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A NONDESTRUCTIVE TEST FOR AIRCRAFT HALON BOTTLES, THE DEVELOPMENT OF AN ACOUSTIC EMISSION APPLICATION

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ABSTRACT

An acoustic emission test for aircraft Halon bottles has been developed in response to a need expressed by the U.S. Airline Industry. During this development many choices had to be made about test methods, procedures and analysis techniques. This paper discusses these choices and how successful they were. The test itself was designed to replace the currently required hydrostatic test for these bottles. The necessary load is applied by heating the sealed bottles. Acoustic emission is monitored, during the heating, by six sensors held in position by a special fixture. A prototype of the test apparatus was constructed and used in two commercial Halon bottle repair and test facilities. Results to date indicate that about 97 percent of the bottles tested show no indications of flaws. The other three percent have had indications of possible flaws in non-critical areas of the bottles. All bottles tested to date have passed the hydrostatic test subsequent to the acoustic emission test.

INTRODUCTION

The world aircraft industry employs spherical steel bottles containing pressurized Halon 1301 (CF_3Br) to extinguish engine and cargo hold fires. US Department of Transportation, (DOT) regulations require periodic testing of these bottles for structural integrity. The only test method currently approved by DOT regulations is a hydrostatic test which measurers inelastic expansion of the bottles. This test requires that the sealed bottles be opened, emptied, pressurized with water in a water bath, refilled with Halon 1301 and then resealed. It should be noted that the failure rate for the hydrostatic test is extremely small.

The production of Halon 1301 throughout the world was stopped in January 1994 because of its ozone depleting properties. At this time no substitute material exists which combines both Halon 1301's outstanding fire extinguishing effectiveness and low toxicity. The US airline industry has been granted an exemption by the DOT to continue using Halon 1301 through the year 2000. The cost of Halon 1301 from existing stores has rapidly increased even though all Halon from the bottles undergoing hydrostatic testing is recovered, refined and reused. A test of the bottle integrity which did not require opening the bottles would save much time and expense for the worlds airlines as well as eliminating one source of loss of the world's dwindling Halon 1301 supply.

The DOT has granted exemptions to allow acoustic emission testing of gas cylinders on gas transportation trailers in place of the hydrostatic test. This procedure is now widely used throughout the United States. In this test, the cylinders are monitored with an acoustic emission system while subjected to an over pressure of 110% of their maximum working pressure. This is accomplished during the normal filling procedure of the cylinders. An extensive testing program was able to set failure criteria for these cylinders. A similar acoustic emission test of aircraft Halon bottles would appear a natural application.

The Federal Aviation Administration (FAA) and the Air Transport Association (ATA) have sponsored a program to develop an acoustic emission test for aircraft Halon 1301 bottles to supplement or replace the hydrostatic test. This paper describes the development of that test.

DESIGN OF AN ACOUSTIC EMISSION TEST

The fundamental problem in designing any acoustic emission test is to develop a method for applying a test load in a realistic manner. For a permanently sealed vessel, one practical method to increase the internal pressure is to heat the bottle and its contents. The question was whether sufficient pressure for an acoustic emission test could be generated easily and safely. Halon 1301 has a critical temperature at $153^{O}F$ and at 70^{OF}, a vapor pressure of 199 psi. To insure that the material is rapidly expelled despite cooling by expansion, the bottle is usually over pressured with dry nitrogen gas, typically to a pressure of 600 psi.

Initially a rough estimate of the pressure temperature curve of the Halon 1301-Nitrogen mixture was obtained by heating a Halon bottle equipped with a small pressure gauge. The resulting data showed that sufficient pressure could be generated for an acoustic emission test. Later, theoretical curves were obtained from Walter Kidde Co. for a variety of bottles. A typical curve is shown in Figure 1. From these curves, it is seen that a temperature of $145^{O}F$ will produce a pressure in most Halon bottles about 30% above the bottle pressure at $110^{O}F$. $110^{O}F$ is a temperature which the industry estimates will seldom be exceeded in normal service. Therefore heating a Halon bottle to $145^{O}F$ exceeds the 110% overpressure criteria and will provide a valid acoustic emission test.

