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AN ECONOMIC^s EVALUATION OF ULTIMATE DISPOSAL^{waste} OF
LIQUID RADIOACTIVE WASTES BY THE FLUIDIZED BED
CALCINATION PROCESS

J. I. Stevens

PHILLIPS
PETROLEUM
COMPANY

ATOMIC ENERGY DIVISION

NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION

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Contract AT(10-1)-205

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A B S T R A C T

The costs of fluidized bed calcining of the acidic and re-acidified forms of Purex and Thorex wastes have been determined. The wastes were assumed produced by a chemical processing plant recovering unburned fuel from 1500 tonnes/year of uranium converter fuel at a burnup of 10,000 Mwd/tonne and 270 tonnes/year of Thorium converter fuel at 20,000 Mwd/tonne. Also, investment costs for storage of the calcine in vented, air cooled, annular bins installed in underground concrete vaults were determined.

The cost of fluidized bed calcining was determined at processing rates of 45, 60, and 75 gallons per hour for solids storage in bins varying from 3 to 22 inches thick and installed in underground concrete vaults containing 4, 12, 20, and 40 nested annular bins, each nest with an overall diameter of up to 12.5 feet. Aging had negligible effect on costs, except as it permitted thicker bins to be used.

The lowest cost, 0.47×10^{-2} mills/kwh_e, was for processing acidic Purex and Thorex wastes at 75 gph with storage in an underground concrete vault containing 40 of the 12.5-foot-diameter nested bin arrays. And the highest cost, 2.9×10^{-2} mills/kwh_e, was for processing re-acidified Purex and Thorex wastes at 45 gph with storage in an underground concrete vault containing 4 nested bin arrays.

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I. SUMMARY

An economic evaluation of fluidized bed calcining of radioactive wastes with storage of the free-flowing granular product in nested arrays of vented, annular bins has been prepared. It was assumed that the fluidized bed plant would convert to solids the radioactive wastes from a 6-tonne* per day nuclear fuel plant processing 1500 tonnes per year of uranium-converter fuel at a burnup of 10,000 megawatt days per tonne and 270 tonne per year of thorium-converter fuel at a burnup of 20,000 megawatt days per tonne. This hypothetical nuclear fuel processing plant is capable of processing all of the fuel from a 15,000 Mwe nuclear economy. The results of this study may be directly integrated into the results of a series of Oak Ridge National Laboratory studies now being prepared for a number of different liquid and solids storage concepts, as well as conversion of liquids to solids by pot calcination.

The fluidized bed conversion of radioactive liquid wastes to solids should give volume reductions up to fifty per cent greater than pot calcination for those solutions which are converted to refractory solids. For wastes containing large amounts of salts with low fusion temperatures (e.g., Na_2SO_4), the volume reduction factor obtained by pot calcination may be two and one-half times that of the fluidized bed process. The ramifications of these reduction factors on over-all processing costs are developed in detail in this report and briefly summarized in the following paragraphs.

The fluidized bed process, inherently continuous in nature, would be expected to have lowest operating costs at the highest possible processing rates. The maximum calcination rate required for re-acidified wastes from the hypothetical fuel processing plant is approximately 45 gph for a 300-day operating year. This rate is, fortuitously, within the operating range of the 60 gph Demonstrational Waste Calcining Facility (DWCF) at the Idaho Chemical Processing Plant (ICPP). Consequently, plant investments for the DWCF were used extensively in estimating the plant investments in this report. Also, operating costs were determined for calcining rates of 60 and 75 gph. Direct and indirect operating costs plus depreciation allowances for a fluidized bed calcination process estimated to require an investment of about \$4,600,000 are as follows:

45 gallon/hour	\$3.82/gallon
60 gallon/hour	2.86/gallon
75 gallon/hour	2.29/gallon

These costs range from 0.32×10^{-2} to 0.96×10^{-2} mills/kwh_e depending on the processing rate and whether the wastes are in the acidic or re-acidified states.

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

Storage of the granular solids was assumed to be in nested annular, vented, air cooled, stainless steel bins contained in underground concrete vaults. The thickness of the bin is dependent upon the age, volume reduction factor, and thermal conductivity of the solids within the arbitrarily selected bin surface temperature of 300°F and centerline temperature of 1650°F. Bin and vault costs, when combined with the operating costs and depreciation allowances, result in total costs ranging from 0.47×10^{-2} to 2.91×10^{-2} mills/kwh_e---the former for a 75 gph processing rate of aged, acidic wastes and the latter for a 45 gph processing rate of short cooled, re-acidified wastes.

For the processing rates and storage methods considered in this economic evaluation of the fluidized bed conversion of radioactive wastes to solids, the fluidized bed process is economically superior to the pot calcination process in every instance except where an aged, re-acidified waste must be processed at a rate of 45 gallons per hour.

II. INTRODUCTION

The ultimate disposal of highly radioactive liquid wastes by conversion or incorporation into stable, solid media is being extensively investigated in the laboratories of atomic energy establishments throughout the world. A considerable number of these processes are either approaching the hot pilot plant stage or are in the demonstrational stage. An extensive evaluation of a combination of operations and interim storage methods has been proposed at Oak Ridge National Laboratory and two reports (1, 2) have been issued. The ORNL approach to the problem is to establish operating and storage costs of various operational concepts in such a manner that the total cost of many combinations of individual operations can be determined by a summation procedure. It is the purpose of this report to present an economic evaluation of the fluidized bed process of converting radioactive liquid wastes to solids on a basis comparable with the ORNL studies.

The basis for the ORNL studies is a 6-tonne* per day plant for recovering by the Purex or Thorex process the unburned fuel in 1500 tonnes per year of uranium-converter fuel at a burnup of 10,000 megawatt days per tonne and 270 tonne per year of thorium-converter fuel at a burnup of 20,000 megawatt days per tonne. This hypothetical plant represents a facility capable of processing all the fuels from a 15,000-Mw_e nuclear economy which may be in existence by 1970. The operational elements of the ultimate waste disposal scheme to be evaluated in the ORNL studies are: (1) interim liquid storage, (2) conversion to solids by pot calcination, (3) interim storage of solids in pot, and (4) shipment as either liquids or calcined solids. The ultimate disposal methods to be evaluated in the ORNL studies are: (1) calcined solids in salt deposits, (2) calcined solids in vaults, (3) calcined solids in vertical shafts, (4) liquids in salt deposits, (5) liquids in deep wells, (6) liquids by hydrofracture, and (7) liquids in tanks. Since the fluidized bed technique of conversion of radioactive liquid wastes to solids is essentially a processing step equivalent to the conversion of liquid to solids via pot calcination, this economic study of the fluidized bed process will permit ready inclusion into the combination of preliminary operation and ultimate storage methods proposed in the ORNL studies.

The process design bases for this study will be the pilot plant and design information on fluidized bed calcining of radioactive wastes that has been developed by Argonne National Laboratory, by Phillips Petroleum Company, and by the Hanford Atomic Products Operations. Plant investments and operating costs will be based on appropriate modifications of the construction and operating costs for the Demonstrational Waste Calcining Facility installed at the Idaho Chemical Processing Plant (ICPP).

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

III. GENERAL PROCESS DESCRIPTION

The development of the fluidized bed as a process tool in the petroleum industry and its subsequent extension to many other industries led naturally to its consideration by workers in the field of nuclear energy. The application of the fluidized bed technique to denitration of uranyl nitrate solutions was the first large scale use of the technique in the atomic energy industry. The fluidized bed calcination work at Argonne National Laboratory appealed to Phillips Petroleum personnel as a desirable technique for the conversion of radioactive liquid wastes to solids. The advantages of the fluidized bed process were reasoned to be: (1) the absence of moving parts in the conversion vessel, (2) applicability to continuous processing, (3) ease of transporting solids to storage via pneumatic means, and (4) conversion of the fuel alloy, aluminum, into an oxide which would serve as a retaining medium for fission products. Work at both ANL and Phillips determined the feasibility of converting radioactive wastes, such as those generated from the processing of MTR-type (aluminum) fuel elements, into solids. The laboratory investigations in 6-inch-diameter pilot plant calciners, by ANL and Phillips, established that operationally significant information could only be obtained in a facility capable of processing high activity wastes.

