AN ECONOMIC ANALYSIS OF SPENT FUEL MANAGEMENT AND STORAGE

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ABSTRACT

Spent fuel management is becoming a key issue not only in the countries that have already experienced years of nuclear operation but also in the Asian countries that started nuclear utilization rather lately. This paper summarizes the key aspects that essentially determine optimal conditions for desired spent fuel management strategies from the engineering-economic point of view, in both national and regional perspectives. The term 'desired' is intended to highlight positive and beneficial aspects of such strategies, namely mobile and timely exploitation of spent fuel storage. Among all, the economy of scale, the economy of scope, the learning-by-doing effect, and benefits of R&D are reviewed theoretically and empirically, and the paper overviews to what extent these factors are implemented in solving spent fuel management strategy optimization problem.

1. FOREWORD

According to global energy projections published by authorized international institutions such as World Energy Council (WEC and IIASA. 1995), there are large expectation for nuclear energy as a key contributor to the global energy supply towards future, i.e. up to the middle of the next century. This is especially true for Asian countries which are expected to continue high growth of energy demand whereas not necessarily rich in natural resource endowment. However, if they follow such rapid expansion of nuclear exploitation, they may be at a time in the future forced to shift to an energy system based on 'plutonium (Pu) economy' with fast breeder reactor (FBR) technology to play the central role, or otherwise face supply shortage, temporary or persistent, of natural uranium. If Asian countries do not go towards Pu recycle, spent fuel management will become even more serious a problem as more discharged spent fuel will remain as to be managed.

Spent fuel management for Asian countries is, moreover, not a future problem but already becoming a key issue even now. Needless to say, the countries that have already experienced years of nuclear operation are all facing various difficulties with spent fuel management, either difficulty of siting final repository or of reprocessing. Japan is an obvious example with quite a few power stations that are facing already at risks of overflow of reactor pools. Even the Asian countries that started nuclear utilization more recently , such as Taipei, China, are about to face such risks, and this sort of risk will spread out to other Asian countries sooner or later.

This paper is intended to formulate an analytic framework of optimal spent fuel management, with a special emphasis on factors and their trade-off relations influencing choices of spent fuel storage.

2. THE ROLE OF SPENT FUEL STORAGE

One might eventually regard spent fuel storage with a negative perception as a postponement of decision or transfer of responsibility to future generations. In this paper, the author wishes to emphasize the positive aspects of spent fuel storage, which should be recognized more clearly and explicitly in order to develop desired future strategies.

There are three roles of importance in storage. Firstly, it has a function of emergency management. If an excess amount of spent fuel is generated beyond the capacity of storage pool co-located with power reactors, some additional storage devices are required to secure continuation of operation of the power reactors under such risks. Secondly, storage is necessary to manage spent fuel as running stock and feed to reprocessing facilities. This not only secures smooth operation of the reprocessing plant but also helps in flexibly balancing supply and demand of plutonium, which is the function specified clearly in Japan's current fuel cycle policy as 'energy resource stockpile' (Atomic Energy Commission of Japan. 1994.) Finally, and even more importantly, the author puts an emphasis on the third role. While storing spent fuels and wastes properly, one could take time for technology R&D of treatment and processing after storage, or further refinement of future strategy to incorporate more advanced technologies. The cost incurred for the storage would well be paid back by the revenue and benefit to be obtained from those technology improvements in the subsequent processes. This means, after all, that storage would be an opportunity to yield profit in the overall strategy, and also helps better to maintain flexibility and compatibility with socio-economic circumstances surrounding nuclear development.

Spent fuel storage is not a process that can not be helped in order to avoid temporal overflow of spent fuel stockpile, but rather should be recognized as an appropriate way to choose in conjunction with promotion of research and development.

3. THE ECONOMICS OF STORAGE: THE ECONOMIES OF SCALE AND SCOPE, THE LEARNING EFFECT AND R&D BENEFITS

Theoretically, there are four factors that predetermine optimal conditions on how, where, when and for how long time storage devices are to be installed.