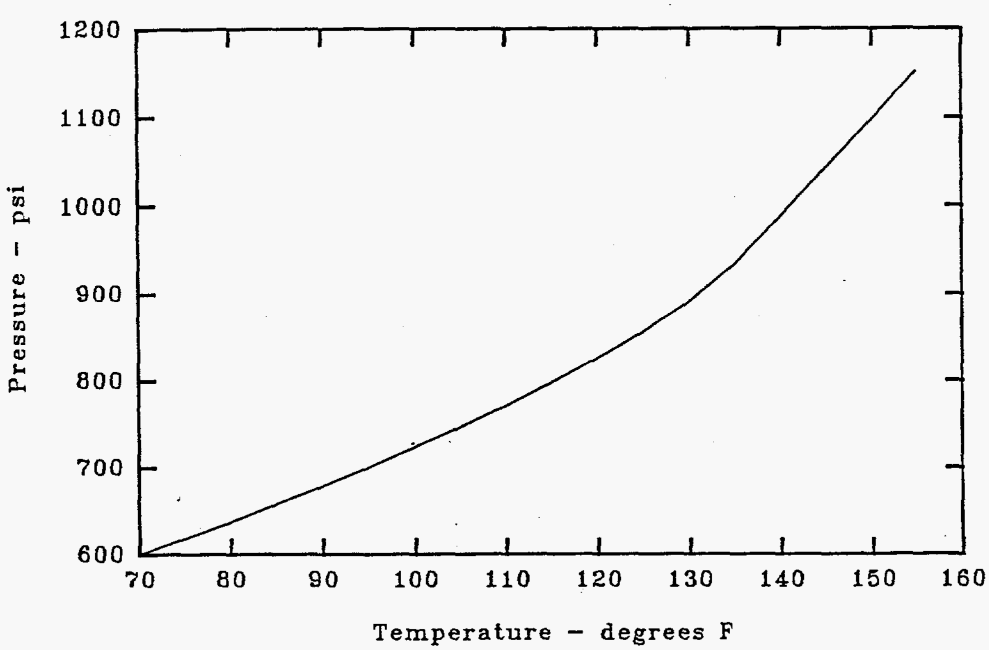

Fig. 1 Temperature - Pressure curve for a Halon Bottle

The next problem was to determine what type of acoustic emission signals might be seen in the bottles. Several Halon bottles were heated in an industrial oven while being monitored by a six channel AE system. Some emission was detected, mostly of low ampli-

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tude. Studies of the propagated waves in the bottle wall were then conducted by breaking pencil leads on the bottle and digitizing the received signals from sensors on the bottle. Several facts became apparent. First, the waves contained frequencies at least from 20 to 400 KHz. Second, the wave forms were consistent with transmission of both extensional and flexural modes. Two possible problems were seen. The predominate mode generated by the lead break was the flexural mode. This mode was highly susceptible to scattering and/or distortion by lugs and plates welded to the bottle walls. Examples of waveforms from three sensors excited by the same event are shown in Figure 2. The other problem was that at frequencies below 100 KHz, waves traveled in the liquid Halon as well as the wall. The spherical geometry of the cavity produced focusing and random wave superpositions. Occasionally a lead break would produce a huge signal at a sensor long after the wave appeared to have decayed. These appeared at various sensor locations and the arrival times suggested 10 to 15 round trips of the waves in the Halon. It was found that signals from these waves were eliminated when 300 KHz sensors were used with 250 KHz high pass filters. After extensive testing of several sensors at temperatures up to 300^{O}F, the PAC Nanno 30 was chosen.