In late 1957, the design and construction criteria were prepared for a Demonstrational Waste Calcining Facility (DWCF). The 60-gallon per hour processing rate of this facility was chosen on the basis of being capable of obtaining significant engineering design data and operational experience for other AEC installations and, at the same time, appreciably reducing the volume of liquid wastes in underground tank storage at the ICPP. Because of indefinite fuel processing commitments at the ICPP, it was determined that recovery of nitric acid for reuse was not economically or operationally justified. Consequently, the process flowsheet described in the ensuing paragraphs is not the one which would be installed at a nuclear fuel processing plant that could reuse acid.

In the DWCF, liquid waste from the storage tanks in combination with a recycle stream from the liquid scrub system (Figure 1) is fed to the pneumatic atomizing nozzles which are submerged below the gas-solid interface of the fluidized bed. The calciner is heated by circulating the liquid eutectic of the sodium-potassium alloy, NaK, through bayonet-type tubes immersed in the fluidized bed. Preheated fluidizing air enters the calciner beneath the grid plate and flows through distributor holes to agitate the bed of solids. Typical superficial fluidizing velocities are expected to be from 0.5 to 2.0 ft/sec, and the bulk densities of the product, alumina, from calcining MTR-type wastes have been found to be in the region of 60-100 lbs/cu ft. The resulting product consists of nearly spherical solid particles having an inter-particle porosity of about 41 per cent. The solids are pneumatically transported to the solids storage bins; a schematic diagram of the system is shown in Figure 2. These bins are composed of a central cylindrical section

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surrounded by two annular sections so arranged that they fill sequentially by overflow of the solids through pipes radiating from the inner cylinder to the outer annuli. The thickness of the installed solids storage bins is such that the centerline temperature of the calcined solids will not exceed a temperature of 400°C , the normal calcining temperature, for an MTR-type waste at two years from reactor discharge, i.e., with an estimated heat generation rate of $2.1 \text{ BTU}/(\text{hr})(\text{gal})$. These bins, of stainless steel type 410, will be convection cooled by forced draft air; however, it is estimated that, for wastes from four to five years after reactor discharge, natural draft convection cooling through a short stack will be adequate to maintain centerline temperatures at or below 400°C . Because the fluidized bed calciner will operate in the range of $300\text{--}500^{\circ}\text{C}$, there will be residual nitrates present in the stored solids. The bin system is equipped, therefore, with a breather system to permit long-term removal of the products of radiolytic degradation, presumed to be small amounts of nitrogen oxides and water.

The off-gases from the calciner, heavily laden with fines, first go through a cyclone, the underflow of which may be returned to the calciner or sent to storage, while the outlet from the cyclone goes to a liquid scrubbing system. Since it is not economical at the ICPP to recover slightly contaminated acid for reuse in the plant, it was decided, during the process design stage, to attempt to clean the nitrogen-oxide-bearing air stream to a degree permitting safe rejection

of the nitrogen-oxide vapors to the atmosphere. Consequently, the installed system for cleaning of off-gases should give exceedingly valuable information on the large-scale cleaning of highly radioactive vapors and gases. In this system, the temperature of the off-gases is lowered to near the dewpoint of the recirculated nitric acid scrubber by quenching the off-gases with cooled nitric acid. The off-gases from the quench tank go to a venturi scrubber for additional particulate removal prior to being reheated and passed through silica gel adsorbers. In this recirculated acid system, it is expected that, as the acid approaches its equilibrium concentration, the fission product ruthenium will be incompletely removed by liquid scrubbing. Data (3) indicate that these equilibrium relationships will cause a portion of the ruthenium to stay with the liquid scrub stream and a portion go into the off-gas stream. However, subsequent experimental data indicate that the recycle of scrubbing solution to the calciner may result in sufficient retention of ruthenium within the calcined solids to require minimum ruthenium removal by the silica gel adsorbers. The efficiency of silica gel as a ruthenium adsorbent, determined in laboratory experiments (4, 5), is the basis for design of silica gel adsorbers. Furthermore, the use of a silica gel bed for adsorption of ruthenium gives another process advantage, i.e., the filtering ability of the stagnant bed of solids is expected to be appreciable. Leaving the adsorbers, the off-gases pass through high-efficiency filters prior to entering the suction side of the off-gas blowers where they are compressed, without cooling, for injection into the plant stack along with the ventilating air from the ICPP.

The process design bases of the Demonstrational Waste Calcining Facility have been reported (6) and should be consulted for information of greater detail than is possible to record in this report. At the present time, cold shakedown runs of this facility are in progress. Until radioactive spike tests are performed, no definitive information will be available as to whether the final filtration of the off-gases will achieve the required degree of particulate removal. Also, the carryover of fine particulate into the quench system has been much greater than anticipated during the process design. It may be necessary to modify further the process flowsheet shown on Figure 1 before "hot" operation is achievable.

IV. WASTE COMPOSITIONS AND PROCESSING RATES

The Purex and Thorex wastes considered in the pot calcination studies (2) were assumed to enter the calcination plant in the acidic state. If the wastes had been neutralized for interim liquid storage purposes, it was assumed that these neutralized wastes must be re-acidified to avoid, during calcination, the formation of solid sodium nitrate which is not sufficiently stable in the presence of high temperatures and radiation for ultimate storage. The fluidized bed calcination technique, operating in the 400-500°C range with MFR-type wastes, produces alumina containing about one milliequivalent of nitrate per gram of solids. Consequently, as was earlier noted, a vented solids storage system has been installed to avoid long-term pressure buildup due to radiolytic decomposition of the residual nitrates. Since the fluidized bed calcining of a waste with a high sodium nitrate concentration is improbable, it is assumed that wastes of the compositions of the acidic and re-acidified types used in the ORNL studies, repeated in Table 1, can be satisfactorily calcined in a fluidized bed.

Table 1

COMPOSITION OF PUREX AND THOREX WASTES				
	Purex		Thorex	
	Acidic	Re-acidified	Acidic	Re-acidified
Volume, gal/tonne	50	80	400	770
H ⁺ , <u>N</u>	7.3	4.5	-	-
Na ⁺ , <u>N</u>	0.7	6.3	-	5.9
Fe ³⁺ , <u>N</u>	1.1	0.7	-	-
NO ₃ ⁻ , <u>N</u>	8.4	5.2	6.7	3.5
OH ⁻ , <u>N</u>	-	-	0.5**	0.2**
SO ₄ ⁼ , <u>N</u>	0.7	6.3	-	5.9
Al ³⁺ , <u>N</u>	-	-	7.2	3.7
Solids vol, gal/tonne	7.1	13.5	60	133
	(porous)	(melted)	(porous)	(melted)
	Na ₂ SO ₄	Na ₂ SO ₄	Al ₂ O ₃	Na ₂ SO ₄
	⁺ Fe ₂ O ₃	⁺ Fe ₂ O ₃		⁺ Al ₂ O ₃

** Acid deficient; OH⁻ actually present as Al(OH)(NO₃)₂.

Although the greater portion of pilot plant data on fluidized bed calcinations have been obtained from simulated aluminum-type waste solutions, the feasibility of fluidized bed calcination of wastes with compositions essentially equivalent to those shown in Table 1 has been reported (7, 8). Consequently, it is believed that the fluidized bed process is applicable to calcination of Purex and Thorex wastes both in the acidic and re-acidified states.

