COMMERCIAL NUCLEAR WASTE MANAGEMENT--COST AS A FUNCTION OF STRATEGY

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ABSTRACT

Design parameters and operating conditions are rapidly being set for components of the nuclear waste management system. An opportunity exists to perform system economic optimization studies that could provide insight into the functional relationships among system parts, design decisions, and alternate technologies. The interrelationships among these components are complex, and the results of optimization studies are sensitive to specific assumptions, plant designs, and the particular data base used. Certain conclusions can, however, be reached that are relatively independent of uncertainties, and limits can be placed on others to bracket the uncertainties. Several options and alternatives are open to waste management planners, and the value of the optimization study is to identify which combination leads to minimum cost without compromising licensibility, health, and safety. This paper discusses an economic comparison of various alternatives and options and combinations thereof, with the intent of identifying limits in the cost base that lead to a break-even situation among selected alternatives and options. If the repository is to be designed to accept optimized canisters, the consolidation option is favored if consolidation and collection costs are less than $30/kg U, assuming consolidation occurs at the reactor site. If consolidation occurs at the repository, consolidation is favored if consolidation and collection costs are less than $14/kg U. Consolidation costs in the literature vary from $20 to $25/kg U. For the conditions specified and the data used in the calculation, the choice of whether to consolidate or not depends upon where consolidation occurs. Similarly, for the disposal of high-level waste from reprocessing, the ceramic waste form is economically attractive if the cost of immobilizing the waste is less than $33/kg U, as compared with the current estimate of $22/kg U. This is referenced to a glass waste immobilization cost of $22/kg U.

The monitored retrievable storage facility is a critical component of the optimized waste management system if its cost is less than approximately $100/kg U. If the cost exceeds this value, little can be gained by aging waste. Recent literature reports costs ranging from $25 to $200/kg U; therefore, a better data base is needed before the decision is made not to age waste.

The cost of disposal of high-level nuclear waste is more expensive than the disposal of spent fuel. This is related to the high cost of transuranic waste disposal and the requirement to collect and store radioactive krypton.

For the disposal of high-level nuclear waste, ceramic technology is less costly than glass technology if the cost of waste immobilization in ceramic is up to 50% greater than assumed in our study.

Also reported is a study of the back-end of the fast breeder reactor (FBR) fuel cycle. A key finding of our study is that, when expressed as a cost per unit electrical generation, waste disposal cost for the FBR fuel cycle is approximately one-third that for the light water reactor (LWR) fuel cycle.

INTRODUCTION

This is the fourth in a series of papers on the economics of commercial nuclear waste management. In the first paper,[1] we developed the methodology to perform a systems analysis of a waste management system incorporating a variety of system alternatives and options. The model assumes a steady-state power economy based on light water reactors (LWRs). In our second paper,[2] we demonstrated that an economic optimum (minimum cost solution) exists in commercial nuclear waste management systems based on the concept that the equations describing nuclear waste management are over specified, and the maximum allowable canister diameter is a system-dependent parameter, constrained by a combination of the thermal limits of the monitored retrievable storage (MRS) facility and repository. This maximum allowable canister diameter is achieved by aging the spent fuel element (SFE) waste or high-level nuclear waste (HLW) in an MRS. Our third paper[3] presented a sensitivity analysis of this economic optimum solution. In the present paper, we give the economic conditions that bound the selection of alternatives and options for the back-end of both the LWR and FBR fuel cycles. Costs are presented in constant 1982 dollars. Further, we assume waste is emplaced in a basalt repository, similar to that being developed by Rockwell Hanford.[4] Since the issuance of Ref. 4, changes have occurred in the design of the reference waste packages for this repository. These changes include elimination of the buffer from the SFE waste package, imposition of a centerline temperature limit on the SFE waste package, and a change in the outside diameter of the overpack for the HLW waste package. This paper does not treat these changes. The net impact of these changes on the conclusions in this paper should not be large; however, they have not been evaluated.

During our work we have tried to both benchmark our model and data base and validate our findings where possible. Consensus has been found in the methodology, though differences in the data base have lead to different conclusions.

ALTERNATIVES AND OPTIONS IN THE BACK-END OF THE FUEL CYCLE

Options and alternatives open to waste management policy makers for fuel from LWRs are shown in Fig. 1a. One of the assumptions inherent in this study is that all waste forms assumed here (spent fuel, glass, and ceramic) meet licensing requirements and therefore cost comparisons are for the same effectiveness criteria. Spent fuel discharged from the reactor may be shipped after some minimal cooling period directly to the repository for overpacking and emplacement or be consolidated before overpacking and emplacement. An option exists to age the spent fuel after consolidation. Aging the fuel before consolidation is not considered by us a viable option. We believe that if an MRS facility is to be built, then the economic approach would be to consolidate the fuel prior to storage, reducing the cost of the storage facility. No economic incentive exits to store unconsolidated fuel in an MRS, ship the unconsolidated fuel to a repository, and then perform consolidation at the repository.

