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How to Measure Rock Pressures: New Tools

GEORGE B. GRISWOLD

FOR A ROCK PRESSURE MEASUREMENT to have significance, it must be performed in solid rock beyond the blast-fractured zone adjacent to a mine opening. Furthermore, if premining stress is desired, the measurement must be made at a distance sufficient to escape the deflected stress envelope surrounding the mine opening. While Hast and USBM techniques satisfy these requirements, a newly developed 3-axis gage can make a stress determination for each stress relief core —a real asset when measurements are made in highly fractured rock.

Besides describing this gage, this article will detail the development of rock pressure measuring systems. Tools, techniques and mathematical formulas will be reviewed.

The newly developed gage, designed by the author, is extremely simple (Fig. 1). Borehole deformation is detected along three axes by small beryllium-copper transducer rings. The rings are so closely stacked that the three measurements are made within ¾ in. along the axis of the hole. Contact between the wall of the hole and the transducer rings is made by pairs of ⅛-in.-dia steel balls. A fourth ring, not in contact with the hole, is used as a temperature compensator. The transducer springs are freely suspended; the outer tube acts merely to protect the gage during drilling.

The gage is considerably smaller than earlier models. Designed for a ⅝-in. hole, it allows the stress relief hole diameter to be reduced from 6 to 2½ in., saving considerable drilling time and cost. Because hole size is reduced, measurement depths can be considerably increased by using conventional lightweight diamond drills. The gage is made waterproof by flooding with grease, which keeps the contact balls in place during insertion into the gage's hole.

The gage's reliability is shown in Fig. 2, where the gage has been tested in a steel cylinder subjected to pressure in a hydraulic testing machine. The graph shows the borehole deformation sensed along the three transducer spring axes against the theoretical deformation curve. Plans are being made to use this gage in stress measurement determinations in an underground mine.

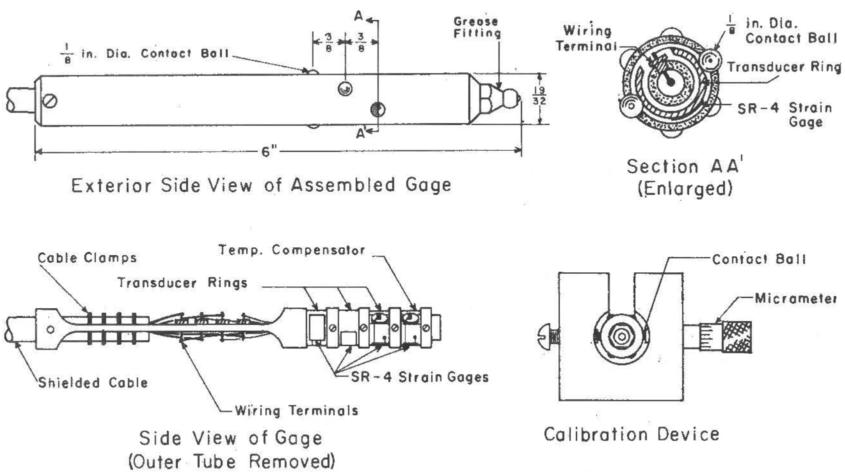

FIG. 1. Simple, but effective rock pressure gage uses beryllium-copper transducer rings for precise measuring. Smaller size permits deeper testing.

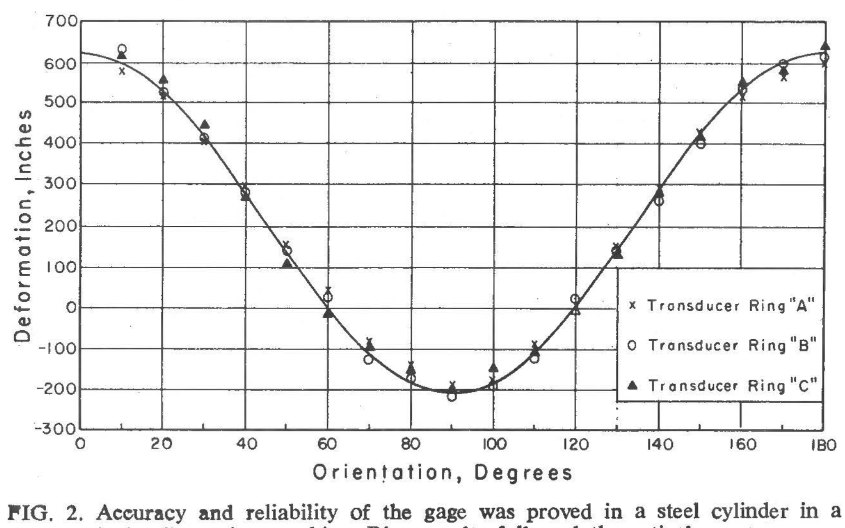

FIG. 2. Accuracy and reliability of the gage was proved in a steel cylinder in a hydraulic testing machine. Ring results followed theoretical curve.

