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EVALUATION OF ULTIMATE DISPOSAL METHODS FOR LIQUID AND SOLID RADIOACTIVE WASTES

PART I. INTERIM LIQUID STORAGE

R. L. Bradshaw
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CHEMICAL TECHNOLOGY DIVISION

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EVALUATION OF ULTIMATE DISPOSAL METHODS FOR LIQUID AND SOLID RADIOACTIVE WASTES. Part I. INTERIM LIQUID STORAGE

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ABSTRACT

As the first part of a study to evaluate the economics of the various steps leading to and including the permanent disposal of high-activity liquid and solid radioactive waste, costs of interim liquid storage of acid and alkaline Purex and Thorex wastes were estimated for storage times of 0.5 to 30 years. A 6-ton/day plant was 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. Tanks of Savannah River design were assumed, with stainless steel construction for acid wastes and mild steel construction for neutralized wastes. The operating cycle of each tank was assumed to consist of equal filling and emptying periods plus a full (or dead) period. With interim storage time defined as filling time plus full time, tank costs were minimum when full time was 40 to 70 percent of the interim storage time, using present worth considerations. For waste storage times of 0.5 to 30 years, costs ranged from 2.2×10^{-3} to 9.5×10^{-3} mill/kwh$_e$ for acid wastes and from 1.7×10^{-3} to 5.1×10^{-3} mill/kwh$_e$ for neutralized wastes.

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1.0 INTRODUCTION

A study has been undertaken to evaluate from economics and hazards standpoints the various methods of highly radioactive liquid and solid waste disposal being considered by the Laboratory and to evaluate the various operations leading to those ultimate storage methods.[1,2,3] It is expected that this study will indicate the optimum combination of preliminary operations and final ultimate disposal methods out of the large number of combinations possible. Such an evaluation is a necessary prerequisite to the most meaningful experimental study of radioactive waste disposal. Conceptual designs of ultimate storage methods which must be made for cost estimation purposes should also be a valuable guide to later experimental programs. In this first report the costs of storing Purex and Thorex liquid wastes in acid and alkaline form were estimated for times of up to 30 years. Funds for financing the interim storage facility were assumed to be allocated in a single lump sum, so that the present worth concept was applied for facilities not immediately needed. An interest rate of 4 percent was assumed.

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 1970. The preliminary operations to be evaluated are:

1. Interim liquid storage
2. Conversion to solids by pot calcination
3. Interim storage of solids in pots
4. Shipment as either liquids or calcined solids

The ultimate disposal methods to be evaluated are:

1. Pot-calcined solids in salt deposits
2. Pot-calcined solids in vaults
3. Pot-calcined solids in vertical shafts
4. Liquids in salt deposits
5. Liquids in deep wells
6. Liquids by hydrofracture
7. Liquids in tanks

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*The spelling "tonne" is used in this report to mean metric ton.

A cost estimate of each preliminary step as a function of time since reactor discharge and of each ultimate disposal method as a function of decay time prior to storage will be made for acid and neutralized Purex and Thorex wastes. From the set of graphs obtained, the disposal cost of any of the four types by any of the disposal methods can be calculated for any solid and liquid interim storage period. The hazards evaluation will be made separately from the economic evaluation, since it will be more qualitative in nature and would decrease the accuracy of the total evaluation if these were combined into a single study.

The lower activity-level chemical decladding wastes which might also be produced in fuel processing are not considered in this study because of the present uncertainty concerning their characteristics. It is assumed that if they are produced, they will fall in a special category of intermediate-level wastes requiring different management than that applied to high-level raffinates.

The helpful advice of W. G. Stockdale on cost estimates is gratefully acknowledged.

2.0 HEAT GENERATION RATE IN PROCESSING PLANT EFFLUENT

If a stream of radioactive material is accumulated, the change in the number of atoms of any nuclide i in the accumulated stream is given by

$$\frac{dN_i}{dt} = FC_i - \lambda_i N_i \tag{1}$$

where N_i = number of atoms of nuclide i

t = time since start of accumulation, hr

F = flow rate of stream, gal/hr

C_i = concentration of nuclide i in stream, atoms/gal

λ_i = radioactive decay constant, hr^{-1}

If F and C_i are constant with time, eq 1 may be integrated as follows:

$$\int_0^t dt = \int_0^{N_i} \frac{dN_i}{FC_i - \lambda_i N_i} \tag{2}$$

$$t = \frac{1}{\lambda_i} \ln \frac{FC_i}{FC_i - \lambda_i N_i} \tag{3}$$

$$N_i = \frac{FC_i}{\lambda_i} (1 - e^{-\lambda_i t}) \tag{4}$$

The heat generation rate in the accumulated stream at any time t may be obtained from

$$\sum_{i=1}^{n} \lambda_i N_i E_i = F \sum_{i=1}^{n} E_i C_i (1 - e^{-\lambda_i t}) \tag{5}$$

where n = number of radioactive nuclides in the stream

E_i = radioactive decay energy, Mev/disintegration, including daughters

With the dimensions listed, the heat generation rate would be obtained in units of Mev/hr, in which case use of the conversion factor 1.52×10^{-16} Btu/Mev is convenient.

In the following calculations, 120 days was assumed to have elapsed between reactor discharge and processing plant discharge. The uranium-converter fuel was assumed to have been irradiated for 3×10^7 sec (~1 year) at a flux of 3×10^{13}, and to have initially 5.1×10^{25} atoms of U-235 per tonne of fuel (2% enriched). The specific waste volumes for the uranium-converter were assumed to be 50 gal per tonne of fuel for acid waste and 60 gal/tonne for neutralized waste.

The correlations of Blomeke and Todd[4] were used to calculate the concentrations of 15 nuclides in the 120-day-old waste stream (Table 1). However, elimination of nuclides contributing less than 70×10^4 Btu/hr to $F\sum E_i C_i$ changed the results < 0.5%, and eight nuclides were used for subsequent calculations. Values for $1 - e^{-\lambda_i t}$ for the eight nuclides of interest as a function of accumulation time are also shown in Table 1. Heat generation rates from the uranium-converter waste stream as a function of accumulation time are shown in Table 2a. The total heat generation rate as a function of accumulation time and decay curves following the cessation of accumulation after 0.5 to 30 years were calculated and plotted (Fig. 1a). Values for $e^{-\lambda_i t}$ for the eight important nuclides for values of t ranging from 0.5 to 90 years may be obtained by subtracting values for $1 - e^{-\lambda_i t}$ from unity.

Table 1. Nuclide Concentrations in the Uranium-Converter Waste Stream

Nuclide	λ, hr^{-1}	N_s/N^o_{25}	N_τ/N_s	N_t/N_τ	N_t/N^o_{25}	E_i, Mev	$1.52 \times 10^{-16} \times C_iE_i$, Btu/gal x 10^4	$1.52 \times 10^{-16} \times FC_iE_i$, Btu/hr x 10^4	$1 - e^{-\lambda_i t}$ 0.25 y	0.50 y	1 y	3 y	10 y	30 y	60 y	90 y
Ba-140		1.4×10^{-3}	1.0	0.0019	0.026×10^{-4}	3.115	0.12	1.04								
Pr-143		1.4×10^{-3}	1.0	0.0029	0.041×10^{-4}	0.31	0.02	0.17								
Ce-141		3.3×10^{-3}	1.0	0.082	2.70×10^{-4}	0.260	1.09	9.5								
Te-129		0.19×10^{-3}	1.0	0.087	0.165×10^{-4}	1.806	0.46	4.0								
Ru-103		2.0×10^{-3}	1.0	0.14	2.8×10^{-4}	0.607	2.64	22.9								
Sr-89	5.33×10^{-4}	5.4×10^{-3}	1.0	0.23	12.65×10^{-4}	0.487	8.44	73.2	0.690	0.904	0.991	1.0	1.0	1.0	1.0	1.0
Y-91	4.96×10^{-4}	7.5×10^{-3}	0.98	0.25	18.75×10^{-4}	0.512	13.1	114	0.663	0.887	0.987	1.0	1.0	1.0	1.0	1.0
Zr-Nb-95	4.57×10^{-4}	8.7×10^{-3}	0.95	0.28	23.6×10^{-4}	1.66	67.8	587	0.634	0.865	0.982	1.0	1.0	1.0	1.0	1.0
Te-127		0.088×10^{-3}	0.92	0.43	0.348×10^{-4}	0.32	0.17	1.5								
Ce-144	9.95×10^{-5}	3.8×10^{-2}	0.55	0.80	167×10^{-4}	1.18	252	2180	0.195	0.352	0.572	0.926	1.0	1.0	1.0	1.0
Ru-106	7.92×10^{-5}	3.0×10^{-3}	0.47	0.85	12.0×10^{-4}	1.31	24.0	208	0.159	0.293	0.500	0.875	0.999	1.0	1.0	1.0
Eu-155		0.012×10^{-3}	1.0	0.87	0.104×10^{-4}	0.76	0.12	1.04								
Pm-147	3.05×10^{-5}	4.4×10^{-2}	0.24	1.00	110×10^{-4}	0.074	12.3	107	0.064	0.125	0.233	0.550	0.930	1.0	1.0	1.0
Sr-90	2.83×10^{-6}	1.30	0.024	1.00	338×10^{-4}	0.93	487	4230	0	0.013	0.025	0.071	0.220	0.515	0.775	0.892
Cs-137	2.40×10^{-6}	1.13	0.025	1.00	271×10^{-4}	0.798	335	2900	0	0.011	0.021	0.061	0.187	0.467	0.716	0.849
								10,440								

