CHAPTER 5

Spent Nuclear Fuel Management Simulation - Coordination of Storage Installation and Transportation -

5. Spent Nuclear Fuel Management Simulation: Coordination of Storage Installation and Transportation.

After summarizing methodologies of analyzing spent nuclear fuel management and storage needs, spent nuclear fuel accumulation in the future and its appropriate management strategy for Japan are analyzed by "SFTRACE" (Spent Fuel Storage, TRAnsportation and Cost Evaluation System), which consists of 3 sub-models; a) the economic cost data base for spent nuclear fuel storage technologies, b) the long-range simulation of reactor mix and plutonium (Pu) utilization, and c) the detailed simulation of spent nuclear fuel management strategies.

The long-range simulation sub-model presents a macroscopic overview on how much amount of spent nuclear fuel stockpile should be addressed nationwide at a certain time point. A preliminary calculation shows that the spent nuclear fuel storage needs in Japan to the year 2050 will vary significantly, from a decrease towards zero or a continuous increase up to 20,000-25,000tHM.

The sub-model for spent nuclear fuel management simulation is the tool to demonstrate nationwide strategies to deal with spent nuclear fuel accumulation, either at each power station site or a number of centralized facilities in the given time horizon, with associated needs of transportation. An illustrative analysis shows trade-off relationship among factors involved in spent nuclear fuel management strategies, such as between "away from reactor (AFR)" storage capacity and overall transportation requirements, which vividly demonstrates the usefulness of the integrated analytic tool. This chapter is based on Nagano (2002a) and Nagano (2003).

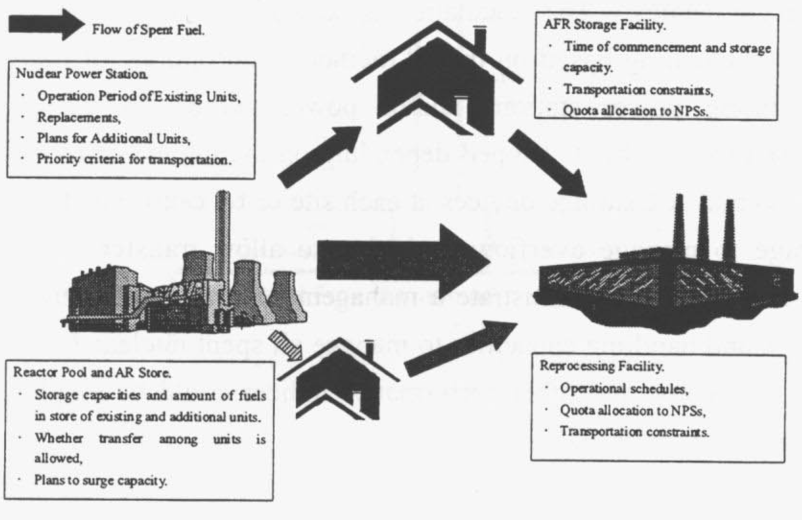


Figure 5.1.1-1: Factors to be considered in spent nuclear fuel management strategy analyses.

5.1. Methodology and Model Structure.

5.1.1. Methodology for Projecting Spent Nuclear Fuel Balances and Needs for Storage.

Figure 5.1.1-1 illustrates factors that should be taken into account in making spent nuclear fuel management strategy analyses. In the case of a country where direct disposal of spent nuclear fuel is taken as national policy, the item 'reprocessing facility' in Fig. 5.1.1-1 should be replaced with 'geological repository.' Even in this direct disposal case, the following observations will apply as well. Numbers of facilities to be covered will depend on specific scope or geographical boundary of the analysis, reflecting the purpose of analysis. There exist three types of methodologies for spent nuclear fuel balance calculation, as described in the following sections.

(1) Accounting for Each Power Station and/or Power Utility.

This microscopic accounting focuses on accumulation of spent nuclear fuel discharges at each nuclear Power station (NPS) site and/or power utility company every year against available storage capacity. If there is anticipated an overflow of spent nuclear fuel surpassing the storage capacity, its enhancement within the site, i.e. At Reactor (AR) Storage, is to be planned. Clearly, all power stations and/or utility companies must prepare by this method a most realistic picture as well as, if necessary, an emergency control scenario.

(2) Long-range Simulation.

This macroscopic calculation is applied to cover a larger geographical scope, for a power company possessing multiple power stations, for a region or for a country with multiple power companies. The calculation is basically a summation of all relevant results of micro-accounting based on the 1st method, with options of transfer of spent nuclear fuel among power stations and/or power companies where applicable. Numbers of scenarios can be developed depending on the choice of overall strategies, whether by individual AR storage devices at each site or by centralized storage facility, i.e. AFR Storage to manage overflows, whether to allow transfer among sites, etc. While by this method one can illustrate a management strategy if there are available sufficient storage and handling capacities to manage all spent nuclear fuels to appear in a time horizon, economic and other performance indices could be employed to judge which strategy is the most desirable.

(3) Long-range Optimization.

Spent nuclear fuel management scenarios can be far more complicated if there is an option of Pu recycling, which yields variety of spent nuclear fuels (UO_2 and MOX) at different time points. This methodology is intended to optimize the whole national strategy for nuclear energy production and utilization in terms of at which magnitude Pu recycling is to be done, at which level the capacity of spent nuclear fuel reprocessing services have to be installed, and thereby how the whole spent nuclear fuel management strategy should look like. Clearly, emphasis should be given on national reactor mix strategy, with fuel cycle strategy with spent nuclear fuel management as its core in a coordinated manner. The model could cover not only nuclear energy production sector, but also be integrated with a model of the whole energy systems so that an optimal level of nuclear energy production is figured out as well. Examples of long-range optimization technique are found in the applications of FCOM (Fuel Cycle Optimization Model) presented in Section 3.1, with its further elaboration to an integrated energy-environment projection framework, LDNE21 (Linearlized Dynamic New Earth 21) model, which is described in Section 3.2.

5.1.2. The Model Structure.

The model the author has developed is named as SFTRACE (Spent Fuel Storage, TRAnsport and Cost Evaluation System), which is mainly based on the long-range simulation methodology, with full incorporation of micro-accounting for each power station site, described in the previous section. Figure 5.1.2-1 shows the overview of the framework. SFTRACE consists of three sub-models;

- a storage cost data base,
- a long-range reactor mix simulation, and

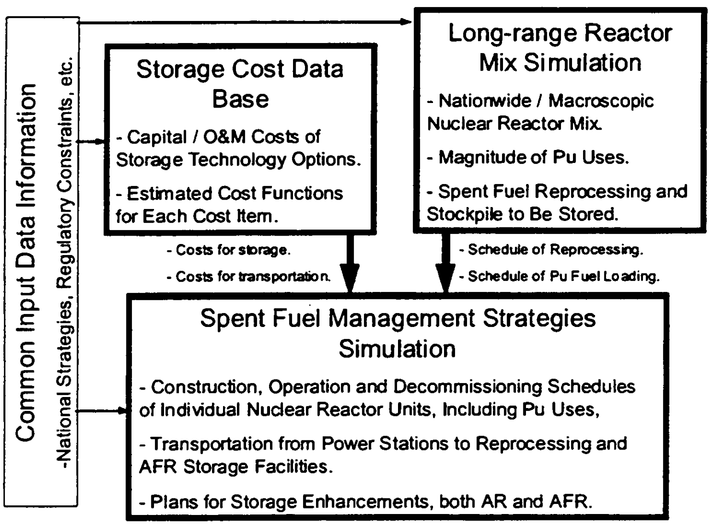


Figure 5.1.2-1: The Structure of Sub-Models of SFTRACE.

Table 5.1.2-1: The Structure of the Cost Data Base.

Cost category	Cost	Cost item	
Costs of storage for pool, metal cask, concrete cask storage systems	Capital cost	Construction cost	Cost functions against key variables
		Equipment cost	
		Decommissioning cost	
		Metal cask and/or concrete cask purchase	
	O&M cost	Utility costs with/without cask handling	
		Labor costs with/without cask handling	
		Maintenance cost	
		Miscellaneous and contingency costs	
Transportation cost from NPP to AR/AFR or reprocessing plant	Cask cost	Fees for lease of transportation casks	
	Cask handling cost	Labor costs	
	Inland transportation cost	Fees for lease of crane and trailers	
		Labor costs	
	Sea transportation cost	Royalty for port	
		Fees for lease of ships including fuel	
		Labor costs	
		Insurance fee	

➢ a simulation of spent nuclear fuel management strategies.

For the details of SFTRACE, see CRIEPI (2002).

(1) The Storage Cost Data Base.

The cost data base for spent nuclear fuel storage contains the whole set of data of individual cost items for pool, metal cask and concrete cask storage technology options, as well as relevant transportation costs. The data base is also implemented with cost functions of each item against specific key variables. Construction cost, for example, is expressed as a function of storage capacity, reflecting degree of the economy of scale. Table 5.1.2-1 shows the items in the data base.

(2) The Long-range Reactor Mix Simulation Sub-Model.

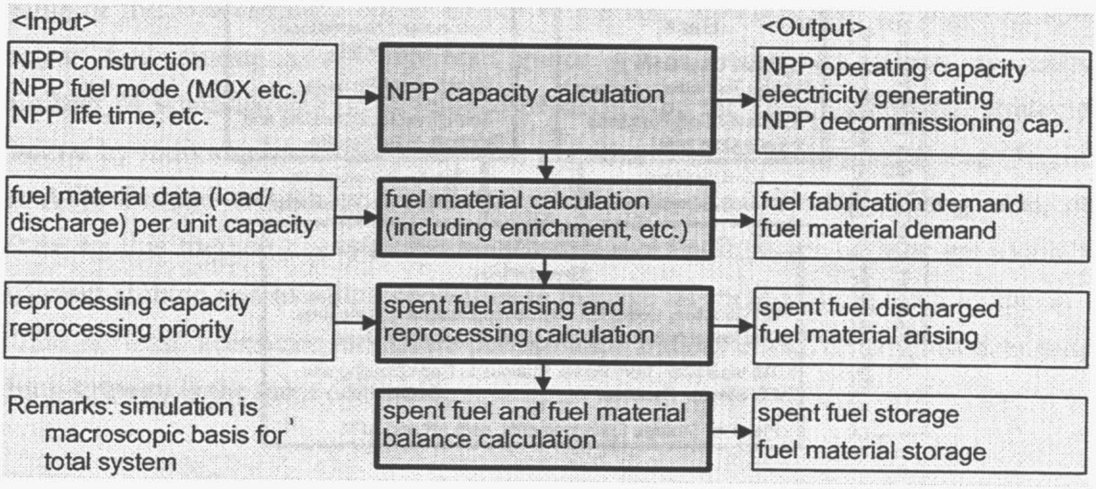


Figure 5.1.2-2: The Outline of the Long-range Reactor-Mix Simulation Sub-model.

