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NEGATIVE HYSTERESIS EFFECT OBSERVED DURING CALIBRATION OF THE U.S. BUREAU OF MINES BOREHOLE DEFORMATION GAUGE

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NEGATIVE HYSTERESIS EFFECT OBSERVED DURING CALIBRATION OF THE U. S. BUREAU OF MINES BOREHOLE DEFORMATION GAUGE

Harold C. Sanow

ABSTRACT

The U. S. Bureau of Mines borehole deformation gauge (BMG) was designed in the early 1960's to allow rock stress measurements by the overcoring method. Since that time it has become a de facto standard against which the performance of other borehole deformation gauges is often judged. However, during recent in situ stress studies in the Climax Stock at the Nevada Test Site a strange "negative hysteresis" in the order of 300 to 500 microstrains was observed in standard calibration data. Here, the relaxation curve lies below the indentation (compression) curve as if the system were to somehow respond with an energy release. Although other investigators in the rock mechanics community have apparently observed this behavior, it has not been seriously studied. Therefore, a precision micro-indentation apparatus has been designed and used to perform a series of tests allowing a better understanding of the BMG button to cantilever interaction. Results indicate that the hysteresis effect is caused by differential motion between the button base and the cantilever resulting from the geometric motion inherent in the cantilever. The very large apparent hysteresis is mainly caused by cycling opposing cantilevers through the instrument's entire dynamic range, and the fundamental imprecision inherent in use of the standard micrometers to calibrate the BMG. Laboratory mean hysteresis magnitudes for a polished cantilever typically range from 3 to 25 microstrain for 100 and 1000 microstrain relaxations on 1000 microstrain deflection loops intended to simulate typical field data. The error percentage is thought to remain fairly constant with deformation loop size, and is sufficiently small such that it can be safely ignored. The hysteresis effect can probably be reduced, and instrument stability improved by machining a small 90 degree cone in the cantilever in which a slightly larger mating cone on the base of the indentation button would reside.

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INTRODUCTION

The Lawrence Livermore National Laboratory (LLNL), with funds provided by the U. S. Department of Energy (DOE), has conducted a large scale short term study involving the temporary emplacement of high level, spent reactor fuel underground at a site located in the northern Nevada Test Site (Ramspott, 1979). This Spent Fuel Test Facility - Climax (SFT-C) is located approximately 1400 ft underground in a Cretaceous age quartz monzonite and granodiorite stock whose geologic and structural characteristics are summarized by Wilder and Yow, 1984.

The facility itself consists of the main central canister drift located between two smaller heater drifts all oriented N61W, and the S76W oriented tail drift (Fig. 1). The shaft and most drifts located to the east of it were previously excavated for a nuclear weapons effects test. During the spent fuel test, the highly radioactive fuel rod assemblies were placed in selected steel lined holes located in the canister drift floor. Electrical resistance heaters, whose thermal output was carefully regulated to match the radioactive decay of the spent fuel, were placed in the remaining canister drift holes. Additional heaters were placed in floor borings in both heater drifts. Their output was periodically increased during the course of the experiment. This design allowed the SFT-C to simulate many of the anticipated characteristics of a much larger repository and enables its thermal and structural response, measured by several different instruments, to be compared to computer generated simulations.

An extensive in situ state of stress measurement program has been conducted at the SFT-C. Standard overcoring techniques were used in the ISS (In situ State of Stress) series boreholes whose locations are shown in Figures 2A, 2B, and 2C. The main objectives were as follows. 1. An initial attempt to measure the free field state of stress by the U. S. Geological Survey in ISS-1, -2, and -3 (Fig. 2A). 2. To measure the post test stress state in the north and south canister drift pillars using ISS-4, -5, -6, and -7 (Fig. 2B). 3. To measure thermally induced changes in the stress gradient away from canister and south heater drift heat sources using ISS-8 (Fig. 2B). 4. To measure the free field state of stress that exists away from the excavation using ISS-8, -9, -10, and -11 (Fig. 2B and 2C). Both the standard U. S. Bureau of Mines Gauge (BMG) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) soft inclusion (SI) type gauge were used. Both gauge types were equipped with thermistor temperature sensors that allowed accurate bottom hole temperature measurements, drilling fluid temperature control, and careful temperature matching at the end of each test. Preliminary results are presented in a report by Creveling, et al., 1984.

The BMG was used in this study because of its ruggedness and long history of apparently successful use in mining and civil construction. It measures the "secondary principal" stresses that exist in the plane perpendicular to the borehole axis. The CSIRO SI gauge, which will not be discussed further in this report, is relatively new and has the advantage of yielding a complete state of stress determination from a single overcore measurement. However, it was during the beginning of the post test measurement series that an odd "negative hysteresis" result was observed during calibration of the BMG using standard techniques. It is this strange hysteresis that will be discussed in this report following a brief description of the BMG itself.

U. S. BUREAU OF MINES GAUGE (BMG)

The U. S. Bureau of Mines borehole deformation gauge (BMG) was designed in early 1962 by Obert, et al. to allow rock stress measurements by the overcoring method. Very simply, the BMG consists of a 1.38 in. diameter by 14.4 in. long stainless steel body that contains six stiff Be-Cu cantilevers on which twelve foil-type resistance strain gauges have been bonded (Fig. 3A). These gauges are wired such that opposite cantilevers are paired to form three thermally self-compensating and extremely sensitive "full" Wheatstone Bridge circuits. Six compound stainless steel buttons, each with a single "O-ring" fluid seal, penetrate the gauge body on a transverse plane (Fig. 3B). The inner steel button tip bears directly on the cantilever while the outer tungsten carbide tip bears against the borehole wall. Metal washer shims, placed between the threaded button halves, are used to adjust total button length thereby allowing for the continual drilling induced changes in borehole diameter (Fig. 3C). The apparatus's physical design coupled with the strain gauge output is such that one microstrain unit approximately equals one microinch of button motion. Hereafter microstrain and microinch will be abbreviated MS and MI, respectively.

STANDARD CALIBRATION TEST

The USBM gauge is calibrated in the field using a simple aluminum support fixture shown in Figure 4. Two horizontally opposed micrometers bear directly on the exposed button ends where they provide both the indentation force and the deflection standard against which the BMG response is plotted. Unfortunately, these micrometers are inherently two orders of magnitude less sensitive to linear motion than is the BMG, and they are not designed to provide the substantial physical force (about 16 lbf) required to move the cantilevers through their entire dynamic range while simultaneously making accurate measurements. Briefly, the standard calibration procedure is as follows.

1. The BMG, with cantilevers fully relaxed, is securely clamped in the calibration jig.

2. The micrometers are advanced until initial cantilever contact is observed, and then to the next exact 0.001 in. division. This becomes the reference point for all subsequent measurements.

3. Both micrometers are first advanced by 0.002 in. increments (0.001 in. final) through the full dynamic range (0.015 in. each side) of the instrument while the resulting microstrain values are recorded, and then relaxed using the same sequence. The resulting strain indications (in microinches per inch) are typically plotted vs. the sum of the micrometer deflections as shown in Figure 5.

4. The jig clamps are loosened allowing BMG axial rotation such that the micrometers are aligned with the sensing buttons for the second and lastly, the third channels. Steps 2 and 3 are repeated, and the results are graphed as before.

BMG CALIBRATION HYSTERESIS

Negative hysteresis, hereafter referred to simply as hysteresis, has been observed during standard calibration tests performed both in the SFT-C and under laboratory conditions. Both the loading (upper) and unloading (lower) curves themselves tend to be quite linear as shown in Figure 5, with typical linear regression coefficients of 0.9999 and above. Also, at first the amount of the hysteresis appears inconsequentially small (typically 125 to 300 MS. This is because one is viewing the entire dynamic range of the instrument. A clearer presentation is shown in Figure 6 where individual hysteresis plots obtained by subtracting the respective unloading from loading data for five typical trials are plotted vs. total micrometer (BMG) indentation. Here, the ordinate directly shows the magnitude of the hysteresis which in this case averages approximately 200 MS. Also note that the hysteresis appears on the first relaxation interval, and persists relatively unchanged until near the end of the BMG range where almost total cantilever relaxation occurs. Typical overcore data obtained from SFT measurements ranges from a few tens to several hundreds of MS depending on the particular stress in and modulus of the rock, and the particular BMG axis under consideration (Creveling, et al., 1984). Thus, the hysteresis values shown in figure 6 could range from a minimum of 20% to a value that often exceeds two of the three measured differentials obtained during overcoring tests.

The loading and unloading curve offset shown in Figure 5 is called negative hysteresis because it is as if the BMG were somehow responding with an energy release during the unloading portion of the calibration cycle. Friction in the BMG, which is common in many instrument systems, would cause the opposite result. During a typical overcoring test, the EX sized (1.5 in.) borehole containing the BMG first contracts, and then dilates as the overcoring induced compressional stress wave passes through the instrument's measurement plane. This physical deformation cycle, which is similar to the standard calibration loop, raises the concern as to whether some unknown and variable portion of the final measured deformations might contain a significant (several tens of percent) hysteresis component.

CAUSES OF NEGATIVE HYSTERESIS

Several possible causes have been proposed to explain the source of the observed hysteresis in the BMG. They include the release of energy stored in the button O-ring seal and button itself, the complex interaction between button and micrometer tip, and differential motion between the button and the cantilever blade. Each cause is briefly discussed below.

The lower one-half of all six cantilever buttons are grooved to receive a fairly tight fitting rubber O-ring seal needed to prevent drilling fluids incursion during tests. As each piston is progressively indented during the compressional loading portion of the calibration cycle, this O-ring will move outward in its notch and tend to roll inward before the cylinder wall friction is overcome (Fig. 7). This stored energy would be recovered on the first unloading increment of the relaxation cycle. In addition, the piston itself is composed of male and female halves that may have several "length adjustment" washers placed between them (see Fig. 3C). These stamped sheet metal washers have rolled edges or may be warped, and in the field may be greasy or dirty. The result is that the piston may be compressible to some extent. This stored energy would be progressively recovered by the force reduction that occurs during relaxation of the relatively stiff cantilevers.

A second source of hysteresis could be the complex interaction that can occur between the micrometer tip and the button, and other intrinsic problems associated with this calibration method. For example, depending on its design, a standard micrometer is two to three orders of magnitude less sensitive than the BMG. It is also not designed to exert the up to 16 lbf needed to fully depress a cantilever while at the same time providing a high quality deflection length standard. The micrometer shaft also rotates as it bears on the BMG piston - one direction for compression and the opposite direction for relaxation. Because of the potential for minor BMG misalignment when using the calibration jig, the point of rotation may not occur directly on the button axis (Fig. 8). This would then cause both a rotation and tipping moment to be exerted on the button that, in turn could cause differential motion between the cantilever top and button base at low contact stresses.

