ACOUSTIC EMISSION MONITORING OF A HIGH PRESSURE TEST OF A STEEL REACTOR CONTAINMENT VESSEL MODEL

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Abstract

A mixed-scale steel model of a boiling water reactor (BWR) containment vessel was pressurized to failure in December 1996. The instrumentation included an acoustic emission (AE) source location system in addition to strain and displacement gauges. Post-test analysis showed general agreement between the location of AE sources and the regions of distortion and failure. The analysis also gives the pressure dependence of the different emitting regions. The general location plot of the emission shows that much of the emission was located around the stiffening ring on the conical shell section.

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1. Introduction

A program to investigate the response of nuclear containment structures to pressure loading beyond their design loads is being conducted at Sandia National Laboratories. This program is sponsored by the Nuclear Power Engineering Corporation of Japan and the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research. In the test described in this report, a mixed-scale model representative of a steel containment vessel (SCV) for an Improved Mark II Boiling Water Reactor was used. The geometric scale is 1:10. The same materials were used for the model as for the actual plant and the scaling on the wall thickness was set at 1:4. A steel contact structure was placed over the SCV model to simulate some of the features of the reactor shield building in an actual plant.

The instrumentation for the test included over 800 data channels consisting of strain gauges, displacements sensors, temperature and pressure gauges and video monitoring. It also included an acoustic emission (AE) source location system operating independently of the other data channels. This system monitored the entire surface of the SCV above the ring support girder. The purpose of the acoustic monitoring was to detect and approximately locate emission sources that occurred in the shell of the vessel during the pressure test in real time and then to try to gain additional information by a more sophisticated post test analysis. This real time monitoring could not give accurate locations because the available commercial real time programs were not designed to accommodate the complex geometry of the model.
2. Acoustic Emission Testing

Acoustic emissions are acoustic waves produced by materials subjected to a stress. (1, 2) There are many mechanisms, which can generate such waves but almost all involve a relatively rapid rearrangement of the internal structure of the material on a microscopic level. In a large structure, such as the SCV, the important sources of emission will be crack initiation and flaw growth. Other sources, which may be seen, are spallation or fracture of corrosion particles, rubbing of adjacent surfaces due to expansion of the structure with increased stress and, in the case of pressure vessels, gas flow. The emissions generated by these sources travel as bulk acoustic waves until they reach the surface of the structure where they change acoustic mode and become surface or plate waves. These waves will propagate along the surface of the structure where they can be detected by piezoelectric sensors. For structures with low to moderate acoustic attenuation, an emission of moderate amplitude can excite most of the sensors on the structure. This enables an AE test to monitor an entire structure with a reasonable number of sensors. When the structure is stressed, only flaws, which are affected by the applied stress field will generate emission. Flaws in regions which are not stressed or do not grow under the applied stress will not generate emission. The absence of AE during the stressing of a structure is the sign of a sound structure. Thus an AE test is a negative test, which puts stringent requirements on the knowledge that the AE system is functioning normally.

Acoustic emissions are unfortunately not simple waves. They are produced by discrete events in the material and are transient, not continuous, waves. By the time that they reach a sensor, they have become a combination of different acoustic propagation modes and may contain both bulk and surface bounded modes as well as reflected waves from different surfaces and discontinuities in the structure. The acoustic velocities differ for different acoustic modes and some of the bounded modes have frequency dependent velocities. To add to the complexity, the events that produce AE occur semi-randomly in time and stress level. One is never able to predict the exact time (or location) at which an event will occur. This is in contrast to ultrasonic testing where a signal with a known waveform is introduced into a known location on the structure at a known time. While there is no physical difference between an ultrasonic and an AE wave, the differences in generation of the waves result in quite different methods of analysis.

Growing cracks in a material produce readily detectable AE. However, other types of flaws may not. Any emissions produced by creep are extremely low amplitude and appear to be usually below the equipment noise level. Ductile tearing appears to produce some emission but much less and of lower amplitude than does a crack. On the other hand, a flake of rust spalling off a surface can produce very large amplitude emission. In testing pressurized vessels, the most prevalent source of extraneous acoustic noise is flowing gas, either from pressurizing the vessel or from a leak. The one thing working to the testers advantage is that the gas flow noise seems to be strongly dependent upon the internal pressure in the vessel. In the SCV, flow noise dropped below the sensitivity of the system (the threshold was set at 175 microvolts out of the sensor) at about an internal pressure of 0.35 MPa (50 psi).