Table 2. Heat Generation Rate in Waste Streams as a Function of Accumulation Time

Nuclide	N_t/N_τ	N_t/N^o_{25} x 10-3	$1.52 \times 10^{-16} \times C_iE_i$, Btu/gal x 10^4	$1.52 \times 10^{-16} \times FC_iE_i$, Btu/hr x 10^5	$1.52 \times 10^{-16} \times FC_iE_i\ (1 - e^{-\lambda_i t})$, Btu/hr x 10^5 0.25 y	0.333 y	0.50 y	1 y	3 y	10 y	30 y	60 y	90 y
(a) Uranium-Converter Waste													
Sr-89	0.23	1.265	8.44	7.32	5.05		6.61	7.26	7.32	7.32	7.32	7.32	7.32
Y-91	0.25	1.875	13.1	11.4	7.56		10.1	11.2	11.4	11.4	11.4	11.4	11.4
Zr-Nb-95	0.28	2.36	67.8	58.7	37.2		50.8	57.6	58.7	58.7	58.7	58.7	58.7
Ce-144	0.80	16.7	252	218	42.5		76.7	125.0	202.0	218.0	218.0	218.0	218.0
Ru-106	0.85	1.20	24.0	20.8	3.31		6.10	10.4	18.2	20.8	20.8	20.8	20.8
Pm-147	1.00	11.0	12.3	10.7	0.585		1.34	2.49	5.89	9.95	10.7	10.7	10.7
Sr-90	1.00	33.8	487	423	0		5.50	10.6	30.0	93.0	218.0	328.0	377.5
Cs-137	1.00	27.1	335	290	0		3.19	6.10	17.7	54.2	135.8	208.0	246.0
				1044	96.2		160	231	351	473	681	863	950
(b) Thorium-Converter Waste													
Sr-89	0.23	1.265	2.26	2.83		2.21	2.56	2.80	2.83	2.83	2.83	2.83	2.83
Y-91	0.25	1.875	3.66	4.57		3.47	4.06	4.51	4.57	4.57	4.57	4.57	4.57
Zr-Nb-95	0.28	2.36	15.07	18.83		13.80	16.29	18.50	18.83	18.83	18.83	18.83	18.83
Ce-144	0.80	16.7	73.57	91.97		22.81	32.37	52.60	85.20	91.97	91.97	91.97	91.97
Ru-106	0.85	1.20	6.12	7.65		1.57	2.24	3.82	6.69	7.64	7.65	7.65	7.65
Pm-147	1.00	11.0	3.12	3.90		0.317	0.488	0.915	2.15	3.63	3.90	3.90	3.90
Sr-90	1.00	33.8	111.60	135.5		0	1.81	3.49	9.90	30.69	71.84	108.11	124.44
Cs-137	1.00	27.1	89.77	112.2		0	1.24	2.35	6.84	20.99	52.40	80.34	95.26
				381		44.0	61.0	89.0	136	181	254	317	349

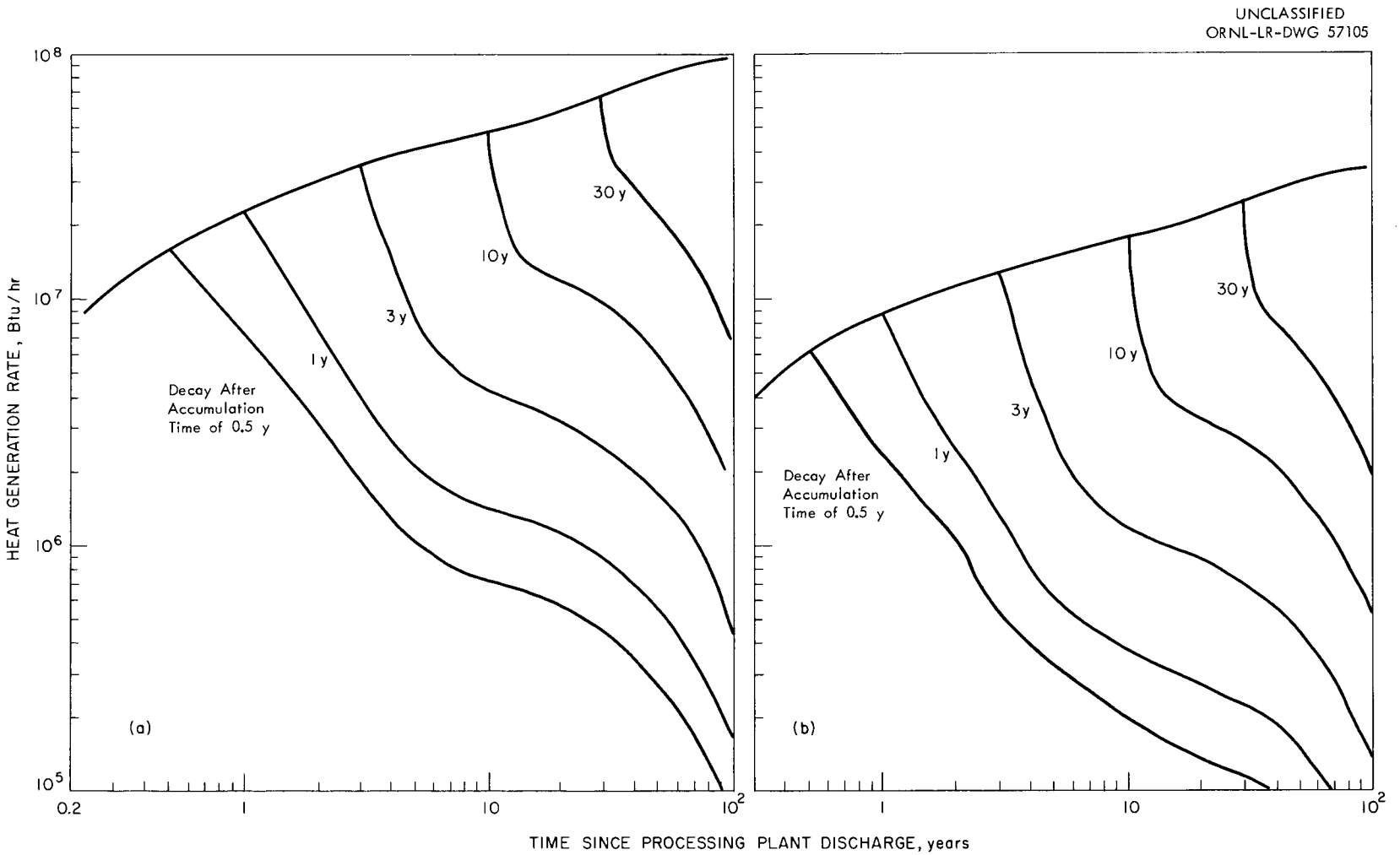

Fig. 1. Heat generation rate in (a) Uranium converter waste from 1500 tonnes/year of fuel irradiated to 10,000 Mwd/tonne and (b) Thorium converter waste from 270 tonnes/year of fuel irradiated to 20,000 Mwd/tonne as a function of accumulation and decay time.

