Benchmarking of the Computer Code and the Thirty Foot Side Drop Analysis for the Shippingport RPV/NST Package*

S.E. Bumpus, M.A. Gerhard, J. Hovingh, D.J. Trummer, M.C. Witte

Lawrence Livermore National Laboratory, Livermore, California, United States of America

INTRODUCTION

This paper presents the benchmarking of a finite element computer code and the subsequent results from the code simulating the 30 foot side drop impact of the RPV/NST transport package from the decommissioned Shippingport Nuclear Power Station.

The activated reactor pressure vessel (RPV), thermal shield, and other reactor external components were encased in concrete contained by the neutron shield tank (NST) and a lifting skirt . The Shippingport RPV/NST package, a Type B Category II package, weighs approximately 900 tons and has 17.5 ft. diameter and 40.7 ft. length. For transport of the activated components from Shippingport to the burial site, the Safety Analysis Report for Packaging (SARP) demonstrated that the package can withstand the hypothetical accidents of DOE Order 5480.3 including 10 CFR 71.

Mathematical simulations of these accidents can substitute for actual tests if the simulated results satisfy the acceptance criteria. Any such mathematical simulation, including the modeling of the materials, must be benchmarked to experiments that duplicate the loading conditions of the tests. Additional confidence in the simulations is justified if the test specimens are configured similar to the package.

BENCHMARK

Benchmarking of the finite element computer codes DYNA2D and DYNA3D (Hallquist) for the mathematical simulations of the accidents consisted of three activities as described below.

Drop Tests

The test specimens were simplified models measuring approximately 1/10 of the major dimensions of the Shippingport RPV/NST package. The test specimens were composed of steel and the concrete that was specified for the outer portion of the package. The total

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length and diameter of the 1820 pound test specimen are 51.6 and 22.0 inches, respectively.

The benchmark tests for the Shippingport RPV/NST package were performed by Westinghouse Hanford Corporation. These tests included end, corner, and side drops from a height of 30 feet onto a steel pad. In addition, to ensure crush-up of the concrete , an end drop and a side drop were performed from a height of 45 feet.

The test data included not only deceleration histories from a transducer mounted on the simulated RPV but also measurements of the permanent deformation in the outer shell . A further description is given by Burgess (1989).

Concrete Characterization

The computer code DYNA simulates the behavior of concrete with a pseudo-tensor concrete/geologic model. However, because the concrete is an especially formulated grout, the default material properties based on compressive strength normally used in DYNA are not appropriate.

SRI International performed characterization tests on the concrete. The necessary material properties, (including the shear modulus, Poisson's ratio, tensile cut-off stress, and the cohesion and pressure hardening coefficients) were determined from confined triaxial tests. In addition, the compressive strength of the concrete was determined using unconfined tests. The complete description of these tests and results are given by Simons and Gefken (1988).

Mathematical Simulation of Benchmark Tests

The benchmark test specimen was modeled using the finite element mesh generator code SLIC (Gerhard). The steel components in the test specimen were modeled as DYNA kinematic/isotropic elastic-plastic material, while the concrete was modeled as DYNA pseudo-tensor concrete/geologic material using the properties measured by SRI. The concrete/steel shell interfaces were modeled as frictionless contact surfaces which allow the shell to separate from the concrete.

Both the round and flat end drops were simulated using the axisymmetric 2-D code DYNA2D. The corner and side drops were simulated using the 3-D code DYNA3D. The output from the simulations included not only a deceleration history of the node corresponding to the location of the transducer on the specimens, but also the deformed shape of the impact area.

Comparison of Benchmark Results

The deceleration histories and the permanent deformation measured for each test specimen were compared to those computed using DYNA. For comparison purposes the deceleration histories included the peak deceleration, the impulse (the product of the peak deceleration times the time-width of the acceleration history at half the peak acceleration) and the time interval from initial impact to the time when the deceleration returned to zero.

A comparison of the deceleration history from the simulation and test of a 30 foot, round end corner drop is shown in Figure 1. The ripple on the measured deceleration history is characteristic of the 2 kHertz filter used to reduce the higher harmonics which overloaded the charge amplifier on the early drops (1A, B; 2B). The ripple on the simulated results is due to the size of the time intervals used between plotted points. Thus, the simulation curve can be better estimated by the use of more frequent plot time intervals or by "eyeball" smoothing.

A comparison of the simulated and test results for all the tests is given in Table 1. The difference between the simulated and test results (normalized to the test results) ranges from -61% to +140%. Of the 33 comparisons, 15 are positive differences, which denotes that the simulations over-estimate the impact. Of the negative differences, 10 were less than 20%, with 7 less than 10%.

