# Back-end of the nuclear fuel cycle

**J.S. Choi**
Division of Nuclear Fuel Cycle and Waste Technology,
International Atomic Energy Agency,
Vienna

**Abstract.** Current strategies of the back-end nuclear fuel cycles are: (1) direct-disposal of spent fuel (Open Cycle), and (2) reprocessing of the spent fuel and recycling of the recovered nuclear materials (Closed Cycle). The selection of these strategies is country-specific, and factors affecting selection of strategy are identified and discussed in this paper.

## 1. INTRODUCTION

The generation of nuclear energy in nuclear reactors produces spent fuel (SF). The spent fuel discharged from the reactor is stored in wet pools at reactor sites. When the pool is filled, or when the reactor is at the end of its operating life, the spent fuel would be removed, stored in At-Reactor (AR) storage on site, or transported to away-from-reactor (AFR) storage facility, pending on decisions of final disposal in a geologic repository. This strategy for managing the back-end nuclear fuel cycle is generally called “Direct-Disposal, or Open Cycle”. Many countries manage their back-end nuclear materials in this manner, including those which have not made the final decision for the disposition of spent fuel. For them (with a “Wait-and-See” option), spent fuel is kept in wet/dry storage facilities on an interim basis.

The spent fuel could be reprocessed to separate plutonium and uranium from other highly radioactive materials. The separated plutonium could be fabricated as MOX fuel and recycled back to the reactor to produce nuclear energy. This back-end fuel-cycle strategy (so-called “Reprocessing and Recycling”, or “Closed Cycle”) were selected in the 70s’ by several countries primarily because of resource conservation. The strategy also provided the utilities an outlet for their spent fuel (e.g., to the reprocessors). Now, when the separated plutonium and reprocessed high-level radioactive wastes (HLWs) are returned, the utilities would have to deal with the utilization and disposition of these materials.

For the Closed Cycle, the separated plutonium can be utilized as MOX fuel in reactors, or safely and securely stored until decision for its final disposition is made. Beside plutonium, storage for the separated reprocessed uranium is required until its recycle to the reactor is economically viable. Also, the vitrified HLW needs to be stored until final geologic repository is available.

These back-end fuel-cycle strategies are different, due mainly to the management of different nuclear materials arising from these strategies (e.g., either SF, or separated fissionable nuclear materials, and HLWs). In this paper, we attempt to closely examine each strategy to identify important factors determining the strategy and affecting the current and future nuclear systems.

## 2. BACK-END FUEL CYCLE STRATEGIES

Current strategies of the back-end nuclear fuel cycles are: (1) direct-disposal of spent fuel (Open Cycle), and (2) reprocessing of the spent fuel and recycling of the recovered nuclear materials (Closed Cycle). One may include a third option (3), called "Wait and See" as decision for final disposition of spent fuel has not been made.

These strategies consist of common components, they are:

- Spent fuel management (for all 3 strategies)
- Management of separated fissionable materials (for the Closed Cycle)
- Geologic repositories (for all 3 strategies)

*Spent Fuel Management*

The back-end fuel cycle begins with spent fuel discharged from the nuclear reactors. As of 1998, the total amount of power-reactor spent fuel discharged world-wide is about 220,000 t HM. Of this, about 75,000 t HM were reprocessed, and the remaining 145,000 t HM is stored.

Figure 1 shows schematically an Open Back-End Cycle. Spent fuel is managed at each stage of the Cycle with specific considerations and controls. For examples: when spent fuel is stored at reactor pools during reactor operation, the consideration is to ensure adequate storage capacity is provided so that potential loss of full core reserve (FCR), a requirement for safe reactor operation, would not occur. Assurance of control for such consideration would be provided by the plant management. When the power plant is at the end of its operating life, or when the plant site needs to be decommissioned and decontaminated, special provisions must also be provided by plant management that the spent fuel is transported to AFR facilities for interim storage.

