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EVALUATION OF ULTIMATE DISPOSAL METHODS FOR LIQUID AND SOLID RADIOACTIVE WASTES

V. EFFECTS OF FISSION PRODUCT REMOVAL ON COSTS OF WASTE MANAGEMENT

J. J. Perona
J. O. Blomeke
R. L. Bradshaw
J. T. Roberts

OAK RIDGE NATIONAL LABORATORY
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CHEMICAL TECHNOLOGY DIVISION
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ABSTRACT

In a study based on optimistic expectations of waste composition from future fission product separations processes, estimated costs for management of wastes from which 90 and 99% of all fission products had been removed were from 70 to 80% of those for management of waste from which no fission products had been removed.

This cost difference is not believed to be sufficient to pay for the separation and final disposal of the fission products, which was not included in the waste management costs; hence, separation does not represent an economic route for waste management unless a substantial market for the fission products exists to pay most of the costs.

As a basis for this study, it was assumed that after fission product removal the waste was identical to neutralized Purex waste in volume and composition of major ingredients. The sequential steps in the management of waste from processing 1500 metric tonnes per year of uranium converter fuel irradiated to 10,000 Mwd/tonne were: interim storage of liquid waste, conversion to solids by pot calcination, interim storage of calcined solid waste, shipment of 1000 miles, and final disposal in a salt mine. Minimum-cost schemes were worked out involving optimum choices of interim liquid and solid storage times, diameter of the waste-calcination cylinder, and age at time of burial in the salt.

Costs for wastes from which fission products had been removed were least for calcination in 24-in.-diam vessels, were not strongly affected by age, and fell in the range of 0.017 to 0.019 mill/kwh$_e$. The lowest cost for acid Purex waste without fission product removal was about 0.024 mill/kwh$_e$, obtained by using either 12- or 24-in.-diam calcination vessels and buried in salt after allowing 30 years for decay of the fission products in the calcined wastes. These costs are equivalent to about $1600 per tonne of fuel for acidic Purex, and about $1100 to $1200 per tonne for the depleted wastes.

INTRODUCTION

This report, the fifth part of a study[1-4] to evaluate the economics and safety of the various steps leading to and including the permanent disposal of highly radioactive liquid and solid wastes, contains estimates of the costs of treatment of Purex waste from recovery of uranium converter fuel and disposal as calcined solids in salt formations with and without prior removal of fission products. The removal of selected ones from high-activity wastes has been practiced on a very limited scale to provide isotopes for use in medicine, research, and industry. However, it has not been economically feasible to remove more than 80 to 90% of most species, and the wastes after fission product removal have often been more difficult to manage because of their greater volumes and higher content of inert solids. It is conceivable that a growth in demand for fission products and improved processes now under development for their recovery could result in routine processing of large quantities of waste without creating effluents requiring more complicated and expensive waste management.

The object of this study is to compare two costs: management costs for wastes from which large fractions of fission products have been removed by improved processes representative of the best future technology and the costs for managing the original wastes with all fission products present. Three cases were studied, each representing a different degree of uniform removal of all fission products: 0, 90, and 99%. The waste was assumed to be acid Purex waste produced by a plant processing 1500 tonnes/year of uranium converter fuel irradiated to 10,000 Mwd/tonne. (The spelling "tonne" is used in this report to mean metric ton.)

Although removal of 90 and 99% of the fission products simplifies the subsequent handling of the wastes from the standpoints of heat dissipation and shielding requirements, the isotopes remaining represent a hazard requiring management under essentially the same conditions of safety as are demanded for the original waste. Costs were estimated in each case, therefore, for the interim storage of liquid waste, pot calcination of waste, interim storage of calcined waste, shipment of the calcined solids, and disposal of the solids in a salt mine. Treatment and disposal schemes were then worked out to minimize the total costs.

No attempt was made to estimate the costs of fission product removal or subsequent disposal of used fission product sources, because there is not yet sufficient information about the separations processes or source characteristics to permit accurate cost estimates.

SIMPLIFYING ASSUMPTIONS

For this study, a number of assumptions were necessary either for simplicity or because of uncertainties about future separation processes for fission products. It is believed that the following assumptions which form the basis for this study do not compromise the objective or greatly restrict the applicability of the results.

1. Fission product separations are performed with acid Purex waste. In other studies of this series, costs were estimated for the management of a combination of Purex and Thorex wastes assumed to be produced by a 6-tonne/day plant processing uranium and thorium converter fuels from a 15,000-Mw_e nuclear economy. For the present study, only a single type of waste (Purex) was selected. Purex waste, because of its greater chemical simplicity, is generally conceded to be a preferred one from which to extract fission products.

The Thorex process[5] for thorium fuels produces a waste with a high content of aluminum, making recovery of fission products difficult. A new "Acid Thorex" process,[6] which has been developed on a laboratory scale, produces a waste similar to Purex if evaporated to 100 and 120 gal/tonne in acid or neutralized form (compared with 50 and 60 gal/tonne for Purex). Judging from its aluminum and iron content, calcination of the Acid Thorex waste would yield a volume of solid waste, per tonne of fuel processed, also about twice that of calcined Purex. Since thorium converter fuel was assumed to be irradiated to 20,000 Mwd/tonne in the previous studies, fission product concentrations would be the same for the two wastes in either the liquid or the solid state. Therefore, if the Acid Thorex process is successfully demonstrated, all waste management costs (including those estimated in this study) would be approximately the same for thorium converter fuel as for uranium converter fuel.

2. The waste is treated for removal of 90 and 99% of all fission products. Present technology would allow the removal of 90 to 99% of any particular fission product, but removal of the remainder would become increasingly difficult. Therefore, rather than attempting to explore the effects of removal of the many different fission products singly or in the many combinations of groups of two or three at various recovery levels,

which represents the present state of technology, it seemed reasonable to study the limiting case of uniform removal based on a future technology for supplying a market that can use all the fission products.

3. The wastes after fission product removal are identical in volume and chemical composition to neutralized Purex waste. A process for recovery of all important fission products has not yet been developed, although ORNL and Hanford Laboratories are working on such integrated processes.[7,8] In a very preliminary Hanford flowsheet[9] formaldehyde-treated Purex waste at 30 gal per tonne of uranium would first be centrifuged, resulting in removal of about half the zirconium-niobium. Cesium would be recovered by precipitation as the phosphotungstate, and strontium and rare earths would be recovered by solvent extraction with di(2-ethylhexyl) phosphoric acid and tributyl phosphate. Of the important fission products, only ruthenium would not be removed. A rather optimistic approximation of the liquid-waste composition from the process is 8.0 $\underline{M}$ Na^+, 1.1 $\underline{M}$ NO_3^-, 0.7 $\underline{M}$ SO_4^{2-}, and 3 $\underline{M}$ CO_3^{2-}, and it should have a specific volume of 60 gal per tonne of uranium. Because this stream is alkaline and has the same specific volume, its costs for interim liquid storage would be similar to those for neutralized Purex, with adjustments for lower cooling requirements due to fission product removal.

Pretreatment for pot calcination would probably consist of adding a 10% excess of sulfuric acid to destroy carbonate. The carbon dioxide would be boiled off, and this would be followed by addition of a calcium salt to form calcium sulfate and prevent sulfate decomposition during calcination. The resultant calcined solids (like calcined reacidified Purex waste) would consist primarily of sodium sulfate and have a specific volume of about 13 gal per tonne of uranium processed. Therefore, pot calcination, interim storage of solids, shipping and disposal costs would be similar to those for reacidified Purex waste, with downward adjustments for lower cooling and shielding requirements due to fission product removal. These assumptions are believed to be optimistic.

4. The costs of separating the fission products and for all subsequent management of the fission product concentrate cannot now be estimated. The costs of fission product separation, source preparation, marketing, and eventual disposal of fission product sources cannot be estimated with a reasonable degree of reliability until much further development of the fission product industry has taken place. Nevertheless, this

study, within the scope herein defined, can provide a quantitative estimate of the reduction in costs of waste management to be gained by fission product removal. If this reduction were large, a subsidy could be paid for fission product separation and management.

COSTS FOR INTERIM STORAGE OF LIQUID WASTE

Discussed in this section are the costs for the interim storage of liquid wastes prior to calcining for permanent storage. The conceptual design and methods of cost estimation used in Part I of this report series are used in these studies.[1] Tanks of Savannah River type are assumed, with sufficient cooling coils to hold the waste temperature at 140°F. Mild steel tanks and cooling coils are used for storing alkaline wastes from which the fission products had been removed. Pumps circulate cooling water through the coils and through a heat exchanger, where the primary cooling water is cooled by exchange with a secondary loop including a cooling tower.

