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EVALUATION OF ULTIMATE DISPOSAL METHODS
FOR LIQUID AND SOLID RADIOACTIVE WASTES
VI. DISPOSAL OF SOLID WASTES IN
SALT FORMATIONS

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OAK RIDGE NATIONAL LABORATORY

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HEALTH PHYSICS DIVISION
CHEMICAL TECHNOLOGY DIVISION

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MAY 1968

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EVALUATION OF ULTIMATE DISPOSAL METHODS FOR LIQUID
AND SOLID RADIOACTIVE WASTES

VI. DISPOSAL OF SOLID WASTES IN SALT FORMATIONS

R. L. Bradshaw	J. O. Blomeke
J. J. Perona	W. J. Boegly, Jr.

ABSTRACT

This is a study of the cost of disposing of high-level solidified wastes in bedded salt formations. A conceptual design of a salt mine is developed for disposal of wastes from the recovery of spent uranium and thorium reactor fuels from a 15,000-Mw (electrical) nuclear power economy. The waste products are contained in "pots" 6, 12, and 24 in. in diameter by 10 ft long and are buried in vertical holes in the floor of a mine 1 sq mile in area and located 1000 ft below the surface. The operating life of this mine and the costs of the mining and disposal operations are calculated, using rather conservative mine stability criteria, for various waste ages, pot sizes, and waste compositions.

The life of the mine was found to range from about 12-1/2 years for wastes aged 1 year at the time of burial to about 70 years for wastes aged 30 years at burial. The initial capital outlay required to start waste disposal operations ranges from about \$8.4 million to \$10.7 million. The annual capital and operating costs for the facility are dependent on waste combinations and pot sizes and vary from about \$2.6 million for a 1-year-old waste to about \$1.2 million for 30-year-old wastes.

Using present worth considerations, the money to be set aside annually at the time of waste generation ranges from about \$2.5 million for a 1-year-old waste to about \$400,000 for a waste 30 years old at the time of disposal. In terms of the cost per kilowatt-hour of electricity generated, these amounts correspond to about 19×10^{-3} mill and 3×10^{-3} mill respectively.

1. INTRODUCTION

This report is one of a series devoted to the engineering, economics, and safety aspects of high-level waste management. The intent of these studies is to develop the optimum combination of operations for the management of high-level wastes from the processing of power reactor fuels and to serve as a guide in directing research and development work currently under way in this field.

As in the previous studies of this series, a 6-tonne/day fuel processing plant is assumed that would handle the fuel from a 15,000-Mw (electrical) [56,000 Mw (thermal)] nuclear power economy, producing 1.32×10^{11} kwhr of electricity annually. (In this report, "tonne" refers to metric ton.) This plant would process 1500 tonnes/year of uranium converter fuel at a burnup of 10,000 Mwd/tonne using a Purex process flowsheet, and 270 tonnes/year of thorium converter fuel, irradiated to 20,000 Mwd/tonne, using a Thorex process flowsheet. Management of the resulting Purex and Thorex wastes in both acid and neutralized forms and of Thorex wastes made into an alumina-silica-borax-type glass is considered.

In previous reports, conceptual designs and estimated costs were presented for storage of these wastes as liquids in tanks for periods up to 30 years,¹ converting the wastes to solids by evaporation to dryness and calcination in stainless steel pots,² interim storage of the solidified wastes in water-filled canals for periods up to 30 years,³ and shipment

¹R. L. Bradshaw, 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 (Aug. 7, 1961).

²J. J. Perona, 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 (Sept. 27, 1961).

³J. O. Blomeke, J. J. Perona, H. O. Weeren, and R. L. Bradshaw, Evaluation of Ultimate Disposal Methods for Liquid and Solid Radioactive Wastes. Part III. Interim Storage of Solidified Wastes, ORNL-3355 (Oct. 14, 1963).

of the waste-filled pots to permanent disposal sites.⁴ In addition, the effects of fission product removal on costs of waste management have been evaluated,⁵ and comparative costs have been estimated for final disposal of solidified wastes in concrete vaults, hard rock, and salt formations.⁶ (Although the costs for disposal in salt used in the latter two reports are based on preliminary analyses and are not identical to those developed in this report, the differences are not such as to change any significant conclusions drawn in the previous reports.) For purposes of comparison, a study has also been made of the costs of perpetual storage of wastes as liquids in tanks.⁷

In September 1955, at the request of the Division of Reactor Development, USAEC, the Earth Sciences Division of the National Research Council considered the possibilities for disposal of high-level radioactive wastes in geologic structures. As a result of these deliberations, storage in natural salt formations was proposed as perhaps the most promising method.⁸ Some of the advantages of salt deposits as repositories for radioactive wastes are as follows:

⁴J. J. Perona, R. L. Bradshaw, J. O. Blomeke and J. T. Roberts, Evaluation of Ultimate Disposal Methods for Liquid and Solid Radioactive Wastes. Part IV. Shipment of Calcined Solids, ORNL-3356 (Oct. 4, 1962).

⁵J. J. Perona, J. O. Blomeke, R. L. Bradshaw, and J. T. Roberts, Evaluation of Ultimate Disposal Methods for Liquid and Solid Radioactive Wastes. V. Effects of Fission Product Removal on Costs of Waste Management, ORNL-3357 (June 12, 1963).

⁶J. J. Perona, R. L. Bradshaw, and J. O. Blomeke, Comparative Costs for Final Disposal of Radioactive Solids in Concrete Vaults, Granite, and Salt Formations, ORNL-TM-664 (Oct. 23, 1963).

⁷J. O. Blomeke, E. J. Frederick, R. Salmon, and E. D. Arnold, The Costs of Permanent Disposal of Power-Reactor Fuel-Processing Wastes in Tanks, ORNL-2873 (September 1965).

⁸Committee on Waste Disposal, Division of Earth Sciences, National Research Council-National Academy of Sciences, Disposal of Radioactive Wastes on Land, National Research Council Publication 519 (1957).

1. Salt is essentially impermeable, due to its plastic properties.
2. Salt is widely distributed and abundant, underlying about 500,000 sq miles in the United States, and known reserves exceed 6×10^{13} tons.
3. The cost of developing space is low, due to its good structural strength and relative ease of mining.
4. The thermal conductivity of salt is good ($2.5 \text{ Btu hr}^{-1} \text{ ft}^{-1} \text{ }^{\circ}\text{F}^{-1}$ at 200°F).
5. Salt formations in the United States are located in areas of low seismicity.

This report presents a conceptual design and cost estimate for permanent disposal of solidified wastes produced in the pot calcination facility described previously.² It is assumed that Purex and Thorex wastes are evaporated to dryness and calcined in cylindrical pots 6, 12, or 24 in. in diameter with a length of 10 ft. Thorex glass is produced only in 6-in.-diam vessels. The number of vessels produced annually by processing the wastes in differing chemical states and in different sized pots is given in Table 1, together with the volume of solids contained in each case. The total number of pots produced per year would be the sum of any one of the Purex numbers from the table plus any one of the Thorex numbers. Fission product heat in the wastes as a function of their age is given in Fig. 1. The calcination vessels arrive at the salt mine containing fission products which have been out of the reactor for periods ranging from 1 to 30 years. The pots are lowered 1000 ft into the mine and placed in individual vertical holes drilled into the floor.

Cost calculations are grouped into two increments. One is solely a function of the life of the mine; the other is a function of the number of waste containers handled annually. Total costs are presented only for storing the Purex and Thorex wastes together in the same facility, but the incremental costs can be used to estimate costs for disposal of the wastes in separate installations, if desired.

It is expected that any future disposal facility will differ in a number of respects from the hypothetical case considered in this study;

Table 1. Number of Calcination Vessels per Year and Volume of Solids
per Pot as a Function of Waste Type and Vessel Diameter

Waste Type	6-in.-diam		12-in.-diam		24-in.-diam	
	Volume of Solids per Pot (ft ³)	Total Number of Pots per Year	Volume of Solids per Pot (ft ³)	Total Number of Pots per Year	Volume of Solids per Pot (ft ³)	Total Number of Pots per Year
Acid Purex	1.40	925	5.62	231	22.5	58
Reacidified Purex	1.05	2320	4.21	580	16.9	145
Acid Thorex	1.40	1390	5.62	348	22.5	87
Reacidified Thorex	1.05	4110	4.21	1028	16.9	257
Thorex glass	1.56	1800

Fig. 1. Heat Generation Rate in Calcined Solids as a Function of Time Since Reactor Discharge.

consequently, much additional information on the probable effects on costs of changing important parameters is included in several appendixes. The effects of charges or credits for disposal of the mined salt are treated in Appendix A, the effects of varying the salt extraction ratio are discussed in Appendix B, the effect of mine depth on costs is considered in Appendix C, and the effect of mine size is given in Appendix D. Other concepts for disposing of the wastes in salt are discussed in Appendix E, and a method for estimating the disposal costs for solidified wastes having other characteristics than those assumed here is given

in Appendix F. Finally, estimates are presented in Appendix G of the space requirements for disposing of all the high-level process wastes from the United States nuclear power economy through the year 2065. A selected bibliography of further information on salt formations and on the theoretical and experimental studies concerned with disposal of wastes in salt formations is also included.

Many aspects of the conceptual design, operational techniques, and costs used in this study are based on the results and experience obtained in the course of Project Salt Vault,⁹⁻¹⁵ and the invaluable contributions

⁹F. M. Empson, R. L. Bradshaw, W. J. Boegly, Jr., W. C. McClain, F. L. Parker, and W. F. Schaffer, Jr., "Project Salt Vault: Design and Operation," Proceedings of International Symposium on Solidification and Long-Term Storage of Highly Radioactive Wastes, Richland, Washington, February 14-18, 1966, CONF-660208, pp. 671-84 (November 1966).

¹⁰W. F. Schaffer, Jr., W. J. Boegly, Jr., F. L. Parker, R. L. Bradshaw, F. M. Empson, and W. C. McClain, "Project Salt Vault: Design and Demonstration of Equipment," Proceedings of International Symposium on Solidification and Long-Term Storage of Highly Radioactive Wastes, Richland, Washington, February 14-18, 1966, CONF-660208, pp. 684-706 (November 1966).

¹¹R. L. Bradshaw, T. F. Lomenick, W. C. McClain, W. J. Boegly, Jr., F. M. Empson, and F. L. Parker, "Project Salt Vault: Effects of Temperature and Radiation on Plastic Flow and Mine Stability," Proceedings of International Symposium on the Solidification and Long-Term Storage of Highly Radioactive Wastes, Richland, Washington, February 14-18, 1966, CONF-660208, pp. 707-22 (November 1966).

¹²K. Z. Morgan et al., Health Phys. Div. Ann. Progr. Rept. July 31, 1964, ORNL-3697, pp. 19-31.

¹³K. Z. Morgan et al., Health Phys. Div. Ann. Progr. Rept. July 31, 1965, ORNL-3849, pp. 10-18.

¹⁴K. Z. Morgan et al., Health Phys. Div. Ann. Progr. Rept. July 31, 1966, ORNL-4007, pp. 15-26.

¹⁵K. Z. Morgan et al., Health Phys. Div. Ann. Progr. Rept. July 31, 1967, ORNL-4168, pp. 18-31.

of all who have participated in that project are gratefully acknowledged here.

2. CONCEPTUAL DESIGN FOR DISPOSAL IN FLOOR

In this study, it is assumed that disposal is carried out in a bedded (approximately horizontal) salt formation in a facility designed especially for the purpose. The shipping casks are received at a surface facility where the waste, in cylindrical containers 6, 12, and 24 in. in diameter by 10 ft long, is unloaded and inspected before being lowered, one container at a time, down a shaft into a motorized carrier at the working level of the mine. The carrier moves from a containment cell at the base of the shaft to the disposal area, where the cylinder is lowered into a vertical hole in the floor and covered with crushed salt.

2.1 Surface Waste-Handling Facilities

The surface facilities are located on two levels and are contained in a concrete block building having foundations about 65 ft square (Fig. 2). At ground level, space is provided for unloading casks; for offices and a change room; and a maintenance shop and decontamination solution makeup area. Shipping casks, containing up to thirty-six 6-in.-diam, nine 12-in.-diam, or four 24-in.-diam cylinders,⁴ are unloaded from railroad cars using an overhead 100-ton bridge crane. They are brought into the building and lowered into the cell block through an access hole in the floor (Figs. 3 and 4). This access is sealed with a sliding horizontal lead shield, 1 ft thick. The cask is opened with the aid of a remotely controlled manipulator, and the cylinders of waste are removed from the cask with an overhead crane and placed in an area where they are inspected for defects incurred in shipment. If necessary, individual cylinders can be recanned using the manipulator and a remote welder provided for the purpose.

Decontamination of the cask can be performed using solutions prepared at ground level. After use, these solutions are collected in a tank in the liquid waste collection cell, located beneath the inspection area.

Fig. 2. Topside Hot Cell Ground Floor Plan.

Fig. 3. Topside Hot Cell Section C-C.

Fig. 4. Topside Cell Block and Operating Area.

A 50-gal/hr evaporator, also in this cell, concentrates the solution for temporary storage prior to disposal off site.

Following inspection, the cylinders are placed on a motorized dolly which transfers them along tracks into the shaft room (Fig. 4). Storage space is provided in this room for the contents of two shipping casks, and an overhead bridge crane is used to attach the cylinders to the hoist cable for lowering, one at a time, down the shaft to a motorized carrier at mine level. An electrically operated cable hoist is used to lower the cylinders down the shaft.

Areas of personnel access are shielded from the radiation areas with 6 ft of concrete or its equivalent, and all operations inside the cell block

are observed from the operating gallery through four windows filled with zinc bromide solution and with closed-circuit television. The walls and floor of the deepest part of the cell block where casks are unloaded and decontaminated are lined with stainless steel. All other walls and floors inside the cell block are painted with an epoxy protective coating.

Ventilation equipment, consisting of fans, deep-bed roughing filters, polishing filters, and a 200-ft-high stack, is provided outside the building; and the surface and mine level radiation areas are maintained at a negative pressure with respect to operating areas and the remainder of the mine.

2.2 Mine-Level Hot Cell

The cylinders of waste are lowered from the cell block at the surface to the mine working level through a shaft, lined with 30-in.-ID steel casing, cemented in place so that water cannot enter either the shaft or the mine. A room (Fig. 5), shielded with 6 ft of concrete or the equivalent, is provided at the base of the shaft for transfer of the cylinders into a motorized transporter. The transporter is driven into the room and positioned under the waste shaft, and the lead cell doors are closed. A cylinder is then lowered into the transporter, the shaft hoist cable is disconnected, and both the carrier shield and shaft are closed. The transporter is then driven out of the cell into the mine.

