

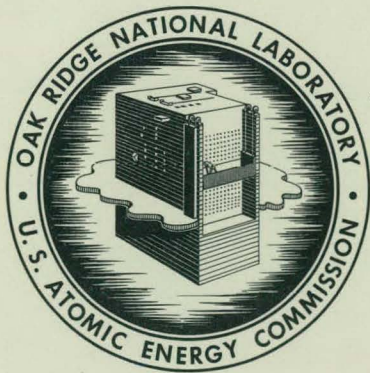
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EVALUATION OF ULTIMATE DISPOSAL METHODS
FOR LIQUID AND SOLID RADIOACTIVE WASTES.
SHIPMENT OF CALCINED SOLIDS

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OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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CHEMICAL TECHNOLOGY DIVISION

and

HEALTH PHYSICS DIVISION

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AND SOLID RADIOACTIVE WASTES
SHIPMENT OF CALCINED SOLIDS

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CONTENTS

	Page
Abstract	1
1.0 Introduction	2
2.0 Heat Transfer Limitations on Carrier Sizes	3
3.0 Cask Shielding and Weight	8
4.0 Costs	14
5.0 References	23

EVALUATION OF ULTIMATE DISPOSAL METHODS FOR LIQUID
AND SOLID RADIOACTIVE WASTES
IV. SHIPMENT OF CALCINED SOLIDS

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ABSTRACT

The costs of shipping calcined Purex and Thorex wastes were calculated assuming the wastes were produced by a plant processing 1500 metric tons/year of uranium converter fuel at a burnup of 10,000 Mwd/ton, and 270 metric tons/year of thorium converter fuel at 20,000 Mwd/ton. Calculations were made for Purex waste calcined in acidic and reacidified (after alkaline storage) forms and for Thorex waste calcined in acidic and reacidified forms and with constituents added for producing an acidic Thorex glass.

Shipping casks of iron, lead and uranium were considered at \$0.25, 0.75 and \$5.00/lb. Casks were cylindrical in shape and up to 60 in. inside diameter, which is large enough to contain four 24-in.-dia, nine 12-in.-dia, or thirty six 6-in.-dia cylinders of calcined waste. Cask weights ranged up to 100 tons. The cask design did not include liquid coolants or mechanical cooling equipment, and couriers were assumed not required. Minimum waste age prior to shipping because of temperature limitations ranged up to 11 years for acidic Purex with four 24-in.-dia cylinders/cask.

Rail freight rates of \$24, \$44 and \$65/ton were assumed for distances of 500, 1000 and 1500 miles with rates 30% less for the return of the empty casks. Total costs were lowest in all cases for lead casks, and for 1000 mile round-trip shipments ranged from 5.5×10^{-4} mill/kwh_e for acidic Purex waste at 30 years of age in casks containing four 24-in.-dia cylinders to 1.6×10^{-2} mill/kwh_e for acidic Thorex at 0.33 years in casks containing four 6-in.-dia or one 12-in.-dia cylinders. Costs for 3000 mile round-trip shipments were higher by factors of 2.0 to 2.4.

1.0 INTRODUCTION

This report, the fourth part of a study 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 shipping calcined solids in the 6-, 12-, or 24-in.-dia cylinders, 10 ft long assumed produced by the pot calcination plant. Heat transfer calculations were made to define limiting ages of the calcined waste as a function of the number of cylinders that would be transported in a single air-filled cask with no mechanical cooling equipment. Costs were calculated as function of cask size, cask shielding material (iron, lead, and uranium), distance shipped and age at time of shipping.

Costs studies of interim liquid storage and conversion to solids by pot calcination were published as ORNL-3128 and -3192 (1,2), respectively. Some tentative costs for the disposal of calcined solids in salt deposits are given in ORNL-3314 (3). It is expected that the overall study will indicate the optimum combination of preliminary operations and final storage methods out of the large number of combinations possible. Such an evaluation is a prerequisite to the most meaningful experimental study of radioactive waste disposal.

A 6-tonne*/day plant is assumed, processing 1500 tonnes/year of uranium converter fuel at a burnup of 10,000 Mwd/tonne and 270 tonnes/year of thorium converter fuel at a burnup of 20,000 Mwd/tonne. This hypothetical plant would be processing all the fuel from a 15,000-Mw_e nuclear economy, which may be in existence by 1975. The preliminary operations to be evaluated are: (1) interim liquid storage; (2) conversion to solids by pot calcination; (3) interim storage of calcined solids; (4) shipment; (5) removal of significant fission products. This last item was added to the outline recently. The ultimate disposal methods to be evaluated are: calcined solids in salt deposits, vaults, and vertical shafts and liquids in salt deposits, by hydrofracture, and in tanks.

A study of shipping of liquid wastes has not been undertaken because of a currently strong feeling among most workers that routine shipping of liquid wastes would be too hazardous to be feasible. The results of

*Metric ton.

the hazards analyses to be undertaken will be expressed as insurance costs, which may be one of the major cost items in the shipping of liquid waste.

Acknowledgment. Radiation buildup and shielding calculations were done with IBM-7090 codes written by E. D. Arnold and B. F. Maskewitz. Radiation heat transfer within tube bundles was calculated with an IBM-7090 code written by J. S. Watson.

2.0 HEAT TRANSFER LIMITATIONS ON CARRIER SIZES

The number of cylinders of calcined waste that may be transported in a single cask is subject to the limitation that the temperature of the calcined waste not exceed the maximum calcination temperature of 1650°F, or, in the case of lead casks, that the melting point of lead (621°F) not be approached. Since the heat generation rate of the waste decreases continuously with age, a minimum permissible age can be calculated for each combination of cylinder size, cask size, and shielding material. An upper limit on cask size exists beyond which the handling and transportation of the cask becomes impractical. For this study an upper limit of 100 tons was assumed.

Casks were assumed to be hollow cylinders, with the relation between the inside diameter of the cask and the number of cylinders of a given diameter contained by it as shown in Fig. 1 and Table 1. In sizing the casks, clearance between the outer cylinders of the array and the cask wall was set as $R/3$. The cylinders would be held by a spacing structure in a square array, which would permit better heat transfer than a triangular array. Casks for more than thirty six 6-in.-dia, nine 12-in.-dia, or four 24-in.-dia cylinders weigh more than 100 tons and were assumed to be unmanageably large.

Surface temperatures of the cylinders were calculated by methods developed for the study of heat transfer in spent reactor fuel rod assemblies in shipping casks (4). Heat transfer between cylinders in the array and between cylinders and the inner surface of the cask was calculated as if radiant heat transfer alone contributed. Cylinders were assumed to have radially symmetric temperature distributions. The conservative procedure of neglecting convective heat transfer and conductive heat transfer through the spacing structure tends to compensate for the less than infinite

