Impact Analysis and Testing of Tritiated Heavy Water Transportation Packages Including Hydrodynamic Effects

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INTRODUCTION

Ontario Hydro has recently designed a new Type B(M) Tritiated Heavy Water Transportation Package (THWTP) for the road transportation of tritiated heavy water from its operating nuclear stations to the Tritium Removal Facility in Ontario. These packages must demonstrate the ability to withstand severe shock and impact scenarios such as those prescribed by IAEA standards. The package, shown in figure 1, comprises an inner container filled with tritiated heavy water, and a 19 lb/ft^3 polyurethane foam-filled overpack. The overpack is of sandwich construction with 304L stainless steel liners and 10.5 inch thick nominal foam walls. The outer shell is 0.75 inch thick and the inner shell is 0.25 inch thick. The primary containment boundary consists of the overpack inner liner, the containment lid and outer containment seals in the lid region. The total weight of the container including the 12,000 lb. payload is 36,700 lb. The objective of the present study is to evaluate the hydrodynamic effect of the tritiated heavy water payload on the structural integrity of the THWTP during a flat end drop from a height of 9m. The study consisted of three phases:

i) Developing an analytical model to simulate the hydrodynamic effects of the heavy water payload during impact.

ii) Performing an impact analysis for a 9m flat end drop of the THWTP including fluid structure interaction.

iii) Verification of the analytical models by experiment.

METHOD OF ANALYSIS

The non-linear transient dynamic analysis of impacting structures involves both non-linear geometric and material behaviour affecting wave propagation in two and three-dimensional continua. A two material structure such as the THWTP, where steel and polyurethane foam interface, further complicates the problem. In addition, the consideration of the fluid-structure interaction (FSI) of the liquid payload with the containing structure adds another difficult facet to the problem. Due to the inherent complexity of the problem, the finite element method was applied using the Ontario Hydro version of the computer code DYNA3D (Hallquist 1983, Sauvé 1987). This code is an explicit three-dimensional finite element computer program for analyzing the large deformation dynamic response of inelastic solids. A contact algorithm permits gaps and sliding along zone boundaries and material interfaces. Spatial discretization is achieved by the use of four, six or eight-noded isoparametric solid elements, four-noded thin shell elements and two-noded beam elements. A number of material models and equations of state are available to cover a broad range of material behaviour. The equations of motion are numerically integrated using the explicit central difference operator which is conditionally stable with respect to time step size. The foam, rigid and fluid portions of the package were modelled using eight node hexahedron linear isoparametric elements whereas the inner and outer stainless steel shells close to the impact zone were modelled using a quadrilateral thin shell element formulation. The loading on the models was obtained in terms of an initial velocity applied to the complete region defining the package, using the following relation from rigid-body mechanics: $V_o = \sqrt{2gh}$, where V_o, h and g are the initial velocity at impact, drop height, and gravitational constant respectively. $V_o = 523.3$ in/sec for a 9m drop.

MATERIAL MODELS

For the severe impact scenario addressed in this analysis, the solid material models must be capable of providing an adequate representation of the moderately large strain regime. This entails a non-linear description of the material behaviour in the post-yield region. The 304L stainless steel material was modelled using a von Mises yield criterion with an isotropic hardening rule. Although data on 304L stainless steel are well documented, those for polyurethane foams are not. Polyurethane foams exhibit a pressure dependent behaviour. They crush and compact under pressure due to the presence of voids. The modelling of the polyurethane foam followed the approach described in (Sauvé et al, 1987, 1988). An elementary isotropic plasticity theory is utilized in which a pressure dependent flow rule governs the deviatoric behaviour, and the yield function is defined in terms of the second invariant of the deviatoric stress tensor, the hydrostatic pressure and constants obtained from experiment. The pressure versus volumetric strain behaviour is described using an experimentally determined equation of state. Elastic unloading is assumed to a tensile cutoff pressure using an unloading bulk modulus. If failure under hydrostatic tension occurs, pressure is left at the cutoff value and the deviatoric stress components are zeroed.