The tank costs for neutralized Purex are used, except that cooling-coil surface (and hence cost) is less by factors of 10 and 100 for wastes from which 90 to 99% of the fission products had been removed. Tank costs for fission product removal wastes are shown as a function of tank sizes in Fig. 1. Coil costs are less than 3% of tank costs for wastes from which 90% of the fission products have been removed, so that the difference in total tank costs for 90- and 99%-depleted wastes is negligible. Tank costs for acid Purex waste previously calculated[1] are also shown in Fig. 1. Spare tankage and present-worth concepts are applied as before to obtain capital costs per year for tanks as a function of storage times. In Fig. 2, tank capital cost per year for different dead storage periods is plotted against the interim liquid storage time, 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 liquid-storage time. The dashed curve represents the loci of minimum tank capital costs per year as a function of the interim liquid-storage time.

Tank farm cost items are: cooling towers, heat exchangers, pumps, pump motors, and cells and secondary containment for heat exchangers and pumps. Heat loads from uranium converter waste and costs of tank farm

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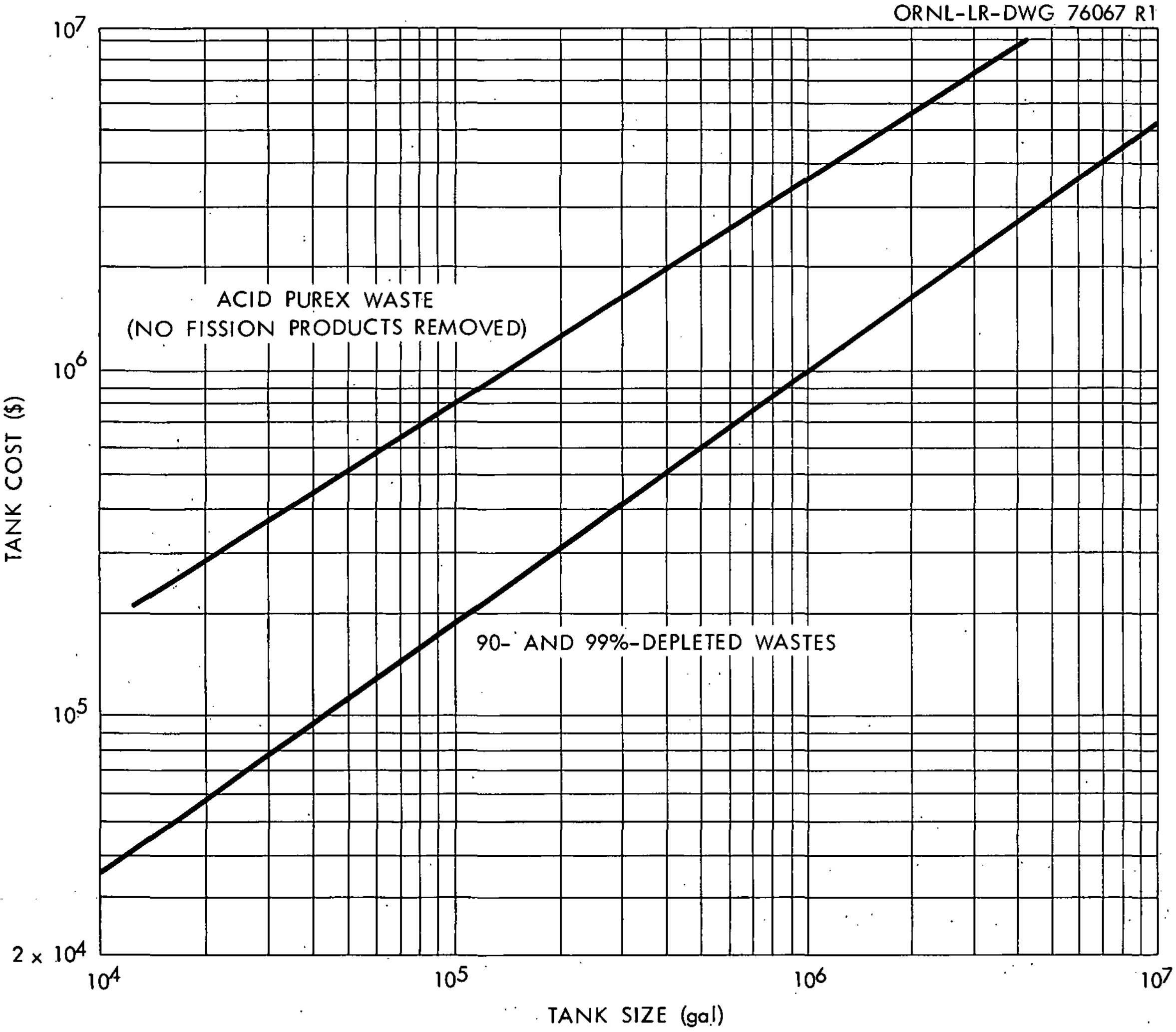

Fig. 1. Cost of tanks, including cooling coils.

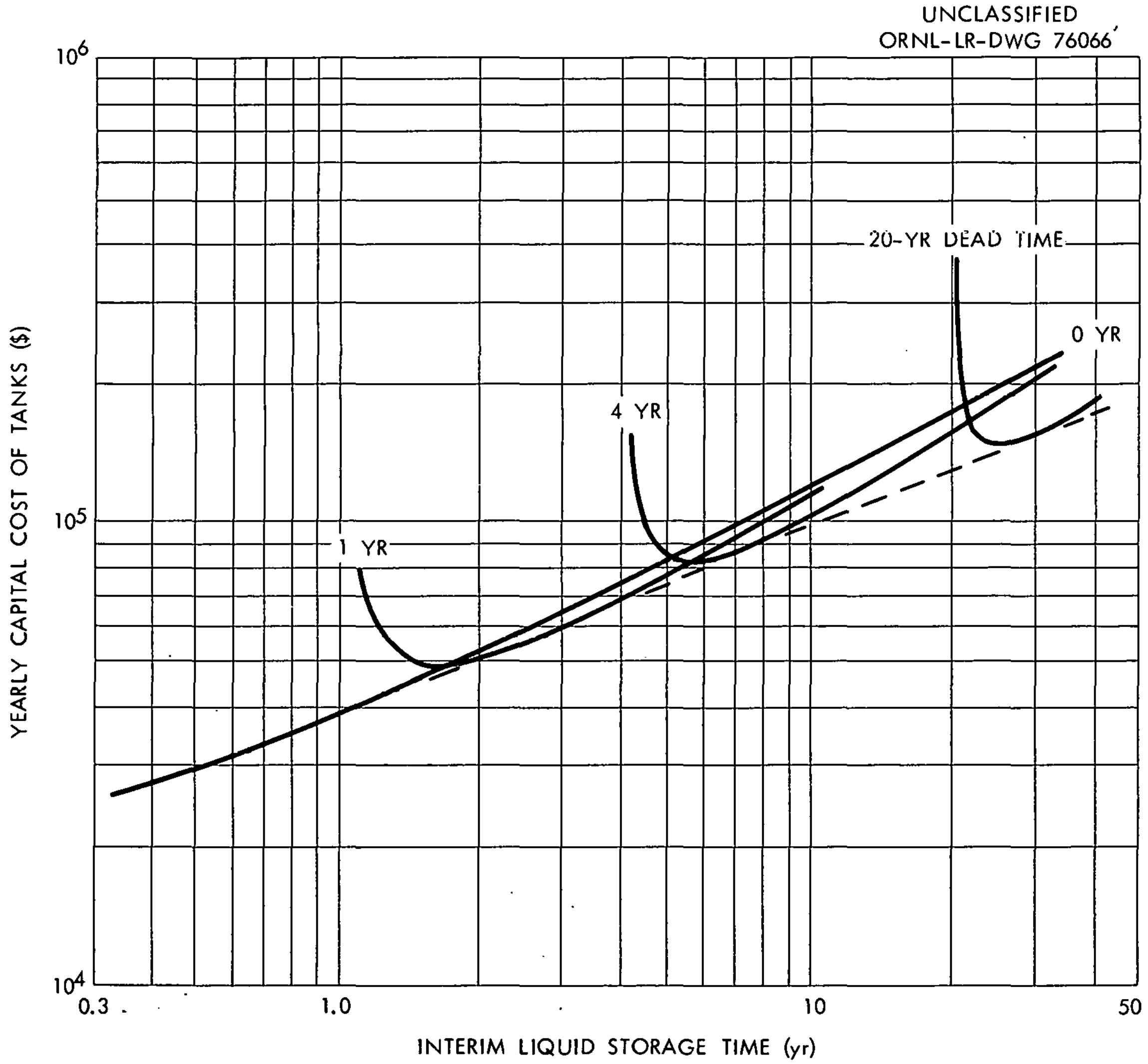

Fig. 2. Yearly capital costs for tanks for depleted wastes.

items are given in Table 1 as functions of interim storage period for 90%-depleted wastes. Cell and secondary containment costs are amortized over 60 years, and all other costs over 20 years. Tank farm capital costs are summarized in Table 2 as a function of interim storage period for 90%-depleted wastes. Tank farm costs per year are less than 10% of the total capital costs per year for the 90%-depleted wastes, and therefore cooling equipment costs are assumed to be negligible for the 99%-depleted waste.

