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Development of Titanium Load Cells for Support Load Determination

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Development of Titanium Load Cells for Support Load Determination

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DEVELOPMENT OF TITANIUM LOAD CELLS FOR SUPPORT LOAD DETERMINATION

by

Michael J. Beus[1] and Earl L. Phillips[2]

ABSTRACT

This Bureau of Mines report describes the development of load cells for measuring compressive loads in timber and rock-bolt support systems commonly used in coal, metal, and nonmetal mines.

Design and evaluation is covered in detail to insure a reliable, accurate, and practical instrumentation scheme. The load cells are relatively inexpensive and adaptable to various size support systems. User-oriented procedures are emphasized, and design equations were reduced to a series of nomographs. Laboratory evaluation, destructive testing, environmental testing, and tests to determine the effect of extraneous loads were conducted. Field performance was evaluated in conjunction with ongoing Bureau projects at a metal mine in North Idaho and a coal mine in Utah.

Load cells utilizing a titanium alloy as the cell body and weldable strain gages as the strain-sensing components satisfied the basic design and performance criteria, and with minor design modifications, the load cells can be adapted to many mining applications.

INTRODUCTION

This report summarizes recent research and development, funded under Coal Mine Health and Safety, that was conducted by the Bureau of Mines to provide load cells (<u>7</u>)[3] to monitor rock-bolt and crib loads at the Sunnyside coal mine in conjunction with the Single Entry Project. The instrumentation developed fulfills immediate requirements for the Spokane Mining Research Center's (SMRC) continuing research effort towards determining the loading response of a support system to geologic and construction variables at underground excavations. This report should also serve as a guide to those mining companies that are establishing or expanding their own research groups as a result of

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[1] Mining engineer.

[2] Engineering technician.

[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

the growing emphasis on safety and wish to fabricate their own load cell instrumentation as an integral part of a mine support-evaluation research project.

By determining the load history of a support in relation to measured variables, researchers can improve its efficiency and safety by modifying load transfer mechanisms, support orientation, support density, type of support, etc. Knowledge of support loads also enchances support prediction technology as well as providing an indication of impending face conditions[4] (1-2, 8, 13-14).

Load cells for almost every application are commercially available from numerous instrumentation firms. However, based on the literature[5] and manufacturer's specifications (3-5, 13, 18, 23-25, 31, 33-35, 37 - 38) none of the load cells would satisfy all of the requirements, prime considerations being reliability, cost, and compatibility with mine support systems. Rejection of commercially produced load cells does in no way deny their designed capabilities in other related functions.

Typical applications of load cell instrumentation to mine support systems are shown in figure 1A and 1B and figure 2A, 2B, 2C, and 2D. By conducting the design and fabrication of this instrumentation, exact compatibility requirements can be met, and an intimate knowledge of performance is obtained. Thus, the response of the load cells to conditions in the field can be determined, the interpretation of field data is greatly enchanced, and timesaving on-the-job repairs are possible.

ACKOWLEDGMENTS

Robert G. Sullivan and Blaine E. Crea of the Battelle Memorial Institute in Richland, Wash., provided technical assistance, under a related services agreement, in the application of electron beam gun welding and effects of extraneous loading, respectively. Arthur Brown, mine superintendent at Hecla Mining Co.'s Lucky Friday mine in Mullan, Idaho, and Donald Ross, mine manager at Kaiser Steel's Sunnyside mine in Sunnyside, Utah, provided initial field test sites and installation assistance.

PRELIMINARY EVALUATION

The general categories of load measurement devices considered in this study was hydraulic, mechanical, photoelastic, and electronic (10). A preliminary evaluation, based on literature searches and minimum laboratory

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[4] An in-house technical report describes set loads as a function of face advance and conditions at the face at the Henderson Tunnel, Colorado. The data shows that the instrumented steel sets, after stabilizing for 2 months following the installation, underwent significant load increases when a major fault zone was penetrated 800 feet away.

[5] Personal communication with Bob Anderson of the Missouri River Div., Corps. of Engineers, Omaha, Nebr., and Walter Mystowski, State Department of Highways, Idaho Springs, Colo.

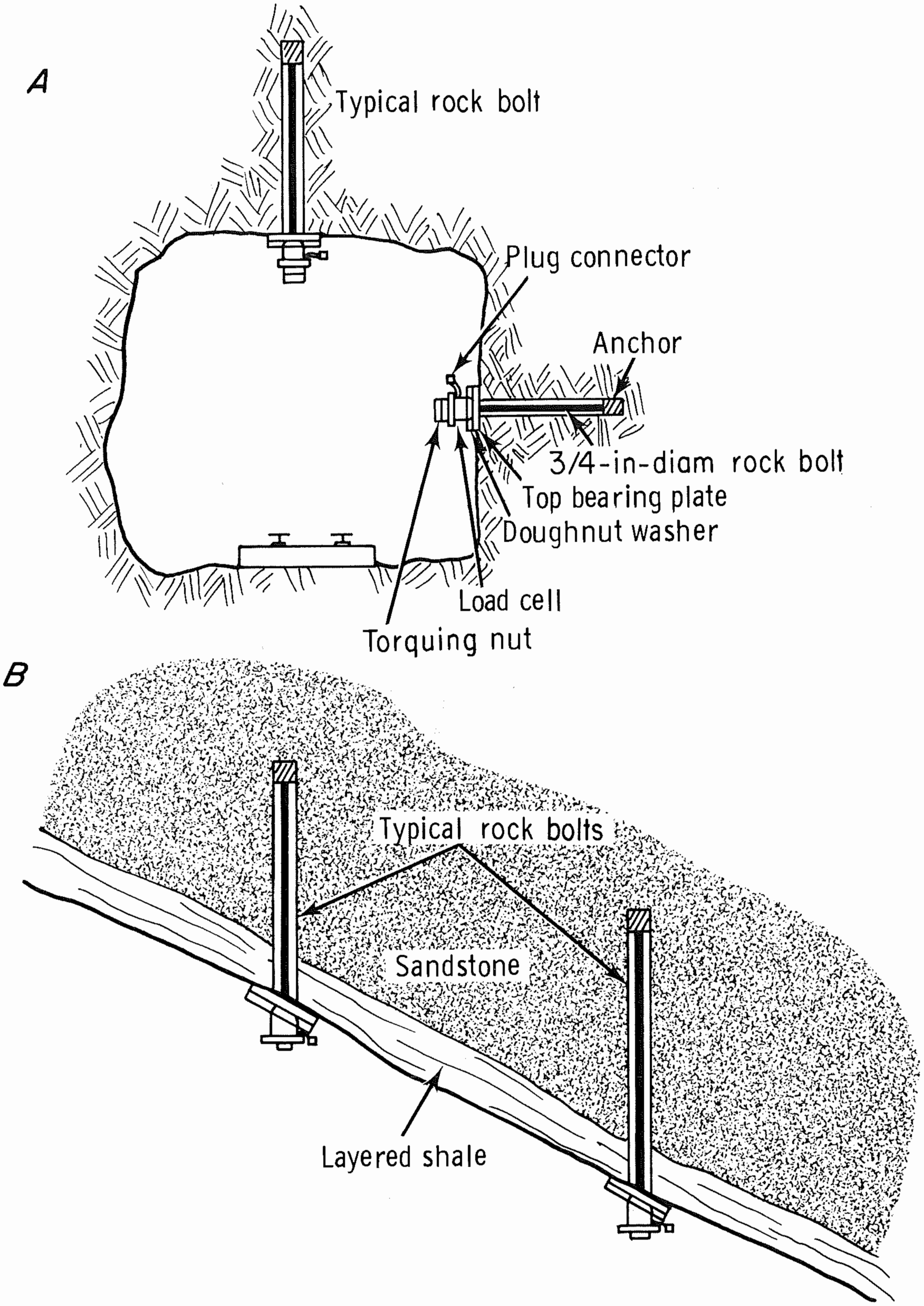

FIGURE 1. - Applications of rock-bolt load cells. *A*, Massive rock; *B*, layered rock.

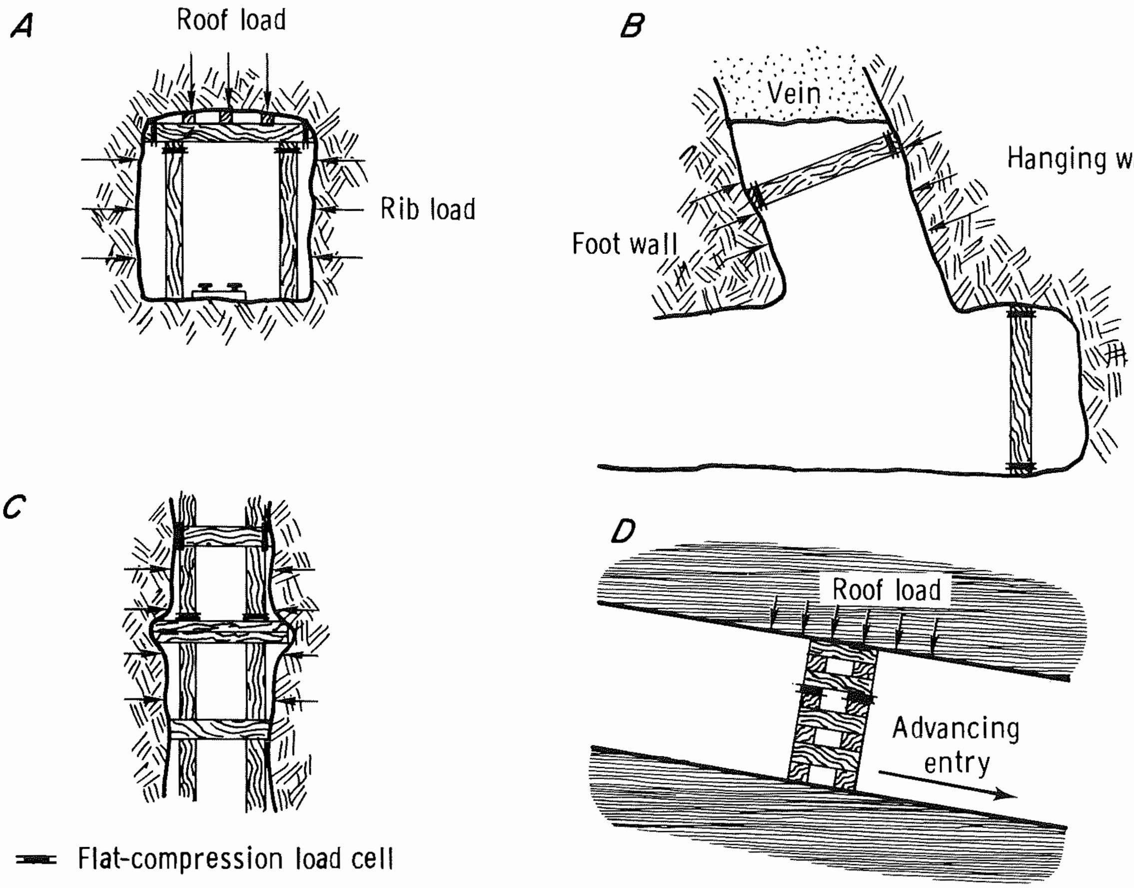

FIGURE 2. - Applications of flat-compression load cells. *A,* Drift or tunnel sets; *B,* stulls or posts; *C,* shaft sets; *D,* cribs.

testing, indicated that existing instrumentation would not completely satisfy the desired performance criteria.

