Plutonium is generated as a by-product in today's uranium-fuelled nuclear reactors. To be utilized, it must first be separated by chemical reprocessing from other radionuclides in used nuclear fuel discharged from the reactors, then fabricated into a new fuel element such as mixed-oxide (MOX) fuel, and recycled back into the reactors. If plutonium is not utilized, it should not be reprocessed and separated from other radioactive elements in used fuel. For some used fuel, reprocessing is required for safety reasons, such as the used Magnox fuel in the United Kingdom (UK)[1]. If there is no practical use for the separated plutonium (Pu) recovered from reprocessing, it can be processed into suitable disposition forms, such as borosilicate glass or Synroc, and disposed of in a geologic repository when it is available.

**The Imbalance of Separated Civil Plutonium**
There is at present a substantial global stock of separated civil plutonium, resulted from the imbalance between the Pu sources and Pu sinks [2,3]. The Pu sources result mainly from the operation of the reprocessing plants, but also from plutonium recuperated from un-irradiated remnants, such as from those terminated R&D activities (i.e., critical experiment) and fresh MOX fuel left over from shut-downed nuclear power plants (NPPs, i.e., Fugen, Pheonix, Monju, etc.). The United States (US) and the Russian Federation (RF) also declared an excess of 50 t of weapons-grade plutonium (W Pu) each from their dismantled nuclear-weapons stockpiles [4]. The US declares the ex-defense Pu as civil plutonium [5]. The Pu sinks can be considered either at: 
- Fabrication plants where plutonium is intimately admixed with another constituent, such as UO₂ and fabricated into MOX fuel;
- End users, mainly NPPs where plutonium-bearing fuel such as MOX fuel is irradiated;
- Disposition facilities where plutonium is processed and made into chemical forms suitable for geologic disposal.

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As both fabrication plants and disposition facilities involve plutonium being progressively converted into MOX fuel and disposition forms, respectively with internal recycle of plutonium scrap and recuperation of plutonium from waste streams, they are not in the same manner as "sinks" as that in the end-users (i.e., NPPs) or in the geologic disposal media.

The imbalance of separated civil plutonium is dominated by the operation of reprocessing plants in a few countries where there is no utilization (or disposition), or not sufficient capacity of Pu mofication (i.e., fabrication of plutonium into MOX fuel, the primary chemical form of plutonium-bearing fuel used in today’s nuclear reactors). The stocks of separated plutonium in these countries are simply stored and accumulated. There are also countries, notably France, which are actively recycling the separated plutonium recovered from reprocessing as MOX fuel in light-water reactors (LWRs). Nevertheless, the growing stock of global separated plutonium poses a concern for nuclear proliferation [6].

**The Guidelines for the Management of Plutonium**

To allay such concern and to promote transparency, the Guidelines for the Management of Plutonium were formed in 1998 where nine countries holding separated plutonium stocks would declare their annual holdings to the International Atomic Energy Agency (IAEA, INFCIRC549) [7]. Over 20 years of declarations from 1996 to 2016, the total separated civil plutonium stocks in these nine countries has risen from 160 t (in 1996) to 330 t in 2016. Figure 1 shows the status of civil plutonium stocks from 1996 to 2016 in these nine countries reporting to the INFCIRC549. The figure draws a distinction between countries with reprocessing but no (or not sufficient) utilization programs (shown as Group 1) and countries with plutonium utilization programs (shown as Group 2). It shows the plutonium stock in Group 1 continues to grow, and in Group 2, it passes the peak (around 2005-6) and levels off (around 2012). Although not all countries holding separated civil plutonium adhere to the Guidelines, the declarations disclose more than 90% of the total global civil plutonium stock.

