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Steel Containment Vessel Model Test: Results and Evaluation[1]

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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. A concentric steel contact structure (CS), installed over the SCV model and separated at a nominally uniform distance from it, provided a simplified representation of a reactor shield building in the actual plant. The SCV model and contact structure were instrumented with strain gages and displacement transducers to record the deformation behavior of the SCV model during the high pressure test. This paper summarizes the conduct and the results of the high pressure test and discusses the posttest metallurgical evaluation results on specimens removed from the SCV model.

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. This program consists of testing two models: a SCV model and a prestressed concrete containment vessel (PCCV) model. The program investigates 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 compares analytical predictions to measured behavior.

MODEL DESCRIPTION

The SCV model is representative of the steel containment vessel of an improved Mark II boiling water reactor plants in Japan. The geometric scale is 1:10. Because the model was fabricated of the same materials used in the construction of the actual plants, the scale on the wall thickness was set at 1:4. The portion of the model above the material change interface, which is slightly below the equipment hatch centerline (Fig. 1), was fabricated of SGV480, a mild steel, while the lower portion of the model and the reinforcement plate around the penetration were fabricated from high strength SPV490 steel. The equipment hatch cover and top head were non-functional in the model and were welded shut. The design pressure of the prototype containment is 0.31 MPa, whereas the scaled design pressure for this mixed scale model is 0.78 MPa.

The model was fabricated in Japan and shipped to Sandia National Laboratories, Albuquerque, NM, USA for instrumentation and testing. After the model was delivered to Sandia, a 38 mm thick steel (ASTM SA516 Grade 70) contact structure (CS) was installed over the SCV model prior to testing to represent some features of the reactor shield building in the actual plant. An elevation view of the SCV/CS assembly is shown in Fig. 1. A nominal gap of 18 mm was maintained between the SCV model and the CS. Instrumentation of the model consisted of more than 800 channels of strain gages, displacement transducers, temperature and pressure sensors, and an acoustic emission device, in addition to video monitoring.

TEST OBECTIVES

The objectives of the SCV model test were:

1. to provide experimental data for checking the capabilities of analytical methods to simulate the pressure response of a steel containment well into the inelastic range and after making contact with the CS,
2. to investigate the failure mode(s) of the SCV model, and
3. to provide experimental data useful for the evaluation of actual steel containments.

HIGH PRESSURE TEST

The high pressure test of the SCV model was conducted on December 11-12, 1996, at Sandia National Laboratories. The test itself is detailed in References 1 and 2. After approximately 16.5 hours of continuous, monotonic pressurization using nitrogen gas, the test was terminated when a tear developed at a pressure of 4.66 MPa or roughly six times the design pressure. Rapid venting of the model was observed and the pressurization system, operating at capacity (37 scmm, standard cubic meters per minute), was unable to maintain pressure in the model.

Posttest visual inspection of the interior of the model revealed a large tear, approximately 190 mm long, adjacent to the weld at the edge of the equipment hatch reinforcement plate (Fig. 2). The tear appears to have initiated at a point roughly 30 mm below the material change interface (around 8 o'clock when viewed from the inside) in the high strength SPV490 steel shell, and propagated in both directions along the weld seam before it stopped. Interestingly, while the right side of the equipment hatch did not tear, significant necking was observed at a location symmetric with the tear (Fig. 3).

In addition, a small meridional tear, approximately 55 mm long, was found in a vertical weld (at an azimuth of 201^0) underneath a semi-circular weld relief opening at the middle stiffening ring (Fig. 4). Some evidence suggests that this small tear might have occurred first but did not grow, and the pressurization system was able to compensate for any leakage through this tear.

This tear also had a counterpart at a similar, diametrically opposed detail. While no tear developed at this location, necking in the weld was observed.

After this initial inspection of the interior of the model, the contact structure was removed to allow inspection of the exterior of the model. In addition to the observations noted above, visual inspection revealed evidence of the pattern of contact between the model and the CS in the form of crushed instrumentation lead wires and transfer of mill markings from the interior of the CS. In addition, concentrated crack patterns in the paint indicated that global strains in the higher strength SPV490 shell were concentrated at the vertical weld seams while the uniformly distributed cracks in the SGV480 shell indicate that the hoop strains were fairly uniform.