The cell is about 28 ft by 30 ft by 15 ft high and is lined with stainless steel. A ZnBr_2 -filled window is provided for direct viewing from outside the cell, and tanks, a pump, and piping are provided for limited decontamination.

2.3 Underground Waste Transporter

The underground waste transporter is shown in Fig. 6. It consists of a standard two-wheel diesel tractor and a specially designed trailer and lead shield. The shield may be moved on the trailer such that the vertical center can be positioned anywhere within a 2-ft square, thus reducing the need for exact positioning of the trailer over the disposal

Fig. 5. Plan View of Underground Hot Cell.

hole or under the waste shaft. The shield may also be moved vertically so that it will be in contact with the floor when the waste can be lowered into the hole.

The transporter shown in Fig. 6 is one designed by W. F. Schaffer, Jr., for use in Project Salt Vault¹⁰ and does not contain all of the features envisioned in this study. Not shown is an off-gas pump and filter system which would keep the shield at a slight negative pressure to prevent the

Fig. 6. Underground Waste Transporter.

spread of contamination in the event of a leaky container. The shield would be longer and heavier than the one shown, probably necessitating the addition of two extra trailer wheels.

The machine for Project Salt Vault is capable of a 180° turn in a 25-ft-wide tunnel without having to back and can readily be positioned to within 1 ft. The addition of extra wheels will probably increase the turning radius, but by backing, it should still be capable of turning in a 25-ft-wide tunnel. The tractor will be capable of pulling the trailer at speeds in excess of 5 mph.

2.4 Mine Layout

The size of the underground area served by one set of mining and waste handling shafts should be determined by an economic balance between

the capital investment amortized over the operating life of the mine and the operating costs, which are a function of haulage distance. Since many of these costs are themselves functions of other parameters, such as waste type and age at burial, it was decided to use a fixed size for the mine in this study. A 1-sq-mile area was chosen as a reasonable size, since this gives a maximum haulage distance of 1 mile, which is about the maximum in several existing salt mines.

One quadrant of the 1-sq-mile disposal area is shown in Fig. 7. This pattern was established on the basis that: (1) the operation will be conducted so that the salt mining is completely isolated from the disposal operations, (2) the ventilating air shall never pass a filled disposal room before it reaches the current disposal area, and (3) the mine will

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Fig. 7. One Quadrant of 1-sq-mile Mine.

remain structurally stable throughout the period of time that it is being filled.

In order to meet the first two criteria, it is necessary to mine a double tunnel completely around the quadrant and excavate the entire first row of rooms before disposal operations start. The third criterion, mine stability, dictates the maximum width of the rooms, the minimum width of the supporting pillars between rooms, and the absence of rooms immediately around the shaft area. The length of the rooms has some bearing on the stability, but is more arbitrary than the other dimensions. This subject is discussed in more detail in Section 3.

The disposal procedure is to store the first wastes in the most remote room and then work back toward the shaft, one room at a time and one row of rooms at a time. Salt mining is carried out simultaneously in the next row toward the shaft. As each row of rooms is filled, the access tunnel for that row is sealed to prevent air circulation. As each quadrant is filled, the access tunnels for that quadrant are sealed.

2.5 Disposition of Wastes in Floor

A waste container is lowered from the surface hot cell into the underground transporter, which then moves out to the current disposal room. Once in the room, the trailer is positioned over a disposal hole, the fine positioning is done by moving the shield on the trailer, and the shield is lowered to the floor. The doors on the bottom of the shield are opened, and the container is lowered into the hole by the transporter hoist. Before the transporter is moved, the hole is backfilled with crushed salt from a hopper mounted either on the waste transporter or on a separate motorized vehicle.

Figure 8 shows the cross section of a hole and 6-in.-diam container after backfilling with salt. The holes are assumed to be 4 in. larger in diameter than the waste containers. Not shown in the sketch is a tapered section which might be necessary in the top part of the hole, to guide the container. The top of the waste container is assumed to be about 7-1/2 ft below the floor surface to provide radiation shielding. Seven and one-half feet of crushed salt would have shielding properties about

Fig. 8. Cross Section of Hole and 6-in.-diam Cylinder.

equal to that of 5 ft of solid concrete. Thus it is not necessary to limit access to the room except, possibly, during the waste transfer operation.

A typical pattern of cylinders in the floor is shown in Fig. 9. Optimum use of space, from the standpoint of heat transfer, dictates the staggered rows, with each container spaced equidistant from all adjacent

Fig. 9. Typical Pattern for Disposal of Cylinders in Floor.

containers. The room height of 15 ft is dictated by requirements for clearance on the waste transporter and shield.

2.6 Salt Handling Procedure

Development of the initial shaft bottom is done through an 8-ft-ID shaft equipped with a 3-1/2-ton-capacity skip. (This shaft will be used for ventilation and emergency exit during disposal operations.) The second shaft (16 ft in diameter) is then sunk, peripheral tunnels are excavated in two directions such that they meet at the extreme corner of the mine, and the first row of rooms are excavated. During this initial development, which is assumed to take about two years, 9.8×10^5 tons of salt is hoisted to the surface.

Excavation of the second row of rooms begins at the time the waste-disposal operation starts. After initial development, approximately 50% of the salt is used to backfill the waste-filled rooms and corridors; the remainder is hoisted topside for sale or other disposition.

The procedure will be: drill with Jumbo rigs, undercut with Goodman short-wall undercutter, load powder using a Wagnermobile with "cherry-picker" attached, load salt onto vehicles with Joy loaders, haul to grizzly and crusher with diesel shuttle cars, haul half of the salt from crusher to shaft bottom with Westinghouse-LeTourneau rear-dump trucks and the other half of the salt through an airlock into the waste-disposal tunnel to the room to be backfilled. The vehicles used to haul salt into the waste tunnels will be diesel-electric shuttle cars. Salt will be delivered to a stowing machine which backfills the room.

2.7 Ventilation System

The ventilation air is forced down an air compartment in the 16-ft shaft by fans located at the surface. At the mine level, the air is split into two streams: one for mining ventilation and one for ventilation of the waste handling and disposal areas (Figs. 10 and 11). To keep the air streams separated, curtain walls are installed in crosscuts and in the area around the shafts. About 100,000 cfm of air for mining ventilation circulates around the quadrant in the inner tunnel and exhausts via the skip compartments in the 16-ft shaft. As much as 25,000 cfm of air for diesel exhaust ventilation in disposal areas passes through ducts into the center, or disposal, tunnel and normally exits through the 8-ft shaft. An exhaust fan is installed at the surface to assist air flow up this shaft and to maintain a negative pressure in the waste tunnel relative to the mining tunnel.

To prevent the escape of activity up the 8-ft shaft, an air monitor will be installed at the exit-air end of the current waste disposal corridor such that contaminated air would have at least 1/2 mile to travel before reaching the shaft bottom. This monitor is set to cut off the 8-ft shaft fan, close the duct from the waste air tunnel near the shaft bottom,

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Fig. 10. Shaft-Bottom Area Showing Operating and Ventilating Patterns for Disposal in Southeast Quadrant.

ORNL-DWG 64-3906R1

Fig. 11. Shaft-Bottom Area Showing Operating and Ventilating Patterns for Disposal in Southwest Quadrant.

open a duct to the waste-shaft bottom hot cell, and start a 25,000-cfm blower in the topside hot cell (if it is not already running). Under these circumstances, all diesel drivers will receive automatic warnings to shut off engines. Normal waste tunnel ventilation will be based on diesel requirements and will not ordinarily be filtered, but, when routed through the waste shaft and hot cells, the air will be filtered and released through a stack.

3. MINE SPACE REQUIREMENTS

In this chapter, the operating life of the 1-sq-mile mine is estimated for disposal of the wastes described in the Introduction. This is done by first calculating the net and then the gross mine area required annually, based on conservative considerations of mine stability under the prevailing conditions.

3.1 Net Storage Area Requirements

In order to make the most efficient use of mine space, it is desirable to allow the salt temperature to rise as high as practical, and based on considerations of salt stability, 200°C is taken as a conservative limit for the temperature at the wall of the container hole. In most bedded deposits, salt contains numerous small inclusions of water (up to about 1% by volume) which are released with some violence at temperatures above 250°C. Although the release of this water and the simultaneous shattering of the salt does not appear to have any detrimental effects on the disposal operation, it is clearly preferable to maintain temperature below the range where the phenomenon occurs until more experience has been gained. Furthermore, the plastic flow of salt is accelerated by thermal stresses and elevated temperatures in the pillars and roof of the mine,¹⁵ and the 200°C maximum allowable salt wall temperature appears to be a good, although somewhat conservative, limit from this standpoint.

A conservative approach to calculating the required spacing between waste containers is to assume that the entire mine (including the area

taken up by supporting pillars, corridors, etc.) is filled at once with containers. If the containers are equally spaced on triangular centers in the floor, each package will be in the middle of a hexagonal area (Fig. 9). If there is a large number of containers, all containing identical heat sources and all placed in the mine simultaneously (an infinite array), it may be assumed that no heat flows across the vertical boundaries of the hexagonal area. (As will be shown presently, for the case used in this study, this results in a calculated temperature rise which is conservative by a factor of about 1.7.) For cylindrical heat sources, if the hexagonal boundary is approximated by a circle, the problem reduces to that of a single finite-length cylindrical heat source in the center of an infinitely long cylinder whose sides are perfectly insulated. It has been shown in field tests¹⁶ that an insignificant error is introduced by assuming the heat source to be a line in the center of the cylinder. An equation to fit the above assumptions was derived for a decaying heat source (Fig. 12), and a code was written to allow computation on the IBM 7090 computer.

In the equation of Fig. 12, "a" is the radius of the infinite-length right circular salt cylinder which is approximating the right hexagonal prism. Thus, to a first approximation, 2a is the center-to-center spacing between waste cylinders. (Actually, for the area to be equal to that of the hexagon, the spacing between cans would be 1.9a.) The temperature rise was calculated for a number of different values of "a" using the thermal conductivity and diffusivity of salt at 300°C (a conservative assumption, although other calculations have indicated that the peak temperature rise is not a strong function of the thermal properties chosen). Taking 200°C as the maximum allowable salt temperature and 20°C as the ambient in the mine, the value of "a" was then determined for each waste type and cylinder diameter as a function of age (Fig. 13). It may be noticed that for most waste types and cylinder diameters there is a minimum burial age representing the earliest time those wastes can be

¹⁶R. E. Blanco and E. G. Struxness, Eds., Waste Treatment and Disposal Progress Report for June and July 1962, ORNL-TM-396, pp. 43-45 (Dec. 19, 1962).

$$\begin{aligned}
V = & \sum_{i=1}^m \frac{Q_i}{\pi \rho c a^2} e^{-\lambda_i t} \left\{ \frac{1}{\lambda_i} \left[e^{\lambda_i t} \operatorname{erf} \frac{b}{\sqrt{4\kappa t}} - 1 + e^{(\lambda_i t - b^2/4\kappa t)} \operatorname{Rw} \left(\sqrt{\lambda_i t} + \frac{jb}{\sqrt{4\kappa t}} \right) \right] \right. \\
& + \sum_{n=1}^{\infty} \frac{J_0(\alpha_n r)}{(\lambda_i - \kappa \alpha_n^2) J_0^2(\alpha_n a)} \left[e^{(\lambda_i - \kappa \alpha_n^2)t} \operatorname{erf} \frac{b}{\sqrt{4\kappa t}} - 1 + \cosh \left(b \sqrt{\frac{|\lambda_i - \kappa \alpha_n^2|}{\kappa}} \right) \right. \\
& \left. \left. + \frac{1}{2} e^{-b \sqrt{|\lambda_i - \kappa \alpha_n^2|/\kappa}} \operatorname{erf} \left(\sqrt{|\lambda_i - \kappa \alpha_n^2|} t - \frac{b}{\sqrt{4\kappa t}} \right) - \frac{1}{2} e^{b \sqrt{|\lambda_i - \kappa \alpha_n^2|/\kappa}} \operatorname{erf} \left(\sqrt{|\lambda_i - \kappa \alpha_n^2|} t + \frac{b}{\sqrt{4\kappa t}} \right) \right] \right\}
\end{aligned}$$

WHERE

V = TEMPERATURE RISE IN INFINITE CYLINDER AT A RADIAL DISTANCE, r , FROM THE CENTER OF THE CONTINUOUS LINE SOURCE, °F

Q_i = HEAT GENERATION OF i th NUCLIDE AT TIME OF BURIAL OF WASTE, Btu/hr-ft

ρc = VOLUME HEAT CAPACITY OF MEDIUM, Btu/ft³·°F

a = RADIUS OF INFINITE CYLINDER, ft

λ_i = DECAY CONSTANT OF i th NUCLIDE, hr⁻¹

t = TIME AFTER BURIAL OF WASTE, hr

$2b$ = LENGTH OF LINE SOURCE, ft

κ = THERMAL DIFFUSIVITY OF MEDIUM, ft²/hr

$\operatorname{Rw}(\)$ = REAL PART OF COMPLEX ERROR FUNCTION $w(z)$, DIMENSIONLESS

$j = \sqrt{-1}$

α_n = POSITIVE ROOTS OF $J_1(\alpha a)$, EXCLUDING $\alpha_n = 0$

r = RADIAL DISTANCE FROM CENTER OF INFINITE CYLINDER, ft

Fig. 12. Equation for Temperature Rise in Infinite Cylinder Due to Finite Line Source.

buried without the salt subsequently exceeding 200°C. For example, a 24-in.-diam cylinder of acid Purex waste cannot be buried until it is about 30-1/3 years old, and the spacing between cylinders must be more than 50 ft. On the other hand, a 6-in.-diam cylinder of reacidified Thorex waste can be buried at any time (0.33 year is assumed as the age of the waste at the time of its production in the processing plant), with the spacing being as low as about 3 ft at 30 years of age.

Fig. 13. "a" as Function of Waste Age for 180°C Peak Temperature Rise.

With these values of "a," the area per cylinder is calculated and then converted into net mine space requirements in terms of acres per year.

An additional calculation is required to obtain the temperature rise at the center of the waste cylinder for each condition, and this calculation is done in a conventional manner by assuming that there is an air gap between the waste container and the wall of the salt hole which is one-third larger in diameter than the waste container. Radiative, convective, and conductive heat transfer mechanisms were all taken into account. (Subsequent tests have shown that the temperature differential between the container and the salt wall is lower when the hole is back-filled with crushed salt than when the air gap exists; so these calculations

tions are conservative.) In all cases, the limiting temperature was found to be the 200°C salt wall rather than the 900°C temperature at the center line of the waste container.