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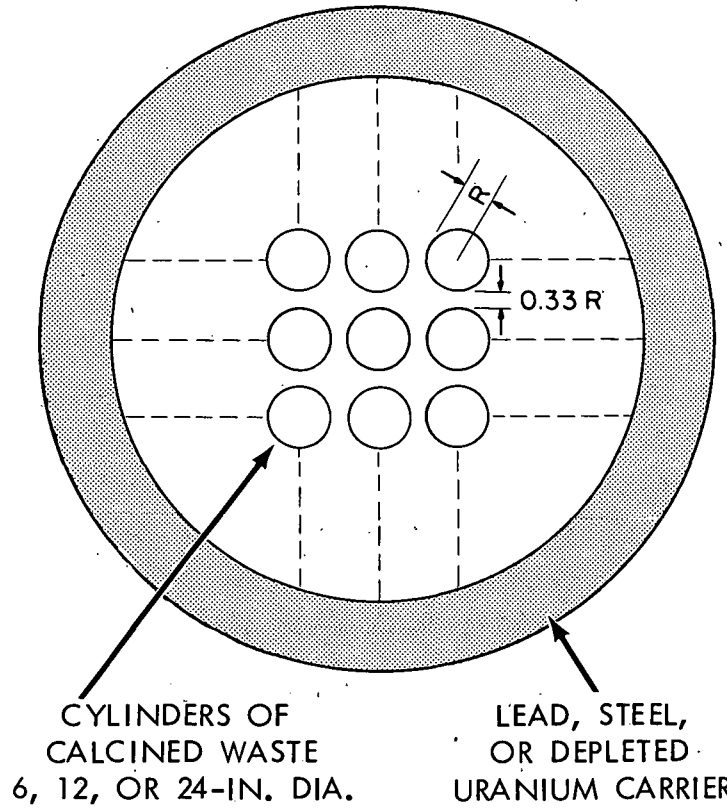


Fig. 1. Plan View Sketch of Carriers for Cylinders of Calcined Wastes

Table 1. Number of Cylinders of Calcined Waste as a Function of Cask Diameter

Carrier Inside Dia, in.	No. of Cylinders per Cask		
	6-in.-dia	12-in.-dia	24-in.-dia
60	36	9	4
40	16	4	-
28	9	-	1
16	4	1	-
10	1	-	-

thermal conductivity of the waste, which would tend to impose secondary asymmetric temperature gradients on the cylinders. The surface temperature of the hottest cylinder in each cask-size cylinder-size combination is plotted as a function of heat generation rate in Fig. 2.

An emissivity of stainless steel of 0.55 was used (4). With a ratio of cylinder axis spacing to cylinder radius of 2.33 (Fig. 1), values for the geometrical factors F_{12} , F_{13} , and F_{14} were 0.148, 0.0868, and 0.00740, respectively. Corresponding values for the factors \mathcal{F}_{12} through \mathcal{F}_{16} were 0.119, 0.0760, 0.00731, 0.190, and 0.284.

In order to place four 24-in.-dia cylinders in a 60-in.-i.d. cask, a closer spacing than indicated in Fig. 1 would have to be used. Because the cylinders would be nearly touching, the heat transfer calculations for this case were done manually, assuming three-fourths of the surface of each cylinder radiating to the cask wall and one-fourth insulated. The effects of this change in spacing on four 12-in.-dia cylinders is shown in Fig. 2b.

Temperature differences across the cask wall are sufficiently small that the different thermal conductivities of lead, iron, and uranium (19, 26, and 15 Btu/hr·ft·°F) do not appreciably affect the final results. The exterior surfaces of the casks were assumed to have fins that halved the heat flux at that surface.

The temperature at the center of a cylinder was calculated from the equation

$$T_{\text{axis}} - T_{\text{surface}} = QR^2/4k$$

where T = temperature, °F

Q = heat generation rate, Btu/hr·ft³

R = radius of cylinder, ft

k = thermal conductivity of calcined solid, Btu/hr·ft·°F

The values used for thermal conductivity were

<u>Waste type</u>	<u>k</u>
Acidic Purex	0.25
Reacidified Purex	0.75
Acidic Thorex	0.20
Reacidified Thorex	0.67
Acidic Thorex Glass	0.56

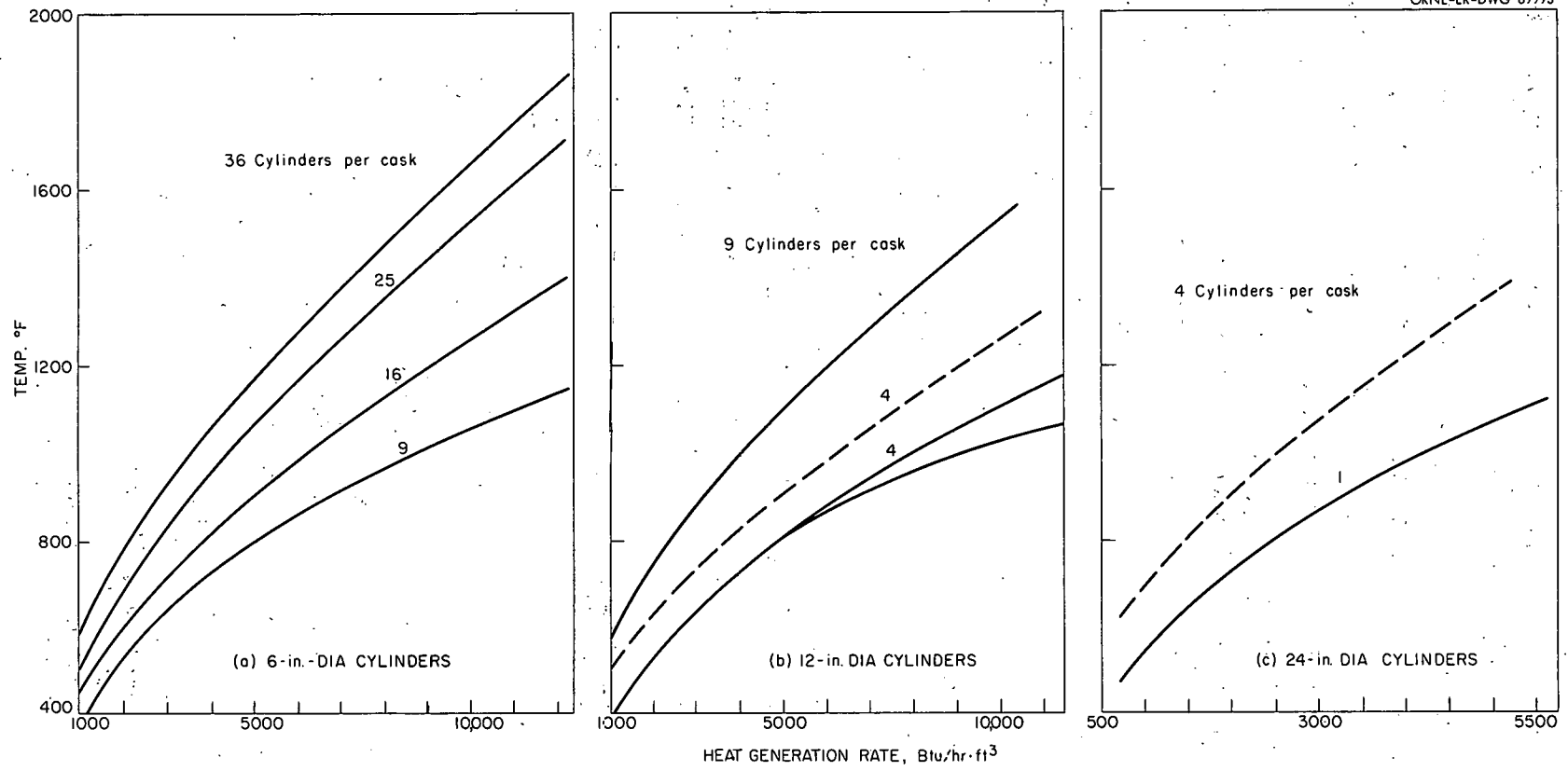


Fig. 2. Surface temperature of hottest cylinder during shipping --- no radiant interchange between cylinders.

