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WASTE DISPOSAL

TO: Stuart McLain

FROM: Floyd L. Culler, Jr.

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Economics of Liquid Waste Disposal

The processes required to prepare liquid fission product wastes for ultimate disposal have not yet been developed. Neither has any unanimity of thought, supported by adequate development work, been reached concerning the form that wastes should take. Sites and methods of permanent disposal have not been determined. In truth, the nature of radioactive wastes which will result from a nuclear power economy have not been determined. For these reasons and others even an order of magnitude estimate of the actual costs involved in the disposal of liquid wastes cannot be made.

However, it is possible to establish rough guides as to what disposal costs an 8mill/kwh nuclear power economy can support. Such a study made by H. R. Zeitlin,⁽¹⁾ was made assuming that there is no income from fission product utilization. This study is reproduced in its entirety in the following section. The costs are given in dollars per gallon of waste and represent the total allowable expenditure for the wastes from the time that they leave primary separation in the radiochemical separations process until they reach their final resting place.

Economic Requirements for Radioactive Waste Disposal in a Nuclear Power Economy

by

H. R. Zeitlin, June, 1955

1.0 ABSTRACT AND SUMMARY

An attempt has been made to define the limits on the tolerable cost per initial gallon of liquid radiochemical process waste as a function of 1) reactor operating and design characteristics, 2) the radiochemical separations process employed and 3) the fraction of 8 mill/kwhr power which is allocated to the disposal of wastes. The allowable cost of waste disposal for the case in which the reactor burnup is 5,000 MWD (heat)/ton, the processing waste volume 1200 gals/ton, and the allocated cost for waste disposal 2% (or 0.16 mills/kwhr_e) is \$4/gallon.

2.0 PURPOSE AND RESULTS OF STUDY

Ultimate disposal of radioactive liquid wastes, particularly those resulting from the processing of spent reactor fuels, has in the past

appeared to be a problem, the solution of which would place a significant economic burden on a future nuclear power economy. Waste disposal costs of the order of one dollar per initial gallon of liquid wastes resulting from the standard solvent extraction separations processes seemed to be an upper limit to what can be allowed for the ultimate disposal of these wastes. These cost limits do hold for certain reactor-processing complexes, but are for the most part not in accord with the characteristics of the contemplated nuclear power economy.

It is the purpose of this memo to indicate what the allowable cost limits are in the more general case, the one in which the pertinent reactor-processing-cost variables are taken into consideration.

In Figures 1 through 6 is plotted the allowable disposal cost per initial gallon of waste as a function of the burnup of the spent reactor fuel that is being processed, the parameters being the gallons of radioactive waste resulting from the process per ton of spent reactor fuel and the fraction of the cost of 8 mill/kwhr_e allocated to disposal of these liquid wastes. (See Table I for the range of the variables employed.)

It should be noted that these six curves were derived using values of the variables which are representative of the reactor and processing characteristics now being proposed for an economic (low enrichment) nuclear power economy. A similar curve (for only one value of fraction of power cost allocated to waste disposal) using values of the variables representative of a premium power (high enrichment) economy is plotted in Figure 7.

It can be seen that allowable costs for waste disposal can vary from \$0.80 to \$80.00 per gallon for a low enrichment economic nuclear power economy and from \$.08 to \$4.80 for a high enrichment power economy, depending on the reactor and process characteristics and on the fraction of the total cost of power allocated to waste disposal.

It should be noted that although both high and low activity wastes result from processing of reactor fuels, and low activity wastes will presumably be cheaper to dispose of, no differentiation was made in Figures 1 through 6. Therefore, on the assumption that one-fourth of the allocated portion of the total power cost went for low activity disposal, another series of curves shown in Figure 8, was determined to indicate the allowable cost of disposing of low activity wastes.

3.0 CONCLUSIONS

The areas shown shaded in Figures 1 through 6 probably well represent an average of the operating characteristics of reactors and chemical processes that will exist in a low enrichment economic nuclear power economy. From these areas, it can be seen that as the allocated portion of the total power cost varies from 1% to 10% (i.e., $0.08 \frac{\text{mills}}{\text{kwhr}_e}$ to $0.80 \frac{\text{mills}}{\text{kwhr}_e}$) the allowable cost

for waste disposal will vary between \$1.60 and \$64.00.

Since there are many areas in the economic picture of nuclear power which may be in error to three or more percent, an allocated cost for waste disposal of three percent does not appear unreasonable. Therefore, a cost range of \$5.00 to \$20.00 per gallon of initial high activity waste may be a better basis to use in determining the direction which waste disposal research and development should follow.

