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EVALUATION OF THE IRAD SONIC EXTENSOMETERS
FOR APPLICATION IN
THE CANADIAN UNDERGROUND RESEARCH LABORATORY
(FY 1983)

H. D. GLENN
L. S. BUTLER

SEPTEMBER 1983

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

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OR 2096-6

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I. INTRODUCTION

The Canadian government is studying the feasibility of disposal of high-level nuclear waste in deep underground vaults situated in granitic formations of the Canadian shield. For this purpose the Atomic Energy of Canada, Ltd. (AECL), is developing an Underground Research Laboratory (URL) to examine technical problems related to nuclear waste disposal in granitic intrusives. The experience gained by the Lawrence Livermore National Laboratory (LLNL) in conducting the Spent Fuel Test-Climax (SFT-C) in a granite intrusive at the Nevada Test Site (NTS) was thought to be applicable. To provide a mechanism for performing research of mutual benefit to the AECL and the U. S. crystalline rock programs, a U. S./Canadian Cooperative Agreement was formulated which is administered and funded by the U. S. Department of Energy's Office of Crystalline Repository Development (DOE-OCRD).

Initially, the SFT-C Program was planned as a 3- to 5-year test¹ and instrumentation was selected² which was specified to be capable of surviving the environment for that period of time. An extensive array of instrumentation was installed at the Climax site to provide an experimental basis for checking the finite element codes used to numerically simulate the experimental results.³ A significant fraction of the instrumentation initially installed experienced failure. Failure was primarily attributed to the hostile environment to which the instrumentations were subjected.⁴ The need to identify or develop instruments to provide long-term monitoring of geotechnical parameters in nuclear waste repositories has been recently reviewed.⁵ One of the more promising instruments that could potentially satisfy many of the requirements cited⁵ is the IRAD sonic extensometer.⁶ The principal advantage of this system is that it is portable and the sonic probe is only inserted in a borehole at the time readings are made. Consequently, the IRAD sonic extensometer can be stored in a benign environment and not be continuously exposed to the hostile environment that previous instrumentation experienced. This system does use magnetic anchors that are permanently emplaced but they are of rugged construction that should be impervious to the environment in the borehole. In addition, the anchors are not spring-loaded in the direction of the borehole axis (as are other types of extensometers) and are, therefore, not as likely to be affected by shock loading from blasting for excavation, nor tension induced creep.

This report supplements an earlier study⁷ that discussed the suitability of using the IRAD sonic extensometer in the Underground Research Laboratory proposed by the Atomic Energy of Canada, Ltd. In particular, it addresses the first and fourth recommendations made in that report concerning the basic accuracy of the instrument and evaluation of the electronic circuitry, respectively.

II. EXPERIMENTAL SYSTEMS

Our basic objective in the design of a test facility was to determine the accuracy of the IRAD sonic extensometer in measuring small displacements of the magnetic anchors. As described previously⁶, a current pulse generates a magnetic field that interacts with the permanent magnetic field at each anchor. The interaction of the two magnetic fields induces a magneto-strictive pulse. The magneto-strictive effect generates a stress wave that propagates with its characteristic sonic velocity, ≈ 9177.5 ft/s (2.797 Km/s), from the magnetic anchor location to the probe head where it is converted by a transducer into an electronic signal. Following amplification in the probe and again in the MB-7D readout, the electronic signal triggers a quartz oscillator based time interval counter (TIC). Then an electronic signal from a second magnetic anchor again triggers the TIC and the distance between the two magnetic anchors is calculated based on a prescribed value for the sonic wave velocity in the probe. The distance between the two magnetic anchors is shown with a liquid crystal display (LCD) on the MB-7D box to the nearest 0.001 in. (0.025mm).