In this way maximum permissible heat generation rates were calculated for various cask-size cylinder-size combinations to limit the axial temperature in the hottest cylinder to 1650°F. Corresponding minimum permissible ages at the time of shipping were then obtained from Fig. 3, which is a plot of heat generation rate versus age for the various wastes. Minimum ages ranged from 0.33 year, the assumed age at the time of discharge from the fuel processing facility, for many cases, to 11.3 years for shipping acidic Purex waste in a carrier containing four 24-in.-dia cylinders (Table 2). For some cases with lead casks, the limiting ages were controlled by the melting point of the lead rather than the maximum waste cylinder temperature.

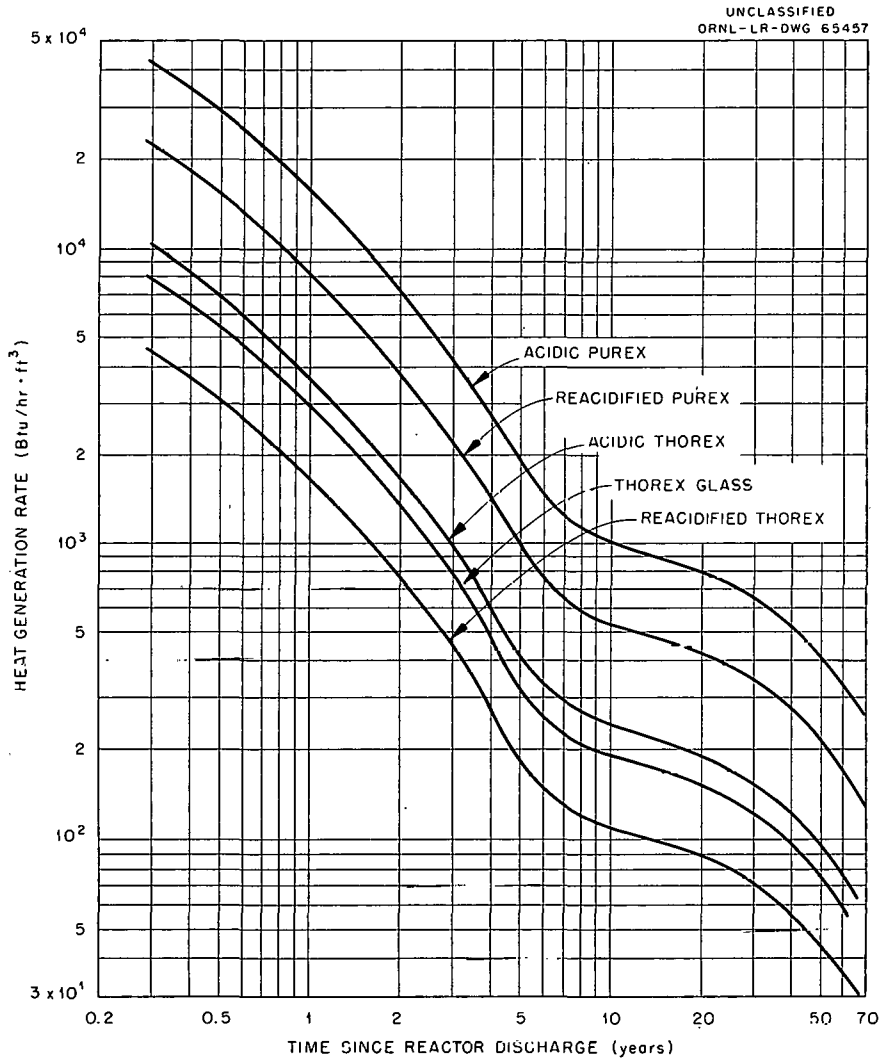


Fig. 3. Heat Generation Rate as a Function of Age for Calcined Solid Wastes Assuming Optimum Dead Storage Times.

Table 2. Minimum Permissible Shipping Ages for Cylinders of Calcined Wastes

Waste Type	Age, years						
	36 6-in.-dia	16 6-in.-dia	4 6-in.-dia	9 12-in.-dia	4 12-in.-dia	4 24-in.-dia	1 24-in.-dia
Acidic Purex	2.40 ^a	1.75 ^b	1.35	3.80	3.30	11.30	8.60
Reacidified Purex	1.00 ^c	0.69 ^d	0.39	1.40 ^c	1.00 ^d	3.00	2.70
Acidic Thorex	0.66 ^e	0.47	0.33	1.35	1.15	3.50	3.20
Reacidified Thorex	0.33	0.33	0.33	0.33	0.33	0.82	0.70
Acidic Thorex glass	0.33 ^f	0.33	0.33	-	-	-	-

^a2.80 years for lead carriers

^b1.90 years for lead carriers

^c1.70 years for lead carriers

^d1.10 years for lead carriers

^e0.82 years for lead carriers

^f0.63 years for lead carriers

3.0 CASK SHIELDING AND WEIGHT

In the study of interim storage of liquid wastes carried out as the first part of this evaluation, the operating cycle of a tank was assumed to consist of equal filling and emptying times plus a full (or dead) time. With interim storage time defined as filling time plus full time (equivalent to average liquid residence time), an economically optimum full time was found as a function of interim storage time (1). Using optimum full time, the total photons per second for nine energy groups were calculated as a function of interim liquid storage time for Purex and Thorex wastes (Table 3). The nine energy groups are 0.30, 0.63, 1.10, 1.55, 1.99, 2.38, 2.75, 3.25, and 3.75 Mev. An IBM-7090 code was used with the assumption that the reactor fuel was discharged to the processing plant in 120-day batches (5).

Photon emission rates from individual cylinders were obtained by dividing the numbers in Table 3 by the number of cylinders of calcined waste which would be produced from that amount of accumulated waste.

Table 3. Photon Emission Rate from Accumulated Waste Streams as a Function of Interim Storage Period

Waste Type	Interim Storage	Full	Group I 0.30 Mev	Group II 0.53 Mev	Group III 1.10 Mev	Group IV 1.55 Mev	Group V 1.99 Mev	Group VI 2.38 Mev	Group VII 2.75 Mev	Group VIII 3.25 Mev	Group IX 3.75 Mev
	Time, years	Time, years									
Purex	0	0	6.96×10^{18}	1.53×10^{19}	5.60×10^{18}	2.86×10^{17}	3.00×10^{16}	6.10×10^{16}	9.50×10^{15}	2.20×10^{15}	9.80×10^{14}
	1.4	0.4	6.00×10^{18}	8.50×10^{18}	2.55×10^{18}	2.50×10^{17}	2.90×10^{16}	6.00×10^{16}	1.40×10^{15}	6.00×10^{14}	1.40×10^{14}
	5.7	3.4	1.55×10^{18}	2.65×10^{18}	3.05×10^{17}	1.30×10^{17}	1.63×10^{16}	3.40×10^{16}	2.90×10^{15}	3.20×10^{12}	1.80×10^{10}
	9.5	6.2	9.30×10^{17}	3.00×10^{18}	2.60×10^{17}	9.70×10^{16}	7.50×10^{15}	1.55×10^{14}	5.20×10^{10}	2.10×10^{11}	-
	31	22.3	2.60×10^{17}	6.40×10^{18}	2.95×10^{17}	3.90×10^{16}	3.20×10^{14}	7.50×10^{14}	9.90×10^{10}	-	-
Thorex	0	0	2.51×10^{18}	5.69×10^{18}	2.03×10^{18}	1.03×10^{17}	1.10×10^{16}	2.21×10^{16}	3.45×10^{15}	7.84×10^{14}	3.52×10^{14}
	1.4	0.4	2.10×10^{18}	3.20×10^{18}	9.30×10^{17}	9.20×10^{16}	1.10×10^{16}	2.20×10^{16}	5.10×10^{15}	2.10×10^{14}	5.50×10^{13}
	5.7	3.4	5.80×10^{17}	9.70×10^{17}	1.10×10^{17}	4.90×10^{16}	5.80×10^{15}	1.40×10^{15}	1.00×10^{15}	1.20×10^{12}	6.30×10^9
	4.5	6.2	3.40×10^{17}	1.10×10^{18}	9.20×10^{16}	3.60×10^{16}	2.70×10^{15}	5.60×10^{15}	1.90×10^{14}	7.70×10^{10}	-
	31	22.3	8.00×10^{16}	2.30×10^{18}	1.10×10^{17}	1.43×10^{16}	1.20×10^{14}	2.70×10^{14}	3.60×10^{10}	-	-