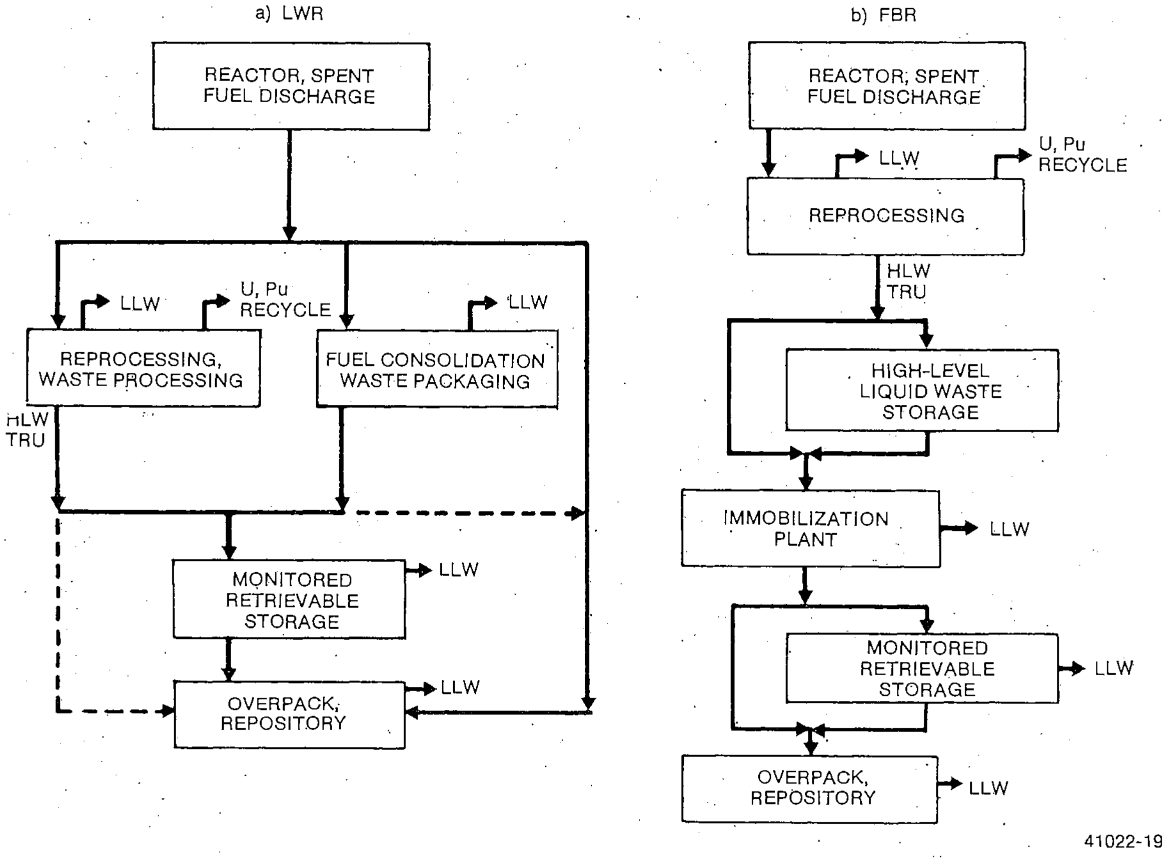
In the reprocessing alternative for LWRs, the immobilized waste may be shipped directly to the repository for overpacking and emplacement or be aged in an MRS prior to overpacking and emplacement. Since the SFE alternative is less expensive than the reprocessing alternative when the value of recoverable materials is excluded,[2,5] the incentive for reprocessing is the recovery of valuable materials from the spent fuel. Therefore, aging the fuel before reprocessing is not considered a viable option for a steady-state waste management cycle, such as we are considering here. The storage of high-level liquid waste (HLLW) is not considered a viable option because the economics of the LWR fuel cycle do not depend on a rapid turnaround of valuable fuel materials. Delayed reprocessing offers economies in the reprocessing plant that in general offset inventory charges for the material being stored.

The alternatives and options open to waste management planners for the back-end of the FBR fuel cycle (Fig. 1b) are similar to those for the back-end of the LWR fuel cycle, except the disposal of SFE is not a viable alternative (fuel reprocessing and recycle of fissionable material to the reactor is an inherent part of the FBR fuel cycle; the economics of the FBR fuel cycle are strongly dependent on the rapid turnaround of fissionable material in the spent fuel). For the FBR waste system, we have included the option of storing HLLW from the reprocessing plant.

DESCRIPTION OF ANALYTIC APPROACH

Key system components of the back-end of the nuclear fuel cycle, excluding fuel conversion, fabrication, and recycle to the reactor, are integrated to construct an overall waste management system. The condition that is optimized is cost and not schedule. It is recognized that schedule is a part of any optimization process for a non-steady-state environment; but the study here assumed steady-state conditions exist. Selecting from among various alternatives and options and using technologies different from those now considered may lead to optimization in terms of costs but not necessarily in terms of schedule.

A systems approach is used in the analysis of waste management costs. In this approach, all of the


a) LWR

b) FBR

Fig. 1. Flowsheet of waste disposal alternatives.

alternatives and options are identified that are considered viable. The operating parameters are analyzed for each component of the system, and the independent system parameters are identified. A series of generalized engineering and economic algorithms is developed for each component of the system, and these algorithms are linked to provide a multidimensional solution of the form:

$$\text{Cost} = f(\%, A_R, A_I, A_E, T_{CL}, T_C,$$

$$T_{BF}, h_{MRS}, \ldots), \text{ or}$$

cost is a function of such variables as waste fraction (%), age at reprocessing (A_R), age at immobilization (A_I), age at emplacement (A_E), waste form centerline temperature limit (T_{CL}), canister temperature limit (T_C), backfill temperature limit (T_{BF}), heat transfer coefficient in the MRS (h_{MRS}), and so forth. One of the important findings from this portion of the study is that the problem is over specified: there are n variables and n+1 equations. Variables that relate to design requirements set by considerations outside of waste management, such as temperature limits and heat transfer coefficients, should be considered as independent variables. One of the two remaining variables, canister diameter and waste form loading, should be considered as an independent variable and the other as a dependent variable. Both our work and the work of McKee have shown that minimum cost is achieved when the maximum waste loading permitted by the immobilization process is used. Therefore, for this study, we assume the dependent variable is canister diameter as calculated by the controlling equations. This is the maximum canister diameter to meet the conditions specified for a particular case. Arbitrarily setting this parameter to some smaller value leads to nonoptimum (more costly) economics but one that is permitted by the system of equations.

Solutions are then obtained by analyzing the functional relationships among system parameters. In the analysis of a multidimensional problem such as this, absolute values are of lesser interest than the slopes of the cost solution at the intersections of planes (or surfaces) or the existence of extrema (minima in our case). The general observations relative to the properties of the solutions include:

- It is less expensive to dispose of spent fuel than reprocessing wastes, whether or not reprocessing costs are included. This is mainly driven by the cost of disposal of TRU and krypton waste from reprocessing.
- Waste volume reduction is one of the keys to reduced waste management costs. Another key is emplacement of the maximum size waste package allowed from system considerations.
- Aging HLW or SFE before emplacement in a geological repository can lead to significantly reduced nuclear fuel waste management costs. The thermal requirements of the repository are met by this aging.
- An economic optimum exists in nuclear waste management based on aging waste in an MRS.
- For this economic optimum, waste management costs are relatively insensitive to the:
    - Emplacement mode in the repository (immediate or delayed backfill)
    - Temperature limits of the engineered barriers in the repository
    - Waste loading above approximately 50 wt. %
    - Age of the waste at immobilization for wastes cooled more than approximately 15 yr (not including storage fees for the first 15 yr).
- For this economic optimum, waste management costs are relatively sensitive to the:
    - Centerline temperature limit for the waste form
    - Waste loading below approximately 30 wt. %
    - Age of the waste at immobilization for waste cooled less than approximately 6 yr (not including storage fees for the first 6 yr)
    - Design of the waste canister.
- To achieve optimum economics, the thermal limits of the MRS set the waste form conditions of diameter and waste loading.