The thorium-converter fuel was assumed to have been irradiated for 3×10^7 sec at a flux of 3×10^{13} n/sec·cm^2 and to have initially 1.05×10^{26} atoms of U-235 per tonne of fuel [95% ThO_2-5% enriched (93%) UO_2]. The specific volumes for the thorium-converter waste were assumed to be 400 gal per tonne of fuel for acid waste and 642 gal/tonne for neutralized waste. The correlations of Blomeke and Todd were again used because a similar comprehensive work for U-233 has not yet been done and the fission yield curves for U-233 and U-235 are not too dissimilar.[5] Heat generation rates in thorium-converter waste are shown in Table 2b and Fig. 1b.

3.0 TANK FARM DESIGN

For purposes of cost estimation, a conceptual design of a tank farm was used and the major items were size estimated. A tank farm layout was used similar to that of Stockdale, Blomeke, and Arnold.[6] The tanks were assumed to contain cooling coils that would hold the radioactive waste solutions at 140°F. Experience with alkaline waste storage in mild steel and acidic aluminum waste storage in stainless steel has shown that corrosion rates in either system can be expected to average a few tenths of a mil per year at temperatures near 150°F. Pumps would circulate cooling water through the coils and through a heat exchanger, where the primary cooling water would be cooled by exchange with a secondary loop including a cooling tower (Fig. 2).

Pumps in the primary loop and heat exchangers would be housed in modular cells with concrete walls 2 ft thick, each cell containing two 2000-ft^2 heat exchangers and a 1000-gpm pump. Thus, in the event of contamination of one primary cooling coil loop, maintenance could be carried out with a minimum of exposure and with no release of activity to the secondary loop.

Tanks of the Savannah River type were chosen, because their design would be more nearly acceptable over a wide range of environments, and the resultant cost figures would be more conservative (higher). A sketch of this design, showing the inner liner sitting in a steel saucer and surrounded by an air space through which heated air for dehumidification is circulated, is shown in Fig. 3. The tank has internal columns for support and is equipped with cooling coils arranged in both horizontal and vertical banks. A water-cooled

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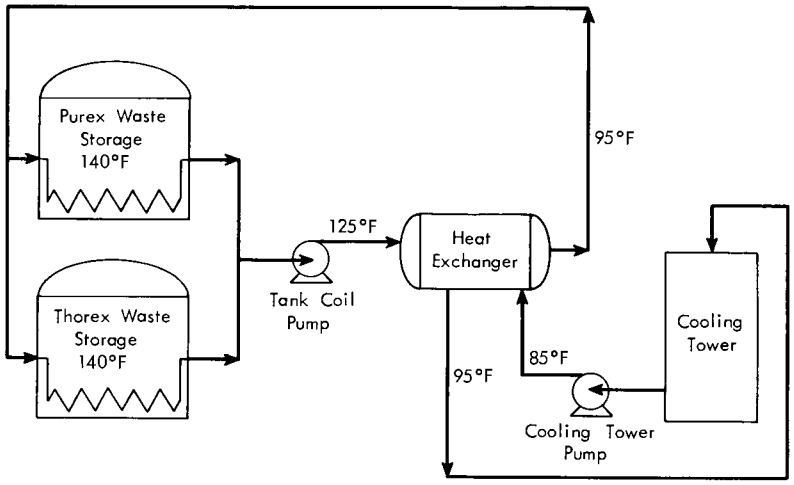

Fig. 2. Schematic diagram of tank farm cooling system.

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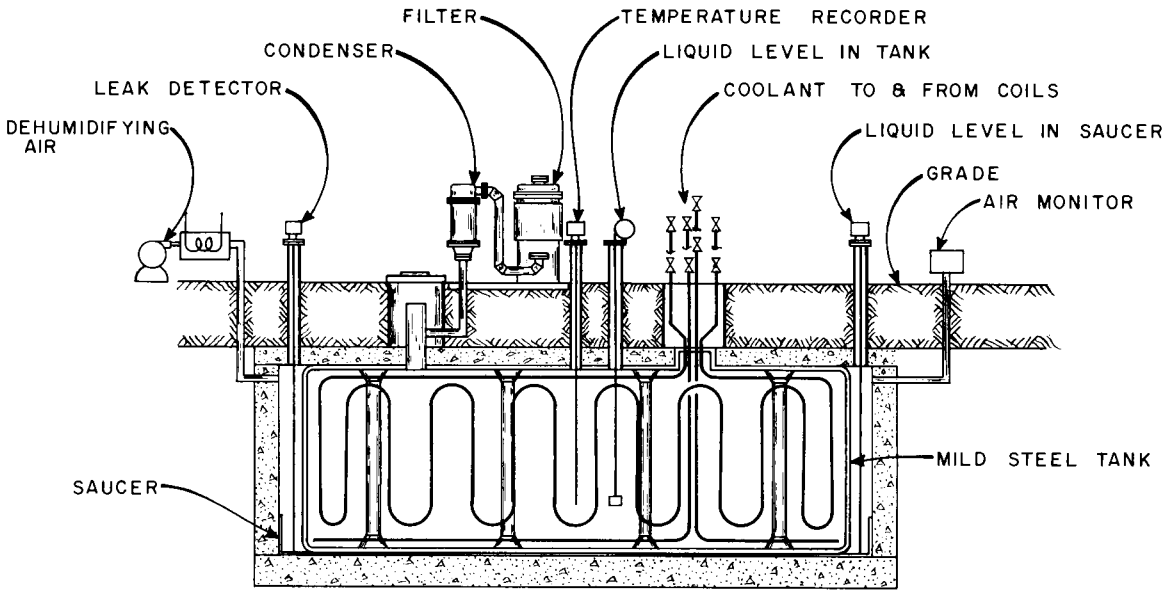

Fig. 3. Savannah River type waste storage tank.

reflux condenser and filter are supplied to take care of the heat load in the event of a cooling-system breakdown. Additional facilities include level indicators, sampling and monitoring devices, and means for evacuating the tank when the occasion demands. The tops of tanks would lie between 6 and 9 ft below grade.

4.0 COST OF TANKS

Acid wastes were assumed stored in stainless steel tanks with stainless steel cooling coils, and neutralized wastes in mild steel tanks with mild steel coils. In order to estimate the costs of stainless steel tanks of Savannah River design, a breakdown of Savannah River costs was inspected and those attributable to the cost of the metal were adjusted. Cooling coil lengths were calculated to take care of the peak heat flux in each tank, and coil costs were added to costs for empty tanks.

Costs of mild steel tanks of Savannah River design as a function of tank size were reported by Stockdale et al.[6] (Fig. 4). A breakdown of costs for the construction of 750,000-gal tanks shows that about 50% of the total costs were due directly to the tanks (Table 3, middle column). This figure was obtained by comparing the tank cost of $3,205,700 for eight tanks to the sum of the first three items in the column, which is $6,085,000. The majority of the other costs in the column should be attributed to the tank farm, which will be cost-estimated separately. The costs directly attributable to fabricated metal were assumed to be 5 times as high for stainless steel as for mild steel. The factor 5 was obtained by averaging a factor of 3 obtained from Peters[7] for costs of 100,000-gal stainless steel and mild steel tanks and a factor of 7 obtained from literature from the Gray Tool Company. If x represents the cost of a mild steel tank of Savannah River design without cooling coils, obtained from Fig. 4, the cost of a similar stainless steel tank is given by

$$x(0.50)(5) + x(0.50) = 3.0x \qquad (6)$$

The calculations for lengths of cooling coils are summarized in Table 4. Five waste volumes were chosen in the range 100,000 to 3,000,000 gal and the times required for the accumulation of these volumes were calculated. Corresponding maximum heat generation rates were obtained from Fig. 1. The