Table 2. Total Capital Cost for Tank Farms (Excluding Cost of Tanks) for Interim Storage of 90%-Depleted Waste

	Duration of Interim Storage (yr)				
	0.5	1	3	10	30
Sum of 20-year-amortized items	$22,100	$30,700	$44,900	$61,800	$86,700
Cost per year (includes interest)	1,630	2,260	3,300	4,550	6,380
Sum of 60-year-amortized items	36,000	36,000	44,000	52,000	66,000
Cost per year (includes interest)	1,590	1,590	1,940	2,300	2,920
Total cost per year	3,220	3,850	5,240	6,850	9,300

Operating cost items are: make-up water for the cooling tower, electricity, and labor. Water and power costs are directly proportional to the heat load, and ranged from $2,000 to $7,000 a year for storage periods of 0.5 to 30 years for 90%-depleted waste. A labor force of six men is estimated, consisting of four watchmen and one supervisor for round-the-clock surveillance, plus one man-year of maintenance service available on an as-needed basis from the processing plant. Thus the total labor cost is $75,000/year based on six man-years at $12,500 per man-year, including overhead. Most of the maintenance labor would be used on the cooling system; hence, the maintenance labor is less for the storage of depleted waste from that for the three man-years assumed for other wastes.

Total costs per year are converted to mills/kwh$_e$, using the assumed electrical output of the uranium converter reactors of 9.72×10^{10} kwh$_e$/year. For the 90%-depleted waste, costs ranged from 0.0011 to 0.0025 for storage periods from 0.5 to 30 years (Fig. 3). Costs for 99%-depleted wastes were 4 to 6% less. Cost for acid Purex wastes ranged from 0.0018 to 0.0069 mills/kwh$_e$.

Table 1. Capital Costs of the Cooling Systems in Tank Farms for Interim Storage of 90%-Depleted Liquid Wastes

The heat-generation rates set the costs.

Cost-Item No.		Duration of Interim Storage (yr)				
		0.5	1	3	10	30
	Heat-generation rate, Btu/hr	1.6×10^6	2.3×10^6	3.5×10^6	4.7×10^6	6.8×10^6
1	Cost of cooling tower	$3,200	$4,600	$7,000	$9,500	$13,600
2	Cost of heat exchangers ($1900 each)	$5,700	$7,600	$11,400	$15,200	$22,800
	Heat exchanger surface, ft^2	530	770	1160	1580	2270
	No. of 200-ft^2 units	3	4	6	8	12
3	Cost of cooling tower pumps ($1000 each)	$8,000	$10,000	$14,000	$20,000	$28,000
	Pump duty, gpm	320	460	700	950	1360
	No. of 100-gpm units (1 spare each)	8	10	14	20	28
4	Cost of tank-coil pumps ($1000 each)	$2,000	$4,000	$6,000	$8,000	$10,000
	Pump duty, gpm	100	150	230	320	450
	No. of 100-gpm units (1 spare each)	2	4	6	8	10
5	Cost of pump motors ($325 each)	$3,200	$4,500	$6,500	$9,100	$12,300
	Electric pump motor, 4 hp (1 spare each)	10	14	20	28	38
6	Cost of pump and heat-exchanger cells and secondary containment	$36,000	$36,000	$44,000	$52,000	$66,000

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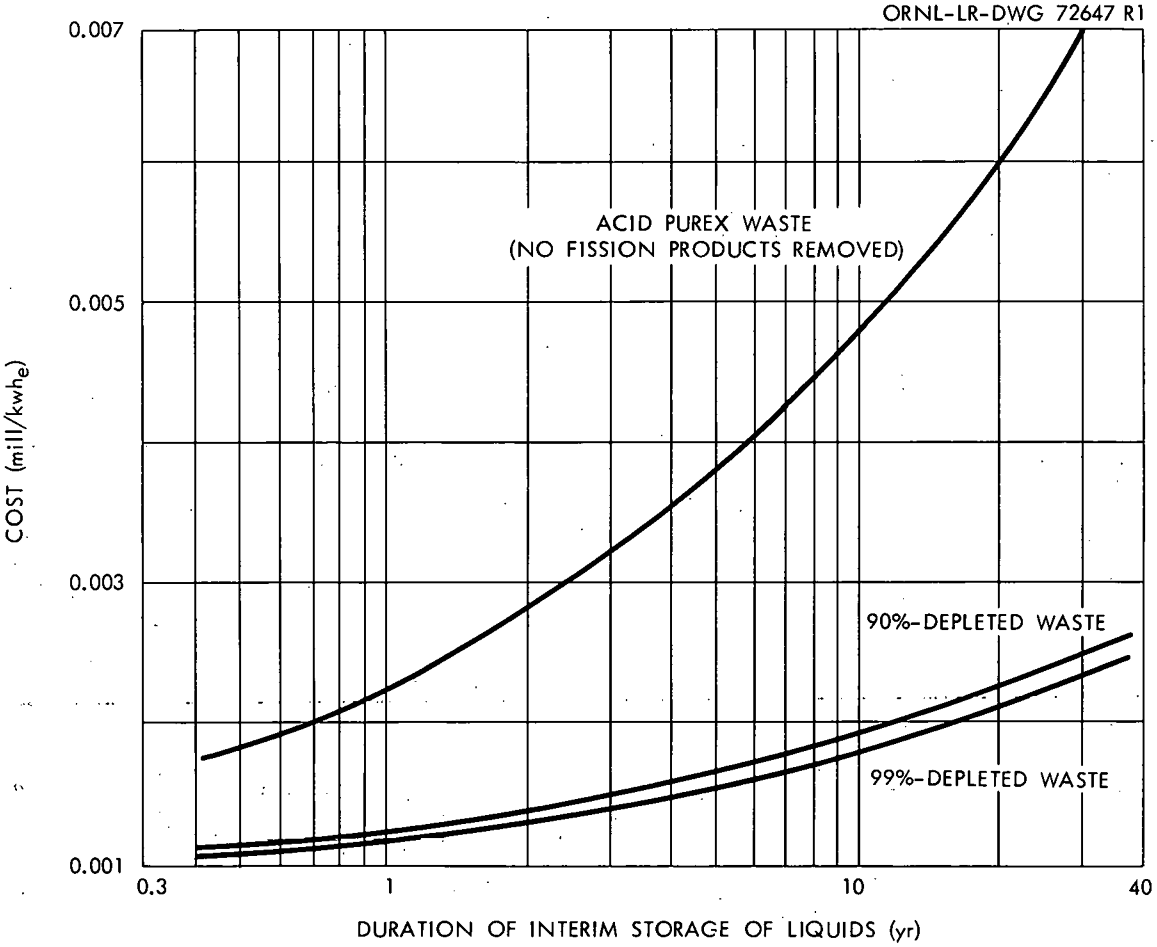

Fig. 3. Costs for interim storage of liquids.

COST OF POT CALCINATION

With respect to the cost of pot calcination, the same conceptual designs and methods of cost estimation are used as in the second study of this series.[2] Total costs are made up of pot costs, capital costs, and operating costs. Pot costs are obtained by multiplying the cost per vessel ($500, $855, and $2515 for 6-, 12-, and 24-in.-diam pots) by the number produced per year. The processing of depleted wastes would require the same number of vessels as would reacidified Purex, because the specific volumes of the two wastes are about the same. Two filling cycles were assumed for filling the pots 60% full of solids, and the number of vessels produced per year with depleted waste is 2320, 580, and 145 for 6-, 12-, and 24-in.-diam cylinders (Table 3).

Capital and operating costs were expressed as functions of plant floor area in the previous report.[2] Total floor area was subdivided into a calcination area, which was proportional to the number of pot lines required, an evaporator and off-gas equipment area, and a testing and decontamination area. Methods for calculating plant floor area for the various waste types and cylinder sizes are also given in the previous report.[2]

Fission product removal would permit a reduction in shielding-wall thickness in the pot-calcination plant. This would reduce capital costs, but with removal levels of only 90 and 99% (decontamination factors of 10 and 100) this reduction in cost is negligible. Therefore the costs of pot calcination are the same for reacidified Purex waste and the depleted wastes.

The costs of reducing liquid wastes to solids by pot calcination vary from 21.5 to 11.3 x 10^{-3} mills/kwh_e for depleted wastes and from 12.3 to 8.1 x 10^{-3} mills/kwh_e for acid Purex waste from which no fission products have been removed (Table 3). Costs are highest for processing in 6-in.-diam vessels, and appear to approach a minimum with 24-in.-diam vessels (Fig. 4).