FLUID MODEL DEVELOPMENT

In order to simulate the interaction of liquid D_2O payload with the THWTP structure, a mathematical characterization of the liquid is necessary. The basic approach taken in developing the hydrodynamic model is the formulation of a three dimensional hexahedron isoparametric element in terms associated with a fluid continuum, and incorporating it into the DYNA3D computer code. The primary variables of velocities are obtained at the nodes with the hydrostatic pressure sampled at the element centroid. A barotropic equation of state which relates volumetric strain to pressure is used to characterize the fluid behaviour. The formulation considers the fluid as a compressible media only, so that no tension fields are permitted. A subset of the three dimensional Navier-Stokes momentum equations are used to develop the model. The Galerkin weighted residual method is applied to the differential equations resulting in a discretized approximation of the continuum. The reduced set of equations used to develop the model are:

$$\rho \dot{v}_i + \frac{\partial P}{\partial x_i} = 0 \qquad (i = 1,2,3)$$

where ρ is the fluid density, v_i are the velocity components and P is the pressure. The assumptions inherent in the model are: i) an inviscid model with an isotropic stress state is considered, ii) for relatively small disturbances the convective terms are neglected and, iii) body forces are considered small by comparison to the dynamic forces and are ignored.

Equation of State

Neglecting friction the mean pressure is obtained using an equation of state $P = f(\rho)$ where ρ is the density. The form used for the fluid in this analysis is given by:

$$P = K \frac{\Delta\rho}{\rho_o}$$

where K is the bulk modulus and ρ_o is the original density. From the conservation of mass;

$$P^t = K\left[\frac{V_o}{V_t} - 1\right]$$

where V_o, V_t are the original volume and volume at time "t" respectively.

Discretization of Flow Equations

Considering 1-dimensional flow, the equations reduce to:

$$\rho\frac{\partial u}{\partial t} + \frac{\partial P}{\partial x} = 0$$

Applying Galerkin's Method (Integral or Weak form of the equilibrium equations) and considering a 2-node linear shape function to approximate the exact solution u:

$$\bar{u} = Nd = \sum_{i=1}^{2} N_i d_i$$

where d_i are the nodal values of velocity u. Ignoring surface traction boundary conditions and assuming a unit cross sectional area leads to:

$$\int_o^L N_i\rho\frac{\partial\bar{u}}{\partial t}\,dx + \int_o^L N_i\frac{\partial P}{\partial x}\,dx = 0$$

Integrating the second term by parts and substituting for $\bar{u}$ leads to:

$$M\dot{d} + F_{int} = F_{ext} \qquad \text{(in matrix form)}$$

where; $\quad M = \rho\int_o^L N^t N dx \qquad F_{int} = -\int_o^L \frac{\partial N^T}{\partial X} P dx = \int_o^L B^T P dx$

In order to verify the formulation, a one-dimensional isoparametric element is derived in closed form and implemented into a one-dimensional computer code. The verification test consisted of a rigid pipe, 1000 in. in length, filled with water travelling at an initial velocity of 100 in./sec subjected to an instantaneous valve closure at one end. As seen in figure 2, the shock wave propagation obtained from the 1-D code agrees closely with both the amplitude and shape of the analytical solution.

DISCRETIZATION IN 3-DIMENSIONAL SPACE

Following the derivation of the integral form of the equations given for the 1-D case, the three dimensional discretized equations at the element level are as follows;

$$M^e \dot{d}^e + F^e_{int} = F^e_{ext}$$

The velocity fields are approximated by the interpolation of nodal variables using linear shape functions, N_i, as before. The element considered is the eight noded linear isoparametric hexahedron element, where shape functions N_i are given by:

$$N_i = \frac{1}{8}(1+rr_i)(1+ss_i)(1+tt_i)$$

for natural coordinate system $r = s = t = \pm 1$

The element mass matrix is given as;

$$M^e_{ij} = \rho \int_v N_i N_j \, dV$$

Since a lumped mass formulation is used to take advantage of the efficiency of the central difference operator, the mass matrix, shown in column form, is:

$$M_i{}^e = \rho \frac{V}{8} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}_i \qquad \text{For } i = 1, 8 \text{ nodes}$$

The element hydrostatic internal force vector $F^e{}_{int}$ at time t is given as:

$${}^tF^e{}_{int} = -\int_v B^T P dv$$

$$B_i = \left[\frac{\partial N_i}{\partial x} \quad \frac{\partial N_i}{\partial y} \quad \frac{\partial N_i}{\partial z} \right] \quad ; \quad P = (\sigma_x + \sigma_y + \sigma_z)/3$$

