Instrument To Measure the Initial Deformation of Rock Around Underground Openings
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By Michael J. Beus, Earl L. Phillips, and Galen G. Waddell

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INSTRUMENT TO MEASURE THE INITIAL DEFORMATION OF ROCK AROUND UNDERGROUND OPENINGS

by

Michael J. Beus,¹ Earl L. Phillips,² and Galen G. Waddell³

ABSTRACT

This Bureau of Mines report describes a tunnel stress relaxation gage (TSR) developed to measure initial radial displacement around full-sized underground openings.

The TSR technique was shown to be a valid concept in previous field verification tests. Sensitivity has been improved by employing a titanium alloy cantilever in the transducer head, which also permits a deeper sensor location. Use of improved fabrication methods such as stainless steel bellows and sputtering techniques and use of an environmental chamber for testing greatly increased overall reliability. A miniature data acquisition system (DAS) was interfaced directly to the transducer for increased versatility and containment entirely within a borehole. The present TSR system is suitable for use around full-size underground excavations, particularly machine-bored openings. Field evaluation of the improved instrumentation verified the design goals.

INTRODUCTION

This report summarizes development and modification of a tunnel stress relaxation gage (TSR) designed to measure initial and long-term deformation around underground excavations. The work was conducted by the Spokane Mining Research Center of the Bureau of Mines to provide suitable measurement devices for determining rock movement ahead of large underground openings.

Past research (1-4, 13)⁴ has shown that the rate and magnitude of deformation around existing underground openings in the Coeur d'Alene mining district

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⁴Underlined numbers in parentheses refer to items in the list of references preceding the appendix.
is indicative of general ground conditions and can be used to determine potential unstable areas requiring artificial support. Following this earlier research, a prototype tunnel stress relaxation gage was designed and built for measuring ground movement ahead of, and adjacent to, an advancing underground opening (15). The thesis was that deformation measurements thus obtained would yield a complete record of deformation history. This would permit better evaluation of the immediate and long-term stability of the opening and the effectiveness of the installed support system in arresting deformation. The data record also would allow calculation of the two-dimensional stress field acting in a plane normal to the direction of excavation (12).

Field verification tests around drilled and blasted openings (11) and machine-bored raises (14) proved the validity of the TSR concept, although several shortcomings became apparent in the design of the instrument. Lack of sensitivity in the transducer head, combined with extreme weight conditions, prevented insertion of the deformation sensor beyond the influence of the test site opening. Susceptibility of the electronic components to the mine environment caused many of the probes to malfunction before any meaningful deformation data could be obtained. The external mounting gear was extremely susceptible to blast damage and other interference from mining activities. Modifications to the TSR probe have resulted in a much more reliable and versatile instrument for use around shafts, raises, or tunnels.

ACKNOWLEDGMENTS

Acknowledgment is extended to SMRC's instrumentation personnel, particularly Elmer Guidice, for assistance in evaluating the self-contained system. Further appreciation is expressed to the research staff of Battelle Northwest Laboratories for providing metallurgical advice and unique expertise. Arthur Brown, mine superintendent at Hecla Mining Co.'s Lucky Friday mine in Mullan, Idaho, and James Robison, senior engineer with the Callahan Mining Corp. in Osburn, Idaho, cooperated in providing field test sites and installation assistance.

DESIGN CRITERIA

The initial design goals were fabrication of an instrument suitable for use around full-scale underground excavations as shown in figure 1. The TSR measurement system (fig. 2) consists of the TSR probe (extension tube and transducer head), a deformation-sensing plug, an adjustable mounting head, and an anchored support reference pipe. The sensing plug is epoxied into the end of a borehole parallel with the mine opening and accepts the ball end of the transducer head. Movement of this plug resulting from excavation causes deflection of the probe. The extension tube is inserted at the opposite end to the adjustable mounting head, which is rigidly clamped to the support reference pipe. This support pipe is cemented into the wall rock for a stable "zero movement" reference. The mounting head permits three-dimensional adjustment of the transducer for proper preload, orientation, and length, and is used for centering the extension tube in the borehole.
FIGURE 1. - Schematic of TSR gage installed around a raise bore.
The primary criterion established for initial prototypes of the TSR probe was that it be capable of measuring and recording radial rock deformation before the mining activity passed the sensing plane and during and after its passage, the sensing plane being the depth at which the sensing plug and tip of the transducer head are located. A measurement range of 0.3 inch and a system resolution of 0.0001 inch were selected based on results of previous deformation studies around full-sized openings in "hard rock" (that is, an elastic modulus range of 5-10 x 10^6 psi). A strain-gaged cantilever in a full-bridge signal additive configuration mounted on the end of a 5-foot-long extension tube met initial design objectives. However, the beryllium-copper cantilever used in the initial transducer was too stiff in relation to the stainless steel extension tube. This prevented insertion of the sensor to greater depths around the opening because of decreased cantilever deflection and subsequent reduced strain gage output with increasing extension tube length. At 8 feet, the sensitivity was about half of what was originally specified because of excessive extension tube deflection. The wall thickness of the extension tube could not be increased for greater stiffness, because of system weight limitations. The approach to both of these problems was to utilize a high-strength, low-modulus material, such as titanium or aluminum alloy, for the cantilever and to maximize the stiffness-to-weight ratio of the extension tube.