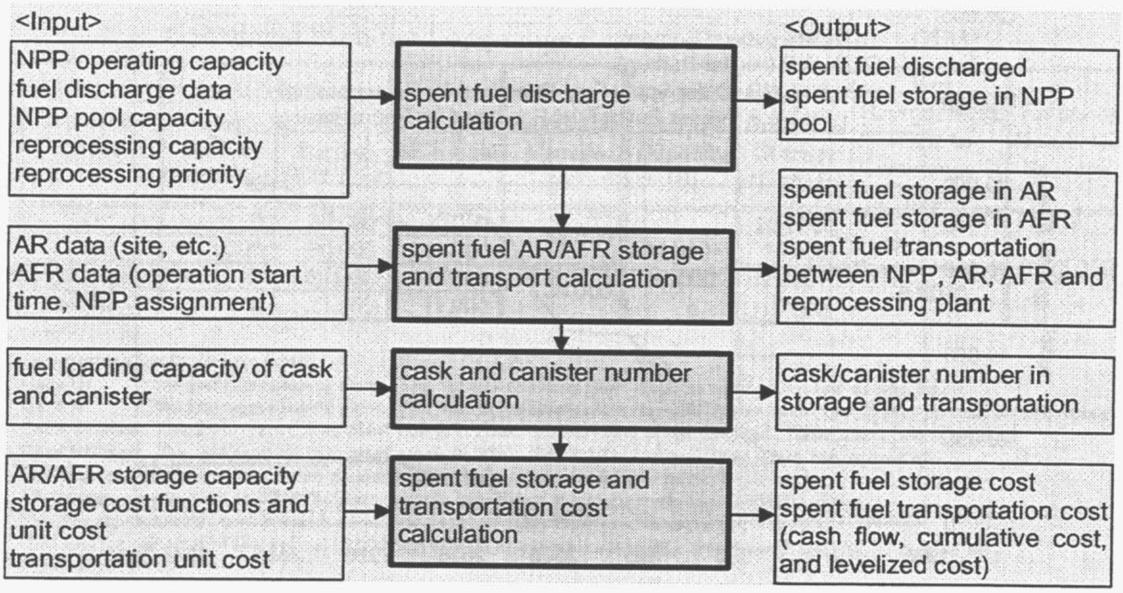


Figure 5.1.2-3: The Outline of the Simulation Sub-Model of Spent Nuclear Fuel Management Strategies.

The outline of the sub-model is shown in Figure 5.1.2-2. This sub-model starts with a set of assumption of total nuclear power generation capacity, either with light water reactors (LWRs, hereafter) and/or other types of reactor. The key feature of this sub-model is capability of material balance calculation, not only to calculate all input and output materials related to operation of those power reactors, but also to determine appropriated level of plutonium (Pu) uses. From spent nuclear fuel reprocessing facility, whose operation schedule is also assumed, corresponding amount Pu is generated at corresponding isotopic composition. The model calculates degrees of recycling so that all Pu is to be consumed at a certain lag-time for recycling. As a result, composition of discharged spent nuclear fuel will vary depending on the degree of Pu recycling.

(3) The Simulation Sub-Model of Spent Nuclear Fuel Management Strategies.
Figure 5.1.2-3 shows the overview of this sub-model. The main feature of the whole framework covers the whole system consisting all relevant facilities, i.e. nuclear power plants (NPPs), AR and/or AFR storage facilities already planned or installed, reprocessing facility, and transportation services between any two of those points. As specified in Figure 5.1.2-3, the sub-model traces all spent nuclear fuel, either in terms of tHM or assembly depending on the purpose, with current location, transportation to another location, and “disappearance” into reprocessing facility. Together with

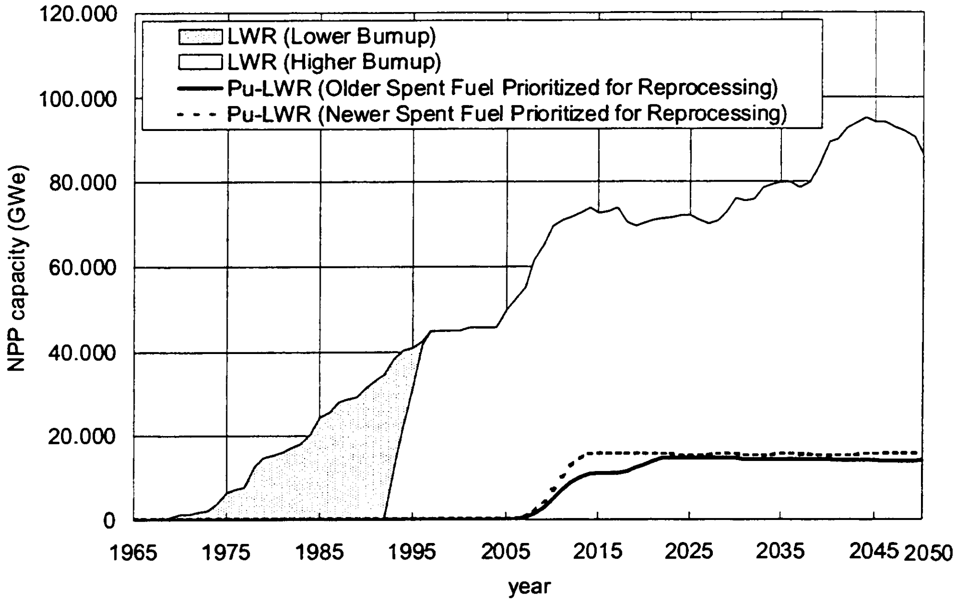


Figure 5.2.1-1: An Illustrative Results from Long-range Reactor Mix Simulation.

information on storage capacity at each NPP, one can identify individual risks of overflow, or storage needs in other words, and then the sub-model allows to install additional capacity either at NPS (AR store) or another location as a centralized manner (AFR store).

5.2. The Illustrative Simulation Results.

5.2.1. Pu Utilization in LWRs and its Implication on Spent Nuclear Fuel Management[8].

Figure 5.2.1-1 shows the results from the long-range reactor mix simulation. The major assumptions include:

- The national nuclear power generation capacity is based on all existing generating stocks under 40 years lifetime, all those under construction and planning. Additional construction is assumed to reach 70GWe in 2010 specified in the national policy aimed at fulfilling 'Kyoto' target. After then, further new construction is added in order to compensate decommissioning plants, which are to be replaced with new 1350MWe unit 16 years after disconnection from grid. Because of irregularity of the past construction, this replacement rule will result in temporal increase of generation capacity in 2030-2040, as shown in Fig. 5.2.1-1.

[8] For more details of this simulation analysis, see Nagano (2002b).

Table 5.2.1-1: The Spent Nuclear Fuel Management Requirements in the Year 2050 Calculated from the Long-range Reactor Mix Simulation. [tHM]

Simulation Cases	Spent Low Burnup UO2 Fuel	Spent High Burnup UO2 Fuel	Spent MOx Fuel	Total Amount to Manage (A)	Total AR Storage Capacity (B)	Needs for Additional Storage (C=A-B)	2nd Reprocessing Plant to Commence in 2020	Range of Needs for Storage
O	0	39,000	10,000	49,000	24,000–27,000	22,000–25,000		0–25,000
N	7,000	30,000	11,000					
O+2Rep	0	21,000	13,000	34,000		7,000–10,000	Δ8000	
N+2Rep	0	23,000	11,000					

Assumptions for Projection Cases.
Case O: No 2nd reprocessing plant. The 1st reprocessing plant receives older spent fuel as prioritized.
Case N: No 2nd reprocessing plant. The 1st reprocessing plant receives newer spent fuel (higher burnup) as prioritized.
Case O+2Rep: The 2nd reprocessing plant starts in 2030. No MOx fuel is reprocessed. Older spent fuel prioritized.
Case N+2Rep: The 2nd reprocessing plant starts in 2030. Spent MOx fuel and older spent fuel prioritized.
The total nuclear power generation capacity is 70GWe in 2010 and 80GWe in 2050, respectively.
AR capacity is assumed at 300MTU/GWe, slightly larger than the current average (270MTU/GWe).
The 2nd reprocessing plant is assumed with capacity of 800MTHM/year to commence in 2030.
UO2 fuel for reload is of low burnup (33,000MWd/MTU at average) until 1992, and thereafter of higher burnup at 45,000MWd/MTU.

- Spent UO_2 fuel are reprocessed either;
  - Case O: Older fuel, which are of lower burnup (33,000MWd/tU average) and have been cooled for longer time, are prioritized for reprocessing. Because of smaller Pu content, this case will result in smaller Pu yield than the other case, and
  - Case N: Newer fuel, which are of higher burnup (45,000MWd/tU average, loaded from 1990 onward) and have been cooled for no less than 5 years but shorter time than others, are prioritized for reprocessing.
- Reprocessing service is provided at 800tHM/year from 2005 to 2050. Only UO_2 fuel can be serviced.
- All recovered Pu is recycled in LWRs as fully compatible MOX fuel to UO_2 fuel.

  The Case O and Case N will result in different yield of Pu after reprocessing, which cause different magnitude of Pu recycling in LWRs as shown in Fig. 3.2.1-1. This in turn generates different composition of UO_2 and MOX spent nuclear fuel, though the total amount is the same.

Table 5.2.1-1 shows the implications on spent nuclear fuel management requirements. In Table 5.2.1-1, the first two cases correspond to the Case O and N, respectively. The latter two cases are the same as Case O and N, with addition of the 2nd reprocessing plant of 800tHM/year to commence in 2030, with sensitivity case of starting 10 years earlier (i.e. in 2020) as shown in Table 5.2.1-1. Although underlying assumptions should yet be verified, the following observations are derived from this illustrative runs:

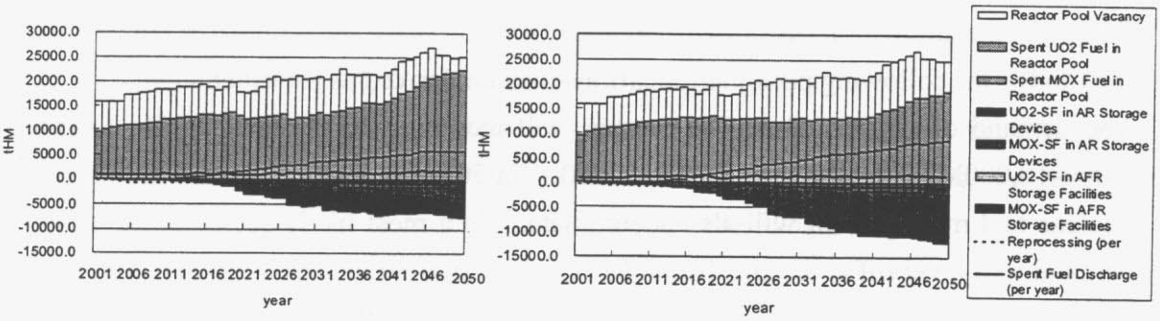
- Spent nuclear fuel discharge and its accumulation can be forecasted with relatively good precision in a medium-term, e.g. by the year 2030, spent nuclear fuel storage needs will continuously grow up to some 10,000tHM.

- In a long-run up to the year 2050, the spent nuclear fuel storage needs in Japan will vary significantly, from decreasing towards zero to keeping continuous increase up to 20,000-25,000tHM in 2050.
- Not only the total amount, the composition of spent nuclear fuel stockpile (i.e. well cooled low burnup UO_2, new high burnup UO_2, MOX) will vary toward the future depending on the overall strategy. Careful planning is necessary for proper management, e.g. designs of storage facility, container for storage and/or transportation.

5.2.2. Spent Nuclear Fuel Management Strategy Planning.

Since details of operational procedures at each NPP are not necessarily available or compatible to the model, here is shown an illustrative example of what this sub-model can tell based on a preliminary set of data. Figure 5.2.2-1(a) and (b) shows the results from the spent nuclear fuel management strategy analysis, using the similar assumptions to Fig. 5.2.1-1 and Table 5.2.1-1. The sub-model generates detailed results on amount of spent nuclear fuel by category (i.e. UO_2 and MOX) and by vintage (i.e. years since discharge), as well as their locations. While Fig. 5.2.2-1 is drawn as all 'overflowed' spent nuclear fuel will be accommodated at AR storage devices, the model can consider AFR installation possibility. Here, 3 types of AFR storage strategies are considered as illustration.

- Each of the 10 utility companies will manage their own spent nuclear fuel and install AFR storage facility individually.
- Several utility companies cooperate to install regional AFR storage. In this case, 3 regional blocks are set to install each AFR facility.
- All utility companies cooperate to install national AFR storage.



