AN EVALUATION OF PRE-CONCEPTUAL DESIGNS OF REPOSITORIES IN CRYSTALLINE ROCK

An Economic Analysis of Thermal Limits

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ABSTRACT

Temperature limits presumably have an effect on the performance of the waste form and repository over their lifetimes. These limits dictate the size of waste packages and the spacing with which they are emplaced in the repository. Relatively stringent limits lead to relatively small waste packages and/or relatively large spacings. Relatively small waste packages and relatively large spacings in turn lead to relatively high disposal costs. Three sets of thermal limits, the reference, non-restrictive, and restrictive cases, are postulated and their cost implications for the disposal of CHLW in a crystalline repository are analyzed. Further, these costs are analyzed for two emplacement strategies, single waste packages in a vertical borehole and multiple waste packages in a vertical borehole.

INTRODUCTION

In designing large, complex engineered systems, one usually begins by examining alternative design concepts having relatively little detail and moves toward a single concept having much greater detail. This process of successively screening and elaborating design concepts often involves resolving numerous design issues which can be quite complex and may require tradeoffs not readily apparent.

One issue arising during the screening process involves the choice of thermal limits applicable to the repository and waste form. These thermal limits constrain the allowable temperatures in the repository and waste form over their lifetimes. If one arbitrarily makes these thermal limits too constraining by setting their limiting values too low, one may bear a significant cost in constructing and operating the repository but realize little marginal change in the waste form or repository performance. On the other hand, if the thermal limits are not constraining enough, one's dollar cost may be relatively low but the waste form and repository performance over time may not be acceptable. Obviously, it would be advantageous to have some insight into this thermal design issue early in the design process in order to better guide the subsequent investigations.

This paper summarizes an economic analysis of the thermal design issue discussed above. The analysis is intended to provide an estimate of the waste isolation system costs associated with a range of limiting thermal values. The following sections describe the scope of the analysis, the design bases assumed, the approach used, and the results of the investigation.

OBJECTIVE/SCOPE

The objectives of this analysis are twofold. The first is to explore and compare the economic implications of imposing various sets of thermal limits on the design of a commercial high level waste (CHLW) repository in crystalline rock. The second is to determine the sensitivity of those implications to changes in the waste emplacement strategy. That is, given a set of thermal limits, does a change in the waste emplacement configuration have a significant effect on disposal costs. These objectives are pursued within the following scope. First, the analysis is pre-conceptual and preliminary since no actual crystalline repository or corresponding waste package designs exist at the current time. Rather, existing conceptual designs for salt and tuff provide a representative basis for the crystalline repository and waste package designs.[1] Second, the analysis is relatively macro in scale for two reasons; most of the existing data are macro and the design issues themselves, at this stage of the crystalline investigation, are macro. Third, the analysis is parametric. This parametric approach involves scaling hypothetical "reference", pre-conceptual repository and waste package designs as necessary to satisfy the thermal constraints imposed upon the isolation system's performance. It also involves the consideration of two waste emplacement schemes; single waste packages in vertical boreholes and multiple waste packages in deep, vertical boreholes. And finally the analysis is broad; it addresses the implications of the thermal limits and emplacement configurations within the context of the whole waste isolation system including waste transportation, vitrification, and disposal.

DESIGN BASES

The hypothetical crystalline repository layout used in this analysis is patterned after a salt repository design. The layout is illustrated in Fig. 1. Main corridors lead from the shaft and pillar region to the emplacement area. Access corridors lead to rooms that are parallel to the main corridors. For this analysis, the room-to-room spacing is fixed at 17.5 meters. The spacing of packages in the boreholes (pitch) is allowed to vary within the constraints of the appropriate thermal limits. The variation of waste package pitch is discussed in a later section.

The glass waste form assumed in this analysis conforms to that in PNL 3838 with the exception that in this analysis the waste form is longer and, its diameter is allowed to vary.[2] This waste form variation is discussed in a subsequent section.