A third possible hysteresis source is differential (shearing) motion between the button base and the top of the cantilever blade. By its very nature, this point of contact moves about an arc whose radius is defined by the effective length of the cantilever blade between the base and button contact point. The direction of contact point motion will depend on the initial angle formed by the cantilever blade and the button axes, and on whether the cantilever is deflected though the neutral (90 degree) angle or not. The three possible geometric situations, which depend on the exact manner in which the BMG is manufactured, are shown in Figures 9A, 9B, and 9C. Figure 9A is the case where the relaxed cantilever blade is angled slightly outward. In Figures 9B and 9C the blade is initially parallel to the instrument case (reference line) and angled slightly inward, respectively. The small shear displacement components, shown by the arrows located in the button base (see Figs. 9), are generated by the intrinsic cantilever blade motion. Its direction (either inward or outward along the blade), and magnitude is determined by the blade deflection direction and the initial angle formed by the blade and button axes as mentioned above.

INDENTATION APPARATUS DESIGN

In an attempt to learn the source of the negative hysteresis in the BMG, a precision deflection apparatus hereafter referred to as a micro-indenter (MID), shown in Figure 10, has been designed and built at LLNL. It consists of the following main parts shown diagrammatically in Figure 11. BMG support is provided by two precision "V-blocks" that are carefully aligned and securely attached to the apparatus base plate. BMG deflection is done through a long stiff lever arm pivoted at its support end, and that is raised and lowered in the vertical plane by a micrometer thread. This arm carries a short polished and hardened steel rod that bears directly on either the BMG button or the cantilever itself, and whose motion is very nearly one dimensional. All these parts are mounted on a rigid base plate that is equipped with a bubble level and three leveling screws.

The entire MID apparatus has been designed such that it can be used under an extensively modified GCA Corporation Model VLM 200 Laseruler (LR), a laser based interferometer device shown in Figure 12. The precision probe tip of this apparatus bears directly on the indenting rod as shown in Figure 13. This machine has a resolution of less than one MI and a repeatability on the MID of +- 1 to 2 MI. It is located in an environmentally controlled metrology laboratory where the temperature variation during five trials is typically within +- 0.25 deg. C. Initial MID tests were conducted on an Bausch and Lomb Model 25C Optical Gauge having a resolution and repeatability of about 10 MI and 50 MI, respectively. This instrument clearly did not have the required resolution or stability needed to investigate subtle BMG behavior, but it did demonstrate the need for a pre-load spring to remove a small amount of "slack" in the two spherical suspensions in the MID deflection arm drive assembly. These tests also gave valuable insight into the overall behavior of the BMG and MID system that resulted in saving a great deal of time during the subsequent Laseruler trials.

MEASUREMENT METHODS

During the course of this investigation several different types of measurements were made on the BMG. The micro-strain resolution level of this instrument demands the utmost in care and patience during the conduct of tests if the results are to be meaningful. For maximum dimensional stability, the BMG is mounted in the MID test fixture which is in turn placed under the LR at least four hours in advance of testing. All contact measurement surfaces must be kept as clean as possible, and the height of the indentation button is adjusted so that the carrier arm is level at mid-deflection. Each test consists of five individual compression and relaxation cycles on a single button followed by a five to fifteen minute creep relaxation period if required.

The BMG data acquisition system is shown in Figure 14. It consists of a standard battery powered Vishay P-350A Strain Indicator and SB-1 Switch and Balance unit. Both units were calibrated by the LLNL instrument shop and certified as performing within their specifications in advance of testing. BMG temperature was measured using a compound thermistor and linearizing resistor array, shown in Figure 15, that is thermally coupled to cantilever No. 3 (C-3). A Hewlett-Packard Model 6101A DC Power Supply and Model 3468A DMM, the latter, controlled by an HP-41C hand held calculator, was used to provide a continuous temperature output in degrees Celsius.

Several different types of tests were performed using the LR and MID under differing conditions. These tests differed from the standard calibration method in that the compression or relaxation interval spacing is achieved by first presetting the desired strain indication, and then adjusting the MID to yield that approximate reading, followed by a final strain reading. All motions were unidirectional in the sense that absolutely no motion reversal was allowed during a trial except at the previously selected range end point. If the operator missed the selected data interval by an unacceptable amount, the trial was entirely repeated. All standard button tests were done without shim washers for maximum button stiffness. Additional test conditions are outlined in Table 1.

TEST RESULTS

The test results are divided into two sections to facilitate information presentation. Series-I, which includes tests 1, 1A,

TABLE 1. Test Conditions

Test No.	Pre-load MS	Test Range Start MS	Test Range Finish MS	Cantilever Nos.	Indentation Conds. Std. Button	Indentation Conds. Direct Cant.	Indentation Conds. Other (1)
				Series - I			
1.	100	0	15,000	1 & 3	X		
1A.	100	0	15,000	1			X
2.	100	0	15,000	1 & 3		X	
				Series - II			
3A.	---	3,250	4,250	1 & 3	X	X	
3B.	___	7,250	8,250	1 & 3	X	X	
3C.	---	11,250	12,250	1 & 3	X	X	

NOTES: 1. This was a precision fitting hardened steel button without an O-ring.

2. Tests 3A, 3B, and 3C were conducted +- 500 MS about the lower, middle, and upper one-quarter points of the BMG's dynamic range, respectively.

and 2, consists of full dynamic range trials using standard buttons, a specially fabricated solid button, and direct cantilever indentation, respectively. These tests were intended to provide information on the fundamental magnitude of the hysteresis problem. Series-II includes tests 3A, 3B, and 3C which are restricted range tests conducted about and centered on the lower, middle, and upper one-quarter points of the BMG dynamic range, respectively. These tests, done with both standard buttons and by direct cantilever indentation, were intended to simulate the range of typical overcore test data; and to learn the amount of hysteresis that might commonly occur during such tests.

Series - I

Test No. 1 - Standard Button

This test sequence consists of full deflection range cyclic tests with indentation occurring through standard buttons that did not contain spacing washers. Cantilevers Nos. 1 (C-1) and 3 (C-3), which are BMG channels Nos. 1 and 3, respectively; were tested and the results shown in Figures 16A and 16B, respectively. These figures show the hysteresis as the ordinate with total LR measured deflection as the abscissa. A preload of 100 MI was used to remove the button creep and low contact stress friction effects that occur just before complete cantilever relaxation.

The data shown in Figures 16A and 16B are the means of five individual hysteresis values each obtained from a single loading cycle trial previously described. The associated standard deviation values are shown as the short dashes located above and below their respective mean value which is itself shown as a "+". The plotting code incorporates subroutines that converge data (by linear projection along their respective regression determined slopes) from the five individual trial measurements to a mean deflection (x-axis) point before the statistical measures of hysteresis are calculated. This standard format will be used for all graphs of similar data.

Both curves in Figures 16A and 16B have very similar convex upward shapes. Also, a small amount of hysteresis appears on the first unloading increment which is shown as the right-most data point. The amount of hysteresis increases toward mid-span where it reaches a maximum of about 115 MI (Fig. 16A) and 80 MI (Fig. 16B) before declining to a low value at the 100 MI preload (zero point). The standard deviation values are, for the most part, reasonably low indicating the overall good quality of the data sets. The lower values for C-3 (Fig. 16B) compared to C-1 (Fig. 16A) may be caused by the fact that these C-3 data were obtained later in the testing program and therefore, reflect test system improvements, and increased operator skill and experience. The differences could also reflect a fundamental difference in the behavior of these two button cantilever systems. In general, the overall curve shape seems to suggest a hysteresis mechanism associated with the basic cantilever motion. Two questions posed immediately by these results concerns (1) the nature of the button base to cantilever intersection point and (2) the influence of the O-ring seal on the motion of the standard button within the BMG body.

Test No. 1A - Steel Button

One particular area of concern is the effect of the O-ring fluid seal on the standard button motion. This seal, even though well lubricated by silicone jelly, is a source of some friction but more importantly, it, and not the actual button body, is the true button support member. Therefore, a precision solid steel button, with a shape similar to that of the standard button, was made and custom fitted to the minimum dimension of what was discovered to be a slightly oval shaped cylinder in the BMG body located over cantilever C-1 see Figs. 3A and 3B). Following final polishing, the button was heat treated to increase its surface hardness.

Mean and standard deviation results of five full range trials are shown in Figure 17. Here, both mid-range hysteresis values are much larger than those values measured for the standard buttons described previously, while the maximum hysteresis value is essentially the same. The curve shape is also similar, but not as regular suggesting that either "tipping" or some other non-coaxial motion of this button might have occurred near mid-deflection. In general, this button did not perform very well. In fact, the O-ring support seems to at least give the standard button hysteresis curve a more predictable shape. At this juncture it became clear that the fundamental behavior of the cantilever itself should be examined in greater detail.

Test No. 2 - Direct Indentation

Full range direct cantilever indentation tests were conducted with the front BMG case removed (Figure 15) under test conditions essentially identical to those previously described. Differences are: 1. the BMG body is now supported on only one V-block rather than two as before, and 2. a one-half inch diameter hardened steel rod, with a large highly polished contact radius (8 in.), is now bearing on the cantilevers. Results are shown in Figures 18A and 18B for tests on C-1 and C-3, respectively.

The curves shown in Figures 18A and 18B, and Figures 16A and 16B are strikingly similar. Both direct indentation curves are again convex upward, but slightly more straight sided than the rounded curves obtained with the standard button. Again the hysteresis appears immediately on the first unloading increment, reaches a maximum close to mid-span, and then decays to a low value. However, the effect is somewhat less pronounced than with the standard buttons with maximum values of 60 vs. 115 and 70 vs. 80 MS for C-1 and C-3 tests, respectively. These results suggest that the same basic mechanism is operating in both cases.

Button - Cantilever Interaction

Because of the similarity of the standard button and direct cantilever test results described above, the nature of the contact region between cantilever and indenter was examined microscopically. Figure 19 shows the cantilever blades and associated strain gauges, thermistor, and wiring. Note the small, faint, and slightly oval shaped mark roughly centered on the reflective cantilever blade surface. This and other button contact marks have been observed using both white and phase contrast optical techniques to gain insight into their physical features.

Figure 20 is a white light photomicrograph of the contact area shown in Figure 19. The cantilever blade free end is toward the upper left. The standard button contact area is the highly disturbed blackish region located in the lower right corner of the photo. Interference fringe examinations indicate that these surface dimples can be up to 0.0024 in. (60 microns) deep and often contain crushed mineral grains in their base. Particularly note the many arcuate ridge lines located near the upper center of the photo. These ridges are displaced relatively toward the unsupported cantilever end from the main button contact area. These lines occupy a region that is slightly wider (0.016 in.) than the standard button contact area (0.01 in.diameter) measured from the photo. For comparison, Figure 21 shows a cantilever blade surface following tests using the highly polished large radius indentation rod. The slightly disturbed contact region (estimated about 0.02 in.) is gradational with normal blade surface imperfections. These findings will be addressed again in the discussion section of this report.

Test Series - II

During in situ stress measurement tests in rock, operators must adjust the cantilever button length using spacing washers to obtain initial installation deflections approximately in the BMG mid-deflection range. One typically avoids the lower quarter of the instrument range because of the low button to borehole wall contact stresses that are developed on BMG insertion. This situation would lead to poor quality data because of drill rod induced vibration, circulation pump surges in strain indications, frangible particulates located between the button and borehole wall, etc. The upper range of the BMG must also be avoided because of potential nonlinear strain gauge responses, and the possibility of causing permanent BMG damage. Thus, field data are typically acquired from about the middle one-half of the instrument's dynamic range.