The differences between the test and simulation results are partially due to the assumption that the test pad acted as an unyielding surface. This assumption causes the simulated results to be more severe than the test results because the test pad absorbs part of the kinetic energy from the specimen. In addition, the impact of the side and flat end drop of the test specimens was not perfectly flat as simulated.

Further discussion of the benchmark tests and their simulations is given by Goldmann et al., and Fischer et al. The close agreement between the simulated and test results (considering the large number of variables including simulated material properties, geometry, and impact and the uncertainties in the test measurements) justified confidence in the use of DYNA to predict the dynamic structural response of the Shippingport package.

30 FOOT SIDE DROP OF SHIPPINGPORT PACKAGE

Brief Description of Package

The structural evaluation of the package included impact end, side and oblique drops for the hypothetical accidents. The major components of the RPV/NST package are the RPV and closure head, the thermal shield, the upper and lower core barrels, the filler plates, the bottom plate, and the NST. These components, as well as the RPV wall, are radioactive. In addition, other radioactive structural components of the reactor core were placed within the RPV. The radioactive contents are nondispersible (i.e., remain below the radioactive release limits for accident conditions). Significant radiation shielding is provided primarily by the thick-wall of the RPV. The external radiation levels can increase significantly only if the RPV/NST package fails catastrophically and allows large components such as a core barrel to become exposed. The lifting beam, skirt, and the concrete fill material are also part of the package.

The NST annulus is filled with 120 to 130 lb/ft^3 density concrete having a minimum 28-day compressive strength of 2000 psi. The concrete mix was designed to be fluid enough to fill all voids. The annular space between the inner wall of the NST and the RPV is filled with a 4-in.-thick blanket of fiberglass insulation and the concrete. In addition, the lifting skirt is also filled with this concrete .

Concrete and steel materials are primarily used in the construction of the RPV/NST package. The concrete provides additional shielding of the radioactive contents, forms a monolithic package, and acts as an energy-absorbing material. The steel in the NST outer shell confines the package radioactive contents, and the steel in the RPV wall provides radiation shielding.

Two different formulations were used for the concrete fill in the RPV/NST package. Both formulations are grout-like because sand is the aggregate. Both concretes were formulated to be lightweight, have good flowability, and have a low heat of hydration. The concrete in the RPV is formulated to be slightly expansive to ensure that the components are firmly fixed in place. The concrete in the NST region is formulated to have little or no shrinkage.

The steel and concrete in the package used the same DYNA material models as used for the benchmark simulations. A soil and crushable foam model is used with DYNA3D to represent the insulation. This model includes a bulk unloading modulus, and a pressure-vs-volumetric strain curve to describe the pre- and post-yield behavior. Since the insulation has virtually no elastic strength, the yield strength and the elastic shear modulus were set to the order of 1 psi.

Methods of Analysis

A hypothetical accident specified in 10 CFR 71.73 is a thirty foot free drop onto a flat, unyielding surface, striking so as to produce the maximum damage.

The three-dimensional, half-symmetry finite element model was generated using SLIC and used to perform detailed impact analyses. This model is composed of concrete surrounding the vessel, grout inside the vessel, the head and flange, the vessel including the nozzles, insulation surrounding the vessel, the ring girder, the outer shell, the plates making up the lifting beam, and16 circular bolts attaching the lifting beam to the head. The 42 bolts between the closure head and vessel flange are modeled as 16 bolts with increased cross-sectional areas. The shell/concrete and lifting beam/concrete interfaces are modeled as frictionless contact surfaces.

This analysis was performed with DYNA3D using an initial velocity of 527.5 in/sec in the negative y direction of the model. The orientation of most interest is the 30 foot drop on the side because localized cracking may occur in the end plate and outer shell.

Results

The 0.676 strain in the end plate is sufficiently high that ductile rupture may occur. However, from the maximum principal stress contours shown in Figure 2, this principal strain is highly localized. Although rupture may initiate at the point indicated on the figure, this rupture will arrest before reaching the values corresponding to the 25.6 ksi contour, which is in the elastic region. In the skirt, a maximum principal plastic strain of 0.174 indicates that rupture may occur. However, ductile rupture may not initiate because the strain pattern is nearly uniaxial and the maximum principal strain is less than the uniaxial fracture strain of 0.20. If rupture initiates at the point indicated on the figure, this rupture will arrest before it reaches the 32.3 ksi contour, which is in the elastic region and approximately 6" away.

Acceptance Criterion

The acceptance criterion established for the package prohibits a rupture of the outer shell under any condition that could cause the release of significant radioactive material to the environment. This criterion was quantified as a finite plastic strain criterion defined by the onset of plastic instability in the material.

Evaluation of Package

The structural analyses show that there is only one condition, namely the 30 foot side drop, in which local ductile rupture might occur and then, only at the juncture of the skirt and lower end plate. Because of the large stress gradient, the rupture will not compromise the ability of the outer shell to perform its function to protect the concrete shielding and to contain the radioactive components so long as brittle fracture is of no concern.