A single emission, either detected by one sensor or detected by enough sensors to have its source located, is mainly an indication that something happened. A growing flaw will generate a
series of emissions as the stress level increases. Unstable crack growth generates a rapidly increasing number of emissions. A steady rate of emissions from one region generally indicates stable flaw growth. A region where the emissions stop as the stress level increases either has arrested flaw growth or the emissions are not from a stress driven flaw. Because of the random occurrence of acoustic emissions, a small gap in the emissions as the stress increases means nothing but a total cessation of emissions indicates a source, which is not detrimental to the integrity of the structure.

Several terms unique to AE testing will be used in this paper and will be defined here. When an acoustic wave passes underneath a sensor and the amplitude of the wave detected by the sensor exceeds a preset threshold, the system is triggered and records the time and other parameters of the wave. This is called a hit. When several sensors are triggered by the same acoustic wave at times consistent with travel from a single point on the structure, the data set is called an event. If the time data from an event is used to calculate a location on the structure and the calculated location is consistent with acoustic travel times to at least the first six sensors hit, the event is called a located event. The term event is also used to describe the physical occurrence of some phenomena in the structure, which generates the acoustic wave. A data set event can be generated by waves from several events in the structure and thus not result in a located event.

3. Experimental Details

An elevation drawing of the SCV model and contact structure is given in Fig. 1. The design pressure of the prototype containment vessel is 0.31 MPa (45 psig) while the design pressure for the SCV model is 0.78 MPa (113 psig). The model consists of sections with different geometries and wall thicknesses. The first section above the ring support girder is a short cylindrical shell. This is joined to a section of a conical shell. Attached to the conical shell is a section of a spherical shell, which is joined by the knuckle section to another cylindrical shell. A thick steel ring welded to this cylindrical shell represents the flange to which the top head is bolted on the actual vessel. The top head is a cylinder with a flattened sphere as a top. Several stiffener rings representative of the actual vessel are on the inside of the SCV model. A representation of an equipment hatch is welded to the conical shell section. The thickness of the structure varies at different heights. A typical thickness in the conical section is 9.6 mm. The bell-shaped steel contact structure installed over the model was made of 38 mm thick steel. The nominal gap between the contact structure and the SCV was 18 mm and the SCV was expected to close this gap and come into contact with the contact structure around 3.5 MPa.

The acoustic emission (AE) system used was a 24 channel Physical Acoustics Corp. (PAC) Spartan AT source location system. The sensors were PAC R151 sensors, which have a maximum sensitivity around 150 kHz. These sensors feature an integral 40 dB preamplifier powered from the main AE system through the signal cable. Twenty-four sensors were applied to the model with magnetic hold-downs and acoustically coupled with silicone vacuum grease. The paint on the model surface was removed and the metal ground smooth before the sensor was mounted. Locations of the sensors are given in Table 1. The "vertical distances" listed are the measured distances along the interior or exterior surface of the vessel, starting from the ring
support girder. Sensors 1 through 16 and 22 and 23 were mounted inside the model because the contact structure prevented their placement on the outside. A schematic of the sensor locations is given in Fig. 2. The cables to these sensors ran through pressure tight coaxial feed throughs located in the bottom head. Sensors 17 through 21 were mounted on the outside of the model above the contact structure. Sensor 24 was mounted in the middle of the equipment hatch on the outside. The computer for the AE system was located in the control center and connected to the system electronics by approximately 900 m of fiber optic cable.

The Spartan system collects a full set of analog AE parameters. A test time for the detection of each AE signal is assigned to the data set. The accuracy of the time measurement is 0.25 μs. The pressure inside the model was also recorded on each data set. Each set was immediately written to the hard disk before any analysis was performed. This allows the use of post-test analysis programs, which are completely independent of any programs built into the AE system. The maximum data collection rate is around 2000 hits/s. Several built-in location programs for
Table 1  Sensor Locations