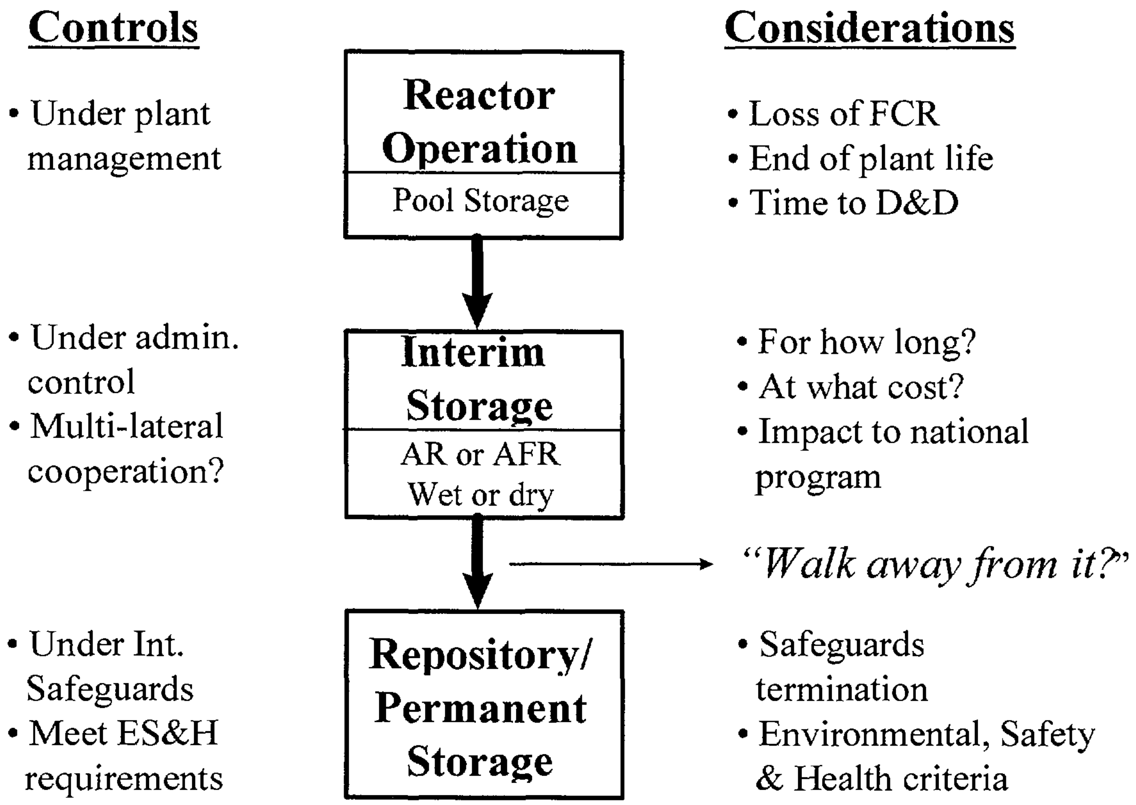

*FIG. 1. Spent fuel management.*

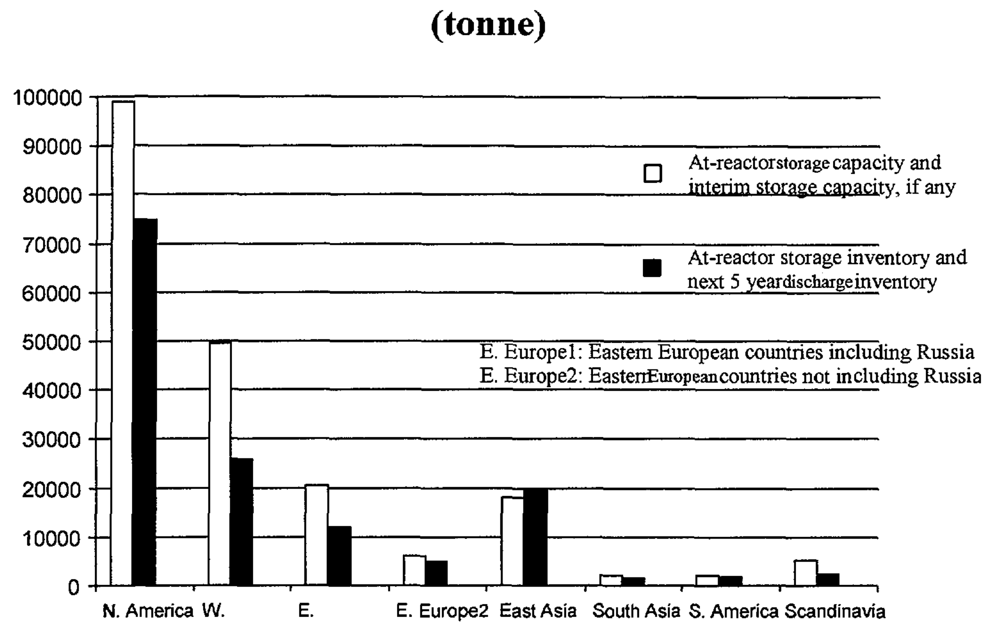

*FIG. 2. Spent fuel capacity and inventory by regions.*

There are an increasing number of nuclear utilities whose SF inventories may exceed their planned storage capacities. Additional AR and/or AFR storage capacities would be needed. The timing of such need is different for each utility, and/or each country if the utility is state-owned. Figure 2 shows a comparison of spent fuel inventory and planned storage capacity, on a regional basis. The datum is based on Year 1998, and a 5 year additional spent fuel discharged is added to the inventory for the comparison to ensure that the utility and/or country would have at least 5-year time period to prepare for such need.

Technologies for spent fuel storage, both wet and dry are well-developed and commercially available. Considerations at this stage of spent fuel management are: interim storage for how long? at what costs? and what are the potential impacts to national programs if multilateral arrangement is pursued?

For an Open Cycle, spent fuel is to be disposed of in a geologic repository. Two features in spent fuel demand specific considerations and controls. These are: (1) spent fuel contains special nuclear fissionable materials, requiring institutional controls and international safeguards, (2) radioactivity in the spent fuel is generally higher than that of the original uranium ore, requiring a long-time decay or engineered containment to provide a safety assurance. For as long as these two considerations remain unresolved, one cannot simply "walks away" from a spent-fuel repository. As a result, the Open Cycle may remain open and spent fuel management may not be completed.

### *Management of Separated Fissionable Materials*

Figure 3 shows schematically a Reprocessing and Recycling Cycle (Closed Cycle). It is different from that of Figure 1 by an additional stage, e.g., spent fuel reprocessing. There is considerable experience in the civil reprocessing of spent fuel on an industrial scale in some countries. France is successfully operating reprocessing plants for oxide fuels. It has already reprocessed more than 13,000 t HM in its La Hague plants, while the United Kingdom (UK)'s Thorp plant has reprocessed about 1,500 t HM of AGR and LWR spent fuels. France and UK have also reprocessed about 60,000 t HM of gas-cooled fuel at the UP1 and B205 plants respectively. Russia's RT-1 plant has a capacity of 400 t HM/y and to date some 4,000 t HM of WWER fuel has been reprocessed. Reprocessing experience in India and Japan is equally relevant although their installed plant capacities are not as large. Japan is building a 800 t HM plant at Rokkasho-mura with completion expected in 2005.

