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Posttest Analyses of the Steel Containment Vessel Model

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ABSTRACT

A high pressure test of a scale model of a steel containment vessel (SCV) 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. This test is part of a program to investigate the response of representative models of nuclear containment structures to pressure loads beyond the design basis accident. The posttest analyses of this test focused on three areas where the pretest analysis effort did not adequately predict the model behavior during the test. These areas are the onset of global yielding, the strain concentrations around the equipment hatch and the strain concentrations that led to a small tear near a weld relief opening that was not modeled in the pretest analysis.

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. The purpose of the program is to investigate the response of representative models of nuclear containment structures to pressure loads beyond the design basis accident. This investigation includes conducting pneumatic overpressurization tests of scale models to failure and an analysis program to compare analytical predictions with measured behavior. As a part of the research program, a scaled SCV test model of an improved Mark II boiling water reactor (BWR) containment was pressurized to failure during a high pressure test. The model used mixed geometric scaling where the overall size was scaled at a 1:10 ratio and the shell thickness was scaled at a 1:4 ratio. This mixed scaling was used to keep the overall model size reasonable while avoiding the use of very thin steel plates. An elevation view of the model is shown in Fig. 1. The design and the special features of the SCV model are described in detail in Reference 1.

This paper summarizes the posttest analysis effort, which concentrated on three areas where the pretest analysis did not accurately predict the model's behavior. The first area looked into the reasons why the pretest analysis did not accurately predict the pressures at which global yielding occurred in the shell, away from any discontinuities such as the equipment hatch. The second attempted to explain the occurrence of a large tear near the equipment hatch where the pretest analyses predicted relatively low strains. The third area investigated the mechanism(s) that led to a small tear below a weld relief opening in the middle stiffening ring. This detail was not recognized to be a significant strain concentration prior to the test and was not investigated in the pretest analysis.

COMPARISON OF PRETEST ANALYSIS RESULTS TO TEST DATA

The conduct and the results of the high pressure test are summarized in References 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 as shown in Fig. 2. In addition to the large tear, a small meridian tear, approximately 55 mm long, was found next to a vertical weld near a semi-circular weld relief opening in the middle stiffening ring.

The pretest analysis results are documented in detail in Reference 3. The pretest predictions for the behavior of the SCV model overestimated the pressure at which general hoop yielding occurred near the mid-height of the upper conical shell section. This discrepancy between predicted and measured global hoop strains is shown in Fig. 3. The pretest predictions overestimated the pressure at which the global yielding occurred and consistently under-predicted deformations and strains after yielding up to the model failure. This discrepancy is significant enough to preclude simple explanations (e.g. variations in material properties or residual stress effects) and was, therefore, the focus of a significant portion of the posttest analysis effort.

Recognizing the presence of a large discontinuity to act as a significant strain concentration, detailed pretest analyses focused on the equipment hatch and top head as potential failure locations. Of these, the area around the equipment hatch appeared to be the most susceptible to failure. The pretest calculations predicted the failure of the SCV model in the vicinity of the equipment hatch at pressure levels very close to the actual failure pressure, however, at a different location than where the tear occurred. The pretest analysis predicted failure in the SPV490 shell, in an area that was locally thinned area as a result of excessive grinding of the weld joining the two materials. The maximum strains and ultimate tearing occurred below this location, at the weld between the SPV490 plate and the thicker equipment hatch reinforcement plate. The test data indicated that there was no significant strain concentration at the thinned spot. The posttest analysis attempted to explain the mechanism that led to the large tear and explain why the pretest analysis did not predict the development of high strains there.

Finally, the posttest analysis addressed the small tear that occurred at the intersection of a vertical seam weld and the middle stiffening ring.