In conclusion it is obvious that to reduce the stringent economic requirements dictated to the disposers of radioactive wastes (i.e., geologists, biologists, oceanographers, sanitary engineers, designers of tanks, pits, and fancy gadgets for treatment of wastes, etc.) it is necessary to design reactors with ever increasing processing cycle times and design chemical processes with ever decreasing volumes of wastes per unit weight of reactor fuel processed.

* * *

Table 1
Range of Variables

<u>Variable</u>	<u>Range</u>
Burnup: Low enrichment (economic power)	1000 to 10,000 MWD/ton
High enrichment (premium power)	0.20 to 0.50 MWD/gm U ²³⁵ *
Processing Waste Volumes:	
Low enrichment: High activity	600 to 2400 gals/ton
Low activity	300 to 1200 gals/ton
High enrichment: High activity	
Al elements	0.05 to 0.30 gals/gm U ²³⁵ *
Zr elements	0.5 to 1.5 gals/gm U ²³⁵
S.S. elements	0.05 to 0.30 gals/gm U ²³⁵
Low activity	0.2 to 0.6 gals/gm U ²³⁵
Fraction of Power Cost Allocated to Waste Disposal	1% to 10% (0.08 to 0.8 $\frac{\text{mills}}{\text{kwhr}_e}$) ⁺
Reactor Thermal Efficiency = 25%	

* Grams of U²³⁵ as charged to the reactor

+ Based on a total power cost of 8 $\frac{\text{mills}}{\text{kwhr}_e}$

Fig. 1 Allowable Waste Disposal Cost As A
Function of Burnup and Process Waste Volume

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Fig. 2 Allowable Waste Disposal Cost As A
Function of Burnup and Process Waste Volume

Fig. 3 Allowable Waste Disposal Cost As a Function of Burnup and Process Waste Volume

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Fig. 4 Allowable Waste Disposal Cost As A
Function of Burnup and Process Waste Volume

Fig. 5 Allowable Waste Disposal Cost As A
Function of Burnup and Process Waste Volume

Fig. 6 Allowable Waste Disposal Cost As A
Function of Burnup and Process Waste Volume

Fig. 7 Allowable Waste Disposal Cost for

Highly Enriched (Premium Power) Reactors

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Fig. 8 Allowable Low Activity Waste Disposal Cost
As A Function of Burnup and Process Waste Volume

Using the foregoing report as an overall guide, it is possible to define the limits of what waste disposal can cost. At present, it is the consensus of expert opinion that chemical reprocessing costs cannot exceed about 1 mill/kwh of electricity. Of this 1 mill/kwh, the waste disposal costs should not exceed 0.2 mill/kwh, which must include all charges from primary separation step to ultimate disposal. Thus the allowable disposal costs given in Figure 2 of Zeitlin's study may represent the waste costs that can be permitted in a nuclear power economy, in which all costs are covered by the return from power. Fortunately, then the possibility that income from the sale of certain fission products, and from the utilization of radiation (primarily gamma) may defray part of or possibly all of the costs of handling and disposing of the bulk of the wastes.

Steps in Liquid Waste Disposal

It is impossible to predict that exact chemical procedures and steps that will lead to safe radioactive waste disposal; equally uncertain is the choice of the nature of the ultimate disposal container and environment. However, it is possible to define in a more or less general fashion the steps that will lead to ultimate disposal of waste, and to suggest possible means of accomplishing each of the generalized steps, basing the suggestions on experience, development work now in progress, or on opinion. Having done this much, it is then possible to place costs on the better understood stages of the general scheme, to thereby determine how much money can be allowed for those steps as yet undeveloped.

A generalized scheme for waste disposal is shown in Figure 12, in which the general steps are:

1. Production of wastes, under which the radiochemical process produces the major waste volume.

2. Treatment, to concentrate, remove fission products and other elements from the raw waste, neutralization, or solid waste preparation. Such treatment steps can come either before or after decay cooling; depending upon the nature of the process, the activity levels, and the economic balance. It is probable that such operations as evaporation and neutralization would follow immediately after the primary chemical process, that Cs, Sr, and hazard controlling heavy elements removal might best be accomplished as part of the initial process. It is likely that preparation of wastes into solid form might best be accomplished after some decay period of several years to reduce the problem of controlling heat released by decaying fission products.
3. Decay Cooling, will follow any treatment step except possibly solid waste preparation, or can logically follow immediately after primary chemical separation. During this decay cooling period certain wastes can be allowed to self-concentrate since the concentration of fission products in the waste will be sufficient to cause liquid wastes to boil for a considerable period of time. Reflux and/or draw-off condensers and possibly cooling coils will be required during this period. Decay cooling can be accomplished in metal tanks of varying size and material of construction, or possibly in a membrane-lined earth pit filled with sand or agglomerate that serves as a filter and shield. The length of the decay cooling period must be determined by economic balance or discussed later. Direct disposal of waste to its final resting place in the form of a fused solid (preferable fission product fused) is being studied by the Health Physics and Ceramics group at ORNL.
4. Treatment and Packaging. Certain steps of waste treatment may be economically and technically desirable after the decay cooling period; the same possibilities exist as for treatment before decay cooling.