The second test series is intended to simulate the BMG operation characteristics observed in field data recently acquired at the Climax Stock. The individual tests consist of 1000 MS cycles (+- 500 MS) essentially centered on the lower (Test 3A), middle (Test 3B) , and upper (Test 3C) one-quarter points of the BMG dynamic range. Cantilevers C-1 and C-3 have been tested using both direct indentation and the standard BMG button, and the results are presented as the mean and standard deviation of five individual trials in the format previously described. The results are presented below.

Test No. 3A - Lower One-quarter Point

Figures 22A through 22C present the mean and standard deviation results of hysteresis trials conducted about the lowermost one quarter point, located at about 3750 MS, of the BMG range. Note the scale changes for both axes, and that the standard deviation from five trials is commonly less than three MI. Direct indentation results for cantilevers C-1 and C-3 (Figures 22A and 22C, respectively) show nearly straight line curves with slightly negative slopes. Initial hysteresis values are 5 MS or less, which increases to about 15 MS at the cycle end.

Standard button indentation results are shown in Figures 22B and 22D for C-1 and C-3, respectively. These results yield nearly flat curves that have very slightly negative (friction?) values (-2 MS) that may not be significant, to slightly positive values (+5 MS). The slight convex upward shape shown in Figure 22D is probably not significant.

Test No. 3B - Middle One-quarter Point

The middle range test results are presented in Figures Nos. 23A through 23D in the same manner as previously described. The direct indentation data, shown in Figures 23A and 23C, have the same basic shape and values as previously described. However, the data for C-1 appear to be displaced upward from about 3 to 8 MS.

The standard button indentation results for C-1 (Fig. 23B) show essentially no hysteresis and are very reproducible. The C-3 results (Fig. 23D), however, show a strong negative slope and hysteresis values that have previously been described for direct indentation tests. Causes for this result will be presented in the discussion section of this report.

Test No. 3C - Upper One-quarter Point

Data for the upper range are presented in Figures 24A through 24D. These tests proved to be very difficult to conduct in a controlled manner because the MID is now heavily loaded by both the highly deflected cantilever and the pre-load spring. This caused "sticktion" in the micrometer thread used to drive the MID arm (see Fig. 11) which, in turn, made it very difficult to achieve accurate 100 MS data intervals. Therefore, it is gratifying to note that the data quality, as shown by the standard deviations, did not seem to significantly degrade when compared to the results previously described.

Direct indentation results shown in Figures 24A and 24C are essentially identical to the lower and middle one-quarter point results presented above. The initial hysteresis is about 3 MS on the first relaxation interval, and it increases to about 19 MS on the last interval.

Standard button test data given in Figures 24B and 24D are also consistent with the results for the middle range tests. C-1 shows essentially no hysteresis except at the very end of the unloading cycle. C-3, however, exhibits almost 25 MS of hysteresis in a manner almost identical to the middle range test result. These data will also be treated in the discussion section below.

DISCUSSION OF RESULTS

Full Range Test Series

The first test series dealt with full dynamic range tests intended to assess the fundamental behavior of the BMG. It is suggested that the convex upward curve shapes shown in Figures 16 and 18 result from complex motions that occur between the cantilever and the slightly conical standard button base. First, it should be recalled that the hysteresis curves are derived from a complete monotonic loading cycle. The button and cantilever is first pre-loaded, and then incrementally loaded (without any relaxation adjustments) to the desired maximum deflection. Therefore, the first hysteresis value obtained is the right-most data point on the graph, and originates from the first unloading increment. The following hysteresis values are differentials calculated from successive unloading steps, with reference to the respective loading step, back to the (100 MS) pre-load value.

During this cyclical process, the point contact stress progressively increases and then decreases. At first, friction keeps the contact point between the button base and the somewhat rough and oxidized cantilever blade surface at the initial point as shown in Figure 25A. As cantilever indentation continues, however, very small differential stick slip motions occur as the contact point moves outward toward the free end of the cantilever (Fig. 25B). These motions are probably not directly detectable (there is nothing to form a reference), but cause the formation of microscopic "compression ridges" shown in Figure 20. Upon unloading, contact stress is progressively reduced and the button rotation increases because the contact point is located slightly too far out on the cantilever blade. This effect appears in the resulting data as a "negative" hysteresis although they are presented herein as positive numbers.

Restricted Range Test Series

The restricted range (+- 500 MS) tests conducted about the lower, middle, and upper one-quarter points of the BMG dynamic range have also been extremely revealing. Direct cantilever indentation results show that from 2 to 5 MS of hysteresis initially appears and increases in an fairly linear fashion to from 15 to 19 MS with 1000 MI of relaxation which is less than 2% of the hysteresis cycle. Standard button test results show that hysteresis did not appear during the three C-1 tests. During the C-3 lower one-quarter point test, a nearly constant 5 MS was observed (<0.5%). However, both the middle and upper one quarter point tests of C-3 yielded hysteresis curves almost identical in form and magnitude to their respective direct indentation tests. A tentative explanation follows.

It is believed that this effect resulted from the fact that the upper surface of the C-3 blade was polished, using a series of progressively finer abrasives and finishing with a less than 79 microinch (2 micron) garnet. This operation, which occurred before the middle and upper one quarter point tests, removed all surface oxidation and machining marks, and all previous indentation dimples. This polished surface allows differential button-to-cantilever motions similar to those that occur with the micro-indenter button. Microscopic examination of the C-3 blade following all testing revealed only minor surface disturbance as previously described for the large radius highly polished micro-indenter button. Apparently many standard button cycles on an oxidized machined cantilever surface are required to form an indentation feature such as shown in Figure 20.

Effect on Overcoring Test Results

The amount of hysteresis that would be present in a typical BMG data set obtained during an overcoring test will be strongly dependent on the frictional characteristics of each of the six cantilever blade and button systems within a specific tool. If a given cantilever blade surface is "rough", and no lubrication (such as the silicone jelly used on the O-ring fluid seal) is present between the standard button and the blade surface, then the behavior is likely to be similar to that observed for the C-1 test series (Figs. 22B, 23B, and 24B) and essentially no hysteresis will be present. In contrast, if the cantilever blade surface is very smooth or lubricated, then the blade to button behavior is likely to be similar to the C-3 test results shown in Figures 23D and 24D. Here the about 3 MS of hysteresis appears on the first 100 MI unloading interval (3%), and then increases in a fairly linear fashion to from 20 to 25 MS at 1000 MI total relaxation (2% to 2.5%). The general hysteresis effect is to make the commonly measured dilational borehole motions appear overly large, but what is the approximate magnitude of this effect on typical overcore test data?

As previously mentioned, fifty successful BMG tests were recently conducted at the SFT-C facility at NTS. All data sets obtained from these overcoring tests yielded final gauge channel differentials less than 1000 MI (max. = 952 MI). The following discussion assumes that all cantilever blades are very clean and smooth, which is the worse case scenario. Then, representative values for the mean and standard deviation of the hysteresis associated with small BMG motions (<= to 100 MI) and for large BMG motions (1000 MI) is about 3 +-2 MS and 25 +-6 MS, respectively. These mean values, plus and minus two standard deviations, bracket the 95% confidence interval assuming that these data are normally distributed about their mean. Thus, the small motion data could have hysteresis values ranging from essentially zero to possibly as much as 7% of deformation while large motion data could have hysteresis ranging from 1.3% to 3.7% of deformation. However, it is believed that the latter values are more likely to be representative of the true hysteresis magnitude because they are derived from relatively larger and inherently more accurate measurements. When one recalls the nature of the environment in which overcore stress measurements are made, it seems likely the other sources of error such temperature, vibration, asperity crushing and so forth equal or exceed the magnitude of the hysteresis error. Therefore corrections to the SFT-C data set seem unnecessary at this time.

CONCLUSIONS

The following conclusions and observations are presented with regard to the results of the micro-indenter tests conducted on the standard BMG apparatus.

1. The negative hysteresis appears to be caused by differential motion between the base of the standard button and the upper cantilever surface. On loading, the contact stress increase coupled with blade deflection results in this contact point slipping outward toward the free end of the cantilever. This causes progressively more severe button tipping on relaxation which appears as negative hysteresis.

2. The amount of hysteresis observed during standard calibration tests appears to be related to the size of the BMG deflection cycle which is, in turn, calculated with reference to a particular origin point. Data from 1000 MI cycles, chosen to represent the typical range of overcore data, obtained from the middle one half of the BMG dynamic range indicate that hysteresis is commonly less than 25 MS. This is well within the range of other test uncertainties. Therefore, corrections to overcore data do not seem warranted.

3. Occasionally, during overcoring tests, sudden "jumps" are observed in the indicated strain values. Although it is possible that these data discontinuities are caused by the crushing of borehole wall asperities or mineral grains, the sudden cantilever load change could also cause subtle differential motions between the button base and cantilever. Because of this and other uncertainties in the data, it does not seem reasonable to wait for the last small fraction of strain to appear at the end of overcore tests.

4. By its very nature, the standard calibration method using horizontally opposed micrometers is inherently less accurate and results in large system hysteresis. This calibration method is useful for determining the slope of the deflection vs. strain curve from point values obtained throughout the entire BMG dynamic range using the linear regression method. Any slight non-linearity will be masked, and other errors are assumed to be random.

6. The standard O-ring supported compound button as tested without spacing adjustment washers installed seems to work reasonably well. During overcore tests, however, great care must be taken when making button length adjustments to keep the entire system clean and tight.

7. The micro-indenter apparatus and BMG support system worked better than had been anticipated during its design. The standard deviation of five loading cycle trials is about +- 5 MI, Repeated measurements with the carefully reworked Laseruler system were typically +-2 MI. The micro-indenter did require modifications to remove slack in the micrometer spherical suspensions, careful dry lubrication of the drive thread, and the addition of a preload spring to the indenter arm. Careful temperature control is mandatory to obtain measurements of this quality.

8. A small amount (typically <80 MS) of either cantilever creep or strain gauge bond creep has been observed after complete unloading following full deflection range cycles. This memory effect appears to exponentially decay to near zero in about 15 to 20 minutes depending on how long the cantilever blade was heavily deflected. Creep was not apparent at the 100 MS preload and no permanent zero point shift was observed at any time during the trials.

RECOMMENDATIONS FOR FUTURE WORK

The following two recommendations are offered with regard to future work to improve the overall performance of the BMG.

1. It seems likely that the observed hysteresis effect could be significantly reduced by improved button base and cantilever blade surface design. One such improvement, shown in figure 26, would be to machine a small cone on the standard button base part. This could be made to fit within a similar conical depression, carefully machined so as to be coaxial to the button

cylinder in the BMG case, in the upper surface of the cantilever blade. This latter cone would have a smaller conical angle and the result would be to create a bearing circle between the two cones. An additional advantage is that one would know that the same contact point can be reestablished following spacing washer adjustment or O-ring lubrication. Cantilever motion will slightly distort this circle into an ellipse, but the effect may be tolerable. Tests would be needed to establish the merits of such a scheme.

