# Radioactive Waste Isolation

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**ABSTRACT**

Due to the long half lives involved, waste products from the commercial nuclear fuel cycle must be isolated from the biosphere for time periods of the order of hundreds of thousands of years. Several alternatives have been considered for accomplishing this task. This paper addresses the deep geological isolation of radioactive wastes in rock salt. The typical repository in salt will be a room and pillar lay out at a depth in the range of 1000 to 3000 feet with waste canisters emplaced in vertical holes in the floor. Rock salt was recommended as a candidate medium for waste disposal in 1957 primarily because of its plastic nature, abundance, ease in mining, and the associated lack of circulating fresh water. Studies have continued over the past twenty years of the suitability of rock salt for nuclear waste disposal. The purpose of this paper is to examine design concepts and give a preliminary assessment of the options available to designers at the conceptual stage. Naturally, the final designs must be tailored to the conditions that exist at a particular site.

## INTRODUCTION

The nuclear fuel cycle used for commercial power generation results in the production of radioactive wastes that must be isolated from the biosphere for time periods of the order of one million years. These wastes take different forms, depending on whether a closed fuel cycle that includes reprocessing of spent fuel from reactors is used as shown in Figure 1, or whether a once-through fuel cycle is used. In the once-through cycle, spent fuel rods would be dispensed after being through the power reactor only once. The high-level waste (HLW), resulting from the reprocessing cycle, and the spent fuel, resulting from a once-through cycle, are both thermally and radioactively hot. The extremely long time periods that these wastes must be isolated from the biosphere result in a unique waste management problem. Several concepts have been suggested to handle nuclear wastes; these concepts are discussed in the technical alternatives document[1]. These alternatives include 1) extraterrestrial disposal wherein the nuclear wastes would be shot into space; 2) seabed disposal where the nuclear wastes would be placed in holes drilled in the ocean floor; 3) ice sheet disposal where the waste would be placed in the polar ice caps; 4) deep continental geologic formation disposal where emplacement would be beyond the biosphere with no intent for retrieval; 5) waste disposal in a matrix of drilled holes rather than mined caverns; 6) disposal by hydrofracturing of geologic media surrounding a borehole (this method is presently being used for disposal of intermediate-level liquid radioactive waste at Oak Ridge National Laboratory); 7) deep-well injection disposal where liquid wastes are forced through a pipe into a deep geologic formation; and 8) the rock melting concept that makes use of the large amount of thermal energy from the radioactive waste to heat the host rock to its melting point, wherein the molten rock mixes with the radioactive waste and finally crystallizes as the energy released, decays with time. At the present time, disposal of radioactive wastes in conventionally-mined caverns appears to be the most logical choice. In this paper, concepts related to the isolation of radioactive wastes in mined caverns in salt deposits will be discussed. No underground radioactive waste disposal facilities exist in the United States. However, site selection and conceptual design are in progress (Fig. 2).

