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ON-LINE SAFETY MONITORING
OF A LARGE HIGH PRESSURE
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ABSTRACT: Four years of experience with on-line monitoring of a large autoclave used primarily for forming bonds and material densification is reported. The purpose of this work is to confirm that no flaws are growing in the autoclave during operation. Failure of this device during operation could endanger personnel and would damage property. Its loss would seriously curtail several ongoing research efforts.

The vessel is monitored with a commercial mini-computerized flaw location system. Four 4-sensor arrays are attached to the exterior of the device to receive acoustic emission signals. Computed locations are stored on cassette tape and selected portions can be displayed on a cathode ray screen. It is shown that although the mini-computer is implemented with two dimensional location software, the information can be reprocessed in a central computer to produce locations in three dimensions.

Long term storage of data, data display, noise analysis, calibration, and computerized location error analysis is discussed.

No degradation by flaw growth has been detected in this device to date. This is the expected result, since it has an estimated 30-year life.

KEY WORDS: acoustic emission, pressure vessel, autoclave, nondestructive inspection, flaw growth, on-line monitoring, flaw location.

INTRODUCTION

The ever increasing sophistication of pressure vessel technology coupled with an increasing emphasis on safety has intensified the search for a thorough and cost effective means of nondestructive inspection for pressure systems in critical service. The most pressing needs are in the nuclear power and chemical process industries, where a pressure system failure could cause both large economic losses and perhaps extensive loss of life.

The high pressure autoclave that is the subject of this discussion is a reasonable prototype of a chemical process component in terms of its size and structural complexity. Much of the experience gained in the process of monitoring for safety assurance should be transferable to chemical and nuclear systems. This vessel is operated intermittently, thus there is an opportunity to perform diagnostic tests on the effectiveness of the monitoring system on a continuing basis. The accumulation of experience over a four year period will be reported here.

An acoustic emission [1,2] flaw detection and location system is used to perform on-line safety monitoring of the autoclave. The system is designed to detect a subcritical flaw as it grows by small step-wise increments anywhere in

the vessel. Coincident with each incremental step, a transient mechanical disturbance (the acoustic emission) is propagated in the flawed test body. The acoustic emission signal is detected by four arrays of piezoelectric sensors distributed over the surface of the vessel and acoustically coupled to it. Arrival times of the propagating pulse at each of four sensors within an array are measured. These arrival times, along with a knowledge of the appropriate velocity of sound in the vessel, permits the location of an incrementing flaw. The monitoring system utilizes computer aided data acquisition, analysis, and display techniques to perform the location function in real time.

The upper and lower quarters of the autoclave vessel are virtually solid, whereas many pressure vessels can be considered thin-walled. Details of how the data processing and analysis was extended to permit flaw location in a solid are discussed in this report.

The accuracy with which a flaw can be located depends upon the choice of sound velocity and the accuracy of the arrival time measurements. A special study of these parameters is discussed.

A composite of all the data accumulated over the four year period of this study, indicating that the autoclave vessel is operating safely, will be reported.

MATERIAL AND PHYSICAL CHARACTERISTICS

MATERIAL

The vessel is fabricated from HY-100 (Mod) steel with a yield strength of 1 034 MPa. No material from the fabrication was available upon which laboratory tests could be performed to establish acoustic emission behavior from incrementing cracks. Figure 1 shows the record from a failing compact fracture toughness specimen of 4330 V(Mod) steel. This steel has strength and toughness characteristics similar to the HY-100 (Mod).

It is assumed that the two steels produce similar acoustic emission records. The figure shows that many thousands of acoustic emissions accompany the crack extension, starting at approximately 70 percent of the catastrophic failure load. Each emission can be used to locate the crack once. Each growing crack should be repeatedly located thousands of times before it reaches critical size.

Fig. 1. Acoustic emission record of a failing compact fracture toughness specimen of 4330V (Mod) steel.

FRACTURE ANALYSIS

A fracture mechanics analysis of the vessel has been performed by Prado [3]. Several assumptions had to be made in this analysis, as is usually the case. He assumed that an elliptical surface crack of dimensions 2.5 x 20 mm could be detected by nondestructive testing techniques, and that the critical crack size was 30 x 244 mm. Experimental values for crack growth rate of similar steels were used to derive a cycle-life estimate. He concluded that the service life of the vessel was about 11,000 cycles.