SUMMARY AND CONCLUSIONS

The DYNA code was benchmarked by comparing the results of drop tests with their simulations. The close agreement between the benchmark test and simulated results justified confidence in using DYNA to predict the dynamic response of the Shippingport package. Dynamic analyses of the package showed that the maximum damage occurs in a 30 foot side drop. The results indicated that local rupture may occur, but because of the large stress gradients, the rupture will not propagate a sufficient distance to allow a release of radioactive material exceeding the limit that transport regulations allow.

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TABLE I SUMMARY OF BENCHMARK RESULTS

TEST	1A(2)	2A	2B(2)	3A	3B	4	5	6A	6B(1)	7
Height, feet	30	1	30	30		45	45	30	30	30
Impact Surface	Round End	Side	Side	Round:Corner:Flat		Round End	Side	Round End	Flat End	Side
Peak Acceleration, g's										
Test	NA	257	NA	966 : axial : -429 337 : radial : 226		1067	3002	1352	-1594	1155
Simulation	910	340	-1900	630 : axial : -390 320 : radial : 170		1150	4000	910	-1900	2700
% Difference		+32		-35 : axial : -9 -5 : radial : -25		+8	+33	-33	+19	+130
Impulse/mass, ft/sec										
Test	NA	4.2(3)	NA	87 : axial : -71 31 : radial : 32		87	74	103	-26	71
Simulation	61	13	-61	51 : axial : NA 29 : radial : NA		74	77	61	-61	68
% Difference *				-40 : axial : -5.3 : radial :		-15	+4.3	-41	+140	-4.5
Deceleration Time, ms										
Test	NA	1.5	NA	4.5 : axial : 7.5 3.75 : radial : 8.0		3.8	1.09	3.5	1.25	2.5
Simulation	3.7	1.98	1.27	4.0 : axial : 7.0 4.0 : radial : 8.0		3.7	1.44	3.7	1.27	1.5
% Difference		+32		-11 : axial : -67 +6.7 : radial : 0		-2.6	+32	+5.7	+1.6	-40
Permanent Deformation, inch^2										
Test	80	NA	270	7.5 x 10.8	5.5 x 17.0	130	290	85	NA	240
Simulation	80	NA	210	6.0 x 11.2	4.4 x 11.6	110	310	80	NA	210
% Difference*	0		-22	—	—	-15	+6.9	-5.9		-13

$$* \% \text{ Difference} = \frac{\text{Simulated} - \text{Test}}{\text{Test}} \times 100$$