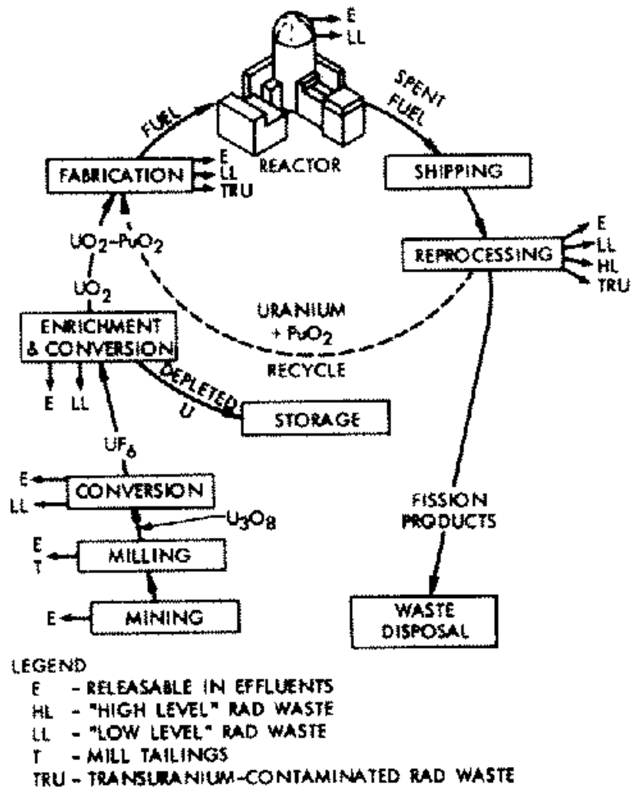


**Figure 1.** Commercial Nuclear Fuel Cycle and Types of Waste Generated.

The disposal of radioactive wastes in salt formations was first suggested by the National Academy of Sciences in 1957[2], and work on this concept has continued to the present. In recent years, the alternative of deep geologic disposal in nonsalt rocks has also been considered. Alternate host lithologies currently being considered are granitic, basaltic, argillaceous, and carbonate rocks. Recent work in this area includes the generic environmental impact statement work managed by OWI[3] and several international programs.

The purpose of this paper is to discuss some of the design concepts necessary to translate a basic concept, such as disposal of radioactive wastes in conventionally-mined caverns in salt, to actual designs for geologic repositories. Space and time will not allow a consideration of all the concepts involved; however, additional information can be found in the annual progress report for the National Waste Terminal Storage Program[4].

## CONCEPTS

Conceptual designs are in progress that translate the basic concept of isolation in underground cavities in salt into safe, workable, practical, and relatively economic designs. In order to do this, several factors must be considered. Some of these factors are discussed below.

**Site selection.** One of the basic keys to success in underground radioactive waste isolation is proper site selection. The basic concept of exploration for potential sites for repositories is composed of a study that proceeds from general to specific areas. The general studies are sometimes referred to as regional studies; in these studies, the major salt deposits within the United States are considered for siting of repositories. In order to select more specific study areas, general geological criteria[5] and two sets of screening specifications were recently published[6, 7]. These publications discuss screening specifications for Gulf Coast salt domes and similar specifications for bedded salt in the Salina basin in New York and Ohio (Fig. 3). These screening specifications begin with a statement of the geological evaluation criterion, then discuss the pertinent factors affecting the criterion, and finally, evaluate the value of the specification.

The brief consideration of these criteria include 1) the depth of the repository host rock is such that the minimum depth be approximately 310 m or 1,000 ft, while the maximum practical depth be less than approximately 650 m; 2) the vertical extent of the host rock should be such that it precludes breaching of geological containment during excavation of the repository or breaching by the radioactive heat production after wastes are emplaced; 3) the host rock shall have sufficient lateral extent to provide adequate space to develop and operate a repository; 4) the rate and amount of predictable regional uplift and/or subsidence of bedrock shall not pose a threat to the physical integrity of the repository; 5) faults and other structural characteristics of the repository site shall not compromise the repository operation, engineering design, or geological containment; 6) expected igneous activity shall not compromise geological containment; 7) the hydrological properties of the repository rock, together with the surrounding material, shall not permit the transport of hazardous amounts of wastes by ground water to the biosphere; 8) the water content of the repository host rock shall be sufficiently low so that water liberated by heat will not compromise containment; 9) radiation from stored wastes shall not affect the host rock in such a way as to compromise the containment; 10) the repository rock shall not react chemically with the waste form or with its container so as to compromise geological containment or operational safety; 11) the mechanical properties of the repository rock will not jeopardize construction operation and the physical integrity of the repository; 12) the in situ state of stress shall not be such that the construction operation and physical integrity of the repository will be jeopardized; 13) predicted seismic activity in the region of the repository shall be low enough so as not to pose a threat to safe operation or the physical integrity of the repository; 14) the geological, geographical, and topographical setting of the repository shall be compatible with site development including transportation, utilities, and disposal of excavated materials; 15) areas potentially attractive