(a) Case O (b) Case N

Figure 5.2.2-1: An Illustration by Spent nuclear fuel Management Strategy Simulation. (Note: The legend shows 'UO2-SF in AFR Storage Facilities' and 'MOX-SF in AFR Storage Facilities', which do not appear in the both figures, since the calculations are done assuming there is no AFR devices installed.)

Table 5.2.2-1: An Illustration of Simulation Results; AFR Storage Installation, Cumulative Transportation Needs and Spent Nuclear Fuel Amount in AFR Store in 2050 [tHM].

AFR Strategy	Case O: Older Fuel Prioritized for Reprocessing						Case N: Newer Fuel Prioritized for Reprocessing					
	AFR Storage		Transportation			Fuel Stored in AFR in 2050	AFR Storage		Transportation			Stored Fuel in AFR in 2050
	Installed Capacity	Time of Installation	NPP to AFR		AFR to Repro.		Installed Capacity	Time of Installation	NPP to AFR		AFR to Repro.	
			UO2	MOx	UO2				UO2	MOx	UO2	
Individual 10 AFRs	9750	2011-2047	15000	3700	11500	7200	11100	2011-2047	9100	1600	400	10000
Regional 3 AFRs	8550	2014-2027	15000	3800	11000	7800	11200	2014-2027	9400	1600	400	10600
National 1 AFR	8150	2014	15800	3800	12000	7800	11700	2014	9800	1600	400	11000

The results are shown in Table 5.2.2-1. Because of the rule of reprocessing priority, there appears a trade-off between AFR storage capacity and total transportation needs; in order to limit total magnitude of storage, more frequent transport in and out with AFR facilities are needed. Another trade-off is found in total storage capacity and geographic cooperation. Individual treatment can be done when an entity encounters needs and thus economize investment schedule, while centralized strategy must inevitably do all investment as early as the first entity encounters needs. These aspects clearly demonstrate the necessity of the integrated analytic tool such as SFTRACE, which is capable to adequately analyze trade-off relationships among factors involved in spent nuclear fuel management strategy.

Further elaboration and validation are needed with the data set used here in order to judge which strategy is the best favored.

5.2.3. Observations.

Although the simulation runs described above are solely for the purpose of validation of the model, the following policy implications may be derived as robust enough.

The demand of spent nuclear fuel storage will increase steadily and rapidly, to reach 7,000-10,000MTU by the year 2020 to 2030. In 2050, uncertainties surrounding spent nuclear fuel management will also accumulate. In a most likely scenario, the storage demand will level off at around 10,000MTU after 2020-30 to 2050, which recommends to install a storage capacity of around 10,000MTU by the year 2020. While this storage capacity may be prepared either by individual and dispersed AR devices and/or by centralized AFR facilities, attentions should be given to coordination of the whole spent fuel management system to properly adjust various trade-off relations, such as geological distribution of storage facilities and transportation.

5.3. Concluding Remarks.

In this chapter, the author tried to summarize methodologies of spent nuclear fuel management strategy analyses, with illustrative examples by SFTRACE. While the tool is robust enough to analyze variations of conditions, the set of assumptions and data used in the simulation runs stay just for illustrative purposes and needs further elaboration. The author wishes to use the tool to analyze Japan's realistic as well as emergency-control typed scenarios in order to obtain strategies for Japan which are robust enough against future uncertainties.

REFERENCES FOR CHAPTER 5:

CRIEPI (2001) "*Demonstration Tests of Recyclable Fuel Resources –Development of Concrete Modular Storage Technologies-*," Final Report for Fiscal Year 2000 submitted to the Government [in Japanese].

Nagano, K. and K. Yamaji (1989) "The Needs and Economics of Spent nuclear fuel Storage in Japan," Slate, S.C. et al. (ed.) "*High Level Radioactive Waste and Spent nuclear fuel Management*," Vol.II, pp.473-482, The American Society of Mechanical Engineers.

Nagano, K. (2002) "A Systems Analysis of Spent nuclear fuel Management in Japan," *Proc. of PBNC-2002 International Conference*, Oct. 21-25, 2002, Shenzhen, China (2002).

Nagano, K. (2002b) "A Strategic Consideration on Nuclear Fuel Cycle with Spent Nuclear Fuel Management as its Core," *J. Nucl. Fuel Cycle and Environment,* **8** [2], Atomic Energy Society of Japan, (2002) [in Japanese].

Nagano, K. (2003) "A Systems Analysis of Spent nuclear fuel Management in Japan (1): Projection of Material Balances and Storage Needs," *J. Nucl. Sci. Tech.*, **40** [4], Atomic Energy Society of Japan (to be published.)

Yamaji, K. and K. Nagano (1989) "Optimal Reactor Strategy for Plutonium Utilization," *Proc. for IFAC/IFORS/IAEE Int'l Comf. On Energy Systems, Management and Economics (ESME89)*, Tokyo, Japan, (1990)

CHAPTER 6

Economic Assessment of Spent Nuclear Fuel Storage

6. Economic Assessment of Spent Nuclear Fuel Storage.

6.1. Introduction.

Analytical methods for economic analyses of spent nuclear fuel storage are categorized in three layers; a) static engineering-economic cost estimates, b) dynamic strategy analyses, and c) specific project financing assessments. This chapter discusses each of the three methods with numerical examples of applications. As a conclusion, the author maintains that users should choose the most suitable type of method or calculating tool in accordance with their specific purposes. General guidelines of choosing methodologies are elaborated as the conclusion. This Chapter is based on Nagano (2002b) and Nagano (2003).

6.2. Methodologies for Economic Analyses of Spent Nuclear Fuel Storage.

6.2.1. Classification of Analytic Methodology for Economics of Spent Nuclear Fuel Storage.

Methodologies employed in a study may vary according to its own purpose. In the case of economic analysis of spent nuclear fuel storage, the author is inclined in the following categorization of the tools:

- Engineering-economic cost calculation; engineering estimates of cost items are gathered and summed up in terms of monetary unit per unit of service, e.g. tHM of fuel stored. Static, fixed assessment is employed for a specific storage facility project.
- Strategic projection of spent nuclear fuel management systems; all spent nuclear fuel arising, storage, reprocessing and disposal are simulated in a dynamic framework. Regional or national scale projection is conducted against a certain long-range time horizon.
- Project financing assessment; private or public investment to a storage service project is assessed if it can be justified. Static, life-cycle analysis with performance indices such as internal rate-of-return (IRR), pay-back time, etc.

Table 6.2.1-1 shows the comparison among the three types of methodologies. In the following sections, each of those categories is presented with examples.

6.2.2. Engineering-Economic Cost Calculation.

This simple methodology formed the keynote in the earlier study of IAEA (1994), which is the best elaborated document in the field. In short, the method calculates the levelized unit cost of storage. The Net Present Value (NPV) of a project is a measure of the value of a project, defined as a sum of all the discounted cost stream associated

Table 6.2.1-1: Comparison of Methodologies in Economics of Spent nuclear fuel Storage.

Category	A. Engineering-economic Cost Calculation	B. Strategic Projection of Spent Fuel Management Systems	C. Project Financing Assessment
Object	Project / Storage Facility	Utility / Region / Country	Project / Storage Facility
Index	Levelized unit cost of storage. Variation: cost paid as lump-sum [$/tHM] or fee paid every year [$/tHM/year]	Amount of spent fuel to be stored against time, with possiblity to calculate total system costs by combining unit storage cost obtained from A.	IRR, pay-back time, NPV and other indices for investment appraisal.
Purpose and strength	Comparison of techniques, e.g. pool, cask, etc.	Projecting when storage is needed at which magnitude.	To decide whether to invest the project or not.
Potential User	Utilites / Owners of NPSs / Government	Utility / Region or national government	Private investors / Consultants / Regulators
Drawback	Static; adjustment needed when apply the results in different time horizen / Not easily converted to unit cost per kWh generated	Number of scenarios needed on which technology option is employed at which capacity at which location.	Static / All specifications of the project to be assessed should be fixed prior to the calculation / Dependence on specific institutional conditions

with the project, i.e.

$$NPV = \sum \frac{C_i}{(1+d)^i} \tag{1}$$

where Ci is the cost or expenditure in the i-th year, d is the discount rate, i is the year index. The levelized unit cost of storage is the unit price of storage service which equalizes the NPV of the cash flow of income and the NPV of the expenditure for the whole lifetime of the project, i.e.,

$$LUC = \sum \frac{C_i}{(1+d)^i} \Big/ \sum \frac{M_i}{(1+d)^i} \tag{2}$$

where Mi is the amount of spent nuclear fuel transported into the storage facility in the i-th year. Thus, the formula (2) is based on the assumption that the storage fee is paid upon receipt of spent nuclear fuel at a uniform unit price, which is LUC, namely;

$$\sum \frac{LUC \times M_i}{(1+d)^i} = \sum \frac{C_i}{(1+d)^i} \tag{3}$$

Figure 6.2.2-1 shows an example from Saegusa (1998), where the type of methodology is employed to the technology comparison at 3,000MTU AFR storage under the Japanese circumstances. Although the water pool storage is a mature technology with plenty of experiences by existing reactor pools, its economics may suffer from high capital investments as well as high O&M costs due to requirements of forced circulation and quality control of cooling water. The metal cask has been receiving highest priority in implementing storage facilities in short and medium terms, with its superb modularity and economics compared to water pool. For a longer perspective, research is ongoing for the other dry storage technologies, aiming at better economic performances. Key issues of research include;

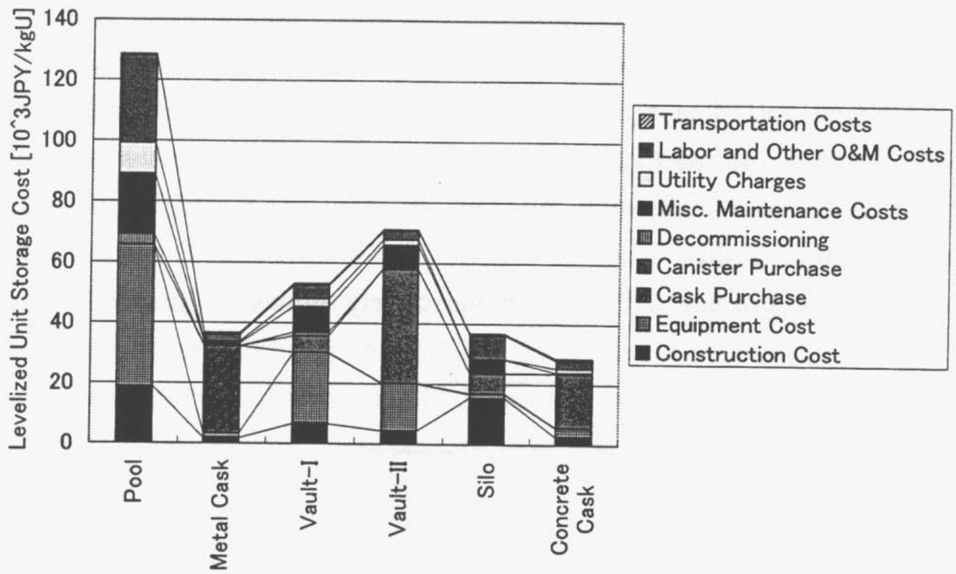


Figure 6.2.2-1: Comparison of Levelized Unit Storage Costs (source: Saegusa (1998))

- Long-term integrity of concrete materials,
- Long-term integrity of canisters, and
- Safety standards in O&M, especially unloading/loading for transportation.