Thus, negligible decay during calcination processing was assumed. For example, the photon emission rate of 0.30-Mev photons from a 24-in.-dia cylinder of acidic Purex waste after 5.7 years of interim storage would be

$$\frac{1.55 \times 10^{18} \text{ photons/sec}}{(58 \text{ cylinders/year})(2.3 \text{ years accumulation time})} = 1.16 \times 10^{16} \frac{\text{photons}}{\text{sec-cylinder}}$$

Annual production rates for cylinders of the other waste types and cylinder sizes are given in Part II of this study (2). For no interim liquid storage, the values in Table 3 must be divided by the number of cylinders produced from a 120-day batch of reactor fuel.

Shielding calculations for the various combinations of cylinder size and cask size were performed on the IBM-7090 (6). Lead thicknesses to decrease the dose to 10 mr/hr at 3 meters as a function of age of the waste are plotted in Figs. 4 and 5 for the various waste types. Lead thicknesses to obtain 200 mr/hr at the surface were less in all cases. Title 10 of the Code of Federal Regulations specifies that the external radiation levels must not exceed 200 mr/hr at any accessible cask surface or more than 10 mr/hr at a distance of 1 meter from the cask except when shipped by rail, in which case the latter limit is extended to 10 mr/hr at 3 meters. Shipment by rail freight was assumed for this study because rail freight appears to be as cheap as motor freight for distances greater than about 400 miles, while the largest casks could probably not be transported by motor freight (7).

Shielding calculations were carried out for iron, lead and depleted uranium carriers for the various waste types and cylinder-size cask-size combinations. Over the ranges of cask geometries and source characteristics considered in this report, it is sufficient to use iron/lead shielding thickness ratios of 1.7 and of uranium/lead shielding thickness ratios of 0.56.

Weights of casks were calculated assuming the casks were hollow cylinders 10 ft long to which were added end disks of the same thickness as the cylinder walls. In addition, the weights of the larger (60 and 40 in. i.d.) casks were increased 10% to account for structural material. Casks weights as a function of wall thickness and inside diameter are given in Fig. 6.

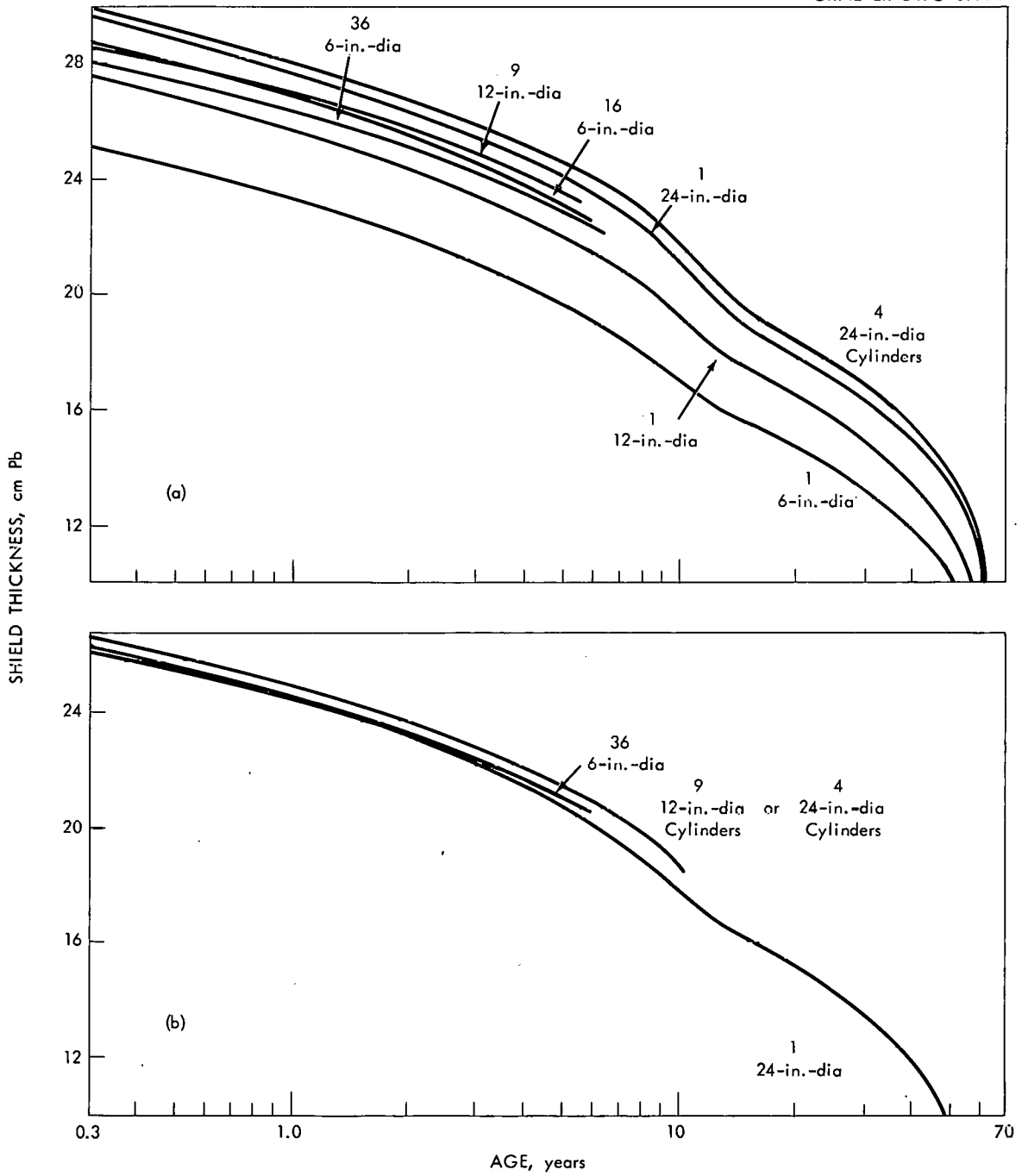


Fig. 4. Carrier wall thickness to give 10 mr/hr at 3 meters for various cylinder size-carrier size combinations for (a) calcined acidic Purex waste and (b) calcined reacidified Purex waste filled twice.

