MATERIALS FOR POTASSIUM LUBRICATED JOURNAL BEARINGS

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FOREWORD

The work described herein is being performed by the General Electric Company under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-2534. Its purpose, as outlined in the contract, is to evaluate materials suitable for potassium lubricated journal bearing and shaft combinations for use in space system turbogenerators and, ultimately, to recommend those materials most appropriate for such employment.

R. G. Frank, Manager, Physical Metallurgy, Materials and Processes, is administering the program for the General Electric Company. L. B. Engel, Jr., T. F. Lyon, W. H. Hendrixson and B. L. Moor are directing the program investigations. The design for the friction and wear testers was executed by H. H. Ernst and B. L. Moor.

I. INTRODUCTION

The program reviewed in this thirteenth quarterly report, covering activities from April 22, 1966 to July 22, 1966, is performed under the sponsorship of the National Aeronautics and Space Administration. Its purpose is to evaluate materials suitable for potassium lubricated journal bearing and shaft applications in space system turbogenerators operating over a 400° to 1600°F temperature range. The critical role of bearings in such systems demands the maximum reliability attainable within today's state-of-the-art. Achieving this reliability requires an interdisciplinary approach employing the best mechanical designs of journal bearings combined with the selection of the optimum materials to serve as the structural members. Satisfying this latter requirement constitutes the aim of this program.

A number of investigators have conducted studies in this field and their contributions have advanced the state-of-the-art considerably (Section V, Ref. 1 Although their work is significant, there are no common criteria for a comparison of the existing data. Therefore, establishing a unified approach to the development and evaluation of materials for potassium lubricated bearing application is deemed essential. The program involves a comprehensive investigation of material properties adjudged requisite to reliable journal bearing operation in the proposed environment. This includes: 1) corrosion testing of individual materials and potential bearing couples in potassium liquid and vapor, 2) determination of hot hardness, hot compressive strength, modulus of elasticity, thermal expansion and dimensional stability characteristics, 3) wetting tests by potassium and 4) friction and wear measurements of selected bearing couples in high vacuum and in liquid potassium.

In cooperation with the cognizant NASA Technical Manager, 14 candidate materials were selected (Table I) from a compilation of existing data on available materials. The materials reviewed fall into four broad categories:

- Superalloys and refractory alloys with and without surface treatment.
- Commercial metal bonded carbides
- Refractory compounds such as stable oxides, carbides, borides and nitrides
- Cermets based on the refractory metals and stable carbides

Each material is procured from appropriate suppliers to mutually acceptable specifications and subsequently, is subject to chemical, physical and metallurgical analyses to document its characteristics before utilization in the program. After the documentation of processes and properties, the candidate materials undergo corrosion, dimensional stability, thermal expansion, compression and hot hardness testing. Considering the bearing material

requirements and the information obtained on the candidate bearing materials which were subjected to both potassium and non-potassium testing, seven materials combinations listed below were selected in cooperation with the NASA Technical Manager. Potassium corrosion and wetting tests and friction and wear measurements in high vacuum and liquid potassium have proceeded with these combinations.

Rotating Disc	Stationary Rider
*1. Grade 7178	Mo-TZM
2. Mo-TZM	Grade 7178
*3. Grade 7178	Grade 7178
4. Carboloy 907	Mo-TZM
5. Carboloy 907	Carboloy 907
6. TiC+10%Cb	Mo-TZM
*7. TiC+10%Cb	TiC+10%Cb

Those materials combinations marked with an asterick (*) were selected for friction and wear testing in both liquid potassium and high vacuum. Where significant differences in hardness exist, the softer material, i.e., Mo-TZM alloy, was selected as the rider material (stationary specimen) to facilitate wear-in during testing in liquid potassium. Couple No. 2 was selected to determine what affect a hard rider material would have on the wear pattern of a soft disc material in comparison with the reverse combination.

The decision to place considerable emphasis on the refractory metal bonded carbides was based on their excellent stability at the higher temperatures. Also, it has been shown in recent friction and wear tests and full scale bearing tests, using liquid potassium as a lubricant, that the hard/hard combinations appear to be superior to the hard/soft combinations. The superiority of the hard/hard combination over the hard/soft combination is believed to be due to the tendency of wear debris from the hard material to become imbedded in the soft material of the hard/soft combination resulting in a cutting action. Therefore, emphasis is being placed on the hard/hard combinations.

The ultimate product of this program will be a recommendation, substantiated with complete documentation, of the material or materials which have the greatest potential for use in alkali metal journal bearings in high speed, high temperature rotating machinery for space applications.

II. SUMMARY

During the thirteenth quarter of the program, the topics abstracted below were covered and the results presented in this report.

Eight friction and wear tests were conducted in the high vacuum friction and wear tester. The candidate bearing material combinations that were tested were: Mo-TZM alloy vs Carboloy 907, Carboloy 907 vs itself, Grade 7178 vs Mo-TZM alloy, and Mo-TZM alloy vs TiC+10%Cb. Tests were conducted at RT, 400°, 800°, and 1200°F, at pressures of 10^{-9} torr, and speeds of 800 SFM. The average coefficient of friction values for these materials are high with values generally exceeding 0.8. The coefficient of friction for Carboloy 907 vs itself at 1200°F and a Hertzian stress of 370,800 psi was 0.57. Although all the data are not fully evaluated, there appears to be a trend of decreasing friction with interfacial temperature.

Four friction and wear tests were completed successfully in liquid potassium. The candidate bearing materials that were tested were: Mo-TZM alloy vs Grade 7178, Grade 7178 vs itself, and TiC+10%Cb vs itself. The tests were conducted at 400° and 800°F and at speeds of 1000 SFM. Chemical analyses of the potassium sampled before and after the tests were conducted indicated an oxygen content of less than 10 ppm. The average coefficient of friction for TiC+10%Cb vs itself at 400°F was exceptionally low with a calculated value of 0.07. In this case, the coefficient of friction decreased from 0.15 to 0.04 over the 60-minute test period. A test load of 2.8 lbs to produce a Hertzian stress of 300,000 psi had been applied.

All of the elevated temperature compression tests of 13 candidate bearing materials have been completed and the results reported. The tests were conducted in a vacuum of 10^{-6} torr and at temperatures of 800°, 1200°, and 1600°F. The elastic limit was exceeded for the following materials at the indicated temperatures: at RT and above, Mo-TZM, tungsten, Star J, Carboloy 907, Carboloy 999, and Zircoa 1027 (ZrO_2); at 800°F and above, Grade 7178; at 1200°F and above, TiC+5%W, TiC+10%Mo, TiC+10%Cb, and TiB_2; at 1600°F, TiC. Lucalox (Al_2O_3) was the only material to exhibit elastic behavior to fracture at all test temperatures.

III. TEST PROGRAM

A. COMPRESSION PROPERTIES

All compression tests have been completed on specimens of thirteen candidate bearing materials at temperatures of 800°, 1200°, and 1600°F. Depending on the type of material that was being tested, a strain rate of 0.005 inch/inch/minute was maintained through the 0.2% offset or until fracture occurred. No attempt was made to control the strain rate beyond the 0.2% offset due to the difficulty in applying the load at a uniform rate as the specimen deformed plastically. The valve setting on the testing machine to achieve a 0.005 inch/inch/minute strain rate in the elastic region was left unchanged for the duration of the test. The modulus of elasticity was calculated from the elastic portion of the stress-strain curve which was obtained by means of an LVDT/extensometer system. The extensometer was attached directly to the specimens during all tests. Values for unit strain were based on an effective gauge length which is equal to the measured gauge length + 1.44 x wall thickness. The effective gauge length was determined experimentally using an instrumented Mo-TZM alloy specimen[2]. Further details of the facilities, testing procedures, and calibration methods used for the LVDT/extensometer system and load cell are described in Quarterly Progress Reports No. 7[3] and 11[2].

The elevated temperature compression data along with the data obtained previously at room temperature are reported in Table II and presented in Figures 1 to 13. From these data it is readily apparent that the strength of the Carboloy 999 specimens at room temperature and the strength of Carboloy 907 and Grade 7178 specimens at room temperature and 800°F exceeded the 115,000-lb limit of the Baldwin testing machine. A 115,000-lb load on the specimens produces a compressive stress in excess of 600,000 psi. In the cases where considerable plastic flow was observed and fracture did not occur within the load limit of the tesing machine, the tests were terminated at a total strain of 5%. Tests were terminated at a total strain of 5% for the following materials: Mo-TZM alloy (all test temperatures), unalloyed tungsten (800°, 1200°, and 1600°F), and Carboloy 907 (1600°F). The 1200°F and 1600°F tests for Carboloy 999 were arbitrarily terminated at 3.3% and 2% total strain respectively.

Examination of the load-strain curves in Appendix A, Figures A-1 to A-13, revealed the existance of an elastic limit for each of the following materials at the indicated temperatures:

Material Class	Candidate Material	Indicated Temperature at Which Material Deviated from Elastic Behavior			
		RT	800°F	1200°F	1600°F
A. Nonrefractory Metals and Alloys	Star J	X	X	X	X

	Candidate Material	Indicated Temperature at Which Material Deviated from Elastic Behavior			
		RT	800°F	1200°F	1600°F
B. Refractory Metals and Alloys	Mo-TZM Alloy	X	X	X	X
	Tungsten	X	X	X	X
C. Fe-Ni-Co Bonded Carbides	Carboloy 907	X	X	X	X
	Carboloy 999	X	X	X	X
D. Refractory Compounds - Oxides, Carbides, Borides	Lucalox (Al_2O_3)	-	-	-	-
	Zircoa 1027 (Z_rO_2)	X	X	X	X
	TiC	-	-	-	X
	TiB_2	-	-	X	X
E. Refractory Metal Bonded Carbides	TiC+5%W	-	-	X	X
	TiC+10%Mo	-	-	X	X
	TiC+10%Cb	-	-	X	X
	Grade 7178	-	X	X	X

All of the specimens tested at a lower temperature than the temperature indicated in the above tabulation exhibited elastic behavior until fracture occurred. The maximum elastic strain and the total strain at fracture or termination of the test for each material are given in Table III. Deviation from elastic behavior of the Carboloy, Grade 7178, and Zircoa 1027 materials at the lower temperatures is associated with grain boundary slip due to the presence of weaker cobalt-rich and molybdenum-rich phases in the grain boundaries of the Carboloy and Grade 7178 material, respectively, and weaker, secondary phases formed by the additions of stabilizing elements in the Zircoa 1027 material. However, since atomic bonding in the refractory metal bonded carbides is believed to be metallic in nature, plastic flow of the pure carbide crystals should be expected to occur at some temperature. The inflection in the strength curve for Zircoa 1027 may be associated with crystallographic transformation.

Of the refractory metal bonded TiC materials, the 10% columbium addition had the most apparent effect on the deformation behavior of a TiC compact. The TiC+10%Cb material was the only solid state bonded TiC containing body to exhibit a 0.02 % deviation from elastic behavior at a temperature as low as 1200°F. The TiC specimen exhibited elastic behavior until fracture at all temperatures except 1600°F. Lucalox (Al_2O_3) was the only material to exhibit elastic behavior to fracture at all test temperatures.

In order to observe the initiation of failure, attempts were made to terminate the test just prior to fracture. This was accomplished by closely watching the load/strain plot as the specimens were loaded and releasing the load at the appropriate time. Post-test examination of the specimens in which this technique was tried revealed the inception of failure in three of the specimens that were tested at 1200°F: Carboloy 907 (MCN 1036-G-6) after 3.2% total strain (2.77% plastic strain), Carboloy 999 (MCN 1035-G-5) after 3.3% total strain (2.89% plastic strain), and TiC+5%W (MCN 1043-G-2) after 0.74% total strain (0.06% plastic strain) and one of the specimens that was tested at 800°F: Zircoa 1027 (MCN 1040-G-7) after 1.6% total strain (1.09% plastic strain). Photographs of the specimens showing longitudinal cracks in the gauge section are presented in Figures 14 to 17. Initiation of failure also was observed in the unalloyed tungsten specimens tested at 1600°F (MCN 1038-G-8) and at 1200°F (MCN 1038-G-7) after termination of the test at 5% total strain, shown in Figure 18. The pattern of cracking in the tungsten specimen is very similar to the shape of the pieces from a similar specimen that fractured at room temperature, Figure 19. Photographs of specimens that did not fail, showing the extent of plastic deformation, are presented in Figures 20 thru 26.

B. FRICTION AND WEAR IN HIGH VACUUM

The high vacuum friction and wear test program was completed during this report interim. The final eight friction and wear tests were conducted at room temperature, 400°, 800°, and 1200°F, at speeds of 800 SFM, and at initial pressures in the 10^{-9} torr range. A total of 65 tests were conducted in the program.

The results of the test are summarized in Table IV. Coefficient of friction values were high in all tests and, again, it is evident that a high wear rate results when the relatively soft Mo-TZM alloy is utilized as the rotating disc material in combination with a hard rider material. Short testing times of less than 60 minutes is the result of high friction between the specimens which leads to slippage in the magnetic drive. The static breakaway torque of the tester is regularly measured at about 50 in.-lb, allowing a friction force of 25 lbs at the specimen contact point two inches from the center of rotation. Although it is strongly believed that the short test times indicate welding of the specimens, the average friction coefficients during the period of rotation are reasonable. In several tests, a distinct exponential rise in friction force can be detected just before slippage. Abnormally high wear and large increases in specimen temperatures are invariably observed when slippage occurs. More significance should be attached to the short testing times than to the coefficients of friction.

Sanborn traces showing the changes in friction coefficient with time, photographs of the test specimens illustrating wear patterns, weight change data, and surface finish measurements are presented in Appendix B. No attempt will be made to present an analysis and interpretation of the test data until all of the test results have been thoroughly evaluated. All of the raw test data have been resolved and all of the friction and wear results have been calculated and the values verified by recalculation on a computer.

C. FRICTION AND WEAR IN LIQUID POTASSIUM

Test Loads - The high temperature compression data reported in Table II of this report were utilized in computing the desired test loads as percentages of the 0.2% compressive yield strength or of the ultimate compressive strength. The computation was carried out on a computer. The results, shown in Table V, will be used during all friction and wear testing in liquid potassium.

Test Assembly KII - The liquid potassium friction and wear tester was assembled for the first series of tests to be conducted in liquid potassium. Incorporated in the assembly build-up were 7207 angular contact ball bearings with machined retainers coated with a mixture of 62%BaF_2+38%CaF_2. The coating was applied to the retainers at NASA-Lewis Research Center.

After appropriate bakeout cycles, the system was evacuated to a pressure of 1.5×10^{-6} torr using a getter-ion pump. Subsequently, the tester was pressurized with argon to a pressure of 15.0 psig and purified potassium was transferred from the facility hot trap through a five-micron filter to the Cb-1Zr alloy sump to a level of 0.125 inch below the lower specimen holder. Prior to transferring the potassium to the sump, the potassium was hot trapped for 50 hours at 1200°F.

Using calibration and test procedures decribed in Quarterly Progress Report No. 12[4], the following test was conducted in liquid potassium:

Assembly No.	Test No.	Test Material Rider	Test Material Disc	Temp, °F	Speed, SFM	Load
KII	104K10K	Mo-TZM	7178	400	1000	K(0.081 lb)

The external heating elements attached to the inner wall of the double wall Type 304 SS test chamber, which surrounds the Cb-1Zr alloy sump, were used to heat the potassium to the test temperature. The shaft was rotated to a speed of 955 RPM (1000 SFM test speed) and after a period of 14 minutes to permit the test specimens to reach the test temperature, the Mo-TZM alloy rider specimen located in the calibrated upper loading arm was permitted to contact the rotating Grade 7178 disc specimen for a 10 minute run-in period. The test temperature was measured at the following four locations:

Chromel/Alumel Thermocouple Location	Measured Temp., °F
Thermowell in upper loading arm in contact with rider specimen	370
Thermowell protruding in potassium spray over lower disc specimen	395
Thermowell in potassium liquid, 0.375 inch from liquid level	408
Thermowell at bottom of Cb-1Zr alloy sump	410

After the run-in period, the test load was applied and the test proceeded for 60 minutes. The test results are summzrized in Table VI. The average coefficient of friction for the Mo-TZM alloy vs Grade 7178 combination was calculated to be 0.25.

