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ESTIMATED COSTS FOR MANAGEMENT OF HIGH-ACTIVITY POWER REACTOR PROCESSING WASTES*

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ABSTRACT

Economic and safety evaluations of alternative methods for management of high-activity wastes from power reactor fuel processing provide a means for deriving the optimum combination of operations and can indicate the most promising methods to be developed for a competitive nuclear power economy. Although the cost of long-term storage of these wastes as liquids is acceptable, the safety as a permanent disposal method is considered inadequate. A scheme believed to be acceptably safe consists of interim storage as liquids in tanks, followed by pot calcination of the wastes to produce relatively small volumes of stable solids, interim storage of the pots, and, finally, shipment of the pots to salt mines for permanent disposal. Total costs are estimated to range from 2.6×10^{-2} to 4.8×10^{-2} mills/kwh$_e$ and are believed to represent an acceptable contribution to the cost of nuclear power.

A 6-tonne/day fuel processing plant is assumed which would handle the fuel from a 15,000-MW$_e$ nuclear power economy. This plant would process 1500 tonnes/yr of uranium converter fuel at a burnup of 10,000 Mwd/tonne and 270 tonnes/yr of thorium converter fuel irradiated to 20,000 Mwd/tonne.

Costs of each operation for the resulting Purex and Thorex wastes in acid and in alkaline form, and for interim storage times from 0 to 30 years, were extracted from a series of earlier studies made of individual management operations. Interim liquid

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storage costs were based on tanks of Savannah River design. Pot calcination costs were estimated for processing in acid and re-acidified (after alkaline storage) forms, using calcination pots 6, 12, and 24-in. in diam and 10 ft high. Costs of interim solid storage in water-filled canals were estimated for times equal to the difference between those of interim liquid storage and 30 years, the assumed age at final disposal. Costs of shipping the solidified wastes 500 miles to a salt mine at age 30 years were based on use of lead-shielded carriers, and it was assumed the pots were finally buried vertically in the salt at the minimum spacing required to dissipate the decay heat safely.

Total management costs were less in all cases for acid wastes than for neutralized ones. Minimum costs of 2.6×10^{-2} mills/kwh$_e$ for acid wastes and 3.2×10^{-2} mills/kwh$_e$ for alkaline wastes, equivalent to \$1950 and \$2350/tonne fuel processed, were obtained at interim liquid storage times of 3 and 30 years, respectively. All costs lay well below the range of 0.08 to 0.16 mills/kwh$_e$ which has been suggested previously as allowable for waste management.

1. INTRODUCTION

An important, and as yet unresolved, aspect of the development of nuclear power is the formulation of suitably safe and economic methods for management of the high-activity wastes to be produced during recovery of the irradiated fuels. Although the costs of permanent or "perpetual" storage of these wastes as liquids in tanks is acceptable, the safety as a permanent disposal method is considered inadequate. At Oak Ridge National Laboratory, a number of alternatives are under consideration, and in some cases, experimental investigation, which are expected to give the necessary degree of safety within an economic framework that could be supported by a competitive nuclear power economy.

As can be seen from the Figure 1, effective management will probably consist of a series of operations, performed over a period of several years. Following their production in a fuel processing plant, the wastes may be subjected to such preliminary operations as partial removal of fission products, interim, or temporary, storage as liquids in tanks, conversion to solids by a process such as pot calcination, interim storage as solids, and, finally, shipment of the solids. Acceptable disposal methods for the solids might be burial in salt mines or storage in concrete vaults. Other possibilities are seen in the direct disposal of the wastes as liquids by perpetual storage in tanks, in salt formations, or by injection through wells into deep, permeable geological formations.

Economic and safety analyses of each of these steps are being undertaken, and the ORNL report numbers given here refer to the economic studies which have been published. This paper presents the economics for what we believe to be the safest path, that is, interim liquid storage, pot calcination, interim solids storage, and shipment to a salt mine for permanent disposal. The paper to be presented by Perona will analyze the effects of fission product removal on the costs of waste management by this same series of operations.

2. BASIS OF STUDY

As a basis for this study (Table 1), a 6-metric ton per day fuel processing plant is assumed which would handle the fuel from a 15,000-electrical-megawatt nuclear economy. This plant would process 1500 tons/year of uranium converter fuel at a burnup of 10,000 Mwd/ton and 270 tons/yr of thorium converter fuel irradiated to 20,000 Mwd/ton. Management of the resulting Purex and Thorex wastes in both acid and neutralized forms, with specific volumes as indicated, was considered. Costs per kilowatt-hour of electricity produced were computed for each management step, assuming 4% interest on the capital investments and using present worth considerations where applicable.