Photoelastic methods were eliminated on the basis of insufficient sensitivity and difficulties in interpretation of the fringe patterns, particularly if more than one person is involved in reading the gages. Also, photoelastic devices tend to become unstable over long periods of time and eccentric loading is difficult to resolve (27-28). Mechanical measuring devices are the cheapest, but again sensitivity requirement could not be met, and any loads calculated from deformation would be questionable because of the wide range of stiffness values inherent in mine timber. Hydraulic systems initially appeared to be a prime candidate, having already been developed in-house and previously reported in other projects (21). Preliminary testing in the field indicated that the sensitivity, compatibility, and long-term stability of these hydraulic systems were insufficient. [Also, the calibration could be lost in a flat jack hydraulic cell if used with steel support systems and the deformation in the cell exceeded the elastic limit (13, p. 104).] Electronic strain-gage-type transducers seemed to be the only system capable of meeting the sensitivity requirements (10). After permissibility was granted for use of an electronic readout device in coal mines, all efforts were concentrated on developing an electronic load measurement system, although hydraulics still remained an important backup consideration. Epoxy-bonded strain gages have been used in all previous load-cell instrumentation, but experience has shown that their stability and life is limited in underground applications (3, 15, 20-22, 25, 32, 38). Weldable strain gages have shown an excellent tolerance to underground environments with virtually no protection in previous applications to mine and tunnel support systems[6] (14, 20). The gage is inherently protected against environments normally encountered in mining operations. Load cells utilizing this type of strain gage as the strain-sensing component appeared to be quite promising.

Titanium, stainless steel, and aluminum alloys were considered for the load-cell body and their relative properties (29) are shown in table 1. Titanium alloy RMI 6AL-4V was chosen on the basis of strain response, thermal expansion coefficient, strength-to-weight ratio, and corrosion resistance, despite its disadvanatages in cost, weldability, machinability, and availability.

TABLE 1. - Alloys considered for load-cell body

Parameters considered	Stainless steel No. 304	Ti RMI-5AL 2.5SN	Ti RMI-6AL 4V	Ti RMI-3AL 2.5V	Al 7075 T6
Poisson's ratio.............	0.27	0.33	0.33	0.33	0.33
Yield strength.........psi..	35,000	115,000	120,000	75,000	67,000
Ultimate strength......psi..	85,000	120,000	130,000	85,000	76,000
Modulus of elasticity..psi..	29 x 10^6	16 x 10^6	16.5 x 10^6	15 x 10^6	10.4 x 10^6
Coefficient of thermal expansion......µin/in/° F..	9.2	5.2	5.0	5.3	12.8
Resistance to corrosion.....	Excellent	Excellent	Excellent	Excellent	Fair
Weldability.................	Excellent	Good	Fair	Fair	Fair
Machinability...............	Fair	Fair	Fair	Fair	Good
Availability (round and flat bar or tubing.........	Excellent	Good	Good	Good	Good
Cost........................	Good	Fair	Fair	Fair	Good
Strain response[1]....µin/in..	1,200	7,200	7,300	5,000	6,400
Strength-to-weight ratio[2]...	1.2 x 10^{-5}	7.1 x 10^{-5}	7.5 x 10^{-5}	4.4 x 10^{-5}	6.6 x 10^{-5}

[1] Strain response is used here as the total strain reaction of the material to the yield stress.

$$\varepsilon = \frac{\sigma(\text{Yield})}{E}$$

[2] Defined as the ratio of yield strength to density.

PERFORMANCE CRITERIA

The data from an underground test, as in a laboratory test, are only as good as the instrumentation used to obtain them. In addition, there are numerous uncontrollable factors in a mine that affect the reliability of the data and the confidence in it. For this reason and on the basis of the preliminary evaluation, the following performance requirements were established in hopes that a large degree of confidence could be obtained from field data.

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[6] Work cited in footnotes 4 and 5.

The requirements desired for an instrumentation scheme to monitor loads on an artificial support system are as follows:

1. Capability to survive an underground environment including high dust concentrations, corrosion, temperatures from 50° to 120° F, and 100 percent humidity (including water immersion).

2. Easily and quickly installed and read.

3. Sensitive to ±0.02 percent of the full loading capacity of the support. Use of a Budd P-350[7] readout device or equivalent is assumed because of its acceptance and relative success in underground usage.

4. Not impede installation of the support nor affect in any way the stability and strength of the support.

5. Be adaptable to larger or smaller capacity with minor alternations.

6. Be compatible for posts, caps, stulls, cribs, or rock bolts.

7. Be relatively inexpensive.[8]

8. Be stable over long periods of time.

9. Be permissible for use in coal mines.

10. Be compact and relatively light in weight.

LOAD-CELL DESIGN

The body for load-cell transducers was designed using strength of the material as the limiting criteria. Obviously, this approach results in maximum sensitivity to the loads of interest, axial compression, while perhaps sacrificing other desirable characteristics such as minimum sensitivity to other loads. Effects of extraneous loads are discussed in a later section.

A thin cylindrical shell appeared to be the best geometrical shape for load-cell application in terms of simplicity and compatibility with most mine support systems. Strain gages can be alined perpendicular around the periphery of the shell, and the section can be sandwiched between bearing plates. As load is applied to the bearing plates, it will be sensed as strain in the cell body, thus indicating, through calibration, the applied load.

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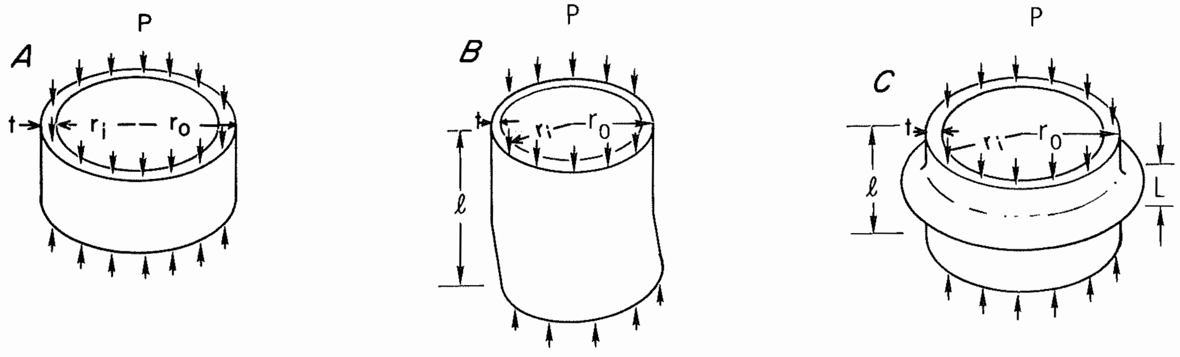
[7] Reference to specific equipment, trade names, or manufacturers does not imply endorsement by the Bureau of Mines.

[8] Considering the number of units needed in planned field projects, the final cost was limited to <$200/unit, making them suitable for use in large number (quantities >100).



Cylindrical shell under axial compression

Column failure

Shell buckling

FIGURE 3. - Modes of failure for thin cylindrical shells under axial compression. *A*, Pure compression; *B*, column buckling; *C*, shell buckling.

Theory

The simplest design case would be to consider the load cell as a short cylindrical section of homogeneous material and uniform cross section under an axial compressive load (fig. 3A) and assume a linear load-deformation relationship according to Hooke's Law. Design relationships for determining the wall thickness of the cylinder, if it is to remain within the proportional limit under compressive axial loading, are as follows:

$$A = \frac{P\ (SF)}{\sigma_y}, \qquad (1)$$

$$A = \pi(r_o^2 - r_i^2), \qquad (2)$$

$$r_i = (r_o^2 - \frac{A}{\pi})^{1/2}, \qquad (3)$$

and

$$t = r_o - r_i, \qquad (4)$$

where P = maximum expected load,

SF = required safety factor,

σ_y = yield strength of the material,

A = required cross-sectional area of the cylinder,

r_o = outside radius of the cylinder,

r_i = inside radius of the cylinder,

and t = required wall thickness.

For a cylinder not constrained against lateral movement, the elastic stability of the system should be considered. The most common example of elastic stability problems is Euler's column buckling theory, which states that the maximum load a member will sustain is not determined by the strength of the material but by the stiffness, and failure may occur before the proportional limit of the material is reach (26, p. 47).

The Euler buckling load for a fixed end column under end load (fig. 3B), is determined by the following equation (19, p. 209; 26, p. 341):

$$\sigma_{cr} = \frac{4\pi^2 E}{(1/R)}, \tag{5}$$

where σ_{cr} = the critical stress at which buckling failure will occur,

E = modulus of elasticity,

1 = effective length of the column,

and R = radius of gyration.

The ratio 1/R is the slenderness ratio in which

$$R = I/A \text{ or } [(r_o^2 + r_i^2)/4]^{1/2}, \tag{6}$$

where I = moment of inertia of cross section about central axis perpendicular to the plane of the buckling,

and A = area of the cross section.

Assuming that the upper bound critical stress is equal to the yield strength of the material, the minimum 1/R ratio for which equation 5 would be applicable can be determined. By solving the equation for a critical stress equal to 145,400 psi and E = 16.5 X 10^6 psi (see table 1), a slenderness ratio for this material of 67 is obtained. Therefore, to qualify as an Euler column, the cylinder must satisfy the condition that $1/R \geq 67$.

Thin cylindrical shell buckling phenomena (fig. 3C) is perhaps more applicable than an Euler column (12, 36), particularly with a short cylinder; that is, $1/r_o \leq 1$ (12, p. 449). To determine if the fixed end condition affects the calculated buckling load, the buckling length has to be calculated. This is the length of a half wave of buckling according to the following equation (36):

$$\frac{L}{m} = \pi\left[\frac{r_o^2\ t^2}{12\ (1 - \mu^2)}\right]^{1/4}, \tag{7}$$

where L = length required for buckling to occur,

m = made of buckling (number of half waves),

and μ = Poisson's ratio.

Simplified,
$$\frac{L}{m} \simeq 1.74\ (r_o t)^{1/2}. \tag{8}$$

To determine the critical stress at which elastic buckling will occur, the following equation is used (26, pp 273 and 352; 36):

$$\sigma_{cr} = \frac{Et}{r_o\ [3(1 - \mu^2)]^{1/2}}. \tag{9}$$

Again assuming that buckling will occur somewhere below the yielding point, the upper bound critical stress is set equal to a yield stress of 145,400 psi. By rearranging equation 9 and solving for r_o/t, a ratio equal to 69 is obtained. For r_o/t ratios ≥ 69, equation 9 should be used for design purposes; and if <69, equations 1 through 4 are valid.

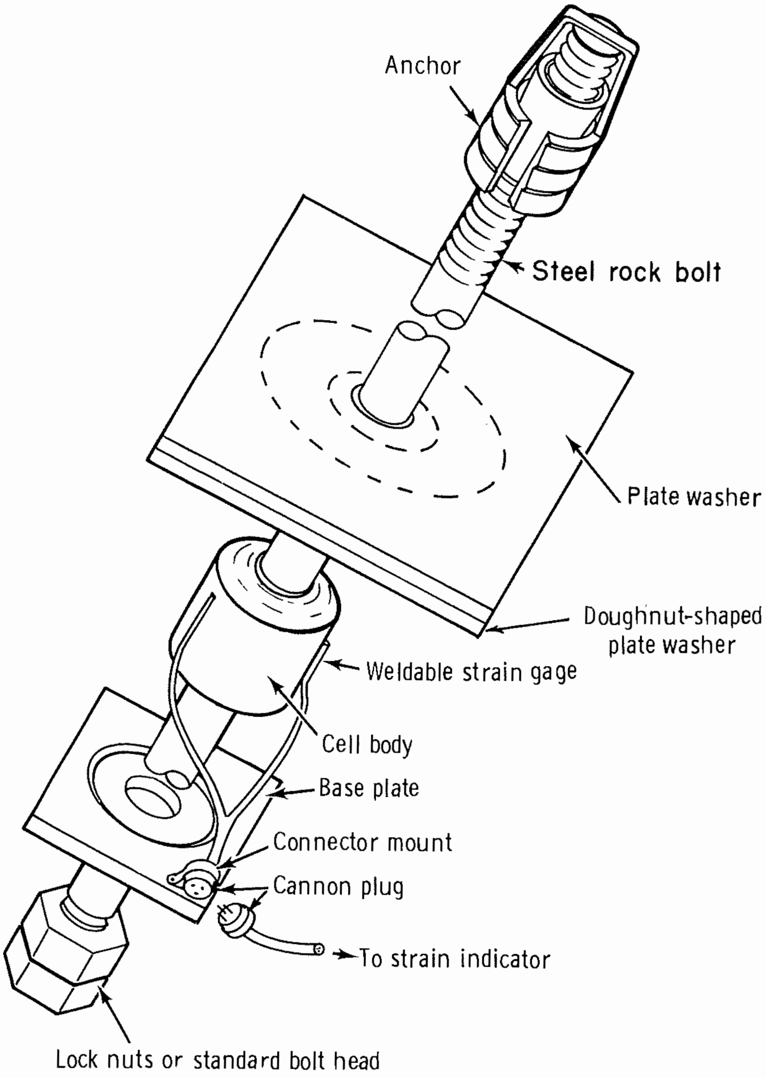


FIGURE 4. - Cutaway view of rock-bolt load cell installed on a bolt.