A positive argon pressure was maintained in the tester and within the surrounding argon atmosphere of the environmental tank and the flange over the lower loading arm port (containing the thermowells for measuring the temperature of the potassium in the sump and over the lower disc specimen) was removed and replaced with a loading arm. Further leak checking at this time uncovered a leak in the diaphragm located at the top of the tester and in the main Wheeler flange. Although the leak in the diaphragm was repair welded successfully, it was decided not to replace the copper gasket in the main flange at this time. To do so would require complete disassembly and cleaning the residual potassium from the tester. Subsequently, the tester was evacuated to a pressure of 5×10^{-4} torr (argon). The system was repressurized with argon to a pressure of 15.0 psig and the second test was conducted:

Assembly No.	Test No.	Test Material Rider	Test Material Disc	Temp., °F	Speed, SFM	Load
KII	304H10K	7178	7178	400	1000	H(0.829 lb)

The test results are reported in Table VI. The average coefficient of friction for the Grade 7178 vs Grade 7178 combination was calculated to be 0.15.

The potassium was sampled for chemical analysis during the transfer from the Cb-1Zr alloy sump to the disposal tank after the second test of Assembly KII and distillation of the residual potassium in the tester was initiated. The auxiliarycryogenic cold trap was incorporated in the tester for the distillation cycle. Distillation was carried out for 48 hours at a pressure of 4×10^{-3} torr and at a temperature of 890°F. However, potassium condensed on the disc specimens and the disc specimen holders due to the inability to heat the internal components to the same temperature as the chamber wall and it was necessary to disassemble the tester components as completely as possible in the argon atmosphere in the surrounding environmental chamber, bag the components, and clean them with hexanol/alcohol and steam.

Results of the chemical analysis of the potassium sampled after the second test showed an oxygen content of 7 ppm, Table VII. The analytical procedure used was the inert gas amalgamation method.

Test Assembly KIII - The BaF_2/CaF_2 coated components of the second set of main shaft bearings were outgassed for four hours at 600°F and at a pressure of 4×10^{-6} torr. The bearings were not assembled during the outgassing operation so that the differential thermal expansion of the components would not result in indentation of the balls or races.

The tester was reassembled with the potassium immersion heater in place and the shaft was rotated at 1000 RPM for approximately 15 minutes in air. Subsequently, the system was evacuated to a pressure of 7.5×10^{-7} torr as a preliminary system checkout prior to welding the potassium inlet and exit tubes. Upon completion of welding the potassium inlet and exit tubes of the tester to the facility, the system was helium leak tested and, after appropriate bakeout cycles at temperatures of 450°F, the system was evacuated to a pressure of 2.0×10^{-7} torr. The Cb-1Zr alloy immersion heater, which had been installed in Assembly KIII, was evacuated to a pressure of 1.5×10^{-6} torr by the use of an independent pumping system. Subsequently, the tester was backfilled with argon to a pressure of 15.0 psig and purified potassium was transferred from the facility hot trap through a five micron filter to the Cb-1Zr alloy sump. Prior to transferring the potassium to the sump, the potassium was hot trapped for 50 hours at 1200°F.

Using calibration and test procedures described in Quarterly Progress Report No. 12[7] and above for Assembly KII, the following two tests were conducted:

Assembly No.	Test No.	Test Material Rider	Test Material Disc	Temp. °F	Speed SFM	Load
KIII	308H10K	7178	7178	800	1000	H(2.91 lb)
KIII	704H10K	TiC+10%Cb	TiC+10%Cb	400	1000	H(2.81 lb)

The test results are reported in Table VI. The coefficient of friction calculated for test 704H10K (TiC+10%Cb vs itself) was exceptionally low with an initial value of 0.15 steadily decreasing to a value of 0.04. Sanborn traces showing the changes in friction with time, photographs of the test specimens illustrating wear pattern, weight change data, and surface finish measurements are presented in Appendix C. No attempt will be made to present an analysis and interpretation of the test data until all of the test results have been evaluated.

Analytical samples of the potassium were taken from the transfer line from the hot trap to the Cb-1Zr alloy sump prior to test 308H10K and from the transfer line from the sump to the disposal tank after test 308H10K. The results of duplicate analyses by the inert gas amalgamation method show the oxygen content to be 5.5 and 6 ppm, respectively, Table VII. Spectrographic analyses for metallic impurities also were obtained and the results are shown in Table VII.

Potassium Immersion Heater - The final shipment of 14 Cb-1Zr alloy sheathed, BN/Al_2O_3 insulated immersion heating elements were received from Watlow Electric. Quality assurance tests were completed and the results are reported in Table VIII. Of the 14 heating elements, three elements were rejected because of possible cracks in the welds (penetrant inspection) and three elements are questionable because of uneven spacing of the Nichrome V wires (radiographic inspection). The low insulation resistance, i.e., on the order of 2.0 megohms is believed to be the result of adsorbed water vapor. After appropriate bakeout in vacuum, the resistance of the insulation should increase substantially, i.e., $>$10,000 megohms.

The performance of the seven element immersion heater assembly used in Test Assembly KIII was excellent. Approximately 1120 V.A. or 50 V.A./sq. in. of heater surface area was utilized to heat the potassium in the sump to 800°F.

Main Shaft Bearings - The proposed vendor for the special 7207, Type 440C SS main shaft bearing was visited and approved as a procurement source. Subsequently, an order was placed for ten bearings. The retainers are to be coated with BaF_2/CaF_2 at NASA-Lewis Research Center, Cleveland, Ohio, under the direction of H. E. Sliney. As described previously, BaF_2/CaF_2 coated bearings were utilized in Assemblies KII and KIII and although some retainer rubbing noises were evident, each set of BaF_2/CaF_2 lubricated retainers used in the main shaft bearing assembly successfully withstood the 140 minutes of testing at 955 RPM.

IV. FUTURE PLANS

The summary which follows enumerates the steps to be pursued during the succeeding quarter.

A. Complete the liquid potassium friction and wear test program. Material combinations of Mo-TZM alloy vs Grade 7178, Grade 7178 vs itself, and TiC+10%Cb vs itself will be tested at temperatures to 1200°F.

B. Complete the analysis of the friction and wear data obtained in high vacuum.

C. Initiate preparation of the final report.

V. REFERENCES

(1) "Materials for Potassium Lubricated Journal Bearings," Quarterly Progress Report No. 1, Ctr. NAS 3-2534 (July 22, 1963), SPPS, MSD, General Electric Company; Report NASA-CR-54006.

(2) "Materials for Potassium Lubricated Journal Bearings," Quarterly Progress Report No. 11, Ctr. NAS 3-2534 (January 22, 1966), SPPS, MSD, General Electric Company.

(3) "Materials for Potassium Lubricated Journal Bearings," Quarterly Progress Report No. 7, Ctr. NAS 3-2534 (January 22, 1965), SPPS, MSD, General Electric Company; Report NASA-CR-54345.

(4) "Materials for Potassium Lubricated Journal Bearings," Quarterly Progress Report No. 12, Ctr. NAS 3-2534 (April 22, 1966), SPPS, MSD, General Electric Company.

PUBLISHED REPORTS

Quarterly Progress Reports	For Quarter Ending
Report No. 1 (NASA-CR-54006)	July 22, 1963
Report No. 2 (NASA-CR-54007)	October 22, 1963
Report No. 3 (NASA-CR-54073)	January 22, 1964
Report No. 4 (NASA-CR-54113)	April 22, 1964
Report No. 5 (NASA-CR-54169)	July 22, 1964
Report No. 6 (NASA-CR-54264)	October 22, 1964
Report No. 7 (NASA-CR-54345)	January 22, 1965
Report No. 8 (NASA-CR-54646)	April 22, 1965
Report No. 9 (NASA-CR-54892)	July 22, 1965
Report No. 10 (NASA-CR-72027)	October 22, 1965
Report No. 11 (NASA-CR-72028)	January 22, 1966
Report No. 12 (NASA-CR-72041)	April 22, 1966

TABLE I. CANDIDATE BEARING MATERIALS

Material Class	Candidate Material	Nominal Composition
A. Nonrefractory Metals and Alloys	Star J	17%W-32%Cr-2.5%Ni-3%Fe-2.5%C-Bal. Co
B. Refractory Metals and Alloys	Mo-TZM (Arc Cast; Stress-Relieved)	0.5%Ti-0.08%Zr-0.02%C-Bal. Mo
	Tungsten (Arc Cast; Stress-Relieved)	99.96%W (Min.)
C. Fe-Ni-Co Bonded Carbides	Carboloy 907	74%WC-20%TaC-6%Co
	Carboloy 999	97%WC-3%Co
	K601	84.5%W-10%Ta-5.5%C
D. Refractory Compounds - Oxides, Carbides, Borides	Lucalox	99.8%Al_2O_3(Min.)-0.1%MgO-0.02%SiO_2-0.02% CaO-0.02%Fe_2O_3
	Zircoa 1027	95.5%ZrO_2-Bal. Proprietary
	Titanium Carbide	94%TiC-4.25%WC-0.9%Ni-0.1%Fe-0.68%Co
	Titanium Diboride	98%TiB_2-0.39%Fe-0.30%C
E. Refractory Metal Bonded Carbides	TiC+5%W	90%TiC-4.79%WC-5%W-0.36%Fe
	TiC+10%Mo	85.4%TiC-10.5%Mo-3.99%WC-0.13%Fe
	TiC+10%Cb	83.6%TiC-9.54%Cb-5.85%WC-0.73%Co-0.33%Fe
	Grade 7178	85.6%W-6.9%Mo-1.8%Cb-0.3%Ti-5.7%C

TABLE II. COMPRESSION PROPERTIES OF CANDIDATE BEARING MATERIALS

Material Class	Candidate Material	Specimen Identity MCN No.	Test Temp. °F [7]	Proportional Limit, psi	0.02% Offset psi [1]	0.2% Offset psi [1]	Strength at 1% Total Strain, psi	Ultimate Strength psi	Modulus of Elasticity psi x 10^6 [2]	Remarks
A. Nonrefractory Metals	Star J (As Cast)	1047-G-2	RT	57,700	87,000	152,500	189,000	270,500	29.8	
		1047-G-8	RT	52,900	74,500	147,800	195,200	277,000	33.6	
		1047-G-9	800	55,400	71,300	113,500	153,000	219,000	32.7	
		1047-G-10	800	56,500	71,300	108,000	155,000	221,000	31.2	
		1047-G-1	1200	45,600	61,400	105,000	150,000	213,000	27.6	
		1047-G-3	1600	47,200 [6]	57,200 [6]	76,000 [6]	102,000 [6]	121,000	25.5 [6]	Test terminated at 3.1% total strain.
B. Refractory Metals and Alloys	Mo-TZM (Arc Cast; Stress-Relieved)	1037-G-1	RT	73,300	89,400	102,000	102,000	107,200	38.7	Test terminated at 5% total strain.
		1037-G-2	RT	68,300	86,000	104,200	104,300	111,000	40.8	Test terminated at 5% total strain.
		1037-G-9	RT	83,800	99,600	115,500	115,500	119,000	38.6	Test terminated at 5% total strain.
		1037-G-10	RT	57,600	83,800	112,500	112,000	112,500	39.8	Test terminated at 5% total strain.
		1037-G-3	800	42,000	52,500	73,400	79,200	79,800	(3)	Test terminated at 5% total strain.
		1037-G-4	800	38,500	47,500	71,800	81,800	84,500	(3)	Test terminated at 5% total strain.
		1037-G-14	800	43,500	55,000	71,800	76,000	82,300	(3)	Test terminated at 5% total strain.
		1037-G-15	800	--	40,300	69,200	74,500	79,600	(3)	Test terminated at 5% total strain.
		1037-G-16	800	39,900	57,600	70,700	75,900	79,600	(3)	Test terminated at 5% total strain.
		1037-G-5	1200	31,700	52,800	70,200	77,500	78,600	(3)	Test terminated at 5% total strain.
		1037-G-6	1200	44,500	57,600	72,300	76,000	78,500	(3)	Test terminated at 5% total strain.
		1037-G-8	1200	35,500	47,200	68,200	73,800	77,500	(3)	Test terminated at 5% total strain.
		1037-G-7	1600	28,800	44,500	68,100	72,800	76,000	(3)	Test terminated at 5% total strain.
		1037-G-17	1600	40,800	51,100	63,900	68,000	71,200	(3)	Test terminated at 5% total strain.
	Tungsten (Arc Cast; Stress-Relieved)	1038-G-2	RT	68,700	91,400	132,000	142,500	157,000	48.7	
		1038-G-3	RT	84,200	120,800	147,000	152,000	154,000	50.6	
		1038-G-1	800	20,200	25,700	37,300	46,700	>57,700	(3)	Test terminated at 5% total strain.
		1038-G-4	800	13,200	18,500	26,900	35,400	>52,800	(3)	Test terminated at 5% total strain.
		1038-G-7	1200	14,200	18,500	26,400	30,600	>41,000	(3)	Test terminated at 5% total strain.
		1038-G-8	1600	15,200 [6]	19,400 [6]	25,200 [6]	28,800 [6]	32,500	--	Test terminated at 5% total strain.
C. Fe-Ni-Co Bonded Carbides	Carboloy 907	1036-G-1	RT	296,000	422,000	---	---	>608,000	72.3	Test terminated at 0.98% total strain (115,000-lb load).
		1036-G-2	RT	307,000	438,000	---	---	>607,000	70.8	Test terminated at 1.0% total strain (115,000-lb load).
		1036-G-3	800	266,000	346,000	515,000	520,000	>607,000	61.6	Test terminated at 1.9% total strain (115,000-lb load).
		1036-G-4	800	244,000	335,000	505,000	505,000	>610,000	58.5	Test terminated at 2.5% total strain (115,000-lb load).
		1036-G-6	1200	227,000	289,000	422,000	440,000	516,000	52.2	Test terminated at 3.3% total strain.
		1036-G-9	1200	314,000	347,000	422,000	346,000	475,000	32.7	
		1036-G-5	1600	198,000	213,000	241,000	198,000	256,000	13.2	Test terminated at 5% total strain.
		1036-G-7	1600	200,000	221,000	250,000	186,000	271,000	11.0	Test terminated at 5% total strain.
	Carboloy 999	1035-G-1	RT	306,000	422,300	---	---	>608,000	81.1	Test terminated at 0.83% total strain (115,000-lb load).
		1035-G-2	RT	367,000	479,000	---	---	>612,000	77.7	Test terminated at 0.85% total strain (115,000-lb load).
		1035-G-3	800	195,000	240,000	374,000	438,000	542,000	67.7	
		1035-G-5	1200	210,500	253,000	339,000	364,000	528,000	51.7	Test terminated at 3.3% total strain.
		1035-G-7	1600	98,400	123,000	199,000	239,000	>270,000	40.5	Test terminated at 2% total strain.
D. Refractory Compounds - Oxides, Carbides, Borides	Lucalox (Al_2O_3)	1039-G-1	RT	---	---	---	---	360,700	49.7	
		1039-G-3	RT	---	---	---	---	325,000	51.8	
		1039-G-5	800	---	---	---	---	364,600	43.7	
		1039-G-7	1200	---	---	---	---	332,000	40.3	
		1039-G-9	1600	---	---	---	---	276,000	38.0	
	Zircoa 1027 (ZrO_2)	1040-G-1	RT	152,000	178,000	220,000	226,000	240,000	29.9	
		1040-G-5	RT	89,200	114,000	236,000	240,000	265,800	29.1	
		1040-G-2	800	83,800	104,700	149,000	130,000	167,000	12.5	
		1040-G-7	800	81,100	115,100	170,100	141,000	180,000	15.9	Test terminated at 1.6% total strain.
		1040-G-4	1200	137,100	161,000	193,000	187,000	200,000	17.3	
		1040-G-8	1600	136,000	147,000	181,000	173,000	186,000	17.5	
	Titanium Carbide (TiC)	1042-G-5	RT	---	---	---	---	420,000	57.0	
		1042-G-6	RT	---	---	---	---	365,000	56.1	
		1042-G-1 [4]	800	---	---	---	---	424,000	49.8	
		1042-G-2	1200	---	---	---	---	312,000	42.2	
		1042-G-4	1600	146,600	208,000	---	---	248,000	39.1	

TABLE II. (Cont'd)