Current Practices

During the last several years, considerable emphasis has been placed on the determination of rock pressure in underground mines. In the past, rock mechanics' study was limited to model studies in the laboratory or purely mathematical approaches based on the theory of elasticity.

Recently, stresses around mine openings have been studied by measuring deflections of the roof and walls. Reed and Mann[1] described many effective strain measuring instruments for use in open stope mines. Engineers at the Climax Molybdenum mine reduced concrete repair by detecting high stress zones through a program of systematic deflection measurements in slusher drifts.[2] Valuable studies were made by the USBM on changes in pillar strains in New Mexico uranium mines.[3] To improve safety and reduce costs, these techniques should be used more extensively.

However, strain instruments attached to the walls or in pillars of an existing mine opening will sense only the change in stress about that opening and not the total stress acting. This is illustrated in its simplest form in Fig. 3.

Three pillars and the walls of an open stope support its roof. If two pillars are mined out, there will be a readjustment of the forces in the roof so that the stope walls and the remaining pillar carry the additional load. If a strain measuring device were imbedded in the remaining pillar before the commencement of pillar-robbing, it would record the new load shifted to the pillar. However, this strain reading does not yield information as to what the total load is on the pillar. The total load, along with the physical

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And Proved Techniques Aid Mine Design

properties of the pillar, is the sole criterion for determining its support capabilities. In this instance, the total stress on the pillar is composed of three components: (1) the original stress before mining, (2) the stress increase due to the initial room and pillar development, and (3) the added weight caused by the extraction of the nearby pillars.

In a horizontally bedded deposit where tectonic forces are not active, a reasonable estimate of the premining stress can be computed directly by knowing only the mining depth and the density of the rock. And, in the simple example of Fig. 3, a fair estimate of the increase in load due to the initial mining might be made by knowing the area each pillar supported. Therefore, knowing only the final load increase is enough to arrive at the final pillar load.

Most rock stress problems, unfortunately, are far more complex. Active tectonic forces, variability in the physical properties of the mine rock, old fractures and faults and uneven surface topography may make estimation of the premining stress of a given spot in the rock very difficult. The irregular shape of mine openings and superposition of stress envelopes around adjacent workings also make it difficult to predict the effect mining has had on the original stress field.

There is a need, therefore, for techniques whereby the total stress field can be determined at a desired point in a mine. Several such methods are now in use.

Essentially, all pressure measurements are based on strain. The common bourdon tube used to measure pressure in fluids is actually a strain instrument, the tube being straightened (strained) with increase in pressure. The bourdon tube is not a pressure instrument until this straightening effect is calibrated against previously known pressures. Engineers have a tendency to forget that all so-called load cells, whether based on differential transformers, magnetic inductance, resistance wire gages or magnetostrictive devices, are cells which correlate pressure to strain. Herein lies the first of three difficulties in measuring rock pressure; we must measure the strain in the rock, an extremely small quantity, difficult to record. If strain is known, then stress can be computed from Hooke's law:

$S=Ee$

where S=stress (force/unit area)
E=modulus of elasticity of material (force/unit area)
e=strain (change in length/length)

The second difficulty is that the direction in which the strain-causing forces are acting must be known. To establish the directions of the principal stresses in a plane, three separately oriented strain mensurations within that plane must be performed. The third difficulty results because the rock is already in a stressed state which must be completely relieved before the accompanying strain-relief can be measured.

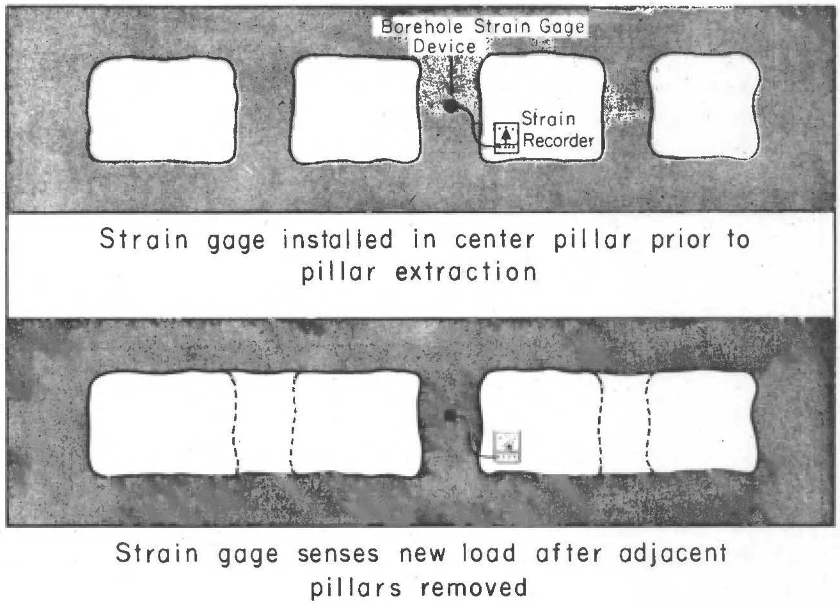


FIG. 3. Fallibility of a strain gage attached to a pillar in an existing mine opening is shown when pillars are removed. Total stress is now measured.

