COMPARATIVE STUDY OF WASTE EMPLACEMENT CONFIGURATIONS FOR THE NUCLEAR WASTE REPOSITORY IN BASALT

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ABSTRACT

Various alternative waste emplacement concepts were evaluated and compared in order to select a waste emplacement configuration for the Nuclear Waste Repository in Basalt (NWRB). Based on screening of 51 feasible configurations, 11 alternative waste emplacement concepts warranted further evaluation. All of these configurations were analyzed in sufficient detail to assess the technical feasibility of each configuration and to allow a comparative evaluation. Based on the evaluation, the alternatives of greatest merit are, in order of preference:

- Horizontal short-hole emplacements with single canisters close to room walls, with holes either at a 90° or 45° angle to the room
- Angled short-hole emplacement in the floor
- Asymmetric, long-hole, horizontal multiple canister emplacement
- Angled short-hole emplacement off the floor corner.

Other alternatives, including an in-room and a vertical emplacement configuration, were found to have significantly lower merit. This paper summarizes the technical evaluations that have lead to this conclusion.

INTRODUCTION

The United States Department of Energy is studying the feasibility of constructing a repository for permanent disposal of nuclear waste in the deep basalt formations beneath the Hanford site near Richland, Washington. As part of this feasibility study, a conceptual design for the Nuclear Waste Repository in Basalt (NWRB) was prepared by the joint venture of Raymond Kaiser Engineers Inc. and Parsons Brinckerhoff Quade & Douglas, Inc.[1] The conceptual design employs a waste emplacement concept in which up to 17 canisters of commercial high-level waste (CHLW) or 13 canisters of spent fuel are placed in long (61-m) horizontal holes off the walls of parallel placement rooms. This waste emplacement concept was selected for the conceptual design based on the functional design criteria established for the NWRB[2] and on other available information.[3, 4]

Since the repository conceptual design was prepared, expansion of the geotechnical data base provided new information that warranted a reevaluation of alternative waste emplacement concepts and associated underground designs. Furthermore, it was desired that this reevaluation consider the development and demonstration testing needs associated with alternative design concepts as well as the potential advantages of using improved mining techniques and equipment.

ANALYSES AND EVALUATION

Evaluation Basis

The basic functional requirements for the design of the NWRB are described in the Functional Design Criteria (FDC) prepared by Rockwell Hanford Operations,[2] and these requirements have been used as the basis for this evaluation. The FDC waste receipt basis used for this study specified a total receipt of 47,400 metric tons of high-level waste over a 20-year receiving period. Half of this amount was assumed to be spent nuclear fuel, and the other half was assumed to be CHLW from spent fuel reprocessing. More recent design bases specify an increased quantity of waste (70,000 metric tons), all of which would be in the form of spent fuel. This change in waste receipt basis is considered to have no effect on the comparisons of waste emplacement concepts developed in this study.

Figure 1 shows the canister designs that are based on concepts developed by Westinghouse.[3] The spent fuel canister contains either three consolidated pressurized water reactor (PWR) assemblies or seven boiling water reactor (BWR) assemblies; for the evaluation, however, the spent fuel canisters were assumed to contain only PWR fuel because a PWR canister will generate higher decay heat than a BWR canister. At present, canister designs have been modified to contain either four consolidated PWR assemblies or nine BWR assemblies. This design modification is considered to have no effect on the comparisons of waste emplacement concepts developed in this study. The waste is assumed to be 10 years old at the time of placement, and the initial decay heat generation rates per canister are:

- o Spent fuel canister (PWR): 1.65 kW
- o CHLW canister: 2.28 kW.