Using the chain rule of differentiation, derivatives in the global coordinate system are related to those in the element natural coordinate system through the Jacobian, J. Numerical integration of F^e_{int} at time t is carried out in the natural coordinate system using a one point Gauss Quadrature rule ($r = s = t = 0$):

$$^{t}F^{e}_{int} = -\int_V B^T P dv = -8\ B^T(0,0,0)P|J(0,0,0)|$$

where 8 $|J(0,0,0)|$ approximates the element volume, which is, in fact, exact for a parallelpiped. The central difference operator is used for the temporal solution of this problem which is governed by a rate constitutive relation. The existing DYNA3D hourglass viscosity formulation which is necessary to control zero energy hourglass modes arising from one point quadrature was applied. In addition, the artificial bulk viscosity method used in DYNA3D to eliminate shock discontinuities was included. Good correlation of the displacement time history and shock wave shape between the 1-D code, DYNA3D, and classical results for the test case is achieved as seen in figure 2. Details of the mathematical derivation, verification case, and implementation are given in (Sauvé and Morandin, 1988).

THWTP ANALYTICAL MODEL

The overall model for the 9m flat end drop simulation is shown in figure 3. Since both the THWTP and the drop orientation are symmetric, one quarter of the package is modelled with appropriate boundary conditions on the planes of symmetry. The THWTP assembly is modelled using several component models which represent: a) the overpack outer and inner shells and foam core, b) D_2O container, c) liquid payload and d) the overpack upper lid portion. The mesh was developed to provide the refinement needed in the vicinity of the point of initial impact while allowing a progressively coarser mesh in areas remote from the impacting surface. The model consists of 1670 node points with 1098 solids representing the polyurethane foam, fluid, rigid body portion of the model and the unyielding target. In addition, 486 shell elements represent the stainless steel D_2O inner container and the inner/outer liners of the overpack. The analytical model is shown in figure 3. The clearance between the inner D_2O container and the inner liner of the overpack is accounted for using the contact algorithm in DYNA3D. The inner surface of the overpack defines the master surface which limits the potential motion of the inner container. The target is modelled as a rigid unyielding surface. The results indicate considerable interaction of the liquid payload, the inner container, and the inner liner of the overpack (figure 4). The D_2O container and the inner liner of the overpack initially come into contact at 2.6 ms. Full spread of contact is developed at 3.5 ms at which time all components of the THWTP are loaded and the fluid hydrostatic pressure is no longer localized. At various subsequent stages of the transient, the average package decelerations range from 427 g at .20 ms to 139 g at 5 ms when the complete package is decelerating. The fluid initially responds acoustically until the first shock wave reaches the D_2O container wall at 0.6 ms. At this point the fluid response is attenuated by the flexibility of the container shell and subsequently by the combined effects of the container and the overpack when they impact later in the transient. Essentially the fluid response is governed by the deceleration. The distribution in the hydrostatic pressure of the fluid is mainly due to the variation of flexibility of the inner container as it interacts with the overpack. A peak localized hydrostatic pressure occurs at the bottom of the inner container early in the transient and reaches a quasi-steady value in the later stages. The time history of hydrostatic pressure at the bottom of the inner container is shown in figure 5. A maximum effective plastic strain of 5.3 percent occurs in the junction of the 1.00" thick flat head and the 0.25" cylindrical shell of the container.

VERIFICATION TEST

The analysis was verified by a nine-metre drop test, using a quarter-scale model of the THWTP. This model (shown in figure 6) included all of the main components of the transportation package, including the liquid payload container and foam-filled overpack. It was instrumented with two pressure transducers mounted at the bottom of the water container and four accelerometers - two on the bottom of the water container and two on the outer surface of the overpack. Figure 5 shows the pressure time histories from the pressure transducers, one near the centre of the container and one close to the edge. It should be noted that the time span of the test result is compressed relative to the analysis because of scaling effects. Agreement between analytic prediction and test results is very good as seen in figure 5 although some slight time delay is apparent.

