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A DIAMETER GAGE FOR TRUE STRESS-TRUE STRAIN MEASUREMENTS OF TENSILE SPECIMENS AT REDUCED TEMPERATURES

Ira B. Fiscus
The Research Institute
University of Dayton

Lt. James M. Carson
Air Force Materials Laboratory

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FOREWORD

This report covers research pursued by the University of Dayton Research Institute, Dayton, Ohio, initiated under Air Force Contract F33615-67-C-1087 and completed under F33615-68-C-1138, Project 7360, The Chemistry and Physics of Materials, Task 736006, Hypervelocity Impact Studies. The work was administered by the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio with Mr. Alan K. Hopkins as project engineer.

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This technical report has been reviewed and is approved.

Richard J. Vossler, Chief
Exploratory Studies Branch
Materials Physics Division
AF Materials Laboratory

ABSTRACT

The true stress-strain relationship in specimens undergoing tensile tests is being computed from a continuous record of the axial load and of two perpendicular profile traces of the specimen cross section. The displacement of two sets of opposing fingers, in contact with and constantly traversing the specimen, produces a strain-gage output on an oscilliographic record. This record is proportional to the specimen profile. The tensile tests may be conducted at a variety of low temperatures using two cryostats. The first is capable of operation at a number of specific temperatures as low as 77°K and will accommodate either round or flat specimens. The second cryostat is capable of operating at temperatures from 4°K to 77°K with the round specimens only.

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SECTION I

INTRODUCTION

True stress-true strain is a more sensitive measure of a material's metallurgical and mechanical condition than ordinary stress-strain measurements taken during a tensile test. The ordinary measurements are accurate only in the elastic regions of a material and become progressively worse as a specimen plastically deforms and begins to neck. Ordinary stress is the load on the specimen divided by the specimen's original cross-sectional area. True stress is defined as the axial load on the specimen divided by the minimum instantaneous specimen cross-sectional area:

$$\sigma = \frac{P\text{ (axial load)}}{A_i\text{ (min-instant area)}}$$

Strain has traditionally been expressed as the total change in gage length divided by the original gage length. The true strain, ϵ, is expressed as:

$$\epsilon = \int_{L_o}^{L_i} \frac{dL}{L} = \ln \frac{L_i}{L_o}$$

where an initial increment of length (Lo) has been plastically deformed to a length Li. Volume during plastic deformation is conserved. Therefore, the following relationship between specimen length and diameter may be made:

$$V = \frac{\pi D_o^2 L_o}{4} = \frac{\pi D_i^2 L_i}{4}$$

$$\frac{L_i}{L_o} = \frac{D_o^2}{D_i^2}$$

and

$$\epsilon = \ln \frac{L_i}{L_o} = 2 \ln \frac{D_o}{D_i}$$

where Do and Di refer to the original and instantaneous specimen diameters respectively. A similar relationship can be derived for specimens of rectangular cross sections.

True stress is not entirely valid upon the formation of a neck due to the flow stress in the area. Bridgeman has developed a correction equation to account for this effect[1]:

$$\sigma_C = \frac{\sigma}{(1 + 2R/A)\ln(1 + A/2R)}$$

where A is the radius of the specimen at the neck, R is the radius of the external specimen surface at the neck, σ_c is the corrected stress and σ is the ordinary true stress. This correction is a function of A/R and is small for a shallow neck.

SECTION II

DESIGN OF EQUIPMENT

A diameter gage with a position sensing device which repeatedly sweeps the specimen gage length has been designed to obtain needed diameter data. The sensing device in the gage consists of strain gage bridges which generate an electrical signal proportionate to the tensile specimen profile. The design incorporates the basic features of the Powell, Marshall, and Backofen gage[2] and also includes provisions for measuring two specimen dimensions at right angles to one another as in the Nunes, Larson equipment[3]. The diameter gage is shown mounted in testing position on a Baldwin, Model 35, 20,000-pound-capacity testing machine in Figure 1.

The specimen dimensional changes are monitored by two pair of knife edges attached to the ends of cantilevered follower arms. The knife edges contact the specimen; shifts in their relative positions indicate dimensional changes. The entire gage mechanism is mounted on a platform that can be centered and leveled to make the sweep of the knife edges parallel to the specimen axis.

The cantilevered follower arms are moved by a pair of Roh'lix linear actuators mounted on a pair of rotating parallel shafts. Rollers attached to the spring-loaded split blocks of the actuators enable the actuator assembly carrying the follower arms to traverse the rotating shaft between the split blocks as shown in Figure 1. The linear actuators are designed to move 1/2 inch per revolution of the 3/8 inch diameter driven shafts. The actuators' shafts are powered by a variable-speed DC motor, G. H. Heller Model 2 TGO. The sweep rate can be varied from 5 to 150 inches per minute by adjusting the motor speed. This helps insure an optimum amount of data under any test condition. A pair of microswitches in the drive-motor circuit controls the direction of the sweep; the location of the switches determines the the sweep length. The upper microswitch, located on the movable specimen loading rod, increases the sweep span as the specimen gage length increases under load.

The follower arms are formed from 0.370 inch diameter Pyrex glass tubing with a wall thickness of 0.070 inch to reduce thermal losses during testing at low temperatures. The tubes are bonded into stainless-steel sleeves with Eastman 910 adhesive and are attached to reduced area sections containing strain gages. Light-weight aluminum caps bonded to the lower