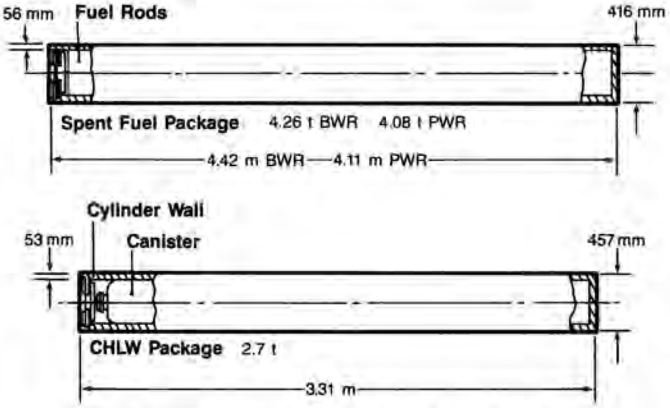
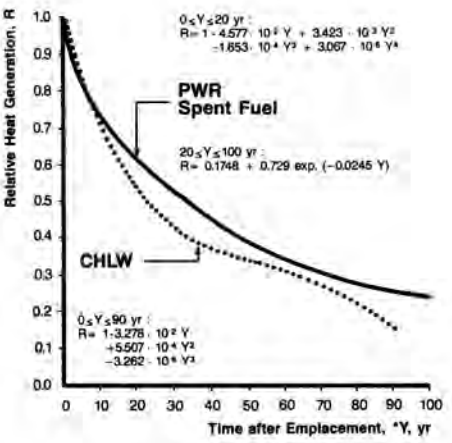


Fig. 1. Dimensions of Spent Fuel and CHLW Canisters.

Figure 2 shows the relative decay heat generation rates over time for both spent fuel and CHLW canisters.



*Emplacement starts 10 years after reactor discharge

Fig. 2. Relative Thermal Decay of PWR and CHLW Canisters.

A self-shielded waste package developed by Westinghouse also was considered as a feasible alternative storage cantainer.[3]

Another important basis for the evaluation is the geotechnical data base. The geotechnical conditions affect many aspects of the waste emplacement configurations, e.g., room size, room shape and orientation, spacing between waste canisters, and boring and excavation methods. The geotechnical data base for this evaluation was selected from the most recent rock data. Because four candidate repository horizons were being evaluated at the time of this study, the geotechnical data base selected is representative of all the candidate basalt flows: Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum. Although not directly traceable to any one of these basalt flows, the data base is sufficiently accurate for comparing alternative waste emplacement concepts. Table I summarizes the geotechnical data base. Other design criteria, such as the characteristics of packing and canister materials, are described in Waste Emplacement Optimization.[5]

TABLE I

Summary of Geotechnical Reference Data

Property or parameter	Value or equation
Compressive strength of rock mass[a]	
Unconfined compressive intact rock strength, σ_c	345 MPa
Material constant (m)	26.17
Material constant (s)	0.053
Nominal rock strength for elastic analyses	276 MPa
Deformation modulus of rock mass	37.9 GPa
Poisson's ratio of rock mass	0.26
Thermal conductivity	1.61 W/m°C
Specific heat	0.92 kJ/kg°C
Density	2,804 kg/m^3
Coefficient of thermal expansion	6.27×10^{-6}/°C
Vertical in situ stress	28 MPa
Maximum horizontal/ vertical stress ratio	2.30
Minimum horizontal/ vertical stress ratio	1.31
Orientation of maximum horizontal stress	N3.7°W
In situ rock temperature	52.2°C

[a] Value determined by the following equation:

$$\sigma_1 = \sigma_3 + (m \ \sigma_c \ \sigma_3 + S \cdot \sigma_c{}^2)^{1/2}$$

where m and s are material constants and σ_c is unconfined compressive strength of intact rock. σ_1 and σ_3 are major and minor principal stress at failure, respectively.

Identification and Screening of Alternatives

The principal objective of this study has been to evaluate all feasible alternative waste emplacement concepts in order to provide a more definitive basis for selecting a final concept for subsequent repository design. To ensure that all feasible alternative waste emplacement concepts were identified and thoroughly considered, a matrix was constructed based on the principal variables in the emplacement configurations. The eight principal variables and their subdivisions are:

- o Location of waste canisters in relation to placement room
  - In wall
  - In floor
  - Within room
- o Number of waste canisters in canister placement hole
  - Single
  - Multiple

- Orientation of canister placement hole
  - To long axis of placement room
    - 90° (horizontal in wall)
    - 45° (horizontal in wall)
    - parallel (in floor)
    - transverse (in floor)
  - To horizontal plane
    - 90° (in floor)
    - 45° (in floor in plane of room's long axis)
    - 45° (in floor in plane of room's cross section)

- Arrangement of canister holes on either side of placement room
  - Symmetric
  - Asymmetric

- Placement room cross section
  - Constant
  - Variable

- Proximity of canisters in placement holes to wall of placement room
  - In close proximity (no stand-off except for required shielding)
  - Displaced away from room wall (stand-off exceeding that required for shielding)

- Numbers of parallel rows of canisters
  - Single
  - Double

- Type of waste package
  - Spent fuel or CHLW canisters
  - Self-shielded canisters.