**Transducer Head**

Both aluminum and titanium possess desirable qualities for cantilever design; that is, excellent corrosion resistance, linear stress-strain behavior, and low elastic drift. Titanium is superior because of its high strength and low modulus, permitting design of an extremely thin and flexible cantilever. Titanium alloy 5 Al-2.5 Sn has a low creep rate, an elastic modulus of 16 x 10^6 psi, and a yield stress of 115,000 psi (2).
The design relationships for the transducer cantilever are typical for an end-loaded beam rigidly fixed on one end \((6, 8, 10)\); that is --

\[ y = \frac{Pl^3}{3EI}, \]  

(1)

and

\[ \sigma = \frac{Pl}{wt^2}, \]  

(2)

where \( y \) = deflection at the end of the cantilever,

\( P \) = force applied to the end of the cantilever,

\( l \) = length of the cantilever,

\( E \) = modulus of elasticity,

\( I \) = cross-sectional moment of inertia,

\( \sigma \) = stress at fixed end of the cantilever,

\( w \) = width of the cantilever,

and \( t \) = cantilever thickness.

These equations can be written in terms of strain as a function of deflection limit, cantilever thickness, and length in the form of

\[ \varepsilon = \frac{3vt}{2l^2}, \]  

(3)

where \( \varepsilon \) = strain at the fixed end of the cantilever.

The thinnest titanium sheet obtainable with any degree of thickness tolerance control is 0.030 inch. The length of the cantilever is 2.95 inches, 1 inch of which is clamped in the cantilever mount, and the width is 0.5 inch. This length was as short as possible for maximum strain, yet left a sufficient length for insertion into the anchor socket. Width was designed to be as narrow as possible but still accommodate four strain gages, two on either side. Solving equation 1 for the end load required to deflect the cantilever 0.3 inch, we obtain \( P = 2.185 \) pounds. Solving equation 2 for this load, the maximum stress in the cantilever is 56,084 psi, resulting in a safety factor of slightly more than 2. The strain level from equation 3 is 3,550 microinches per inch at 0.3-inch deflection. In a four-arm strain-gage bridge configuration, the strain output from the cantilever should be \( 4 \times 3,550 = 14,202 \) microinches per inch. When read on a standard strain indicator, a deformation sensitivity of 0.00002112 inch (21.12 microinches) should be possible.

The complete TSR transducer head is shown in figure 3 and consists of several components. A cantilever mount and hold-down block rigidly fix the cantilever beam in position. A brass ball is fitted on the end of the cantilever.
FIGURE 3. - Exploded view showing component parts of TSR transducer.
to fit into the socket in the sensing anchor. A stainless steel bellows completely encapsulates the strain gages with the transducer. The bellows unit provides a completely sealed transducer, yet does not interfere with the flexibility or deflection of the cantilever. After assembly, the transducer is helium leak-checked and backfilled with argon. Design details are shown in figure A-1 (appendix).

A major fabrication problem was incurred when trying to connect the bellows assembly to the titanium cantilever by conventional brazing techniques. The differential expansion rates of the two metals caused extensive cracking of the joint upon cooling. A technique called sputtering was utilized to coat the titanium with stainless steel. The cantilever was preetched with krypton ions, and a stainless steel coating was applied at a rate of 1,000 A/min. The final coating thickness was 1 to 1-1/2 mils. A silver solder joint was then made between the bellows and the cantilever.

**Extension Tube**

As mentioned previously, the extension tube was redesigned to decrease the weight and increase the stiffness. Various designs were evaluated using stainless steel and aluminum tubing to optimize the stiffness-to-weight ratio \( \frac{K}{W} \), the stiffness being determined as follows (10):

\[
K = \frac{EI}{L},
\]

where \( K \) = stiffness, inch-pounds,

and \( W \) = total weight of tubing, pounds.

The outside diameter of the tubing was specified at 1-1/2 inches to meet drill hole compatibility requirements and cantilever mount dimensions. A minimum length of 8 feet was specified, and a total system weight (transducer head and extension tube) of less than 10 pounds was desired to minimize effects of drilling and blasting vibrations and reference pipe deflection. The weight limitation and commercial availability defined the wall thickness. The moment of inertia is calculated as follows:

\[
I = \frac{\pi(r_o^4 - r_i^4)}{4},
\]

where \( r_o \) and \( r_i \) = outside and inside radius, respectively.

Table 1 shows that slotted stainless steel 304 has the highest stiffness-to-weight ratio; the wall thickness was 0.083 inch. Longitudinal slots 1/2 inch by 1 inch long on 1-1/2-inch centers were cut along the neutral axes, shown in detail in figure A-1. Final weight of the assembled tubing and transducer head is slightly under 10 pounds.
TABLE 1. - Summary of tube design

<table>
<thead>
<tr>
<th>Tubing material</th>
<th>Weight, lb</th>
<th>Moment of inertia, in^4</th>
<th>Modulus of elasticity, 1b/in^2</th>
<th>Stiffness-weight ratio</th>
</tr>
</thead>
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<tr>
<td>AL 6063</td>
<td>8.88</td>
<td>0.19443</td>
<td>10×10^6</td>
<td>2,280.75</td>
</tr>
<tr>
<td>SS 304</td>
<td>10.05</td>
<td>0.0930</td>
<td>29×10^6</td>
<td>2,795.9</td>
</tr>
<tr>
<td>SS 304 (double tube)</td>
<td>10.76</td>
<td>0.07414</td>
<td>29×10^6</td>
<td>2,081.0</td>
</tr>
<tr>
<td>SS 304 (slotted with vertical web)</td>
<td>11.32</td>
<td>0.1063</td>
<td>29×10^6</td>
<td>2,836.0</td>
</tr>
<tr>
<td>SS 304 (slotted)</td>
<td>8.64</td>
<td>0.09127</td>
<td>29×10^6</td>
<td>3,191.0</td>
</tr>
<tr>
<td>SS 304 (drilled)</td>
<td>9.216</td>
<td>0.09127</td>
<td>29×10^6</td>
<td>2,991.7</td>
</tr>
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</table>

ENVIRONMENTAL TESTING AND CALIBRATION

Each TSR probe was thoroughly tested in an environmental chamber. The instruments were arranged in the chamber as shown in figure 4. General test procedures were to subject the instruments to an initial conditioning period followed by a long-term creep and drift test. The probes were exposed to a simulated mine environment for a 2-week period at 120° F and 100 percent relative humidity using typical acid mine water (pH≈5.6). Initial conditioning consisted of subjecting the instruments to several loading and unloading cycles to simulate the intermittent flexing the transducer undergoes prior to and during installation. Table 2 shows strain readings and resistance to ground for the conditioning tests.