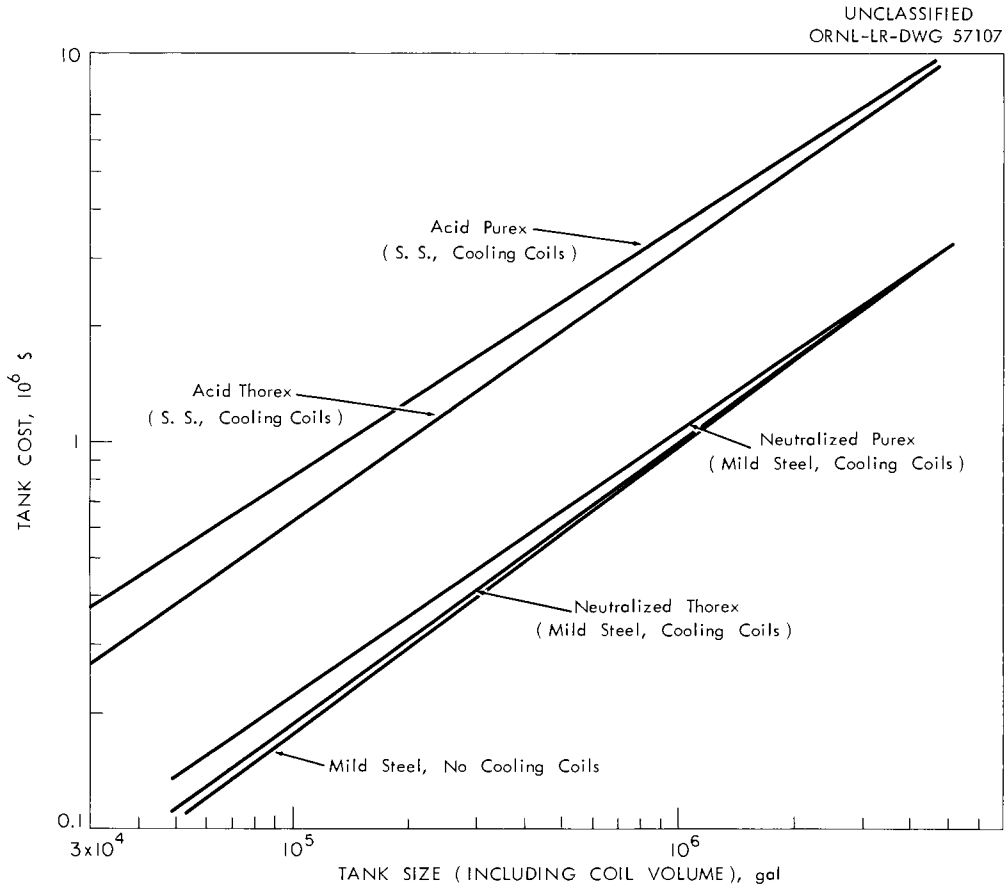

Fig. 4. Costs of tanks of Savannah River design.

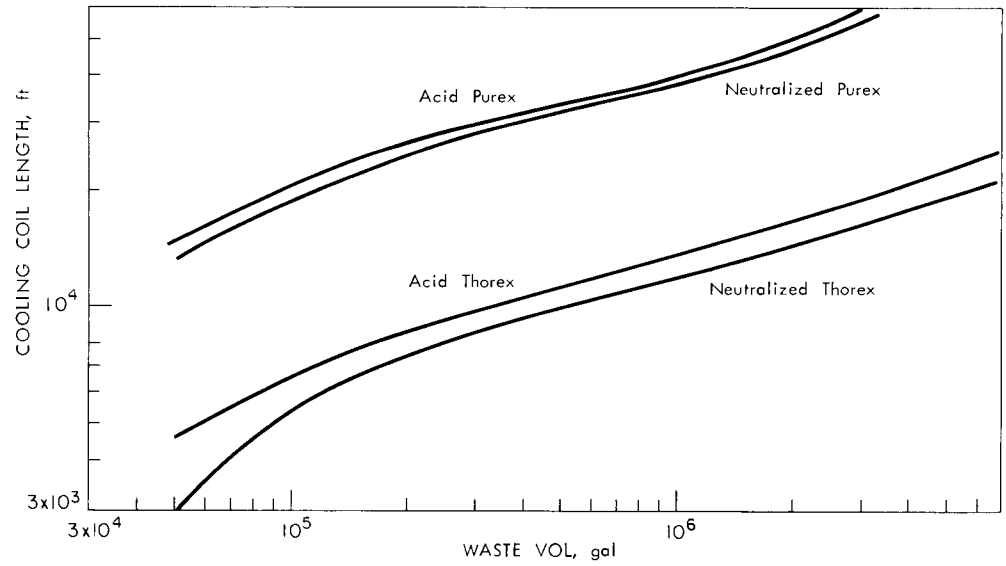

Fig. 5. Cooling coil lengths required to maintain a waste temperature of 140°F as a function of waste volume.

Table 3. Waste Storage Tank Costs[8]

Construction Period 1952-54

Based on material, labor, and distribution (wage increases, administration charges, overhead, etc); to arrive at cost for labor and material costs only, divide figures given by 1.51

Tank Capacity: 750,000 gal per tank

General Construction:

Flat roof, carbon steel, 75-ft-dia tank, encased in concrete; roof supported by eight 2-ft-0-in.-o.d. seamless pipe columns filled with concrete; earth cover 9-ft-0-in.; ground water to top of concrete

Number of tanks	8	8	8
Cooling coils	4 Yes, 4 No	No	Yes
Vent condenser and filter	4 Yes, 4 No	Yes	Yes
Costs			
Excavation and backfill	$ 634,300	$ 634,300	$ 634,300
Tanks (excavation, supports, exam.)	3,205,700	3,205,700	3,205,700
Encasements	2,245,000	2,245,000	2,245,000
Diversion box	332,000	332,000	332,000
Catch tank and drain line	211,400	211,400	211,400
Waste line encasement	160,200	160,200	160,200
Encasements and ventilating	160,100	160,100	160,100
Waste liquid piping	418,600	418,600	418,600
Cooling water piping	120,700	--	241,400
Electrical	337,000	30,400	36,500
Instruments	113,800	102,400	125,200
Cooling coils	571,800	--	1,143,600
Valve houses	43,900	--	87,900
Vent condensers and off-gas filter	45,900	91,800	91,800
Pump house building	58,400	--	116,700
Miscellaneous	294,700	267,700	322,200
Total	$8,650,000	$7,860,000	$9,533,000
Unit costs	$1.44/gal	$1.31/gal	$1.59/gal

Table 4. Calculation of Cooling Coil Lengths

Waste Type	Waste Vol, gal	Time to Fill, years	Maximum Heat Generation, Btu/hr x 10^7	Length of Tubing, ft
Acid Purex	100,000	1.33	2.62	20,400
75,000 gal/year	200,000	2.67	3.38	26,200
	400,000	5.33	4.10	31,900
	1,000,000	13.33	5.05	39,200
	3,000,000	40.00	7.60	59,100
Neutralized Purex	100,000	1.11	2.40	18,700
90,000 gal/year	200,000	2.22	3.18	24,700
	400,000	4.44	3.93	30,600
	1,000,000	11.10	4.85	37,700
	3,000,000	33.33	7.10	55,200
Acid Thorex	100,000	0.93	0.84	6,500
108,000 gal/year	200,000	1.85	1.09	8,500
	400,000	3.70	1.35	10,500
	1,000,000	9.26	1.73	13,500
	3,000,000	27.80	2.40	18,700
Neutralized Thorex	100,000	0.58	0.68	5,300
173,000 gal/year	200,000	1.16	0.92	7,200
	400,000	2.32	1.18	9,200
	1,000,000	5.78	1.53	11,900
	3,000,000	17.33	2.10	16,300

cooling coil tubing was chosen to be 3 in. i.d. with a 6 B.w.g. wall. A heat transfer coefficient for the cooling water inside the tube was estimated at 1000 Btu/hr·ft^2·$^\circ$F using the Dittus-Boelter equation (Reynolds number 1.88 x 10^5, Prandtl number 4.1). A coefficient of 85 Btu/hr·ft^2·$^\circ$F was estimated for the outside of the tube, using a nomograph in McAdams and assuming waste with the properties of water.[9] The resultant overall coefficient was calculated to be 83 Btu/hr·ft^2·$^\circ$F, but a value of 60 was used in order to be conservative. The log mean temperature difference was calculated to be 27.3°F. The length of tubing required is given by

$$\begin{aligned} q &= (U)(2\pi rL)(\Delta T)_{lm} \\ &= (60)(2\pi \cdot 0.25L)(27.3) \qquad (7) \\ L &= 7.78 \times 10^{-4}\ q \end{aligned}$$

where L = length of tubing, ft

q = heat generation rate, Btu/hr

The lengths of cooling coils calculated in Table 5 are plotted against waste volume in Fig. 5. Although the required lengths of cooling coils are of the order of several miles in the larger tanks, the highest ratio of coil volume to tank volume is only about 0.10.