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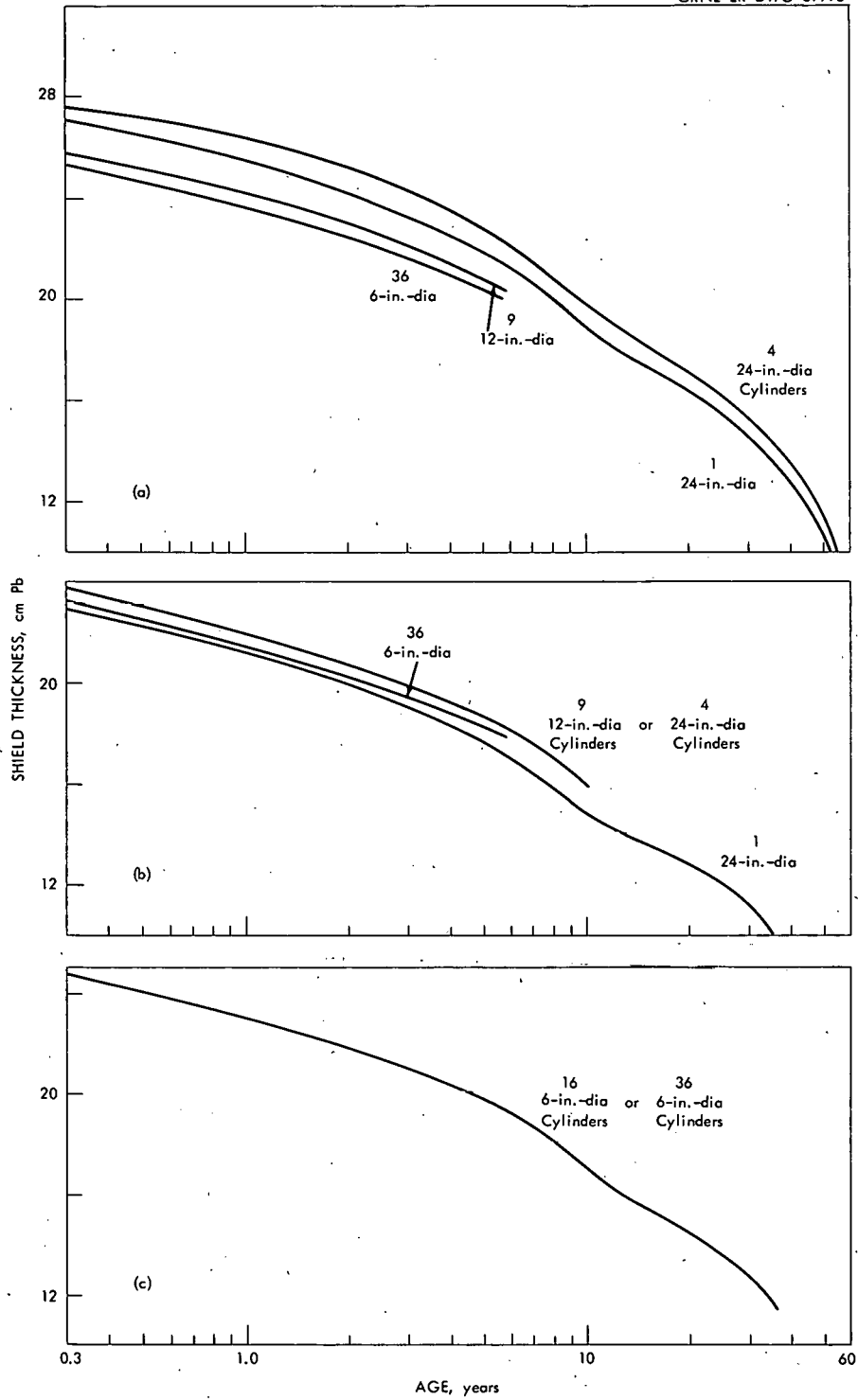


Fig. 5. Carrier wall thickness to give 10 mr/hr at 3 meters for various cylinder size-carrier size combinations for (a) calcined acidic Thorex waste; (b) calcined re-acidified Thorex waste filled twice; (c) acidic Thorex glass.

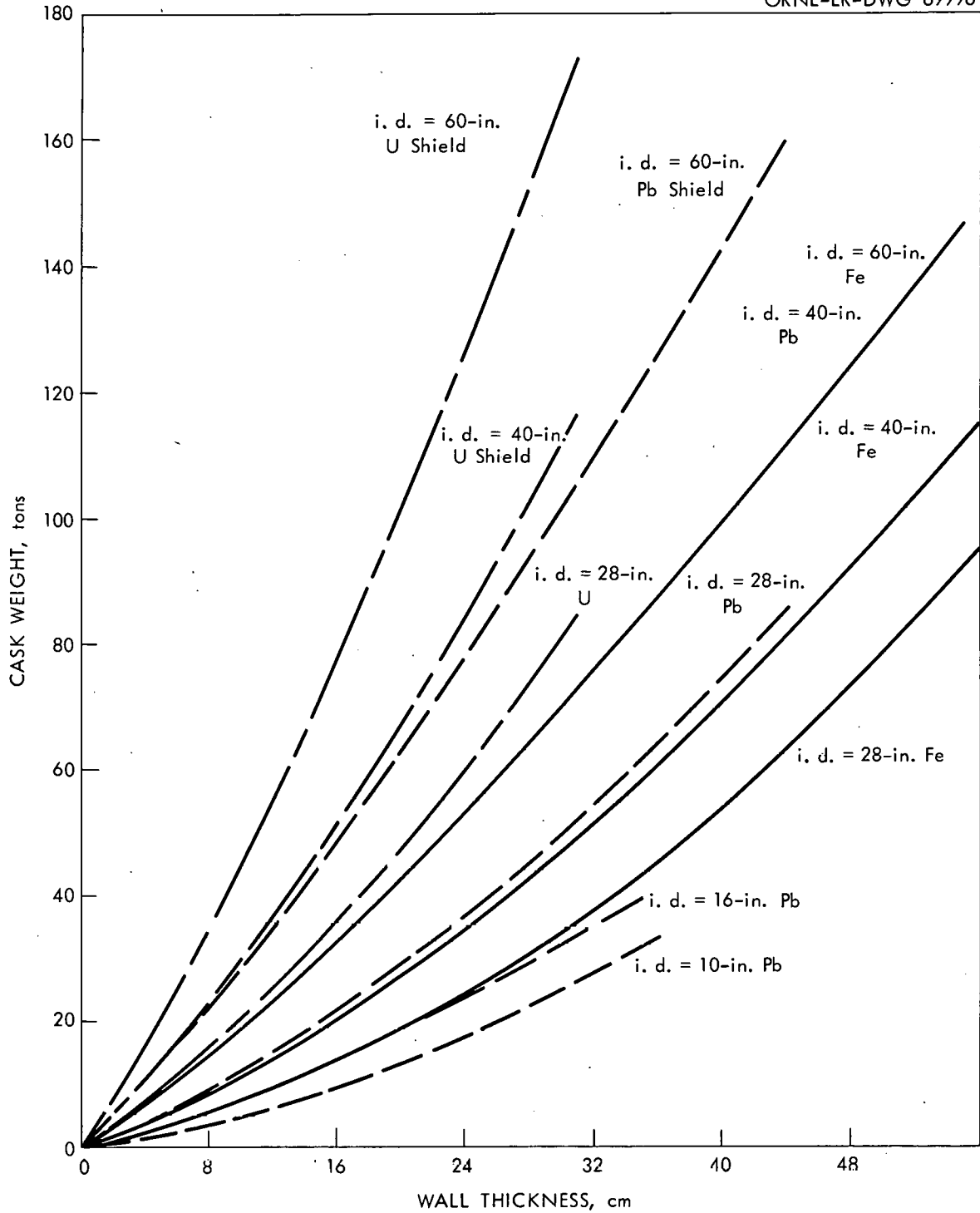


Fig. 6. Weights of iron, lead, and uranium casks as functions of wall thickness and inside diameter.