The final solids volume achieved by various calcination processes will have a significant effect on the solids storage costs. The greatest single factor affecting the final volume of solids from fluidized bed calcining is the product porosity, both intra- and inter-particle porosity. Wheeler, et al. (9) have shown that for alumina the expected inter-particle porosity will be about 41 per cent for solids with median diameters in a practical operating range. The intra-particle porosity was found to vary between 5 and 60 per cent. For the purposes of this report, it has been assumed that the solids volumes, gal/tonne, could be calculated from the absolute densities of the chemical form of the gross components in the wastes by using an inter-particle porosity of 41 per cent and an intra-particle porosity of 30 per cent. For the acidic Purex waste, it was assumed that approximately 67 grams of fission product oxides per liter of waste would result upon calcination and that the absolute density would average 5.0 gm/ml. In this manner, the following solids volume per tonne of fuel were established:

Acidic Purex	4.6 gallons/tonne
Re-acidified Purex	36.4 gallons/tonne
Acidic Thorex	49 gallons/tonne
Re-acidified Thorex	335 gallons/tonne

Comparison of the above volumes with those of Table 1 show the fluidized bed to be capable of significantly greater volume reductions for acidic wastes than by pot calcination, but much lower volume reductions for re-acidified wastes. The significance of these volume reductions and other factors on the designs of the solids storage systems will be discussed in greater detail in a later section.

The processing capacity of the Demonstrational Waste Calcining Facility has been demonstrated to be in excess of the design capacity of 60 gallons per hour, when calcining with a bed of solids of relatively small (0.22 mm) mass median particle diameter. The major limitation on the processing capacity is the ability to attain adequate heat transfer rates to a bed of large (>0.6 mm) mass median particle diameter. The design capacity of the DWCF for a 300-day operating year is 432,000 gallons of liquid waste. However, the present facility should be easily capable of calcining 540,000 gallons per operating year.

V. PLANT INVESTMENTS

The Demonstrational Waste Calcining Facility at the National Reactor Testing Station was designed and constructed on the direct maintenance philosophy for radioactive chemical processing plants. A plan view of the building at the operating corridor level is shown in Figure 3, and elevational views for various sections are shown in Figures 4 through 7. The facility has two waste hold tanks, each capable of holding one day's supply of liquid waste, installed in a cell adjacent to the calciner cell. The largest cell is the off-gas treating cell in which is located the quench tank, venturi scrubber, off-gas heater, quench surge tank and pumps, and the regeneration surge tank for the adsorbers. Operating and access corridors separate this row of cells from a second row which includes the heated adsorber, adsorber manifold, and off-gas filter cells. The transport blower cell and the off-gas blower cell are installed at one end of the corridor spaces. The hot sump tank for collection of drainage from cell floors and decontamination liquids is located in a cell at the lowest elevation.

Above grade are the NaK equipment room - separated from the remainder of the building by double fire doors - the decontamination equipment room, the health physics personnel office, the ventilation equipment room, the switch-gear room, and the filter-crane removal room. The top of the transport blower cell, the calciner cell, the

Figure 3

Plan View of Demonstrational Waste Calcining Facility

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Figure 4

Elevational View of DWCF - Section "A-A" of Figure 3.

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Figure 5

Elevational View of DWCF - Section "B-B" of Figure 3

SECTION "C-C"

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Figure 6

Elevational View of DWCF - Section "C-C" of Figure 3

SECTION "D-D"

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Figure 7

Elevational View of DWCF - Section "D-D" of Figure 3

off-gas cell, the adsorber cells, and the off-gas blower cells are at ground level. Radiation shielding plugs for these cells are covered with a rain and snow shield. The shielding plugs can be removed with a mobile crane to permit installation or removal of process equipment.

The floor areas of the various cells and rooms are tabulated in Table 2.

Table 2

DWCF FLOOR AREAS	
<u>Item</u>	<u>Area, Sq. Ft.</u>
Waste Hold Tank Cell	440
Off-Gas Cell	735
Adsorber Cells (2)	465
Adsorber Manifold Cell	380
Off-Gas Blower Cell	865
Transport Air Blower Cell	250
Filter Cells (3)	185
Sample Room	225
Operating Corridor	765
Office	75
NaK Equipment Room	645
Decontamination Equipment Room	1240
Ventilation Equipment Room	430
Locker and Shower Room	425
Filter Removal Room	405
Health Physics Office	335
Switch Gear Room	175
Hot Sump Tank Cell	310
Access Corridor	350

The total investment in the Demonstrational Waste Calcining Facility at the National Reactor Testing Station is approximately \$5,500,000, including the solids storage system which is estimated as approximately \$500,000. Consequently, about \$5,000,000 is the investment in the process facility. However, these investment costs are known to be high because they include payment to the architect-engineer for several conceptual studies at different processing rates, for various process schemes, and for mockup and test of unique equipment designs. During construction, the prolonged labor strike in the steel industry significantly lengthened the overall construction period. Furthermore, the DWCF includes space in the off-gas cell for the addition of other gas cleaning equipment, if needed. Since beginning cold tests, process modifications to the solids transport system have eliminated the need for the solids transport blower cell and equipment.

The estimated plant investment for a 60 gph fluidized bed calcination facility using the process flowsheet of Figure 1 is shown in Table 3. The estimated investment for a facility with shielding wall thickness shown in Figures 3 through 7 has been based on elimination of the off-gas cell space provided for additional off-gas cleaning equipment and elimination of the solids transport blowers and cell. Also shown in Table 3 are the estimated facility investments for providing 5-, 6-, and 7-foot-thick walls at all places of normal personnel access. Where available and applicable, the purchased price of process equipment was used in the estimates after increasing by a factor of 1.07 - the ratio of the Marshall and Stevens Construction Indexes for December 1961 and December 1958.

Table 3

ESTIMATED PLANT INVESTMENTS FOR A MODIFIED DWCF

Item	Present	Shielding Walls		
	<u>Shielding Walls</u>	<u>5-foot-thick</u>	<u>6-foot-thick</u>	<u>7-foot-thick</u>
Site Preparation	\$ 2,300	\$ 2,300	\$ 2,300	\$ 2,300
Yard Area	14,300	14,300	14,300	14,300
Calciner Building	596,000	667,000	684,000	702,000
Calciner Feed System	52,000	52,000	52,000	52,000
Calciner System	190,000	190,000	190,000	190,000
NaK System	121,000	121,000	121,000	121,000
Off-Gas System	602,000	602,000	602,000	602,000
Solids Transport System	13,000	13,000	13,000	13,000
Decontamination System	46,000	46,000	46,000	46,000
Sampling System	59,000	59,000	59,000	59,000
Instrumentation	467,000	467,000	467,000	467,000
Instrumentation Piping	143,000	143,000	143,000	143,000
Electrical	93,000	93,000	93,000	93,000
Insulation	20,000	20,000	20,000	20,000
Utilities	<u>160,000</u>	<u>160,000</u>	<u>160,000</u>	<u>160,000</u>
Sub-Total	\$2,576,600	\$2,647,600	\$2,664,600	\$2,682,600
Construction Overhead (40%)	1,029,400	1,059,100	1,065,800	1,073,100
Engineering (15%)	386,000	396,300	398,600	402,800
Contingency (20%)	<u>516,000</u>	<u>524,000</u>	<u>533,000</u>	<u>536,500</u>
TOTAL	<u>\$4,508,000</u>	<u>\$4,632,000</u>	<u>\$4,662,000</u>	<u>\$4,695,000</u>

Certain pieces of process equipment and instruments are estimated to have high depreciation rates. These items are listed in the following tables.

Table 4

PROCESS EQUIPMENT COSTS AMORTIZED OVER FIVE YEARS	
Quench and Regeneration Pumps	\$ 21,000
NaK Pump	14,500
Venturi Scrubber	<u>7,700</u>
Sub-Total	\$ 43,200
Construction Overhead (40%)	17,300
Engineering (15%)	6,500
Contingency (20%)	<u>8,600</u>
TOTAL	<u>\$ 75,600</u>

Table 5

PROCESS EQUIPMENT COST AMORTIZED OVER TEN YEARS	
Blowers	\$ 58,000
Instrumentation	467,000
Decontamination Pumps	2,300
Calciner	<u>112,700</u>
Sub-Total	640,000
Construction Overhead (40%)	256,000
Engineering (15%)	96,000
Contingency (20%)	<u>217,000</u>
TOTAL	<u>\$1,119,000</u>

Table 6

INVESTMENT AMORTIZED OVER FIFTY YEARS				
Item	Present Shielding Walls	Shielding Walls		
		5-foot-thick	6-foot-thick	7-foot-thick
Site Preparation	\$ 2,300	\$ 2,300	\$ 2,300	\$ 2,300
Yard Area	14,300	14,300	14,300	14,300
Calclner Building	596,000	667,000	684,000	702,000
Utilities	<u>160,000</u>	<u>160,000</u>	<u>160,000</u>	<u>160,000</u>
Sub-Total	\$ 772,600	\$ 843,600	\$ 860,600	\$ 878,600
Construction Overhead (40%)	309,000	337,400	344,200	351,400
Engineering (15%)	115,900	126,300	129,100	133,300
Contingency (20%)	<u>154,500</u>	<u>168,700</u>	<u>172,100</u>	<u>175,700</u>
TOTAL	<u>\$1,352,000</u>	<u>\$1,476,000</u>	<u>\$1,506,000</u>	<u>\$1,539,000</u>

The sum of the 5-, 10-, and 50-year amortized items is subtracted from the total investments to give the estimated investment for equipment assumed to be amortized over a period of 20 years. Because this equipment is independent of shielding wall thickness, the total, in each case, is \$1,961,400.