TABLE 2. - Strain and resistance to ground for initial conditioning tests

<table>
<thead>
<tr>
<th>Time, hr</th>
<th>Temperature, °F</th>
<th>Relative humidity, pct</th>
<th>Loading, g</th>
<th>Strain, μin/in</th>
<th>Resistance to ground, million ohms</th>
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<td>0925</td>
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<td>1230</td>
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<tr>
<td>1445</td>
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¹Astronomical (military) time figures; all taken on November 30, 1971.
FIGURE 4. - Instruments installed in environmental chamber; inset shows lead weights used to deflect the transducer.
Long-term creep and drift tests were then conducted. Lead weights were placed on the ball end of the cantilever for a deadweight load equal to 20 percent of the deflection limit, and resistance-to-ground readings were taken daily. Table 3 shows typical values for the 2-week testing period.

<table>
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<th>Date</th>
<th>Time, hr</th>
<th>Temperature, °F</th>
<th>Relative humidity, pct</th>
<th>Loading, g</th>
<th>Strain, μin/in</th>
<th>Resistance to ground, million ohms</th>
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<tr>
<td></td>
<td>1137</td>
<td>78</td>
<td>43</td>
<td>200</td>
<td>+2,060</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

No significant drift was observed under constant load, and resistance to ground remained infinite during initial conditioning and long-term stability testing. Fewer than 10 percent (1 out of 12) of the upgraded TSR transducers were affected by the simulated mine environment. The one failure was traced to an inferior bellows unit which allowed moisture to penetrate into the strain-gaged area, causing resistance readings to fall below 40 megohms—the lowest value before strain output was grossly affected.
Following evaluation in the environmental chamber, each gage was calibrated in a testing frame to determine system resolution and the combined error due to effects of hysteresis, nonlinearity, and nonrepeatability.

The calibration apparatus consists of a bracket for the adjustable mounting head and a linear slide, both rigidly bolted to a 2-foot-thick concrete wall (fig. 5). To calibrate the instrument, it is clamped firmly into the mounting head, as shown in the figure, forming a "zero movement" reference base. The transducer head is lined up with a precision micrometer, which is mounted to the linear slide on ball bushings, providing almost perfect linear motion. The spindle of the micrometer is centered over the ball on the cantilever, and downward deflection is applied in 0.025-inch increments until a full 0.3-inch deflection is reached. The load on the cantilever is then relieved, the instrument is released from the mounting head and moved to a new position, and the calibration procedure is repeated. Since the sensitivity changes with respect to position or length of the extension tube in the mounting head, calibration is repeated in 3-inch increments from 60 to 87 inches. Output from the strain-gaged cantilever is read on a strain indicator or data acquisition system (DAS), resulting in a microstrain (or microvolt on the DAS) reading at each deflection setting and each position increment.

A nonlinear least-squares regression analysis was used to handle the calibration data, improving accuracy and permitting interpolation or prediction of

FIGURE 5.- Calibration jig to accommodate varying instrument lengths.
slope factors at noncalibrated lengths. A linear relationship of the form
\[ y = p_1 + p_2 \times x, \]  
(6)
was applied to the calibration data,
where \( y \) = deflection of the cantilever,
\( p_1 \) = \( y \) axis intercept of the calibration curve,
\( p_2 \) = average slope of the curve for a given instrument length (also a measure of sensitivity expressed as deformation per output unit),
and \( x \) = strain, or voltage output.

A family of calibration lines is shown in figure 6. The maximum error\(^6\) of four calibration runs at instrument lengths of 5, 6, and 7 feet was typically less than 0.5 percent. Sensitivity at the 5-foot length was 0.000011 inch when read with a DAS, about three times the sensitivity of previous instruments. Average hysteresis was less than 0.07 percent, compared with 0.33 percent with the beryllium-copper cantilever. The total output at 0.3-inch deflection was about 75 percent of the calculated maximum output. Two things account for this: (1) The strain-gage centerline cannot physically be placed at the location of maximum strain on the cantilever, and (2) the output signal is progressively decreased due to extension tube deflection.

A least squares fit was next made relating the average slope values computed from the initial analysis to each calibrated instrument length from 60 to 87 inches in 3-inch increments. A parabolic relationship of the form
\[ m = k_1 + k_2 l + k_3 l^2 \]  
(7)
best fit this data; in this relationship \( m \) = the slope of the calibration line at any given instrument length, and \( k_1, k_2, \) and \( k_3 \) = constants which describe the curve of that particular instrument.

Figure 7 shows a typical set of curves for three different instruments.\(^6\) Since we may not know precisely beforehand what the actual installed length of the instrument will be,\(^7\) equation 7 can be used to predict the actual slope value for that instrument after installation. The deformation from field data can then be computed by
\[ \delta = m (x_2 - x_1), \]  
(8)
where \( \delta \) = change in deformation,
and \( x_2 \) and \( x_1 \) = difference in corresponding output values from the readout device.