These variables do not apply to all waste emplacement configurations. For example, variables related to the orientation of canister placement holes in the walls of the placement room do not apply to configurations in which canisters are placed within the placement room.

Canister placement holes were assumed to have circular sections. The cross-sectional shape and size of placement rooms are not included in the variables listed above; rather, these must be selected based on the functional requirements of the specific configurations. The shape and size of placement rooms also must satisfy room stability requirements, i.e., the thermomechanical stresses due to excavation and waste thermal loading must be below the rock strength.

A matrix of 51 possible waste emplacement configurations was developed using the 8 principal variables and their subdivisions. A two-stage screening process was used to combine or eliminate many of the 51 candidate concepts. In the first stage, the candidate concepts were examined by both qualitative and semiquantitative techniques, including the results of previous waste emplacement studies. This examination screened out combinations of variables that either have no obvious merit in relation to the evaluation criteria or define an emplacement configuration similar enough to another combination of variables so that separate evaluation would be redundant. In the second stage, candidate concepts were evaluated by independent considerations of constructibility, waste handling, effects on the basalt rock, and relative cost. A detailed description of the elimination process has been documented in Waste Emplacement Optimization.[5] Eleven emplacement concepts were selected for detailed study, as described later.

Technical Analysis of Selected Alternatives

For a proper evaluation, each alternative was analyzed technically, and conceptual designs were developed to a comparative level. The principal analyses performed in this evaluation were thermal and rock stress analyses.

Thermal analyses were performed to determine the maximum temperatures of the rock and manmade components for various canister spacings in order to select minimum spacings based on temperature criteria. Also, the thermal analyses provided thermal data input for the stress analyses and for determining the ventilation requirements.

Rock temperatures were determined for an assumed series of decaying finite-line sources emplaced in the basalt media in an infinite array. Temperatures were calculated for characteristic times and locations and for decaying heat source variations. Ventilation analyses involved computing the heat flux at the placement room wall and deriving air and rock temperatures as a function of the inlet air temperature, time, airflow rate, and position in the placement room.

Rock stress analyses were performed to determine the minimum spacing of waste canisters based on rock stress and to assess the effects of room shape on rock stress and room stability. Two basic models were used to calculate stresses. Stresses around circular holes were calculated using the closed-form solution developed by Kirsch.[6] Stresses around noncircular openings were calculated using a boundary-element computer program (BELP).[7]

Room and hole stresses were determined first for the in situ stress field. After the waste is emplaced, the heat generated by the waste transfers to the surrounding rock mass and causes a stress increase. This increase was calculated and added to the in situ stress to obtain the total stress. It is assumed that the rock is confined in the horizontal but not in the vertical direction.

For each alternative, to select appropriate waste canister spacings on the basis of rock stress, it was necessary to assess uniformly the effects of rock stresses on room and hole stability. The simplest way to do this was to select a maximum tangential boundary stress limit at a critical location, e.g., the crown of the placement hole or room. This provided an effective basis for comparing the alternatives. It was presumed that with equal theoretical boundary stresses, the effects on room or hole stability also will be nearly equal. The conclusions are valid as long as the selected maximum stress is within a reasonable range.

Based on the uniformly applied temperature and stress criteria, a minimum allowable canister spacing was selected for each alternative. Then the waste repository systems were designed and the layouts developed for each alternative. Also, the waste handling and packing material placement methods were established, and the total comparative ventilation and air-conditioning requirements were defined for each alternative. Finally, the comparative total costs were estimated. A detailed description of the analysis method is presented in Waste Emplacement Optimization.[5]

Description of Selected Alternatives

This section presents a brief description of the eleven alternative concepts that were evaluated Except where noted otherwise, the minimum packing material thickness is 0.15 mm.

Alternative 1 employs long horizontal placement holes, each containing multiple canisters, as shown in Fig. 3. (Note that in Figs. 3 through 13, the value k is the ratio of horizontal to vertical in situ stress.) Placement holes are 0.76 m in diameter, 138 m long, and arranged asymmetrically along the placement rooms. The placement room is a 6.7- by 3.3-m oval room. Spacings are 18.6 m for CHLW and 12.6 m for spent fuel. Each placement hole has either 39 CHLW or 31 PWR canisters spaced 0.15 m apart. The distance to the first canister from the drift is 1.10 m for CHLW and 2.83 m for PWR.