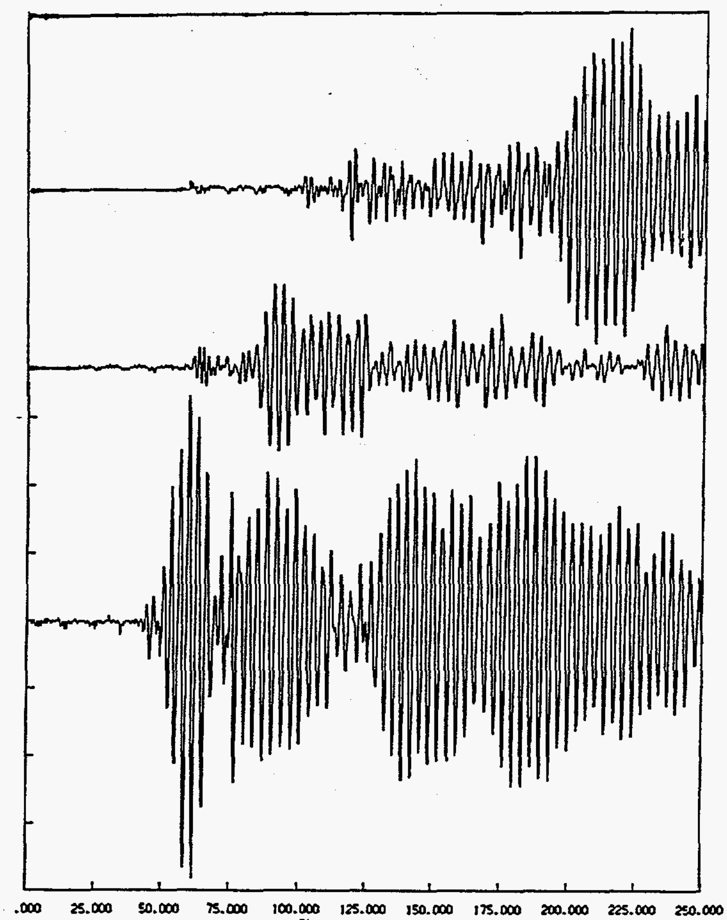

Fig. 2 Three waveforms from the same event. Time is microseconds

At this point, the decision on whether to use a single sensor test or a source location test was necessary. These bottles are relatively small and a single acoustic emission would be detectable anywhere on the bottle, making a single channel test quite feasible. However, the test unit is intended for an industrial type environment. Extraneous signals detected by a single channel can be almost impossible to differentiate from real acoustic emission. A source location system gives much stronger noise differentiation. Seldom does an extraneous signal hit multiple sensors in the right order, and with suitable time delays at each sensor, such that the calculated location corresponds to a location on the surface of the specimen. The other major advantage to source location is that one can differentiate between random sources scattered over the surface of the vessel and sources concentrated in a small region. The choice of source location makes for a much better test, even though the execution is more difficult.

The choice of source location led to the design of a fixture. Most airline Halon bottles are spheres and most are between 5 and 16 inches in diameter. The ideal sensor layout on a sphere is six sensors at the ends of the x, y and z axes i.e. the six arbitrary poles of a sphere. By rotating the coordinate system, one can locate the sensors on two parallel planes. As long as two sensors are at the ends of a diameter of a sphere, they can be moved in or out and retain their angular relationship with the other sensors, also located at the ends of diameters. Thus the fixture could accommodate a range of sphere sizes and the only variable that would have to change in a location program would be the radius of the sphere. Figure 3 shows a fixture designed in this way.

