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ULTRASONIC CHARACTERIZATION AND COMPUTERIZED
ANALYSIS OF GRAPHITE BILLETS*

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ABSTRACT

A computer aided, ultrasonic test system for graphite billets has been developed, the primary purpose of which is to select the optimum location within the billet of a re-entry vehicle nose tip. An on-line mini-computer provides process control functions and initial data processing. Further data processing and billet quality analysis are provided by a large computer. Visualization of the internal structure is aided by the use of a computer-controlled plotter.

The ultrasonic test system consists of a commercial ultrasonic tester with an automatic scanning and immersion system. Position readout indicators provide scan position and part rotation information. A special interface module receives ultrasonic test data from the tester and converts this information to analog voltages, while an auxiliary function module, controlled by the mini-computer, digitizes and records the position and ultrasonic information on magnetic tape.

The large computer analyzes the ultrasonic flaw data in terms of the up to 3300 possible nose-tip locations within the billet. In evaluating each particular nose-tip location, every flaw indication is assigned a weight. These weights are totaled for that cone location. The 15 positions having the lowest weights are presented to the design engineer for his final selection.

The plotter is used to provide graphical pictures of the flaws within the billet to aid the engineer in his selection of the optimum position of the nose tip. Plots

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are made showing all of the flaws in the billet by subdividing into slabs which run parallel to the billet axis and into discs perpendicular to the axis. Such plots show the flaw distribution in a clear, concise manner. Further programs plot histograms of the data with respect to three location parameters.

Acknowledgment

Many people have contributed to this project. The contributions of the following persons are particularly acknowledged: I. Auerbach, 9328, for his overall technical assistance; L. Bennett and W. Shurtleff, 7524, for their design and development of the H-21 computer program;¹ R. Halbgewachs, 9422, for the development of the CDC 6600 cone location computer program;² L. Hammes, 7524, for his design and fabrication assistance on the interface equipment; and B. Stiefeld, 7361, for the development of the 3-D visualization program.

INTRODUCTION

Reentry vehicles and various other vehicle applications require nose tips which can survive the high thermal and mechanical stress levels encountered during the reentry environment. Failure of the nose tip and/or its associated heat shield would normally result in the loss of the vehicle or in a severely altered mission. Therefore, the integrity of the nose tip must be maintained.

Graphite has proved to be a useful material in nose-tip applications; however, completely homogeneous graphite is very difficult to acquire. ATJ-S graphite, manufactured by the Union Carbide Company using proprietary processes,³ was selected for our application. Other types of graphite were also considered for the reentry vehicle application.

Graphite strength properties are drastically altered by discontinuities in the material. These discontinuities, which are prevalent in the material, may be noncarbon inclusions, high-density carbon inclusions, voids, porous areas, cracks, low-density areas, or sudden density changes. More broadly, any variation in the material, which could be a stress riser or contribute to a loss of cross-sectional area could be detrimental to the end use.

Recognizing that a billet of ATJ-S (Fig. 1) contains many discontinuities, it is then desirable to locate these discontinuities and to position the nose tip in such a manner as to avoid including any discontinuity in the finished part. Should this be unfeasible, it is desirable to avoid clustered discontinuities and to determine the location of those flaws remaining in the nose tip.

Because of a shortage of time for our test program and an even greater shortage of material, no definitive attempt was made to correlate ultrasonic echo characteristics to flaw characteristics. A report by Southern Research Institute⁴ indicates that ultrasonic echoes are indicative of true discontinuities in the material. The approach taken at Sandia was that any discontinuity was undesirable in our nose-tip application.

An ultrasonic nondestructive testing system was developed to locate all such discontinuities, record certain characteristics, and analyze these by use of a computer. The primary test system consists of fixturing, an ultrasonic test system, a signal processing interface, an on-line computer, and peripheral equipment. In addition to the primary test system, a large computer and computer-plotter are used for analysis.

PURPOSE OF THE REPORT

The purpose of this report is to describe the nondestructive testing and data analysis system used for evaluating the quality of ATJ-S graphite billets and to discuss the test results. The system will be described in two sections. The primary test section will include only the on-line test equipment, and the final data analysis section will describe the programming for the full-size computer and the computer-plotter.

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p3A

PRIMARY TEST SYSTEM

Our primary test system as shown in Fig. 2 consists of an ultrasonic test system, an electrical interface, an on-line computer, an input-output console, and a rack of peripheral equipment including a magnetic tape recorder.

Ultrasonic Test System

The ultrasonic test system consists of an immersion tank with associated fixturing and the ultrasonic tester. The immersion tank (Fig. 3) provides a mechanical system for both the test item and ultrasonic probe manipulation. The actual water tank is 3 feet deep, 4 feet wide, and 6 feet long. Water, immersing the test billet, provides coupling of the sound wave from the ultrasonic transducer into the billet. Absorption of water by the graphite billet is prevented by a strippable coating of polyvinyl chloride.

A billet is placed on a set of rollers (Fig. 4) which can incrementally or continuously rotate the part, while a potentiometer provides electrical analog signals of the rotational position of the billet. Angular increments are determined at the control panel on the bridge.

A traversing bridge spans the tank and, ordinarily, is free to roll to and fro. However, for this test, it is fixed to locate the transducer over the billet. The transducer is mounted on a search tube held in a manipulator (Fig. 5) which is, in turn, mounted on the bridge. The search tube can be moved back and forth axially, over the part, and a potentiometer provides an analog indication of the distance of the transducer from the end of the billet.

In the scanning operation, the ultrasonic transducer is positioned over the billet and perpendicular to it. The transducer moves, automatically, from one end of the billet to the other, stops, and retraces the path. During the pause at the end of the billet, the billet is rotationally incremented. On the retrace, then, the sound beam is scanning new material.

Bridge controls (Fig. 6) provide variable angle incrementing, variable transducer scanning speed, and selective start and stop positions. Manual controls on the search tube manipulator provide variable transducer-to-billet spacing (water travel) and variable entry angle.