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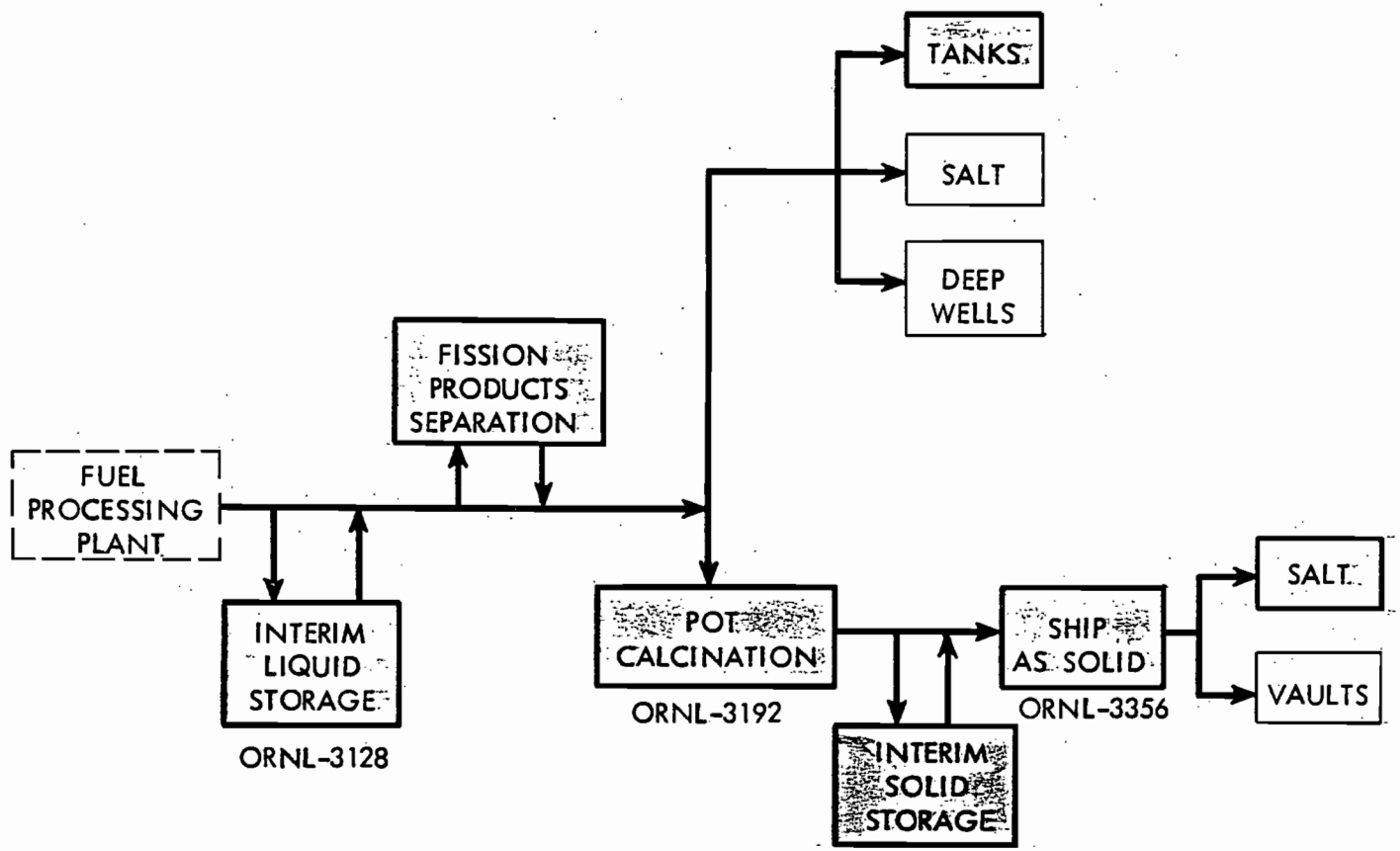

Fig. 1. Management of High-Activity Wastes.

Table 1. Basis for Study

	15,000 Mw_e Nuclear Economy	
	Uranium Converter Fuel	Thorium Converter Fuel
Metric tons/yr	1500	270
MWD/ton	10,000	20,000
gal/ton acidic	50	400
gal/ton neutralized	60	640

3. INTERIM LIQUID STORAGE[1]

Costs of interim storage of the wastes as liquids were estimated assuming use of tanks of Savannah River design. These facilities, which consist of a steel tank inside a concrete housing with annuli to permit accumulation and detection of leakage were chosen because their design would be more nearly acceptable over a wide range of environments. Acid wastes were assumed stored in stainless steel tanks and neutralized wastes in mild steel tanks. Fission product decay heat was removed during storage by use of submerged cooling coils. The operating cycle of each tank was assumed to consist of equal filling and emptying periods plus a full (or dead) period. Tank costs were optimized for each waste type as shown in Figure 2. A family of curves of tank capital cost per year for different dead storage periods is plotted against the interim liquid storage period, where interim storage is defined as filling time plus dead storage time. Each curve, for a fixed dead storage time, has a minimum value at some value of interim storage time. The rise in the curve at the low end is due to the fact that as the interim storage time approaches the dead storage time the number of required tanks becomes large, the volume of an individual tank becomes small, and the cost per gallon of capacity increases with decreasing tank size. The rise in the curve for longer storage periods is due to the increasing total capacity requirements. The dashed curves are the loci of minimum tank capital costs per year as a function of the interim liquid storage time and occurred when dead time was 40 to 70 per cent of the interim storage time.

Total costs of interim liquid storage as a function of the storage time are given in Figure 3. The costs vary from 1.7×10^{-3} to 2.2×10^{-3} mill/kwh$_e$ for 0.5-year storage to 5.1×10^{-3} to 9.5×10^{-3} mill/kwh$_e$ for 30 years' storage depending on the waste combinations chosen. These costs assume that, for a given interim storage period, the optimum dead storage period is used.

4. POT CALCINATION[2]

Pot calcination is a process currently under development at ORNL for converting wastes to thermally stable solids suitable for permanent disposal. The process entails evaporation to dryness and calcination at ~900°C in a stainless steel "pot" which, when sealed, could serve as the shipping and permanent storage vessel. The pots would range in diameter from 6 to 24 inches, depending on the fission product heat generation rates, and would be about 10 ft long. The process is suitable for handling a variety of waste types and can be used to incorporate wastes in glassy solids.

In this study, calcination of acid and reacidified (after alkaline storage) Purex and Thorex wastes in vessels 6, 12, and 24 in. diam. by 10 ft long was assumed, as well as was production of a glass from Thorex waste. Some of the possible combinations