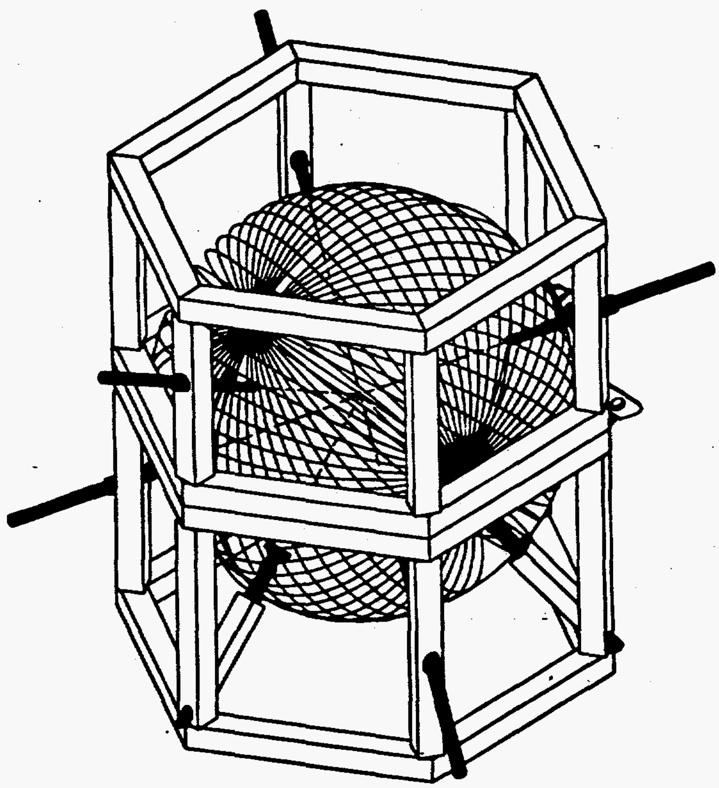

Fig. 3 Drawing of the fixture

The six sensors are positioned at the end of rods which lie along diameters of the bottle. The sensors are spring loaded against the surface. Hard rubber pads glued to the sensor wear plates act as the couplant. Adjusting the distance of the sensors from the center allows the fixture to accommodate spheres from 5 to 16 inches in diameter. The fixture opens like a clam shell to allow easy loading of the bottles. Fixture and bottle sit on a sliding shelf of an industrial oven.

With the fixture, the sensor placement and the loading method all chosen, the next decision was to chose an acoustic emission system. The signals seen in the preliminary tests were small, usually with peak amplitudes under 50 dB. Furthermore the flexural wave, which had the highest amplitude signal component, was subject to distortion on many of the possible signal paths. The decision was to go for a maximum sensitivity. This would increase the probability of triggering on the extensional wave. There was also the fact that a crack inside the wall would produce a large extensional wave component while a lead brake or a crack in a doubler plate weld would produce a large flexural wave component. To rate the severity of the emission source, a large dynamic range was needed in the system. For these and other reasons, the Physical Acoustic Corp. (PAC) AEDSP-32/16 digital acoustic emission board was chosen as the basis of the system. This board can be run at a trigger level of 25 dB (17 microvolts out of the sensor) with almost no false triggering. It also has a dynamic range of approximately 80 dB.

Three of the two channel boards are mounted in a 66 MHz 486 computer. These boards contain a digital processor with a 16 bit word and a maximum digitization frequency of 8 MHz. The boards use dedicated signal processing chips to calculate various AE signal parameters in real time from the digital record. I chose to record the following parameters for each AE hit: The test time (accuracy, 1/4 of a microsecond), the AE count, the peak signal amplitude, the signal rise time, the signal length, the area under the voltage time curve (variously called signal strength, "energy" or marse), and finally, the digitized wave form for each hit. This digital record contains 2048 words digitized at a 4 MHz rate for every hit on a sensor. The emission signal is usually longer than the digital record, but this record length is long enough to get the type of wave mode that was triggered on and the peak amplitude. The digital signal is not used in the analysis and never looked at unless there are questions about the data. When questions do arise, the ability to go back and look at the stored wave forms is invaluable.

The typical acoustic emission program for a sphere with six sensors treats the surface as eight flat triangles. Since the equations for distances between points on the surface of a sphere are well known, it was decided to use true spherical geometry for the calculation of the location of the sources. However, as was said, these bottles are not smooth spheres. At the relatively low signal amplitudes (35 to 50 dB) seen in most emissions on these spheres, the distortion of the waves can produce triggering on either the extensional or the flexural portion of the wave, making the calculation of the exact source position difficult. To achieve reasonably accurate location on detected signals, only over-determined data sets are used in the calculation (an event where the emitted acoustic wave excites 4 or more sensors). A non-linear least squares program was written in Fortran to calculate the most probable location of the event on the sphere. It was then modified by PAC to work with their hardware. This location program first tries to locate the source with the extensional wave velocity. If that does not produce a good fit to the data (a fitting parameter estimates the goodness of fit), the flexural velocity is tried. The computer ignores the event if it can not locate the source position with a relatively good fit by using one of these two wave velocities. Approximately 80% of all the events are located. This percentage approaches 100% as the peak amplitude of the wave exceeds 50 dB (300 microvolts) out of the sensor.