TEST RESULTS

More than 97% of the instruments survived the high pressure test. The failed gages, which consisted primarily of those on the exterior of the model, were damaged when the model made contact with the CS. The raw strain data were corrected to compensate for temperature variations and cross-axis strains, and the displacement data were corrected to account for any movement of the center support column to which the displacement transducers were anchored. The complete data record is included in the SCV Test Report [2]. A brief summary of the test data follows.

Local Response Adjacent To The Equipment Hatch

An extensive array of single element, strip and rosette strain gages was installed around the equipment hatch to characterize the local strain distribution. Figure 3 shows the locations of a few critical strain gages around the equipment hatch viewed from inside the model. A strip gage (STG-I-EQH-16), adjacent to the upper end of the tear, registered a maximum strain of 4.2%, and the two rosette gages (RSG-I-EQH-12 and -8) above it recorded maximum strains of 3.7% and 2.8%, respectively. The rosette gage (RSG-I-EQH-22) slightly below the lower end of the tear recorded a maximum strain of 1.3%. However, the highest strain reading of 8.7% was recorded by a strip gage (STG-I-EQH-37) at 3 o'clock, just above the material change interface. Figure 5 shows the strain data recorded by these gages around the equipment hatch.

Global Response

The global response of the SCV model was monitored using free-field strain gages and an array of internal displacement transducers that measured the strains and displacements at several elevations along four cardinal azimuths (0°, 90°, 180°, and 270°). Maximum free-field hoop strains ranging from 1.7 to 2.0% were measured at 4.5 MPa at the upper conical shell section (Fig. 6). Hoop strains calculated from the displacement measurements ($\Delta r/r$) were consistent with the strain gage measurements at these locations.

Figure 7 shows the spatial variation of displacements at the cardinal azimuths at 4.5 MPa. It should be noted that the displacement pattern is fairly axisymmetric with the exception of 90°, the azimuth where the equipment hatch is located, where the displacements in the lower conical shell section, below the material change interface, are much larger than at the free-field azimuths (0°, 180°, and 270°). This is of particular interest because this area was actually displaced inward during fabrication of the SCV model and this is the area where the large tear occurred.

Acoustic Emission Data

In addition to the strain and displacement transducers, 24 acoustic emission sensors (18 interior and 6 exterior) were installed on the model. Posttest analysis of the data collected by these sensors indicated two regions with high acoustic emissions during the test. One region located just below the equipment hatch began generating significant acoustic activity at approximately 4.25 MPa. The proximity of this region to the equipment hatch suggests that significant material distress leading to the large tear might have begun at this pressure. Another region had a significant increase in acoustic emissions beginning at 3.75 MPa; however, this region is not very close to the small tear. Therefore it is not clear whether the initiation of the small tear is related to this pressure.

POSTTEST INSPECTION AND EVALUATION

In addition to the posttest visual inspection described above, a detailed metallographic evaluation of the SCV model was conducted to characterize the local failure mechanisms and provide some insight into both the global and local response of the model. This detailed evaluation and analysis is described in Reference 3. Briefly, sections were removed from the model surrounding the tears and areas of necking or other obvious structural distress. Fractographic inspection of the failure surfaces indicated that the tearing mechanism was ductile and did not display any evidence of flaws or other defects that might have acted to initiate failure. It was therefore concluded that the model failure resulted from strains exceeding the material strength, and it is possible to characterize failure based on the material properties of the steel.

After this inspection, smaller sections were removed from the model and polished cross-sections normal to the model surface were examined using a scanning electron microscope to characterize the grain structure. Hardness tests were also performed on these polished specimens to look for variations in material properties. A section through the major tear surrounding the equipment hatch is shown in Fig. 8. The results of these inspections revealed changes in the grain structure of the SPV490 material in the heat affected zone (HAZ) surrounding the reinforcement plate weld and a significant reduction in the hardness of the HAZ and adjacent parent material. Using well-established relationships between hardness and tensile strength, these results indicate a significant reduction in tensile strength along with a corresponding, though less well-defined, reduction in the yield strength of the material. These results indicate that one possible explanation for the strain patterns observed around the equipment hatch and in the weld seams of the SPV490 shell may be due to this localized microstructural alteration and reduced hardness and strength in the HAZ of the SPV490 alloy plate.

CONCLUSION

The high pressure test of the SCV model conducted at Sandia National Laboratories on December 11-12, 1996 was considered a success with regard to the specified test objectives.