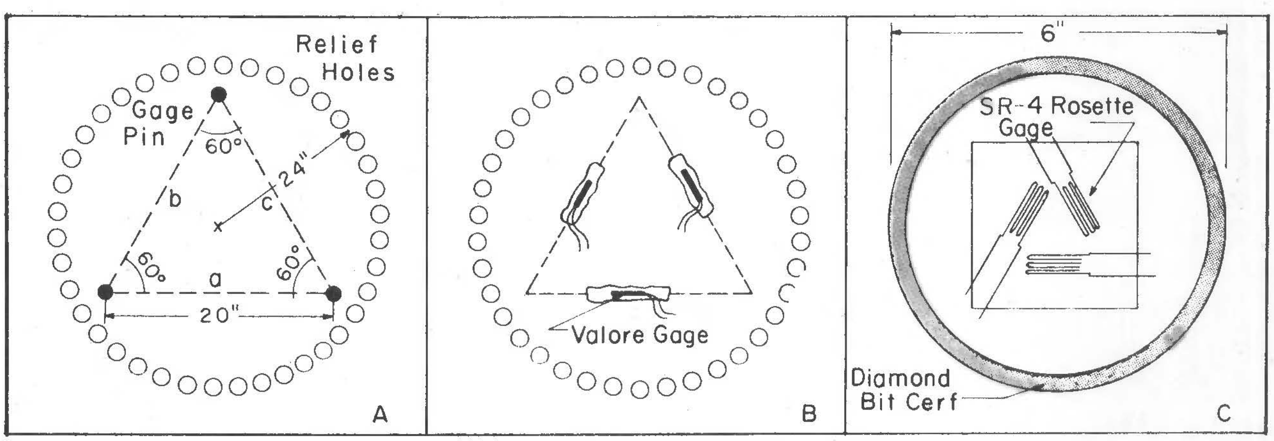


FIG. 4. Early techniques of rock pressure measurement involved three-pin setup at the Hoover Dam, the valore-type wire resistance gage, and the Bureau of Reclamation's improvement on the latter, using a diamond drill core.

Early Techniques Reviewed

One of the earliest attempts to measure total rock pressure was by the Bureau of Reclamation in a tunnel under Hoover Dam in 1932.[4] The basic procedure used is shown in Fig. 4A. Three steel pins were set in the tunnel wall, and the distances between the pins were precisely measured. Stress relief was accomplished by drilling a series of 30-in.-deep holes on a 4-ft dia around the gage points and then chipping out between. The distance between the gage points was again measured to find the amount of strain in three directions. This information, along with the modulus of elasticity and Poisson's ratio of the rock, was sufficient to compute principal stresses and their direction in the plane of the wall. The following equations were used:*

$$S = E\left[\frac{e_a + e_b + e_c}{3(1-\mu)} + \frac{1}{1+\mu}\sqrt{\left(e_a - \frac{e_a + e_b + e_c}{3}\right)^2 + \left(\frac{e_c - e_b}{\sqrt{3}}\right)^2}\;\right]$$

$$T = E\left[\frac{e_a + e_b + e_c}{3(1-\mu)} - \frac{1}{1+\mu}\sqrt{\left(e_a - \frac{e_a + e_b + e_c}{3}\right)^2 + \left(\frac{e_c - e_b}{\sqrt{3}}\right)^2}\;\right]$$

$$\phi = \frac{1}{2}\tan^{-1}\left[\frac{\frac{1}{\sqrt{3}}(e_c - e_b)}{e_a - \left(\frac{e_a + e_b + e_c}{3}\right)}\right]$$

e_a, e_b and e_c = strain at 60°-orientations
S = maximum principal stress
T = minimum principal stress
E = modulus of elasticity of rock
μ = Poisson's ratio of rock
ϕ = angle from maximum principal stress to a-axis

Fig. 4B shows the same technique, using valore-type wire resistance gages imbedded in slots, with a grout which closely matches the elastic properties of the rock. Such gages allow more precise strain measurements. The Bureau of Reclamation further improved the method by using a standard SR-4 wire resistance strain gage rosette bonded to a flat surface ground on the wall. Stress relief was accomplished by drilling over this gage with a 6-in.-dia thin-wall diamond bit (Fig. 4C). The USBM has used the same technique at the Climax Molybdenum mine.[5]

A more elaborate scheme for measuring the stress in the wall of a mine opening is the flat jack method perfected by the USBM[6] and illustrated in Fig. 5. Four parallel valore-type strain gages are imbedded in the wall, as shown, and initial gage readings are taken. Next, a horizontal slot is cut which causes stress relief along an axis normal to the slot, i.e., parallel to the strain elements. The accompanying strain relief is immediately detected by gages A and B. Next, a disk-shaped bladder, called a flat jack, is grouted into the stress relief slot. The flat jack is pressurized with hydraulic fluid until the original (pre-slotting) strain reading is re-established in gages A and B. The pressure in the flat jack is then equal to original rock pressure acting normal to the cell.