3.1 The Economy of Scale

This widely-known phenomenon is defined as the larger the capacity of a certain process, the lower the unit cost of production, as in the following formulas:

$$\frac{TC(p)}{TC_0} = \left(\frac{p}{p_0}\right)^{\gamma} \qquad \text{..........(1)}$$

$$\frac{UC(p)}{UC_0} = \frac{\frac{TC(p)}{p}}{\frac{TC_0}{p_0}} = \left(\frac{p}{p_0}\right)^{\gamma-1} \qquad \text{..........(2)}$$

where,

$TC(p)$: Total cost of production at the capacity p,
TC_0 : Total cost of production at the reference capacity p_0,
γ : Scale exponent ($0 \leq \gamma \leq 1$),
$UC(p)$: Unit cost of production at the capacity p,
UC_0 : Unit cost of production at the reference capacity p_0.

The smaller the value of γ, the more evident the scale merit and the smaller the unit cost of production. If the capacity is proportional to the volume (i.e. l to the third, where l is a representative length) and the total cost is proportional to the area (i.e. l to the second), then the scale exponent equals to 2/3=0.67. This is particularly true where a scale-up can be done simply by expanding the size and capacity of machinery equipment.

In the field of nuclear power generation, the scale exponent experienced in the power plants constructed in the United States is evaluated as 0.7 (Mooz, 1978.) or not identifiable (Mooz, 1979.) Another example is found in the small and medium reactor study conducted by IAEA (IAEA, 1984.) It concluded that the scale exponent is in the range of 0.4-0.5 with the lower number applied to the smaller capacity, i.e. in the range of 200-400 MWe. These imply that although statistical credibility is low, we could, to some extent at least, believe in this phenomenon in the case of nuclear power plants.

In the case of spent fuel storage, an IAEA study generated through a worldwide survey a diagram that shows how the unit storage cost declines as capacity expands for various storage technology options (IAEA. 1990.) Although it is difficult to figure out specific number of γ, superiority of water pool and vault storage for AFR (away from reactor) storage at large capacity (i.e. 3,000 MTHM (metric ton of heavy metal) and more) can be seen clearly. Dry cask storage shows no significant scale merit when capacity becomes 1,000 MTHM and larger. Another example of diagram reported for the United States (Anderson. 1995) shows us a large potential of scale economy for vault storage in the capacity range of 200-1,000 MTHM, as γ even smaller than the '2/3 power theorem'.

In the Japanese situation, a sensitivity analysis shows about the storage cost of water pool storage, dry cask storage and vault storage along with the storage capacity from 1,000 to 5,000 MTHM, as values at 0.802 for water pool, 0.874 for dry cask and 0.823 for vault (Yamaji et al., 1987.) In another assessment, in the range of 3,000-10,000 MTHM, we can see γ at around 0.7 for water pool, 0.8-0.9 for dry cask and vault (Nagano et al., 1990.) Although these individual examples are not explanatory enough to prove any rule, it is implied that scale economy is expected in the case of water pool storage to a larger extent than for dry cask storage. Furthermore, the scale economy of spent fuel storage is more evident in a smaller range of storage capacity, e.g. 500-1,000 MTHM.

3.2 The Economy of Scope

This is considered as efficiency improvement and cost reduction through enhanced coordination and collaboration among different production processes. Such benefit is obtained from, for example, shared use of common resources and equipment.

In the field of spent fuel management, the economy of scope has its importance in strategic planning of whether individual storage devices are installed to each power plants or collective storage facilities in rather small number of places. In this case, the above mentioned scale economy should also be paid attention to. Moreover, it should not be overlooked that the burden of transportation of spent fuel would differ substantially between these cases.