The capital recovery factors at 4 per cent compound interest, i.e., amortization over the given period at 4 per cent interest, are as follows:

5 year	0.22463
10 year	0.12329
20 year	0.07358
50 year	0.04655

The total annual amortization for the four cases considered above is shown in the following table:

Table 7

	TOTAL ANNUAL AMORTIZATION COSTS			
	Present Shielding Walls	5-foot-thick	Shielding Walls 6-foot-thick	7-foot-thick
5 Year Amortization	\$ 16,980	\$ 16,980	\$ 16,980	\$ 16,980
10 Year Amortization	137,960	137,960	137,960	137,960
20 Year Amortization	144,320	144,320	144,320	144,320
50 Year Amortization	<u>62,940</u>	<u>68,710</u>	<u>70,100</u>	<u>71,640</u>
TOTAL ANNUAL AMORTIZATION	<u>\$ 362,200</u>	<u>\$ 367,970</u>	<u>\$ 369,360</u>	<u>\$ 370,900</u>

VI. SOLIDS STORAGE SYSTEM

The ultimate storage of the solids produced during the conversion of liquid radioactive wastes may be attained by a variety of methods. Storage of calcined solids in salt deposits, vaults, and vertical shafts will be among the ultimate disposal methods evaluated by ORNL (1, 2). Since the ORNL studies will also develop costs for shipment of wastes as liquids or solids, this report will be limited to estimating the investment for storage of fluidized bed produced solids in vented, air-cooled, annular bins located in underground concrete vaults.

A schematic representation of the storage bins for the solids produced by the DWCF is shown in Figure 2. The central cylindrical portion of each bin is 36 inches in diameter. The two annular sections surrounding it are 24 inches thick and all sections are separated by a two-inch-wide passage through which cooling air is blown. The annular sections are 20 feet deep and the cylindrical section is 24 feet deep. The calcined solids are removed from the pneumatic transport line by a high efficiency cyclone. The solids leaving the bottom of this cyclone fall into a central distributor pot from which they flow sequentially into the four nests of bins through pipes installed at an angle greater than the angle-of-repose of the solids. There are no mechanical distributing devices in the solids storage bins. These bins are designed to maintain a centerline temperature of 400°C , or less, when filled with calcined alumina containing fission products generating approximately $125 \text{ BTU}/(\text{hr})(\text{ft}^3)$. At these conditions, the wall of the bins should not exceed 95°C (203°F) although the structural design of the bins will permit a wall temperature of 170°C (338°F) to be maintained indefinitely.

Consideration of the heat removal mechanisms for vented-bin storage to keep centerline and surface temperatures of 1650°F and 300°F , assumed in the ORNL studies, indicates that either forced or natural draft convection cooling will be required. For this report, it is assumed that forced convection air cooling will be used. It is immediately apparent, therefore, that within these limits the costs for storage of solids can be divided into three relatively independent parts for economic evaluation purposes. These costs are for (1) the underground concrete vault, (2) the solids storage bins, and (3) the air cooling system. It is apparent, upon further consideration, that the unit volume costs for the concrete vault should decrease with the size of the vaults, whereas the costs of the solids storage bins and the air cooling system will be a function not only of the volume of solids to be stored but also of the specific volumetric heat generation rate of the solids. A more detailed discussion of these effects is given in the following paragraphs.

The temperature difference between the axis and the wall of a solid cylinder with uniform internal heat generation and constant thermal conductivity is given by the following equation.

$$T_{\text{axis}} - T_{\text{wall}} = \frac{QR^2}{4k}$$

where T = Temperature, $^{\circ}\text{F}$

Q = Heat generation rate, $\text{BTU}/(\text{hr})(\text{ft}^3)$

R = Radius of cylinder, ft.

k = Thermal conductivity of solid, $\text{BTU}/(\text{hr})(\text{sq.ft.})(^{\circ}\text{F}/\text{ft.})$

The temperature difference between the mid-plane of an annulus and the wall can be shown to be essentially that for a plate; therefore, the following equation gives the relationship between temperature at mid-plane and wall.

$$T_{\text{mp}} - T_{\text{wall}} = \frac{QX^2}{2k}$$

where X is the half-thickness of the annulus in feet, the other terms are the same as for the cylinder. Comparison of the two equations shows that for an allowable temperature difference at the same volumetric heat release rate, the thickness of the bins can be $\sqrt{2}$ times as great as the pot diameter. Consequently, the heat flux at the surface of the annular bins would then be $2/\sqrt{2}$ times the surface heat flux of a cylinder with the same temperature differences. However, calculations indicate that the maximum heat fluxes will not exceed the heat removing capacity of the air stream at practical operating velocities, and that the investment cost for cooling equipment can be considered approximately dependent on the allowable thickness of the bins.

The thickness of the annular bins will be based on the following criteria: (1) a maximum allowable temperature difference of 1350°F , (this will allow the mid-plane temperature to reach 1650°F while the surfaces are held at 300°F), (2) the solids volumes previously calculated, (3) no melting of solids with high sodium sulfate content, and (4) the following thermal conductivities for the calcined solids.

<u>Waste Type</u>	<u>Thermal Conductivity</u> <u>$\text{BTU}/(\text{hr})(\text{sq.ft.})(^{\circ}\text{F}/\text{ft.})$</u>
Acidic Purex	0.25
Re-acidified Purex	0.13
Acidic Thorex	0.20
Re-acidified Thorex	0.13

The following bin thicknesses are calculated to be comparable to the pot diameter of the ORNL studies.

	<u>ORNL Pot Diameter Inches</u>	<u>Annular Bin Thickness</u>
Acidic Purex	6"	3"
	12"	6"
	24"	12"
Re-acidified Purex	6"	5"
	12"	10"
	24"	20"
Acidic Thorex	6"	3"
	12"	6"
	24"	12"
Re-acidified Thorex	6"	5.5"
	12"	11"
	24"	22"

The estimated investment for bins of various thicknesses has been obtained by using the ratio of the mass of the metal (3/16"-thick walls of stainless steel type 410) to the mass of metal in the present DWCF bins raised to the 0.66 power (10) and multiplying the resultant fraction by \$111,000 - the cost of the present DWCF bins. The estimated cost of bins is predicated upon shop fabrication and rail shipment to the construction site; consequently, the overall diameter of the pre-fabricated nest of bins is limited to approximately 12.5 feet. Because only an integral number of annuli of a given thickness was used in each nest of bins, the plot of unit cost and volume versus bin thickness (Figure 8) is not a straight line.