<table>
<thead>
<tr>
<th>Sensor</th>
<th>&quot;Vertical&quot; Distance - mm</th>
<th>Azimuth Angle - Degrees</th>
<th>Sensor</th>
<th>&quot;Vertical&quot; Distance - mm</th>
<th>Azimuth Angle - Degrees</th>
</tr>
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<td>515</td>
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<td>15</td>
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<td>510</td>
<td>274</td>
<td>16</td>
<td>3400</td>
<td>315</td>
</tr>
<tr>
<td>5</td>
<td>1650</td>
<td>41</td>
<td>17 *</td>
<td>3805</td>
<td>351</td>
</tr>
<tr>
<td>6</td>
<td>1670</td>
<td>131</td>
<td>18 *</td>
<td>3805</td>
<td>90</td>
</tr>
<tr>
<td>7</td>
<td>1670</td>
<td>221</td>
<td>19 *</td>
<td>3805</td>
<td>171</td>
</tr>
<tr>
<td>8</td>
<td>1670</td>
<td>311</td>
<td>20 *</td>
<td>3805</td>
<td>270</td>
</tr>
<tr>
<td>9</td>
<td>2690</td>
<td>356</td>
<td>21 *</td>
<td>37 mm from top head center</td>
<td>225</td>
</tr>
<tr>
<td>10</td>
<td>2690</td>
<td>96</td>
<td>22</td>
<td>1210</td>
<td>67</td>
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<td>1215</td>
<td>113</td>
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<tr>
<td>12</td>
<td>2665</td>
<td>276</td>
<td>24 *</td>
<td>center of eq. hatch</td>
<td></td>
</tr>
</tbody>
</table>

*  located on outside of model
different geometries are contained within the system to analyze data in real time. None of these programs included a conic section, which is the underlying geometry of the SCV model. The best approximation for real time location was to divide the representation of the model into two parts, a cylinder with the average diameter of the cylindrical, conic and spherical sections and a separate short cylinder with a spherical cap to represent the top head. These two graphs resulting from this representation showed approximate source locations and were capable of indicating a tight clustering of located events during the test. The major problem with this set up was that the low acoustic attenuation allowed a large AE event to excite most of the sensors on the model. The computer considered the bottom and top arrays to be completely separate and therefore often plotted two locations, one on each graph, for a single event.

When the sensors were installed, each sensor was tested by breaking a 0.5-mm-diameter lead near the sensor on the surface of the model. The output waveforms from the sensors were digitally recorded and the few sensors, which had low output amplitude, were re-coupled or had the surface under them reground until all sensors had approximately equal sensitivity. After the model was closed, lead breaks on the outer surface were made to insure that all sensors were working and that the locations on the real time maps were reasonably accurate. More checks were made on the sensors and the programs during the low-pressure tests.

The SCV model was pressurized with nitrogen gas. This gas was generated by evaporating liquid nitrogen and heating the gas to room temperature. Gas was introduced into the model through a pipe into the bottom head. The pressurization schedule for the high-pressure test called for the gas pressure inside the vessel to be raised in steps with pressure holds between the steps. The holds were to last for approximately 15 minutes each. The pressure increment started at 0.137 MPa (20 psi) and decreased in size toward the end of the test. Each pressure step took

![Graph](image)

**Fig. 3** Pressure as a function of time in the SCV.
about a minute and a half to complete. There was always a small decrease in the pressure during the holding period due to cooling of the gas. This pressurization schedule was continued with a few longer holds until the SCV model failed.

4. Real Time Tests

One of the preliminary low-pressure tests of the SCV model was conducted with the AE system operating. In this test the model was subjected to the maximum pressure, which it saw before the high-pressure test, 1.26 MPa (183 psig). From the start of the pressurization, large amounts of AE were produced by the flow noise from the pressurizing gas. The noise did not diminish until after an extended hold at 0.21 MPa (30 psig). When the pressurization resumed, the noise level rapidly decreased. During the rest of the pressurization, only seven located events were seen by the system. These occurred between 0.78 MPa (113 psig) and 1.26 MPa. There was no clustering of the event sources, and all were located in different triangles formed by the three nearest sensors to the source.