Application

The theory presented in the previous section can be reduced to a system of nomographs. Load cells for almost any mine support system can be developed by applying the following design procedure. It should be recognized that the general shape of the load cell will be dependent upon its application as a rock-bolt load cell or a flat-compression load cell.

The minimum acceptable height and diameter of a load cell for use with conventional rock bolts is based on rock-bolt compatibility, strain-gage length, and material availability. A schematic drawing is shown in figure 4. Solid round bar titanium is used for the cell body, so an integral hemispherical ball can be formed on one end of the cylinder. This arrangement compensates for nonaxial loading.

The minimum overall height of a flat-compression load cell is limited by

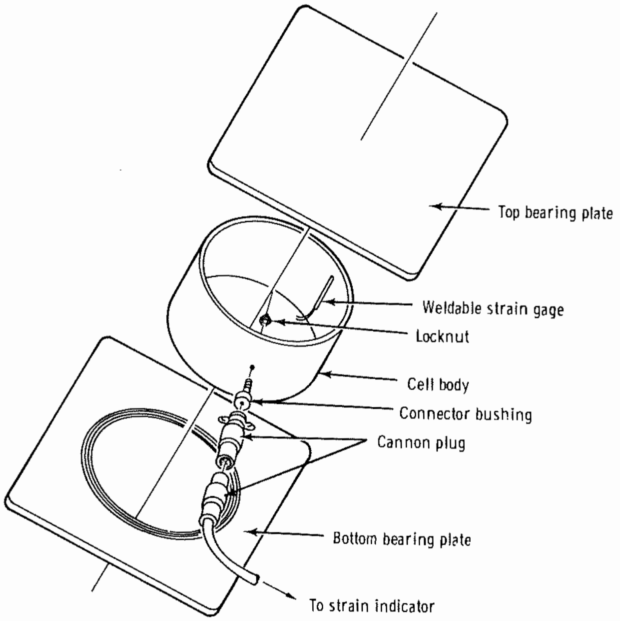


FIGURE 5. - Cutaway view of flat-compression load cell.

strain-gage length and stability requirements. The outside diameter of the cylinder is selected so as to provide maximum stability and compatibility to the application and yet allow protection between the bearing plates for the connector plug. Also by setting the edge of the cylinder as close to the edge of the bearing plate as possible, moments that could set up tensile stresses are minimized. A schematic diagram of the flat-compression load cell is shown in figure 5.

The design procedure consists of first determining the tentative load-cell specifications:

1. Specify the design load based on ultimate compressive strength of the structure into which the cell is to be placed. This should normally be determined by an actual strength test of the support member under the expected loading condition.

2. Apply a reasonable safety factor (SF) based on the expected quality of machining and fabrication in the load cell and the variability of strength in the support member.[9]

3. Specify the approximate outside diameter of the load-cell body, the general criteria being "compatibility with support," (that is, to match size and shape of support).

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[9] Safety factors are rarely specified for mine supports because it is not yet within the state-of-the-art of support prediction technology to fully determine the magnitude, direction, and nature of loads to be borne by an underground support system. For this reason, safety factors for the load cells are based upon the ultimate strength of the support, taking into account the variability of the material and ill-defined yield points, such as those found in timber.

4. Specify the physical properties of the material to be used for the cell body (σ_y , E , μ).

Referring to figure 6, determine the cylinder wall thickness required to support the maximum expected load by plotting the design load/yield stress ratio against the chosen outside diameter.

From figure 7, determine if critical buckling stresses are likely to develop. If the radius-to-thickness ratio is unsatisfactory (that is, >69) the wall thickness should be redesigned using figure 8.

Figure 9 can be used to determine if the slenderness ratio is satisfactory. Column buckling is probably not a consideration for the size and shape of load cells considered in this report.

An example of load-cell specifications using the aforementioned procedure is as follows:

Design load	kips	200
Safety factor		2
Diameter	inches	8
Ring material		Ti RMI 6Al-4V
Modulus of elasticity (E)	kips/sq in.	16.5×10^3
Yield strength of the material (σ_y)	kips/sq in.	145.4
Poisson's ratio (μ)		0.33

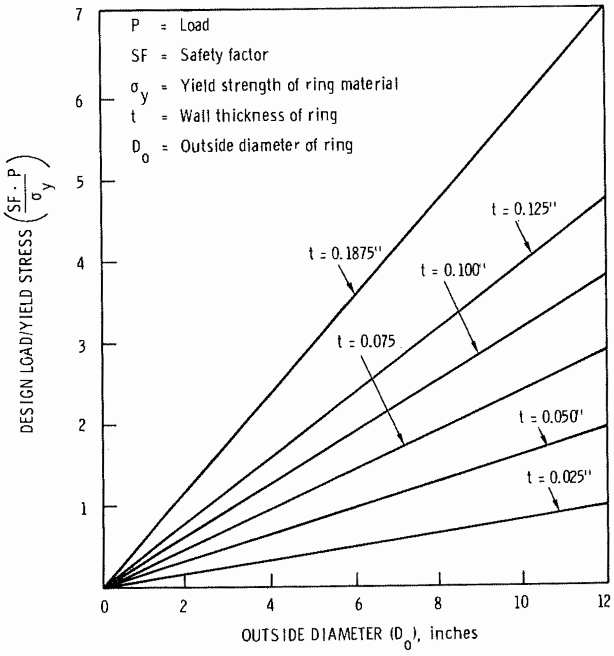


FIGURE 6. - Wall thickness required to support maximum expected load under pure axial compression.

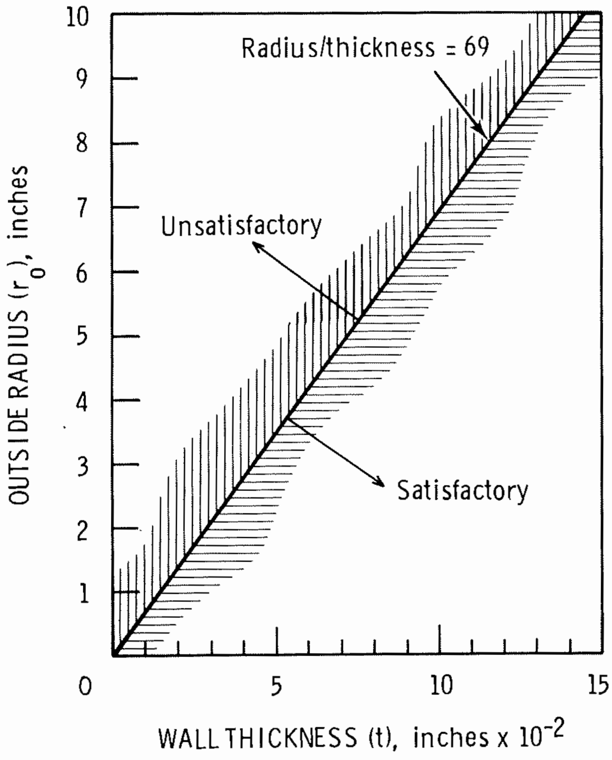


FIGURE 7. - Test for critical buckling stresses.

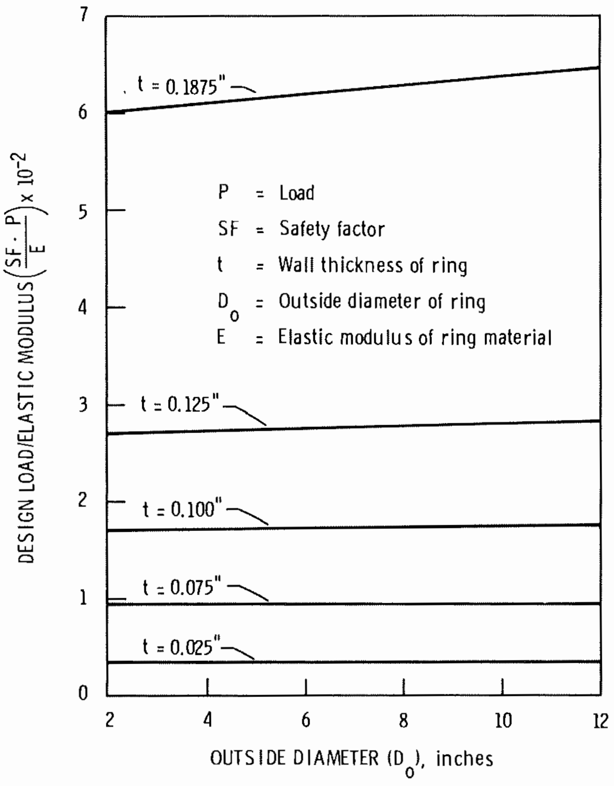


FIGURE 8. - Wall thickness required to support maximum expected load under shell buckling criteria.

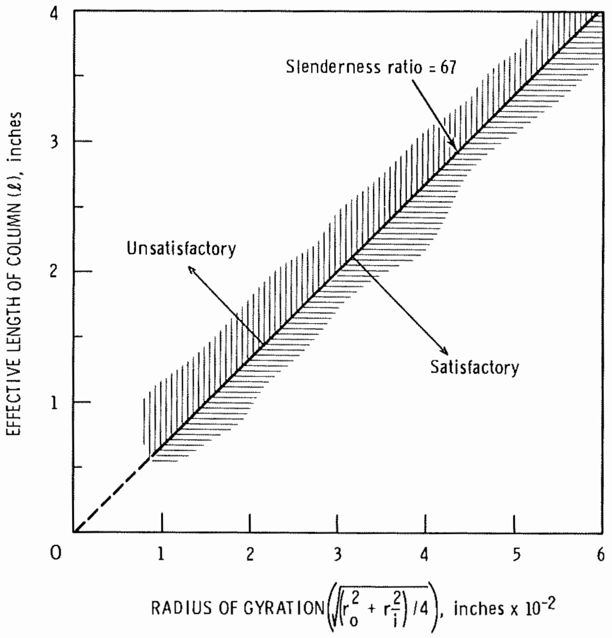


FIGURE 9. - Test for column buckling failure.

