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Round Robin Analyses of the Steel Containment Vessel Model[1]

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DISCLAIMER

ABSTRACT

A high pressure test of the steel containment vessel (SCV) model was conducted on December 11-12, 1996 at Sandia National Laboratories, Albuquerque, NM, USA. The test model is a mixed-scaled model (1:10 in geometry and 1:4 in shell thickness) of an improved Mark II boiling water reactor (BWR) containment. Several organizations from the United States, Europe, and Asia were invited to participate in a Round Robin analysis to perform independent pretest predictions and posttest evaluations of the behavior of the SCV model during the high pressure test. Both pretest and posttest analysis results from all Round Robin participants were compared to the high pressure test data. This paper summarizes the Round Robin analysis activities and discusses the lessons learned from the collective effort.

INTRODUCTION

The Nuclear Power Engineering Corporation (NUPEC) of Japan and the US Nuclear Regulatory Commission (NRC) are co-sponsoring a Cooperative Containment Research Program at Sandia National Laboratories, Albuquerque, NM, USA. As a part of this program, a SCV model was pressurized to failure during the high pressure test. The purpose of the program is to investigate the response of representative models of nuclear containment structures to pressure loading beyond the design basis accident by conducting static, pneumatic overpressurization tests of scale models at ambient temperature and to compare analytical predictions to measured behavior.

The program sponsors invited several organizations to perform independent pretest predictions and posttest evaluations of the deformation behavior of the SCV model during the high pressure test. Eight organizations participated in the Round Robin pretest analysis; seven of these organizations also participated in the Round Robin posttest analysis.

Argonne National Laboratory (ANL) [USA]
Agenzia Nazionale per la Protezione dell Ambienti (ANPA) [Italy]
Bhabha Atomic Research Centre (BARC) [India]

General Dynamics Electric Boat Division (GD-EB) [USA]
Japan Atomic Energy Research Institute (JAERI) [Japan]
Nuclear Power Engineering corporation (NUPEC) [Japan]
Sandia National Laboratories (SNL) [USA]
Staatliche Material prüfungsanstalt, Universität Stuttgart (MPA Stuttgart) [Germany]

Each organization was supplied with design details of the SCV model, the instrumentation layout, and the steel material test data. The design and the special features of the SCV model are described in Reference 1. The participants were asked to submit pretest and posttest analysis results at the pre-selected locations on the SCV model. Pretest and posttest meetings were held to allow the participants to discuss analysis results and to share analysis experiences. This paper summarizes the Round Robin pretest and posttest analysis results and their comparisons to the high pressure test data and discusses the insights gained from this exercise.

HIGH PRESSURE TEST RESULTS

The conduct and the results of the high pressure test are described in References 1and 2. The test was terminated at a pressure of 4.66 MPa, or roughly six times the design pressure when a large tear, approximately 190 mm long, developed adjacent to the weld at the edge of the equipment hatch reinforcement plate (Fig. 1). This tear was located below the material change interface in the high strength SPV490 steel shell. In addition, a small meridional tear, approximately 55 mm long, was found in a vertical weld underneath a semi-circular weld relief opening at the middle stiffening ring.

The posttest metallurgical evaluation results found that heat from the welding process caused a localized microstructural alteration and reduced hardness and strength in the SPV490 heat affected zone [3]. The large tear along the equipment hatch reinforcement plate resulted from local plastic deformation and ductile shear fracture.

ROUND ROBIN ANALYSIS MODELS

Each participant was supplied with the same information necessary for the independent analyses. The participants chose the finite element codes and decided the modeling procedures to be used in the analyses. Table 1 contains a summary of the participants' analysis models. No other instructions or guidelines were given to the participants and they were free to pursue their independent analysis approach based on their own experience and intuition.

ROUND ROBIN PRETEST PREDICTIONS

All participants provided the pretest predictions at 43 pre-selected standard output locations where either strain gages or displacement transducers were installed to record the local deformation behavior of the model to facilitate comparisons with the analysis results. In addition, participants provided pretest predictions on failure pressure and location on the model, onset of local yielding, and contact pattern between the model and the contact structure (CS). The details of all participants' pretest predictions are documented in Reference 4.