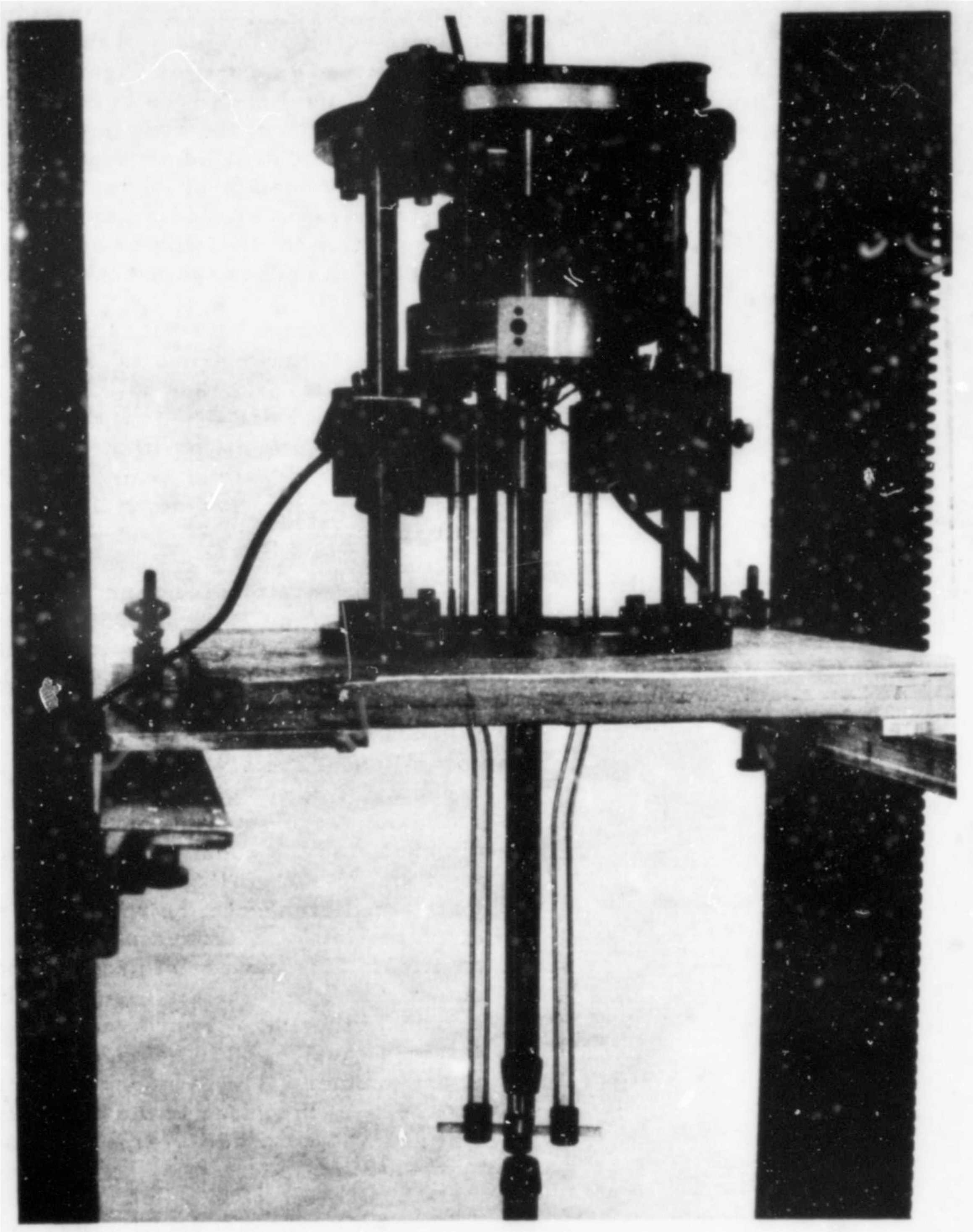

Figure 1. Diameter Gage Mounted in Testing Position

ends of the glass tubes carry 3/16 inch diameter, Kel-F plastic rods machined to knife edges at the point of contact with the specimen as shown in Figure 2. The position of the Kel-F rods is adjustable, and the position of the rods in the caps determines the preload between knife edge and the specimen. Prestressing the strain-gaged elements produces a spring action in the follower arms to hold the knife edges against the specimen.

The length of reduced cross section in the follower arms is 0.060 inches thick and 0.375 inches wide. Two pair of strain gages are attached to the reduced sections on the arms positioned 180° apart. Thus, a pair of arms forms the four-active-arm Wheatstone Bridge circuit shown in Figure 2.

The strain gages used are 120-ohm, SR 4, Type FAE-25-1256L, with a gage factor of 2.0 and physical dimensions of approximately 1/4 inch length by 1/8 inch width. As the arms move to follow a reduction in specimen area, gages 1 and 4 are strained in tension and gages 2 and 3, in compression. Thus, a linear voltage output proportional to the change in the specimen dimension is produced. The bridge balance is maintained even when the specimen is displaced laterally from a calibrated position. This movement produces no output signal because the gages, normally strained in the same sense, now are strained equally and in an opposite sense to one another. The symmetry and close proximity of the gages in the bridge circuit generates the necessary temperature compensation.

An 18-channel oscillograph, Consolidated Electrodynamics Corporation (CEC), records the strain-bridge outputs. In addition, the outputs from a precision linear potentiometer, Bourns

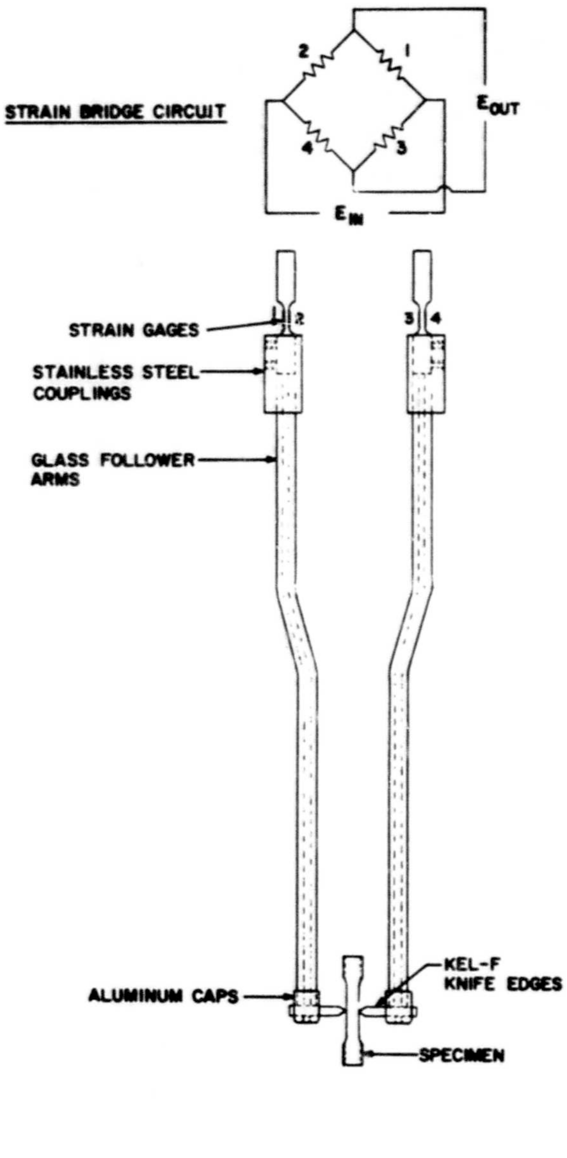

Figure 2. Follower Arms of the Diameter Gage

Model 108, attached mechanically to the load indicator of the Baldwin testing machine, indicates the specimen load. The recoiling, lower load arm operates a switch in the sweep motor control circuit as the test specimen fractures. Switch actuation stops the follower arm sweep and prevents damage to the knife edges.