No determination of the elastic constants of the rock is necessary because the repressurization of the rock is done *in situ*. Also, there is no need to duplicate the elastic properties of the rock with the grout used to imbed the flat jack or the strain meters. This particular gage installation can be used to record subsequent pressure changes in the wall by recording the strain in gages C and D.

These gages were placed in such a position as to be unaffected by the stress relief slot, but they will still sense any subsequent change in the over-all stress. If these gages show such a change, say from e_o to e_1, then the flat-jack pressure is changed until an identical strain increment is produced on gages A and B. This pressure change equals the change in rock stress.

The rock pressure determination methods thus far described have a common handicap: Pressure can be determined only on or for a short distance into the rock. Theory and photoelastic model studies have proved that an envelope of deflected stress exists around any void in an elastic media—such as a tunnel in hard rock. The shape of this envelope is dependent on the direction of the original stress field and the geometry of the opening. For simple geometric shapes, the stress distribution around the tunnel can be predicted. Most mine openings, however, are far from simple geometric shapes for a single cross-section and thus present an exceptionally complex stress envelope. Secondly, and possibly more influential, is the effect of the numerous fractures in the wall caused by blasting during the creation of the mine opening. These two factors combined cause any pressure measurement made near the walls of a mine opening to be a unique measurement; and extrapolation of this pressure, even a short distance away, is guesswork.

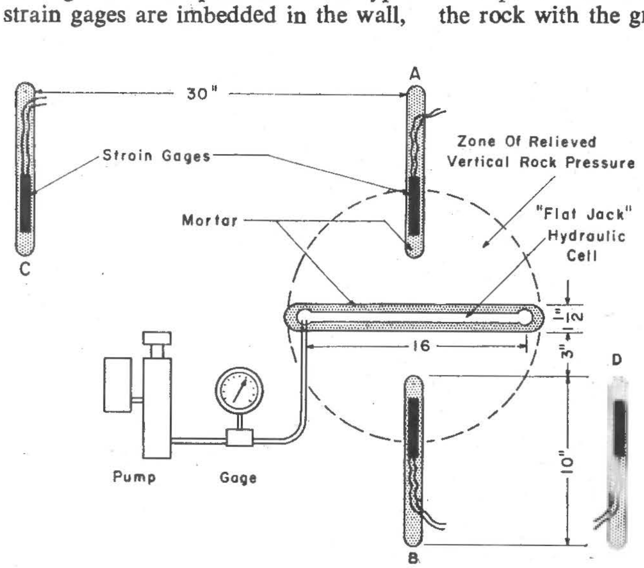


FIG. 5. The "flat-jack" system has been proved in testing at St. Joe and elsewhere.

Current Techniques Reviewed

A Swedish researcher, Nils Hast, was the first to develop a technique to measure rock pressure at considerable distances into the rock and, as such, was the first to collect a reliable sample of rock preassure.[8] Hast's method, sequentially shown in Fig. 6, utilizes the same method of large-diameter diamond drilling to cause stress relief that has been described earlier. The important added feature is that a magnetostrictive load cell is inserted into a small gage hole in advance of the large-diameter stress relief hole. This procedure has allowed pressure measurements to be made as far as 50 ft into the rock.

The magnetostrictive gage used was calibrated to read directly in stress by using a suitable factor to correct for the difference between the elastic mod-

*The derivation of these equations can be found in most texts on strength of materials, elasticity or experimental stress analysis. The basis of the derivation is Hooke's Law.