Figure 2 shows schematically the generalized solution with age of emplacement. In the left portion of this curve, the repository controls (i.e., the thermal limitations of the repository establish the maximum allowable diameter for the waste package). As the waste is aged before emplacement, the diameter of the waste package increases until it reaches the maximum diameter that could have been stored in the MRS, based on the thermal limits of the MRS and the age of the waste at the time of immobilization. The right portion of the curve relates to waste that has been aged in the MRS longer than is required to meet the repository limits; it is for a waste package diameter no larger than could be stored in the MRS at the time the waste was immobilized. The intersection of these two portions of the curve then is the economic optimum (minimum cost solution).

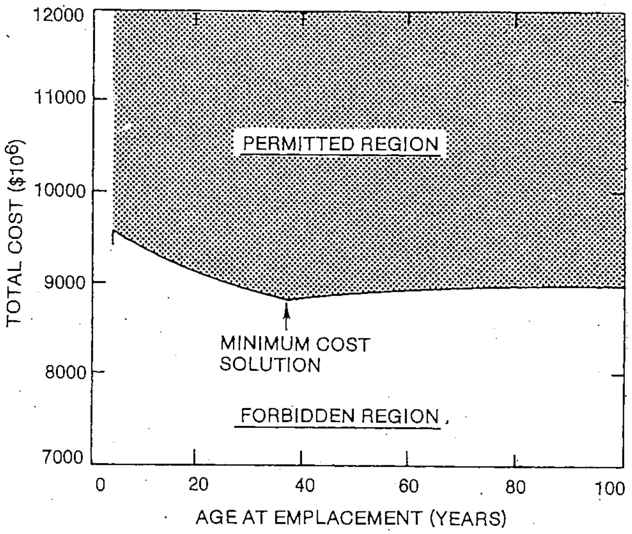


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Fig. 2. Generalized solution.

SPENT FUEL ALTERNATIVES AND OPTIONS, LWRs

One route available to waste planners is the disposal of spent fuel. Several design parameters exist that affect choices relating to the relative economics of a waste management system. Although all of these design parameters can be varied and an economic impact can be associated with each variation, two parameters are of particular interest: fuel consolidation and the use of an MRS to age fuel before emplacement.

Fuel Consolidation

Spent fuel as it is discharged from the reactor is a relatively low-density waste form. Removal of fuel pins from the fuel elements and close packing of the pins inside a canister (consolidation) offer the potential of cost savings for a waste management system based on the disposal of a compact spent fuel waste form. If spent fuel is to be consolidated, choices have to be made as to the location of consolidation (at the reactor site, at a central site or MRS if used, or at the repository). Savings in system economics through consolidation result from reduced transportation costs if consolidation occurs before shipment and from reduced repository costs because fewer waste packages have to be handled and emplaced. These savings may, however, be offset by the added cost of consolidation and by the cost of disposing of the fuel element skeletons, end pieces, and other generated radioactive waste (such as krypton released due to cladding failures during consolidation).

Table I breaks down cost for six cases of interest: two cases in which the ages of waste emplacement are 10 yr (reference emplacement time from Refs. 4, 6, and 7) and 5 yr (approximately the emplacement time for a steady-state power economy based on LWRs[8]). A subcase in each set is the optimum canister diameter for the emplacement of consolidated fuel [the same diameter as HLW canisters at 10 yr emplacement; e.g., 30 cm (12 in.)]. Another subcase in each set is the emplacement of unconsolidated fuel in the same diameter canister as for optimized consolidated fuel. The final subcase in each set is the emplacement of unconsolidated fuel in an optimized canister diameter. Because the SFE canisters from Ref. 6 assume that spent fuel is not an acceptable waste form, a 10-cm- (4-in.-) radius buffer is added so the release criterion after the containment period (from 10 CFR 60) can be met. A more recent document[7] that studied several SFE canister alternatives did not include the buffer in any of the canister designs. The waste canister designs assumed in our model for all waste forms are those described in Ref. 6. Elimination of the buffer will reduce repository costs reported in Table I for the optimum solutions by approximately a factor of two through the use of larger diameter canisters (the thermal limit on the buffer, 300°C, limits the maximum allowed emplacement diameter). For this analysis, it was assumed fuel is consolidated at the reactor site and that consolidation costs \$23/kg U (consolidation is reported[9,10] to cost from \$20 to \$25/kg U). No penalty was assumed at the repository for the processing of canisters of variable sizes.

In comparing options and alternates, it is not only necessary to determine whether or not overall costs compare favorably, but also to establish which components of cost both drive the economics and establish the sensitivity of the conclusion. In comparing the consolidation versus unconsolidation alternatives, equations of the following form apply:

$$C_u = P_u + T_u + S_u + R_u$$

$$C_c = P_c + T_c + S_c + R_c + K_c + T_c \quad ,$$

where C is overall system cost, P is packaging cost, T is transportation cost, S is storage cost (MRS), R is repository cost, K is krypton collection and storage cost, T is cost for disposal of TRU waste, the subscript u represents unconsolidated fuel, and the subscript c represents consolidated fuel.

The cost difference (Δ) between the alternatives can then be expressed as:

$$\Delta = (P_c - P_u) + (T_c + T_u) + (S_c - S_u)$$
$$+ (R_c - R_u) + K_c + T_c$$

If Δ is negative, the consolidation alternative is favored. If Δ is positive, the unconsolidated fuel alternative is favored. By adjusting one or more key parameters such that Δ is zero, a breakeven situation exists.

From Table I, such comparison can be made, as an example, for optimized canister diameter with fuel 10 yr old at emplacement. Then:

$$\begin{aligned}
P_c - P_u &= 40.68 - 24.42 = + 16.26 \\
T_c - T_u &= 14.93 - 26.60 = - 11.67 \\
S_c - S_u &= 0 \quad - 0 \quad = \quad 0 \\
R_c - R_u &= 59.03 - 71.02 = - 11.99 \\
K_c - K_u &= 23.81 - 0 \quad = \quad 23.81 \\
T_c - T_u &= 2.23 - 0 \quad = \quad \underline{2.23} \\
\Delta &= + 18.64
\end{aligned}$$

From this, it can be seen that: (1) for the costs as specified, disposal of unconsolidated fuel is the preferred alternative; (2) the cost savings associated with consolidation are related to transportation and repository components; (3) a decision that fuel assembly skeltons and end pieces need not be disposed of in a repository does not change the conclusion relative to the economic viability of the consolidation alternative, and (4) the decision to permit atmospheric venting of the krypton that may be released during the consolidation process alters the conclusion from this study. Since one of the components of the packaging cost is the cost of consolidation (assumed here to be \$23/kg U), a breakeven situation can be calculated for consolidation costs based on decisions on TRU waste disposal and krypton collection and storage. Further, since the term $T_c - T_u$ is relatively large compared with T_c and T_u, changes in future transportation costs significantly affect the choice of the economic alternative. The term $R_c - R_u$ is relatively small compared with R_c and R_u; therefore, future changes is repository costs will have a lower effect on the choice of alternative than transportation cost changes. The same type of analysis can, and should, be applied to choices for all alternatives and options.