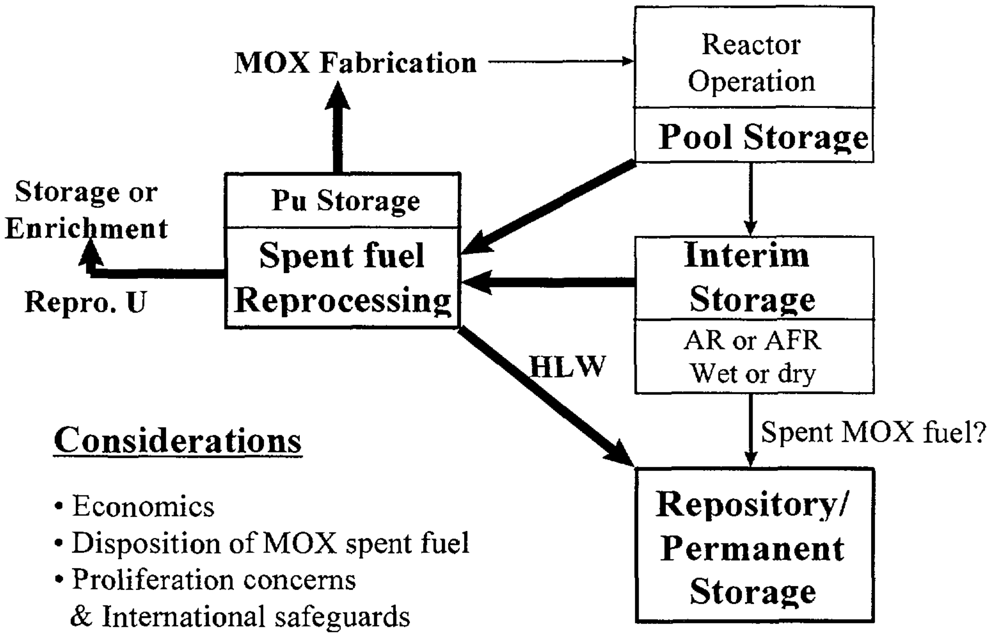

*FIG. 3. Reprocessing and recycling.*

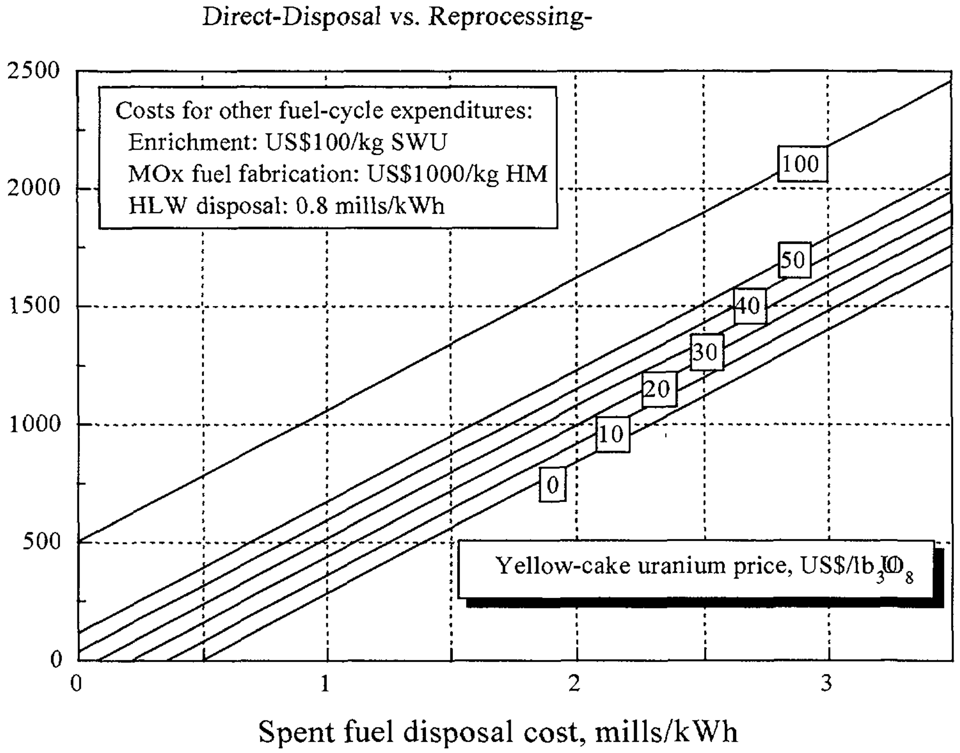

*FIG. 4. Break-even fuel reprocessing cost (US$/kg HM).*

Spent fuel reprocessing is a costly expenditure. Figure 4 indicated that for a fuel reprocessing cost of $1000 per kg HM and a spent fuel direct-disposal cost of 1 mill per kWh (which is the fee paid by the US utilities to the US Department of Energy (DOE) to dispose of their spent fuel), the unit price for natural uranium would have to be as high as $80 per pound (more than $200/kgU), a price almost 7 times higher than the current spot price.