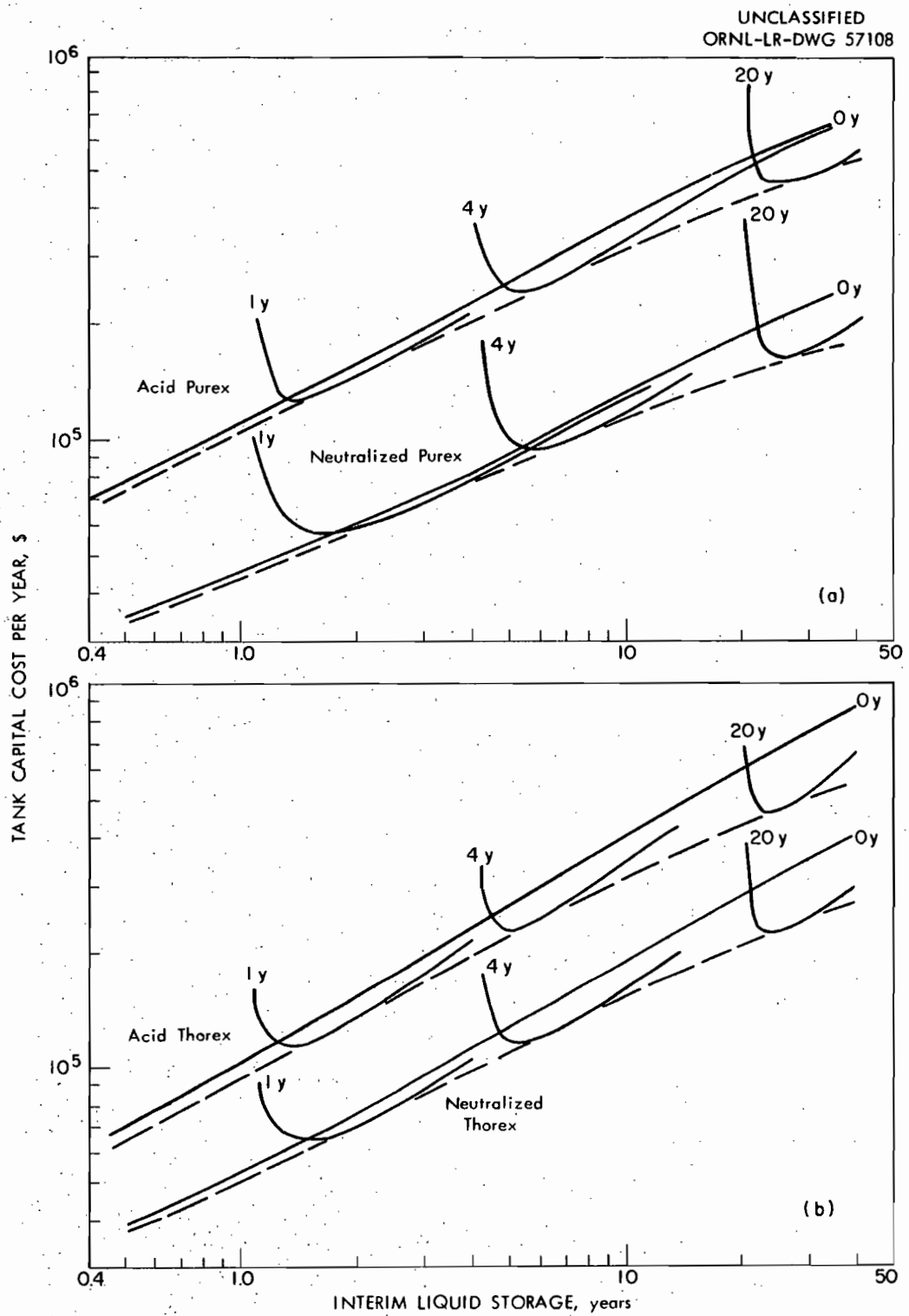

Fig. 2. Tank Capital Cost Per Year as a Function of Interim Storage Time with Parameters of Dead Time for (a) Purex Waste and (b) Thorex Waste. Locus of Optimum Dead Times.

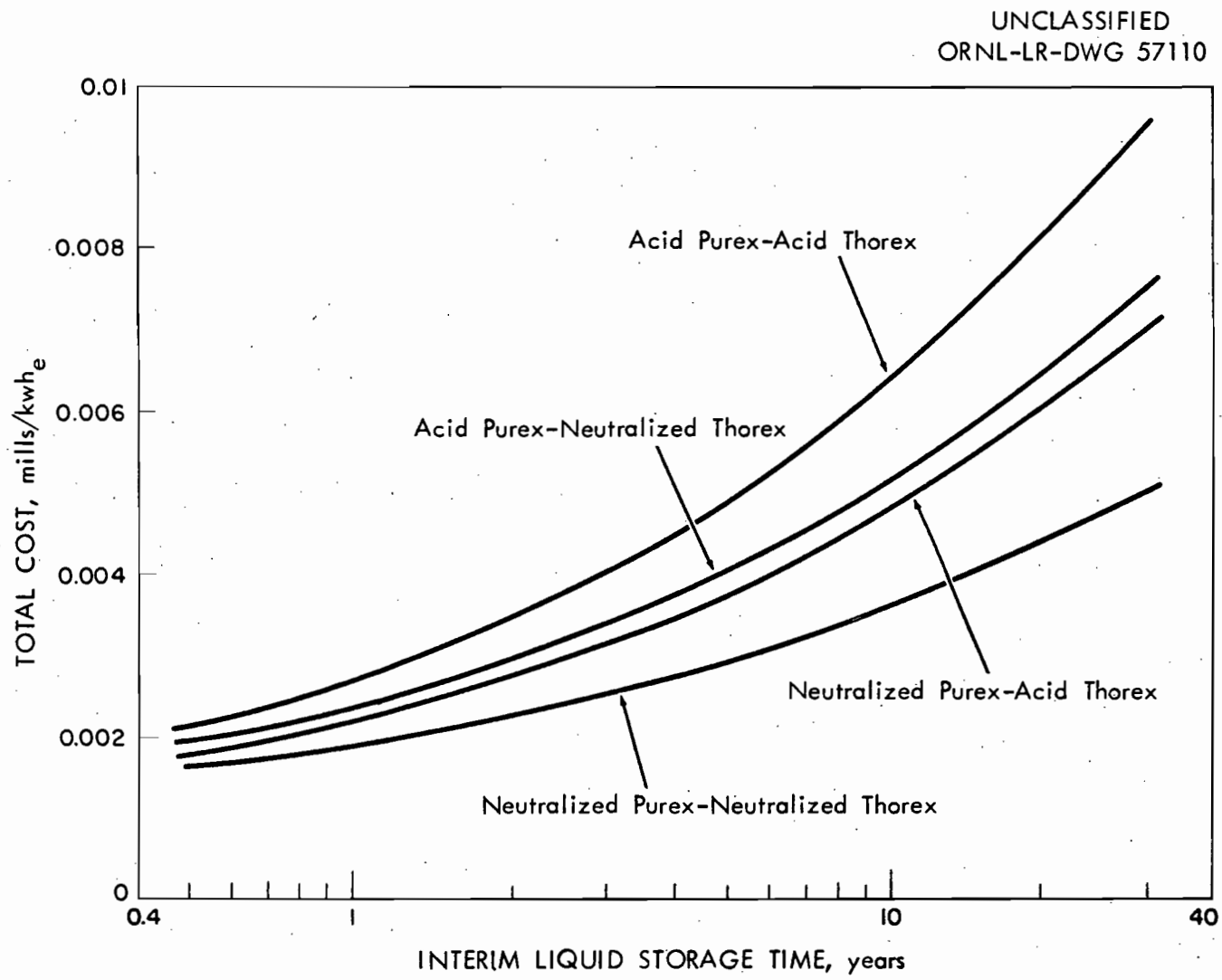

Fig. 3. Cost of Interim Storage as a Function of Storage Time for all Combinations of Acid and Alkaline Purex and Thorex Wastes.

