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STATUS REPORT ON WASTE DISPOSAL IN NATURAL SALT FORMATIONS

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HEALTH PHYSICS DIVISION

STATUS REPORT ON WASTE DISPOSAL IN NATURAL SALT FORMATIONS

F. L. Parker, L. Hemphill, and Julian Crowell

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STATUS REPORT ON WASTE DISPOSAL IN NATURAL SALT FORMATIONS**

By F. L. Parker,* L. Hemphill,* and Julian Crowell+

The hazards created by radioactive fallout from the weapon-testing programs prompts an investigation into the source, magnitude, and disposition of the other radioactive debris generated in our nuclear age. The major source of radioactive wastes from peacetime uses of nuclear energy will be those produced by the irradiation of fissionable fuel in nuclear power reactors. The present rate of world-wide bomb testing has been estimated to be 10 megatons of fission bombs per year.(1) This rate could be continued with safety for the next thirty years, but should be reduced to 5 megatons per year for indefinite testing.(1) If the growth of nuclear power in the United States proceeds as predicted by Lane, we may expect to have 700,000 megawatts (thermal) of installed capacity by the year 2000.(2) Assuming a utilization factor of 100 per cent, we shall produce over five hundred times as much radioactive waste per year as we are producing in bomb tests. If we assume that world-wide usage of nuclear energy will approximate that of the United States by the year 2000, peacetime uses will generate a thousand times more fission products than bomb tests. The total peacetime fission-product load is actually greater, because megaton bombs send over half of their fission products into the stratosphere

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**For Hearings on Industrial Radioactive Waste Disposal Problems before the Special Subcommittee on Radiation of the Congressional Joint Committee on Atomic Energy.

where the average airborne time is ten years, allowing for decay of many of the short and intermediate-lived fission products before their return to the earth by fallout.[3] Therefore, it is imperative that safe means be found to handle the radioactive waste products from nuclear reactors.

Sources of Radioactive Wastes

The major source of radioactive wastes in the future will be from stationary central power stations. Radioactive wastes from marine, research, test, irradiation, and package power reactors will be negligible in comparison. The fission products are formed when a neutron splits the fissionable atom into two unequal fragments (fission products) with the simultaneous release of neutrons and energy. Fission products, the principal radioactive constituents of reactor wastes, are produced in individual yields ranging from 0.00001 to 6.5 per cent. This is a function of the fissionable material and the energy of the neutrons. The fission products remain inside the fuel elements in a heterogeneous type reactor until the fuel elements are dissolved. If the nuclear economy were such that the fuel elements could be stored until the fission products decay, then the waste-disposal problem would be relatively trivial, involving only the safe storage of solid fuel elements. However, the present low burnup of the fissionable material, approximately 2-20 per cent, makes it necessary to process the fuel elements to recover the unspent fissionable material. If, in the future, high burnup rates can be achieved, chemical reprocessing of the fuel elements may not be necessary. It is also possible that the supply of fissionable material, at reasonable cost, may become so great that the reprocessing and recovery costs are greater than the cost of initial mining and processing. For the present, at least, it is necessary to reprocess the fuel elements to recover the fissionable material. Many

schemes have been developed to reprocess present-day fuel elements as well as proposed elements. The fuel reprocessing field is in a constant state of flux. Therefore, we have limited our interest, initially, to the two existing processes producing the largest volumes of waste. Eventually the other waste streams will be studied.

Waste Processes

The two processes of immediate interest are called Redox and Purex. Their characteristics, as well as those of other processes now in use, are given in Table I.[4] The fuel elements are removed from the reactor and cooled, allowing the shorter half-lived fission products to decay. The fuel element is then dissolved. The Purex and Redox systems, being aluminum clad and aluminum alloyed, use nitric acid. Stainless steel and zirconium fuel elements would have to be dissolved in aqua regia and gaseous HCl respectively. The fissionable and fertile materials are then separated from the fission products and cladding material by solvent extraction. The uranium is soluble in the organic solution and is separated from the aqueous phase containing the fission products and cladding material. This is repeated a number of times to gain the required purity for the reclaimed fuel. The Purex and Redox systems differ in their organic solvents and the salting agents used to help the separation, 30 per cent TBP in hydrocarbon and HNO_3, and hexone and $Al(NO_3)_3$ respectively. Over 99.9 per cent of the fission products are removed in the first solvent extraction. Table II[5] shows the chemical constituents of the first cycle extraction as well as the volume and activity of the waste to be expected.

Magnitude of Waste Problem

Based on the predicted growth of the electrical industry and the

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TABLE I. PROCESSES FOR CHEMICAL SEPARATION OF FISSIONABLE MATERIALS

Process	Organic Solvent	Aqueous Solvent	Irradiated Metal Feed	Salting Agent
For Separation and Decontamination of U and Pu				
Redox	Hexone	HNO_3	Natural U, Al can	$Al(NO_3)_3$
Metal Recovery	12.5% TBP in hydrocarbon	HNO_3	Caustic precipitated U, fission products	HNO_3
Purex	30% TBP in hydrocarbon	HNO_3	Natural U, Al can	HNO_3
TTA chelation	0.25 M TTA in hexone	HNO_3	Natural U, Al can	$Al(NO_3)_3$
For Separation and Decontamination of Enriched U and Al				
25	Hexone	HNO_3, $Hg(NO_3)_2$ catalyst	U-Al alloy	$Al(NO_3)_3$
25, TBP	5% TBP in hydrocarbon	HNO_3, $Hg(NO_3)_3$ catalyst	U-Al alloy	HNO_3-$Al(NO_3)_3$

TABLE II. CHARACTERIZATION OF FIRST CYCLE HIGH LEVEL AQUEOUS WASTES FROM SELECTED SOLVENT EXTRACTION PROCESSES(1)

Process	Chemical Properties, Constituents (M), Approximate, Exclusive of Fission Products and Heavy Elements																		Waste Volume, gal/g U^{235} Consumed (4)	Approximate Specific Gravity	Approximate Concentration of U in Feed g/liter	Waste Activity(2 × 5)		
	H	Al	Fe	Cr	Ni	Zr	Na	NH_4	NH_3	Sn	Mn	Mg	Hg	NO_3	F	SO_4	PO_4	Cl				curies/gal	Total watts/gal(3)	BTU/hr/gal
Redox	-0.2	1.2	*	*	*		0.46							4.1					0.27	1.18	450	1720	8.6	29.4
Purex	2.5 to 7.0		*	*	*		*							2.5 to 7.0		*			0.34	1.07	300	1320	6.7	22.7
Hexone-"25"	-0.2	1.5	*	*	*			0.5					0.01	4.5					0.31 to 0.13	1.23	2-5	1620 to 3940	8.1 to 20.2	27.7 to 69.0
TBP-"25"	0.5	1.6	*	*	*								0.01	5.5		0.02	*		0.22 to 0.11	1.29	3-6	2580 to 5160	12.9 to 26.0	44.1 to 88.6
Zirconium-HF for enriched U	0.8 to 2.0	0.8		0.1		0.5				0.02				2.3	3.0				~1.50	~1.1	0.3	350	1.75	6.0
Stainless Steel-H_2SO_4 for enriched U-235	2.6	0.25	0.05	0.01	0.03		*				0.001			2.4		0.30			~0.35	~1.3	2-3	1500	7.5	25.0

Notes: (1) Wastes are untreated; they are essentially as they leave the solvent extraction plant and are subject to further treatment such as evaporation, neutralization, chemical treatment for fission product removal, etc.

(2) Basis for activity numbers: Irradiation period 4000 mwd/t for natural uranium
5×10^{13} n/cm^2/sec
4000 grams U^{233} chain per ton of thorium
53% burn-up for U^{235} in enriched fuel elements
100 days decay cooling from time of reactor discharge

(3) After 100 days' decay, the distribution of energy is approximately 50% γ and 50% β.

(4) Waste volume per gram U^{235} consumed is an inverse function of burnup; i.e., for hexone-25 at 20% burn-up, the gal/g U^{235} = (53/20) (0.14).

(5) Waste activity varies approximately as the (irradiation level)$^{0.2}$; and indirectly with the concentration of fissionable or fertile material in the fuel.

percentage of that which will be nuclear power, Zeitlin, et al. have predicted the waste volumes and activities to be expected if present processing schemes are used, Figures 1 and 2.[6] Assuming a waste volume of 820 gallons per ton of spent fuel reprocessed and a nuclear generating capacity of 700,000 thermal megawatts and a burnup of 4000 megawatt days per ton, there will be an accumulated volume of one-half billion gallons of waste by the year 2000 and 3.5×10^{11} curies of activity.

If the present system of storing wastes in tanks is continued, the operating and capital cost of storage at $1.00 to $3.00 per gallon for 20 years of waste storage quickly becomes astronomical.[7] The hazard associated with such large amounts of liquid wastes at the surface where they may be subject to earthquake, sabotage, and explosion is great. Therefore, cheaper and safer methods of storage of radioactive wastes are needed. This is a preliminary report describing the advantages and problems of one suggested method - ultimate storage or disposal in natural salt.

Disposal of Wastes on Land

At the request of the Reactor Development Division of the AEC, the National Research Council (Earth Sciences Division) called a meeting at Princeton University in September 1955 to discuss the disposal of high level radioactive waste products in geologic structures. The conference was divided into two groups, those concerned with disposal at depths less than 1000 feet below the surface and those concerned with disposal at depths of 10,000 to 15,000 feet. As a result of these deliberations, the order of feasibility of radioactive waste disposal in geologic structures was determined to be: (1) storage in salt beds, salt domes, abandoned salt mines, and related structures; (2) storage of ceramic material or a slag formed from high-level wastes in sheds on the

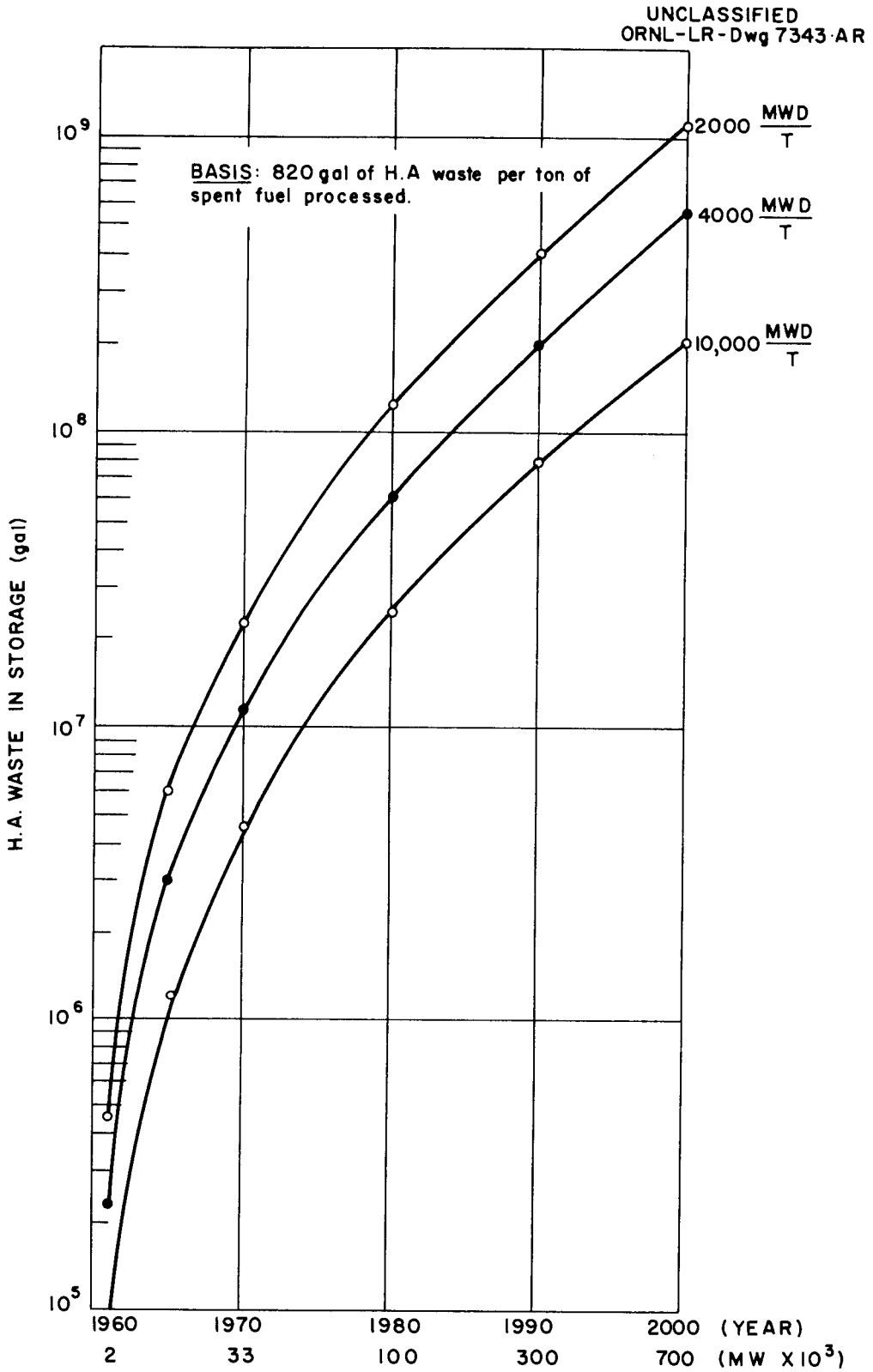

Fig. 1. Accumulated Volume of High Activity Waste.