The reduction in heat generation would permit the depleted wastes to be calcined in 24-in.-diam vessels with no interim liquid storage, that is, at an age of 0.33 years.

Table 3. Costs for Pot Calcination

Diameter of Pot (in.)	Number of Pot Lines	Number of Pots Produced per Year	Floor Area (ft^2)	Cost of Pots ($/yr)	Operating Cost ($/yr)	Capital Cost ($/yr)	Total Cost ($/yr)	Total Cost Expressed in mills/kwh_e
				Acid Purex Waste (No Fission Products Removed)				
6	3	925	900	462,000	580,000	160,000	1,200,000	12.3×10^{-3}
12	3	231	820	197,000	546,000	144,000	887,000	9.1×10^{-3}
24	2	58	710	145,000	507,000	134,000	786,000	8.1×10^{-3}
				Depleted Waste				
6	7	2320	1400	1,160,000	734,000	192,000	2,086,000	21.5×10^{-3}
12	4	580	960	496,000	592,000	156,000	1,240,000	12.8×10^{-3}
24	4	145	930	365,000	581,000	153,000	1,100,000	11.3×10^{-3}

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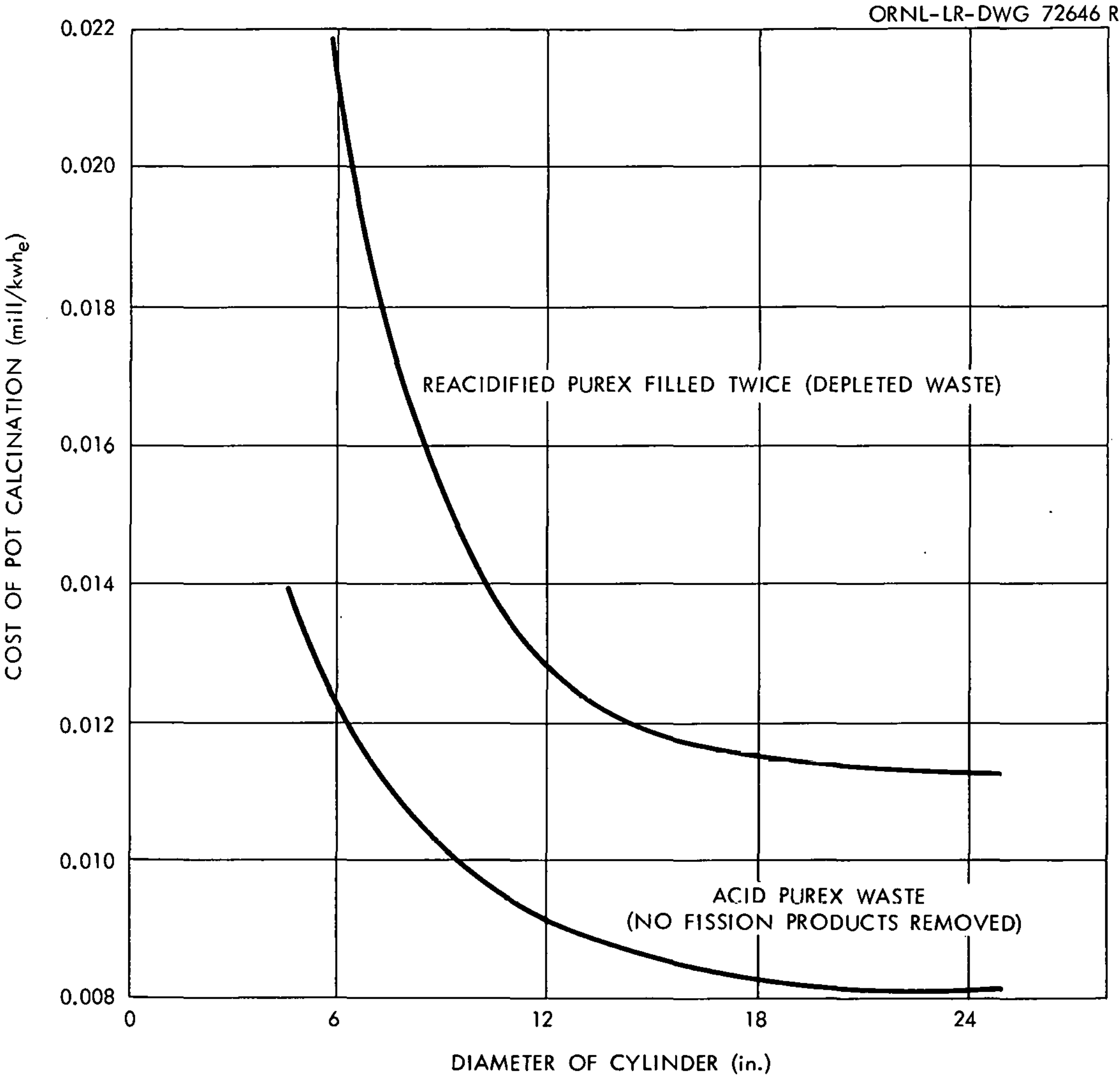

Fig. 4. Costs for pot calcination

COSTS OF INTERIM STORAGE OF CALCINED SOLIDS

For the interim storage of calcined solids, the same conceptual designs and methods of cost estimation were used as in the third study of this series.[3] In that report, the cylinders are assumed stored in concrete-walled canals filled with water as a shielding material. The water also serves as a coolant and is continuously withdrawn and circulated through heat exchangers in which heat is transferred to a loop connected to a cooling tower. A portion of the water is withdrawn from the primary cooling loop and sent through a demineralizer system.

The canal walls are coated with an epoxy paint for water tightness and to make decontamination possible. The canals are designed with 25% excess capacity and compartmentalized so that canal segments can be emptied and maintained. Aluminum partitions are used to subdivide the water flow through the canals to expedite detection and location of any leaky cylinders.

Fission product removal permits the water depth to be lowered 1 to 2 ft, but the total canal depth, with 12 ft of water required to cover the tops of the cylinders and 12 to 16 ft required for shielding, is 24 to 28 ft. A lighter crane for shipping cask handling can be used with the depleted wastes than with untreated wastes, but total capital costs are not appreciably affected by shielding considerations.

The cost of the cooling system decreases significantly with fission product removal, and becomes a small enough part of the total cost that the difference in total costs for the interim storage for 90%- and 99%-depleted wastes is not appreciable. The cooling system costs for 90%-depleted waste are less than 2% of the total yearly costs (Table 4).

The only important operating expense is for labor. As in the case of interim liquid storage, four watchmen and a supervisor are assumed required for round-the-clock surveillance. In addition, one health physicist and one maintenance man are assumed required, resulting in a total labor cost per year of $87,500, including overhead. Most of the maintenance labor would be used on the cooling system; hence the maintenance labor is reduced for the storage of depleted wastes from the 3 man-years assumed for other wastes.

Table 4. Costs of Interim Storage of Calcined Solids Made from Depleted Wastes

Item	Duration of Interim Storage (yr)			
	1	3	10	30
Capital cost (excluding cooling system), \$/yr	29,400	49,000	109,000	199,000
Cooling system cost (90% removal), \$/yr	2,800	3,800	4,900	6,700
Overhead, engineering, and contingency, \$/yr	24,100	39,600	85,500	154,000
Total capital cost, \$/yr	56,300	92,400	199,000	360,000
Total, including operating cost, \$/yr	144,000	180,000	286,000	447,000
Total cost, mills/kwh_e	1.5×10^{-3}	1.8×10^{-3}	2.9×10^{-3}	4.6×10^{-3}

Costs of interim storage of calcined fission product removal wastes ranged from 0.0015 to 0.0046 mills/kwh_e for storage period of 1 to 30 years (Fig. 5). For short storage periods, where cooling system costs were important, storage of fission product removal wastes was cheaper than storage of acid Purex. For long storage periods, the larger number of cylinders of fission product waste to be stored caused the costs for acidic Purex to be cheaper.

COST OF SHIPMENT OF CALCINED SOLIDS

With respect to the shipping cost of calcined solids, the same conceptual designs and methods of cost estimation were used as in the fourth study of this series.[4] Heat transfer considerations do not limit the cask size for fission product removal wastes up to the largest size considered manageable, which is 60 in. in inside diameter and would hold four 24-in.-diam, nine 12-in.-diam, or thirty-six 6-in.-diam cylinders. Depleted wastes can be shipped at their assumed minimum age of 120 days in the largest cask.