\(^6\) Defined as the maximum deviation from the "best fit" calibration line of a single data point divided by the full range.
\(^6\) For maximum accuracy each instrument must be calibrated individually; a trial calculation testing three different instruments to a common calibration curve caused an additional 1.5 percent error.
\(^7\) Variable factors such as opening size, geometry, orientation, and anchor-instrument hole alinement determine the installed instrument length.
FIGURE 6. - Calibration plot of TSR 4B showing deflection versus microvolt output for 5-, 6-, and 7-foot lengths.

FIGURE 7. - Parabolic curve fit of TSR's 4B, 5B, and 6B relating calibration slope to instrument length.
SELF-CONTAINED SYSTEM

The externally powered and recorded TSR system severely limited application of the concept around blasted openings because of susceptibility of the exposed portions to blast damage. The approach to designing a blastproof system was to completely enclose the TSR in the borehole in which it was installed with no external wiring or anchors. A requirement for such a system would be the capability of self-contained data recording and an anchoring system completely inserted into the borehole.

A device that possessed the capability of self-contained recording was developed under contract (7) for the Bureau of Mines by Battelle Northwest Laboratories at Richland, Wash. A schematic of the system is shown in figure 8. The initial prototype utilized punched paper tape for data recording and an LVDT transducer. Prototype II replaced the punched paper tape with a completely solid-state system utilizing programmable read only memories (PROM's) for data storage. Prototype III, which was developed under a related services agreement with Battelle through ERDA, utilized the TSR transducer head and extension tube and had the added feature of remote shutoff to save battery power in the event of an interrupted excavation cycle.

Transducer-Recorder System

Components of the transducer-recorder system for the "self-contained TSR" (SCTSR) are shown in figure 9. Figure 9A shows the communication electronics, consisting of red- and green-light-emitting diodes (LED) and photo diodes. These components control the functions of the instrument simply by different length exposure of light from a miner's cap lamp onto the photo diodes. The functions are (1) turn the instrument on, (2) establish reference position, (3) manual readout, (4) automatic recording, and (5) instrument turnoff.

The initial power-up requires 20 seconds of light exposure after which the instrument will accept either a 3-second light command for reference positioning or a 1-second exposure for manual readout. The reference position mode is of 60-second duration before automatic time-out, and permits adjusting and preloading the cantilever to about midpoint deflection (0.15 inch), indicated by red and green LED transfer. Manual readout consists of alternating red or green LED flashes, representing 0 and 1 respectively in binary coded decimal form. A 10-digit binary number (1 or 0 × 2^0 ...2^9) is obtained, from which the deflection or change in deflection of the cantilever can be determined.

The instrument is put into automatic recording mode by a second 20-second exposure to light. It will automatically record up to 1,024 eight-digit numbers in binary form on the PROM's. Sampling interval is controlled by a preset timing control switch which provides cycling rates of 30 seconds, 15 minutes, 30 minutes, or 1 hour. For example, if the 15-minute data sampling interval was chosen, the memory "chips" would be full in [(1,024 × 15) ÷ 60] 256 hours, or 10.7 days. A third 20-second exposure of light to the photo diodes shuts the instrument off to save battery power if data recording is not required or if the instrument needs to be removed for recharging and data retrieval. The
FIGURE 8. - Schematic showing component parts of the self-contained system.
communication electronics are sealed behind plexiglass in the end piece of the instrument and capped to prevent exposure of the photo diodes to ambient light.

Figure 9B is the power pack and consists of six Gates D size, lead-acid rechargeable batteries and one Mallory mercury throwaway battery. The Gates batteries are good for up to 42 days of operation at room temperature before recharging; the efficiency is decreased considerably by higher temperatures.

*Reference to specific equipment, trade names, or manufacturers does not imply endorsement by the Bureau of Mines.*
FIGURE 9. - Component parts of self-contained TSR:—Continued: $C$, Logistics control and recording electronics; $D$, modified TSR extension tube and electronics containment tube.

Figure 9C shows the control logic, conversion, and recording electronics, which are mounted on back-to-back circuit boards. The four PROM's and electronic timing switch are also located here. The entire assembly (electronics and power pack) is housed in a hermetically sealed stainless steel containment tube which is rigidly attached to the TSR extension tube (fig. 9D). A four-prong plug connection interfaces the TSR transducer with the self-contained recorder with a ground to the tube. Design drawings of the SCTSR containment tube are shown in figures A-2 and A-3 (appendix).

Data are retrieved by removing the PROM's from the instrument and plugging into a reader interfaced with a Hewlett-Packard teletype (fig. 10), which provides printed paper or punched tape output. The reader converts the binary information from the PROM's into binary-coded decimal (BCD) form for output on paper. Each digit represents roughly 0.0003 inch; that is, the 3-inch deformation range divided by 1,024 ($1 \times 2^9$) resolution elements. Since each memory address has a capacity of an eight-digit ($2^7$) binary number, only one-quarter of the full 0.3-inch deflection range can be written in any one address. Any conversion exceeding $1 \times 2^7$ or 256 BCD numbers automatically initiates start of a new eight-digit number; the full 0.3 inch is specified by an unwritten, but logical, BCD number of $256 \times 3$ plus a written number of 256.
FIGURE 10. - Reading the PROM's with reader and teletype.
The flow diagram to convert SCTSR data to deformation and time information is shown in figure 11. The punched tape output is read from the teletype, and punched cards or direct disk or tape storage is obtained. The data is logically stored and/or converted for plotting as a function of time and excavation advance.