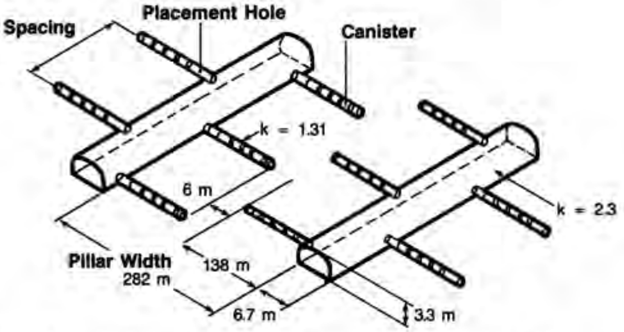


Fig. 3. Alternative 1: Asymmetric, Long-hole Horizontal Waste Emplacement Configuration.

Alternative 2 employs long horizontal placement holes, each containing multiple canisters, as shown in Fig. 4. Placement holes are 0.76 m in diameter, 138 m long, and arranged symmetrically along the placement rooms. The placement room is a 4.5- by 3.3-m oval. An alcove, 6.7-m wide by 3.3-m high, is developed at each placement hole to allow hole drilling and canister placement. Spacings are 28.8 m for CHLW and 17.4 m for spent fuel. Each hole contains 39 CHLW or 31 PWR canisters spaced 0.15 m apart. The distance to the first canister from the drift is 1.10 m for CHLW and 2.83 m for PWR.

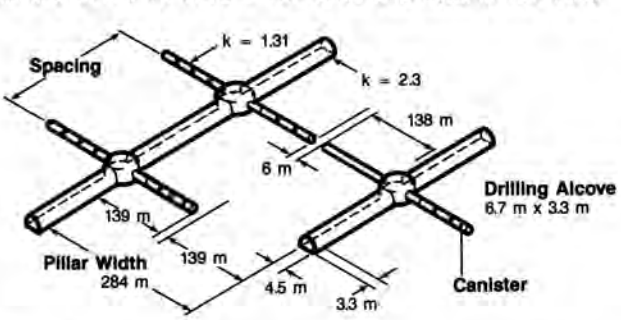


Fig. 4. Alternative 2: Symmetric, Long-hole Waste Emplacement Configuration.

Alternative 3 employs short horizontal placement holes with a single canister per hole placed close to placement room walls, as shown in Fig. 5. Placement holes are 0.76 m in diameter, 6.1 m long, and arranged symmetrically along the placement room. The placement room is a 6.7- by 3.3-m oval. Spacings are 4.72 m for CHLW and 3.81 m for spent fuel. The distance from the drift is 2.77 m for CHLW and 1.98 m for PWR.

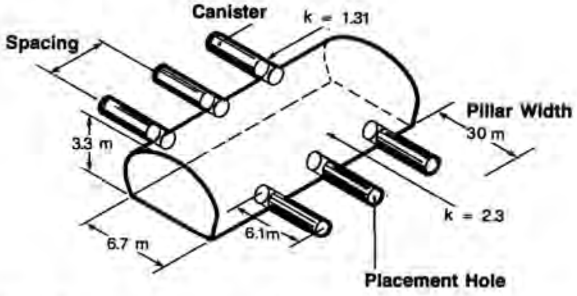


Fig. 5. Alternative 3: Horizontal Short-hole Waste Emplacement Configuration.

Alternative 4 employs short horizontal placement holes with a single canister per hole, displaced from the drift walls as shown in Fig. 6. Placement holes are 0.76 m in diameter, 10.7 m long, and arranged symmetrically along the placement room. The placement room is 6.7 by 3.3 m and oval-shaped. Spacings are 4.11 m for CHLW and 3.81 m for spent fuel. The distance to the canister from the drift is 7.35 m for CHLW and 6.55 for PWR.

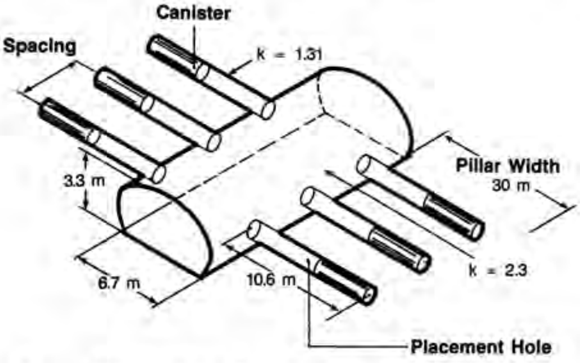


Fig. 6. Alternative 4: Horizontal Extended Short-hole Waste Emplacement Configuration.