- *Mono-recycling of separated plutonium in LWRs*

The separated plutonium can be fabricated as MOX fuel and recycled back to the reactor to produce nuclear energy. As of 1998, there are 40 nuclear power reactors in Belgium, France, Germany, Japan and Switzerland licensed to use MOX. Of these, 32 LWRs are loaded partially (~>30% core) with MOX fuel.

MOX fuels are currently used as replacement fuels in LWRs. They are in the reactor core partially replacing the $UO_2$ fuel. The MOX fuel assemblies (FA) design is basically the same as that of the $UO_2$ FAs, thereby preserving the thermal-mechanical integrity of the reactor. The plutonium contents (total or fissile) and the burn-up for the MOX FAs are limited such that when they are loaded into the core, they would not compromise the safety margins established as the licensing bases for the reactor. Table 1 shows the experience with MOX-use in LWRs[4]. It includes the licensing limits, expressed in terms of maximum MOX loading in the core, and the maximum concentration of plutonium in the MOX fuel.

TABLE I. EXPERIENCE WITH MOX-USE IN THERMAL REACTORS

| Country | Operating reactors | Reactor licensed to use MOX | "Moxified" reactors | First MOX loading date[1] | Licensing limits, % Max in-core | Max $Pu_t$ conc |
|---|---|---|---|---|---|---|
| Belgium | 7 | 2 | 2 | 1995 | 33 | 7 |
| France | 57 | 20 | 17 | 1987 | 30 | 5.3 |
| Germany | 21 | 11 | 10 | 1972 | 50 | -- |
| Switzerland | 5 | 4 | 3 | 1984 | 40 | -- |
| Japan | 52 | 3 | 0 | pending | 33 | 13 |

[1] from Booklet: "Cogema: Reprocess to recycle," Feb. 1999.

The discharged spent MOX fuel assemblies are currently not reprocessed. This is because of the low economic incentive for recycling the plutonium from spent MOX fuel. Also, there is a limit to the number of recycles in LWRs because multiple-recycling degrades the fissile plutonium content to a level below that required to maintain the reactivity of the core. The discharged MOX spent fuel would require interim and/or long-term storage. It may eventually be disposed of in a geologic repository.

The global separated plutonium inventory will continue to grow, due to an imbalance between its production and utilization. On separated civil plutonium alone, the total at the end of 1998 was about 200 tonne. It will be in excess of 250 tonne by the end of the decade. Figure 5 predicts the future trends of the global separated civil plutonium inventory.

- *Storage of Reprocessed Uranium and Vitrified HLW*

The separated reprocessed uranium in the Closed Cycle is needed to be stored as currently its recycle to the reactor is not yet economically viable, due to the relatively low price of natural uranium. Also, storage for the vitrified HLW is needed until the final geologic repository is available. A HLW repository do not contain the large quantity of spent nuclear materials and do not require the same decay time for radioactivity to reach to the uranium ore level as in a spent fuel repository. It may have an advantage from the standpoint of acquiring for public acceptance. However, if spent MOX fuel is to be disposed of in a HLW repository, same constraints for a spent-$UO_2$-fuel repository will be applied. Also, the repository may have to deal with additional considerations because of the higher radioactivity and heat content in the spent MOX fuel.