The data on the PROM's are erased by exposure to high-intensity, short-wave, ultraviolet light. The memories are erased with a 15- to 30-minute exposure with the lamp held 1 inch away. They are checked in the reader to insure that all memory addresses are cleared before reinstalling in the instrument. The timing control switch is set at the desired rate, and the instrument is reassembled. An extra set of batteries and PROM's can be used to expedite the data recovery process.

FIGURE 11.- Flow diagram of data storage and retrieval from SCTSR with sample teletype output.
Anchor System

A unique, internal, in-the-hole anchoring and adjustment system was developed to enable complete insertion of the SCTSR into the installation hole. Deep and shallow anchors (fig. 12) were designed to fit into a 3-inch (NX) borehole with a 6-inch-diameter reamed collar. The deep-deformation-sensing anchor (fig. 12B) is grouted at a predetermined depth in the NX borehole. It has a slotted opening in one end to accept the ball end of the transducer and allows only unidirectional motion to be transmitted, eliminating error caused by side loading.

The shallow anchor (fig. 12A) replaced both the adjustable mounting head and support reference pipe, eliminating hole alinement problems and instrument interference associated with the externally anchored TSR. It consists of an aluminum anchor shell which is grouted to the rock and a removable adjusting mechanism with retaining rings.

The deep and shallow anchors are fixed to an installation tool by threaded stock and a flanged collar as shown in figure 13A. The shallow anchor is set at a predetermined position so that when the TSR instrument is installed, the ball end of the cantilever will just engage the socket in the deep anchor. Latex rubber grout seals are cut with a gasket cutter to the proper size, set

FIGURE 12: SCTSR anchor assemblies; A, Shallow anchor and adjusting mechanism; B, deep anchor.
into grooves on the anchor, and wrapped with nylon lacing string. Grout tubes are attached to both anchors, extended down the center of the installation tool, and left protruding from the lower end. After the assembly is inserted and wedged into position, Hallemite POR-ROK expanding cement is mixed to the proper consistency and injected into the annular space between the grout seals and the walls of the borehole with a grout injection device (fig. 13C).

After curing for about one-half hour (longer if the hole is water filled), the installation tool is removed and replaced with the TSR instrument and adjusting mechanism as shown in figure 13B. The instrument is fixed to the adjusting device by upper and lower collets. After inserting the instrument through the shallow anchor and engaging the transducer cantilever ball into the deep anchor slot, the assembly is rigidly clamped into place with the retaining rings and Allen screws. Allen screws are also used to pre-load the transducer to 0.1-inch deflection. As the adjusting screws are turned, beveled nuts wedge between the anchor shell and adjusting flange, deflecting the bottom of the instrument. To adjust the system, the two opposing screws on a line parallel with the direction of the movement are turned until the red and green light transfer point is reached. After adjustment, all screws are tightened to complete the installation. Detailed design drawings of the SCTSR anchor system are shown in figures A-2 and A-3.

**Laboratory Evaluation**

Calibration of the SCTSR was conducted prior to environmental
testing. The procedure was similar to that used for the externally powered TSR, except that only the full extended length was calibrated (since the installed length would always be the same). Each deflection increment was maintained for at least 30 minutes, and about 60 records on the PROM were obtained for each setting. Output was also read manually through the LED's. Sensitivity of the instrument at the 8-foot length, as determined from the average slope of the deflection versus output curve, was 0.000287 inch per bit. The maximum deviation from linearity was 1.4 percent and the drift of BCD output information at any one increment setting was typically less than ±0.4 percent.

The environmental evaluation was conducted in a large environmental chamber (fig. 14). A simulated borehole using thick-walled aluminum tubing was

FIGURE 14. - SCTSR in a simulated borehole in the environmental chamber.
inserted through the chamber ceiling at a fixed 45° angle. This angle was chosen because of limited headspace, and it represents one of the most difficult installation situations which could be encountered underground. The deep anchor area in the "borehole" consisted of a piece of removable plexiglass tubing so that the grouting efficiency could be observed and the anchor removed and reused. The shallow anchor portion is split and hinged for anchor removal and reuse.

The system was tested in the "self-contained mode" for periods of 10 days, 20 days, and 40 days under harsh environmental conditions simulating expected underground usage. All the movable components in the SCSR were thoroughly coated with grease for ease of installation and adjustment and for rust protection. Preloading the transducer cantilever to the LED transfer point was easily accomplished with the Allen screw adjustment, and visual observation of the ball and socket arrangement showed good lateral alignment. The adjusting screws were uniformly tightened to maintain system alignment and preload. Initial readings were taken, and the instrument was put into the automatic recording mode for each test. Manual readings were taken periodically to check the instrument for any malfunction (fig. 14).

Temperature in the chamber was maintained at 98°F and 100 percent relative humidity (R.H.) during the 10-day test. No malfunction of the instrument was apparent during this test period, but a constant creep rate of 880 micro-inches per day was indicated by the PROM output. During the subsequent 20-day evaluation at 90°F and 74 percent R.H., the creep rate increased, and after 11 days readings became erratic. The instrument was removed and disassembled, and megameter readings indicated the transducer strain gages had shorted to ground. The electronics were repaired, and the 20-day evaluation then resumed. The chamber was maintained at 90°F and 74 percent R.H. in the first 12 days, and at 100°F and 75 percent R.H. in the last 8 days. At the completion of the test the instrument was removed and disassembled, the PROM's were read, and the output was punched on black tape for computer plotting. The batteries were 45 percent and 25 percent discharged, the three nearest the electronics being discharged the most. Figure 15 shows a plot at the LED transfer point as a function of time. The data indicate a downward creep during the first 3 days before leveling off to a constant output. This is the apparent time required for the system to reach equilibrium with changing temperature conditions. The 24-hour cyclic nature of the data is also apparent. Portions of the SCSR, including the transducer, protruded through the ceiling of the environmental chamber, exposing the SCSR transducer to the variable outside room temperature. There was a slight drop in average output when the temperature was increased 10°, but at any one setting the instrument appeared quite stable.