STRESS ANALYSIS

A finite element structural analysis [4] of the vessel produced the stress maps used in the fracture mechanics analysis. Figure 2 is a sketch of the vessel. The last (innermost) thread of the large annular nut at the top of the vessel is the location of the highest stress in the vessel. According to the analysis, only a small volume in the vicinity of this thread may have experienced yielding during the 1.5X proof test that was part of the acceptance procedure. The last (uppermost) thread of the annular nut at the bottom experiences somewhat lower stresses.

SOUND PATH DISCONTINUITIES

Six seal gaskets, the working volume, and the coolant channels are significant sound path discontinuities in the vessel. In addition, there are five small cross section toroidal voids at the thread terminations. Referring again to Fig. 2, there is a flat seal at the -0.32 to -0.34 m level under the annular nut. There are three seal rings at the -0.57 to -0.62 m level at radii of 0.146, 0.229, and 0.356 m. Two further seals are associated with the bottom closure. There is a Bridgeman seal under the bottom plug at the -2.70 to -2.76 m level. There is a ring seal at the -2.76 level and at 0.356 m radius.

The working volume of the vessel has a compound wall composed of two cylinders shrink-fitted together. The outer cylinder is 0.216 m thick and the inner cylinder is 0.127 m thick. As shown in Fig. 2, cooling channels are located at the interface between the two cylinders. Contrary to what is shown in the sketch, these channels are semicircular, 9.53 mm in radius with the diameter facing out. The channels are spaced apart by 42.9 mm. The channels are broken into three loops, each spanning approximately one-third of the working volume height.

Fig. 2. Sketch of the autoclave vessel.

Each of the systems incorporated a minicomputer to perform the location calculations. Each of the systems contained software that assumed the location was being performed on a two-dimensional body, i.e., a body whose dimension normal to the surface on which the sensors are mounted is small compared to the lateral dimensions of the test body. This was not a good approximation for the autoclave body, and the usefulness of the computed locations had to be evaluated.

THEORETICAL

A proof that the commercial flaw location systems collected sufficient data to permit calculation of an acoustic emission source location in three dimensions was developed as part of the feasibility study. The data extracted from the commercial system for this purpose was essentially the arrival times of the acoustic emission wave at the four sensors. The relationship between the two dimensional calculation performed by the commercial system, the visual display of the calculated locations, and the three dimensional calculation which had to be performed off-line on a large computer was established. More discussion on this relationship will follow in a later section. The theory

for location in three dimensions follows. The theory assumes that the operating acoustic emission source propagates a constant velocity, spherically expanding impulsive mechanical disturbance into an infinite medium. This is a relatively good assumption for the upper and lower portions of the vessel studied here, Fig. 2.

M, N, U, W are labels given to the four sensors in an array. These symbols also represent vectors of position for the four sensors. T_M , T_N , T_U , T_W identify arrival times of the acoustic emission wave at each of the four sensors. The M sensor is assumed to be the first sensor struck in this discussion.

The relations

$$\Delta N = (T_N - T_M) * C$$

$$\Delta U = (T_U - T_M) * C$$

(1)

$$\Delta W = (T_W - T_M) * C$$

express the distance the acoustic wave travels to reach each of the last three sensors struck, in addition to the distance it traveled to strike the first sensor, M. In these expressions, C is the appropriate velocity of sound.

The total distance, $\underline{D}$, the acoustic wave traveled to reach each transducer can be expressed by the matrix equations

$$\| \underline{M} - \underline{P} \| = \underline{D}$$

$$\| \underline{N} - \underline{P} \| = \Delta \underline{N} + \underline{D}$$

(2)

$$\| \underline{U} - \underline{P} \| = \Delta \underline{U} + \underline{D}$$

$$\| \underline{W} - \underline{P} \| = \Delta \underline{W} + \underline{D}$$

The symbol $\| \quad \|$ stands for vector length. $\underline{P}$ is the vector of position for the source point, and the unknown quantity to be calculated.

The implicit square roots of Eqs. (2) are eliminated by squaring these equations.