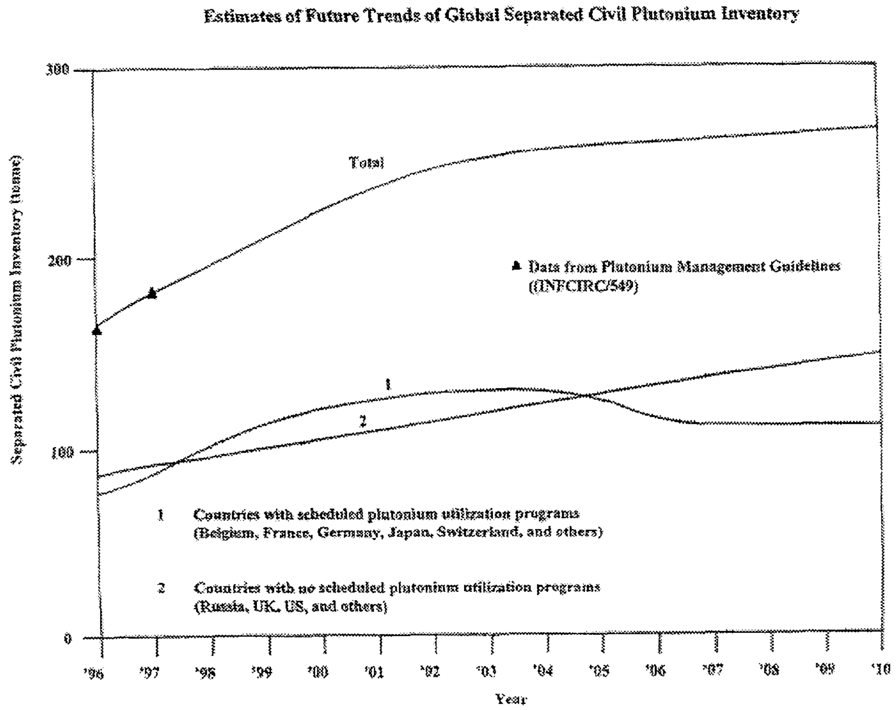

*FIG. 5. Estimates of future trends of global separated civil plutonium.*

### *Geologic Repositories*

Regardless of back-end fuel-cycle strategies, spent fuel (either MOX or $UO_2$) and high-level waste (HLW) ultimately would have to be disposed of in a geologic repository. Several countries have embarked on their respective national repository programs, at specific or demonstration sites, e.g., the US, Sweden and Germany, etc. The developed repository technology is site-specific, e.g., the US selected a site in Yucca Mountain with an oxidizing medium, while Sweden's demonstration site in Granite and Germany's in Salt are both in reducing environment. The timing for a repository is country-dependent, e.g., a country with a nuclear phase-out program may need to have a geologic repository sooner than those operating a continuous nuclear program, because of political sentiment. The challenge for repository development is institutional and political, e.g., how to overcome the NIMBY (not-in-my-back-yard)-mentality and obtain public and stakeholders' acceptance and support for a repository site, especially the local public and governments.

For countries with small nuclear power programs and therefore relatively small amounts of spent fuel and radioactive wastes, and for countries with dense population and small geographic areas, consideration of regional and multilateral co-operative arrangements for repository development may be attractive. These countries may have limited potentials to develop their own systems for the back-end fuel cycles. Furthermore, it may not be in the interest of the international community that repositories are spread out all over the world which may constitute a proliferation risk. However, the challenge is again institutional and political, e.g., how to ensure that an attempt for a regional co-operative framework would not jeopardize individual country's national repository program.

## 3. FACTORS DETERMING THE BACK-END FUEL-CYCLE STRATEGY

As countries select their back-end fuel-cycle strategy most suitable for their respective nuclear programs, factors determining such strategies will be country-specific. As a result, it would be difficult to quantify one set or even a few sets of factors which will be universal for all countries. However, it may be do-able to identify some important factors and qualitatively categorize them into such groupings as: economical, technical, political, and institutional, for options available in each strategic components evaluated in the previous section. Tables 2, 3 and 4 provided examples of how this can be done for components: (1) spent fuel management, (2) management of separated civil plutonium, and (3) geologic repositories, respectively.

TABLE II. SPENT FUEL MANAGEMENT
Responsible Party: Generators (Private/State Utilities)

| **Factors Determining options** | **Options** | | | |
|---|---|---|---|---|
| | | **Prolonged storage** | | |
| | **Reprocessing**[1] | **AR**[2] | **AFR**[3] | **AFR (Multi-national)** |
| **Economics**<br>Life-cycle costs | $R | $X | $Y | $Z |
| **Technical**<br>Safety: cladding material | rapid deterioration | cladding interity over storage time | | |
| **Political:** | | | | |
| National Policy | Y or N[4] | NA[5] | Y or N | NA |
| Suppliers' consent right | Y or N | NA | NA | Y or N |
| **Institutional** | | | | |
| Contract based | Y | NA | Y | Y |
| Environmental laws | Y | Y | Y | Y |

[1] Include transportation, reprocessing, Pu use/store, storage of rep. U and HLW.

