DESIGN OF A WASTE PACKAGE FOR EMPLACEMENT IN BASALT

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ABSTRACT

The Basalt Waste Isolation Project's (BWIP) Waste Package Program has been developed as part of the U.S. Department of Energy's National Waste Terminal Storage Program to provide a focal point for the selection of materials and development of designs for site-specific, multiple barrier assemblages for spent fuel and processed high-level waste disposal in basalt. This paper will report the results of a joint effort among the BWIP, Westinghouse-Advanced Energy Systems Division, Office of Nuclear Waste Isolation, and Kaiser Engineers, Inc./Parsons Brinckerhoff Quade & Douglas, Inc. to develop conceptual designs for waste packages to be emplaced in a repository located in basalt. During Fiscal Year 1982, practical designs for commercial and defense high-level waste and circular bundles of spent fuel rods from three pressurized water reactor assemblies or seven boiling water reactor assemblies were developed on the basis of cost effectiveness. Each of the designs is based upon environmental and regulatory performance factors that were used in the developing package design criteria. The reference conceptual design, based on site-specific environmental conditions, consists of a waste form contained by a low carbon steel canister which is then surrounded by a backfill mixture of bentonite clay and crushed basalt. The conceptual waste packages have been utilized by the BWIP in updating the conceptual designs for a nuclear waste repository in basalt and, thus, have been fully integrated into the remainder of the engineered repository structure.

INTRODUCTION

Conceptual designs have been generated for waste packages to be emplaced in a repository in basalt that are expected to meet the functional requirements based on performance criteria being established by the Nuclear Regulatory Commission and the Environmental Protection Agency. Designs based on three concepts were developed to the degree necessary to evaluate performance, derive cost data and to provide the repository designer with information pertinent to the repository design. A reference waste package conceptual design was selected on the bases of waste package cost and associated repository excavation costs. The designs represent simplified versions of early concepts based upon reevaluation of site-specific environmental conditions and the repository conceptual design for a repository in basalt.

EARLY NWRB WASTE PACKAGE CONCEPT

Early BWIP waste package concepts reflected the constraints of the early repository conceptual design for a nuclear waste repository in basalt (NWRB)(1). Specifically, the waste was to be emplaced vertically in holes extending from the floor of access tunnels. The waste package concept used for the initial repository design consisted of six components (Fig. 1). Components which were intended to be installed prior to waste emplacement consisted of (1) a perforated aluminum borehole liner which surrounded (2) compressed blocks of sodium bentonite/basalt backfill, which, in turn, surrounded (3) a mullite retrieval sleeve. In addition, the "emplacement assembly" consisted of (4) a titanium alloy overpack, containing (5) a carbon steel canister of waste, with (6) graphite buffer material in the space between the overpack and canister.

The six-component package resulted primarily from the unrealistic assumptions regarding the environment surrounding the waste package. It was assumed, for example, that the backfill would become saturated with water prior to any necessary retrieval operations. The swelling backfill material would fill the void space between the overpack and the host rock and exert a high swelling pressure, which would grasp the "emplacement assembly" and make retrieval difficult. The mullite retrieval sleeve was incorporated to prevent the swelling of backfill from clamping the overpack, thus simplifying retrieval operations. Subsequently, examination of the backfill temperature and atmospheric pressure conditions between the time of waste emplacement and retrieval operations has shown that the assumed backfill saturation and swelling against the overpack cannot occur prior to permanent closure of the repository.

Similarly, the need for a titanium alloy overpack was based on the assumption that high-oxygen groundwater would be in contact with the overpack throughout its life. Consequently, a material resistant to corrosion in high-oxygen groundwater was needed to assure waste form containment. Subsequent evaluations and materials test results indicate that contact between the waste form container and high-oxygen groundwater will be limited.(2) It is estimated that the period of this contact will be at most a matter of only days or weeks after permanent closure of the repository. The corrosion of a carbon steel overpack during this period, for example, would be insignificant with respect to the thickness of material required for structural adequacy. Therefore, the corrosion allowance for canister/overpack materials should be based upon the low-oxygen groundwater conditions controlled by the presence of the basalt.

From these and other observations of the pronounced impact of the environmental conditions upon the waste package component performance, it was concluded that reevaluation of environmental conditions related to their effect on waste package materials performance was needed in support of waste package conceptual design efforts. The following section presents the results of that review and reevaluation.