Alternative 5 employs short horizontal placement holes with a single canister per hole, displaced from the drift walls as shown in Fig. 7. Placement holes are 0.76 m in diameter, 9.1 m long, arranged symmetrically along the placement room, and oriented at 45° to the placement room axis. The placement room is 5.5 by 3.3 m and oval-shaped. Spacings are 6.10 m for CHLW and 5.18 m for spent fuel. The hole distance from the drift to the canister is 5.82 m for CHLW and 5.03 m for PWR.

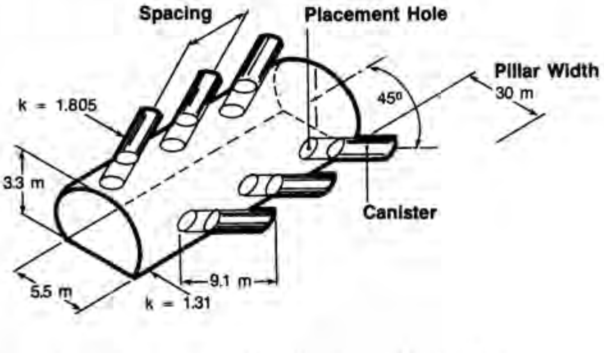


Fig. 7. Alternative 5: Horizontal, Angled Short-hole, Waste Emplacement Configuration.

Alternative 6 employs short vertical placement holes with a single canister per hole, as shown in Fig. 8. Placement holes are 0.76 m in diameter, 5.5 m deep, and arranged along the centerline and vertical to the drift axis. The placement room is 6.1 by 6.1 m and horseshoe-shaped. Spacings are 4.10 m for CHLW and 3.35 m for spent fuel. The distance from the drift to the canister is 2.16 m for CHLW and 1.37 m for PWR.

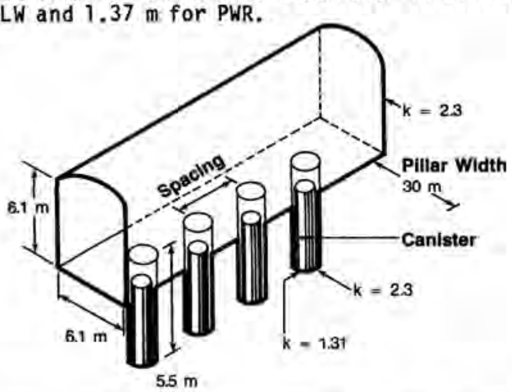


Fig. 8. Alternative 6: Vertical Short-hole Waste Emplacement Configuration.

Alternative 7 employs short, angled placement holes with a single canister per hole, as shown in Fig. 9. Placement holes are 0.76 m in diameter, 9.1 m deep, arranged along the drift centerline, and angled at 45°. The placement room is 4.5 by 4.7 m and horseshoe-shaped. The spacing is 3 m for both CHLW and spent fuel. The hole distance from the drift to the canister is 5.82 m for CHLW and 5.03 m for PWR.

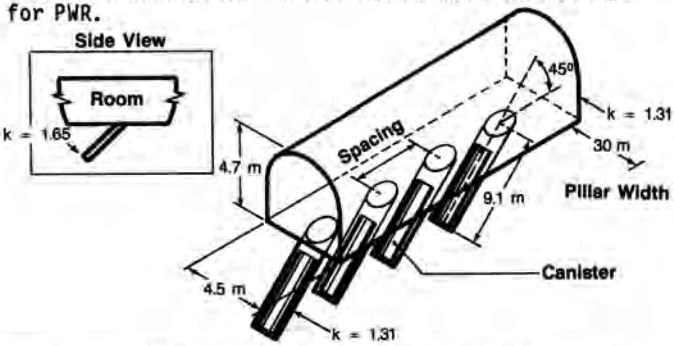


Fig. 9. Alternative 7: Vertical, Angled Short-hole, Waste Emplacement Configuration.