3.2 Criteria for Determination of Gross Mine Area

After the net mine space requirements are determined, several considerations are involved in determining the gross mine area. Most of these have to do with the overall stability of the mine, either directly or indirectly. Referring to Fig. 7 in Section 2.4, it is obvious that the peripheral tunnels, the shaft area, etc., also are involved in the gross mine area, and thus in the determination of the life of the mine. For example, in the row of rooms closest to the shaft area, the first room should be about 300 ft down the cross tunnel from the central tunnel (shaft pillar) area. In the other rows of rooms there should be at least 100 ft of salt between the tunnel and the first room in order to serve as a heat and overburden load barrier for the central tunnel area.

Laboratory studies have shown that in salt mines, support pillars should have widths at least twice their height in order to assure that there cannot be sudden catastrophic failure, even under shock loading.¹⁷ Since the room height is 15 ft, this means that the minimum pillar width should be 30 ft. In bedded salt a good rule of thumb for maximum room width is about 50 ft, and it should probably be less than this if there is not at least a minimum of 3 ft of good quality salt in the roof before reaching the first shale layer. The wider the rooms and the narrower the pillars (the higher the extraction ratio), the longer will be the life of the mine. Thus it is desirable to use an extraction ratio as high as possible consistent with the desired operating stability in the mine.

For the purposes of this study, a mine depth of 1000 ft is assumed, and an extraction ratio of 50% is believed to be appropriately conservative.

¹⁷L. Obert, U.S. Bureau of Mines, personal communication, September 1963. (Referenced in internal memorandum to F. L. Parker from R. L. Bradshaw and W. J. Boegly, Jr., Oct. 28, 1963).

Assuming we wish to use 50-ft-wide rooms, a 50% extraction ratio calls for 50-ft-wide pillars with stresses in the pillars limited to a conservative 2000 psi. Under these conditions, little trouble would be expected at ambient temperature from pillar spalls or ceiling layer sags. Figure 7 is based on 50% extraction, and the entire mine has a net space of 8.26×10^6 sq ft (552 rooms, 50 by 300 ft in cross section, each). Consequently, the net mine area for this configuration is 29.7% of the gross (1-sq-mile) area.

3.3 Specific Case of 50% Salt Extraction

With 50% salt extraction, it is obvious that the situation assumed in the temperature rise calculations of Section 3.1 (waste covering the entire mine area) is quite different than the actual case, and in many instances the calculated temperature rises would be expected to be higher than the actual temperature rises by perhaps as much as a factor of 2. Consequently, an additional set of calculations was performed for a 10-year-old waste. (Cesium-137 and ^{90}Sr are the only significant heat-producing nuclides remaining at this time, and they have an effective half-life of about 30 years.) In these calculations, the waste is assumed to be in the rooms only and is buried in the mine a room at a time as in an actual sequence of operations. The calculations are limited to the one case of the 30-year half-life waste in a 6-in.-diam acid Purex pot. For the waste of concern in this series of reports, any waste 10 years old or older may be assumed to have a 30-year half-life, and thus these calculations will apply. The results indicate that the peak temperature rise at the wall of the 6-in.-diam pot is only 106°C rather than 180°C when spacing between waste containers determined by the infinite array calculation is used. Thus, the net storage area requirements as indicated by the infinite array calculations are conservative by a factor of about 1.7. Nevertheless, the infinite array calculations are used for the determination of net and gross mine space. It should be noted that the 1.7 factor could be expected to be different if the salt extraction ratio is other than 50% (Appendix B).

For the 30-year half-life wastes, the time to reach the peak temperature at the wall of the pot was found to be of the order of two to three decades (Fig. F-2), but for wastes whose age at burial was less than about 3 years, the time to reach the peak temperature generally ranged from only a few hundred to a few thousand hours. Since heat fronts move very slowly through salt, the peak temperatures in very young wastes are not greatly affected by wastes buried more than a few feet distant, and the temperatures calculated with the infinite array code would be about correct. For wastes between 3 and 10 years of age the situation is indeterminate, and for wastes older than 10 years the array calculation is definitely conservative, as indicated above.

For the wastes which are less than about 3 years old, limiting the spacing between containers so that the maximum salt temperature does not exceed about 200°C at the wall of the hole will result in lower temperatures in the pillars than would be the case with the older wastes (because the total integrated heat input to the room will be less). Thus, from the standpoint of the overall stability of the mine, the infinite array calculation would be conservative for these wastes also. There is also reason to believe that for these short-cooled wastes it may be permissible to allow the temperature at the wall of the salt hole to go considerably higher than 200°C. Tests in Project Salt Vault have indicated that the small quantity of water which is normally present in the salt migrates slowly into the hole without causing any apparent trouble. In an actual disposal operation, where the hole is backfilled with crushed salt, the presence of the crushed salt would prevent any violent release of the water, as the temperatures exceeded 250 to 300°C and the salt shattered. Since this temperature front would move out rather slowly and would not extend very far from the waste container, the effect of water release might not be significantly different from that which takes place more slowly at temperatures below 200°C. The infinite array calculation was found to be about a factor of 1.7 conservative for wastes aged 10 years or more, and if this same factor is applied to the very young wastes a peak salt temperature near 330°C, a not unreasonable value, would be expected. We believe, therefore, that the infinite array calculation is about equally conservative (a factor of about 1.7) for wastes of any age at burial.

3.4 Life of Mine for 50% Extraction

Based on 50% extraction and the mine design as discussed previously, the life of the mine has been calculated for various waste types, pot sizes, and waste combinations. Figure 14 shows the results for disposing of the Purex and Thorex wastes independently. (The abbreviations on the curves refer to waste type and pot diameter; see labels in Fig. 13.) Remembering that Thorex wastes come from the processing of 270 tonnes/year of 20,000 Mwd/tonne burnup (5.4×10^6 Mwd total exposure) and the Purex represents the processing of 1500 tonnes/year of 10,000 Mwd/tonne (15×10^6 Mwd total exposure), one would expect the life of the mine to be about three times as long for a facility handling only the Thorex as it would be for one handling only the Purex waste. That this is so may

Fig. 14. Life of Mine as Function of Age at Burial for Various Waste Types and Vessel Diameters.

be seen in Fig. 14. (A mine life of more than 100 years is probably unrealistic, but calculations will be carried through for illustrative purposes.) It may also be seen that a space premium must be paid for handling certain waste types in certain size containers before some minimum age, and that, in fact, some waste types in some size containers cannot be placed in the mine before a certain minimum age without exceeding the 180°C temperature rise limit on the salt. For example, acid Thorex in 24-in.-diam cylinders always requires a mine space premium (that is, shortened life of the mine) and cannot be buried before an age of 4 years. On the other hand, reacidified Thorex in 6-in.-diam pots can be placed in the mine immediately after fuel processing (0.33 year) and always requires the minimum space.

More important for this study is the life of the mine for a facility which handles different possible combinations of Purex and Thorex wastes simultaneously (Fig. 15). Generally speaking, the minimum ages at burial in this figure are governed by the Purex waste, since its volumetric heat generation rate is greater. (Actually, the Thorex could be buried at ages as indicated on the previous figure, but for the purposes of this study the same minimum age has been assumed to apply for both.) The

Fig. 15. Life of Mine as Function of Age at Burial for Various Combinations of Waste Types and Vessel Diameters.

earliest age at burial is about 1 year, and the life of the mine for wastes this young is only about 12-1/2 years. For certain combinations of waste types and pot diameters, the life of the mine may exceed 70 years for wastes which are 30 years old at the time of burial. It is obvious that it is advantageous to store the wastes for at least a few years before burial in salt. For example, while the mine only lasts 12-1/2 years for wastes 1 year old, the life would be extended to about 40 years if the waste is 3-1/2 years old at burial.

In the calculations which follow in later sections, many costs will be related to the life of the mine. It will be shown how Fig. 15 may then be used to determine disposal costs for the various waste types, combinations, and ages at burial.

4. SALT HANDLING COSTS

4.1 Quantities of Salt to Be Handled

There will be 552 rooms per mine, each 50 ft wide $\times$ 300 ft long $\times$ 15 ft high. The center area around the shafts, two tunnels around the periphery of one quadrant, and one row of rooms (25 rooms in first row) must be excavated initially in order to meet the ventilation criteria. The total volume of initial excavation amounts to 14.78×10^6 ft³ of salt, or 9.8×10^5 tons. The cost of this initial excavation is amortized over the life of the first quadrant of the mine at 4% interest.

The second and third quadrant of the mine will each have one less peripheral tunnel to excavate and no center area to excavate. The final quadrant (which will be prepared while the third one is being filled) will have two less peripheral tunnels to excavate. However, for simplicity it has been assumed that the remaining tunnel development is spread over the entire life of the mine.

The volume of salt involved in excavating the remaining rooms and waste tunnels in the first quadrant is 31.58×10^6 ft³, or 21.0×10^5 tons. As the first quadrant is being mined, it will be necessary to develop the peripheral tunnels around the next quadrant so that as the last

row of rooms in the first quadrant is being filled, the first row of rooms in the second quadrant can be mined. This mining will be assumed to be a part of the annual mining. The entire operation requires about 1.18×10^7 tons of salt to be mined, of which about 0.10×10^7 is required by the initial development. This leaves 1.08×10^7 tons to be mined during the waste disposal operations. This excavation and cost accrual will be done simultaneously with waste storage.

The quantity of salt mined as a function of the life of the mine is as shown in Table 2 and in Fig. 16.

Table 2. Quantity of Salt Mined as a Function of Life of Mine

Life of Mine (years)	Quantity of Salt Mined	
	tons/yr	tons/day ^a
10	10.80×10^5	4320
20	5.40	2160
40	2.70	1080
80	1.35	540
160	0.675	270
320	0.338	135

^aTwo hundred fifty days per year operation.

If the rooms are backfilled with salt as they are filled with waste and the corridors are also backfilled as rows of rooms are completed, only about 50% of the salt excavated will have to be disposed of (void space in crushed salt is approximately 40%). Thus the quantity of salt to be delivered to the topside facility is assumed to be one-half of the quantity mined.

Fig. 16. Quantity of Salt Mined as Function of Life of Mine.

4.2 Cost of Initial Mining of Peripheral Tunnels and Rooms

The mining operations which have been assumed for this study are based on relatively minor modifications of conventional salt mining practice. The model used was the mine of the Canadian Rock Salt Company at Ojibway, Canada.¹⁸ This mine started operation in 1955, is located at a depth of about 1000 ft, and is designed for production of 500 tons/hr. Where data for this mine were not applicable, data for the Carey Salt

¹⁸C. Mamen, "Rock Salt Mining at Ojibway," Can. Mining J., 37-43 (January 1956).

Company's new 300-ton/hr mine at Cote Blanche, La., were used. The initial mining costs are estimated to be \$1,595,000 and are incurred over a two-year period (Table 3).

Table 3. Total Cost of Initial Mining
Peripheral tunnels and first row of rooms

Item	Cost (\$)
	$\times 10^3$
Explosives at \$0.10/ton of salt	98
Diesel fuel at \$0.15/gal	32
Electric power at \$0.01/kwhr	54
Interest charges on shaft, hoist, etc., at 4%/year	216
Amortization of mining machinery	221
Direct wages and salaries	388
Overhead and contingencies (100% of wages and salaries)	388
Maintenance supplies and misc. (15%/year of original cost of mining machinery)	198
	\$1,595,000
	\$1.63 per ton of salt

Starting at the shaft bottom and working four tunnels toward the extreme corner of the mine gives four working faces (plus crosscut faces every 200 to 300 ft). At 10 ft of advance per shot, in a 15 × 25 ft tunnel this is 250 tons/shot per face, or 1000 tons/shift. Two hundred and sixty days (or shifts) of operation will take the tunnels to the point that rooms may be developed. The shaft facility will handle 300 tons/hr, and thus three rooms may be excavated simultaneously (500 tons/shot per room) if hoisting is 9 hr/shift. Three rooms will be completed in 30 days, and thus 25 rooms will require about 270 days (or shifts). The entire operation will require about 530 shifts, which is reasonable to accomplish in a two-year period.

The first year of mining will require a maximum round-trip haulage distance of 1 mile, handling about 1100 tons/day on a 250-day/year basis. The second year of mining will require a maximum haulage distance of 2 miles round trip, handling about 2800 tons/day on a 250-day basis.

Personnel Requirements

Personnel requirements will be higher the second year (34) than the first year (24). Some night work will be required the first year due to the limited number of working faces. The total direct wages and salaries will be \$165,000 the first year and \$223,000 the second year. The total direct wages and salaries for the peripheral development are thus \$388,000.

Explosives

Figured at \$0.10/ton of salt, based on the Ojibway mine experience, or for the peripheral development, \$98,000.

Diesel Fuel

Diesel fuel at \$0.15/gal for the trucks transporting the salt amounts to \$32,000.

Electric Power

Power (at \$0.01/kwhr) for the main hoist (800 hp), ventilation fans (100 hp), and mining machinery amounts to \$54,000 over the two-year period.

Interest Charges on Shaft, Hoist, Etc.

The installed cost of two shafts, hoists, headframes, power distribution system, ventilation, skip loader, repair shop, and handling and storage facilities topside is \$2,703,000 (see next section). These items generally have a life of 20 years or more, so only an interest rate of 4% is charged against peripheral development. Four percent interest for two years equals \$216,000.

Equipment Costs

The mining equipment, whose life has been rated in terms of so many tons of salt handled, is amortized at 4% over a period determined by dividing the aggregate life by 4.9×10^5 tons/year for items needed both years and by 2.8×10^5 or 7.0×10^5 otherwise.

<u>Item</u>	<u>First Year</u>		<u>Second Year</u>	
	<u>Number Required</u>	<u>Cost</u>	<u>Number Required</u>	<u>Cost</u>
Jumbo drill rings	2	\$16,000	2	\$ 16,000
Joy loaders	2	10,800	2	10,800
Forklift cherrypicker	1	4,500	2	11,000
Undercutter	2	7,700	2	7,700
Westinghouse-LeTourneau truck	3	33,700	8	90,000
Grizzley and crusher	1	6,400	1	6,400
		<u>\$79,100</u>		<u>\$141,900</u>

Total equipment costs = \$221,000

Maintenance Supplies and Miscellaneous

Yearly maintenance supplies were estimated at 15% of the original cost of the mining equipment: first year cost = $625,000 \times 0.15 = \$78,900$, second year cost = $796,000 \times 0.15 = \$119,500$, and two-year maintenance supplies and miscellaneous costs = \$198,000.