An example of the economy of scope in the other sense can be found in Gorleben, Germany, where a pilot plant for spent fuel conditioning is now under construction. This facility will be used not only for testing and demonstration of the spent fuel conditioning technique, i.e. rod consolidation, but also a repair facility for deficient dry casks received in the adjacent cask storage facility, which does not have a hot cell of its own. Another example worth mentioning here is in Wuerenlingen, Switzerland, where ZWILAG, an extensive waste storage facility, is under construction. As this facility will store all kinds of radioactive wastes generated in all over Switzerland, some of the facilities and resources would be possibly used commonly for various purposes and types of wastes.

The economy of scope would be even more pronounced in considering regional or international collaboration, not only actual operation of nuclear fuel cycle but also research and development of technology options, with respect to appropriate sharing of burdens, skills and resources, and fruits of such activities.

3.3 The Learning Effect

This famous phenomenon is expressed in the following formulas:

$$C(n) = C_0 \cdot d \cdot \left(\frac{n}{2}\right)^{-b} = C_0 \cdot n^{-b} \qquad \text{(3)}$$

$$\delta = 2^{-\beta} \qquad \text{(4)}$$

where,

- $C(n)$: Production cost of the n-th unit of product,
- C_0 : Initial production cost,
- β : Learning coefficient ($0 \leq \beta$),
- δ : Learning factor ($0 \leq \delta \leq 1$).

The learning factor δ is the rate of cost improvement at each time when the cumulative number of production doubles. The learning effect was found in many industrial production processes such as automobile manufacture. One can easily imagine that this effect is more evident in such production process where a large number of standardized products or operations are repeated. In the field of nuclear energy, the learning coefficient in the United States was evaluated as -80.92 US$(1978)/kWe (Mooz. 1978), which is understood that each time when the cumulative number of reactor unit becomes 2.72 times, the unit cost of construction becomes 80.92 US$(1978)/kWe lower. In the subsequent round of evaluation, the number was even larger as -96.23 (Mooz, 1979.)

For spent fuel storage, there are little data available for now on to what extent we could expect from this learning-by-doing effect. It could be mentioned that we have observed a significant decline of price of storage casks. In a 1987 study (Yamaji et al., 1987), the price for a cask was reported as more than 300 million JPY(1987), but experts say that we have captured technology improvement during these years and now the price could be well 20-30% lower than this. Note that this would be resulted from either technological progress of cask manufacture or simply enlarged competition in the real market. These are both considered, after all, as fruits of learning-by-doing effect in a broad sense. Moreover, as there are yet few commercial spent fuel storage facilities in Asia, further improvement forged by more competition will be very likely as the market grows.

This learning effect is also an important factor to determine whether standardized unit storage devices are installed sequentially according as demand increases or a large capacity is installed at the beginning at one time. In this case, a trade-off with the economy of scale becomes an issue that needs to be carefully examined.

3.4 Benefit from Research and Development

As discussed in Chapter 2, storage has an important role to secure time for research and development. The following is an attempt of mathematical formulation to capture cost-benefit relations of storage and R&D in the strategic analysis of spent fuel management (Nagano, 1997, Nagano, 1998.)

Suppose that a unit (1 tonne) of spent fuel is discharged from a reactor plant, which is to be stored until it will be reprocessed or disposed. From the reprocessing, corresponding amount of Pu will be recovered, which will then be fabricated as mixed oxide (MOX) fuel and reloaded to the reactor or another. The problem to be addressed here is to optimize the duration of storage to maximize total utility function, i.e.;

$$TU = -f_1(x) - e^{-rx} \cdot f_r \cdot (1-i_r)^x - e^{-rx} \cdot f_2(y) \cdot (1-i_2)^x - e^{-r(x+y)} \cdot f_m \cdot (1-i_m)^{(x+y)} - e^{-r(x+y)} \cdot f_3(z) \cdot (1-i_3)^{(x+y)} + e^{-rT} \cdot U \rightarrow \max. \quad (5)$$