Fig. 4 Total event locations seen in the real time test.
The pressurization curve for the high-pressure test is shown in Fig. 3. During the initial gas flow, there was again excessive AE. The gas flow noise stopped at about 0.35 MPa and the first located emission was seen at 0.44 MPa (64 psi). Figure 4 shows the events located by the bottom and the top sensor arrays during the test. There are some areas that appear suspicious but nothing that would indicate imminent failure. Figure 5 shows curves of the total signal strength from the located events versus the pressure for the two arrays. There is an apparent change in the slope of the curves around 3.5 MPa (508 psi) but again nothing that suggested that the vessel was about to fail. There was certainly an increase in the AE rate above 3.5 MPa and this was communicated to the test director but nothing appeared serious right up to the appearance of a major leak at 4.62 MPa (672 psi). After the leak started, no more located events were seen. However, the leak produced large amounts of AE. Figure 6 is a graph of the total signal strength from all of the hits during the test as a function of pressure. The fill noise during the start of pressurization and the leak noise at the end of the test are quite obvious. These two regimes generated most of the AE seen during the test. The test was terminated when the leak prevented further increases in the pressure in the vessel. Post-test examination of the interior showed a tear in the wall near the equipment hatch.

![Graph showing total signal strength vs. pressure for top and bottom sensor arrays.](image)
The AE system did detect activity from the area near this tear. It can be seen in Fig. 4 as the group of events in the center of the triangle formed by sensors 2, 5 and 6. However, this activity did not appear any worse than several other areas seen in Fig. 4. Metallographic examination of the tear showed that it was primarily ductile in nature. Ductile tears produce fewer and lower amplitude emissions than do growing cracks. The real time AE monitoring did detect an increase in the damage rate in the vessel, located the region that failed and immediately indicated a serious leak. While it did not predict the failure of the vessel it should be noted that catastrophic failure did not occur.

Fig. 6 Total hit signal strength for entire test showing gas inflow noise and leak noise.

5. Post-Test Analysis

Post-test analysis of the AE data from this test was done for several reasons. An accurate calculation of the locations of the AE sources allows the use of a clustering algorithm to determine locations where serious damage might be occurring. It also allows a determination of the pressure dependence of the AE from each one of the clusters. For possible future tests, it tells whether the highly approximate location set up used in real time is sufficiently valid to be worth using again or whether the locations calculated in real time from such a distorted set up are meaningless.

The first problem to be faced in the post-test analysis was the determination of which collections of hits constituted an event. The data file consisted of a sequence of hits ordered according to their time of occurrence. The question is, how does one take this data set and decide which hits belong to an event. An event definition time must be chosen. This is the time interval between the detection of the first and the last hit in an event. It will depend, in part, upon the attenuation of the material in the structure. The low attenuation of the steel in the SCV model allowed a moderate amplitude emission to travel over the whole surface of the model, exciting almost every sensor. For a flexural wave, an emission would take about 1.8 ms to travel the distance between a
sensor on the bottom on one side of the model to one on the top on the other. An event defini-
tion time much shorter than this would define multiple events where only one actually occurred and a time much longer could combine several real events into one. The most important point in determining an event is to find the first sensor hit. This sensor defines the starting time for the event. Missing the first sensor makes the calculated location for that event almost meaningless as there is an unknown interval, which must be added to each travel time. For the SCV model, an event definition time of 2.0 ms was chosen and a manual search of the data and the selected hits for each event showed this to be a reasonable value.

Location on a plane requires that a minimum of three sensors be hit. The three unknowns are the initial time of the event and the x and y coordinates of the source. For accurate data, this is all that is needed. Unfortunately, in the real world, AE data is very seldom highly accurate. Attenuation and dispersion of the waves in the plate cause the waveform to vary at different sensors on a uniform plate. Different acoustic modes travel at quite different velocities. The mode, which is detected, depends in part on the geometry of the crack and in part of the geometry of path that the acoustic wave takes to the detecting sensor. Reflections from discontinuities (including welds) in the plate and surface attachments to the plate can greatly affect the waveform for some acoustic paths. For these reasons, a fixed trigger level (which is used in this and most AE source location systems) will produce uncertainties in the measured time of arrival at the sensor. Two methods of alleviating some of these uncertainties were used in this analysis. First an over determined data set was used when possible. The arrival times at the first six sensors on the cone to be excited comprised the event data set. If six sensors were not hit, data from as few as three was used. A non-linear least squares fitting program was used to calculate the most probable location of the source. This program also calculated a goodness of fit parameter (one minus the ratio of the average deviation between the calculated and the measured times over the average standard deviation of the time data) for the calculated answer. Data sets which had a goodness of fit parameter of less than 0.85 and those whose calculated location was more than 1400 mm away from the center of the triangle formed by the first three sensors hit were not included in the set of located events.