Overhead and Contingencies

Overhead and contingencies were figured at 100% of direct wages and salaries, or \$388,000.

Total Cost of Initial Mining

The total cost of the initial mining (assumed to take place over a two-year period) is as shown in Table 3. Amortizing these costs over the life of the mine at 4% interest results in costs as shown in Table 4.

Table 4. Cost of Initial Mining as Function of Life of Mine

\$1,595,000 initial mining cost

Life of Mine (years)	\$/year at 4%	Mill/kwhr (electrical)
		$\times 10^{-3}$
10	197,000	1.49
20	117,000	0.89
40	81,000	0.61
80	67,000	0.51
160	64,000	0.48
320	64,000	0.48

4.3 Salt Mining Costs During Operation of Waste Disposal Facility

Mining Shaft Requirements and Costs

The sizes of the mining and access shafts are governed by the ventilation requirements, the volume of salt which must be handled, and the size of the largest piece of equipment which must be lowered into the mine. To complete the initial mining requirements within two years, the facilities must be capable of handling about 5×10^5 tons of salt per year, or 250 tons/hr. A 16-ft-diam shaft and an 8-ft-diam shaft are specified for this mine, based on facilities currently in use at two salt mines of roughly comparable size. The Ojibway mine in Canada has a 16-ft main shaft, and a "men and materials" shaft of unspecified size to serve a production of 500 tons of salt per hour. The Carey Salt Company's 300-ton/hr Cote Blanche mine in Louisiana has a 14-ft-diam production shaft and a shaft 7 ft 8 in. in diameter serving both for "men and materials" and 76,000 cfm ventilation.

Shaft costs and shaft equipment costs (below) are estimated from information obtained in personal communications from salt mine officials and from experience gained in the course of Project Salt Vault.⁹

16-ft shaft (\$1150/ft, plus collar and foundations) grouted, complete	\$1,300,000
8-ft shaft (\$700/ft, plus collar and foundations) grouted, complete	783,000
Total initial cost	<u>\$2,083,000</u>

The total initial shaft cost is charged off over the life of the mine, up to a maximum life of 100 years, at 4% interest (Table 5).

Shaft Equipment Requirements and Costs

The costs of headframes, hoist, skips, etc., sized to handle about 2000 tons/day (250 tons/hr), are estimated as follows:

16-ft shaft hoist, headframe, skips, controls, etc.	\$211,000
8-ft shaft hoist, headframe, skips, controls, etc.	<u>109,000</u>
Total initial cost	\$320,000

Shaft equipment costs are amortized over the life of the mine, up to a maximum life of 20 years (Table 5).

Other 20-year-life Equipment Requirements and Costs

Other items assumed to be governed by the 2000-ton/day (8-hr day, 250-day year) requirements are: power cables and electrical distribution system, ventilation, skip loader, handling and storage equipment top-side, and repair shop. These are amortized over the life of the mine, up to a 20-year maximum life (Table 5).

Power cables and electrical distribution	\$ 50,000
Ventilation	25,000
Skip loader	50,000
Repair shop	25,000
Topside handling and storage	<u>150,000</u>
Total initial cost	\$300,000

Personnel Requirements and Costs

Table 6 gives the direct wage and salary costs for the mining personnel; waste handling personnel are not included.

Table 5. Total Yearly Mining Costs (\$/year) as Function of Life of Mine^a

Item	Life of Mine (years)					
	10	20	40	80	160	320
Mining shafts	257×10^3	153×10^3	105×10^3	87×10^3	85×10^3	85×10^3
Shaft equipment	40	24	24	24	24	24
20-year life items	37	22	22	22	22	22
Mining equipment	304	194	94	57	49	44
Wages and salaries	367	247	157	112	89	86
Explosives	108	54	27	14	7	3
Diesel fuel	32	16	8	4	2	1
Electric power	39	20	10	5	2	1
Maintenance, supplies and miscellaneous	304	194	94	57	49	44
Overhead	367	247	157	112	89	86
Total	\$1,855,000	\$1,171,000	\$698,000	\$494,000	\$418,000	\$396,000
\$/ton:	1.72	2.17	2.59	3.66	6.20	11.70
10^{-3} mill/kwhr (electrical)	14.00	8.87	5.29	3.74	3.16	2.99

^aExclusive of initial mining of peripheral tunnels and rooms.

Table 6. Personnel Costs as Function of Life of Mine

Life of Mine (years)	Mining Personnel	Cost	
		\$/yr	\$/ton
10	58	367,000	0.34
20	38	247,000	0.46
40	23	157,000	0.58
80	16 1/2	112,000	0.83
160	13	89,000	1.32
320	12 1/2	86,000	2.54

Other Underground Mining Equipment Requirements and Costs

All underground mining equipment is assumed to fall into two categories, based on hours of life at rated capacity, and is amortized over the period of time represented by the capacity-hour rating up to a maximum of 40 years for 20,000-hr equipment and 20 years for 10,000-hr equipment (Table 7). Twenty-thousand-hour equipment accounts for less than 10% of the yearly costs shown in Table 7, and it may be noted that the initial capital cost for mining machinery varies with the size of the operation (life of the mine).

Table 7. Costs of 10,000- and 20,000-hr Mining Equipment as Function of Life of Mine

Life of Mine (years)	Initial Cost (\$)	Yearly Cost (\$)	Cost (\$/ton Salt)
10	1,639,000	304,000	0.28
20	1,171,000	194,000	0.36
40	673,000	94,000	0.35
80	513,000	56,500	0.42
160	463,000	48,500	0.72
320	463,000	43,500	1.29

Explosive Costs

Costs were figured at \$0.10 per ton of salt (Table 5).

Diesel Fuel Costs

Costs were figured at \$0.15/gal (Table 5).

Electric Power Costs

All electric power consumption rates are assumed to be directly proportional to the tons of salt mined per year (\$0.036/ton). Power costs are based on a unit cost of 10 mills/kwhr (Table 5).

Maintenance Supplies and Miscellaneous Costs

Costs for maintenance supplies and miscellaneous items are estimated as equal to the yearly amortization costs of the 10,000-hr and 20,000-hr mining equipment (Table 5).

Overhead

Overhead is taken as 100% of direct wages and salaries (Table 5).

Total Yearly Mining Costs

Table 5 summarizes the yearly costs for all the items charged to salt mining. Costs are totaled in terms of dollars per year, dollars per ton of salt mined, and mills per kilowatt-hour (electrical). Not included in this table is the cost of the initial mining of peripheral tunnels and rooms (Table 4).

5. WASTE HANDLING COSTS

The costs included in this chapter pertain to the surface and mine-level facilities and equipment, the waste shaft, and the operating costs incurred in receiving, handling, and final burial of the radioactive waste containers.

5.1 Topside Facility

The surface waste handling facilities were described in Section 2.1; therefore, only the assumptions used to arrive at the costs are covered here. The yearly costs for all the items charged to the surface waste handling facility are summarized in Table 8. Costs are totaled in terms of dollars per year and mills per kilowatt-hour (electrical). The total capital cost of this facility is \$1,648,000.

Table 8. Annual Costs (\$/year) for Surface Waste Handling Facilities as Functions of Life of Mine

Item	Life of Mine (years)					
	10	20	40	80	160	320
Surface construction	99,300	59,200	40,700	40,700	40,700	40,700
Equipment	70,500	42,100	42,100	42,100	42,100	42,100
Instrumentation	11,800	11,800	11,800	11,800	11,800	11,800
Site preparation	21,600	12,900	8,800	7,300	7,100	7,100
Total	203,000	126,000	103,400	101,900	101,700	101,700
10 ⁻³ mill/kwhr (electrical)	1.53	0.95	0.78	0.77	0.77	0.77

Surface Construction

Items included under surface construction are assumed to have a normal amortization period of 40 years and thus were amortized over the life of the mine, or 40 years maximum. The initial costs, shown below, totaled \$460,000, to which is added 75% for engineering, construction overhead, and contingencies, bringing the total installed cost of the surface construction to \$805,000.

Building. - Building costs consist of 40,000 ft³ of office space, etc., at \$2/ft³, and 21,600 ft³ of operating area at \$4/ft³, for a total of \$166,000.

Cell Block. - Cell block costs include \$10,000 for excavation and backfill at \$2.50/yd³, \$101,000 for concrete at \$100/yd³, \$80,000 for four ZnBr₂ windows, \$20,000 for stainless steel cell lining at \$20/ft², \$5,000 for epoxy lining at \$1.50/ft², and \$21,000 for lead doors at \$0.30/lb. Total for the cell block is \$237,000.

Stack. - A 200-ft-high steel-lined stack, 5 ft OD at the top, is estimated to cost \$57,000.

Equipment

Items included in this category are considered to have a normal life of 20 years, and thus were amortized over the life of the mine, or 20 years maximum. Again, the 75% for engineering, construction overhead, and contingencies was added to the base total of \$327,000, bringing the installed total to \$572,000. The individual items were: filters and fans, \$57,000; remote manipulator, \$55,000; 100-ton bridge crane, \$125,000; two 5-ton cranes, \$12,000; decontamination solution evaporator and tankage, \$43,000; dolly, \$10,000; remote welder, \$15,000; and 3-ton cable hoist for waste shaft, \$10,000.

Instrumentation

Radiation monitors, other Health Physics equipment, closed-circuit television, etc., are estimated at \$55,000 base, or \$96,000, including the 75% overhead. Normal life is assumed to be 10 years.

Site Preparation

Site preparation is estimated at \$175,000, including the overhead. Amortization is over the life of the mine, or 100 years maximum.

5.2 Waste Shaft

A 30-in.-diam steel-cased waste charging shaft extends from the topside hot cell to the underground hot cell. A shaft of this size can be sunk by conventional rotary drilling methods. The shaft installed for Project Salt Vault⁹ is 19.1 in. in finished diameter, and the installed cost was about \$65,000. Prior to bidding, estimates based on previous installations

ranged from \$74,000 to \$125,000. Using prices based on previous installations, the estimates for a 30-in. shaft range from \$110,000 to \$205,000. Since the Project Salt Vault shaft cost was lower than the lowest preliminary estimate (primarily due to the relative ease of drilling in the type of sedimentary rock usually associated with the flat-lying salt deposits), it seems reasonable to use the higher figure for the 30-in. shaft but to assume that this includes the engineering, overhead, and contingencies. Thus the capital cost of the installed waste charging shaft is \$205,000. This is amortized over the life of the mine, or 50 years maximum, at 4% interest. Annual costs as a function of the life of the mine are shown in Table 9.

Table 9. Waste Shaft Costs as Function of Life of Mine

Life of Mine (years)	Waste Charging Shaft Costs (\$/year)
10	25,300
20	15,100
40	10,400
80	9,600
160	9,600
320	9,600

5.3 Mine-Level Facilities

The costs charged to the mine-level waste-handling facilities include the hot cell and miscellaneous underground equipment discussed below. The total installed cost is \$834,000; annual costs are shown in Table 10.

Hot Cell

The mine-level hot cell was described in Section 2.2. The total base cost of the hot cell is estimated at \$327,000, to which is added 75% for the engineering, overhead, and contingencies, bringing the installed cost to \$572,000. Included in the costs were: \$48,000 for concrete at \$100/yd³; \$20,000 for the ZnBr₂ viewing window; \$82,000 for stainless steel lining at \$20/ft²; \$10,000 for decontamination equipment and drainage;

Table 10. Capital Costs (\$/year) for Mine-Level Facilities
as Function of Life of Mine

Life of Mine (years)	Mine-Level Hot Cell	Miscellaneous Mine-Level Equipment	Total
10	70,500	32,400	102,900
20	42,100	32,400	74,500
40	28,900	32,400	61,300
80	23,900	32,400	56,300
160	23,300	32,400	55,700
320	23,300	32,400	55,700

\$50,000 for shaft seals, interlocks, and miscellaneous; and \$117,000 for two lead doors at \$0.30/lb. Annual costs as a function of the life of the mine are shown in Table 10.

Miscellaneous Mine-Level Equipment

A dump truck is needed for such jobs as hauling fine salt for backfilling disposal holes and for transporting equipment. A Jeep is needed for personnel. A high-lift dozer is required for moving salt and scraping roadways. Maintenance and repair facilities and safety equipment will also be required. A loading hopper is needed to handle fine salt used in hole plugging. Electrical, communications, and other miscellaneous facilities will also be required.

With the fine salt backfill in the holes and rooms backfilled with crushed salt, airtight room seals are probably not necessary; however, plastic curtains are used to minimize air circulation until the rooms are entirely backfilled with salt. Corridors will also be sealed with plastic after all the rooms are filled. The cost for such seals should be negligible.

It is assumed that there are alarm-type beta-gamma air monitors located at the bottom of the mine shaft, at the mining face, at the bottom of the waste shaft, at the current storage area, and at the air exit end of the current storage corridor. These instruments read out locally, at the bottom of the shaft, and at the head facility. The usual health physics survey meters are required.

The total cost, including the usual 75%, is \$262,000 and is amortized over 10 years (Table 10).

5.4 Costs Which Are Function of Pots per Year

Certain costs are not a direct function of the life of the mine but are a function of the number of waste pots handled per year. These costs are considered in detail below and summarized in Table 11 and Fig. 17.

Table 11. Costs Which Are a Function of Number of Pots per Year

Number of Pots per Year	Initial Capital Cost (\$)	Capital Cost (\$/year)	Number of Personnel	Wage and Salary Costs (\$/year)	Maintenance and Overhead Costs (\$/year)	Total Costs (\$/year)
<1000	300,000	37,000	10	75,000	75,000	187,000
1001	350,000	43,000	10	75,000	75,000	193,000
2000	350,000	79,000	10	75,000	75,000	229,000
2001	600,000	74,000	15	113,000	113,000	300,000
3000	600,000	100,000	15	113,000	113,000	326,000
3001	650,000	109,000	15	113,000	113,000	335,000
4000	650,000	146,000	15	113,000	113,000	372,000
4001	900,000	150,000	18	135,000	135,000	420,000
5000	900,000	172,000	18	135,000	135,000	442,000
5001	1,200,000	178,000	18	135,000	135,000	448,000
6000	1,200,000	200,000	18	135,000	135,000	470,000
6001	1,500,000	223,000	21	158,000	158,000	539,000
8000	1,500,000	286,000	21	158,000	158,000	602,000

Waste Transporters and Hole Drillers

The size of the pot calciner vessel and the age of the waste determine the weight of the underground transporter shield, and the pot diameter determines the capital and operating costs of the hole driller. However, these variables do not influence total costs in a significant manner; in the interest of simplicity, a shield thickness of 12 in. lead is used for all cases and both transporter and driller costs are taken as a function only of the number of pots handled annually.