A pair of 12 volt lead-acid storage batteries connected in series drives the oscillograph, used to record the strain bridge outputs and also serves as an input for the CEC bridge balance. The battery voltage is applied to a precision voltage regulator before being applied to the bridge balance. A Federal Model FTR 3300-DS power supply provides the battery charge. A schematic of the electrical components is shown in Figure 3.

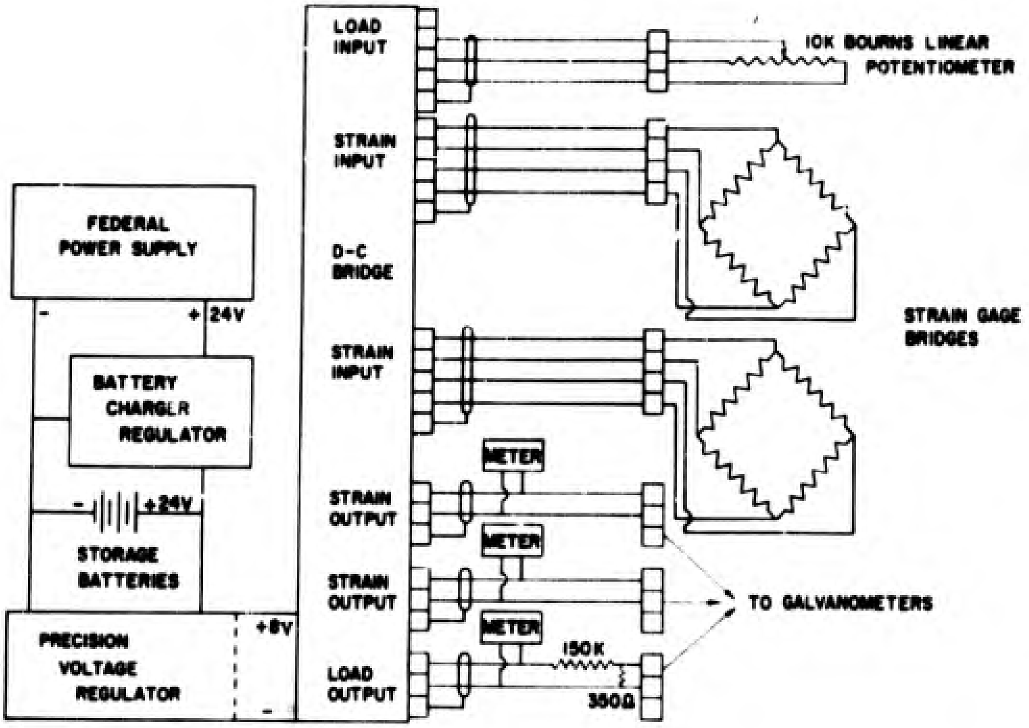

Figure 3. Schematic of Electrical Components

The maximum bridge excitation voltage of 8 volts used with an oscillograph galvanometer with a sensitivity of 0.138 millivolts per inch chart deflection results in an overall sensitivity of 60 to 1 or 7-1/2 inch chart deflection per 1/8 inch diameter change. Excitation voltage can be varied between 4 and 8 volts.

The diameter gage can be used for testing sheet materials by changing the follower arms. A specially designed set of grips, small in size and with a load capacity of 20,000 pounds, will accomodate flat specimens of thicknesses ranging from 1/32 to 1/2 inch. These grips, each made of a pair of serrated plate jaws, are clamped to the specimen with two SAE 1/2-20 bolts. Figure 4 is a photograph of the grips. All flat specimens used with this instrument have a standard gage width of 1/2 inch and gage lengths of 2-1/4 inches. The plates are pinned to a yoke attached to the load arm.

A jig has been developed to insure accurate alignment of the flat specimens mounted into the grips with the load axis. This jig is shown in Figure 5. Locating pins center the grip area of the specimens in the grip jaws as the clamping bolts are tightened.

The load arms for both flat and round specimens are fitted with ball and socket joints to allow for specimen alignment. The ball and socket joints fit into tee slots provided on the testing machine. The round specimen pull rod-internally threaded specimen grip is machined from Westinghouse 545 Alloy steel-bar stock, that was selected for its high tensile and impact strength at reduced temperatures. A 0.3 inch diameter hole, drilled in each 5/8 inch diameter load arm from the threaded grip end along the axis of the rod to a depth of approximately 5 inches, reduces heat transfer. The specimen grip in the area of the internal thread is increased in size to compensate for stress concentrations under load in this area.

A coolant bucket constructed by insulating a metal can is used for testing both round and flat specimens at 77°K with liquid nitrogen and at 195°K with a dry ice-acetone mixture. Support rods were soldered to the can, insulation applied, and the bucket wound in resin-impregnated fiber glass for structural support. The load arm is sealed into the bottom of the bucket using a wet sponge with teflon disk caps on either end. This gives an adequate seal that is flexible for alignment purposes.

A liquid helium dewar is used for testing rod specimens with 1/4 inch diameter, 1-1/4 inch gage length, and SAE 3/8-24 ends. The test chamber of the dewar is a cylinder 4-1/4 inches in diameter and 4 inches in depth. The test dewar, patterned after a vessel developed for Watertown Arsenal, was designed and built by Sulfrain Cryogenics, Inc. A cutaway view is shown in Figure 6.

Helium is transferred into the tensile dewar through a conventional insulated transfer line, enters the top of the test chamber and runs parallel to the test specimen. Helium vapor is released into the test chamber through perforations in a 3/16 inch diameter tube. A copper radiation shield surrounds the specimen and the helium transfer tube inside the test chamber. Test-chamber temperature may be controlled by regulating the rate of helium transfer into the dewar, i.e., by adjusting the pressure differential between the test dewar and helim storage dewar. Test temperatures range from approximately 4°K to 77°K.