Assuming that the radiochemical plant is not within easy transfer distance of an ultimate disposal site, all wastes concentrated or otherwise must be "packaged" for shipment in heavy shielded containers.

5. Shipment from the chemical plant after decay cooling and packaging is required. Shipping costs will depend upon the activity level of the wastes, which determines the weight of shielding which must accompany each shipment. Thorough study of carrier design, shielding materials, types of transport, and the legal and hazard problems of waste shipment must be made. The economic balance between the costs of decay cooling vs shipping costs is discussed later in this report.
6. Ultimate Disposal. Many possibilities for ultimate disposal have been discussed, but no definition or choice is possible without rather extensive and expensive development work. However, the possibility of storing wastes in protected tanks of limited lifetime must be considered as a prime contender, particularly if Cs and Sr (and heavy elements) are removed from bulk wastes and stored as concentrates in small, highly safe areas such as dry caves. The economics of the final disposal are important to the nuclear power economy, but the evaluation of hazard from this step must be the controlling factor in the selection of the ultimate disposal method.
7. Fission Product Use is indicated as a side stream, since any use of fission products from the wastes must terminate in disposal after a useful decay period. The economic importance of the use of radiant energy from fission products and, for that matter, all possible uses of products from a nuclear reactor, is relatively great. Therefore, emphasis must be placed on research and development of uses of fission products. Such research and development can be divided into several broad areas of development:
 - a. Extraction of useful fission products from wastes such as Cs^{137} , possibly Zr-Nb, iodine, possibly technecium, and others to a much more limited extent.
 - b. Preparation of many large gamma irradiation sources (of the order of size to produce 10^7 to 10^8 r/hr in air close to the source) for use by groups interested in the exploration of the uses of gamma radiation. This source preparation can be done only in AEC sponsored facilities at present.
 - c. Fundamental research on the nature of the effects of radiant energy on many systems.

- d. Applied research and development on particular uses such as food sterilization or preservation, reaction rate and catalytic effects, etc.
- e. Market surveys and development of markets for radiation processed products.
- f. Evaluation of the decay cooling period of reactor fuel elements as a radiation period.

Random Accumulation of Costs and Information for Certain Steps in the Waste Disposal Scheme

Certain steps in the waste disposal scheme suggested in Figure 12 have received some cost analysis. However, cost studies have not been made on any consistent basis; the effects of plant capacity and many other variables have not been taken into account. Most of this cost study work is contained in classified reports, but unit costs from these can be extracted without classification difficulty. These costs should not be used with confidence, but they may serve as a guide to what can be expected. Much more careful cost studies will be required as development progresses.

1. Evaporation

a. ⁽²⁾ Capacity:	700,000 gal salted feed/year	
Volume reduction factors:	2:1 and 10:1	
Amortization of building:	10 year period	
Depreciation of equipment:	5 year period	
	<u>2:1 vol. red</u>	<u>10:1 vol. red</u>
Costs:		
Direct charges \$/gal feed	0.065	0.07
Amortization, etc.	<u>0.223</u>	<u>0.223</u>
	0.288	0.293

Note: Condensate may require further treatment which should not cost more than \$0.10 per gallon.

- b. Self-concentration - probably would not exceed five cents per gallon of raw waste for 4:1 concentration factor, including disposal of condensate (with necessary decontamination factor), to ground.

2. Waste Tank Costs

- a. Mild steel concrete tanks with reflux condensers - \$0.22 to \$0.40 per gallon including operating charges. ⁽³⁾

- b. Stainless steel tanks with internal cooling coils and reflux condensers in heavy concrete enclosures - \$1.50 to \$2.00/gal for 350,000 gal capacity. Probably includes operating expense.
- c. Self-supporting API stainless steel tanks on concrete pad with earth cover - \$0.75 to \$0.80/gal in 500,000 to 1,000,000 gal capacity range.⁽⁴⁾
- d. Stainless steel tanks with internal cooling coils and reflux condensers in concrete enclosures - \$1.50/gal in 750,000 gal capacity range. Cost includes operating expense.
- e. Estimated cost of 5,000,000 gal membrane-lined and sand-filled pit - \$0.14 gal.