2. A new and field worthy BMG calibration fixture should be designed and tested that abrogates the need for micrometers if at all possible. Such a device might be a carefully prepared thick walled metal cylinder designed to fit within the biaxial cell. Here, the BMG would be placed in the coaxial 1.5 in. diameter hole and the entire billet which is in turn placed in the standard biaxial cell (Worotnicki and Walton, 1979). A second possible method would be to use a stepped cone type calibrator such as W. Beloff has described to D. Wilder (personal communication) in Mr. Beloff's work at the BWIP site.

ACKNOWLEDGEMENTS

Several individuals have made significant contributions to this work. Dale Wilder and Patrick Burklund were involved with the initial trials conducted at NTS that clearly established the presence of the negative hysteresis effect. Pat Burklund also assisted with micro-indenter design and participated in measurements made during its early shakedown trial period. Mark Fowler did an excellent job of device fabrication. The patient assistance and instruction by Dennis Mergo and Herman Hauschildt significantly improved the quality of the Laseruler based MID measurements. Wes Patrick, Dale Wilder, and Francois Heuze kindly reviewed the manuscript. This work was performed for the Spent Fuel Test - Climax project, under the direction of Wesley Patrick, using funds provided by the NNWSI. His patience and helpful discussions are gratefully acknowledged.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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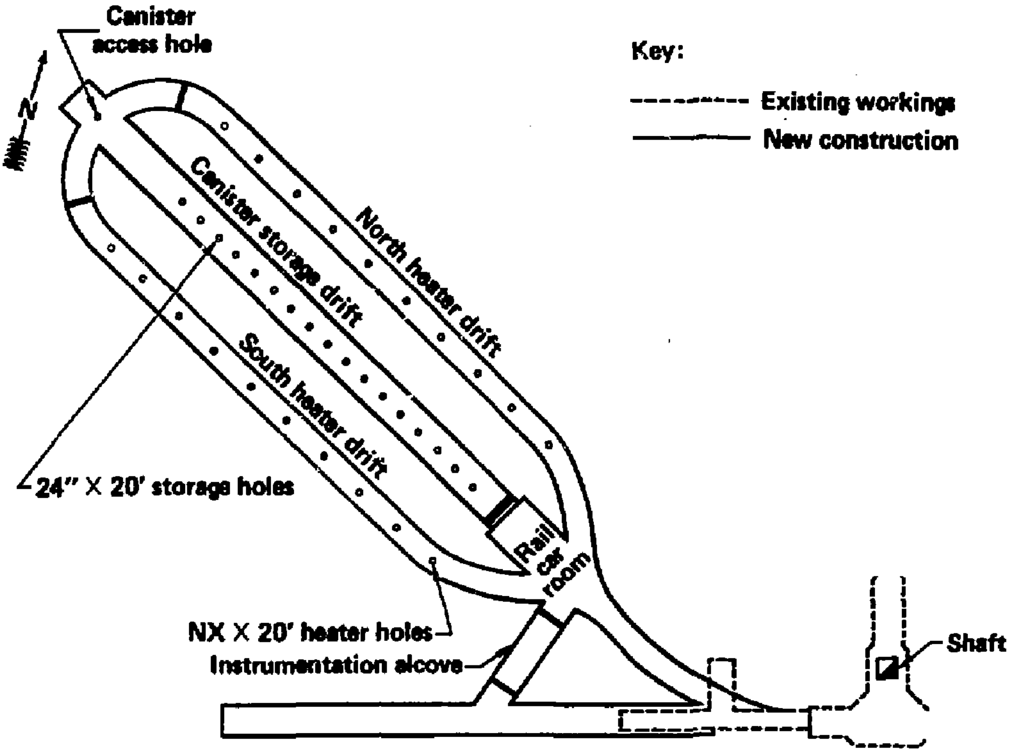

Fig. 1. Plan view of the Spent Fuel Test - Climax showing the main drifts, heater and canister emplacement holes, and access shaft and borehole associated with the test.

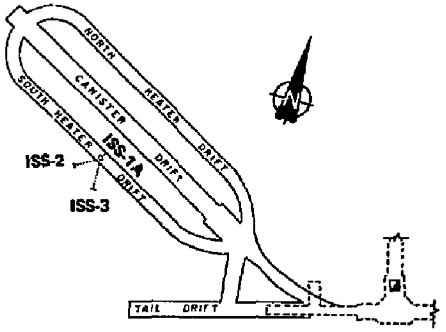

Fig. 2A. Plan view of the ISS-1, -2, and -3 boreholes used by the U. S. Geological Survey for the initial in situ state of stress measurements.

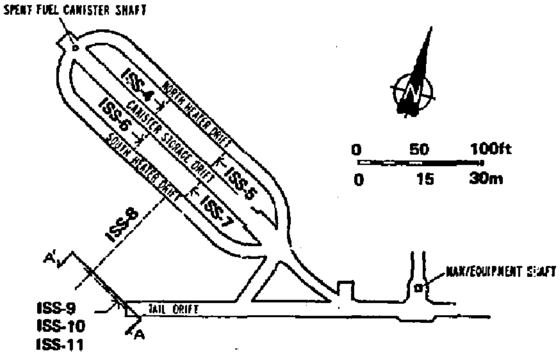

Fig. 2B. Plan view of boreholes ISS-4 through ISS-11 used for subsequent state of stress measurements.

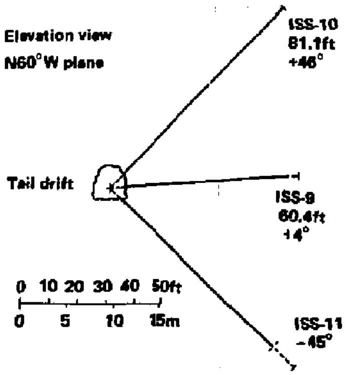

Fig. 2C. Elevation view of the N61W plane (Section A-A' of Fig. 2B), located near the tail drift end, that contains boreholes ISS-9, -10, and -11.

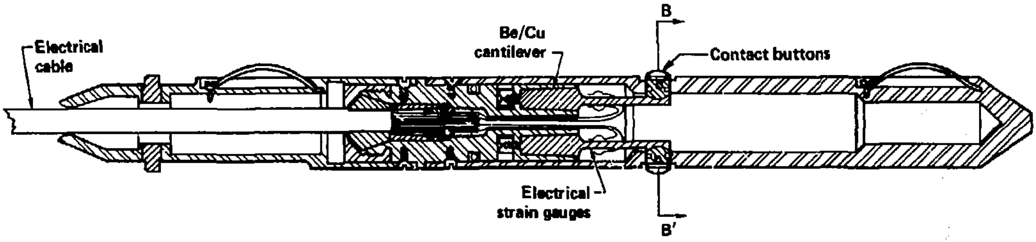

Fig. 3A. Longitudinal view of the U. S. B. M. reversed case borehole deformation gauge Model 100, Mk. II (modified from Rogers Arms and Machine Co., Inc. drawing).

NOTE: SCALES VARY

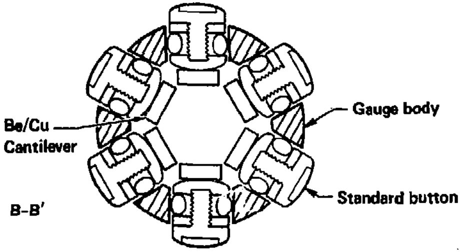

Fig. 3B Transverse section B-B' of the U.S. B. M. reversed case borehole deformation gauge taken through the standard button axes (source as noted in Fig. 3A).

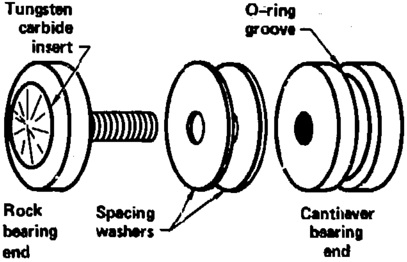

Fig. 3C. Exploded view of the standard compound cantilever button for the U. S. B. M. borehole deformation gauge.

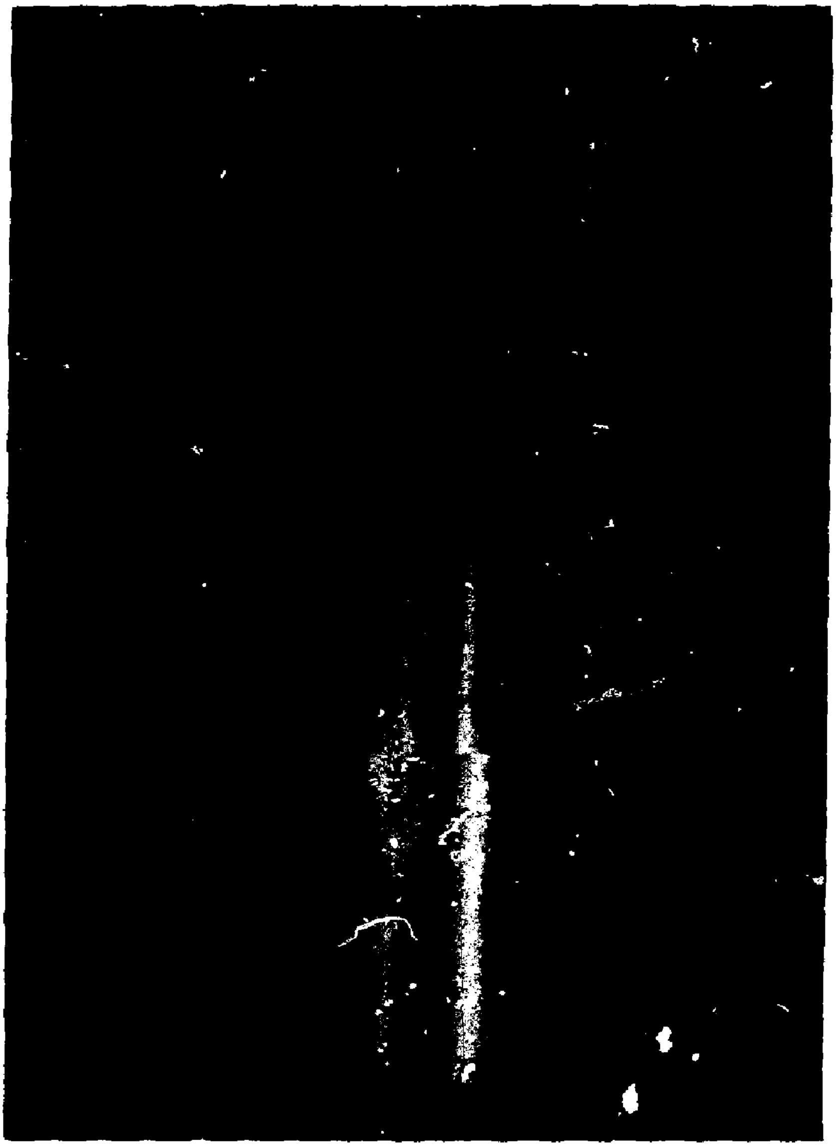

Fig. 4. The standard U. S. B. M. borehole deformation gauge calibration fixture with the horizontally opposed end bearing micrometers.