The second method of reducing the uncertainty in the locations was to use a simple procedure developed by Ge and Kaiser (3) to determine what acoustic velocity should be used for the travel time from the source to each sensor hit. The dispersion curves for steel plates at frequencies between 120 and 150 kHz show an extensional wave velocity around 5.2 x 10^6 mm/µs and a flexural wave velocity of 3.3 x 10^6 mm/µs. Similar wave speeds were roughly measured in the vessel so these figures were used in the post-test analysis. To partially determine whether a sensor in an event data set was triggered by an extensional wave or a flexural wave, the distances between the first and subsequent sensors hit were calculated. Ge showed that if the measured time difference between the excitation of two sensors was greater than the time it would take for an extensional wave to travel between the two sensors, the wave from the source could not be traveling at the extensional velocity. If the time difference is greater than the time it would take for a flexural wave to travel between the two sensors, in this experiment, the system probably triggered on a waveform that was distorted by dispersion, scattering or multiple paths. The following procedure was thus used. Initially an extensional velocity was assumed for the waves to all sensors. The sensors, which could not have had an extensional velocity, were assigned the flexural veloc-
ity. Those whose arrival times were later than 10% greater than the flexural velocity would have allowed were dropped from the data set. If the calculation with these velocities did not have a goodness of fit parameter that exceeded 0.85, a flexural velocity was assumed for all sensors. If the parameter still did not exceed 0.85 with all flexural velocities, that event was not included in the set of located events.

The SCV model is primarily a thin metal shell. The shell thickness can be considered only as contributing a small uncertainty in the time measurements. To simplify the problem to location on a plane, the conical section was theoretically cut down the zero-degree longitude and the surface unrolled onto a plane. This can be done without distortion of a conical surface. The cylindrical surface below the cone was also treated as lying on the same plane as the cone. The distortion produced by this procedure was not thought to have a significant effect on the location of the events on the cylindrical surface. The intention had been to treat spherical surface above the conical section as a cone, if possible or a slice of a sphere if necessary. The head of the vessel was to be treated as a cylinder with a hemisphere on top of it. These latter two calculations proved unnecessary because of the small number of widely scattered events originating on these surfaces. The events on these surfaces were calculated using a planar approximation of a surface within the triangle formed by the three first hit sensors.

A total of 446 events out of 650 data sets on the conical section met all the criteria and were kept in the set of located events. Many of the discarded events were either of very low amplitude or appeared to have another event mixed in with them. The accuracy of the location calculations were approximately plus or minus 50 mm. This uncertainty is produced primarily by the uncertainties in the triggering points on the individual waveforms. The uncertainty due to a finite thickness of the shell is 10 mm or less.

In order to determine what AE was produced by possibly serious damage and what was of a more benign nature, a cluster-seeking program was written. A cluster was defined as a collection of located events located within a confined area. The definition of a cluster is quite arbitrary. A crude estimate of the area of the conical plus cylindrical sections divided by the number of located events gave a rough density of one event per 7000 mm$^2$. It was decided that a cluster should have at least ten times that density. Also with the uncertainty in the location accuracy, the smallest area that made much sense was a circle with a 100 mm radius. The criteria for the existence of a cluster was then set as four or more events within a circle of radius 100 mm (an 8-inch diameter circle). As each point was calculated, the program checked to see if it were within 100 millimeters of any previous point. Two points within this distance form the nucleus of a cluster. The center of the cluster is then calculated. Each succeeding point is checked to see if it is either within 100 mm of a cluster center or if it starts another cluster with another solitary point. If it is within the 100 mm, it is added to the cluster and a new center calculated. A growing flaw will show a steady or increasing emission rate as the stress field is increased. A source, which does not emit with increasing stress field, is either a flaw that has arrested or an event that does not affect the structures integrity, such as a corrosion particle flaking off. Therefore, if the cluster did not contain at least one event at a pressure greater than 90% of the failure pressure, it was defined as not a significant cluster.
Fig. 7 Map of the flattened conical section and cylindrical skirt.