3. Neutralization

Neutralization of acid wastes will increase the total volume of wastes, hence the storage volume and cost. No general comment is possible here since neutralization of each waste type presents a unique problem. Neutralization of wastes highly salted with $\text{Al}(\text{NO}_3)_3$ increase raw volume by a factor of 4 to 4.5, but makes it possible to store wastes in cheaper mild steel tanks. Specific cost studies have indicated that for waste tanks above 750,000 gallons in size, it is cheaper to use stainless steel tanks at \$1.00/gal cost than to neutralize and store in mild steel at a cost of \$0.35/gal.

4. Cesium-Strontium Removal

The principle long-lived fission products are cesium-137 and strontium-90. After about seven years decay of stored fission products, these two isotopes contribute over 90% of the radioactive decay energy of the fission product wastes. In addition to that strontium-90 has the lowest maximum permissible concentration in water by a factor of approximately 10^3 (8×10^{-7} $\mu\text{c/ml H}_2\text{O}$). Cesium-137 is possibly the only fission product that can be isolated for use as a gamma radiation source. Removal of cesium and strontium therefore offers the following attractions:

- a. Long-term heat generation in bulk fission product wastes would be greatly reduced.
- b. The effective disposal rate of wastes to ground (or ground water) could be a factor of approximately 10^3 greater if strontium is

removed with overall decontamination factors of 10^7 or greater (ignoring hazards for heavy elements that could be present in wastes such as Pu^{239} and Pu^{240} , Am, Cm).

c. Utilization of cesium may provide some monetary return.

W. A. Rodger⁽⁶⁾ at Argonne has observed that the removal of strontium must be quantitative to materially affect the disposal picture for the bulk of fission product wastes. His calculations are reproduced in summary in the following Tables 1 and 2 from IDO-14363 (Pt. I).

Table 1*

50-YEAR ACCUMULATION OF LONG-LIVED ISOTOPES AND REQUIRED DISPERSAL VOLUMES

Basis: 2.2×10^6 MW Installed Reactor Capacity = 3 Tons Fission Products/Day

Isotope	Accumulated Quantity in 50 years, curies	Maximum Permissible ^c Concentrations in		Volume Required to Dilute to Tolerance	
		Water	Air	Water	Air
		$\mu\text{c/ml}$	$\mu\text{c/m}$	cubic miles	cubic miles
Zr ⁹⁵	1.3×10^{11}	4×10^{-3}	4×10^{-7}	7.8×10^3	7.8×10^7
Ce ¹⁴⁴	1.1×10^{11}	4×10^{-2}	7×10^{-9}	6.6×10^3	3.8×10^9
Ru ¹⁰⁶	1.0×10^{11}	0.1	3×10^{-8}	2.4×10^2	8×10^8
Pm ¹⁴⁷	5.1×10^{10}	1	2×10^{-7}	12	6×10^7
Sr ⁹⁰	8.6×10^{10}	8×10^{-7}	2×10^{-10}	2.6×10^7	1×10^{11}
Cs ¹³⁷	8.1×10^{10}	1.5×10^{-3}	2×10^{-7}	1.3×10^4	9.7×10^7
Tc ⁹⁹ a	2.0×10^7	3×10^{-2}	3×10^{-6}	0.2	1.6×10^3
Pu ²³⁹ b	2.8×10^6	1.5×10^{-6}	2×10^{-12}	4.5×10^2	3.4×10^8

* Taken from IDO-14363 (Pt. I), p. 328, by W. A. Rodger, Argonne National Laboratory.

a Decay Neglected.

b Based on a Loss of 0.1% in Processing.

c From National Bureau of Standards Handbook 52 (1953).

Table 2*

EFFECT OF RESIDUAL Sr^{90} ON DISCARDABILITY OF WASTE

<u>Per Cent Sr Remaining</u>	<u>Decontamination Factor</u>	<u>Years' Storage Required^a</u>
0	∞	13 years
0.00001	10^7	13 years
0.0001	10^6	90 years
0.001	10^5	180 years
0.01	10^4	270 years
0.1	10^3	360 years
1.0	10^2	450 years
10.0	10	540 years
100.0	1	630 years

* Taken from IDO-14363, (Pt.I), p. 329, by W. A. Rodger, Argonne National Laboratory.

a To point where ~ 1 cubic mile water will dilute activity to tolerance.

Rodger further observes that processes that achieve separation factors of the order of 10^6 to 10^7 such as solvent extraction have been developed for plutonium and uranium. He states that it is possible that processes with similar separation factors might be developed for cesium-strontium removal, but that the costs of such processing may be comparable to those incurred by the initial separation of uranium and plutonium from fission products. It is possible that income from sale or use of fission products could partially offset this separation cost.