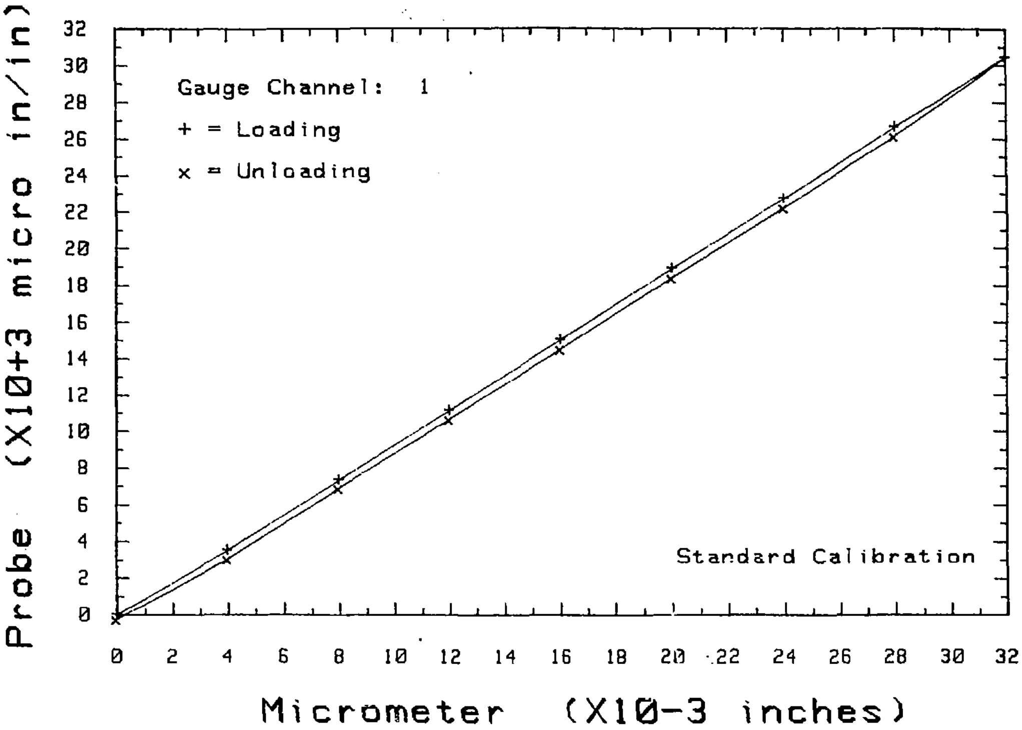

Fig. 5. Graph of typical standard calibration data loop showing the total micrometer induced BMG deflection (x-axis) vs. the BMG response in dimensionless strain units (y-axis) obtained from the calibration apparatus shown in Fig. 4.

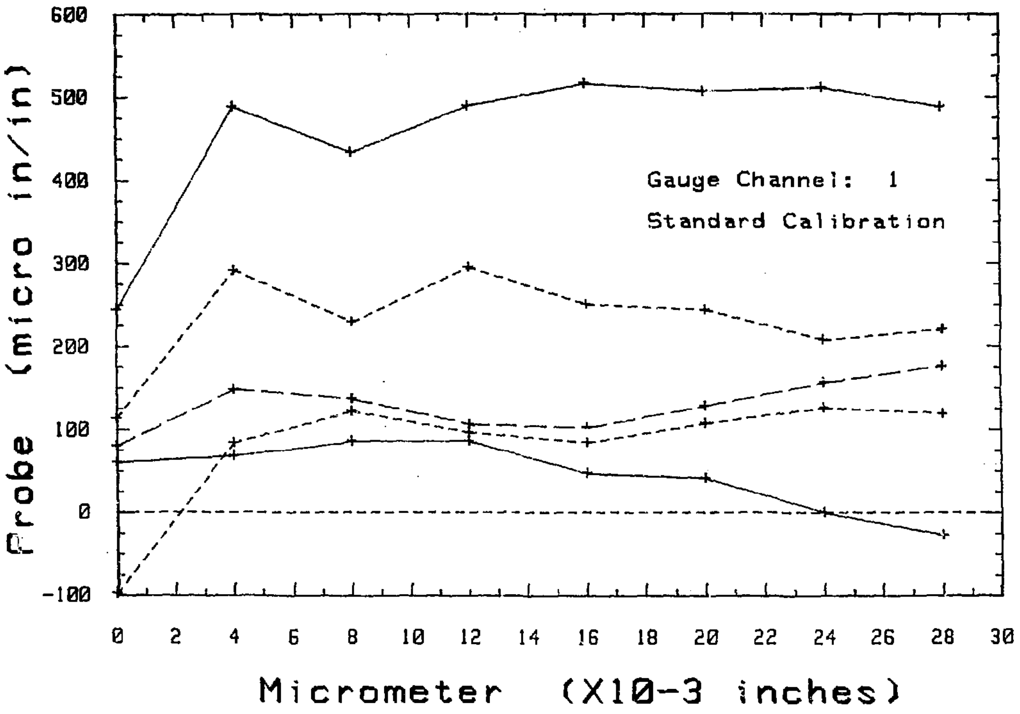

Fig. 6. Typical range of variation for five hysteresis plots obtained by subtracting the respective unloading from the loading data. Results were obtained serially using the standard micrometer calibration method. By adopted convention, the hysteresis of concern in this study is always shown as positive values.

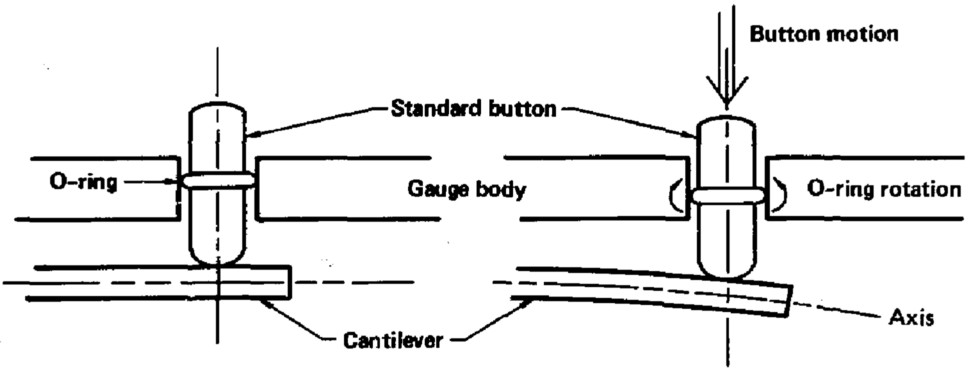

Fig. 7. Hypothesis concerning rotational strain energy stored in the single O-ring fluid seal during compression of the button.

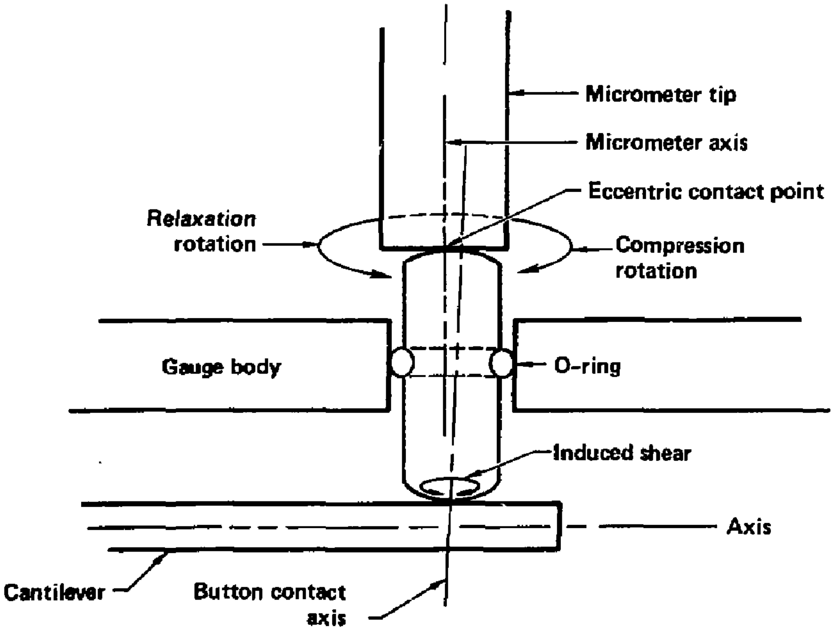

Fig. 8. Hypothesis concerning rotation and tipping forces exerted on the button by friction and non-coaxial contact between the rotating micrometer tip and the button during the standard calibration operation.

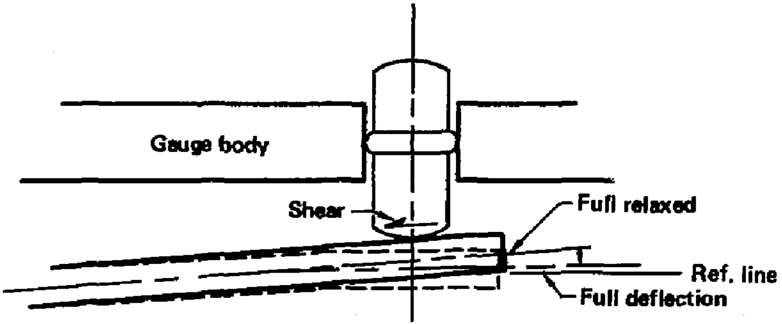

Fig. 9A. A small inward directed shear force is generated at the button cantilever interface by a cantilever arc located above the reference line.

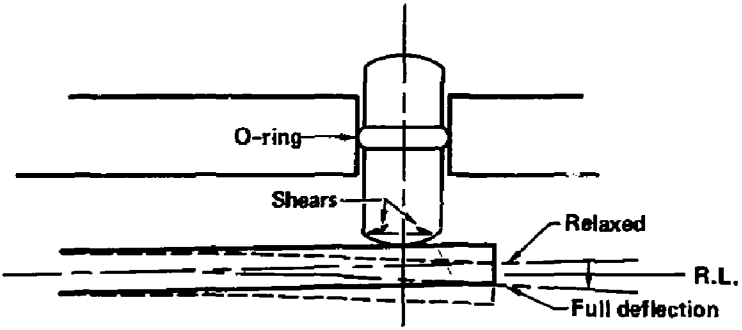

Fig. 9B. Small inward and outward directed shearing forces are generated at the button cantilever interface by a cantilever arc including the reference line.