An Immerscope* 424D ultrasonic tester (Fig. 7) is used to obtain the defect indications. A high-voltage pulse is fed to a piezoelectric crystal in the ultrasonic transducer located in the immersion tank. The crystal vibrates at its resonant frequency for a few cycles creating a pulse of sound in the water. The crystal used in this application is a focused, 5-MHz, lithium sulfate disc with a 4-inch focal length in water. The focal spot size is 0.10 inch.

Sound pulses travel through the water and impinge on the graphite billet. A portion of the sound penetrates the billet while a large portion is reflected. Ratio (R) of reflected-to-transmitted amplitudes is determined by the acoustic

*Commercial names throughout this report are used for identification purposes only and their use does not necessarily constitute an endorsement.

F2

p. 4A

f3

p4 B

Billet

Transducer

To
Potentiometer

Fixture

P4C
P3

F7

P 4 F

impedance (Z) mismatch. In water, where ρ is the density (gm/cc) and V is the sound velocity (in/sec),

$$Z_1 = \rho V = 1 \times 60,000 = 60,000 \text{ gm-in/cc-sec.}$$

In the billet, nominally,

$$Z_2 = \rho V = 1.8 \times 90,000 = 162,000 \text{ gm-in/cc-sec.}$$

Then,

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{162,000 - 60,000}{222,000} = 0.46.$$

Therefore, 46 percent of the incident wave amplitude is reflected and unusable for flaw detection.

Of the remaining 54 percent, a small portion may be reflected by a flaw. In addition to the interface losses, the signals are further attenuated by the graphite material. That portion of the echo which does return to the transducer creates a slight mechanical stress on the crystal which causes a low amplitude voltage to be generated. The Immerscope takes the echo-generated voltage signals from the transducer, amplifies, rectifies, and integrates them and displays them on the cathode ray tube (CRT). Instrumentation controls are set such that the first echo appearing on the tube is from the front surface with the flaw echoes appearing later in time. Time delay between the front surface echo and the flaw echoes is directly proportional to the depth of the flaw from the outside surface. The constant of proportionality is the sound velocity in the part.

It is interesting to note that, when evaluating graphite materials, an abundance of "noise" echoes is present. These signals originate from minute interfaces in the material and are of interest. However, because of the tremendous number of these, some are disregarded as explained in the section on the interface circuits.

The transducer is pulsed 200 times per second with each pulse lasting 2 to 3 microseconds. The remainder of the time, about 5000 microseconds, it is quiescent and waiting for echoes. As these echoes are received and displayed on the CRT, they are also transmitted, in parallel, to the interface for further processing.

Interface System

The interface system (Fig. 8) provides the mating function between the ultrasonic tester and the computer. Three main functions are:

- Signal amplitude discrimination.
- Signal amplitude and location analog conversions.
- Computer control-signal generation.

INTERFACE

Signal amplitude discrimination determines whether a particular ultrasonic signal will be considered. All signals with amplitude less than a predetermined level are rejected, and this level is determined by the echo amplitude from ultrasonic standard test blocks. For example, assume that the minimum echo acceptance level will be equal to the echo amplitude from a flat-bottom hole 0.030 inch in diameter. If the amplitude of the echo from such a standard hole is 40 percent of full scale on the CRT, the accept-reject level in the interface is set at 40 percent. Signals greater than this are processed; lesser signals are squelched.

In the amplitude and location conversion system, the time from the front surface echo to the flaw echo is converted to a proportional DC voltage. Since the velocity in the material is measured prior to this test, the DC voltage is proportional to the depth of the flaw. A second conversion equating the amplitude of the echo to a DC voltage is also made.

The interface (Fig. 9) operates as follows. The first signal or front surface echo is fed by the splitter to a ramp generator where a voltage ramp is started and fed to the depth peak-readers which begin reading the ramp. The second signal or first flaw echo is fed to a depth peak-reader at which time the ramp is inhibited to that reader and the voltage level at that time is held. The third signal or second flaw echo is fed to the second depth peak-reader and the operation is repeated.

Five channels are available to read five flaw echoes occurring from the same sound pulse. (During manual scanning operations previous to the construction of this system, multiple flaws had been noted with the transducer fixed in position.)

Simultaneously, with the peak-reading operation, the echoes are fed to the amplitude peak-readers where the peak amplitude is read and held. As echo signals are received, a signal is sent to the computer by the computer input control, informing the computer that test data are available and which data channels to interrogate.

Computer and Recording System

Our on-line computer (Fig. 10) is a Honeywell H-21 having an 18-bit word, 4096-word memory bit, 6-microsecond cycle time. Sixteen priority interrupt channels are available. An ASR 35 teletype provides input/output communication with the computer.

Other peripheral equipment includes a 40-microsecond converter with 16 A/D channels and seven D/A channels. A 100-step per second, incremental drive, digital, magnetic-tape recorder is also provided.

This system provides several functions:

- . System control.
- . Analog-to-digital data conversion.
- . Data formation.
- . Data recording.
- . Data real-time print-out.

Interface

Tape Recorder

H-21 Computer

Teletype

F10
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Data recorded by the system consists of the billet description and the flaw descriptions. The billet is described by its radius and length, while each flaw is described by four parameters. Angular position and distance from the end as determined by the fixture potentiometers, and depth and amplitude as determined by the ultrasonic tester and the interface serve to describe the flaws.

Operation of the computer is as follows. At the "run" signal, the computer commands the bridge to scan the billet. Data from the interface and the position indicators are stored during the scan. As the transducer reaches the end of the billet, an end-of-part (EOP) signal is generated, stopping the scan. The computer examines all the data, discriminates against some, organizes the data into the proper format, and records it. At the option of the operator, a real-time "quick look" print-out on the teletype may be performed in either octal or decimal numbers or both. At the end of the test, the operation is stopped and the operator is informed, via the teletype, of the number of flaws recorded and the number of sweeps in the 360-degree rotation.

