37% after 30 years storage and 42% after 70 years storage.

The losses are even larger for plutonium derived from BWR UOX fuel and more so from MOX fuel, but of course smaller for the other types of plutonium (much smaller for Magnox plutonium and negligible for WPu), as can be derived from Table 1.

In all cases, delaying plutonium utilization constitutes a waste of fissile material resources.

4.2 Plutonium Utilization in FBRs

In FBRs, all plutonium isotopes are fissile and americium is less of a nuclear poison than in LWRs.

To illustrate the effect of aging on the fissile value of plutonium issued from PWR fuels mentioned in Table 1, plutonium from 55 GWd/tU spent UOX fuel will lose 10% of its equivalence value (i.e. its technical value as fissile material) after 10 years storage, 22% after 30 years storage and 26% after 70 years storage. Plutonium from 33 GWd/tHM spent MOX fuel (i.e. the majority of the current spent MOX inventory) will lose 17% of its equivalence value after 10 years storage, 36% after 30 years storage and 42% after 70 years storage [4].

In comparing those figures to the ones quoted in Section 4.1, it is clear that equivalent fissile material losses due to plutonium aging occur at a slower rate for use in FBRs than for use in LWRs.

4.3 Plutonium Aging as a Concern in Fissile Material Management

Not utilizing the plutonium generated in NPPs is a waste of fissile resources. Delaying its utilization also results in a reduction of fissile material resources and, in most cases, increases the americium liability (which is second to plutonium for long-term radiotoxicity in geological repositories, see Section 5).

Conserving the plutonium inventory for a better utilization in future FBRs of the generation four ("GEN IV") era rather than less efficiently recycling it in the current GEN II or the new GEN III reactors might seem attractive. However, it must be placed in perspective with when and how fast GEN IV reactors are likely to be deployed.

A nuclear renaissance is currently observed everywhere. Media report extensively about the situation in Asia and the US, less about Europe. Besides Switzerland, nuclear projects in the European Union are also spreading [20]:
- Finland: a fifth nuclear unit will become operational in 2011. The two current operators have submitted a request for one additional unit each on their own site and a new operator has requested authorization to build reactors on four new sites.
- France: Flamanville-3 will become operational in 2012.
- The Baltic states and Poland have agreed to construct in common a new NPP in Lithnia, to enter into operation by 2015.
- Bulgaria: two reactors are foreseen at Belene (start of operation in 2011 and 2013).
- Romania: Cernavoda-2 has started operation in September 2007 and restart of construction of units 3 and 4 is scheduled.
- UK: a "White Paper on Nuclear Power" [20] promotes new NPPs, necessary to prevent decline of the british economy.
- The Netherlands: the Dutch Environment Ministry has set the conditions ruling a potential construction of new NPPs.
- Slovenia: construction of a second nuclear reactor is envisaged.
- Poland: construction of a first nuclear reactor is envisaged in the country, besides the Polish participation to the new NPP in Lithnia.
- Hungary: construction of a second nuclear reactor is envisaged.
- Czech Republic: industry wants to invest in new nuclear reactors.
- Slovakia: a projet is initiated to construct an additional unit at the Mochovce site by 2013.

A few of the 26 reactors currently under construction worldwide, like Okliluoto-3 and Flamanville-3, and of the additional reactors that will come into operation in the 2010s will be GEN III prototypes, but most of them will still be GEN II. Massive deployment of GEN III reactors can only reasonably expected for the 2020s, one decennia after the first ones have started operation. Based on this

experience, introduction of GEN IV reactors, amongst which the sodium-cooled FBR ("SFR") is a forerunner in their development stage, is targeted for the 2030s [21], but can more realisticly be expected in 2040s [22]. It means that their deployment could start in the 2050s.

After 30 years storage, plutonium from 55 GWd/tU spent UOX fuel has lost 22% of its equivalence value, i.e. its technical value as fissile material, for use in FBRs (Section 4.2) and 26% after 70 years storage. Adopting equivalence formulas examplified in [4], plutonium issued from 60 GWd/tU spent MOX fuel has only a 1 or 2% lower equivalence value than plutonium from 55 GWd/tU spent UOX fuel. So, adopting a wait-and-see policy, in expectation of plutonium utilization in FBRs to be deployed in an undefined future leads to a net loss of fissile material resources.

Conclusion is that to consume part of the plutonium by producing electricity today from MOX fuel in LWRs is much more efficient than to let it lose value by storage in expectation of a potential use in FBRs 30 to 70 years later.