Results in Figure 1 deviate from those in Figure 2, which were results presented at the Plutonium 2000 Conference in October 2000 in Brussels, Belgium [8] that the plutonium in Group 2 has peaked later (as compared to 2004 in Figure 2) and leveled off at a higher stock level (by approximately 20 tPu). This is because the plutonium utilization program in Japan has not proceeded as previously planned, due to the falsification of MOX fuel assembly data by BNFL in 1999 [9], and the shut down of NPPs in the wake of the Fukushima nuclear accident in 2011 [10].

In addition to the total, which is the sum of Groups 1 and 2 stocks, Figure 1 also shows a total plus the ex-defense plutonium stock declared by the US. Previously in Figure 2, the US civil stock included in Group 2 were those stored in West Valley, the now-dismantled commercial reprocessing plant.
Figure 1 Declared Separated Civil Plutonium Stocks in Plutonium Management Guidelines

Source: Calculated and plotted by J. Choi, using data from INFCIRC/549
In addition to their declarations of civil plutonium stocks, each of the governments of the nine countries within the Guidelines is committed to management of plutonium in ways which are consistent with its national decisions on the nuclear fuel cycle and which will ensure the peaceful use or the safe and permanent disposal of plutonium. The formulation of that strategy will take into account the:

- Need to avoid contributing to the risks of nuclear proliferation, especially during any period of storage before the plutonium is either irradiated as fuel in a reactor or permanently disposed of;
- Need to protect the environment, workers and the public;
- Resource value of the material, the costs and benefits involved and budgetary requirements; and
- Importance of balancing supply and demand, including demand for reasonable working stocks for nuclear operations, as soon as practical.
The Guidelines stated the importance of maintaining a balance of supply and demand of separated plutonium for nuclear operations. This importance is more profound in the aftermath of the 9/11 terrorists attack in 2001 in the US, as stocks of separated plutonium would surely be targets of terrorists seeking to acquire the improvised nuclear devices (INDs).

A key factor in balancing the supply and demand of plutonium for nuclear operations in countries actively reprocessing used fuel, fabricating MOX fuel and recycling MOX fuel into NPPs is the working stock required for these operations. As plutonium produced by aqueous reprocessing\(^2\) and MOX fuel assemblies sent to the NPPs usually involve just storage, there is no active processing of the separated plutonium and hence, there wouldn’t be a need for working stocks of plutonium in these operations.\(^3\) The operation in the current reprocessing and recycling fuel cycle that need to have a working stock of plutonium is the MOX fuel fabrication plant where plutonium is progressively converted into the MOX fuel, with internal recycle of plutonium scrap and recuperation of plutonium from waste streams.

How much separated plutonium is required as working stock in the MOX fuel fabrication plant to keep a supply-and-demand balance? In other word, what amount of plutonium constitutes a reasonable working stock for MOX fuel fabrication? These questions are explored below.

**Working Stock of Plutonium for MOX Fuel Fabrication**

The working stock, or “the running process inventory” of plutonium for an industrial-scale MOX fuel fabrication plant is the amount of plutonium sufficient to support the annual throughput of the plant, plus contingencies for unexpected events happening, which affect the operation. The amount of plutonium for contingencies should be able to take into account:

- The uncertainties associated with the time and administrative procedures in transporting the plutonium from the re-processor to the fuel fabricator,
- The uncertainties associated with the quality control and the allocation of plutonium to various customers,
- The buffer store of plutonium at the fabrication plant before moxification, and
- The buffer store of MOX fuel assemblies at the fabrication plant before transport to the NPPs.

\(^2\) Japan’s reprocessing in Tokai-mura involves a blending of Pu nitrate with Uranyl nitrate to produce a 50-50 mix of PuO\(_2\)-UO\(_2\), but the blending is conducted in aqueous and the dry Pu-bearing product is stored. It is presumed that the same process would be employed at the Rokkasho-mura Reprocessing Plant (RRP) when and if it is operated.