The waste package design assumed in this analysis consists of an overpack 3.58 meters in length; its diameter is allowed to vary in conjunction with the waste package pitch, both being subject to thermal constraints. The overpack thickness, although it

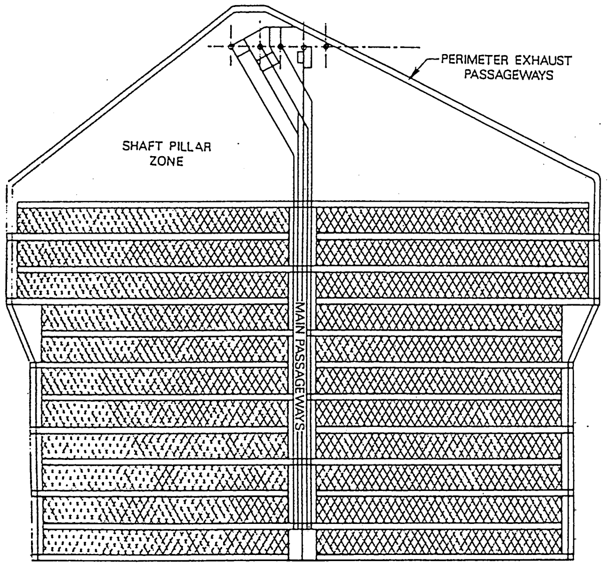

Fig. 1. Hypothetical Underground Repository Layout.

varies with diameter, is approximately one-half the thickness of the waste package designed for salt repositories; this thickness reduction reflects the difference between the hydrostatic pressure in a crystalline repository as opposed to the lithostatic pressure in a salt repository.

One of two options is assumed for the emplacement of the CHLW; emplacement of a single waste package in a vertical borehole six meters deep, or emplacement of nine waste packages in a vertical borehole approximately 100 meters deep. Each type of emplacement assumes no backfill around the packages, but rather, an air gap.

A summary of the these and other major design parameters assumed in this analysis is listed below.

- Repository capacity: 70000 MTU equivalent
- Waste type: CHLW and associated TRU
- Geology: Crystalline
- Waste package: "long-lived" Westinghouse designs
- Waste form composition: PNL 3838
- Waste age: 10 years at emplacement
- Waste emplacement: CHLW - vertical boreholes, 1 package per hole and 9 packages per hole; RHTRU-vertical boreholes, 1 package per hole
- Waste transportation: rail
- Number of repository shafts: 5
- Annual waste throughput: 3000 MTU equivalent.

APPROACH

A parametric approach is used in analyzing the impact of thermal limits on repository design and cost. Several steps are involved. First, representative sets of thermal limits that might be important to repository performance are identified. Specific values for the selected thermal limits are then assigned either on the basis of literature or judgment. Next, heat transfer calculations are performed. In these calculations, the spacing and quantity of waste in a package are varied so that one obtains a curve for each limit, i.e., a locus of points relating watts per package and areal loading. Superimposing the curves on a single figure then indicates which limits constrain the design; one's design space becomes obvious. The final step involves searching the design space for the optimum disposal cost. A systems approach, which considers the costs of vitrification and transportation, as well as disposal, is used in this last step.

The two major dimensions of the approach, the thermal analysis and economic analysis, are discussed in more detail below.

Thermal Limits

Thermal limits represent constraints imposed on the maximum temperatures allowed in the repository and waste form after waste emplacement. These constraints serve to preclude unsatisfactory repository performance and undesirable release of radionuclides to the biosphere through time.

In this analysis, five separate generic thermal limits constrain the design of waste packages and the crystalline rock repositories in which the packages are to be ultimately emplaced. Those limits are:

- A waste centerline temperature limit, a limit which may not be exceeded without adversely affecting the structure of the waste form;
- A "near-field" rock temperature limit, a limit which may not be exceeded without adversely affecting the integrity of the repository host rock;
- A "far-field" rock temperature limit, a limit which may not be exceeded without adversely affecting the repository site's isolation capabilities;
- A time dependent waste centerline temperature limit, a limit which constrains leaching and dissolution of the waste form following loss of containment; and
- A time dependent "near-field" temperature limit, a limit also intended to constrain leaching and dissolution of the waste form following loss of containment.