Observations from Table I include:

- If a constant canister diameter is to be used in the repository for all wastes and consolidation is done at the reactor site, then fuel consolidation is the economically preferred alternative.
- If the repository canister handling system is sufficiently flexible to handle a variety of canister diameters, the unconsolidated fuel alternative is the economically preferred alternative. The cost of disposing of the transuranic waste (TRU) generated and the

TABLE I

COST COMPARISONS FOR SPENT FUEL CONSOLIDATION WITH NO MRS
($/kg U)

	10 yr Old at Emplacement			5 yr Old at Emplacement		
	Canister Diameter Optimized for Consolidated Spent Fuel	Unconsolidated Spent Fuel	Canister Diameter Optimized for Unconsolidated Spent Fuel	Canister Diameter Optimized for Consolidated Spent Fuel	Unconsolidated Spent Fuel	Canister Diameter Optimized for Unconsolidated Spent Fuel
Fuel	LWR	LWR	LWR	LWR	LWR	LWR
Form	SFE cons	SFE uncons	SFE uncons	SFE cons	SFE uncons	SFE uncons
Transportation mode	Rail	Rail	Rail	Rail	Rail	Rail
Diameter, in.	12.00	12.00	16.00	9.86	9.86	14.68
Age at packaging*	10.00	10.00	10.00	5.00	5.00	5.00
Age at emplacement	10.00	10.00	10.00	5.00	5.00	5.00
Can/cask	9.17	9.17	5.54	13.16	13.16	6.42
KW/cask	19.2	9.6	10.8	28.2	14.1	16.4
KW/can	2.094	1.047	1.947	2.142	1.071	2.553
Canister per hole	12	12	12	12	12	12
MTU per canister	1.797	0.898	1.671	1.166	0.583	1.390
Packaging - capital	3.53	5.34	5.20	3.61	5.47	5.24
Packaging - operating	27.53	5.50	5.43	27.58	5.56	5.45
Can costs	9.62	19.23	13.79	12.18	24.36	15.21
Chemical costs	0.67	1.33	0.90	0.89	1.77	1.01
Transportation costs	14.93	29.86	26.60	16.04	32.07	27.57
Repository - capital	21.18	42.35	25.36	30.77	61.54	29.45
Repository - operating	37.18	72.37	44.76	52.43	102.50	51.50
TRU waste disposal	2.23	0	0	2.23	0	0
Krypton collection and storage	23.81	0	0	23.81	0	0
Total	140.66	175.98	122.04	169.53	233.28	135.42

*Not including buffer. Add 8 in. to obtain diameter at emplacement.

cost of collecting and storing radioactive krypton potentially released during the consolidation process offset the cost savings of consolidation.

- If the repository canister handling system is sufficiently flexible to handle a variety of canister diameters and it is assumed that the cladding failure rate during consolidation is sufficiently low so that the krypton can be vented to the atmosphere, then consolidation is the preferred alternative as long as consolidation costs are less than approximately $30/kg U.

- Shipment of unconsolidated spent fuel to the repository, for consolidation at the repository, adds approximately $16/kg U to the consolidated spent fuel alternative. Therefore, for the case above, with the assumption that fuel consolidation occurs at the repository, consolidation is the preferred alternative as long as consolidation costs are less than approximately $14/kg U.

Spent Fuel Aging

One option open to the waste management planners is the aging of spent fuel in an MRS before emplacement in the repository. For the reference design used in our study, no temperature limit was imposed on the spent fuel. The thermal limit for this alternative is associated with the buffer (300°C). On this basis, the most economical waste package is the largest diameter package that can be emplaced [91 cm (36 in.) for our model]. Ref. 11 contains a fuel cladding temperature limit at emplacement of 380°C. If this limit were to be incorporated in our model, the cost curves would be slightly higher because of longer storage times to meet this thermal limit in the repository. The conclusions on aging would be unchanged.

Figure 3 shows the optimization calculations for the spent fuel alternative with aging. The cost includes krypton disposal costs and assumes the buffer is

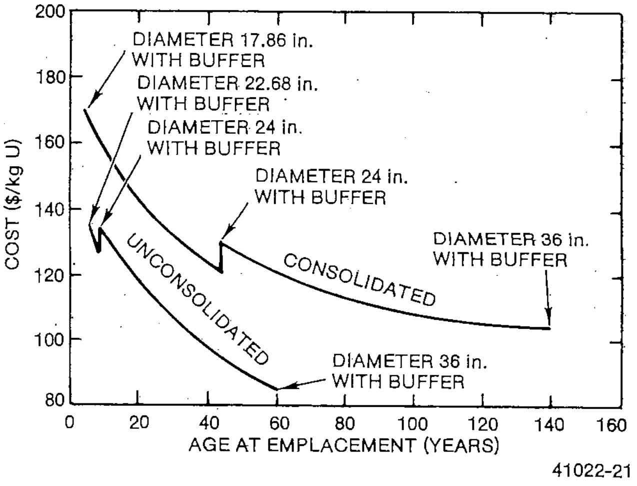

Fig. 3. Spent fuel disposal costs (includes storage of krypton).

added to the waste package at the repository. Because the model assumes that fuel is consolidated when it is received at the MRS, a constant krypton collection and storage charge is made ($23.81/kg U). No attempt has been made in the optimization procedure to include the time for krypton collection. From Fig. 3, based on the assumptions made, fuel consolidation is not cost effective. If, however, krypton can be released to the atmosphere and MRS storage times of 140 yr are acceptable, consolidation is the economic choice as long as consolidation costs are less than $28/kg U. For shorter storage times, consolidation becomes cost effective if the cost of consolidation is approximately $20/kg U or less and krypton does not have to be collected and stored.

The cost algorithm used in our model to develop MRS costs is an extension of the one developed by McDonnell for Savannah River Plant defense waste.[12] The model was extended by us to include variable waste package diameter and heat content. For the spent fuel alternative, packaging costs are also included in the model, independent of where the fuel is packaged. Typically, SFE packaging costs are $24 and $37/kg U for unconsolidated and consolidated fuel, respectively, including the cost of the storage canister, and MRS costs are approximately $10/kg U, depending on the particular storage conditions. The total MRS costs then, assuming packaging of the spent fuel at the MRS, would be approximately $34 and $47/kg U for unconsolidated and consolidated fuel, respectively, not including the cost of collecting and storing krypton.