The applications of similar methodology include Yamaji et al. (1987), Nagano and Yamaji (1989) for comparison of pool and metal cask techniques, and Nagano et al. (1990) for AFR storage, though cost data used in those early studies have become

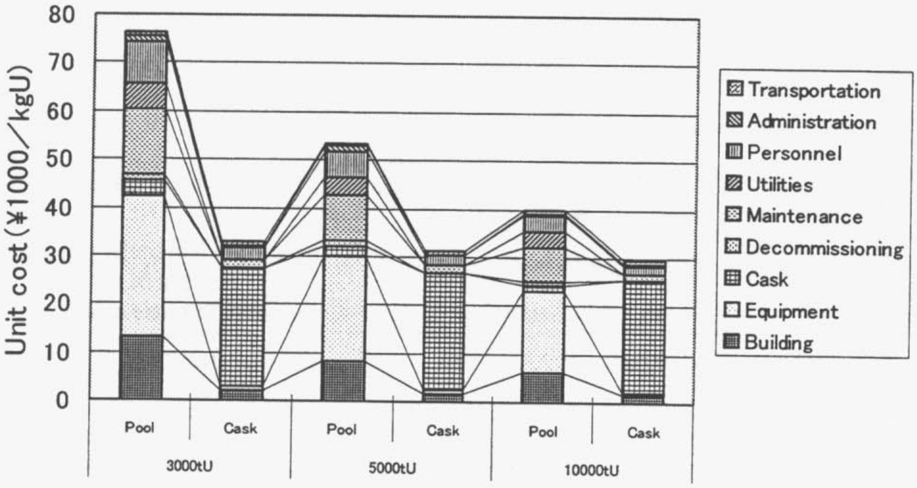


Figure 6.2.2-2: Comparison of Unit AFR Storage Costs for Storage Capacity 3,000-10,000MTU.

(source: Ito et al. (2000), Ito et al. (2001))

obsolete by now. The latest example is Ito et al. (2000) and Ito et al. (2001), whose main result is shown in Figure 6.2.2-2. Here is found similar conclusions as Figure 6.2.2-1, though cost data reflect further development and improvement during the period. Figure 3-3 shows the cost data used for the case of 5000tU storage capacity in Figure 6.2.2-2, both lump-sum and net present value (NPV) in the year of commencement of facility.

Among all these examples, this technique clearly shows its strength in technology

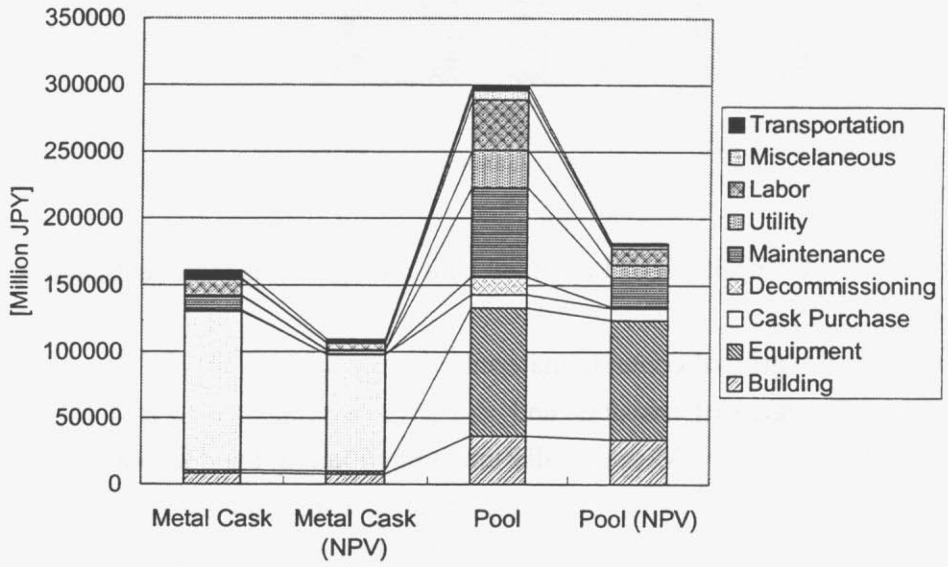


Figure 6.2.2-3: Cost Data for 5,000tU Storage Facility. (Source: Ito et al. (2000))

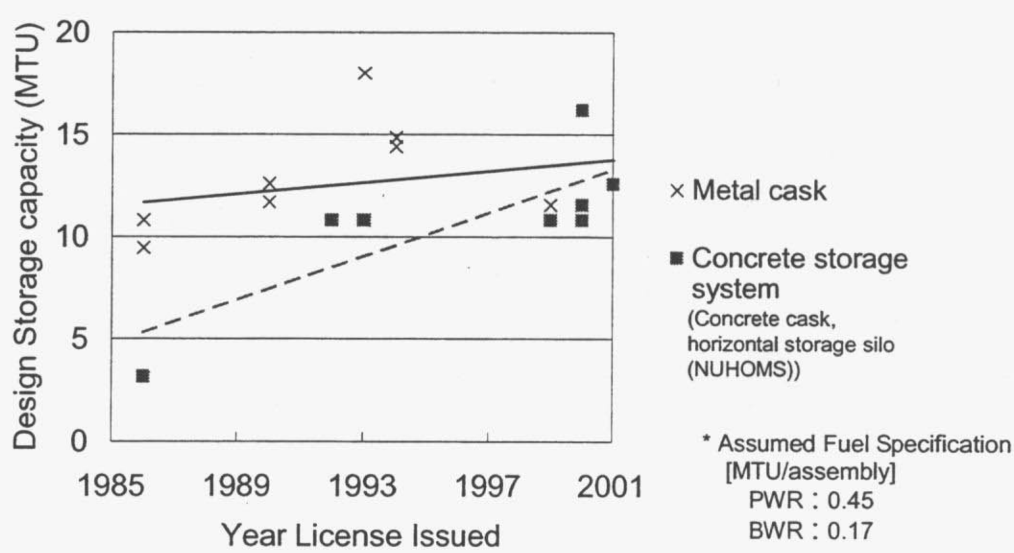


Figure 6.2.2-4: An Attempt to Capture Technological Improvement; Unit Capacity per Container Experienced in the United States. (source: CRIEPI (2001))

assessment, especially in finding key cost items with possibilities of innovation, such as cask fabrication in metal cask storage, or canister fabrication in concrete modular techniques. In the meantime, the method does not necessarily covers those indirect costs related to running the organization who owns and operates the facility. Therefore, it is concluded that while the methodology is beneficial in pre-project period where one tries to find which is the best technology option to implement, supplementary analysis is required in the stage of actual implementation with physical investments.

Another viewpoint found in Figure 6.2.2-2 and 6.2.2-3 is the importance of innovation. There are several aspects which essentially drives the cost improvements against time:

- Economy of scale, which is performance improvement by expanding total or unit capacity,
- Economy of scope, which is performance efficiency improvement by shared uses of common resources and opportunities, and
- Learning-by-doing effect, which is performance improvement by accumulating experiences and/or RD& D efforts.

Attempts to discuss all those aspects in the field of spent nuclear fuel storage in a coherent manner have been made in Nagano (1998a), Nagano (1998b), Nagano (1999) and Nagano (2002a). Just as an example, Figure 6.2.2-4 shows such an attempt to address storage efficiency improvement in terms of unit container capacity along time observed in the past in the United States (CRIEPI (2001)). Further efforts are needed to fully capture technological characteristics of spent nuclear fuel storage, and ultimately to be able to precisely forecast future cost improvements.

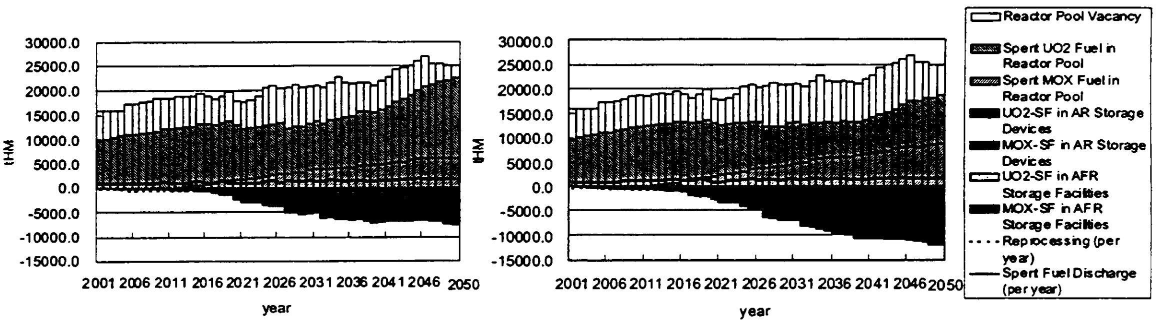
6.2.3. Strategic Projection of Spent Nuclear Fuel Management Systems.

Storage demands should be projected over time in order to plan storage facilities. Although this type of tools is not directly analyze the economics of spent nuclear fuel storage, it is yet as important as to determine preconditions for storage projects to be assessed.

The integrated analytic tool SFTRACE (Spent Fuel Storage, TRAnsportation and Cost Evaluation System) described in Chapter 5 is intended to provide the functions of this category. As explained in Chapter 5, SFTRACE starts with spent nuclear fuel generation at each NPS based on a set of assumption of national nuclear energy production and Pu recycling strategy. Spent nuclear fuel balance calculation follows and, if there are found overflow of spent nuclear fuel stockpile beyond built-in pool storage capacity, additional storage devices are planned in the scenario generator, and calculation is modified accordingly. After completion of material balance simulation, cost evaluation is executed against storage technology options to be applied for those additional storage measures.

While the model is complete, data sets used in the following illustrative runs are preliminary ones, which need further elaboration and validation. Here, the results of spent nuclear fuel management requirements in Case O and Case N illustrated in Figure 5.2.2-1 and Table 5.2.2-1 are used for the extension to the economic assessment. For the underlying assumptions for Case O and Case N, see Section 5.2.1. Figure 6.2.3-1(a) and (b) are the reproduction of Figure 5.2.2-1(a) and (b), in which considerable amount of spent nuclear fuel accumulate (below the horizontal axis), necessary to be taken care of by additional storage measures, while some vacancies still remain in reactor pools in operation, reflecting different situations among power utility companies and/or NPP sites.

For those stockpile of spent nuclear fuel overflowed from reactor pools, either AR or AFR storage measures are planned. As described in Section 5.2.2, it is assumed that individual AR devices are implemented at early stage of the time horizon when the storage demand is limited in quantity. Later on, centralized AFR storage facilities are considered when a sudden increase of storage demand is anticipated. At this point, a speculative assumption is given to AFR storage for the three different levels of centralization:



(a) Case O (b) Case N

Figure 6.2.3-1: An Illustration by Spent nuclear fuel Management Strategy Simulation (reproduced of Figure 5.2.2-1).

(Note: The legend shows 'UO2-SF in AFR Storage Facilities' and 'MOX-SF in AFR Storage Facilities', which do not appear in the both figures, since the calculations are done assuming there is no AFR devices installed.)

Table 6.2.3-1: An Example of Strategic Simulation; AFR Storage Installation, Cumulative Transportation Needs and Spent nuclear fuel Amount in AFR Store in 2050 [tHM] (reproduced of Table 5.2.2-1).

AFR Strategy	Case O: Older Fuel Prioritized for Reprocessing						Case N: Newer Fuel Prioritized for Reprocessing					
	AFR Storage		Transportation			Fuel Stored in AFR in 2050	AFR Storage		Transportation			Stored Fuel in AFR in 2050
	Installed Capacity	Time of Installation	NPP to AFR		AFR to Repro		Installed Capacity	Time of Installlation	NPP to AFR		AFR to Repro	
			UO2	MOx	UO2				UO2	MOx	UO2	
Individual 10 AFRs	9750	2011-2047	15000	3700	11500	7200	11100	2011-2047	9100	1600	400	10000
Regional 3 AFRs	8550	2014-2027	15000	3800	11000	7800	11200	2014-2027	9400	1600	400	10600
National 1 AFR	8150	2014	15800	3800	12000	7800	11700	2014	9800	1600	400	11000

- Each of the 10 utility companies will manage their own spent nuclear fuel and install AFR storage facility individually.
- Several utility companies cooperate to install regional AFR storage. In this case, 3 regional blocks are set to install each AFR facility.
- All utility companies cooperate to install national AFR storage.