The design load/yield stress ratio is 2.75. Plotting against an 8-inch-diameter ring in figure 6 give a wall thickness of $\simeq$ 0.115 inch. Verifying this thickness in figures 8 and 9 for critical stresses indicates that the basic design is sound. If concentrated nonuniform loads are expected (see pp. 15-16 for a discussion on effect of nonuniform compressive loads), the load-cell-bearing plates should be designed using figure 10 to maintain nonlinearity of less than 2 percent. For this example, it can be seen that an 8-inch-diameter ring with a wall thickness of 0.115 inch must have a bearing plate 1.25 inches thick to stay within the stated error limits. The final specifications for the load cell are as follows:

Load range (P)....................kips..	200
Safety factor (SF).....................	2
Diameter (D_o)..................inches..	8
Wall thickness (t)...............inch..	0.115
Bearing-plate thickness (t).....inches..	1.25
Ring material..........................	Ti 6AL 4V
Bearing-plate material.................	Mild steel

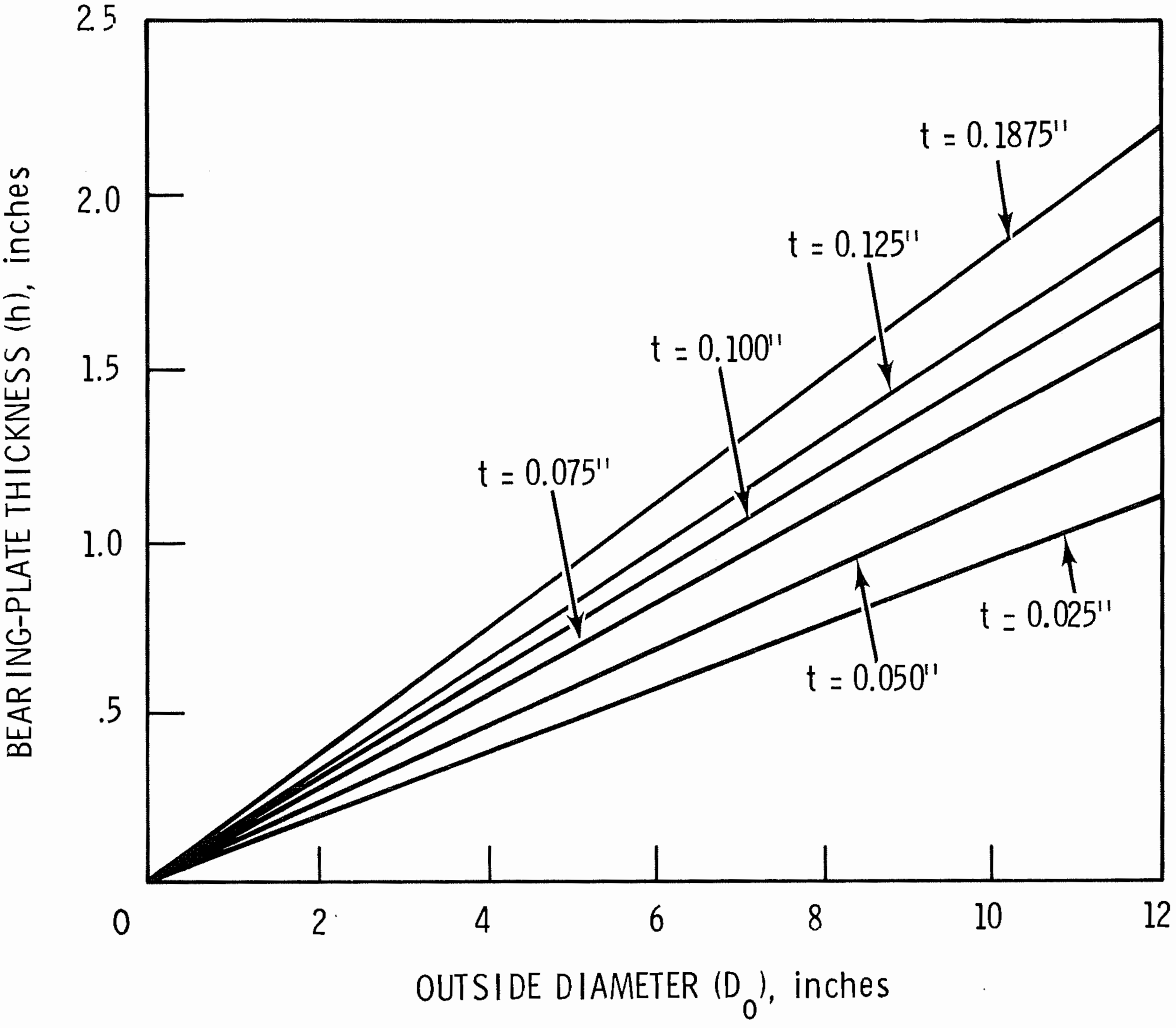


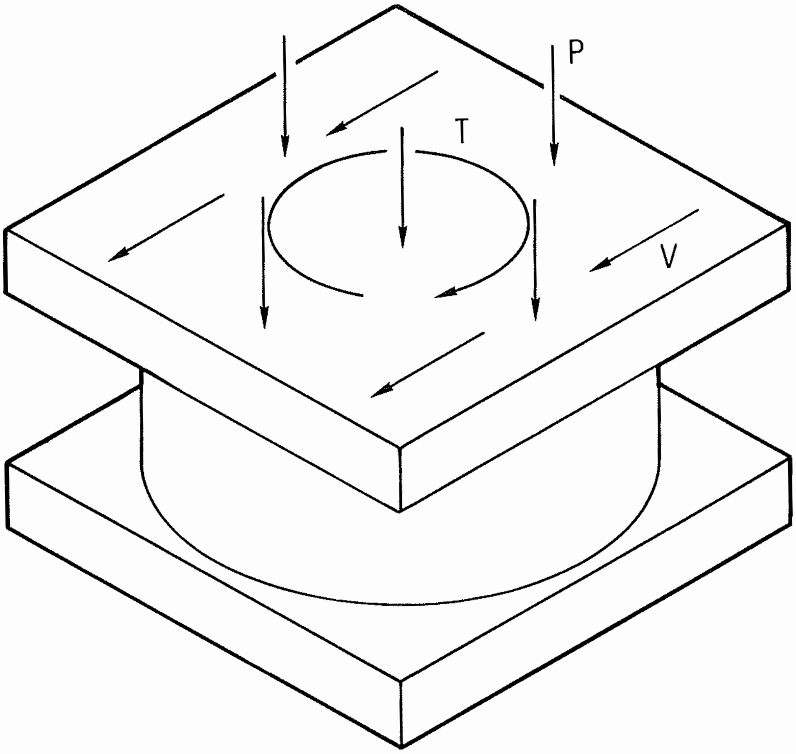
FIGURE 10. - Minimum bearing-plate thickness (h) for a given ring diameter (D_o) and thickness (t) to allow less than 2 percent nonlinearity.

EFFECT OF EXTRANEOUS LOADS

Only the uniaxial compressive loads that are transmitted to the load cells by the supports in which they are placed are of interest. For this reason, the effects of extraneous loads such as torsion, shear, and moment should be investigated (fig. 11).

The moment applied to the flat-compression load cell can be resolved into a nonuniform compressive load applied to the top plate of the cell. All loads except compression are limited to an upper bound by either the frictional stress which can be maintained between the support and the load cell, or the geometric stability of the load cell. The upper bound for the friction forces is low enough that damage to the load cell due to these forces can be ruled out for any designs that fall within the bounds of the parameters considered in this report.

The rock-bolt load cell is relatively insensitive to torsion and moments caused by nonuniform compressive loads, limited to negligible frictional forces on the ball-and-socket interface. Shear loads that are transmitted to the cell are limited to friction forces between the bearing-plate interfaces and the degree of freedom the rock-bolt system has to move in the lateral direction. The combined effect of extraneous loading on the rock-bolt load cell was investigated experimentally, and results are presented in a later section.



T = Torque   V = Shear   P = Axial compression

FIGURE 11. - Possible loads that could be applied to the load cell.

The trouble and expense of a ball-and-socket or loading button device for the flat compression load cell is not justified. Stability and load alinement problems when the cell is installed would appear to be rather large. The effect of torsion and shear cannot justify their use as these effects will be shown to be negligible. The effects of eccentric loading could be eliminated by a ball and socket, but more massive and rigid bearing plates would be a more cost effective alternative.

Torsion

The response of the flat-compression load cell is not affected by applied torque as long as the strain gages are applied either parallel with the axis of the ring or perpendicular to the axis of the ring because the gages are insensitive to transverse strains (36). Misalinement of the gages with respect to this axis has been shown to produce an erroneous signal (17). Due to the various misalinement combinations that are possible, the error signal can be either cancelled out or reinforced by misalinement of more than one gage. The problem of erroneous readings due to applied torque is minimized during the fabrication of the cell by exercising care in alining the gages prior to welding them to the ring.

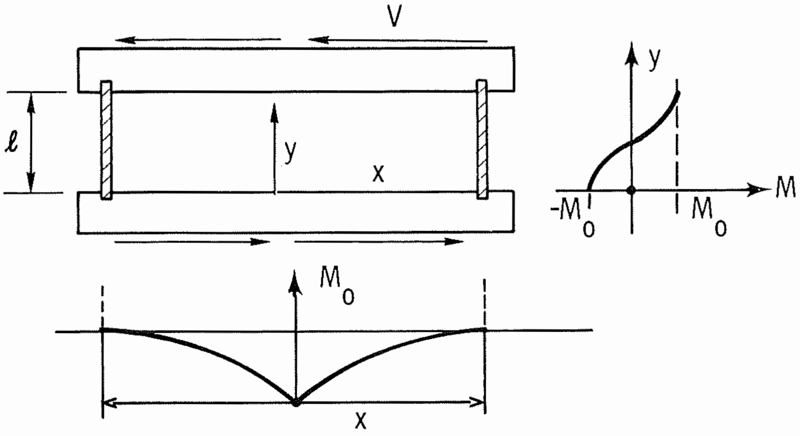


FIGURE 12. - Moment distribution from shear forces.

Shear

Figure 12 shows the moment through a section of wall of the ring due to an applied transverse load and also shows the maximum moment distribution. Note that the moment as a function of y is an odd function about the point $y = 1/2$. If the strain gage is applied so that its active length is centered at a point equidistant from the top and bottom plates, the area of the strain gage affected by the positive strain will be exactly balanced by the area affected by the negative strain, and the net change in gage resistance will be zero. Again, extreme care in centering the gages on the cell should negate the shear effect.

Nonuniform Compressive Stress

There are two main reasons why a load cell might be subjected to a nonuniform compressive stress. The portion of the support resting on the cell will in general not mate perfectly with the surface of the bearing plate and/or the support will have a moment in it superimposed on the net compressive stress in the load cell. As far as the load cell is concerned these two situations are the same.

There are wide variations in load distributions possible, and it is impossible to know beforehand what kind of a distribution will be imposed on the load cell in service. If the bearing plates can be made to operate as reasonably rigid bodies, then the stress distribution imposed on the sensing ring, although not a constant, will vary linearly and as the gages are now arranged, a linear variation in strain will be integrated to give an average value for the whole ring. Regardless of how thick the end plates are made, they will have some elasticity and will act as beams on elastic foundations.

The departure of bearing plates from rigid body motion was analyzed by allowing a linear variation of compression on the surface of the bearing plate and then calculating the deviation from linearity of the strain distributions imposed on the ring (26, 30). A representative worst case is a linearly varying distribution that ranges from zero at one edge of the cell to a maximum at the other edge as shown in figure 13. By allowing a 2-percent maximum deviation from linearity in the strain distribution, the thickness of the bearing plate necessary to maintain this deviation can be calculated. Although there are other loadings more extreme than the one chosen here, a reasonable amount of care during installation will minimize the effects of point loading.