SITE-SPECIFIC WASTE PACKAGE ENVIRONMENT(2,3)

External Pressure

The design value used for external pressure on the canister for the period of time prior to permanent closure of the repository is 0.15 MPa (slightly above atmospheric pressure). The design value used for

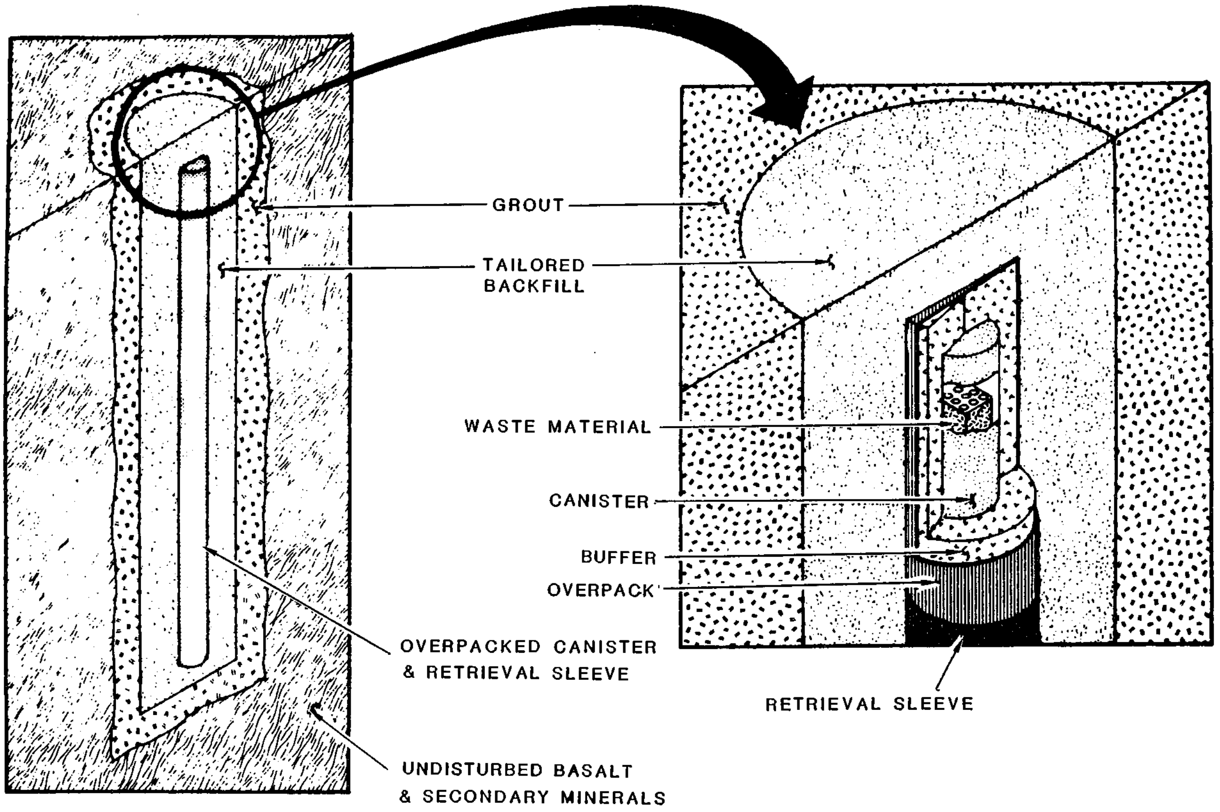

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Fig. 1. Early Nuclear Waste Repository Located in Basalt.

external pressure during the remaining design life of the canister is the hydrostatic pressure at repository depth. The relationship between repository depth and hydrostatic pressure at the Hanford Site is given by the equation:

$$\text{Pressure (MPa)} = 0.063 + 0.00979 \text{ Depth (meters)}$$

For a repository located in the Umtanum basalt flow (1,128 meters), the design pressure is 11.1 MPa; for one located in the Cohassett basalt flow (945 meters), the design pressure is 9.3 MPa.

Ambient Temperature

The ambient temperature of the host rock used for design is based upon repository depth, as governed by the equation:

$$\text{Temperature } (^{o}\text{C}) = 14.83 + 0.038 \text{ Depth (meters)}$$

For a repository located in the Umtanum basalt flow (1,128 meters), the ambient temperature is 58°C; for one located in the Cohassett basalt flow (945 meters), the ambient temperature is 51°C.

Groundwater composition, Eh and pH

The groundwater composition in the Grande Ronde basalt flows is a low ionic strength (about 20 milliequivalent total cations plus anions) water. Sodium is the dominant cation, with varying amounts of minor cations (potassium, calcium, and magnesium), depending upon location within the Grande Ronde basalt. The chemically dominant anions are chloride and sulfate; there also is a relatively high fluoride content compared to the limit established for potable water. The dissolved silica content of the groundwater in contact with basalt tends to follow a solubility limit for amorphous silica as a function of temperature. The chemical variations of groundwater within the Grande Ronde basalt result in a range of chemical behaviors characteristic of sodium chloride and sodium chloride-sodium sulfate solutions. The Eh and pH of the groundwater both fall within a narrow range, relatively independent of variations in sulfate and chloride ions.