The discrimination mentioned earlier rejects certain undesired signals. Signals occurring during the scan before or after the ends of the part originating from fixture parts are rejected. Signals occurring deeper in the part than one radius are also rejected to avoid duplication since these are picked up after 180-degree rotation of the billet.

The output of this operation is a magnetic tape record compatible with a CDC 6600 computer where further analysis is accomplished. In addition, an optional teletype print-out of all data is available.

FINAL DATA ANALYSIS

The primary test system just described acquires data which, if acquired by hand scanning, would require many man-hours and provide less precise data. System justification is also enhanced by the ease in which the data can be inserted into the CDC 6600 computer for analysis.

Analysis proceeds in two phases. First, a number of piece-part positions within the billet are examined and the coordinates of the best of these are delivered to the requestor for his selection. Second, in order to aid the requestor in his selection, histograms of the flaw distribution are drawn and orthogonal views of the flaws for 3-D simulation are drawn. This latter capability was added a few months after the initial program was instituted.

Piece-Part Location

In order to obtain piece parts, in this case nose tips (Fig. 11), with the optimum properties, a careful analysis of all possible positions within the billet must be made. The hollow nose tip is a cone approximately 10 inches long, 4 inches in diameter at the base, and 0.4 inch in wall thickness. In some cases, the cone may be truncated. The billets are usually 8 inches in diameter by 11.5 inches long.

A Fortran program has been written which, with some constraints, analyzes all possible cone positions. The major constraints are as follows:

F11

87A

- . No part of the cone will intersect the outer 1/8 inch deep skin of the billet.
- . No part of the cone will intersect material within 1/4 inch of the ends of the billet.
- . The axis of the cone will be parallel to the billet axis.

Since there are still an infinite number of possible positions, certain increments are established by the requestor each time a computer run is started.

Perhaps the easiest way to explain the program operation is by example (Fig. 12). The first location to be examined is with the axes of the cone and billet coincident and with the base of the cone at a specified distance, say, 1/4 inch from one end of the billet.

The computer evaluates that location and assigns a weighting factor. The cone position is translated out along a radius to give ΔR . This location is evaluated and weighted. Now the cone axis is moved along the circle with radius ΔR for a selected angular increment, $\Delta \theta$. Weighting is again performed.

When that circle is circumscribed, the radius is increased to $2\Delta R$ and the process repeated around that circle. It is desired, however, to retain an equal-volume relationship. Therefore, each time the radius is increased by ΔR , the angular increment is cut in half; e.g., at radius = ΔR , $\Delta \theta$, at radius = $2\Delta R$, $\Delta \theta/2$, and at radius = $3\Delta R$, $\Delta \theta/4$, etc.

At a certain $N\Delta R$, the sum of $N\Delta R$ and the cone radius is equal to or greater than the radius of the billet minus 1/8 inch. In other words, the cone intersects the 1/8 inch billet skin. Now, the process is halted, the base of the cone is incremented (ΔA) down the billet axis, the axis of the cone is again made coincident with the billet axis, and the process is repeated.

After several increments, $N\Delta A$, down the axis, the tip of the cone intersects the 1/4 inch skin on the other end of the billet. The process is again halted, the cone is reversed with respect to the billet, and the entire process is repeated.

By selection of the ΔR , $\Delta \theta$, and ΔA , the requestor may require the computer to evaluate any desired locations. Depending on the number of flaws, this usually varies from 200 to 2000 positions. The more flaws, the greater the number of positions necessary for optimum selection.

As the evaluation proceeds, the computer retains a number of these positions, say, 5, 10, or 15 as selected by the requestor, which have the lowest weighting factor. At the end of the run, these positions are printed out along with the four parameters describing each flaw included in the cone volume.

Cone weighting factors are selected by a repetitive weighting of each flaw with respect to the cone volume in each position (Fig. 13). In assigning the weight to each flaw, two factors are considered: (1) the amplitude of the echo from that flaw, and (2) the position of that flaw with respect to the wall thickness. That is, each flaw, which, according to its position coordinates, will be included in the wall of the cone is assigned a weighting factor, f , = 1. Weighting factors are assigned to flaws near the cone in a linearly decreasing manner. Then the weighting factor is multiplied by the echo amplitude, say,

F13

p8B

60 percent, to assign the weight to that flaw, and summing the flaw weights results in a total weight for that cone position. That is, $f \times A = w$ and $\sum w = W$.

A clustering parameter and a crack potential factor are also computed. The clustering parameter counts the number of flaws within a certain radius, r , of each flaw. A similar, but different number results in a crack potential factor. Imagine all flaws connected to all other flaws by lines. Counting the lines equal to or shorter than r helps the requestor in selecting the cone location.

Heretofore, we have been concerned only with conical shapes; however, the program is adaptable to at least six configurations. These are hollow or solid cones, truncated cones, and cylinders (Fig. 14). Any size piece part may be considered. For example, a recent application involved truncated cones approximately 3 inches long and 3 inches in diameter. Since the billets are 8 inches in diameter by 12 inches long, it was desired to cut more than one part per billet. The program was run in the normal fashion retaining the 15 best positions. Since these positions were not exclusive, the program was run again. This time, however, the billet was theoretically cut in half which yielded two right cylinders with 15 positions retained for each half. A third run was made, with the billet "cut" in thirds which yielded 45 more positions. Of the 90 positions thus generated, some of which were duplicated, it was possible to pick the desired 6 unique locations for piece parts.

While a million or more calculations are involved in a billet with 2000 to 3000 flaws and many possible nose-tip positions, the speed and memory capacity of the CDC 6600 computer reduces the operation to a matter of seconds.

In certain cases, after a cone location has been selected, it may be desired to select the best of the "scrap" material for fabrication of auxiliary parts. By searching for the "best" cylinder of small size not intersecting the cone, this is easily accomplished.

Data Presentation Displays

When the requestor receives the positions determined by the former program as having the lowest weight, he is still faced with the problem of selecting the actual position at which the cone or other part will be machined. To help him in that selection, two other computer outputs are prepared.