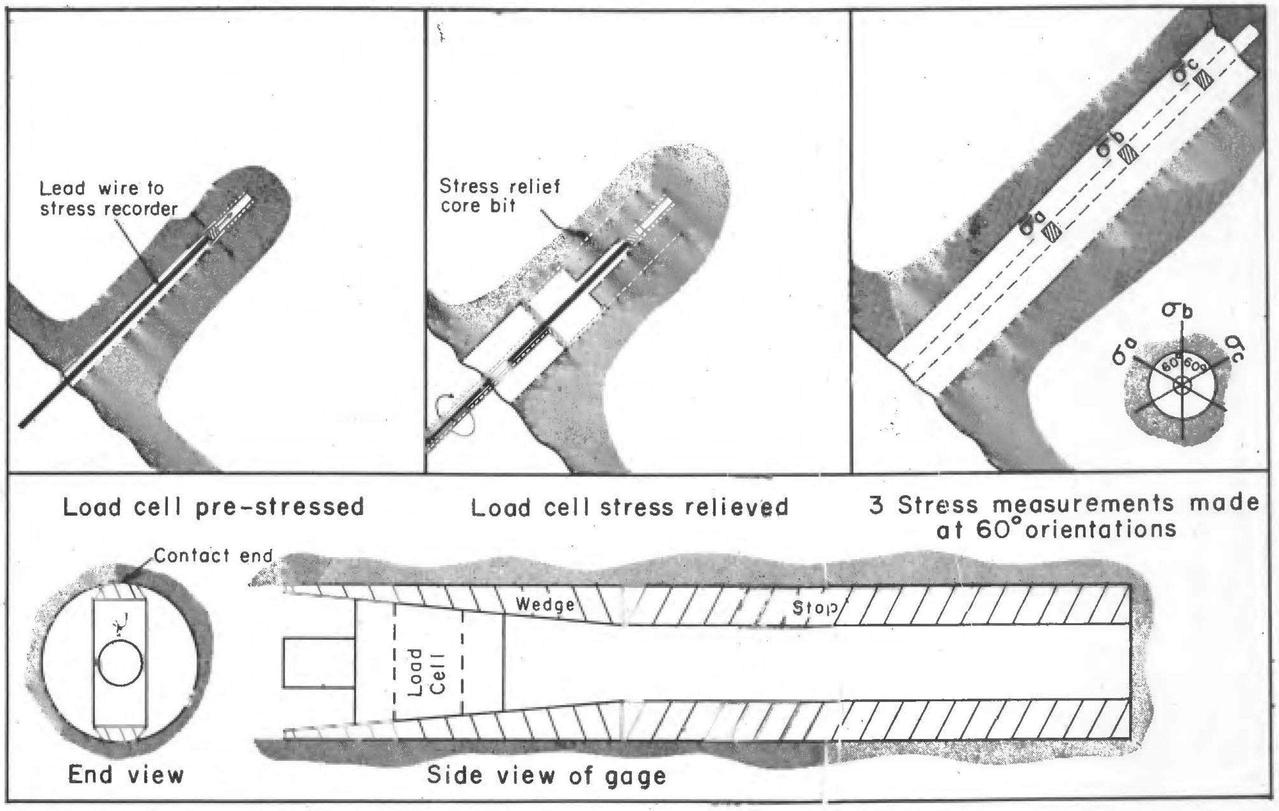


FIG. 6. The modern method developed by Nils Hast uses the same large-diameter diamond drill for stress relief mentioned in Fig. 4, but adds the magnetostrictive load cell in a small-gage hole in advance of the large-diameter hole.

uli of the gage and the particular mine-rock tested. To record stress relief, the gage must be prestressed to a level above the expected rock pressure after implacement in the hole by a special, remotely operated wedge. The stress in the direction of the gage axis was then computed as

(prestress-final stress) x calibration factor.

The principal stresses and their orientation can be computed for a plane normal to the axis of the test hole by special formulas developed from Kirsch's equations for the stress distribution about a circular hole in a uniformly stressed plate.[8, 9]

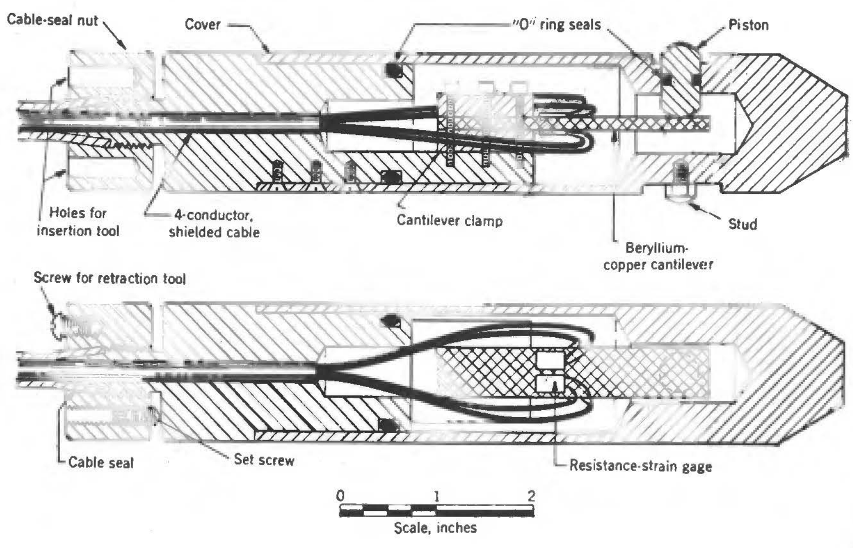
$$S = 1/2 \left\{\sigma_a + \sigma_b + \sigma_c + \sqrt{1/2 \left[(\sigma_a - \sigma_b)^2 + (\sigma_b - \sigma_c)^2 + (\sigma_c - \sigma_a)^2\right]}\right\}$$