Determination of Optimum Cooling Period for Wastes After Processing, Before Shipment to Disposal Site

In the overall waste disposal scheme shown in Figure 12 an indicated hold period for wastes at the chemical processing plant of 5 to 10 years is shown. There is an optimum hold period for wastes determined by balancing waste storage costs vs shipping costs, since shipping costs will decrease as the decay cooling period increases due to a reduction in required shielding weight of waste carriers. H. R. Zeitlin and J. W. Ullmann have made a study of cooling time, irradiation levels and shipping costs for various shipment distances.⁽⁵⁾ The study is reproduced in its entirety in the following section.

Radioactive Waste Economics: Optimum Storage
Time Prior to Shipping to Disposal Site

by

H. R. Zeitlin and J. W. Ullmann

October, 1955

1.0 INTRODUCTION

One of the potentially attractive schemes for the ultimate disposal of radioactive waste is simply to pour the waste into pits. The best geological location for these pits may not coincide with the optimum location for a processing plant and transport will be required.

It may be necessary or desirable to remove some fission products from the waste, particularly the long-lived activities, prior to disposal into the ground. The influence of fission product removal on shipping costs will depend on which elements are removed and to what extent. Since no firm flowsheet has been generally accepted for this step, its effect on waste disposal economics is not considered in this memo.

As waste is cooled, the cost of storage increases and the cost of shipping decreases by virtue of having to ship less shield weight. The optimum cooling time will depend on the irradiation history of the fuel, the cost of storage and the cost of shipping.

2.0 SUMMARY

For 250 gallon batches of waste (800 gal/ton) from fuel irradiated 400 days to 10,000 MWD/T, optimum cooling times were determined. Three distances between processing and disposal sites, and three unit storage costs were considered. The results appear in the following table:

Table I Optimum Cooling Times			
Storage Cost \$/gal/yr	0.013	0.041	0.30
Type Storage	Hanford	Hanford	Idaho, S.R.
Ownership	Government	Private	Private
Optimum Cooling Time (years) for One Way Shipping Distance of:			
200 mi.	9	6-1/2	0
500 mi.	11	7-1/2	5-1/2
1000 mi.	14	9	6-1/2

The conclusions that can be drawn are that as the storage cost increases it becomes economical to ship shorter cooled waste. As the shipping distance increases, it becomes economical to store waste longer. In the case of 30¢/gal/yr storage, for 200 miles shipment, essentially no storage should be provided beyond that required for surge in filling carriers.

The above conclusions are based on 10,000 MWD/T fuel. For less highly irradiated material, the optima would shift in the direction of shorter cooling times.

3.0 STORAGE COSTS

Tank storage of liquid wastes may be an essential step in a scheme for ultimate waste disposal. Storage reduces the heat generation and radiation problems attendant with shipping and subsequent processing. As an example, the rate of heat generation for fuel irradiated a long time (to fission product saturation) at 25 MW/ton is shown in Figure 1 as a function of cooling time; 800 gallons of waste per ton have been assumed.

To determine an optimum storage time to be employed in the overall storage - shipment - treatment - disposal cycle, an estimate of the cost of storing a unit volume per unit time is necessary. The following assumptions were made:

- (1) Lifetime of underground storage tank of 50 years
- (2) Purex-type waste
- (3) Tank farm operating personnel of 2 men/shift.

Cost data available were:

Hanford 15,000,000 gallon tank farm (including diversion boxes, piping to existing lines overhead): \$0.16/gal.

Savannah River 4,800,000 gallon tank farm (including cooling coils, condenser, filter): \$1.44/gal.

Idaho 300,000 gallon tank farm (stainless steel vessels): \$1.77/gal.

Fixed charges were calculated for initial investments of \$0.25 and \$2.00 per gallon at three different annual rates. 12 percent and 15 percent per year represent the range used by utility companies to write off investments inclusive profit, taxes, and interest on capital. 4 percent per year might be the rate for a government-owned burial site (2 percent amortization plus 2 percent average interest).

The cost of land $\frac{\$5000/\text{acre}}{1,000,000 \text{ gal/acre}}$ = \$0.005/gal was neglected compared to the initial cost of tankage.

Direct operating costs (based on a 20,000,000 gallon farm which has reached steady state) will be:

$$\frac{2 \text{ men/shift} \times 4 \text{ shifts} \times \$4500/\text{man-year}}{20,000,000 \text{ gal}} = \$0.0018/\text{gal/year}$$

Allowing for 67 percent overhead, the direct charge will be \$0.003/gal/year.