POSTTEST ANALYSIS RESULTS

Global Yielding

The initial efforts to explain the discrepancy between the pretest analysis and the test data on global yielding focused on the SPV480 material model used in the pretest analysis. Figure 3 indicates that the pressure required to initiate general hoop yielding of the SCV model was overestimated by approximately 30% and, furthermore, the post yield radial deformations (or hoop strains) of the model were consistently larger than the predicted by roughly the same percentage. It was determined that the material model assumed in the pretest analysis overestimated the strength of the material in the low strain (< 2%) region. The pretest analysis put more emphasis on matching the material model at high strains (> 10%) due to the desire to predict the pressure in the model at failure when presumably the strains would reach high levels. The small errors in the material model at the low strains were not thought to be significant when the model is near failure but in retrospect they were enough to contribute to the differences shown in the figure.

Using a material model based on the lower envelope of the coupon tests and with a better match to this data in the low strain regime resulted in global analysis results which were closer to the experimental data, still with some unexplained discrepancies. Figure 4 compares the pretest, posttest and test data for the hoop strain at the middle of the upper conical shell section, where the global hoop strains were largest and global yielding first occurred. Likely explanations for the persistent discrepancy include the loss of the Luder's strain plateau as a result of rolling operations during manufacturing and residual stress effects that are not present in the coupon data. The posttest analysis is detailed in Reference 4.

Local Analysis Results Around The Equipment Hatch

The large tear that terminated the high pressure test occurred in the vessel wall in the heat affected zone (HAZ) of the SPV 490 shell adjacent to the weld with the equipment hatch reinforcement plate. Posttest metallurgical investigations revealed that heat from the welding process caused a localized microstructure alteration and reduced strength in the base metal [5]. An estimate of the reduced strength of the material in the HAZ was made based on hardness measurements. The assumed reduced strength curve for the SPV490 HAZ is plotted in Fig. 5. The posttest analysis included a strip of elements with reduced strength representing the HAZ along the equipment hatch reinforcement plate. The equivalent plastic strain contours from this model, shown in Fig. 6, indicate the highest strains occur at the location of the tear. This differs from the pretest analysis and seems to explain the observed behavior. The presence of this local zone of weaker material may also have acted as a 'structural fuse' relieving local strains in the surrounding material, including the thin spot.

Analysis Of The Small Tear

The pretest analysis did not recognize the potential of the intersection of the vertical seam weld and the middle stiffening ring as a strain concentrator and therefore did not predict the occurrence of the small tear at that location. This detail was modeled in the posttest analysis to determine if the geometric discontinuities associated with the weld relief opening could account for the formation of the small tear. No attempt was made to model the geometry or local material properties of the welds in this analysis. It is speculated that this tear initiated before the development of the large tear and then arrested, possibly due to the confining presence of the contact structure. The small tear was located in the parent SCV shell material next to the vertical weld seam. Unlike the large tear, the HAZ in the SGV480 did not appear to have undergone any phase change or strength reduction. The posttest analysis indicates that the tear was most likely initiated due to a large geometry-induced strain concentration associated with the weld relief opening. A contour plot of the equivalent plastic strains on the interior surface of the SCV model is shown in Fig. 7. The peak strains are concentrated in two areas on either side of the vertical centerline of the opening due to some local bending that occurs in the SCV wall. The tear might also have failed to propagate due to the highly localized effect of the strain concentration that diminishes rapidly with increasing distance from the stiffening ring. The posttest analysis confirms the presence of a large strain concentration coinciding with the location of the small tear.

CONCLUSION

The posttest analysis effort focused on simulating the observed responses of the SCV model and addressing the discrepancies between the pretest analysis results and the test data. This analysis effort suggests a few insights that may improve the future analytical predictive capabilities.

1. Realistic and accurate material models were critical for simulating the structural responses of the SCV model. Most of the material in this model experienced strains less than 2%, so it is important that the stress-strain relationship in the low strain regime is accurately modeled to capture events such as the global yielding. In some cases, the material properties in the as-built configuration, such as the SPV490 HAZ, need to be included in the analysis model because they can change the areas where high strains and subsequently failures can occur. A better understanding of the in-situ material properties and material strain history may also improve the accuracy of the predictions.