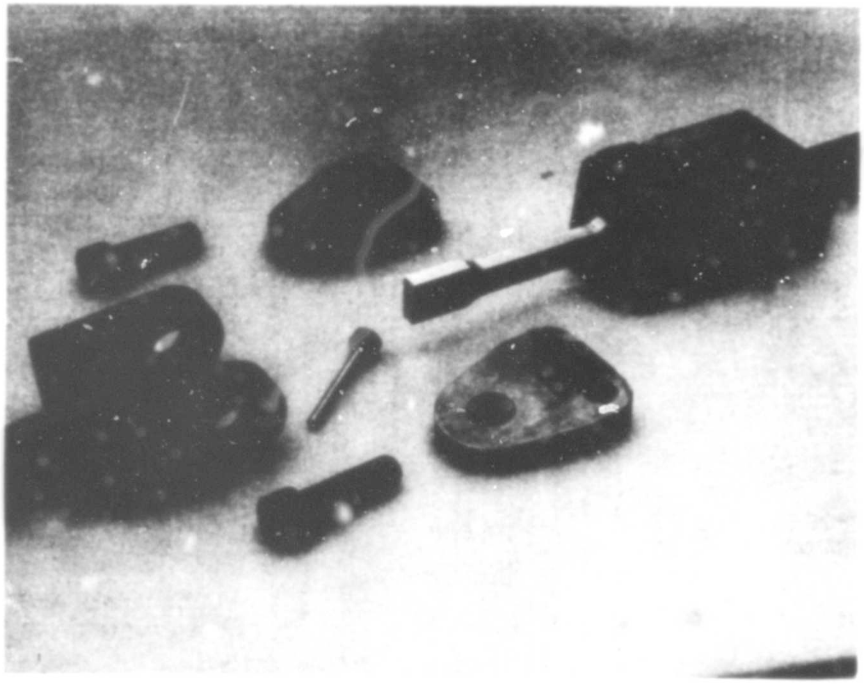

Figure 4. Flat-Specimen Grips for Use With Diameter Gage

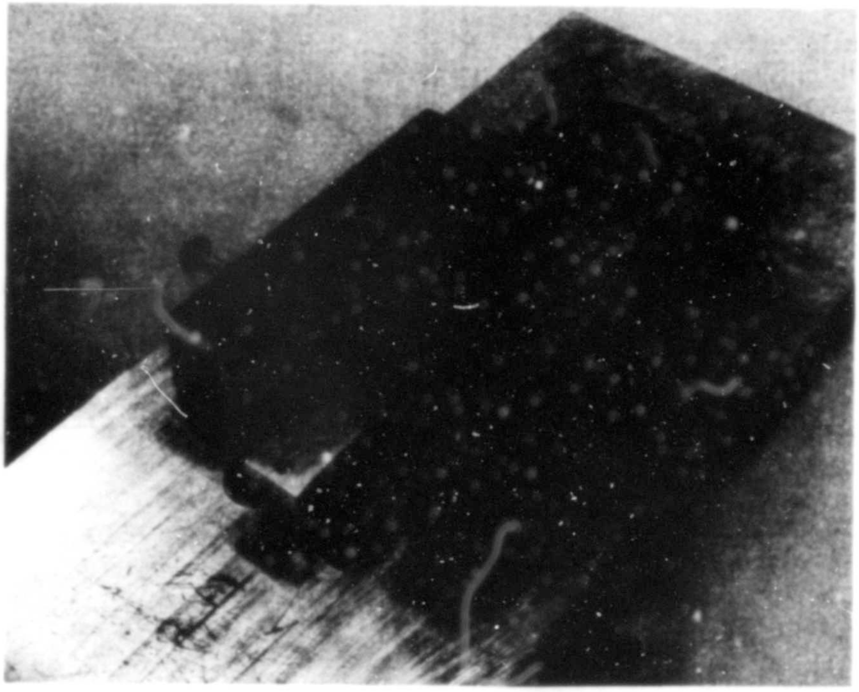

Figure 5. Jig for Alignment of Flat Specimens in Grips

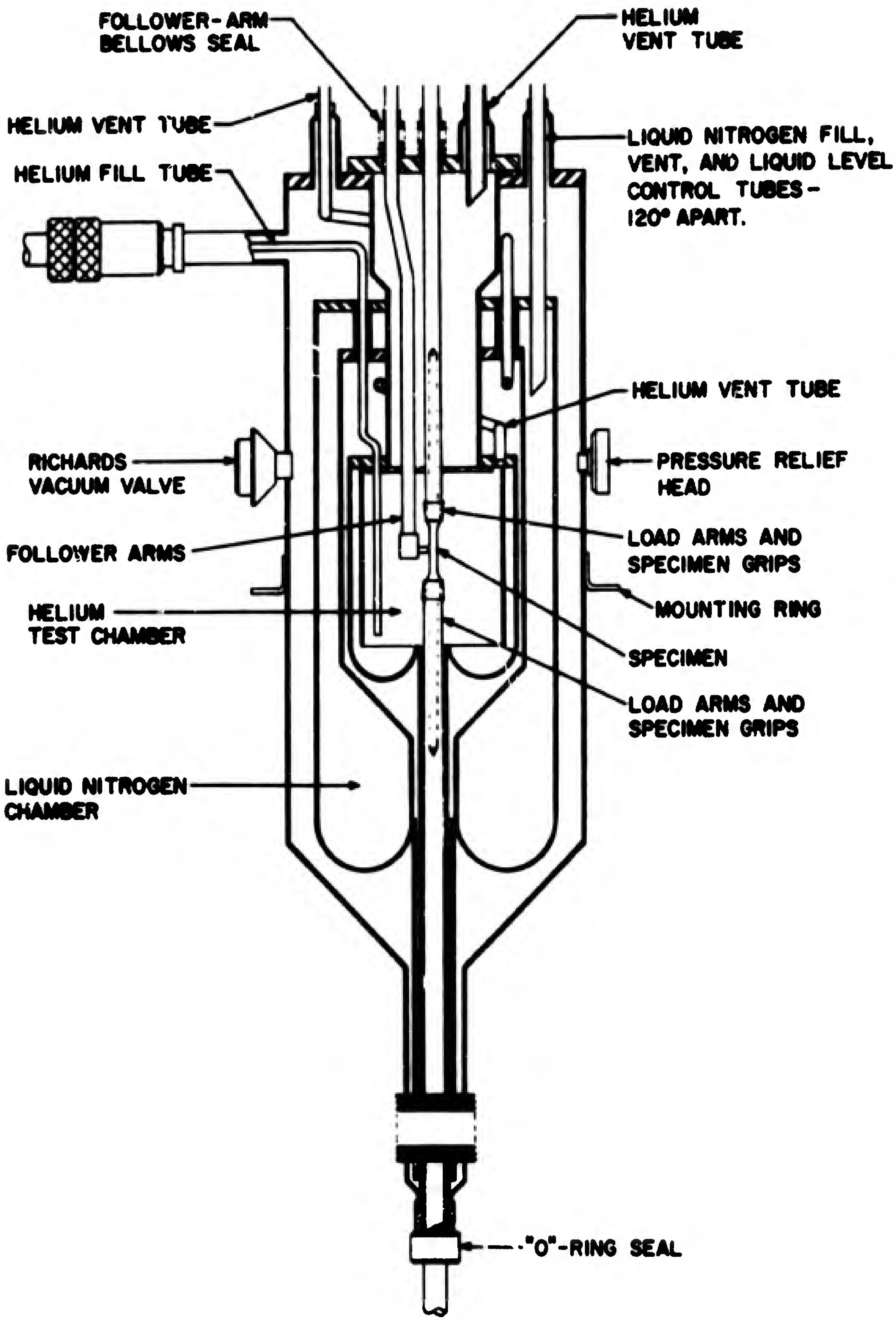

Figure 6. Cutaway View of Liquid Helium Dewar

The diameter gage is designed to be bolted directly to the top plate of the helium dewar. Each follower arm is sealed into the dewar by means of an electrodeposited nickel bellows attached to the glass rods through a nylon-tube fitting. The nickel bellows has a 0.0025 inch wall thickness, a 100,000 cycle life at 1-1/4 inch deflections, and stiffness of approximately 5 pound/inch in the axial direction and negligible for small deflections at right angles to the bellows axis. A low-melting-point sealing wax is used to attach the bellows to the dewar and the fittings to the bellows. The moveable load arm is sealed into the dewar with a brass bellows soft-soldered to the dewar and to a rubber-sealed-tube fitting. A styrofoam block surrounds the load arms and follower rods in the upper portion of the dewar to reduce heat transfer by this route.

Alignment problems are greatly simplified if only one set of knife edges is used during tests using the helium dewar. Preliminary testing at higher temperatures has indicated that round specimens undergo little appreciable distortion during testing. The openings left in the helium dewar by omitting one set of follower arms can be used to exit the leads from a temperature sensor (platinum resistance type) for monitoring test-chamber temperature.

SECTION III

METHOD OF OPERATION

A typical tensile test demonstrates the capabilities of the system as well as the more important techniques employed to obtain the maximum data and accuracy from the system. Calibrations are made, the tensile specimen is mounted, and the test is continued to specimen fracture.

A stepped specimen is used prior to a test to produce several known diameter deflections on the oscillograph record at a sweep rate equal to that used in the test. Also, the two Wheatstone bridges are balanced, and the voltage of the two bridges is adjusted in order to achieve maximum sensitivity for the measurement of the diameter of the specimen to be tested. These calibration points later are fitted to a least squares line whose slope is a measure of the system sensitivity.

The voltage applied to the load-measuring linear potentiometer is also adjusted prior to a test to insure maximum sensitivity. This adjustment is necessary because the full range of a given Baldwin load scale is not always used.

The tensile specimen is mounted, and the entire pull-rod assembly is allowed to swing as a pendulum in order to allow proper alignment and to obtain axial loading.