of waste ages and vessel diameters are not permissible because of the excessive temperatures that would occur in the solids due to internal heat generation. Curves of specific heat generation rates as a function of time since reactor discharge (Figure 4) were obtained from plots of total heat generation rate vs interim liquid storage time and from the assumed waste production rates from the 6-ton/day plant. Assuming a maximum allowable temperature difference of 1350°F between the axis and outer wall of the vessel, while the surface was held at 300°F, maximum permissible heat generation rates were calculated for the three vessel diameters. They are denoted by the ticks on each of the curves in this figure.

The lowest cost (Table 2) was 0.87×10^{-2} mill/kwh$_e$ for processing acid Purex and Thorex wastes in 24-in.-diam vessels, and the highest was 5.0×10^{-2} mill/kwh$_e$ for processing reacidified Purex and Thorex wastes in 6-in.-diam vessels. About 7 years of interim liquid storage would be required before acid Purex could be processed in 24-in.-diam vessels.

5. INTERIM SOLIDS STORAGE[3]

Facilities were designed for storage of the cylinders of solidified wastes in water-filled canals for periods as great as 30 years (Figure 5). Although the wide range of parameters studied resulted in facilities of different sizes and geometrical configurations, they consisted, in essence, of a central facility canal, storage canals, and a service area containing water cooling and purification equipment.

The central facility canal was designed for receiving cylinders of waste from the calcination plant, for storing them briefly to permit observation of defective containers, and for routing them to the proper canal for interim storage. It also served for underwater loading of the cylinders into casks prior to shipping off-site. This canal was 30 ft wide, 40 ft deep, and varied in length from 24 ft to 146 ft depending on the number and size of the storage canals. It was equipped with bridge cranes of 100- and 5-ton capacities mounted on track overhead. The larger crane was provided for lifting the shipping casks and the 5-ton crane was for manipulating the individual cylinders under water.

The cylinders of solidified waste were stored upright in canals adjoining the central facility. They were arranged in parallel rows, each row consisting of two cylinders staggered back-to-back with a space between rows for moving them in and out. The lengths of 48-ft wide canal required for the different waste types and storage times varied from 14.5 ft for 1-yr storage of acid Purex to 1920 ft for 30-yr storage of reacidified Thorex, but were broken into more practical and economically-sized segments as shown here. The canals were made of 1-ft-thick reinforced concrete around the sides and on the bottom with interior walls 2-ft-thick separating them from the central facility and each other. The depth of the canals, as determined by the

