EVALUATION OF THE IRAD FLEXIBLE PROBE SONIC EXTENSOMETER

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ABSTRACT

Evaluation of the IRAD sonic extensometer was initiated with an electronic-circuit analysis which indicated accuracy of ±0.001 in. (0.025 mm). Readings from two sonic probes consistently were low by 2% for distances between magnetic anchors, but were accurate to ±0.002 and ±0.003 in. (0.051 and 0.076 mm) for small displacements. Although a series of shock testing subjected magnetic anchors to peak accelerations of from 1,100 g to 32,000 g, the anchors generally did not experience detectable damage. Sonic probe readings exhibited a sensitivity to temperature changes with two of the four segments monitored exceeding the correction factor cited by the manufacturer.

INTRODUCTION AND BACKGROUND

Atomic Energy of Canada, Ltd. (AECL) is developing the Underground Research Laboratory (URL) to examine technical problems related to nuclear waste disposal in granite intrusives. The experience gained by the Lawrence Livermore National Laboratory (LLNL) in conducting the Spent Fuel Test--Climax (SFT--C) project at the Nevada Test Site (NTS) was applicable to these investigations. Initially, the SFT--C project was planned as a 3- to 5-year test. Instrumentation was selected that was specified to be capable of surviving the test environment for that period of time. An extensive array of instruments was installed at the Climax site to provide an experimental basis for checking the computer-based models used to simulate the experimental results numerically. A significant fraction of the instruments initially installed failed. Failure was attributed primarily to the hostile environment to which the instruments were subjected.

The need to identify or develop instruments to provide long-term monitoring of geotechnical parameters in nuclear waste repositories has been reviewed recently. One of the more promising instruments, one that could potentially satisfy many of the requirements cited, is the IRAD flexible-probe sonic extensometer. The principal advantage of this system is that it is portable, and the sonic probe is inserted in a borehole only at the time readings are made. Consequently, the IRAD sonic extensometer, unlike instruments used previously, can be stored in a benign environment between measurements and not be continually exposed to a hostile environment. The anchors are not spring-loaded in the direction of the borehole axis (as are other types of extensometers) and are not as likely to be affected by shock loading from blasting for excavation nor by tension-induced creep. This system can use up to ten permanently emplaced magnetic anchors per borehole, but they are sturdy and should withstand the environment in the borehole.

The IRAD sonic extensometer was subjected to a variety of experimental tests to examine different aspects and sensitivities of the system. The results from those experimental tests are described in the following four sections. We first present a description of the electronic circuit analysis. We isolated the portion of the reading variations due to the electronic circuits for the MB-7D readout from that due to the sonic probe itself. This analysis provides a basic understanding of how the system functions. Then we discuss our investigations of the accuracy of the MB-7D readout when measuring the distance between two magnetic anchors and to small changes in the position of a magnetic anchor. The third section concerns the anchoring system's response to shock interaction generated by nearby chemical explosives. Finally, the sensitivity of the sonic probe is examined for temperature changes in the range of 20 to 50°C.

Most of the results reported here were conducted with a sonic probe (S/N 1001) that had been carefully selected at IRAD for our use. A second sonic probe (S/N A1012RP) was taken out of stock and not screened. For the sake of simplicity, we have designated the two probes the "selected" and "stock" probes, respectively. While both probes were used in the electronic circuit analysis and accuracy tests, only the selected probe was used in the high-explosive (HE) and temperature studies. This choice was based on the better accuracy of the selected probe. It was not considered operationally feasible or necessary to field both probes in the last two studies cited. This report supplements an earlier study about the suitability of using the IRAD sonic extensometer in the URL. For a more detailed discussion of the diagnostics and experimental results than is presented in this paper, the reader is referred to Reference 10.

EVALUATION OF THE ELECTRONIC CIRCUITRY IN THE MB-7D READOUT BOX

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 was essentially limited by the inherent accuracy of ±0.001 in. (0.0254 mm) for a binary-coded decimal (BCD) counter. The crystal oscillator appeared to
be very stable and capable of greater accuracy. An external-pulse generator was used to simulate first the drive pulse and then the return pulse. For drive pulses with amplitudes greater than 1.4 V, the MB-70 provided reliable readings, with both probes, for magnetic-anchor separations of 1 ft and 18 ft (0.31 m and 5.49 m). The MB-70 readings and the waveforms for the return signals demonstrated a high degree of insensitivity to variations in the shape of the drive pulse. The external pulse generator was then used to simulate a return signal directly into the MB-70 amplifier. Following amplification, this signal activates the Schmitt-trigger circuit that starts and stops the MB-70 display via the counter circuit. Variation of the pulse shape indicated that an input amplitude of greater than 190 mV was needed to ensure a trigger for the Schmitt circuit. In reality, the counter circuit is sensitive only 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-70 readout box.