(1) Footprint invarient

(2) accelerometer saturated

(3) did not hit flat; initial impulse is also 4.2 ft/sec

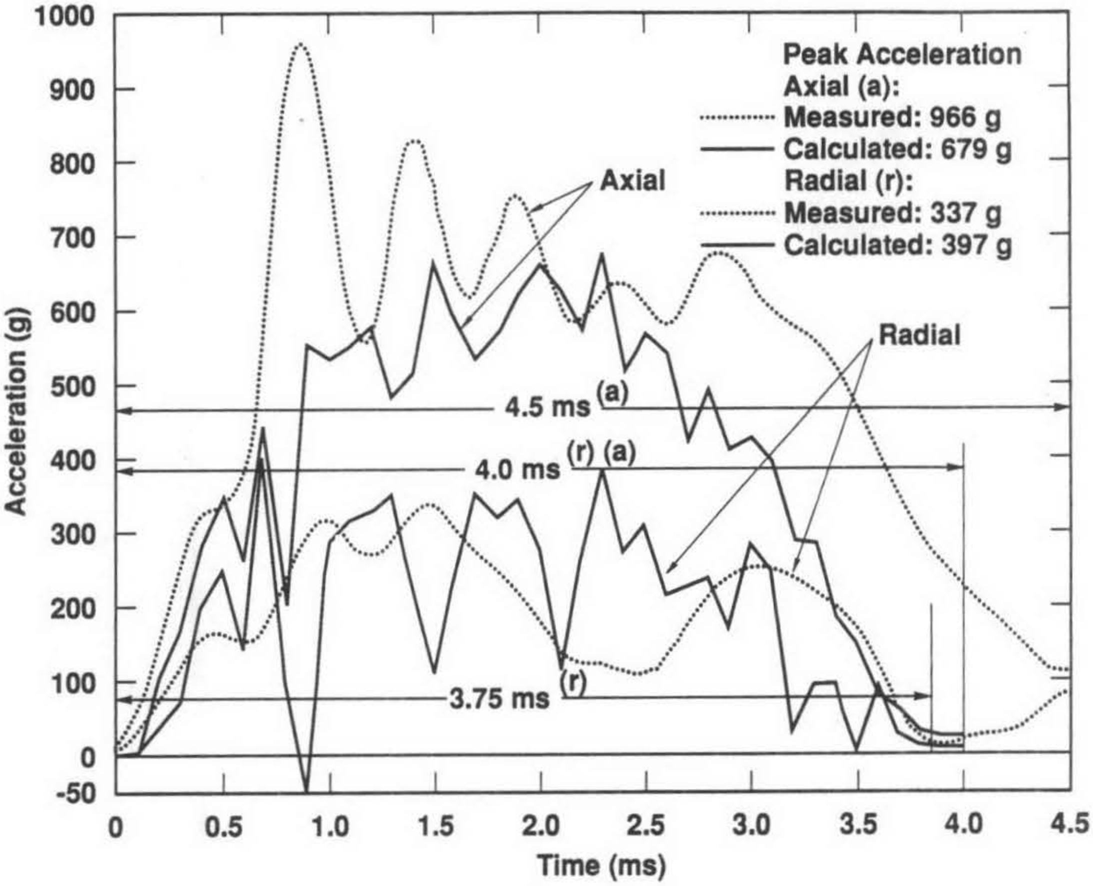

Figure 1. Benchmark 30 foot, round end corner drop accelerations: a comparison of the simulation calculations with the test measurements.

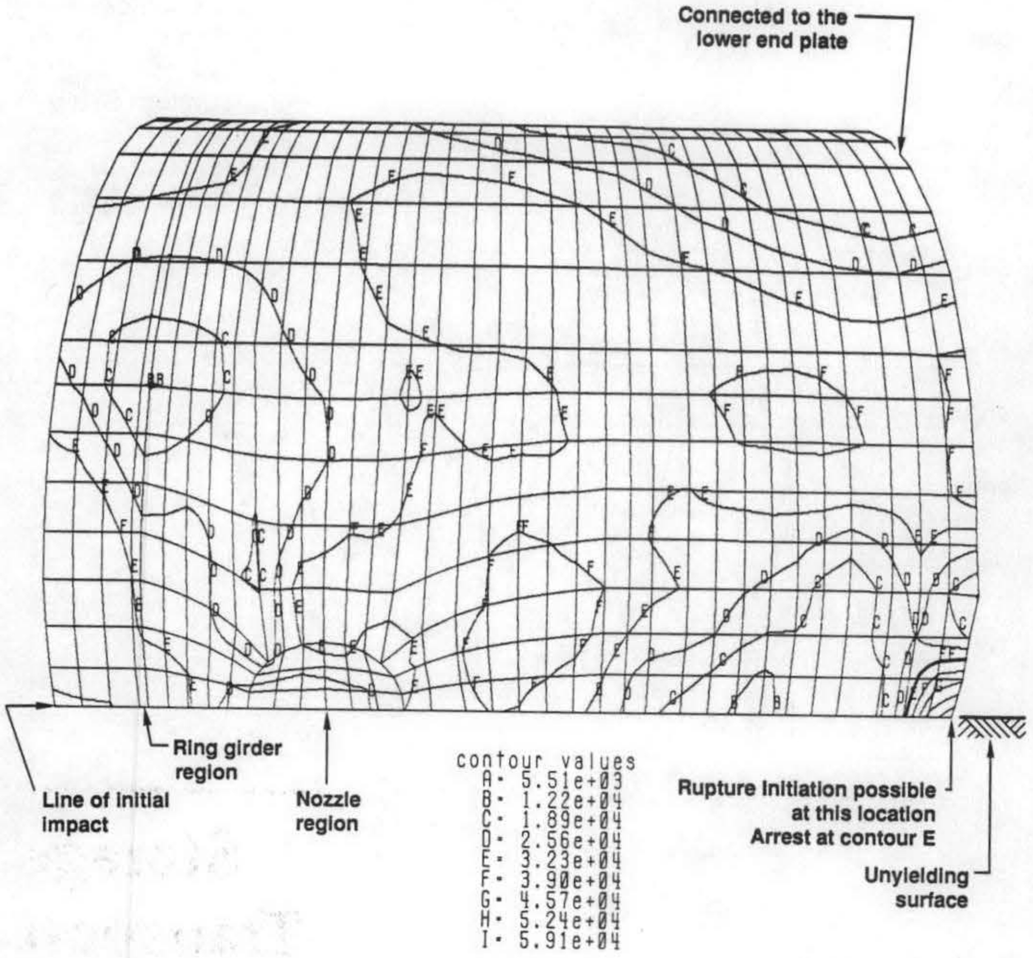

Figure 2. Contours of maximum principal stress in the lifting skirt of the package after the simulated 30 foot side drop.

Session VI-2

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