Table 5. Total Costs of Tanks with Cooling Coils

Waste Type	Tank Size, gal	Cost of Tank Without Coils	Length of Coil, ft	Cost of Coil	Total Tank Cost
Acid Purex	110,000	$ 5.65 x 10^5	20,400	$3.06 x 10^5	$ 8.71 x 10^5
	212,000	9.46	26,200	3.93	13.39
	415,000	15.30	31,900	4.79	20.09
	1,018,000	30.50	39,200	5.83	36.33
	2,274,000	53.40	54,000	8.10	61.50
Neutralized Purex	109,000	1.85 x 10^5	18,700	0.47 x 10^5	2.32 x 10^5
	212,000	3.10	24,700	0.62	3.72
	414,000	5.00	30,600	0.76	5.76
	1,018,000	10.00	37,700	0.94	10.94
	3,026,000	21.50	55,200	1.38	22.88
Acid Thorex	103,000	5.34 x 10^5	6,500	0.97 x 10^5	6.31 x 10^5
	204,000	8.84	8,500	1.27	10.11
	405,000	14.95	10,500	1.57	16.52
	1,006,000	30.50	13,500	2.02	32.52
	3,009,000	65.60	18,600	2.79	68.39
Neutralized Thorex	102,000	1.75 x 10^5	5,000	0.12 x 10^5	1.87 x 10^5
	203,000	2.90	7,000	0.17	3.07
	404,000	4.90	9,000	0.22	5.12
	1,006,000	9.80	12,000	0.30	10.10
	3,008,000	21.40	16,000	0.40	21.80

Cooling coil costs were obtained using $2.50 per foot for fabricated and installed mild steel coils and $15.00 per foot for stainless steel coils. These costs assume that labor plus indirect costs are equal to 1.5 times the material costs. Total costs of tanks with cooling coils for the storage of acid and alkaline wastes are given in Table 5, and are plotted in Fig. 4.

In calculating the yearly costs for tanks which must be charged to the yearly electricity production, the following were assumed: (1) tanks costs are amortized over a period of 60 years; (2) capital invested in tanks will be charged an interest rate of 4 per cent per annum; (3) present worth capital can be invested at 4 per cent per annum to accumulate the required funds for building tanks as they become needed; (4) one spare tank (for each waste type) will be built initially; (5) the number of operating tanks, exclusive of the spare, is such that there will always be a total freeboard equivalent to one tank volume; (6) after the initial filling cycle, waste is removed from the farm at the same rate it comes in.

Based on the above assumptions the required number of tanks including the spare is

$$N = 1 + 2\left(\frac{2F + D}{2F}\right) = 3 + D/F \qquad (8)$$

where F and D are the filling and dead storage times, respectively, and the emptying time is assumed equal to the filling time. However, only two tanks are built initially, the spare and one operating tank, and the remainder are built as needed.

One dollar borrowed at 4 per cent interest can be amortized in 60 years at $0.0442 per year. In Table 6 are shown the repayment costs per tank per year based on the 0.0442 factor and tank costs obtained from Fig. 4 plus a fixed sum of $125,000 to cover three items which are proportional to the number of tanks. These are (see p 23): $85,000 for piping, ventilating, and waste line encasement; $15,000 for sampling facilities; and $25,000 for electrical and instruments. In Table 7 are shown the "present worth factors" as a function of tank filling time and waste dead storage time. These factors, when multiplied by the cost per tank, give the total capital needed to build all the required tanks, and when multiplied by the cost per tank per year, give the total yearly principal and interest payments required to repay the total tank capital. The values in Table 6 are thus multiplied by those in Table 7 to give Table 8, the total tank costs per year. As an example, the waste volume of an acid Purex tank with a filling time of one year and a dead storage time of one year will be 75,000 gal and the volume including coils will be 83,000 gal. From Fig. 4 the cost is found to be $730,000. To this is added the fixed sum of $125,000, giving a total of $855,000. This value times 0.0442 gives a repayment cost per year of $37,800.

Table 6. Repayment Costs per Tank per Year

Filling Time, Years	Waste Type: Acid Purex	Neutralized Purex	Acid Thorex	Neutralized Thorex
0.125	$ 17,450	$ 8,090	$ 12,500	$ 8,400
0.250	19,200	9,460	16,750	10,100
0.500	26,300	11,600	23,650	13,100
1	37,800	15,200	34,900	17,900
3	68,800	25,200	68,300	33,000
10	142,500	49,700	151,000	70,900
20	-	76,700	248,000	114,000
30	277,000	99,300	326,000	153,000

Table 7. Present Worth Factors as a Function of Filling Time and Dead Time

Dead Time, years	0.125 y Filling Time	0.250 y Filling Time	0.500 y Filling Time	1 y Filling Time	3 y Filling Time	10 y Filling Time	20 y Filling Time	30 y Filling Time
0	-	-	2.98	2.96	2.89	2.68	-	2.31
1	10.78	6.85	4.88	3.89	3.15	2.72	-	-
4	-	17.58	10.17	6.45	3.91	2.86	-	2.32
20	-	-	29.9	16.0	6.75	3.44	2.66	-

The total number of tanks required is $N = 3 + 1/1 = 4$. Two of these tanks will be built immediately (the initial tank plus the spare) and their present worth factor will be 2 (unity for each tank). At the end of the first year the first tank will be full and another tank must be built, but the present worth, at 4 per cent interest, of this tank is only 0.9615. At the end of the second year the second tank will be full and a fourth tank, which has a present worth of 0.9246, must be built. At the end of the third year

Table 8. Total Tank Costs Per Year

Filling Time, years	0 Dead Time	1 y Dead Time	4 y Dead Time	20 y Dead Time	0 y Dead Time	1 y Dead Time	4 y Dead Time	20 y Dead Time
	Acid Purex				Neutralized Purex			
0.125	-	188,000	-	-	-	87,300	-	-
0.250	-	131,000	337,000	-	-	64,800	166,000	-
0.500	78,400	128,000	267,000	787,000	34,600	56,600	118,000	347,000
1	112,000	147,000	242,000	606,000	45,000	59,100	98,000	244,000
3	199,000	216,000	269,000	464,000	72,900	77,300	98,600	170,000
10	382,000	-	407,500	490,000	133,000	135,000	142,000	171,000
20	-	-	-	573,000	-	-	-	204,000
30	640,000	-	642,600	-	229,000	-	-	-
	Acid Thorex				Neutralized Thorex			
0.125	-	135,000	-	-	-	90,600	-	-
0.250	-	115,000	294,000	-	-	69,200	178,000	-
0.500	70,500	115,000	241,000	708,000	39,000	64,000	133,000	392,000
1	103,000	135,000	225,000	559,000	53,000	69,600	115,000	287,000
3	197,000	215,000	267,000	461,000	95,400	104,000	129,000	223,000
10	405,000	-	431,000	520,000	190,000	-	203,000	244,000
20	-	-	-	661,000	-	-	-	304,000
30	753,000	-	-	-	354,000	-	-	-

the initial tank has been filled for one year, set in dead storage for one year, and emptied for one year so that now the cycle can be repeated. Thus, the total present worth factor is 3.8861. This factor times the $37,800 per year per tank gives a total tank cost per year of $147,000 (Table 8).