The particular set of values assigned to the above generic limits leads to a specific repository and waste package performance over the repository's lifetime. The issue of concern in this analysis is the choice of limiting values assigned to the various generic limits, e.g., should one limit the waste centerline temperature to 500°C or 400°C, the "near-field" temperature to 350°C or 200°C, etc.

In resolving these thermal design issues, one should be aware of the incremental performance gained or lost by the choice of a particular set of limiting values vis-a-vis the incremental cost. This analysis focuses on the incremental cost of assigning one set of limiting values to the generic thermal limits as opposed to some other set.

In order to explore these costs, three cases have been created for each of the emplacement configurations, i.e., three cases for the single package borehole configuration and three cases for the multiple package configuration. Each of the cases involves a set of five limiting temperature values, one for each of the five generic thermal limits listed above. These cases and their respective limiting temperature values are shown below in Table I.

TABLE I.

	Cases		
Limit	Reference	Non-Restrictive	Restrictive
Centerline	500°C	500°C	400°C
Near-field	350°C	350°C	100°C
Far-field	85°C @ 50m	85°C @ 75m	85°C @ 5m
Time Dependent Centerline	150°C @ 300 yr	150°C @ 500 yr	150°C @ 200 yr
Time Dependent Near-field	100°C @ 300 yr	100°C @ 500 yr	100°C @ 200 yr

Each of the five thermal limits shown above can be represented as a curve whose locus indicates the combinations of waste package loading and areal thermal density leading to the corresponding limiting temperature. That is, each point on a given curve would represent a waste package loading and repository thermal density combination leading to the same limiting value, e.g., a 500°C centerline temperature. The actual calculation of points on these curves is accomplished using a relatively simple, three-dimensional heat transfer code, TEMP.^{3}

When one superimposes all five thermal limit curves they define a "design space" containing allowable combinations of waste package loading and areal thermal emplacement density. Figures 2 through 4 illustrate the superimposition of the five thermal limit curves for each of the three cases involving one package per borehole and Figs. 5 through 7 illustrate the superimposition for the three cases involving nine packages per borehole. The "design space" in these figures is formed by the curves representing the minimum emplacement density (w/m^2) for a given waste package loading (w/pkg.). For example, the design space in Fig. 2 is the area labeled ABCD. Every point within this space represents an allowable waste package loading and emplacement density combination. Points outside of this space, however, represent combinations which violate at least one of the limiting temperatures. Within the "design space" for a given waste age and waste form - and corresponding power levels - one may thus trade certain increases/decreases in the waste package loading (or waste form size) for corresponding increases/decreases in the repository's areal thermal emplacement density (or waste package pitch) without violating the specific set of limiting temperatures.

Economic Analysis

The design and economic implications associated with the sets of thermal limit curves illustrated in Figs. 2 through 7 are explored with the use of a parametric, waste disposal life-cycle cost model, WADCOM^4. WADCOM is a relatively simple, aggregated representation of the nuclear waste management system life cycle costs. It is intended to provide its users with a quick and flexible way of exploring design issues and their implicit tradeoffs. Its logic is the product of a number of factors. First, because the design issues and parameters of interest can affect costs throughout the waste's life cycle, the model is broad in scope. It contains submodules representing spent fuel generation, waste transportation, waste vitrification, interim storage, and disposal and is consequently able to highlight both direct and indirect implications of various design issues. Second, because the design data at this particular time are not fully defined, WADCOM is a relatively aggregated model. This type of relatively aggregated model seems more consistent with the quality of the existing data and the nature of the issues than a more detailed model. Finally, because the model is intended to provide a comparatively rapid insight into the issues and their implications, the WADCOM computer logic is fairly simple.