For a typical in situ application, the surrounding media would normally be devoid of magnetic materials. To simulate this aspect of the in situ environment, the bench fixture used in the laboratory tests was constructed of non-magnetic materials. For example, the cart used to support each magnetic anchor (Fig. 1) was fabricated using aluminum stock. Although the two micrometers (shown in Fig. 1) were commercially obtained, they were constructed of non-magnetic materials. In addition, the four springs used to support each magnetic anchor and maintain positive contact with the micrometers and the four set screws for securing the position of each cart, were all made of brass. Finally, the track on which the carts were located was a 20-ft. long aluminum I-beam. The aluminum I-beam, collar anchor and a total of five carts with magnetic anchors were assembled in the laboratory

on a wooden bench well away from any metallic surfaces or instrumentation that might influence or induce perturbations to the readings. By maintaining strict control on the surroundings, we strove to eliminate extraneous effects that might influence the measurements.

An example of extraneous effects that can alter results of the measurements would be changes in temperature during the time interval measurements were being taken. To reduce the effect of this potential problem, the test facility was located in a thermostatically-controlled laboratory at the Lawrence Livermore National Laboratory (LLNL). To gain further assurance about possible temperature changes the aluminum I-beam was monitored at the appropriate quadrature locations⁸ with five thermistors. Each thermistor was physically bonded to its station using a thermally conductive epoxy. Leads from each thermistor were electrically connected to individual channels of a Hewlett-Packard 3467A digital readout. Temperature readings were taken at the beginning, then at 30 minute intervals, and finally at the end of each series of displacement readings. Over the course of each series of readings the largest temperature change recorded was $\leq 0.2^{\circ}\text{C}$. This temperature change was small enough that no corrections were required or incorporated into the final tabulation of the displacement readings (the greatest error for the longest test interval was ≈ 0.0005 in.).

III. EXPERIMENTAL RESULTS

This section is partitioned into three subsections. The first subsection concerns the accuracy of the MB-7D readout when measuring the distance between two magnetic anchors. This measurement defines how well the sonic probe matches the sonic velocity factor used in converting the time interval between return signals from two magnetic anchors into a distance reading shown on the LCD display. The second subsection determines the accuracy of the MB-7D readout to small changes in the position of a magnetic anchor. The last subsection examines the electronic circuits. This approach isolates that portion of the reading variations which is due

to the electronic circuits and that portion which is due to the sonic probe. This analysis also helps identify what segments of the electronic circuit might be modified to improve performance or accuracy.

A. Distance Correction Factors

The first run, using the test facility described in the previous section, was a check on the accuracy of the sonic extensometer to record the distance between two magnetic anchors. To conduct this test, two carts were separated a distance of 5 ft. and a series of three readings were taken. This process was repeated after moving the second cart to give separations of 10- and 15-ft. The cart separations were determined via a tape bonded to the side of the aluminum I-beam. To check how accurately we positioned the carts the above series of readings were repeated. The above check was performed using a probe (S/N 1001) that had been carefully selected⁹ at IRAD for our use. On 21 June 1983 we received a second sonic probe (S/N A1012RP) that was "out of stock" and not subjected to the prescreening selection conducted for the earlier sonic probe. For sake of simplicity let us designate the two probes the "old" and "new" probes, respectively. Following receipt of the new probe it was subjected to the same runs as performed previously with the old probe. In all cases repositioning of the second cart after the first set of runs at 5-, 10-, and 15-ft. gave readings that indicated the repositioning was reproducible to within 0.01 inches. Results from the above runs provided the following correction factors, C_f , for the two probes.

$$(\text{old}) C_f = 1.0213$$

$$(\text{new}) C_f = 1.0195$$

At all three distances the readings for both sonic probes were low by about 2%. This means the above correction factors should be multiplied by any sonic probe reading to obtain the actual distance between the corresponding magnetic anchors. For the displacement measurements reported here, the above correction factors add 0.001 in. to those readings of 0.03 in. or larger.