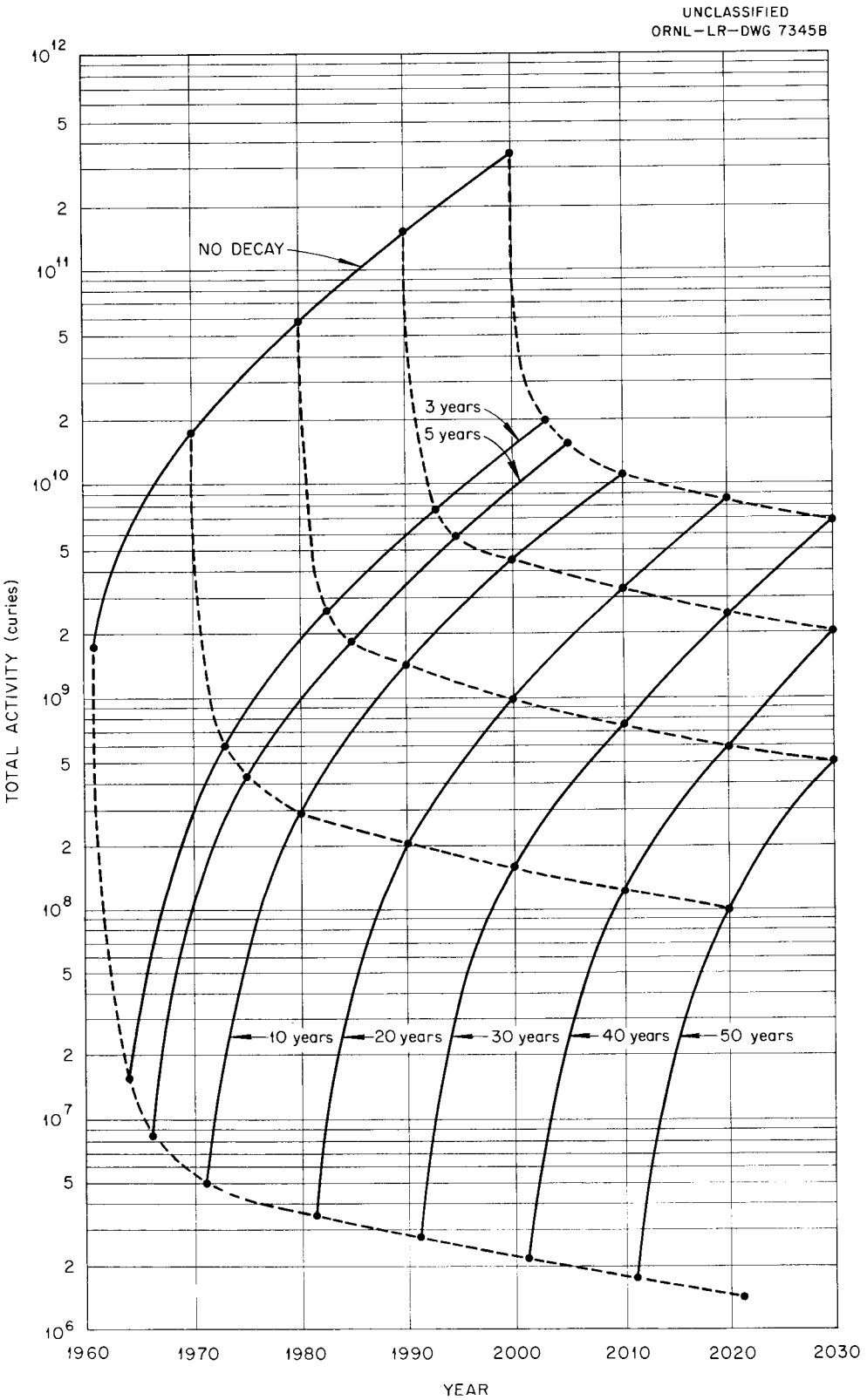

Fig. 2. Total Accumulated Activity Resulting from a Predicted Nuclear Power Economy.

surface in arid areas, or in dry mines; (3) disposal of the liquid wastes in porous media such as sandstone at comparatively great depths.[8]

Disposal of Wastes in Salt Cavities

The suggestion for the use of cavities in salt formations for the storage of radioactive wastes was prompted by the knowledge that the petroleum industry has been storing liquified petroleum gases economically and safely in salt formations since 1950. The first storage in dissolved cavities in salt beds took place at Hutchinson, Kansas, and Upton County, Texas, in 1949. However, it was not until 1950 that storage in the Keystone Oil Field of Winkler County, Texas, proved so successful that the use of underground storage in salt for petroleum products was widely accepted.[9] The growth in storage capacity since that time has been spectacular, from zero storage in 1950 to 7,000,000 barrels* in 1952, and over 25,000,000 barrels in early 1957.[8][10]

The use of salt cavities for the storage of liquified petroleum gases was based upon lower costs and greater safety. Figure 3 shows comparative costs for surface and underground storage.[11] For large volumes dissolved or mined caverns are much cheaper per unit volume than above ground storage. The greater safety of underground storage from a strategic point of view is obvious. It provides the maximum possible protection against the hazards of our nuclear age.[12]

If the disposal of radioactive wastes in salt should prove equally successful, then one of the most vexing problems in the nuclear power complex would be solved.

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*42 gallon barrels.

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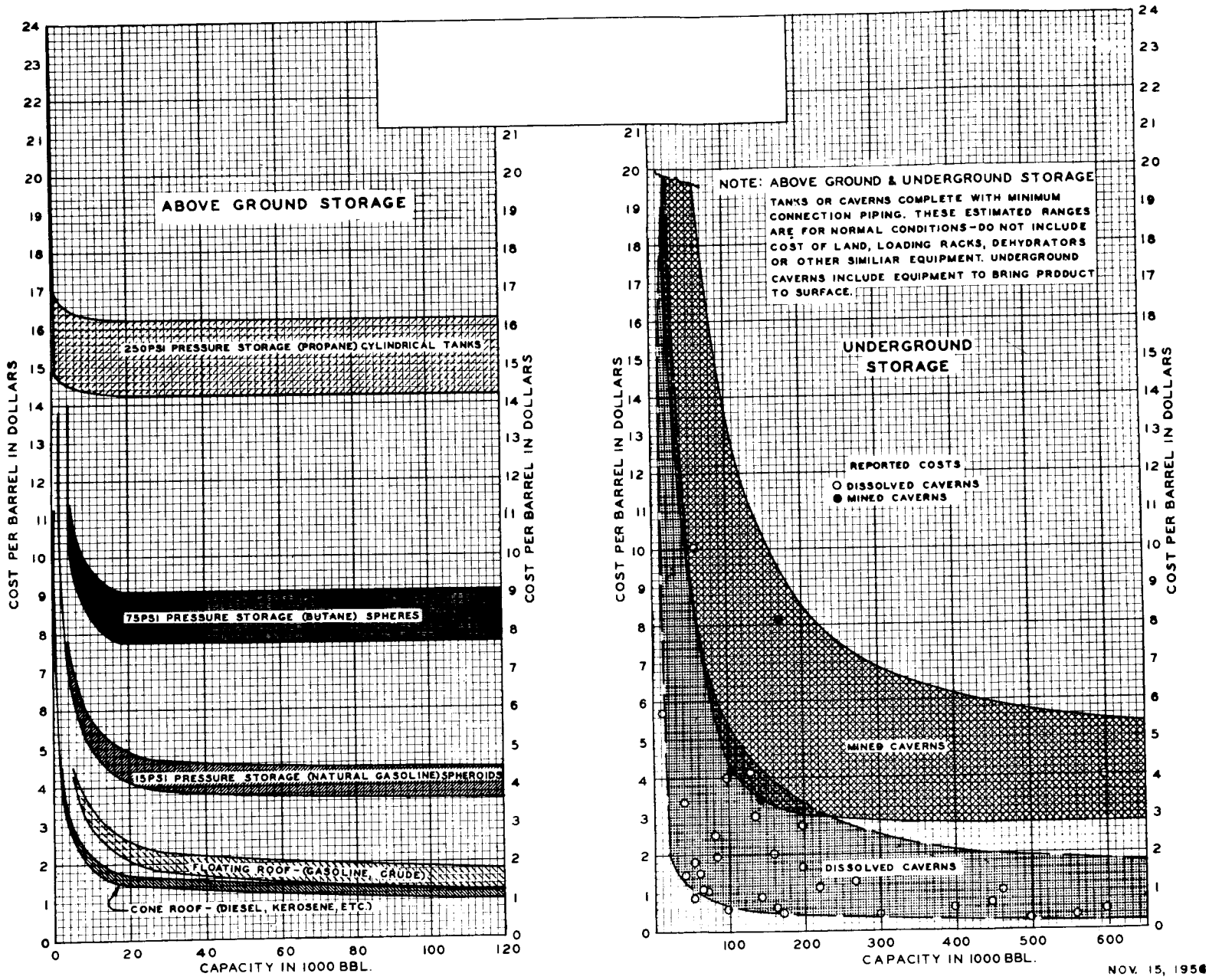

Fig. 3. Comparison of Construction Cost Ranges for Various Types of Product Storage.

Advantages of Disposal in Salt Cavities

The proposed use of salt formations as a storage and disposal media for radioactive wastes is predicated upon the following properties of salt:

(1) Impermeability of Salt. Salt is impervious to the passage of water. Since salt goes so easily into solution, approximately 36 grams per 100 milliliters of water, we can reason that if water had been able to penetrate any of the salt formations, it would have left cavernous holes and caves similar to those developed in limestones by the passage of water through cracks and faults. Actually, we could expect even larger holes and caverns in salt than in limestone on the basis of the relative solubility of salt and dolomitic limestone: (35.7 gm compared to 0.032 gm per 100 ml of cold water) a ratio of 1100 to 1.

However, the salt has moved plastically to repair these cracks and faults and, therefore, only the surfaces of the deposits have come into contact with water. The plastic movement of salt is well illustrated above the potash mines of Carlsbad, New Mexico, where surface slumps of 5 to 7 feet have occurred without cracks appearing in the salt formation overlying the potash.

In salt mines some empirical tests have also shown the plastic movement of salt. At the Neu-Stassfurt Mine in Germany, at the turn of the century, measurements were made by placing fitted lead bars into holes 40 millimeters in diameter and 50 centimeters deep.(13) The bars at a depth of 1640 feet were jammed after a few months, those at 964 feet jammed after 2 years, and above 820 feet the holes remained open. Few of the salt mines in this country are below 1000 feet. Hence, there are few measurements of plastic flow under conditions likely to occur in mines. Most tests have been short-term tests, whereas in a disposal site we would be most concerned about the long-term

effects of moderate loads continuously applied. Other manifestations of the plasticity of rock salt are shown by the solid state physicists who cleave off the surface layers of salt crystals and then bend them into random shapes. Barnes also comments upon the plasticity of salt after the surface of the crystal has been wetted.[14] This accomplishes the same thing as the cleavage; the stressed planes are either annealed or removed.

A massive illustration of the plasticity of salt is shown in the salt domes of the Gulf Coast area. Here the salt has flowed plastically through weaknesses in the overburden to form large plugs of salt in and among the overlying sediments. This will be discussed in greater detail in the section on the geology of the salt formations.

There is some disagreement as to the impermeability of salt. Tests during the development of dissolved cavities in salt have shown that salt may be somewhat permeable. In these solution cavities, however, it is possible to have lenses of impurities and it may be through these layers, or along the interfaces, that the fluid moves. However, liquified petroleum gases (LPG) and gasoline have been stored in salt without losses and salt mines have been operating for over 100 years without evidence of seepage of water. Therefore, the wastes stored in salt should not reach nor contaminate surface or ground waters due to the fact that they will not come into contact with these waters.

(2) Wide Distribution of Salt. Salt is widely distributed, as shown in Figure 4.[15] Except for the Pacific Coast States, rock salt deposits are relatively close to all major population centers of the United States. The cost of shipping fuel elements to the fuel element reprocessing plant at the disposal site, or from the reprocessing plant to the disposal site, is a major cost in the over-all fuel recycling-waste disposal cycle, as high as 60 to 70

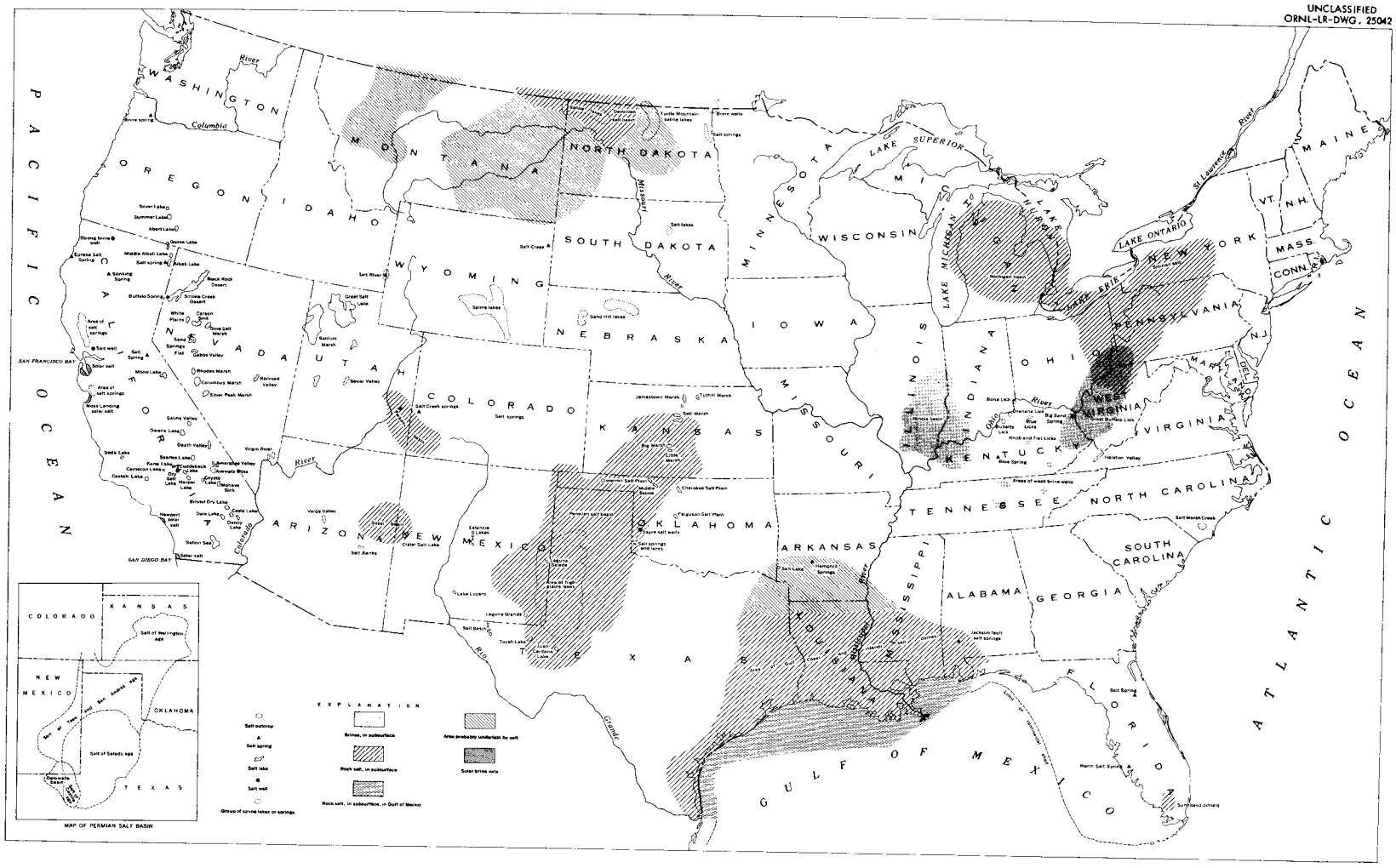

Fig. 4. Index Map of Salt Occurrences in the United States.

per cent.[16] Therefore, the short distances from nuclear power plants to the salt-disposal sites could be a major saving.