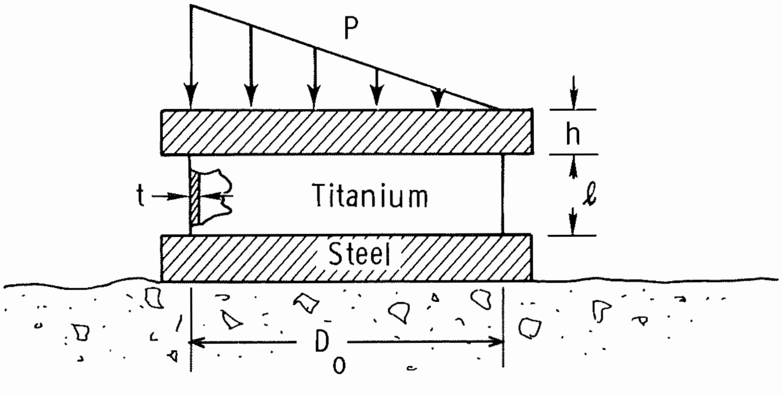


FIGURE 13. - A "worst case" load imposed on the cell.

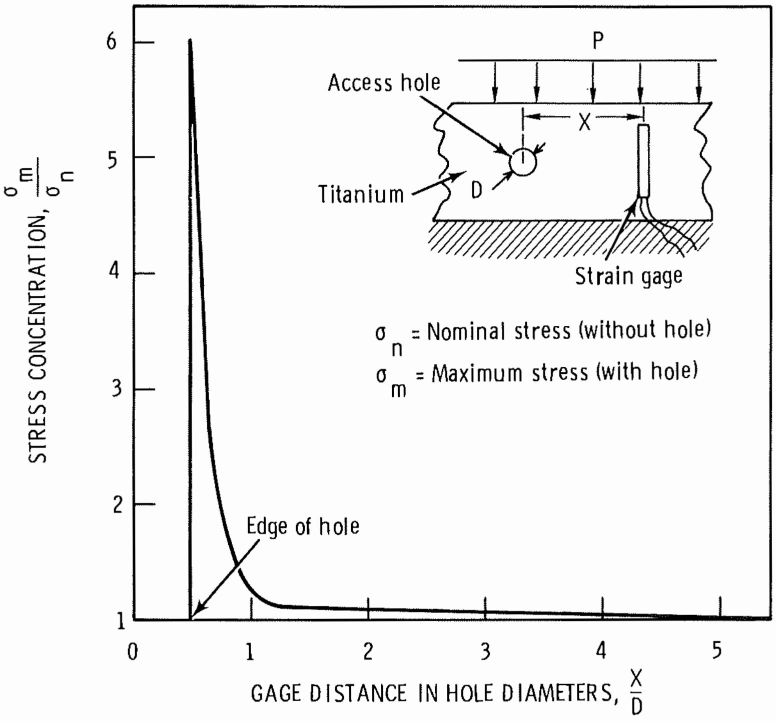


FIGURE 14. - Stress concentration as a function of gage distance (in hole diameters).

Again, if supports such as steel or concrete are being instrumented or rock bolts are bearing on uneven surfaces, a nonlinear distribution would definitely be a possibility, and figure 10 should be used for bearing-plate design.

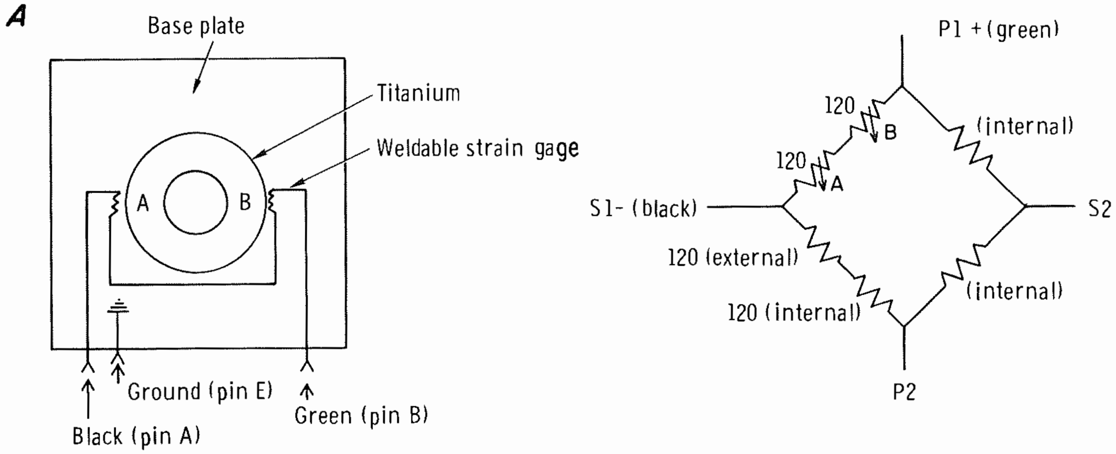
Access Hole for Connector Plug

During the initial stages of fabrication and testing of the flat-compression load cell it became apparent that it would be desirable to attach the connector plug directly to the sensing ring. The effect of drilling an access hole in a ring under constant load is shown in figure 14 (30, 34). Note that for a 1/4-inch-diameter hole, the stress concentration factor may be assumed negligible at five-hole diameters from the center of the hole, and no significant strain effect would be seen by a gage located 1.25 inches from the center of the hole. At eight-hole diameters, the change from nominal stress has decayed to 0.2 percent, that is, $\sigma_m/\sigma_n = 1.002$, which is probably considerably less than the error associated with any readout device.

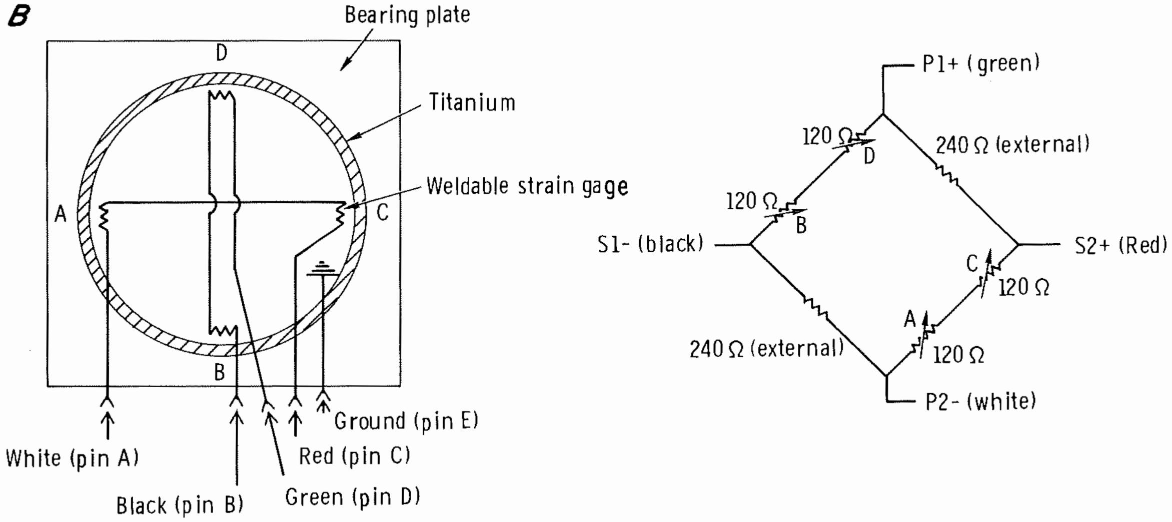
FABRICATION

The following section summarizes the fabrication and calibration of the load cells. The rock-bolt load cell is machined out of solid 2-inch-round bar stock with a ball formed on one end of the shell. A commercially available, doughnut-shaped rock-bolt washer is machined on a ball end mill to the proper sphericity to accept the ball end of the cell body. Molybdenum disulfide lubricant is applied to this ball-and-socket surface to minimize friction and wear at extreme loads and temperatures and harsh environments. The cell body is press fitted and epoxied into a groove in the base plate, and the gages are applied (16) 180° opposite and wired in series to form a 240-ohm quarter bridge (fig. 15A). A mechanical design drawing of a rock-bolt load cell is shown in figure 16.

The flat-compression load-cell body is fabricated from flat strips of titanium sheet. Nine-inch-diameter seamless tubing was initially sought for the shell, but it is not commercially available and thickness tolerances on



QUARTER BRIDGE CIRCUIT



FULL-BRIDGE CIRCUIT

FIGURE 15. - Electrical schematic diagram for load cells. *A*, Quarter bridge rock-bolt load cell; *B*, full-bridge flat-compression load cell.

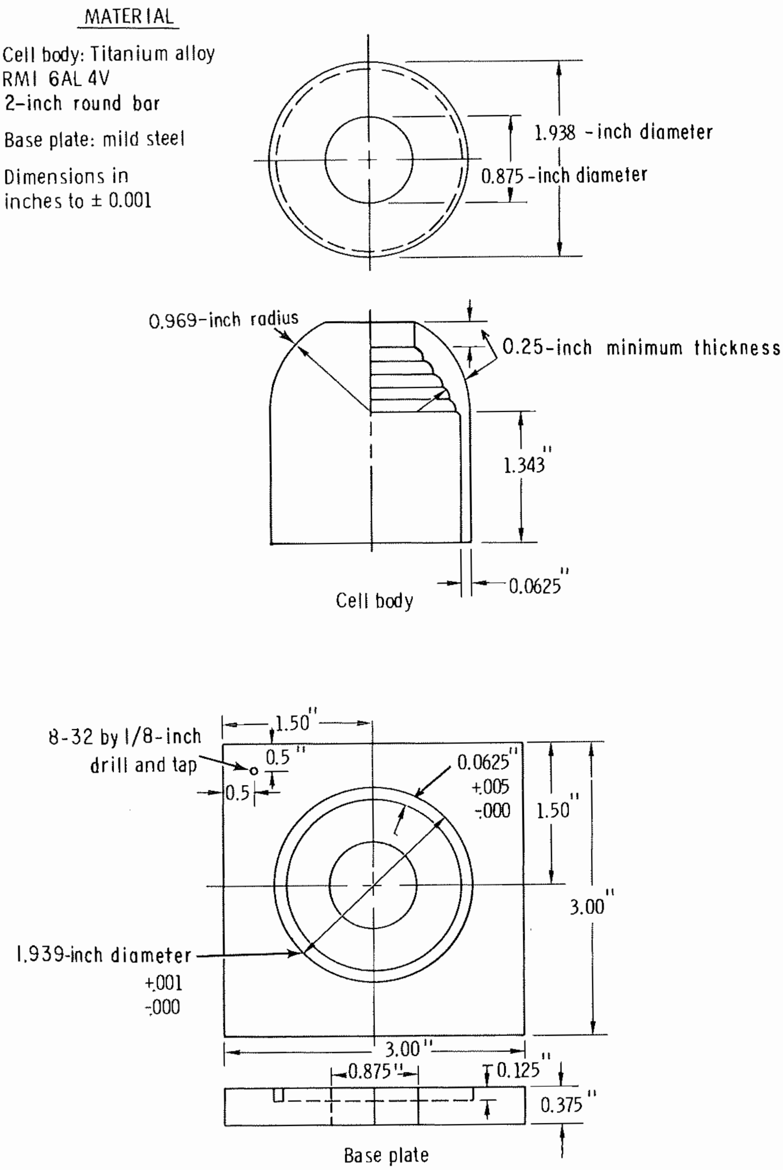


FIGURE 16. - Mechanical design drawing of the rock-bolt load cell.

tubing are quite variable. The flat strips, after being machine rolled and butt welded[10] to form a cylindrical shell, are machined to exact parallelism and flatness tolerances. Four gages are mounted vertically (16) at 90° to each other around the inside surface of the cell body; the two opposite pairs of gages are wired in series to from two 240-ohm circuits, and the bridge is completed with external resistors and the internal completion network, as shown in figure 15B. The cylinder is then fitted and epoxied into a groove between a top and bottom bearing plate. A mechanical design drawing of the flat-compression load cell is shown in figure 17.