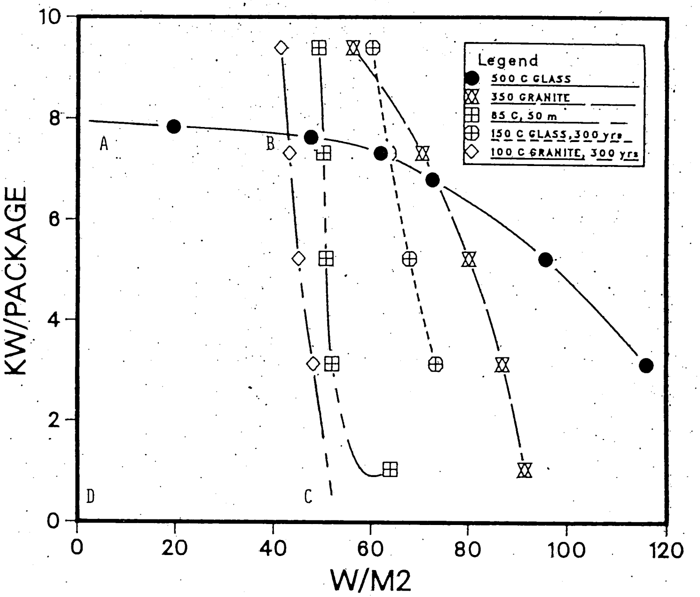

Fig. 2. Reference Case: CHLW in Granite
One Package per Vertical Borehole

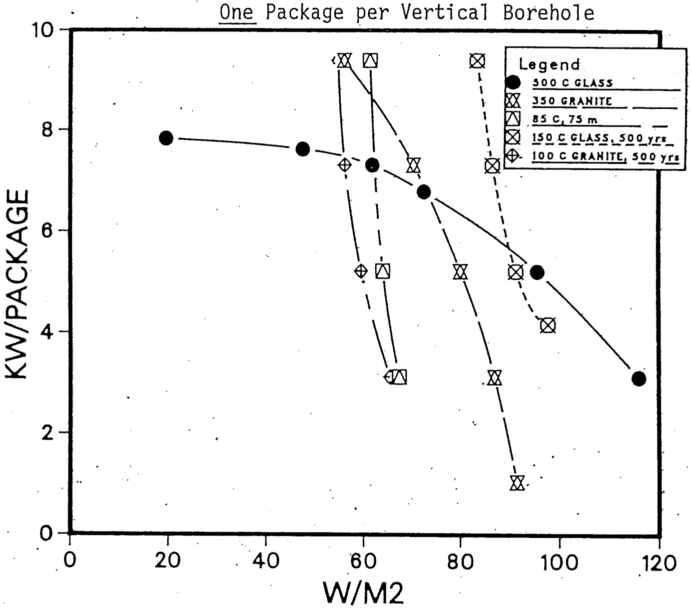

Fig. 3. Non-Restrictive Case: CHLW in Granite
One Package per Vertical Borehole

Two additional features of the model are noteworthy. First, as mentioned previously, the model is parametric. It embodies relatively simple scaling rules which are used to extrapolate the "reference" design and costs implicit in the model's input data. Second, the model is able to optimize the waste package diameter with respect to either repository or total system costs. This optimization is achieved by searching every point on the respective "design space" boundary for the combination of waste package diameter and emplacement density leading to the lowest total system or repository cost.