4.0 COSTS

Total shipping costs were the sums of cask, rail freight, and handling costs. Because the casks do not contain liquid coolants or mechanical cooling equipment, it is assumed that couriers will not be required. Cask costs were calculated assuming \$0.25/lb for iron, \$0.75/lb for lead, and \$5.00/lb for uranium. The cost for iron casks is based on British estimates for 48-ton casks for their next generation magnox-clad uranium-metal power reactor fuels and range from \$0.09 to \$0.12/lb for cast iron and from \$0.17 to \$0.20/lb for cast steel (8).

For lead casks, Culler listed six casks in 1957 which ranged from \$0.27 to \$0.68/lb and considered \$0.50/lb a good average (9). Some more recent costs are the 70-ton Savannah River cask at \$0.98/lb, the ORNL shielded transfer tank (model 2) at \$0.89/lb, and the ORNL-HAPO Sr⁹⁰ carrier at \$0.74/lb (10,11).

The assumed cost for depleted uranium casks is the most speculative because only a few small casks have been built of uranium and these are not well documented. Furthermore, all the known uranium casks are owned by the AEC so that purchase of the uranium and commercial reduction to metal and casting were not involved. A rough estimate of the commercial cost of fabricating uranium into small (3000 lb) castings is (12)

Cost of UF ₆	\$2.60/lb
Conversion to metal	1.55
Casting simple shapes	<u>0.85</u>
	\$5.00/lb

Cask costs would also include purchase and fabrication of structural steel; however, much larger castings would be required and should cost less per unit weight. Casks were amortized over 10 years at 4% interest (annuity factor 0.123).

Freight costs are usually a matter of negotiation between the shipper and the carrier and may vary significantly with time and in different parts of the country. Based on rail freight rates from Oak Ridge to Atlanta, Memphis, Kansas City, Minneapolis, Denver, Salt Lake City and San Francisco (7), rates of \$24, \$44, and \$65 per ton for loaded casks were used for distances of 500, 1000, and 1500 miles, with rates 30% less for return of empty casks. Casks loaded with cylinders of calcined waste weigh about 15% more than when empty.

Seven days were assumed required for a 1000-mile round-trip, broken down as follows:

Loading	1 day
Traveling loaded	2
Unloading and decontamination	2
Traveling empty	<u>2</u>
Total	7 days

For 2000- and 3000-mile round-trips, 9 and 11 days, respectively, were assumed. Transit times are required in order to estimate the number of casks that must be purchased.

Handling costs consisted of labor costs for loading, unloading, and decontaminating operations plus amortization costs for an unloading crane. The cost of a 100-ton bridge crane was included in the pot calcination plant study, and is assumed to be used for a loading crane. A labor force of three men was estimated at \$40/man-day including overhead, which amounts to \$360/trip. The unloading crane was estimated at \$1000 per ton capacity and amortized over 20 years at 4% interest (annuity factor 0.0736).

As an example, consider the shipment of acidic Purex waste in 24-in.-dia vessels in lead carriers after 11.3 years of interim storage for a round-trip distance of 2000 miles. The shipment can take place in 60-in.-i.d. carriers each containing four cylinders (Table 2). Twenty-one cm of lead shielding is required (Fig. 4a) and each cask will weigh 66 tons empty (Fig. 6) and 76 tons loaded. Each cask will cost (66 tons) x (\$0.75/lb)(2000 lb/ton) = \$99,000. The number of trips per year will be (58 cylinders/year)/(4 cylinders/trip) = 14.5. The number of casks that must be purchased is 14.5(9 days/trip)(year/365 days) = 0.36, or a single cask is required which will stand idle part of the time. The costs may now be listed as

Cask cost:	(\$99,000)(0.123)	= \$ 12,000/year
Freight cost:	$\frac{[(76 \text{ tons})(\$44/\text{ton}) + (66 \text{ tons})(\$31/\text{ton})]}{\times (14.5 \text{ trips/year})}$	= 78,000
Handling cost:	labor - (\$360/trip)(14.5)	= 5,000
	crane - (66,000)(0.0736)	= <u>5,000</u>
Total		\$100,000/year

With 9.72×10^{10} kWh_e/year produced by the uranium converter reactors, this cost may be expressed as 1.03×10^{-3} mill/kwh_e.

The effects on costs of cask shielding material and distance shipped are shown in Figs. 7 and 8 for the largest cask (60-in.-i.d.) containing four 24-in.-dia, nine 12-in.-dia or thirty six 6 in.-dia cylinders at minimum ages. Shipping costs were lowest in all cases for lead casks. For 1000-mile shipments the use of iron casks cost less than uranium casks but at 3000 miles the cost with uranium casks was less than with iron and approached the cost of lead casks.

The effects of aging on costs for lead casks for 1000-mile round-trips are shown in Figs. 9 and 10. Costs for shipping at 30 years of age are roughly half of the costs at 120 days, although for many cases shipping at 120 days is not permissible due to heat transfer considerations. Costs for 1000-mile round-trip shipments in lead casks range from 5.5×10^{-4} mill/kwh_e for acidic Purex waste at 30 years in casks containing four 24-in.-dia cylinders to 1.6×10^{-2} mill/kwh_e for acidic Thorex at 0.33 year in casks containing four 6-in.-dia or one 12-in.-dia cylinders.

Costs for 3000-mile shipments may be obtained with the factors in Table 4, which are ratios of costs for 3000- to 1000-mile shipments. The factors range from 2.0 to 2.4 and are generally accurate to ± 0.1 over the range of ages 0.33 to 30 years. Costs for 2000-mile shipments can be approximated by linear interpolation.

Table 4. Approximate Ratios of Costs for 3000-mile Round Trip to Costs for 1000-mile Round Trip.

Table 4. Approximate Ratios of Costs for 3000-mile Round Trip to Costs for 1000-mile Round Trip

	Cylinder/Cask Ratio					
	4 24-in.-dia	1 24-in.-dia	36, 6, or 9 12-in.-dia	16, 6, or 4 12-in.-dia	4, 6, or 1 12-in.-dia	1 6-in.-dia
Acidic Purex	2.0	2.1	2.2	2.3	2.2	2.1
Reacidified Purex filled twice	2.4	2.2	2.3	2.4	2.2	-
Acidic Thorex	2.2	2.2	2.4	2.3	2.2	-
Reacidified Thorex filled twice	2.3	2.2	2.3	-	-	-
Acidic Thorex glass	-	-	2.4	2.3	-	-

Calculations for reacidified wastes in which the calcination vessel undergoes only one filling cycle were not completed when it became clear