Table 6.2.3-1 summarizes the results of spent nuclear fuel management strategies for those cases, in terms of cumulative requirements of transportation as well as AFR storage installation, which is a reproduction from Table 5.2.2-1. Based on these management scenarios, strategic cost analyses were undertaken, whose results are shown in Figure 6.2.3-2. Figure 6.2.3-2 shows the overall economic performances of those scenarios with different sets of storage technologies applied for AR/AFR storage, in terms of levelized total spent nuclear fuel management costs in relative term (i.e. NPV of costs for storage facilities plus costs for transportation divided by NPV of discharged spent nuclear fuel quantities).

Although it is premature to compare among scenarios because of the data limitation, these results clearly underscore the unique strength of this integrated tool, as those trade-off relations within the whole system can be evaluated, such as the one between transportation and storage, between reactor operation strategy and spent nuclear fuel management strategy, and among different degrees of regional cooperation.

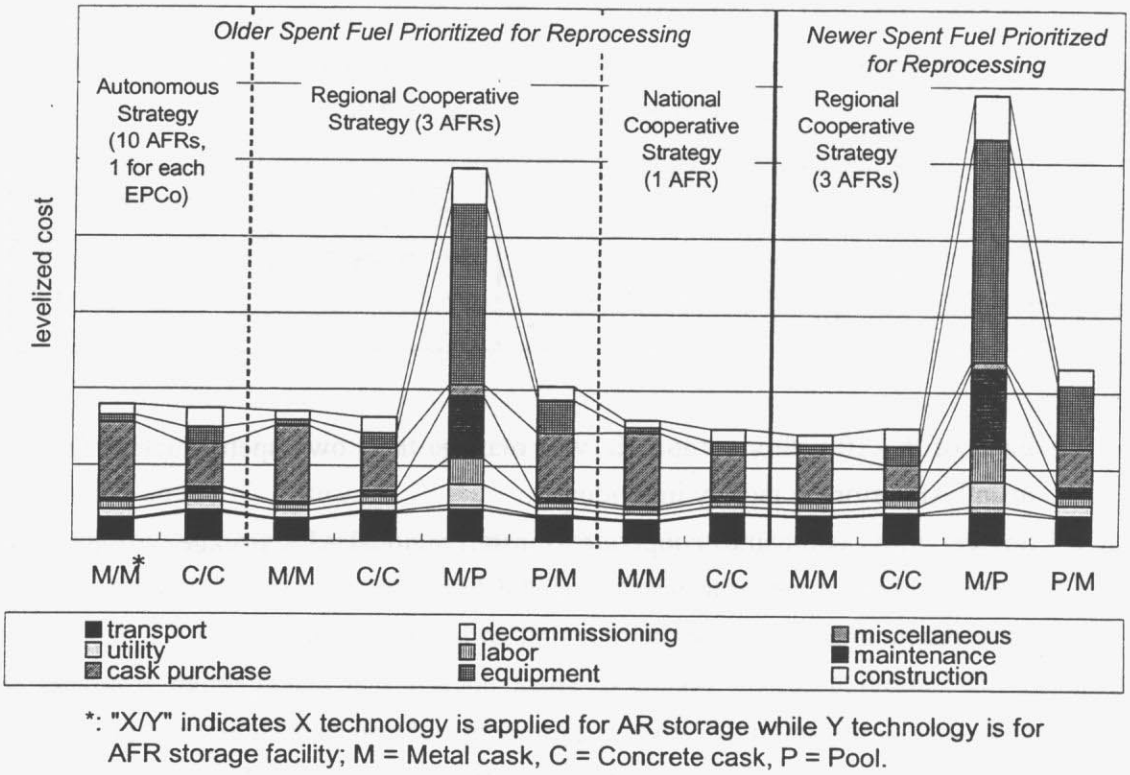


Figure 6.2.3-1: Results of Overall Cost Comparison (in relative scale).

6.2.4. Project Financing Analysis for Private Investment in Spent Nuclear Fuel Storage Services.

In determining actual investment for a project, overall financial health is to be assessed. The software for this analysis may be available as book-keeping typed commercial packages. Application to spent nuclear fuel storage project, however, may require fine tune-up against specific features of spent nuclear fuel storage businesses. The most peculiar point is, in the author's view, how to determine prices for storage services.

The author developed a project financing assessment tool, whose overview is reported in CRIEPI (2001). Table 6.2.4-1 shows the differences in cost item coverage in this tool and the conventional engineering-economic cost estimation described in Item 6.2.2, typically applied in Figure 6.2.2-1 and Figure 6.2.2-2. Data requirements are larger and more specific in the context of entity to invest the project, as well as institutional rules and regulations in the country or region where the investment is to be made.

Table 6.2.4-2 shows the performance indicators in assessing efficiency and performance of investments. For notations of the variable in Table 6.2.4-2, see Appendix. Table 6.2.4-3 is the reference set of preliminary data used for the following numerical example, which are mostly taken from Japanese actual rules and experiences, but not necessarily fully verified.

The sample calculation was done based on engineering-economic conditions for the case of metal cask storage at 5,000tHM capacity in Figure 6.2.4-1. The focus was the price schemes for the storage service vendor as a private company limited. In determining storage service price, one can choose any combination of the following two factors;

- *IC*, which is the Initial fixed charge payable for once upon receipt of spent nuclear fuel at storage facility, in terms of [¥/tHM], and
- *AF*, which is the annual fee per unit of fuel stored [JPY/tHM/year].

Calculation was done to explore several alternatives with *IC* and *AF*, which satisfy those short- and long-term criteria listed in Table 6.2.4-2. While numerous numbers of such combinations can be found, Table 6.2.4-4 summarizes the service price settings taken up in this illustrative simulation. Because of the preliminary nature of this sample calculation, qualitative aspects of the analysis should be paid attentions to while absolute values do not have significant meanings.

Table 6.2.4-1: Comparison of Cost Item Coverage between Engineering-Economic Cost Calculation (6.2.2.) and Project Financing Analysis (6.2.4.); the Case of Private Firm.

Item			(6.2.2.)	(6.2.4.)	Remark
A.	Operating profits and losses	Sales revenue	×	○	
B.		Production costs	See table below		
C.		Administration and Marketing costs	See table below		
D.	Non operating profits and losses	Interests, Dividends	×	○	Income
E.		Financial costs	×	○	Expenditure
F.		Miscellaneous	×	×	
G.	Ordinary operating profits and losses				(A－(B＋C))＋(D－(E＋F))
H.	Extraordinary gain and loss	Extraordinary gain	×	×	Sale of assets, etc.
I.		Extraordinary loss	×	×	Securities sold, etc.
J.	Transfer to reserve		×	○	Decommissioning
K.	Net profit and loss before tax				G－(－H＋I＋J)
L.	Taxes	Corporate income tax	△	○	Included in labor's cost in (6.2.2.)
		Residents taxes	△	○	
M.	Net profit and loss after tax				K－L
N.	Balance brought forward from the previous term				
O.	Undivided profit from the current term				M＋N
P.	Distribution of net profit	Dividends	×	○	
		Rewards to executives	×	○	
		Surplus reserve	×	×	
Q.	Balance carried forward to the following term				O－P

Item				(6.2.2.)	(6.2.4.)	Remark
B	Production cost	Labor content (Salaries, bonuses, retirement allowance, social insurance)		△	○	Lump-sum in (6.2.2.)
		Materials		○	○	
		Repair, Maintenance		○	○	
		Utilities		○	○	Energy, Water, etc.
		Decommissioning		○	○	
		Insurance		△	○	Included in labor content in (6.2.2.)
		Depreciation		△	○	Implicit in (6.2.2.)
		Taxes and Public Charge	Fixed asset tax	△	○	Included in labor content (6.2.2.)
			Business tax	△	○	
			Consumption tax	△	○	
C	Administration and Marketing costs	Labor content (Salaries, bonuses, retirement allowance, social insurance)		×	○	Not considered in (6.2.2.)
		Director's remuneration		×	○	
		Communication, Trip		×	○	
		Consumables		×	○	
		Gavel, rent,		×	○	
		Miscellaneous		×	○	
		Depreciation		×	○	
		Taxes and public charge		×	○	

○ : Estimated explicitly △ : Estimated inclusively × : Not Considered.

Table 6.2.4-2(a): Short-term Performance Indices in Financial Analyses.

Characteristics	Indicator	Calculation / Formula	Criteria for judgment
Profitability - Corporate competitiveness .	Gross profit rate	$=\frac{[\text{Ordinary profit and loss}]}{[\text{Sales revenue}]}$	Not significantly less than alternative business opportunities.
	Period between beginning of operation and first recording of positive profit	$=t(0<[\text{Profit after tax}])-t_0$	7 or 8 years after commencement of the business.
	Period between beginning of operation and first recording of surplus profit	$=t$(0<[Surplus profit carried forward]) - t_0	Less than mean legal durable years of facilities and equipment
Liquidity - Analysis of fund raising capacity.	Equity ratio	$=\frac{\sum_{t=t_1}^{t_2}(I_t+E_t)}{\sum_{t=t_1}^{t_2}(I_t+F_t+E_t)}$	(Assumed to be constant at 20% in the study.)
	Fixed asset ratio	$=\frac{[\text{Fixed asset}]}{\text{Net worth equity capital}}$	Not significantly less than alternative business opportunities.
Others - Principle s of financial management.	Shortage of working fund	= [Net cash from operating activities] + [Net cash used for financing activities]	[Cash and cash equivalents at the end of each year] $\geqq 0$
	Insolvency	=[Total assets] - [Total liabilities]	[Total assets] − [Total liabilities] $\geqq 0$

Table 6.2.4-2(b): Long-term Performance Indices in Financial Analyses.

Characteristics	Indicator	Calculation / Formula	Criteria for judgment
Attractiveness	NPV : Net Present Value	$=\sum_{t=t_1}^{t_2}\frac{(Pn_t+Dp_t)}{(1+i)^{(t_0-t)}}-\sum_{t=t_1}^{t_2}\frac{(As_t+Ao_t)}{(1+i)^{(t_0-t)}}$	[NPV] > 0
	ROI : Return on Investment	$=\sum_{t=t_1}^{t_2}\frac{(I_t+F_t+P_t)}{(1+i)^{(t_0-t)}}=\sum_{t=t_3}^{t_4}\frac{(D_t+R_t)}{(1+i)^{(t_0-t)}}$	ROI > $WACC$: Weighted average cost of capital $WACC=\frac{D_t+R_t}{\sum_{t=t_1}^{t_2}I_t+Fr_t}$

Table 6.2.4-3: The Preliminary Data for the Case of Private Business Initiative.