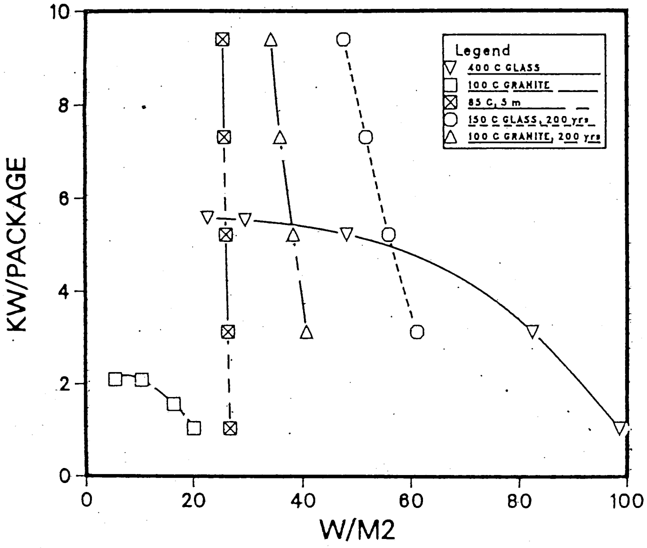

Fig. 4. Restrictive Case: CHLW in Granite
One Package per Vertical Borehole

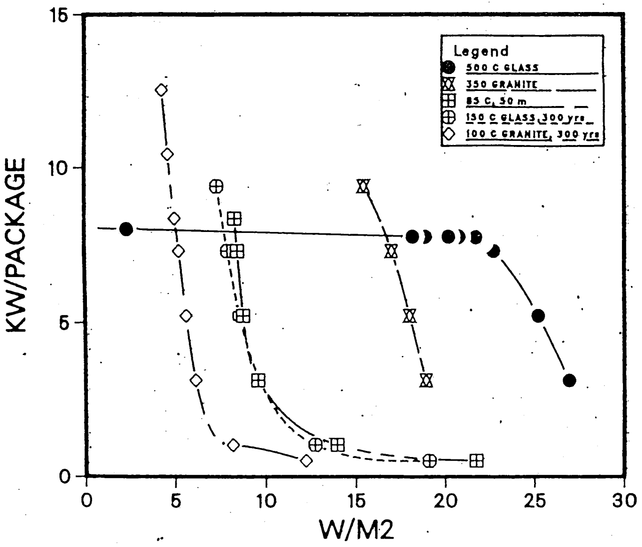

Fig. 5. Reference Case: CHLW in Granite
Nine Packages per Vertical Borehole

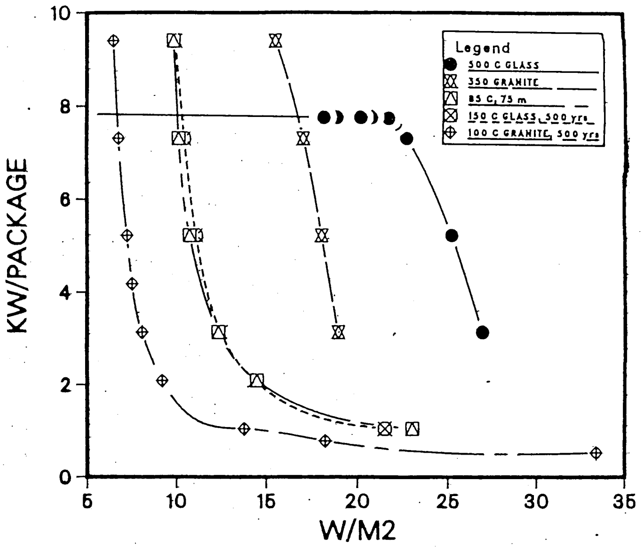

Fig. 6. Non-Restrictive Case: CHLW in Granite
Nine Packages per Vertical Borehole