The pH of the groundwater is nominally 9.4 at a basalt temperature of 58°C; at a basalt temperature of 300°C, the groundwater pH is nominally 7.8. The ambient Eh of the Grande Ronde groundwater has been estimated to be approximately -0.45 volts, based on evaluation of the basalt mineral phases and groundwater composition. Results of hydrothermal tests show that reaction between basalt and groundwater to remove dissolved oxygen occurs quite rapidly. For example, in a test at 150°C and 300 bars, the dissolved oxygen content of simulated Grande Ronde groundwater in contact with crushed basalt decreased from 8.5 mg/l (average) to 0.4 mg/l (average) in 190 hours. A reasonable extrapolation of the available 150°C data indicates that the dissolved oxygen would be less than 10^{-3} mg/l (about one part per billion) in about 600 hours. It has been inferred from these data, and comparable results from other experiments, that the Eh of groundwater in the repository near field will be returned to the Eh of ambient Grande Ronde basalt groundwater, by reaction with basalt, in a few month's time after permanent closure of the repository. The ambient groundwater Eh and pH conditions also provide a favorable regime for limiting the solubility, and therefore transport, of many radionuclides.

NWRB WASTE PACKAGE ENVIRONMENT MODIFICATION UPON WASTE EMPLACEMENT

Pressure

Prior to permanent closure of a repository in basalt, the external pressure on waste form canisters will be atmospheric. This is because the waste package storage boreholes are not sealed from the access tunnels which are ventilated for operating personnel habitability. However, after permanent closure of the repository, groundwater will seep into the backfill material, pressurizing the void space between the borehole wall and the canister. When the pressure exceeds the water vapor pressure corresponding to the temperatures within the waste package, liquid water will replace water vapor in the void space. The external pressure on waste canisters will then rise until it reaches the ambient hydrostatic pressure.

Temperature

The major influence of the emplaced waste upon the environment prior to and after permanent closure is caused by the decay heat of radioactive material and the resulting high temperatures. Soon after emplacement of the waste, temperatures at the emplacement borehole surface exceed 100°C. Since the waste package borehole is not sealed during the repository operating period, groundwater seeping into the borehole will vaporize rapidly. At expected rates of groundwater entry into the emplacement boreholes, the air in emplacement boreholes would be displaced by water vapor in a day or two after a borehole is filled with waste.

The temperature of the emplacement borehole surface will continue to rise, reaching peak temperature of 235°C between five and ten years after emplacement for commercial high-level wastes from processed spent fuel (Fig. 2). These temperatures are well below the design temperature limit (300°C) for backfill. The rock temperature will decline to approximately 170°C to 200°C at the time of permanent closure of the repository. The expected temperatures will prevent contact between the canister material and liquid groundwater until after permanent closure of the repository.

Following permanent closure of the repository, the temperature will continue to decline reaching 100°C in the approximately 400 years (commercial high level waste). At this time, the heat generation rate of the commercial high level waste is low enough that the temperature of the waste is within 5°C of the borehole surface temperature.

Groundwater Composition, Eh and pH

During the time of pressure buildup to hydrostatic pressure and concommitant saturation of the backfill after permanent closure of the repository, the groundwater Eh will be reestablished at approximately -0.45 volts by reaction with basalt. Temperature effects on the gross groundwater chemical composition as a result of high temperature reaction with the basalt and the backfill are minimal. The conditions for long-term corrosion of the canister are, therefore, exposure to anoxic, alkaline groundwater at temperatures of 190°C and below.

WASTE PACKAGE CONCEPTUAL DESIGNS

The reevaluation of the environmental conditions presented in the previous section under which the waste package is required to perform leads to the following conclusions:

- Retrievability of the waste package is simplified because the repository is not expected to fill with groundwater and establish hydrostatic pressure until after permanent closure, eliminating the need for mullite retrieval sleeve.
- Crushed basalt in the waste package backfill will provide Eh control of the groundwater contacting the canister which limits corrosion and radionuclide solubilities,