Halite, or sodium chloride, as it occurs in nature, varies to a marked extent depending upon its history. Having been usually formed by the concentration of saline waters and the precipitation of salts, the bedded deposits are interstratified with the other sediments of the saline waters - commonly clay, marl, sandstone, limestone, gypsum, anhydrite, dolomite, and shale. Consequently, the constituents of salt and its properties can vary quite widely.

There are two basic types of salt structures, bedded and dome. The salt formations in the northern part of the United States as typified by the deposits in the Salina formation underlying 100,000 square miles beneath New York, Pennsylvania, West Virginia, Ohio, and Michigan; the Permian formation underlying 120,000 square miles beneath Kansas, Colorado, Oklahoma, Texas, and New Mexico; and the Charles and Jefferson formations in the western part of the United States, underlying 15,000 square miles beneath Montana and North Dakota, are bedded deposits of sedimentary origin. There the salt occurs in beds of variable thicknesses with overlapping lenses of varying purity. A known stratigraphic succession of the layers of rock salt beds cannot be predicted to extend for distances of more than a few hundred feet, though it may extend many miles. Commercially important deposits of bedded salt are found in New York, Michigan, Ohio, and Kansas. They extend from the outcrop downward to depths of more than 5,000 feet.

Bedded salt also occurs in several western states. Salt of Permian age is found in the Sevier Valley in Utah. Salt, believed to be of Pennsylvanian age, occurs in the Colorado River drainage in eastern Utah and western Colorado,

the Paradox salt basin. The extent of the salt has not been fully determined but apparently is not less than 10,000 square miles.

In the southwest, salt occurs in the Delaware Basin of New Mexico and Texas. The margins of the area are known only approximately, but the total area underlain by salt may be as large as 70,000 square miles.

In northern Louisiana, southern Arkansas, and east Texas, bedded rock salt of Jurassic (or Permian) age has been reached in widely separated wells. The Eagle Mills (Louann) salt is seldom fully penetrated in wells, but thicknesses of 500 to 1500 feet are normal. It is estimated that this horizon underlies an area of 180,000 square miles on the Gulf Coast. Salt domes also rise from this formation.

The greatest number of salt domes in the United States occurs in the Gulf Coast section, though several salt anticlines and domes have also been found in southeastern Utah and southwestern Colorado. Here salt from older sedimentary formations has flowed upward through fractures and weaknesses in the overlying rocks (sp. gr. 2.6 vs. sp. gr. 2.2 for salt) to form plugs and domes in the overlying sediments. The diameter of the plug may be as much as 4 miles. The distance to the top of the domes varies from just below ground surface to depths greater than 10,000 feet.

The known salt domes are over 200 in number. The best known group of salt domes is the Five Islands of southern Louisiana, characterized by surface uplifts overlying the salt masses, and by the shallowness of the salt, less than 300 feet from the surface. At a depth of 1000 feet, these domes are a mile or more in diameter.

A more detailed description of the location of salt deposits is presented in the Appendix to reference 8.

At present the main interest in salt domes has been that of oil companies searching for oil along the salt barriers. The oil companies are also finding it highly profitable to store 1 billion gallons of LPG in cavities created by solution mining in salt domes. This is more than four times the volume of high-level radioactive wastes expected to be produced from now till the year 2000.

(3) Volume of Salt. The volume of salt in these domes in Texas and Louisiana alone is more than 3×10^{11} cubic feet at depths less than 1000 feet and more than 5×10^{12} cubic feet at depths less than 5000 feet,[17] or enough to provide the world's need of salt (at the present rate of consumption) for over 6000 years. These deposits, of course, are infinitesimal in comparison to the enormous amounts in the bedded deposits underlying wide geographic areas.

As of 1943, the estimated reserves of salt in the various states totaled 60,000 billion tons as shown in Figure 5.[18] In Figure 4 it is observed that large deposits of salt in North Dakota, Montana, Arizona, New Mexico, Arkansas, Mississippi, and Alabama, have been located since that time, and this estimate must, therefore, be increased. It is obvious that there is no shortage of salt. There is little likelihood that we will contaminate or render useless a valuable natural resource. There remains, of course, the salt in the ocean if that improbable event should occur. If all the salt in the ocean were recovered it would total 4 1/2 million cubic miles.

(4) Structural Properties of Salt. The strength of salt as a structural material is such that cavities 100 feet high, 100 feet wide, and 3000 feet long, can be opened at depths 700 feet below the ground surface and remain open without support of any kind. Figure 6, taken at the Kleer mine

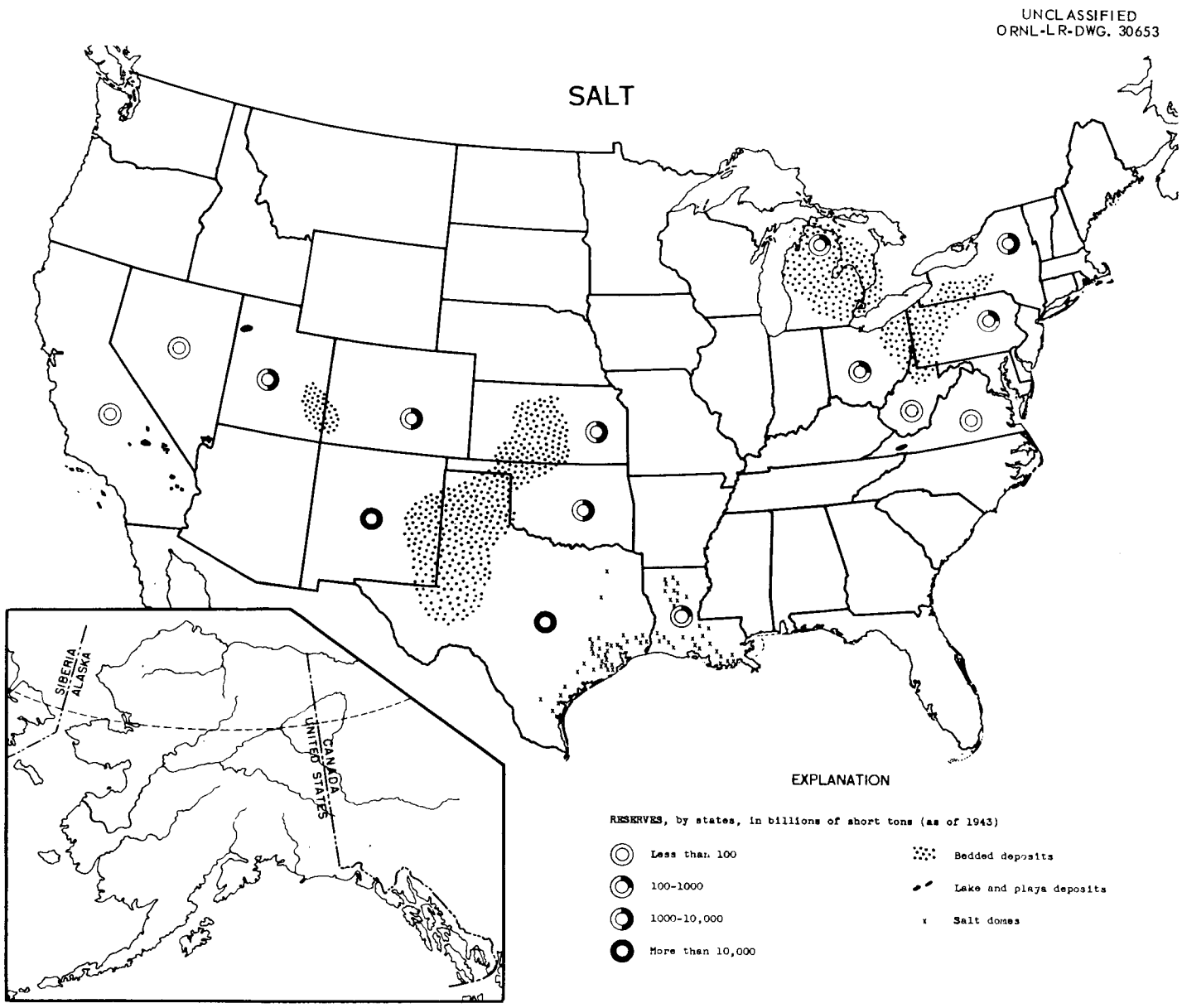

Fig. 5. Distribution of Estimated Salt Reserves of the United States as of 1943, by States.

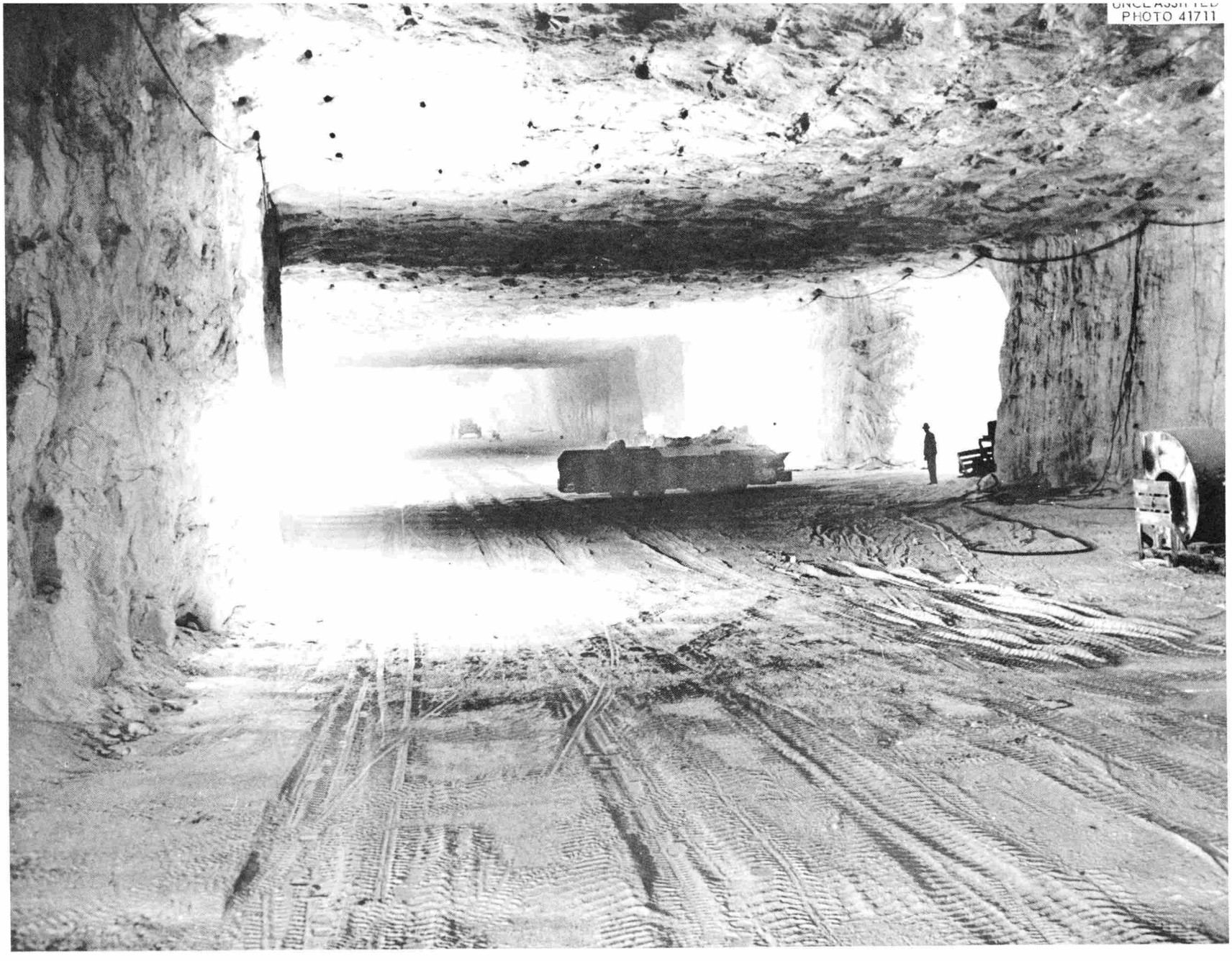

Fig. 6.

of the Morton Salt Company at Grand Saline, Texas, shows the inside of a typical dome deposit mine. In Colombia, South America, there is even a cathedral inside a salt mine. The compressive strength of rock salt is about 5000 pounds per square inch. This compares with a compressive strength of 50,000 pounds per square inch for steel, 12,000 pounds per square inch for granite, and 5000 pounds per square inch for sandstone. As discussed earlier, the physical constants given for salt are a function of the history and composition of the specimen and the variations in samples can be quite striking.