B. Displacement Measurements

To conduct these measurements, all five carts containing magnetic anchors were located on the 20-ft. aluminum I-beam at the appropriate quadrature locations.⁸ The third cart was set at the middle (10 ft.) of the I-beam and represents the null point (i.e., the micrometer settings on this cart were not changed). Then the second and fourth carts were located ≈ 64.616 inches or equidistance on either side of the third cart. Finally, the first

and fifth carts were spaced ≈ 44.125 inches from the second and fourth carts, respectively. In summary, the spacings between the five carts would be 44.125-, 64.616-, 64.616- and 44.125-inches. The standard metallic collar anchor was not used in this series of tests because the construction varies considerably from that of the typical polymer body c-anchor contained in each cart.

In the displacement results that are presented, only the micrometers located on carts two and four were changed. The changes were confined to these carts in order to compensate for any non-linearities that might accompany the movement of the magnetic anchors. The non-linearity of major concern was variability in the spring constant as movement of the magnetic anchor either compresses the four brass springs or allows the springs to expand. For example, say we adjust the micrometers on the second cart to move the magnetic anchor a distance of 0.005 inches. In so doing we should shorten the first interval (44.125 in.) between the first two anchors by the above amount and we should at the same time expect to lengthen the second interval (64.616 in.) between the second and third anchors a corresponding amount. Failure of the anchors to move the prescribed micrometer settings should be seen in both readings and provide the opportunity to compensate for the discrepancy. Although the above problem occurred frequently (approximately 50% of the time), the differences generally were small, of the order of 0.001 in.

In conducting the displacement tests we followed a standard procedure. The micrometers on the second and fourth carts were changed in the following fashion: 0.001 in. increments from 0.0- to 0.01-in., 0.005 in. increments from 0.01- to 0.02-in., and 0.01 in. increments from 0.02- to 0.05-in. Two MB-70 readings were recorded for each micrometer settings and for each interval between the magnetic anchors. Each recorded reading consisted of a mental (subjective) average of about 25 different readings that were spaced about one second apart and which appeared on the LCD display following the depression of the pulse switch. Generally each of the 25 readings only varied in the final digit (.001 in.) position since all 25 readings were for the same distance interval between two magnetic anchors. The fact the last digit was the only one that generally changed greatly aided the mental averaging that must be done, but it does make the final reading adopted a very subjective measurement. For the old probe the final digit (.001 in.) values varied by at least two digits but not more than four digits. The

corresponding variability for the new probe was from at least four digits to not more than seven digits. Essentially the range over which the 25 readings varied for the new probe was about twice that of the old probe. This made the mental averaging process more difficult and possibly more prone to error for the new probe. However, in presentation of the experimental results we will only give the range for the subjectively averaged readings for each micrometer setting. The reader is reminded that the LCD display on the MB-7D readout may have had readings that varied over a much larger range than will be shown in the following graphic presentation of the experimental results for the variability of the average readings.

The range of the averaged displacement readings from the MB-7D display versus the micrometer settings are shown in Fig. 2. This figure represents results for the first and second intervals when using the old probe. Note that in Fig. 2 we broke both axes between 0.012- and 0.015-inches and made a scale change. This graphic format was followed on all the experimental displacements results that will be shown. Fig. 3 shows the corresponding results for the third and fourth intervals using the old probe. The results in each figure represents the range for two intervals to compensate for displacement discrepancies due to non-linearity in the spring constant that was mentioned earlier. The results for Fig. 2 corresponds to micrometer changes that shortened the first interval, but lengthened the second interval. In Fig. 3 the fourth interval was shortened and the third lengthened. The results displayed in Figs. 4 and 5 correspond to Figs. 2 and 3, respectively, but the direction of the micrometer movements were reversed. The springs were being compressed in Figs. 2 and 5 and were being relaxed in Figs. 3 and 4.