Item			Assumed Rate	Remark
Cost of fund raising	Dividend		Dividend rate: 10 %	
	Interest	Long-term debt	Interest rate: 4.0 %	No standstill agreement Payment period: 10 years Equal payment
		Short-term debt	Interest rate : 5.0 %	Overyear
Production cost	depreciation		Manner of depreciation: constant percentage method Durable years: Legal basis Depreciation ratio: according to above condition	Durable years(year) Buildings: 38 Cask 20 Equipment 7
	Liability insurance Indemnity fee		The low on compensation for nuclear damage amount of claim: Premium rate: 0.1 % Rate of fee: 0.05%	 assumed same as non-life insurance amount of indemnity: ¥12 thousand million
	Non-life insurance		Nuclear property insurance Premium rate: 0.1 %	Maximum amount covered: 2.5% of net worth equity capital
Tax	National	Corporate income tax	Tax rate: 30.0 %	Standard tax rate
		Consumption tax	Tax rate: 5.0 %	Include local tax
	Local	Residents tax	Tax rate: 12.3 % + 5.0 % Per capita basis: ¥ 70 thousand~¥ 38 hundred thousand	Standard tax rate According to scale of corporation
		Business tax	Tax rate: 5.0%, 7.3%, 9.5%	According to amount of income Standard tax rate
		Fixed asset tax	Tax rate: 1.40%	Standard tax rate

General administrative cost	Rate of cost: 24.0% of Production cost (after tax)	Average value of all industries for 10 years
Addition to reserve	Equally dividing total decommissioning cost per operating period of	
Income from investing (Interest received)	Investment yield: 0.54%	Certificate of deposit (1997～1998)

Table 6.2.4-4: Illustrative Cases of Storage Service Prices Determination.

Case No.	*IC* [10^6JPY/tHM]	*AF* [10^6JPY/tHM/y]	Remark
IC	100%	0%	Lump-sum.
AF	0%	100%	"Parking-lot."
Comb.	30% of Case IC	Adjusted accordingly.	

The illustrative results are shown in Figure 6.2.4-2(a)-(c), where financial performances and health are checked throughout the planning horizon. Analysis is carried out by searching a price range to find out if the price level maintains the project feasible and viable. The total costs of each of Figure 6.2.4-2(a)-(c) are shown in Figure 6.2.4-3.

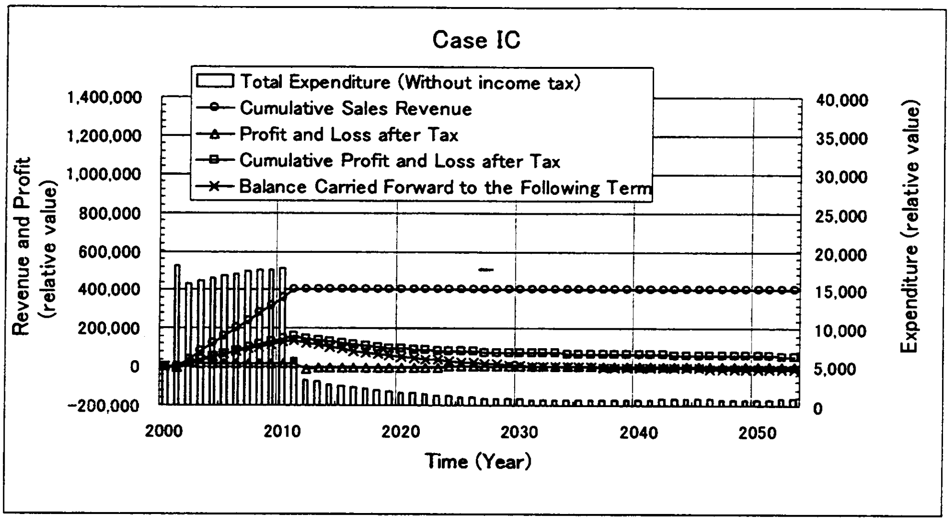


Figure 6.2.4-1(a): Financial Health of a Storage Project; An Example of Case *IC*.

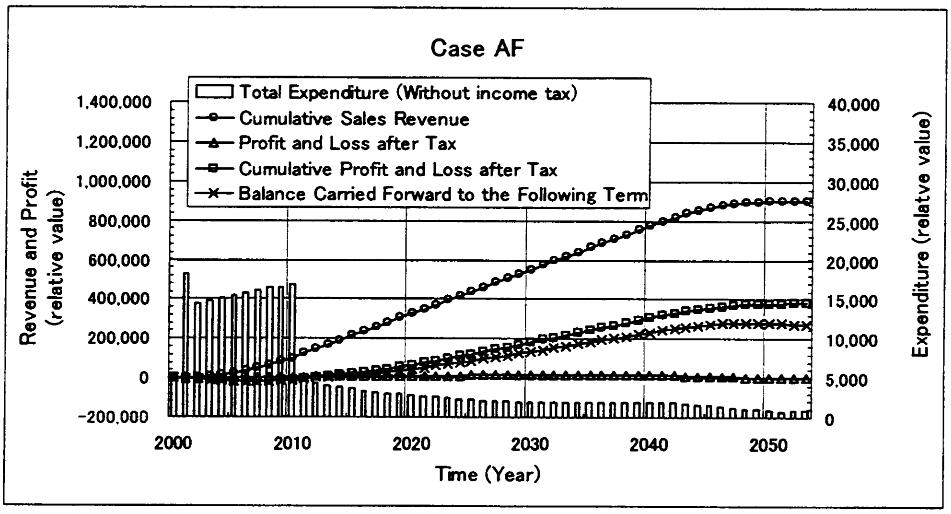


Figure 6.2.4-1 (b): Financial Health of a Storage Project; An Example of Case *AF*.

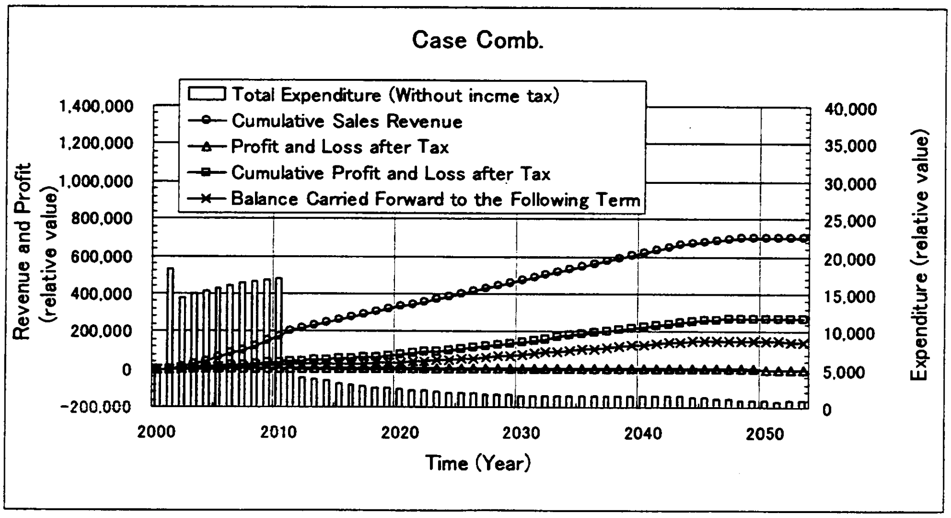


Figure 6.2.4-1(c): Financial Health of a Storage Project; An Example of Case *Comb.*

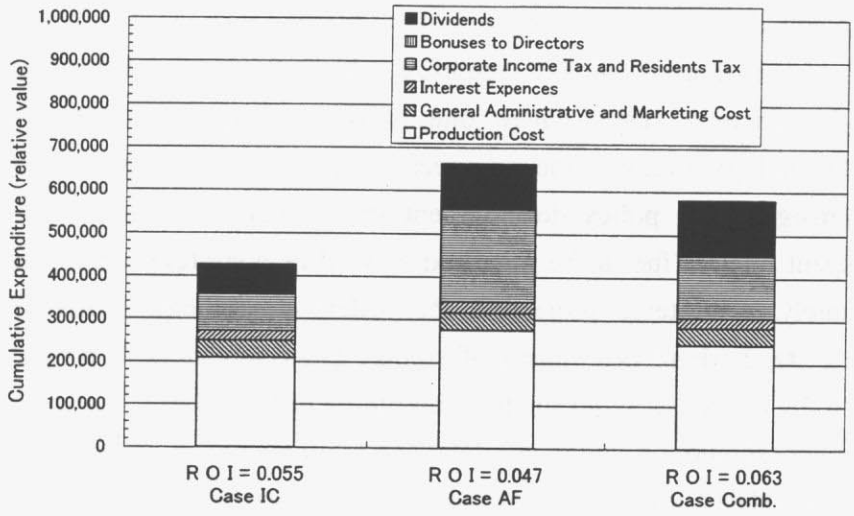


Figure 6.2.4-2: Comparison of Total Costs.

Because of capital investment intensive nature of spent nuclear fuel storage businesses, Case AF, or "parking-lot" scheme in other words, makes substantive deficit in early ears of the operation. If one tries to ease them by raising the annual price, it will in turn generate excessive profit in late years. After all, an alternative way of costing should be implemented against this pricing scheme, such as lease of storage casks instead of purchase.

Case IC, or lump-sum payment upon receipt, might be better favored in view of compensating initial investment. This business operation turns out to be, however, such that at the beginning a huge reserve of fund is built up, which gets deducted as the project goes during years of storage without making any profits. No profit earning means the business entity will not generate any corporate tax payment or dividend, which is reflected in Figure 6.2.4-2 as its total cost is the lowest among other price schemes. While this pricing scheme shows an efficient way to execute storage services, there are rooms of discussion if such business operations are justified in the light of social moral principles.

Case Comb. will ease the difficulties of both cases above. Numerous combinations of IC and AF are feasible, while in this calculation IC was set as 30% of the Case IC as gives the most balanced profile in between. However, it should be noted that no simple optimization can be made, since different price choices do not necessarily generate much differences in financial performances. One should carefully choose a price scheme with the combinatory pricing.

6.3. Recommended Guidelines for Choices of the Methodologies.

First of all, potential users should recognize which stage of development they are standing. In planning status where one needs to find potentially feasible and promising technology options, the engineering-economic cost assessment provides appropriate insights. In policy development stage where one needs to know exact amount of spent nuclear fuel to be managed as well as a strategy which takes care of them adequately, a strategic projection tool offers great help. Finally, in policy implementing stage where healthiness of storage project matters, a project financing analysis is vitally needed to avoid sudden bankruptcy of the policy.

Another remark should be given to data availability. Each method has its own requirements on data. Special attentions should be given that information on the whole nuclear energy production scenario of the target region or country is necessary to perform the strategic projection, which may be associated certain degree of uncertainty into the future. Also, detailed institutional rules and regulations must be defined in attempting the project financing analysis, which might sometimes be yet to come.

Finally, the objectives of analysis do matter. To find R&D direction and targets, an engineering-economic cost analysis should be repeated. To determine appropriate policy of spent nuclear fuel management, strategic projection shows the way. To decide whether to enter into the business, or to maintain economic stability of ongoing project, detailed financial analysis provides the essential arm.

6.4. Concluding Remark

This chapter discussed methods and tools for economic analyses of spent nuclear fuel storage, which are categorized in three layers; a) static engineering-economic cost estimates, b) dynamic strategy assessments, and c) specific project financing assessments. After presenting specific examples of each, the author gathered observations on what should be done in expanding those methodologies to be suitable for potential users of such analytical tools.

REFERENCES FOR CHAPTER 6:

Atomic Energy Commission, Japan (2000) "*The Long-term Program of Research, Development and Utilization of Nuclear Energy,*" whose unofficial English translation version is available at: http://aec.jst.go.jp/jicst/NC/tyoki/siryo/tyoki_e/siryoe.htm

CRIEPI (2001) "*Demonstration Tests of Recycle Fuel Resources –Development of Concrete Modular Storage Technologies,*" Final Report for Fiscal 2000 submitted to the Government. (in Japanese)

CRIEPI (2002) "*Demonstration Tests of Recycle Fuel Resources –Development of Concrete Modular Storage Technologies*," Final Report for Fiscal 2001 submitted to the Government. (in Japanese)

IAEA (1994) "*Cost Analysis Methodology of Spent Fuel Storage*," Technical Reports Series No.361, International Atomic Energy Agency, Vienna.