(5) Thermal Conductivity of Salt. Salt has a high coefficient of thermal conductivity in comparison to other rocks as shown in Table III.

The higher coefficient of thermal conductivity, though low by comparison with the metals, will enable the heat generated by the fission product decay to be more quickly dissipated to the surrounding areas than would be possible in other rock media.

(6) Containment in Salt. One other advantage in the use of salt as a disposal medium for radioactive wastes is that radioactive materials still remain accessible if, at some future time, recovery should seem desirable. The value of some of the rarer elements produced by fission-product decay could help to pay for the disposal operations. Other disposal methods preclude the recovery of valuable by-products, except at extraordinary effort and expense. Glueckauf has estimated, at 1955 prices, that the resale of the decayed fission products - ruthenium, rhodium, palladium, and xenon - alone would amount to $180,000 per ton of U235 burned.[19]

(7) Economics of Developing Space in Salt. The cost of developing space in salt formations is low. Under average conditions solution cavities can be formed for 1 to 5 cents per gallon for capacities of 1 to 2 million

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TABLE III.
THERMAL CONDUCTIVITIES

MATERIAL	TEMPERATURE (°C)	Btu/(hr (sq ft) (°F/ft)
COPPER	100	222.8
IRON (99Fe 1 C)	100	26.1
BASALT	20	1.3
CONCRETE	20	0.5
EARTH'S CRUST, AVG.	20	1.0
FELDSPAR	20	1.4
GYPSUM	0	0.8
QUARTZ ⫼ TO AXIS	100	5.2
⊥ TO AXIS	100	3.2
ROCK SALT	100	2.8
SANDSTONE	40	1.1
SOIL, DRY	20	0.1

gallons.[20] Larger cavities are cheaper. Wells are drilled to the rock salt and water pumped down to dissolve the salt, and then the brine is pumped back to the surface. Solution cavities, in addition to their lower cost, could handle liquid wastes and even some solid wastes. Excavated cavities are higher in price; normal costs range from 2[21] to 10 cents per gallon.[20] The structural qualities of salt allow modern excavating equipment to be used without regard to headroom considerations as is evident in Figure 6. Therefore, space can be easily and cheaply mined; in fact, so much so that the salt sells for as little as $3.00 per ton at the mine.[22] Mined cavities allow access to the disposal area, give greater flexibility in the use of the space, allow the cavity to be placed in the soundest formations, allow inspection prior to use, and eventually would make recovery of the decayed fission products easier. This would be true for both solid and liquid wastes. Table IV shows the relative advantages of various underground reservoirs for petroleum products.[23] The same relative ratings should hold for underground storage of radioactive wastes.

(8) Seismic Disturbances in Salt Areas. Salt formations are located in areas of low seismicity; therefore, we may expect only small and infrequent disturbances to the structure.

Figure 7 shows that in the areas in which salt formations are located, few, if any, earthquakes of appreciable force have occurred.[24]

Problems in the Disposal of Waste in Salt Cavities

Despite all the favorable factors, the storage of radioactive wastes in salt has not yet taken place because the conditions involved in waste storage will be different than those ordinarily encountered in LPG storage or mining of salt. The degree to which the desired structural properties of salt are

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TABLE IV.

COMPARATIVE RATINGS OF UNDERGROUND RESERVOIRS FOR PETROLEUM STORAGE

Type of Reservoir	Cost of Construction	Lack of Contaminants	Cost of Injection and Recovery	Total of Factor Ratings	Economic Preference Rating
Solution cavity in salt dome	1	1	2	4	I
Solution cavity in bedded salt	1	2	2	5	II
Mined cavity in shale or salt	3	2	1	6	III
Mined cavity in hard rock	5	1	1	7	IV
Natural trap reservoir in porous rocks	1	3	4	8	V
Abandoned mine or natural cavern (would be rated high if easy to seal)	3	5	1	9	VI

Underground storage considered impractical in areas of volcanic rocks, mineralization, extremely complex structure, or excessive general permeability.

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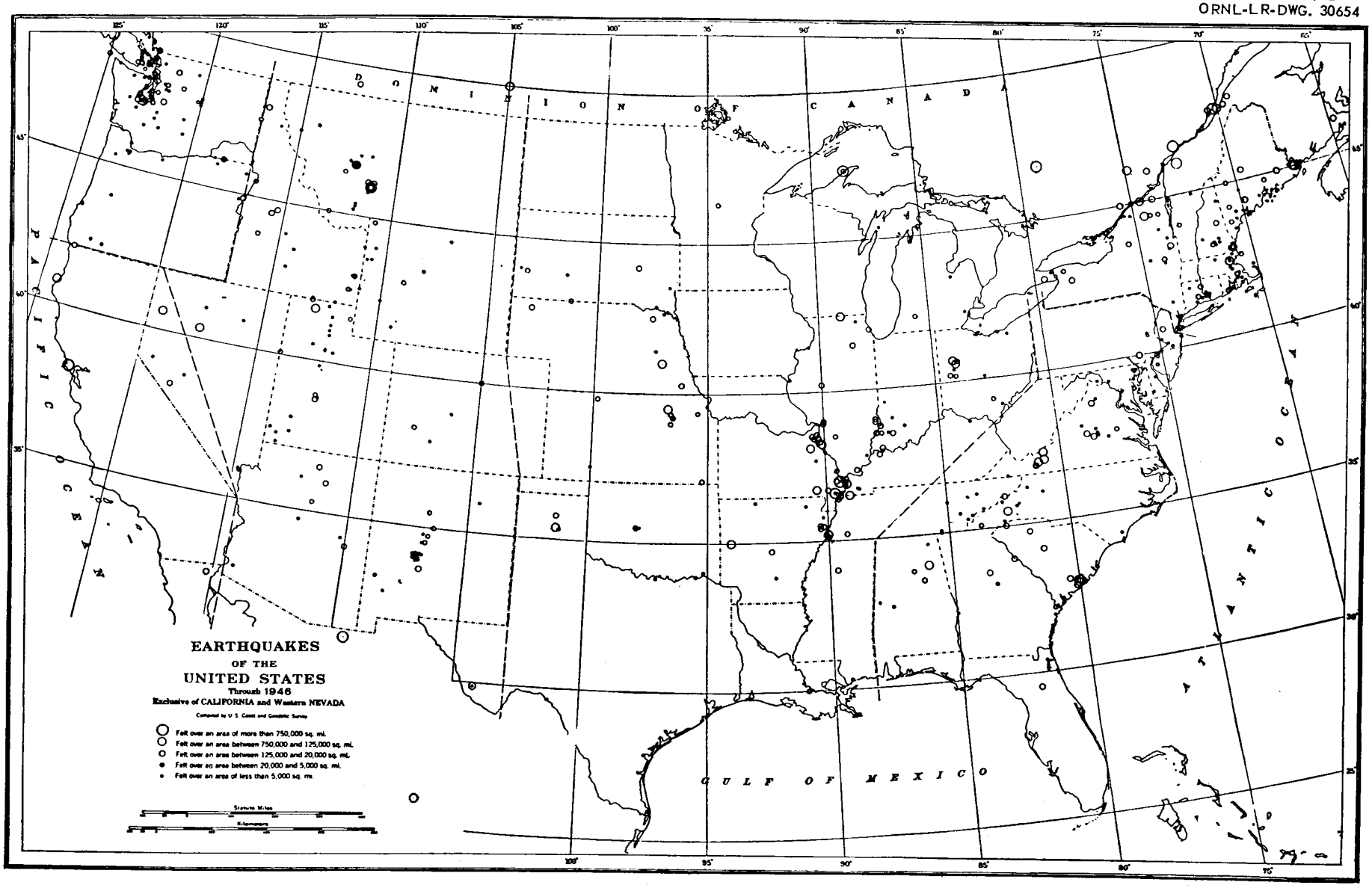

Fig. 7.

affected by liquid wastes, pressure, temperature, and radiation will determine the role of salt in the disposal of radioactive wastes.

A seven-point research program to determine these effects has been initiated at the Oak Ridge National Laboratory as shown in Figure 8.

I Heat Calculations. As will be shown in Section III the plasticity of salt and therefore the structural integrity changes to a considerable degree with temperature and pressure. Therefore, it is necessary to determine the temperature rise in salt due to the storage of radioactive wastes in cavities in salt formations. Initial attempts to determine the maximum temperature possible in a salt cavity have been confined to the simpler geometric cases - flat plane, sphere, and a cylinder.

To further simplify the calculations, the heat generating source (the decaying fission products) was assumed to be constant. The thermal conductivity, the density, and the specific heat were assumed to be independent of the temperature. Finally, the heat was assumed to be dissipated by conduction alone, no changes in state were allowed, no convective currents were permitted in the wastes, and the salt surrounding the cavity was assumed infinite in extent. All these assumptions, except the last one, are on the safe side, that is, in the actual case, the temperatures will be reduced. The solution can be further simplified by solving for the steady state case only.

If the law of conservation of energy is applied, the heat in the sphere after time, t, is equal to the heat originally in the sphere, plus the heat entering, minus the heat leaving, plus the heat generated in the sphere or:

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dT_w}{dr}\right) = \frac{-A_o}{K_w}$$

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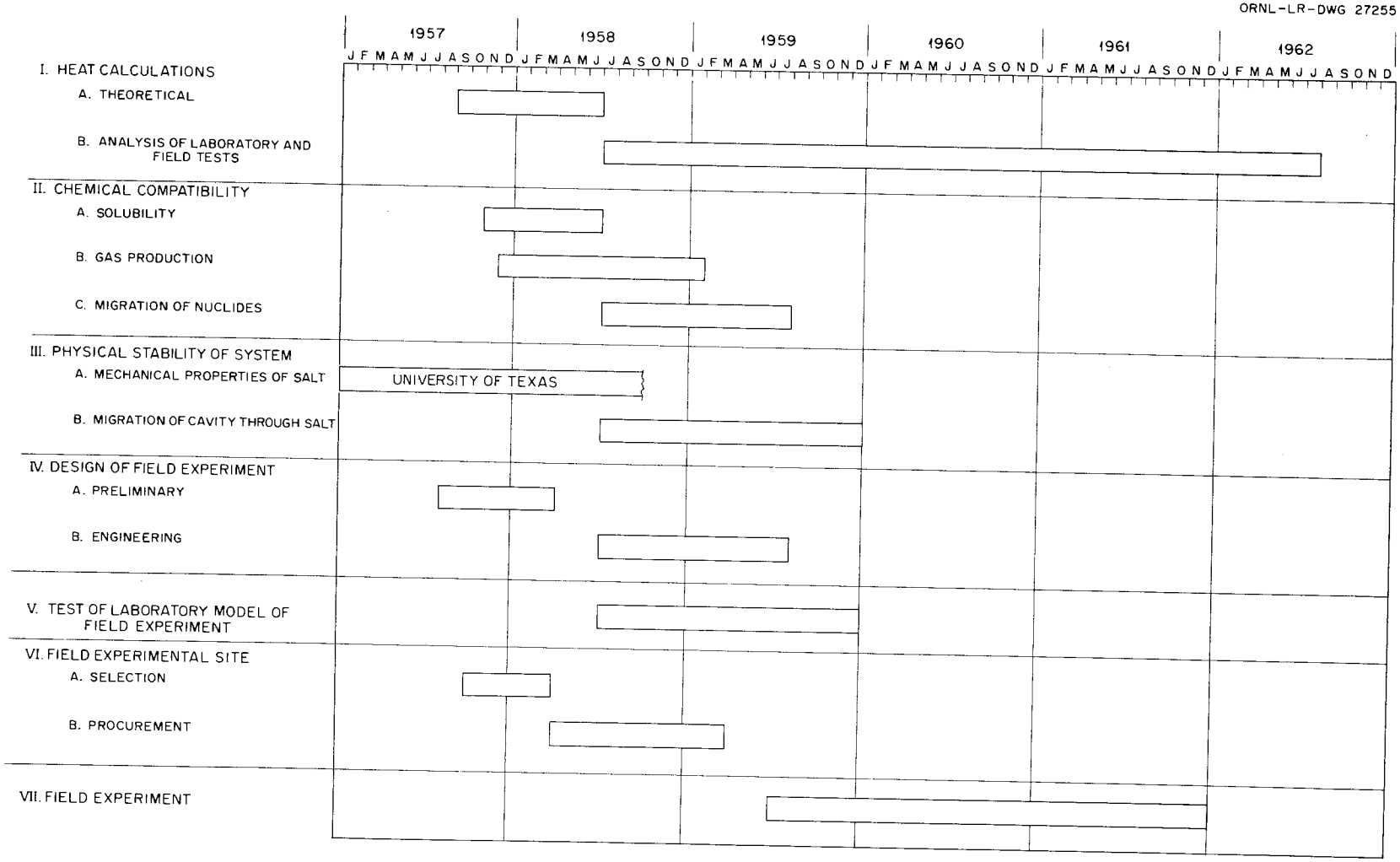

Fig. 8.