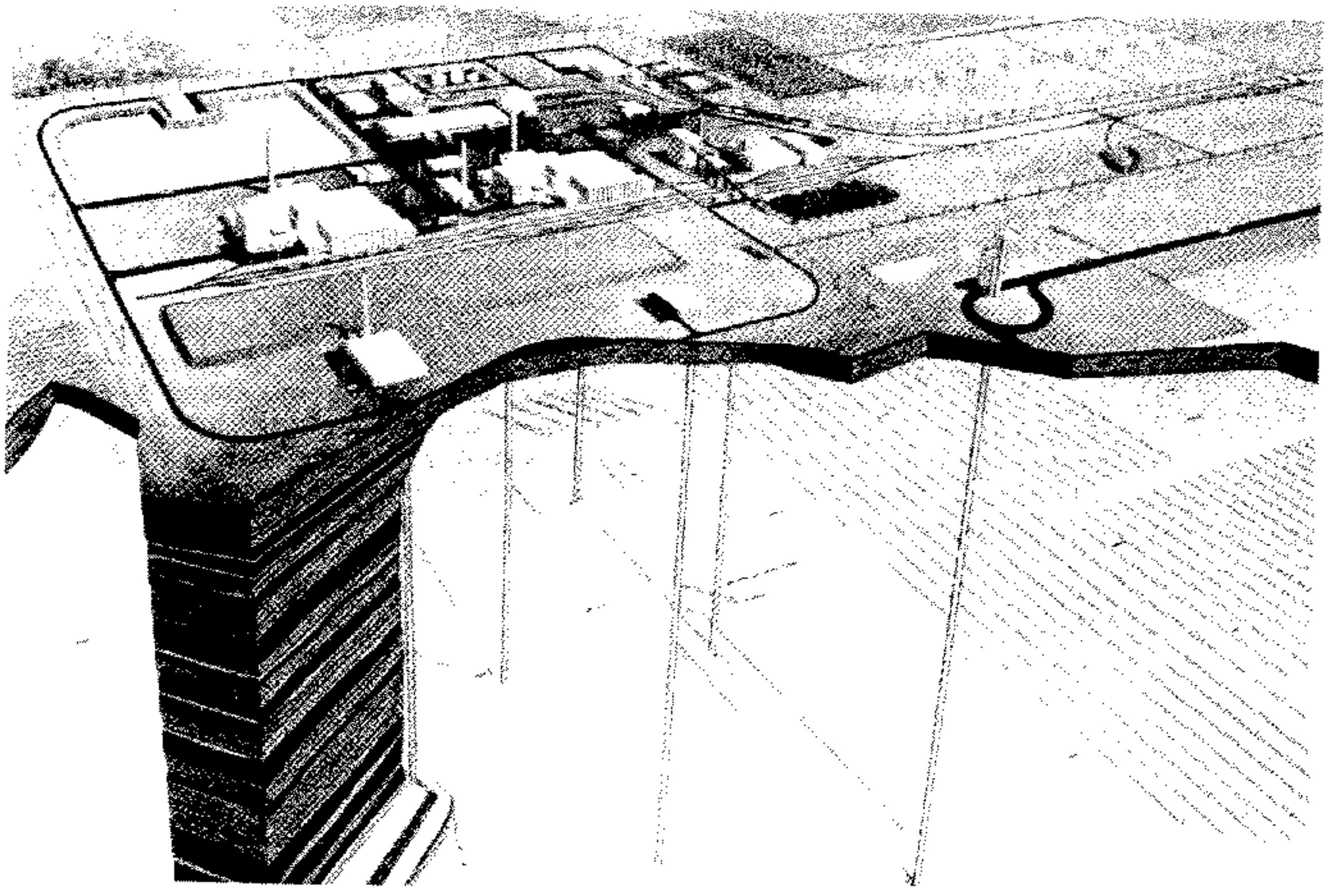

Figure 2. Artist's Perspective of National Wate Terminal Storage Repository 2.