The identity that for any vectors $\underline{A}$, $\underline{B}$,

$$\| \underline{A} - \underline{B} \|^2 = (\underline{A} - \underline{B})^T (\underline{A} - \underline{B}) = (\underline{A}^T - \underline{B}^T) (\underline{A} - \underline{B}) =$$

$$\underline{A}^T \underline{A} - \underline{A}^T \underline{B} - \underline{B}^T \underline{A} + \underline{B}^T \underline{B} = \| \underline{A} \|^2 - 2 \underline{A}^T \underline{B} + \| \underline{B} \|^2$$

is used. The superscript T stands for the transpose of a vector. Note that $A^T B = B^T A$ since both are scalar quantities.

The squares of the equations are

$$\begin{aligned}
 \|M\|^2 - 2P^T M + \|P\|^2 &= D^2 \\
 \|N\|^2 - 2P^T N + \|P\|^2 &= D^2 + 2D\Delta N + \Delta N^2 \\
 \|U\|^2 - 2P^T U + \|P\|^2 &= D^2 + 2D\Delta U + \Delta U^2 \\
 \|W\|^2 - 2P^T W + \|P\|^2 &= D^2 + 2D\Delta W + \Delta W^2
 \end{aligned}
 \tag{3}$$

Substitution of D^2 from the first of equation set (3) into each of the last three equations leads to a set of equations containing a first order term in P and to the elimination of $\|P\|^2$,

$$\begin{aligned}
 \|M\|^2 - \|N\|^2 + 2P^T (N - M) &= -(2D\Delta N + \Delta N^2) \\
 \|M\|^2 - \|U\|^2 + 2P^T (U - M) &= -(2D\Delta U + \Delta U^2) \\
 \|M\|^2 - \|W\|^2 + 2P^T (W - M) &= -(2D\Delta W + \Delta W^2)
 \end{aligned}
 \tag{4}$$

Equation set (4) can be expressed in matrix notation as

$$QP = DV_1 + V_2 \quad (5)$$

where

$$Q = \begin{bmatrix} (N_x - M_x) & (N_y - M_y) & (N_z - M_z) \\ (U_x - M_x) & (U_y - M_y) & (U_z - M_z) \\ (W_x - M_x) & (W_y - M_y) & (W_z - M_z) \end{bmatrix}$$

$$P = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} \quad V_1 = \begin{bmatrix} -\Delta N \\ -\Delta U \\ -\Delta W \end{bmatrix} \quad V_2 = 1/2 \begin{bmatrix} -\Delta N^2 + \|N\|^2 - \|M\|^2 \\ -\Delta U^2 + \|U\|^2 - \|M\|^2 \\ -\Delta W^2 + \|W\|^2 - \|M\|^2 \end{bmatrix}$$

Each symbol in the Q matrix is a vector component of a position vector locating a sensor with respect to the origin of coordinates.

It can easily be shown that elimination of D from the equation set (4) leads to a singular solution for the system, thus another solution must be sought.

For any matrix B , $B(S_1 Y_1 + S_2 Y_2) = S_1 B Y_1 + S_2 B Y_2$, where S_1 and S_2 are scalars and Y_1 and Y_2 are vectors. Using this rule, and applying Q^{-1} to both sides of equation (5) one obtains

$$P = DQ^{-1}V_1 + Q^{-1}V_2 = DV_3 + V_4 \quad (6)$$

where $QV_3 = V_1$ and $QV_4 = V_2$

Substitution of equation (6) into the first of equations (3) yields a quadratic expression in D :

$$D^2 = \|M\|^2 - 2(DV_3^T + V_4^T)M + (DV_3^T + V_4^T)(DV_3 + V_4).$$

This expression has the form

$$ED^2 + FD + G = 0 \quad (7)$$

where

$$E = (\|V_3\|^2 - 1)$$

$$F = 2(V_3^T V_4 - V_3^T M)$$

$$G = \|V_4\|^2 - 2V_4^T M + \|M\|^2$$

A solution may be obtained by first solving the two linear problems $QX = V_1$ and $QX = V_2$. The solutions yield V_3 and V_4 . Using V_3 and V_4 , equation (7) can be solved, yielding two solutions for D , D_1 , and D_2 . Then solving the two linear problems given by (6), two solutions for P , P_1 , and P_2 are finally obtained.

The possibility of two valid source points cannot always be excluded. However, one possible source point usually falls outside the physical volume of the vessel. In this case, selection of the valid source point is automatic.