And if the law is also applied outside the sphere the equation is:

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dT_s}{dr}\right) = 0$$

Furthermore, if the law of continuity is applied at the boundary of the sphere so that the temperature at the boundary is the same inside and outside the sphere, and if the heat flux at the boundary of sphere is the same inside and outside the sphere, mathematically:

$$T_w = T_s$$

$$\text{and } K_s \frac{T_s}{r} = K_w \frac{T_w}{r}$$

where r = radial distance from center of sphere, Ft

T_w = temperature in the waste solution, ^oF

T_s = temperature in the salt, ^oF

K_s = thermal conductivity, salt $\frac{BTU}{Hr} \frac{Ft}{Ft^2\ ^oF} = \frac{BTU}{HrFt\ ^oF}$

K_w = thermal conductivity, waste $\frac{BTU}{Hr} \frac{Ft}{Ft^2\ ^oF} = \frac{BTU}{HrFt\ ^oF}$

A_o = heat generating source, $\frac{BTU}{Hr\ Ft^3}$

a = radius of sphere, Ft

b = radius of salt media, Ft

t = time, hours

k = thermal diffusivity $= \frac{K}{c\rho} = Ft^2/Hr$

c = specific heat, $\frac{BTU}{lb\ ^{o}F}$

ρ = density, lbs/Ft^3

$C = c\rho$ = specific heat per unit volume $\frac{BTU}{^{o}F\ Ft^3}$

$$\text{erfc } x = 1 - \text{erf } x = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-\xi^2} d\xi$$

$$i^n \text{ erfc } x = \int_x^{\infty} i^{n-1} \text{ erfc } \xi \, d\xi \qquad n = 1, 2, \ldots,$$

β^2 = variable of integration = $\frac{a^2}{4k(\tau - t)}$ and $\frac{a^2}{k(\tau - t)}$

λ = decay constant, $\frac{1}{hours}$

τ = a fixed value of t, hours

If it is further stipulated that the temperature is zero at the outside boundary of the salt and that the rate of change of temperature with respect to the radius at zero radius is zero, then the solution of the steady state temperature in the waste is equal to:

$$T_w = \frac{A_o}{3} \left[\frac{a^2}{K_s} - \frac{a^3}{K_s b} + \frac{a^2}{2K_w} - \frac{r^2}{2K_w} \right]$$

and if b is assumed infinite and r = 0

$$T_w = \frac{A_o}{3} \left[\frac{a^2}{K_s} + \frac{a^2}{2K_w} \right]$$

and if $K_w = K_s$, $T_w = A_o \frac{a^2}{2K_s}$ and if $K_w \longrightarrow \infty$ (that is the waste is considered infinitely well stirred) then:

$$T_w = \frac{A_o a^2}{3K_s}$$

If we limit the maximum temperatures to be permitted at the edge of the sphere, then the maximum concentrations of heat generating sources (fission products) allowed in spheres of various sizes are shown in Figure 9.[25] If it is assumed that there is thermal convection in the wastes, all other conditions remaining the same, then the permitted concentrations of fission products in spheres are shown in Figure 10.[25]

Professor Birch of Harvard University has solved analytically the transient problem for a flat plate and a sphere with a decaying heat generating source for the case of equal conductivity and specific heat for the waste and the salt and for the case of infinite conductivity of the waste or a well-stirred waste.[26] The former is the same as the correct solution for the equations on page 287 and page 288 of Carslaw and Jaeger or:[27]

$$0 \leq r < a \qquad T(r,t) = \frac{A_o t}{C} \left[1 + \frac{2a}{r} \left(i^2 \operatorname{erfc} \frac{a+r}{\sqrt{4Kt}} - i^2 \operatorname{erfc} \frac{a-r}{\sqrt{4Kt}} \right) \right.$$

$$\left. + \; 2 \frac{\sqrt{4Kt}}{r} \left(i^3 \operatorname{erfc} \frac{a+r}{\sqrt{4Kt}} - i^3 \operatorname{erfc} \frac{a-r}{\sqrt{4Kt}} \right) \right]$$

and for $r > a$

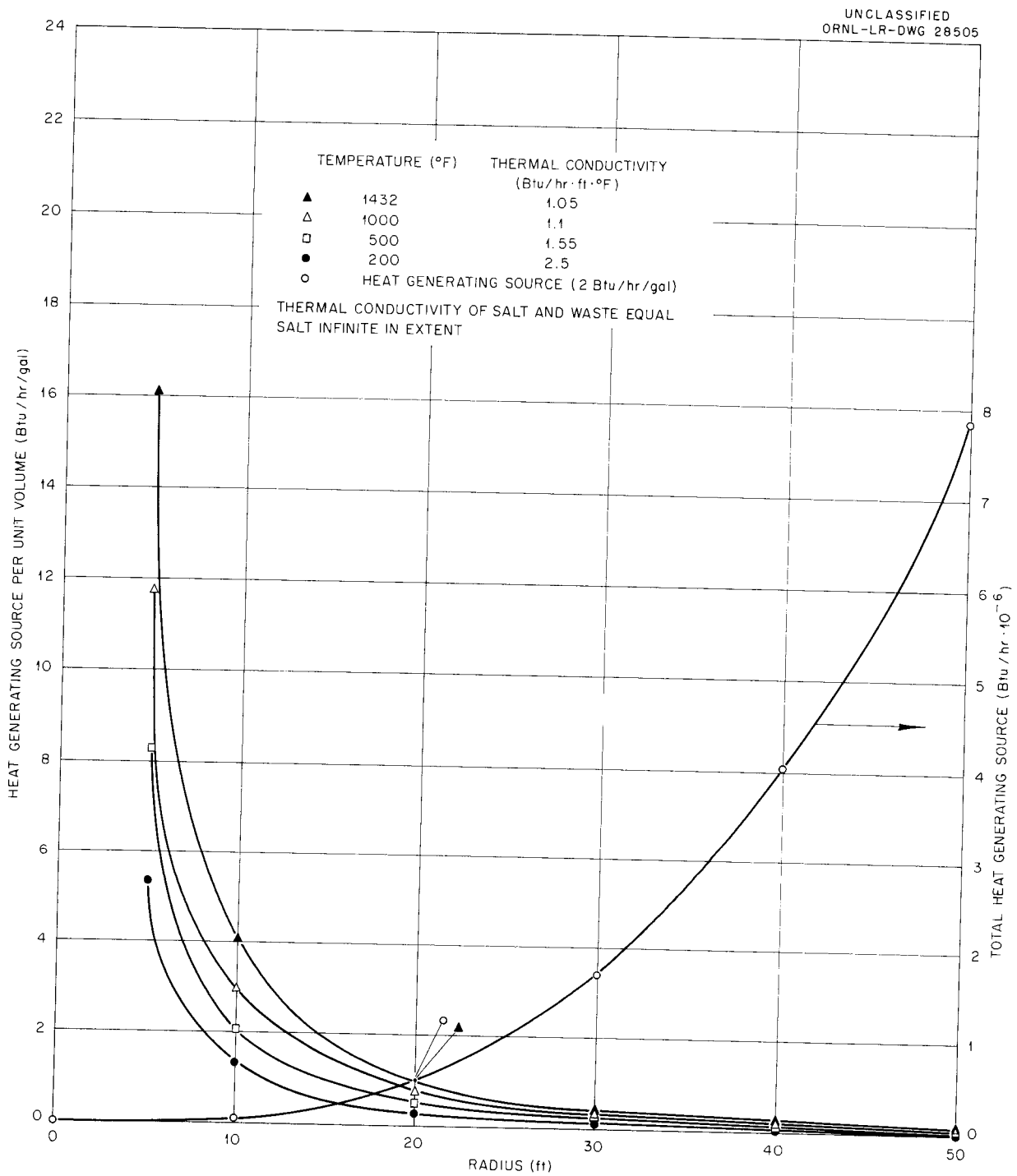

Fig. 9. Heat Source Required to Achieve Steady State Temperature in a Sphere.

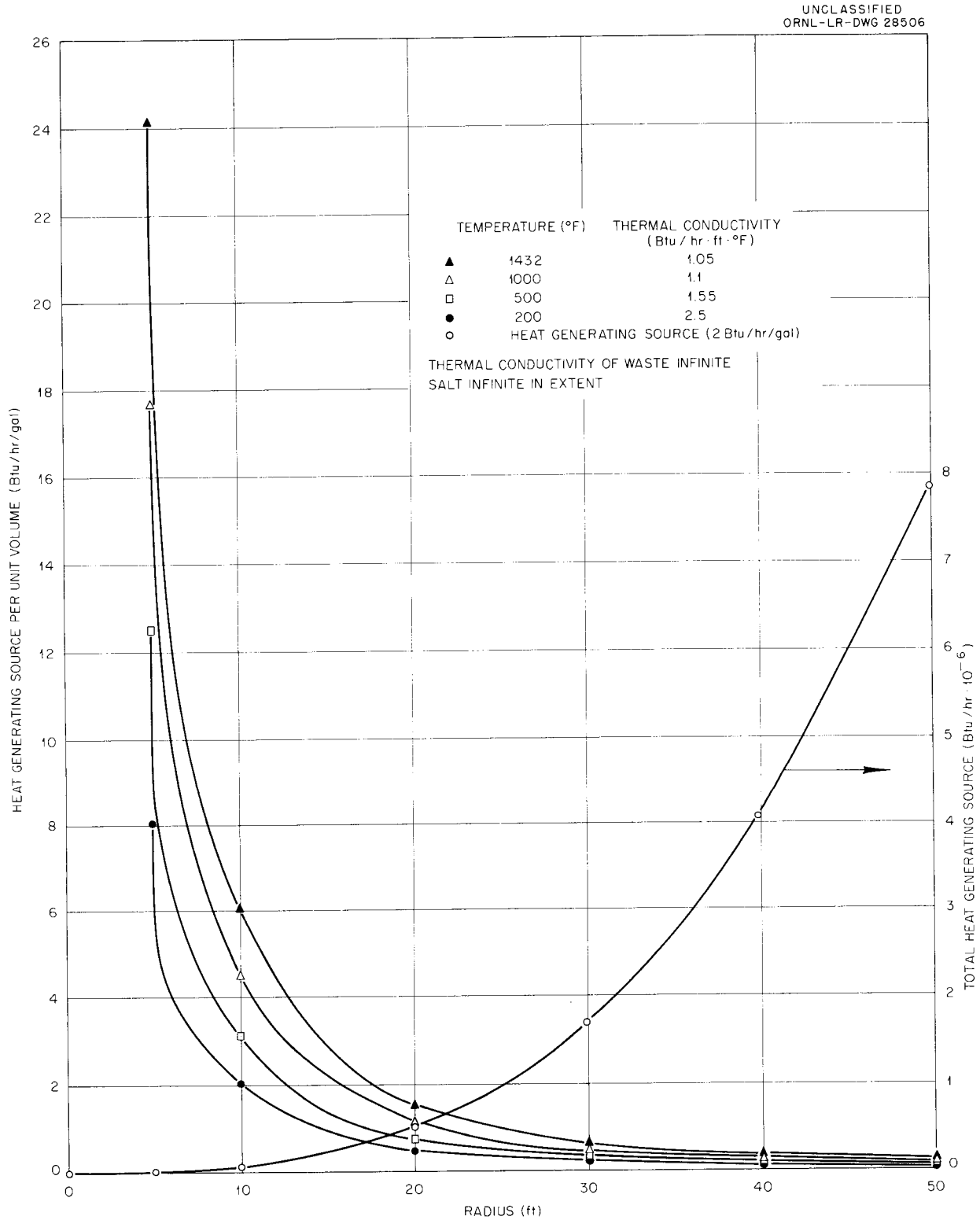

Fig. 10. Heat Source Required to Achieve Steady State Temperature in a Sphere.

$$T(r,t) = \frac{2Aat}{Cr}\left[i^2 \operatorname{erfc} \frac{r-a}{\sqrt{4Kt}} + i^2 \operatorname{erfc} \frac{r+a}{\sqrt{4Kt}} + \frac{4Kt}{a}\left(i^3 \operatorname{erfc} \frac{r+a}{\sqrt{4Kt}} - i^3 \operatorname{erfc} \frac{r-a}{\sqrt{4Kt}}\right)\right]$$

These, of course, reduce to the results obtained by Julian Crowell when the steady state is reached (i.e., when $t \longrightarrow \infty$). When the heat generating source is assumed to decay exponentially, Birch derives the following solution:

$$r = 0; \quad T(0,t) = \frac{A_o a^2}{2CK}\left\{ e^{-\lambda t} \int_{a/\sqrt{4Kt}}^{\infty} e^{\lambda a^2/4K\beta^2}\left(\operatorname{erf}\beta - \frac{2\beta}{\sqrt{\pi}} e^{-\beta^2}\right)\frac{d\beta}{\beta^3}\right\}$$

and for $r = a$

$$T(a,t) = \frac{A_o a^2}{3CK}\left\{ 3e^{-\lambda t} \int_{a/\sqrt{Kt}}^{\infty} e^{\lambda a^2/K\beta^2}\left(\operatorname{erf}\beta - \frac{2}{\beta\sqrt{\pi}}\, 1 - e^{-\beta^2}\right)\frac{d\beta}{\beta^3}\right\}$$

The functions in the last two equations are not tabulated and, therefore, must be integrated numerically.

Numerical integration by hand of a number of cases can be quite tedious. However, Professor Schecter of University of Texas working independently has solved the above equations, assuming a decay rate varying with

time and had it programmed on the ORACLE (digital computer at ORNL). His results give the maximum temperature for any waste concentration in any size sphere for 2, 6, and 10-year cooled wastes.[28] They do not give, however, the time-space distribution of the temperature. The proper size of a test cavern which would give temperature results in a reasonable time was determined by the temperature, time, and space relationship of a 6-year cooled waste, (2 BTU/hr/gal) with a constant heat generating source (for ease in computation).