The effect of vault volume on total vault construction costs is shown in Figure 9. These costs were obtained from pre-construction estimates by the Fluor Corporation for underground concrete vaults for liquid waste storage tanks (11) and for the vault portion of the present DWCF solids storage system. The slope of a line through these data is 0.55. Costs for the three- and four-tank vaults shown in Figure 9 lie above the line because these vaults included internal walls which would not be required for a vault containing the type of solid storage bins considered in this report. The cost of underground storage vaults, as a function of vault volume, can be satisfactorily estimated by raising the volume ratio of two vaults to the 0.55 power and multiplying by the estimated cost of the vault whose volume is the denominator in this ratio. The estimated vault investment cost for the present four-bin system, shown in Table 8, is for a single vault approximately 25-1/2 feet square and 40 feet deep with the bin venting and cooling equipment located,

Figure 8

Bin Costs and Volumes as A Function of Bin Thickness

Figure 9

Vault Cost as A Function of Size

Table 8

ESTIMATED INVESTMENT FOR A SOLIDS STORAGE SYSTEM				
	Present Storage 24"-thick bins	Bins		
		3"-thick	6"-thick	12"-thick
No. of bins	4	4	4	4
Total Volume of Bins (ft ³)	7,800	5,350	6,300	7,300
Cost of Bins	111,000	280,000	201,500	154,000
Cost of Vault	145,000	145,000	145,000	145,000
Cost of Cooling Equipment	46,000	73,000	57,500	53,000
TOTAL DIRECT COST	\$302,000	\$498,000	\$404,000	\$352,000
Construction Overhead (40%)	120,800	199,200	161,600	140,800
Engineering (15%)	45,800	74,200	60,600	52,800
Contingency (20%)	60,400	99,600	80,800	70,400
TOTAL INVESTMENT	<u>\$529,000</u>	<u>\$871,000</u>	<u>\$707,000</u>	<u>\$616,000</u>

respectively, in a small shielded room atop the vault and in a small transite shed above the shielded room. The estimated cost for cooling equipment is based upon providing blowers with sufficient capacity to remove the heat of radioactive decay from the surface of the bins at the estimated maximum heat flux. Consequently, more cooling capacity has been provided than would be required for wastes with lower specific heat generation rates; however, since the estimated investment for cooling and venting equipment is only about 15 per cent of the total solids storage costs, no effort was made to estimate investments for all possible heat generating rates.

From the investments estimated in Table 8 and the curves shown in Figure 8, along with the previously established relationship for vault cost as a function of volume, the following costs of bins, cooling and venting equipment, and vault volumes have been established on the bases of (1) usable volume of bin defined as filling with solids to 90 per cent of the total bin volume, and (2) installing venting and cooling equipment in units each capable of serving four nested bin arrays. These costs are compiled in Table 9.

Table 9

ESTIMATED INVESTMENT COSTS FOR VAULTS, BINS, AND COOLING EQUIPMENT							
Bin Thickness (Inches)	Bin Investment Costs	Cooling Equipment Investment Cost	Vault Volume Costs				
	<u>\$/usable gallon of bin volume</u>	<u>\$/usable gallon of bin volume</u>	<u>\$/usable gallon of bin volume</u>	<u>No. of Bins Per Vault</u>			
				4	12	20	40
3	13.60	3.54	7.05	4.30	3.42	2.51	
5	9.45	2.51	6.08	3.71	2.95	2.16	
5.5	8.95	2.46	5.94	3.62	2.88	2.11	
6	8.33	2.41	5.85	3.56	2.84	2.08	
10	6.10	1.94	5.31	3.24	2.58	1.89	
11	5.75	1.91	5.24	3.20	2.54	1.86	
12	5.49	1.89	5.17	3.15	2.50	1.84	
20	4.05	1.53	4.90	2.99	2.38	1.74	
22	3.80	1.53	4.84	2.95	2.35	1.72	

VII. OPERATING AND TOTAL COSTS

At high processing rates, the operating crew for the fluidized bed process of waste disposal will be smaller than for a batch process of equivalent capacity such as pot calcination. This is due to the continuous operation and the high degree of instrumentation control which can be incorporated in the process, and the fact that no remote manipulative operations are required.

The wages and salaries, maintenance, and overhead costs shown in Table 10 are on the same bases used in ORNL-3192. The estimated cost for supplies has been based, in part, on operating experience at the ICPP and upon engineering estimates of the frequency of replacement of process filters, silica gel beds, etc.

Table 10

OPERATING LABOR, MAINTENANCE, SUPPLIES, AND OVERHEAD COSTS

	<u>Number of People</u>
<u>Operators</u>	
Shift	12
Day	2
<u>Shift Supervisors</u>	5
<u>Instrument Mechanics</u>	5
<u>Health Physicists</u>	<u>1</u>
	25

ANNUAL COSTS

Wages and Salaries (\$7500/manyear)	\$187,500
Maintenance (10% of 5, 10, and 20 year Capital items)	317,300
Overhead (50% of above)	252,400
Materials, Supplies, Decontamination Chemicals, etc.	<u>110,000</u>
	\$867,200

For a continuous process such as the fluidized bed calcination of radioactive wastes, it is difficult to establish cost estimates as a function of plant area or volume as was done in ORNL-3192 for the pot calcination process. Since the total annual operating costs should be relatively constant for a continuous process such as fluidized bed calcination, it appears that the best approach to establishing operating costs is on the basis of a unit volume of liquid waste

calcined. Furthermore, since annual amortization charges, Table 7, are nearly identical, regardless of shielding wall thickness, it is equally reliable to establish amortization costs as a function of unit volume of liquid calcined. Consequently, the total of operating labor, maintenance, supplies, and overhead costs, as well as an average annual amortization charge of \$369,000, will be established for calcining rates of 45, 60, and 75 gallons per hour during a 300-day operating year. The annual capacity at these rates is 324,000, 432,000, and 540,000 gallons, respectively. The costs per gallon for total operating and amortization charges are shown in Table 11.

Table 11

OPERATING AND AMORTIZATION COSTS AS A FUNCTION OF PROCESSING RATE

<u>Processing Rate, gph</u>	<u>Total Operating Costs (\$/Liquid Gallon)</u>	<u>Amortization Costs (\$/Liquid Gallon)</u>
45	2.68	1.14
60	2.01	0.855
75	1.61	0.685

A typical calculation is shown as an example of the manner by which the previously established unit costs can be used to synthesize the cost of fluidized bed calcining of the liquid wastes assumed for this study. Consider the case of fluidized bed calcining of the acidic Purex wastes from 1500 tonnes per year of uranium converter fuel and 270 tonnes per year of Thorium converter fuel as acidic Thorex wastes. Assume that these wastes are calcining at the rate of 60 gph and that three-inch-thick storage bins are required for the acidic Purex calcine and six-inch-thick bins for the acidic Thorex calcine. Further assume that a vault containing 12 bins will be available.

Total Operating Costs:

(1500 tonnes/yr) x (50 liquid gal/tonne) x (\$2.01/liquid gal) = \$150,700

(270 tonnes/yr) x (400 liquid gal/tonne) x (\$2.01/liquid gal) = 216,000

Amortization Costs:

(1500 tonnes/yr) x (50 liquid gal/tonne) x (\$0.855/liquid gal) = 64,200

(270 tonnes/yr) x (400 liquid gal/tonne) x (\$0.855/liquid gal) = 92,400

Bin Storage:

(1500 tonnes/yr) x (4.6 solid gal/tonne) x (\$21.44*/solid gal) = 150,200

(270 tonnes/yr) x (49 solid gal/tonne) x (\$14.30**/solid gal) = 189,500

Total Annual Operating Costs \$863,000

* For 3"-thick bins \$14.60/usable gallon of bin volume (bin cost)
3.54/usable gallon of bin volume (cooling cost)
4.30/usable gallon of bin volume (vault cost)
\$21.44

** For 6"-thick bins \$ 8.33/usable gallon of bin volume (bin cost)
2.41/usable gallon of bin volume (cooling cost)
3.56/usable gallon of bin volume (vault cost)
\$14.30

The volume of acidic wastes considered in the above example is that generated from the processing of the nuclear fuel required in a 15,000 Mw_e nuclear economy (1). This electrical generating rate corresponds to 1.31×10^{11} kWh_e/year. Therefore, the above costs are equivalent to 0.65×10^{-2} mills/kWh_e. This cost, which includes the cost of the underground vault for the solids storage bin, is approximately 55 per cent of the cost estimated for pot calcination of the same waste. Tables 12, 13, and 14 record the estimated costs for calcining rates of 45, 60, and 75 gph for acidic and re-acidified Purex wastes and acidic and re-acidified Thorex wastes.

