Nuclear waste package fabricated from concrete*

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1 INTRODUCTION

After the United States enacted the Nuclear Waste Policy Act in 1983, the Department of Energy must design, site, build and operate permanent geologic repositories for high-level nuclear waste. The Department of Energy has recently selected three sites, one being the Hanford Site in the state of Washington. At this particular site, the repository will be located in basalt at a depth of approximately 3000 feet deep.

The main concern of this site, is contamination of the groundwater by release of radionuclides from the waste package. The waste package [1] basically has three components: the containment barrier (metal or concrete container, in this study concrete will be considered), the waste form, and other materials (such as packing material, emplacement hole liners, etc.). The containment barriers are the primary waste container structural materials and are intended to provide containment of the nuclear waste up to a thousand years after emplacement. After the containment barriers are breached by groundwater the packing material (expanding sodium bentonite clay) is expected to provide the primary control of release of radionuclide into the immediate repository environment.

2 DEFINITION OF LOADING CONDITION

The loading conditions on the concrete container (from emplacement to approximately 1000 years), will be twofold; (1) internal heat of the high-level waste which could be up to 400°C; (2) external hydrostatic pressure up to 1300 psi after the seepage of groundwater has occurred in the emplacement tunnel. A suggested container is a hollow plain concrete cylinder with both ends capped.

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DISCLAIMER

Structurally, the main concern of the concrete container is the creep and shrinkage effects due to the thermal loading. Experimental results indicate that creep of concrete accelerates at high temperatures. Although some experimental work has been generated in the high-temperature response of concrete, much more research remains to be done [2]. In order to fill the need, a viscoelastic formulation of creep was incorporated into a transient code, STRAW [3], developed at Argonne National Laboratory. This formulation is based on a linear creep law which provides an approximate constitutive model for creep and shrinkage of concrete loaded elastically and subjected to temperatures up to about 500°C.

The response of concrete at high temperatures cannot be calculated without the knowledge of the changes in the moisture content and its distribution, as well as the pressure of the pore water. Moisture content and pore pressure calculations have been formulated and developed elsewhere and are available in the finite element program TEMPOR2 [4]. This program can handle the temperature, moisture distribution and pore pressure calculations of concrete for temperatures up to 800°C. Thus, the information from this program can be used in the structural analysis.

3 HIGH TEMPERATURE CREEP FORMULATION

The total strain, ε, of concrete at high temperature can be subdivided into three components:

(1) $$\varepsilon = \varepsilon^M + \varepsilon^T + \varepsilon^H$$

where ε^M is the mechanical strain (strain caused by stress), ε^T is the thermal dilatation, and ε^H is the hygral strain (strain caused by moisture changes, either shrinkage or swelling).

The creep law is assumed to be linear, i.e., it follows the principle of superposition. The linearity assumption is acceptable for concrete stressed to less than about one-half of its compressive strength. Thus, if the stress, σ, is assumed to be constant,

$$\varepsilon^M = \sigma\ J(t,t')$$

(2) $$J(t,t') = \frac{1}{E_0} + \frac{g(\hat{w})\phi_T f_w}{E_0}\ \phi_1\ \left(t_e'^{-m} + \alpha\right)\ (t - t')^n$$

in which $J(t,t')$ is the compliance function (creep function) that represents the strain at age t caused by a unit stress that has been acting since age t'. At variable moisture content, w, and variable temperature, T, the compliance function may be approximated by the double power law as given in Eq. (2), where E_0 is the asymptotic modulus (~ 1.5 times the conventional elastic modulus for 28 day old concrete); m, n, α and ϕ_1 are parameters for a given concrete, t is the current time (days), t' is the time of loading, t_e' is the equivalent hydration time, ϕ_T is a function of temperature, f_w is a function of moisture content and $g(\hat{w})$ is function of moisture rate and strain rate. Detailed explanations of the functions t_e', ϕ_T, f_w, and $g(w)$ are given in Ref. [5]. Thermal and hygral strains, including stress dependency, are described in detail in Reference 6.