Figure 7 shows the locations of all located events and the significant clusters superimposed over the events. It is a map of the flattened conical section with the cylindrical skirt attached. Included are the positions of the sensors, the two visible tears in the SCV model and the stiffener ring. A group of overlapping clusters is counted as one cluster and all clusters are identified with a letter. In cluster D, the two clusters do not touch but both appear associated with the crack lying between them.

In Fig. 5, the total signal strength was shown as a function of pressure for the entire test. Figure 8 shows the total signal strength as a function of pressures for clusters A, B, C and D. These were the largest clusters, and all are graphed on the same scale. The curves for clusters E, F and G were very similar to that for D. The curve for H had about half the envelope strength of D and the curves for I and J were each composed of four very small events around 4.5 MPa. These curves show the severity (from an AE standpoint) of the clusters and allow one to determine at what pressure flaw growth started for each. Finally, the number of located events in each 50 mm high slice of the conical section and skirt is shown Fig. 9. The peak of this curve corresponds very well to the position of the strengthening ring.

The nine events located on the spherical slice were well scattered. No two events were close enough to form a cluster under the definition given above. Only one occurred above 4.4 MPa.
The 21 events detected from the top head were scattered over seven of the triangles formed by the sensors on the head. Three triangles had four or more events in them. In two of these triangles, the events were well scattered, both in space and pressure. In the third triangle, formed by sensors 13-17-18, there were four events located within a cluster radius of 20 mm (essentially all at the same point to the accuracy of this calculation). However, the highest-pressure event in this cluster occurred at 3.65 MPa (530 psig). So the cluster was not caused by any structural problems.

6. Discussion

The only significant AE occurred in the conical section and to a lesser extent, the cylindrical skirt. The top cap, the spherical slice, the knuckle region and their attendant welds gave no signs of any serious problem. Examination of Fig. 7 shows that most of the clustering of the emission sources borders the location of the stiffening ring, about two thirds of the way up the conical

Fig. 8 Total signal strength as a function of pressure.
Fig. 9 Distribution of located events as a function of "vertical distance" above the ring support girder.

Figure 9 shows that the highest density for all located events was also at the locus of the stiffening ring. The only serious cluster not located near this ring was A which was associated with the flaw that terminated the test. Clusters I and J are each comprised of four events, with all events in each having a very low signal strength. They are not considered of any significance, at least below the failure pressure.

The large tear in the SCV model occurred just above cluster A on Fig. 7. It was located in an area near the equipment hatch. This region had been ground smooth and was somewhat thinner than the rest of the conical shell. The tear was roughly 250 mm in length. Most of the events in this cluster are located below the locus of the tear. It is thought that they were produced by the tear and that this offset was caused by acoustic path distortions produced both by the hatch opening and by the tear itself. The plot of the signal strength as a function of pressure for cluster A (seen in Fig. 8) shows several well-spaced events below 4.0 MPa but most of the events appear above 4.2 MPa. Emission continued until the test was stopped. The events which appeared at lower pressure may have been produced by minor flaws in the weld joining the hatch to the conical section. It should be noted in the graph for cluster A in Fig. 8 that there is no emission immediately prior to the leak. The last located event in cluster A occurred 3 minutes and 36 seconds before the acoustic leak signal was seen. This shows clearly that the opening, which stopped the test, was a ductile tear and not a propagating crack.
The cluster at B, whose activity plot is also shown in Fig. 8, extends down the model from the stiffening ring. No flaw was visible on the structure in this region. However, the paint on the outside of the model (which had been hidden by the contact structure) showed many vertical parallel cracks, Fig. 10. Laboratory tests showed that fracture of a paint chip from the vessel could produce very large AE signals. Unfortunately, visual examination of the paint cannot determine whether the cracks occurred by paint fracture or by slow tearing. There were at least two other areas on the vessel, which had similar paint cracks but they did not produce a strong cluster at high pressures. The best interpretation would appear to be that the upper emission locations were associated with the stiffener ring with at least some of the lower emissions produced by paint cracks.