The batteries were recharged, the PROM's were erased and reinstalled, the data cycle was changed to 4,000 seconds, and the instrument was reassembled for the 6-week test. The temperature inside the chamber during the course of this test was increased by 10° increments, starting at 55°F and ending at 105°F. Relative humidity remained at 70 to 80 percent. The instrument was installed and the cantilever was loaded to about 60 percent of its deflection limit. Prior to putting the instrument into the automatic recording mode, it was allowed to temperature-stabilize for 3 days.
FIGURE 15. - Plotted output of 3-week environmental stability test at the LED transfer point.

At the end of 6 weeks of continuous operation in the self-contained mode, the instrument ceased to respond to light commands. After disassembly, it was found that the mercury battery was dead. The Gates lead-acid batteries were 55 percent and 30 percent discharged again, the batteries nearest the electronics discharging faster. It was also noted during disassembly that the TSR-to-SCS connector was extremely corroded, and there was standing water inside the TSR extension tube. Figure 16 shows the deformation versus time plot for the 6-week environmental test, as computed from the PROM data record. Again, there is a slight drop in average output for each incremental temperature increase, the temperature sensitivity being more pronounced at chamber settings either above or below the outside room temperature conditions. The plot indicates that high temperature differentials between the ends of the instrument result in increased sensitivity to changing temperature. This could be significant in deep mines where temperature differentials between the collar of a borehole and 10-foot depth often are as high as 30°. No long-term drift tendencies were apparent, and consistent output was obtained under sustained "self-contained" operation.
FIGURE 16. - Plotted output of 6-week environmental stability test at the LED transfer point.

Upon completion of the environmental stability tests, the anchors were examined for grouting effectiveness. Figure 17 shows the anchor-grout bond to the walls of the aluminum and plexiglass tubing. Difficulty was encountered when trying to remove the anchors for reuse, and dislodging the deep anchor required considerable force. The POR-ROK cement was evaluated in a downhole filled with water in preparation for the field installation around a shaft. The grout displaced an 8-foot head of water and after setting 2 hours provided as effective an anchor as if no water had been present. Running water might present some difficulty because it would tend to erode the water-based cement before it had a chance to set.

No serious difficulties were encountered with the SCTSR at elevated temperatures, high humidity, and an extended period of data recording. Most of the debugging of the basic data acquisition package was completed by Battelle under contract. The system was designed for a capability of at least 8 weeks of "self-contained" operation and recording in an underground environment, depending on temperature and battery conditions. It was shown that at elevated temperatures (>100° F) the battery life expectancy decreases considerably. The TSR transducer connector and extension tube also require better water-resisting features.
FIGURE 17. - Deep anchor being removed from the plexiglass tubing. The shallow anchor has been removed from the simulated borehole.

FIELD TESTING

Raise Borehole

The modified externally anchored and recorded TSR's were field-tested to evaluate sensitivity and reliability. The test site was a raise borehole in stope 108 on the 3850 level of Hecla Mining Co.'s Lucky Friday mine. Three 8-foot-long instruments were installed around the proposed 5-foot-diameter ventilation raise, as shown in figure 18. The proposed raise was to be oriented down the steeply dipping lead-silver-zinc vein at about 63° from horizontal to intercept a drift driven just above the 3850 level.

Three horizontal holes, 5 feet deep, were drilled in the sidewalls 60° apart and as close to the back as possible, using a jackleg with a 1-1/2-inch pilot and 3-1/2-inch reamer bit. The support reference pipe, heavy wall schedule 80, 2-3/8 inches in outside diameter, was inserted into the hole and grouted into place with Lumnite high-strength, early-set cement. The final position of the support pipes, and thus the head, is determined by the distance of the sidewalls from the raise bore and by the ability to drill the reference pipe holes exactly as desired. The head was bolted on and adjusted at the proper angle to provide a drill guide for the TSR installation hole. The 3-1/2-inch reamer bit was again used with a stoper drill. Depth and orientation of this hole are critical and were dependent largely on conditions
around the proposed excavation and skill of the drill operator. The objective was to place the deformation-sensing anchor of the TSR as deep as possible and 12 inches from the excavation walls in such a manner that the exposed portions of the completed installation are reasonably well protected from the raise bore bit and falling cuttings.

The pilot hole gage of the reamer bit leaves a centered 4-inch-deep hole in the end of the TSR installation hole. A number 4 size glass bottle filled with ROC-LOC epoxy is attached to the deformation sensing plug, and the assembly is screwed on the end of the installation tool. This tool is inserted through the mounting head and tapped with a hammer to crush the bottle against the back of the pilot hole to release the epoxy. After the sensing anchors are set and the epoxy has cured (usually one-half hour), the installation tools are removed and the TSR gages are installed, as shown schematically in figure 18.

The cantilever is deflected 0.1 inch towards the proposed excavation by moving the transducer head away from the excavation walls with the adjusting screws. This "preloading" permits hole dilation deformation to be recorded (due to abutment loading) and subsequent closure to be monitored without the cantilever deflecting back across the null point. Lead wires were strung 200 feet down the manway and along the haulage level to a data acquisition station (fig. 19). The data system was especially built for the TSR and has been previously reported (5). Field telephones were installed at the raise bore machine on the 3650 level, at the data acquisition station, and at the installation site at the bottom of the raise. This permitted communication while preloading the instruments and during the raise-boring operation. After the proper preload was obtained, the TSR's were centered in the borehole, tightened in the mounting heads, and allowed to stabilize for several hours before raise boring began. An unloaded "dummy" instrument was sampled during each data acquisition cycle to insure that there was no malfunction.