To generalize the preceding formulation to time-variable stresses, one can proceed under the assumption of linearity and determine an equivalent rate-type formulation. The Maxwell chain unit is used in the rate-type formulation. An efficient numerical algorithm for a step-by-step solution has been previously presented [7].

4 ANALYTICAL RESULTS FOR CONCRETE CONTAINER

Figure 1a shows the full view of the container with an inner cavity size of 156 in. long and 20 in. in diameter, and with 12 in. thick plain concrete for both the cylinder and end walls. The external hydrostatic pressure of 1363 psi is also indicated on the outside of the container. This pressure was estimated from a Basalt Waste Isolation Project (BWIP) report [1]. In modeling this structure, only a quarter section is needed, due to symmetries. The finite element mesh used in the STRAW code analysis is shown in Figure 1b with the appropriate boundary conditions. Note that the mesh consists of 100 nodes and 76 axisymmetric continuum elements.

The assumptions made for the loading history is as follows: 1) time period was considered from 56 to 1056 years (approximate life of concrete container after depository is sealed up); 2) hydrostatic pressure is constant during the time period; 3) thermal condition is a uniform 400°C which is generated from the waste and is constant during the time period (this is on the conservative side, since the heat would decay during this 1000 year time period); 4) since the temperature is assumed to be constant, no thermal or shrinkage effects are considered during the time period because concrete is at 400°C and dry (this may be unconservative and will be discussed later).

Concrete properties are assumed as: 1) $f' = 7100$ psi (compressive strength) at 400°C [6]; 2) values used in Eq. 2 are $E_o = 8000$ ksi, $n = 0.09$, $m = 0.33$, $\alpha = 0.05$, $\phi_1 = 5.25$, $t' = 56$ years (20440 days); 3) the temperature function $\phi_T = \exp\ [U_a/R\ (1/T_o - 1/T)]$ where $U_a/R = 4000$°K (activation energy/gas constant), $T_o = 293.15$°K, $T = 673.15$°K; and 4) $f_w = g(w) = 1.0$ because shrinkage assumed not to be present.

Results of the total displacement (= elastic + creep) are shown in Figure 2 for selected points where maximum displacement would occur for the r-z coordinate system. The deformation history was obtained by using time steps (12 total) of 0.1, 0.9, 9, 90, 1000, 10000, 40000, 60000, 60000, 60000, 60000 and 73900 days with t' = 20440 days (56 years) which would be about 1000 years. Also plots of the stresses at selected sections in the container are given in Figure 3. Note the stresses are given for the r-z plane in terms of σ_r, σ_z and σ_{rz} (shear) and also σ_θ (hoop), along with the principal stresses, σ_1 and σ_2 for r-z plane. Notice that for the time period of 1000 years the concrete container is stressed by a constant hydrostatic pressure (stress remains constant in concrete) and only the deformation of the container changes in time (creep).

5 CONCLUSIONS

A 12 in. thick container gives a maximum compressive stress of about 3400 psi (Figure 3b) and a maximum tensile stress of about 180 psi (Figure 3e). With an assumed maximum compressive strength of 7100 psi and an approximate tensile strength (ACI formula) of $6\sqrt{f'_c} = 500$ psi the viscoelasticity formulation is valid for the analysis presented.

The concrete container should be able to last at least 1000 years (required by BWIP) and will probably last longer based on the conservative loading (no temperature decrease from 400°C) used in the analysis.

In assuming that the moisture condition (dried concrete) remains unchanged due to a constant temperature of 400°C due to the nuclear waste may be unconservative. Over the 1000 year period in question, the heat generation of the waste will decay in time. As this occurs, moisture will eventually migrate back into the concrete which will cause swelling along with hygral and thermal strains with stress dependencies [6]. This type of behavior was not covered in the study, but should be investigated if such a design were to be implemented for a waste container. Such analyses could be carried out with the current computer codes TEMPOR2 and STRAW.