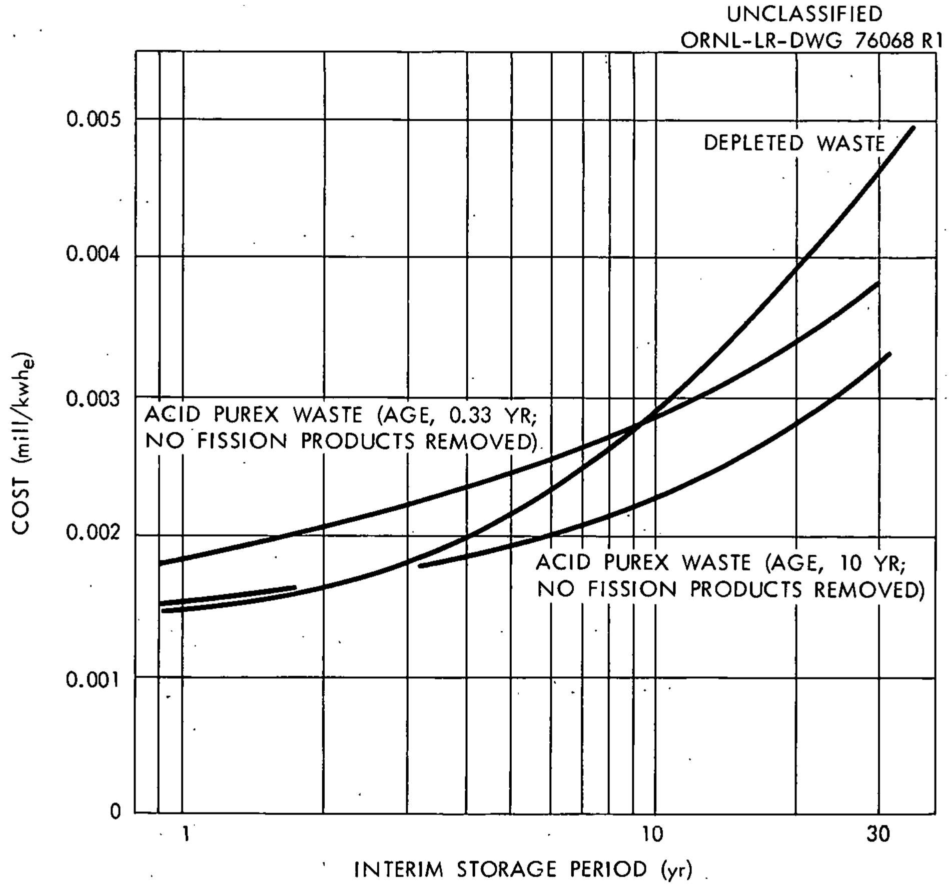

Fig. 5. Costs for interim storage of calcined solid wastes as functions of storage period and age at start of storage.

In that report, the casks are assumed to be hollow cylinders, with the waste cylinders held inside in a square array by a spacing structure. The waste cylinders are assumed to be separated by a distance equal to a third of their radius. The casks do not contain liquid coolants or mechanical cooling equipment; hence it is assumed that couriers would not be required.

Lead was chosen as the shield material, because it was shown to result in lower shipping costs than would iron or uranium shielding.[4] Fission product removal reduced shielding thickness requirements about 25% for 90% removal and about 50% for 99% removal, compared with acid Purex waste (Fig. 6) from which no fission products have been removed. Cask weights (empty) ranged from 71 to 28 tons for 90%-depleted waste and from 55 to 14 tons for 99%-depleted waste for ages at shipping of 0.33 to 30 years (Table 5). Cask costs were estimated assuming $0.75/lb, including engineering and overhead. Costs per year were obtained by amortizing over ten years at 4% interest.

Table 5. Costs and Weights of Shipping Casks for Depleted Wastes as a Function of Age at Time of Shipping

Items	Age of Depleted Waste (yr)				
	0.33	1	3	10	30
	90%-Depleted Waste				
Thickness of shield, cm of Pb	22.2	20.6	18.6	14.5	10
Weight of cask, tons	71	65	58	43	28
Cost of cask	$106,000	$97,500	$87,000	$64,500	$42,000
Cost of cask per year	$13,100	$12,000	$10,700	$ 7,900	$ 5,150
	99%-Depleted Waste				
Thickness of shield, cm of Pb	17.9	16.2	14.1	10.2	5.2
Weight of cask, tons	55	49	42	29	14
Cost of cask	$82,500	$73,500	$63,000	$43,500	$21,000
Cost of cask per year	$10,100	$ 9,000	$ 7,700	$ 5,300	$ 2,560

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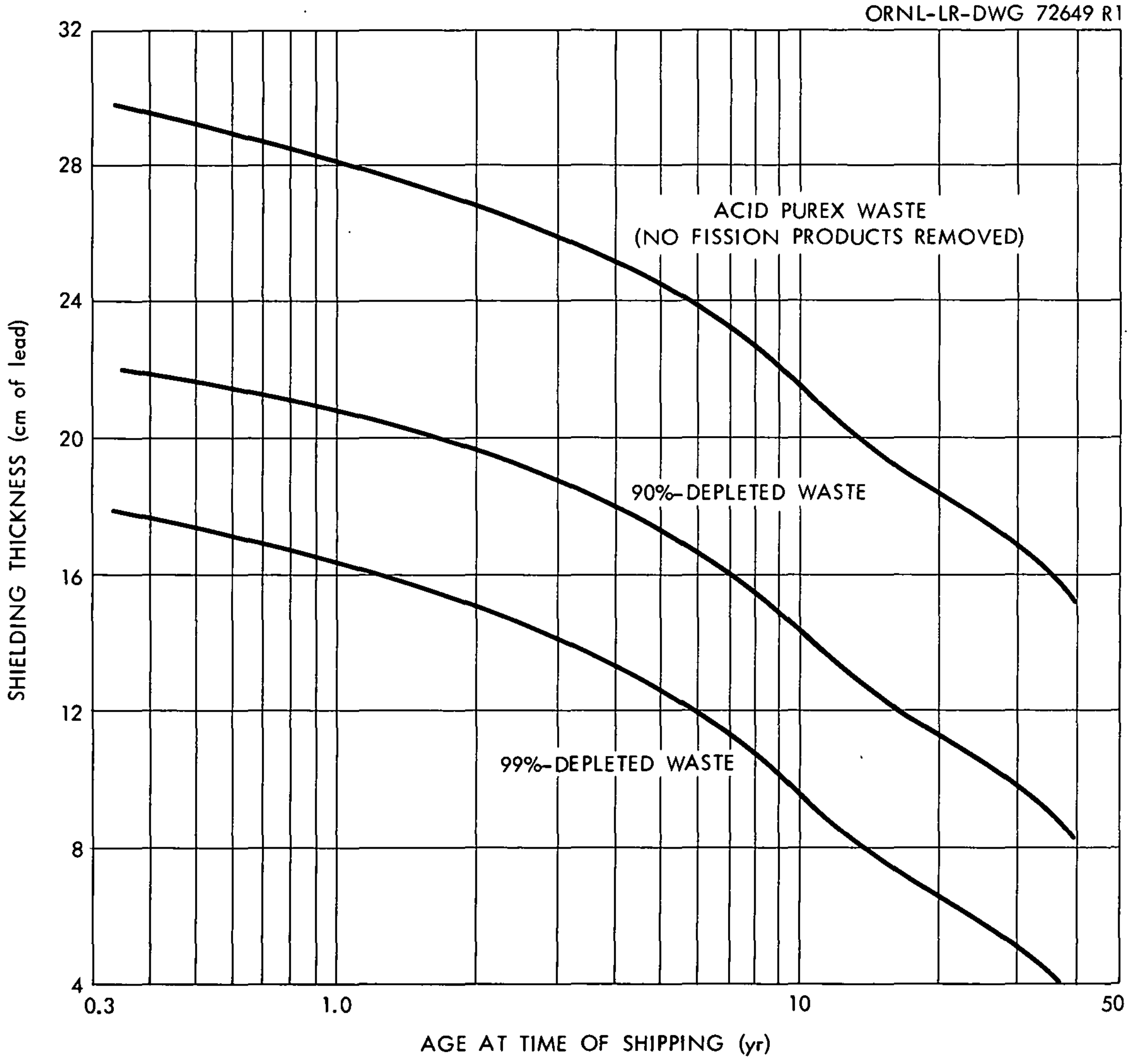

Fig. 6. Carrier wall thickness as a function of age and degree of fission product removal.

For purposes of this study shipping costs are calculated for a one-way distance of 1000 miles (2000-mile round trip), which is about in the middle of the range of interest. Of the three cost items, namely cask, freight, and handling, the freight costs account for 80 to 90% of the total in all cases (Table 6). Rail freight costs were computed assuming a rate of $44 per ton for loaded casks, with a 30% discount for return of the empty casks. Handling costs consisted of labor costs for loading, unloading and decontaminating operations, plus amortization costs for an unloading crane.