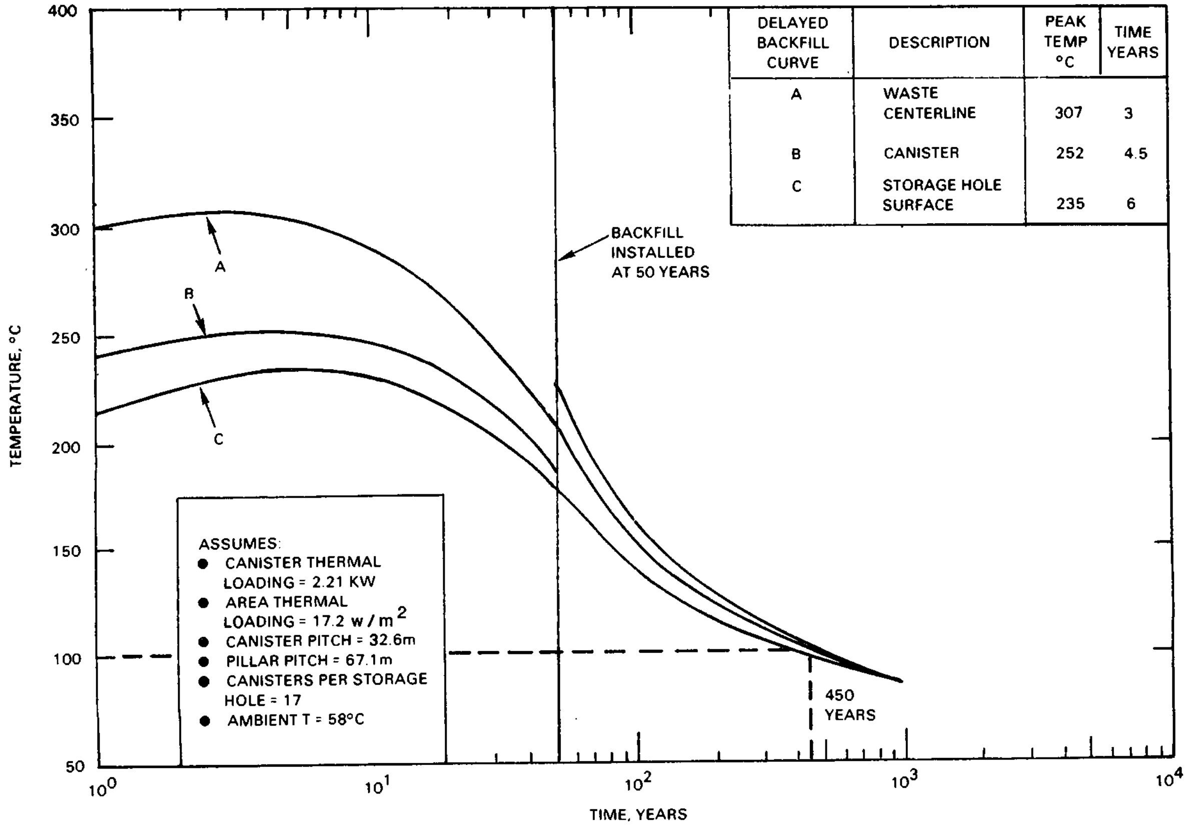

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Fig. 2. Commercial High Level Waste Package Temperature Estimates.

eliminating the need for a buffer material and the titanium alloy overpack.

- Peak waste package temperatures are reached before permanent closure, limiting the temperatures under which aqueous corrosion of the canister occurs.

As a consequence of these conclusions, a simplified waste package consisting of the waste form, canister, and backfill material was considered feasible. The primary function of the waste form is to prevent or retard release of radionuclides should containment be breached during shipping, handling, and after emplacement in the repository. The function of the canister is to physically contain the waste form after emplacement of the waste in the repository for a period of 1,000 years after permanent closure of the repository. The primary function of the backfill is to aid the waste form in controlling hazardous radionuclide release to the host environment to less than 10^{-5} of the inventory per year after 1,000 years.

The canister design must be interfaced with operations at the geologic repository. Repository conceptual design was reevaluated to determine the impact of a horizontal to vertical rock stress ratio of 2:1 at the repository horizon. In this situation, the underground access tunnels needed to be approximately twice as wide as they were high. This required waste package concepts to be compatible with horizontal emplacement so that tunnel height could be minimized. An economical repository configuration (based upon excavation costs) required emplacement of waste packages in long boreholes between access rooms. This required at least one waste package concept to be suitable for emplacement in long boreholes.

As a result, three waste package concepts were examined during waste package conceptual design.(4) All three concepts met the requirement for horizontal emplacement. One concept was suitable for long borehole emplacement, one for single package boreholes, and one for emplacement in access tunnels. The major difference in the first two concepts was in the configuration of the backfill component. The third concept utilized a thick canister wall to provide radiation shielding for operating personnel during repository operations. Based on cost considerations, the first concept was chosen as the reference waste package conceptual design. The second and third concepts were considered to be alternates.