A dial indicator sensing the cross-head motion of the Baldwin testing machine is monitored in order to insure an initial strain rate of approximately 1%/min. This cross-head motion is recorded throughout the test on the oscillograph by means of a manually produced pulse to an otherwise unused channel every 0.005 inch during the test. Another pulse denotes various known loads throughout the test. This load pulse in conjunction with the deflection of the load line on the oscillograph at the time of the pulse is used to derive a load calibration line by fitting the points to a least squares line and obtaining the equation representing oscillograph deflection as a function of load.

A fairly slow sweep rate, approximately 6 seconds to traverse the 1-1/4 inch gage length of the specimen, produces the most accurate profile of the specimen. A large number of sweeps over the specimen is possible at this rate since the tests are typically slow, i.e., from 10 to 40 minutes. However, the use of the slow sweep rate can result in the failure to record a diameter measurement near fracture. For this reason, as the specimen necks, the positions of the two microswitches controlling the sweep distance are adjusted to shorten the length of the traverse and to thus cover only the immediate area of the neck.

A second calibration record is made following the test, again using the calibration specimen. This record insures the vailidity of the test.

SECTION IV

DATA REDUCTION

A typical tensile test provides the following data: load, two perpendicular diameter measurements, cross-head motion, and time (Appendix I). Figure 7 is a composite oscillographic output recording these data for the diameter calibration, a point during the test, and specimen fracture. The deflections produced by changes in load and diameter are measured from the bottom fixed reference line. The distance between the top and bottom fixed reference lines is monitored to account for any record dimensional changes during developing. The lighter vertical lines on the record are time marks; each denotes 1/2 second. Since the oscillograph is normally run at the rate of .6 in/sec, a convenient measure of time is that three feet of record equals approximately one minute.

The load and diameter calibration points are read as well as approximately 15 to 30 measurements of the load and the two specimen diameters at times spaced throughout the test. The readings of the two diameter traces decrease or increase slightly depending upon whether the diameter-measuring mechanism is respectively moving up or down the specimen. The strain gage output is affected by either inward or outward bowing of the glass follower