Each load cell is calibrated under standard test conditions in a manner that simulates an actual field installation. A test is conducted by placing the cell between wood blocks or inserting on rock bolts with a load applied by a testing machine (fig. 18). This represents a rock load being applied to the support, thus the load cell, the output being read on a strain indicator.

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[10] The quality of the weld on the flat-compression load cell is very critical and directly affects the performance of the cell. Gas tungsten-arc welding, using helium as a shielding gas, was initially tried but proved unsatisfactory. An electron beam welder at Battelle Northwest in Richland, Wash., was next tried and yielded a satisfactory weld without altering the strength characteristics of the parent metal. The welding is performed in a chamber that can be operated either at a vacuum or back-filled with inert gas, thus producing an ultrahigh purity weld in highly reactive materials such as titanium (9). Electron beam welding is recommended and is available commercially.

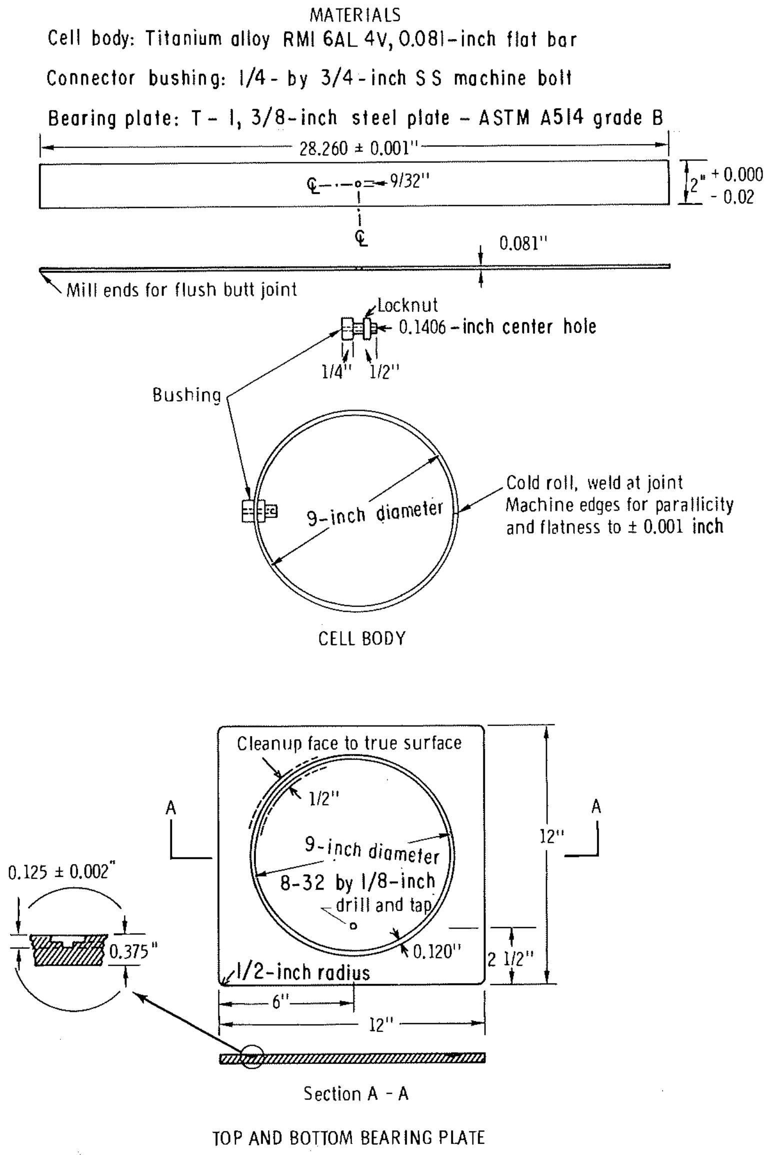

FIGURE 17. - Mechanical design drawing of the flat-compression load cell.

LABORATORY EVALUATION

The load cells were briefly evaluated in the laboratory prior to initial field installation to insure that the design and assembly procedures were adequate.

Destructive compression tests were conducted to determine adequacy of the design and ultimate strength of the cells under simulated installation conditions. During testing of a rock-bolt load cell with a design wall thickness of 0.050 inch, failure occurred at 55,000 pounds (fig. 19A), approximately 94 percent of the certified ultimate strength of that particular "heat" of titanium.[11] Note the uniformity of the failure indicating a very evenly distributed load. Further strength testing of this cell was not conducted since the experimental results closely approached the theoretical design. The actual strength of the cylinder will, of course, be lowered accordingly by poor machining, improper assembly, and local geometrical defects in the material, but the chosen safety factor should be more than adequate to offset these problems.

A flat-compression load cell designed with a 0.050-inch wall was evaluated in a loading machine under simulated installation conditions, and a buckling failure occurred at 87,048 psi (123,000 pounds), 60 percent of the theoretical yield point. This failure, which could have been predicted from

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[11] The "Certification of Test" on Heat #K-3083 by Titanium Metals Corp. of America showed a yield strength of 145,400 psi and an ultimate strength of 159,800 psi after heat treatment for 1 hour at 1,750° F and a rapid water quench.

FIGURE 18. - Calibration of the rock-bolt load cell in the testing machine.

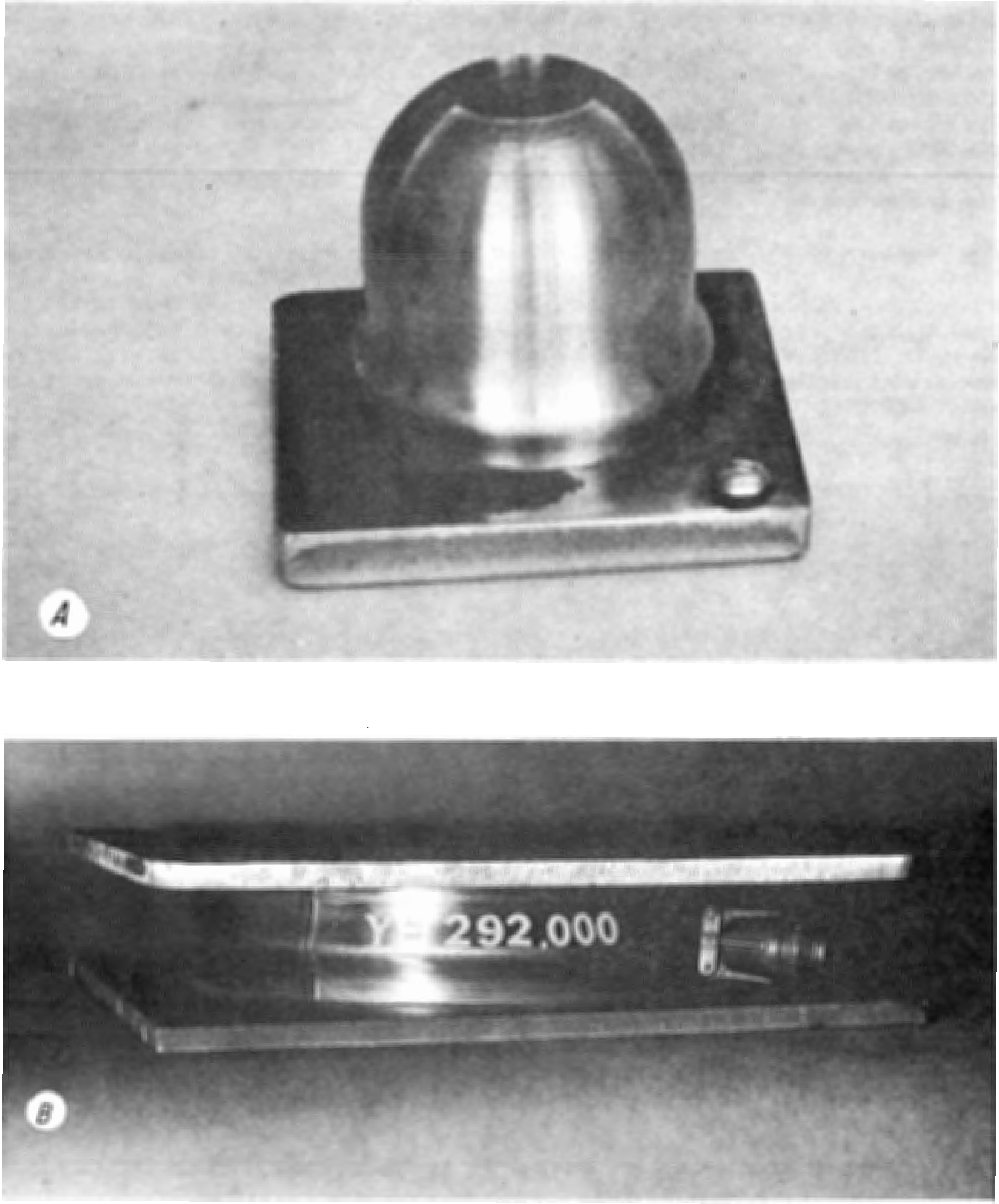

FIGURE 19. - Destructive testing of load cells. *A*, Failure patterns of rock-bolt load cell; *B*, buckling failure of 0.080-inch-thick flat-compression load cell.

figure 7, was too close to the loads expected to be encountered in the field, so the cell was redesigned using figure 8 with a wall thickness of 0.080 inch. This thickness should not buckle according to the buckling criteria, with a r_o/t ratio of 56. Upon destructive testing, failure occurred this time at 292,000 pounds (fig. 19B), 89 percent of the theoretical yield point. Again stress concentrations caused by poor machining and welding would tend to affect the design load.

Because of the greater liklihood of serious geometrical irregularities and their greater relative effect, the stresses actually developed by thin-walled cylinders fall short of the theoretical value by a wider margin than in the case of solid bars. Therefore, the theoretical stresses should be regarded as an upper limit, approached more or less according to the closeness with which the actual dimensions approximate the geometrical form assumed in the design calculations (26, p. 339).

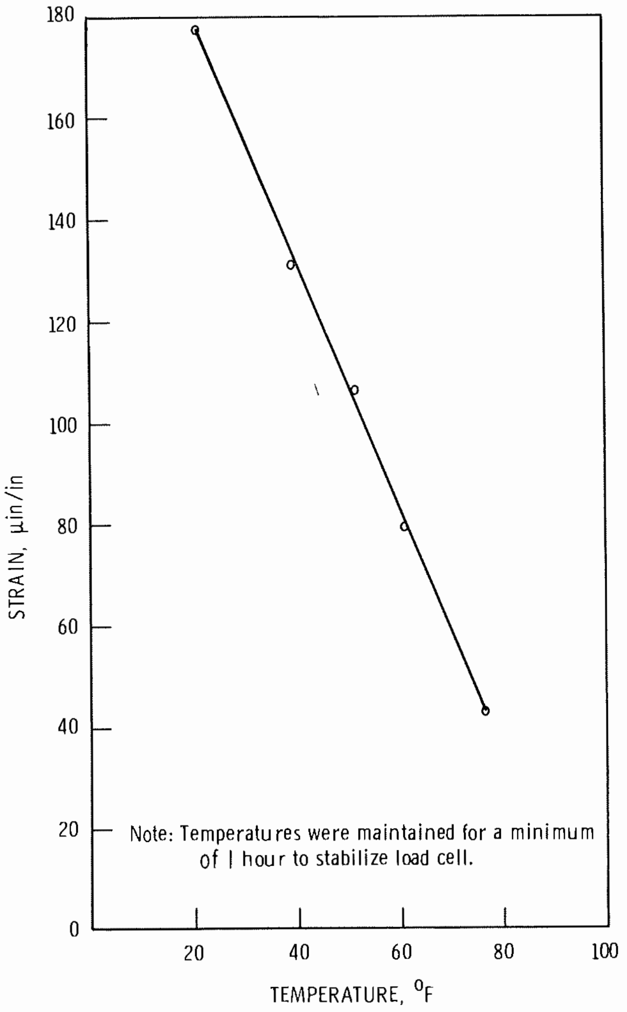

FIGURE 20. - Sensitivity of load cells to temperature.