The reference conceptual design consisted of the waste form (in the case of commercial high-level waste, the waste form consisted of borosilicate glass in a stainless steel container; for spent fuel, the waste form was fuel rods from pressurized water reactor or boiling water reactor fuel assemblies), a carbon steel canister, and a backfill comprising 75% crushed basalt/25% sodium bentonite.

For emplacement in long boreholes (Fig. 3), it was envisioned that the canistered waste form would be placed on supports within the boreholes. Subsequently, the backfill material would be emplaced by pneumatic transfer to surround the canisters. The backfill would be in the form of a suitable mixture of pellets and crushed material.

The first alternate design differs from the reference design with respect to the method of incorporating the backfill component of the waste package. The backfill is placed inside the canister during assembly of the waste form and the canister. Because of required assembly and emplacement hole clearances, the backfill mixture is required to have as high a density as possible. Consequently, the backfill is in the form of highly compressed blocks.

The other alternate design differs from the reference and the first alternate design in that canister wall thickness was based upon radiation shielding effectiveness rather than structural and corrosion requirements. In this case, the backfill would not be an integral part of the canister/waste form assembly. The backfill could consist of compressed blocks and pellets/crushed basalt mixtures, either alone or in combination.

The dimensions of the reference waste package conceptual designs are listed in Table I. The alternate designs are of comparable lengths, but the widths and weights of the handled assemblies are considerably greater. The costs of the various commercial high level waste waste package concepts and associated costs of repository excavation are shown in Table II. The early NWRB concept was examined only for spent fuel; because of the shorter length of the commercial high-level waste container, the cost of the comparable design was estimated by applying the proportional length to the cost of all items except the shield plug. The reference conceptual design represents a considerable cost savings over the early waste package concept and the current alternate concepts.

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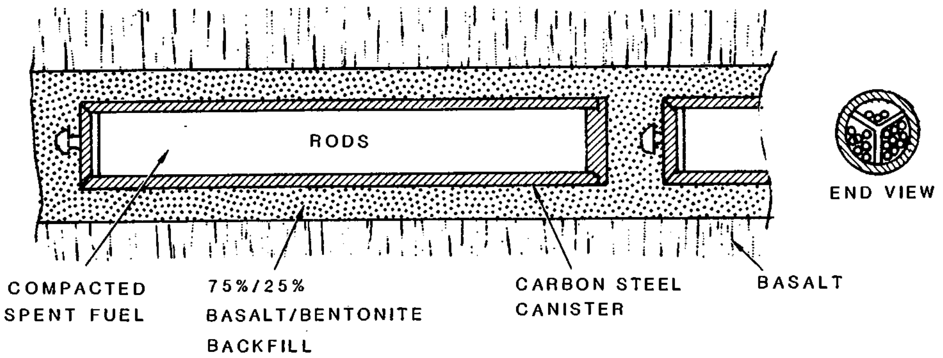

Fig. 3. . NWRB Reference Commercial High-Level Waste Package Conceptual Design.

TABLE I. Waste Package Dimensions - Conceptual Design

	Carbon Steel Canister			Backfill	Borehole
Waste Type	O.D. (cm)	Wall (cm)	Length (m)	Thickness (cm)	Diameter (cm)
CHLW[a]	45.7	5.3	3.2	15.3	76
DHLW[b]	81.3	8.6	3.3	15.3	112
Spent Fuel	41.7	5.6	4.03	15.3	73.7

[a] Commercial high-level waste

[b] Defense high-level waste

TABLE II. Waste Package and Excavation Costs.[a]

Component	Early NWRB conceptual design	Reference BWIP	1st Alternate -W	Self-Shielded -W
Canister	$11,300	$ 3,650	$17,400	$126,700
Buffer		-0-	-0-	-0-
Retrieval Sleeve	2,100	-0-	-0-	-0-
Backfill	5.500	2,050	4,000	9,500
Hole Liner	3,000	-0-	-0-	-0-
Shielding Plug	1,100	130	1,100	-0-
Package Guide and Support	-0-	500	-0-	-0-
Excavation	4,800	5,500	6,700	2,200
Total Per Package	$27,800	$11,830	$29,200	$138,400
Number of Packages	10,400	10,400	10,400	3,467
Total Cost	$289M	$123M	$304M	$480M
Differential (From Reference)	+$166M	-0-	+$181M	+$357M

[a] Costs do not include cost of stainless steel waste form container which is the same for all concepts.