1. The test provided experimental data for checking the capabilities of analytical methods well into the inelastic range of the model. While it appears that some generalized contact was occurring at the time of the failure, it is not clear that the data are adequate to confirm the validity of contact algorithms in the analysis codes.

2. The test confirmed the critical nature of discontinuities, such as penetrations, as potential failure mechanisms. The test also identified the potential significance of local changes in material properties due to welding and local fabrication details on potential failure modes. The measured global strains at failure of 2% are also consistent with previous tests of steel containment vessel models [4].
3. The test results should provide useful information for the evaluation of prototypical containment structures by focusing attention on critical details and analysis methodologies.

REFERENCES

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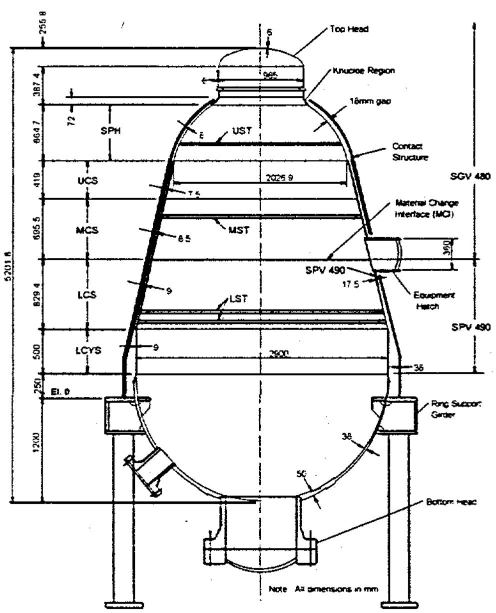