The clusters at B, C, D, E, F, G and H all appear to be associated with the stiffening ring. This ring was welded to the inside of the conical section shell. The ring was a complete circle, but the weld was omitted and two small holes cut on the inside portion of the ring 180 degrees apart. One of these holes was situated at the position of the tear in cluster D. The metal of the conical shell stretched and tore underneath the ring where the weld had been omitted. The other hole was located just at the end of cluster C. Here the metal of the shell deformed but did not tear. Metallographic sections from around the tear at D did not show any cracking. However, strain gauge data from the test showed large deformations in the conical shell around the stiffening ring. It appeared that the ring prevented the expansion of the shell in its immediate vicinity but had no effect on the expansion of the rest of the shell. This caused a distortion of the shell in the form of a trough along the ring. The small gaps in the weld, a few centimeters wide, allowed the unrestrained shell in that region to try to follow the rest of the shell, resulting in ductile deformation and tearing. It is interesting to note that the cluster at D is actually two clusters with a gap.
in the middle, exactly at the position of the ductile tear. This may be a coincidence but varying fitting parameters in the location program never placed any emission locations just at the tear. This is consistent with the tear being ductile and not a propagating crack.

The question then becomes what produced the AE in the vicinity of the stiffening ring. There was elastic distortion of the metal shell at the ring during the test but elastic distortion does not produce AE. The answer came when sections of the ring were cut out. The ring was welded to the shell from the top and bottom. However there was not full penetration of these welds, leaving a void between the shell and ring between the welds. This void varied from the shell and ring being in actual contact to gap of a millimeter or more. This type of weld geometry leaves portions of the weld-base metal intersection with very sharp intersection angles. These can act as starter points for micro cracking. In addition, any weld flux trapped in this void can crack with small changes in the void geometry. Both micro-cracks and flux cracking produce AE. The best explanation for the concentration of the located events around the stiffener ring is that they were produced by micro cracking in the weld root driven by the elastic distortion of the shell produced by the ring.

It had been expected that when the contact structure and the conical shell touched, AE would be produced. Such emission would be generated by the two surfaces sliding against each other. This emission would be characterized very long events. No such events or hits were seen. However, examination of the contact regions showed that wiring running between the two structures was flattened. This wiring, and to a lesser extent, the thick paint on the outside if the conical shell would tend to prevent direct contact of the metal structures. The only evidence of the effect of the contact structure is seen in Fig. 8, the curve for cluster C. Here, while there is emission all the way to the failure pressure, the rate drops off suddenly at 4.0 MPa. This could be explained by the contact structure reducing the amount of elastic expansion in the conical shell in this region above 4.0 MPa.

7. Conclusions

The real time AE monitoring of the high-pressure test of the SCV model showed that damage in the model was increasing above 3.5 MPa. It also located the general area where the tear occurred which stopped the pressurization. Furthermore, it showed a large gas leak at 4.62 MPa. It did not predict failure of the vessel but catastrophic failure of the vessel did not occur. The lack of a real time program, which could be adapted to the exact geometry of the SCV model prevented accurate location of the AE sources but gave enough information to indicate the general condition of the vessel throughout the test.

The post-test AE analysis showed two regions on the SCV model, which suffered damage during the high-pressure test. Cluster A is located approximately at the site of the ductile tear that ended the test. The AE data in Fig. 8 indicates that major damage occurred between 4.20 and 4.30 MPa. However, Fig. 6 shows that the large gas leak did not start until 4.62 MPa. This leads to the conclusion that some cracking in the metal occurred from 4.2 to 4.3 MPa at this site but that ductile tearing did not open the large leak path until 4.62 MPa. The other damaged region was the area on the conical shell lying along the strengthening ring. This includes clusters B
through H. The lack of penetration of the upper and lower welds attaching this ring to the conical shell created both a void between the ring and the shell and many possible crack initiation sites. AE activity curves for the clusters along the ring indicate that some micro cracking started at the base of this ring around 3.5 MPa. This cracking was driven by the distortion in the expanding conical shell caused by the local restraint produced by the ring. It does not appear that the ductile deformation and tearing in the shell metal caused by two gaps in the welds along the ring produced any AE. The conclusion drawn is that ductile tearing and not crack propagation produced the leak paths in SCV model. The ductile tearing did not generate detectable AE at the threshold of detection used (the trigger threshold was 45 dB - 180 µV out of the sensor).

The overall conclusions of this report are that this model showed no significant damage at pressures up to 3.5 MPa. The region where the large ductile tear occurred produced enough emissions to locate it before it occurred. The design and construction of the stiffening ring on the conical section produced detectable damage starting at 3.5 MPa.

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