Data Histograms

In order to show any bias of the location of flaws within the billet and thus reveal nonuniform manufacturing techniques, histograms (Fig. 15) are prepared which display the number of flaws in a given segment of the billet. Three histograms are prepared which give the number of flaws, in percent of the total, as functions of angle from the centerline, length from the end, and radial distance from the center in equal-volume increments.

Angular distribution is calculated at some angular increment (i.e., 36 degrees), yielding ten bars on the histogram. Length down the billet is usually broken into ten parts also. Such divisions provide equal-volume

A
Angle Increment
Total Count 3478

<u>Dimension</u> <u>Limit</u>	<u>Percentage</u>
30.00	11.96***
60.00	5.64***
90.00	9.55***
120.00	7.45***
150.00	6.90***
180.00	6.56***
210.00	5.18***
240.00	9.23***
270.00	7.39***
300.00	7.62***
330.00	8.65***
360.00	12.94***

B
Length Increment
Total Count 3478

<u>Dimension</u> <u>Limit</u>	<u>Percentage</u>
1.56	11.27***
2.62	14.49***
3.68	12.13***
4.74	8.40***
5.80	6.93***
6.86	5.89***
7.92	11.47***
8.98	11.07***
10.04	9.55***
11.10	8.80***

C
Equal Value
Total Count 3478

<u>Dimension</u> <u>Limit</u>	<u>Percentage</u>
1.24	29.56***
1.75	10.41***
2.14	10.03***
2.47	10.06***
2.76	8.40***
3.03	7.68***
3.27	5.03***
3.50	6.01***
3.71	8.83***
3.91	4.00***

5/5

89B

increments. However, dividing the radius into equal increments does not yield equal volumes, and so, in order to do this, the radial divisions were established as follows where the volume of a cylinder is proportional to the area.

Divide the cross-sectional area of billet, A_B , by 10

$$\frac{A_B}{10} = \Delta A = \text{const}$$

$$\text{Area of cylinder} = \pi(R_L^2 - R_S^2) = \Delta A$$

where

R_L = radius, large

R_S = radius, small.

Then

$$R_L = \sqrt{\Delta A/\pi + R_S^2}.$$

For the first computation,

$$R_S = 0$$

$$R_{L_1} = \sqrt{\Delta A/\pi}$$

while in the second

$$R_{L_2} = \sqrt{\Delta A/\pi + R_{L_1}^2}$$

and, for the next,

$$R_{L_3} = \sqrt{\Delta A/\pi + R_{L_2}^2}.$$

Thus, ten equal-volume increments are created and plotted as histograms.

3-D Data Plots

Another aid to the requestor is 3-D data plots showing each flaw position in the billet. A true isometric or similar view could become cluttered beyond comprehension for a billet with a large number of flaws. Since spatial viewing was desirable, a means of accomplishing this was devised.

First, the billet was "cut into pieces" by the computer (Fig. 16), and then the pieces were displayed in orthogonal views by a Stromberg-Carlson 4020 plotter. Slabs were cut parallel to the billet axis and the 0 to 180 degree plane -- four

slabs on the left (270 degrees) and four on the right (90 degrees) running from end to end on the billet and numbered 1, 2, 3, 4 from the center to the outside. Slices were cut perpendicular to the axis (parallel to the end surfaces). Usually, eight slices are cut.

The plotter prints, in series, the outline of the left slabs 4, 3, 2, 1, showing all flaws located in each individual slab with division lines indicating the slices, then the eight circular slices with all flaws in each slice and division lines shown for the slabs, and then the right slabs are printed. Examples of a slab and slice print-out are shown in Figs. 17A & B.

Grid lines were spaced at each 1/2 inch so that dimensions could be established as marked by small numbers on the plot. Each slice and slab was identified and the overall dimensions were given. A simple comparison of the views (Fig. 18) will locate any flaw in its spatial relationship to the billet. Clustering of flaw indications is obvious.

A code disclosing the amplitude range of each flaw echo was adopted:

<u>Symbol</u>	<u>Percent Full Scale</u>
O	0 - 20
U	20 - 40
X	40 - 60
⊗	60 - 80
*	80 +

It is possible to have echo amplitudes greater than 100 percent of full scale. Normally, if the echo from a 0.030 inch diameter flat-bottomed hole is adjusted to 40 percent of full scale, the echo from a 0.060 inch diameter equivalent flaw will be more than 2-1/2 times as high or greater than 100 percent on the CRT. While the Emscope CRT will not show the maximum amplitude, the peak-readers will generate a voltage equivalent to the maximum.

DISCUSSION OF RESULTS

As of this point in the program, 21 billets have been evaluated by the system. Of these, four were analyzed for location of multiple small cones rather than one large cone. Some of these billets were AXF-5Q graphite made by the Poco Graphite Company. To truly judge the results, one should look at the success or failure of the end product.

Several nose tips have been cut from the billets as prescribed by this test system. Two full-scale reentry vehicles, using nose tips selected by the system, were exposed to moderate reentry conditions at the Pacific Test Range. The flights were completely successful. Other nose tips have been subjected to other types of environmental tests and these also successfully withstood the load.

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CENTER SLICE NO. IS

8.0

LIMITS ARE

10.28

11.75

F17A

P11A

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RIGHT SLAB NO.

1.0

2.0

3.0

4.0

1.0

3.0

6.0

7.0

8.0

RIGHT SLAB LIMITS ARE

0.0

9

F17B

P11B

CENTER SLICE 1

RIGHT SLAB 3

Fig

pic

Prior to the construction of the scanning system, the billets were manually scanned and the data were manually recorded. Punched cards were then prepared and fed into the computer. On one billet, the hand-scanning operation required over 40 manhours with the average about 8. Two to four hours were required for card preparation. With the new system, initial setup and calibration require about one hour, but subsequent setups require only a few minutes. Seven billets were tested in one day, dramatically illustrating the time-savings possible with this system. Even more important is the increased precision possible with the automatic process as compared to hand scanning and measurement.