Ito, C, T. Saegusa and K. Nagano (2000) "*Economical Evaluation on Spent nuclear fuel Storage Technology away from Reactor*," Research Report No.U99047, CRIEPI, Tokyo. (in Japanese)

Ito, C, T. Saegusa and K. Nagano (2001) "Economical Evaluation on Spent nuclear fuel Storage Technology away from Reactor," *J. Nucl. Fuel Cycle and Environment*, **8** [1], Atomic Energy Society of Japan. (in Japanese) .

Nagano, K and K. Yamaji (1989) "The Needs and Economics of Spent nuclear fuel Storage in Japan," Slate, S.C. et al. (ed.) "*High Level Radioactive Waste and Spent nuclear fuel Management*," Vol.II, pp.473-482, The American Society of Mechanical Engineers.

Nagano, K. et al. (1990) "Economic Analysis of Spent nuclear fuel Storage Technology in Japan," IAEA-SR-171/22, in "*Spent Fuel Storage: Safety, Engineering and Environmental Aspects*," IAEA Working Material No.IAEA-SR-171, IAEA.

Nagano, K. (1998a) "A Mathematical Analysis of Storage in the Fuel Cycle Back-end System," *Denryoku-keizai Kenkyu (Economics and Public Utilities)* No.39, pp.1-12, CRIEPI, Tokyo. (in Japanese)

Nagano, K. (1998b) "An Economic Analysis of Spent Fuel Management and Storage," *Proc. for PBNC'98*, Banff, Canada.

Nagano, K. (1999) "*Interim Storage of Spent nuclear fuel in Japan -Facts and Theoretical Prospects-*," paper presented at Workshop on Interim Storage of Spent nuclear fuel and Management of Excess Fissile Material, Harvard Univ., February 18-19, 1999.

Nagano, K. (2002a) "A Strategic Consideration on Nuclear Fuel Cycle with Spent nuclear fuel Management as its Core," *J. Nucl. Fuel Cycle and Environment*, **8** [2], Atomic Energy Society of Japan (in Japanese).

Nagano, K. (2002b) "*Methodologies for Economic Analyses of Spent nuclear fuel Storage*," paper presented at IAEA Technical Meeting on Economics of Spent Fuel Storage, St. Petersburg, Russia, September 9-12, 2002.

Nagano, K. (2003) "A Systems Analysis of Spent nuclear fuel Management in Japan (2): Methodologies for Economic Analyses of Spent nuclear fuel Storage," *J. Nucl. Sci. Tech.*, **40** [4], Atomic Energy Society of Japan (to be published.)

OECD/NEA (1985) "*The Economics of Nuclear Fuel Cycle*," OECD, Paris.

OECD/NEA (1989) "*Plutonium Fuel: An Assessment*," OECD, Paris.

OECD/NEA (1994) "*The Economics of Nuclear Fuel Cycle*," OECD, Paris.

Saegusa, T. (1998) "Activities and Future Issues on Research of Spent nuclear fuel Storage in Japan," *Nuclear Eye* Vol.44, No.4, pp.14-19, Nikkan-kogyo Shinbunsya, Tokyo (in Japanese).

Saegusa, T. et al. (1999) "*Dry Storage Technologies for High Burnup and MOX Spent nuclear fuels*," Summary Report No.U27, CRIEPI, Tokyo.

Yamaji, K., K. Nagano and T. Saegusa (1987) "*Comparative Economic Evaluation of Spent nuclear fuel Storage Technologies*," Research Report L87001, CRIEPI, Tokyo (in Japanese).

Appendix: Notation of Variables.

Table A-1: Notational of Variables.

Variable	Notation	Unit
i	DCFrate : Discounted Cash-flow Rate.	-
I_t	Investment in year t.	Currency (e.g. JPY)
D_t	Dividend in year t.	Currency (e.g. JPY)
Dp_t	Depreciation in year t.	Currency (e.g. JPY)
t	Time.	(date)
t_0	Reference date for discounting (year)	(date)
t_1	Date of the commencement of investment and loan.	(date)
t_2	Date of the termination of investment and loan.	(date)
t_3	Date of the commencement of dividend and repayment.	(date)
t_4	Date of the termination of dividend and repayment.	(date)
R_t	Interest payment of long-term debt (after tax) in year t.	Currency (e.g. JPY)
F_t	Net increase in long-term debt in year t.	Currency (e.g. JPY)
Fr_t	Total Long-term debt in year t.	Currency (e.g. JPY)
B_t	Repayment of long-term debt in year t.	Currency (e.g. JPY)
P_t	Net increase in cash and cash equivalents in year t.	Currency (e.g. JPY)
Pn_t	Profit and loss after tax in year t.	Currency (e.g. JPY)
E_t	Purchase of fixed assets from cash and cash equivalents in year t.	Currency (e.g. JPY)
As_t	Purchase of fixed assets in year t.	Currency (e.g. JPY)
Ao_t	Demand for working capital in year t.	Currency (e.g. JPY)

CHAPTER 7

Conclusions

7. Conclusions.

7.1. Summary of the Previous Chapters.

Spent nuclear fuel discharged from nuclear power reactors has accumulated to a considerable amount in Japan and the other countries with nuclear power generation stocks, which will lead to risks of their overflow beyond the existing management capacities at those nuclear power plants. If such overflow happens, the power plant has to be shut down until appropriate measures have been taken. Meanwhile, uncertainties have accumulated surrounding final treatment facilities, either reprocessing or geological disposal, reflecting difficulties to find appropriate sites caused by oppositions of local and/or general public and other factors. As a result, spent nuclear fuel has to be stored for the time being in interim devices for a certain time period, e.g. 20 years to 40-50 years, until such time that they can be moved to their final destination.

Under the objective to review theoretical background and thoughts relevant to policy considerations on spent nuclear fuel management and storage ranging from their discharge to final treatment, to obtain quantitative images, and ultimately to present desirable policies and their implications in medium and long range in Japan, this dissertation is intended to answer for those essential key questions including the following, to which it presented first the theoretical framework to obtain answers and then answers at the moment while encompassing underlying uncertainties:

- When and to what extent spent nuclear fuel storage will be required, and which type of technology options should be applied?
- How long should it be the appropriate storage duration? How does it connect to the overall nuclear fuel cycle program?
- Which should be chosen, AR (At Reactor) storage, AFR (Away From Reactor) storage or a combination of both?
- How will it cost?
- How will the price for storage services be determined?

After presenting these objectives and key questions in Chapter 1, the dissertation first discussed in Chapter 2 the present status of spent nuclear fuel management in Japan, which clarifies where the dissertation stands at this moment. As spent nuclear fuel accumulates at all the nuclear power plants in Japan, enhancement measures of the management capacity, such as re-racking, have already been implemented by now where available. Since opportunities for further enhancement are narrow and scarce, implementation of AFR storage is justifiably needed in an appropriate time range. In fact, relevant institutional developments, namely policy formulation, such as statements in the Long-term Program of Research, Development and Utilization of Nuclear Energy, as well as legislation, especially the amendment of the Law for Regulation of Nuclear Reactors, Nuclear Facilities and Nuclear Materials, have already been completed and implemented. This clearly justifies the needs for the policy analyses in this dissertation, such as strategic planning of storage projects and their economic assessments.

Chapter 2 also dealt with the historical evolutionary patterns of spent nuclear fuel storage technologies. Various types of storage technique have been developed and are now available. Recently, new dry storage techniques, which are characterized as a combination of metal canisters and concrete blocks including concrete cask storage and horizontal silo storage, are receiving higher shares in the market. The analysis of the historical patterns of worldwide market penetration of various techniques, however, found no clear sign of retirement of any technology from the global market, while each technique has comfortably found its own "*niche*" with its specific strength and features to form cohabitation of all. This may reflects the very characteristics of spent nuclear fuel storage market with limited number of projects for long lifetimes. This observation at this moment, meanwhile, does not rule out possibilities of different patterns of market evolution to take place in the future, since the world market will expand whilst choices of techniques will be put more on invisible hands of market economy.

Chapter 3 presented the energy and nuclear fuel cycle modeling frameworks, with which the author attempted to describe optimal patterns of nuclear fuel cycle management in harmony with nuclear energy utilization pathways. Chapter 3 started with the development of Fuel Cycle Optimization Model (FCOM) and extended to its integration with the LDNE21 global energy model, in order to analyze spent nuclear fuel management in an overall framework of nuclear fuel cycle and the global energy system. FCOM solves a long range (90 years) cost minimization problem of the LWR (light water reactor) – FBR (fast breeder reactor) symbiotic system based on linear programming. The optimal solution provides a desirable evolutionary pattern of plutonium (Pu) economy with Pu supply from reprocessing of spent LWR fuel as its key parameter. FCOM's superb feature is, despite a compact model, to obtain an optimal solution of management of spent LWR fuel integrated with reactor mix patterns. Through numerical experiments, it was concluded that spent LWR fuel storage is chosen to adjust future uncertainty as it gives flexibility to the whole nuclear fuel cycle to allow spent LWR fuel reprocessing according to Pu demand. The illustrative simulation runs showed that, while reprocessing of spent LWR fuel is undertaken in

accordance with Pu demands, storage of spent LWR fuel provides the adjustment function between Pu supply and demand. This means that storage of spent nuclear fuel should be chosen actively as a measure to cope with uncertainty towards future as it gives flexibility to the management and operation of the whole nuclear fuel cycle.
Chapter 3 further extended to the integration of FCOM into the long-range global energy model LDNE21 (Linearlized Dynamic New Earth 21). In this application, FCOM serves as a nuclear energy sub-model within the LDNE21 framework, which analyzes optimal global energy pathways in terms of minimum discounted total system costs up to the year 2100 under a certain set of global environmental and other constraints. The illustrative simulation runs showed that, under a constraint of atmospheric concentration of carbon dioxide (CO_2) to be kept below 550ppm in the year 2100, the optimal global energy strategy will be chosen under competition between nuclear power generation and combined cycle generation by coal. This underscores the importance of nuclear fuel cycle and spent nuclear fuel management modeled in FCOM against global energy pictures. Meanwhile, necessity of global shift towards Pu economy does not necessarily maintain.

Chapter 4 presented a theoretical analysis of optimal choice of storage duration. In this analysis, the fundamental roles and benefits of storage were understood as twofold; 1) postponement of subsequent processes, which leads to a decrease of present value of those costs, and 2) gains through R&D by earning time with storage. As the result, it was concluded that there could appear an optimal storage duration, which equalizes the following two indices; a) the incremental storage cost for 1 more year, in other words the marginal cost, and b) the increase of the sum of above mentioned benefits, or the marginal utility, through 1 year extension of storage. In the case of uncertainty, this optimal storage duration is prolonged accordingly through a risk-averse attitude. These findings stand also in the case of direct disposal of spent nuclear fuel. This analysis, however, omitted certain factors such as specific lifetimes of storage containers and/or facilities, or societal anxieties, which may lead to additional costs when storage duration is prolonged.

Chapter 5 dealt with the methodologies of material balance calculation ranging discharge, storage, transportation and final processing of spent nuclear fuel. They are categorized into the following two kinds; 1) a microscopic accounting for each power station site or each power utility company, and 2) a macroscopic analysis, either simulation or optimization, in a region-wide or nationwide scale. In Chapter 5, development of a Japan-wide simulation tool SFTRACE (Spent Fuel Storage, TRAnsportation and Cost Evaluation System) was discussed. SFTRACE is mainly based on the 2nd methodology while taking the 1st microscopic accounting aspect fully into account. The illustrative simulation runs revealed various trade-off relations, such as the one between storage capacity to be installed and transportation requirements, the other among geographic coverage of AFR storage facilities as to whether to construct one to serve all over Japan or several to serve segmented regions. These trade-offs clearly demonstrate the necessity and usefulness of integrated analytic tools such as SFTRACE.