Table 12

TOTAL COST OF FLUIDIZED BED CALCINING AT 45 GALLONS/HOUR FOR VARIOUS WASTES
WITH STORAGE IN VARIOUS COMBINATIONS OF BIN AND VAULT SIZES

COSTS; Mills/kwh _e										
ORNL-3192 Pot Diameters Equivalent to Listed Bin Thickness	6-in.-dia Purex 6-in.-dia Thorex	6-in.-dia Purex 12-in.-dia Thorex	6-in.-dia Purex 24-in.-dia Thorex	12-in.-dia Purex 6-in.-dia Thorex	12-in.-dia Purex 12-in.-dia Thorex	12-in.-dia Purex 24-in.-dia Thorex	24-in.-dia Purex 6-in.-dia Thorex	24-in.-dia Purex 12-in.-dia Thorex	24-in.-dia Purex 24-in.-dia Thorex	
ACIDIC PUREX - ACIDIC THOREX										
Number of Bins Per Vault	Bin Thickness	3-in. Purex 3-in. Thorex	3-in. Purex 6-in. Thorex	3-in. Purex 12-in. Thorex	6-in. Purex 3-in. Thorex	6-in. Purex 6-in. Thorex	6-in. Purex 12-in. Thorex	12-in. Purex 3-in. Thorex	12-in. Purex 6-in. Thorex	12-in. Purex 12-in. Thorex
4		0.91×10^{-2}	0.83×10^{-2}	0.79×10^{-2}	0.87×10^{-2}	0.79×10^{-2}	0.75×10^{-2}	0.85×10^{-2}	0.82×10^{-2}	0.73×10^{-2}
12		0.89×10^{-2}	0.82×10^{-2}	0.78×10^{-2}	0.83×10^{-2}	0.75×10^{-2}	0.72×10^{-2}	0.81×10^{-2}	0.74×10^{-2}	0.70×10^{-2}
20		0.85×10^{-2}	0.78×10^{-2}	0.75×10^{-2}	0.81×10^{-2}	0.74×10^{-2}	0.71×10^{-2}	0.80×10^{-2}	0.73×10^{-2}	0.69×10^{-2}
40		0.83×10^{-2}	0.77×10^{-2}	0.73×10^{-2}	0.80×10^{-2}	0.73×10^{-2}	0.70×10^{-2}	0.78×10^{-2}	0.71×10^{-2}	0.68×10^{-2}
ACIDIC PUREX - RE-ACIDIFIED THOREX										
Bin Thickness	3-in. Purex 5.5-in. Thorex	3-in. Purex 11-in. Thorex	3-in. Purex 22-in. Thorex	6-in. Purex 5.5-in. Thorex	6-in. Purex 11-in. Thorex	6-in. Purex 22-in. Thorex	12-in. Purex 5.5-in. Thorex	12-in. Purex 11-in. Thorex	12-in. Purex 22-in. Thorex	
4	2.15×10^{-2}	1.85×10^{-2}	1.65×10^{-2}	2.11×10^{-2}	1.80×10^{-2}	1.62×10^{-2}	2.09×10^{-2}	1.78×10^{-2}	1.59×10^{-2}	
12	1.97×10^{-2}	1.69×10^{-2}	1.51×10^{-2}	1.94×10^{-2}	1.65×10^{-2}	1.47×10^{-2}	1.92×10^{-2}	1.63×10^{-2}	1.45×10^{-2}	
20	1.92×10^{-2}	1.64×10^{-2}	1.46×10^{-2}	1.87×10^{-2}	1.60×10^{-2}	1.43×10^{-2}	1.85×10^{-2}	1.58×10^{-2}	1.41×10^{-2}	
40	1.86×10^{-2}	1.58×10^{-2}	1.41×10^{-2}	1.82×10^{-2}	1.55×10^{-2}	1.38×10^{-2}	1.81×10^{-2}	1.53×10^{-2}	1.36×10^{-2}	
RE-ACIDIFIED PUREX - ACIDIC THOREX										
Bin Thickness	5-in. Purex 3-in. Thorex	5-in. Purex 6-in. Thorex	5-in. Purex 12-in. Thorex	10-in. Purex 3-in. Thorex	10-in. Purex 6-in. Thorex	10-in. Purex 12-in. Thorex	20-in. Purex 3-in. Thorex	20-in. Purex 6-in. Thorex	20-in. Purex 12-in. Thorex	
4	1.66×10^{-2}	1.58×10^{-2}	1.55×10^{-2}	1.46×10^{-2}	1.39×10^{-2}	1.35×10^{-2}	1.34×10^{-2}	1.27×10^{-2}	1.23×10^{-2}	
12	1.52×10^{-2}	1.45×10^{-2}	1.42×10^{-2}	1.35×10^{-2}	1.28×10^{-2}	1.24×10^{-2}	1.23×10^{-2}	1.17×10^{-2}	1.13×10^{-2}	
20	1.50×10^{-2}	1.42×10^{-2}	1.39×10^{-2}	1.32×10^{-2}	1.25×10^{-2}	1.21×10^{-2}	1.20×10^{-2}	1.13×10^{-2}	1.10×10^{-2}	
40	1.45×10^{-2}	1.38×10^{-2}	1.35×10^{-2}	1.28×10^{-2}	1.21×10^{-2}	1.17×10^{-2}	1.17×10^{-2}	1.10×10^{-2}	1.07×10^{-2}	
RE-ACIDIFIED PUREX - RE-ACIDIFIED THOREX										
Bin Thickness	5-in. Purex 5.5-in. Thorex	5-in. Purex 11-in. Thorex	5-in. Purex 22-in. Thorex	10-in. Purex 5.5-in. Thorex	10-in. Purex 11-in. Thorex	10-in. Purex 22-in. Thorex	20-in. Purex 5.5-in. Thorex	20-in. Purex 11-in. Thorex	20-in. Purex 22-in. Thorex	
4	2.91×10^{-2}	2.60×10^{-2}	2.41×10^{-2}	2.71×10^{-2}	2.40×10^{-2}	2.22×10^{-2}	2.59×10^{-2}	2.28×10^{-2}	2.1×10^{-2}	
12	2.64×10^{-2}	2.36×10^{-2}	2.17×10^{-2}	2.46×10^{-2}	2.18×10^{-2}	2.07×10^{-2}	2.35×10^{-2}	2.06×10^{-2}	1.88×10^{-2}	
20	2.56×10^{-2}	2.28×10^{-2}	2.11×10^{-2}	2.39×10^{-2}	2.10×10^{-2}	2.00×10^{-2}	2.27×10^{-2}	1.99×10^{-2}	1.82×10^{-2}	
40	2.47×10^{-2}	2.20×10^{-2}	2.03×10^{-2}	2.31×10^{-2}	2.03×10^{-2}	1.93×10^{-2}	2.20×10^{-2}	1.92×10^{-2}	1.75×10^{-2}	

Table 13

TOTAL COST OF FLUIDIZED BED CALCINING AT 60 GALLONS/HOUR FOR VARIOUS WASTES
WITH STORAGE IN VARIOUS COMBINATIONS OF BIN AND VAULT SIZES