Almost all cracks in metals produce multiple acoustic emission bursts as they grow. The decision was made to use a program which searches for clusters of sources to try to separate emission signals produced by cracks from signals produced by random events such as corrosion spalling. An algorithm was written which detects and locates spatial clusters of event sources. A cluster is arbitrary defined here as all events which fall within a circle on the surface of the sphere having a radius of 15 degrees of arc of a great circle. The center of the cluster is the average coordinates of all the included locations. Note that if the crack grows any distance, the actual shape of the cluster will approximate an oval. In addition, an average value of an acoustic emission parameter for the cluster (currently, the average ringdown count from the first hit sensors) is calculated as an indicator of the severity of the cluster. The 15 degree radius corresponds to a circle about 3 inches in diameter on a eleven inch diameter sphere. This cluster size was based on data from an intentionally flawed bottle. The extended testing indicates that it is a reasonable choice for the spherical Halon bottles used in the air fleet.

A PROTOTYPE SYSTEM

The Halon bottle tester is intended to be used both in commercial bottle testing facilities and in aircraft maintenance facilities. The overall design philosophy was that the system should be able to be run by any aircraft mechanic even if he had little knowledge of acoustic emission. To that end the system must be simple to use and the operator should not be involved in interpreting the data. The computer program must be capable of passing or rejecting most of the bottles, turning the decision over to an acoustic emission expert only in a very small minority of the cases. The key to the computers ability to make decisions is the clustering algorithm. The intention is to base the pass/ reject criteria on the presence, size and intensity of the clusters. To determine the criteria, we needed a testing program which would use this tester on a large number of real bottles. The first step in this program was to build a prototype tester.

The prototype incorporates three PAC AEDSP cards mounted in a personal computer case as the acoustic emission system and a Russell industrial oven to heat the bottles. The fixture with the sensors is mounted on a sliding shelf in the oven. This shelf allows the fixture to open and the bottle to be loaded outside the oven. The coils of the heating elements are encased in a sheath and the surface temperature of the sheath is limited to a maximum temperature of 800^{O}F. This is to prevent thermal decomposition of the Halon 1301 in the event of an accidental release. The oven air temperature is limited to a maximum of 200^{O}F. Relays are installed in the oven to allow the computer to operate the heaters and circulation fan. The computer reads the skin temperature of the bottle with a thermocouple taped to the lower surface. Also incorporated in this system is an auto sensor test in which each sensor is pulsed and the amplitude of that signal is measured at all the other sensors. This test checks both the electronics and the acoustic coupling. Figure 4 is a photograph of the prototype.