Another improvement realized with this system is the capability of handling a higher sensitivity test. While ultrasonically scanning a billet, a certain "noise" level appears on the CRT which results from smaller and smaller interfaces in the material. Operator fatigue and discrimination capabilities limited the number of these which could be measured to about 1000. With the new system, this number is greatly increased and has been used to record over 11,000 discrete points (some of these were multiple indications of the same flaw). The actual number is not as important, however, as the precision in location and amplitude measurements.

The reliability of finding significant flaws manually was not measured but is undoubtedly rather low. With this system, however, the reliability is well over 99 percent (0.99).

CONCLUSIONS

The ultrasonic data system has been in operation for several months and certain conclusions may be drawn.

- . The system primary test provides a rapid and accurate method of acquiring and recording ultrasonic data.
- . The final data analysis system provides a rapid and accurate means of evaluating test data.
- . Visual aids, such as histograms and 3-D presentations, are valuable in reaching decisions concerning the products.
- . The system can be adapted to many materials and many piece parts.
- . The automation and computerization concepts can be applied to even more tests and products.

APPENDIX A

Preparation of Billets and Calibration

Procedure for the Immerscope - H-21 Computer System

The ATJ-S billets are first mechanically measured and the dimensions noted. The billets have serial numbers scribed on one flat end and this becomes the reference or base end of the billets. An arbitrary point is chosen on the reference end of the billet and is marked as 0 degrees. The angular position of the billets increases in a clockwise direction looking at the reference end.

A polyvinyl chloride coating is next sprayed on the billets, thus providing a strippable layer to protect the billets from water. In addition, the PVC coating provides a suitably smooth surface for ultrasonic inspection.

The H-21 computer provides four pieces of print-out information about each defect within the billet. These are:

1. Flaw amplitude in percent of full scale.
2. Depth of flaw in inches.
3. Angle of part in degrees.
4. Position of flaw from left or reference end in inches.

The calibration procedure consists of giving the H-21 the necessary data, in the form of DC voltages, for calculating the four pieces of information.

The DC voltages for calibrating the first two items above (flaw amplitude and depth) are static simulations of what, in the actual test, are dynamic occurrences. The other two items (angle of part and flaw position) are interrogations of DC voltages on potentiometers that are proportional to angle and horizontal position.

The flaw amplitude calibration voltage is obtained by putting a flaw signal on the Immerscope CRT that is 100 percent full scale. The amplitude channel of the interface is now applied to an auxiliary oscilloscope and a DC voltage, generated by a variable DC power supply, is inserted into the H-21 that is equal to the dynamic DC signal generated by the sample and hold circuitry. The H-21 now has a reference for flaws of 100 percent amplitude and during billet inspection will compare all flaw levels to this reference and print out data proportional to this reference.

The depth of flaw is obtained in much the same manner. The H-21 is told the radius (in inches) of the specimen and is then given a DC voltage that simulates that radius. The H-21 will now compare all flaw signals received

from the interface to the known reference for the radius of the specimen and place them in the proper position, depth-wise, in the billet.

The angle of the part is obtained by interrogating a rotation potentiometer connected to the end of the billet. The calibration consists of inserting into the computer the voltage equal to 360 degrees. The H-21 program, as written, is limited to calculating the angle from 0 to 360 degrees; therefore, 0 degrees on the billet must be aligned to correspond to 0 volts on the potentiometer.

The position of the flaw from the left, or reference end, is obtained by interrogating the potentiometer located on the immersion-tank scanning fixture. The length (in inches) of the specimen is inserted into the computer. The difference between two DC voltage levels, set by manually positioning the ultrasonic transducer over both ends of the specimen, is then proportional to the length of the billet.

Initiating the H-21 computer data entry program provides a print-out on the teletype as illustrated on Fig. A1.

Step-by-step procedure for calibrating the system under computer control is as follows:

1. Type in length of specimen.
2. Type in radius of specimen.
3. Bring into the computer, through an A/D converter, the following:
 - a. Far (right) limit (EOPR on Fig. A1) by positioning the ultrasonic transducer over far (right) end of specimen, using Immerscope CRT as a reference.
 - b. Left (near) limit (EOPL on Fig. A1) by positioning the ultrasonic transducer over the left (near) end of the specimen, again using the Immerscope CRT as a reference.
 - c. Radius of specimen (MAXD on Fig. A1) using a dual-channel oscilloscope with the video from the Immerscope on channel one input and the sweep interval from the Immerscope on channel two input. With the Immerscope sweep controls, set front and back ultrasonic echoes of the billet on the oscilloscope. Measure the transit time of the ultrasonic signal through the billet. Now, the Immerscope sweep controls are set so that sweep interval on the oscilloscope is $1/2$ the transit time through the billet. The inputs to the oscilloscope are then disconnected and replaced by D1 (first distance channel) of the interface and an external DC power supply. The DC power supply is then set to match the level of D1. Note: Caution must be taken so that no flaws are present on the Immerscope CRT. With the power supply thus set, disconnect from oscilloscope and insert this level into the computer where it is sampled and stored.
 - d. Reading for 360 degrees (ORA 360 degrees on Fig. A1) by rotating the billet until maximum voltage appears on the rotation potentiometer. This voltage is then inserted into the computer where it too is

ENTER THE FOLLOWING CONSTANTS ACCURATE TO NO MORE THAN + OR - .01

THE SPECIMEN LENGTH IN INCHES = 12.50	14.37	IN OCTAL
THE SPECIMEN RADIUS IN INCHES = 2.55	02.43	IN OCTAL

YOU WILL NOW GET A HALT ON THE COMPUTER. POSITION THE ULTRASONIC ARM OVER THE FAR (RIGHT) END OF THE SPECIMEN AND THEN GO TO "STEP AND RUN" ON THE COMPUTER.