COSTS, Mills/kwh _e										
ORNL-3192 Pot Diameters Equivalent to Listed Bin Thickness	6-in.-dia Purex 6-in.-dia Thorex	6-in.-dia Purex 12-in.-dia Thorex	6-in.-dia Purex 24-in.-dia Thorex	12-in.-dia Purex 6-in.-dia Thorex	12-in.-dia Purex 12-in.-dia Thorex	12-in.-dia Purex 24-in.-dia Thorex	24-in.-dia Purex 6-in.-dia Thorex	24-in.-dia Purex 12-in.-dia Thorex	24-in.-dia Purex 24-in.-dia Thorex	
ACIDIC PUREX - ACIDIC THOREX										
Number of Bins Per Vault	Bin Thickness	3-in. Purex 3-in. Thorex	3-in. Purex 6-in. Thorex	3-in. Purex 12-in. Thorex	6-in. Purex 3-in. Thorex	6-in. Purex 6-in. Thorex	6-in. Purex 12-in. Thorex	12-in. Purex 3-in. Thorex	12-in. Purex 6-in. Thorex	12-in. Purex 12-in. Thorex
4		0.77×10^{-2}	0.70×10^{-2}	0.66×10^{-2}	0.73×10^{-2}	0.66×10^{-2}	0.61×10^{-2}	0.71×10^{-2}	0.64×10^{-2}	0.60×10^{-2}
12		0.76×10^{-2}	0.68×10^{-2}	0.65×10^{-2}	0.69×10^{-2}	0.62×10^{-2}	0.58×10^{-2}	0.67×10^{-2}	0.60×10^{-2}	0.57×10^{-2}
20		0.72×10^{-2}	0.65×10^{-2}	0.61×10^{-2}	0.68×10^{-2}	0.61×10^{-2}	0.57×10^{-2}	0.66×10^{-2}	0.59×10^{-2}	0.56×10^{-2}
40		0.70×10^{-2}	0.63×10^{-2}	0.60×10^{-2}	0.67×10^{-2}	0.60×10^{-2}	0.56×10^{-2}	0.65×10^{-2}	0.58×10^{-2}	0.55×10^{-2}
ACIDIC PUREX - RE-ACIDIFIED THOREX										
Bin Thickness	3-in. Purex 5.5-in. Thorex	3-in. Purex 11-in. Thorex	3-in. Purex 22-in. Thorex	6-in. Purex 5.5-in. Thorex	6-in. Purex 11-in. Thorex	6-in. Purex 22-in. Thorex	12-in. Purex 5.5-in. Thorex	12-in. Purex 11-in. Thorex	12-in. Purex 22-in. Thorex	
4		1.94×10^{-2}	1.64×10^{-2}	1.45×10^{-2}	1.90×10^{-2}	1.60×10^{-2}	1.41×10^{-2}	1.88×10^{-2}	1.58×10^{-2}	1.39×10^{-2}
12		1.77×10^{-2}	1.48×10^{-2}	1.30×10^{-2}	1.73×10^{-2}	1.44×10^{-2}	1.27×10^{-2}	1.71×10^{-2}	1.43×10^{-2}	1.25×10^{-2}
20		1.71×10^{-2}	1.43×10^{-2}	1.26×10^{-2}	1.67×10^{-2}	1.39×10^{-2}	1.22×10^{-2}	1.66×10^{-2}	1.38×10^{-2}	1.20×10^{-2}
40		1.65×10^{-2}	1.38×10^{-2}	1.21×10^{-2}	1.62×10^{-2}	1.34×10^{-2}	1.17×10^{-2}	1.60×10^{-2}	1.33×10^{-2}	1.15×10^{-2}
RE-ACIDIFIED PUREX - ACIDIC THOREX										
Bin Thickness	5-in. Purex 3-in. Thorex	5-in. Purex 6-in. Thorex	5-in. Purex 12-in. Thorex	10-in. Purex 3-in. Thorex	10-in. Purex 6-in. Thorex	10-in. Purex 12-in. Thorex	20-in. Purex 3-in. Thorex	20-in. Purex 6-in. Thorex	20-in. Purex 12-in. Thorex	
4		1.50×10^{-2}	1.42×10^{-2}	1.38×10^{-2}	1.30×10^{-2}	1.22×10^{-2}	1.18×10^{-2}	1.18×10^{-2}	1.10×10^{-2}	1.06×10^{-2}
12		1.36×10^{-2}	1.29×10^{-2}	1.25×10^{-2}	1.19×10^{-2}	1.12×10^{-2}	1.08×10^{-2}	1.07×10^{-2}	1.00×10^{-2}	0.97×10^{-2}
20		1.33×10^{-2}	1.26×10^{-2}	1.22×10^{-2}	1.15×10^{-2}	1.08×10^{-2}	1.04×10^{-2}	1.04×10^{-2}	0.97×10^{-2}	0.93×10^{-2}
40		1.28×10^{-2}	1.22×10^{-2}	1.18×10^{-2}	1.11×10^{-2}	1.04×10^{-2}	1.01×10^{-2}	1.00×10^{-2}	0.93×10^{-2}	0.90×10^{-2}
RE-ACIDIFIED PUREX - RE-ACIDIFIED THOREX										
Bin Thickness	5-in. Purex 5.5-in. Thorex	5-in. Purex 11-in. Thorex	5-in. Purex 22-in. Thorex	10-in. Purex 5.5-in. Thorex	10-in. Purex 11-in. Thorex	10-in. Purex 22-in. Thorex	20-in. Purex 5.5-in. Thorex	20-in. Purex 11-in. Thorex	20-in. Purex 22-in. Thorex	
4		2.67×10^{-2}	2.36×10^{-2}	2.17×10^{-2}	2.67×10^{-2}	2.17×10^{-2}	1.98×10^{-2}	2.35×10^{-2}	2.04×10^{-2}	1.86×10^{-2}
12		2.41×10^{-2}	2.12×10^{-2}	1.94×10^{-2}	2.22×10^{-2}	1.94×10^{-2}	1.83×10^{-2}	2.11×10^{-2}	1.82×10^{-2}	1.65×10^{-2}
20		2.32×10^{-2}	2.04×10^{-2}	1.87×10^{-2}	2.15×10^{-2}	1.87×10^{-2}	1.76×10^{-2}	2.03×10^{-2}	1.75×10^{-2}	1.58×10^{-2}
40		2.24×10^{-2}	1.96×10^{-2}	1.79×10^{-2}	2.07×10^{-2}	1.80×10^{-2}	1.70×10^{-2}	1.96×10^{-2}	1.68×10^{-2}	1.51×10^{-2}

Table 14

TOTAL COST OF FLUIDIZED BED CALCINING AT 75 GALLONS/HOUR FOR VARIOUS WASTES
WITH STORAGE IN VARIOUS COMBINATIONS OF BIN AND VAULT SIZES