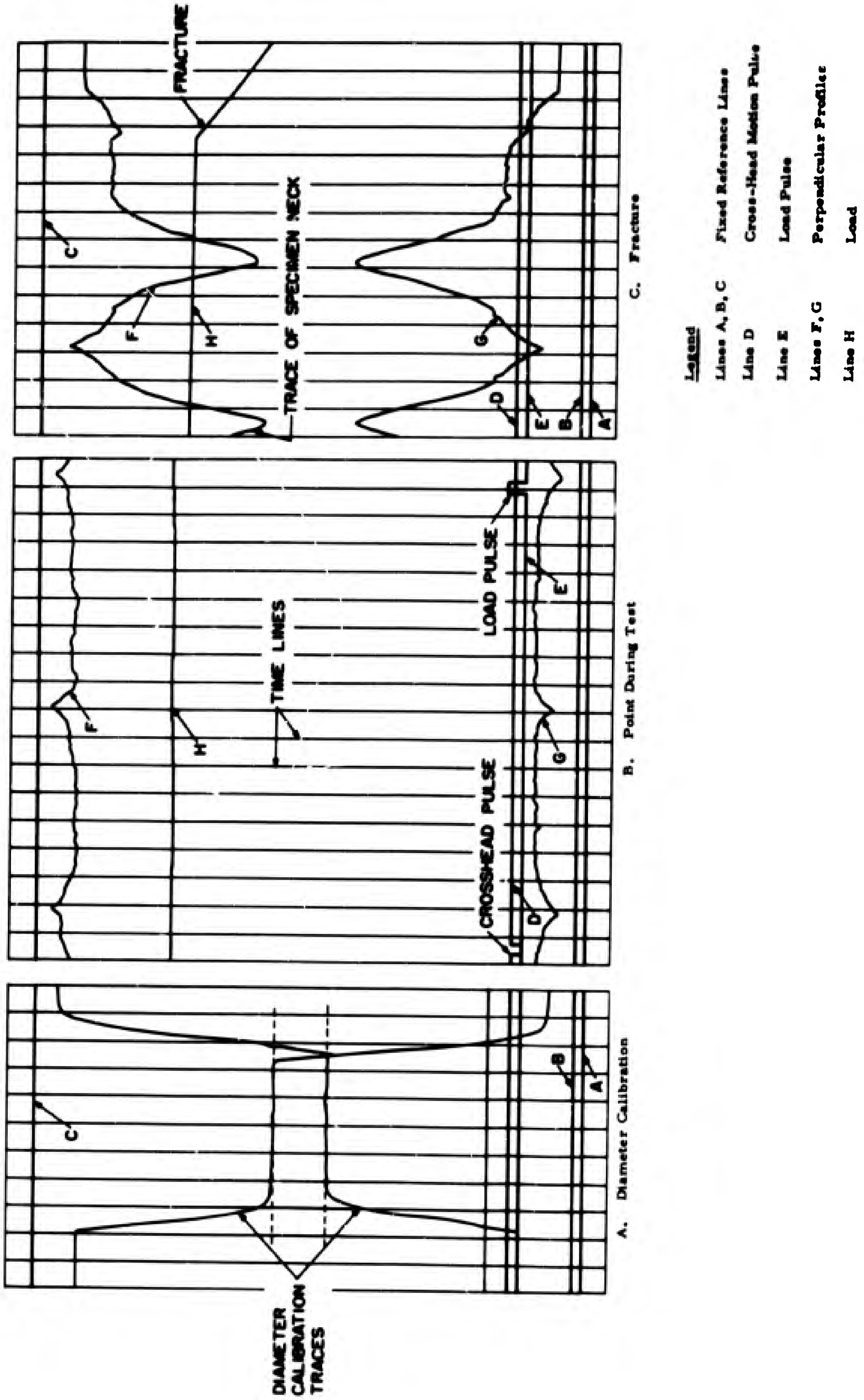

Figure 7. Oscillographic Output From a Typical Tensile Test

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rods as a result of the moment created by the friction force acting on the knife edges. Adjacent profiles of the neck always are measured and averaged to cancel the slight variation in the two diameter traces.

A computer program fits the two diameter and the load calibrations to a least squares line. The initial measured diameter of the tensile specimen and the initial deflection recorded on the oscillograph produce the origin of the line for the two diameter calibration equations. Locating the origin is required since a zero shift may result when a calibration specimen is removed and a tensile specimen inserted. The computer program also produces the standard deviation of these calibration points from the least squares lines and then uses these lines to find the two specimen diameters, the load, the area, the true stress, and the true strain at the various points read during the test. Additional points may later be measured from the oscillograph record if needed to describe accurately the true stress-true strain relationship (Appendix I).

SECTION V

ERROR ANALYSIS

The standard deviations of the calibration points from the least squares lines serve as a basis for an error analysis of the system. The standard deviation of the load-measuring system includes the nonlinearity (±.08%) of the linear potentiometer, the reading of the Baldwin load dial, and the measuring of the load deflection on the oscillograph output. A determinate error of 1%, the general limit of accuracy of the Baldwin load-measuring system, is added; this figure is considered conservative in the higher ranges of a scale.

The standard deviation of the diameter calibration points includes the measurement of the deflection on the oscillograph and the change in readings from the sensing arms moving up or down the specimen. A determinate error exists in locating the origin of the least squares diameter lines: a combination of measuring the diameter of the calibration specimen (±.0001 in. ≈ ±.04%) and of measuring the deflection of the diameter line on the oscillograph record (±.01 in. ≈ .017%).

Other possible errors exist, but have not been considered in the analysis. For instance, the cross section of a specimen at the point of fracture is not always circular. Since the two diameters measured are not necessarily the major and minor axes, the area is not calculated exactly although any error is reduced by measuring two diameters. Normally the eccentricity of this cross section is nearly zero; thus, the error is relatively small. The surface of a specimen often crinkles during a tensile test and is recorded as jitter in the two diameter traces shown in Figure 8. Thus, the diameter as well as the shape of the cross section measured are somewhat ambiguous, but the effect is small in comparison to the specimen diameter. Finally a number of factors may cause a shift in the system sensitivity. A significant shift would be reflected in the diameter calibration made after the test and invalidate a test. Analysis of test results to date indicate that none of the above factors has significantly affected the results.

Tables I through III contain the tabulated results of the error analysis. For this analysis, typical standard deviations (σ) of .025 were used for both the load and diameter calibrations and a slope of 60 was used for the diameter calibration equation. The indeterminate error or standard deviation percentage changes as load increases and diameter decreases during a test. These changes are somewhat offsetting. The tables show that the percent error of the system depends upon the load and reduction in cross-sectional area of a particular test; but, in general, the true stress of a specimen may be found within ±2 to 4%.

TABLE I
ERROR ANALYSIS OF LOAD-MEASURING SYSTEM*

t value**	Total Error (Percent)		
	500 lb. Load	1000 lb. Load	2000 lb. Load
1	3.3	2.1	1.6
2	5.6	3.3	2.1

* Determinate error = 1%; indeterminate load calibration error σ = .025 or 11.4 pound.

** Standard deviation units from the mean.

TABLE II
ERROR ANALYSIS OF DIAMETER CALIBRATION POINTS*

t value	Total Error (Percent)		
	.125 inch diameter	.200 inch diameter	.250 inch diameter
1	.4	.3	.2
2	.7	.5	.4

* Determinate error = .04 + .017% or .06%
Indeterminate error σ = .025 = .0004 in.

TABLE III
ERROR ANALYSIS OF TOTAL SYSTEM

t value	Load (pounds)	Total Error (Percent)		
		.125 inch diameter	.200 inch diameter	.250 inch diameter
1	500	4.1	3.9	3.7
2	500	7.0	6.6	6.4
1	1000	2.9	2.7	2.5
2	1000	4.7	4.3	4.1
1	2000	2.4	2.2	2.0
2	2000	3.5	3.1	2.9

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2. G. W. Powell, E. R. Marshall, and W. A. Backofen, "A Diameter Gage and Dynamometer for True Stress-Strain Tension Tests at Constant True Strain Rate", Proceedings of the American Society for Testing Materials, Vol. 55, p. 797-809, 1955.