Finally, the return signals from five magnetic anchors located at quadrature positions (11) along the track (see below) were compared for the two probes using the MB-70 drive pulse. The five return signals for the selected probe exceeded 500 mV and were uniform in amplitude. For the stock probe, the five return signals were less than 400 mV at the first anchor 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 stock probe may be less than the 190-mV threshold at distances greater than 18 ft (5.49 m).

We conclude from these studies that the accuracy of the MB-70 readings is primarily controlled by the sonic probe. An accuracy of 10.001 in. (0.0254 mm) is possible with the MB-70 electronics, and we attribute this variation 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 it was not investigated further. The BCD counter is a basically well-designed system. We originally felt that redesigning the magnetic anchor might improve the accuracy of the readings. However, the readings appear to be insensitive to changes in the 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-70 readings.

MEASUREMENT ACCURACY AT AMBIENT TEMPERATURES

The experimental procedure used to evaluate these IRAO sonic extensometers provided a good quantitative estimate of accuracy. Experiments with the test bed indicated that the MB-70 readings for distance between two magnetic anchors were consistently 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. Since the error is systematic, it can be adequately compensated for without making such modifications.

To conduct the displacement measurements, all five carts containing magnetic anchors were located on a 20-ft (6.1-m) aluminum T-beam at the appropriate quadrature locations.(11) The third cart was set at the middle (10 ft [3.0 m]) of the T-beam and represented the null point (i.e., the micrometer settings on this cart were not changed). Then the second and fourth carts were located on either side of the third cart, each at a distance of 64.616 in. (1.641 m). Finally, the first and fifth carts were spaced 44.125 in. from the second and fourth carts, respectively.

In summary, the spacing between the five carts would be 44.125, 64.616, 64.616, and 44.125 in. (1.121, 1.641, 1.641, and 1.121 m). The standard, metallic-collared anchor was not used in this series of tests because their construction varies considerably from that of the typical, polymer-body C-anchor contained in each cart.

By locating the magnetic anchors at the appropriate quadrature positions and using two micrometers on each cart to make small displacements, it is possible to make the following assessment about the accuracy of the MB-70 readings for both sonic probes. The MB-70 generally records 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. (1.27 mm), the MB-70 reading error is equal to or less than 0.002 in. (0.051 mm) for the selected probe and 0.003 in. (0.076 mm) for the stock probe.

SENSITIVITY TO HIGH-EXPLOSIVES SHOCKS

Portions of the IRAO extensometer system may be subjected to harsh environments for long periods of time during field measurements in underground applications. The sonic probe is normally not exposed to harsh environments for significant periods of time since it is inserted into the borehole just prior to each measurement and removed promptly thereafter. Generally only the magnetic anchors (and possibly the guide tube) remain permanently in the borehole after their installation. An example of the harsh environment possible is strong shocks from chemical explosives used in mining or excavating close to the borehole during early phases of construction. Since we must often measure displacements very near an excavated face, we must be concerned about the possible shock effects on the integrity of the magnetic anchors. We describe here a series of high-explosives (HE) tests made to investigate the effect of strong shocks on these anchors.

Experimental Procedure for the High-Explosives Tests

The experimental plan for examining the IRAO extensometer system's response to strong shocks is illustrated in Figure 1. An approximately 1.5-in. (38-mm) diam. borehole (ST1) used for shock testing was drilled with a jackleg to a depth of 22 ft (6.71 m). The hole was instrumented with a radial accelerometer at a depth of 11.0 ft. (3.35 m) from the tunnel wall. This radial accelerometer (RA5) was oriented to measure the radial shocks from line charges placed in parallel boreholes. A second borehole (ST3) with the sonic probe (S10) and core drilled parallel to, but 6 in. (150 mm) below, the first borehole; it also had a depth of 22 ft (6.71 m). This borehole was instrumented with five magnetic anchors at the quadrature positions over a 16 ft. (4.88 m) interval centered at a depth of
containing the five magnetic anchors. Two of the accelerometers originally intended for the ST1 borehole were shifted to these two instrumented holes. To retain the same radial orientation to the line charges (e.g., as for RA5), the two accelerometers (RA2 and RA3) were mounted flush against the end of each borehole. Accelerometers RA2 and RA3 were 0.64 and 0.71 ft. (195 and 216 mm), respectively, from the center of the borehole containing the magnetic anchors.