At least one of the solutions to equation (7) is positive. It remains to interpret the meaning of a negative solution for D . It has so far been impossible to prove that a solution yielding a negative D should always be excluded. However, a large number of cases involving the negative D solution have been studied, and all have yielded an invalid solution for the source point P . Solutions involving a negative D are automatically excluded as a result of this study.

In summary, this theory shows that location of an acoustic emission source in a three dimensional body requires a) measurement of four arrival times, from b) four sensors whose positions are known and c) an appropriate speed of sound for the test body, d) implementation of the algorithm for calculating the source location.

EXPERIMENTAL PROCEDURE

SENSORS AND SENSOR PLACEMENT

The sensors employed are Model S-750, a commercial product of Dunegan/Endevco^[1]. The sensors have a peak sensitivity of -75 dB re: 10 V per Pa at 0.16 MHz and have a relatively uniform sensitivity near -90 dBV over the 0.27 to 0.80 MHz range according to spark impulse calibration.

Figure 3 is a computer drawn, three-dimensional representation of Fig. 2. The four large dots show the placement of sensors in one of the four sensor arrays used to monitor the vessel. Figure 4 is a planar layout of the cylindrical surface of the vessel, showing placement of the four sensor arrays. The code above each indicated sensor location gives the array number first, followed by the sensor number. Thus, 0S3 designates array 0, sensor 3. The size of array 1 was recently changed to half the size of the other three. This small array is designated as array 1' in the figure.

Fig. 4. Planar layout of cylindrical surface showing sensor locations and cooling oil ports.

Change of size for the one array gives a capability for studying detection efficiency and location accuracy as a function of array size. Circled V's in the figure show location of the inlet and outlet ports for cooling oil. The cooling oil maintains the outer surface of the vessel at room temperature or slightly above during operation.

CONNECTIONS TO SYSTEM CONSOLE

The sixteen sensors are connected to preamplifiers by cables 6 metres long. The cable length is dictated by the size of the autoclave vessel and the distance from it to the control room for the facility. Each preamplifier has been field modified to have a lower frequency response of 0.02 MHz.

A second set of sixteen cables connect the preamplifiers to the data acquisition and processing console.

ON-LINE DATA ACQUISITION, PROCESSING AND DISPLAY

A Dunegan/Endevco Model 1032 Source Location system [1] is used for the above purpose. A minicomputer equipped with a special preprocessing unit is the heart of this system. The system is capable of selecting only those

signals delivered to it by the acoustic emission sensors that are above a preselected amplitude level. It is capable of noting the first sensor struck by an acoustic emission, and noting which array the sensor is in. All other arrays are then disabled for a predetermined time, roughly the transit time of the signal around the test body. It then measures the difference in arrival times of the signal between the first sensor struck and each of the other three sensors in the selected array. The array identification and the arrival time differences are then transmitted to the minicomputer for processing to determine location.

Commercially available software is capable of calculating location on the assumption that the test body is a thin-walled pressure vessel. However, the data it stores is sufficient to permit a location calculation in a solid body, as has been shown.

The data stored by the minicomputer on magnetic tape and available at its teletype output is as follows: 1) The event number. 2) The array number. 3) Four time differences (one zero), each associated with the appropriately identified sensor. 4) Location of the event in an X-Y coordinate system natural to the array, assuming the body is two-dimensional. 5) The acoustic emission count, giving a measure of the amplitude of the event. 6) The time at which the event occurred. 7) One or more parametric values, such as temperature and pressure.

For each test, it is required that the size of the array and the velocity of sound be entered via the keyboard to the computer storage.

A parallel output displays the located events as dots on a storage cathode ray tube (CRT), referenced to the pertinent array, giving a real time picture of the acoustic emission activity in the vessel. While one such array is being viewed, an auxiliary display shows the relative activity in each of the other arrays.

ON-LINE DATA INTERPRETATION

Aside from routine matters, the most important data interpretation task is to visually monitor the CRT display to assure that no source is becoming critically intense. Such sources are indicated by a clustering of location indications on the CRT. Prompt identification of such sources, in time to initiate shut-down procedures, is the principal reason for on-line monitoring. Despite the fact that the commercial system, with its two-dimensional software, calculates the location positions incorrectly, it can be used effectively to identify these repeating sources. Figure 3 illustrates this point. Near the upper part of the figure

there is a distorted circle containing 36 dots. This is the superposition of the minicomputer calculated location for 36 points on the circle C_1 of the computer drawn representation of the vessel. The circle C_1 represents the last thread of the annular nut shown more clearly in Fig. 2. It is the circle upon which the highest stresses in the vessel exist. Note that each point on the circle is resolved.