Chapter 6 discussed the framework of economic analyses of spent nuclear fuel storage. Based on the methodological review of the following three categories, numerical applications are presented for each of them; 1) an engineering-economic cost calculation to assess levelized unit costs, 2) a total cost assessment with strategic planning, and 3) a project financing appraisal and storage price induction. Based on latest sets of data and information, the levelized unit storage costs lay in a reasonable range of 30-70 kJPY/kgU, which corresponds to 0.07-0.17 JPY/kWh at burnup of 49,000MWd/tU with no discounting applied between power generation and storage. With the strategic planning application, several key parameters were identified such as the geographic coverage of AFR centralized storage devices, economy of scale and others. Finally, the project financing appraisal method was applied to explore viable storage pricing schemes which maintain the project of 5,000MTU metal cask storage facility as healthy enough against financial criteria. Because of the highly investment intensive nature of the project, a combinatory pricing scheme of storage service is highly recommended with an initial payment upon receipt of spent nuclear fuel at the storage facility and annual fee payments per unit of spent nuclear fuel stored for each year of storage duration.

7.2. Policy Recommendations for Spent Nuclear Fuel Management in Japan.

As the conclusion of the analyses described in these Chapters, policy recommendations for planning and implementation of spent nuclear fuel management in Japan are given as follows.

The demand of spent nuclear fuel storage will increase steadily and rapidly, to reach 7,000-10,000MTU by the year 2020 to 2030. In 2050, uncertainties surrounding spent nuclear fuel management will also accumulate. In a most likely scenario, the storage demand will level off at around 10,000MTU after 2020-30 to 2050, which suggests storage capacity of 10,000MTU must be installed by the year 2020. As concerns to the storage duration as well as the long-term planning of spent nuclear fuel management, unless utility values of Pu uses will improve significantly, processes after storage should be planned with reference of lifetime expiration of the storage facility.

7.3. Future Issues and Extensions.

Since the study yet remains at an intermediate stage, further efforts to extend and yield many more results are needed. Among all, spent nuclear fuel management simulation (Chapter 5, especially SFTRACE) and economic analyses are just standing at completion of analytic tools. Combining realistic data sets with those models and frameworks, the author wishes to produce practical suggestions and recommendations to Japan's policy planning for nuclear energy utilization in harmony with its fuel cycle. Concerning the economic analysis, the author wishes to contribute the ongoing IAEA collaborative research venture on "Economics of Spent Fuel Storage," which intends to revise the past document, IAEA (1994). The contents of this dissertation will benefit the revised version to come.

At the same time, the author looks at other areas of nuclear fuel cycle back end, especially final disposal of high-level radioactive wastes (HLW). Besides scientific and technical basis of geological disposal, there are found lots of social problems that would hinder progresses in the area. This is caused by multiple reasons, including lack of understanding and knowledge about the issue itself among the general public, as well as insufficient efforts for public involvement and risk communication, and in turn might result in standstill of final disposal and, ultimately, stalemate of the overall nuclear energy utilization.

The author has already started some attempts to explore this new research area, examining the implementation processes in European counties including Finland and Sweden, and produced some preliminary results in the field including Nagano and Tanabe (2002), Nagano (2002) and Nagano (2003). He wishes to pursue this line further as his highest priority in the near-term, and ultimately to combine all the insights obtained from both HLW disposal study and this spent nuclear fuel management study to generate overall strategic analysis for Japan's fuel cycle back-end systems, as currently being employed in France under the 1991 Nuclear Waste Law (for more details of French strategy based on the information as of late 1990s, see Nagano (1999).)

Through these efforts, the author wishes to contribute to better formulate and implement Japan's nuclear energy and fuel cycle strategies.

REFERENCES FOR CHAPTER 7:

IAEA (1994) "*Cost Analysis Methodology of Spent nuclear fuel Storage,*" Technical Reports Series No.361, International Atomic Energy Agency, Vienna.

Nagano, K. (1999) "*On the Fuel Cycle Back-end Policy in France -1991 Waste Law and Recent Developments-,*" Research Report No.Y98011, Central Research Institute of Electric Power Industry, Tokyo. (in Japanese)

Nagano, K. and T. Tanabe (2002) "*Retrievability Concepts on Geological Disposal of Radioactive Wastes,*" Research Report No.Y02001, Central Research Institute of Electric Power Industry, Tokyo. (in Japanese)

Nagano, K. (2002) "High Level Radioactive Waste Management Policies and Reflections of Citizens' Opinions in Selected European Countries," *Denryoku-keizai Kenkyuu (Economics and Public Utilities)* No.48, pp.1-13, Central Research Institute of Electric Power Industry, Tokyo. (in Japanese)

Nagano, K. (2003) "Processes for Consensus Building and Role Sharing –Lessens Learned from HLW Policies in European Countries-," *J. Nucl. Fuel Cycle and Environment,* **9** [2], Atomic Energy Society of Japan. (in Japanese, to be published)

ACKNOWLEDGEMENT

ACKNOWLEDGEMENT

Some of the works described in this dissertation, namely Chapters 3 and 4, have come out of "Demonstration Tests of Concrete Modular Storage Technologies" at CRIEPI (Central Research Institute of Electric Power Industry) sponsored by Nuclear and Industrial Safety Agency, Ministry of Economy, Trade and Industry, the Japanese Government. While the author extends his utmost gratitude for this support, it should be understood that all the views and implications expressed in this dissertation are the author's own. All possible errors and mistakes are of the author's sole responsibility.

POSTSCRIPT

"*Rome was not built in a day.*"

Looking back the way I came to be as I am, I really recall not just about what I have done by myself but far more about invaluable helps and supports from my mentors, friends, colleagues, and family members and relatives.

Prof. Atsuyuki Suzuki has never saved his kind support to me by offering words of guidance, scolding and encouragements, besides numerous advices on research direction and substances. I cannot imagine what words could express my utmost gratitude to Prof. Suzuki. I would put it simply that I do feel proud of being the one among many other pupils of Prof. Suzuki.
Prof. Kenji Yamaji, formerly my boss at CRIEPI, guided me into the field of system analyses in energy and nuclear fuel cycle, namely optimization model development as well as spent nuclear fuel management analyses. All the ideas and thoughts in this dissertation originated from my initial research at CRIEPI under Prof. Yamaji's supervision. In short, all my achievements owe Prof. Yamaji's knowledgeable guidance and support.
Profs. Syuichi Iwata, Shin-ya Nagasaki and Syuichi Hasegawa kindly accepted the roles in the evaluation panel of this dissertation. Those comments raised upon the panel were stimulating, encouraging and essential to complete the dissertation. Indeed, this dissertation has never taken the shape as it is without their advices.
I graduated from the B.A. course at the Faculty of Nuclear Engineering, under supervision of Prof. Yasumasa Togou (now President of JNC, Japan Nuclear Cycle Development Institute) and Prof. Shunsuke Kondo. Especially, I do recall Prof. Kondo gave me all necessary fundamental instructions to be a researcher. In my 2 years as M.A. student, I owe many from Prof. Ryouhei Kiyose. Besides many other professors and lecturers, I would like to extend my utmost gratitude to them.

Throughout my professional research carrier at CRIEPI for 16 years, I feel no doubt that I have been extremely lucky to come across with number of acquaintances and friends. As I cannot imagine what words of thanks could truly deserve for their intimate and generous helps and supports, I would herewith just raise their names: Mr. & Mrs. Koichi Osada, Ms. Yuko Mori and other staffs of JKL Co. Ltd. Mr. Hideto Miyachika, Ms. Rieko Yasuoka and other staffs at SRC Co. Ltd. Mr. Eiji Yoshimura, Mr. Masahiro Teramura, Mr. Satoshi Sahara, Mr. Takanori Kagimoto, Mr. Mikihiko Yamamoto and

other staffs at Toyo Engineering Co. Ltd. Dr. Tadashi Aoyagi, Dr. Hiroo Ohkkubo, Mr. Kuniyuki Nishimura and other staffs at Mitsubishi Research Institute, Inc. Mr. Takao Ikeda, Mr. Kiyoshi Oyamada and other staffs at JGC Inc. Dr. Kazuaki Matsui, Mr. Shigenobu Hirusawa and other staffs at Institute of Applied Energy. I am absolutely sure that the professional engagement and cooperation with all of these colleagues will continue as fruitful as they have been.

Quite a few insights which constitute this thesis have been obtained through my participation in seminars and joint study ventures at IAEA (International Atomic Energy Agency). Among many other members and participants, I have pleasure to extend my special thanks to Dr. Jor-Shan Choi, who served as Scientific Secretary for the joint program "Factors Determining the Long-term Back-end of Nuclear Fuel Cycle Strategy," now at Lawrence Livermore National Laboratory, and Dr. Jae-Sol Lee, Scientific Secretary for the ongoing joint program "Economics of Spent Fuel Storage." While the former opened my eyes wide to the whole nuclear fuel cycle back-end perspective and gave the opportunities to obtain many new ideas, the latter helps me to better focus on the subject and also awards me opportunities to give presentations of the achievements described in this thesis. Besides those scientific inputs from the activities, I very much appreciate these two precursors for their personal kindnesses and friendship.

Needless to say, my utmost gratitude should go to my colleagues at CRIEPI, with names of just a few; Dr. Taketoshi Taniguchi, Dr. Tatsujiro Suzuki, Mr. Takashi Morikiyo, Mr. Tomoyuki Tanabe, Ms. Tomoko Tsuchiya, Dr. Hiromi Yamamoto, Mr. Taishi Sugiyama, Mr. Osamu Kimura, Dr. Toshiari Saegusa, Dr. Hayaichi Yokoyama and Mr. Satoshi Fukuda. Among others, I would like to extend my special thanks to Mr. Susmu Yoda, former President of CRIEPI.

I wish to express my heartfelt regards to past and current officers and staff members of IIASA (International Institute for Applied Systems Analysis), Laxenburg, Austria, which I was affiliated as guest scholar during October 1990-January 1992 and as Secretary to The Japan Committee for IIASA, its Japanese national member organization. When I went to Austria, I was quite premature as both professional researcher and human being. Indeed, the training given to me in every sense through association with IIASA induced me to write this dissertation in English. Just to raise a few names that come up across in my mind; Prof. Yuri Sinyak, Dr. Nebojša Nakićenović, Dr. Arnulf Grübler, Dr. Leo Schrattenholzer, Dr. Ger Klaassen, late Prof. Gordon J. MacDonald, Dr. Peter E. de

Janosi, Mr. Marc Clark, Dr. Atsushi Inaba, Prof. Motoyasu Nagata, and Prof. Kenji Sugimoto.
And among all, very special thanks should be extended to Prof. Yoichi Kaya, Professor Emeritus of Univ. of Tokyo and Director-General of RITE (Research Institute of Innovative Technologies for the Earth). The intimate acquaintance to Prof. Kaya, then Council Member to IIASA representing Japan, was realized when I was at IIASA. He opened up my eyes toward numerous directions and ways, especially in traveling in Europe besides research on energy.

"*If I wasn't hard, I wouldn't be alive. If I couldn't ever be gentle, I wouldn't deserve to be alive.*"

- Raymond Chandler "*Playback*" (1958).

To family members. Having grown up as healthy and solid naturally owes to my mother, Kino Nagano. Thanks to my brother Masahiko and his family, Sayuri, Miho and Maya. Gratitude to Isamu and Hisako Yoshino, my parents-in-law, as well as Carl and Mikiko Denieul, brothers-in-law.

And finally, but atop of all; to Yuriko, my beloved partner for life.

November 2002
Koji Nagano

長野浩司