$$T = 1/2 \left\{\sigma_a + \sigma_b + \sigma_c - \sqrt{1/2 \left[(\sigma_a - \sigma_b)^2 + (\sigma_b - \sigma_c)^2 + (\sigma_c - \sigma_a)^2\right]}\right\}$$

$$\tan 2\phi = \sqrt{3}\left[\frac{\sigma_b - \sigma_c}{2\,\sigma_a - (\sigma_b + \sigma_c)}\right]$$

moreover, $\dfrac{\sin 2\phi}{\sigma_b - \sigma_c} > 0$

σ_a, σ_b and σ_c = stress at 60°-orientations
S = maximum principal stress
T = minimum principal stress
ϕ = angle between principal stress and a-axis



Because the magnetostrictive gage device was designed to function as a load cell, careful attention had to be given to installation. The pressure-sensitive contact ends of the gage must be in intimate and uniform contact with the walls of the hole.

The USBM recently developed a deformation-sensitive gage which can be used in conjunction with the same stress relief drilling method used by Hast.[10, 11] The principle of the gage operation is shown in Fig. 7. Since this gage simply measures deformation of the hole during stress relief by

FIG. 7. Improvement on the Hast design permits installation with much less care. Deformation is measured.

means of a strain-gage-instrumented cantilever, the extreme installation care required by Hast's gage is largely eliminated. The bureau gage has a wall contact pressure of only 10 to 30 lb, just enough to make a rigid contact. As before, three consecutive measurements at 60° rotations are made to determine stress in a plane normal to the axis of the test hole. Deformation of the hole is measured instead of stress; therefore, different equations must be used to resolve the principal stress:[12]

$$S - T = \frac{\sqrt{2}E}{6d(1-\mu^2)}\sqrt{(U_a - U_b)^2 + (U_b - U_c)^2 + (U_a - U_c)^2}$$

$$S + T = \frac{E}{3d(1-\mu^2)}(U_a + U_b + U_c)$$

$$\tan 2\phi = \frac{\sqrt{3}\,(U_b - U_c)}{2U_a - U_b - U_c}$$

U_a, U_b and U_c = hole deformation at 60°-orientations
S = maximum principal stress
T = minimum principal stress
ϕ = angle between maximum principal stress and a-axis
E = modulus of elasticity
d = diameter of gage hole
μ = Poisson's ratio

Although the Hast and Bureau of Mines gages are successful in measuring rock pressure in virgin rock, there is some doubt as to the reliability of combining three separate stress measurements taken at separate places along the hole into one principal stress determination. This is particularly true in fractured rock. Furthermore, stress relief drilling is very cumbersome because an electrical lead wire must pass from the gage back through the drill rod to the strain-measuring instrument. This cumbersome drilling procedure must be performed three times for a single stress determination for a plane.

During the last two years, a variety of 3-axis borehole deformation gages have been tested with the aim of overcoming the two difficulties cited above. This work resulted in the development of three basic types of gages. Of the three, only one now is considered fully reliable, but since each is novel in design, all will be described.

The first, and least successful, design employed the use of a small SR-4 foil rosette strain gage bonded to a small plexiglass disk. The particulars of the gage and the sequence of borehole installation are shown in Fig. 8.

The gage was bonded to the walls of the hole with a casting-type epoxy resin. A thin coating of paraffin over the center of both sides of the gage disk caused the epoxy grout to bond to the walls of the hole at only the outer edge of the disk. The gage was designed to be installed in a 1½-in.-dia drill hole using a 5- to 6-in. stress relief hole. Because the modulus of elasticity of the plastic was much less than the rock, it was hoped that the gage would faithfully record the deformation of the circular drill hole during stress relief. Several rock stress measurements were performed using this method in steeply dipping limestone beds at American Smelting & Refining Co.'s Waldo Mine near Magdelena, N.M. This procedure has been abandoned becasuse of: (1) difficulty in installation because of the safety precautions necessary when handling epoxy resins; (2) cost—each gage is a single-use item; the SR-4 rosette costs \$5 to \$20; (3) bonding—even though epoxy resins are famous for their high bonding strengths, a truly uniform bond between the plexiglass disk and the wall probably never was achieved; (4) lack of a realistic method to determine if all the borehole deformation was sensed by the strain rosette; (5) tendency of plastic to creep considerably after installation, giving rise to false strain readings.