\(^3\) This may not be true for a pyro-chemical reprocessing as it involves series of dry processes with Pu-bearing salts and ingots in dry process streams.
Melox, an industrial-scale MOX fuel fabrication plant in Marcoule, France, which started up in 1995, began its first year of production at licensed capacity of 100 tHM in 1997. It increased its capacity to 145 tHM in 2003 following the closure of the Cadarache Plant, and again increased it to 195 tHM in 2007 after the closure of the Dessel Po Plant in Belgium [11]. Figure 3 shows the annual throughputs of the Melox Plant [12].

Figure 3 Annual MOX Fuel Production Throughput of the Melox Plant


Melox/Marcoule is located thousand kilometers away from the La Hague Reprocessing Plant, the source of its plutonium, and has multiple customers, both domestic and international. Before 2007, Melox operated at or near its licensed capacity. Since 2007, its annual throughput had maintained at the level of about 65% of licensed capacity, serving primarily the need of its domestic customer, EdF (which is about 120 tHM/y for 20 PWRs). To deal with the many possible contingencies for its operation (such as worker strikes in transportation, logistical and security difficulties in international transport of MOX fuel assemblies, etc.) it is likely that Melox would operate with a reasonable working stock of plutonium equivalent to 2 years of fabrication capacity [13]. For a plant with smaller capacity, co-located reprocessor, dedicated customer and less contingencies, like the now-dismantled Dessel Po Plant (capacity factor of 35 tHM), its working stock of
plutonium was close to its annual throughput, which is about 2 tPu (MOX fuel contained 5.5% Pu /tHM) [14].

To shed some light on how a plant’s capacity factor (or throughput) relates to the working stock the plant needs for operation, Figure 4 compares the plutonium used in Melox’s MOX fuel production (i.e., throughput) and the French declaration to the Guidelines (INFCIRC/549) of separated plutonium in the course of fabrication, and plutonium contained in un-irradiated semi-fabricated, or unfinished products at fuel fabricating plants or elsewhere. Figure 4 does not directly show the working stocks of Melox (as the declarations shown before 2003 included both production in Melox and Cadarache) but merely shows the relationship between annual throughputs and the amount of plutonium resided at the fabrication plant(s).

**Figure 4 Comparison of Plutonium France Declares at MOX Fabrication Plants and Plutonium for Production Throughput at the Melox Plant**

![Figure 4](image-url)

Source: Calculated and plotted by J. Choi, using INFCIRC/549 data and Figure 3 throughputs

Figure 4 shows that before 2007, the French declared plutonium residing at its MOX fuel fabrication plants (both Melox and Cadarache before 2003) are about 2 times that of the production throughput at Melox. After 2007, the declared amount at Melox is below or near its production throughput. The declared plutonium at Melox is not its working stock because some of the finished MOX fuel assemblies may have transported out to NPPs during the year before the accounting is taken for declaration. Nevertheless, it shows that after 2007 when Melox is primarily serving its domestic customers, its production may encounter fewer contingencies than in previous years involving both domestic and international customers.
Beside the contingencies associated with administrative controls, logistics, and buffer storage requirements, there are also contingencies on quality control and allocation of plutonium to various customers, which may involve the adjustments of plutonium isotopic compositions needed to account for the loss of fissile content and growth of $^{241}$Am, as well as technological constraints with reprocessing and MOX fuel fabrication.

**Plutonium Isotopic Compositions**

The origin of the used nuclear fuel (PWR, BWR, AGR, etc.), the discharge burn-up, the storage time before reprocessing, the storage time after reprocessing and many other secondary factors affect the isotopic composition of each plutonium batch to be processed. An example of the variety of isotopic compositions is given in Table 1.