It is assumed that one salt hole driller and one transporter can handle one pot per hour, or 2000 pots per year, assuming 250 working days per year. Additional machines are required for more than 2000 pots per year.

Fig. 17. Total Annual Costs for Items Which Are a Function of the Number of Vessels per Year.

Based on experience with the underground transporter built for Project Salt Vault, the transporter for handling calciner pots would cost about \$210,000, including a shield-tilting mechanism. The chief difference between the two would be the larger shield needed for the pots. The complete shield for Project Salt Vault has a 15-in. ID, an inside height of 9 ft, and weighs about 25 tons. The transporter for 24-in.-diam pots requires a shield of about 50 tons (30 in. ID and 11 ft inside height). Also, the pot transporter has an attached hopper holding sufficient salt to backfill the hole above the waste container (about 2 tons, or 50 ft³, of salt for a 2-ft-diam pot).

An additional item which will be needed is an air monitor and radio-iodine trap to detect leaky pots during underground transport to the burial room.

The \$210,000 figure includes design and construction overhead; so a figure of \$250,000 per unit should be sufficient to cover all costs, including contingencies.

Holes are bored to a depth of 8-1/2 ft to take 6-, 12-, or 24-in.-diam cans. In order to facilitate loading, hole diameters will be 10, 16, and 28 in.

The number of holes may range from about 2300 to 6400 if 6-in. cans are used, from 600 to 1600 for 12-in. cans, and from 150 to 400 for 24-in. cans. If some combination of pot diameters is used, the number of holes will lie within the above limits. A modified oil-well-type drill, using air as the drilling fluid and equipped with an air cleaning unit, is specified. The complete rig costs \$50,000.

The life of both the transporter and the hole driller is 10,000 operational hours (5 years at 8 hr/day, 250 days/year) or no more than 10 calendar years. For operations which require the use of the machines 1000 hr or less per year (≤ 1000 pots per year), no spare units are required. For operations requiring between 1000 and 2000 hr use per year, one spare transporter tractor and miscellaneous other spare parts for the transporter and hole driller are required, costing \$50,000. For operations requiring 2000 to 3000 hr use per year, two transporters and two hole drillers are required. For 3000 to 4000 hr use, two units plus the spare tractor are required; 4000 to 5000 hr use, three units, 5000 to 6000 hr use, four units, and 6000 to 8000 hr use, five units.

The initial capital costs and the annual costs as a function of the number of pots per year are shown in Table 11. Since the amortization period varies with the number of pots per year and the number of machines assumed (including spares), the yearly costs are not as discontinuous as the initial capital costs.

Operating Costs

The size of the pot should not significantly affect the operating costs; therefore it is assumed that only the number is important. The

maximum number of pots per year is for the case of disposing reacidified Purex and reacidified Thorex wastes (Table 1). In this instance, 6430 pots, or one every 19 min (8 hr/day, 250 day/yr), must be handled. One hoist operator and one operator at mine level should be able to handle this, but it is approaching the limit for single shift operation with only one waste charging shaft. One hole driller and one transporter can handle up to one pot per hour.

For up to 2000 pots per year, ten employees are required, as follows:

- Combination hoist and manipulator operator
- Combination unloading crane, manipulator, decontamination,
and remote welding operator
- Combination shaft bottom operator and underground supervisor
- Waste transporter operator
- Health Physicist
- Combination High-lift dozer operator, curtain hanger, and
assistant to transport operator
- Equipment maintenance man
- Hole borer operator
- General superintendent
- Secretary

For 2000 to 4000 pots per year, add one hole-driller operator, one transporter operator, one assistant transporter operator, one shaft bottom operator, and one topside operator, for a total of 15 employees. For 4000 to 6000 pots per year, an additional transporter operator and an assistant, a hole-driller operator, and an additional maintenance man are required, totaling 18 employees. For 6000 to 8000 pots per year, the employees will total 21. Salaries are assumed to average \$7500/man-year.

Overhead and maintenance of the waste handling facilities and equipment are assumed to equal 100% of the direct wages and salaries. The total of these operating costs as a function of the number of pots per year is shown in Table 11.

6. OTHER COSTS

6.1 Purchase of Land

According to a personal communication from salt company personnel, land with salt rights can be purchased for \$250 to \$350/acre in Kansas. If a 1.38-mile square (1.9 sq miles) of land is purchased for a 1-mile-square mine, a 1000-ft buffer zone will be left around the boundaries. The total surface area is 1215 acres.

Allowing a 1/3 premium over the \$350 estimate, or \$470/acre, the total land cost is \$570,000. These costs, on an annual basis, are given in Table 12.

Table 12. Land Costs as a Function of Life of Mine

	Life of Mine (years)					
	10	20	40	80	160	320
\$/year at 4%	70,000	42,000	28,800	23,800	23,000	23,000
10 ⁻³ mill/kwhr (electrical)	0.53	0.32	0.22	0.18	0.17	0.17

6.2 Deactivation of Mine

After the entire square mile of mine area served by one set of shafts is completely filled with waste, the shafts will be sealed and a minimum-surveillance program will be instituted. According to a personal communication on July 12, 1965, from Ball Associates, Ltd., Denver, Colorado (a company which has had experience in sealing shafts of this type), a few hundred bags of Bentonite clay and fill material available in most locations would provide an impervious seal. For this purpose, \$100,000, including engineering, overhead, and contingencies, is allocated.

Surveillance consists mainly in providing assurance that no contamination of the ground water occurs and that no drilling into the disposal area is permitted. It is assumed that \$10,000/year is sufficient to

provide for this minimum surveillance. Since this surveillance must be maintained for an extended period of time, a perpetual annuity fund of \$250,000 is established.

Thus, a fund of \$350,000 must be available at the time the mine is to be deactivated. It is assumed that a sinking fund is set up at 4% interest to accumulate this amount. The annual costs for providing this fund are shown in Table 13.

Table 13. Deactivation Costs as a Function of Life of Mine

Life of Mine (years)	Deactivation Cost	
	\$/year	mills/kwhr (electrical)
		$\times 10^{-3}$
10	29,200	0.22
20	11,800	0.09
40	3,700	0.03
80	630	0.00
160	0	0.00
320	0	0.00

7. TOTAL COST OF DISPOSING OF WASTES IN HOLES IN FLOOR OF 1000-FT-DEEP MINE

The costs which have been developed in the previous sections are summarized in this section and presented in various forms which have proved useful. The effects of certain variables on the total costs of a disposal operation are covered in some of the appendices.

7.1 Initial Capital Costs

Table 14 shows the total initial capital outlay which must be made before the facility can start waste disposal operations. Two of the items are shown to have a range of costs. The mining machinery costs depend on the rate at which salt must be mined during the disposal operation and

Table 14. Total Initial Capital Outlay Required to Start Operation at 6 tonnes/day

Item	Initial Capital Cost (\$)	Remarks
Initial mining (peripheral tunnels and row of rooms)	1,595,000	1-sq-mile mine
Mining shafts and auxiliary equipment	2,403,000	
Other top and bottom developments required for operation	300,000	
Mining machinery (range)	513,000 1,639,000	80-yr-life mine 10-yr-life mine
Topside facility	1,648,000	Includes hot cell, offices, stack, equipment, and site preparation
Waste shaft (30 in. ID)	205,000	
Mine-level facility	834,000	Hot cell and miscellaneous equipment
Transporters and hole drillers (range)	300,000 1,500,000	≤1000 pots/year 8000 pots/year
Land-purchase	570,000	1 sq mile with 1000-ft buffer - 1215 acres
Deactivation costs ^a	350,000	29,200 \$/year for 10 years, 630 \$/year for 80 years
Total initial capital	\$8,368,000 to \$10,694,000	

^aFor reference purposes only; not included in total.

thus are a function of the life of the mine. (For the development of the initial mined area, which was assumed to take place over a period of two years, the minimum investment in mining machinery would be too small, but the amount set aside for mining machinery amortization as a part of the initial mining costs should be adequate to cover rental of the needed

extra equipment.) The second variable cost is for the waste transporters and hole drillers, running from a minimum of \$300,000 to a maximum of \$1,500,000 if as many as 8000 waste containers must be handled each year.

The deactivation cost shown in Table 14 is not really an initial cost, but represents an amount which must be available at the termination of mine operations. This item is shown only for reference purposes and is not included in the total of Table 14.

7.2 Annual Costs for Items Which Are Functions of Life of Mine

Table 15 summarizes the annual costs for items which are functions of the life of the mine in terms of dollars per year and mills per kilowatt-hour of electricity originally produced. Most of the items are the capital costs (Table 14) amortized over the life of the mine at 4% annual interest. The annual mining costs include the amortization of both the mining shafts and the mining machinery as well as the other costs included in the actual mining.

The last item, deactivation of mine, represents the cost of a \$350,000 sinking fund to mature at the end of the useful life of the mine. From a plot of the total costs vs mine life (Fig. 18), it may be noted that the annual costs do not decrease significantly for mine lives greater than 80 years. In the event the disposal operation is such that the mine life is of this order of magnitude, many of the original assumptions related to the size of the mine, shafts, etc., should be changed to smaller specifications.

7.3 Annual Costs for Items Which Are Functions of Number of Pots per Year

The total annual costs in dollars per year, discussed in Section 5.4, are summarized in Table 11 and Fig. 17 as a function of the annual number of waste containers, ranging from 0 to 8000 per year. The range of costs in both dollars per year and mills per kilowatt-hour of electricity generated is also entered in Table 16, with the totals from Table 15.

Table 15. Total Annual Costs for Items Which Are Functions of Life of Mine

		Life of Mine (years)					
		10	20	40	80	160	320
Initial mining costs	\$ per year	197,000	117,000	81,000	67,000	64,000	64,000
	10^{-3} mills/kwhr	1.49	0.89	0.61	0.51	0.48	0.48
Annual mining costs (including shafts and machinery)	\$ per year	1,855,000	1,171,000	698,000	494,000	418,000	396,000
	10^{-3} mills/kwhr	14.00	8.87	5.29	3.74	3.16	3.00
Topside waste handling facility	\$ per year	203,000	126,000	103,000	102,000	102,000	102,000
	10^{-3} mills/kwhr	1.53	0.95	0.78	0.77	0.77	0.77
Waste shaft	\$ per year	25,000	15,000	10,000	10,000	10,000	10,000
	10^{-3} mills/kwhr	0.19	0.11	0.08	0.08	0.08	0.08
Mine-level waste handling facility	\$ per year	103,000	75,000	61,000	56,000	56,000	56,000
	10^{-3} mills/kwhr	0.78	0.57	0.46	0.42	0.42	0.42
Purchase of land	\$ per year	70,000	42,000	29,000	24,000	23,000	23,000
	10^{-3} mills/kwhr	0.53	0.32	0.22	0.18	0.17	0.17
Deactivation of mine	\$ per year	29,000	12,000	4,000	1,000	0	0
	10^{-3}	0.22	0.09	0.03	0	0	0
Subtotal	\$ per year	\$2,482,000	\$1,558,000	\$986,000	\$754,000	\$673,000	\$651,000
	10^{-3} mills/kwhr	18.8	11.8	7.47	5.70	5.09	4.93

Fig. 18. Total Annual Costs for Items Which Are a Function of the Life of the Mine.

7.4 Total Annual Costs as Functions of Waste Age and Combination

To develop the total annual cost for the disposal of the combined Purex and Thorex wastes from the 15,000-Mw (electrical) [56,000-Mw (thermal)] nuclear power economy, it is necessary to determine the life of the mine, the various possible combinations of waste type and pot size, and the total number of pots per year, all as a function of the age of the waste at the time of burial. These variables are given in Table 17 for waste

Table 16. Ranges of Costs for Disposing of Wastes in Floor
of 1000-ft-deep Mine as Functions of Life of Mine
and Waste Containers Per Year

	Life of Mine (years)					
	10	20	40	80	160	320
Costs Which Are Functions of Life of Mine						
Annual, \$	2,482,000	1,558,000	986,000	754,000	673,000	651,000
Unit, 10 ⁻³ mill/kwhr (electrical)	18.8	11.8	7.47	5.70	5.10	4.93
Costs Which Are Function of Number of Waste Containers per Year (0-8000)						
Annual, \$	187,000 to 602,000					
Unit, 10 ⁻³ mill/kwhr (electrical)	1.42 to 4.56					
Total Cost Ranges						
Annual, \$	2,669,000	1,745,000	1,173,000	941,000	860,000	838,000
	to	to	to	to	to	to
	3,084,000	2,160,000	1,588,000	1,356,000	1,275,000	1,253,000
Unit, 10 ⁻³	20.2	13.2	8.89	7.12	6.52	6.35
mill/kwhr	to	to	to	to	to	to
(electrical)	23.4	16.4	12.0	10.3	9.66	9.49

ages at burial from 1 (the minimum allowable for the combined waste types) to 30-1/3 years. The possible combinations of waste types, pot diameters, and mine lifetimes are obtained from Fig. 15. The number of pots per year is obtained from Table 1.

The total cost ranges for various mine lives and numbers of waste containers per year are also shown in Table 16.