Shipping costs are lower for 24-in.-diam cylinders than for 6 or 12-in.-diam cylinders because the casks would contain a smaller fraction of void space with 24-in. cylinders. Costs for shipping acid Purex waste were lower than those for 90%-depleted waste and in the same neighborhood as those for the 99%-depleted waste, because the lower specific volume (gallons of waste per ton of fuel processed) of acid Purex tends to offset its thicker shielding requirement. Shipping costs for acid Purex and depleted wastes up to 30 years of age fell in the range of 0.5 to 5 x 10^{-3} mill/kwh$_e$ (Figs. 7 and 8).

COST OF FINAL STORAGE OF CALCINED WASTE IN SALT MINES

In the conceptual design, a shipping cask containing cylinders of calcined waste is unloaded from a rail car and moved into a hot cell, which contains cask decontamination and cylinder-recanning facilities, cylinder storage space, and encloses a shaft down which the bare cylinders are lowered one at a time to the working level. Offices and a changehouse are also located at the hot cell. A second, larger shaft is located nearby for use in the salt mining operations. It was assumed that the hot cell and pair of shafts would serve a one-square-mile disposal area.

Upon reaching the storage level, a cylinder of waste is loaded remotely into a motorized, shielded carrier, which is driven through the mine corridors until a mined room is reached which is ready for final storage use. The amount of undisturbed salt left between these rooms would be determined by the heat-generation rate of the waste and the desired degree of closure of the room due to plastic flow of the salt. The waste cylinders are placed in holes drilled in the floor of the salt room. The

Table 6. Shipping Costs for Depleted Wastes as Functions of Age at Time of Shipping and Diameter of Waste Cylinder

Item	Age of Waste in 6- or 12- in.-diam Cylinders					Age of Waste in 24-in.-diam Cylinders				
	0.33 yr	1 yr	3 yr	10 yr	30 yr	0.33 yr	1 yr	3 yr	10 yr	30 yr
90%-Depleted Waste										
Number of casks required	2	2	2	2	2	1	1	1	1	1
Cost of cask, \$/yr	26,200	24,000	21,400	15,800	10,300	13,100	12,000	10,700	7,900	5,150
Freight cost, \$/yr	376,000	344,000	307,000	227,000	148,000	210,000	191,000	171,000	127,000	82,600
Handling cost, \$/yr	32,000	32,000	31,000	29,000	27,000	22,000	22,000	21,000	19,000	17,000
Total cost, \$/yr	434,000	400,000	359,000	272,000	185,000	245,000	225,000	203,000	154,000	105,000
Total cost, mill/kwh_e	0.0045	0.0041	0.0037	0.0028	0.0019	0.0025	0.0023	0.0021	0.0016	0.0011
99%-Depleted Waste										
Number of casks required	2	2	2	2	2	1	1	1	1	1
Cost of cask, \$/yr	20,200	18,000	15,400	10,600	5,100	10,100	9,000	7,700	5,300	2,550
Freight cost, \$/yr	290,000	258,000	221,000	154,000	74,300	162,000	145,000	124,000	85,700	41,300
Handling cost, \$/yr	30,000	30,000	29,000	27,000	25,000	20,000	20,000	19,000	17,000	15,000
Total cost, \$/yr	340,000	306,000	265,000	192,000	104,000	192,000	174,000	151,000	108,000	58,800
Total cost, mill/kwh_e	0.0035	0.0031	0.0027	0.0020	0.0011	0.0020	0.0018	0.0015	0.0011	0.0006

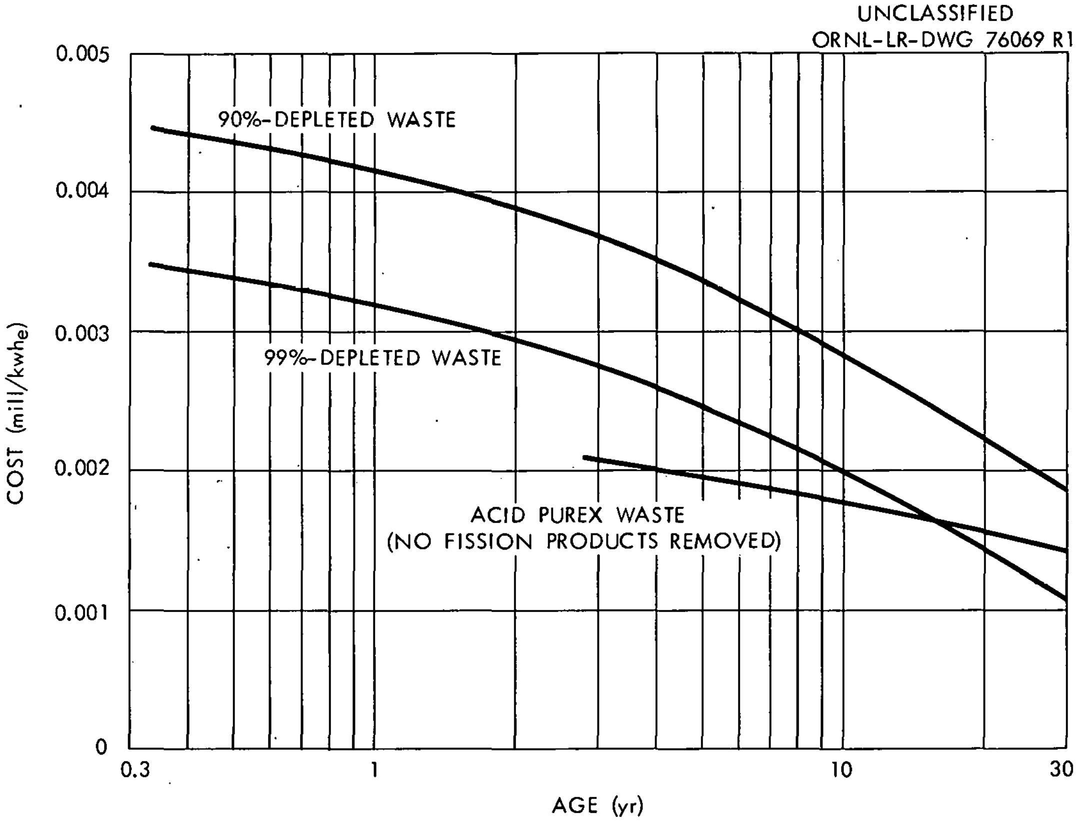

Fig. 7. Costs for shipping calcined wastes in 6- or 12-in.-diam cylinders 1000 miles to a disposal site.

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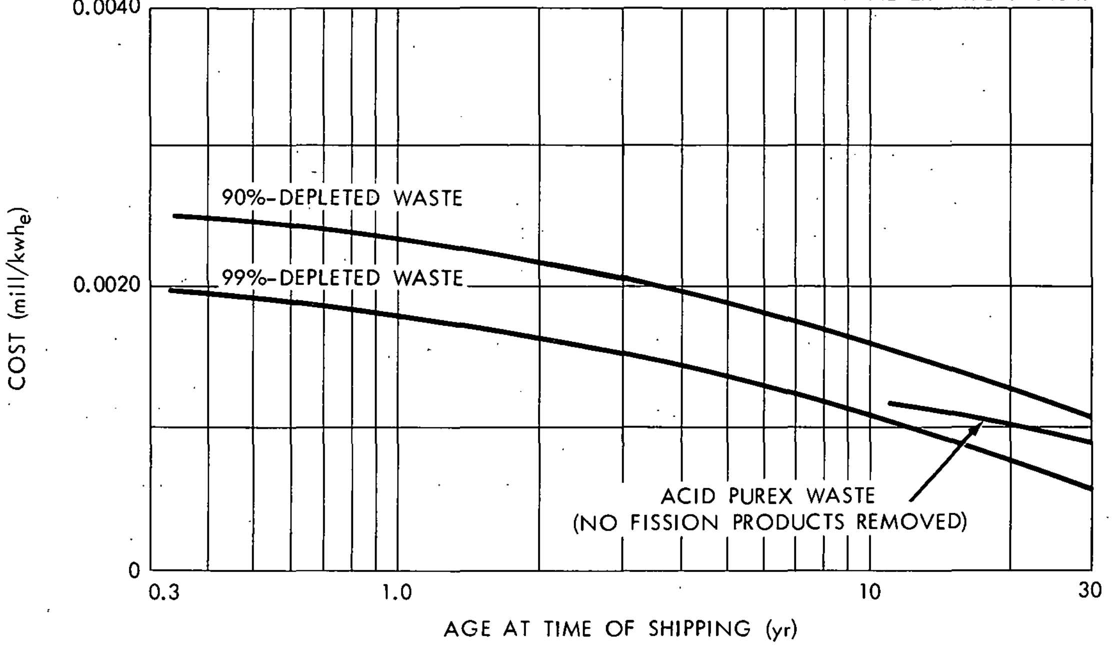

Fig. 8. Costs for shipping calcined wastes in 24-in.-diam cylinders 1000 miles to a disposal site.

distance between the holes is governed by heat transfer considerations, the criteria being that temperatures reached during calcination must not be exceeded during final storage and that peak salt temperatures must not exceed 400°F. After lowering the cylinder into place, the hole is backfilled with several feet of crushed salt to permit access to the room.