Material Class	Candidate Material	Specimen Identity MCN No.	Test Temp. °F [7]	Proportional Limit, psi	0.02% Offset psi [1]	0.2% Offset psi [1]	Strength at 1% Total Strain, psi	Ultimate Strength psi	Modulus of Elasticity psi x 10^6 [2]	Remarks
D. Refractory Compounds - Oxides, Carbides, Borides	Titanium Diboride (TiB_2)	1048-G-3	RT	---	---	---	---	332,000	66.0	Specimen cracked and deviated from straight line portion of curve at 229,000 psi.
		1048-G-10	RT	---	---	---	---	363,000	68.7	Specimen cracked and deviated from straight line portion of curve at 311,000 psi.
		1048-G-1 [4]	800	---	---	---	---	362,000	55.9	
		1048-G-5	1200	200,000	277,000	343,000	---	345,000	47.2	
		1048-G-7	1600	103,000	143,000	212,000	212,000	215,000	44.5	
E. Refractory Metal Bonded Carbides	TiC+5%W	1043-G-8	RT	---	---	---	---	424,000	53.8	Specimen cracked and deviated from straight line portion of curve at 358,000 psi.
		1043-G-9 [4]	RT	---	---	---	---	394,000	64.2	
		1043-G-4 [4]	800	---	---	---	---	390,000	45.2	
		1043-G-2	1200	>263,000 [5]	---	---	---	349,000	47.0	Test terminated at 0.74% total strain.
		1043-G-1	1600	208,000	250,000	311,000	---	311,900	39.9	
	TiC+10%Mo	1044-G-2	RT	---	---	---	---	380,000	41.4	
		1044-G-5	RT	---	---	---	---	328,000	49.7	
		1044-G-6 [4]	RT	---	---	---	---	304,000	54.6	
		1044-G-7 [4]	800	---	---	---	---	454,000	43.2	
		1044-G-1	1200	---	---	---	---	405,000	43.7	
		1044-G-9	1200	345,000	---	---	---	396,400	42.3	
		1044-G-4	1600	208,000	252,000	---	---	267,000	35.0	
	TiC+10%Cb	1045-G-8 [4]	RT	---	---	---	---	321,000	57.6	
		1045-G-9	RT	---	---	---	---	376,000	60.0	Specimen cracked and deviated from straight line portion of curve at 324,000 psi.
		1045-G-3	800	---	---	---	---	410,000	50.7	
		1045-G-5	800	---	---	---	---	357,000	47.8	
		1045-G-6	1200	315,000	352,000	---	---	352,000	47.3	
		1045-G-2	1200	251,000	310,000	---	---	310,000	47.2	
		1045-G-10	1600	91,500	136,000	---	---	278,000	47.7	
		1045-G-7	1600	207,000	250,000	---	---	290,000	47.8	
	Grade 7178	1046-G-9	RT	---	---	---	---	>603,000	75.3	Test terminated at 0.08% total strain (115,000-lb load).
		1046-G-4	RT	---	---	---	---	>605,000	76.6	Test terminated at 0.78% total strain (115,000-lb load).
		1046-G-2	800	247,000	364,000	567,000	538,000	>602,000	59.2	Test terminated at 1.17% total strain (115,000-lb load).
		1046-G-7	800	265,000	367,000	---	564,000	>603,000	57.1	Test terminated at 1.23% total strain (115,000-lb load).
		1046-G-3	1200	222,000	264,000	421,000	450,000	558,000	57.3	
		1046-G-10	1200	304,000	378,000	508,000	519,000	>551,000	60.0	Test terminated at 1.20% total strain (105,000-lb load).
		1046-G-6	1600	173,000	220,000	371,000	412,000	474,000	46.1	
		1046-G-8	1600	189,000	275,000	390,000	420,000	>472,000	40.6	Test terminated at 1.75% total strain (90,000-lb load).

(1) Specimens were tested at a strain rate of 0.005 in/in/min through 0.2% offset.

(2) Effective gauge length equal to measured gauge length + 1.44 X the specimen wall thickness at the gauge section.

(3) Stress-strain curve was not defined sufficiently at the low loads for the calculation of E.

(4) Specimen was loaded elastically to determine E; subsequently, the load was released, the extensometer was removed, and the specimen was loaded to failure.

(5) Test was terminated at 349,000 psi. Stress strain recorder ran out of ink at 263,000 psi and indicated no plastic strain. Measurement of specimen after test showed 0.06% plastic strain. Chips also had broken out of gauge section indicating test was stopped just prior to failure of specimen.

(6) Estimated, extensometer travel was interrupted during initial loading of specimen.

(7) Elevated temperature tests conducted at pressures < 1.0 x 15^5 torr.

TABLE III. COMPRESSION PROPERTIES OF CANDIDATE BEARING MATERIALS

Candidate Material	Specimen Identity	Test Temp.	Max. Elastic Strain, %	Total Strain at Termination of Test, %	Total Strain at Fracture, %
Star J (As Cast)	2	RT	0.18	---	2.7
	8	RT	0.14	---	3.0
Mo-TZM (Arc Cast; Stress-Relieved)	1	RT	0.18	5	---
	2	RT	0.15	5	---
	9	RT	0.20	5	---
	10	RT	0.14	5	---
Tungsten (Arc Cast; Stress-Relieved)	2	RT	0.14	---	3.2
	3	RT	0.16	---	2.0
Carboloy 907	1	RT	0.41	0.98	---
	2	RT	0.43	1.0	---
Carboloy 999	1	RT	0.37	0.83	---
	2	RT	0.47	0.85	---
Lucalox (Al_2O_3)	1	RT	0.69	---	0.69
	3	RT	0.61	---	0.61
Zircoa 1027 (ZrO_2)	1	RT	0.50	---	1.19
	5	RT	0.30	---	1.28
Titanium Carbide (TiC)	5	RT	0.74	---	0.74
	6	RT	0.64 (1)	---	0.64 (1)
Titanium Diboride (TiB_2)	3	RT	0.33 (2)	---	0.33 (2)
	10	RT	0.43 (2)	---	0.43 (2)
TiC+5%W	8	RT	0.66 (2)	---	0.66 (2)
	9	RT	0.61 (1)	---	0.61 (1)

TABLE III. (Cont'd)

Candidate Material	Specimen Identity	Test Temp.	Max. Elastic Strain, %	Total Strain at Termination of Test, %	Total Strain at Fracture, %
TiC+10%Mo	5	RT	0.65	---	0.65
	6	RT	0.53(1)	---	0.53(1)
TiC+10%Cb	8	RT	0.54	---	0.54
	9	RT	0.53(1,2)	---	0.53(1,2)
Grade 7178	9	RT	> 0.80	0.80	---
	4	RT	> 0.78	0.78	---
Star J (As Cast)	9	800°F	0.17	---	3.0
	10	800°F	0.18	---	3.0
Mo-TZM (Arc Cast; Stress-Relieved)	3	800°F	0.13	1.8	---
	4	800°F	0.16	5.0	---
	14	800°F	0.22	5.0	---
	15	800°F	0.06	5.0	---
	16	800°F	0.09	5.0	---
Tungsten (Arc Cast; Stress-Relieved)	1	800°F	0.075	5.0	---
	4	800°F	0.055	5.0	---
Carboloy 907	3	800°F	0.43	1.9	---
	4	800°F	0.42	2.5	---
Carboloy 999	3	800°F	0.28	---	2.3
Lucalox (Al_2O_3)	5	800°F	0.84	---	0.84
Zircoa 1027 (ZrO_2)	2	800°F	0.67	---	1.8
	7	800°F	0.51	1.6	---
Titanium Carbide (TiC)	1	800°F	0.82(1)	---	0.82(1)
Titanium Diboride (TiB_2)	1	800°F	0.60(1)	---	0.60(1)
TiC+5%W	4	800°F	0.84(1)	---	0.84(1)

TABLE III. (Cont'd)

Candidate Material	Specimen Identity	Test Temp.	Max. Elastic Strain, %	Total Strain at Termination of Test, %	Total Strain at Fracture, %
TiC+10%Mo	7	800°F	1.05(1)	---	1.05(1)
TiC+10%Cb	3	800°F	0.8	---	0.8
	5	800°F	0.75	---	0.75
Grade 7178	2	800°F	0.42	1.17	---
	7	800°F	0.46	1.23	---
Star J (As Cast)	1	1200°F	0.16	---	3.5
Mo-TZM (Arc Cast; Stress-Relieved)	5	1200°F	0.07	5.0	---
	6	1200°F	0.10	5.0	---
	8	1200°F	0.09	5.0	---
Tungsten (Arc Cast; Stress-Relieved)	7	1200°F	0.07	5.0	---
Carboloy 907	6	1200°F	0.43	3.2	---
	9	1200°F	0.96	---	4.5
Carboloy 999	5	1200°F	0.41	3.3	---
Lucalox (Al_2O_3)	7	1200°F	0.82	---	0.82
Zircoa 1027 (ZrO_2)	4	1200°F	0.79	---	1.83
Titanium Carbide (Tic)	2	1200°F	0.74	---	0.74
Titanium Diboride (TiB_2)	5	1200°F	0.40	---	1.0
TiC+5%W	2	1200°F	0.68	0.74	---
TiC+10%Mo	1	1200°F	0.93	---	0.93
	9	1200°F	0.82	---	0.95

TABLE III. (Cont'd)

Candidate Material	Specimen Identity	Test Temp.	Max. Elastic Strain, %	Total Strain at Termination of Test, %	Total Strain at Fracture, %
TiC+10%Cb	6	1200°F	0.65	---	0.77
	2	1200°F	0.52	---	0.66
Grade 7178	3	1200°F	0.40	---	2.0
	10	1200°F	0.51	1.2	---
Star J (As Cast)	3	1600°F	0.18 (3)	3.1	---
Mo-TZM (Arc Cast; Stress-Relieved)	7	1600°F	0.09	5.0	---
	17	1600°F	0.16	5.0	---
Tungsten (Arc Cast; Stress-Relieved)	8	1600°F	0.05 (3)	5.0	---
Carboloy 907	5	1600°F	1.5	5.0	---
	7	1600°F	1.8	5.0	---
Carboloy 999	7	1600°F	0.24	2.0	---
Lucalox (Al_2O_3)	9	1600°F	0.73	---	0.73
Zircoa 1027 (ZrO_2)	8	1600°F	0.77	---	1.7
Titanium Carbide (TiC)	4	1600°F	0.38	---	0.75
Titanium Diboride (TiB_2)	7	1600°F	0.23	---	1.02
TiC+5%W	1	1600°F	0.52	---	0.97
TiC+10%Mo	4	1600°F	0.59	---	0.93
TiC+10%Cb	10	1600°F	0.19	---	0.72
	7	1600°F	0.43	---	0.77
Grade 7178	6	1600°F	0.37	---	2.5
	8	1600°F	0.46	1.75	---

Footnotes on next page.

TABLE III (Cont'd)

(1) Specimen was loaded elastically to determine E; subsequently, the load was released, the extensometer was removed, and the specimen was loaded to failure.

(2) Specimen cracked and deviated from straight line portion of curve at reported strain level.

(3) Estimated extensometer travel was interrupted during initial loading of specimen.

TABLE IV. SUMMARY OF FRICTION AND WEAR TESTS CONDUCTED IN HIGH VACUUM

Assembly No.	Arm No.	Test No.	Test Material: Rider	Test Material: Disc	Test Temp °F	Increase in Rider Specimen Temp, °F(1)	Speed SFM	Compressive Load: lbs.	Compressive Load: Hertzian Stress psi	Compressive Load: (%)0.2%CYS or UCS: Rider	Compressive Load: (%)0.2%CYS or UCS: Disc	Test Duration Minutes	Chamber Pressure, Torr: Start	Chamber Pressure, Torr: Maximum	Average Coefficient Friction	Wear Rate in.^{3}/10^{10} ft.: Rider	Wear Rate in.^{3}/10^{10} ft.: Disc	Remarks
HVFT TESTS																		
XX	1	500H08B	Carboloy 907	Carboloy 907	80	555	800	1.26	299,850	43	43	60:00	1.4×10^{-9}	9.5×10^{-9}	0.87	-9.526	+0.1701	Test interrupted due to bearing failure.
XX	2	408K08B	Mo-TZM	Carboloy 907	800	12	800	0.077	89,130	89	14	60:00	4.8×10^{-9}	9.2×10^{-9}	0.87	+0.2223	0	----
XX	3	508K08A	Carboloy 907	Carboloy 907	800	23	800	0.076	49,980	8	8	60:00	6.2×10^{-9}	9.2×10^{-9}	0.88	+0.0741	-0.3705	----
XX	4	508H08B	Carboloy 907	Carboloy 907	806	141	800	0.339	190,770	31	31	60:00	8.5×10^{-9}	8.5×10^{-9}	1.00	-0.5789	-1.902	----
XXI	1	512708A	Carboloy 907	Carboloy 907	1200	72	800	2.58	370,800	75	75	3:54	6×10^{-9}	9.5×10^{-9}	0.57	-5.009	-40.075	Test terminated due to slippage of magnetic drive.
XXI	2	208K08B	7178	Mo-TZM	800	15	800	0.077	90,680	15	90	13:35	1.6×10^{-9}	8.5×10^{-9}	0.84 1.05	-3.838	-213.7	Test terminated due to continued load cell cable breakage. Test extremely rough.
XXI	3	604K08C	Mo-TZM	TiC+10%Cb	410	50	800	0.080	89,370	85	30	60:00	8×10^{-9}	9.5×10^{-9}	0.97	-0.2147	-0.4153	Test extremely rough.
XXI	4	512H08A	Carboloy 907	Carboloy 907	1207	12	800	0.119	132,990	27	27	60:00	8.8×10^{-9}	9.3×10^{-9}	0.64	-0.4765	-1.191	----

(1) Measured with sheathed chromel-alumel thermocouples located in thermowell in contact with side of rider specimen approximately 1/4 inch away from interface.

TABLE V. CALCULATED LOADS P_{90} (P_{75}), TO PRODUCE STRESSES BETWEEN POTASSIUM FRICTION AND WEAR SPECIMENS EQUAL TO 90% (0.2% CYS) OR 75% UCS

Pair	Material	Poiss. Ratio ν (-)	Temp. °F	E (10^6 psi)	0.2% CYS (1) or UCS (10^5 psi)	P_{90} (2) (lb)	Tray Load (lb) Arm 5 (4) 5^WK	Tray Load (lb) Arm 6 (5) 6^WK	P_{75} (3) (lb)	Tray Load (lb) Arm 5 (5) 5^W75	Tray Load (lb) Arm 6 (5) 6^W75
1	TZM / 7178		400			K_{400}=0.098,322	0.181,62	0.180,67			
			800			K_{800}=0.101,74	0.187,94	0.186,95			
			1200			K_{1200}=0.089,480	0.165,29	0.164,42			
3	7178 / 7178	0.22	400	62.900	6.852,5				9.999,7	18.471	18.374
			800	56.500	6.300,0				9.630,9	17.790	17.697
			1200	57.350	5.580,0				6.495,0	11.998	11.935
	TiC / TiC	0.25	400	52.180	4.000,0				H_{400}=2.805,1	5.181,6	5.154,4
			800	48.050	3.835,0				H_{800}=2.915,3	5.385,2	5.356,9
			1200	46.110	3.310,0				H_{1200}=2.035,5	3.760,0	3.740,2
	Mo-TZM	0.30	400	40.410	1.0575						
			800	37.330	1.0069						
			1200	34.240	0.9354						

(1) Use strength of weaker material (Mo-TZM) when dissimilar materials are used (Pair 1).

(2) $P_{90} = 0.058,660\ (0.2\%\ CYS)^3 \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_1^2}{E_2}\right]^2$

(3) $P_{75} = 0.57870\ P_{90}$.

(4) $5^WX = 1.8472\ P_X$, Run-in $5^Wr = 0.115,45$ (or 5^WK).

(5) $6^WX = 1.8375\ P_X$, Run-in $6^Wr = 0.114,84$ (or 6^WK).

TABLE VI. SUMMARY OF FRICTION AND WEAR TESTS CONDUCTED IN LIQUID POTASSIUM

Assembly No.	Arm No.	Test No.	Test Material Rider	Test Material Disc	Test Temp °F	Increase in Rider Specimen Temp, °F(1)	Speed SFM	Compressive Loads lbs.	Compressive Loads Hertzian Stress psi	Compressive Loads (%)0.2% CYS or UCS Rider	Compressive Loads (%)0.2% CYS or UCS Disc	Test Duration Minutes	Chamber Pressure Pre-test, torr	Chamber Pressure Test, psig	Average Coefficient Friction	Wear Rate $in.^3/10^{10}$ ft. Rider	Wear Rate $in.^3/10^{10}$ ft. Disc	Remarks
KFT TESTS																		
KII	5	104K10K	Mo-TZM	7178	410	10	1000	0.081	89,070	84	13	60:00	1.5×10^{-6}	15.2	0.25	-0.25	-12.33	
KII	6	304H10K	7178	7178	394	36	1000	0.829	224,040	33	33	60:00	5×10^{-4}	15.2	0.15	-0.14	-7.87	
KIII	5	308H10K	7178	7178	787	69	1000	2.91	317,200	50	50	60:00	2×10^{-7}	15.2	0.18	-0.49	*	* Disc fractured
KIII	6	704H10K	TiC+10%Cb	TiC+10%Cb	396	32	1000	2.81	299,960	75	75	60:00	2×10^{-7}	15.2	0.07	-0.05	--	C.F. decreased from 0.15 to 0.04 during test

(1) Measured with sheathed chromel-alumel thermocouples located in thermowell in contact with side of rider specimen approximately 1/4-inch away from interface.