$$s.t. \quad T = x + y + z \quad \text{......} (6)$$

where,

- TU : Total utility at net present value at the year of the spent fuel discharge,
- $f_1(x)$: Cost of spent fuel storage for x years,
- f_r : Cost of reprocessing,
- i_r : Rate of reprocessing cost reduction due to 1 year addition of R&D,
- $f(y)$: Cost of storage of the corresponding amount of Pu for y years,
- i_2 : Rate of Pu storage cost reduction due to 1 year addition of R&D,
- f_m : Cost of MOX fuel fabrication with the corresponding amount of Pu,
- i_m : Rate of MOX fabrication cost reduction due to 1 year addition of R&D,
- $f_3(z)$: Cost of storage of the corresponding amount of MOX fuel for z years,
- i_3 : Rate of MOX fuel storage cost reduction due to 1 year addition of R&D,
- U : Utility obtained from the MOX fuel burning at T years from the discharge of the original spent fuel,
- r : Discount rate.

At this moment, the utility of Pu burning (either by FBR or light water reactor (LWR)) is not very clear, as implied by major countries' withdrawal from FBR development. If U is assumed as zero for simplification, then the original utility maximization problem turns to the total cost minimization. For another simplification, let various improvement rates i_x equal to i uniformly. Then, the formula (5) turns to formula (7).

$$TU = -f_1(x) - e^{-(r+i)x} \cdot f_r - e^{-(r+i)x} \cdot f_2(y) - e^{-(r+i)(x+y)} \cdot f_m - e^{-(r+i)(x+y)} \cdot f_3(z) + e^{-rT} \cdot U \rightarrow \max. \quad \text{......} (7)$$

The assumption of uniform rate of technology improvement is translated as increase of discount rate from r to $(r+i)$ superficially. However, the nature of technology improvement is not merely a function of time spent for R&D but indeed also influenced by the experiences accumulated throughout research, development and commercialization. This is one of the largest issue, among all in this report, that needs further refinement. Now to solve to problem, the *laglange* coefficient is introduced.

$$I = TU - \lambda(T - x - y - z) \quad \text{......} (8)$$

Then, the following 4 necessary conditions for optimality are derived:

$$\frac{\partial I}{\partial x} = -f_1'(x) + (r+i)e^{-(r+i)x} \cdot f_r + (r+i)e^{-(r+i)x} \cdot f_2(y)$$
$$+ (r+i)e^{-(r+i)(x+y)} \cdot f_m + (r+i)e^{-(r+i)(x+y)} \cdot f_3(z) + \lambda = 0 \quad \text{.............(9)}$$

$$\frac{\partial I}{\partial y} = -e^{-(r+i)x} \cdot f_2'(y) + (r+i)e^{-(r+i)(x+y)} \cdot f_m$$
$$+ (r+i)e^{-(r+i)(x+y)} \cdot f_3(z) + \lambda = 0 \quad \text{...........................(10)}$$

$$\frac{\partial I}{\partial z} = -e^{-(r+i)(x+y)} \cdot f_3'(z) + \lambda = 0 \quad \text{..................................(11)}$$

$$\frac{\partial I}{\partial T} = -r \cdot e^{-rT} \cdot U - \lambda = 0 \quad \text{...(12)}$$

Here, another assumption for simplification, $f_3(z)=0$, is introduced. This seems reasonable as fresh spent fuel, if once fabricated, should be used instantly. Then, from equation (11);

$$\lambda = 0 \quad \text{...(13)}$$

Thus, the first implication is derived from equations (12) and (13). If the utility function of Pu uses *U* is positive, then *I* is a uniformly declining function of *T* and thus *T*=0, which means that storage of spent fuel is not used and spent fuel should be reprocessed immediately. In turn, if *U* is negative, I is a uniformly augmenting function of *T*, which means that storage of spent fuel should be utilized as long as appropriate.

$$f_1'(x) = e^{-(r+i)x} \cdot f_2'(y) + (r+i)e^{-(r+i)x} \cdot (f_r + f_2(y)) \quad \text{..................(14)}$$

If one can assume that Pu storage is always too costly, then;

$$f_1'(x) = (r+i)e^{-(r+i)x} \cdot f_r \quad \text{...(15)}$$

The equations (14) or (15) is the fundamental form of condition to determine the optimal duration of each of the storage options, which makes the following two equal:

- the increase of cost of storage due to 1 year prolongation of storage duration, and
- the decrease of the net present value of total cost of all processes after the storage due to a 1-year delay caused by prolonged storage.