Understanding what is shown in Figs. 2-5 may require a little explanation. Lets consider two micrometer settings in Fig. 3. For a micrometer setting of 0.007 in., the magnitude of the MB-7D displacement readings in the third interval were: 0.005- and 0.006-in.; and the fourth interval: 0.006-in. and 0.007-in. Thus the range for these two intervals is 0.005-0.007 in. as shown in Fig. 3. Similarly for micrometer setting of 0.030 in., the range for the two intervals was 0.028-0.030 in., but appears less than the micrometer setting at 0.007 in. because of the scale change. Examining the four figures reveals several interesting features. The MB-7D readings have a tendency to read a value equal to or less than the micrometer settings. Variability of the readings increase with range, i.e., the

readings for the third and fourth intervals are more variable than the first and second intervals. Then there is the rather obvious fact that although the range of the readings at the larger displacements (0.015-0.050-in.) may be comparable to the smaller displacements (0.0-0.01 in.) the percentage variability is considerably greater for the smaller displacements. The basic conclusion from the tests results is for displacements ≤ 0.05 in., the reading error is equal to or less than ± 0.002 in. for the old probe.

When the new probe was received, it was subjected to the same displacement tests conducted on the old probe. Figures 6-9 represent those results and they correspond to Figs. 2-5, respectively. The reader is reminded that the new probe did not experience any prescreening selection process and represents what might be termed an "off the shelf" item. Generally, the remarks about the old probe readings can be applied to the newer probe. The basic conclusion from test results with the new probe is for displacements ≤ 0.05 in., the reading error is equal to or less than ± 0.003 in. The greater accuracy of the old probe is readily evident when comparing the two sets of figures for the two probes.

C. Evaluation of the Electronic Circuitry

The basic operation and functions of various components of the electronic circuits for the IRAD sonic extensometer systems were described earlier. In this subsection we shall examine in detail only the electronic circuit in the MB-7D readout box. An attempt was made to examine the pre-amplifier circuit located in the head assembly of the probe. However, return signals from the magnetic anchors were too weak for us to accurately measure without significantly altering the waveforms. Consequently, an analysis of the preamplifier in the probe head of the sonic extensometer system was not obtained. The components of the MB-7D readout that were examined and the order that they will be reported are: crystal oscillator, counter circuit, probe drive generator, return pulse amplifier and Schmitt trigger (a threshold detection circuit), and a comparison of the return signal from the two probes.

1. Crystal oscillator stability

The frequency of 110.13 MHz was chosen for the oscillator since at this frequency the period of one cycle corresponds to the time that the stress pulse takes to travel 0.001 in. along the sonic probe. Thus, the display on the MB-7D box corresponds to the oscillator count and is also equivalent to the distance in inches between two magnetic anchors. The resolutions for

these distance readings would theoretically be 0.001 in. Since the crystal oscillator is so fundamental to the distance measurements, a check of the crystal stability was made. The MB-7D crystal oscillator was rewired so that the crystal was in a free running mode to ensure an accurate reading on the external frequency counter. Frequency readings were taken hourly during the day for a three day period. Over this period the frequency of the oscillator was:

$$110.12994 \pm 0.0001 \text{ MHz}$$

An error of this magnitude normally would not show up on the MB-7D readout due to its six digit resolution. Consequently, the crystal oscillator is capable of achieving an accuracy of better than 0.001 in.

2. Counter circuit

An important part of each distance reading with the MB-7D readout is the electronic circuit used to count the number of cycles between two return pulses. To evaluate the accuracy of the counter circuit, the sonic probe input was disconnected and an external time synthesizer was used to simulate the return signals from the sonic probe. Initially a time interval of 393.70078 μ s was input to simulate the distance of 43.359 in. which corresponds approximately to the first quadrature interval for the displacement readings. For the above time interval, the MB-7D readings ranged from 43.358 to 43.360 in. with an average reading of 43.359 in. Then the time interval was increased by increments of 0.00908 μ s to simulate the displacement of 0.001 in. This pattern of time increment changes was continued until the corresponding displacement of 0.01 in. was attained. Then the time increments were increased to correspond to additional displacements of 0.005 and 0.01 in. The time increment format followed the format used in the displacements measurement with the sonic probe and magnetic anchors set at the quadrature positions. For example, with the time synthesizer set at 393.79158 μ s, an increase of 0.0908 μ s, the MB-7D displays had readings of 43.369 and 43.370 in., with an average reading of 43.369 in. This corresponds to a displacement of + 0.01 in. with respect to the original setting and is in agreement with the total change in the time increments. In addition to increasing the time interval to simulate positive displacements, a comparable set of readings were taken where the time interval was decreased to simulate negative displacements. In summary, the time synthesizer was used to simulate displacements of 0.001 in. from 0.0 to $\pm$ 0.01 in., 0.005 in from $\pm$ 0.01 to $\pm$ 0.02 in., and 0.010 in. from