Experimental Results of High-Explosives Tests

The line charge at 8 ft (2.44 m) from boreholes ST1 and ST2 was detonated in the first HE test. Then the line charges at 4, 2, and 1 ft (1.22, 0.61, and 0.30 m) from boreholes ST1 and ST2 were shot in a sequence of separate tests. The line charge at 2 ft (0.61 m) produced small rock fragments and caused a small amount of rock dust to appear in the borehole at 1 ft (0.30 m). However, we cleaned this borehole with compressed air before emplacing the line charge for the 1-ft (0.30-m) test.

The peak acceleration values from line-charge detonations at 8, 4, and 2 ft (2.44, 1.22, and 0.61 m) are shown in Figure 2. The solid triangles on this graph represent radial-acceleration measurements obtained during bench blasting for the canister drift at the Cline facility.(12) The dashed line drawn through the acceleration data is an extra-
dation of the solid line, which was taken from Reference 12; the dashed line appears to fit all of the experimental results. The results for RA3 are consistently higher than the results for the other two stations. This may be due partially to the fact that RA3 is located further from the free surface and, therefore, has reduced rarefaction effects.

Gages RA2 and RA3 were installed flush against the flat end of the boreholes, while RA5 would not have been in as good contact with the side wall of the ST1 borehole because of its 0.75-in. (19-mm) radius of curvature. Whether this difference in mounting procedure affected the shock coupling remains primarily conjectural since the results for RA2 are lower than RA5 for the shots at 8 and 4 ft. (2.44 and 1.22 m) and higher at 2 ft (0.61 m). The anomalously low response for RA5 at 2 ft (0.61 m) may be due to the presence of microcracks induced by the shock wave since RA5 is closer than RA2 by 0.68 ft (0.21 m) to the 2 ft (0.61 m) line charge.

Three radial accelerometers (RA2, RA3, and RA5) failed immediately following arrival of the shock wave from the detonation of the line charge at 1 ft (0.30 m). Postshot examination of the magnetic-anchor borehole (ST1) indicated the hole closed at a distance of 7.66 ft (2.32 m) from the tunnel wall. No remnants or fragments of the magnetic anchors, located at 3.60- and 6.54-ft (1.09- and 1.99-m) depths from the tunnel face, were seen in ST2. The hole appeared to be blown free of all debris and dust. We hypothesize that the ground shock pulverized both anchors, and then their fragments were blown into the tunnel by air extruded as the last 2-ft line charge, the collar anchor and guide tube were removed before the shot. The collar anchor and guide tube were removed to prevent possible damage from surface spall. In addition, the guide tube was supported by the magnetic anchors and, therefore, did not come in contact with the walls. Consequently, there was some concern that the high accelerations at the magnetic anchors might give them sufficient inertial force to crimp the guide tubes.

This paragraph presents a brief discussion of the magnetic-anchor readings given in Table 1. The preshot and postshot readings for the 8- and 4-ft (2.44- and 1.22 m) line charges differ by 0.002 to 0.003 in. (0.051 to 0.076 mm). This variability is approximately within ±0.002 in. (0.051 mm) cited for the accuracy of the IRAD sonic probe. The postshot readings are in close agreement with the preshot reading of the next shot of the series. The exception to this statement is the 0.005- to 0.006-in. difference observed for the third interval between the postshot reading for the 8-ft shot and preshot reading for the 4-ft shot. No explanation exists for this difference other than the possible closure of microcracks that might have been introduced or a strain relaxation effect during the 24 hour period between these two tests. In addition, it is not known whether the preshot removal and postshot replacement of the collar anchor and guide tube contributed to the consistent 0.004- to 0.006-in. (0.102- to 0.152 mm) shift in the readings for the first three intervals before and after the shot at 2 ft. The much larger shift of 0.015 to 0.016 in. (0.381 to 0.406 mm) in the reading for the fourth interval probably represents the effects of shock-induced strain or microcracks in the granite. However, if we compare the preshot readings at 8 ft (2.44 m) with the preshot readings at 2 ft (0.61 m), then a definite trend can be seen. The first and third intervals appear to be within the accuracy bounds, but the second and fourth intervals increased consistent with shock effects on the rock from detonation of the 8- and 4-ft (2.44- and 1.22 m) line charges.