The calculated unit charges for the six cases are tabulated below:

Table 2 Unit Storage Costs (\$/gal/yr)			
\$0.25/gal Initial Investment			
Rate for Fixed Charge	15%	12%	4%
Fixed Charge	0.038	0.030	0.010
<u>Direct Charge</u>	<u>0.003</u>	<u>0.003</u>	<u>0.003</u>
Total	0.041	0.033	0.013

Table 2 (cont'd)			
\$2.00/gal Initial Investment			
Rate for Fixed Charge	15%	12%	4%
Fixed Charge	0.30	0.24	0.08
<u>Direct Charge</u>	<u>0.003</u>	<u>0.003</u>	<u>0.003</u>
Total	0.30	0.24	0.08

4.0 SHIELDING REQUIRED FOR SHIPPING WASTE

The number of curies of a fission product per watt of reactor operating power will be:

$$\frac{\text{Curie}}{\text{Watt}} = \frac{3.1 \times 10^{10} \text{ fission/sec/watt}}{3.7 \times 10^{10} \text{ dis/sec/curie}} (Y_1)(1-e^{-\lambda_1 t_0})(e^{-\lambda_1 t_c}) = 0.84 Y_1(1-e^{-\lambda_1 t_0})e^{-\lambda_1 t_c}$$

Where: Y_1 = fraction fission yield

λ_1 = decay constant, day⁻¹

t_0 = reactor operating time, days

t_c = cooling time, days

A typical (based on Project Separations tabulation) reactor specific power of 1000 MW/40 T = 25 MW/T is assumed. On this basis, the reactor operating time for various irradiation levels is tabulated below:

Table 3	
Operating Time for Various Irradiation Levels	
MW D/T	Days Operating
2000	80
4000	160
8000	320
10000	400

Fission products to be considered for the shielding calculations are Ba¹⁴⁰(La¹⁴⁰), Zr⁹⁵, Nb⁹⁵, Ce¹⁴⁴(Pr¹⁴⁴), Cs¹³⁷ and Ru¹⁰⁶(Rh¹⁰⁶). The following table gives the solutions for the number of curies of each of these fission products present at time of discharge from the reactor for various reactor operating times.

Table 4						
Curies Per Watt at Discharge Time						
Nuclide	λ_1	Y_1	Curies/watt Reactor Power for Operating Time of:			
			80 day	160 day	320 day	400 day
Ba ¹⁴⁰ (La ¹⁴⁰)	0.0541	0.063	0.052	0.053	0.053	0.053
Nb ⁹⁵	0.0198	0.064	0.042	0.051	0.054	0.054
Zr ⁹⁵	0.0107	0.064	0.031	0.044	0.052	0.053
Ce ¹⁴⁴ (Pr ¹⁴⁴)	0.00239	0.061	0.0087	0.016	0.027	0.031
Cs ¹³⁷	5.75×10^{-5}	0.059	2.5×10^{-4}	4.5×10^{-4}	8.9×10^{-4}	1.1×10^{-3}
Ru ¹⁰⁶ (Rh ¹⁰⁶)	0.0019	0.0038	4.5×10^{-4}	8.3×10^{-4}	1.5×10^{-3}	1.7×10^{-3}

Figures 2-5 show the curies/watt for each of the above fission products as a function of irradiation and cooling times.

Since 800 gallons of high activity waste per metric ton and a specific power of 25×10^6 watts have been assumed: $\text{curies/gal} = \frac{A(\text{curies/watt}) \times 2.5 \times 10^7}{800} = 3.1 \times 10^4 A$

The curies/gal are tabulated below for 400 days irradiation at 25 MW/ton:

Table 5 Curies/gal for Various Cooling Times								
Nuclide	γ Energy (Mev)	%	γ curies/gal for cooling time of:					
			100 day	500 day	1000 day	3000 day	10000 day	30000 day
La ¹⁴⁰	3.0	1	0.068	--	--	--	--	--
	2.5	5.4	0.37	--	--	--	--	--
	1.5	94	6.4	--	--	--	--	--
Nb ⁹⁵	0.75	100	240	0.084	--	--	--	--
Zr ⁹⁵	0.73	100	560	7.4	0.035	--	--	--
Pr ¹⁴⁴	2.2	1	7.7	3.1	1.0	1.4×10^{-4}	--	--
	1.5	2	15.4	6.2	2.0	2.8×10^{-4}	--	--
	0.7	4	30.8	12	4.0	5.6×10^{-4}	--	--
Cs ¹³⁷	0.66	92	31	31	29	23	18	6.2
Rh ¹⁰⁶	2.4	0.25	0.11	0.053	0.020	--	--	--
	1.6	0.5	0.22	0.11	0.041	--	--	--
	1.0	2	0.86	0.41	0.16	--	--	--
	0.9	1	0.43	0.21	0.08	--	--	--
	0.6	12	5.2	2.5	0.97	--	--	--

Shielding calculations were made for a 4 foot I.D. carrier holding 250 gallons of waste from fuel irradiated 400 days (10000 MWD/T). A maximum permissible dose rate of 10 mr/hr at the wall of a 9 foot wide railroad car was the basis for determining the shield thickness. The method of KLX-24 gave the results found in Table 6.