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

<table>
<thead>
<tr>
<th>Type GWd/tU$^1$</th>
<th>WPu$^2$</th>
<th>GCR$^3$ 5 – 6</th>
<th>AGR$^4$ 18 – 24</th>
<th>PWR$^5$ 33</th>
<th>PWR$^5$ 50</th>
<th>BWR$^6$ 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu in Used Fuel, %, tPu/tHM</td>
<td>-</td>
<td>0.24</td>
<td>0.45</td>
<td>0.9 – 1.0</td>
<td>~1.2$^7$</td>
<td>0.8 – 0.9</td>
</tr>
<tr>
<td>$^{238}$Pu</td>
<td>0.0</td>
<td>0.3</td>
<td>0.6</td>
<td>1.6</td>
<td>2.6</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>94.0</td>
<td>69.0</td>
<td>54.0</td>
<td>58.0</td>
<td>50.0</td>
<td>55.0</td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>5.5</td>
<td>25.0</td>
<td>31.0</td>
<td>25.0</td>
<td>28.0</td>
<td>23.0</td>
</tr>
<tr>
<td>$^{241}$Pu + $^{241}$Am</td>
<td>0.5</td>
<td>4.2</td>
<td>10.0</td>
<td>10.0</td>
<td>11.0</td>
<td>14.0</td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>0.02</td>
<td>1.1</td>
<td>5.0</td>
<td>5.5</td>
<td>8.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Sources: Table values cited from notes by H. Bairiot [13] for:
1 – Burn-up value, in unit of GWd/tU
2 – Weapons-grade plutonium
3 – Gas-cooled reactor, i.e., Magnox
4 – Advance gas-cooled reactor
5 – Pressurized water reactor
6 – Boiling water reactor
7 – estimated value

Table 1 shows a combine of $^{241}$Pu and $^{241}$Am, in which the $^{241}$Am results from the beta decay of $^{241}$Pu, with a half-life of 14.4 years. This is the only way to maintain a constant of any given quantity of plutonium during storage and fabrication periods, during which the Am is not removed. Stripping of Am takes place only during reprocessing of the used fuel. Therefore, it must be taken into account in the bookkeeping of plutonium quantities that 38% of $^{241}$Pu would be converted into $^{241}$Am 10 years after reprocessing.

It is important to take this into account. For instance, if the plutonium issued from reprocessing used PWR fuel discharged at 33 GWd/tU were introduced as MOX fuel
in a PWR 10 years after reprocessing, it would have lost 22% of its equivalent fissile value. In other words, either the \(^{241}\text{Am}\) would need to be removed or the \((\text{Pu} + \text{Am})\) content of the MOX fuel would need to be increased by a factor of about 1.28 to compensate for the additional americium. If such plutonium would be issued from used fuel discharged at 50 GWd/tU, the loss would have been 29% and the compensation factor of about 1.4. This is an effect frequently overlooked in evaluating the future evolution of the separated plutonium stock. This effect is of course negligible for weapons-grade plutonium and minor for plutonium discharged from Magnox reactors.

**Reprocessing and fabrication constraints**

Core management calculations performed by (or on behalf of) the utility define the plutonium content and isotopic composition of each fuel assembly or each group of four or eight fuel assemblies positioned symmetrically in the reactor core. It provides the input of plutonium content and isotopic composition of each batch of used fuel sent to reprocessing. Although symmetrically positioned fuel assemblies do not evolve identically (due to the adjacent fuel assemblies, to slight differences in coolant temperature or void fractions, to movement of control rods, etc.), the differences are small and those assemblies can be considered as sibling. Even in the most optimistic case of eight sibling PWR fuel assemblies, a uniform plutonium batch at this stage is thus involved only about 34 to 43 kg of Pu.\(^4\)

For the La Hague Reprocessing Plant, which handles multiple domestic and international customers, the reprocessing schedule for used fuel assemblies is considered as commercial information disclosed only to the customers. Each individual customer has his own policy about the release of this part of the information. At the reprocessing plant, each batch of used fuel is fed to the shear in an uninterrupted sequence determined by the necessity of optimizing the operation of the reprocessing plant. As such, the first homogenization of the plutonium isotopic takes place at the shearing and dissolving stage. A further blending of the individual plutonium sources occurs at the finishing stage, where plutonium is purified, converted to oxide and packaged into containers. This final stage is purposely utilized to constitute homogeneous batches of typically 90 kg Pu.