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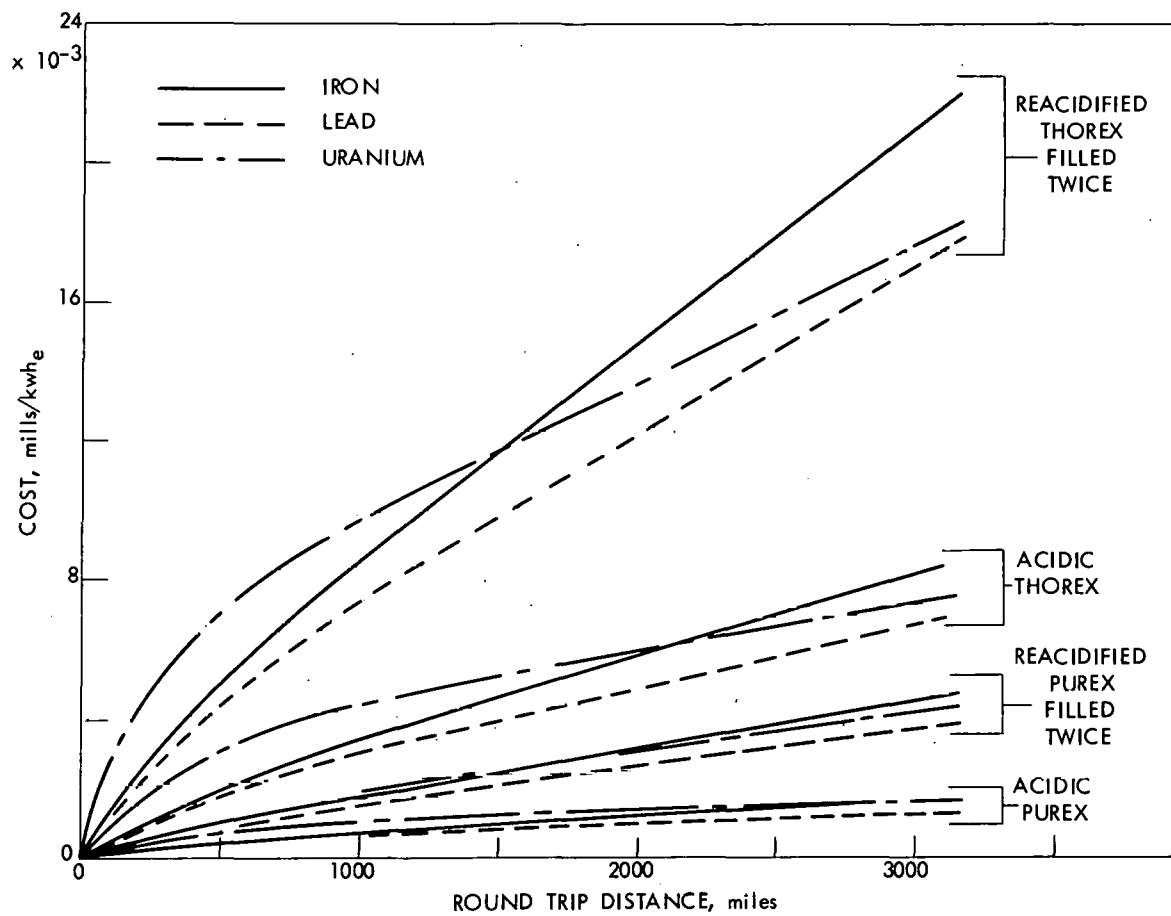


Fig. 7. Shipping costs using carriers containing 4 24-in. dia. cylinders.

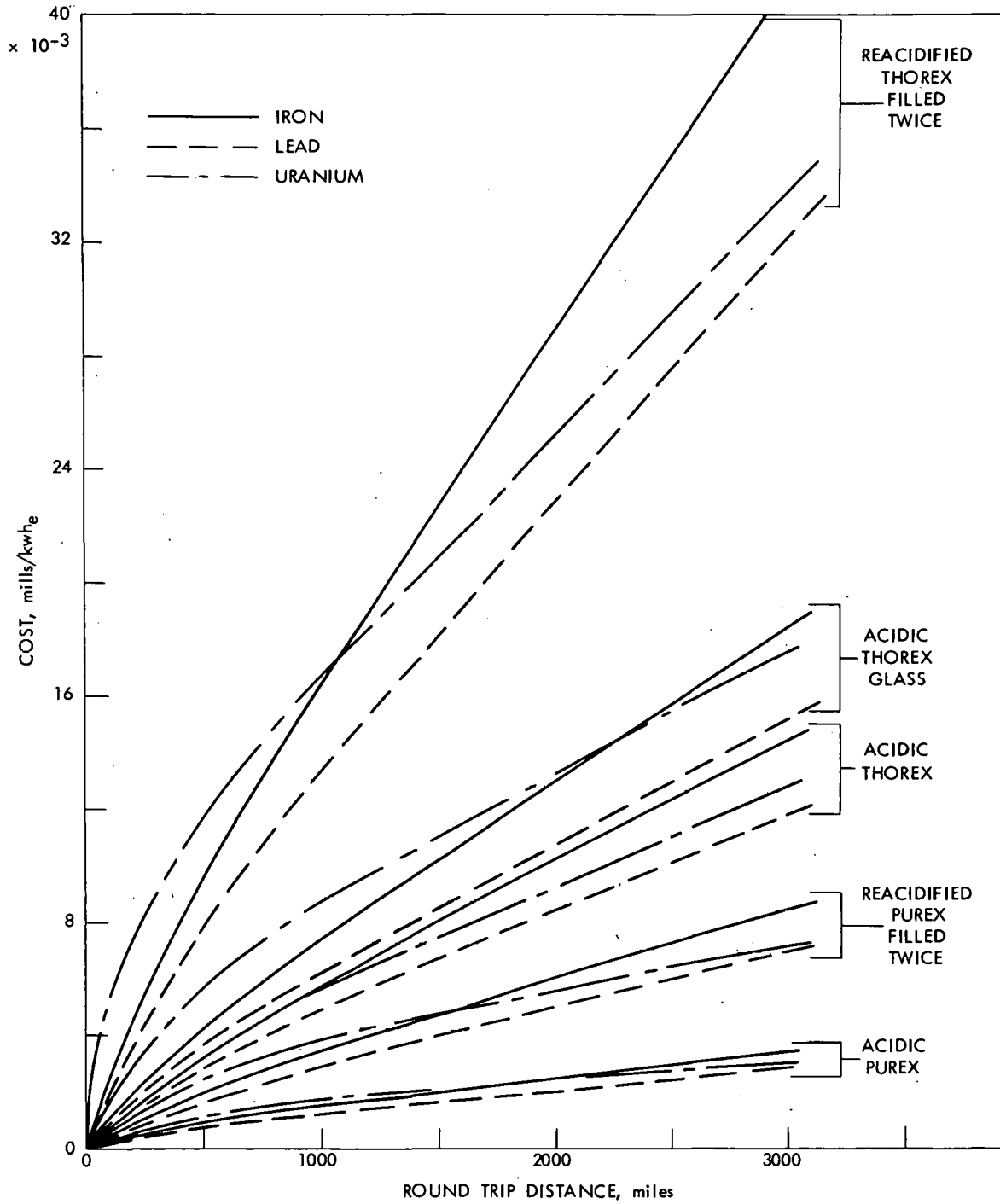


Fig. 8. Shipping costs using carriers containing 36 6-in. dia. cylinders or 12-in. dia. cylinders.