In summary, the pretest predictions of the deformation behavior and failure of the model are dependent on the details of the model features that were included in the analysis models as detailed in Table 1. Two organizations incorporated the locally thinned sections, which were detected prior to the high pressure test, around the equipment hatch into the numerical models. The results from these analytical models indicated that the locally thinned areas were the most vulnerable sections for failure and predicted the failure pressure very close to the model failure pressure. Generally, participants predicted the model failure to take place in the locally thinned section around the equipment hatch, around the knuckle region, or at the top head apex.

The participants did not accurately predict the occurrence of the large tear and its ductile shear failure mechanism, partly because the reduced strength in the heat affected zone (HAZ) in SPV490 steel around the large tear was not known prior to the high pressure test. Likewise, the small tear at the middle stiffening ring was also not predicted. What was troublesome to participants was the constant underprediction of hoop strains at the upper conical shell section between the test data and the analysis results at Standard Output Location # 24 (Fig. 2). This location, which is far away from structural and geometrical discontinuities, represents the global free-field behavior of the model. As indicated in Fig. 2, the pretest analysis results underpredicted the onset of yielding by 15 to 30%.

Most participants experienced numerical stability difficulties in simulating the contact between the model and the CS. Analysis results indicate that these results are sensitive as to how the two structures interact at the contact interface. Participants agreed that it is important to improve the understanding and simulations on the part of the numerical contact algorithms.

ROUND ROBIN POSTTEST EVALUATION

The Round Robin posttest evaluation effort focused on improving the simulation of the global free-field model behavior at the upper conical shell section and the large tear along the equipment hatch reinforcement plate. Nine additional locations were added to the 43 pretest standard output locations in response to these two issues. The Round Robin posttest evaluation results are described in detail in Reference 5.

Global Free-Field Model Behavior

Extensive uniaxial tensile tests were performed on the specimens of SGV480 and SPV490 steel plates in the prefabrication state, and the participants used these material property data to construct the material models in the analyses. Unfortunately, fabrication processes such as rolling might alter some of these material properties. This residual stress effect may be partially responsible for the observed discrepancy at Standard Output Location # 24. The pretest analysis results from the participants also indicate that the assumed material model for the SGV480 steel played a sensitive role in predicting the global free-field behavior. The participants provided an improved posttest simulation of the free-field hoop strains as demonstrated in Fig. 3. However, the discrepancy in the onset of yielding still remained.

Large Tear Along Equipment Hatch Reinforcement Plate

The posttest metallurgical evaluation results indicate that the heat from the welding process caused a localized microstructural change and reduced hardness and strength in the SPV490 steel

[3]. The reduced strength in the SPV490 HAZ has been identified as the leading factor for the large tear. Most participants incorporated some effect of the strength reduction in the SPV490 HAZ in the numerical models. The posttest analysis results of hoop strains at 90^0 and 270^0 of the local equipment hatch coordinate were compared with the recorded data by strain gages, STG-I-EQH-16b and -37a, in Figures 4 and 5, respectively.

SUMMARY

The Round Robin participants, using different finite element codes and analysis methodologies, performed the pretest predictions and posttest evaluation of the deformation behavior of the SCV model and produced analysis results that offer many similarities. In general, the pretest and posttest analysis results from the participants compared fairly well to the test data. Most participants chose to use the design configuration of the SCV model, as a practical matter, to construct the numerical models. The analysis results so generated have provided a reasonably good representation of the general structural behavior of the SCV model, except in some sections where local details become dominating and act as strain risers. The numerical models will not be able to predict the local strain concentrations caused by these local details that are not included in the models.