2. Local structural details and geometric discontinuities, which are not critical design details, such as the weld relief opening at the middle stiffening ring, can act as significant strain concentrators that can lead to failure, and should be carefully evaluated in predictive exercise. Obviously, the analysis model will not be able to predict the high strain concentrations around these areas if they are not included in the models.

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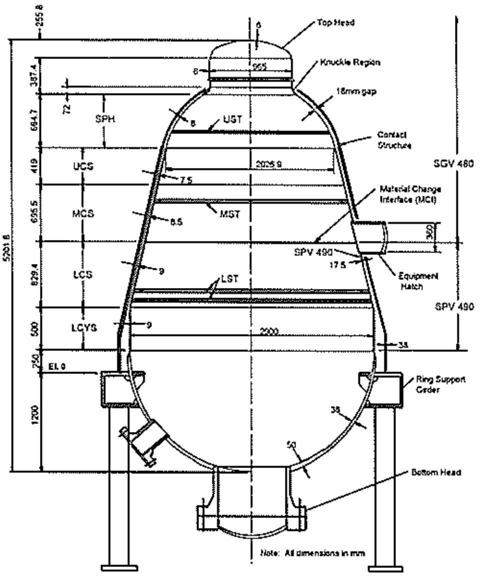

Nomenclature

Location Designation	Description
THD	top head
KNU	knuckle
SPH	spherical shell
UST	upper stiffener
UCS	upper conical shell
MST	middle stiffener
MCS	middle conical shell
MCI	material change interface
LCS	lower conical shell
LST	lower stiffeners
LCYS	lower cylindrical shell