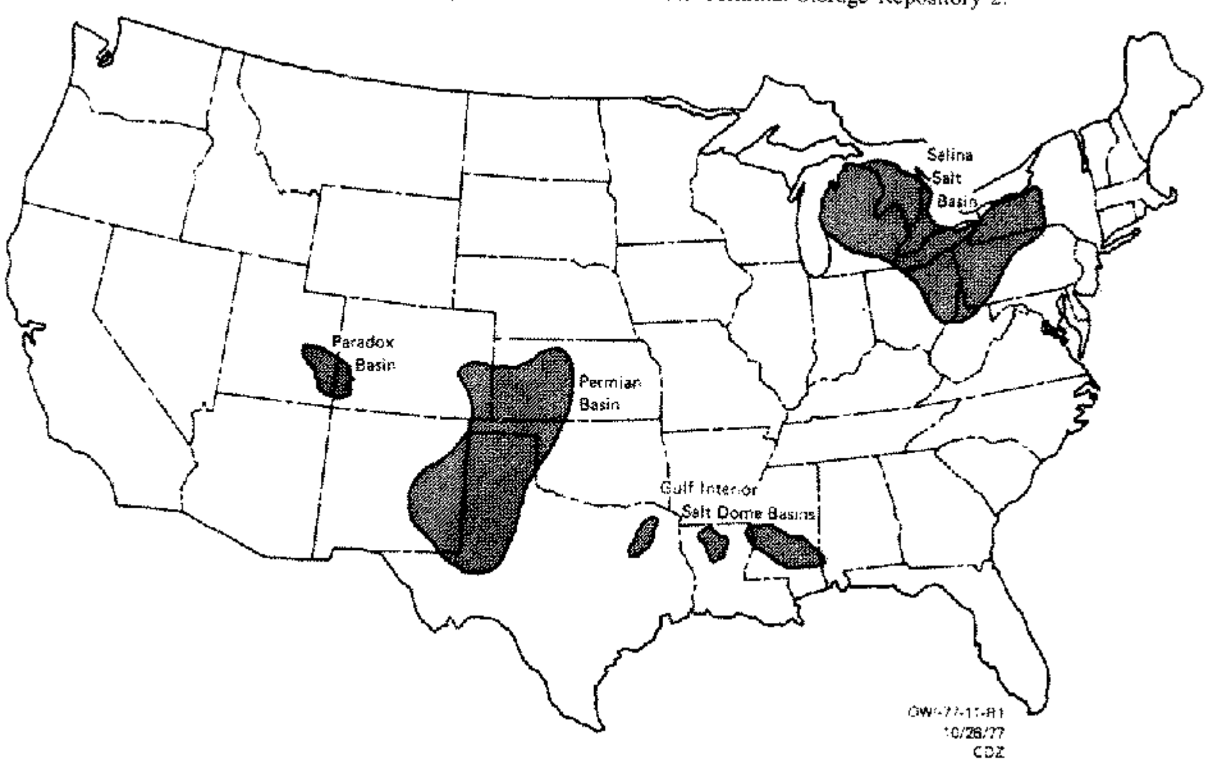


Figure 3. Salt Basins Being Investigated for Terminal Storage of Radioactive Waste.

for development of mineral resources shall be avoided as much as possible; 16) areas potentially attractive for development of surface or subsurface water resources shall be avoided as much as possible; and 17) anticipated conflicts involving land use will be minimized. This set of general criteria can be applied to any of the rock types considered at the present time as host for a radioactive waste repository.

**Facility design concepts.** Conceptual designs for repositories in salt are proceeding based on the assumption that acceptable sites will be found. A general description of the conceptual facilities follows. The conceptual repository consists of a relatively conventional room-and-pillar mine at a depth of approximately 2,000 ft. which provides for emplacement of canistered solidified HLW or spent fuel in vertical emplacement holes drilled in the floors of the rooms (Fig. 4). Vertical shafts provide the means for moving the solidified wastes in specially-designed containers from the surface to the subsurface storage area. The area of the underground workings will be approximately 2,000 acres. Surface facilities for receiving the wastes and the support buildings will occupy approximately 200 acres and will be the only surface evidence of the repository. All facilities at the repository will be designed to fulfill standards that will allow the facility to be licensed by the Nuclear Regulatory Commission (NRC). Surface facilities will be designed to maintain their integrity under natural disasters such as earthquakes and tornadoes.

Several aspects of the underground design will be considered in the following paragraphs. Various excavation methods to develop the room-and-pillar configuration have been considered. For example, the conventional drill-blast cycle has several advantages. It is flexible in producing a variety of sizes and shapes of caverns underground, is considered by many to be the most economical means of exca-