The current literature has been searched for the cost of spent fuel storage. But because different bases were used in the references, the validity of the comparison is limited. Except when noted, the costs are reported as constant 1982 dollars, as used in our study, with no krypton collection and storage costs.

Johnson reports costs for 30,000 and 72,000 MTU MRSs required in the event of repository delays of 5 and 10 yr, respectively, of approximately $25/kg U.[13] This cost includes receiving, disassembly, canning, transfer, and field drywell storage of spent fuel. Refs. 9 and 10 report storage costs for spent fuel of approximately $50/kg U, including fuel consolidation. Dippold[14] reports storage costs for up to 100 yr of approximately $100/kg U. Reference 15 reports costs for passively air-cooled storage to 100 yr of from $85 to $180/kg U, depending on the type of storage facility used. Ref. 16 reports that the use of an MRS would increase the levelized cost of waste management by $4/kg U. Ref. 8 quotes a levelized cost for a 7500 MTU MRS of from $170 to $200/kg U, depending on the type of storage used.

A wide range therefore exists in the literature on MRS costs. If MRS costs are approximately $60/kg U higher than assumed in our model (or approximately $100/kg U), then no economic benefit exists in aging the waste before its emplacement in the repository. The bottom line is that a better data base is needed for key cost items such as the MRS.

FUEL REPROCESSING AND DISPOSAL OF HIGH-LEVEL WASTE, LIGHT WATER REACTORS

Spent fuel contains materials of potentially high economic value. Disposal of spent fuel in the repository, while isolating potentially hazardous materials from the environment, also precludes or makes difficult the recovery of these resources. An alternate to spent fuel disposal is therefore fuel reprocessing, with the recovery of valuable and potentially valuable materials. The wastes from reprocessing must be disposed of in an environmentally safe manner. These wastes include HLLW and TRU wastes, low-level wastes, and gaseous wastes (radioactive krypton). As with spent fuel, many design parameters are needed to define the waste management system. The list is similar to the spent fuel list, except waste form parameters must now included. The present U.S. waste management program calls for immobilization of HLLW into a glass waste form with from 25 to 30 wt. % waste loading and burial of the waste in a geological repository with no aging of the waste, except as may be required by delays in repository availability. Our work[1] and the work of McKee[17] have indicated that minimum cost is achieved when the maximum waste loading compatible with a particular immobilization process and the maximum canister size compatible with the repository are used. A difference exists as to whether an alternate waste form to glass will result in lower system costs. We[2] and Dippold[14] both found that aging the waste before emplacement leads to system economies; we found the economies exist when calculated in constant dollars, and Dippold found the economies exist when calculating discounted dollars. Two key questions that remain outstanding are related to alternate waste form selection and the benefit of aging.

Waste Form and Waste Loading with No Aging

The present goal of the U.S. program is, once reprocessing becomes a reality, to immobilize the HLLW in a borosilicate glass containing up to 30 wt. % waste. To be able to characterize the glass waste form, storage conditions are to be such that the glass centerline temperature does not exceed 500°C. To date, no glass with this waste loading has been fabricated from commercial HLLW. The French waste disposal program has prepared waste glass from HLLW, but limit waste loading to approximately 15 wt. % [their waste canister diameter is 50 cm (20 in.) and the lower waste loading is used so centerline temperatures do not exceed 500°C]. State of the art for a glass waste form is then 15 wt. % waste loading. An alternate waste form is a ceramic product prepared by hot isostatic pressing containing 60 wt. % waste.[18] The centerline temperature limit for this waste form is assumed to be 850°C. This assumption is believed to be very conservative but needs to be tested. This assumption is related to the requirement of having no phase changes with time so that the waste form remains characterized. The relative economics of these three waste forms are shown in Table II. These analyses assume emplacement of the optimum-sized canister containing 10-yr-old waste. Reprocessing plant costs do not include conversion facilities. If the cost of this facility is included, reprocessing costs would be approximately twice those reported here.

From this table, with the limitation that 10-yr-old waste be emplaced, state-of-the-art glass technology increases waste management costs over the U.S. reference costs by approximately 10%. The ceramic waste form technology has the potential of reducing waste management costs by from 5 to 10%. The ceramic waste form is competitive with the U.S. reference glass if immobilization costs are less than $33/kg U, compared to our estimated $22/kg U. This is referenced to a glass immobilization cost of $22/kg U.

Aging of HLW

As with spent fuel, the option exists to age HLW waste before its emplacement in the repository. By this aging, thermal limits of the repository are met with larger waste packages than can be emplaced with canisters containing hotter waste. The size of the waste packages is determined by waste form and canister

TABLE II

HLW DISPOSAL COSTS WITH NO WASTE AGING
($/kg U)

	State-of-the-Art Glass	U.S. Reference Glass Waste Form	Ceramic Waste Form
Fuel	LWR	LWR	LWR
Form	Glass	Glass	Ceramic
Transportation mode	Rail	Rail	Rail
Waste fraction %	15.0	25.0	60.0
Diameter, in.	17.94	12.87	6.88
Age at reprocessing	5.00	5.00	5.00
Age at immobilization	5.00	5.00	5.00
Age at emplacement	10.00	10.00	10.00
Can/cask	4.56	8.09	26.68
KW/cask	10.3	16.6	45.6
KW/can	2.261	2.055	1.709
Type of vault storage	Forced air	Forced air	Forced air
Canister per hole	17	17	17
Volume per canister	12.608	6.343	1.310
Form density	178.5	193.4	324.5
MTU per canister	2.328	2.116	1.760
Reprocessing - capital	12.50	12.50	12.50
Reprocessing - operating	10.00	10.00	10.00
Immobilization - capital	9.17	8.30	7.72
Immobilization - operating	12.90	10.75	10.11
Canister costs	3.39	2.68	4.53
Chemical costs	0.12	0.07	0.06
Transportation costs	23.19	14.37	5.24
MRS - capital	1.15	1.21	1.33
MRS - operating	2.34	2.46	2.70
Repository - capital	15.44	14.76	12.36
Repository - operating	21.41	18.85	18.75
Liquid waste storage	0	0	0
TRU waste disposal	78.03	78.03	78.03
Krypton collection and storage	34.28	34.28	34.28
Total	223.92	208.25	197.60

limits in the storage facility (MRS). The current Department of Energy program is focusing on air-cooled MRSs with passive cooling systems. This type of facility was selected over air-cooled systems with active cooling systems and over water-cooled systems because of its lower cost and few safety-related components. The cost analyses of passively cooled MRSs did not include the economic impact of waste aging on overall waste management economics. Our analysis indicates that forced-air-cooled MRSs, similar to that used by the French, offer significant cost advantages over passive systems. For waste from reprocessed LWR fuel, there is little to be saved by using a water-cooled MRS.