Based on this conceptual design, costs are calculated for the disposal of Purex and Thorex wastes.[10,11] Sixty to 85% of the total costs of disposal were due to mining costs, which were calculated on the basis of $2 per ton of salt mined.

The removal of fission products decreases the heat generation rate of the waste and thus allows closer spacing of the cylinders in the floor of the room. For depleted wastes, the limiting salt temperature of 400°F is the controlling rather than the limiting calcination temperature of 1650°F at the axis of the waste cylinder. Mine space requirements range from 2 to 6 acres/yr for acid Purex waste, 0.2 to 1.3 acres/yr for 90%-depleted waste, and 0.04 to 0.17 acres/yr for 99%-depleted waste (Fig. 9). The minimum age at which acid Purex waste in 24-in.-diam cylinders can be placed in the salt formation is about 30 years, so only a single point is plotted for this case. Minimum center-to-center spacings are assumed to be 2, 5.3 and 8 ft for 6, 12 and 24-in.-diam cylinders. Six-in. cylinders filled with 99%-depleted waste are stored at the minimum spacing for all ages.

Disposal costs were calculated assuming that total closure of the salt rooms by creep or flow of the salt would be permissible, provided that the time required would be on the order of decades. Accordingly, 60% of the salt could be extracted for a room 1000 ft below the surface. About 25 to 30% of the mined space would be required for corridors and ventilation tunnels, and the remainder would be available for storage space.

All mining costs, including amortization of the mining lift but not the shaft, are included in the mining charge of $2/ton. Costs for waste-handling facilities are given in Table 7. Amortization factors are computed at 4% interest.

Total costs for disposal in salt mines of wastes up to 30 yr in age range from 6.7 to 13.2 x 10^{-3} mill/kwh$_e$ for acid Purex waste (no fission product removal) and from 3.7 to 5.6 x 10^{-3} mills/kwh$_e$ for depleted waste (Fig. 10).

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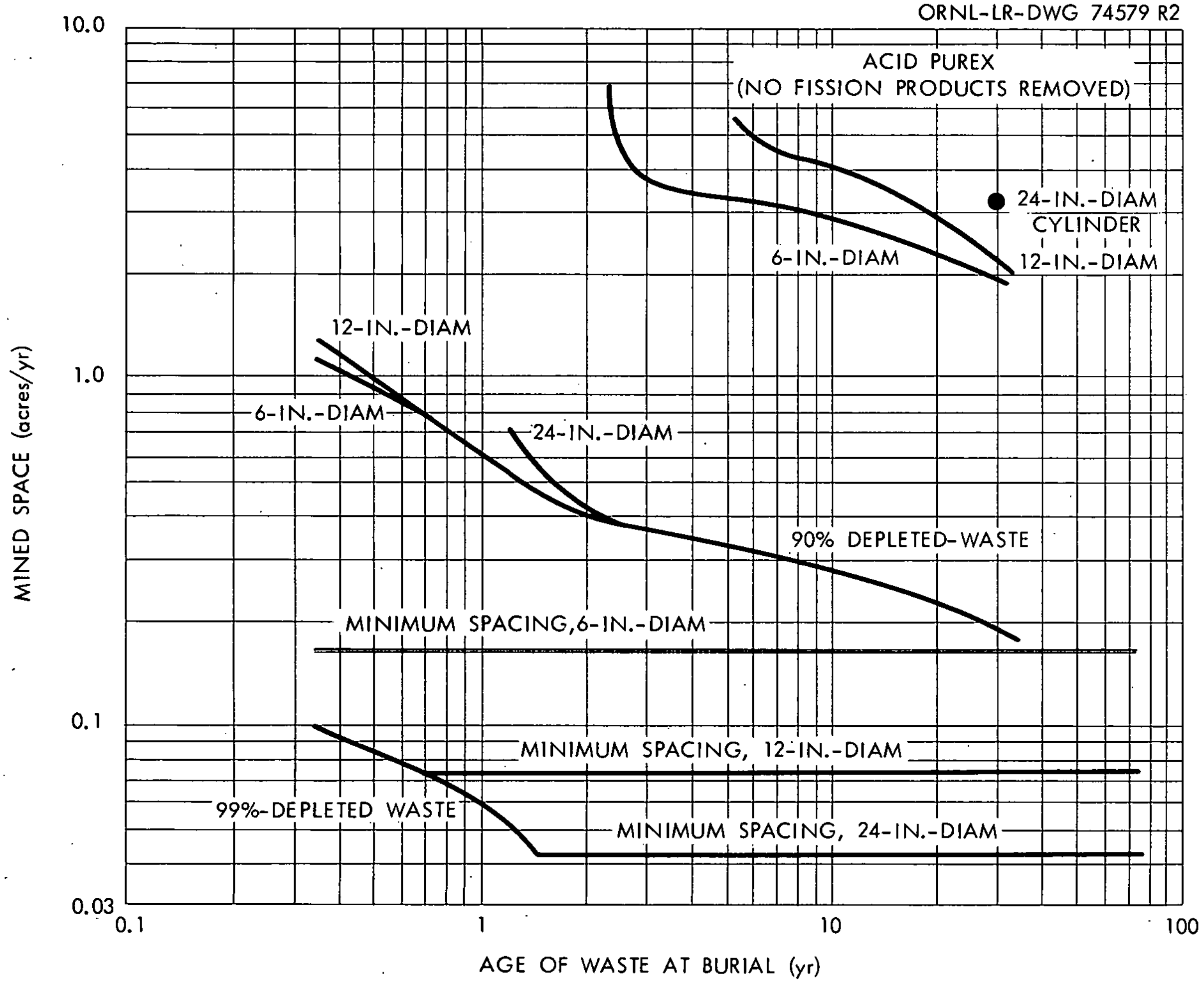

Fig. 9. Mined space requirements in a salt mine for storage of cylinders of calcined waste.

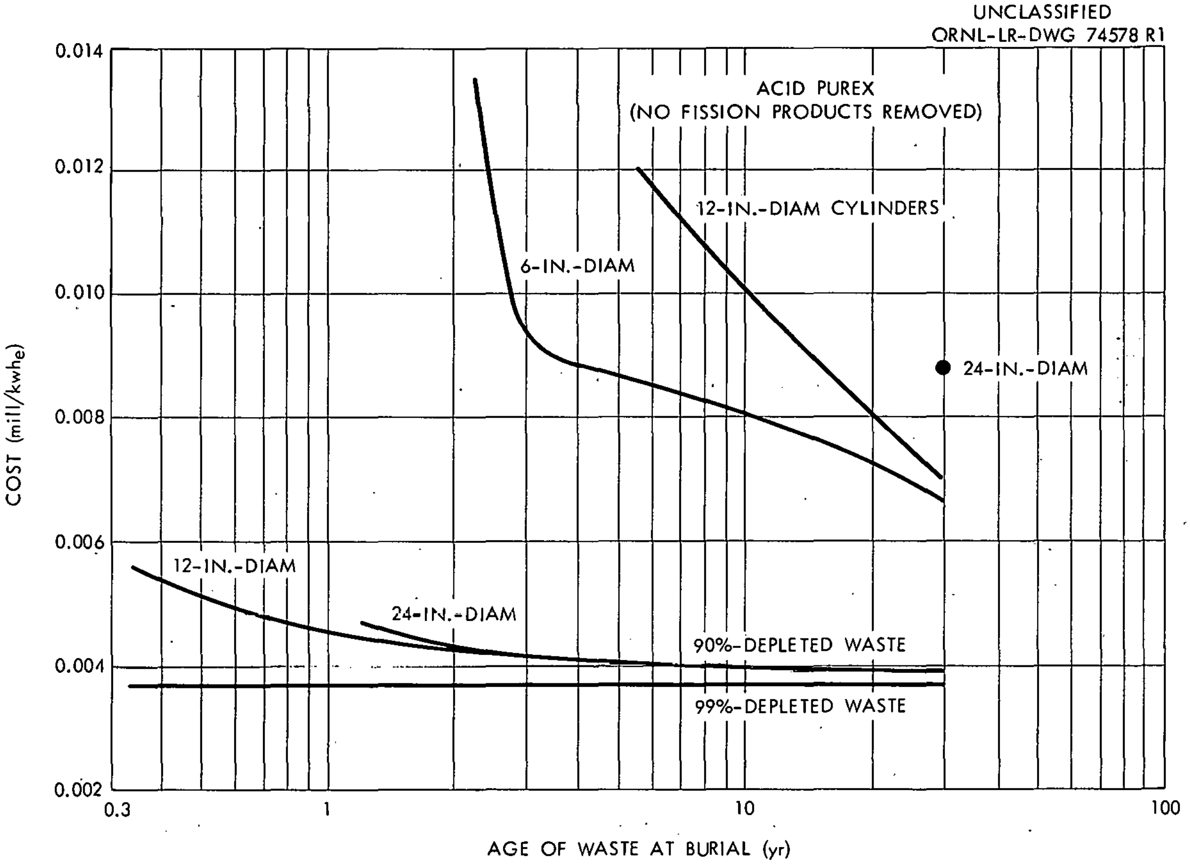

Fig. 10. Costs for burial in a salt mine.