3. John Nunes and Frank R. Larson, "A Method for Determining the Plastic Flow Properties of Sheet and Round Tensile Specimens", Watertown Arsenal Laboratories, Technical Report No. WAL-TR-III 1/1, March 1961.

APPENDIX I

COMPUTER OUTPUT - TEST OF OFHC COPPER AT 77°K

Appendix I is the computer output for a single tensile test. It contains the calibration of the two sets of diameter sensors (pg. 18, 19) and of the load (pg. 20). Finally (pg. 21), it contains the measurements at the various points during a test and the resulting data reduction and computation that produce the various true stress-strain points that are plotted in Figure 8.

TABLE IV
COMPUTER OUTPUT FOR A TENSILE TEST

```
24 POINTS - RIGHT
```

CALIBRATION[1]	DEFLECTION[2]	DEVIATION[3]
0.2491	5.5300	0.0088
0.2000	3.7600	0.0271
0.1644	2.4500	0.0137
0.1250	1.0000	-0.0013
0.1250	1.0000	-0.0013
0.1644	2.4200	-0.0163
0.2000	3.7200	-0.0129
0.2491	5.5100	-0.0112
0.2491	5.5300	0.0088
0.2000	3.7600	0.0271
0.1644	2.4600	0.0237
0.1250	1.0000	-0.0013
0.1250	1.0000	-0.0013
0.1644	2.4200	-0.0163
0.2000	3.7200	-0.0129
0.2491	5.5100	-0.0112
0.2491	5.5200	-0.0012
0.2000	3.7500	0.0171
0.1644	2.4400	0.0037
0.1250	1.0000	-0.0013
0.1250	1.0000	-0.0013
0.1644	2.4200	-0.0163
0.2000	3.7200	-0.0129
0.2491	5.5100	-0.0112

THE LEAST SQUARES LINE IS Y = A + BX WHERE
A= -3.551445 B= 36.421729
A2=[4] -4.007349

THE STANDARD DEVIATION IS 0.013773

---

1. Diameter of stepped calibration specimen.
2. Oscillograph deflection produced by strain gages.
3. Deviation from the least squares line.
4. Corrected Y intercept of least squares line (zero shift effect).

24 POINTS - LEFT

CALIBRATION	DEFLECTION	DEVIATION
0.2491	0.6600	-0.0174
0.2000	2.4700	0.0039
0.1644	3.7500	-0.0131
0.1250	5.1900	-0.0084
0.1250	5.2100	0.0116
0.1644	3.7700	0.0069
0.2000	2.4800	0.0139
0.2491	0.6900	0.0126
0.2491	0.6600	-0.0174
0.2000	2.4500	-0.0161
0.1644	3.7500	-0.0131
0.1250	5.1900	-0.0084
0.1250	5.2100	0.0116
0.1644	3.7700	0.0069
0.2000	2.4900	0.0239
0.2491	0.6900	0.0126
0.2491	0.6700	-0.0074
0.2000	2.4600	-0.0061
0.1644	3.7500	-0.0131
0.1250	5.1900	-0.0084
0.1250	5.2000	0.0016
0.1644	3.7700	0.0069
0.2000	2.4800	0.0139
0.2491	0.6800	0.0026

THE LEAST SQUARES LINE IS Y = A + BX WHERE

A= 9.752276 B= -36.430747

A2= 10.279619

THE STANDARD DEVIATION IS 0.012142

20 POINTS - LOAD

CALIBRATION[5]	DEFLECTION	DEVIATION
0.	1.3200	-0.0370
100.0000	1.4700	-0.0329
250.0000	1.7100	-0.0118
350.0000	1.8600	-0.0077
500.0000	2.1000	0.0134
600.0000	2.2500	0.0175
750.0000	2.4600	0.0086
850.0000	2.6000	0.0027
1000.0000	2.8400	0.0238
1100.0000	2.9900	0.0279
1250.0000	3.2000	0.0191
1350.0000	3.3400	0.0132
1500.0000	3.5600	0.0143
1600.0000	3.7000	0.0084
1750.0000	3.9300	0.0195
1850.0000	4.0700	0.0136
2000.0000	4.2700	-0.0053
2100.0000	4.4000	-0.0212
2250.0000	4.6100	-0.0301
2350.0000	4.7500	-0.0360

