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ECONOMIC AND ENVIRONMENTAL EVALUATION OF NUCLEAR WASTE DISPOSAL BY UNDERGROUND IN SITU MELTING

J. J. Cohen, R. L. Braun, L. L. Schwartz, and H. A. Tewes

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MASTER

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ECONOMIC AND ENVIRONMENTAL EVALUATION OF NUCLEAR WASTE DISPOSAL BY UNDERGROUND IN SITU MELTING

Abstract

Disposal of high-level nuclear waste by the Deep Underground Melt Process (DUMP) is reviewed and evaluated relative to other proposed methods for waste management. Although the potential environmental impact (population exposure to radiation) for the DUMP concept

was found to be lower than that for alternative disposal methods, the difference is of small significance. The economic advantages, however, were substantial. A potential 80% cost savings relative to other geologic disposal methods is indicated.

Introduction and Description of Concept

DUMP, for Deep Underground Melt Process, was proposed in 1972 for the management of high level nuclear waste.¹ The concept (as depicted in Fig. 1) called for direct placement of liquid radioactive waste from fuel reprocessing operations deep underground into rubble-filled void spaces (called chimneys) formed by the underground nuclear detonations. Capacities and properties indicated on Fig. 1 are for a typical 5 tons, d fuel reprocessing plant.

Figure 2 depicts the time sequence of this waste disposal process. During the waste addition phase, decay heat maintains self-boiling conditions within the cavity; the vapor effluent is condensed at the surface and either recycled through the plant, or directly reinjected for cooling the cavity. Following waste addition, the cavity is allowed to boil dry and the

access holes are sealed. Subsequently, the decay heat melts the waste plus surrounding rock. The molten rock dissolves the waste and the molten system continues to grow, reaching its maximum radius in times typically estimated at tens to hundreds of years. When the rate of conductive heat loss from the system exceeds that of the radioactive decay heat output, the system begins to cool and refreeze. Total resolidification would require millennia. By that time all fission products will have essentially decayed away, and the only remaining radioactive components will be the actinides. The final result would be the encapsulation of this radioactive material in an insoluble rock matrix deep underground.

At a thousand years following the initial emplacement the relative hazard of

Fig. 1. Waste disposal in a nuclear chimney.

this resolidified rock, based on its actinide content, would be less than 1% of that of naturally occurring pitchblende as determined by the method discussed by Claiborne.²

Review

This concept for waste disposal and its modifications have been discussed and analyzed by other authors.³⁻⁷ One such modification is the direct placement of waste, either in liquid or presolidified form, in underground cavities excavated by conventional means⁸ as depicted in Fig. 3. Another modification involves using refractory capsules which contain the waste and which, by melting the rock immediately beneath them, embed themselves deep within the earth.^{9,10} A vexing problem with this latter approach is the selection of a container material that can maintain its integrity in a molten rock system.

In all these concepts the heat from radioactive decay melts rock *in situ* deep underground and an insoluble rock matrix eventually encapsulates the waste. We have selected the acronym DUMP as a generic designation for these radioactive waste disposal methods.

ADVANTAGES OF DUMP

Potential advantages of DUMP include:

- Elimination or reduction of many processing operations and their attendant risks. These operations include interim storage, chemical separation, and solidification.
- Potential for safe disposal of all levels of liquid waste, including intermediate and low level.

Fig. 2. Sequence of events in the DUMP process chimney starting with liquid waste addition.

Fig. 3. Liquid waste emplacement in a mined cavity.

- Elimination of radioactive waste transportation and its attendant risks.
- Permanent binding of the radioactive waste in a rock matrix deep underground, assuring its permanent elimination from the biosphere.
- Provision of a secure disposal method, assuring permanent safety from effects of disasters such as floods, sabotage or warfare.

Evaluations of the concept performed by various groups¹¹⁻¹³ indicate that it shows great promise as a safe, efficient, and economic solution to the waste management problem. However, no comprehensive research efforts have as yet been undertaken to determine its feasibility.

PROBLEM AREAS

Possible Policy Conflicts

In assessing the DUMP concept, certain problem areas have been identified. These include a possible conflict with AEC policy, which requires retrievability of wastes and storage at a single centralized facility.¹⁴ An inherent weakness in this policy is that where retrievability is possible, the risk of unauthorized retrieval becomes apparent. In this regard, retrievability may be equated with vulnerability. We believe, however, that if a safe and effective ultimate disposal method can be proven the requirement for retrievability can be eliminated.