Table 7. Costs and Amortization Periods of Waste-Handling Facilities

Item	Cost	Amortization Period
Waste and mining shafts (total)	$1,000,000	Life of facility
Hot cell	680,000	Life of facility
Bottom facility	300,000	Life of facility
Motorized carrier	100,000	20 yr
Hole driller	50,000	20 yr
Instrumentation	30,000	10 yr

TOTAL WASTE-MANAGEMENT COSTS

The term "total waste-management cost" is used here to mean the cost of disposal in a salt formation plus the costs of all necessary preliminary steps. Recall that the cost of disposal is a function of the age of the waste at burial, diameter of the cylindrical container, and degree of fission product removal. Thus, total waste-management costs reflects these functions.

Minimum ages for burial in salt are 2.3, 5.5 and 30 yr for untreated acid Purex waste (no fission products removed) in 6, 12 and 24-in.-diam vessels; and 1.2 yrs for 90% depleted waste in 24-in.-diam vessels. For all other cases for depleted wastes, the minimum age is 0.33 yr, the assumed age at the time of discharge from the fuel processing plant. In addition to minimum burial ages, there are minimum pot-calcination ages for acid Purex waste, which are 0.6, 2.2 and 6.5 yrs for 6, 12, and 24-in.-diam-vessels.

Prior to computing the costs of interim storage, it next must be observed that storage as calcined solid is cheaper than storage as liquid for untreated acid Purex waste, but for the depleted wastes, liquid storage is cheaper. Even so, some liquid storage must be used for untreated acid Purex waste due to the minimum pot-calcination ages. In obtaining the total waste management costs in Table 8, the minimum cost of interim storage is used, subject to the various minimum age requirements.

Table 8. Analysis of Costs of Waste Management Based on Diameter of Cylindrical Container, Age of Waste at Burial, and Degree of Fission Product Removal

Diameter of Cylinders (in.)	Age of Waste at Time of Burial (yr)	Costs (Multiply All Numbers by 10^{-3})					
		Interim Liquid Storage	Pot Calcination	Interim Solid Storage	Shipping 1000 Miles	Disposal in Salt	Total Cost (mill/kwh$_e$)
		Acid Purex Waste (No Fission Products Removed)					
6	2.3	2.9	12.3	-	3.0	13.2	31.4
6	2.8	3.1	12.3	-	3.0 or 2.1	9.8	28.2 or 27.3
6	10	1.9	12.3	2.8	1.8	8.1	26.9
6	30	1.9	12.3	3.7	1.4	6.7	26.0
12	5.5	4.0	9.1	-	1.9	12.1	27.1
12	10	4.8	9.1	-	1.8	10.1	25.8
12	30	2.9	9.1	3.5	1.4	7.0	23.9
24	30	6.9	8.1	-	0.9	8.8	24.7
		90%-Depleted Waste					
12	0.33	-	12.8	-	4.5	5.6	22.9
12	1	1.2	12.8	-	4.1	4.5	22.6
12	10	1.9	12.8	-	2.8	4.0	21.5
12	30	2.5	12.8	-	1.9	3.9	21.1
24	1.2	1.3	11.3	-	2.3	4.7	19.6
24	10	1.9	11.3	-	1.6	4.0	18.8
24	30	2.5	11.3	-	1.1	3.9	18.8
		99%-Depleted Waste					
24	0.33	-	11.3	-	2.0	3.7	17.0
24	1	1.1	11.3	-	1.8	3.7	17.9
24	10	1.8	11.3	-	1.1	3.7	17.9
24	30	2.3	11.3	-	0.6	3.7	17.9

The results in Table 8 are shown graphically in Fig. 11. For the case of untreated acidic Purex in 6-in.-diam cylinders the largest shipping cask, which results in lowest costs, cannot be used prior to a waste age of 2.8 yr; hence the double entry in Table 8 and the break in the curve in Fig. 11.

Total waste-management cost for acid Purex decreased as age at burial increased, and at 30 yr, the upper limit used in the study, was about 0.024 mill/kwh$_e$ with both 12- and 24-in. diam cylinders. Costs for depleted wastes were cheaper with 24-in.-diam vessels and not so strongly affected by age, falling in the range of 0.017 to 0.019 mill/kwh$_e$ for both 90- and 99%-depleted wastes for ages from 0.33 to 30 yr. Relatively little cost reduction (about 7%) is achieved by increasing the fraction of fission products removed from 90% to 99%.

CONCLUSIONS

A rather optimistic estimate of the amount to be gained in waste management costs with removal of 90 to 99% of the fission products is about 0.006 mill/kwh$_e$, which is equivalent to about $400 per tonne of uranium processed. Thus, the cost of managing wastes that contain only 1% of the fission products is 70% as much as the cost for wastes containing all the fission products. Because this saving is not nearly enough to pay for fission product separation, packaging, and disposal, such practices would not be carried out as part of a waste management scheme but would necessarily depend on a large and diverse market for fission products to pay the major portion of these costs.

It may not be amiss to speculate that the major interest in fission product recovery will continue to be for the longer-lived fission products, and that large scale separation of shorter-lived fission products may never be economically feasible. Therefore, the waste management costs for burial at ages below five to ten years should be applied with caution.

Any conclusions to the effect that the depleted wastes have the advantage of being "less hazardous" should be tempered by the realization that they are more voluminous, more soluble, have a lower melting point, and are much less suitable for "glass-making" than acid Purex waste.

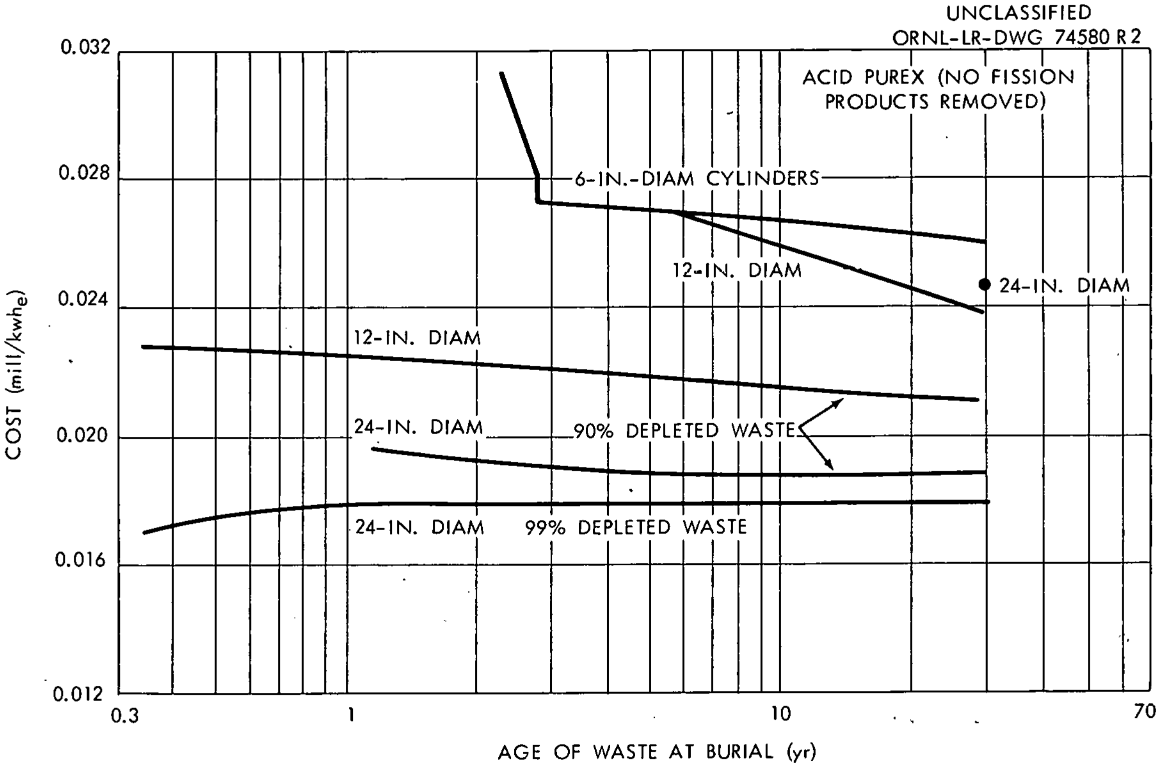

Fig. 11. Total costs for interim storage, calcination, shipment, and disposal in a salt mine.

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