COSTS, Mills/kwh _e										
ORNL-3192 Pot Diameters Equivalent to Listed Bin Thickness		6-in.-dia Purex 6-in.-dia Thorex	6-in.-dia Purex 12-in.-dia Thorex	6-in.-dia Purex 24-in.-dia Thorex	12-in.-dia Purex 6-in.-dia Thorex	12-in.-dia Purex 12-in.-dia Thorex	12-in.-dia Purex 24-in.-dia Thorex	24-in.-dia Purex 6-in.-dia Thorex	24-in.-dia Purex 12-in.-dia Thorex	24-in.-dia Purex 24-in.-dia Thorex
ACIDIC PUREX - ACIDIC THOREX										
Number of Bins Per Vault	Bin Thickness	3-in. Purex 3-in. Thorex	3-in. Purex 6-in. Thorex	3-in. Purex 12-in. Thorex	6-in. Purex 3-in. Thorex	6-in. Purex 6-in. Thorex	6-in. Purex 12-in. Thorex	12-in. Purex 3-in. Thorex	12-in. Purex 6-in. Thorex	12-in. Purex 12-in. Thorex
4		0.69×10^{-2}	0.62×10^{-2}	0.58×10^{-2}	0.65×10^{-2}	0.58×10^{-2}	0.53×10^{-2}	0.53×10^{-2}	0.56×10^{-2}	0.52×10^{-2}
12		0.68×10^{-2}	0.60×10^{-2}	0.57×10^{-2}	0.61×10^{-2}	0.54×10^{-2}	0.51×10^{-2}	0.50×10^{-2}	0.52×10^{-2}	0.49×10^{-2}
20		0.64×10^{-2}	0.57×10^{-2}	0.53×10^{-2}	0.60×10^{-2}	0.53×10^{-2}	0.50×10^{-2}	0.58×10^{-2}	0.51×10^{-2}	0.48×10^{-2}
40		0.62×10^{-2}	0.55×10^{-2}	0.52×10^{-2}	0.59×10^{-2}	0.52×10^{-2}	0.48×10^{-2}	0.57×10^{-2}	0.50×10^{-2}	0.47×10^{-2}
ACIDIC PUREX - RE-ACIDIFIED THOREX										
	Bin Thickness	3-in. Purex 5.5-in. Thorex	3-in. Purex 11-in. Thorex	3-in. Purex 22-in. Thorex	6-in. Purex 5.5-in. Thorex	6-in. Purex 11-in. Thorex	6-in. Purex 22-in. Thorex	12-in. Purex 5.5-in. Thorex	12-in. Purex 11-in. Thorex	12-in. Purex 22-in. Thorex
4		1.82×10^{-2}	1.51×10^{-2}	1.33×10^{-2}	1.78×10^{-2}	1.47×10^{-2}	1.28×10^{-2}	1.76×10^{-2}	1.45×10^{-2}	1.27×10^{-2}
12		1.65×10^{-2}	1.36×10^{-2}	1.18×10^{-2}	1.61×10^{-2}	1.32×10^{-2}	1.14×10^{-2}	1.59×10^{-2}	1.30×10^{-2}	1.12×10^{-2}
20		1.59×10^{-2}	1.31×10^{-2}	1.13×10^{-2}	1.55×10^{-2}	1.27×10^{-2}	1.10×10^{-2}	1.54×10^{-2}	1.25×10^{-2}	1.08×10^{-2}
40		1.55×10^{-2}	1.26×10^{-2}	1.09×10^{-2}	1.50×10^{-2}	1.22×10^{-2}	1.05×10^{-2}	1.48×10^{-2}	1.20×10^{-2}	1.04×10^{-2}
RE-ACIDIFIED PUREX - ACIDIC THOREX										
	Bin Thickness	5-in. Purex 3-in. Thorex	5-in. Purex 6-in. Thorex	5-in. Purex 12-in. Thorex	10-in. Purex 3-in. Thorex	10-in. Purex 6-in. Thorex	10-in. Purex 12-in. Thorex	20-in. Purex 3-in. Thorex	20-in. Purex 6-in. Thorex	20-in. Purex 12-in. Thorex
4		1.40×10^{-2}	1.32×10^{-2}	1.28×10^{-2}	1.20×10^{-2}	1.13×10^{-2}	1.08×10^{-2}	1.38×10^{-2}	1.00×10^{-2}	0.97×10^{-2}
12		1.26×10^{-2}	1.19×10^{-2}	1.14×10^{-2}	1.09×10^{-2}	1.02×10^{-2}	0.98×10^{-2}	1.27×10^{-2}	0.90×10^{-2}	0.87×10^{-2}
20		1.23×10^{-2}	1.16×10^{-2}	1.12×10^{-2}	1.05×10^{-2}	0.98×10^{-2}	0.94×10^{-2}	1.23×10^{-2}	0.87×10^{-2}	0.83×10^{-2}
40		1.19×10^{-2}	1.12×10^{-2}	1.08×10^{-2}	1.01×10^{-2}	0.94×10^{-2}	0.91×10^{-2}	1.20×10^{-2}	0.83×10^{-2}	0.80×10^{-2}
RE-ACIDIFIED PUREX - RE-ACIDIFIED THOREX										
	Bin Thickness	5-in. Purex 5.5-in. Thorex	5-in. Purex 11-in. Thorex	5-in. Purex 22-in. Thorex	10-in. Purex 5.5-in. Thorex	10-in. Purex 11-in. Thorex	10-in. Purex 22-in. Thorex	20-in. Purex 5.5-in. Thorex	20-in. Purex 11-in. Thorex	20-in. Purex 22-in. Thorex
4		2.52×10^{-2}	2.22×10^{-2}	2.03×10^{-2}	2.33×10^{-2}	2.02×10^{-2}	1.83×10^{-2}	2.21×10^{-2}	1.90×10^{-2}	1.71×10^{-2}
12		2.26×10^{-2}	1.98×10^{-2}	1.80×10^{-2}	2.08×10^{-2}	1.80×10^{-2}	1.68×10^{-2}	1.97×10^{-2}	1.68×10^{-2}	1.50×10^{-2}
20		2.18×10^{-2}	1.90×10^{-2}	1.73×10^{-2}	2.00×10^{-2}	1.72×10^{-2}	1.62×10^{-2}	1.89×10^{-2}	1.61×10^{-2}	1.44×10^{-2}
40		2.10×10^{-2}	1.82×10^{-2}	1.65×10^{-2}	1.93×10^{-2}	1.65×10^{-2}	1.55×10^{-2}	1.81×10^{-2}	1.54×10^{-2}	1.37×10^{-2}

VIII. RECOMMENDATIONS

The approach used to develop the costs for fluidized bed calcining of radioactive wastes and the cost of storage of solid wastes in vented, air-cooled, annular bins in underground concrete vaults is believed technically and economically valid and is recommended as an approach to evaluating the economics of fluidized bed calcining at other sites. However, this report has been based on experiences and practices in construction and operation of nuclear fuel and waste disposal processing plants at the National Reactor Testing Station; consequently, the costs developed herein may be considerably modified for other locations and different operating practices. It is believed, however, that local labor, climatic, and geological conditions will have the most significant effect on plant investments.

The following comments should be considered when comparing the storage costs estimated in this report with those to be estimated by ORNL (1, 2) for (1) storage of calcined solids in salt deposits, (2) storage in vaults, and (3) storage in vertical shafts.

- (a) The estimation of the costs of annular bins and concrete vaults has been based on widely accepted engineering ratios and firm construction costs for one or more units.
- (b) The estimated investments for cooling and venting equipment are based, in part, on pre-construction cost estimates for the DWCF storage system using engineering ratios for the equipment needed to remove heat at higher rates. Consequently, the cooling and venting equipment cost estimates are believed to lack the firmness of the bin and vault estimates.
- (c) Users of the costs reported here should be cognizant that investments for spare air blowers, an emergency power supply, and normal and emergency water cooling have not been included. Perhaps these costs, along with operating and surveillance costs, will be most significant when attempting to compare the long-term costs of solids storage in vented, air-cooled bins in underground concrete vaults near the earth's surface with other ultimate disposal methods.

IX. BIBLIOGRAPHY

1. Bradshaw, R. L., J. J. Perona, J. T. Roberts, and J. O. Blomeke, Evaluation of Ultimate Disposal Methods for Liquid and Solid Radioactive Wastes Part I. Interim Liquid Storage, ORNL-3128, August 1961.
2. Perona, J. J., R. L. Bradshaw, J. T. Roberts, and J. O. Blomeke, Evaluation of Ultimate Disposal Methods for Liquid and Solid Radioactive Wastes Part II. Conversion to Solid by Pot Calcination, ORNL-3192, October 1961.
3. May, C. E., B. J. Newby, K. L. Rohde, and B. D. Withers, Ruthenium Behavior in A Nitric Acid Scrubber, IDO-14448, September 1958.
4. Hanson, D. A., B. J. Newby, and K. L. Rhode, The Adsorption of Ruthenium From Nitric Acid - Air Mixtures, IDO-14458, June 1959.
5. Rhodes, D. W., and D. R. Anderson, Capacity Test Data for The Adsorption of Volatile Ruthenium on Silica Gel, IDO-14510, June 1960.
6. MacQueen, D. K., and J. I. Stevens, Design Bases for ICPP Waste Calcination Facility, IDO-14462, April 1959.
7. Jonke, A. A., J. W. Loeding, and L. J. Anastasia, TID-7613, Report of the Second Working Meeting on Fixation of Radioactivity in Stable Solid Media, 6-27, September 1960.
8. Alford, M. D., Personal Communication, September 1960.
9. Wheeler, B. R., E. S. Grimmett, and J. A. Buckham, Development of A Fluidized Bed Calcination Process for Aluminum Nitrate Wastes In A Two-Foot-Square Pilot Plant Calciner Part II. Factors Affecting The Intra-Particle Porosity of Alumina, IDO-14587, July 1962.
10. Bauman, H. Carl, Up-To-Date Equipment Costs, Ind. and Eng. Chemistry 54, 49-60 (1962).
11. Economic Study and Report, Group II CPP Liquid Waste Storage Facilities, Study No. 8, Storage of Neutralized Waste Liquid, AECU-4271, September 1957.

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