TABLE VII. CHEMICAL ANALYSES OF POTASSIUM USED IN FRICTION AND WEAR TEST PROGRAM

Assembly No.	--	--	--	KII-6	KIII-6	
Test No.	--	--	--	304H10K	308H10K	
Condition	As-Received(1)	As-Received(1)	Distilled into Facility Hot Trap(2)	Hot Trapped 50 Hrs. 1200°F	Hot Trapped 50 Hrs-1200°F	
				Post Test	Pre-Test	Post Test
Sample No.(3)	Vendor	GE(3)	GE(3)	351(4)	494(3)	495(5)
Element	ppm	ppm	ppm	ppm	ppm	ppm
O(6)	11	14.5 21.6 26.9 53.8	3.6	6/8	5/6	6/6
Ag(7)	<1	<1		--	<2	<2
Al	<2	<1		--	2	2
B	<10	--		--	<20	<20
Ba	<3	--		--	<5	<5
Be	<1	<1		--	<2	<2
Ca	11	1		--	<2	<2
Cb	--	<1		--	<2	<2
Co	<5	<1		--	<2	<2
Cr	<5	<1		--	<2	<2
Cu	4	<1		--	<2	<2
Fe	12	<1		--	<2	<2
Mg	4	<1		--	<2	<2
Mn	1	<1		--	<2	<2
Mo	<3	<1		--	<2	<2
Na	25	<5		--	<20	<20
Ni	<5	1		--	<2	<2
Pb	<5	<1		--	<10	<10
Si	<25	<1		--	2	2
Sn	<5	<5		--	<10	<10
Sr	<1	--		--	1	1
Ti	<5	<1		--	<2	<2
V	<1	<1		--	<2	<2
W	--	--			<50	<50
Zr	<10	<5		--	<10	<10

Footnotes on following page.

TABLE VII. (Cont'd)

(1) MSA - Drum D-80.

(2) Distillation Temperature - 530°F
Pressure - 3×10^{-5} torr.

(3) Potassium was sampled at approximately 250°F.

(4) Potassium was sampled at approximately 400°F.

(5) Potassium was sampled at approximately 600°F.

(6) Analysis of oxygen as K_2O by inert gas mercury amalgamation method; helium purified by passing through 13X molecular sieve.

(7) Analysis of metallic elements in KCl by spectrographic techniques.

TABLE VIII. INSPECTION RESULTS OF Cb-1Zr ALLOY SHEATHED BN INSULATED IMMERSION HEATERS

Heater Identification	Radiographic Inspection	Distance From Sheath to Tip of Heater Winding, Inch	Fluorescent Penetrant Inspection	Resistance of Heating Element, ohms	Resistance Across BN Insulation at 500 Volts, Megohms
J3NX124 -1	Heater winding uniformly spaced	1/8	No indications	34	2.7
-2	Heater winding uniformly spaced	3/16	No indications	34	4.2
-3	Heater winding uniformly spaced; end plug close to bottom	3/16	No indications	34	4.7
-4	Heater winding uniformly spaced; end plug close to bottom	1/4	No indications	34	2.7
-5	Heater winding uniformly spaced; end plug close to bottom	1/4	No indications	34	1.8
-6	Heater wire spaced unevenly at tip	3/16	No indications	34	3.7
-7	Heater winding uniformly spaced	5/16	Reject - lap or crack in weld	33	1.8
-8	Heater winding uniformly spaced	1/8	No indications	34	3.4
-9	Heater winding uniformly spaced; end plug close to bottom	1/2	Reject - lap or crack in weld	34	3.1
-10	End plug close to bottom; heater wire spaced unevenly at bottom	5/16	No indications	33	2.0
-11	Heater winding uniformly spaced	3/16	Reject - lap or crack in weld	35	19.0
-12	Heater winding uniformly spaced	3/16	No indications	34	2.9
-13	Heater winding uniformly spaced	1/8	No indications	33	2.2
-14	Heater wire spaced unevenly at bottom	1/4	No indications	34	3.5

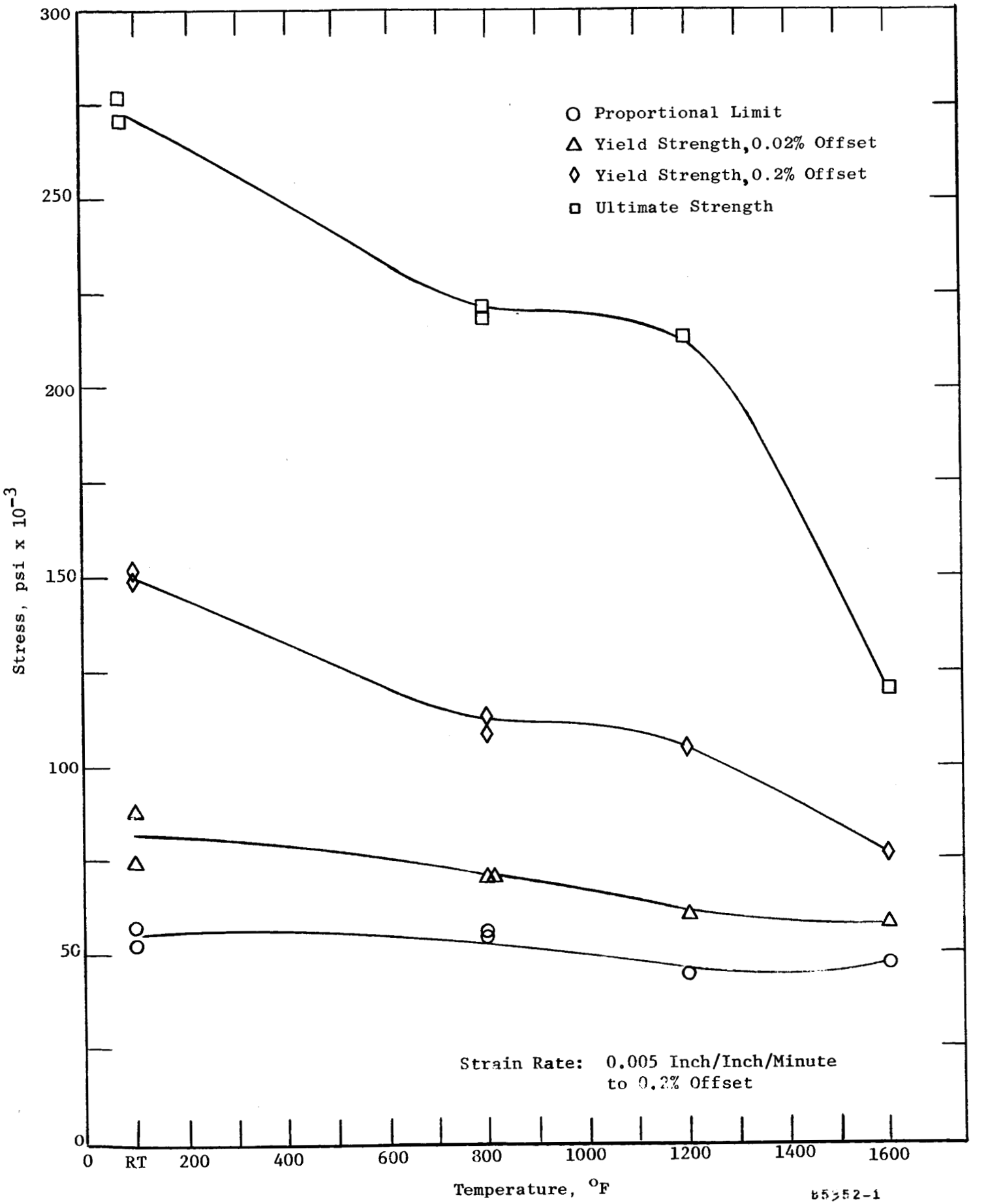


Figure 1. Compression Properties of As Cast Star J.

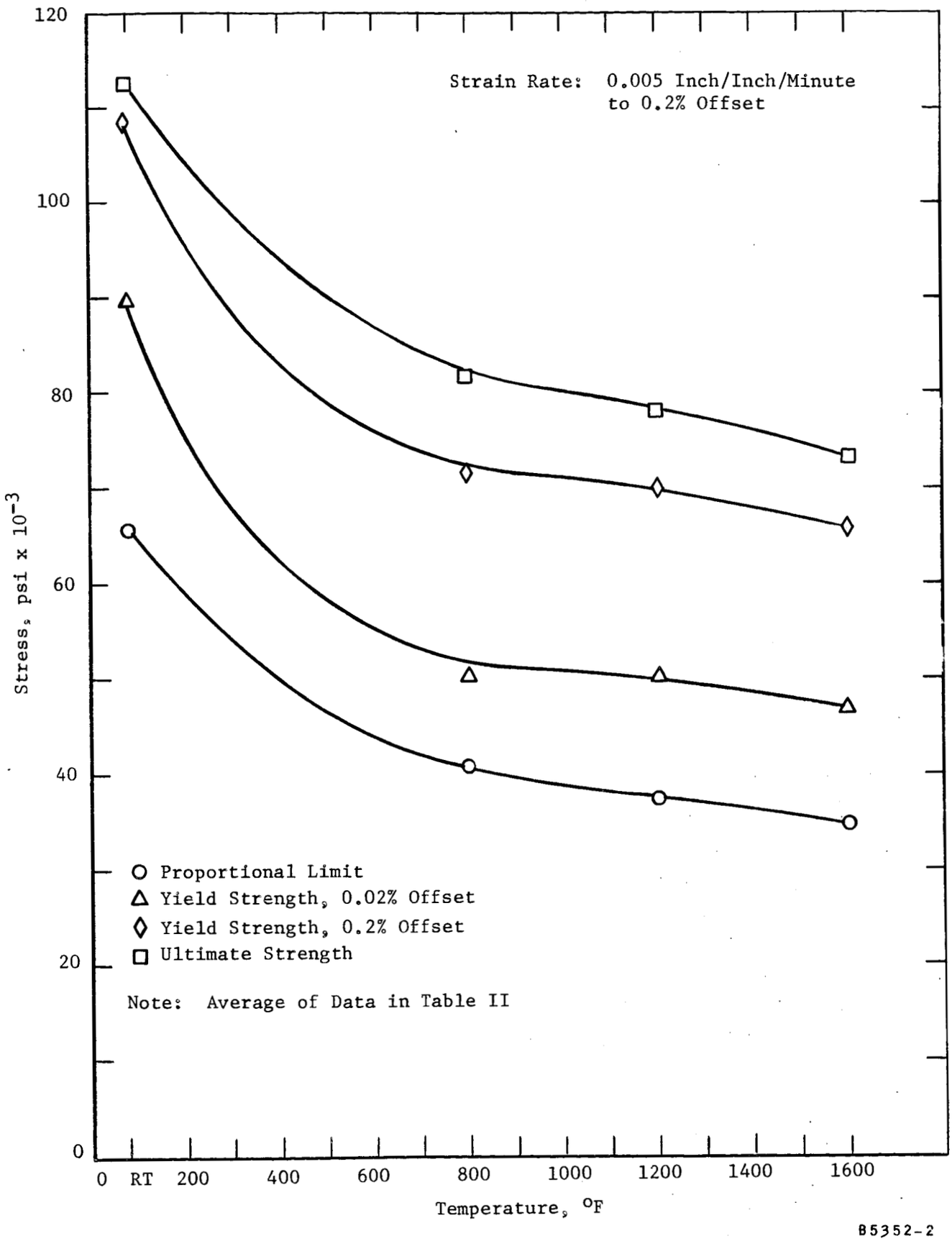


Figure 2. Compression Properties of Stress Relieved Arc Cast Mo-TZM Alloy.

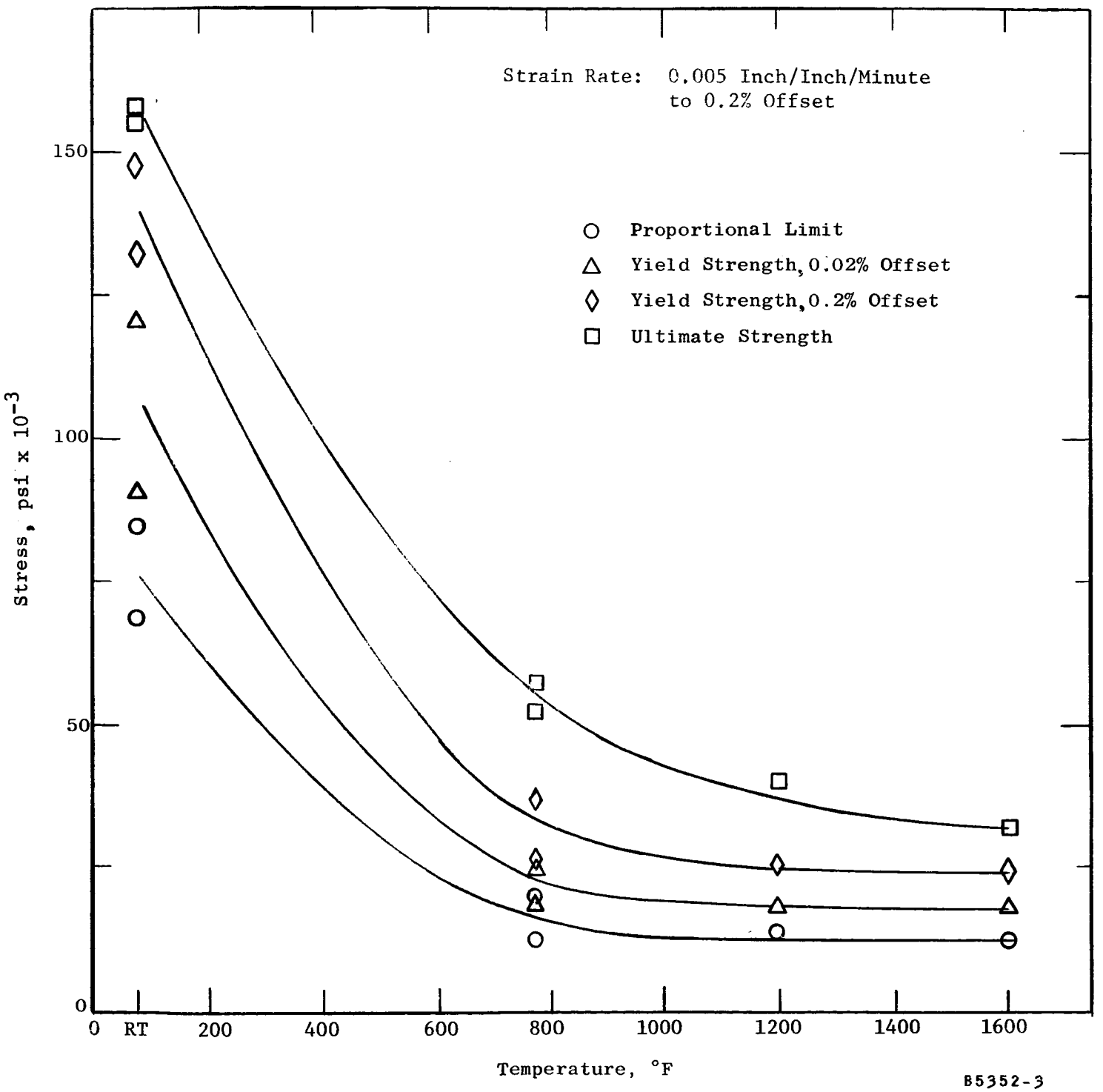


Figure 3. Compression Properties of Stress Relieved Arc Cast Unalloyed Tungsten.