Since the DUMP concept requires permanent disposal at the site where the waste is generated [the fuel reprocessing plant (FRP)], the requirement for one centralized storage facility could not be met unless one FRP could suffice for the entire country. However, the additional risk incurred by increasing the number of disposal sites should be more than offset by the elimination of the need for transportation of the hazardous waste. The DUMP concept would be admirably suited for application at Nuclear Power Parks, since it would allow for siting a safe permanent waste disposal facility within the site boundary. The DUMP concept would also be applicable to the permanent disposal of wastes accumulated at Retrievable Surface Storage Facilities (RSSF).

Misconceptions

A second category of problems is based upon certain misconceptions of the DUMP concept. First, we must emphasize that a nuclear explosive is not necessary to the concept as some appear to believe.¹⁵ Although nuclear chimneys are the most economical and expeditious method for forming the required void space deep underground, the economics of the concept are such that — relative to alternative waste management concepts — the added costs of conventional cavity construction by mining would be trivial. It is currently our opinion that the political and psychological disadvantages of cavity construction using nuclear explosives could outweigh the advantages and unduly delay the development of a potentially valuable technology.

A second misconception is an expressed concern regarding potential ground water contamination during the liquid addition phase, and also at later times. The question of possible ground water contamination can be evaluated for both the liquid waste addition phase and the molten rock phase of the DUMP process.

During the liquid addition phase, the interior of the cavity is maintained at essentially atmospheric pressure. At a depth of 1.5 km, the formation pressure would be about 15 MPa hydrostatic. Therefore, any flow would, of necessity, be from the surrounding formation into the cavity. In applications where pre-solidified waste is added, e.g. disposal of waste accumulated at an RSSF, the waste could remain sealed in containers during the brief addition phase, thereby precluding water contamination problems.

The possibility of ground water contamination during the rock-melting phase of the DUMP process warrants consideration in some detail. Consider the system of molten rock plus radioactive waste resulting from a terminated DUMP operation. The core of the system will have a temperature at or above the melting point of the rock. Any excess heat will go into heat of fusion to melt more rock, the process thereby maintaining essentially uniform temperature within the molten core. Surrounding this core will be a series of decreasing isotherms ranging from the melting point of rock, through the boiling point of water, and eventually reaching the ambient temperature of the native rock. Somewhere in this continuum there will necessarily exist an isotherm at which liquid water will flash to

vapor. This isotherm will serve as a "thermal barrier" separating liquid water from the core and its radioactive contents. This "thermal barrier" prevents water intrusion and minimizes the possibility of water contamination during the rock melting phase.

A third misconception relates to the possible migration of the molten rock mass. We have been unable to identify any physical mechanism that would cause such migration, since conductive heat flow is nondirectional. Assuming that there is such a mechanism, however, it is readily shown that the translational movement associated with a nonspherical growth of the molten rock is very limited. Using the computer model HEAT,¹ developed for calculating the thermal history of the DUMP process, we have performed the calculations modeled in Fig. 4. Input parameters for this calculation are the

Fig. 4. Vertical growth of molten zone.

Fig. 5. Variation of melt volume with distance traveled by molten zone.

same as those given in Figs. 1 and 2. We allow the body of molten rock to grow preferentially in a certain direction by postulating a hemispherical growth in one direction and a cylindrical growth for a fixed angle β in the opposite direction. The higher surface-to-volume ratio associated with a non-spherical shape increases conductive heat transfer from the molten body and thereby decreases the ultimate volume of molten rock. This is shown in Fig. 5 as a function of the growth angle. Thus, even if directional growth were to occur, the increased rate of conductive heat loss would preclude the possibility of movement over any significant distance. Any process of growth or movement would necessarily be self-limiting.

Cost-Benefit Analyses of Several High-Level Radioactive Waste Disposal Concepts

To gain insight into the relative desirability of a number of high-level waste disposal concepts, we have performed generic cost-benefit evaluations of these concepts. Figure 6 gives a categorization of options. These are taken largely from the paper of Kubo and Rose.¹⁵ Three basic approaches to the treatment and disposal of high level nuclear waste are indicated. The first (Pathway 1) seems to be currently favored by the AEC's Division of Waste Management and Transportation, although the ultimate method of disposal of solidified waste has not yet been chosen.