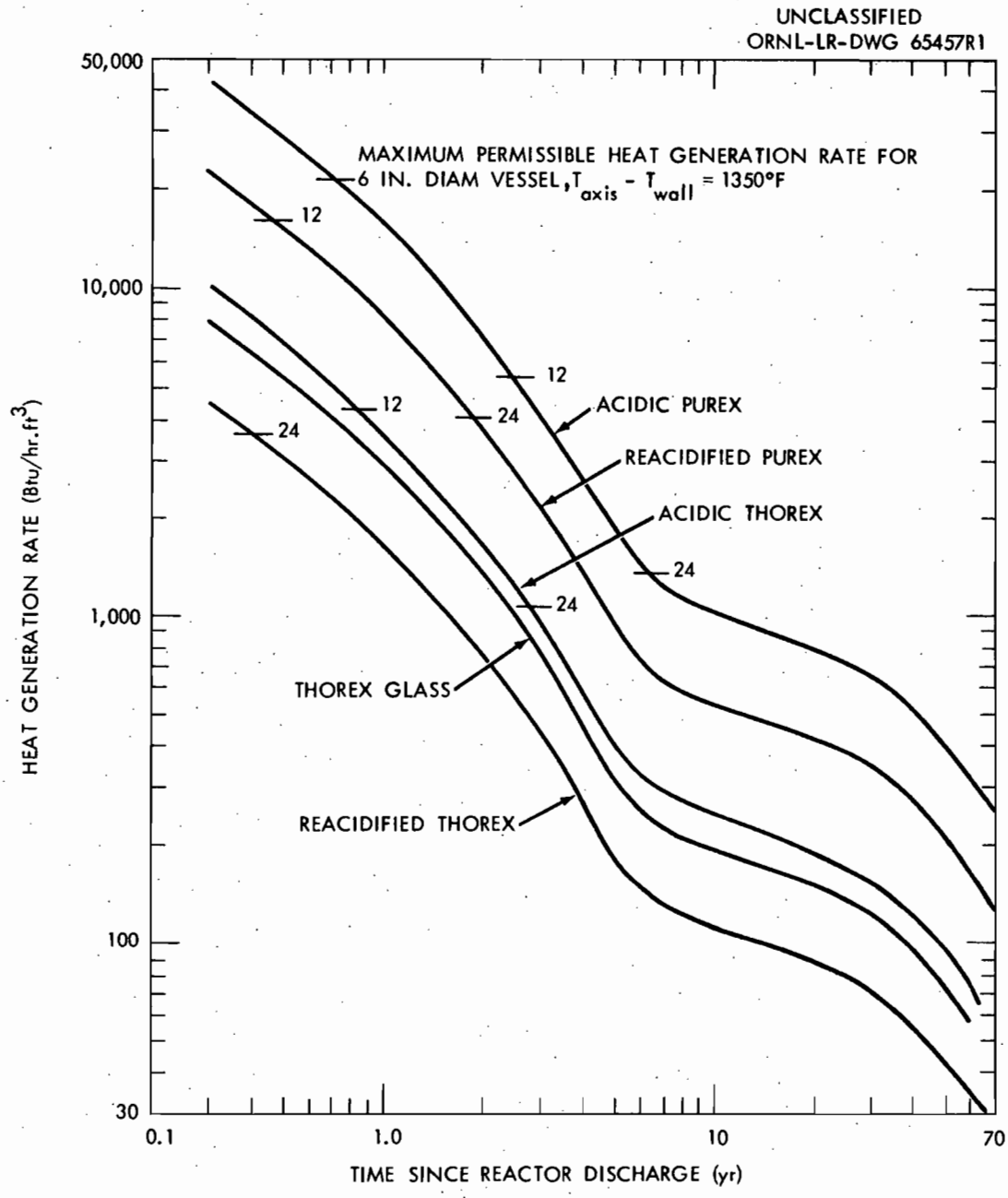

Fig. 4. Heat Generation Rate in Calcined Solids as a Function of Time Since Reactor Discharge.

Table 2. Pot Calcination Costs

Waste Type	Total Processing Cost, mills/kwhe x 10^{-2}		
	6-in.-diam.	12-in.-diam.	24-in.-diam
Acidic Purex-Acidic Thorex	1.6	0.98	0.87
Acidic Purex-Acidic Thorex Glass	2.2	1.9	-
Acidic Purex-Reacid. Thorex	3.8	1.9	1.5
Reacid. Purex-Acidic Thorex	2.8	1.5	1.2
Reacid. Purex-Acidic Thorex Glass	3.4	-	-
Reacid. Purex-Reacid. Thorex	5.0	2.4	1.9

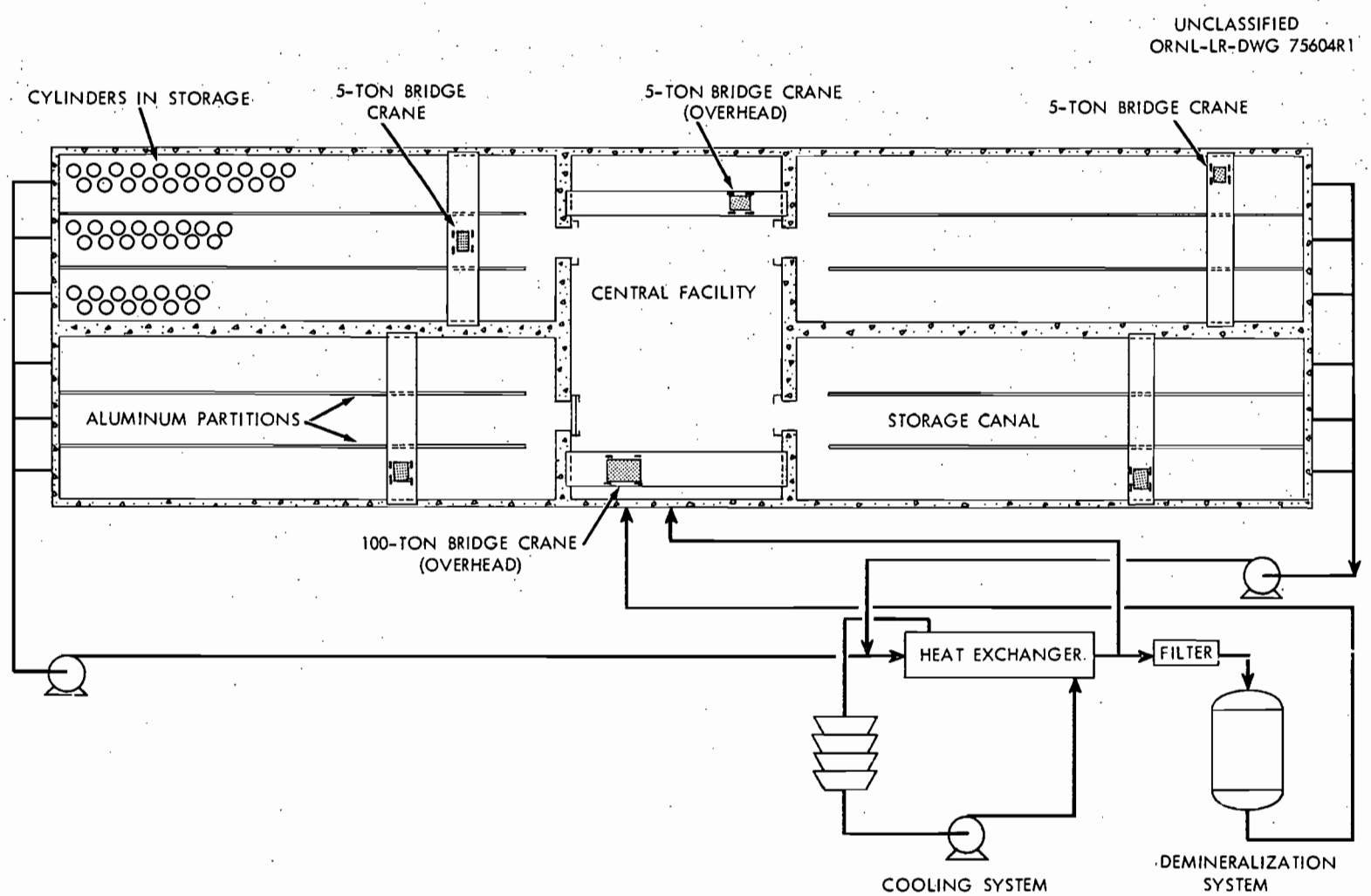

Fig. 5. Concept of Interim Solids Storage Facility.

thickness of water needed for shielding and by the depth required to maintain the cylinders in an upright position varied from 23 to 28 ft. As an aid in locating defective cylinders during storage, aluminum partitions were provided, spaced 8 ft apart along the canal lengths which would channel the water for purposes of monitoring. The canal water was recycled for demineralization and cooling, and a building was provided over the area.