Figure 4 shows the results of optimization studies for the three waste forms of interest. This figure shows that, for the assumptions of our model, considerable savings exist when aging waste before emplacement in a repository; specifically, these savings are $21/kg U (or 10% of the waste management cost) for state-of-the-art glass, $26/kg U (or 12% of the waste management costs) for the U.S. reference glass, and $34/kg U (or 17% of the waste management cost) for a ceramic waste. The key element in each of these cost savings is related to what is assumed for MRS costs. For each of these waste management systems, the MRS cost corresponds to approximately $6/kg U. Therefore, for waste aging to be economically attractive, MRS costs can be four to six times higher than assumed in our model, or approximately $30/kg U. The use of an MRS to age the waste is therefore economic when, with high waste loading, large-diameter canisters cannot be immediately emplaced because of thermal limits in the repository. For wastes with lower heat loadings, such as defense waste and HLW in which the heat generating isotopes of

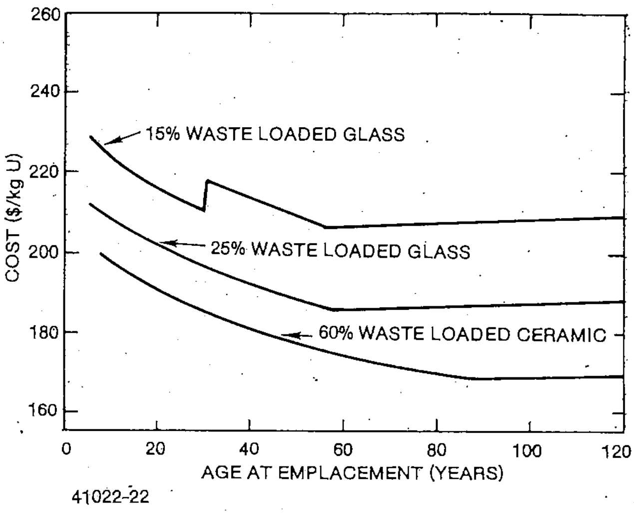

Fig. 4. Optimization of alternate waste forms.

cesium and strontium are removed, no significant advantage exists in using MRSs to age waste, but there is a significant advantage in using waste forms with high waste loading.

To establish the validity of our MRS costs, the literature was searched to determine cost estimates by others. In addition to the work of McDonnell[12] on which our model is based, two references were found in the literature that report costs for storage of immobilized waste. In the first, the cost of storing immobilized waste in a water basin for 5 yr was $13/kg U (in levelized 1982 dollars).[19] The second report was a study of waste storage alternatives in a European setting.[20] The costs did not include decommissioning (approximately half the capital cost) and used a labor rate approximately half that in the U.S. Doubling the reported rate and basing it on constant 1982 dollars yields a cost for storing immobilized waste for 75 yr of $18 and $4/kg U for water basin and air-cooled vaults, respectively. Based on these values, our values for the cost of storing immobilized waste is probably slightly high.

ECONOMIC TRADE-OFF OF SFE AND REPROCESSING ALTERNATIVES

Based on the information developed above, a fairly simplistic estimate can be made of the required credit for recycle plutonium for a break-even situation between disposal of spent fuel and the reprocessing alternative. This comparison assumes that plutonium (Pu-239 + Pu-241) is the only material in the spent fuel for which an economic credit is taken, the recycle uranium is a direct substitute for the U-238 used to dilute the U-235 in fresh fuel, the cost of processing the recycle uranium being equal to the cost of replacement yellow cake, and the cost of fabricating and handling fuel from recycle material is the same as for fresh fuel. Assuming that 10-yr-old waste is to be emplaced, the break-even credits for the state-of-the-art glass waste is $18/g Pu, for the U.S. reference glass is $15/g Pu, and for the ceramic waste form is $13/g Pu.

One of the consequences of reprocessing is that a use must be found for the materials separated during reprocessing or the cost of its disposal must be included in the waste management cost. For our study, we have assumed uranium is recycled as a diluent for enriched uranium and plutonium in the new fuel elements. To recover enough plutonium to fabricate 1 kg of MO_x fuel, 4.5 kg of spent fuel must be reprocessed.[21] Therefore, a cost not included in our analysis (and to our knowledge in no one's waste management analysis) is the cost of disposal of this excess 3.5 kg uranium. If this material is disposed of as a TRU waste, the cost of the reprocessing alternative would be increased by approximately $40/kg U, a significant cost component not currently included in waste management costs. Additional study should be performed to verify this result.

Key assumptions in this analysis is that the cost of reprocessing is $45/kg U (reprocessing plus conversion plants). Figure 5 shows the trend of reprocessing cost estimates.[21] The estimate we use here is reasonable up to 1970. After that, the estimated cost for a reprocessing plant has increased dramatically. If we assume a mean 1982 estimate for reprocessing of $500/kg U, then the break-even credit for plutonium would have to be approximately $90/kg U. Unless the cost of reprocessing is much lower than currently estimated or the value of other materials in the spent fuel is significant, it is unlikely that reprocessing is an economically viable alternative. Figure 6 shows the impact of reprocessing costs on the required break-even credit for plutonium for both the constant emplacement time scenario and for the optimum economic solution. Because of savings in the optimization of the SFE alternative, larger plutonium credits are needed for break-even in the comparison of optimized waste management systems. If the recycle uranium has a value equal to yellow cake, the break-even credit for plutonium would be approximately $10/gm Pu less than that reported above and in Figure 6.