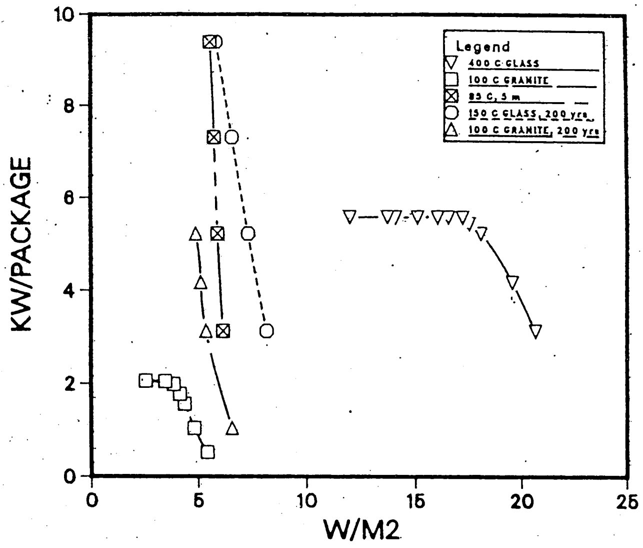

Fig. 7. Restrictive Case: CHLW in Granite
Nine Packages per Vertical Borehole

RESULTS

The consequences of trading waste package loading for areal thermal emplacement density are threefold. First, as the waste form size changes, the number of waste forms needed to contain a given total volume of waste changes in inverse proportion; the capacity of the transportation casks changes likewise. Second, as the package pitch changes, more or less mining is required. And finally, because of the first two changes, the overall costs of disposal change. That is, for a given set of thermal limit curves, waste package diameter is transformed into a corresponding number of waste packages, watts per waste package, and emplacement pitch. Given the relative cost for mining and for fabricating, transporting, and handling waste packages, these combinations of waste package diameter and pitch lead to a disposal cost. One of these combinations leads to a cost which is less than the cost of any other possible combination. The combination is economically optimal within the design space.

The reason for this optimality can be sensed intuitively by considering that at large waste package diameters, although relatively few waste packages are required to accomodate a given volume of waste, the packages must be spaced relatively far apart in order to avoid violating certain of the repository thermal limits. Consequently, mining costs become quite high as the waste package diameter becomes large. On the other hand, as the waste package diameter becomes small, relatively large numbers of waste packages are necessary to accomodate a given volume of waste. Waste package fabrication and handling costs become relatively high as a result. A minimum cost is achieved at waste package diameter and pitch combinations lying somewhere between these two extremes.

As the set of limit curves shifts, as occurs when one moves from the reference to non-restrictive and restrictive cases, for example, the economically optimal waste loading - areal thermal density combination and the associated total system cost change correspondingly. The cost of imposing a certain set of thermal limits on the design of a repository in crystalline rock is thus relative to the costs of other possible sets. It is these relative costs which are of interest in this analysis.

Table II. summarizes the waste isolation system costs for the first three cases in which each vertical borehole contains a single CHLW waste package, i.e., the reference, non-restrictive, and restrictive cases. The costs in this table represent an approximately optimal waste package size (loading) and pitch combination from the perspective of total system (vitrification, transportation, and disposal) costs.

TABLE II.

Cost Results
(optimized with respect to total system)
One Waste Package per Single Vertical Borehole
(Mill 83$)

	Case		
	Reference	Non-Restrictive	Restrictive
Waste Pkg.			
ID (cm)	∿ 49	∿ 44	∿ 19
Pitch (m)	∿ 9.0	∿ 5.4	∿ 2.9
Vitrification	3617	3629	3782
Transportation	1789	1755	1755
Rep./Waste Prep	5362	5267	6493
Total System	10768	10651	12030
Dif. from Reference	0	-117	1262

As shown in Table II., the system costs in the reference case are approximately $120 million greater than the corresponding costs in the non-restrictive case. Most all of this cost difference results from the additional mining necessary to accomodate the difference in waste package pitch.

The most restrictive case leads to the smallest waste package inside diameter and waste package pitch. The case's costs, however, are approximately $1.2 billion more than the costs in any of the other cases. Essentially all of this increase is due to increased repository costs arising from the greater number of waste packages handled and the resulting increased mining costs. Vitrification adds only about $100 million and transportation, because of the greater efficiency achieved in shipping the relatively small waste forms, is actually less than the costs of the reference case.

The second set of cases analyzed involves deep vertical boreholes containing nine CHLW waste packages each. The boreholes in these cases are assumed to be constructed using blind hole drilling methods and are approximately 100 meters deep. The cost per meter for drilling this type of borehole is judged to be somewhat less - because of decreased setup costs - than the comparable cost per meter for drilling the shallower boreholes assumed in the previous three cases. The nine waste packages in these boreholes are assumed to be separated by some type of spacer, such as crushed granite, so that a greater length of borehole must be drilled for each waste package than in the single package borehole cases. Consequently, the borehole costs are somewhat greater than in the single package borehole cases, in spite of the lower per meter drilling costs.

The repository layout in the case of these deep vertical boreholes is assumed to be the same as shown in Fig. 1. The one difference between the deep borehole cases and the shallower borehole cases is the pitch, or distance between boreholes. In the case of the single package borehole cases, the pitch varies from approximately three to nine meters. In the deep vertical borehole cases, the pitch varies from approximately 25 to 75 meters.