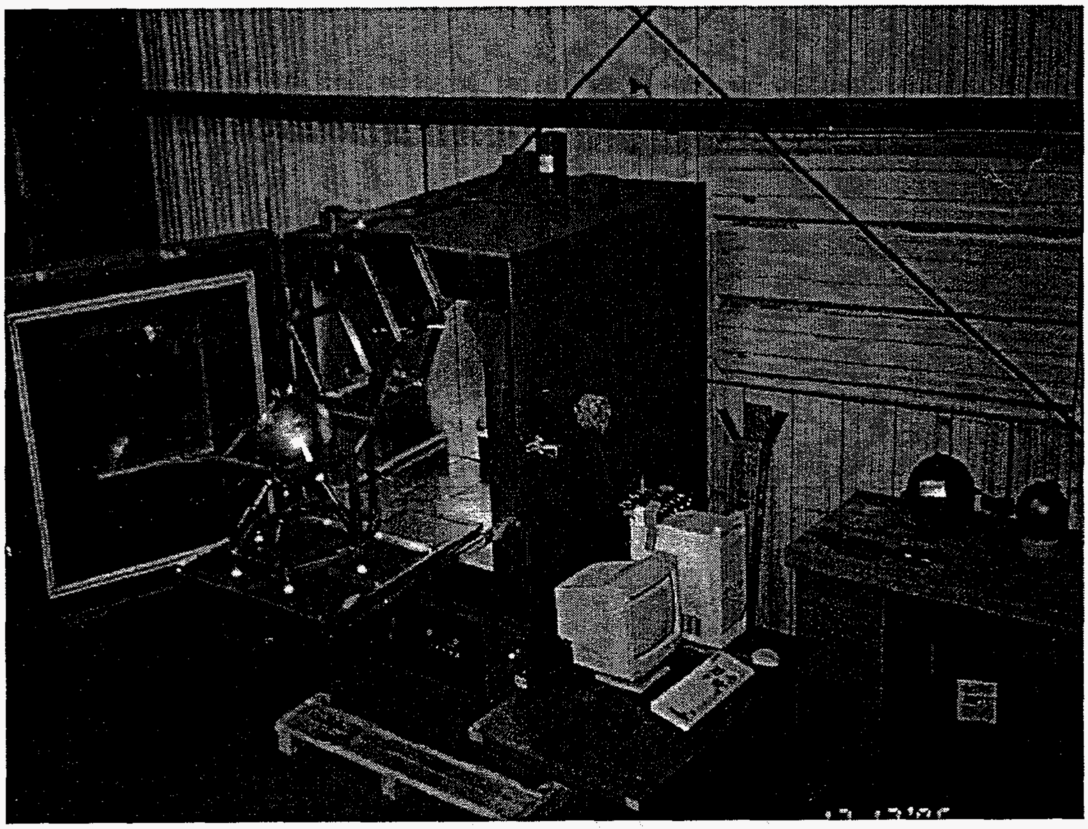

Fig. 4 The prototype system

To run the system, the operator first loads the bottle into the fixture and attaches the thermocouple to the lower skin of the bottle. Next the bottle identification is entered into the spaces requested by the computer. When this data is verified, the computer starts the auto sensor test. If the average of the peak amplitudes of all signals received by each sensor lies within $\pm$ 3 dB. of the average of the signals received by all the sensors, the test is passed. If the test is failed, the operator is instructed to reseat the sensors and try again. After the auto sensor test is passed, the system turns on the oven and circulation fan and starts taking data. When the bottle wall temperature reaches 150^{0}F, the heaters and fan are turned off and the bottle sits for five minutes to allow the Halon inside to reach equilibrium with the bottle wall. The equilibrium temperature is usually between 145 and 150^{0}F. At this point, the computer notifies the operator to remove the bottle from the oven. Throughout the test, the computer is attempting to calculate the locations of every event. It then checks each located event to see whether it is a member of an existing cluster or whether it starts to form a cluster with another event. If a serious cluster forms, (currently defined as one containing more than fifty events with a total count of over 10,000), the computer will shut off the heater and circulating fan and signal the operator to either remove the bottle from the oven or open the door to allow the bottle to cool. A brief report is printed at the end of every test identifying the bottle and stating either that it passed or failed or that the test is indeterminate. Currently, indeterminate is defined to mean that at least one cluster was seen containing 10 or more events.

RESULTS OF THE BOTTLE TESTS

The first experiments conducted with the acoustic emission system and spherical location program were performed on several bottles which had been removed from service by visual inspection. None of these bottles appeared to have a serious flaw. All ports were sealed except for an inlet and outlet pressure fitting. The bottles were filled with water and pressurized. One of the bottle had been dented with a hammer by airline mechanics to insure that it would not be reused. Pressurization to 1200 psi popped out most of the dent. The AE system detected 17 events during this pressurization, 13 of them being located within the three inch circle which contained the dent. This bottle had a 70^{0}F fill pressure of 600 psi and an ultimate design pressure of 2400 psi. The acoustic emission from the dent occurred between 400 and 840 psi. The bottle survived pressurization to 1900 psi with no other significant emission.