Nomenclature

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/CS assembly

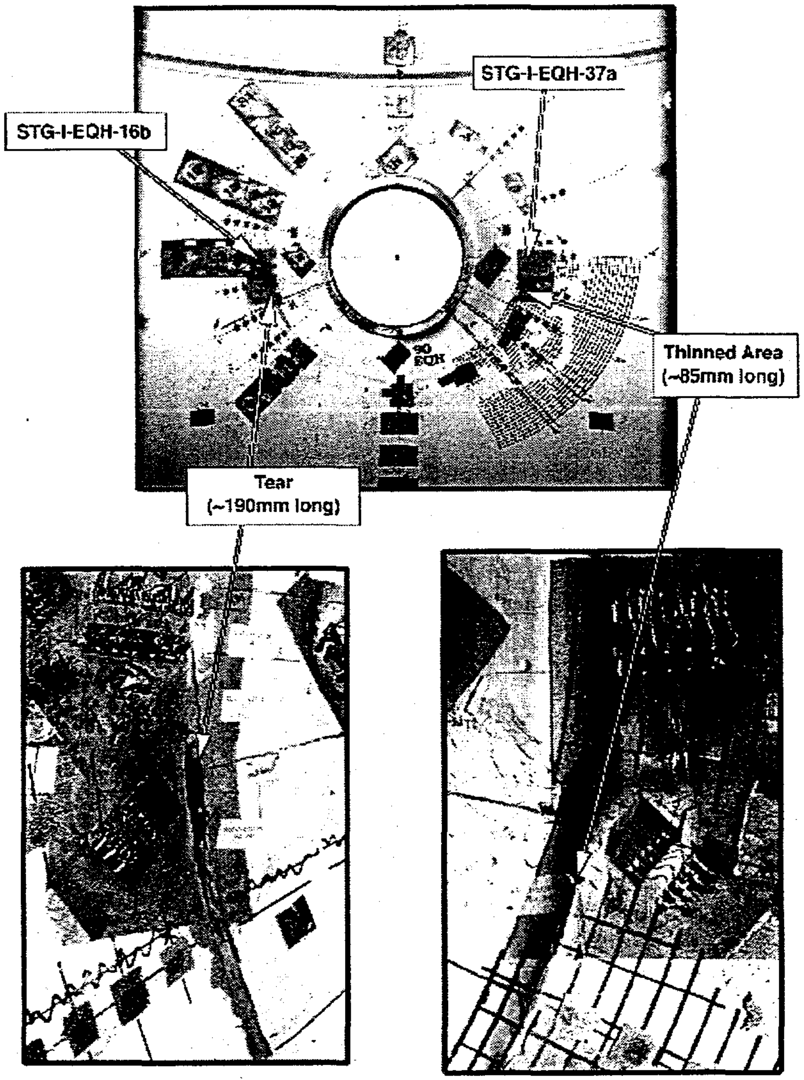


Figure 2. Posttest interior view of the equipment hatch

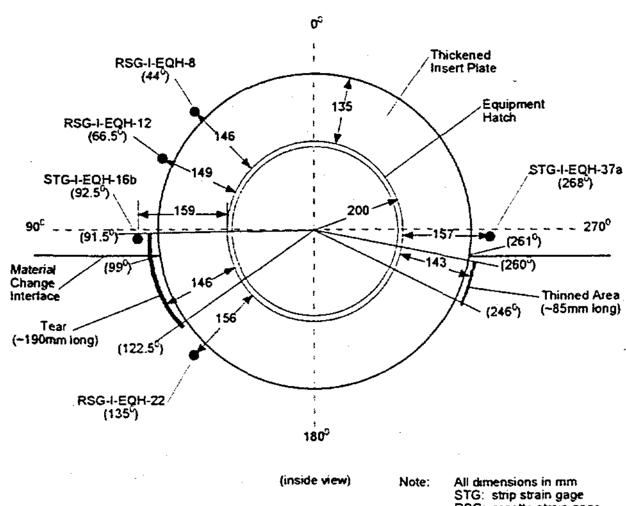
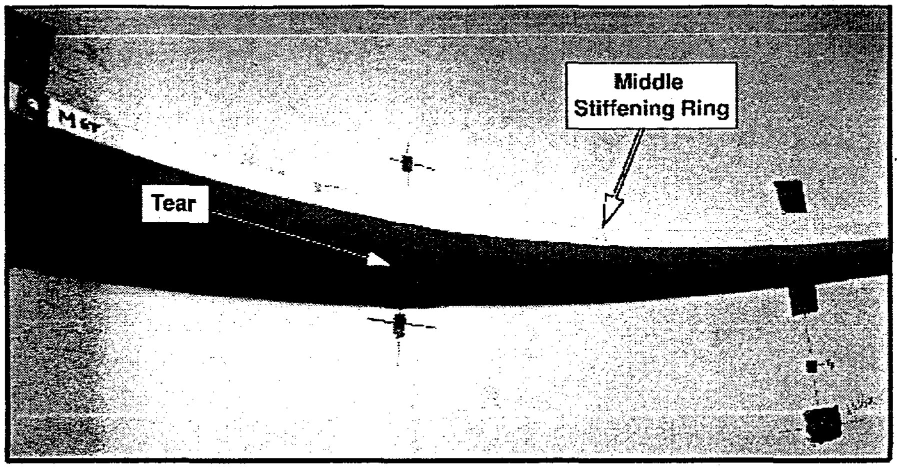