Reaming the 8-inch pilot hole to 5-foot diameter continued uninterrupted except for rod changes every 4 feet of advance. A large slab failure occurred when the 5-foot reamer bit was at the deformation-sensing plane at about...
FIGURE 19. - Data acquisition station at Lucky Friday mine.
7-foot depth. At 12 feet the collar of the hole completely failed, terminating the test. The raise was ultimately abandoned because of difficulty in holding it open long enough for support to be installed.

Figure 20 shows the plot obtained from TSR 3B before it was destroyed by falling rock. This instrument was installed in the competent hanging wall quartzite, permitting a more complete deformation curve to be obtained. The large dilation represents a measure of the incompetence of the rock. The abutment load from the thrust of the advancing reamer bit is believed to force the rock radially outward ahead of the bit. The relatively large movement was probably due to a low effective deformation modulus normal to the bedding and the borehole centerline. Closure started as the 48-inch bit passed the sensing plane; the rock returned to its original position when the 5-foot reamer stage was approximately half a hole diameter beyond the sensing plane. A net closure of 0.07 inch is indicated before the rock failed; about 40 percent of this occurred after raise boring was terminated. In previous tests around raise bores in more competent rock, hole dilation due to abutment load was much smaller and net closure was about one-half of what was indicated here (14).

No information was obtained concerning the biaxial stress field around the hole, time to stability, long-term deformation rate, or effect of support. Erratic results were obtained on TSR's 1 and 2 owing to the constantly slabbing and falling rock which led to eventual destruction of all of the instruments. Of primary importance is that the instruments performed without malfunction, before and during the reaming operation, and under difficult field conditions, as compared to previous attempts.

**Blasted Opening**

The SCTSR was tested in conjunction with an experiment to determine shaft and support design criteria at the Caladay project near Wallace, Idaho. The purpose of testing the self-contained system was to evaluate the performance of the electronics and internal anchor under field conditions and compare the results obtained with similarly installed external TSR's. The test site was at the shaft station at the end of the adit level under about 1,200 feet of overburden. An 8-foot-diameter, one-half-scale, circular shaft and a 5- by 10-foot rectangular shaft were instrumented with TSR's and drilled and blasted with successive rounds to depths of 24 feet. Trim holes were line-drilled
around the proposed opening to form a relatively smooth wall and prevent excessive overbreak. The SCTSR was installed around the perimeter of both excavations, as shown schematically in figure 21. The shots were controlled from the instrumentation room 200 feet down drift from the test site (fig. 22).

A 2-foot round was pulled initially to form a lip around the excavation to protect the instruments from blast damage and stress-relieve the collar of the shaft. A 3-inch (NX) hole was collared about 2 feet from the edge of the openings with a CP 65 diamond drill and drilled to a depth of about 10 feet at 10° off vertical, dipping towards the excavation. The collar of the NX hole was then concentrically overcored to 6-inch diameter to a depth of 3 feet. The anchor system was installed by procedures outlined previously. The shallow anchor was positioned within the most competent area of the 6-inch hole, and the system was then wedged into place and grouted. Several attempts were required to get the proper grout consistency because of standing water in the hole. After setting for about an hour (leftover grout was used to judge when curing was adequate), the installation tool was removed and replaced with the SCTSR's and adjusting mechanism (fig. 23). The instrument was turned on and adjusted to 0.15-inch preload, indicated by the red and green light transfer, and securely locked into place.

The instrument was initially put in the automatic recording mode at the 15-minute sampling interval for an in-the-hole, preblasting, stability test around the circular opening. After 7 days the instrument ceased to respond to light signals and was removed from the water-filled hole and disassembled in the instrument room. The TSR extension tube was full of water up to the SCS plug connection interface. The batteries were checked and were found to
FIGURE 22. - Removing the memories from the SCTSR in the underground instrument room.

be 20 percent and 100 percent discharged, the batteries nearest the electronics being completely discharged. The PROM's were removed and read, and the tele-type output showed about 5-1/2 days of auto recording. The data indicated that the instrument had a downward creep of about 0.0003 inch per hour the first day and about one-half of that rate the second day; it stabilized to ±0.00015 inch for the remainder of the test. The instrument appeared to be generally stable after the first 2 days, except for the dead batteries, which were attributed to a faulty cell; no difficulties were anticipated during later tests.

The SCTSR was set for a 30-second sampling rate, reassembled, and reinstalled around the circular test shaft 90° opposite TSR 5 and 45° to the bedding. The system was turned off while the holes were loaded and prepared for blasting to prevent the possibility of stray currents detonating the round. The instrument was put in the automatic recording mode about 15 minutes before the blast and allowed to continue recording for about 45 minutes after the blast. Manual readings were obtained before and after each shot as a backup to check the recorded data. After the fifth blast, 8 days after installation, the instrument failed to respond to light signals. It was removed and disassembled, and the TSR extension tube was again found to be full of water. The battery packs were discharged 5 percent and 85 percent; the three nearest the electronic package were again excessively drained. The PROM's were read and contained about 30 minutes of recorded data, only about 10 percent of that
expected. A check of the manual readings showed that automatic recording terminated within 15 minutes after the first blast. The problem appeared to be a combination of water and faulty batteries and/or excessive current drain.

The instrument was reassembled with new batteries and installed for the remainder of the test. It appeared to operate normally and was responding properly to light signals requesting manual readouts. After the shaft was completed, the instrument was removed and again found to have nothing written in the PROM's. The instrument was sent to the Battelle Northwest Laboratories for repair and was found to have a defective capacitor.