Table 6 Dosage at Wall of Car (400 days irradiation)						
Energy Group	Days Cooling					
	100	500	1000	5000	10000	30000
2.2 Mev						
Curies-in ² /gal	5800	1800	580	--	--	--
mr/hr:						
no shielding	3.2×10^5	1.0×10^5	3.2×10^4	--	--	--
4" Pb	--	--	64	--	--	--
6" Pb	64	20	6.4	--	--	--
7" Pb	16	5.0	1.6	--	--	--
8" Pb	6.4	2.0	0.64	--	--	--

Energy Group	Days Cooling					
	100	500	1000	5000	10000	30000
<u>1.5 Mev</u>						
Curies-in ² /gal	1.3×10^4	3600	1200	---	---	---
mr/hr:						
no shielding	5.4×10^5	1.5×10^5	5.0×10^4	---	---	---
4" Pb	---	---	25	---	---	---
6" Pb	5.4	1.5	0.5	---	---	---
7" Pb	2.7	0.75	0.25	---	---	---
8" Pb	0.7	0.2	0.06	---	---	---
<u>1.0 Mev (Negligible compared to 1.5 Mev Group)</u>						
Curies-in ² /gal	750	30	120	---	---	---
<u>0.74 Mev</u>						
Curies-in ² /gal	4.6×10^5	4.3×10^3	---	---	---	---
mr/hr:						
no shielding	1.2×10^7	1.1×10^5	---	---	---	---
6" Pb	0.03	---	---	---	---	---
<u>0.66 Mev</u>						
Curies-Cu ² /gal	2.1×10^4	1.9×10^4	1.7×10^4	1.3×10^4	1.0×10^4	3600
mr/hr						
no shielding	---	4.3×10^5	3.8×10^5	2.8×10^5	2.2×10^5	8.1×10^4
2" Pb	---	---	38	28	22	8.1
3" Pb	---	---	---	0.93	0.73	0.27
4" Pb	---	---	---	---	0.02	0.008
<u>Total All Energies</u>						
mr/hr:						
2" Pb	---	---	---	28	22	8.1
3" Pb	---	---	---	0.94	0.73	0.27
4" Pb	---	---	89	---	0.022	0.008
6" Pb	69	22	6.4	---	---	---
7" Pb	19	5.8	1.0	---	---	---
8" Pb	7.1	2.2	0.7	---	---	---

Figure 6 is a plot of the total dose rate at the car wall as a function of the cooling time.

5.0 OPTIMIZATION OF COOLING TIME FOR SHIPPING WASTE

For a fixed irradiation, the combined cost of storage and shipping will be a function of cooling time and shipping distance.

Carrier weights are plotted as a function of shield thickness in Figure 7 for a 450 gallon waste capacity. Using the shield thicknesses from Figure 6 which gave a 10 mr/hr tolerance dose (for 400 day, 10,000 MWD/T irradiation) carrier weights were plotted as a function of cooling time in Figure 8.

It was assumed that the empty carrier must be returned to its point of origin and that carrier cost and handling charges would not be significantly influenced by cooling time compared to freight charges.

The freight charges (round trip) were computed on the following basis:

Table 7 Rail Freight Rates	
One Way Distance Miles	\$/CWT Round Trip
200	1.40
500	2.60
1000	4.50

The optimization was carried out for the three distances of the above table and for unit storage costs of \$0.013, \$0.041 and \$0.30 per gallon per year from Table 1. The basic costs appear in Tables 8 and the combined results in Table 9 and Figures 9-11.

Table 8 Storage and Shipping Costs as Functions of Cooling Time						
Cooling Time (Years)	Storage Cost (\$/gal)			Shipping Cost (\$/gal)		
	\$0.013/gal/yr	\$0.041/gal/yr	\$0.30/gal/yr	200 mi	500 mi	1000 mi
0.5	0.006	0.02	0.15	1.70	3.16	5.46
5	0.06	0.20	1.50	0.74	1.37	2.38
6	0.08	0.25	1.80	0.55	1.02	1.77
7	0.09	0.29	2.10	0.49	0.91	1.58
10	0.13	0.41	3.00	0.44	0.82	1.42
15	0.19	0.61	4.50	0.42	0.78	1.35
20	0.26	0.82	6.00	0.41	0.76	1.32
30	0.39	1.23	9.00	0.40	0.74	1.29

Table 9

Combined Storage and Shipping Costs as a Function of Cooling Time (\$/gal)