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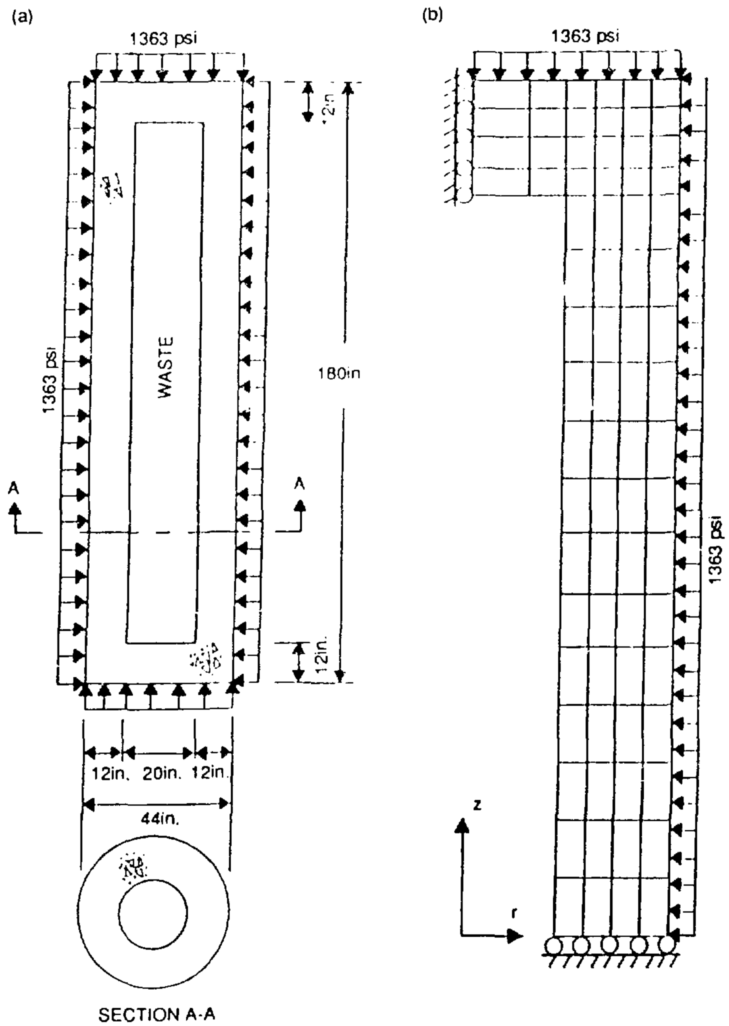

Figure 1. Container geometry and finite element mesh.

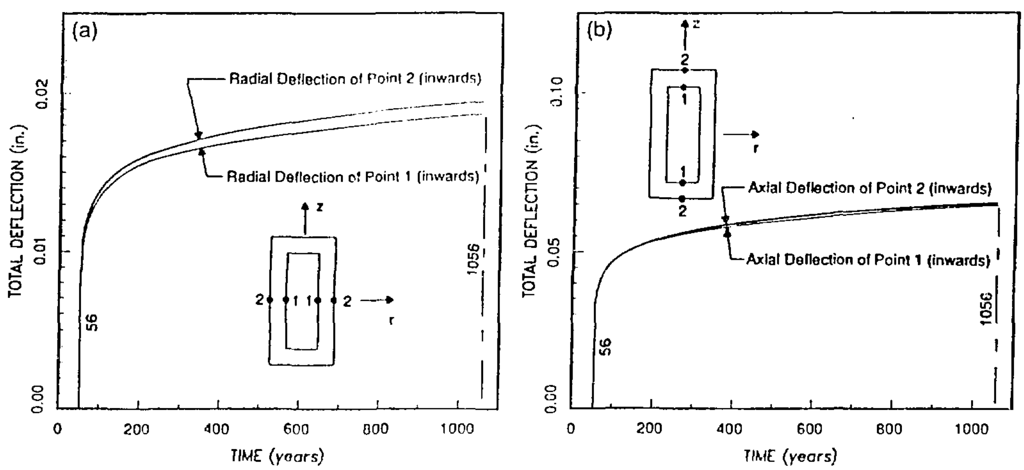

Figure 2. Displacement time plots at various points.