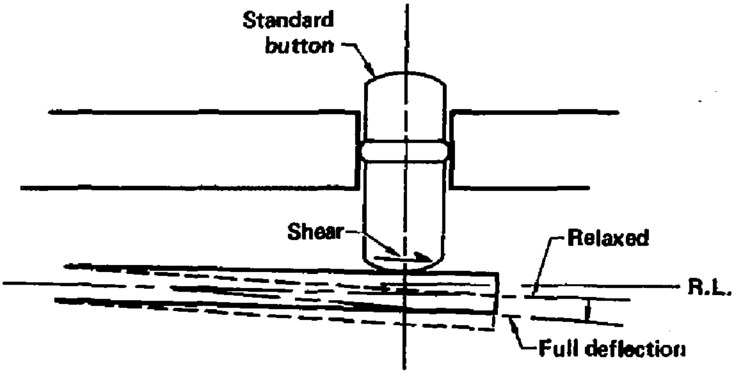

Fig. 9C. A small outward directed shear force is generated at the button to cantilever *interface by a cantilever arc located below the reference line.*

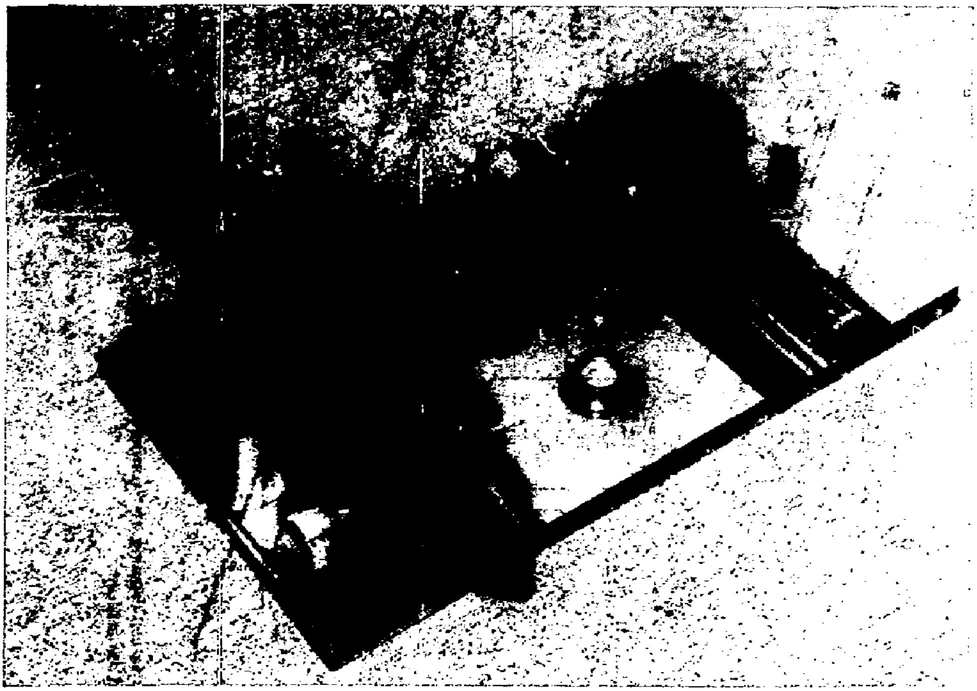

Fig. 10. Micro-indentation apparatus with the BMG installed in the test position.

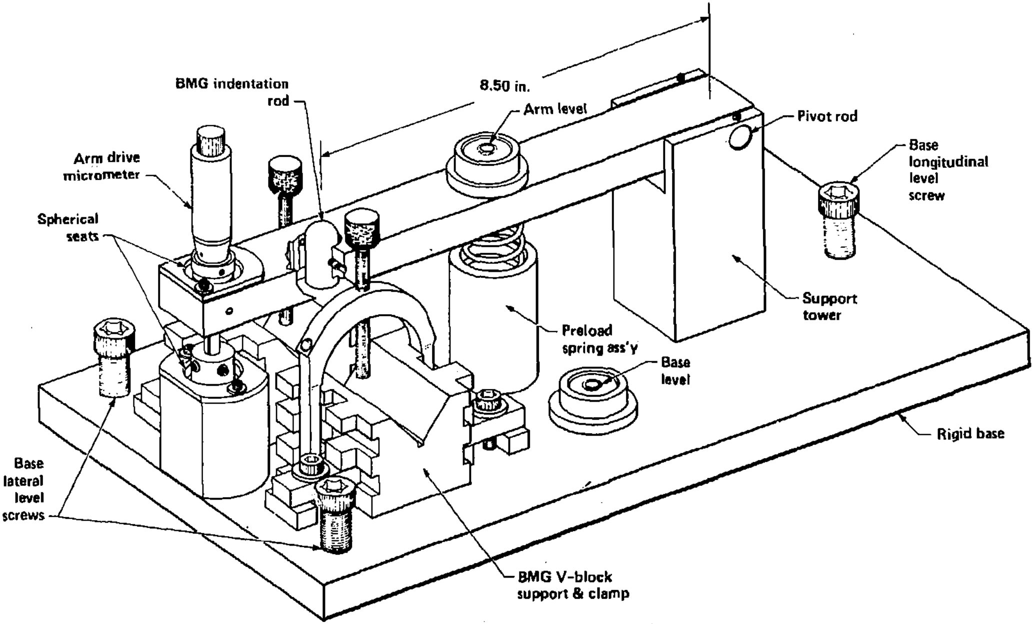

Fig. 11. Projection drawing of the micro-indenter device showing the principal parts and dimensions.

Fig. 12. Micro-indentation apparatus with the BMG set up for testing under the extensively modified Laseruler.

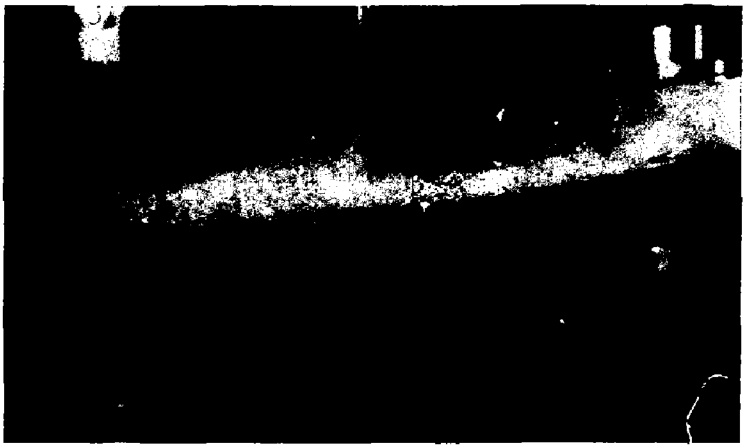

Fig. 13. Detail view of the micro-indenter apparatus showing the indenting arm carrying the hardened indenter rod that bears directly on the BMG buttons. The arm drive micrometer and pre-load spring are shown on the left and right sides of the photograph, respectively.

Fig. 14. Basic electronic apparatus consisted of standard Vishay strain indicator, and switch and balance units; and Hewlett Packard multimeter and DC power supply which is shown under the multimeter. An HP-41C calculator (not shown) was used to control the multimeter and provide temperatures values in degrees C.

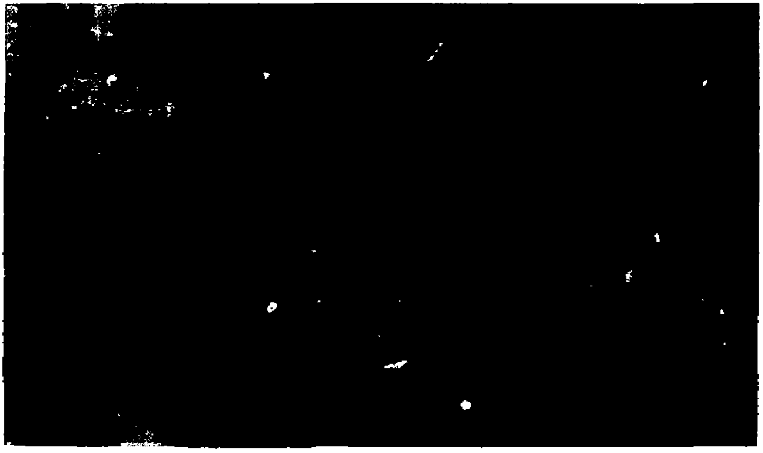

Fig. 15. Detail view of the micro-indenter deflection arm and indention rod similar to Fig. 13. Here the apparatus is modified to allow direct cantilever indentation.

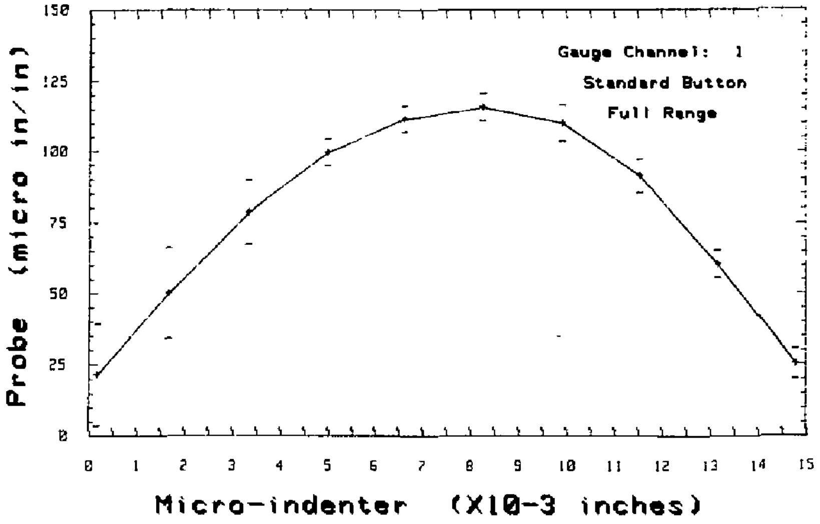

Fig. 16A. Mean hysteresis loop with ± standard deviation values (shown as dashes) for BMG channel 1 (standard button 1) for the test conditions shown.

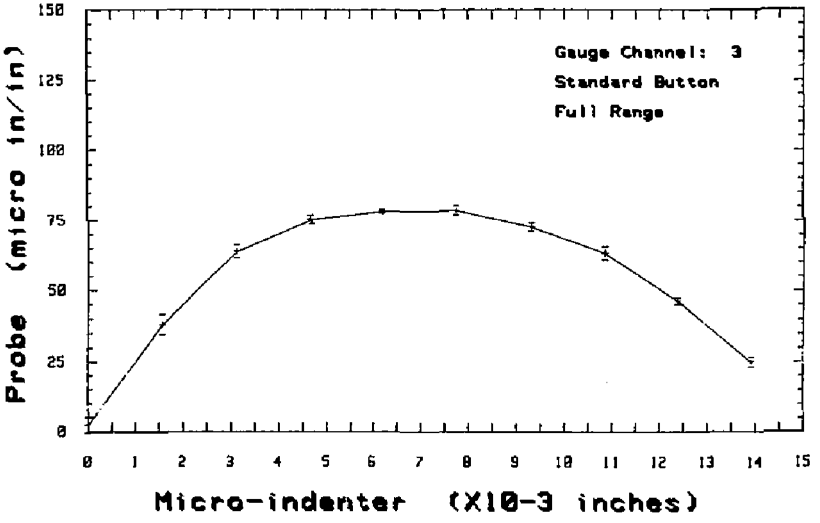

Fig. 16B. Mean hysteresis loop with ± standard deviation values (shown as dashes) for BMG channel 3 (standard button 3) for the test conditions shown.