The data of Table 8 are shown in Fig. 6a and b. In these figures 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 liquid 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

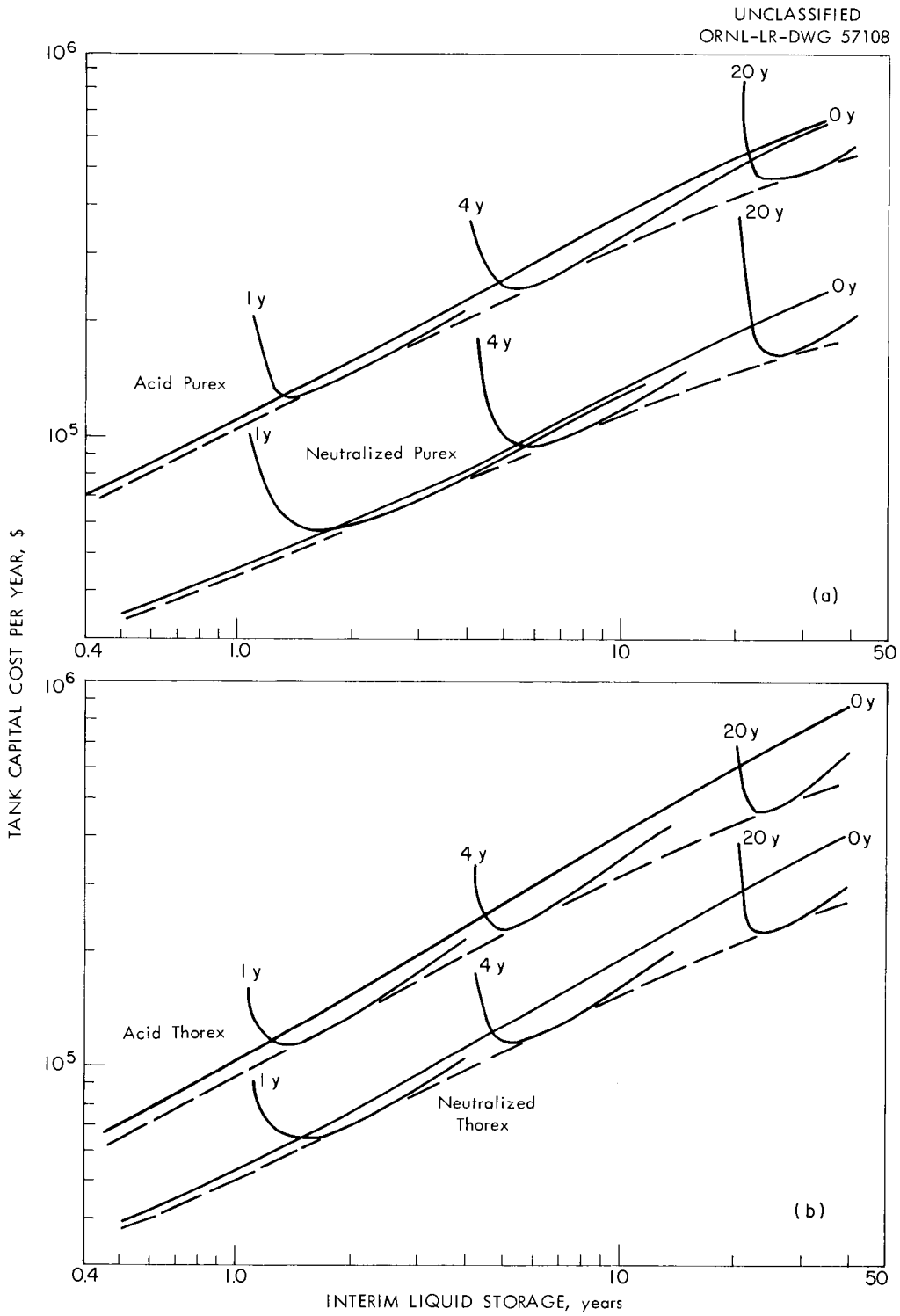

Fig. 6. Tank capital cost per year as a function of interim storage time with parameters of dead time for (a) Purex waste and (b) Thorex waste. — — —Locus of optimum dead times.

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 in Fig. 6a and b are the loci of minimum tank capital costs per year as a function of the interim liquid storage time. Tangency of these curves is along relatively flat sections of the fixed dead storage curves, indicating a more or less broad optimum relation between dead time and interim storage time. In Fig. 7 this relation is plotted. Optimum dead storage times for all four waste types fall within the limits shown on this figure.

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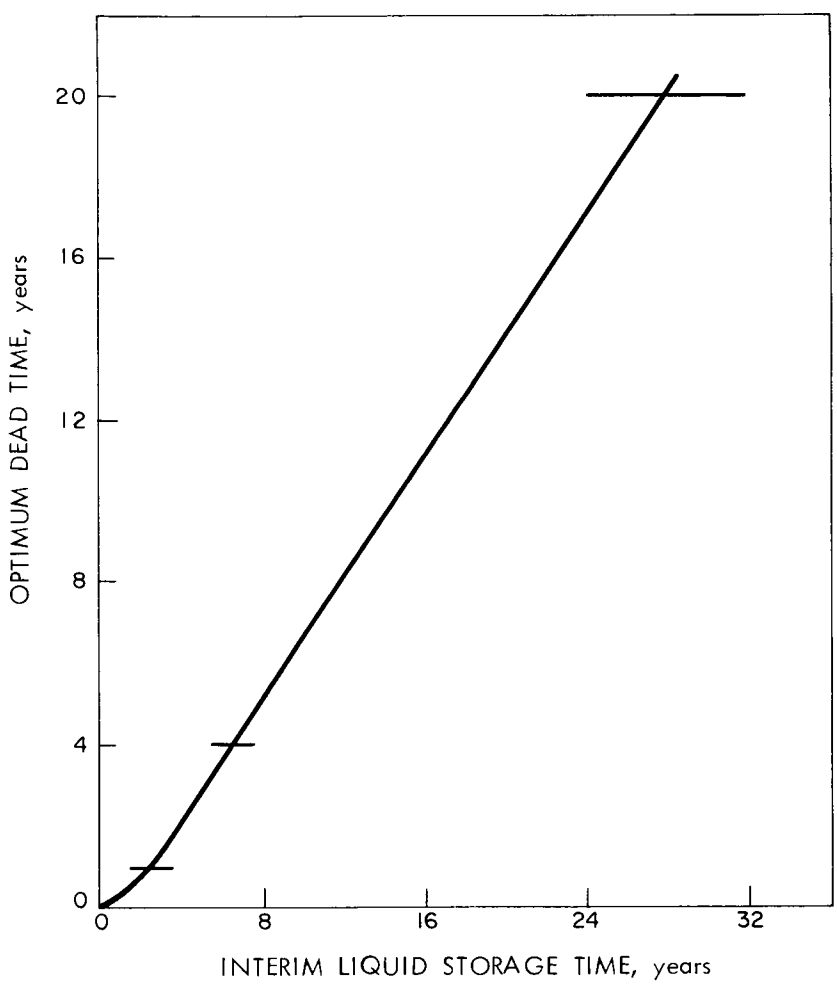

Fig. 7. Optimum dead time as a function of interim liquid storage time.

It is of interest to note, contrary to what might be expected, that at no time (other than the trivial case of zero interim storage) is zero dead storage (i.e., starting to empty a tank as soon as it is full) the most economical choice. This is due to the fact that with zero dead storage the tank utilization is at a minimum. By previous definitions, there is always one spare plus a total of one tank volume in freeboard at any given time. Thus the tank utilization factor is (N - 2)/N. For zero dead storage this factor is 0.33 and for all other dead storage times it is larger since the number of tanks is greater.

5.0 TANK FARM COSTS

Items in the tank farm which were cost estimated are:

1. Cooling towers
2. Heat exchangers
3. Pumps for primary and secondary circuits
4. Electric motors for pumps
5. Cells and secondary containment for housing heat exchangers and primary loop pumps

A reasonable cost for erected cooling towers is $7.00 per gpm for a cooling range (input water temperature - output water temperature) of $10^{o}F$.[10] Applying a cost index figure of 1.44 for the period 1949 to 1960, the cost becomes $10 per gpm. The cost may be converted to a more convenient basis by taking into account the fact that a stream of water at a rate of 1 gpm undergoing a $10^{o}F$ temperature drop gives up 5000 Btu/hr. Therefore the capital cost of erected cooling towers becomes

$$(\$10/\text{gpm})(1/5000\ \text{Btu/hr}\cdot\text{gpm}) = \$0.002/\text{Btu}\cdot\text{hr}$$

For interim liquid storage times of 0.5 to 30 years, cooling tower costs range from $32,000 to $136,000 for Purex waste and $12,600 to $59,000 for Thorex waste (Table 9).