Cooling Time (Years)	Storage at \$0.013/gal/yr			Storage at \$0.041/gal/yr			Storage at \$0.30/gal/yr		
	200 mi	500 mi	1000 mi	200 mi	500 mi	1000 mi	200 mi	500 mi	1000 mi
0.5	1.71	3.17	5.47	1.72	3.18	5.48	1.85	3.31	5.61
5	0.80	1.43	2.44	0.94	1.57	2.58	2.24	2.87	3.88
6	0.63	1.10	1.85	0.80	1.27	2.02	2.35	2.82	3.57
7	0.58	1.00	1.67	0.78	1.20	1.87	2.49	3.01	3.68
10	0.57	0.95	1.55	0.85	1.23	1.83	3.44	3.82	4.42
15	0.61	0.96	1.54	1.03	1.39	1.96	4.92	5.28	5.85
20	0.67	1.02	1.58	1.23	1.58	2.14	6.41	6.76	7.32
30	0.79	1.13	1.68	1.63	1.97	2.52	9.40	9.74	10.29

ORNL-LR-DWG.9547
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FIG. 2 Ba^{140} - Nb^{95} ACTIVITIES

ORNL-LR-DWG. 9550
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ORNL-LR-DWG. 9551
UNCLASSIFIED

ORNL-LR-DWG. 9552
UNCLASSIFIED

529 038

ORNL-LR-DWG. 9553
UNCLASSIFIED

529 040

ORNL-LR-DWG. 9555
UNCLASSIFIED

ORNL-LR-DWG. 9556
UNCLASSIFIED

One heartening conclusion that can be drawn from the results of this study is that it will be economical to store wastes for possibly five to ten years after the chemical plant starts operation. This provides a period of time in which development of satisfactory disposal methods can be developed and eliminates some of the urgency for finding a permanent disposal scheme. A nuclear power economy can be started and chemical processing plants can operate economically with accumulation of wastes in tanks for a reasonable length of time. In fact, it may develop, if the assumptions of the following cost study are valid, that the most economical operating procedure will be to store for decay cooling before shipment.

Base Costs for Waste Disposal

The consideration of cost of ultimate disposal of radioactive wastes must be considered in evaluating any scheme for long-term waste disposal and storage. Although much has been said against storage in tanks, costs for long-term storage (i.e., 400 years for wastes containing Cs and Sr and 50 years for wastes with Cs and Sr removed) are not necessarily prohibitive.

Consider the following case, using data presented by Ullmann and Zeitlin in ORNL-CF-55-10-101 (reproduced in the preceding section).

Assumptions: Tank lifetime 50 years, after which tanks are replaced for total period of 400 years.

Tank Costs: 1) \$0.25/gal
2) \$2.00/gal

Operating Costs: \$0.003/gal/year

Transfer Costs: 7 transfers at \$0.01/gal

Optimum Cooling Period Before Shipping for 500 Miles: 8 years

Assumed Irradiation Level: 4000 Mwd/ton

Waste Production: 800 gal waste/ton

Costs on Per Gal Basis:	<u>At \$0.25/gal</u>	<u>At \$2.00/gal</u>
1) Tankage	\$2.00	\$16.00
2) Operating expense (400 x \$.003/gal/yr)	1.20	1.20
3) Transfers	0.07	0.07
4) Shipping 500 miles	<u>0.82</u>	<u>0.82</u>
	\$4.09	\$17.09

5) Cost per kwh electricity

$$\text{gal per kwh} = \frac{800}{(1000)(24)(10^3)} = 3.4 \times 10^{-5} \text{ gal/kwh}$$

6) Cost of waste per kwh of electricity

<u>At \$0.25/gal</u>	<u>At \$2.00/gal</u>
0.14 mills/kwh	5.8 mills/kwh

Thus if tankage can be obtained for \$0.25/gal as has been experienced at Hanford, the waste storage costs at a central tank disposal area would not be unreasonable. Obviously, using tanks that cost \$2.00 per gallon is prohibitive.

If we consider the case for the bulk of the wastes with Cs and Sr removed, using the same assumptions as above except for one 50 year storage period, costs would be as follows:

	<u>At \$0.25/gal</u>	<u>At \$2.00/gal</u>
1) Tankage	\$0.25	\$2.00
	1.20	1.20
	0.07	0.07
	<u>0.82</u>	<u>0.82</u>
	\$2.34	\$4.09

or 0.08 mills/kwh 0.14 mills/kwh

The foregoing does not take into account the possible hazard from storage of wastes in liquid form. It also ignores the problem of the possible accumulation of heavy elements like americium and plutonium in the wastes.

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HEAVY LINES INDICATE ROUTE AGAINST WHICH COSTS MUST BE COMPARED.
TIMES GIVEN ARE TIME FROM REACTOR SHUTDOWN & ARE ADDITIVE THRU THE DISPOSAL CYCLE.
BROKEN LINES INDICATE ALTERNATE ROUTES.

Fig.12. Schematic Flowsheet For Overall Waste Disposal.