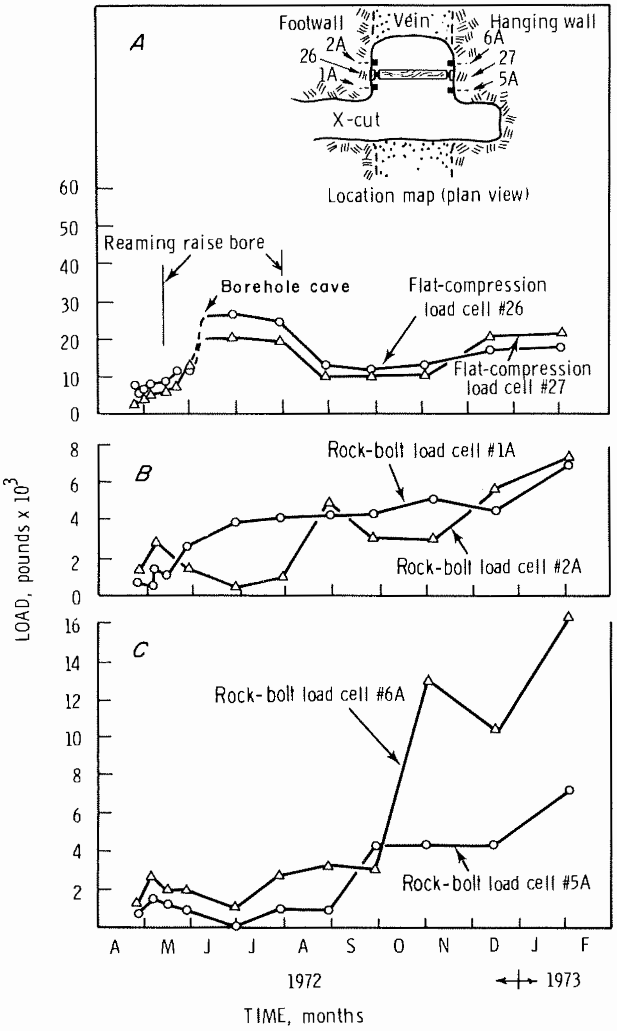

FIGURE 21. - Load history plots. *A*, Flat-compression load cells; *B* and *C*, rock-bolt load cells.

A test was conducted to determine the sensitivity of the load cells to temperature variations and if compensation was needed. Even though the temperature coefficient of the strain gages were matched to that of the titanium, the average rate of strain change with temperature was 2.5 microstrain per degree Fahrenheit (fig. 20). This factor is corrected for in the data analysis program.

A tapwater submersion test was also conducted on the cells to evaluate performance of the strain gages under water pressure. Periodic readings were taken with an ohmmeter to determine if there was leakage to ground, which is indicative of moisture entering the circuit. All resistance readings were greater than 100 megaohms to ground, showing that no leakage was occurring between the load-cell body and the strain gages. This capability was verified in later long-term field tests.

A problem encountered with the rock-bolt load cell was seizing and galling on the ball-and-socket interface while torquing the bolt. Several specialty lubricants (<u>11</u>) were tried in an effort to maintain an effective coat of lubricant on the joint, including bonded lubricant and lubricating paste. Bonded molybdenum disulfide in an aerosol spray can provided the best coating, and after repeated loading cycles, lubricant was still contained. The lubricant is applied immediately after fabrication to protect the surfaces during shipping and storage.

FIELD TESTING

Thirty load cells were initially installed in two underground mines, and after a year of continuous operation, only one has malfunctioned. The first test was in an underground metal mine in North Idaho under very harsh environmental conditions. The primary purpose of the test was to determine the environmental performance of the cells and to verify their functional and operational characteristics before a full-scale installation was begun. After results of this testing indicated that performance requirements had been satisfied, a fabrication area was set up at SMRC, and installation was begun in the Sunnyside coal mine in Utah in conjunction with the Single Entry Project.

Installation in a "Hardrock" Mine

The initial field testing was conducted in April 1972 near an ore discharge chute on the 3850 level of Hecla Mining Co.'s Lucky Friday mine, near Mullan, Idaho (see location map inset in fig. 21). The near vertical vein had been mined out about 50 feet above this level and was unmined below so extreme horizontal loads were not expected. Dripping, slightly acidic water was present, and normal mining activities such as drilling, blasting, mucking, and haulage were in progress. Temperatures were in excess of 90° F, and 100 percent humidity was measured.

Two flat-compression load cells were installed on either end of a 10-inch by 10-inch by 14-foot-long subfloor support cap to monitor axial load in the cap (normal to the vein) (fig. 22). The existing head boards on the ends of

FIGURE 22. - Field test of load cells in a "hardrock" mine. *A*, Flat-compression load cell installed in a cap set; *B*, rock-bolt load cell installed on 6-foot, 3/4-inch rock bolt.

FIGURE 22. - Field test of load cells in a "hardrock" mine. *A*, Flat-compression load cell installed in a cap set; *B*, rock-bolt load cell installed on 6-foot, 3/4-inch rock bolt.—Continued

of the set were blasted out, and new ones were inserted with the load cell sandwiched between them. Meshed aluminum angle and spikes were used to hold the cell until it was wedged tightly in place. Initial readings were then taken and a check for ground was made. Actual installation time for both cells was less than 1 man-hour.

Four rock-bolt load cells were also installed in this area, two in the hanging wall and two in the footwall (fig. 22B). The cells were lubricated and mounted on 3/4-inch by 72-inch rock-bolts, inserted into the boreholes, and torqued with a hand wrench to ≃6,000 pounds. Pre-installation and initial load readings were taken and a ground check was made.

Readings were initially taken once every week and then monthly after the first month. The load history plots are shown in figure 21A, 21B, and 21C. Note that in figure 21A, the load is not identical on either end of the cap. This is probably due to the effect of two supporting posts under the cap, which were not instrumented. Nevertheless, the loads are remarkably close indicating that the cells are functioning properly and no grounding has occurred (verified by periodic ground readings). Figures 21B and 21C show the loads on the rock bolts in the footwall and hanging wall, respectively. The bolts were torqued a week after the initial installation because they were losing load due to anchor slippage.

After 18 months, all of the cells are functioning well and indicating increasing load on the supports, and no leakage of the strain gages to ground has been noted. The bearing plates have become quite badly rusted and corroded because of the constant exposure to dripping water, but the titanium shows no sign of corrosion. The RTV sealant used to seal and secure the connector plug to the base plate was deteriorated on load cell 27, and the plug is dangling loose, making it difficult to make the connection. The connector plugs on subsequent load cells were connected directly to the cell body after an analysis showed that a hole in the cell body would not create any significant stress concentrations. The plug is now more secure and all external wiring is eliminated.

Coal Mine Installation

Installation of load cells in the No. 2 coal mine of Kaiser Steel at Sunnyside, Utah, was begun in June 1972, in conjunction with the Single Entry Project. The first cells were installed in 16th Left entry on wooden crib supports and 3/4-inch by 6-foot rock bolts (See the location map inset in fig. 23A.)

The flat-compression load cells are placed into the crib supports to measure roof load as mining progresses. The crib consists of laying rows of 12- by 12- by 36-inch timbers in a crisscross fashion between the floor and the roof and wedging in tightly. The load cells are inserted when the crib is about halfway finished, one at each corner.

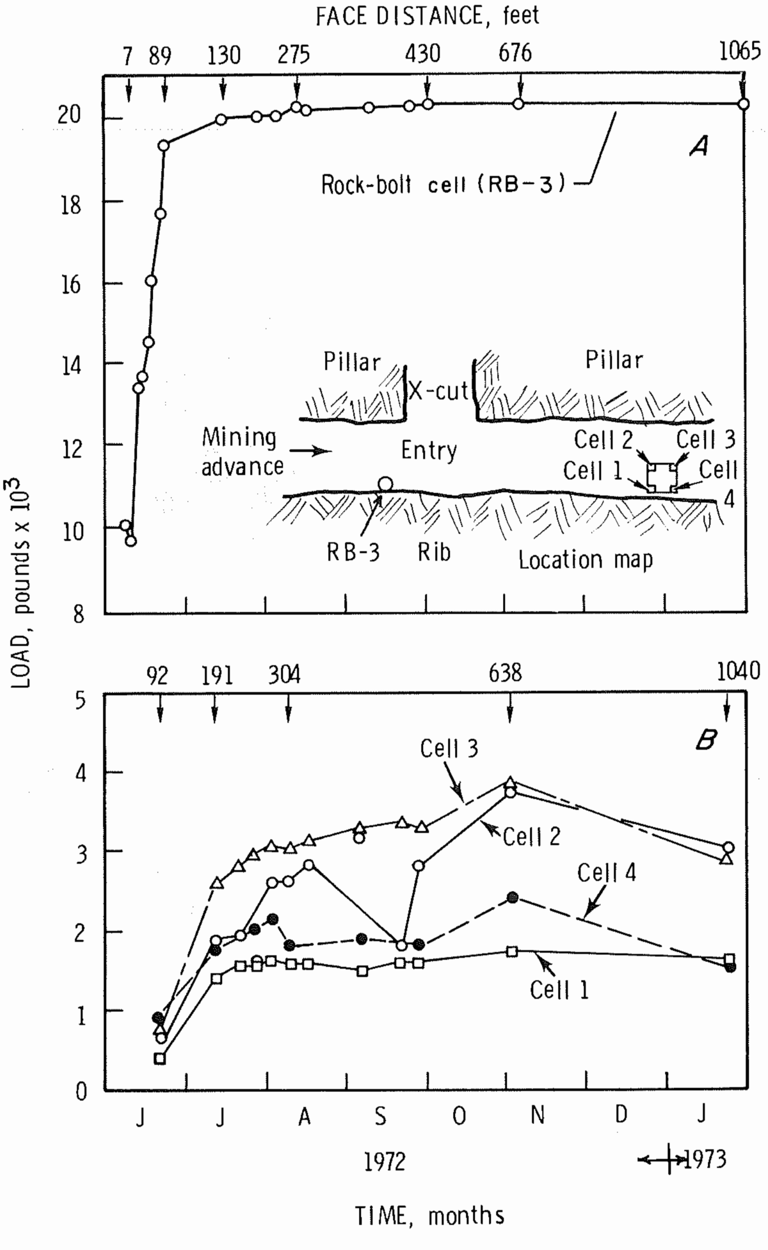

FIGURE 23. - Load history plots. *A,* Rock-bolt load cell; *B,* flat-compression load cell.

The four load cells are connected to a 17-pin readout plug (four conductors per load cell plus one common ground), and the crib is completed. The readout plug is then nailed to the crib and the installation is complete (fig. 24A). Load readings are taken with a strain indicator through a 4-channel switch box (fig. 24B) for ease of reading.

Installation of the rock-bolt load cells was accomplished with minimum interference with the normal rock-bolting cycle. The load cells were inserted onto 3/4- by 72-inch rock bolts, placed in the hole through steel landing mats, and torqued with a rock-bolting machine to 175 ft-lb using double lock nuts. The cell can be retrieved and reused by supporting the roof around the bolt, unscrewing the lock nuts, removing the load cell, and retightening the nuts against the plate washer. Typical load history curves are shown in figure 23A and 23B. Note the "stabilized" load in figure 23A. This could indicate that deformation was arrested or the bolt and/or anchor is yielding.

MODIFICATION AND RETESTING

Several modifications have been or are being made to the load cells as a result of deficiencies found during field testing and evaluation.