The tank farm heat exchanger was sized using a calculated log mean temperature difference of $18^{o}F$ and an assumed overall heat transfer coefficient of 150 $Btu/hr\cdot ft^2\cdot {}^{o}F$, which gives a heat flux of 3000 $Btu/hr\cdot ft^2$. The cost

Table 9. Tank Farm Capital Costs

Item No.		0.5 y Interim Storage	1 y Interim Storage	3 y Interim Storage	10 y Interim Storage	30 y Interim Storage
		Acid Purex, 75,000 gal/year				
	Maximum heat generation rate, Btu/hr	1.6×10^7	2.3×10^7	3.5×10^7	4.75×10^7	6.8×10^7
1	Cooling tower cost	$32,000	46,000	70,000	95,000	136,000
2	Heat exchanger surface, ft^2	5,300	7,700	11,600	15,800	22,700
	Number of 2000-ft^2 units	3	4	6	8	12
	Cost ($7000 ea.)	$21,000	28,000	42,000	56,000	84,000
3	Cooling tower pump duty, gpm	3,200	4,600	7,000	9,500	13,600
	Number of 1000-gpm units (1 spare ea.)	8	10	14	20	28
	Cost ($3750 ea.)	$30,000	37,500	52,500	75,000	105,000
4	Tank coil pump duty, gpm	1,000	1,500	2,300	3,200	4,500
	Number of 1000-gpm units (1 spare ea.)	2	4	6	8	10
	Cost ($3750 ea.)	$7,500	15,000	22,500	30,000	37,500
5	Electric pump motors, 40-hp (1 spare ea.)	10	14	20	28	38
	Cost ($1250 ea.)	$12,500	17,500	25,000	35,000	47,500
6	Pump and heat exchanger cell and secondary containment	$76,000	76,000	99,000	121,000	162,000
		Acid Thorex, 108,000 gal/year				
	Maximum heat generation rate, Btu/hr	0.63×10^7	0.87×10^7	1.30×10^7	1.80×10^7	2.5×10^7
1	Cooling tower cost	$12,600	17,400	26,000	36,000	50,000
2	Heat exchanger surface, ft^2	2,100	2,900	4,330	6,000	8,330
	Number of 2000-ft^2 units	2	2	3	3	5
	Cost ($7000 ea.)	$14,000	14,000	21,000	21,000	35,000
3	Cooling tower pump duty, gpm	1,300	1,740	2,600	3,600	5,000
	Number of 1000-gpm units (1 spare ea.)	4	4	6	8	10
	Cost ($3750 ea.)	$15,000	15,000	22,500	30,000	37,500
4	Tank coil pump duty, gpm	420	600	900	1,200	1,700
	Number of 1000-gpm units (1 spare ea.)	2	2	2	4	4
	Cost ($3750 ea.)	$7,500	7,500	7,500	15,000	15,000
5	Electric pump motors, 40-hp (1 spare ea.)	6	6	8	12	14
	Cost ($1250 ea.)	$7,500	7,500	10,000	15,000	17,500
6	Pump and heat exchanger cell and secondary containment	$51,000	51,000	76,000	76,000	99,000

of an installed 2000-ft^2 mild steel unit was estimated at $7000.[11] Each unit would contain 650 tubes 0.75 in. i.d. and 15 ft long arranged on a square pitch of 2.1 in. The diameter of the shell would be 5 ft. The number of 2000-ft^2 units necessary for interim storage times of 0.5 to 30 years ranged from 3 to 12 for Purex waste and 2 to 5 for Thorex waste.

Since temperature drops are specified in both primary and secondary loops, cooling water rates are determined by the heat generation rate of the waste. A standard 1000-gpm centrifugal pump costing $1500 was chosen.[12] Assuming the labor plus indirect costs to be 1.5 times the initial pump cost, the cost per pump becomes $3750. As a safety factor, one spare pump was assumed for every working pump. The numbers of 1000-gpm pumps and total capital pump costs for interim storage times ranging from 0.5 to 30 years are given in Table 9.

A 40-hp electric motor was chosen for each 1000-gpm pump, which is sufficiently large to deliver 1000 gpm against a 150-ft head of water. Each motor would have an initial cost of $500,[13] and again applying the 2.5 factor, an installed initial cost of $1250.

Electrical and instruments, plus piping, ventilating, and waste line encasement, were estimated at $15,000 and $85,000 per tank, respectively, from the middle column of Table 3. Sampling facilities were estimated at $15,000 per tank.[14] These three items, since they are directly proportional to the number of tanks, have been included in the tank costs shown in Fig. 6. Electrical and instruments was assumed to be a 20-year item, so that a charge of $25,000 is made over the 60-year lifetime of a tank.

For cost estimation purposes a modular cell design was used to house the heat exchangers and primary loop pumps. The modular cell design permits isolation of the pumps and heat exchangers for each primary loop. In the event of contamination of one of the primary loops, normal maintenance and control could be exercised on that equipment associated with other uncontaminated primary loops. Each cell would have inside dimensions of 10 by 20 by 25 ft high, and would allow installation and maintenance of two 2000-ft^2 heat exchangers and a 1000-gpm primary pump and its spare. Assuming the walls and roof slabs to be 2 ft thick, each cell would require about 3800 ft^3 of concrete, or 140 yd^3. Costs for concrete in place for this type of construction, including forms and steel, are about $100 per cubic yard.[15] Therefore a unit cost of $14,000 per modular cell was used. For each tank farm corresponding to a particular storage time and waste type, a 7-ton crane was included at $15,000.

For secondary containment a steel building was cost-estimated which would totally enclose each group of modular cells. Costs for steel buildings ranged from $22,000 for a 30,000-$ft^3$ building to enclose one modular cell to $63,000 for a 135,000-$ft^3$ building to enclose six modular cells. Costs of steel buildings were obtained from "Suggested Procedures for Economic Evaluations for Uranium Recovery Plants," prepared by AEC Grand Junction Operations Office, Jan. 25, 1955.

Tank and tank farm costs for acid Purex and Thorex wastes are summarized in Table 9. Items 1 through 5 were amortized over a 20-year period and the remaining item over 60 years. Tank farm costs are the same for neutralized Purex as for acid Purex and the same for neutralized Thorex as for acid Thorex. These costs ranged from $10,900 to $37,400 per year for Purex waste for interim liquid storage times of 0.5 to 30 years, and from $6,400 to $15,800 for Thorex waste over the same range of storage times (Table 10). Present value annuity factors at 4 per cent interest are $0.07358 per dollar for 20 years and $0.0442 per dollar for 60 years.

Table 10. Tank Farm Capital Costs Per Year (Excluding Tanks)

Waste	0.5 y Interim Storage	1 y Interim Storage	3 y Interim Storage	10 y Interim Storage	30 y Interim Storage
Purex					
Sum of 20-year items	$103,000	$144,000	$212,000	$291,000	$410,000
Cost per year	7,580	10,600	15,600	21,400	30,200
Sum of 60-year items	76,000	76,000	99,000	121,000	162,000
Cost per year	3,360	3,360	4,370	5,350	7,160
Total cost per year	10,900	14,000	20,000	26,800	37,400
Thorex					
Sum of 20-year items	56,600	61,400	87,000	117,000	155,000
Cost per year	4,160	4,520	6,400	8,610	11,400
Sum of 60-year items	51,000	51,000	76,000	76,000	99,000
Cost per year	2,250	2,250	3,360	3,360	4,370
Total cost per year	6,400	6,800	9,800	12,000	15,800

6.0 OPERATING COSTS

Electric power costs were based on the following assumptions: (1) cost of electric power is 1¢ per kilowatt-hour; (2) cooling tower and heat exchanger pump motors are 90% efficient; (3) all pumps (excluding spares) operate continuously; (4) all other power consumptions are negligible.

Cooling tower makeup water calculations were based on the following assumptions: (1) the ratio of mass flow of water to mass flow of air (L/G) in the cooling tower is unity; (2) the temperature drop in the water and the temperature rise in the air are equal and thus, since $C_{pa} = 0.25\ C_{pw}$, 25% of the heat transfer takes place by convection and the remainder by vaporization; (3) water costs are $0.25 per 1000 gal. The cost per year of makeup water is thus $200 per 10^6 Btu/hr of heat generation rate.

Yearly labor costs for operation of the tank farm were assumed to be the same for any combination of waste types stored and for any period of storage. Total yearly costs were estimated to be $100,000 based on 8 man-years at $12,500 per man-year, including overhead. The manpower breakdown is: (1) operation and continuous surveillance will require four shift operators plus a supervisor who fills in as a relief operator; (2) maintenance and miscellaneous services will require three man-years (available on as-needed basis from the processing plant).

Yearly power and water costs as a function of waste type and storage time are shown in Table 11. Labor costs are added, and the total tank farm operating costs (exclusive of capital) are also shown in this table. The total cost is independent of whether acid or neutralized waste is stored and ranges from $128,000 to $194,000 per year for storage times from 0.5 to 30 years.