Based upon Professor Birch's statement, "that heating the liquid some hundred degrees (Centigrade) or so would not produce drastic physical changes, and that plastic deformation of shale or evaporite layers, if sufficiently thick might continue to provide a tight container,"[26] it was decided to limit the temperature rise at the edge of the sphere to 200° F. This would also eliminate any necessary corrections due to changes in state as the temperature is kept below the boiling point of the wastes. Using Crowell's curves, it was found that for 2 BTU/hr/gal waste that a sphere, 10 feet in radius, would not reach a temperature greater than 200° F for the case where the thermal conductivity of the waste is infinite.

Based on Birch's and Goldenberg's equations,[29] the time-space distribution of the temperature for a 20-foot diameter sphere with a constant heat generating source and thermal conductivity of the waste equal to the thermal conductivity of the salt was found to be that shown in Figure 11.

Work is continuing now to determine the time-space distribution of temperature for the case where the heat generating source is decaying as a function of time and where the thermal conductivity in the sphere is equal to infinity.

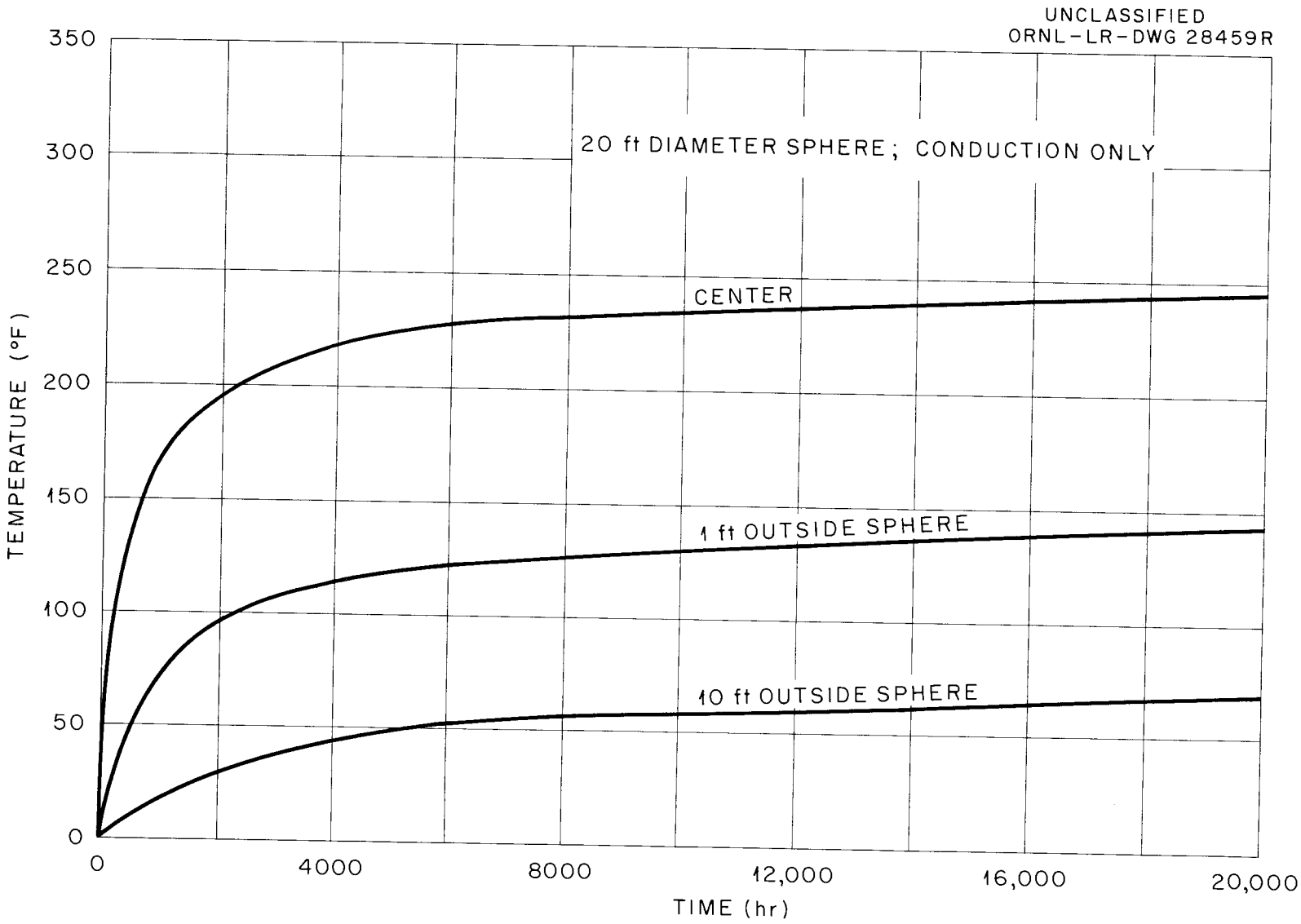

Fig. 11. Time-Space Temperature Distribution of Wastes Stored in Salt Cavities.

In all the cases treated above, the heat has been dissipated solely by conduction. Preliminary studies by G. W. T. Kearsley of the Chemical Technology Division on the use of natural convection for cooling wastes in salt indicate that it may be feasible under certain conditions. Further studies of the use of natural convection systems are under way. Though not restricting ourselves to natural convection and conduction systems, the desirability of such a system is apparent if the cooling periods are considered. If a mechanical cooling system should be required over the long periods that the wastes must be stored, storage in salt cavities might be uneconomical.

II. Chemical Compatibility. Typical chemical composition of rock salt deposits are given in Table V.[30] The chemical composition may be more complex than the simple formulas cited, but these are the compounds analyzed.

Solubility. The studies of the solubility of NaCl and its associated impurities, $CaCl_2$, $MgCl_2$, and $CaSO_4$, with synthetic Purex and acid aluminum nitrate non-radioactive wastes, neutralized and untreated, have shown that the salts are soluble in the neutralized and untreated wastes to the same degree, about 50 to 90 per cent of the solubility in distilled water, depending upon the concentration of the wastes, except for calcium sulfate which is five to ten times as soluble in acid and neutralized solutions. The results obtained by E. Eastwood are shown in Table VI. The solubility changes due to the use of radioactive wastes will be studied.

Gas Production. Chlorine and nitrogen compound gases are generated when the unneutralized wastes and the chloride salts are mixed. The highly acid nitrate wastes upon contact with the sodium chloride oxidizes the chloride and generates a gas which appears to be predominantly chlorine and nitrogen compounds.

TABLE V

COMPOSITION OF ROCK SALT

	Retsof New York	Detroit Michigan	Avery Island Louisiana	Hutchinson Kansas	Natrium West Virginia
Moisture %	0.015	0.114	0.019	0.670	0.350
Water insoluble %	0.962	0.756	0.711	1.407	1.070
$CaSO_4$	0.743	0.872	0.225	0.857	1.600
$CaCl_2$	0.006	0.053	0.010	0.034	0.230
$MgCl_2$	0.002	0.024	0.009	0.066	-----
$MgSO_4$	-----	-----	-----	-----	-----
Na_2SO_4	-----	-----	-----	-----	-----
K Cl	-----	-----	-----	-----	0.310
NaCl	98.262	98.181	99.026	96.970	96.440
	99.990	100.000	100.000	100.04	100.00

SOLUBILITY (g/100 ml)

Waste Type	Rock Salt Grand Saline			Sodium Chloride Analytical Reagent Grade			Calcium Sulfate Analytical Reagent Grade			Magnesium Chloride Analytical Reagent Grade			Calcium Chloride Analytical Reagent Grade		
	2°C	23°C	70°C	2°C	23°C	75°C	2°C	23°C	70°C	2°C	22°C	70°C	2°C	23°C	74°C
Distilled water	32.2	32.5	31.6	31.5	32.5	31.7	0.21	0.21	0.20	44.0	45.5	48.3	51.8*	51.1*	75.2*
2 M HNO_3	26.3	26.9	26.5	25.3	26.9	25.8	1.59	1.65	1.60	41.4	42.7	45.9	49.2*	40.5*	57.2*
4.5 M HNO_3	19.3	20.5	19.1	21.3	20.8	22.4	1.76	1.71	1.83	36.6	40.5	46.3	60.0*	56.1*	63.4*
7.0 M HNO_3	18.1	18.1	17.6	18.2	19.0	17.4	1.93	2.06	2.64	32.7	38.3	41.1	55.4*	42.8*	55.9*
0.10 M HNO_3 1.6 M $Al(NO_3)_3$	23.4	23.1	23.1	22.8	23.4	23.6	1.94	2.03	2.06	36.4	40.3	41.5	42.0*	43.2*	48.3*
0.16 M HNO_3 1.6 M $Al(NO_3)_3$	21.5	22.2	22.0	21.6	22.5	22.1	2.09	2.22	2.11	37.8	41.2	39.6	41.6*	42.7*	41.7*
0.22 M HNO_3 1.6 M $Al(NO_3)_3$	23.2	23.1	22.9	21.3	22.8	21.8	2.03	2.00	2.21	35.2	39.3	40.5	41.9*	40.5*	44.0*

*Formed Gel – Difficult to sample.

SOLUBILITY (g/100 ml)

pH7 With NaOH	Rock Salt Grand Saline			Sodium Chloride Analytical Reagent Grade			Calcium Sulfate Analytical Reagent Grade			Magnesium Chloride Analytical Reagent Grade			Calcium Chloride Analytical Reagent Grade		
	2°C	23°C	88°C	2°C	23°C	85°C	2°C	23°C	85°C	2°C	23°C	80°C	2°C	23°C	85°C
Distilled water	31.4	32.9	32.7	31.9	32.3	32.4	0.19	0.20	0.19	43.8	45.4	47.6	49.4*	58.8*	71.2*
2 M HNO_3	27.6	28.3	27.6	27.9	28.3	28.8	0.69	0.72	0.69	41.2	42.4	46.0	45.6*	53.6*	62.8*
4.5 M HNO_3	24.9	25.0	24.1	24.4	24.5	24.7	0.90	0.90	0.80	38.8	42.7	44.0	*	52.4*	63.0*
7.0 M HNO_3	21.5	21.2	21.6	21.9	22.3	24.0	0.90	0.89	0.83	38.3	39.1	40.0	*	54.2*	65.4*
0.10 M HNO_3 1.6 M $Al(NO_3)_3$	18.0*	20.2*	18.0*	20.4*	24.3*	19.7*	3.49*	3.36*	2.92*	38.4*	42.2*	42.7*	*	74.7*	69.8*
0.16 M HNO_3 1.6 M $Al(NO_3)_3$	19.0*	20.4*	23.1*	15.9*	22.1*	17.9*	3.40*	3.42*	3.25*	38.6*	42.4*	42.8*	*	68.0*	69.2*
0.22 M HNO_3 1.6 M $Al(NO_3)_3$	18.3*	20.7*	18.5*	21.3*	23.5*	20.3*	3.38*	3.25*	2.95*	38.2*	41.6*	42.8*	*	72.6*	66.2*

*Formed Gel – Difficult to sample.

TABLE VI. SOLUBILITY OF SALTS IN WASTE SOLUTIONS.

The rate, volume, and composition of the gas under the varied conditions outlined above are presently under study at Oak Ridge. The effect of radiation upon such a liquid system is to tend to hasten the rate of the reaction and to carry the reaction further as the radiation induces V centers in the sodium chloride which traps holes and upon dissolution oxidizes the chlorides to chlorine.[31] (V centers are holes trapped at positive ion vacancies or aggregates of vacancies. V centers are also formed when the crystals are exposed to the vapor of the halogen.)

If the wastes are previously neutralized, the production of gas is negligible. The effect of radioactive neutralized wastes on salt will be studied.

The results of these experiments indicate that the wastes will have to be neutralized and saturated with salt prior to disposal in salt cavities. The generalized flow sheet will then look something like Figure 12.

Migration of Nuclides. Though salt is generally considered to be impermeable and the dryness of salt mines is convincing testimony to that effect, it is known that water molecules will migrate in rock salt to some extent.[14] The question, therefore, arises as to the permeability of rock salt for specific radionuclides.

The migration of radionuclides in salt has been particularly difficult to determine in the laboratory because undisturbed samples cannot be obtained and tests of the samples used have shown in most cases that the samples were fractured in the mining process. Large samples of rock salt have been obtained and the migration of radionuclides in these blocks at various temperatures will be studied. It is obvious that the typical properties of the salt in the laboratory are not the same as they would be in a mine because of the release of the overburden pressure. Therefore, the tests in the laboratory can only prove that

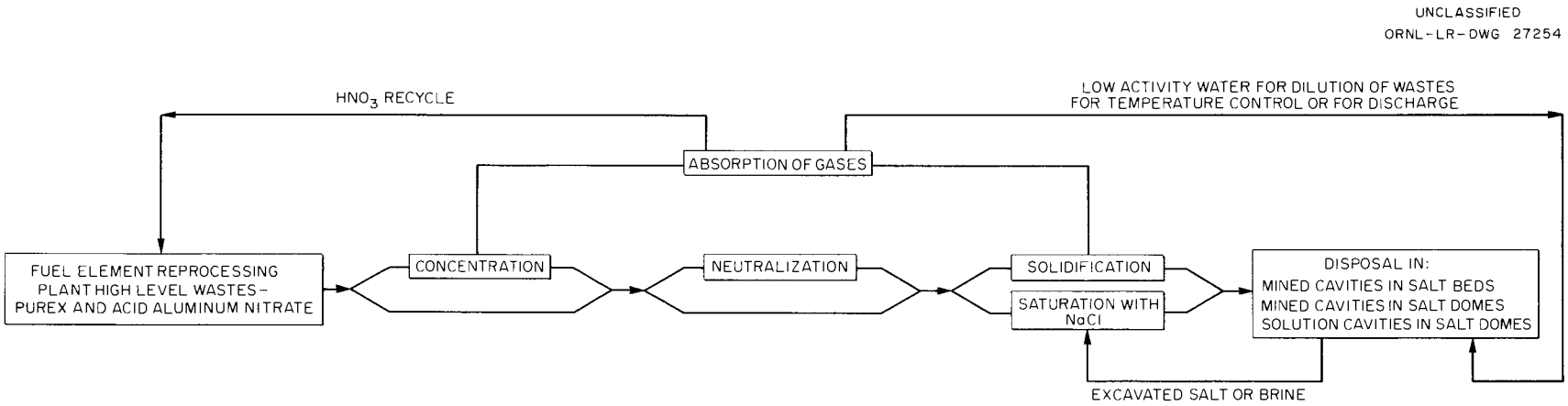

Fig. 12. Disposal of Solid and Liquid Radioactive Wastes in Salt Formations.

salt is impermeable, but not disprove it as the relief of the overburden pressure and the possible fracturing of the sample can only lead to a more permeable sample.