During the course of field testing at the Lucky Friday and Sunnyside mines, erratic readings were noticed on several occasions on the rock-bolt load cell. This was apparently caused by a change in contact resistance in

FIGURE 24. - Field test of load cells in a coal mine. *A*, Completed load cell installation in a crib; *B*, readout assembly for crib load-cell array.

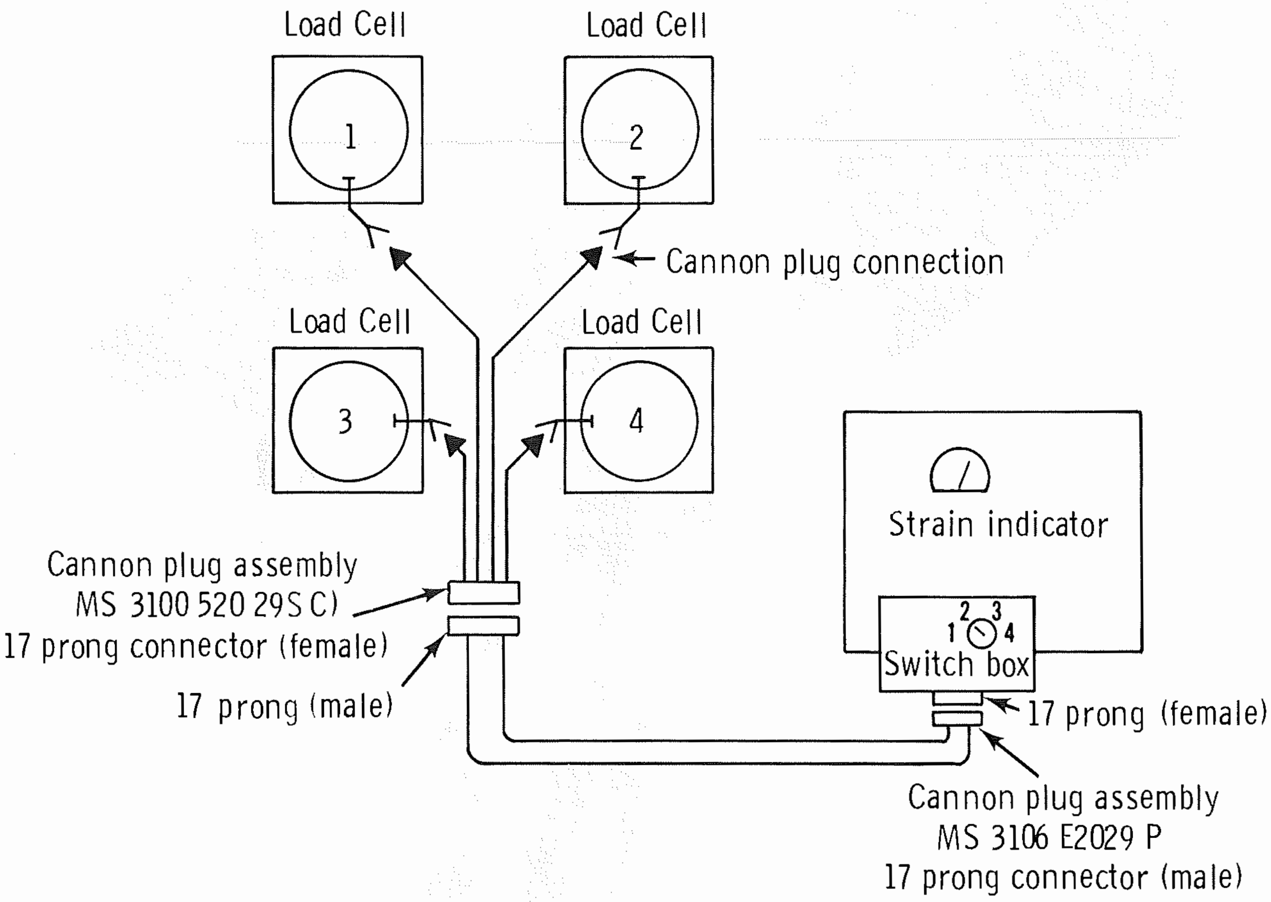

FIGURE 24. - Field test of load cells in a coal mine. *A*, Completed load cell installation in a crib; *B*, readout assembly for crib load-cell array.—Continued

the connector plug whenever the "pigtail" was moved. Also, the "pigtail" was subject to damage when the rock bolt was torqued by machine. The cell was modified into a full-bridge transducer with two active and two passive elements, with shunt calibrating to zero the bridge on each cell, balanced to within 2 percent of one another. The connector plug is rigidly attached to a protective ring around the cell body, and the annular space is filled with a potting compound to seal the internal wiring and the bridge completion network (fig. 25).

This modification has resulted in a more compact load cell for easier installation, torquing, and reading, and the full-bridge configuration compensates for errors due to temperature and lead wire resistance. Temperature changes from 30° to 120° F are compensated for with a thermal sensitivity of less than 1 percent per 100° F change. Load sensitivity is better than 0.02 percent of the full loading range with a combined error (effects of nonlinearity, hysteresis, and nonrepeatability) of less than ±0.2 percent of the

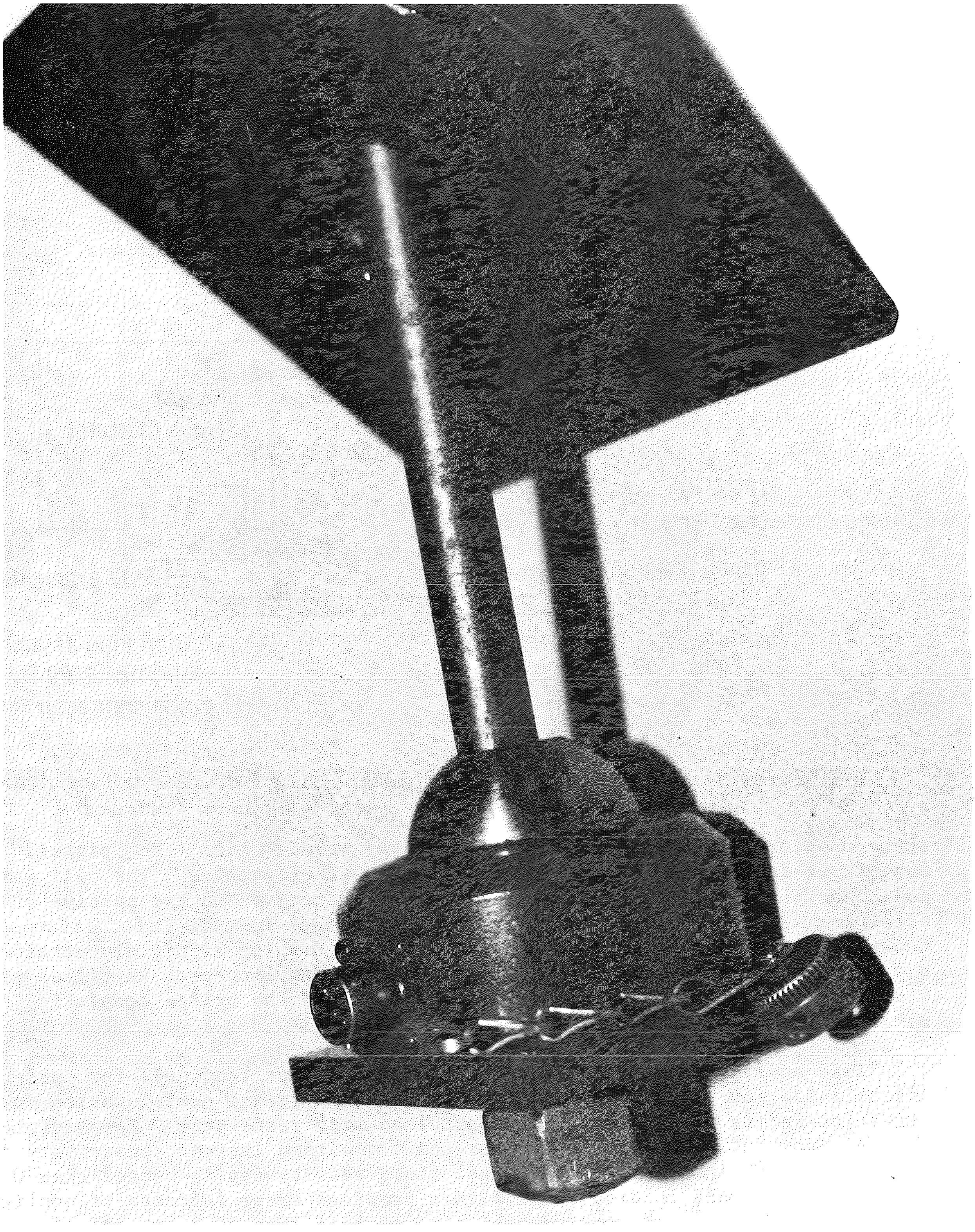

FIGURE 25. - Modified full-bridge rock-bolt load cells.

full-scale output.[12] The effect of a random orientation between applied load and the axis of the load cell was experimentally determined to be less than 5 percent of the full-scale output. This includes a relative angle between bearing plate and cell of up to 7°, beyond which proper operation of the cell is hampered.

These modified cells are currently being used in research projects in the Sunshine, Lucky Friday, and Galena mines in Idaho and coal mines in Ohio and Utah.

SUMMARY AND DISCUSSION

The combination of titanium alloy and weldable strain gages for load-cell construction results in simplicity, exceptional reliability, and long life in a mining environment. Sensitivity is gained by using a cylindrical shell of titanium for the cell body rather than more complex mechanical designs of stainless steel or aluminum with complicated strain gaging techniques. The use of weldable strain gages with their inherent protection against harsh environments, greatly increases the reliability of the load cells. The simple electrical and structural configuration results in significant cost advantages in machining and fabrication, making the cells suitable for use in large numbers. The design and manufacturing procedures can easily be adapted to any size and shape support system and by resolving various machining and fabrication techniques, the components could be utilized in other strain-gage-type tranducers for underground application.

The only major problem encountered during fabrication was the welding of the rings used in the flat-compression load cells. A satisfactory weld can be obtained with conventional gas shielded arc welding found in most machine shops, but the electron beam weld is far superior. Following initial fabrication, destructive tests on the cells showed that design and fabrication techniques were acceptable, and subsequent field tests verified the expected performance of the load cells; long-term stability and resistance to corrosive and humid atmosphere were two areas in which performance was exceptional.

Modifications to the load-cell system should further its utility to the industry with development of an advance warning device and a support-load determination "package." It has been shown that support loads are very indicative of rock load changes and impending face conditions[13] (1-2, 8, 13-14).

Load cells are sensitive to rock movement over a larger area of influence than a rock deformation instrument referenced to a single point within the rock mass. Minute rock movement could result in a significant load increase on the support.

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[12] From Ailtech Product Performance Specification No. 856-3321 and personal communication with Chuck Hedblom, manager, Transducer Projects Div.

[13] Work cited in footnote 4.

A "critical load" warning system could be designed and installed on key supports in a mine, such as at vein intersection crosscuts, where most rock bursts occur as supporting pillars are mined out,[14] or in fault zones in tunnel projects where extensive jump sets or shotcreting is often required. The onsite warning device (light, siren, etc.) could be triggered at a predetermined value based on a "stabilized load: or prefailure load.

The basic goal of this research was to develop suitable support-load indication devices for use with in-house projects. The work has resulted in simple and reliable load cells that can fabricated with very little prior knowledge of load-cell instrumentation. Hopefully, this research will be an incentive to the research groups within the mining industry to monitor support loads as a means of support prediction, support evaluation, and warning of dangerous conditions.

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[14] An in-house technical report describes a rock-bolt load indicator/warning device, developed by Battelle Northwest for the Bureau of Mines, that is currently being used in Idaho mines for rock-burst research.

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