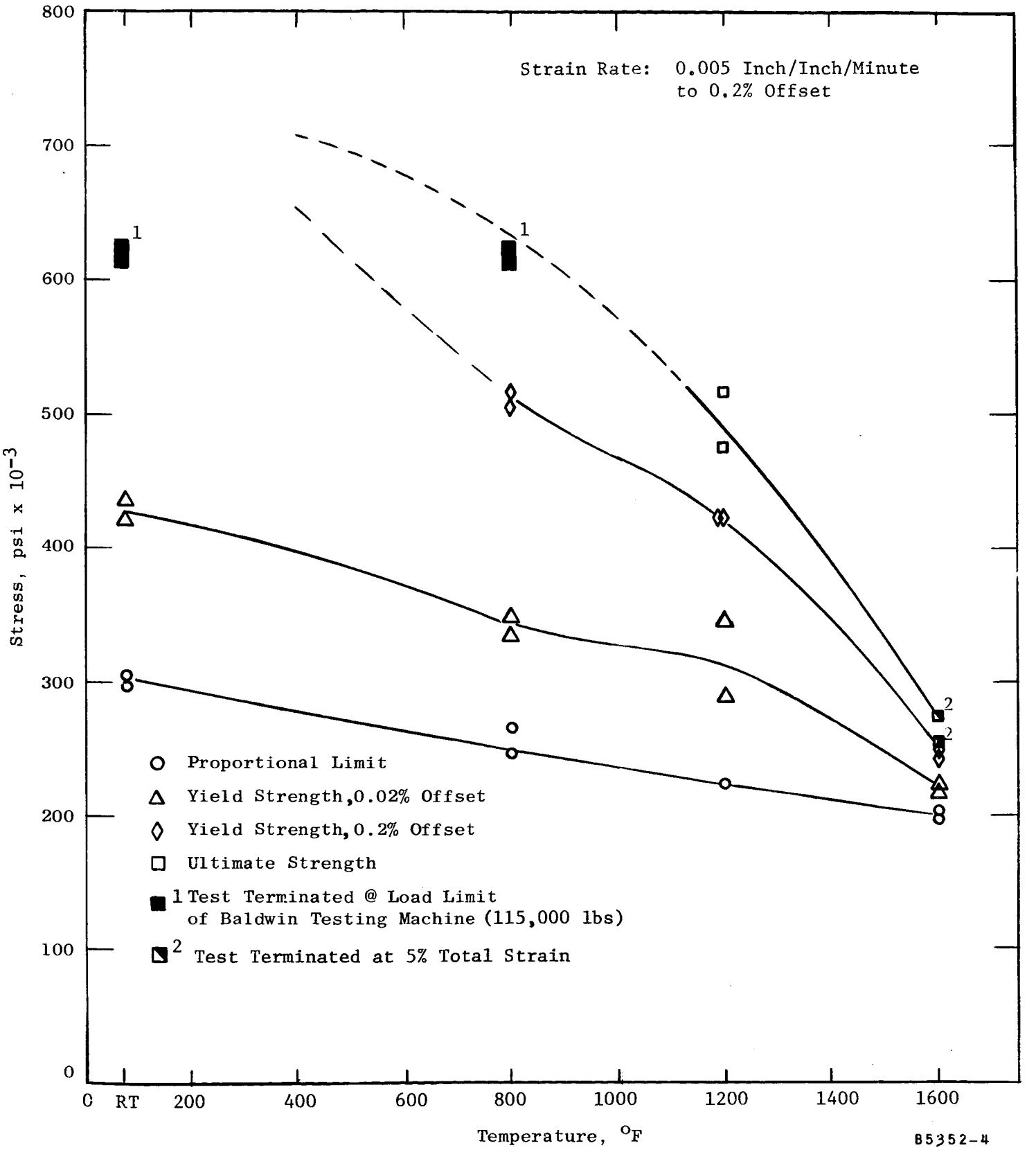


Figure 4. Compression Properties of Carboloy 907.

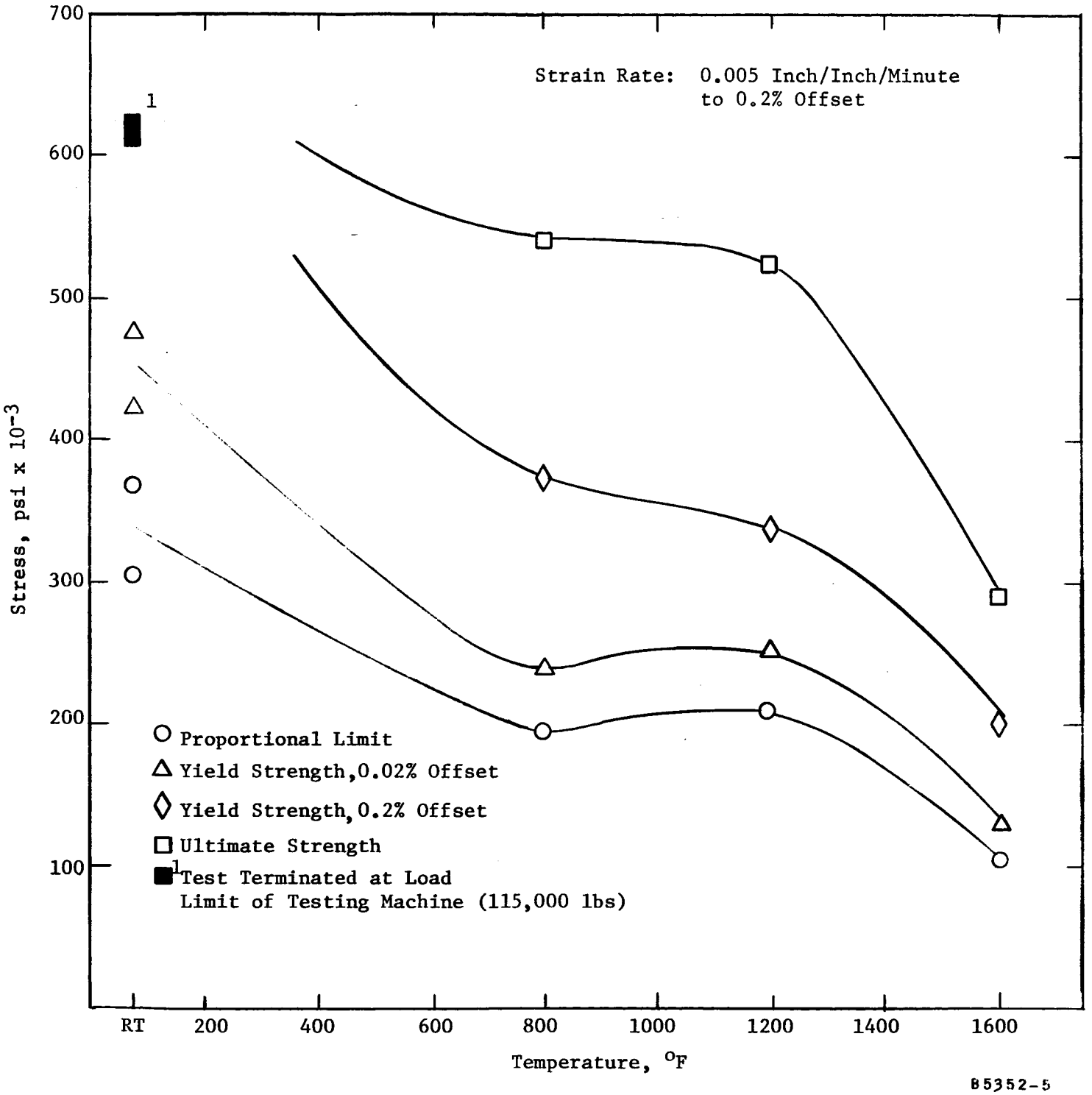


Figure 5. Compression Properties of Carboloy 999.

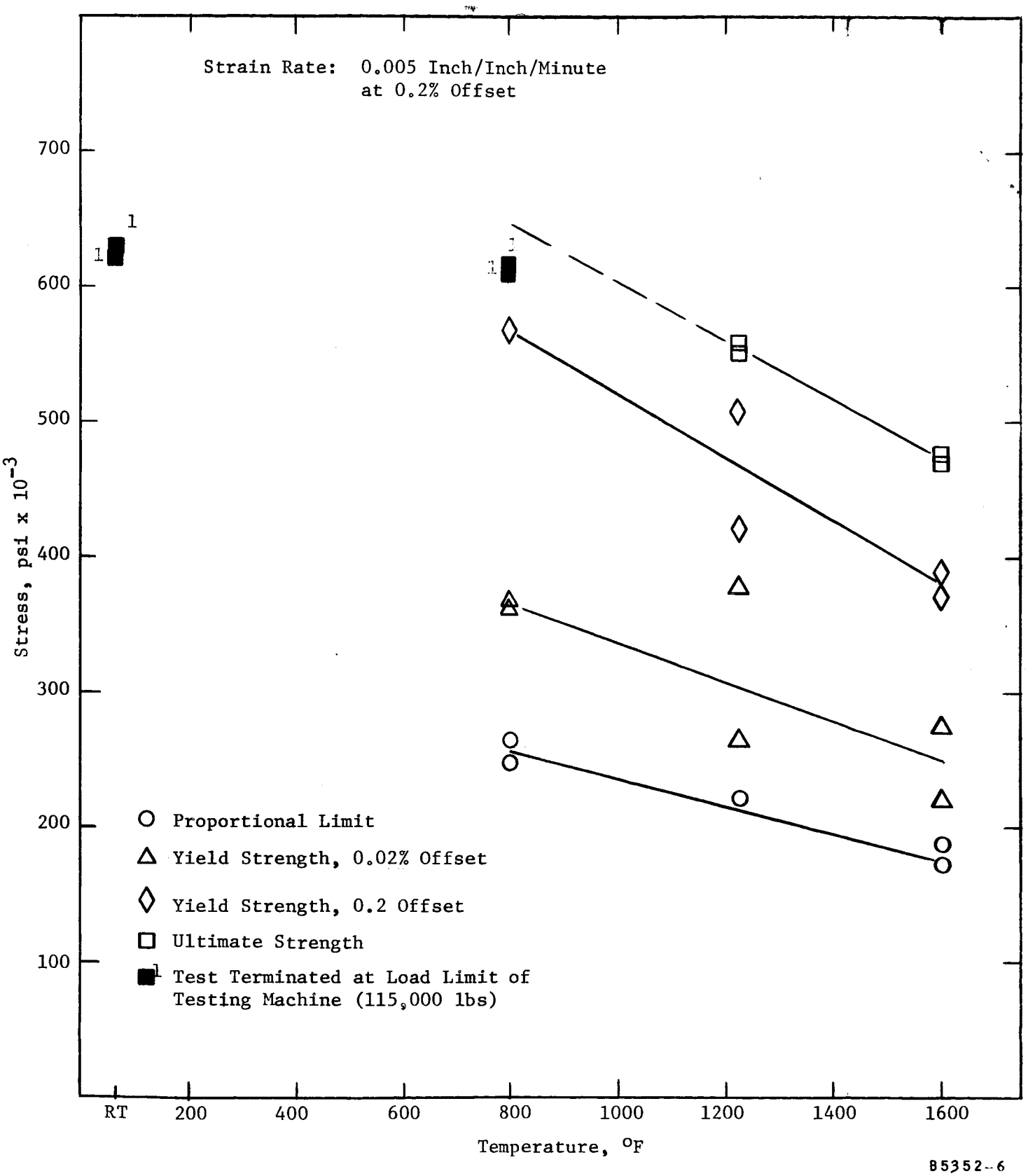


Figure 6. Compression Properties of Grade 7178.

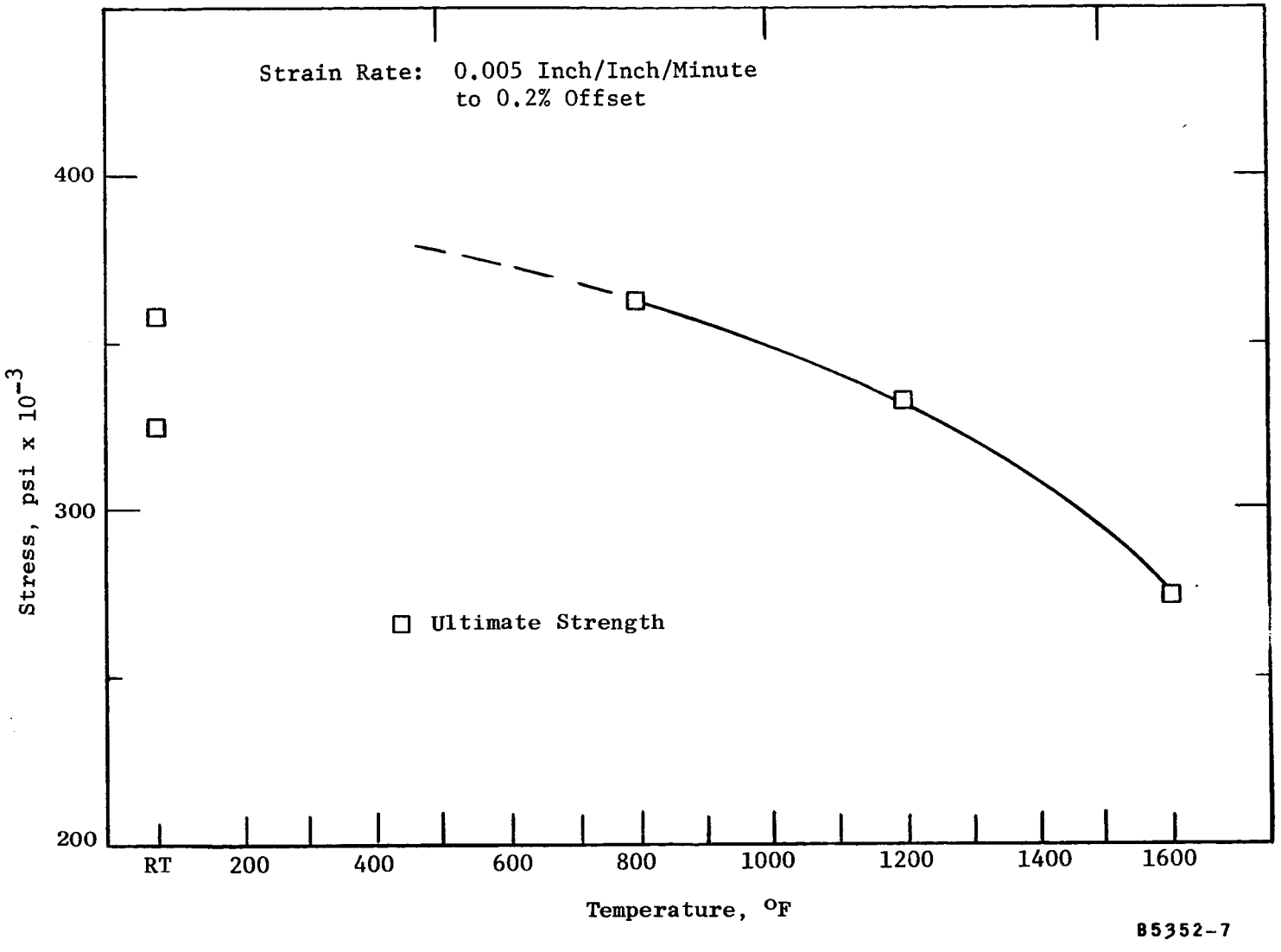


Figure 7. Compression Properties of Lucalox (Al_2O_3).