[2] At-reactor storage.

[3] Away-from-reactor storage.

Tables 2 to 4 identify life-cycle costs for options available in these strategic components are important **economic factors**. For the option chosen, specific life-cycle costs associated with the option are needed as inputs to the decision makers.

**Technical factors** would be different for different options: for example, the need to reprocess the spent fuel may be based strictly on safety ground: that claddings of some spent fuel in wet pools could be deteriorated in such a fast rate that would prohibit any prolonged-storage options. For geologic repository development, R&D efforts are needed to reduce the uncertainty for long-term performance of repository, as well as to meet the licensing requirements.

TABLE III. MANAGEMENT OF SEPARATED CIVIL PLUTONIUM
Responsible Parties: Generators (Private/State Utilities)
Governments (States Holding Stocks)

| Factors Determining options | Options | | | |
|---|---|---|---|---|
| | | Prolonged storage | | |
| | **Prolonged storage** | **MOX[1] in reactors** | **Immobilizations[2]** | **Dirty MOX[3]** |
| **Economics** | $R | $X | $Y | $Z |
| Life-cycle costs | | | | |
| **Technical** | | | | |
| R&D | N | | Y | some |
| Licensing | N | | Y | Y |
| **Political** | | | | |
| National Policy | Y or N[4] | Y or N | Y or N | Y or N |
| Non-proliferation | Y | Y | Y | Y |
| **Institutional** | | | | |
| Contract based | NA[5] | Y or N | Y or N | Yor N |
| Environmental laws | Y | Y | Y | Y |

1. $PuO_2$-$UO_2$ fuel.
2. Plutonium is immobilized in ceramic matrix with HLW.
3. A "quick & dirty" fabrication of MOX fuel, to be disposed of with spent $UO_2$ fuel.
4. Yes or NO.
5. Not Applicable.

TABLE IV. GEOLOGIC REPOSITORY
Responsible Parties: Governments (States Holding Spent Fuel and/or HLW)

| Factors Determining options | Options | |
|---|---|---|
| | **National Repository** | **Multinational repository** |
| **Economics** | $X | $Y |
| Life-cycle costs | | |
| Technical: | | |
| R&D | Y[1] | Y |
| Licensing | Y | Y |
| Political | | |
| National Policy | Y | Y for host countries |
| International support | NA[2] | Y |
| Institutional: | | |
| Contract based | NA | Y |
| Environmental laws | Y | Y |
| Stakeholders' interetsts | Y | Y |

1. Yes.
2. Not applicable.

There are many **political factors** which could affect the back-end fuel-cycle strategies. Only those which are relevant to national policy and supports for the strategic components, and those requiring international co-operation and supports are suggested here. Acquiring the necessary political supports for these components is essential to the successful outcome of the strategy.

**Institutional factors** include many aspects. Some are legalistic and based on contracts among bilateral or multilateral parties. Different countries may have different environmental laws governing each strategic components, e.g., the Russian Federation currently has environmental laws prohibiting the imports of other countries' spent fuel and/or radioactive wastes. There are also international laws governing the transportation of nuclear materials and/or wastes in international sea-lanes and waters. For geologic repository development, local as well as national stakeholders' interests are needed to be satisfied before such development can be proceded.

## 4. SUMMARY

In this paper, we briefly evaluated each component of the back-end fuel-cycle strategies and attempted to identify relevant and important factors affecting these strategies. The aim is to provide background materials for the discussion of topical sessions in the Technical Committee Meeting on "**Factors Determining the Long Term Back-End Nuclear Fuel Cycle Strategy and Future Nuclear Systems.**" It is recognized that factors determining these back-end fuel-cycle strategies are country-specific. The quantification of the identified factors should be evaluated and provided by individual country selecting the most relevant strategy for its current and future nuclear systems.