The second approach (Pathway 2) basically involves partition of the waste

Technical Problems

A third category of problems associated with DUMP is the one we term "real" or technical problems. These include:

- Engineering difficulties.
- Fate of volatile radionuclides.
- Geological alteration due to phase change of a large volume of rock.
- Convective phenomena (shape).
- Consequences of seismic activity during addition phase.
- Chemical compatibility of waste and medium.

Perhaps the most difficult of these would be the engineering problems dealing with waste handling, logistics, and materials. DUMP conductivity phenomenology is presently the subject of ongoing research at Sandia Laboratories.¹⁶

into a short-half-life component, i.e., fission products, and a long-half-life component i.e., the actinides. Such a separation is economic only when the ultimate disposal mode selected is too expensive to be applied to both components of high level waste.

The third approach (Pathway 3) envisages minimal or no treatment of the high level waste prior to disposal. In this paper, only those disposal modes involving geologic disposal will be discussed, inasmuch as in our judgment the other paths and disposal modes (those with shaded backgrounds) are clearly uneconomic or have significant potential uncertainties associated with them.

Fig. 6. Waste management options; Kubo and Rose, Ref. 15.

The first approach is amenable to a number of ultimate disposal modes, including either melting or nonmelting scenarios subsequent to the introduction of the stored waste into wellbores, con-

ventionally mined cavities or cavities created by explosives. Also, a number of geologic media could be used for such disposal, including evaporites, granite, or shale. It can be seen that the "melt-

Table 1. One-hundred-year dose commitment from management of waste resulting from nuclear power generation, man-rem/ 10^3 GW(e)-y.

Operation	Solidification + engineered geologic storage	Solidification + long term RSSF	Solidification + RSSF + conv. geol. disp.	Solidification + RSSF + DUMP	Solidification + DUMP	Direct DUMP
Interim liquid storage	5 000	5 000	5 000	5 000	5 000	5 000 ^a
Solidification	2 000	2 000	2 000	2 000	2 000	—
Interim solid storage	3 000	3 000	3 000	3 000	3 000	—
Transport to RSSF	—	3 000	3 000	3 000	—	—
RSSF	—	10 000	5 000	5 000	—	—
Transport to ultimate storage site	2 000	—	2 000	2 000	2 000	—
Ultimate storage	500	—	500	500	500	500
Total	12 500	23 000	20 500	20 500	12 500	5 500

^a Liquid addition phase.

ing" disposal in rock is one variation of the DUMP concept.

The third approach is, of course, the simplest and least expensive of the DUMP variations since it involves the least treatment and handling of the high level waste. As previously discussed, this concept involves the direct disposal of liquid waste in an underground cavity,

followed by its "self-solidification."

Approaches one and three have been analyzed for both their inherent safety and for their economic costs; the results of these analyses are given in Tables 1 and 2. The assumptions involved in the preparation of Table 1 are outlined in Appendix A. The figures presented in Table 2 were derived from data given in Refs. 1 and 12.

Table 2. Summary cost comparison of various waste management concepts.

Process	Mill/kW(e)/h	10^6 \$/10 ³ GW(e)-y
Solidification + eng. geologic storage	0.05	440
Solidification + long term RSSF	0.04	350
Solidification + RSSF + eng. geol. disp.	0.07	610
Solidification + RSSF + DUMP	0.06	550
Solidification + DUMP	0.03	230
Direct DUMP	0.01	90

Conclusions

Although the "direct DUMP" sequence appears to have less adverse health impact than the alternative concepts, the overall differences appear to be of no great significance. On the other hand, the eco-

nomic savings realized by the implementation of the DUMP process are substantial, i. e., up to 80%. By the year 2000, these savings could amount to several hundred million dollars annually on a national scale.

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Appendix A: Assumptions Involved in Estimating the Environmental Cost of Several High-Level Radioactive Waste Disposal Options

In estimating the relative population exposure to radiation from the different waste disposal methods considered in Table 1, the waste disposal procedure has been divided into seven steps:

1. Interim liquid storage
2. Solidification
3. Interim solid storage
4. Transport to RSSF
5. Holding period at RSSF
6. Transport to ultimate disposal site
7. Ultimate disposal

Our estimates of population exposures accruing from each of these steps are discussed in some detail in the following sections for each of the proposed waste disposal scenarios, and the pertinent assumptions are presented.