Alternative 8 employs short, angled placement holes with a single canister per hole, as shown in Fig. 10. Placement holes are 0.76 m in diameter, 9.1 m deep, and are arranged symmetrically along the lower drift corners, normal to the drift axis and at an angle of 45° to the horizontal. The placement room is 6.0 by 5.2 m and oval-shaped. Spacings are 5.33 m for CHLW and 4.27 m for spent fuel. The distance from the drift to the canister is 5.82 m for CHLW and 5.03 m for PWR.

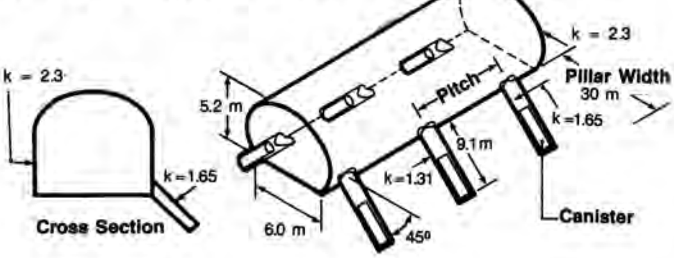


Fig. 10. Alternative 8: Angled, Corner, Short-hole Waste Emplacement Configuration.

Alternative 9 employs placement rooms and crosscuts with the canisters placed in horizontal pipes within the filled placement rooms, as shown in Fig. 11. Placement rooms are 2.4 m in diameter, 305 m long, and contain 0.76-m diameter pipes in the middle surrounded by packing material. The placement rooms are accessed by 6.7 m wide and 3.3 m tall horseshoe-shaped access drifts. Spacings are 27.4 m with 0.6 m canister spacing for CHLW and 15.1 m with 0.15 m canister spacing for spent fuel. The minimum packing material thickness is 0.9 m, including the packing material inside the pipe.

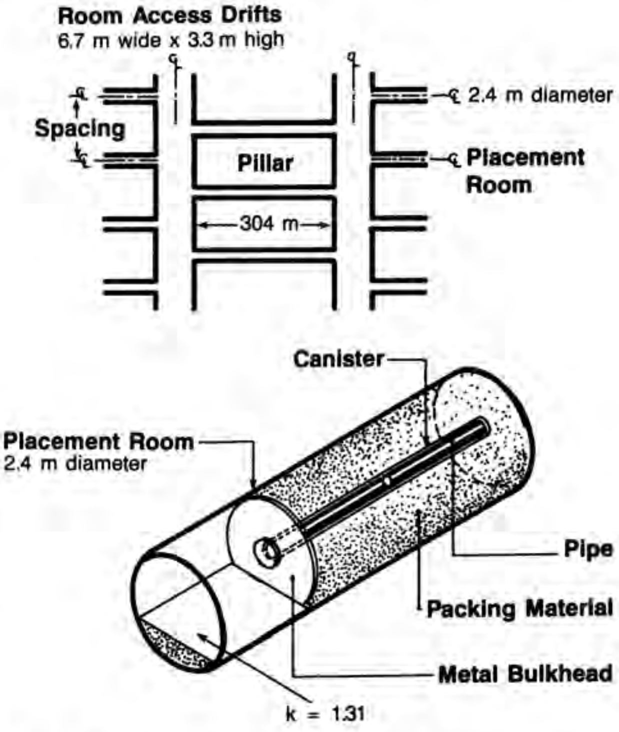


Fig. 11. Alternative 9: Pipe-in-Drift Waste Emplacement Configuration.

Alternative 10 employs short longitudinal canister placement trenches in the floor of the placement rooms, as shown in Fig. 12. Placement rooms are 4.45 by 3.9 m and oval-shaped. The placement trenches are 1.83 m deep by 1.07 m wide and run continuously in the placement room floor. The spacing is 13.7 m for both CHLW and spent fuel. The clear spacing between canisters is 1.24 m for CHLW and 1.37 m for PWR.

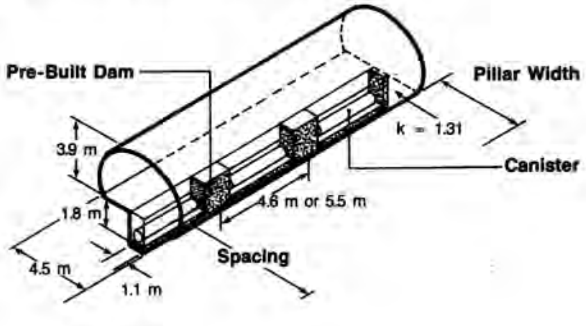


Fig. 12. Alternative 10: Trench-in-Drift-Floor Waste Emplacement Configuration.