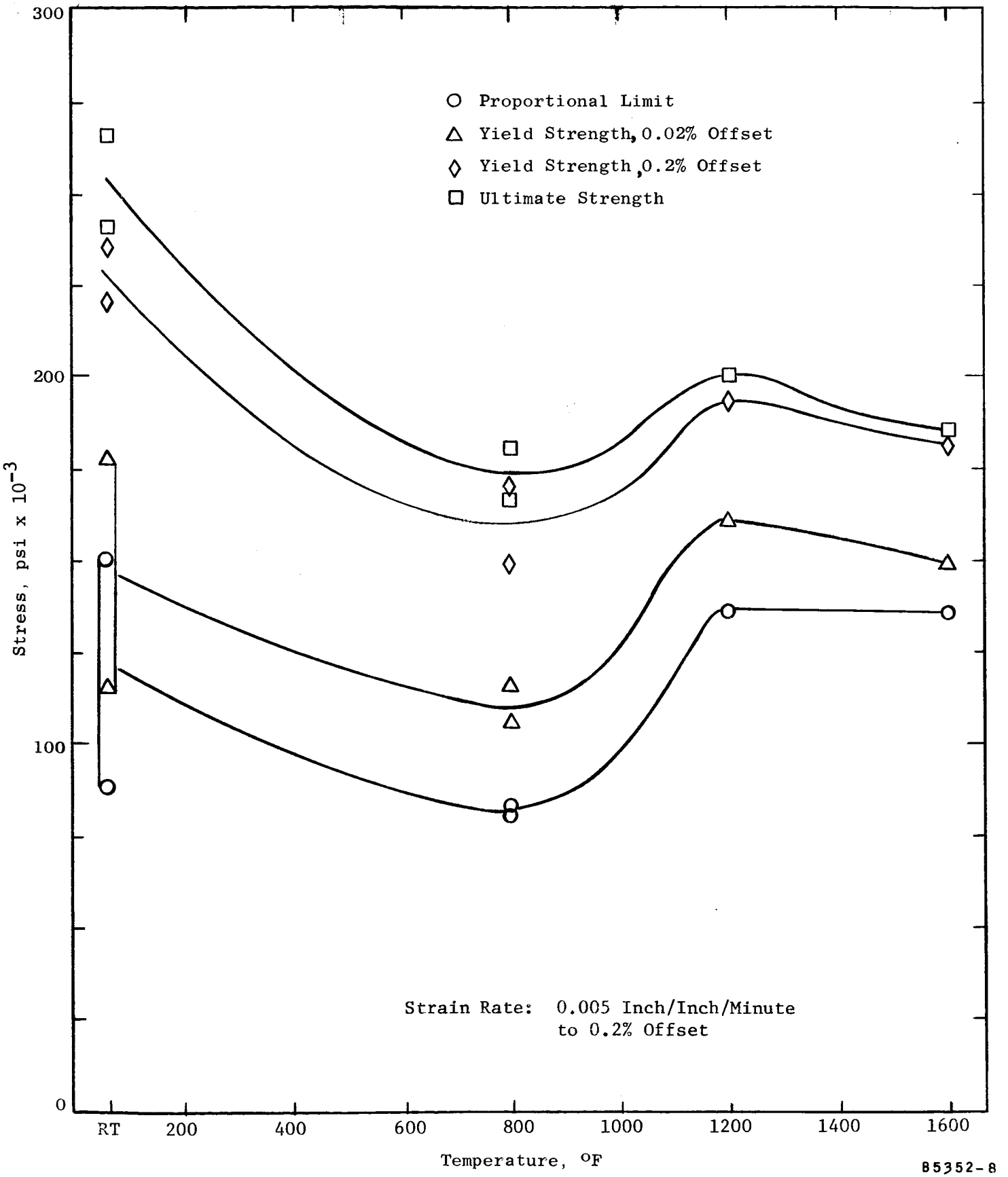


Figure 8. Compression Properties of Zircoa 1027 (ZrO_2).

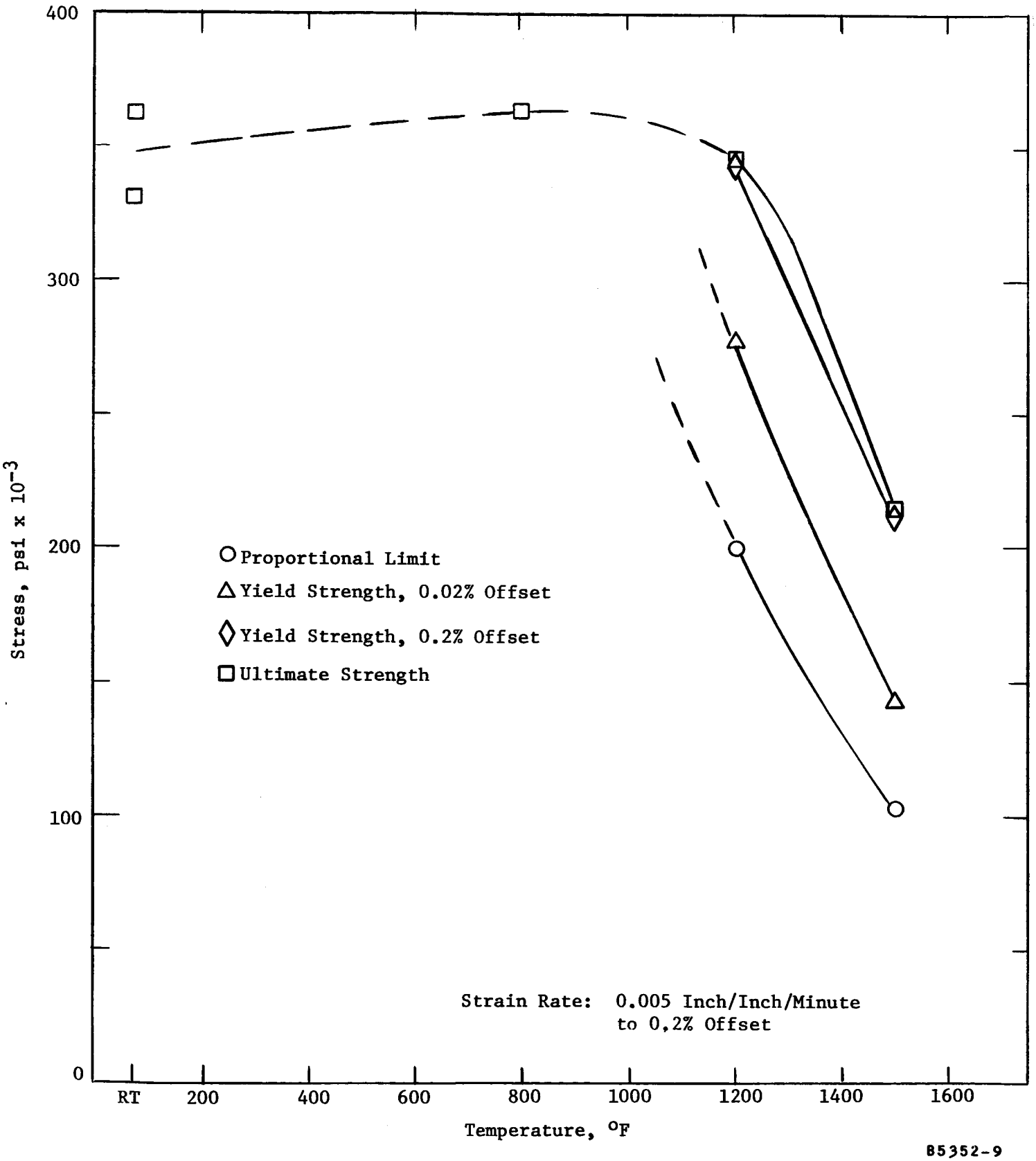


Figure 9. Compression Properties of TiB_2.

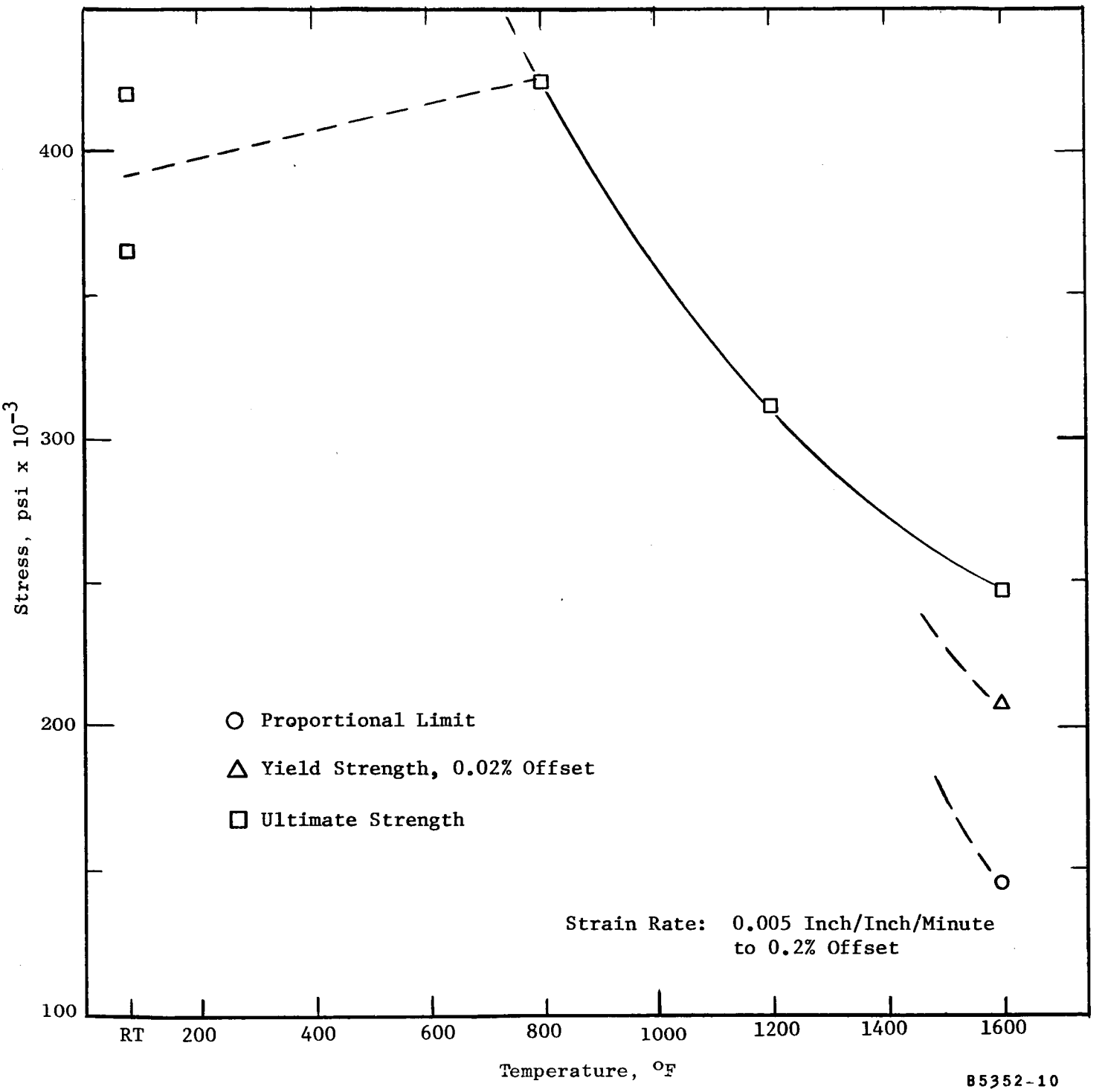


Figure 10. Compression Properties of TiC.

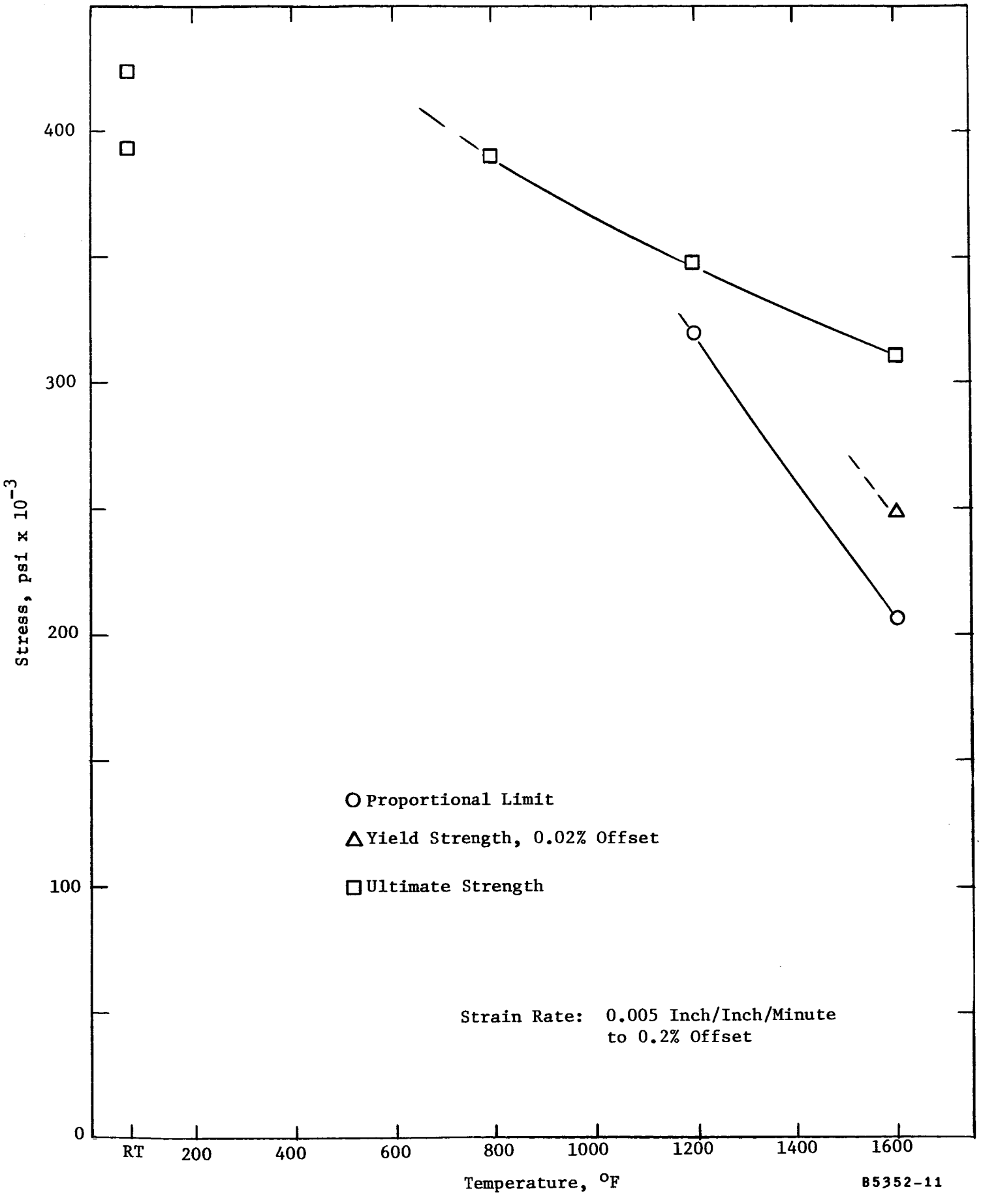


Figure 11. Compression Properties of TiC+5%W

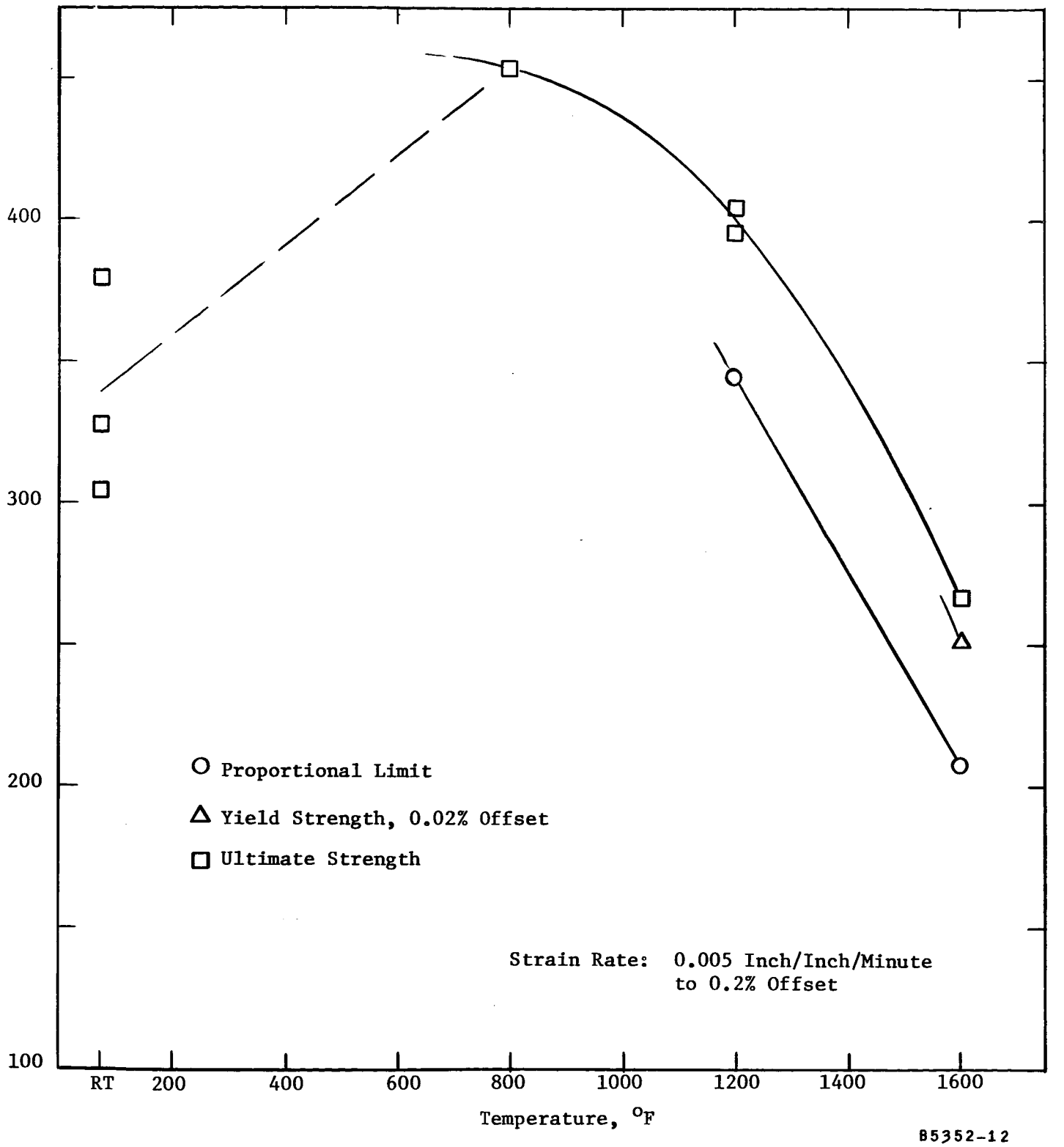


Figure 12. Compression Properties of TiC+10%Mo.