As shown in Figure 6, the costs of interim solids storage ranged from 1.5×10^{-3} mill/kwh$_e$ for 1-yr storage to 4.8×10^{-3} mill/kwh$_e$ for 30-yr storage for the calcined acid wastes and from 1.8×10^{-3} to 6.3×10^{-3} mill/kwh$_e$ for the calcined reacidified wastes. Storage of acid wastes as solids was cheaper by factors of from 2 to 2.7 than than storage of the same wastes as liquids. However, for most storage times, storage of neutralized liquid wastes was slightly cheaper than that of reacidified Purex and Thorex solids.

6. SHIPMENT OF SOLIDIFIED WASTES[4]

In the solids shipment study, heat transfer calculations were carried out to determine waste ages and permissible carrier sizes in the absence of refrigerating equipment or liquid coolants. Carriers were assumed to be right circular cylinders, (Figure 7) with the inner diameter of each carrier and the number of cylinders contained by it determined by the necessity of keeping calcined solid temperatures below the maximum calcination temperature of 900°C. A spacing structure would be required to hold the cylinders in the array as shown. Lead, steel, and uranium were considered as shielding materials, for pots 6, 12, and 24-in. diam by 11-ft long.

Heat transfer among the cylinders and between cylinders and the inner surface of the carrier was calculated as if radiant heat transfer alone was contributing, and the cylinders were assumed to have radially symetric temperature distributions. The exterior surfaces of the carriers were assumed to have fins which halved the heat flux at that surface. Minimum ages for shipment under these conditions (Table 3) ranged from 1/3 year, the assumed age at the time of their production in the fuel processing facility, for many cases to 11.3 years for acid Purex waste in a carrier containing 24-in.-diam cylinders. For some cases with lead carriers, the limiting ages were controlled by the melting point of the lead rather than the maximum waste cylinder temperature. Carriers containing more than the number of cylinders indicated here would weigh more than 100 tons and were assumed to be unmanageably large.

Total costs were computed as a function of age of the waste, shipping distance, and type of shielding material. Lowest costs were always obtained for shipment in the largest casks, and costs were lowest in all cases for lead casks. For 500-mile shipments, they ranged from 5.5×10^{-4} mill/kwh$_e$ for acid Purex at 30 years of age in casks containing four 24-in.-diam cylinders to 1.6×10^{-2} mill/kwh$_e$ for acid Thorex at 0.33 year in casks containing four 6-in.-diam or one 12-in.-diam cylinders.

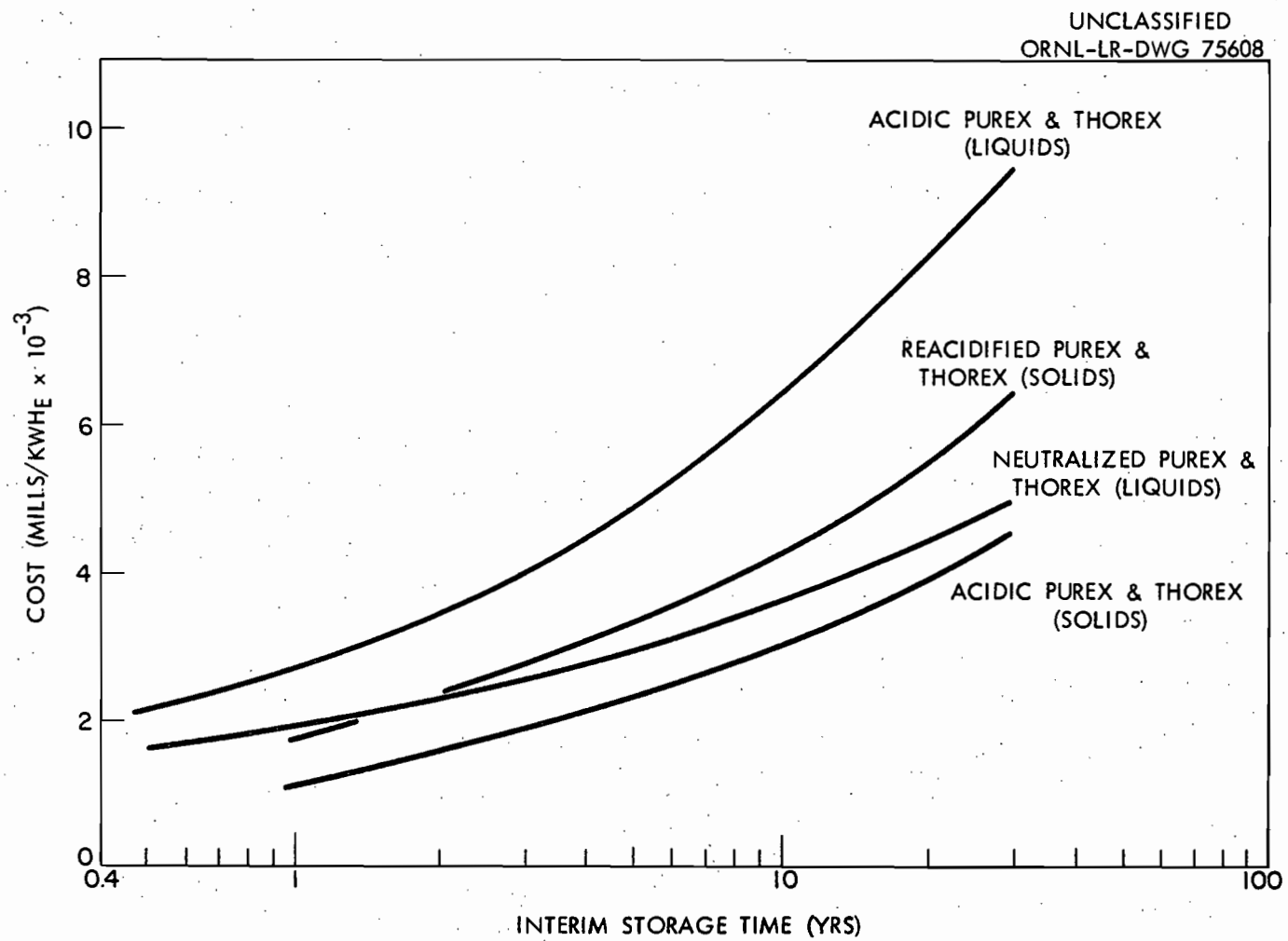

Fig. 6. Comparative Costs of Interim Storage of Liquid and Solid Wastes.