EOPR = 2174

REPEAT THE ABOVE INSTRUCTIONS FOR THE LEFT (NEAR) SIDE OF THE SPECIMEN

EOPL = 1462

STEP-RUN TO BRING IN THE OCTAL READING OF THE RADIUS OF THE SPECIMEN.
MAXD = 1210

STEP AND RUN TO BRING IN THE OCTAL READING OF 360 ON THE ANGLE POT.
ORA360 = 1765

STEP AND RUN TO BRING IN THE OCTAL READING OF MAX AMPLITUDE EXPECTED.
ORFSAM = 1516

sampled and stored. During testing, the voltage should increase as degrees on the reference end of the billet increase. After the above is done, the potentiometer linkage is loosened and the billet is aligned with the 0-degree reference at 0 volts on the potentiometer.

- e. Reading for maximum amplitude expected (ORFSAM on Fig. A1). This is done by using a dual-channel oscilloscope with A1 from the interface connected to channel one and a DC power supply connected to channel two. First, ultrasonically locate a known flaw in an ultrasonic reference block and set the Immerscope gain so that the flaw signal is 100 percent of full scale on the CRT, while making certain no other flaw is present between the front surface echo and the known flaw. Then, set the DC power supply voltage to equal the A1 interface amplitude signal. After the power supply voltage is set, connect it to the H-21 computer where it is sampled and stored.

The above procedure has now given the H-21 the necessary information to allow it to assign to each flaw received a depth within the billet, a distance down the billet from the reference end, a rotational degree location around the billet, and an amplitude which is a relative measure of its size.

The final calibration step is to set the overall sensitivity of the entire system. As mentioned in the introduction of this report, the ATJ-S billets contain many discontinuities. By using the H-21 computer for on-line, real-time analysis and data storage, inspection time is no longer the limiting factor. The amount of data available is now the only test parameter considered. By increasing the sensitivity of the system, enough data can be obtained that the time needed to process the data on the large computer (CDC 6600) becomes prohibitive.

At first glance, the most obvious place to change the sensitivity is the Immerscope gain. This gain cannot be changed now, however, because, as shown in the calibration procedure, this gain is set to known flaw levels and the H-21 assigns flaw levels accordingly. Provision for adjusting sensitivity is provided on the interface. This sensitivity determines the level (percent of full scale on Immerscope CRT) at which the interface will start to accept flaw data. While watching the Immerscope video signal on one channel of an oscilloscope and the flaw interrupt signal (TP3 on card 10 of interface) on the other channel, the sensitivity control on the interface is varied to determine the level at which the flaw interrupt signal will start.

The ATJ-S billets, at the Immerscope gain settings mentioned, have an overall baseline signal, or noise, of 25 to 30 percent of full scale. Therefore, the interface sensitivity control is set so that Immerscope flaw signals between 30 and 40 percent initiate a flaw interrupt to the computer. The above sensitivity level determines the number of data points processed by the computer and stored on magnetic tape. On one comparatively "noisy" billet, 11,493 flaws were recorded when the flaw interrupt sensitivity was set at 30 percent. By reducing the sensitivity so that 40 percent flaws started the interrupt signal, the number of flaws in the same billet was reduced to 3,156. This vividly illustrates that most of the flaw information in ATJ-S billets is near the noise or background level.

The Immerscope gain and sensitivity time control (STC) are set so that a 0.031-inch diameter, flat-bottom hole located 1.0 inch below the surface of ATJ-S material is 80 percent of full scale and the same size flaw at 3.0 inches below the surface is 40 percent of full scale. Knowing these levels for known flaws places some meaning on amplitude readings for flaws from billets which cannot be destructively analyzed or test-drilled with known size holes. The differing responses to the above known flaws vividly illustrate the high attenuation of the ATJ-S material.

APPENDIX B

Real-Time Data Presentation

An example of the real-time print-out as obtained from the teletype is illustrated on Fig. B1. The print-out is controlled by the H-21 computer. The print-out can be initiated or halted any time during the ultrasonic test by operation of a switch on the H-21. The print-out contains all the processed data in engineering units and in the actual readings which are recorded on the magnetic tape.

The first column, Data Block Length, indicates the number of data words processed and recorded on one axial sweep of the ultrasonic transducer over the billet. This number is recorded on the magnetic tape in octal notation along with the octal data words. Since each flaw requires four data words to describe its location and amplitude, dividing the data block length number by four will give the number of flaws for one scan.

The second column, Flaw Level Number, indicates the number of flaws at one instant under the transducer looking through the radius of the billet. It is possible for several flaws to be lined up one on top of the other at one point in the billet. When this occurs, it is highly desirable to be able to record each of the flaws. The electronic interface used in this system is capable of processing information from five flaws at different depths at one instant. The operation of the interface is covered in detail in Appendix C. The print-out of flaw level is as illustrated. When only one flaw is received, only flaw level one is used. When more than one flaw in depth is received, successive flaw levels are used and are indicated by the print-out of two, three, etc., for as many flaws as received up to a maximum of five. The print-out must be in successive ascending numbers, if not it is an indication of a malfunction in the system.

The remaining four columns are the amplitude, depth, angle, and position of the flaws as illustrated. Observation of the four parameters of the flaws is a very useful diagnostic tool. Any unusual deviation in any of the columns is cause for stopping the test. At a glance, it can be seen whether or not the billet is incrementing properly. Depth of flaw and position of flaw are good indicators of proper calibration. Unusually high or low amplitude readings would be scrutinized closely.