III. Physical Stability of the System. The effect of radiation upon NaCl is well known for single crystals. The solid state physicists have found the alkali halides particularly applicable to their studies of crystals, and hence there is a large amount of information available. It appears that there is a finite limit to the radiation damage possible. An upper limit to the concentration of F* and V centers is set by the fact that when an F center gets close enough to the V center, the electron in the F center can tunnel through to the V center and annihilate the positive hole. The maximum degree of decomposition of the salt is indicated to be of the order of one-tenth of 1 per cent.[32]

The structural properties, however, can change to a greater degree. The effect of x-ray irradiation upon rock salt has been to increase its hardness, tensile strength, and modulus of elasticity.[33]

This has been attributed to the pinning of dislocations by vacancies which condense near dislocations in the crystals.[34] The effect of radiation upon salt aggregates is being studied at the University of Texas with samples irradiated at ORNL.

Mechanical Properties of Salt. Most of the experiments to determine mechanical properties of salt have been performed on single and synthetic crystals. Therefore, the results do not have a great deal of pertinence to the problems encountered in salt cavities. These values can vary considerably for rock

---

*F centers - electrons trapped at halogen ion vacancies or when the crystal is exposed to the vapor of the alkali metal.

crystals and aggregates. The values quoted below are for rock salt aggregations of crystals rather than for synthetic and single crystals. Most of this work has been performed by M. Stamatiu, a Roumanian mining engineer, in the early 1930's.[35] The only comparable work on aggregations of crystals is that currently under way at the University of Texas under Professor Gloyna. Table VII gives the mechanical properties of three types of rock salt found in the mines at Slanic-Prahova, Roumania. Table VIII gives the chemical composition of the three types of salt for comparison with American rock outlined in Table V. Since the chemical compositions are very similar we may use these values as a guide for the design of the cavities. For the final designs we shall have to take a number of samples from the salt to be excavated. The work of Stamatiu has shown that even in the same bed, the properties can vary considerably.

The increase in plasticity in rock salt crystals with temperature and pressure is quite rapid as shown in Figure 13.[36] It is apparent then that the temperature and pressures in the waste-disposal cavity will have to be kept below those temperatures and pressures which would cause enough plastic flow to make the structure unsafe. The plastic flow of rock salt aggregate is presently being measured at the University of Texas. It appears that as long as the temperature is kept below 200° C and a pressure of 100 g/mm^2 there will be no short-term plastic deformation in the mine. (1 gram per millimeter squared is approximately one-tenth of an atmosphere.)

Migration of the Waste Storage Cavity Through the Salt. A major deterrent to the storage of liquid radioactive wastes in salt cavities could develop if the heated and evaporating wastes were to condense upon a salt roof, dissolve the salt, and fall back to the wastes. This process, if continued for a period

TABLE VII

PHYSICAL PROPERTIES OF ROCK SALT OF ROUMANIA

	Pounds per Square Inch			
	White salt	Mottled salt	Gray salt	Average for samples from 5 mines
Compression	4720	5260	5320	4680
Tension	132	231	398	142
Bending	409	365	772	425
Shear	328	251	355	355
Unit Compression at Rupture	3.9%		4.14%	0.5 - 4.0
Poisson's Ratio				0.2 - 0.5
Density lbs/Ft^3				122 - 125
Hardness, Mohs Scale				2 - 3
Modulus of Elasticity				$.085 - .284 \times 10^6$

In general, one may say that rock salt behaves as a good concrete.

TABLE VIII

MEAN CHEMICAL COMPOSITION OF ROCK SALT OF SLANIC

Chemical composition	White Salt	Mottled Salt	Gray Salt
$NaCl$	99.6612	99.0036	98.5498
Na_2SO_4	-----	-----	0.5658
$MgCl_2$	0.0966	0.0800	-----
$MgSO_4$	-----	-----	0.1031
$CaCl_2$	0.0114	0.0978	-----
$CaSO_4$	0.0177	0.6327	0.7212
H_2O	0.2924	0.1768	0.0835
Insolubles	0.0080	0.0460	0.0520
Totals	100.0873	100.0369	100.0754

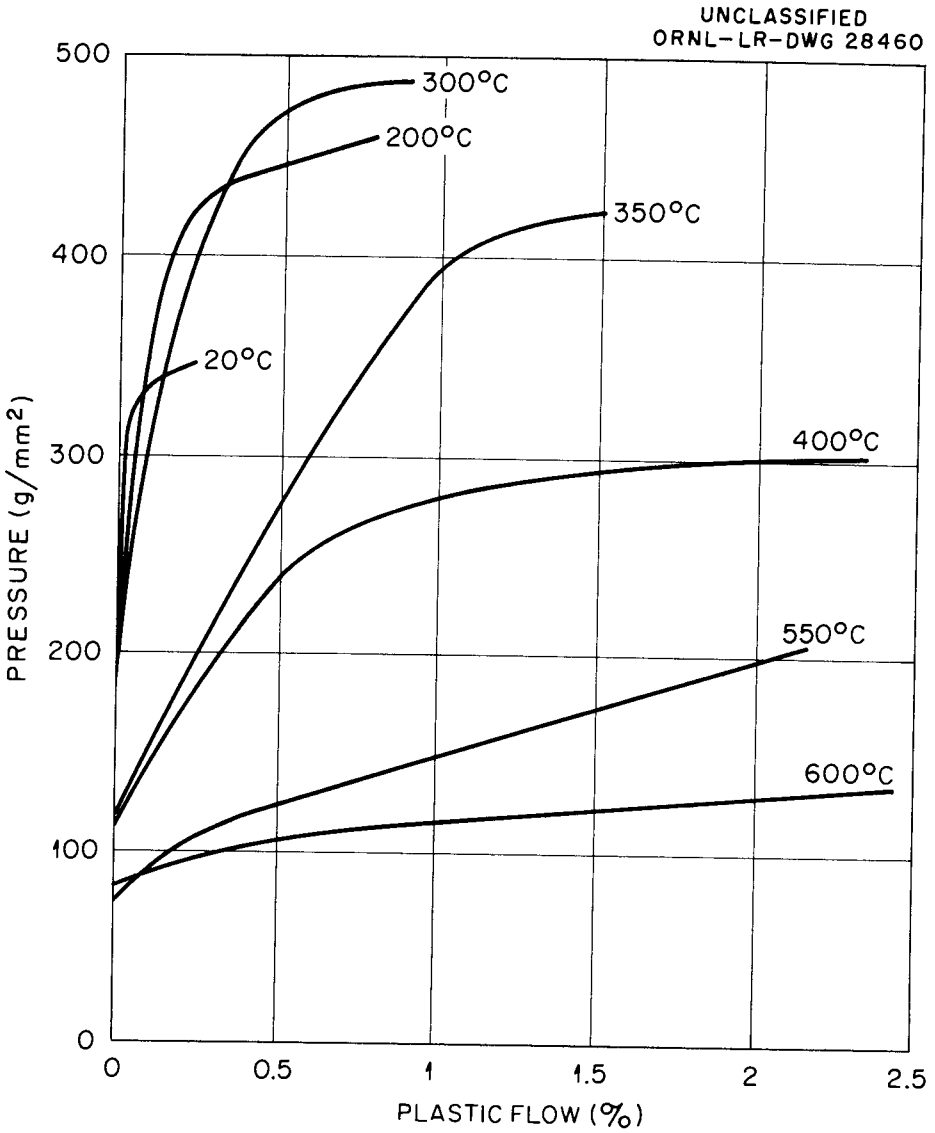

Fig. 13. Plastic Flow Curve for Natural Rock Salt.

of time, could progress through the salt formation and perhaps eventually cause the structural collapse of the mine. The possibility of this occurring will be investigated.

IV. Design of Field Experiment. The problems related to disposing of radioactive liquid wastes in salt formations have been briefly outlined in the preceding pages. In storing solid radioactive wastes the problems are considerably reduced. The only major problem then is the dissipation of the heat generated and the de-entrainment of the aerosols from the convective cooling stream.

The disposal of solid wastes in salt mines offers many advantages and may be the safest and cheapest method if the transformation of the liquid wastes to solid form can be economically achieved. One major advantage in the storage of solid wastes in salt is that they are not required to be nonleachable since no water will come into contact with them. Another advantage is that if the solid forms are properly designed, cooling will be easier and cheaper than cooling of liquid wastes. Cinder blocks might be one design, easy to cast, large surface area to volume, and easy to stack.

However, since there are at present no large amounts of reactor fuel element reprocessing wastes converted to solid form, the field experiment has been designed to test the safety, economy, and efficiency of the disposal of liquid wastes.

A Preliminary Conceptual Design. A preliminary conceptual design of what an operating facility in salt might look like is given in Figure 14. The field experiment is being designed to answer the questions raised in the paragraphs above with reference to this proposed conceptual design. Primarily the test will answer the technical questions of how good an approximation to

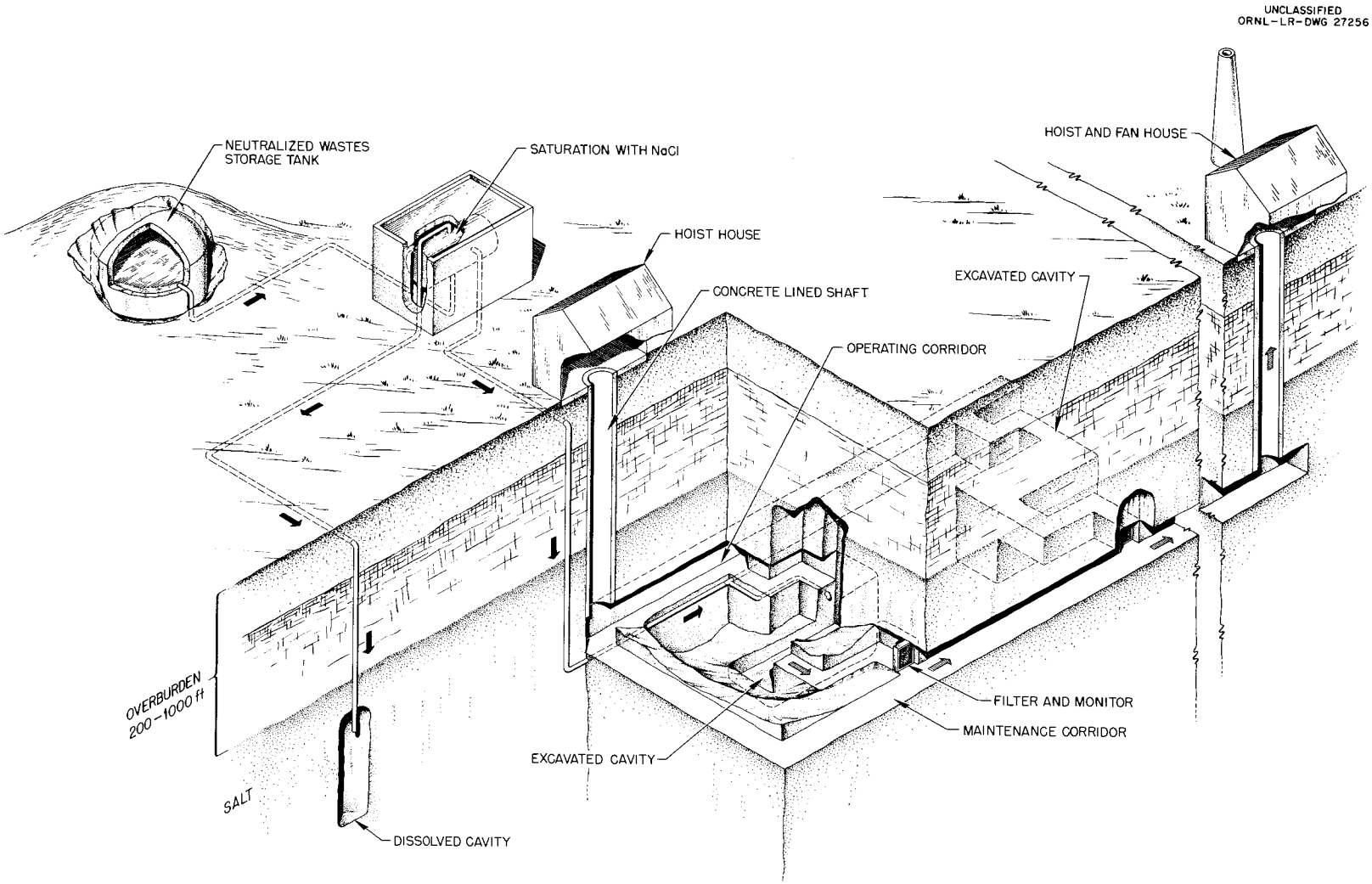

Fig. 14. Disposal of Radioactive Wastes in Salt Formations.

the physical model has our mathematical model been and how representative of field conditions have our tests in chemical compatibility and physical stability of the system been.