The next design was an attempt to overcome the difficulties of the plastic

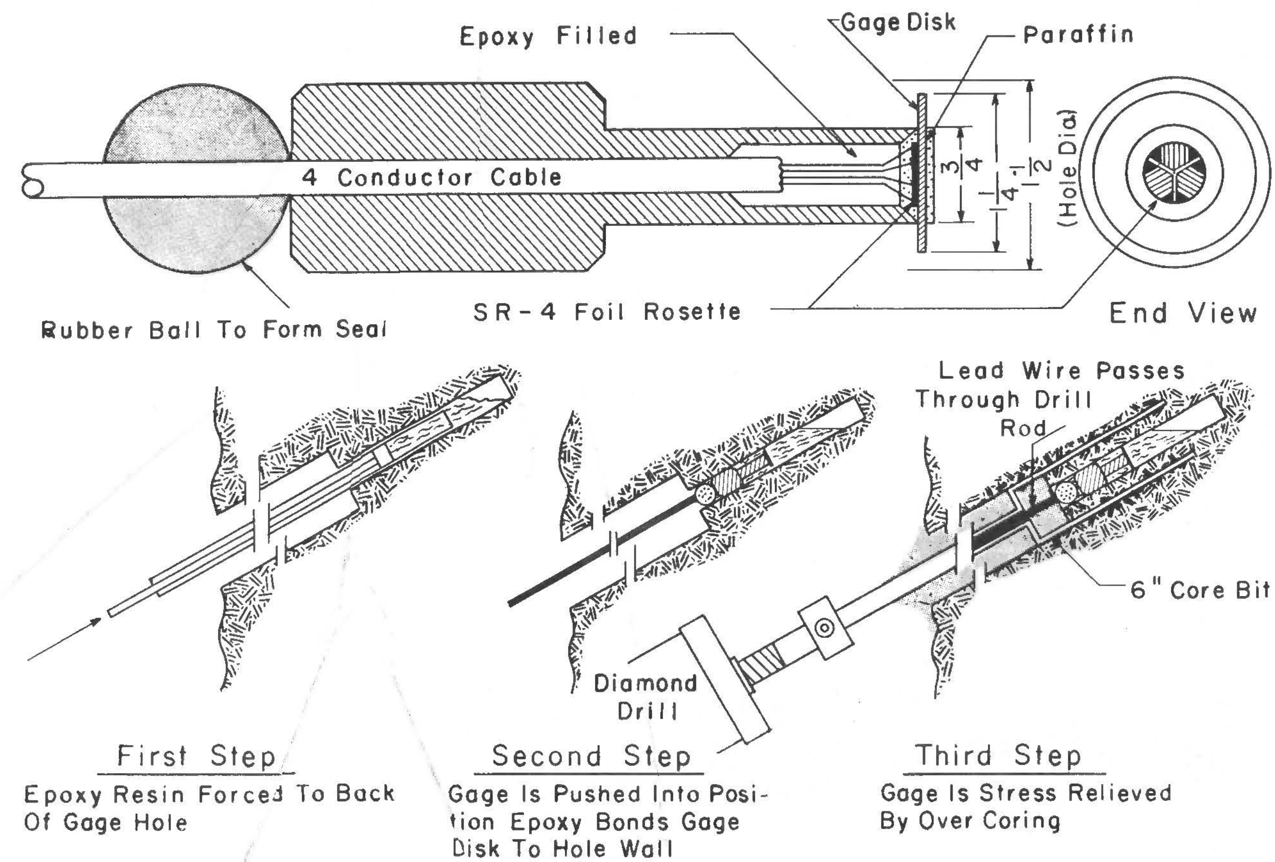


FIG. 8. Problem of combining stress measurements from three points along hole vs measuring at one point is overcome by use of the SR-4 foil rosette strain gage, bonded to a plexiglass disk and contacted with the borehole wall.