Table III. summarizes the waste isolation system costs for the three cases in which each vertical borehole contains nine CHLW waste packages.

TABLE III.

Cost Results
(optimized with respect to total system)
Nine Waste Packages per Single Vertical Borehole
(Mill 83$)

	Case		
	Reference	Non-Restrictive	Restrictive
Waste Pkg.			
ID (cm)	∿ 49	∿ 52	∿ 26
Pitch (m)	∿ 75.5	∿ 64.2	∿ 28.4
Vitrification	3616	3611	3711
Transportation	1789	1805	1789
Rep./Waste Prep	5394	5273	5875
Total System	10799	10689	11375
Dif. from Reference	0	-110	576

The costs in the three cases follow the same pattern as in the previous three cases. That is, the restrictive case is the most costly, followed by the reference and non-restrictive cases, as one would expect. Even the total costs of the three deep borehole cases are similar to the total costs of the previous three cases with the following exception.

The restrictive case results in a relatively small increase, approximately $600 million, over the reference case cost. Consequently, the restrictive case in which the boreholes contain nine waste packages is actually significantly less than the restrictive case in which the boreholes contain a single waste package each. It thus appears that as the limits get relatively more stringent and as the waste packages get relatively smaller, there is a cost incentive for placing multiple packages in boreholes.

CONCLUSIONS

Recalling that the objectives of this analysis were to 1) explore and compare the economic implications of imposing various sets of thermal limits on the design of a CHLW repository in crystalline rock, and 2) to determine the sensitivity of those implications to changes in the waste emplacement strategy, a number of conclusions seem reasonable.

First, not all of the five thermal limits are relevant in each of the six cases. As shown in Figs. 2-7, at most only three of the limits are important in delineating any of the design spaces. The remaining limits tend to fall outside the design space and thus play no part in its delineation. By satisfying the most stringent limits in any of the six cases, one automatically satisfies the remaining limits.

Second, although the imposition of quite restrictive thermal constraints (the restrictive case) can have a significant relative effect on the repository's cost, an effect in excess of $1 billion, the imposition of more moderate thermal constraints (the non-restrictive case) leads to much more moderate difference from the reference cost. There thus appears relatively little to be gained by additional relaxation of thermal limits. Additional conservatism through the imposition of relatively stringent limits could become costly, however. One should thus attempt to gain a thorough understanding of how repository performance is enhanced as thermal limits become more constraining.

Third, most of the cost effects occur within the repository. These cost effects are comprised of the mining and waste package fabrication and handling costs which are in effect traded off for one another in going from one case to another.

And finally, this exploratory analysis suggests that, when room-to-room spacing in the repository is fixed, emplacement strategy has little impact on mining costs when relatively high thermal limits (the reference and non-restrictive cases) and large waste packages are involved. That is, when the waste packages tend to be large, the relatively macro level of precision involved in this analysis suggests that an emplacement strategy involving fixed room-to-room spacing and deep vertical boreholes containing multiple waste packages offers no significant cost advantages over an emplacement strategy involving boreholes containing single waste packages. In fact, the multiple package boreholes may represent a slight cost disadvantage in these cases. However, when the thermal limits are relatively constraining (the restrictive case) and when the waste packages have relatively small diameters compared to their length, emplacing multiple waste packages in a single borehole appears to offer significant cost advantages in spite of the fixed room-to-room spacing. Further, the full extent of this incentive has probably not been discovered in this analysis. That is, one could probably reduce costs even further by decreasing the length of spacer (crushed granite) assumed to exist between each waste package in the multiple package boreholes. In addition, it is highly probable that the multiple package borehole emplacement strategy could be made more cost effective if the room-to-room spacing were made variable. That is, if the fixed room-to-room spacing in the reference and non-restrictive cases shown in Table III were increased and the pitch decreased, so as to maintain a constant thermal areal loading, the room mining costs would decrease. Thus, if the room-to-room spacing were considered in the cost optimization, along with the waste package size and pitch, it is very likely that the multiple package borehole strategy would be more cost effective than the single package borehole strategy for <u>all</u> cases. This more expanded optimization should be further investigated.

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