Figure 1. Elevation view of the SCV model

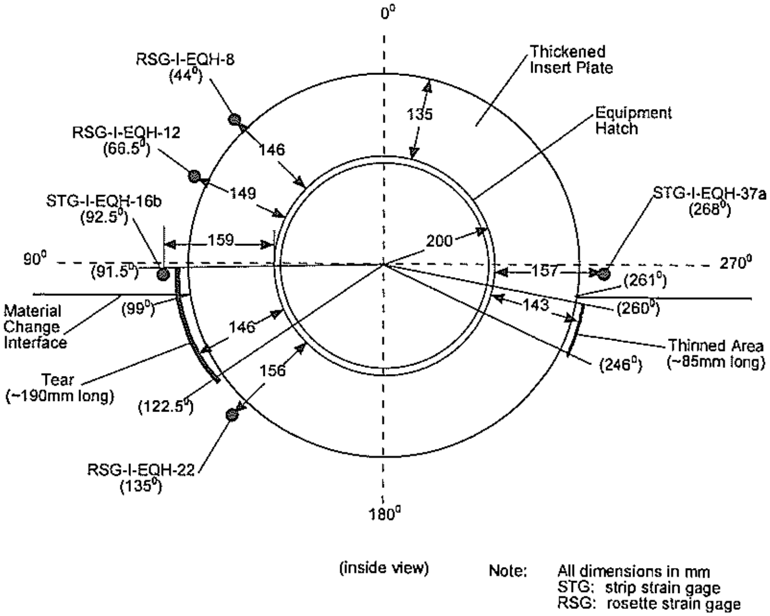

Figure 2. Posttest view of interior elevation of the equipment hatch

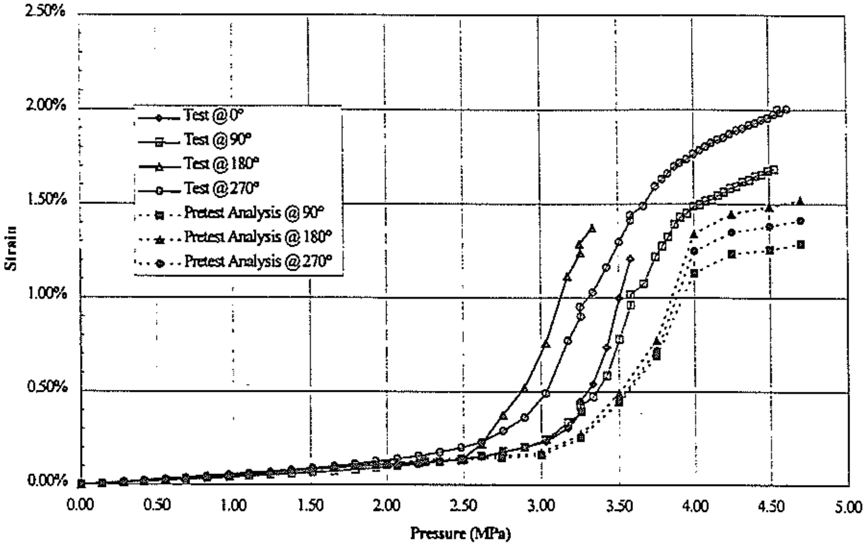

Figure 3. External hoop strains at upper conical shell section

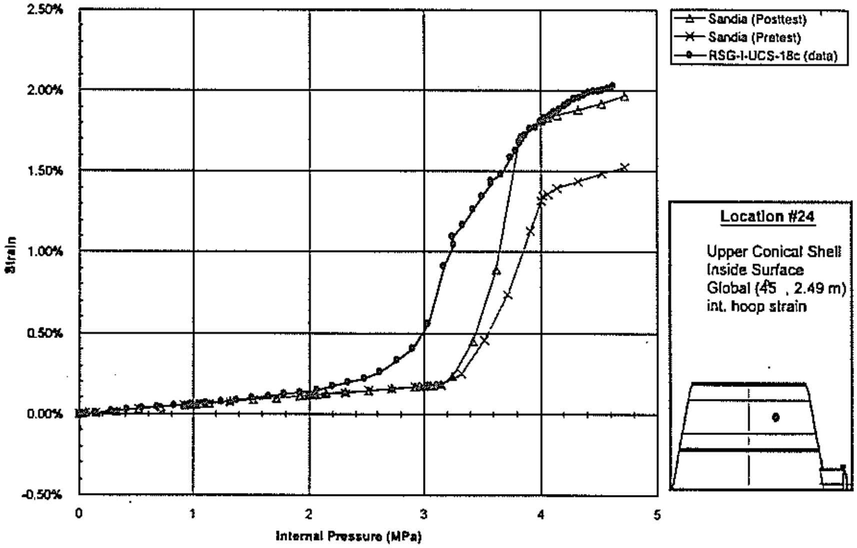

Figure 4. Interior hoop strains at upper conical shell section

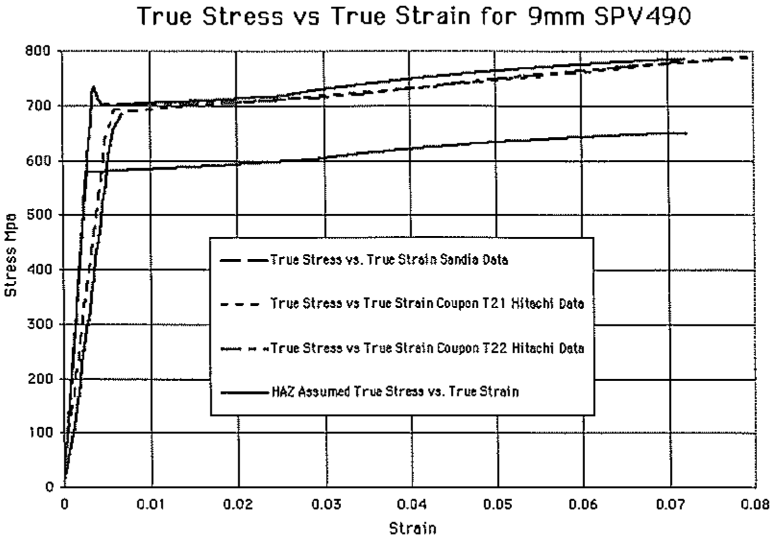