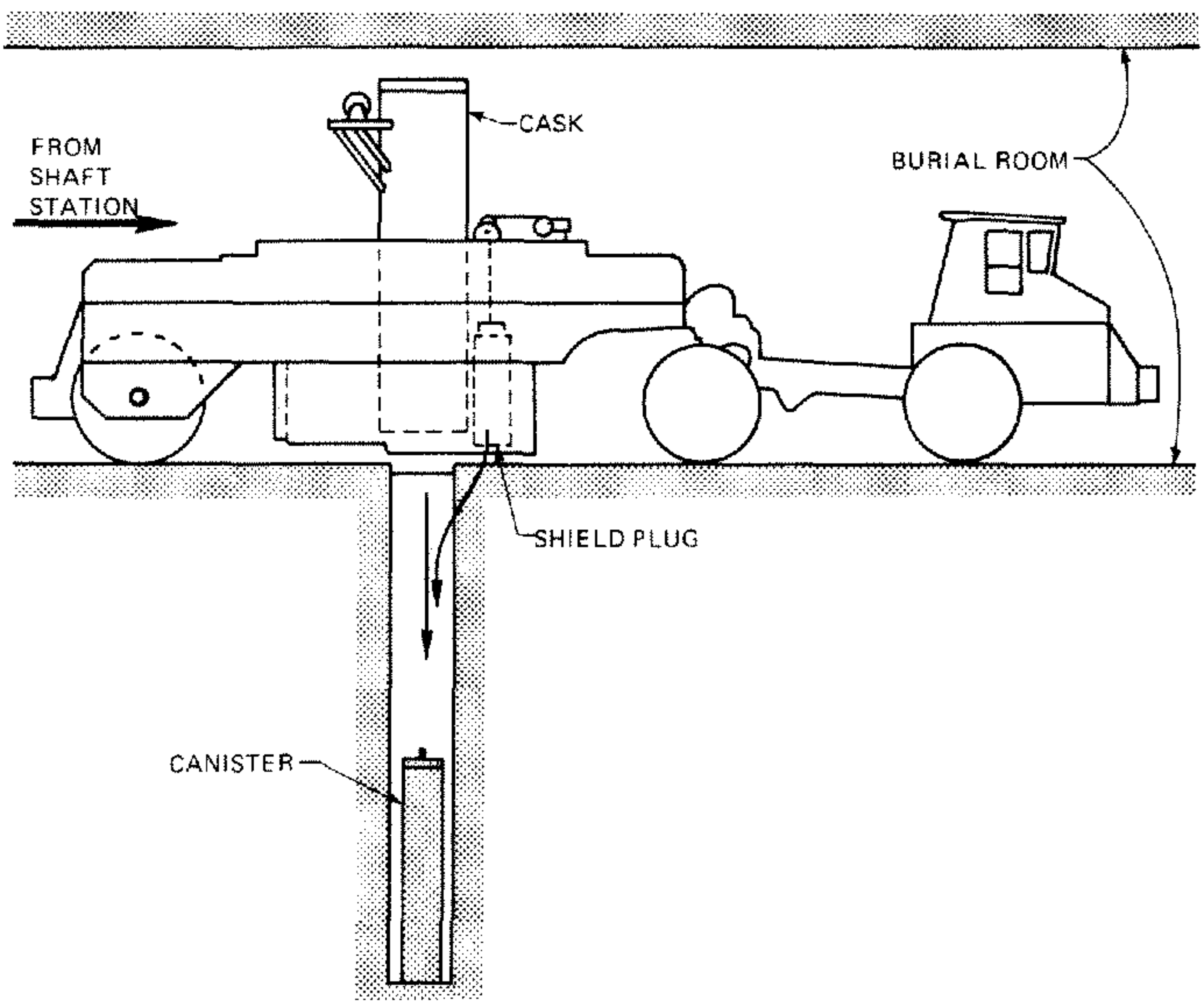


**Figure 4.** Canister Burial in Mine.

vation of the required underground space, and tends to be more labor-intensive thereby minimizing the initial capital investment. However, the conventional drill-blast cycle does have disadvantages that will probably disqualify it as the excavation method for geological repositories in salt. One of these disadvantages is the requirement that explosives be underground during the waste emplacement cycle. Explosives present a potential hazard unless all excavation is completed prior to the start of waste emplacement, which may not be practical. Another disadvantage is that the openings excavated by the drill-blast cycle will have more irregular surfaces than openings produced by continuous miners. Also, the drill-blast cycle could cause blast-induced damage in the pillars that provide the major structural support for the mine. The alternative to conventional drill-blast mining is the use of continuous mining equipment. Continuous mining equipment is not commonly used for mining salt in the United States, although it is used in mining potash. Continuous mining equipment configurations that have been considered include borer, ripper, drum-head, and cutting-head machines. Many of these continuous mining machines have been developed primarily for mining coal but are adaptable to evaporite mining. Continuous miners offer several disadvantages that include a high rate of advance, smooth-walled openings, no explosives, and lower manpower requirements. Disadvantages involved with the use of continous mining equipment include less flexibility in the size and shape of openings and higher initial capital costs. At this time, continuous mining equipment (most likely a borer machine) will probably be used for excavation of the underground space for repositories in salt. For the borer-type machine, the necessary room heights (16 to 19 ft.) will require two passes. Rooms are likely to be long, 500 to 4,000 ft., in order to take advantage of the borer machine advance rate and minimize time-consuming direction changes.