THE LEAST SQUARES LINE IS Y = A + BX WHERE

A= 1.357020 B= 0.001459

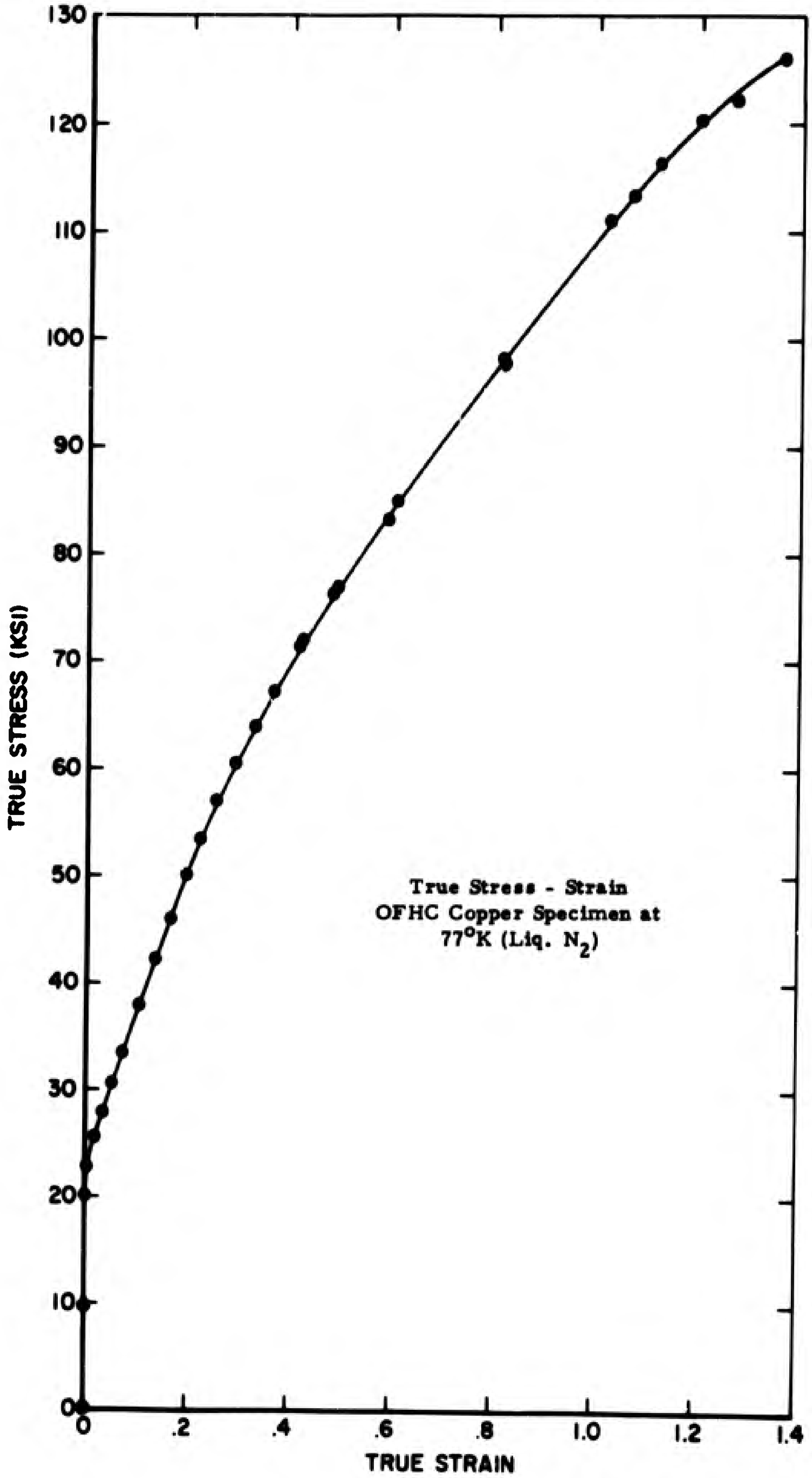
A2= 1.357020

THE STANDARD DEVIATION IS 0.021303

5. Load in pounds.

RIGHT[6]	LEFT[6]	LOAD[7]	DIA.R.[8]	DIA.L.[8]	AREA[9]	LOAD[10]	PSI[11]	Q[12]
5.140	1.110	1.320	0.2512	0.2517	0.04965	-20.4	-410.3	0.00218
5.160	1.110	2.060	0.2517	0.2517	0.04976	486.8	9783.1	0.00000
5.180	1.090	2.800	0.2522	0.2522	0.04997	993.9	19888.7	-0.00436
5.130	1.130	2.980	0.2509	0.2512	0.04949	1117.3	22577.8	0.00546
5.070	1.180	3.140	0.2492	0.2498	0.04889	1226.9	25094.6	0.01753
5.000	1.270	3.310	0.2473	0.2473	0.04804	1343.5	27967.7	0.03521
4.900	1.340	3.460	0.2446	0.2454	0.04713	1446.3	30684.2	0.05417
4.810	1.410	3.600	0.2421	0.2435	0.04629	1542.2	33314.7	0.07218
4.670	1.570	3.810	0.2382	0.2391	0.04474	1686.1	37691.3	0.10640
4.540	1.710	4.010	0.2347	0.2352	0.04336	1823.2	42051.1	0.13770
4.420	1.820	4.180	0.2314	0.2322	0.04220	1939.7	45965.3	0.16475
4.290	1.970	4.320	0.2278	0.2281	0.04081	2035.6	49879.2	0.19819
4.160	2.060	4.450	0.2242	0.2256	0.03974	2124.7	53470.1	0.22487
4.050	2.200	4.550	0.2212	0.2218	0.03853	2193.3	56917.7	0.25561
3.920	2.360	4.630	0.2177	0.2174	0.03716	2248.1	60495.3	0.29188
3.780	2.490	4.700	0.2138	0.2136	0.03591	2296.1	63946.7	0.32625
3.620	2.640	4.730	0.2094	0.2097	0.03449	2316.6	67166.1	0.36646
3.440	2.840	4.770	0.2045	0.2042	0.03280	2344.0	71474.6	0.41687
3.450	2.870	4.770	0.2048	0.2034	0.03271	2344.0	71667.8	0.41955
3.180	3.080	4.760	0.1973	0.1976	0.03063	2337.2	76305.3	0.48519
3.200	3.160	4.760	0.1979	0.1954	0.03037	2337.2	76948.6	0.49355
2.820	3.450	4.700	0.1875	0.1875	0.02760	2296.1	83190.8	0.58934
2.800	3.550	4.700	0.1869	0.1847	0.02712	2296.1	84675.0	0.60699
2.120	4.220	4.490	0.1682	0.1663	0.02198	2152.2	97924.9	0.81710
2.120	4.220	4.500	0.1682	0.1663	0.02198	2159.0	98236.7	0.81710
1.450	4.760	4.240	0.1501	0.1515	0.01786	1980.8	110891.1	1.02442
1.400	4.950	4.170	0.1485	0.1463	0.01706	1932.8	113306.4	1.07045
1.180	5.040	4.080	0.1424	0.1438	0.01609	1871.2	116306.7	1.12905
1.070	5.280	3.990	0.1394	0.1372	0.01503	1809.5	120425.6	1.19733
0.830	5.380	3.850	0.1328	0.1345	0.01403	171 .5	122141.0	1.26598
0.670	5.650	3.710	0.1284	0.1271	0.01282	1617.6	126200.5	1.35631

6. Oscillograph reading of right and left bridge.
7. Corresponding oscillograph load reading.
8. Two specimen diameters computed from least squares line and oscillograph reading.
9. Instantaneous area of specimen.
10. Load computed from least squares line and oscillograph reading.
11. True stress of specimen.
12. True strain of specimen.



130
120
110
100
90
80
70
60
50
40
30
20
10
0
TRUE STRESS (KSI)
0
.2
.4
.6
.8
1.0
1.2
1.4
TRUE STRAIN
True Stress - Strain
OFHC Copper Specimen at
77°K (Liq. N2)

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13. ABSTRACT

The true stress-strain relationship in specimens undergoing tensile tests is being computed from a continuous record of the axial load and of two perpendicular profile traces of the specimen cross section. The displacement of two sets of opposing fingers, in contact with and constantly traversing the specimen, produces a strain-gage output on an oscillographic record. This record is proportional to the specimen profile. The tensile tests may be conducted at a variety of low temperatures using two cryostats. The first is capable of operation at a number of specific temperatures as low as 77°K and will accommodate either round or flat specimens. The second cryostat is capable of operating at temperatures from 4°K to 77°K with the round specimens only.

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