CALIBRATION

Calibration is accomplished by attaching a pulse excited transducer to the test structure after the sensor arrays are in place and their positions are entered into the minicomputer memory.

An electrical pulse applied to the calibration transducer simulates an acoustic emission originating from the surface point to which the calibration transducer is attached. The flaw location system then calculates the transit times of the simulated signal to each of the sensors in the array being calibrated, and from this, the appropriate speed of sound is calculated.

The calibration signal also allows one to assure that all sensors in the array being calibrated are operating. Reference to amplifier gains for signal reception at all of the sensors in the array gives assurance that the sensors are operating with proper sensitivity.

Selection of the gain to be used for each channel involves operator judgement. For this device, 80 dBV is chosen. Gain, trigger level, or both may be adjusted during the actual test if in the judgement of the operator it will improve data acquisition.

A lead break [7] calibrator has been used in place of the pulsed piezoelectric transducer to produce simulated acoustic emissions.

STIMULATION

Pressurization is achieved both by pumping gas into the autoclave volume and by increasing temperature. The specific program for increasing pressure and temperature is set by the requirements of the parts being processed in the vessel.

Figure 5 shows the pressure and temperature as a function of time for one test.

OFF-LINE DATA PROCESSING

The LLL central computer facilities are used to calculate the emission source locations using the data acquired by the minicomputer data acquisition system. The data transferred to the central computer are the array identification, the differential arrival time data, and the

Fig. 5. Example of time, temperature, pressure history.

sound velocity. This permits assignment of the proper set of sensor coordinates and the differential distance calculation indicated by Eqs. (1).

Subroutines DECOMP [8] and SOLVE [9] are used to perform the necessary matrix operations. The algorithm is described in a previous section.

DD80 routines [10] are utilized to generate data displays directly relatable to the test vessel. The vessel is outlined schematically in solid lines, and interior points that are either best candidates for flaw development or for spurious noise generation are outlined by dots. Refer to Fig. 6 which will be discussed again later.

Calculated source location points are then superimposed on this basic diagram. Sparse dots describe a radial line to the axis of the vessel from each of the source locations to aid visual determination of position. These sparsely dotted lines are not completed for those source locations outside, but near the vessel. Calculated locations up to one radius outside the vessel are kept, since poorly conformed signals can lead to erroneous location information. Only locations in, on, or very close to the the vessel are shown in Fig. 6, however.

A statistical display of source locations is also plotted. The distribution of vertical positions for sources inside the vessel is plotted on the left side of the vertical axis. Vertical positions for sources located outside the vessel are plotted on the right. Angular

Fig. 6. Accumulated location data for all process runs. Locations from known noise sources have been removed.

positions for sources located inside the vessel are plotted inside the upper rim, while sources located outside are plotted outside. Radial solutions are shown on the horizontal axis. While this statistical display has small value for a single test, it is a powerful tool for spotting changes in the state of the vessel that might occur over a large number of successive tests.

Storage of all information from all tests in the central computer makes a wide range of post-test analyses possible.

RESULTS AND DISCUSSION

Figure 6 shows the accumulated data from the eight process runs that have been monitored to date. Refer to the previous section for an explanation. The data has been edited to remove definitely known noise responses, and only calculated locations within the vessel are shown. This discussion will argue that all of the calculated locations are due to noise sources, and that no acoustic emission from flaw growth has been detected.

The numbers on the right side of Fig. 6 show the vertical positions of the 16 sensors used in the monitoring process. The sensors are numbered from 1 to 16, starting from OSO, refer to Fig. 4.

The large spike indicated on the Z-axis at approximately 2.4 m below the top of the vessel, on the surface for the R-axis and at approximately 50 degrees on the angular axis is a series of calibration pulses that was used as a "blind" test for the off-line processing.

The numbers in a vertical column, followed by asterisks show positions of the cooling oil ports.

The sealing rings in the vessel leak while sealing, and produce signals confusable with acoustic emission from the material. The seals either stop leaking at low pressure and temperature, or the test has to be aborted and the seals replaced. The monitoring system has been useful in judging the condition of these seals.