With respect to waste emplacement configurations, several options exist. These options include the emplacement of waste canisters in vertical holes drilled in the floors (Fig. 4) of the rooms in one or more rows down the room. However, emplacement holes drilled at other angles from vertical to the horizontal have also been considered. Vertical emplacement holes have several advantages—such as, the fact that the concept has been demonstrated at the Project Salt Vault experiment[8]; and that for emplacement holes near the center of the rooms, the heat sources are placed as far away as possible from the pillars, which provide structural support for the mine. In addition, the concept of vertical emplacement provides easier retrievability if, for some unknown reason, the waste canisters would need to be removed from the repository. Vertical emplacement holes do, however, have some disadvantages. When dealing with long canisters (spent fuel assemblies may be up to 16 ft. in length), the handling requires high room heights, and consequently, more salt must be excavated. The rooms will be backfilled with crushed salt after the waste is emplaced and after a suitable retrieval period (approximately five years) has passed. Only about 50 to 60% of the excavated salt can be replaced in the rooms. The remaining salt must be disposed on the surface. The tonnages of salt involved and the rate of production will probably preclude marketing of the salt. Consequently, the surface disposal of the mined salt may pose a difficult problem. As might be expected, the larger the tonnage mined and backfilled, the higher is the cost of the repository.

An obvious way to reduce the heights of the rooms is to incline the emplacement holes or perhaps make them horizontal. The advantages, of course, are that the tonnage to be mined, stored, and backfilled would be much less, perhaps as much as 50%, with the attendant lower cost. Inclined (including horizontal) emplacement is, however, not without disadvantages. The concept has not been demonstrated as vertical emplacement has. The heat sources, particularly in the case of horizontal emplacement, would be emplaced in the pillars; this emplacement could result in the loss of the structural integrity of the mine because of heat production from the waste canisters. Also, the retrieval of inclined or horizontally-emplaced canisters would probably be more difficult.

With respect to emplacement sequences, both an advancing sequence (away from the shaft pillar) and a retreating sequence (from the periphery of the repository toward the shaft pillar) have been considered. The retreat concept of emplacement has several advantages one of which is the emplacement of heat sources at the furthest possible distances from the shaft pillar area where underground shops, offices, etc. will be located. In addition, by placing wastes around the periphery, waste transportation and mine development personnel can avoid the areas of emplacement. The retreat scheme requires a large amount of initial development because haulage ways and ventilation ways must be developed to the outer edge of the property before waste emplacement can begin. However, this development work adds to the confidence that no geologic anomalies were missed during the exploration program. This initial development does, however, require more time at the start of the project and also a larger initial capital investment.

The advancing emplacement scheme allows ventilation ways and haulage ways to be developed as emplacement progresses from the shaft pillar into the repository storage areas. Less time for initial development and a lower initial capital investment are required in this concept; however, thermal loadings on the ventilation system required to cool the shops, offices, and storage areas in the shaft pillar may be greater than in the retreat emplacement scheme. Haulage distances, both for mined salt and for the waste to be emplaced, increase as development and emplacement advance away from the shaft pillar. Again, this sequence of development minimizes the initial capital investment but requires additional waste transporters in the later years of repository operation.