REFERENCES

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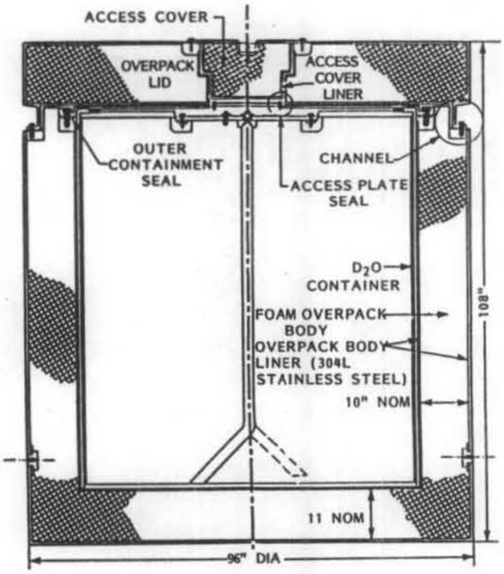


FIGURE 1
TRITIATED HEAVY WATER TRANSPORTATION PACKAGE

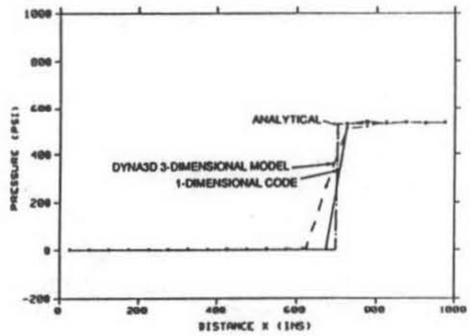


FIGURE 2
FLUID FORMULATION TEST -
PRESSURE DISTRIBUTION TIME = 0.005287 s

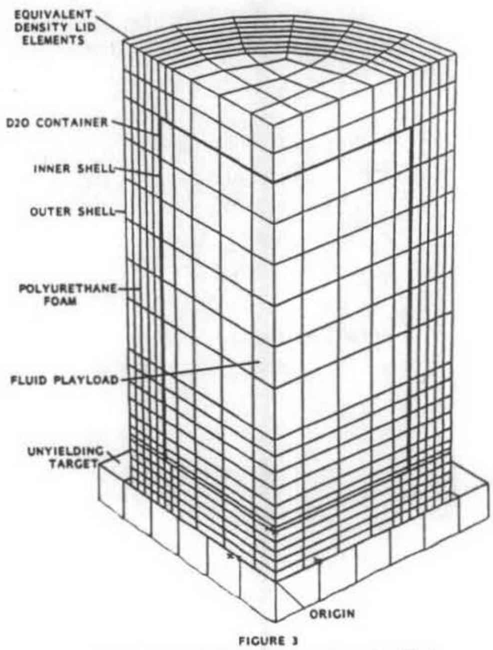


FIGURE 3
OVERALL FULL SCALE THWTP FSI MODEL GEOMETRY

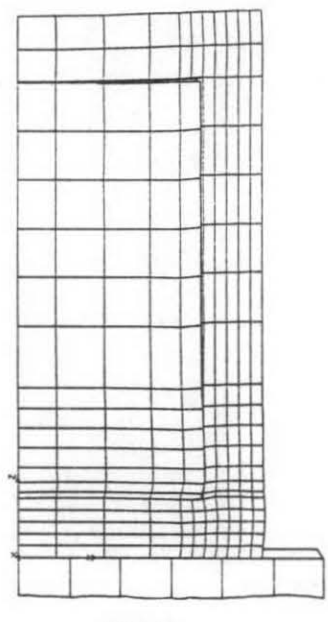
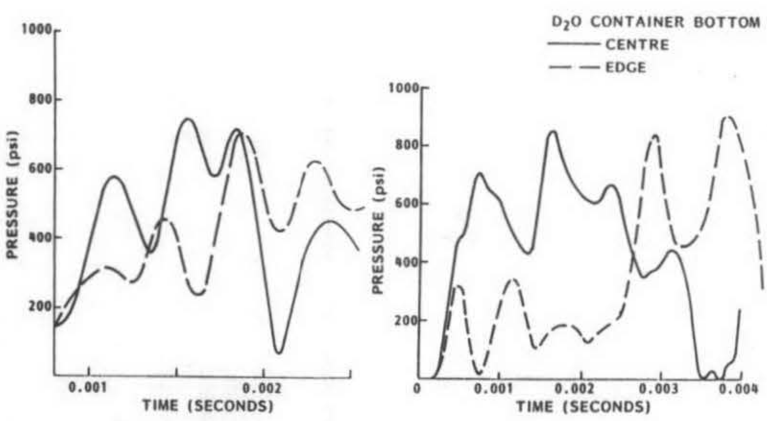


FIGURE 4
DEFORMED VIEW AT CUT PLANE (Y=0.,0.)
TIME=0.004998096 SEC



TEST RESULTS (1/4 SCALE MODEL)

ANALYTIC RESULTS (FULL SCALE MODEL)

FIGURE 5

FIGURE 6