7.0 COST PER KILOWATT-HOUR OF ELECTRICITY

The total capital costs per year for the various waste types as a function of storage time are shown in Table 12. These figures were arrived at by taking tank farm capital costs per year from Table 10 and adding the tank capital costs per year obtained from the optimum curves in Fig. 6.

The total costs per year for storage of all combinations of waste types are shown in Table 13. They are the sums of the appropriate capital costs from Table 12 and the operating costs from Table 11.

Table 11. Total Tank Farm Operating Cost per Year Excluding Capital

Cost Item	0.5 y Storage	1 y Storage	3 y Storage	10 y Storage	30 y Storage
Purex Waste					
Water	3,200	4,600	7,000	9,500	13,600
Power	14,500	20,300	29,000	40,600	55,000
Thorex Waste					
Water	1,260	1,740	2,600	3,600	5,000
Power	8,700	8,700	11,600	17,400	20,300
Labor	100,000	100,000	100,000	100,000	100,000
Total	128,000	135,000	150,000	171,000	194,000

Table 12. Total Capital Costs per Year

Waste Type	0.5 y Interim Storage	1 y Interim Storage	3 y Interim Storage	10 y Interim Storage	30 y Interim Storage
Acid Purex	$85,000	$117,000	$202,000	$342,000	$527,000
Neutralized Purex	44,000	57,000	89,000	140,000	207,000
Acid Thorex	70,000	100,000	178,000	324,000	521,000
Neutralized Thorex	44,000	57,000	95,000	164,000	261,000

Table 13. Total Costs Per Year for Storage of All Combinations of Acid and Alkaline Wastes

Item	0.5 y Interim Storage	1 y Interim Storage	3 y Interim Storage	10 y Interim Storage	30 y Interim Storage
Acid Purex-acid Thorex					
Capital	$155,000	$217,000	$380,000	$666,000	$1,048,000
Operating	128,000	135,000	150,000	171,000	194,000
Total	283,000	352,000	530,000	837,000	1,242,000
Acid Purex-neutralized Thorex					
Capital	129,000	174,000	297,000	506,000	788,000
Operating	128,000	135,000	150,000	171,000	194,000
Total	257,000	309,000	447,000	677,000	982,000
Neutralized Purex-acid Thorex					
Capital	114,000	157,000	267,000	464,000	728,000
Operating	128,000	135,000	150,000	171,000	194,000
Total	202,000	292,000	417,000	635,000	922,000
Neutralized Purex-neutralized Thorex					
Capital	88,000	114,000	184,000	304,000	468,000
Operating	128,000	135,000	150,000	171,000	194,000
Total	216,000	249,000	334,000	475,000	662,000

The wastes which accumulate in one year are the result of continuous operation of 56,000 Mw of thermal power generating capacity (1500 tonnes/year of uranium converter fuel and 270 tonnes/year of thorium converter fuel, irradiated to 10,000 and 20,000 Mwd/tonne, respectively) with a thermal efficiency of 27%. The electrical capacity is thus 15,000 Mw and the total electrical power produced is 1.31×10^{11} kwh_e/year.

The total costs in mills/kwh_e shown in Table 14 for the various combinations of waste types were obtained by dividing the total costs shown in Table 13 by 1.31×10^{11} kwh_e/year

2.68
4.05
2 | 6.68
3.34

Table 14. Costs in Mills per Kilowatt-hour (Elec) for Storage of All Combinations of Acid and Alkaline Wastes

Waste Type	0.5 y Interim Storage	1 y Interim Storage	3 y Interim Storage	10 y Interim Storage	30 y Interim Storage
Acid Purex-acid Thorex	2.16×10^{-3}	2.68×10^{-3}	4.05×10^{-3}	6.39×10^{-3}	9.50×10^{-3}
Acid Purex-neutralized Thorex	1.96	2.36	3.41	5.17	7.50
Neutralized Purex-acid Thorex	1.85	2.23	3.18	4.85	7.04
Neutralized Purex-neutralized Thorex	1.65	1.90	2.55	3.62	5.05

It may be noted from Table 13 that for a storage period of less than one year the yearly labor costs ($100,000) represent approximately one half of the total costs. For 30 years' storage labor costs are reduced to 10 to 15% of the total.

In Figure 8 the total costs of interim liquid storage in mills per kilowatt-hour of electricity (from Table 14) are plotted as a function of the storage period. The cost varies 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 for 30 years' storage depending on waste combinations chosen. These costs assume that, for a given interim storage period, the optimum dead storage period is used.

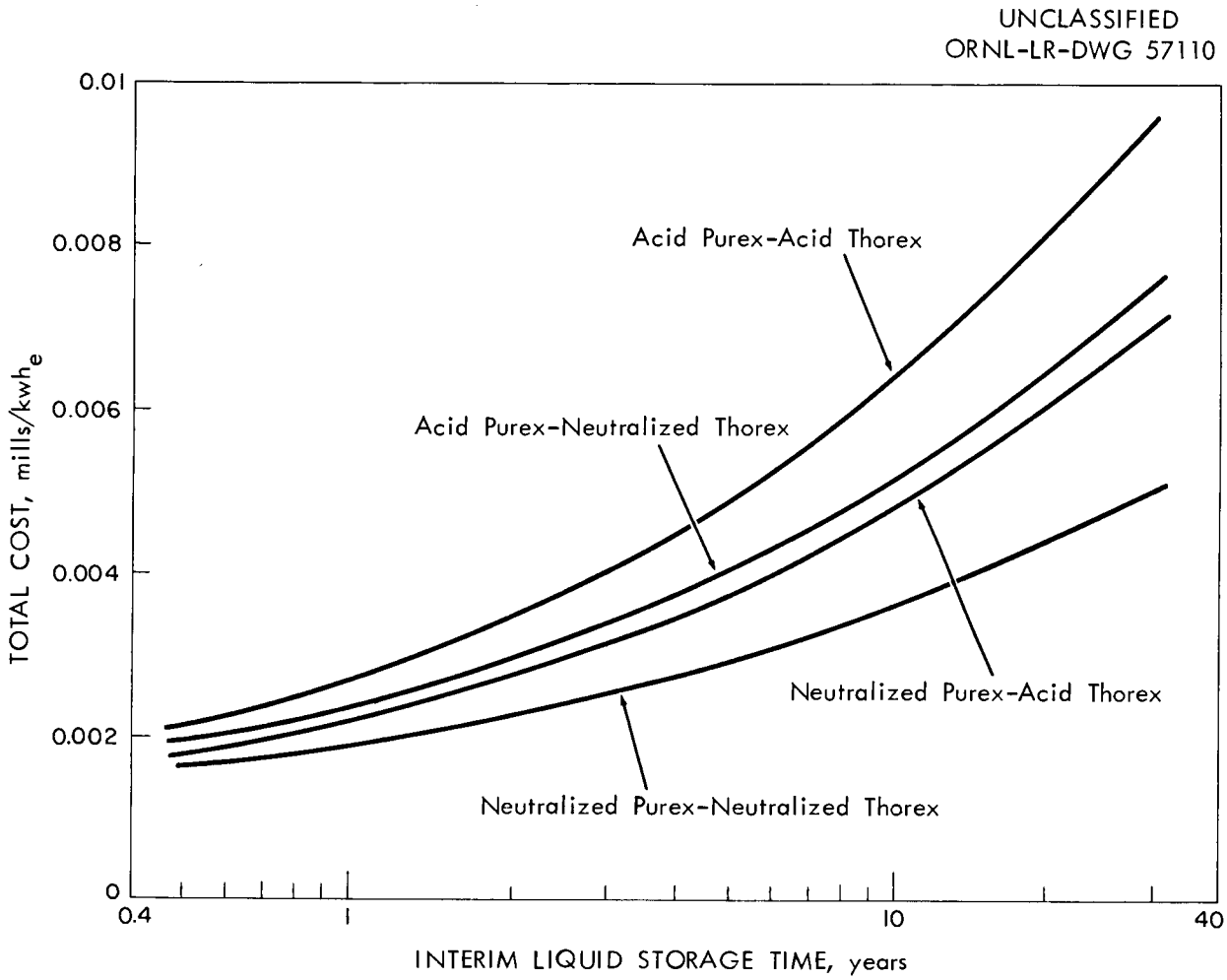

Fig. 8. Cost of interim liquid storage as a function of storage time for all combinations of acid and alkaline Purex and Thorex wastes.

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