After the instrument was returned by Battelle, it was installed around the rectangular test shaft (fig. 23). It was cycled through several times and appeared to be functioning normally. Manual readings were again taken to check the recorded data. After the shaft was completed, the instrument continued to monitor long-term deformation, but it ceased to respond 25 days after installation and 4 days after the last round. It was removed and disassembled in the instrument room, and the battery packs were found to be 10 percent and 70 percent discharged. The PROM's were read; the first one had no data, the second was full, and the third was 30 percent full. Comparisons with the manual readings indicated that the instrument recorded only the first two shots and contained less than 30 percent of the total expected data.

Only data obtained from the LED output were utilized in the analysis. The SCTSR readings before and after each blast around the circular and rectangular shafts are shown in figures 24A and 24B, respectively. These SCTSR deformation data are compared with data from similarly installed externally powered and anchored TSR's as a function of shaft depth.

In figure 24A the SCTSR and TSR 5 were installed 90° apart and at 45° to the bedding planes. Both instruments indicated typical behavior, showing
large initial dilation excursions due to blasting abutment load and subsequent closure as the shaft bottom passed the TSR sensing plane during the fourth blast. A larger initial deformation shown by the SCTSR was probably due to initial stress release adjacent to the shallow anchor causing closure and indicating excessive apparent dilation at the sensing plane. The "zero movement" reference point for TSR 5 was about 5 feet farther away from the edge of the shaft than the shallow anchor of the SCTSR. A thin clay seam also intercepted the SCTSR borehole, which would tend to magnify the deformation. Subsequent points are almost directly comparable, the SCTSR and TSR 5 indicating total net closures of 0.003 inch and 0.002 inch, respectively.

Figure 24B shows the SCTSR compared to TSR's 5 and 8 installed along the 10-foot-long dimension of the rectangular shaft. TSR 8 was at the center of the span, and the SCTSR and TSR 5 were 2-1/2 feet away on either side. Again, relatively typical behavior is noted, although the large initial dilation from abutment loading is not obvious. The point-by-point correlation between the SCTSR and the external TSR's is exceptional, although some divergence is noted after the fourth blast. The "zero reference" anchors of the SCTSR and TSR's 5 and 8 were located 2-1/2 feet and 21 feet away, respectively, from the edge of the shaft. The total net closure as indicated by the SCTSR and TSR's 5 and 8 is 0.04, 0.02, and 0.03 inch, respectively.
A point-by-point analysis of the deformation data obtained from the SCTSR is difficult to evaluate because of the lack of continuously recorded data discussed previously. However, the good correlation with externally anchored TSR's and the general trend agreement indicate that the "in-the-hole" anchoring system is a satisfactory alternative to the external anchor, considering the inherent difficulties of blast interference and hole alignment.

DISCUSSION AND CONCLUSIONS

Redesign of the TSR measurement system has overcome many of the problems encountered with the original prototype. Modification of the transducer head and extension tubing increased sensitivity by a factor of 10, and a deeper sensor location is possible. Improved fabrication and laboratory testing techniques greatly increased the integrity of the electronic components and data reliability as shown by field testing.

The self-contained system interfaced with the TSR for internal recording performed satisfactorily during laboratory testing but proved somewhat unsuccessful in the field test. The electronics and operation are considered far too complex for even the most sophisticated field research. Considering the severity of the field conditions— that is, blasting, water-filled holes, etc.— the fact that the SCTSR functioned even reasonably well is somewhat commendable. However, failure of the recording electronics prevented critical data from being obtained except for the "before" and "after" manual readings.

The anchoring system utilized with the SCTSR was considerably more successful. Data comparison with externally anchored TSR's showed that an in-the-hole anchor concept is feasible, and similar deformations were obtained between the two systems, although as much as 21 feet separated their respective anchor positions. This is significant considering the inherent difficulties of blasting and other outside interference and hole alignment problems encountered with the external anchor.

Based on results of the field evaluation of both the "external" TSR and the SCTSR, an optimum state-of-the-art system would appear to be the externally powered and recording TSR combined with an "in-the-hole" anchoring mechanism. Ideally, a deep extensometer point should be installed as close to the shallow anchor as possible to determine absolute movement at the sensing plane. However, "relative" data are also acceptable if there is sufficient distance between the sensing plane and the shallow anchor. In a future test, best results could probably be expected by TSR's installed in downholes monitoring the ground movements as a raise is advanced from below.
REFERENCES


APPENDIX.—MECHANICAL DESIGN DRAWINGS OF THE TSR TRANSDUCER HEAD AND EXTENSION TUBE AND SCF TUBE COMPONENTS

Assembled drawings

A—Stainless steel extension tubing

B—Stainless steel metal bellows

C—Stainless steel connector disk

D—Titanium cantilever sputtered with stainless steel 304

E—Stainless steel cantilever mount

F—Stainless steel hold down block

G—Brass ball soft soldered to cantilever

Mill slot 0.5 inch diameter 1.0 inch long (both sides)

Typical, 62 slots

Drill and tap for swage lock

0.31-inch-diam access hole for signal cable

0.345" x 0.502" slot for titanium cantilever

4-40 threads 1/4 inch deep

FIGURE A-1. - Design drawing of the TSR transducer head and extension tube.
A-6061-T6 aluminum shallow anchor shell

B-SAE 1020 steel collet nut

C-SAE 1020 steel collet

D-Mild steel outer retainer ring

E-Mild steel adjusting wedge

FIGURE A-3. Component parts of the SCTSR system, sheet 1.