A major source of spurious noise occurs when the electrical heaters are turned on. For this short time period, usually no more than five minutes, no valid data can be taken. A second high noise activity period occurs when the cooling oil starts to circulate. In fact, the cooling ports continue to be "located" throughout each run. The volume and shape of the cooling channels changes at the entrance and exit ports to the vessel. The ports are the locations most often calculated.

Figure 7 shows the location data from a single process run. This indicates a possible additional noise source -- the material being processed. In this case, the material was a powder. It was sealed in thin-walled metal cans, then packed in the process chamber in a material like vermiculite. As the pressure increased, the sealing cans crumpled, perhaps starting with elastic buckling (oil canning). Large relative motion could have occurred between the insulating packing and the metal cans. Sound would have to traverse the high pressure gas to enter the wall of the autoclave vessel, and thus to reach the sensors. The radial locations do not support this hypothesis, but the vertical locations do. Only further experience will confirm this hypothesis. There is no grouping of location data at or near a single point, thus this activity is not attributed to flaw growth.

Figure 8 shows all locations from the accumulated data shown in Fig. 6, but for a selected portion of the vessel. This figure is for a portion of the vessel 75 mm above and below the critical stress circle previously discussed in the section on Material and Physical Characteristics. It is the outer dotted circle in the upper portion (true circle) of the figure. Only one location was recorded in this partial volume. It was on the vessel surface and not near the critical stress circle. This is convincing evidence that no flaw growth has occurred in the vessel. The

Fig. 7. Results from a single test from 69 to 207 MPa. The activity is assumed to originate in the process canister.

**Fig. 8. All data in the volume 0.227 to 0.377 m from top of vessel.
No flaw growth indicated.**

lower, square portion of this figure is a diametral plane of the vessel. All vertical components of the calculated locations are collapsed to this plane. The oval center portion of the figure is retained from the 3-dimensional figure so that the circumferential statistic can be plotted. The upper circle shows all the radial and circumferential components of calculated locations collapsed to a single plane.

Figure 9 shows all locations from the accumulated data shown in Fig. 6, but for another selected portion of the vessel. It encompasses 75 mm above and below the lower critical stress circle. This is the outer dotted circle within the upper portion of the figure. This figure was constructed in the same way as Fig. 8. While calculated locations are indicated, they assuredly do not show clustering on this circle. They are more likely associated with the lower oil port at the -2.69 m level in the vessel. If this is the source then the location calculation is not accurate. The lack of location accuracy is understandable on the basis that this source should produce poorly conformed signals.

Fig. 9. All data in the volume 2.71 to 2.86 m from the top of the vessel.
No flaw growth indicated

SOUND VELOCITY AND LOCATION ACCURACY

Selection of sound velocity is important to the proper operation of a flaw location instrument. The value of the sound velocity derived from various calibration sources is not relatable in a simple way to any of the pure modes normally used to describe sound transmission in solids. A continuing study has been made to quantify this parameter and to understand it better.

The experiment described here was performed independently of the flaw location system, the same off-line computation techniques were used. This experiment used four transient recorder channels, one channel was connected to each of the sensors in array 0 -- see Fig. 4. The lead break calibrator was used to simulate an acoustic emission, and amplitude-time records were taken. The point at which the lead was broken is indicated by "CAL" in Fig. 4. The data was then processed through a cross correlation analyzer. Cross correlation of the signals from each of the remaining sensors with the first sensor struck by the calibration signal permitted a determination of the three relative arrival times. Since the point at which the signal was injected was known and the positions of all four sensors were known, the velocity could be calculated three times. This calculation was performed once for straight

paths through the solid, and again for paths which followed the surface of the vessel. Table 1 shows the results of these calculations.

The results shown in Table 1 are somewhat disturbing. For the actual path taken by the sound from the lead break, the velocities calculated should all be the same. In fact, the deviation from the average is as high as 24% for the straight path calculation and as high as 44% for the surface path calculation.

Figure 10 is an example of the cross correlation analysis. It is for the OS0-OS3 pair (refer to Fig. 4). Under the conditions of this measurement, perfect correlation would have resulted in a signal amplitude of 1.00 volts. Multiplication of the ordinate values by 100 gives the correlation in percent. The other correlation records are similar to the example shown here.