Alternative 11 employs self-shielded containers placed on the floor of the placement rooms, as shown in Fig. 13. Placement rooms are 4.5 by 3.3 m and oval-shaped. Canisters are placed in self-shielded containers that are supported in a central position along the axis of the placement drift. The selected pillar width is 45.7 m for both CHLW and spent fuel. For CHLW, a container spacing of 3.81 m is required within placement rooms. The minimum packing material thickness is 0.82 m.

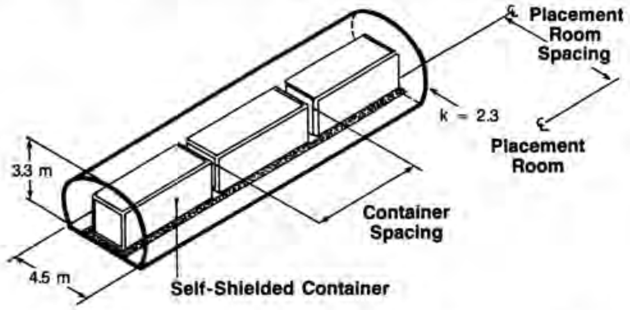


Fig. 13. Alternative 11: General Arrangement - Self-shielded Container in Room.

In addition to the brief descriptions above, Table II summarizes the following important quantities for each alternative: total repository area, total drift length, and the amount of rock excavated. Also listed are comparative cost estimates based on July 1983 dollars, with escalation factors of 1.12 for labor and 1.07 for materials and equipment. These estimates do not include contingencies and costs that are common to all alternatives. For example, shaft and shaft pillar development costs are assumed to be the same for each alternative and have not been included in the estimates. Thus, the costs shown are not total cost, but they do establish a basis for comparing the cost related to each emplacement concept.

TABLE II

Summary of Important Quantities for Various Alternatives

Identification No.	Total area (km^2)	Total drift length (m)	Rock excavation (million ton)	Comparative Cost[a] (million dollars)
1	3.80	35,630	1.64	573
2	5.22	44,177	1.84	589
3	4.25	69,629	4.77	666
4	4.13	83,639	4.71	738
5	4.99	113,278	5.31	739
6	5.96	145,571	11.96	876
7	5.12	123,240	6.23	781
8	4.51	97,724	7.07	774
9	4.80	177,542[b]	3.86[b]	749
10	4.36	184,100	8.63	826
11	5.54	113,419	4.16	1,506

[a] Net present value using 8% discount rate.

[b] Including placement rooms.

For each selected alternative, repository mine development schedules and procedures were developed for waste emplacement, packing material placement, and waste retrieval (if required). Also, development and demonstration testing needs were identified. Because these data are voluminous, they are not presented here, but may be found in the Waste Emplacement Optimization report.[5]

Evaluation of Alternatives

The evaluation was limited to technical criteria related to design and construction, development, and safety. Evaluation of long-term waste isolation performance is recognized as a significant factor in waste emplacement concept selection; this factor was not included in this study, but was subsequently evaluated by Rockwell Hanford Operations. For the technical evaluation, a comprehensive set of important criteria was selected, and each criterion was given a weighted value according to its relative importance. Table III summarizes the criteria used and their relative weights.

TABLE III

Relative Weights for Technical Evaluation

Item	Weight
Economy	
Cost	17
Uncertainty	5
Schedule	
Duration	7
Uncertainty	4
Development	
Risk to schedule	7
Cost	6
Complexity	7
Safety	
Construction	7
Operation	10
Others	
Effect on other activities	7
Adaptability	8
Quality assurance	4
Retrieval	11
Total	100

For each criterion, relative values, determined either by quantitative values such as cost or qualitative merits based on judgment, were assigned to each alternative emplacement concept. For criteria represented by quantitative values, a simple relationship was established between quantitative and relative values by setting the range of relative value between 0 and 5. For criteria represented by qualitative merit, relative values between 1 and 5 were given, as shown in Table IV.