Engineering Design. The engineering design of the field experiment will commence after the location of the experiment is chosen. The design will be influenced by the concurrent experiments on the laboratory model of the field experiment.

V. Test of Laboratory Model of Field Experiment. Special rock salt samples of 4.5 and 27 cubic feet have been obtained from the Kleer Mine at Grand Saline, Texas. The blocks were drilled out rather than blasted and so should have less fractures than the usual samples, but possibly more than the rock salt in place. The temperature distribution, the chemical compatibility, and the structural stability of the cavity will be observed as the wastes are placed into cavities drilled in these blocks.

VI. Field Experimental Site. In order to solve the problems relating to the feasibility of the storage of liquid and solid radioactive wastes in dissolved and excavated cavities, pilot-scale operations will have to be carried out in the field. An active search is now in progress to obtain a field test site for our purposes.

Selection. The desirable criteria in picking a test site are: (1) suitable formation - geology well known with adequate thickness of salt, minimum depth to salt, free of extraneous shafts or core holes, homogeneous salt beds or domes; (2) accessibility - near paved roads, railroads, water transportation, living accommodations, skilled labor, and sufficient water; also near to Hanford, Savannah River, or Idaho Chemical Processing Plant, so

as to be able to obtain radioactive wastes economically, but not to have more weight than a location near the center of the future nuclear power complex; (3) removed from large population centers and active development of natural resources; (4) on Government-owned land if possible as this would make the property available and ease the problem of the supervision of the site for the period necessary; (5) suitable for a permanent disposal facility if the tests should prove to be successful.

There is general agreement that there should first be some tests using synthetic wastes and simulated heat sources followed by tests using hot wastes. In order to expedite the cold tests it would be desirable to run the tests in space presently available. It does not seem likely that hot tests would be permitted in mines still operating. Accordingly, a survey was made of the mines presently operating in the United States. The fourteen mines operating are located as follows: New York, 2; Michigan, 1; Kansas, 3; Louisiana, 4; Texas, 2; and Utah, 2.

On the basis of the desirable criteria, the mines in Louisiana and Texas can be ruled out of consideration, as they are too far from the center of the growth of the nuclear power complex where the first commercial fuel element reprocessing plant is likely to be located. Even for the test facility they are remote from Hanford, Idaho Falls, and Savannah River, the present sources of wastes.

An investigation into the possibilities of radioactive waste storage in salt formations in the northeastern United States has been prepared for us by the Geotechnical Corporation.(37) The report details the salt formations and mines in the area of the United States, bounded on the north by Canada, on the east by the Atlantic Ocean, and on the west by Montana, Wyoming, and Colorado,

and on the south by Oklahoma, Arkansas, Tennessee, and North Carolina.

The one operating mine in Michigan underlies the city of Detroit and would not be suitable for public relations reasons alone. Also the beds are relatively thin and deep lying there.

The mines in the states of New York and Kansas might possibly be used. It seems unlikely, however, that an operating mine will be available even for cold tests as the demands we would make upon the shaft and mining equipment would constitute a hindrance to the usual operations. The only stand-by mine reportedly in good condition is the Carey mine in the town of Lyons, Kansas. All the equipment, including the hoist, have been removed. Therefore, the only savings possible, if this mine could be obtained, would be the cost of the shaft minus the cost of the land and the cost of the mine. The existing space in the mine probably could not be used directly for liquid wastes, but might possibly be used for the storage of solid wastes. Therefore, new space, specifically designed for the storage of liquid waste, would have to be excavated.

The mines in Utah are quite small; they have mined out less than 100,000 cubic feet. Therefore, it does not seem possible to use these mines.

If none of the existing mines were available and suitable, it might be necessary to develop our own test space. Then according to the criteria outlined on the previous page, a site in Ohio along Lake Erie or in Kansas around Hutchinson, might seem most desirable. The depth to salt at Lake Erie is about 2000 feet versus 450 feet at Hutchinson. The thickness of the beds at Lake Erie is about 60 to 70 feet versus 220 feet at Hutchinson. The location on the Great Lakes is nearer the center of the likely nuclear power plants and has deep water transportation available to it. The hazards involved in water transportation, however, may negate this advantage. The Lake area is a more highly

developed and populated area and, consequently, it might be more difficult from a public relations view point to establish a waste disposal facility there. The consequences of a failure in a well-developed area such as one on the Great Lakes are, of course, much greater than those of a failure in the sparsely settled farming country of Kansas.

The greater the depth to the salt, the greater the overburden pressure and hence the lesser the temperature rise possible without plastic flow occurring; therefore, the size of cavity will have to be reduced to maintain the same temperature. Since the cost of the facility will be greatly dependent upon the shaft costs and the size of the storage vaults possible, it would seem that from a first cost point of view the Kansas site would be preferable to the Lake Erie Site.

There is also the possibility that for an experimental site which could not be expanded into a permanent-disposal facility, a drift mine into one of the salt outcrops in the arid west might be adequate.

It would seem that Kansas, at present, offers the greatest promise as a test site. Therefore, we have had the Geotechnical Corporation make an additional, more exhaustive report on an area in Kansas that seems to meet most of the desirable criteria for a test site.(38)

Cost of Test Facility. Assuming that a site in Kansas is chosen, the cost for setting up a test facility has been estimated by the Cost Estimating Department at Oak Ridge. These are Class "D" quotations, "based on generalized criteria, subject to further definition and change. Their degree of accuracy cannot be determined."

Costs have been estimated on two bases, temporary and permanent installations. The following assumptions were made for purposes of the estimate:

TABLE IX

COST ESTIMATE

	Temporary		Permanent	
	A	B	C	D
Shafts, diameter	84" 36"	84" 36"	84" 84"	84" 84"
Winch and cage	2 tons	2 tons	20 tons	20 tons
Filterhouse, blower, etc.	No	No	Yes	Yes
20' x 20' main tunnels, ft	500	500	1000	1000
10' x 10' side tunnels, ft	100	100	300	300
Storage pits	1 parppd*	1 sphere 1 parppd*	1 sphere 1 parppd*	1 sphere 2 parppd*
Tractor	None	None	1	1
Jeeps	1	1	2	2
Man hoist for outlet	Yes	Yes	Yes	Yes
Instrumentation	Yes	Yes	Yes	Yes
Utilities and service, etc.	Yes	Yes	Yes	Yes
	$266,000	$357,000	$529,000	$631,000

*Parallelepiped.

As shown in the cost estimate, the least amount of money for which a test site in Kansas could be prepared is $266,000. If, as is likely, more than one experiment would be carried out, then the cost will rise. There is a limit, however, to the number of experiments that can be performed on a temporary basis. If the experimental site should be constructed so that it could later be used as the permanent storage area, the initial costs will be considerably high - $529,000. If, however, the cost per gallon is considered than the incremental cost per 56,000 gals is only $102,000 or $1.82 per gallon. If the method proves successful and larger caverns can be built the price will still further decrease. Furthermore, if the method of washing cavities is successful, additional substantial reductions in the unit cost of storage will be realized.

Site Procurement. The other possible sites for the field experiment will be investigated and where suitable, a similar cost analysis will be made. The AEC will then be asked to buy or lease the land, or if Government-owned land obtain title to it for use as a field testing site.

VII. Field Experiment. After permission to use the land is obtained and the site prepared, it will be necessary to place the instrumentation in the mine. For the cold run, a synthetic waste and heaters will suffice. However, for a hot run of the order of magnitude of 2 BTU/hr/gal, over a million curies of activity will be required, assuming 93 per cent of the gamma energy and all the beta energy is effective in heating the waste, specifically 3.9×10^6 curies of cesium 137 or 3.3×10^6 curies of strontium 90.

The prospects for success in salt disposal of radioactive wastes appear to be good. The Earth Sciences Division of the National Academy of Science has stated: "Disposal in tanks is at present the safest and possibly the most economical method of storing waste. Disposal in salt is the most promising method

for the near future."[8]

Our goal is an early realization of that promise.

REFERENCES

1. Langham, Wright H., and Anderson, Ernest C., "Potential Hazard of World-wide Sr^{90} Fallout from Weapons Testing," Hearings before the Special Sub-committee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, 85th Congress, 1st Session, June 4, 5, 6, and 7, 1957: Government Printing Office, Pt. 2, p. 1369.

2. Lane, J. A., "Determining Nuclear Fuel Requirements for Large-Scale Industrial Power," Nucleonics 12 10, p. 65, 1954.

3. Libby, W. F., "Radioactive Fallout and Radioactive Strontium," Science 123 3199, April 20, 1956, p. 659 (p. 1465 ref. 1).

4. Culler, Floyd L., Jr., "The Nature and Magnitude of Radioactive Wastes as Influenced by Types of Reactors and Fuel Processing - Present and Prospective," ORNL CF-56-5-2, May 4, 1956, p. 23.

5. Ibid., p. 24.

6. Zeitlin, H. R., Arnold, E. D., Ullmann, J. W., "Economics of Waste Disposal," Nucleonics 15 1, pp. 58-62, 1957.

7. Anonymous, "Summary Report: AEC Reference Fuel-Processing Plant," Division of Civilian Application, Washington, D. C., WASH-743, October 1957, p. 11.

8. Committee on Waste Disposal - Division of Earth Sciences - "Disposal of Radioactive Waste on Land," April 1957, National Academy of Sciences - National Research Council Publication 519, p. 6.

9. Research and Coordinating Committee, Interstate Oil Compact Commission, "Underground Storage of Liquid Petroleum Hydrocarbons in the United States," April 1956, The Interstate Oil Compact Commission, p. 1.

10. National Petroleum Council, "Underground Storage for Petroleum," March 1957, p. 1.

11. Ibid., p. 28.

12. Department of Defense, "Underground Plants for Industry": Government Printing Office, January 1950, p. 5.

13. Busch, B., "Etwas Uber die Expansivkraft des Salzes," Zeitschrift F. Prakt. Geol. 15, pp. 367-371, 1907.

14. Barnes, R. Bowling, "The Plasticity of Rock Salt and Its Dependence Upon Water," Physical Review 44, December 1, 1933, p. 898.

15. Lang, W. B., "Annotated Bibliography of Salt Deposits in the United States," U. S. Geological Survey Bulletin 1019-J, 1957, Plate 4.

16. Arnold, E. D., "The Economics and Hazard Potential of Waste Disposal," ORNL CF 57-7-31, July 8, 1957, pp. 15-17.

17. Weigel, W. M., "The Salt Industry of Louisiana and Texas," Transactions American Institute of Mining and Metallurgical Engineers, 129 1938, p. 442.

18. "Mineral Resources of the United States," Public Affairs Press, 1948, p. 180.

19. Gleuckauf, E., "The Long Term Aspect of Fission Product Disposal," Atomics, September 1955, p. 270.

20. Ref. No. 9, p. 2.

21. Inman, Arthur E., "Salt, an Industrial Potential for Kansas," University of Kansas Research Foundation, 1951, p. 22.

22. Heroy, W. B., Private Communication.

23. National Petroleum Council, "Report of the Committee on Underground Storage for Petroleum," April 22, 1952, Plate II.

24. Heck, N. H., "Earthquake History of the United States," Pt. 1, U. S. Coast and Geodetic Survey, Serial ND. 609, 1947.

25. Crowell, Julian C., Unpublished Results, January 1958.

26. Birch, Francis, "Generation of Heat in Radioactive Waste in Deep Reservoirs," Report for the Committee on Waste Disposal of the Division of Earth Sciences, National Academy of Sciences - National Research Council, 1958, in Press.

27. Carslaw, H. S., and Jaeger, J. C., "Conduction of Heat in Solids," Clarendon Press, Oxford, 1947.

28. Schecter, Robert S., Unpublished Calculations, January 1958.

29. Goldenberg, H., "A Problem in Radial Heat Flow," British Journal of Applied Physics 2, August 1951, p. 235.

30. "Salt," Encyclopedia of Chemical Technology, 1954 Edition, Volume 12, p. 68.

31. Heal, H. G., "The Chemical Effects of Ionizing Radiation in Solids -- I," Atomics, July 1955, p. 207.

32. Heal, H. G., "The Chemical Effects of Ionizing Radiation in Solids -- II," Atomics, August 1955, p. 241.

33. Westervelt, D. R., "Mechanical Effects of Ionizing Radiation in the Alkali Halides," NAA-SR-288, February 3, 1954, p. 13, 14.

34. Gordon, R. B., and Howick, A. S., "The Pinning of Dislocations by X-irradiation of Alkaline Halides Crystals," Acta Metallurgia 4 514-527, p. 515, 1956.

35. Stamatiu, M., "Quelques Proprietes Physico-Mecaniques Du Sel Gemme De Slanic," Anuarul Institutului Geologic Al Romaniel XVII, 1932, p. 501-525.

_____ "Quelques Remarques Sur La Plasticite Du Sel Gemme," Buletinue Societatu Romane de Geologie 3, 1936, p. 143-159.

_____ "New Data on Some Physical and Mechanical Properties of Rock Salt," Bull. Sect. Sci. Acad. Roumaine, 18, 1937, p. 41-51.

36. Theile, Walter, "Temperaturabhangigkeit der Plastizitat und Zugfestigkeit Von Steinsalzkristallen," Zeits. F. Physik 75 11-12, May 6, 1932, p. 770.

37. "Possibilities for the Storage of Radioactive Waste in Salt Cavities in the Northeastern United States," The Geotechnical Corporation, February 15, 1958.

38. "Report on the Suitability of Hutchinson Naval Air Station, Reno County, Kansas, as a Site for Underground Storage of Atomic Wastes," The Geotechnical Corporation, January 23, 1958.

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