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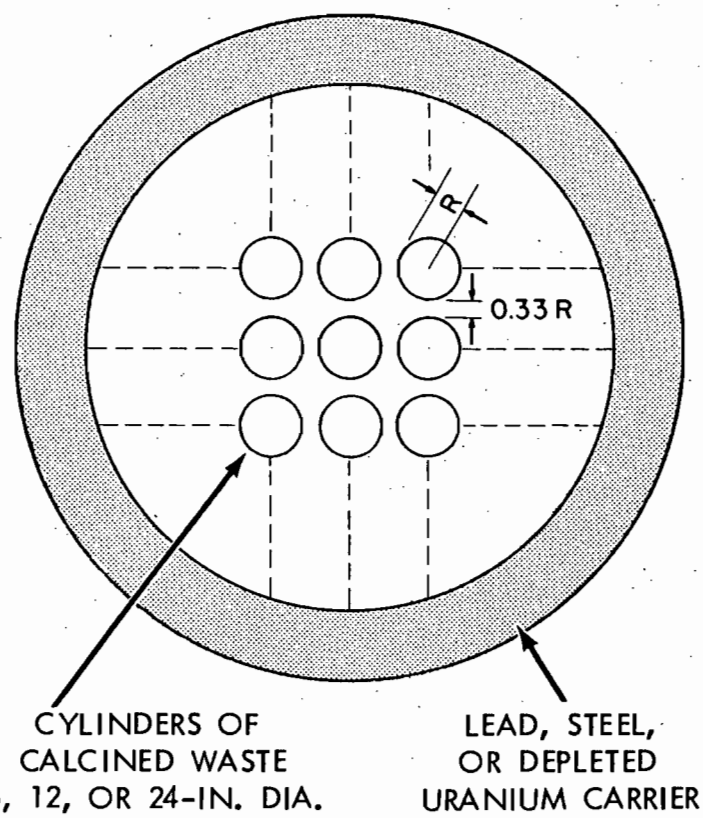

Fig. 7. Plan View Sketch of Carriers for Cylinders of Calcined Wastes.

Table 3. Minimum Permissible Shipping Ages for Cylinders of Calcined Wastes in Iron, Lead, and Uranium casks

Waste Type	36, 6-in.-diam Cyl. Cask	9, 12-in.-diam Cyl. Cask	4, 24-in.-diam Cyl. Cask
Acidic Purex	2.40 yrs[a]	3.80 yrs	11.30 yrs
Reacidified Purex	1.00[b]	1.40[b]	3.00
Acidic Thorex	0.66[c]	1.35	3.50
Reacidified Thorex	0.33	0.33	0.82
Acidic Thorex Glass	0.33[d]		

[a]2.80 Years for lead casks.
[b]1.70 Years for lead casks.
[c]0.82 Years for lead casks.
[d]0.63 Years for lead casks.

7. DISPOSAL IN SALT MINES[5]

To estimate the costs of final disposal of the pot-calcined wastes in salt, a conceptual design of a disposal facility was developed wherein the shipping cask was removed from a rail car, carried into a hot cell where it was unloaded, and the cylinders were then lowered down a shaft into a motorized carrier at the working level of the mine. Figure 8 is a plan view of one quadrant of a 1-sq-mile disposal area, served by a mining and personnel shaft and a waste shaft. Operations would be conducted, making use of the double tunnel arrangement shown here, so that the salt mining is completely isolated from the disposal operations taking place concurrently. The motorized carrier would move from the base of the shaft out to the current disposal area, a room 50 by 300 ft in cross-section and 20-ft high, where the cylinder would be lowered into a hole in the floor and backfilled with crushed salt. Yearly mine space requirements, calculated assuming a maximum allowable salt temperature of 200°C and a maximum waste temperature of 900°C, ranged from 2 to 20 acres/yr for Purex waste and from 0.7 to 10 acres/yr for Thorex waste.

Costs were developed for disposal of various combinations of vessel diameter and waste type in a 1000-ft-deep mine, assuming $2 per ton for salt removal, and ranged from about 6×10^{-3} to 16×10^{-3} mill/kwh$_e$ for disposal of wastes aged 30 and 1 year, respectively.

8. TOTAL MANAGEMENT COSTS

Total management costs, obtained as a function of interim liquid storage time and for shipment and final disposal in salt at age 30 years, are given for acid Purex and Thorex wastes in Table 4. All costs are given in units of 10^{-3} mill/kwh$_e$. Costs for liquid storage increased with storage time to 9.5×10^{-3} mill/kwh$_e$ for 30 years storage. Pot calcination costs decreased as the waste age at time of calcination increased up to 10 years, since the older wastes permitted processing in larger, more economical cylinders. Interim solids storage costs for times equal to the differences between those of interim liquid storage and 30 years, decreased slightly with the required storage time. Costs for 500-mile shipments were simply a function of the number and size of the cylinders which were to be handled, as was the variations in costs for disposal in salt. The total costs for acid waste management were at a minimum of about 26×10^{-3} mill/kwh$_e$, at interim storage times between 3 and 10 years.