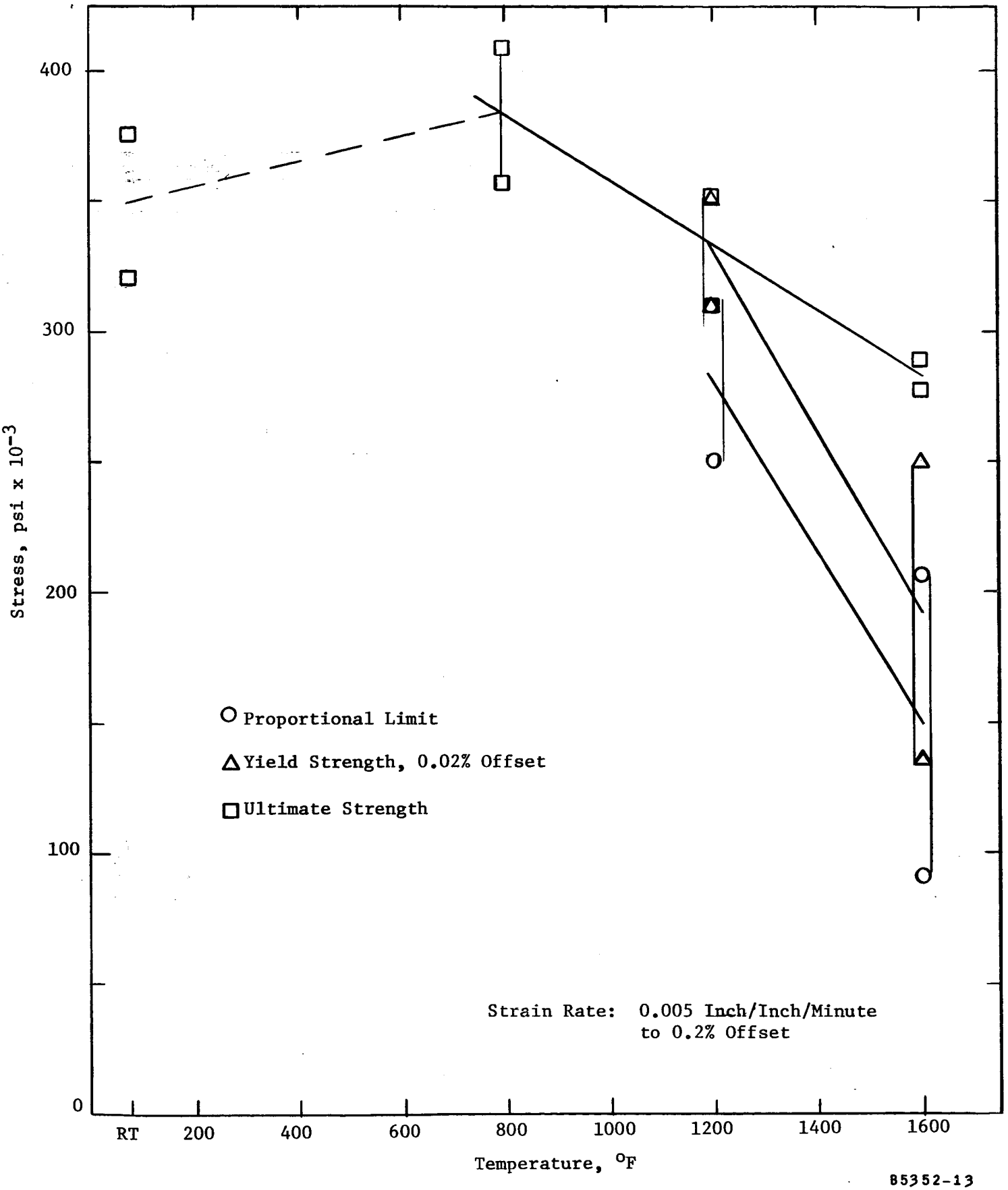
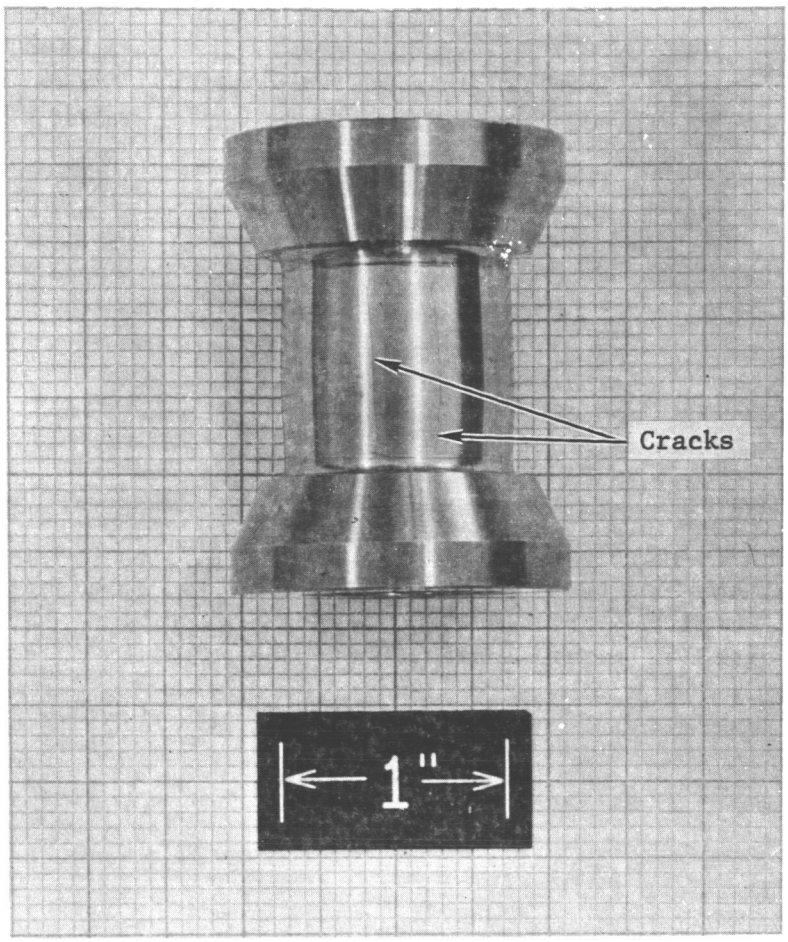
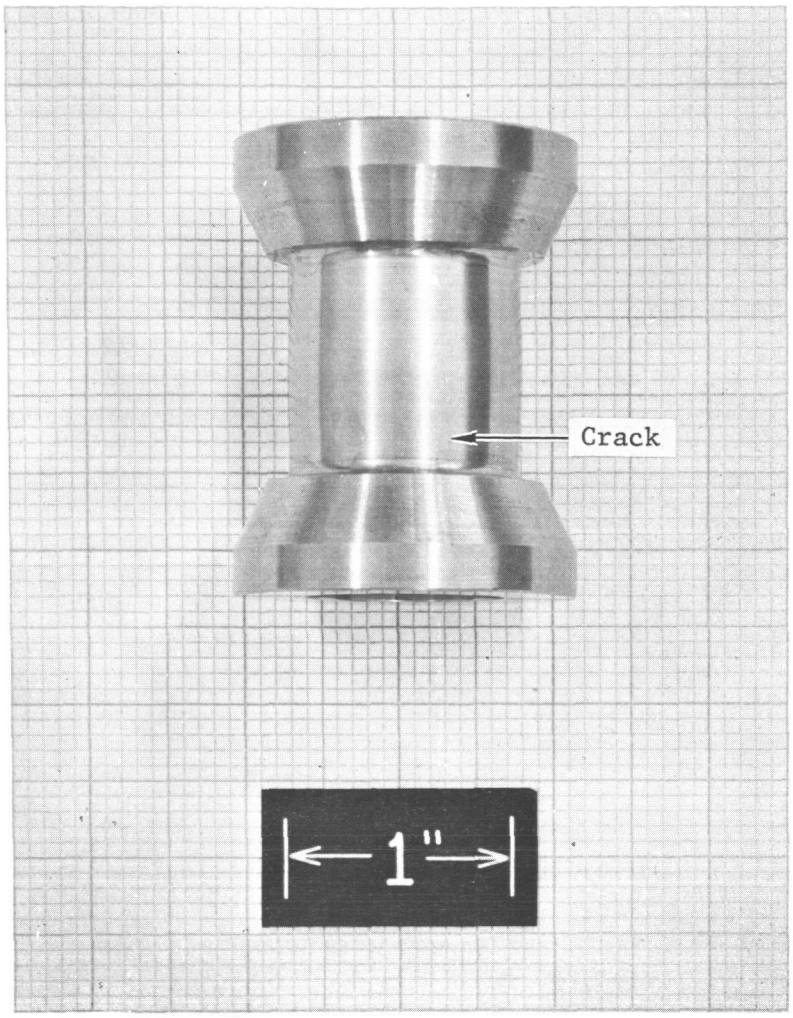


Figure 13. Compression Properties of TiC+10%Cb.



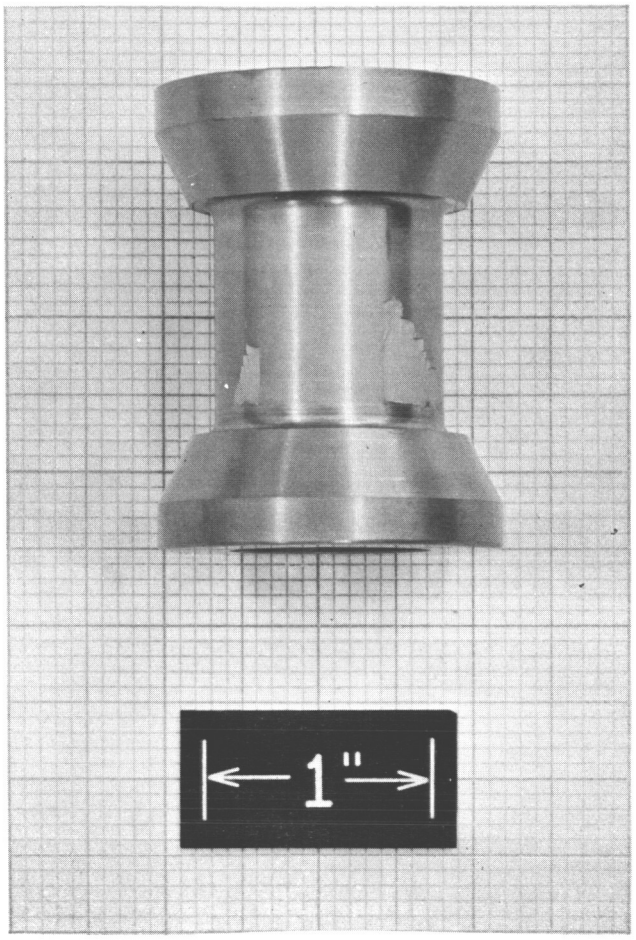
B5352-14

Figure 14. Carboloy 907 Compression Specimen (MCN 1036-G-6) After Being Tested at 1200°F in a Vacuum of 10^{-6} Torr. Test was terminated at 516,000 psi and 3.2% Total Strain (2.77% Plastic Strain). Load was Released Prior to Failure--Note Longitudinal Cracks in Gauge Section.



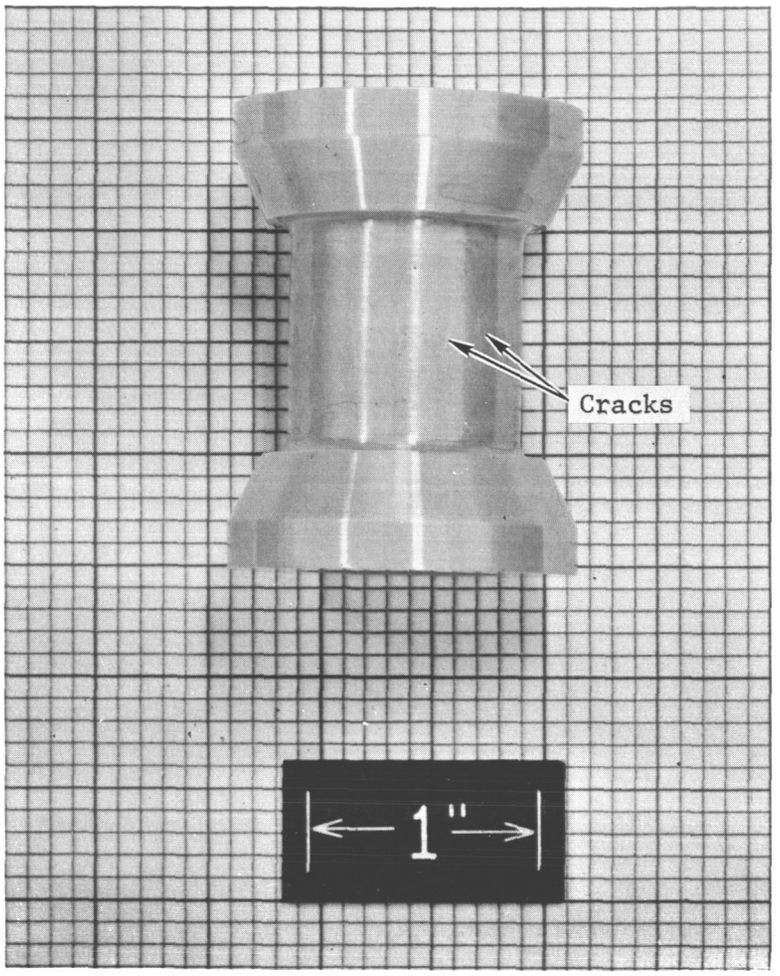
B5352-15

Figure 15. Carboloy 999 Compression Specimen (MCN 1035-G-5) After Being Tested at 1200°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 528,000 psi and 3.3% Total Strain (2.89% Plastic Strain). Load was Released Prior to Failure--Note Longitudinal Cracks in Gauge Section.



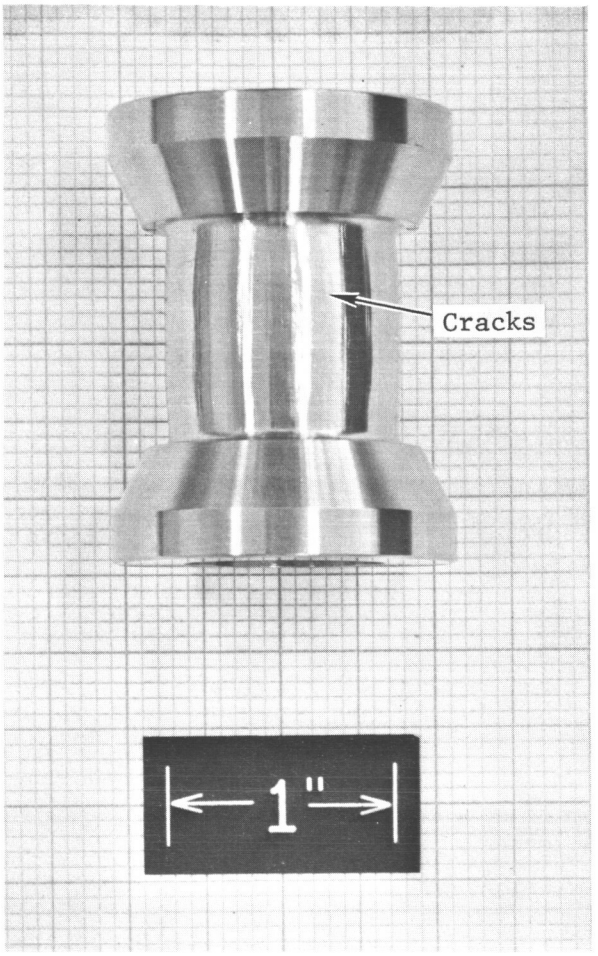
B5352-16

Figure 16. TiC+5%W Compression Specimen (MCN 1043-G-2) After Being Tested at 1200°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 349,000 psi and 0.74% Total Strain (0.06% Plastic Strain). Evidence that Failure had Initiated is Indicated by Spalled Portions of Gauge Section.