± 0.02 to ± 0.05 in. The MB-7D averaged readings very accurately tracked the displacements that were time synthesized. However, each averaged reading had a range of up to ± 0.001 in. Actually a plus or minus one count (± 0.001 in.) variation is inherent in binary coded decimal (BCD) counters. An improved high-frequency counter circuitry would reduce this error but would require a corresponding increase in the crystal frequency.

3. Probe drive pulse.

Following depression of the toggle switch on the MB-7D box a series of drive pulses are generated that propagate along the sonic probe. We examined how reproducible the pulses are and how sensitive the MB-7D readings are to variations in the pulse shape. These features and other aspects of the drive pulse sent to the sonic probe are discussed below.

To determine the repeatability of the pulse shape a series of ten traces were recorded on film. All ten traces for the drive pulse were in excellent agreement, not only in magnitude but in every particular of the waveform. Each drive pulse consisted of an initial rise time of 4ns to the 2 volt level where it plateaus for 30ns. This was followed by another rise of 7-8ns to 3 volts at which level it stayed for the remaining duration of the 1 μ s pulse width. The 30ns step at 2 volts is attributed to an impedance mismatch between the 43 Ω cable that connects the MB-7D box to the probe and the 93 Ω input of the probe head.

An external pulse generator was substituted for the probe drive pulse generator in the MB-7D to simulate the 4ns rise and fall times and 1 μ s width drive pulse. The amplitude of the drive pulse was slowly decreased until at 1.4V the MB-7D failed to give a reading for spacing between anchors of 43.264 in. Thus, any drive pulse with an amplitude equal to or less than 1.4V will not be sufficient to generate a return signal. A pulse height just slightly in excess of the 1.4V threshold indicated no degradation of the return signal or change in the MB-7D reading. To determine whether the threshold was affected by spacing between two magnetic anchors, a check was done at 1 ft. and 18 ft. for both probes. The amplitude from the external pulse generator was slowly decreased until no reading on the MB-7D readout was obtained. For both probes the lower threshold of the drive pulse to generate a return signal was determined to be about 1.4V for both the 1-ft. and 18-ft. separations of two magnetic anchors. The constant threshold voltage of 1.4V is not meant to suggest that attenuation does not occur for the return signal in the sonic probe with distance. From the time the drive

pulse is generated, the amount of amplification for the return signal increases linearly with time. Consequently, return signals from magnetic anchors located further from the probe head undergo a proportionally greater amplification. This fact may clarify the constant 1.4V threshold for the amplitude of the drive pulse to generate a return signal and obtain a MB-7D reading irrespective of the distance between two anchors.

To further investigate sensitivity of the return signal and MB-7D readings, the probe was connected back to the MB-7D. Then two magnetic anchors were set apart a distance of 43.263 in. and the reading recorded. Again the external pulse generator was connected to the probe and sensitivity of the return signals and MB-7D readings examined as a function of changes in drive pulse. Results for the MB-7D readings to changes in the drive pulse shape are summarized in Table 1. With the exception of a small increase in the range of the readings about the average value, the test results suggest a high degree of insensitivity to wide variations of the drive pulse shape. Records of the oscilloscope traces for each entry in the Table did not reveal any discernible change in the waveforms for the return signals.

TABLE 1. Sensitivity of MB-7D readings to variations in the probe drive pulse.