Figure 5. Stress-strain curves for the 9 mm SPV490 steel

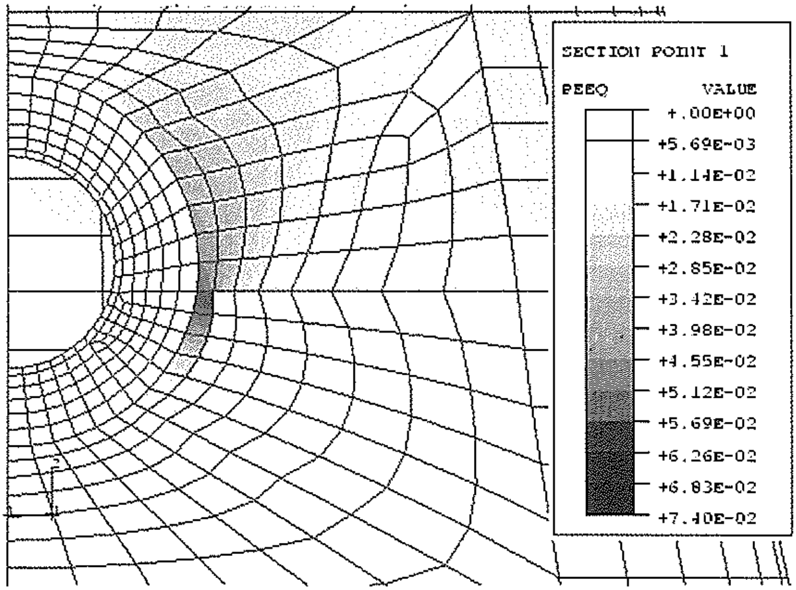

Figure 6. Posttest analysis results of equivalent plastic strain contours around the equipment hatch

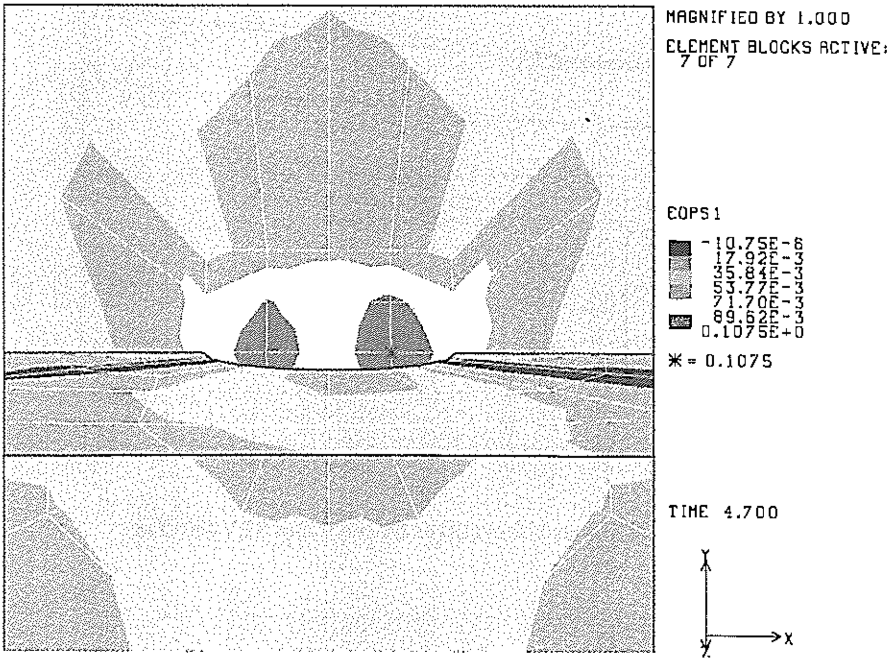

Figure 7. Contours of equivalent plastic strains on interior surface of SCV model adjacent to weld relief opening at middle stiffening ring at a pressure of 4.7 MPa