### SENSITIVITY TO TEMPERATURE CHANGES

In addition to strong shock response, the temperature sensitivity of the IRAD sonic extensometer must be better understood if it is to be used in environments in which changes in temperature may occur during the course of the experiment. For this purpose a temperature bath was designed (Figure 3) that could

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**TABLE 1. MAGNETIC-ANCHOR READINGS DURING HIGH-EXPLOSIVES TESTS**

<table>
<thead>
<tr>
<th>Interval</th>
<th>6-ft. Shot</th>
<th>4-ft. Shot</th>
<th>2-ft. Shot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preshot (In.)</td>
<td>Postshot (In.)</td>
<td>Preshot (In.)</td>
</tr>
<tr>
<td>1</td>
<td>34.555-356</td>
<td>.555-.555</td>
<td>.555-.555</td>
</tr>
<tr>
<td>2</td>
<td>50.877-877</td>
<td>.880-.880</td>
<td>.881-.881</td>
</tr>
<tr>
<td>3</td>
<td>50.492-492</td>
<td>.495-.495</td>
<td>.490-.491</td>
</tr>
<tr>
<td>4</td>
<td>34.611-610</td>
<td>.613-.613</td>
<td>.613-.613</td>
</tr>
</tbody>
</table>

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**FIGURE 3: TEMPERATURE TEST BATH**
be varied over a range of 20 to 50°C and maintain a uniform temperature over its length to within ±0.1°C. The test range was confined to 20 to 50°C because that is the range anticipated during in situ, elevated-temperature tests of large rock masses (such as pillars between storage drifts). The temperature bath was used in conjunction with the bench-test facility used to conduct the tests of displacement accuracy for this study.

Experimental Setup and Procedure

Fabrication of the temperature bath began with two long aluminum tubes. The smaller tube was 22 ft (6.71 m) long and had an outside diameter of 7.5 in. (190 mm) and a wall thickness of 0.25 in. (6.4 mm). It was placed inside a second tube 24 ft (7.32 m) long, 12.0 in. (305 mm) o.d., and 0.25 in. (6.4 mm) thick. Spacers were located so that the two tubes would be concentric. Circular aluminum plates were used to secure the ends of each tube and isolate their interiors from one another. The 2-in. (50.8-mm) space between the two tubes was filled with water. A heat tape, wrapped in a spiral around the outer tube, was used to raise and control the temperature of the interior. The purpose of the water was to moderate temperature changes inside the inner tube. Finally the outer tube was wrapped with fiberglass insulation to reduce heat losses.

The I-beam test bed, used for the displacement measurements, was inserted inside the inner tube. The temperature inside the center tube was monitored with five thermistors attached to the I-beam at the five quadrature positions where the carts containing the magnetic anchors were located. A sixth thermistor at the center of the I-beam (third quadrature position) was used to regulate the temperature of the interior by means of a loop controller and the heat tape. The other five thermistors were used to provide a periodic record of the I-beam temperature and degree of uniformity of the temperature along the I-beam. The six thermistors and the digital-readout system (Hewlett-Packard 3467A) used to record the temperatures were given calibration checks at our temperature laboratory. Calibration was checked before and after the temperature tests and was factored into the data reduction and analysis of the temperature results.

The I-beam test fixture was located in the temperature bath at a specific temperature, and the sonic probe was inserted into the guide tube. An insulating foam plug with a small groove to accommodate the thermistor leads and sonic probe cable was then inserted in the end of the tube. Temperature readings were then taken for the four intervals between the magnetic anchors. The readings taken at 20°C were used as reference values for subsequent readings at 25, 30, 35, 40, 45, and 50°C. The probe was removed after readings at a specific temperature and, therefore, was not in place during the relatively long intervals necessary to establish equilibrium associated with increments and decrements in temperature. A second set of readings similar to the first run was taken as a check on the repeatability of the system.

Experimental Results

Before any temperature runs, the I-beam test fixture (with magnetic anchors and thermistors located at the five quadrature positions) was placed inside the temperature bath. Over the course of the nearly two months that it took to complete the temperature tests, none of the above system components were moved from their original positions. Since the bath initially was at approximately ambient temperature (24°C), it was necessary to lower the temperature before taking the first readings. This was accomplished by circulating cold water through the water reservoir until the temperature was well below 20°C. At this time there was a 0.5°C difference between the first and fifth thermistors, corresponding to the water inlet and outlet. The temperature was allowed to increase slowly until it reached 20°C and was uniform to within 0.1°C along the I-beam. The sonic probe was inserted and a series of readings taken. Then the probe was removed, and the loop controller was set to increase current flow in the heat tape and raise the temperature 5°C. The above sequence was repeated until probe readings had been obtained at 5°C intervals over the range of 20 to 50°C. Finally, a second set of readings, similar to the first run, was taken as a check on the repeatability of the system. At each temperature and for each run, the readings were averaged. The results of differences between the sonic-probe reading and the readings obtained at 20°C for the first and second runs are plotted in Figure 4 for the second interval as an example and at the specific temperatures cited earlier. The solid circles are for the first run and crosses for the second run.