<u>Drive Pulse Source</u>	<u>Rise and Fall Times (ns)</u>	<u>Pulse Width (μs)</u>	<u>Pulse Height (V)</u>	<u>MB-7D Reading (in)</u>
MB-7D	4	1	3	43.263 $\pm$ 0.003
External	4	1	1.4+	43.263 $\pm$ 0.003
External	5	1	13*	43.263 $\pm$ 0.003
External	100	1	3	43.264 $\pm$ 0.004
External	1000	5	3	43.264 $\pm$ 0.004

*Voltage limit of the external generator.

4. Return pulse

The magnetic field associated with the current flow in the drive pulse interacts with the permanent magnetic field at each anchor location. This interaction produces the magneto-strictive effect that distorts the center rod and produces a stress wave that propagates along the sonic probe in both directions. At the probe head the stress waves are detected by a torsional transducer (Villari effect) and converted into an electrical signal.⁶ A typical return signal following amplification in the probe head is illustrated in Fig. 10. When the signal enters the MB-7D readout it undergoes further amplification before activating the Schmitt trigger circuit. Output from the Schmitt trigger circuit serves as input to the counter circuit to start or stop the counter that produces the distance reading shown on the MB-7D display. In the following discussion we shall present results from sensitivity studies for the Schmitt trigger circuit to varying input.

To check the threshold voltage required for activating the Schmitt trigger circuit, an external pulse generator was connected to the input amplifier of the MB-7D readout. The output of the Schmitt trigger was monitored with an oscilloscope to determine what input voltage is needed to activate the Schmitt trigger and provide an output. Table 2 summarizes the results of this test.

TABLE 2. Determination of the threshold voltage required to activate the Schmitt trigger circuit

<u>Input Voltage (mV)</u>	<u>Number of Inputs</u>	<u>Number of Outputs</u>
175	10	0
180	10	4
185	10	6
190	10	10
195	10	10
200	10	10

The tabulated results would indicate that an input voltage of at least 190mV from the probe head into the input amplifier of the MB-7D is required to ensure an output from the Schmitt trigger circuit. The Schmitt trigger output operates at a level of + 5V and drops to approximately zero volts when triggered.

The counter circuit is sensitive to just the leading edge of output from the Schmitt trigger circuit. Fig. 11 illustrates a typical (negative) leading edge of the pulse when the IRAD sonic probe is used in its normal operating mode. Then the external pulse generator was substituted for the probe and used as input to supply a return signal to the amplifier of the MB-7D. The output of the external pulse generator was set at 400mV as the rise/fall times and pulse widths were varied. For example, the first externally generated pulse had a rise and fall time of 100ns and pulse width of 1 μ s. Table 3 summarizes results obtained from this study. The pulse width for each externally generated pulse corresponds to full width at half maximum amplitude.

TABLE 3. Variation of the rise/fall times and width of the input pulse to determine sensitivity to risetime for the Schmitt trigger output

<u>Input Rise/Fall Time</u>	<u>Input Width</u>	<u>Risetime of Schmitt Output Pulse</u>
Normal Pulse	25 μ s	10ns
100ns	1 μ s	10ns
500ns	1 μ s	10ns
1 μ s	2 μ s	10ns
5 μ s	10 μ s	10ns
10 μ s	20 μ s	10ns

The tabulated results indicate the risetime of the output pulse for the Schmitt trigger is insensitive to large changes in the rise/fall times and width of the input pulse.

5. Comparison of the probes

The five magnetic anchors were located along the aluminum I-beam and the magnitude of the return signals were compared from the old probe (S/N 1001) and the new probe (S/N A1012RP). For both probes, the MB-7D box was used to generate the drive pulse. The five return signals from the old probe exceeded 500mV and appeared to be nearly uniform in amplitude. The five return signals from the new probe were less than 400mV and steadily decreased in amplitude to where the last return signal only slightly exceeded the 190mV threshold needed to activate the Schmitt trigger. It is suspected that greater attenuation occurs for the new sonic probe with respect to that for the old probe. This may be the result of greater variability in probe material properties or surface irregularities on the new probe. The ramp amplifier apparently could not compensate for the level of attenuation present in the new probe.