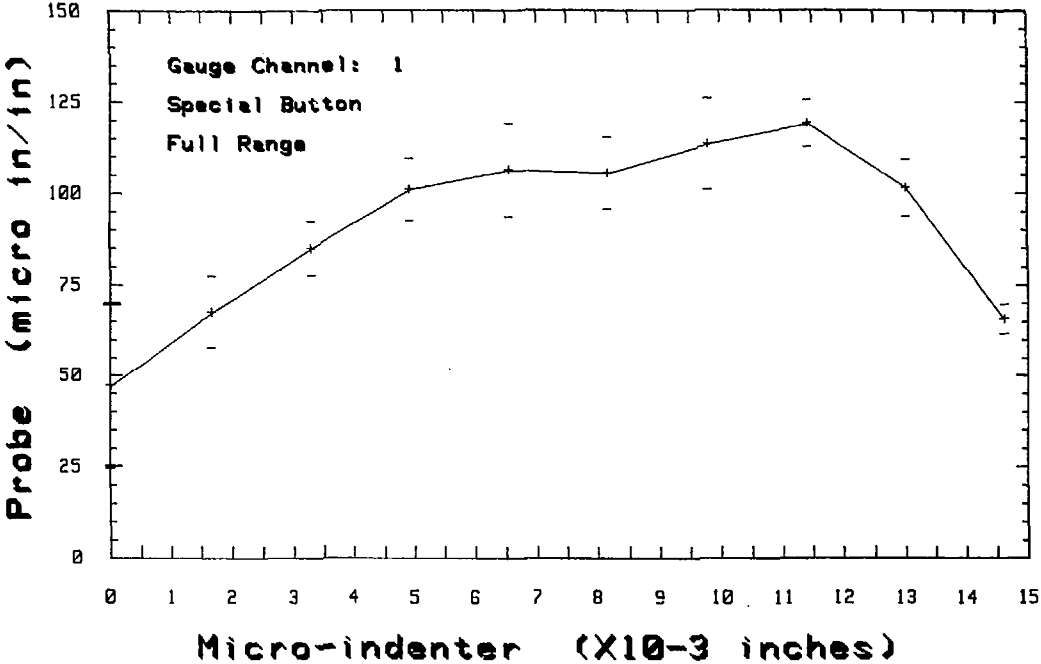

Fig. 17. Mean hysteresis loop with ± standard deviation values (shown as dashes) for BMG channel 1 for the special "fitted" button used in place of the standard O-ring supported button. Other test conditions are as shown.

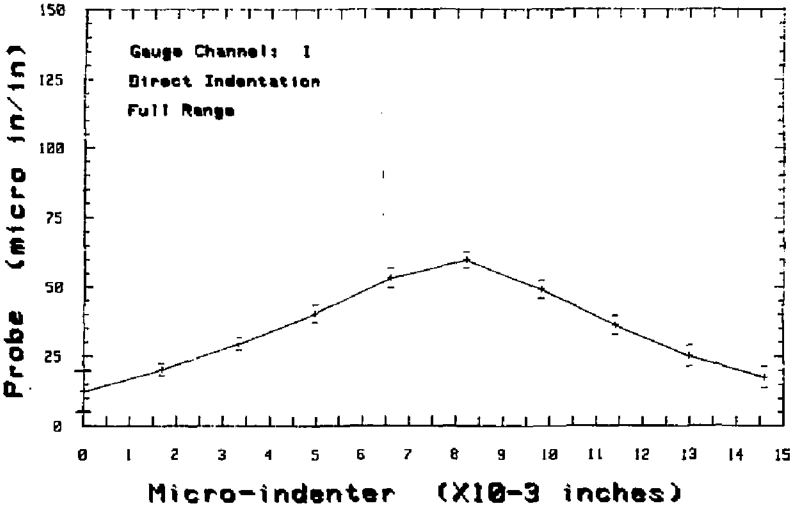

Fig. 18A. Mean hysteresis loop with ± standard deviation values (shown as dashes) for direct indention on cantilever No. 1 (C-1) BMG channel 1. Other test conditions are as shown.

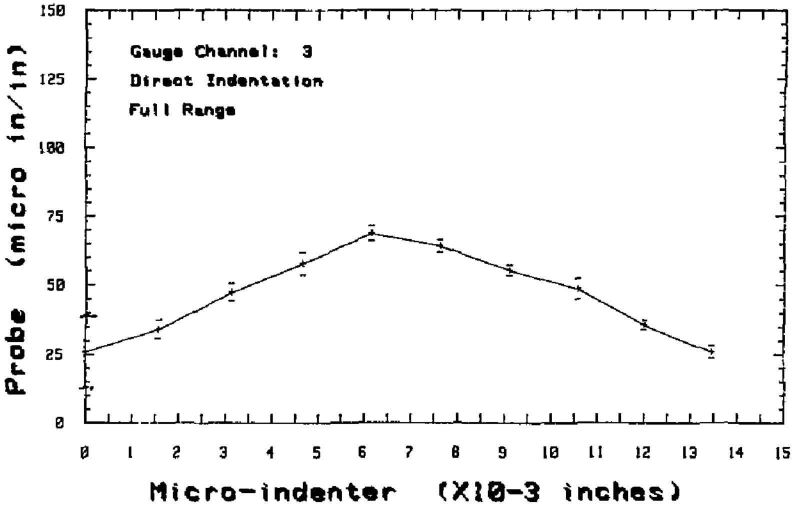

Fig. 18B. Mean hysteresis loop with ± standard deviation values (shown as dashes) for direct indention on cantilever No. 3 (C-3) BMG channel 1. Other test conditions are as shown.

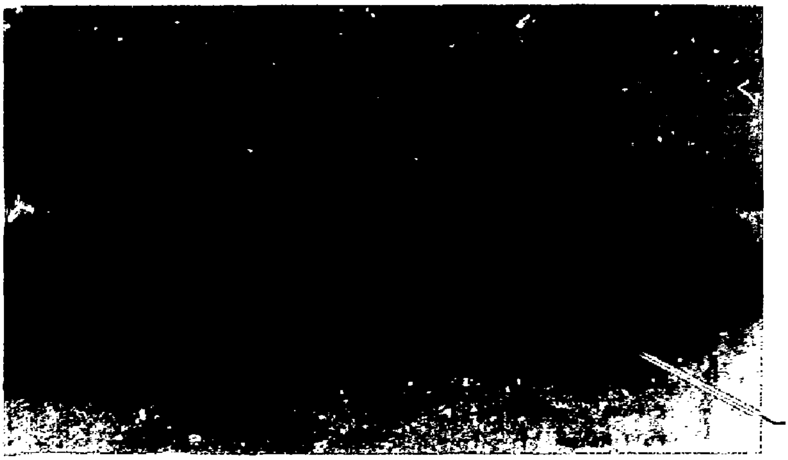

Fig. 19. Standard Be-Cu cantilevers and mounting block for the BMG showing foil strain gauge sensor, wiring with water proofing, and part of the thermistor assembly. Note the small dark spot centered on the light colored (reflective) cantilever blade located slightly to the lower right of photo center.

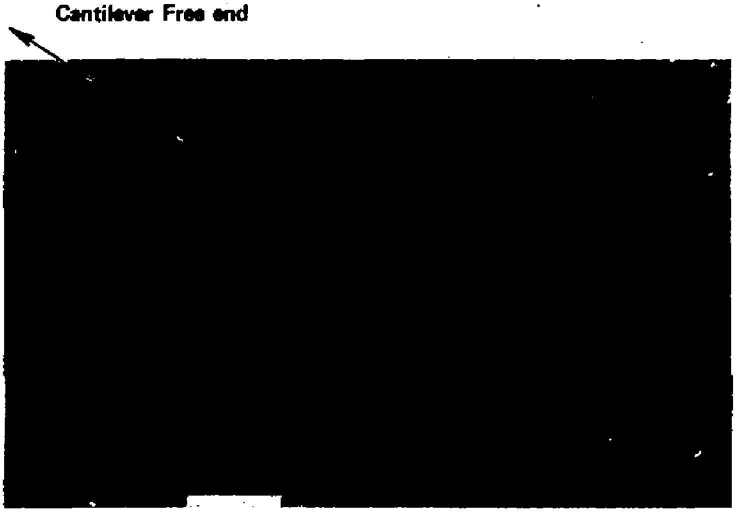

Fig. 20. Photomicrograph of the cantilever surface disturbance caused by the standard button contact pressure generated during full indention cycles. The main contact region is located in the lower right corner of the photograph. Note the arcuate ridges located to the upper left of the main contact region which is also directly toward the free end of the cantilever. Bar scale is 100 micron (0.004 in.). Compare this photo with Fig. 21 below.

Fig. 21. Photomicrograph of the cantilever surface disturbance caused by the large radius highly polished micro-indenter indention rod for comparison with the features shown in Fig. 20. Bar scale is 100 micron (0.004 in.).

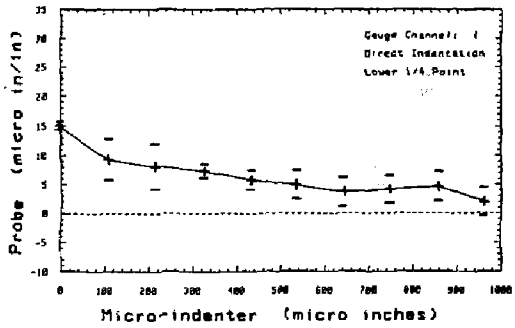

Fig. 22A. Mean hysteresis loop with ± standard deviation values for direct indention on cantilever No. 1 (C-1) BMG channel 1. Data are ±500 MS about the lower one quarter point of the BMG dynamic range.

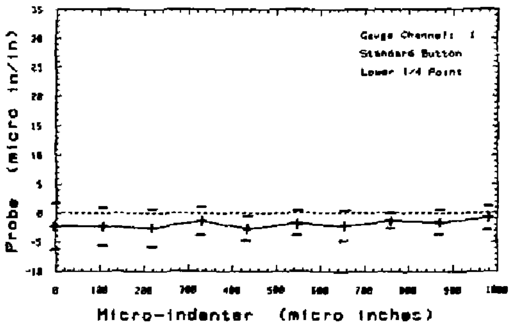

Fig. 22B. Mean hysteresis loop with ± standard deviation values for standard button on cantilever No. 1 (C-1) BMG channel 1. Data are ±500 MS about the lower one quarter point of the BMG dynamic range.

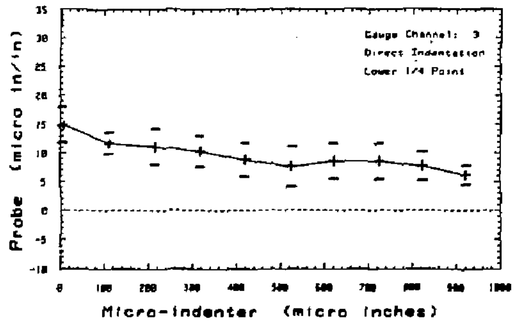

Fig. 22C. Mean hysteresis loop with ± standard deviation values for direct indention on cantilever No. 3 (C-3) BMG channel 3. Data are ±500 MS about the lower one quarter point of the BMG dynamic range.

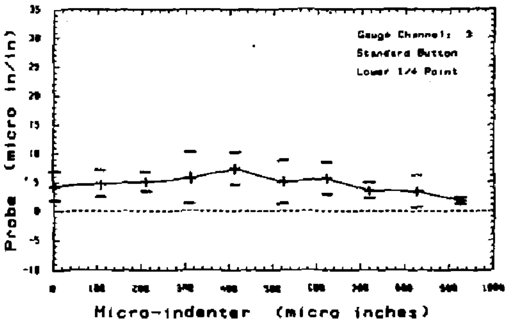

Fig. 22D. Mean hysteresis loop with ± standard deviation values for standard button on cantilever No. 3 (C-3) BMG channel 3. Data are ±500 MS about the lower one quarter point of the BMG dynamic range.