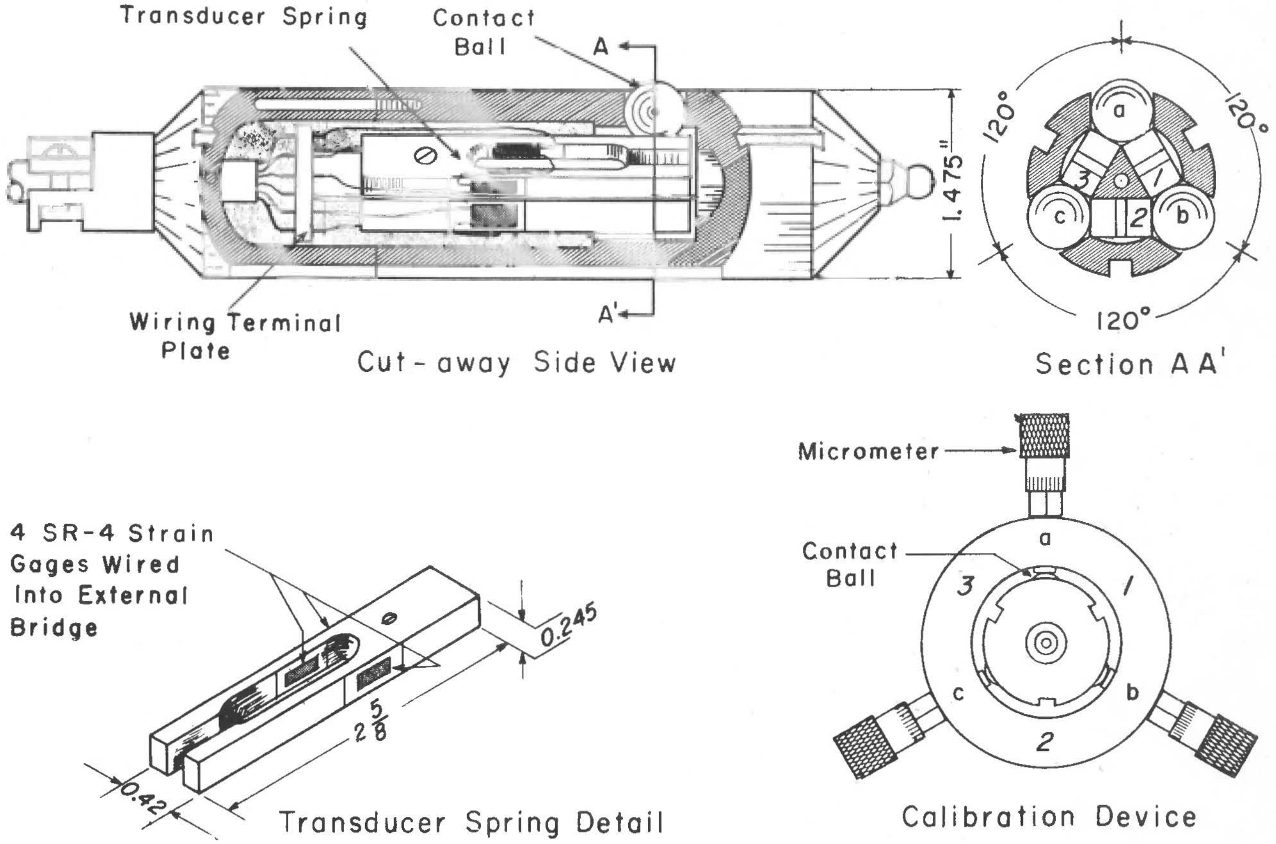


FIG. 9. Fears concerning successful contact of the plexiglass disk led to introduction of steel contact balls mounted to make contact with the borehole wall. Flooding the mechanism with grease provides waterproofing and holds setup in place.

gage. The entire gage was made from stainless steel and was reusable. The instrument, shown in Fig. 9, consisted of three ½-in.-dia-steel balls which contacted the walls of the hole at 120°-orientations, forming a rosette. The deformation of the hole during stress relief passed through each ball into two transducer springs. The deformation of the hole in each of the three directions could be deduced from the geometry of the gage:

$$S_1 \times f_1 = U_a + U_b \qquad S_2 \times f_2 = U_b + U_c$$
$$S_3 \times f_3 = U_a + U_c$$
$$\text{or } U_a = \tfrac{1}{2}(S_1f_1 - S_2f_2 + S_3f_3)$$
$$U_b = \tfrac{1}{2}(S_1f_1 + S_2f_2 - S_3f_3)$$
$$U_c = \tfrac{1}{2}(S_2f_2 - S_1f_1 + S_3f_3)$$

S_1, S_2 and S_3 = strain sensed by transducer springs

f_1, f_2 and f_3 = spring factors

U_a, U_b and U_c = *radial* deformation of hole at 120°-orientations

The transducer spring factors, which correlated the strain signal received from the SR-4 gages mounted on the springs to the movement of the contact balls, were determined by a special calibration cylinder, shown in Fig. 9. The gage was waterproofed by flooding the entire mechanism with water-resistant grease. The viscosity of the grease also held the contact balls in place while the gage was being inserted into the hole.

This particular gage was used with some success in fractured basalt at Banner Mining Co.'s Bonney Mine near Lordsburg, N.M. Stress measurements were made at distances up to 20 ft into the rock. Although the design principle appears valid, considerable difficulty was experienced in obtaining reliable results when the borehole deformations were small. Apparently, there is a tendency for the transducer springs to stick during short displacements.

The most reliable gage designed to date is shown in Fig. 1.

The last gage design developed by the writer is in all probability an interim instrument which will be supplanted by more refined models. Nils Grosvenor, Colorado School of Mines, has developed a 3-axis gage for measuring borehole deformation. The USBM is also designing a new gage. Along with the development of better borehole gages, much work is needed on the theoretical aspects of stress relief drilling. For example, a clear-cut relationship between the gage hole and stress relief core diameters needs to be established. The effect of anisotropic elastic constants for rock needs further study, and little is known about the effect of veinlets traversing a stress relief core. By being able to measure stress *in situ*, we are moving toward a better understanding of the behavior of rocks under static loads.

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