1. Interim Liquid Storage

This storage of waste will take place at the fuel reprocessing plant prior to the next step of waste solidification for all disposal scenarios, with the exception of Direct DUMP. In this latter case, population exposure from the "liquid addition phase," where high level liquid waste is being injected into the underground cavity, is assumed to be equal to the population exposure resulting from liquid waste storage in each of the other waste disposal methods.

As discussed in Ref. A-1, for ultimate storage, a "leak" rate of 0.3%/y gives (480 y after the start of the leak) a maximum 50-y dose commitment of 1500 man-rem, and hence, a 100-y dose

commitment of about 3000 man-rem. This estimate is based on storage of waste from the processing of 167 kt of fuel. For the waste from one year's operation of 1000 GWe nuclear generating capacity, where 26.8 kt of fuel are processed, the 100-y dose commitment would be 500 man-rem. We shall assume that the hazard from interim liquid storage in surface tanks is about 10 times higher than that from storage in geological formations, or 5000 man-rem.

2. Solidification

The solidification of liquid waste will be carried out at fuel reprocessing plants prior to shipment of the waste to a RSSF, and will be one of the steps in all waste disposal scenarios, with the exception of Direct DUMP.

For a waste processing plant which is processing 5 tons/d of irradiated fuel, the amount of actinides released per year will give a 100-y dose commitment of 464 man-rem, as discussed in Ref. A-2. By the year 2000, the total amount of fuel processed per year will be 26.8 kt (for a nuclear generating capacity of 1000 GWe). This implies a processing capacity of about 73 tons/d, or about 15 plants, each with a capacity of 5 tons/d. Thus, by the year 2020, the annual incremental 100-y dose commitment from actinides alone will be $15 \times 464 = 7000$ man-rem.

We will assume that the total annually imposed 100-y dose commitment (including contributions from fission products

such as ^{90}Sr and ^{137}Cs) will be three times the above, or about 20,000 man-rem. We will also assume that the relatively straightforward solidification step will result in a dose commitment only one tenth as large as that from fuel processing, or about 2000 man-rem.

3. Interim Solid Storage

The storage of solidified waste at fuel reprocessing plants prior to shipment to the RSSF (or other disposal site) will be one of the stages in all of the waste disposal scenarios other than Direct DUMP.

We have assumed that the storage of this solidified waste will result in a dose commitment only half of that from the storage of liquid waste, or about 3000 man-rem.

4. Transport to RSSF

In accord with Ref. A-3, we have assumed one shipment accident per each 625 shipments. One shipment per year of solidified waste is assumed to be required for each 1000 MWe nuclear power plant, so about one accident per year will result from a total nuclear electric generating capacity of 1000 GWe. The waste from 270 tons of reprocessed fuel is assumed to contain about 200 kCi of ^{239}Pu .

If the fractional release from each accident is assumed to be about 2×10^{-8} (see Ref. A-3), about 4 mCi of ^{239}Pu would be released in each such accident. On the basis of the approach used in Ref. A-2, the release of this amount of ^{239}Pu would result in a 100-y dose commitment of about 1000 man-rem. Assuming that other nuclides in the release (such as ^{90}Sr and ^{137}Cs) will increase the

dose commitment by a factor of three, then the total 100-y dose commitment would be 3000 man-rem.

5. Holding Period at RSSF

This step obviously applies to only those three scenarios that assume a RSSF. As noted in Sec. 1, Interim Liquid Storage, ultimate disposal in geologic formations is assumed to generate a 100-y dose commitment of 500 man-rem. We shall assume that interim RSSF is one-tenth as secure as geologic disposal; hence, the dose commitment will be about 5000 man-rem. When the RSSF is conceived of as an ultimate (or long term) disposal method, we have doubled this dose commitment to 10,000 man-rem.

6. Transport to Ultimate Disposal

Transport of solid waste long after the waste has been generated by fuel reprocessing is applicable to all waste disposal scenarios with the exception of Long Term RSSF and Direct DUMP.

Since the transportation is taking place many years after processing, we have assumed that radioactive decay of such nuclides will have reduced the hazard to two-thirds of that associated with the Transport to RSSF step, or 2000 man-rem.

7. Ultimate Disposal

The "ultimate disposal" phase applies to all cases except long term RSSF. As noted in the section on Interim Liquid Storage, ultimate disposal is assumed to involve a total 100-y dose commitment of 500 man-rem.

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