Table 18 shows the total annual cost of operating the disposal facility for waste combinations which give maximum and minimum costs. It has been established that all other combinations produce costs which lie between these two extremes. The one exception is for combinations including acidic Purex in 24-in. pots which requires a large space premium even to bury at 30-1/3 years age. These costs were determined with the use of Table 17 and Figs. 17 and 18. For example, take RP6-RT6 with a

Table 17. Life of Mine and Pots per Year for Various Waste Combinations

Age at Burial (years)	Possible Combinations ^a	Life of Mine (years)	Number of Pots per Year
1.0	RP6-RT6	12.5	6430
	-RT12	12.5	3348
1.8	RP6-RT6	29.5	6430
	-RT12	29.5	3348
	-RT24	26.3	2577
2.43	RP6-RT6	34.7	6430
	-RT12	34.7	3348
	-RT24	34.0	2577
	AP6-AT6	30.0	2315
	-ATG6	30.0	2725
	-AT12	30.0	1273
3.0	All previous combinations	37.8	Same as pre- vious com- binations
	RP12-RT6	34.8	4690
	-RT12	34.8	1608
	-RT24	34.8	837
4.0	All previous combinations	41.3	Same as pre- vious
	APG-AT24	31.0	1012
5.0	All combinations possible at 3-year age	42.9	Same as pre- vious
	AP6-AT24	38.5	Same as pre- vious
	RP24-RT6	25.5	4255
	-RT12	25.5	1173
	-RT24	25.5	402
5.5	All combinations possible at 3-year age	43.3	Same as pre- vious
	AP6-AT24	39.9	Same as pre- vious
	RP24-RT6,12,24	30.0	Same as pre- vious
	AP12-AT6	28.0	1621
	-ATG6	28.0	2031
	-AT12	28.0	579
	-AT24	26.7	318
6.0	All combinations possible at 3-year age	43.6	Same as pre- vious

Table 17. (Continued)

Age at Burial (years)	Possible Combinations ^a	Life of Mine (years)	Number of Pots per Year
10.33	AP6-AT24	40.8	Same as pre- vious
	RP24-RT6, 12 or 24	31.7	Same as pre- vious
	AP12-AT6, G6 or 12	32.5	Same as pre- vious
	-AT24	31.0	Same as pre- vious
	All combinations possible at 3-year age	47.0	Same as pre- vious
	AP6-AT24	44.6	Same as pre- vious
	RP24-RT6, 12, or 24	35.6	Same as pre- vious
	AP12-AT6, G6 or 12	36.1	Same as pre- vious
	-AT24	35.0	Same as pre- vious
20.0	All combinations possible at 3-year age	56.7	Same as pre- vious
	AP6-AT24	55.0	Same as pre- vious
	RP24-RT6, 12 or 24	45.5	Same as pre- vious
	AP12-AT6, G6 or 12	46.3	Same as pre- vious
	-AT24	45.5	Same as pre- vious
30.33	All combinations possible at 3-year age	72.7	Same as pre- vious
	AP6-AT24	71.0	Same as pre- vious
	RP24-RT6, 12 or 24	62.7	Same as pre- vious
	AP12-AT6, G6 or 12	64.3	Same as pre- vious
	-AT24	62.7	Same as pre- vious
	AP24-AT6	31.8	1448
	-ATG6	31.8	1858
	-AT12	31.8	406
	-AT24	31.6	145

^aAP = acid Purex; AT = acid Thorex; RP = reacidified Purex; RT = reacidified Thorex; ATG = acid Thorex glass. The numbers 6, 12, and 24 refer to the nominal pot diameters, in inches.

Table 18. Total Costs of Operating the Disposal Facility as a Function of Waste Age at Burial, for Waste Combinations Which Give Maximum and Minimum Costs

Age at Burial (years)	Waste Combination ^a	Annual Costs (10^6 \$/year)			Present Value	
		Costs Based on Life of Mine	Costs Based on Pots per Year	Total	10^6 \$/year	10^{-3} mill per kw hr (electrical)
1.0	RP6-RT6	2.13	0.55	2.68	2.58	19.5
	RP6-RT12	2.13	0.35	2.48	2.38	18.1
1.8	RP6-RT6	1.19	0.55	1.74	1.62	12.3
	RP6-RT12	1.19	0.35	1.54	1.44	10.9
2.43	RP6-RT6	1.08	0.55	1.63	1.48	11.2
	RP6-RT24	1.10	0.31	1.41	1.28	9.7
3.0	RP6-RT6	1.03	0.55	1.58	1.40	10.6
	AP6-AT12	1.03	0.20	1.23	1.09	8.28
4.0	RP6-RT6	0.98	0.55	1.53	1.31	9.90
	RP12-RT24	0.98	0.19	1.17	1.00	7.58
5.0	RP6-RT6	0.97	0.55	1.52	1.25	9.46
	RP12-RT24	0.97	0.19	1.16	0.95	7.23
5.5	RP6-RT6	0.96	0.55	1.51	1.22	9.24
	RP12-RT24	0.96	0.19	1.15	0.93	7.05
6.0	RP6-RT6	0.96	0.55	1.51	1.19	9.03
	RP12-RT24	0.96	0.19	1.15	0.91	6.88
10.33	RP6-RT6	0.92	0.55	1.47	0.98	7.42
	RP12-RT24	0.92	0.19	1.11	0.75	5.66
20.0	RP6-RT6	0.86	0.55	1.41	0.64	4.83
	RP12-RT24	0.86	0.19	1.05	0.48	3.60
30.33	RP6-RT6	0.78	0.55	1.33	0.40	3.04
	RP12-RT24	0.78	0.19	0.97	0.29	2.21
	AP24-ATG6	1.15	0.22	1.37	0.42	3.16

^aFor explanation of nomenclature, see footnote, Table 17.

waste age of one year at burial. From Table 17, it is found that the life of the mine is 12-1/2 years. From Fig. 18, it is seen that the annual costs which are a function of the life of the mine for a 12-1/2-year life are about 2.13×10^6 \$/year. From Table 17, it is seen that the number of pots per year is 6430. From Fig. 17, it is seen that the cost of disposal of this number of pots annually is $\$0.552 \times 10^6$. The total annual cost is then $\$2.68 \times 10^6$. This is the amount which must

be available annually to pay for the disposal operation. As may be seen from Table 18, the annual cost varies from a range of about 2.5 to 2.7×10^6 \$/year for a 1-year-old waste, to a range of about 1.0 to 1.4×10^6 \$/year for a 30-1/3-year-old waste.

For wastes aged more than one year before disposal, the present value was computed at 4% annual interest. Thus, the amount which must be set aside when the power is generated decreases with increasing length of interim storage. The maximum and minimum costs which must be charged to power generation are also shown in Fig. 19. They range from about 2 to 3×10^{-3} mill/kwhr (electrical) for wastes 30 years old at burial to about 18 to 20×10^{-3} mill/kwhr (electrical) for one-year-old waste.

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Fig. 19. Total Costs Which Must Be Charged to Power Generation for Disposal of Wastes in Salt Mines.

8. SUMMARY AND CONCLUSIONS

This is a study of the cost of disposing of high-level, solidified, power-reactor wastes produced by the pot calcination process and contained in cylinders ("pots") 6, 12, and 24 in. in diameter with a length of 10 ft. One disposal facility handles the entire output from a 15,000-Mw (electrical) [56,000 Mw (thermal)] nuclear power economy. The waste products result from the processing of 1500 tonnes/year of 10,000-Mwd/tonne burnup uranium converter fuel and 270 tonnes/year of 20,000-Mwd/tonne burnup thorium converter fuel. Disposal of the resulting Purex and Thorex wastes in both acid and neutralized forms and of Thorex wastes made into an alumina-silica-borax type glass is considered.

A conceptual design of a salt mine especially for disposal of high-level wastes is developed, and the cost of the entire mining and disposal operation is calculated. The mine is 1 sq mile in area and is 1000 ft below the surface. The operating life of the mine for disposal of the wastes from the assumed economy is calculated, using rather conservative mine stability criteria, for various waste ages, pot sizes, and waste combinations.

The life of the mine was found to range from about 12-1/2 years for wastes aged 1 year at the time of burial to about 70 years for wastes aged 30 years at burial. The initial capital outlay required to start waste disposal operations ranges from about $\$8.4 \times 10^6$ to $\$10.7 \times 10^6$. Total annual capital and operating costs for operating the facility are dependent on waste combinations and pot sizes, and varied from about $\$2.6 \times 10^6$ for a 1-year-old waste to about $\$1.2 \times 10^6$ for 30-year-old wastes.

Using present worth considerations, the money to be set aside annually at the time of waste generation ranged from about $\$2.5 \times 10^6$ for a 1-year-old waste to about $\$0.4 \times 10^6$ for a waste 30 years old at the time of disposal. In terms of cost per kilowatt-hour of electricity generated, this corresponds to about 19×10^{-3} mill and 3×10^{-3} mill respectively.

These costs are a relatively small portion of the cost of competitive nuclear power. In fact, previous studies¹⁹ have shown that the estimated cost of the entire waste management scheme, from conversion to a solid through disposal in salt, represents only 1% of 2-mill/kwhr (electrical) power.

The disposal-in-salt costs in this study do not include the effects of charges or credit for the salt which must be disposed of (about 50% of that mined). Since the quality of the salt will likely be poor (containing considerable quantities of shale), it may not be salable. However, if it is necessary to dissolve it and dispose of the brine in a deep porous formation, the additional cost will not be prohibitive, as may be seen in Appendix A.

APPENDIX A

EFFECT OF CHARGES OR CREDITS FOR SALT

In a disposal mine in a bedded salt formation, the purest salt state will likely be chosen for the floor of the mined area. In this way, any problems attributable to the moisture present in the interbedded shale can be avoided. This means that there will probably be shale layers present in the salt zone which is mined for tunnels and rooms, and this would be of little or no commercial value. In at least one commercial mine in the United States, it is necessary to take the ceiling up to a shale layer to obtain a stable room, and several feet of salt are consequently discarded because of the presence of a small amount of shale.

¹⁹J. O. Blomeke, R. Salmon, J. T. Roberts, R. L. Bradshaw, and J. J. Perona, "Estimated Costs of High-Level Waste Management," Proceedings of International Symposium on Solidification and Long-Term Storage of Highly Radioactive Wastes, Richland, Washington, February 14-18, 1966, CONF-660208, pp. 830-43 (November 1966).

Even if the salt were of good quality, it might be of little commercial value because of the location of the mine relative to a market area.

The average value of the salt produced in the United States in 1964 is reported to be about \$6/ton.²⁰ Most of this salt is produced by the brine process and is of higher purity than that from mining of bedded salt. The basis used to compute this "average value" is not known, but mined salt can be extracted for about \$2/ton, delivered topside, before taxes and profit.

As may be seen from Table 5 in Section 4.3, the estimated costs in this study of mining the salt and delivering half of it topside range from about \$1.72/ton for a 10-year-life mine to about \$3.66/ton for an 80-year-life mine. These mining costs, in turn, represent from 35 to 70% of the total yearly costs (Table 15). Thus, if the salt could be sold at or near the cost of its mining, the savings to the overall disposal operation might be substantial.

In the event the salt could not be sold, given away, or hauled away for a nominal fee, it would probably have to be disposed of by dissolution and injection into a nearby porous formation at depths below usable ground water. Generally, such formations can be expected to be available where extensive salt deposits exist, and there is a good likelihood that the water necessary for dissolution will also be available.

Two different studies were utilized in developing approximate costs for disposal as brine in a porous formation.^{21,22} Assuming that 1000 gal of water (available at 10¢/1000 gal) is used to dissolve each ton of salt and that the resulting brine is injected at a depth of 12,000 ft with 900 psi pumping pressure, it is estimated that the maximum cost for disposal of salt would be: \$0.31/ton for a 10-year-life mine, \$0.37/ton

²⁰U.S. Bureau of the Census, Pocket Data Book, USA 1967, p. 260.

²¹C. H. Riggs, L. J. Heath, and D. C. Ward, Salt Disposal Study, Project Dribble, Tatum Dome Area, Lamar County, Miss., USBM, TID-16356 (July 1962).

²²Louis Koenig, Ultimate Disposal of Advanced Treatment Waste, AWTR-8, USPHS, (May 1964).

for a 20-year, \$0.46/ton for a 40-year, and \$0.68/ton for an 80-year-life mine. This represents about 18% of the cost of mining, and thus only a few percent increase in the total cost of operating the facility.

APPENDIX B

EFFECT OF SALT EXTRACTION RATIO

Neglecting possible changes in mine stability, the most important effect of changing the salt extraction ratio in a mine at fixed depth is a change in the life of the mine. If the extraction ratio is defined as the width of a room divided by the sum of the width of the room and one adjacent pillar, the amount of mine space available for waste disposal is directly proportional to the percent extraction. This proportionality is shown in Fig. B-1, where the life of the mine relative to a 50% extraction is plotted against the percent extraction.

Actually, the initial mining is also a function of the extraction ratio. An extraction of 25% would require the initial mining of about 20% less salt than 50% extraction, and an extraction of 75% would require the initial mining of about 20% more salt. Since the contribution of the initial mining is always less than 10% of the total annual costs (at 50% extraction) of the disposal facility, this effect is neglected.

As an example of the effect of percent extraction on cost of disposal in a mine at a depth of 1000 ft, take the case of a 4-year-old waste combination of reacidified Purex in 12-in. pots and reacidified Thorex in 24-in. pots (the minimum cost combination for 4-year-old waste). At 50% extraction the total annual costs are about $\$1.17 \times 10^6$ (Table 18), and the life of the mine is about 41 years (Fig. 15). For 25% extraction the life of the mine is only half that at 50% extraction (Fig. B-1), or about 20-1/2 years. From Fig. 18, the costs which are a function of the life of the mine are $\$1.51 \times 10^6$ /year. The annual cost of items which are a function of pots/year is $\$0.19 \times 10^6$ (Table

Fig. B-1. Relative Life of Mine as Function of Percent Extraction.

18). The total annual costs are thus about $\$1.70 \times 10^6$ for 25% salt extraction, or about a 45% increase. For 62-1/2% extraction (the maximum attainable with 50-ft-wide rooms and a pillar width-to-height ratio of 2), the life of the mine is 1.25 times that at 50% extraction, or about 52 years. The annual cost for this mine life is about $\$0.88 \times 10^6$, making the total annual costs about $\$1.07 \times 10^6$, or about a 9% decrease. For the maximum cost combination (RP6-RT6), the percentage change would be smaller (about 35% increase for 25% extraction and about 7% reduction for 62-1/2% extraction).

It should be noted that the temperature rise (and space utilization) factor of 1.7 referred to in other parts of this report does not apply to cases where the extraction ratio is other than 50%.

APPENDIX C

EFFECT OF MINE DEPTH

The two main variables affected by mine depth are the allowable percentage extraction of salt (and thus the life of the mine as discussed in Appendix B) and the cost of the mining and waste shafts. There might also be a small effect on operating costs due to the different times required to lift salt and to lower waste cans; however, this latter effect is small enough to be neglected.

The shallowest mine depth likely to be used is about 500 ft, for it is not probable that at lesser depths there would be enough salt and layers of low-permeability shale overhead to meet safety criteria for a disposal facility. At 500 ft, the allowable extraction ratio is 75%, but, to meet the stability criteria of rooms no wider than 50 ft and a pillar width-to-height ratio no less than 2, the maximum allowable extraction would be 62-1/2%.

The greatest depth that could be considered is about 3000 ft, and, even at that depth with only 15% extraction, the stability problems would probably be quite troublesome. The maximum depth at which the same stability criteria can be applied as for 50% extraction at 1000 ft is 1500 ft with 25% extraction. Actually, 20% extraction at a depth of 2000 ft would produce stability conditions which would likely be acceptable. Therefore the effects of mine depths of 500 to 2000 ft are investigated in this appendix.