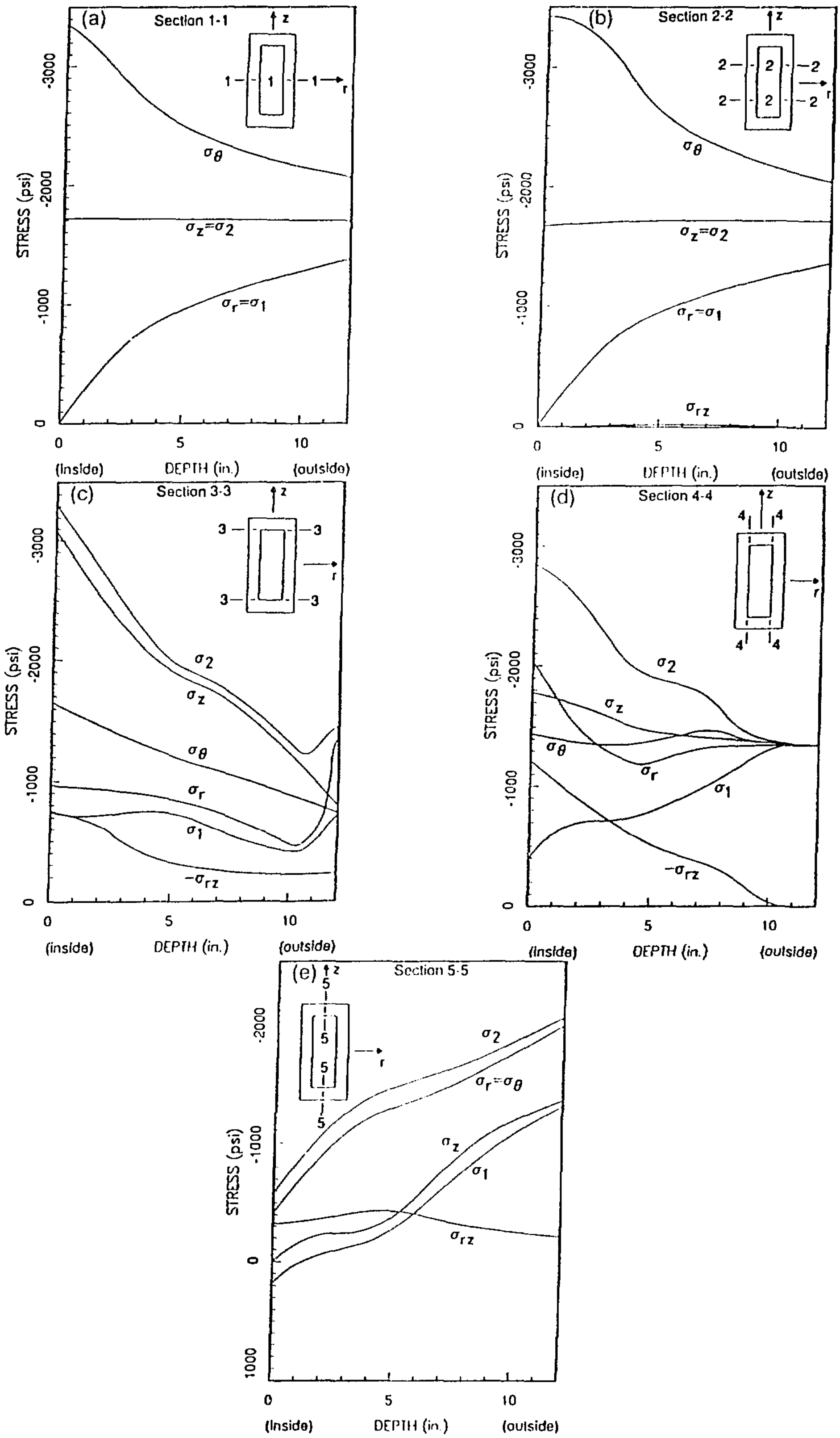

Figure 3. Stress plots at various sections.