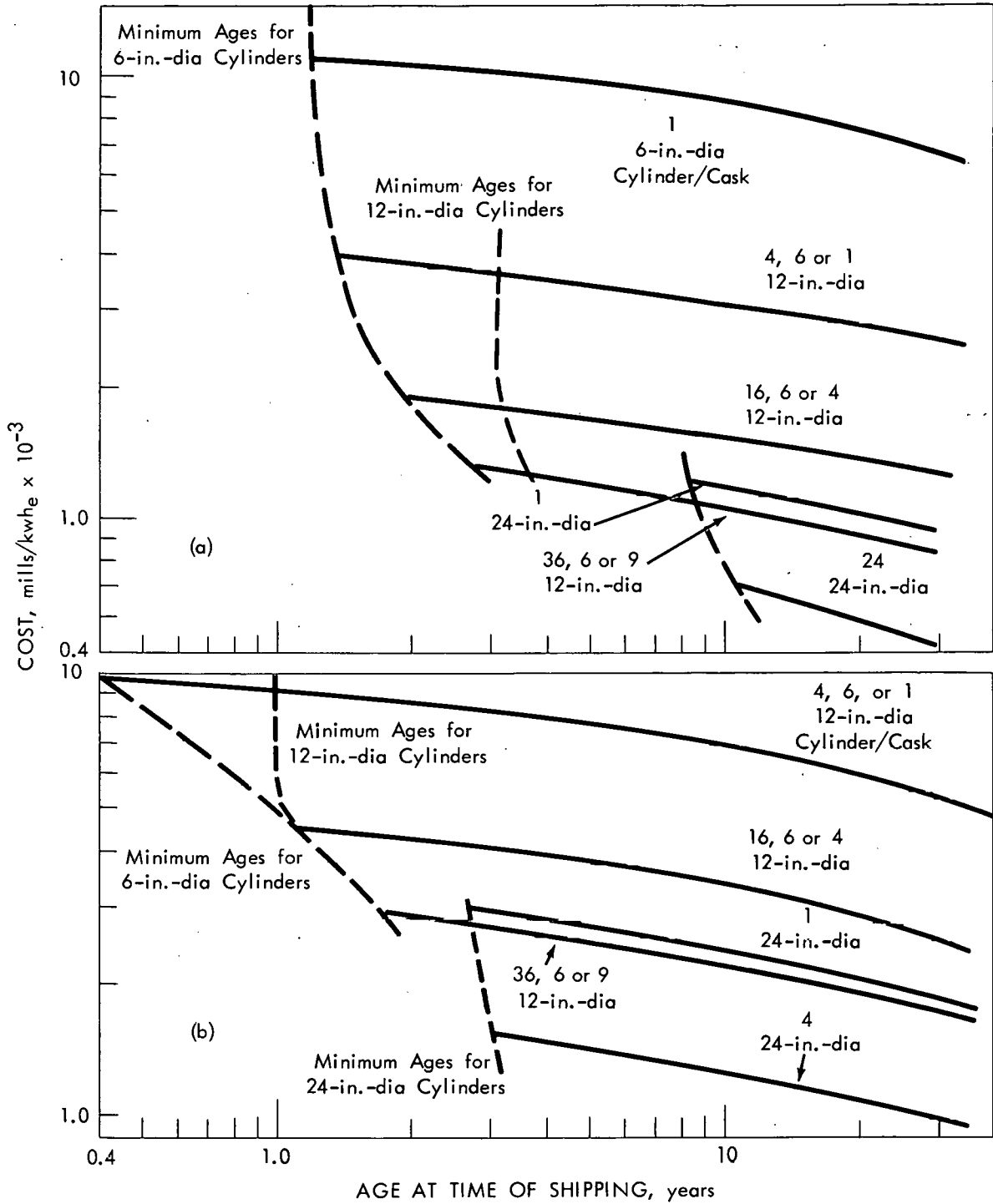


Fig. 9. Shipping costs as a function of age for (a) acidic and (b) re-acidified Purex waste filled twice in lead casks for a shipping distance of 1000 miles per round trip.

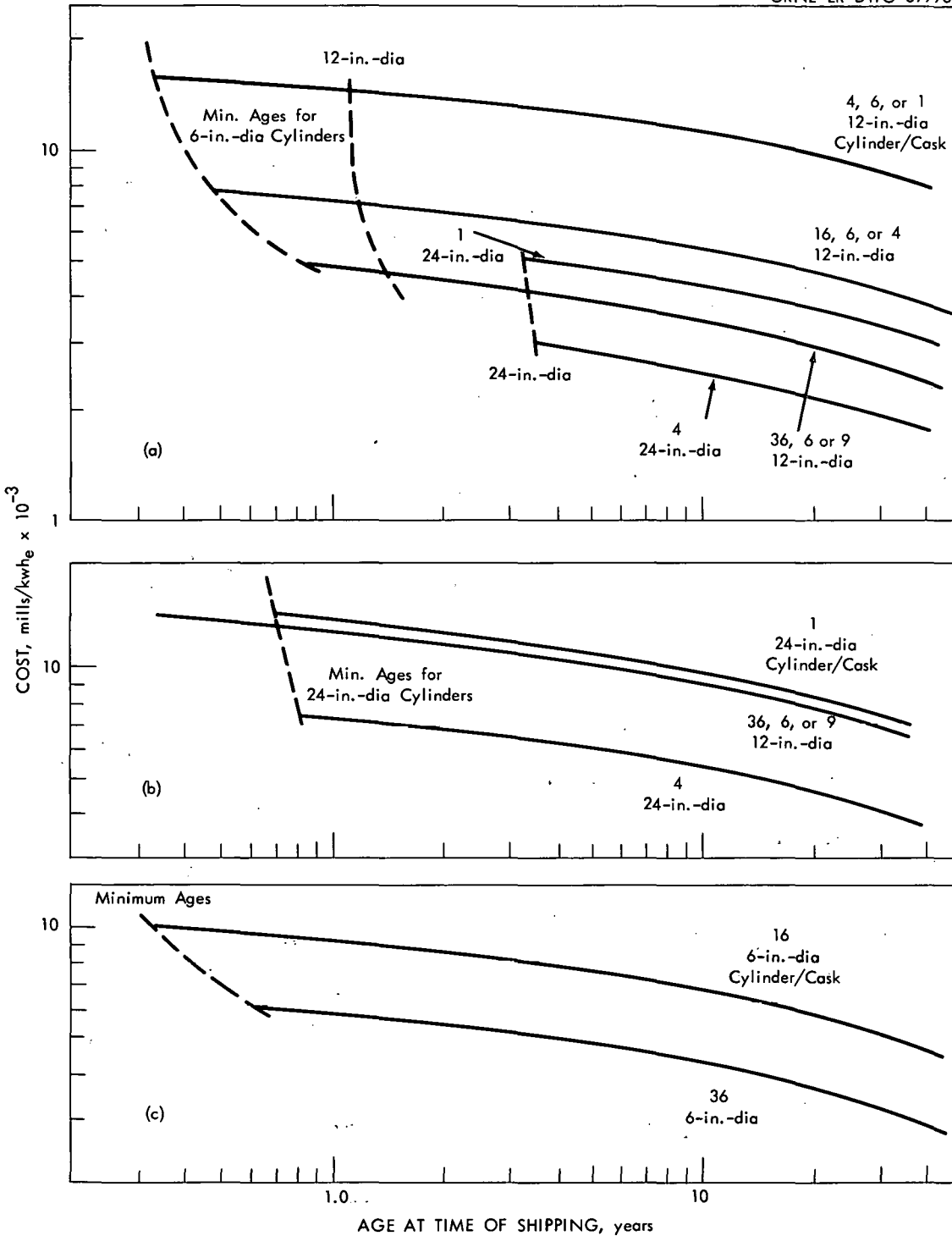


Fig. 10. Shipping costs as a function of age for (a) acidic Thorex waste, (b) re-acidified Thorex waste filled twice, and (c) acidic Thorex glass waste in lead casks for a shipping distance of 1000 miles per round trip.

that costs for those cases would be much higher than for the filled-twice cases. Although required shielding thicknesses are slightly less for filled-once cases (~10% less weight for lead carriers), the resulting 50% more cylinders to be transported more than compensates. Since calcination costs were also much higher for the filled-once case, it was dropped from consideration.

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