At the end of the inspection of the billet, the H-21 computer will type out the message as illustrated on Fig. B1. This is a summary of the complete test and is especially useful for a quick qualitative comparison of one billet to another. Here again, dividing the number of data words by four will give the

1-----ENGINEERING UNITS-----1

1---OCTAL READINGS---1

DATA BLOCK LENGTH	FLAW LEVEL NO.	FLAW AMPLITUDE IN % F/S.	DEPTH IN INCHES	ANGLE OF PART	POSITION OF FLAW FROM LT.	AMP.	DEP.	ANG.	PØS.
12	1	69.24	1.44	0.00	5.62	1072	0702	0000	1256
	1	68.63	2.62	0.00	4.26	1065	1206	0000	1157
	1	57.94	0.70	0.00	0.36	0735	0335	0000	0650
8	1	73.13	0.00	1.76	1.74	1123	0000	0005	0731
	1	52.46	2.24	1.76	12.26	0660	1274	0005	1747
	1	64.74	1.96	20.00	0.13	1025	1152	0070	0654
	1	104.12	2.25	20.33	1.87	1531	1300	0071	0776
	1	60.02	1.20	20.33	4.44	0756	0570	0071	1167
	1	76.95	2.52	20.00	6.37	1151	1421	0070	1322
	1	54.53	0.53	20.33	8.43	0701	0255	0071	1462
12	1	53.81	2.50	180.00	2.57	0673	1200	0770	1037
	2	53.81	2.24	180.00	2.57	0673	1165	0770	1037
	1	74.83	2.52	180.00	6.46	1150	1417	0770	1326
12	1	85.76	0.63	360.00	6.55	1302	0311	1762	1332
	1	70.70	1.44	360.00	5.57	1106	0706	1762	1254
	1	50.41	1.31	360.00	4.24	0637	0630	1762	1155

TEST OVER. HALTING OPERATION.

TOTAL NUMBER OF SWEEPS FOR THIS BILLET IS 360.

TOTAL NUMBER OF DATA WORDS IN ENTIRE TEST 4180.

FB-1 P16A

total number of flaws processed and recorded during the ultrasonic examination of this particular billet. The total number of sweeps can be varied, as desired, and is listed to show how many sweeps were used.

After a few billets were inspected using the Immerscope-interface-H-21 computer system and it became known that the system was operating properly, it was observed that a 100 percent real-time print-out by the teletype of the flaw data from one billet would require too much time. It was not uncommon to require two to three hours to completely inspect one billet and print out the data. In comparison, 15 to 30 minutes were required if the print-out was deleted.

APPENDIX C

Operation of the Interface

This appendix describes the operation of the computer interface used in the Sandia-built ultrasonic test system. Operating as a link between the Immerscope 424D and H-21 computer, this device must convert fast-pulse, ultrasonic flaw signals into a form compatible with the H-21. It is insufficient to know only that a flaw exists; its amplitude and depth must also be known. Since it is possible to receive more than one echo associated with any one excitation pulse, it also becomes necessary to know how many echoes there are. These, then are the requirements of the interface:

1. Determine how many, if any, flaw echoes have been received.
2. Measure their individual amplitudes.
3. Measure their individual depths as a function of time.
4. Inform the computer that the echoes have been received and make all of the above information available in voltage form at the right time.
5. Perform all of the above for each repetition of the excitation pulse (200 times every second).

The location of the transducer over the test part is also necessary information; however, angular and distance coordinates are continuously available from position transducers which are automatically interrogated any time there is flaw information. Since this is a program operation, it is not considered part of the interface.

The interface has the capacity to measure five flaws in any one frame, where a frame is that period of time associated with any one excitation pulse. A detailed description of this interface follows.

Immerscope Adjustment

Refer to Fig. C1. Trace A. This is the overall timing for the ultrasonic system. The first echo seen after the excitation pulse is the front surface. Any flaws in the material would come next, then the back surface echo. This

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entire series repeats every 5 milliseconds, or 200 times per second. Because the transducer is in motion, each frame is "viewing" a slightly different location. The delay and sweep controls on the Immerscope are adjusted so as to display, on the CRT, only that portion of time that is of interest. This portion of time extends from just before the front surface to just beyond half way through the part and is depicted in Fig. C1, Trace B, as the sweep interval. The other half of the cylinder is tested as the part is rotated. This time interval is very important because the echoes from any flaws in the material must occur during this time. By agreement, the first echo on the CRT shall be the front surface; that is, the first signal in time during the sweep interval shall be the front surface. This is necessary to satisfy all the logical requirements that follow.

Peak-Readers

The peak-readers used in this system are custom-made and must respond to very fast signals (less than $1/4$ microsecond rise-time).

These readers respond only to positive signals and will retain the most positive input seen since the last time they were reset to zero. Their inputs may be gated and their outputs inhibited at will. They may also be reset at any time. Ten of these peak-readers are used in the interface: five read echo pulse amplitude and five read echo time or depth. The function of the logic modules is to steer the proper input and gating signals to the ten peak-readers. This may now be considered in some detail.

The Depth Ramp

Figure C2, Trace A, shows a typical CRT display with a front surface echo followed by four flaws. The sensitivity threshold for the interface is determined by a Schmitt trigger and is represented by the dotted line shown in Trace A. As can be seen, the fourth echo is of insufficient amplitude to be considered. Trace B is a pulse representative of the sweep interval. Trace C is the Schmitt trigger output.

If the velocity of the material being tested is assumed to be constant, then the distance a flaw is below the front surface is directly proportional to time. To measure this time, a linear ramp is started with the receipt of the front surface echo and terminated at the end of the sweep interval. This ramp generation time is shown in Trace D and is derived from logical operations using B (sweep time) and C (Schmitt trigger output). The ramp itself is shown in Trace E. This ramp is simultaneously applied to all five depth peak-readers. When the first flaw echo appears, the input to the channel one depth peak-reader is inhibited; that is, the ramp at its input is cut off. As each successive flaw appears, their respective inputs are inhibited. This action is shown in Fig. C3.

The peak value attained at each input will be held by the peak-readers until they are reset.