The present facility design concepts call for a single, large shaft pillar containing between four and five shafts that will fall within the approximately 200 acres allowed for surface facilities. The shafts required for the operation of a repository include a men-and-materials shaft, ventilation shafts, remotely-handled-waste shafts, and contact-handled-waste shafts. Presently, only vertical shafts are being considered. The shafts are being concentrated in the 200 acres provided for surface facilities, and consequently, return ventilation ways must be provided to bring exhaust air back to the main shaft pillar where exhaust air from the emplacement rooms will be filtered to remove any potential contamination. The ventilation concept presently consists of separate systems for excavation activities and emplacement of wastes. Because the filtering of the quantities of air involved is an expensive operation, the dual system provides for air from the mining operations to be exhausted through an exhaust shaft without filtering.

The location of the shaft pillar relative to the underground storage areas is another point for consideration. A centrally-located shaft pillar minimizes haulage distances for the excavated salt (which will be hoisted to the surface) for the transportation of the wastes to their storage areas, and for the transportation of backfill salt temporarily stored on the surface (in the case of a long retrieval period). However, with a centrally-located shaft, temperatures in the shaft pillar may become a consideration, particularly if an advancing emplacement scheme is used. The higher temperatures in the shaft pillar could lead to unacceptable creep closure of the shafts. This higher temperature may be a consideration particularly if unlined shafts are used, as in the case of a repository located in a salt dome.

Another concept of shaft-pillar location is the "panhandle" shaft pillar where the shaft pillar is a rectangular area appended to one side of a rectangular storage area. The panhandle shaft-pillar concept offers the advantage of a very stable shaft pillar because it is surrounded on three sides by undisturbed rock. In addition, the panhandle concept offers potential for expansion to a similar-sized storage facility on the opposite side of the shaft pillar, thus doubling the useful life of the surface plant and shaft pillar. Of course, the advantage of the additional stability in the panhandle concept is reduced when development takes place on the opposite side. The panhandle concept has the disadvantage that relatively longer haulage distances for excavated salt and waste are encountered.

The technology for excavating and constructing an operationally safe repository at a well-selected site is known and should present no unmanageable difficulties. One factor, however, that has a great influence on the design, economics, operational and long-term safety of geological waste isolation is the thermal power output of the nuclear wastes that will be transferred into the host rock mass. The thermal power generated in a repository can be controlled by aging waste on the surface before emplacement, diluting reprocessing wastes, and increasing the spacing betwen emplacement holes.

Currently, no large-scale, long-term experience is available on thermal effects existent in the mining of salt underground. The question of appropriate thermal loadings for salt is discussed in detail in Russell[9]. Basically, the effects of the heat production of the wastes (which decay with time) are considered on three different scales. First, the temperature field that develops in the immediate vicinity of an emplaced canister is considered. Factors considered at this scale include 1) the stability of the emplacement hole i.e. will it creep shut and prevent easy retrievability of the waste canister during the retrieval period; 2) the brine migration, which is a function of both temperature gradient and the absolute temperature of the salt. Single-phase brine inclusions tend to move up the thermal gradient toward the heat source while mixed-phase inclusions tend to move away from the heat source; and 3) the corrosion of the canister material, which will be accelerated by brine migration into the emplacement holes. Corrosion of the waste canisters can prevent easy retrieval of the canisters and can also result in the production of hydrogen gas which may pose an operational hazard.

The second level of detail considered in determining thermal loading is the room scale (sometimes called the near-field region). At this scale, the primary concern is the overall structural stability of the repository rooms. Consequently, the temperature fields that will develop in the pillars are of interest, as is whether or not this temperature will cause creep to accelerate to the point where unacceptable room closures will be experienced and whether either will make the repository unsafe during the operational phase or will make remining necessary before canisters could be retrieved, if retrieval should be necessary. The Project Salt Vault experiment[8] provides some data on the deformations to be expected in the storage rooms and pillars. Recently, computerized simulations using laboratory-determined properties of rock salt have been able to reasonably calculate the deformations that were observed during the Project Salt Vault experiment[10, 11].

The third level of detail for thermal and rock mechanics considerations is the repository scale, or regional scale. Since a large amount of thermal energy will be emparted into the salt rock mass, the rock mass temperature will rise, and thermal expansion will occur. This thermal expansion will result in a gentle doming of the land surface over the repository. The thermal expansion of the large mass of rock, with the resulting upward movement, could conceivably fracture impermeable barriers that prevented the dissolution of the salt by circulating fresh water from overlying aquifers. In addition, the time-dependent upward movement of the ground mass in the localized area of the repository could cause changes in surface drainage and erosion patterns, which could have some environmental impact. Consequently, the large-scale ground movements, in particular their transient nature, are being modeled numerically to gain a better understanding of the phenomena involved. Also, a coupling is being made of the thermal field with the hydrologic field and the deformation/displacement field in the rock mass overlying a repository, which must ultimately be considered on a site-specific basis.