At the fabrication plant, a MOX reload to be delivered consists typically of 7 to 9 tHM, containing some 400 to 600 kg of plutonium. Several reloads may even be manufactured in one single fabrication campaign. As a result, depending on the average Pu content of the MOX fuel and on the campaign size, anywhere from 3 to 11 Pu batches are involved in each fabrication campaign (Melox can operate 90 tHM fabrication campaign). For each reload, the customer requests the fuel assemblies to be interchangeable. It requires the isotopic composition of the plutonium within a MOX reload to be uniform, as far as reasonably achievable. To meet this

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\(^4\) This is calculated as follows: A used PWR fuel assembly contains 465 kgHM and roughly 0.9 to 1.1% plutonium, 465kg \( \times 0.011 \times 8 = 41 \) kg.
specification, the manufacturing processes have been optimized to incorporate in each pellet batch of up to 5 adequately selected Pu containers (each contains typically 3 kg Pu from La Hague). It results in the uniformity of Pu isotopic composition within a MOX reload meeting specifications. The inter-changeability of Pu holdings within the fabrication plant is beneficial for both customer and manufacturer in other respects, including the reduction of the cost related to separate storage of the various scrap streams and to timely transportation of the Pu feed.

For the MOX fuel fabrication facility (MFFF) the US is building for its ex-defense plutonium disposition, the plutonium is weapons-grade and the MOX is for domestic NPPs, and hence, there are few contingencies associated with plutonium quality and customer allocation. However, the source of the plutonium, i.e., where and how the pits are converted into PuO$_2$ may be challenging [16]. MFFF may require a reasonable working stock to support its annual throughput of 3.5 tPu plus a reasonable amount for contingency. As of this writing, the US Department of Energy (DOE) had cancelled the MFFF program on May 16, 2018, due to high costs in completing the plant [17]. The DOE will now pursue the "dilute and dispose" option for disposing of the 34 tPu. Under this option the MFFF may be used as a disposition plant to dilute plutonium and the disposition products will be sent to the Waste Isolation Pilot Plant (WIPP) in New Mexico for disposal. Under this mission change, the disposition plant would require a working stock of WPu in support of its 3.5 tPu annual throughput plus a reasonable amount for an increase in contingencies, including:

- Where and how the pits are converted into PuO$_2$
- Processes, chemicals, diluents, etc. involved in diluting the WPu
- State legislations associated with WIPP acceptance of diluted WPu
- Transportation variants due to possible increase in sizes and volumes of the disposition products (as compared to MOX fuel assemblies)

**Conclusion**

- There is at present a substantial and growing global stock of separated civil plutonium. To reduce the global civil plutonium stocks, countries holding these stocks are encouraged to reduce or stop their reprocessing activities, and increase their utilization or disposition of separated plutonium,
- A key factor in balancing the supply and demand of plutonium for nuclear operations in countries pursing utilization or disposition is the working stock of plutonium required for these operations. Based on industrial operation of fuel fabrication plants (in Belgium and France), a reasonable working stocks may be an equivalence of 1 to 2 years of production throughput, and sufficient for contingencies associated with administrative procedures, transportation logistics and security requirement, buffer storage for source receipt and products sent, as well as quality controls and customer allocations, if multiple clienteles are involved,
The US and the Russia declared an excess of 50 t weapons-grade plutonium each from their dismantled nuclear-weapons stockpiles. They pledged to each disposition of 34 t as MOX fuel in NPPs. The US now decided to forego the MOX fuel option. Instead, it would pursue a “dilute and dispose” option with possibly an increase of contingencies associated with its operation of the disposition plant.

References
6. INFCIRC/549, Communication received from certain member states concerning their policies regarding the management of plutonium, 16, March 1998. INFCIRC/549/Mod.1, 17 August 2009.
11. IAEA Consultancy Meeting, Inventory of the separated plutonium and options for its disposition, 8 – 9 October 2001.