The loss of fissile material inventory by delayed plutonium utilisation is not the only consideration to be taken into account in defining a back-end policy. Issues such as national policies for or against pursuing nuclear electricity generation, public acceptance, available (or accessible) reprocessing and MOX industrial infrastructure, economics, safeguards credentials and/or available geological formations for final disposal of the radioactive waste will all play a part in defining a strategy.

5. WASTE DISPOSAL ASPECTS

Plutonium, including its daughter products, dominates the radiotoxicity of spent fuel [23] over any of the time spans that the various regulatory bodies ask to take into consideration for geological disposal (Figure 1).

Recycling plutonium in LWRs reduces effectively the plutonium inventory. Table 10, based on data from [24], provides the plutonium and minor actinide contents (in kg/tHM initial) of PWR fuel 5 or 30 years after discharge of spent fuel at 45 GWd/tHM. It includes the plutonium balance in case of self-generated plutonium recycle (i.e. recycling in the same reactor in which it was

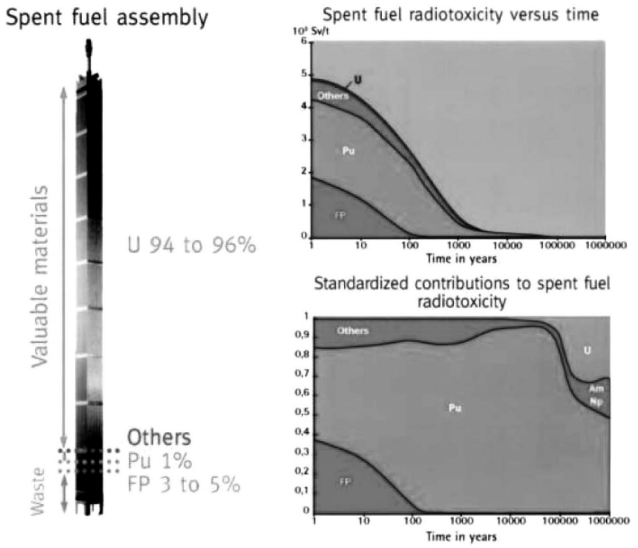

Fig. 1. Radiotoxicity Evolution of the Nuclear Material Initially Contained in Spent Fuel

generaterd), taking into account that one MOX fuel assembly can be manfactured from plutonium separated from seven UOX spent fuel assemblies and that, accordingly, the next reload comprises one fresh MOX assembly for six UOX fresh assemblies. There is still a net production of plutonium, but 55% less than if the reactor had been refuelled with UOX only.

As plutonium is the most radiotoxic constituent of spent fuel, separating and burning it as MOX fuel reduces the long-term environmental legacy of back-end wastes. However, recycling the plutonium in LWRs increases the levels of americium, which is the next most long-term radiotoxic element in fuel waste (Figure 1) and curium, a high short-term heat emitter. Additionally, LWRs cannot fully consume the plutonium as its isotopic characteristics deteriorate by recycling. The most common approach is mono-recycle, in which all the spent UOX fuel is reprocessed, but the spent MOX fuel is destined for final disposal (if not kept as fissile resource for later FBR fuellings). Even so, whatever the future option might be, recycling Pu reduces the required final disposal liability

Table 10. Concentration (kg/tHM) of TRU in PWR Spent Fuels

Spent fuel Time after discharge	UOX 5 yr	MOX 5 yr	MOX 30 yr	6 UOX + 1 MOX 5 yr
Pu	11.1	43.9	39.5	15.8
Np	0.633	0.171	0.371	0.567
Am	0.583	3.74	8.07	1.03
Cm	0.062	0.722	0.341	0.156
Pu in – Pu out	+ 11	- 32	- 36	4.9

Table 11. Volumes of Waste Conditioned for Final Disposal (m^3/tHM Discharged From a LWR)

Cycle option	m^3/t HM
Open cycle (UOX fuel)	2.0
Mono-recycling in LWRs	1.0
Recycling in FBRs Pu from LWR UOX fuel	0.5
Recycling in FBRs Pu from LWR (UOX+MOX) fuel	0.5+
Recycling in FBRs Pu and Am from LWR fuel	0.4

+ : only 2% more

and repository volumes (Table 11) [2].