The thermal loading, in terms of kilowatts per acre of a particular waste type and age, is a site-specific problem. At this conceptual stage, only recommendations that appear to form a reasonable basis for proceeding with the designs can be made. These recommendations are presented in Russell[9].

## SUMMARY

This paper has considered some of the concepts involved in the design of underground radioactive waste repositories. Obviously, the final designs must be tailored to the conditions that exist at a particular site. Work is in progress on site selection, conceptual designs of facilities and underground workings, and the more basic research work needed to provide a firm basis for successful repository design and operation.

## DISCUSSION

**Question:** Dr. H. Dreyer, Oberberamt, 3392 Clausthal-Zellerfeld, W. Germany: Why separate mine ventilation and filtration of mine air? The radiation dose may be kept below a limited minimum in any case so as not to endanger personnel.

**Answer:** Two ventilation circuits are being planned: one for the mining operations and one for waste emplacement operations. Exhaust air from the waste emplacement operations will pass through HEPA filters to prevent the release of any significant amount of radioactivity to the atmosphere. Exhaust air from the mining operations circuit has no potential for radioactive contamination and will be maintained at a slightly higher pressure than the waste emplacement circuit so that any leakage between the circuits will be into the waste operations circuit will be exhausted directly to the atmosphere. The proposed dual ventilation system is attractive because miners will not be working in areas that have potential for contamination and exhaust air from the mining circuit will not have to pass through the relatively expensive HEPA filtration system.

**Questions:** Mr. A. V. Joshi, Kraftvaerksvej 43, DK-7000 Fredericia.

1. When one talks of geological disposal for a period of 250,000 years, does retrievability over a period of 5 to 15 years make sense?

**Answer:** 1. Relatively short retrieval periods make sense because it is during the first 5 to 25 years that close-in temperature and temperature gradients are expected to peak. Nearly all of the mechanisms proposed that would violate the integrity of the containment are thermally driven. Consequently, an option to retrieve will probably be maintained for an initial period to guard against some unforeseen mechanism causing problems in the immediate neighborhood of the canisters. Naturally, such a short retrieval period does not provide a safety mechanism for unlikely difficulties that may develop later in the far field. The probability of any difficulties developing in either the near or far field is very low due to 1) a detailed and thorough site selection process where only the most favorable sites will be accepted and 2) Conservative engineering design based on extensive numerical modeling and conservative criteria.

2. Why not disposal in deep boreholes where the canisters are stacked on top of one another? The heat is thereby dissipated in a greater salt volume.

**Answer:** 2. Several schemes have been proposed wherein canisters are stacked on top of one another in relatively deep emplacement holes. These schemes have certain advantages but have been rejected because of the anticipated response in the far field. Our calculations have shown that ultimately the heat generated by the buried waste is transferred vertically and dissipated to the atmosphere at the surface above the repository. Consequently, the controlling parameter in the far-field response is the thermal power per unit area. In view of this constraint and the increased difficulty in retrieval, if it is ever needed, multiple canisters in a single hole are not being recommended.

## ACKNOWLEDGEMENTS

The concepts of radioactive waste isolation in salt discussed in this paper have been influenced by the basic work done at Oak Ridge National Laboratory, Union Carbide Corporation, Nuclear Division, on this question during the past 20 years. In addition, current contractors working on conceptual design and supporting work should be acknowledged for their contributions, in particular Kaiser Engineers; Stearns-Roger Engineering Company; Parsons Brinckerhoff Quade & Douglas, Inc.; RE/SPEC Inc.; The University of Minnesota; Science Applications, Inc.; Woodward-Clyde Consultants; and Dames & Moore. S.C. Matthews, formerly of the Office of Waste Isolation (OWI) and now with the Office of Nuclear Waste Isolation (ONWI, Battelle Memorial Institute), contributed greatly to the conceptual designs of the facilities discussed herein. Other OWI personnel, too numerous to list, have been instrumental in formulating and clarifying the concepts discussed in this paper.

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