IV. CONCLUSIONS AND RECOMMENDATIONS

The experimental procedure used to evaluate these IRAD sonic extensometers provided a good quantitative estimate of accuracy. Utilizing the test bed indicated that the MB-7D readings for distance between two magnetic anchors were low by about 2%. This error might be eliminated by either modifying the metallurgical composition (decreasing the sonic velocity) of the sonic probe or slightly decreasing the frequency of the crystal oscillator. Whether these modifications are feasible has not been determined. With the magnetic anchors at the appropriate quadrature positions and using the micrometers to make small displacements, it is possible to make the following assessment about the accuracy of the MB-7D readings for both sonic probes. The MB-7D tends to record a displacement that was equal to or less than the actual change in the micrometer setting. Variability of the readings increases with distance from the probe head. Finally, for displacements ≤ 0.05 in., the MB-7D reading error is equal to or less than ± 0.002 in. for the old probe and ± 0.003 in. for the new probe. However, the old probe (S/N 1001) went through a selection or screening process before being shipped while the new probe (S/N A1012RP) was what might be termed an "off the shelf" item.

Evaluation of the electronic circuitry was confined to examination of the MB-7D readout box. An attempt to examine the preamplifier in the probe head was frustrated because signal levels were too low to monitor without significantly altering the waveforms. In the MB-7D readout box the accuracy of the crystal oscillator and counter circuit was essentially limited by the inherent accuracy of ± 0.001 in. for a binary coded decimal (BCD) counter. The crystal oscillator appeared to be very stable and capable of greater accuracy. Studies with an external pulse generator were used to simulate first the drive pulse and then the return pulse. For drive pulses with amplitudes $>1.4V$, the MB-7D provided readings with both probes for magnetic anchor separations of 1 ft. and 18 ft. The MB-7D readings and the waveforms for the return signals demonstrated a high degree of insensitivity to variations of the drive pulse shape. The external pulse generator was then used to simulate a return signal directly into the MB-7D amplifier. Following amplification, this signal activates the Schmitt trigger circuit which starts and stops the MB-7D display via the counter circuit. Variation of the pulse shape indicated that an input amplitude of $\geq 190mV$ was needed to ensure a trigger for the Schmitt circuit. In reality, the counter circuit is just sensitive to the leading edge of the output pulse from the Schmitt trigger circuit. Results indicated that the rise time for the output of the Schmitt trigger was insensitive to a wide range of wave shapes for the return signal that enters the MB-7D readout box.

Finally the return signals from five magnetic anchors located along the track were compared for the two probes using the MB-7D drive pulse. The five return signals for the old probe exceeded 500mV and were uniform in amplitude. For the new probe, the five return signals were less than 400mV and steadily decreased in amplitude with distance from the probe head. This difference may be due to quality of probe fabrication or the materials used in that fabrication. This suggests that the return signal for the new probe may be less than the 190mV threshold at distances greater than 18 ft.

We conclude from these studies that the accuracy of the MB-7D readings is primarily controlled by the sonic probe. An accuracy of ± 0.001 in. is possible with the MB-7D electronics and this variation is attributed to the inherent limitations of the BCD counter circuit. Increasing the accuracy of the BCD counter would require an order of magnitude increase in crystal frequency. This modification does not appear practical but was not investigated in detail. The MB-7D readout seems to be basically a well-designed

system. Originally we felt that a redesign of the magnetic anchor might improve the accuracy of the readings. However, the readings appear to be insensitive to changes in shape of the return signal. Consequently, modifying the magnetic anchor design does not appear promising as a method of increasing the accuracy of the MB-7D readings.