The arrival times were entered into the central computer program and the velocity that calculated the best location for the lead break was determined. This value was 2336 m/sec. The Flaw Location System typically calculates a value near 2900 m/sec for the velocity of sound. Thus, the two values differ by 25%. This somewhat disturbing result must be left without an explanation until further work

Table 1: Velocities Calculated from Cross Correlation

Sensors Correlated	Δt 10^{-6} sec	Straight Path		Surface Path	
		ΔD metre	Velocity m/sec	ΔD metre	Velocity m/sec
OS0 - OS1	13.30	0.039	3017.5	0.025	1907.3
OS0 - OS2	236.72	0.562	2374.9	0.708	2989.6
<u>OS0 - OS3</u>	<u>23.94</u>	<u>0.083</u>	<u>3459.5</u>	<u>0.081</u>	<u>3363.0</u>
Average Velocity			2950.6		2753.3

Fig. 10. Cross correlation record for OS0-OS3 sensors

is done with the cross correlation technique for determining arrival time differences. The answer may lie in the fact that the time differences measured in this case did not produce a consistent data set. The ratios of relative arrival times should have been: 1.00:14.26:2.10. The measured ratio was 1.00:17.80:1.80.

Figure 11 shows the result of calculating the location for the calibration point assuming a range of velocities from 610 m/sec to 2970 m/sec. The higher velocities tended to locate the point outside the vessel. The artificially enhanced spikes on the statistic axes show the true location. The insensitivity of the Z-component of the location calculation should be noted. This has been a consistent feature of all the location accuracy studies performed to date.

A further concern in assessing the ability of flaw location systems to accurately locate a source is the ability of the system to accurately start and stop the time of flight measurement on the same portion of the acoustic emission wave form. The cross correlation record, Fig. 10, indicates that the acoustic emission signal undergoes a substantial change in form as it travels through a test body. This is confirmed by other observations. Using the

Fig. 11. Calculation of calibration signal location assuming a range of velocities from 610 to 2970 m/sec.

data already discussed in this section, a study was made of the location variation caused by one cycle of the acoustic emission pulse being missed, so that the time of arrival was referred to the second oscillation of the pulse rather than the first. The oscillation period was taken as 4 microseconds. Table 2 shows the result of this study.

These results show that the effect of missing one cycle in the arrival time determination at one or more sensors is not a cause for great concern. The study needs to be carried further to define limits on arrival time accuracy and its influence on location calculation accuracy.

CONCLUSION

A successful program of safety monitoring a large high temperature high pressure autoclave has been described. Results show that the autoclave vessel is operating safely and that no flaw growth has occurred.

The program has required a careful and detailed study of all noise sources in the vessel. Understanding of these noise sources, plus development of special data analysis techniques were both necessary to insure success.

Table 2: Effect of Missed Cycle on Location Calculation

Velocity 2337 m/sec				
Sensor Arrival Time Modified	Time Delay Microseconds	x metre	y metre	z metre
None	0	0.40	-0.42	-0.59
0S1 ^a	4	0.40	-0.41	-0.59
0S2	4	0.43	-0.43	-0.59
0S3	4	0.41	-0.42	-0.60
0S2, 0S3	4	0.43	-0.43	-0.60
True Values		0.41	-0.40	-0.62

^aSee Figure 4.

Commercial source location systems, programmed to monitor thin-walled vessels, are useful in monitoring thick-walled vessels or solid bodies. Commercial data displays indicate flaw growth in three dimensional bodies, but do not indicate location accurately. The data they acquire can be used off-line to calculate flaw location.

Problems remain in understanding the single sound velocity used in flaw location instrumentation. Cross correlation analysis should be helpful in reaching a better understanding. The sound velocity calculated by source location systems during calibration appears to be adequate to assure accurate location calculations.

Acoustic emission flaw location technology at its present state of development should be seriously considered for the on-line monitoring of critical pressure systems to assure their safety in service. This report has presented some of the problems, procedures, and payoffs that can be expected in such applications.

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FOOTNOTES

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[+] Prepared for presentation at the ASTM Symposium on Acoustic Emission Monitoring of Pressurized Systems at Ft. Lauderdale, FL, January 1979.

[1] Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U. S. Department of Energy to the exclusion of others that may be suitable.

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