The prototype tester was installed in the Walter Kidde Co. testing facility in Wilson North Carolina. Tests were run on Halon bottles returned by air carriers for repair or testing. Because these bottles were owned by customers and some had tight scheduling requirements, not all of the desired NDT testing could be performed on questionable bottles. All bottles tested with the acoustic emission system subsequently passed the hydrostatic test. One Hundred and fifty-two bottles were tested at this facility. These bottles covered a range of volumes from 86 to 1400 in^3. The shell materials were Nitronic-40 steel (21-6-9), Almar steel and 4130 steel. About 1/3 of the bottles were painted. The test times varied with bottle volume and material. Painted bottles heated more slowly than bare bottles. Over all, the average time to perform a test was about 26 minutes per bottle. The first test of the day usually takes around 45 minutes as the oven must be heated as well as the bottle. The results of these tests are given in Table 1.

TABLE 1

Summary of Bottle Tests at Walter Kidde Co.

8 bottles	No acoustic emission seen.
50 bottles	Random AE Hits but no Located Events.
62 Bottles	Random numbers of AE hits and one or more located events. No cluster with more than 2 events.
28 bottles	Random numbers of AE hits and located events. Clusters with 3 to 6 events in a cluster.
4 Bottles	Relatively high numbers of AE hits and located events. At least one cluster containing 14 or more located events.

Only 4 bottles had more than 15 located events. These had 41, 45, 45 and 297 events. The clustering data showed 15 bottles with clusters containing 3 to 5 events. The four bottles with high event counts all had several clusters, with at least one cluster containing 13 or more events. Two of the bottles showed a cluster covering a doubler plate with a fixture lug mounted on it. These plates were about the same thickness as the bottle wall and were attached to the wall with a fillet weld around the edge of the doubler. One bottle had a weld that was too steep and showed discoloration on the inside of the bottle behind the weld. While the bottle passed the hydrostatic test the fillet weld was probably cracked with the crack running parallel to the bottle wall. The other bottle had an x-ray taken of the fillet weld and a small tungsten inclusion was found inside the weld. This is an ideal situation for crack initiation, again probably with the crack parallel to the wall.

The third of these bottles had the cluster located in the region where a port had previously been removed and a new port with a larger and thicker base had been welded into the bottle. Unfortunately, the weld could not be examined from the inside and we could only speculate that there was some slag or other minor imperfection in it. The last bottle had two clusters with over a hundred counts near the outlet ports and pressure switch. No problems were seen when the welds were x-rayed. The source became apparent when it was realized that the bottle had been refitted with a new shield for the pressure switch. Instead of welding the shield to the bottle, it had been attached with set screws. The clusters were located at the pressure switch shield. The expansion of the bottle caused a relative movement of the set screws, producing the acoustic emission. It should be noted that these clusters had a lot of events but a very low average count per event.

CONCLUSIONS

The prototype system has worked well with no major design deficiencies appearing to date. As expected, the majority of bottles had few located events. Some tests showed several hundred to a thousand hits with no located events. Examination of the digitized waveforms showed that most of these hits appeared to be noise signals. This showed the value of the choice of source location as well as the value of keeping the waveforms. Most test data files are well under three megabytes in length, including the waveform data. The use of cluster detection appears to work well as a method to rate the bottles. The clam shell fixture appears awkward but no technician has had any difficulty in using it. The sensors are occasionally knocked off the end of the mounting rods but repair is easy.

The acoustic emission tester has shown its ability to detect small flaws in Halon bottles. None of the flaws seen yet are serious enough to reject the bottle. Therefore no rejection criteria can be set at this time. While it is hoped that there will be a few truly bad bottles tested, it may be that none will be seen. Then, based upon the current data, the criteria can be set such that the tester will pass all bottles showing no clusters of acoustic events containing more than 10 events. Hydrostatic tests would be required only for bottles with a cluster containing more than 10 events. While not using acoustic emission as the sole test, this would save having to open around 97% of the bottles requiring retesting. Since the Halon bottle tester can be operated in the hanger or repair facility, only the remaining 3% of the bottles would have to be sent out for hydrostatic testing. This alone will result in a considerable savings for the Airline Industry as well as helping to conserve the world supply of Halon 1301.

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