The relation between mine life and mine depth is expressed by curve (a), Fig. C-1. This graph is based on the allowable extraction ratios at different depths, as discussed above, and was constructed using Fig. B-1. To a reasonable approximation, mining and waste shaft costs may be assumed proportional to depth over the range of 500 to 2000 ft. Also, approximately, the total annual charges for shafts are a fixed percentage of the total annual costs for items which are a function of the life of the mine (up to about 80 years mine life). At a depth of 1000 ft the shaft costs represent about 12% of these costs. If the total annual life-of-mine costs are taken as 1.00, then the costs

at 500 ft are about 0.94 and costs at 2000 ft are about 1.12. These factors are plotted as curve (b) in Fig. C-1.

The two factors in Fig. C-1 may be used to estimate the effect of mine depth on cost for any particular set of circumstances. To illustrate, consider the case of the 4-year-old RPl2-RT24 waste discussed in Appendix B. For this case at 1000 ft depth, the life of the mine would be about 41 years (Fig. 14), and (from Table 18 or Fig. 18) the total annual life-of-mine costs would be about $\$0.98 \times 10^6$. The annual costs based on the number of pots per year range from about $\$0.19 \times 10^6$ to $\$0.55 \times 10^6$ (Table 18 or Fig. 17). Thus, total annual costs at 1000 ft depth range from about $\$1.17 \times 10^6$ to $\$1.53 \times 10^6$.

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Fig. C-1. Relative Variation in Total Costs Which Are Functions of Life of Mine Due to Variation in Shaft Costs with Mine Depth and Relative Life of Mine as Function of Depth.

Now at 500 ft, the relative mine life factor is 1.25 [curve (a), Fig. C-1]. Thus, the life at 500 ft would be about 51-1/4 years, and the annual life-of-mine costs would be about $\$0.88 \times 10^6$ (Fig. 18). The relative cost factor due to the shaft cost is 0.94 [curve (b), Fig. C-1], and this factor is multiplied by $\$0.88 \times 10^6$ to give $\$0.83 \times 10^6$. When added to the costs which are a function of the number of pots per year, a range of total annual costs is obtained for disposal in a 500-ft-deep mine of $\$1.02 \times 10^6$ to $\$1.38 \times 10^6$. Thus, the total savings of a mine at 500 ft over one at 1000 ft (for a 4-year-old waste) is from about 10 to 13%.

At 2000 ft the mine life factor is 0.40 (Fig. C-1) and the life would be about 16-1/2 years. From Fig. 18 the life-of-mine costs are about $\$1.75 \times 10^6$. The relative cost factor due to shafts is 1.12 (Fig. C-1), which multiplied by $\$1.75 \times 10^6$ yields $\$1.96 \times 10^6$. Summation gives a range of total costs for disposal in a 2000-ft mine of $\$2.15 \times 10^6$ to $\$2.51 \times 10^6$. Thus the increase in cost for 4-year-old wastes over those for a 1000-ft-deep mine ranges from about 64 to 84%.

The present study applies to mine facilities located in bedded salt deposits. Stability conditions in a dome deposit would probably be better in that the interbedded shale is not present and the room width could probably be more than 50 ft, thus allowing a full 75% extraction at 500 ft without reducing the pillar width-to-height ratio below 2. It is also possible that deeper mines could be tolerated in domes, although this has not yet been investigated.

APPENDIX D

EFFECT OF SIZE OF THE MINE

For the main body of this report a 1-sq-mile mine (gross area) has been assumed, based mainly on the observation that in mines in this country the maximum desirable haulage distance seems to be about 1 mile. In this appendix, the approximate effect on costs of mines with a maximum haulage distance of 0.707 mile (1/2 sq mile of area) and 1.414 miles (2 sq miles of area) will be investigated.

A preliminary look was taken at mines with $1/4$ and with 4 sq miles of area. For the level of waste generation assumed in this study, the $1/4$ -sq-mile mine would last 10 years (considered to be the minimum desirable) only with wastes aged more than 3- $1/2$ years at the time of burial. On the other hand, the 4-sq-mile mine would last 160 years for wastes 3- $1/2$ years old at burial, which is unreasonably long.

Several simplifying assumptions were made: (1) the mining shafts do not vary in size with mine area, (2) the net storage space is proportional to the gross area of the mine, (3) the volume of salt involved in the initial excavation is proportional to the square root of the ratio of mine sizes. The effect of the first assumption will be discussed presently. The other two assumptions are approximately correct, although the smaller mine will have slightly less than proportional net storage space and slightly more than the indicated initial salt to be mined before operations can start. Both of these items would tend to increase costs in the smaller mine.

Cost calculations for these mine sizes are done on the same basis as for the 1-sq-mile mine. A summary comparing costs in the three size mines is shown in Table D-1. The comparisons are made on the basis of the same annual space utilization (tons of salt mined per year) in each mine. The second set of entries in the table is the life of the mine as a function of its size. (As mentioned earlier, a mine life of more than 100 years is unrealistic, and figures for longer lives are shown for comparative purposes only.)

Initial mining costs were assumed proportional to the volumes of the initial excavation and were amortized over the life of the mine at 4% interest.

Annual mining costs include mining shaft amortization, and they vary because of differences in haulage distances.

The topside facility, waste shaft, and mine-level facility were amortized over the life of the mine or 40 years, whichever occurs first.

For purposes of land purchase, a 1000-ft buffer zone is included around the active area of the 1- and 2-sq-mile mines. For the $1/2$ -sq-mile mine, a 500-ft buffer area is provided.

Table D-1. Yearly Costs as a Function of Gross Mine Area and the Quantity of Salt Mined Annually

	1/2-sq-mile Gross Mine Area					1-sq-mile Gross Mine Area						2-sq-mile Gross Mine Area					
Salt mined, 10^5 tons/year	5.4	2.7	1.35	0.67	0.34	10.8	5.4	2.7	1.35	0.67	0.34	10.8	5.4	2.7	1.35	0.67	0.34
Life of mine, years	10	20	40	80	160	10	20	40	80	160	320	20	40	80	160	320	640
Costs dependent on mine life, \$ 10^3 /year																	
Initial mining	140	83	57	47	45	197	117	81	67	64	54	166	114	94	90	90	90
Annual mining	1202	712	511	404	390	1855	1171	698	494	418	396	1832	1192	747	532	435	406
Topside facility	203	126	103	102	102	203	126	103	102	102	102	126	103	102	102	102	102
Waste shaft	25	15	10	10	10	25	15	10	10	10	10	15	10	10	10	10	10
Mine-level facility	103	75	61	56	56	103	75	61	56	56	56	75	61	56	56	56	56
Land purchase	30	18	12	10	10	70	42	29	24	23	23	68	46	38	37	37	37
Mine deactivation	29	12	4	1	—	29	12	4	1	—	—	12	4	1	—	—	—
Subtotal	1732	1041	758	630	613	2482	1558	986	754	673	651	2294	1530	1048	827	730	701
Costs dependent on pots per year, \$ 10^3 /year																	
				187 to 535					187 to 602						187 to 725		
Total costs, \$ 10^3 /year																	
Minimum pots per year	1919	1228	945	817	800	2669	1745	1173	941	860	838	2481	1717	1235	1014	917	888
Maximum of 8000 pots/year	2267	1576	1293	1155	1148	3084	2160	1588	1356	1275	1253	3019	2255	1773	1552	1455	1426

Mine deactivation costs are amortized over the life of the mine.

The costs which are a function of the number of waste containers per year will be the same for all mine sizes with a minimum number (less than 1000) of containers per year. However, for large numbers of containers, the number of waste transporters and drivers will vary, roughly in proportion to the haulage distance. These cost ranges are shown near the bottom of the table.

From a study of the total costs (the final entry in the table), some conclusions can be drawn. For a mining rate of 10.8×10^5 tons/year, the 1/2-sq-mile mine would not be practical because of its very short, five-year, life. At that mining rate, there would appear to be a marginal advantage (less than 10% cost saving) of using a 2-sq-mile mine if the number of waste containers is small. For a mining rate of 5.4×10^5 tons/year, either the 1- or 2-sq-mile mine would appear to be cheapest, depending on the number of waste containers; however, the difference is even smaller. For a mining rate of 2.7×10^5 tons/year, the 1-sq-mile mine has a slight cost advantage, and at 1.35×10^5 tons/year the 1/2-sq-mile mine has a slight cost advantage for a large number of containers. For lower mining rates the 1/2-sq-mile mine has the advantage for any number of waste containers per year. The significant point is that the variations in costs for the various mine sizes is only a few percent.

The effect of varying the size of the mining shaft with the size of the mine was mentioned earlier. This would appear reasonable for the 1/2-sq-mile mine, where the maximum mining rate is only 5.4×10^5 tons/year. However, the shaft and associated equipment costs are generally not more than about 20% of the total annual mining costs. Even though the mining costs are generally more than half the total annual costs, the savings obtained by going to a smaller shaft would result in less than 5% reduction in total annual costs. This small reduction would tend to favor the use of the smaller mine for somewhat higher mining rates than indicated in the previous discussion.

The general conclusion is that the size of the mine is relatively unimportant, within broad limits. It does not seem desirable to use a mine for disposal of a given waste output, if the mine is not big enough

to last at least 10 years. On the other hand, a mine life of more than 100 years is unreasonable. It would appear that there is no sharp optimum size, but a broad optimum lies somewhere between 20 and 40 years life, depending on the number of waste containers handled per year.

APPENDIX E

OTHER CONCEPTS FOR DISPOSAL IN SALT FORMATIONS

As mentioned in the main body of the report, the scheme chosen for cost estimation may not be the most economical, but it is feasible and represents a minimum of departure from current technology. The results of this study show that the costs are reasonable and compatible with the total nuclear power costs of 1-1/2 to 2 mills/kwhr projected for around 1980.

In this study, it has been assumed that waste disposal is being carried out in bedded salt in a mine which has been designed especially for the purpose. Disregarding safety considerations, it might be cheaper to use existing space in abandoned mines. Abandoned mines, however, generally have the following disadvantages:

1. The purest salt strata have been mined, and the existing floor usually contains interbedded shale layers containing several percent water which will be liberated by heating.
2. The amount of salt left as supporting pillars is usually barely adequate to maintain mine stability at ambient temperature, and sometimes then only for a brief time. The effect of the radioactive decay heat has been shown in Project Salt Vault¹¹ to play an important role in salt flow and could well cause problems in mines where its presence had not been anticipated. Actually, in some mines (such as in a large portion of the Lyons mine) where floor heaves and roof falls have been extensive, the cost of cleaning the rooms and tunnels could be nearly as expensive as new mining.

3. The mining pattern is not usually such that it would lend itself to the ventilation and containment concepts outlined in this report and which are considered to be necessary.

All the above disadvantages are admittedly controversial to some extent, however, and abandoned mines cannot necessarily be ruled out. Nevertheless, until some of these problems are better understood, a specially designed mine, or at least a newly excavated space at the periphery of an existing mine are considered to be basic requirements, and the following alternatives to disposal in the mine floor are intended for possible application within these restrictions.

One possibility is that the cans be placed horizontally in the pillars. If the pillars were large compared with the room size and several waste cans were to be placed in a long hole, this would appear to have some merit. However, there would be some additional problems. For example, the mechanics of placing the cans in a long horizontal hole with adequate shielding so that the room could be entered before the hole was completely filled might be more complex than for the single cans in the floor holes. Another, and probably more important, point is that the radioactive decay heat is generated entirely within the pillar and would very likely produce considerably more stability problems than if the cans were in the floor. This would be especially true in the case where there was a shale layer a short distance up into the roof. Nevertheless, further investigation could prove this method to be more economical than burying single cans in the floor.

The storage of cans in racks above the floor is another possibility. On the basis of a preliminary look, we conclude that the costs arising from the remote handling operations and equipment required by this concept more than outweigh any advantages over burial in the floor. One of the principal advantages of the "hole-in-the-floor" method, the additional isolation gained by the 7 to 8 ft of crushed salt above the cans, would be lost. The case for above-the-floor storage has not been studied exhaustively, however, and under some conditions it might prove desirable.

The disposal of multiple cans (up to 20) in floor holes has also been considered. Heat transfer studies indicate that, under some conditions, savings in mine area (up to about a factor of 2) could be effected.

However, for many other conditions the space savings are not so pronounced. There would be some additional problems associated with producing the deeper holes and with finding a sufficiently thick stratum relatively free of shale beds.

Still another possibility is that, instead of opening a mine, deep vertical shafts be drilled from the surface and multiple cans be placed in these holes. Although a cost study of this concept has not been undertaken, experience obtained in having the waste shaft installed for Project Salt Vault, so as to ensure that no groundwater can enter the mine, indicates that installing such shafts and ensuring that they will be sealed and remain watertight for several centuries, would be rather expensive. In dome mines, where the depth of good salt is practically unlimited, the method might prove of value. However, the thought of depending on the integrity of a large number of shafts for several hundred years seems unattractive compared with the four shafts (although much bigger) which must be sealed within the concept of this study.

APPENDIX F

CALCULATIONS OF DISPOSAL COSTS FOR OTHER WASTE TYPES AND NUCLEAR POWER LEVELS

Determination of Costs for Other Power Levels on a Similar Basis as in Body of Report

Within certain limits the data which have been developed in the main body of this report can be used to estimate mine space requirements and disposal costs for other waste types and nuclear power levels. The prime assumption which must be made is that the heat-generating characteristics of the waste as a function of time are essentially the same as those used in this series of studies (Fig. 1) or that the waste has a half-life of 30 years and is comparable with wastes in this report of age 10 years or more.

As pointed out in Section 3 of this report, the heat calculations are based on conservative assumptions in order to give cost numbers that can be achieved in the operation of an early, conservatively operated disposal facility. Also, one can allow a waste concentration in the mine about 1.7 times higher than that used in the main body of this report, and cost studies may be prepared on either basis. (It must be remembered that the factor of 1.7 would be different with other than a 50% extraction ratio.) For example, in the study of the mine space requirements for the expanding United States nuclear power economy (Appendix G), the factor of 1.7 is taken into account.

Appendix G is a good example of the use of the basic data of this report to derive information applicable to other nuclear power levels and assumptions. The main point to be kept in mind is that the waste output in the main body of this report represents the continuous operation of 56,000 Mw (thermal) nuclear power. For any other level of power generation, the waste output is obtained by taking the ratio of the equivalent continuous operating thermal power. The foregoing assumes that the waste containers are 6 to 24 in. in diameter, with the heat source effectively spread over a 10-ft length, and that the heat generation per container is such that no mine space premium must be paid to dissipate the heat. Exceptions to this case are discussed later.