Figure 3. Interior elevation of the equipment hatch



Above **Below**

Figure 4. Posttest view of tear at middle stiffening ring

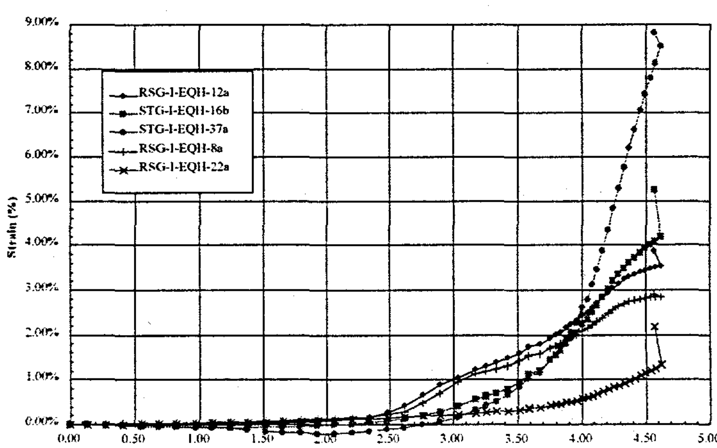


Figure 5. Hoop strains around equipment hatch

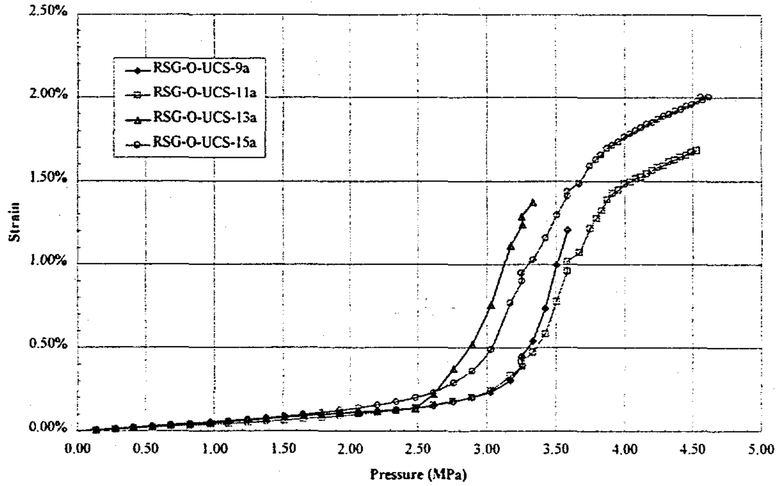


Figure 6. Hoop strains at upper conical shell section, El. 2536 mm

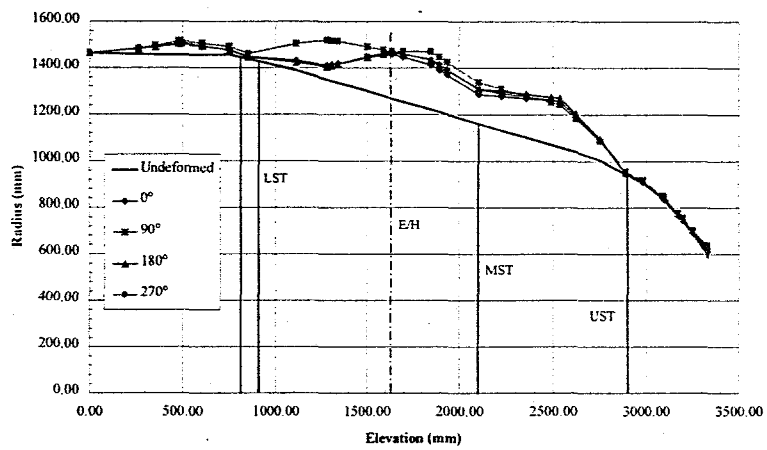


Figure 7. Displacement contours (x10) @ 4.5 MPa

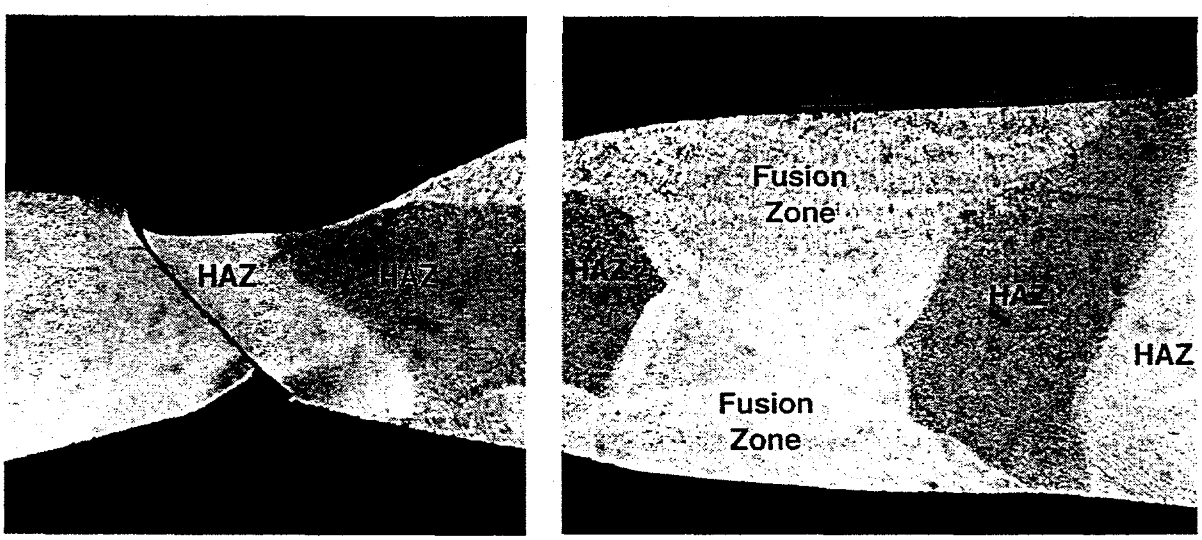


Figure 8. Cross-section through large tear at equipment hatch