![FIGURE 4: DIFFERENCES IN I-BEAM READINGS VS TEMPERATURE](image-url)
As the temperature increases, the 6061-T6 aluminum I-beam undergoes thermal expansion. The coefficient for thermal expansion increases linearly with temperature over the temperature range of 20 to 50°C. The resulting change in length of the I-beam as a function of temperature for each interval is shown as a solid line in Figure 4. When the appropriate values for thermal expansion of the I-beam are subtracted from the corresponding probe readings, we obtain the corrected data points. The increase in magnitude of corrected data points with increasing temperature indicates that a definite temperature dependence exists for the sonic probe. We believe the increase in sonic readings with increasing temperature results from a decrease in the sonic velocity in the nickel-cadmium alloy used in construction of the probe.

To determine the correction factor for this temperature dependence, we first obtained a least-squares fit to the corrected data points for each of the four intervals. The results of that effort are shown by the broken line in Figure 4; the residual values or the difference between the least squares fit and individual corrected data points are also plotted. The net results suggest that, if the appropriate temperature correction is applied to each interval, the final values do not deviate by more than the ±0.002-in. (0.051-mm) accuracy for the sonic probe readings that was originally determined in the displacement tests.

To determine the constancy of the temperature correction, we normalized the results by dividing the slope of the least squares fit by the length for each interval. These values are plotted in Figure 5. Although the length-weighted average value falls within the manufacturer's general experience, the corrections in the third and fourth intervals deviate markedly from the average. Since only one sonic probe (SN 1001) was tested, it would be presumptuous to make generalized statements regarding their temperature sensitivity. If the variations exhibited in these tests are of concern to a particular user, then a comparable study may be warranted. To obtain better definition of the correction factor with distance along the sonic probe, a larger number of quadrature points for the magnetic-anchor locations would need to be studied.

After the probe readings at 50°C, at the end of the second run, the probe was left in the temperature bath for nearly a full day while the bath was maintained at 50°C. Then a series of sonic-probe readings were taken at the temperature of 50°C. The reading changes were within the ±0.002-in. (0.051-mm) error range determined in the displacement-accuracy phase of this evaluation.

RECOMMENDATIONS

On the basis of our analysis, we recommend the following measures for selecting a probe of acceptable quality and for increasing the accuracy and performance of the IRAO sonic extensometer:

1. Carefully screen the sonic probes before making a selection. Prescreening should provide a sonic probe with an accuracy of ±0.002 in. (0.051 mm) for its total length. In addition, the return signals from the farthest interval should substantially exceed the trigger threshold. This would require the cooperation of the manufacturer and might increase costs.

2. Investigate the possibility of establishing additional quality controls in the manufacturing of the sonic probes. An alternative approach would be to establish practical specifications that would satisfy the user's requirements.

3. Establish a test-bed facility at the user's site, similar to the one used at LLNL to perform the accuracy and temperature-dependence tests reported here, to fully document the characteristics of each probe before use.

4. Incorporate a microprocessor into the MS-70 that would provide an average reading that is an arithmetic (objective) average of all the readings. This would eliminate the subjectivity inherent in manually averaged readings, but it would have the disadvantage of not giving the range over which the readings vary. Perhaps a microprocessor could be provided as a field-selectable 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 of the IRAO sonic extensometer. Additional study is required to examine the sonic extensometer's performance in other respects:

The temperature sensitivity of the extensometer must be investigated further if it is to be used to acquire very precise data at elevated temperatures. This test requirement is dictated
by the accuracy requirements of the prospective user and the environment to which the probe may be exposed. The systems and procedures used in the present study might be adopted for such tests.

The anchorage system's response to axial shock generated by nearby explosions should be examined. Such a test should be conducted on a much larger scale than was feasible in the present study, e.g., the bench blasting used to mine the central drift at the Climax facility.

The HB-70 readout box should be modified to allow the option of remote reading if the extensometer is to be part of an automated data-acquisition network.

The probe and probe head should be thoroughly evaluated to determine if they could be made more accurate to ±0.001 in. (0.025 mm) which is appropriate for deformation measurements in hard rock waste repositories.

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REFERENCES


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