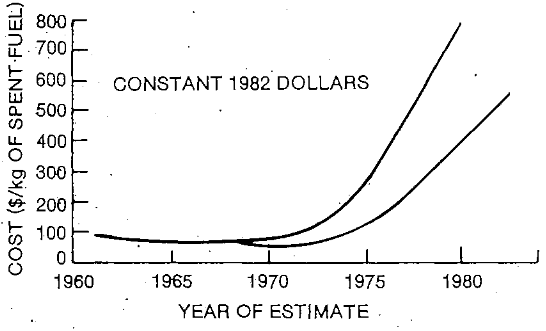

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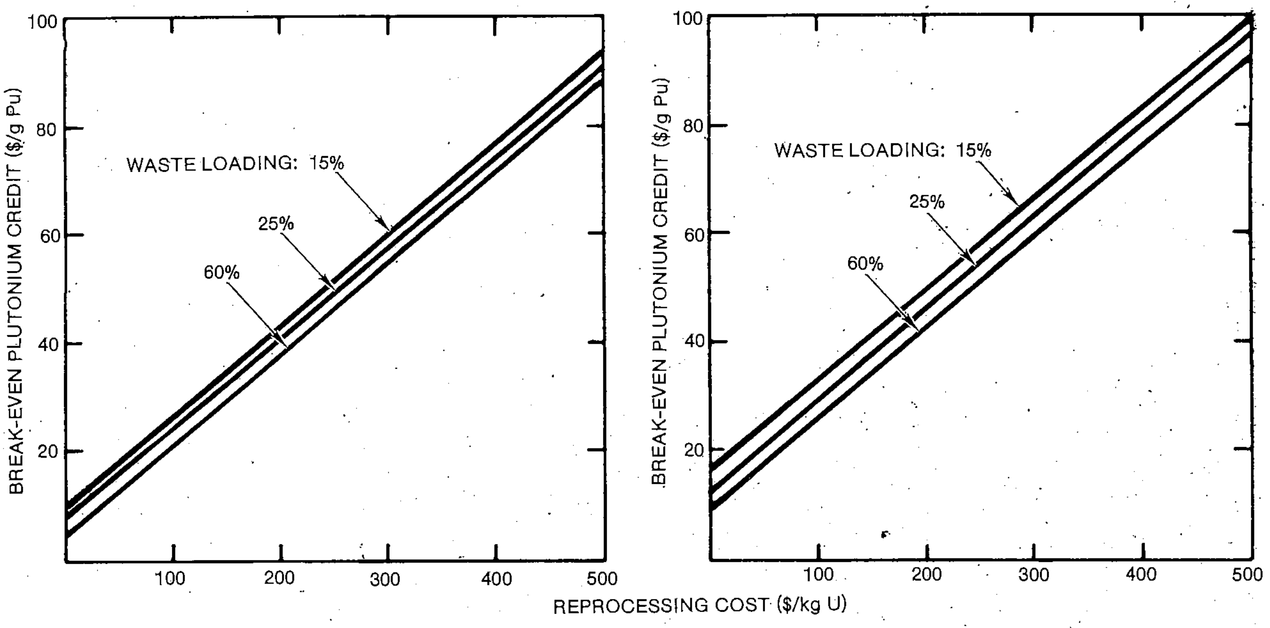
Fig. 5. Reprocessing cost estimates.

WASTE MANAGEMENT OF FAST BREEDER REACTOR FUEL

Unlike the back-end of the LWR fuel cycle, the back-end of the FBR fuel cycle requires not only that fuel be reprocessed, but also that reprocessing occur as rapidly as practical. The disposal of spent fuel is therefore not a viable alternative. Because of the short time to reprocessing, the option of storing HLLW was included in our analysis. The approach to the study of the waste from the back-end of the FBR fuel cycle was similar to that used in the study of the back-end of the LWR fuel cycle. The waste composition and decay heat relationships were taken from Refs. 22 and 23. Because, as with the LWR study, it was assumed a steady-state FBR fuel economy exists, co-reprocessing of core and blanket material was assumed.

Unless it is assumed that the HLLW is stored for several years before immobilization, the type of MRS used to store the waste before emplacement in a repository has a major impact on waste management economics (Table III). Use of a water-cooled MRS as contrasted to a natural convection, air-cooled MRS reduces waste management costs by approximately 30% for glass waste forms and by only 3% for the ceramic waste form. This difference exists because of the difference in optimum storage time for HLLW for glass and ceramic waste forms and is related to the difference in canister design between these two forms.[1] For the U.S. reference waste form, the optimum emplacement time occurs in less than 10 yr; therefore, the waste form diameter is limited by the heat transfer characteristics of the MRS. Because, for the ceramic waste form, optimum emplacement time occurs after the waste is 10 yr old, waste emplaced at 10 yr must have a smaller diameter than allowed by the MRS to meet repository thermal limits.

If a water-cooled MRS is used to store HLW immobilized in glass and either a forced-air-cooled or water-cooled MRS is used to store HLW immobilized in ceramic, little or no advantage exists in the ceramic waste form. The reason for this is not related to the waste forms but rather the package designs assumed for this study. Alternate package designs, for both the glass and ceramic waste forms can significantly affect the conclusions of this study.



a) 10-YEAR-OLD WASTE AT EMPLACEMENT OF BOTH SFE AND HLW

b) ECONOMIC OPTIMUM FOR BOTH SFE AND HLW ALTERNATIVES

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Fig. 6. Break-even credits for SFE and HLW alternates.

TABLE III

COST IMPACT OF TYPE OF MRS ON FBR WASTE MANAGEMENT COSTS

	State-of-the-Art Glass (1 yr at reprocessing and 1 yr at immobilization)					U.S. Reference Glass Waste Form (1 yr at reprocessing and 1 yr at immobilization)					Ceramic Waste Form (1 yr at reprocessing and 3.5 yr at immobilization)				
	10-yr Emplacement		Optimum			10-yr Emplacement		Optimum			10-yr Emplacement		Optimum		
Type MRS	Diameter (in.)	Cost ($/kg U)	Diameter (in.)	Age at Emplacement (yr)	Cost ($/kg U)	Diameter (in.)	Cost ($/kg U)	Diameter (in.)	Age at Emplacement (yr)	Cost ($/kg U)	Diameter (in.)	Cost ($/kg U)	Diameter (in.)	Age at Emplacement (yr)	Cost ($/kg U)
Natural convection, air cooled	7.4	369.2	7.4	2.4	364.8	5.9	332.7	5.9	2.6	330.8	6.5	244.9	9.2	34.1	223.2
Forced convection, air cooled	10.3	290.1	10.3	3.5	286.4	8.5	252.7	8.5	4.4	249.9	6.5	246.7	11.6	59.2	218.2
Water cooled	13.1	254.1	13.2	5.4	252.2	11.3	220.7	11.3	8.4	220.2	6.5	247.2	12.6	72.0	217.0

Because of cost savings associated with a water-cooled MRS and the relatively short storage times required for optimized system economics, further studies of a water-cooled MRS should be done if the glass waste form is to be used to immobilize FBR waste.