Extensive material tests were performed on specimens in the prefabrication state before the test. The material model based on these material data will not provide a good representation of the as-built state of the SCV model when the fabrication processes such as welding alter the material properties. The posttest metallurgical evaluation results indicate that the large tear along the equipment hatch reinforcement plate failed in a ductile shear manner of overstraining in the SPV490 HAZ. Because this as-built state was not known prior to the high pressure test, the pretest analysis results did not predict the large tear. In addition, the posttest analyses can only approximately simulate the occurrence of the large tear due to an insufficient understanding of the full effect of the strength reduction in the SPV490 HAZ.

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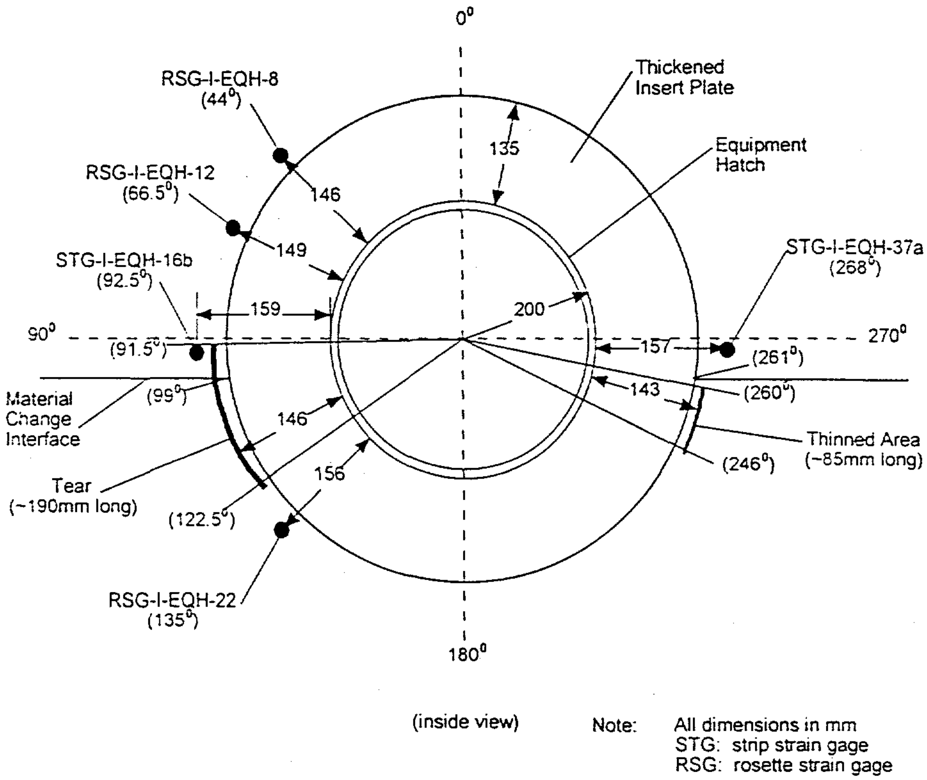