The benefit in repository volumes is somewhat smaller than the gain in conditioned waste volumes, essentially due to a 12 times higher curium inventory in high-level waste (HLW) from spent LWR MOX fuel as compared to HLW from spent UOX fuel. Since curium decays rapidly (Table 10), the effect depends on when insertion of the spent MOX fuel in the underground repository is scheduled.

The economic benefit in final disposal liability is furthermore not proportional to the required repository capacity, since some cost items are independent or only weakly dependent on volumes. The reserves to be constituted by the spent fuel producers, calculated by the waste disposal authorities, ANDRA (France) and NIRAS-ONDRAF (Belgium) [2], illustrate the combined effect of heat release and repository volume dependence on financial liability (Table 12).

6. CONCLUSION

The grades and qualities of plutonium in spent fuel, in separated plutonium holdings and in military arsenals cover a broad range of characteristics. Safeguards keep track of the inventories of civil plutonium, but release of their data is restricted. On a voluntary basis, the major countries having plutonium publish annually their holdings under the auspices of the IAEA. From these data and other investigations, various organizations evaluate the plutonium possessed by each country. The VISTA program provides an opportunity to calculate, from historical data as well as for prospective scenarios, plutonium quantities wordwide, on a regional basis and for individual countries. The total plutonium inventory (civil + military) has most likely reached 2200 t Pu by now (2008).

It constitutes a very large energy potential that finds its best use in FBRs, but can also be efficiently utilized in LWRs. However, for a rational utilization of energy, recycling the plutonium today is a better policy than to store it (as spent fuel or as separated plutonium) until FBRs will be deployed in the future. Additionally, recycling plutonium reduces the repository volume and the financial liabilities for geological disposal of radioactive waste. It might influence the decision about a fuel cycle back-end policy, if adequate geological formations are limited or if the cost level of final disposal is not garantied.

Since, at the current market prices of natural uranium (yellow cake), recycling plutonium as MOX fuel in LWRs increases the fuel cycle cost by a few percents, decision not to utilize the plutonium at all, i.e. adopting an open cycle policy, is an alternative, which is however more often adopted for considerations other than economics: political (national or international) decisions, public acceptance …

Adopting the wait-and-see option results usually from percieved uncertainties about future evolutions of the fuel cycle cost parameters, delays in geological repository developments, versatility of political decisions and other difficult to predict events. It is now the adopted option in a majority of countries.

The reasons why countries have decided for the closed or the open cycle are diverse as can be illustrated by a few examples:

- France and Japan have governments promoting sustainability of nuclear electricity generation, with introduction of FBRs in the longer term. In this context, the long-term policy plan includes establishing an industrial reprocessing and MOX fabrication infrastructure and making best use of the energy potential of plutonium by recycling in LWRs. Public acceptance considerations have an influence on political decisions, such as the shutdown of Superphenix in France or, in Japan, the delaying of MOX loading in LWRs.
- The US has decided for the open cycle in the past century, in the frame of a political decision to promote this option worldwide for fear of nuclear weapons proliferation. The difficulties in developping and commissioning Yucca Mountain and the limited capacity of this repository

Table 12. Financial Reserves for HLW Disposal (Relative to Open Cycle)

Back-end option	ANDRA	NIRAS
Open cycle (no reprocessing)	1.00	1.00
Reprocessing UOX SNF, but open cycle for MOX SNF	0.55 – 0.57	-
Reprocessing UOX and MOX SNF	0.33 – 0.36	0.39 – 0.49

have been instrumental in recently switching mind and being originator of the GEN IV developments.

- Russia had build the BN-350 and BN-600 prototypes in a perspective of further deploying FBRs, but was plagued by restrictions in budget allocation to continue construction of the BN-800 and to develop an industrial MOX fabrication capacity, resulting in accumulation of separated plutonium.
- India has opted for the closed cycle, on account of limited indigeneous uranium reserves.
- In Germany and Sweden, under the influence of anti-nuclear pressure groups, the government decided a nuclear phase-out and imposed the open cycle. Separated plutonium issued from prior reprocessing contrats is still recycled as MOX without delay.
- The UK had (and still has) to reprocess their Magnox fuel for technical reasons and was reprocessing their AGR fuel in a perspective of deploying FBRs. With cancellation of the FBR program, AGR fuel is not reprocessed anymore and all the separated plutonium is stored with no end-use definition. Sizewell-B, the only PWR, would have an absolutely negligible impact on elimination of the plutonium stockpile.
- Canada is pursuing an open cycle policy, since reprocessing costs would be prohibitive with regard to the low plutonium content in spent CANDU fuel.

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