On the basis of our analysis, we feel the most practical recommendations for increasing the accuracy and performance of the IRAD sonic extensometer are:

- (1) Carefully prescreen the sonic probes before making a selection. This would require the cooperation of the manufacturer and may increase costs.
- (2) Investigate the possibility of establishing some quality control program in the manufacturing of the sonic probes. An alternative approach would be to establish practical specifications that would satisfy the users requirements.
- (3) Establish a test bed facility, similar to the one used at LLNL to perform the study reported here to fully document the characteristics of each probe before use.
- (4) Incorporate a microprocessor into the MB-7D that would provide one reading that is an arithmetic (objective) average of all the readings. This would eliminate the subjectivity factor inherent in trying to obtain a mental (subjectively) averaged reading. The principle disadvantage is that knowledge is lost concerning the range over which the readings vary. Perhaps the microprocessor approach could be provided as an option to the present method.
- (5) Adopt a standard method for interpreting the readout data. An example may be to take three successive readings and average the results.

The present study addressed certain basic areas of performance in the acquisition of reliable data using the IRAD sonic extensometer. Additional study is required to examine other aspects of the sonic extensometer performance that have not been addressed in the present study.

- (1) The temperature sensitivity of the IRAD sonic extensometer must be investigated if it is to be used in elevated temperature environment. The bench test bed used in the present study might be adapted for such tests.

- (2) An examination should be made of the anchorage system's response to shock interaction generated by nearby explosions.
- (3) The MB-7D readout should be modified to allow the option of remote control reading of the extensometer if it is to be part of an automated data acquisition network.
- (4) The probe and probe head should be thoroughly evaluated to determine if it could be modified or constructed in such a way as to provide a more accurate reading.

ACKNOWLEDGMENTS

The authors extend their appreciation to: W. F. Ubbes of DOE-Office of Crystalline Repository Development for his interest and support of this work; W. C. Patrick, N. L. Rector, and D. G. Wilder for their valuable suggestions that contributed to the design of the experiments and critical reviews of the report. The authors are also indebted to T. C. Erven, B. O. Sellick, Jr., and W. C. Schnoor for fabrication of the test bed. The authors thank Dr. P. W. Runstadler, Jr. of IRAD Gage for providing information about the electronic circuitry and his critical review of the report.

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Fig. 1. The mobile cart shown contains the magnetic anchor, two micrometers for small displacements, four springs for maintaining positive contact with the micrometers, a pointer and knurled screws for locating and securing the position of the cart to the Aluminum I beam. The sonic probe is normally inserted into or through the Aluminum guide tube that is shown passing through the cart.

Fig. 2. Shown are the range for the averaged displacement readings with the old probe versus the corresponding increase in micrometer settings on the second cart (first and second intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 3. Shown are the range for the averaged displacement readings with the old probe versus the corresponding increase in micrometer settings on the fourth cart (third and fourth intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 4. Shown are the range for the averaged displacement readings with the old probe versus the corresponding decrease in micrometer settings on the second cart (first and second intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 5. Shown are the range for the averaged displacement readings with the old probe versus the corresponding decrease in micrometer settings on the fourth cart (third and fourth intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 6. Shown are the range for the averaged displacement readings with the new probe versus the corresponding increase in micrometer settings on the second cart (first and second intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 7. Shown are the range for the averaged displacement readings with the new probe versus the corresponding increase in micrometer settings on the fourth cart (third and fourth intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 8. Shown are the range for the averaged displacement readings with the new probe versus the corresponding decrease in micrometer settings on the second cart (first and second intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 9. Shown are the range for the averaged displacement readings with the new probe versus the corresponding decrease in micrometer settings on the fourth cart (third and fourth intervals). The axes were broken between 0.012 in. and 0.015 in. and the scales changed to aid in the graphic presentation of the data.

Fig. 10. Return signal using the MB-7D drive pulse generator with the old probe. The vertical scale is 200mV/DIV and the horizontal scale 10 μ s/DIV.

Fig. 11. Leading (negative) edge of the Schmitt trigger pulse. The vertical scale is approximately 0.8V/DIV and the horizontal scale 10ns/DIV.