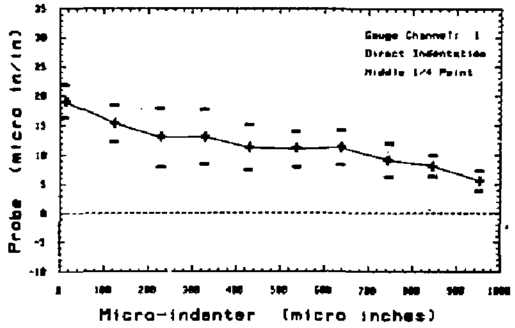

Fig. 23A. Mean hysteresis loop with ± standard deviation values for direct indention on cantilever No. 1 (C-1) BMG channel 1. Data are ± 500 MS about the middle one quarter point of the BMG dynamic range.

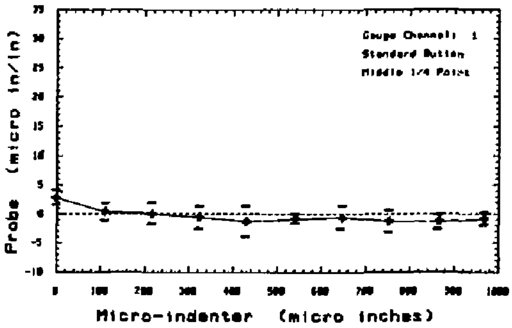

Fig. 23B. Mean hysteresis loop with ± standard deviation values for standard button on cantilever No. 1 (C-1) BMG channel 1. Data are ± 500 MS about the middle one quarter point of the BMG dynamic range.

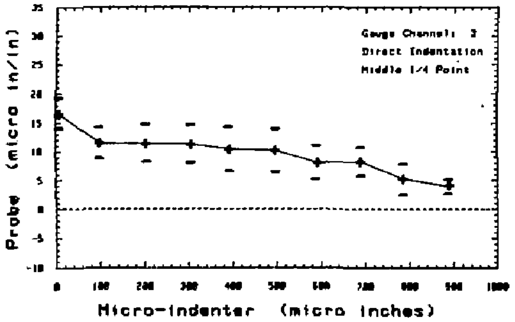

Fig. 23C. Mean hysteresis loop with ± standard deviation values for direct indention on cantilever No. 3 (C-3) BMG channel 3. Data are ± 500 MS about the middle one quarter point of the BMG dynamic range.

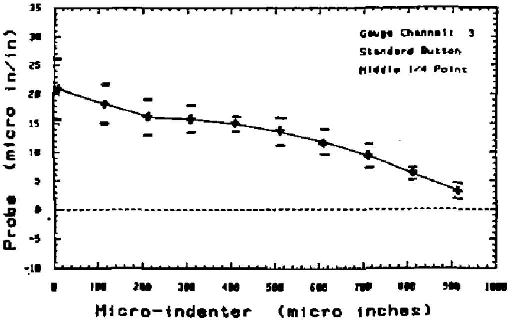

Fig. 23D. Mean hysteresis loop with ± standard deviation values for standard button on cantilever No. 3 (C-3) BMG channel 3. Data are ± 500 MS about the middle one quarter point of the BMG dynamic range.

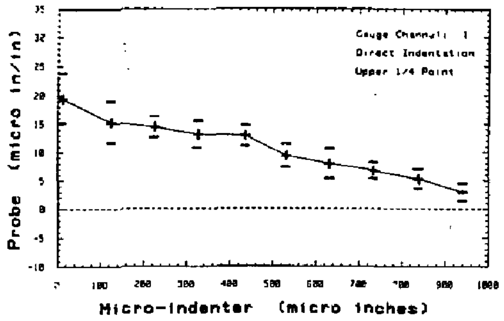

Fig. 24A. Mean hysteresis loop with ± standard deviation values for direct indention on cantilever No. 1 (C-1) BMG channel 1. Data are ± 500 MS about the upper one quarter point of the BMG dynamic range.

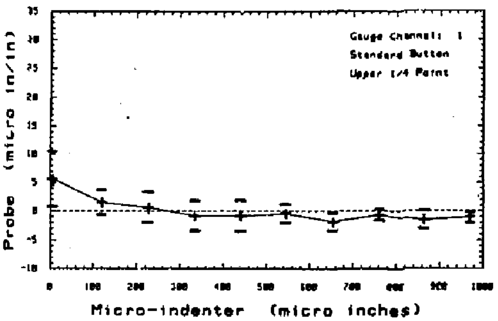

Fig. 24B. Mean hysteresis loop with ± standard deviation values for standard button on cantilever No. 1 (C-1) BMG channel 1. Data are ± 500 MS about the upper one quarter point of the BMG dynamic range.

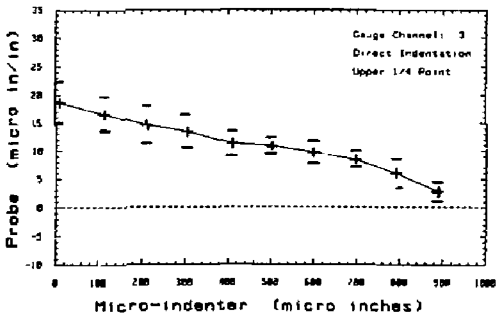

Fig. 24C. Mean hysteresis loop with ± standard deviation values for direct indention on cantilever No. 3 (C-3) BMG channel 3. Data are ± 500 MS about the upper one quarter point of the BMG dynamic range.

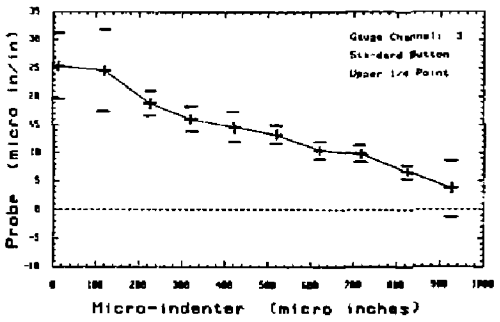

Fig. 24D. Mean hysteresis loop with ± standard deviation values for standard button on cantilever No. 3 (C-3) BMG channel 3. Data are ± 500 MS about the upper one quarter point of the BMG dynamic range.

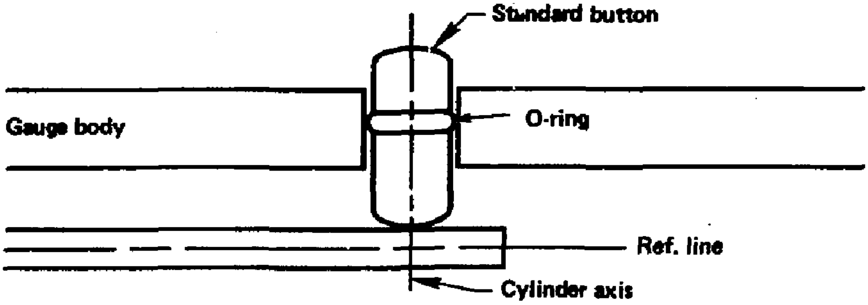

Fig. 25A. Button and cantilever initial state with button axis coaxial to cylinder and perpendicular to cantilever reference line.

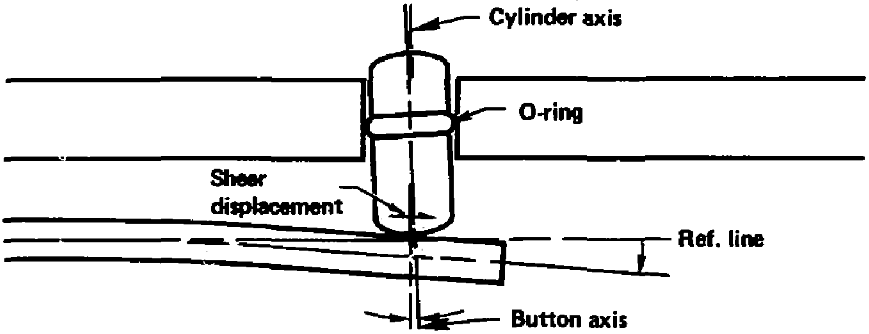

Fig. 25B. Outward directed shear displacement along button to cantilever interface and button axis rotation at full deflection.

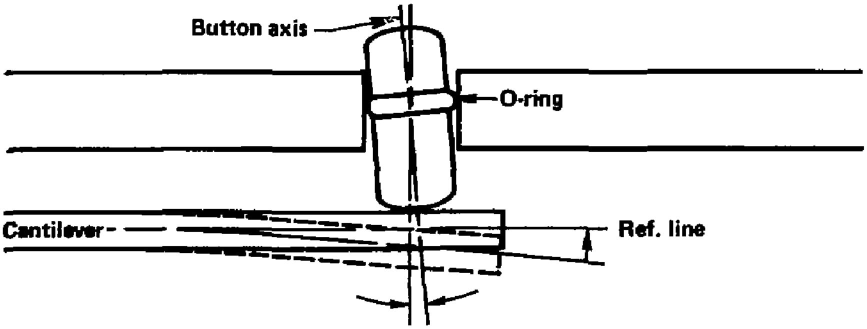

Fig. 25C. Button axis rotation at full cantilever relaxation assuming shear recovery has not yet occured.

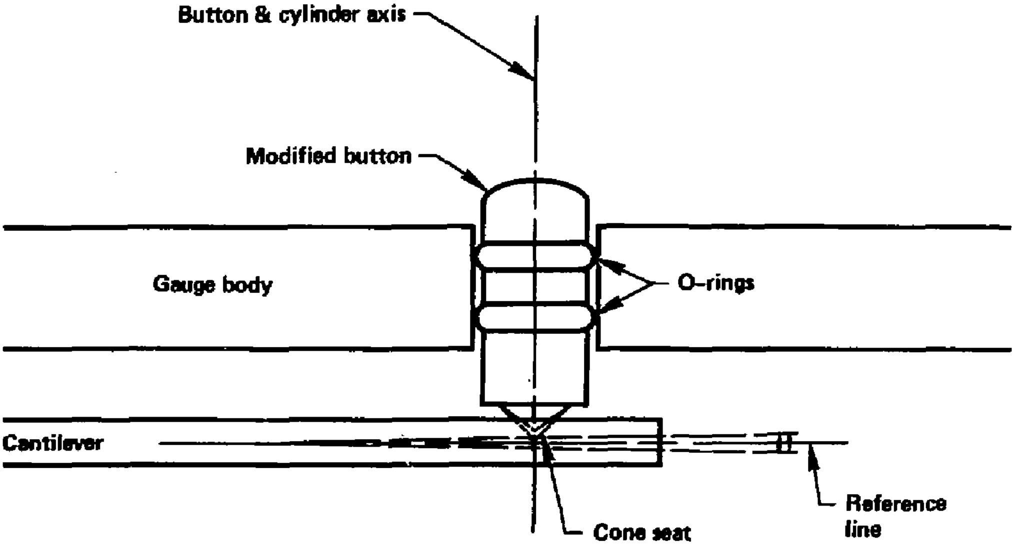

Fig. 26. Potential system improvements include double O-ring support for the button and cone-in-cone indexing system for the button-to-cantilever interface.