Figure 1. Posttest view of the interior elevation of the equipment hatch

Table 1. Summary of analysis models used by Round Robin participants

	Numerical Codes	Type of Model Used	Post-Yield Material Model	SCV/CS Gap Dimension	Shell Thickness of SCV Model	Local Thinning Incorporated ?	Eccentricity due to Different Shell Thicknesses of SCV Model?	Type of Contact between SCV model and CS
ANL	NEPTUNE	3-D 360^0 shell	Isotropic/bi-linear least squares fit	As-built	Design	No	No	elasto-plastic
ANPA	MARC	3-D 90^0 shell	Mean properties; high fidelity fitting total range	As-built at hole measurement # 9	Nominal	Yes	No	Rigid-deformable elastic-plastic surface
BARC	ABAQUS	2-D axisymmetric solid	Isotropic piecewise linear of minimum thickness specimen	As-designed	As-built	No	No	Hard contact with opening and closing
	TABS/NISA	2-D axisymmetric solid	Isotropic piecewise linear; mean values	As-built averaged over circumference	As-built	No	No	Hard contact with opening and closing
GD-EB	ABAQUS	Axisymmetric shell (free field); Axisymmetric solid (knuckle); 3-D shell (equipment hatch)	Isotropic piecewise linear	Average as-built; 21.0/25.7 mm at equipment hatch	Average as-built	Yes	Only at equipment hatch	Elastic-plastic minimum properties
JAERI	ABAQUS	3-D 180^0 shell	Tri-linear fit	Nominal; hard contact	Design	No	No	Elastic
NUPEC	ABAQUS	3-D global; 3-D equipment hatch submodel 3-D top head submodel	Mean properties high fidelity fitting total range	Nominal 18 mm; hard contact	Nominal	No	Only at equipment hatch insert plate	Elasto-plastic (same as equipment hatch material)
SNL	ABAQUS	3-D shell; Axisymmetric continuum top head; 3-D shell equipment hatch	Mean properties; high fidelity fitting total range	Nominal 18 mm; ABAQUS hard contact	Nominal	Yes	Only at equipment hatch insert plate	Elastic-plastic nominal properties
MPA	ABAQUS	3-D 180^0 shell	Isotropic kinemetic hardening model	Nominal 18 mm	Nominal	No	No	ABAQUS surface interaction option

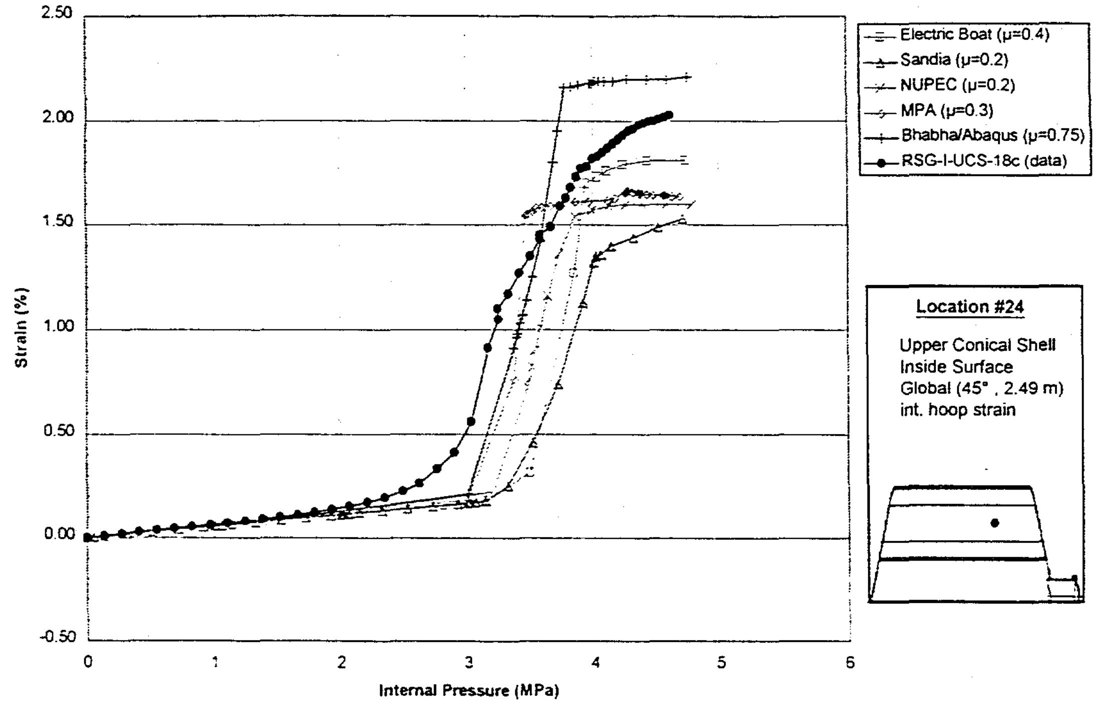

Figure 2. Pretest analysis results of internal hoop strains at upper conical shell section at Standard Output Location # 24