Another optimization alternative is related to the storage of HLLW. An analysis of this alternative indicated that for waste from FBR fuel reprocessing more than 0.8 yr from reactor discharge, storage of HLLW is not an economically viable option for glass waste forms. Figure 7 illustrates this for reprocessing of 0.5-yr-old FBR fuel. A similar result exists for ceramic waste forms except the optimum time for HLLW storage is 3.5 yr. The difference between the glass and ceramic waste forms is related to the canister configuration and the high cost of producing small-diameter ceramic canisters. Results for optimization

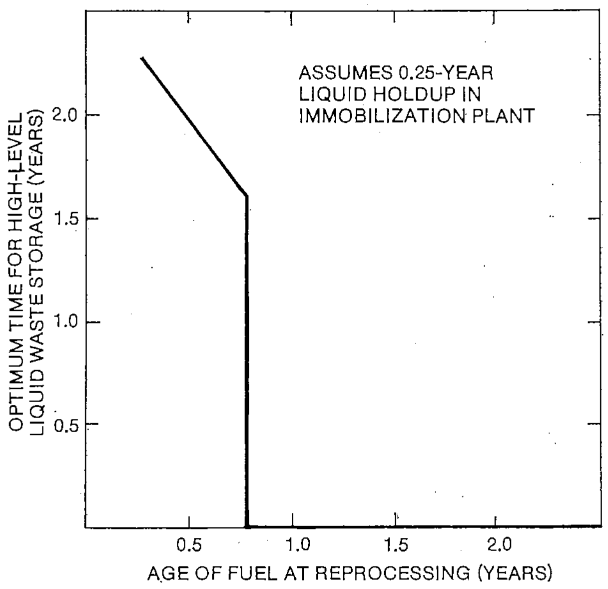

Fig. 7. Optimization of HLLW storage option.

studies of the back-end of the FBR fuel cycle are similar to the back-end of the LWR fuel cycle except that smaller canister sizes and shorter optimum emplacement times are noted.

CONCLUSIONS

Waste management schedules are now set by law. During the legislative process, these schedules were negotiable. DOE accepted all schedule recommendations made by the legislature.[24] To meet these schedules, design parameters are being set without benefit of overall waste management system analyses to establish the economic impact of noneconomic issues and establish that true overall system optimization has been achieved. In this paper, we point out several areas where system optimization can occur, or significant uncertainty exists in system economics based on information published in the literature. To us, what is clearly needed is a program to resolve differences in costs, to place costs on the same bases, and to perform the necessary system analyses to both benchmark and verify system economics.

The spent fuel alternative is a less costly alternative than reprocessing if the products from reprocessing are assumed to have no commercial value. If one accepts a large reprocessing cost, say $500/kg U, then it is unlikely that the value of recovered plutonium will make reprocessing an economically competitive alternative. This situation could be reversed if the reprocessed uranium could be used as a diluent for plutonium in the mixed-oxide fuel or is an economic replacement for natural uranium in an isotopic separations facility. However, even if the economics of reprocessing do not favor this alternative today, the large material resources in spent fuel makes it difficult to accept permanent (or essentially economically irretrievable) disposal of spent fuel as the preferred nuclear waste management system.

If repositories are designed to handle only canisters of a single size for all waste requiring remote handling, consolidation of spent fuel is the least expensive route as long as the cost of consolidation plus the cost to collect and store the krypton potentially released during the consolidation process is less than $84/kg U. The cost of consolidation varies in the literature from 20 to $25/kg U.

If repositories are designed to handle optimized canister diameters for all waste requiring remote handling, consolidation of spent fuel is the least expensive route as long as the cost of consolidation plus the cost to collect and store the krypton potentially released during the consolidation process is less than $14/kg U, assuming consolidation at the repository. If fuel consolidation occurs at the reactor site, the break-even cost is approximately $30/kg U.

The MRS is an economically viable option to age SFE waste before emplacement in a repository if MRS costs are less than approximately $100/kg U. MRS costs vary in the literature from 25 to $200/kg U.

The MRS is an economically viable option to age HLW waste before emplacement in a repository if MRS costs are less than approximately $30/kg U. Current literature values for the cost to store HLW is approximately $5/kg U.

The same advantages exist in the use of alternate waste form technology for FBR waste as for LWR waste if a passive air-cooled waste storage facility is used (either an MRS or a storage vault at the immobilization plant). No economic advantages for alternate waste forms have been identified for FBR waste that do not also exist for LWR waste, though for FBR wastes the savings are greater.

If a water-cooled waste storage facility is used, ceramic technology offers little if any economy over glass technology, using the waste packaging configuration assumed in this study. Alternate waste package designs can reverse this.

Depending on the age of FBR fuel at reprocessing, an economic advantage may exist in the storage of HLLW before waste immobilization. For our model, when FBR fuel is processed less than 0.8 yr and 3.5 yr from reactor discharge for the glass waste form and ceramic waste form, respectively, HLLW storage is an economically viable option.

Significant economies exist in the use of a water-cooled MRS for storing immobilized HLW from the reprocessing of FBR fuel if a glass waste form is used. Little economic gain exists if the ceramic waste form is used assuming the waste package design used in this study.

Using waste forms with high waste loading leads to reduced waste management costs as long as the cost of immobilization does not exceed the cost savings. As an example, use of 60 wt. % loaded waste is economically competitive with 25 wt. % glass as long as immobilization costs for the high waste loading waste form do not exceed glass waste form immobilization costs by approximately $11/kg U. For waste with low heat loadings, such as defense waste and fractionated waste, ceramic technology offers much higher economic incentives.

FBR waste management costs are approximately 10 to 20% higher than LWR waste management costs when expressed on a dollar-per-kg-U basis. However, since FBR fuel is burned to approximately 100,000 MWD/MTU and LWR fuel is burned to approximately 33,000 MWD/MTU, when expressed on a kilowatt-hour basis, FBR waste management costs are approximately one-third those of LWR waste management costs.

One trend observed in nuclear cost estimates is a rapid acceleration of both the magnitude of the estimate and variation among estimators as a function of time over the last few years. This recently lead to the cancellation of partially completed reactors, is undoubtedly one factor in the failure of private industry to enter commercial reprocessing, and may well affect acceptance of waste management as currently proposed. If factors affecting these large increases in nuclear cost estimates are not identified and contained, and if a common data base is not used in the calculation of costs, both future private investment in the nuclear industry and the public and utility acceptance of waste management are open to question. We believe one route to reduce the disparity among cost estimates is to validate and benchmark cost estimates the same way engineering calculations are validated and benchmarked.

A final word in closing. Short-term strategies to meet arbitrarily set schedules can only lead to unnecessarily high costs. If these strategies lead to irretrievable loss of valuable resources, then these strategies can only be classified as shortsighted. The Nuclear Waste Policy Act of 1982 and the waste management mission plan allows for the optional use of an MRS "for the safe and reliable long-term storage of high-level radioactive waste and spent fuel for as long as may be necessary."[25] The use of this option not only may lead to system economies through aging of the waste but also leaves open the choice of utilizing the resources in spent fuel at a later date.

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