The acceptance time for the ramp at the various inputs is shown in Fig. C3 and at the bottom of Fig. C2. Notice that channels four and five receive

THRESHOLD
FOR SCHMITT
TRIGGER

DISPLAY ON CRT

A

B

SCHMITT TRIGGER
OUTPUT

C

D

SWEPTIME DERIVED FROM IMMERSCOPE
UNBLANKING SIGNAL

RAMP TIME (DERIVED FROM LOGIC)

RAMP

E

TIME, FLAW CHANNEL #1

TIME, FLAW CHANNEL #2

TIME, FLAW CHANNEL #3

TIME, FLAW CHANNELS #4, #5
(ALL DERIVED FROM LOGIC)

4818

2-22-5

CHANNEL

CHANNEL

INHIBITED RAMPS FED
TO THE FIVE TIME
(DEPTH) CHANNELS

0180

3-23

completely uninhibited ramps in this example. The reason is that there are no fourth and fifth flaws in this frame. Although this means that channels four and five read maximum depth, i.e., greater than the billet radius, these levels will be rejected by the computer.

Figure C4 shows how these ramp acceptance times are derived. The Schmitt trigger pulses are fed to a BCD counter and the counter output is decoded as shown for the first three channels.

These decoded intervals are gated with the original Schmitt trigger pulses to create the ramp inhibit pulses. These inhibit pulses reset flip-flops which were set by the front surface signal. The output from these flip-flops gates the ramp off and on at the input of the peak-readers. Notice again that the example shows no fourth and fifth inhibit pulses.

These inhibit pulses, operating through one-shots (monostable multivibrators), create the interrupt pulses that tell the computer which flaws have been received and, consequently, which channels to interrogate. For this reason the depth readings of channels four and five are immaterial in this example.

Amplitude Peak-Readers

The five amplitude peak-readers operate in much the same way. The decoded counter output used to determine when to inhibit the ramp inputs to the depth peak-readers is also used to gate the inputs for the amplitude peak-readers. This time, however, no further logical operations are necessary and the decoded intervals are used in their existing state.

The video signal is simultaneously applied to all five amplitude peak-readers. The counter outputs hold the various gates open only long enough to pass the appropriate pulse to the appropriate peak-reader. The effects of this operation are shown in Fig. C5. The amplitudes of the echoes will be held by their respective peak-readers until they are reset.

Output

A pictorial representation of the operation of all the peak-readers is shown in Fig. C6. The actual final output of the peak-readers is inhibited (held at zero volts) until the end of the sweep interval. At that time, the outputs are allowed to rise and remain so for approximately 0.7 millisecond, and then all ten of the peak-readers are reset simultaneously by a 0.16-millisecond pulse. The timing for these events is shown in Fig. C1.

During the 0.8-millisecond interval, the computer interrogates the interface for information. When a channel one flaw interrupt is received, its amplitude is immediately interrogated, followed by its depth, then its coordinates. This information is processed, then stored in the computer's memory. The computer then looks to see if a channel two interrupt has been received. If it has, all channel two information is interrogated in a similar manner. If necessary, this process continues for all five channels. The computer then resets its interrupt lines and waits again for a channel one interrupt.

THESE PULSES
ALSO GENERATE
THE INTERRUPTS
THROUGH 5
SINGLE - SHOTS

Fig 19A
F-2-4

0118B
TC-5

*THE FINAL OUTPUT OF THE PEAK-READERS IS INHIBITED UNTIL THE END OF THE SWEEP INTERVAL (CRT DISPLAY TIME).

9-22-68

After the transducer scans off the part, an end-of-part interrupt is generated which instructs the computer to process and output all the information stored for the entire scan. During this output time, the computer inhibits the scanning mechanism as long as necessary to place all the information on tape. At the present time, this interrupt is generated by an adjustable mechanical switch assembly mounted on the scanning fixture. A later modification will derive the interrupt from the front surface echo; that is, as the transducer leaves the part, the front surface echo disappears.

References

1. Bennett, L. C., Shurtleff, W. W., "A Computerized Ultrasonic Data Acquisition System," Sandia Corp., SC-DR-70-680, Uncl., October, 1970.
2. Hallgewachs, R. D., "Analysis of Optimal Selection of Nose Cones from Billets and Use of the Computer Program Cone," Sandia Corp., SC-RR-70-586, Uncl., September, 1970.
3. Kirkhart, F. P. (Battelle Memorial Institute, Columbus Laboratories), "Characterization of ATJ-S Graphite for Investigation of Graphite Response to Severe Reentry," Sandia Corp., SC-CR-69-6297 (Prepared under Sandia Order No. FAO 48-7044) Uncl., October, 1969.
4. Pears, C. D., Sanders, H. G. (Southern Research Institute), "A Strength Analysis of a Polygraphite," Air Force Materials Laboratory, AFWL-TR-69-204, Part II, Uncl., December, 1969.

FIGURE LIST

Fig. No.

Caption

1. ATJ-S Graphite Billet
2. Block Diagram, Ultrasonic Test System
3. Immersion Tank and Bridge Assembly
4. Rotating Fixture with Billet
5. Search Tube, Manipulator, and Bridge
6. Bridge Control Panel
7. Ultrasonic Tester
8. Signal Interface System (Temporary)
9. Block Diagram, Signal Interface System
10. On-Line Computer System
11. Graphite Nose Tips in Rough Machined Condition
12. Relative Cone Positions Showing First, Second, and Third Positions
13. Weighting Function, f , Versus Thickness, t ; $0 \leq f \leq 1$
14. Six Normal Piece-Part Configurations, All Circular Cross Sections
15. Computer-Plotted Histograms: (A) Angle Increment, (B) Length Increment, and (C) Equal Volume
16. Slice and Slab Generation System
- 17A. Typical Slice Computer Plot
- 17B. Typical Slab Computer Plot
18. 3-D Flaw Correlation
- A1. H-21 Computer Data Entry Sheet
- B1. H-21 Computer Flaw Record
- C1. Ultrasonic System Overall Timing Diagram
- C2. Timing Diagram, Depth Peak-Reader
- C3. Ramp Inhibit Timing Diagram
- C4. Ramp Acceptance Timing Diagram

FIGURE LIST (cont'd)

Fig. No.

C5. Gate Timing for Amplitude Peak-Readers

C6. Peak-Reader Outputs