Management costs for alkaline wastes are shown in Table 5. . The total costs are significantly higher than for acid wastes because of the higher calcination and shipment costs. This is due to the greater volumes of calcined solids produced from alkaline wastes which have been neutralized with caustic. A minimum cost of about

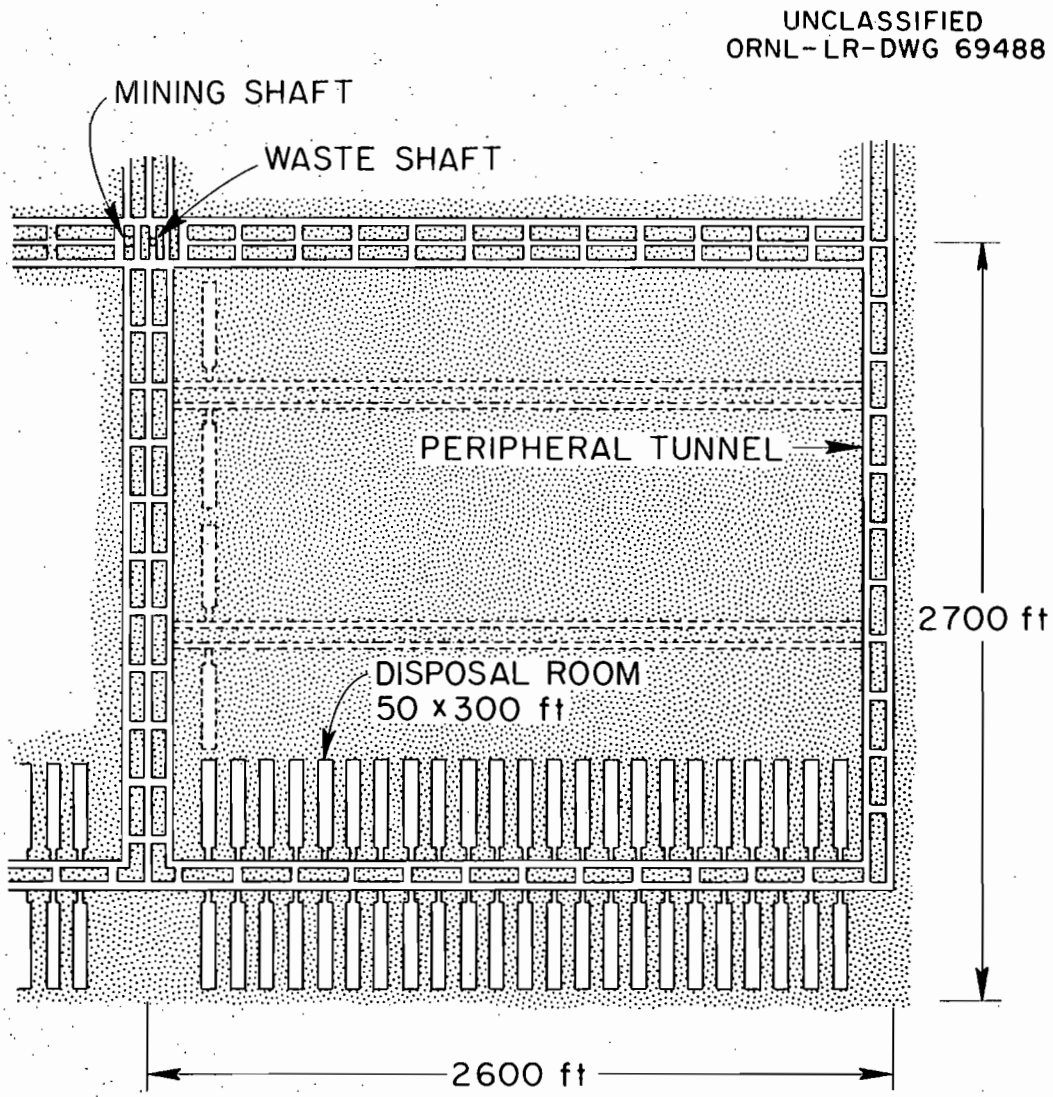

Fig. 8. Plan View of one Quadrant of 1-Mile Disposal Area.

Table 4. Management Costs in Thousandths of a Mill per Electrical KWH for Acid Purex and Thorex Wastes

Management Operation	Interim Liquid Storage Time (Years) 0	1	3	10	30
Int. Liquid Storage	0	2.7	4.0	6.4	9.5
Pot Calcination	16.1	12.4	9.1	8.7	8.7
Int. Solid Storage	4.6	4.6	4.4	3.9	0
Shipment	3.5	3.5	2.8	2.5	2.5
Disposal in Salt	6.1	5.7	6.0	7.3	7.3
Total	30.3	28.9	26.3	28.8	28.0

Table 5. Management Costs in Thousandths of a Mill per Electrical KWH for Alkaline Purex and Thorex Wastes

Management Operation	Interim Liquid Storage Times (Years) 0	1	3	10	30
Int. Liq. Storage	0	1.9	2.5	3.6	5.0
Pot Calcination	25.7	16.9	15.7	15.6	15.6
Int. Solids Storage	6.5	6.4	6.2	5.9	0
Shipment	8.7	5.8	5.1	5.1	5.1
Disposal in Salt	6.6	5.6	6.2	6.2	6.2
Total	47.5	36.6	35.7	36.4	31.9

32×10^{-3} mill/kwh$_e$ was obtained at an interim liquid storage time of 30 years.

Table 6 summarizes the costs for management only of Thorex waste as a glass, prepared in 6-in.-diam cylinders, with no interim liquid storage. The cylinders were stored for 30 years in canals before shipment 500 miles to a salt mine for disposal. The total cost, 85×10^{-3} mill/kwh$_e$, reflects a very high cost for glass preparation, in turn caused by the much lower processing rates than are possible with calcination.

9. CONCLUSIONS

As is true of all economic studies, the results of the present investigation must be interpreted in the light of the basic assumptions and the accuracy of the many cost factors that went into it. While most confidence can be placed in the estimates of liquid waste storage, solids storage in canals, and shipment because construction costs and operating experience actually exist, considerable care was taken in all cases to keep the studies internally consistent and realistic by recourse to current information from development.

While it is not possible to define rigorously the economic limits a nuclear power industry could afford for high-activity waste management, consideration of other costs in the reactor fuel cycle leads us to believe that a 1- to 2- per cent contribution to the power cost for waste management would be acceptable. In terms of 8-mill power, this would amount to 0.08 to 0.16 mills/kwh$_e$. Our present estimates - except those for Thorex glass - lie well below this range, indicating the techniques presently being developed are economically realistic.

Table 6. Management Costs in Thousandths of a Mill Per Electrical KWH for Thorex Glass

Management Operation	Cost
Interim Liq. Storage	0
Glass Preparation	67
Interim Solids Storage	12
Shipment	3
Disposal in Salt	3
Total	85

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