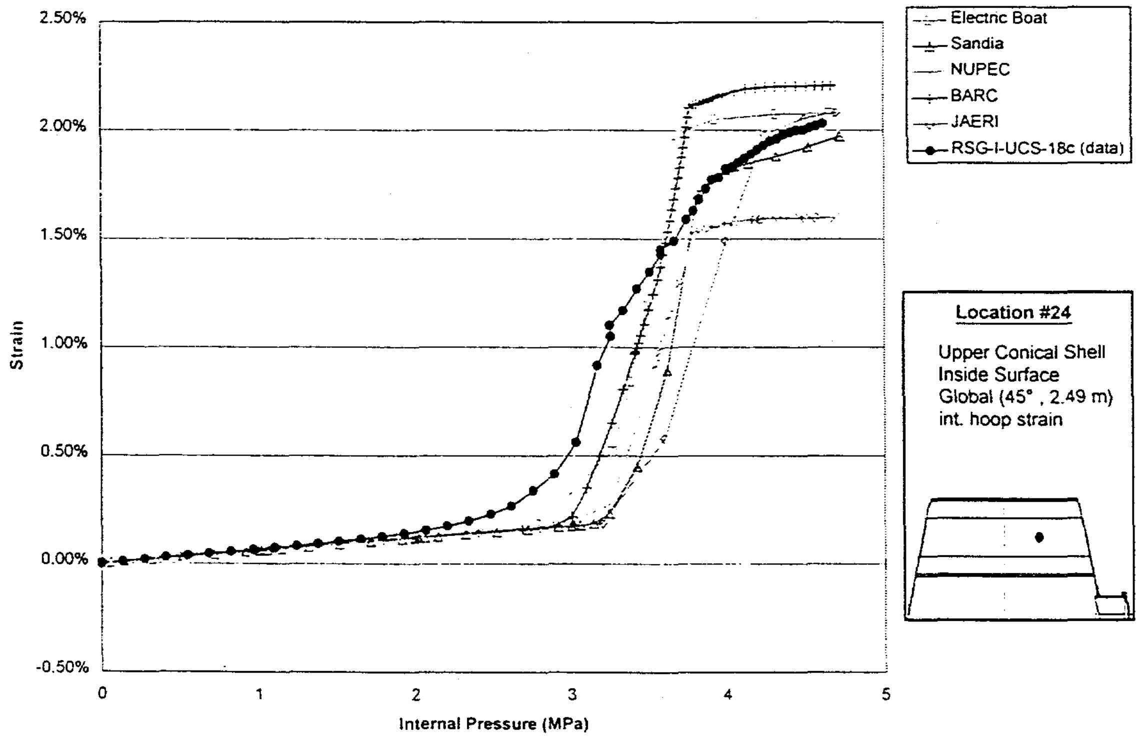

Figure 3. Posttest analysis results of internal hoop strains at upper conical shell section at Standard Output Location # 24