Let us now take as an illustrative example the determination of the cost for disposing of wastes from a nuclear economy operating at a power of 112,000 Mw (thermal), or twice that used in the main body of this report. Assume that the heat generation per container is such that the minimum mine space is required (the waste combination is reacidified Purex in 12-in.-diam pots and reacidified Thorex in 12-in.-diam pots). The waste is buried in the mine at an age of 4 years. Two things must be determined: the life of the mine and the number of waste containers per year. From Fig. 15, it may be seen that the life of the mine for the 56,000 Mw (thermal) case is about 41 years. Since 112,000 Mw (thermal) produces twice the quantity of waste, the mine life for this case will be only about 20-1/2 years. From Table 1 or Table 17, it is found that the number of pots per year for 56,000 Mw (thermal) with the waste combination in question is 1608. For the same heat-generation rate per

container, the 112,000 Mw (thermal) will require 3216 containers per year. Now, to find the operating costs, Figs. 17 and 18 are consulted. For the 56,000-Mw (thermal) level the cost per year for handling 1608 pots is about $\$0.22 \times 10^6$ and the annual cost for a 41-year-life mine is about $\$0.99 \times 10^6$, for a total cost of about 1.21×10^6 \$/year. The corresponding costs for the 112,000-Mw (thermal) case are $\$0.34 \times 10^6$ and $\$1.52 \times 10^6$, for a total cost of about 1.86×10^6 \$/year. Assuming that load factors, thermal efficiencies, etc., are the same, the 56,000 Mw (thermal) represents the generation of 1.32×10^{11} kwhr (electrical), and the 112,000 Mw (thermal) twice this amount. The relative costs which must be available at the time of actual waste disposal thus amount to about 9.2×10^{-3} mill/kwhr (electrical) for the lower power level and about 7.4×10^{-3} for the higher power level. Applying the present value concept at 4% interest (0.855 for 4 years), about 7.9×10^{-3} and 6.3×10^{-3} mill/kwhr (electrical), respectively, must be set aside at the time the fuel comes out of the reactor to cover the cost of disposal in salt 4 years later. Other waste management step costs, such as conversion to solid, are not included in these figures and would have to be calculated as indicated in the other reports in this series.

Determination of Costs for Different Situations

Figure F-1 has been developed to aid in estimating mine space and waste container requirements for situations not quite comparable to the conditions of this study. These data are from a cross plot of data derived from the infinite array calculations, and they are considered only as good approximations. Nevertheless, for most conditions the use of these curves can provide the basis for reasonably accurate cost estimates. Again, with this family of curves, one is limited to waste containers with 10 ft of heated length and with diameters between 6 and 24 in.; however, within limits, some extrapolation to larger or smaller containers can probably be judiciously made.

As an example of the use of Fig. F-1, assume an annual quantity of waste for disposal having a cumulative annual heat generation of 3.6×10^6 Btu/hr. Further, assume that it is desired to dispose of

Fig. F-1. Allowable Average Heat Generation Rate per Square Foot of Floor Area in Mine Rooms as Functions of the Waste Container Diameter, Waste Age at Burial, and Total Heat Generation in the Waste Container.

the waste at 4 years of age in the largest-diameter container possible. An additional factor which must be known for the particular waste is the heat generation per container, and for this case it is assumed to be 3900 Btu/hr per 6-in.-diam by 10-ft-long container. This would mean that a 12-in.-diam pot (four times the volume) would contain a total heat generation of 15,600 Btu/hr. Since the 4-year age comes between two of the families of curves in Fig. F-1, let us examine these curves for 3-1/3 and 6-1/3 years to see what the maximum size container is. It

is obvious that 15,000 Btu/hr in a 12-in.-diam container cannot be buried at either 3-1/3 or 6-1/3 years or, for that matter, at any age. On the other hand, it appears that 3900 Btu/hr in a 6-in.-diam container does not require any space premium (i.e., the Btu hr⁻¹ ft⁻² of mine floor area is at or near the maximum) at either 6-1/3 or 3-1/3 years of age at burial. An additional cross plot might indicate that a can slightly larger than 6 in. in diameter could be used, but the accuracy of such a plot would not be worth the effort. Therefore, assuming that 6-in.-diam containers are used, we find that 925 containers per year are required to handle the 3.6×10^6 Btu hr⁻¹ year⁻¹ of heat evolution.

Now, a cross plot from Fig. F-1 is in order to determine the allowable average heat generation rate per square foot of mine room area for 4-year-old waste. This is done in Fig. F-2, and we find the result to be 28 Btu/hr-ft² of room area. The total net floor area required is thus

$$3.6 \times 10^6 \frac{\text{Btu}}{\text{hr-yr}} \div 28 \frac{\text{Btu}}{\text{hr-ft}^2}$$

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Fig. F-2. Average Heat Generation per Square Foot of Mine Floor Area as a Function of Waste Age for No Space Premium.

or 1.29×10^5 ft²/year. Now, from Section 3.1, there are 552 rooms in a 1-sq-mile mine, each containing 15,000 ft² of disposal area, for a total of 8.28×10^6 ft². This means the mine will last about 64 years at this level of waste input. As a matter of interest, the spacing between containers is easily obtained by taking the 28 Btu/hr-ft² and dividing into the heat generation per can (3900 Btu/hr) to get the area per can of 139 ft². A circle of this area has a radius of about 6-2/3 ft. From Section 3.1, the spacing is 1.9 times this radius, or 12.7 ft.

From Figs. 17 and 18, the annual costs are found to be about 0.19×10^6 for 925 cans per year and 0.81×10^6 for a mine life of 64 years, totaling about 1.0×10^6 \$/year.

Effects of Variation in Waste Container Configuration and Heat Generation

In Fig. F-2 we have a cross plot of data which gives us an approximate average heat generation per square foot of mine room that can be used with containers of 6 to 24 in. diameter by 10 ft heated length without exceeding a maximum salt temperature rise of 180°C, as determined by the calculations for the infinite array of heat sources. It is obvious from Fig. F-1 that, if one is willing to pay some space premium (that is, use less than the maximum heat generation per unit of floor area), one may increase the total heat generation per container within certain limits. Again, from Fig. F-1, for any given waste age and container size, there is an absolute maximum heat generation rate beyond which no increase in spacing between containers will limit the salt temperature rise to the desired value.

Unfortunately, the results of the calculations done for this study are limited in range and accuracy when applied to other container sizes and waste types. Primarily this is because the computer calculations included several approximations and only a limited number of calculations were done, to minimize the rather large machine time requirements. Therefore, the data to follow should be regarded as only approximate, but may still be useful as a guide.

Figure F-3 has been prepared as cross plot and extrapolation from Fig. F-1 for use in determining the approximate absolute maximum heat generation per container for 180°C salt temperature rise for cylinders 4 in. to 5 ft in diameter (upper family of curves), the approximate maximum heat generation for no more than 10% mine space premium (middle family of curves), and the approximate maximum heat generation for no space premium (lower curves). The 1.7 temperature rise (and mine space utilization) factor has not been taken into account in this figure but may be applied as discussed in Section 3.3, if desired.

As an example, suppose one desires to use a 4-ft-diam by 10-ft-long container for disposal of waste 10 years old at the time of burial. From Fig. F-3 (upper family) the absolute maximum heat generation per container would be about 20,000 Btu/hr at the time of burial. However, the space premium required is indeterminate and might be 100% or greater. For a 10% mine space premium the maximum heat generation rate is about 6200 Btu/hr (middle family). For no mine space premium the allowable

Fig. F-3. Allowable Maximum Heat Generation per Container as a Function of Waste Age and Container Diameter for 180°C Salt Temperature Rise. (The 1.7 factor is not included.)

rate would be about 3700 Btu/hr per container (bottom curve). These numbers should be regarded as very approximate since they are from a combination of cross plot and extrapolation.

All of the foregoing is based on the heat sources being 10 ft long. If the case in question has sources of some other length, then a conservative approach is to allow a heat generation which is the same per unit length as the 10-ft source. So far as the overall mine stability is concerned, as long as the average heat generation rate per unit of storage area does not exceed the values given in Fig. F-2, there should be no problem; that is, heat generation rate would be the same as for the 10-ft container. This of course will result in both higher peak salt temperatures as well as higher container and waste temperatures. Some discussion on this point may be found in Section 3.3. It may well be that the salt temperature immediately around the waste container is not critical, and the waste container and waste temperatures would govern. This, of course, has not been proved, and caution should be used in making such assumptions.

If the waste container is longer than 10 ft, similar considerations would apply, and the average heat generation per unit area consideration should again be considered ruling (due to the effect on overall mine stability).

In calculating the disposal costs for waste containers either larger than 2 ft in diameter or longer than about 10 ft, special allowance should be made. Longer containers would probably require higher headroom in the mine and, consequently, increased salt mining costs. Also, the required depth of good salt for the disposal holes might not be available. Larger-diameter containers would require a larger waste shaft, a larger underground waste transporter, and a larger hole driller, among other things. There are too many possible combinations to try to make generalizations, but to take a specific example of 5-ft-diam containers, a size which is considered to be about as large as should possibly be considered, it would probably not be unreasonable to assume that the costs which are a function of the number of waste containers are doubled and the costs which are a function of the life of the mine are increased about 10%.

If the waste container were 15 ft long instead of 10 ft, the mining height would have to be increased by nearly 50%, resulting in something like a 25% increase in costs which are a function of life of the mine and perhaps a 50% increase in costs which are a function of the number of containers per year.

APPENDIX G

PROJECTED SPACE REQUIREMENTS FOR U.S. NUCLEAR POWER ECONOMY TO 2065

The estimates of installed nuclear electrical generating capacity up to the year 2000 were taken to be the same as those developed by Blomeke and Boegly.²³ From the year 2000 to 2060, the figures were derived from the projections shown in Fig. 3, page 44, of the 1962 AEC Report to the President on Civilian Nuclear Power.²⁴ A comparison of the installed electrical capacity derived from this figure for the year 2000 with that of Blomeke and Boegly indicates that the AEC figures are about 14% lower. Thus a multiplying factor of 1.14 was applied to the numbers derived from the AEC up to the year 2060. The results are shown as the lower curve in Fig. G-1. All curves were extrapolated to year 2065.

The upper curve of Fig. G-1 shows the installed nuclear thermal capacity. A thermal efficiency linearly increasing from 30% in 1965 to 44% in 2000 is assumed. Beyond 2000 the efficiency is assumed to remain constant at 44%.

The middle curve in Fig. G-1 shows the equivalent continuously operating thermal nuclear generation. This is based on a reactor load

²³R. E. Blanco et al., Survey of a Site for a Nuclear Fuel Processing Plant and Waste Disposal Area at Oak Ridge, ORNL-TM-1748 (Jan. 13, 1967).

²⁴Civilian Nuclear Power, A Report to the President - 1962, USAEC.

Fig. G-1. Nuclear Power Projection to Year 2065.

factor of 80% until 1980, then decreasing linearly to 70% by 2000, and remaining at 70% thereafter.

In the case considered here of wastes at least 10 years old, essentially only $^{137}\text{Cs-Ba}$ and $^{90}\text{Sr-Y}$ are left as significant heat producers. Therefore only the total megawatt-days of operation and not the residence time of the fuel in the reactor (1 year in this study, and probably 2 or more years in future reactors) is important in determining the waste heat generation rate. Thus the future requirements for salt mine space can be derived directly from the present study.

The assumptions of the main body of this report represent the continuous operation of 56,000 Mw (thermal) [15,000 Mw (electrical)]. The peak allowable temperature at the walls of the holes containing the waste cans is assumed to be 200°C. For the temperature calculation the cesium and strontium are combined and are assumed to have a 30-year half-life. In the main body of this report, for purposes of cost calculation, the infinite array calculation, shown in Section 3.3 to be conservative by about a factor of 1.7 for 30-year half-life wastes, was used. In this appendix, the more accurate calculations for wastes of 30 years half-life are assumed; that is, the space requirements are a factor of 1.7 less than assumed in the main report. Another assumption is that the mine is located at a depth of 1000 ft, typical of many of the deposits in the United States, and that conventional mining practice is used, modified by the special requirements for handling radioactive materials. (Deeper mines would require more gross space, and shallower mines less space.)

The gross mine space requirements (storage rooms, access tunnels, and all unexcavated salt left for overburden support, barriers, etc.) for disposing of the 30-year-old waste from the continuous operation of a 56,000-Mw (thermal) nuclear power economy in the main body of this report is about 8.9 acres/year. Applying the factor of 1.7 mentioned above as giving a more accurate space estimate for 30-year half-life wastes, a gross annual space requirement of 5.25 acres/year for the same thermal power level is obtained. Thus the yearly space committed in any given year can be determined by ratioing the megawatts obtained from curve (b) of Fig. G-1 to 56,000 Mw (thermal) and multiplying by 5.25 acres [curve (b), Fig. G-2].

Curve (a) of Fig. G-2 shows the cumulative gross salt formation space committed up to any given year. This curve was obtained by a graphical integration of curve (b).

Curve (c) of Fig. G-2 shows the gross salt area which might actually be used by any given date, and is merely curve (a) shifted 33 years to the right: 30 years for the interim storage period and 3 years for the period from the time the fuel went into the reactor until the time it was processed.

It is of interest to note that by the year 2065 only about 30,000 acres (an area less than 7 miles square) will have been committed and, assuming 30 years interim storage, only about one-third of this will have actually been used. Considering the fact that about one-fourth to one-half million square miles of the United States is underlain by salt, even though only a small percentage of the area might be suitable for waste disposal, there would not appear to be any scarcity in the fore-

seeable future. Also, in some of the formations, where the salt deposits are several hundred feet thick, more than one level might be used.

As a point of interest, if the waste were to be stored only 10 years instead of 30 years before burial, the gross space commitments would be increased by about a factor of 1.6. In that case the "space used to date" curve would be shifted back to the left 20 years and multiplied by 1.6. As an example, the space used to 2045 would then be about 16,000 acres.

Referring to the discussion in Section 3.3 concerning wastes aged less than 10 years, it appears that the 1.7 factor is probably still valid. If the interim storage period were to be only 4 years instead of 30, the gross space commitments would be increased by a factor of about 1.75. This is only about 10% higher than that for 10 years interim storage. For 4-years interim storage, curve (c) would be shifted back to the left 26 years and multiplied by 1.75. The space used to 2039 would be about 17,500 acres.

Referring to the cost studies of this report and the paper of Blomeke et al.¹⁹ it appears economical to place the wastes in the mine as early as 4 years out of the reactor. On the other hand, in the interest of conserving salt space, longer interim storage periods may be desirable.

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