The latter factor consists of a change of net present value due to 1-year discounting and improvement resulted from R&D efforts taken during the storage duration. Note that the improvement in this notation should be defined in a broad sense, so that reductions of institutional and transaction costs, such as improved public awareness and acceptance, more efficient and appropriate planning into the future, should be recognized as parts of those technology improvement. Also note that the above formulation does apply also for the case of direct disposal, simply replacing suffix *r* for reprocessing with *d* for disposal.

Based on the published cost data (OECD/NEA. 1991 and 1994.), the author tried to solve the original problem numerically. The result is shown in Figure 1. If discount rate *r* (added with the uniform rate of technology improvement *i*) equals to zero, there is no reason to postpone, and the optimal strategy is to skip storage and go immediately to the next step, either reprocessing or disposal. In the cases of positive discount rate and technology improvement, an optimal storage duration could be obtained that minimizes the total system cost. It should be noted that this characteristic is highly dependent to the functional form how storage duration influences to the storage cost.

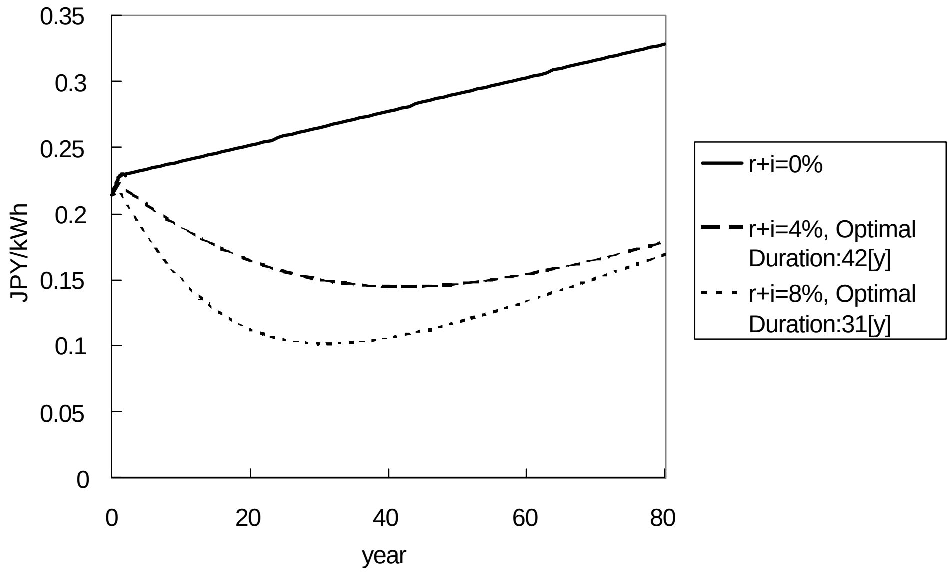

Figure 1: The optimal storage duration based on the problem definition of (FORMULA 5, 6) and cost data from OECD/NEA (OECD/NEA. 1991, 1994.)

4. CONCLUDING REMARKS

This report summarizes the author's attempt to develop a methodological framework for optimal strategy planning of spent fuel management. The key component is the dynamic trade-off relations among the economy of scale, the economy of scope, the learning by doing effect and R&D benefits. In other words, optimization of how large, where, when and how long spent fuel storage should be implemented and utilized is the heart of the issue. The author readily admits that both data collection and development of analytic tools are now at preliminary stages only, and further efforts need to be undertaken. Along with the methodology development and numerical simulations, actual and realistic ways of consensus building and negotiation for strategies of national and regional scales should also be focused and explored, as the author plans to address in the future.

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