TABLE IV

Evaluation of Qualitative Values

Degree	Value
Excellent	5
Good	4
Average	3
Acceptable	2
Barely acceptable	1

The products of weight and relative value for each criterion were summed for each emplacement configuration, and the emplacement configurations were ranked by comparing these sums, as shown in Table V. A similar process of weighting criteria and assigning relative values to selected alternative concepts was conducted by Rockwell Hanford Operations subsequent to this study, including evaluating long-term waste isolation performance. Rockwell's process gave major weight to this criterion. This ranking process also favored the top-ranked alternative concept in this study.

TABLE V

Alternative Configuration Evaluation Matrix, Values Times Weights

	Alternative										
Criterion	1	2	3	4	5	6	7	8	9	10	11
Economy											
Cost	85.0	83.3	71.4	61.2	61.2	40.8	54.4	56.1	59.5	47.6	0
Uncertainty	19.0	19.5	19.5	20.0	20.0	19.5	19.5	19.5	18.5	18.5	10.5
Schedule											
Duration	35.0	35.0	29.4	21.0	35.0	35.0	29.4	35.0	35.0	35.0	35.0
Uncertainty	12.0	10.0	14.0	14.4	12.0	10.0	10.0	13.6	10.0	6.0	12.0
Development											
Risk to schedule	21.0	21.0	30.1	30.1	30.1	30.1	30.1	30.1	26.6	28.0	33.6
Cost	21.0	21.0	26.4	26.4	26.4	26.4	26.4	26.4	24.6	24.0	16.8
Complexity	21.0	21.0	31.5	31.5	31.5	31.5	31.5	31.5	26.6	30.1	33.6
Safety											
Construction	25.2	20.3	22.4	22.4	30.1	4.2	26.6	11.2	19.6	25.9	24.5
Operation	29.0	28.0	35.0	33.0	39.0	21.0	36.0	30.0	26.0	17.0	28.0
Others											
Effects on other activity	28.0	28.0	21.0	21.0	21.0	21.0	21.0	21.0	28.0	14.0	10.5
Adaptability	28.0	24.0	24.0	24.0	20.0	16.0	20.0	24.0	20.0	24.0	20.0
QA	8.0	8.0	12.0	12.0	10.0	16.0	14.0	14.0	10.0	16.0	16.0
Retrievability	22.0	22.0	33.0	27.5	27.5	44.0	38.5	38.5	22.0	33.0	44.0
Total	354.2	341.1	369.7	344.5	363.8	315.5	357.4	350.9	326.4	319.1	284.5
Rank	4	7	1	6	2	10	3	5	8	9	11

CONCLUSION AND RECOMMENDATIONS

Based on the evaluation of alternatives described above, the total weighted values of the five best alternatives are all greater than 350 and within 20 points of each other. Therefore, these five alternatives are considered to be nearly equal in technical performance. They are ranked as follows:

- Alternative 3: horizontal short-hole configuration
- Alternative 5: horizontal, angled, short-hole configuration
- Alternative 7: configuration with angled short holes in the floor
- Alternative 1: asymmetric, horizontal long-hole configuration
- Alternative 8: configuration with angled short holes off the floor corners.

The remaining alternatives are inferior to the five listed above. It must be recognized that the findings reported here are predicated to some degree on the following discussion.

Even the best laboratory data and the best computer models are at this time insufficient to fully analyze the stability of repository drifts and justify their final design. Tests in surface facilities can provide performance data and model input for certain parameters, but the effects of high stresses and temperatures at depth can be determined only at repository depth.

The design concepts presented in this study appear reasonable, but because of the lack of knowledge about high-stress drift performance at depth, many features of the concepts are uncertain. The most notable are:

- It is not certain that the drift shapes selected are the most favorable, although they appear reasonable.
- The maximum allowable calculated induced stress is not well supported; hence, the hole spacing may require modification based on improved data.
- The properties of the rock mass, as opposed to intact rock, are not adequately known.

Certain development and testing should be done to ensure that design and construction of the repository can be performed with adequate confidence. Some of the requirements for short-hole configurations differ from those for other preferred configurations, while others are shared. For the short-hole configuration, demonstration rather than development is desired; for long-hole configurations, substantial development is needed.

In addition to a development and testing program for drift excavation,[8] testing and development are suggested for the following items:

- Hole boring equipment
- Waste transporter
- Placement hole sleeve and portable shield assembly
- Placement system for long holes
- Hole lining equipment for long holes
- Packing material placement equipment.

These items are discussed in greater detail in Waste Emplacement Optimization.[5]

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