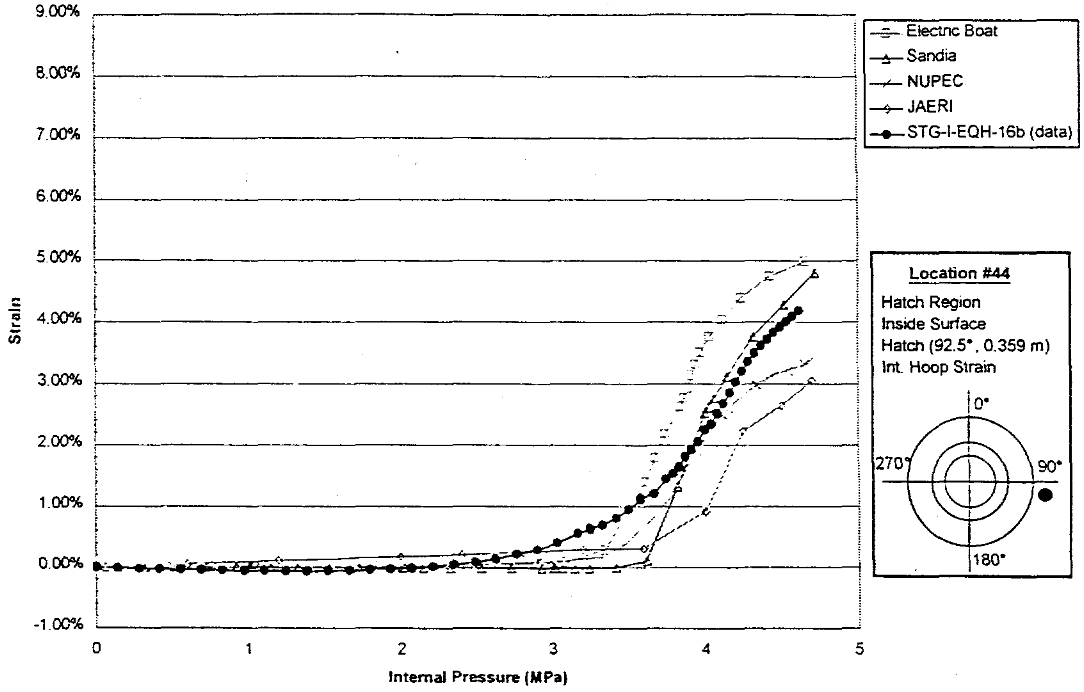

Figure 4. Posttest analysis results of internal hoop strains at 90^0 of equipment hatch

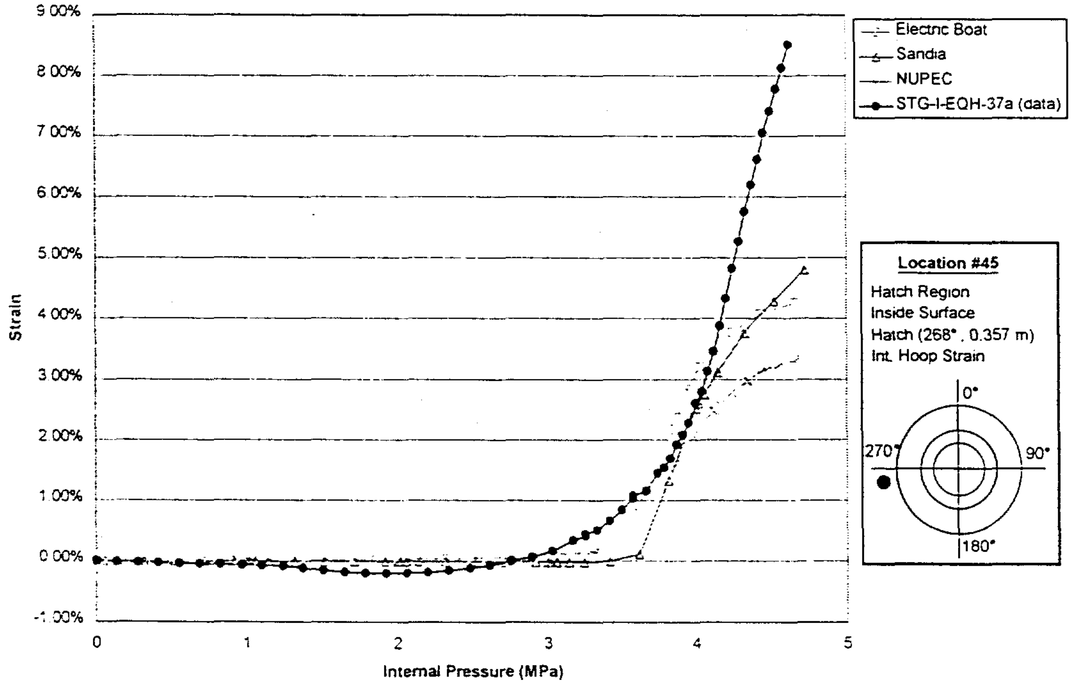

Figure 5. Posttest analysis results of internal hoop strains at 270^0 of equipment hatch