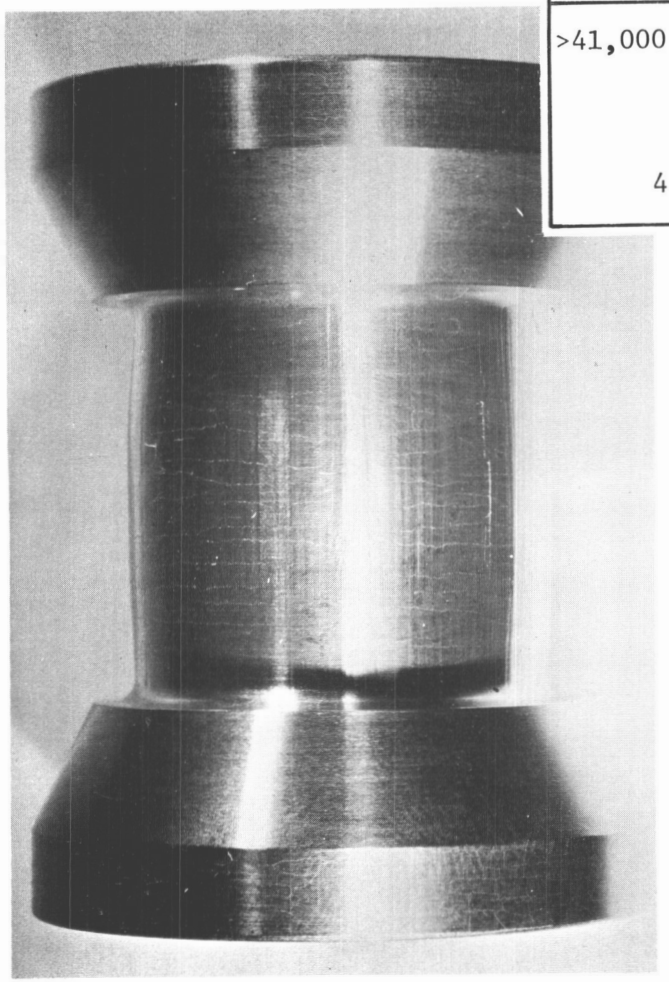
B5352-17

Figure 17. Zircoa 1027 Compression Specimen (MCN 1040-G-7) After Being Tested at 800°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 180,000 psi and 1.6% Total Strain (1.09% Plastic Strain). Load was Released Prior to Failure--Note Longitudinal Cracks in Gauge Section.

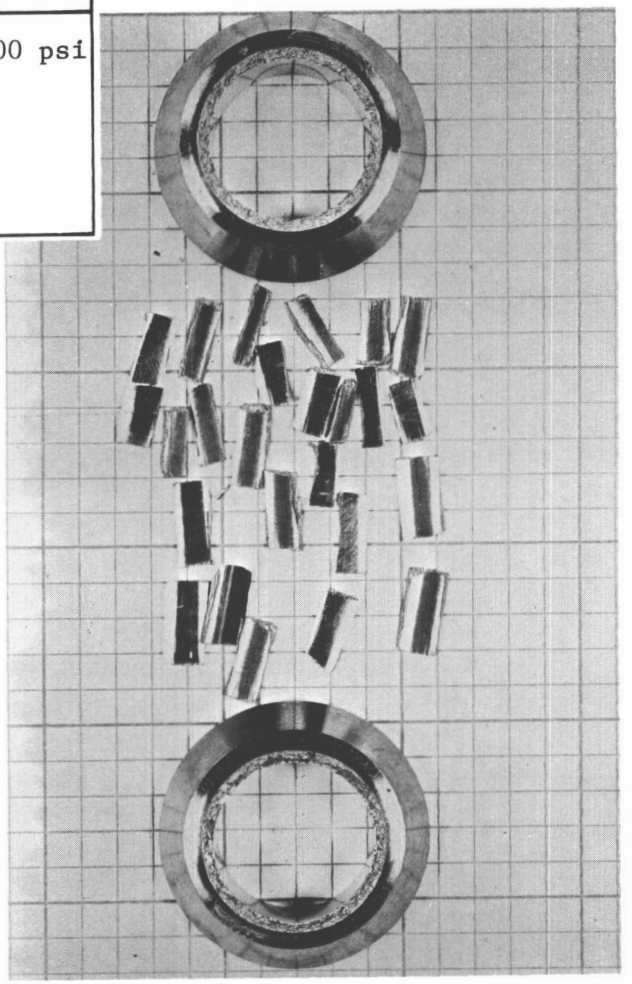


B5352-18

Figure 18. Stress Relieved Arc Cast Unalloyed Tungsten Compression Specimen (MCN 1038-G-7) After Being Tested at 1200°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 41,000 psi and 5% Total Strain (4.93% Plastic Strain). Load was Released Prior to Failure. - Note Crack Pattern in Gauge Section, See Figure 19.

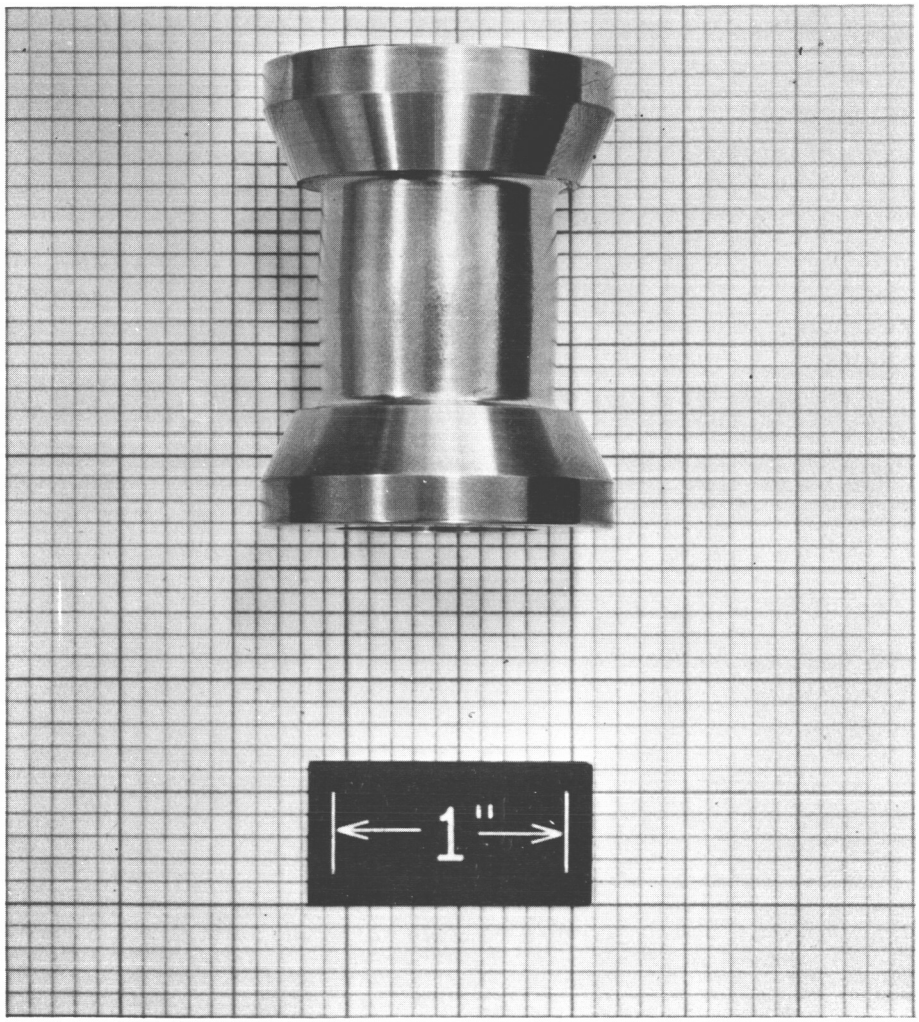


1200°F	Temp.	RT
>41,000 psi	UCS	154,000 psi
5%	Total Strain	2%
4.93%	Plastic Strain	1.84%



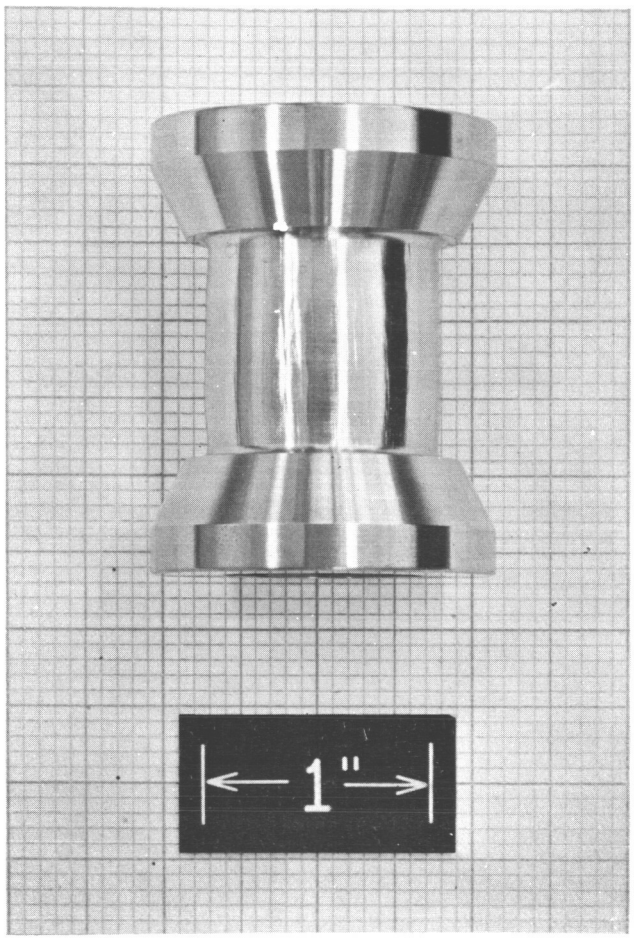
B5352-19

Figure 19. Stress Relieved Arc Cast Unalloyed Tungsten Compression Specimens After Being Tested at 1200°F in a Vacuum of 10^{-6} Torr (Left) and at Room Temperature (Right)--Note Crack Pattern in the Specimen Tested at 1200°F is Similar in Shape to the Fractured Pieces from the Specimen Tested at Room Temperature.



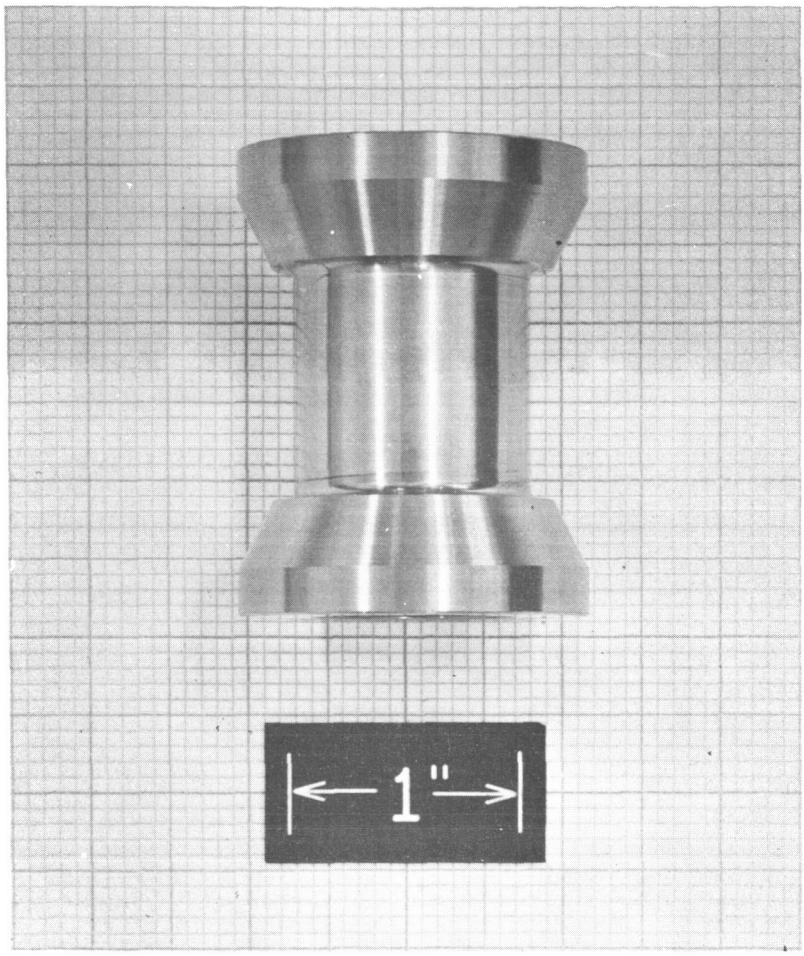
B5352-20

Figure 20. As Cast Star J Compression Specimen (MCN 1047-G-3) After Being Tested at 1600°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 52,800 psi and 5% Total Strain (4.95% Plastic Strain).



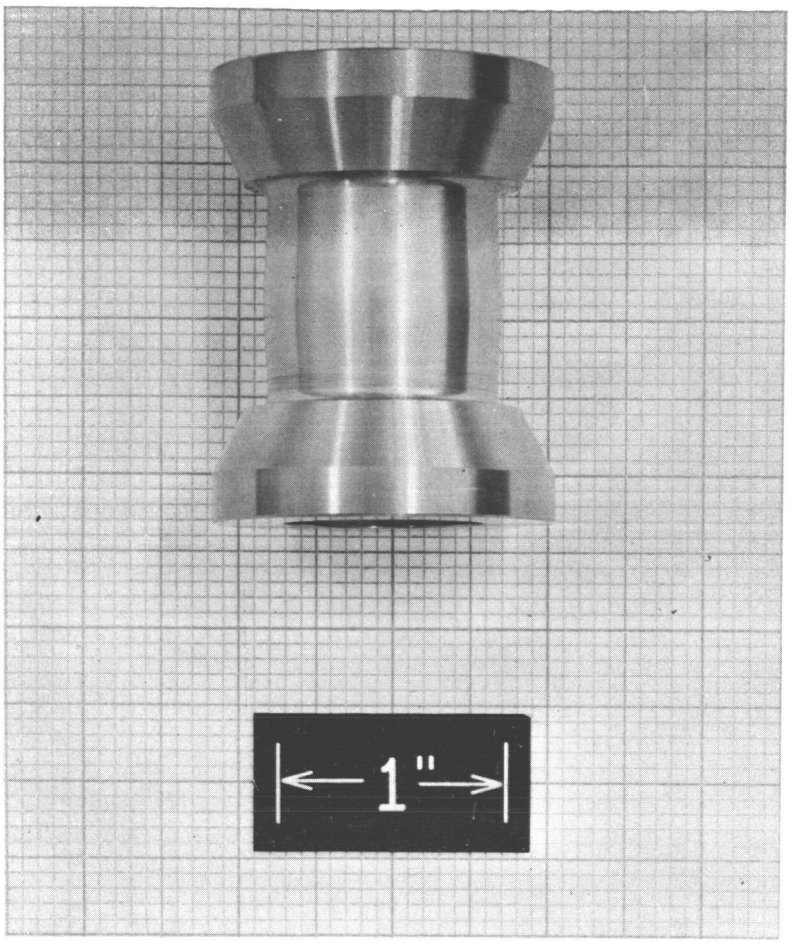
B5352-21

Figure 21. Stress Relieved Arc Cast Unalloyed Tungsten Compression Specimen (MCN 1038-G-4) After Being Tested at 800°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 52,800 psi and 5% Total Strain (4.95% Plastic Strain).



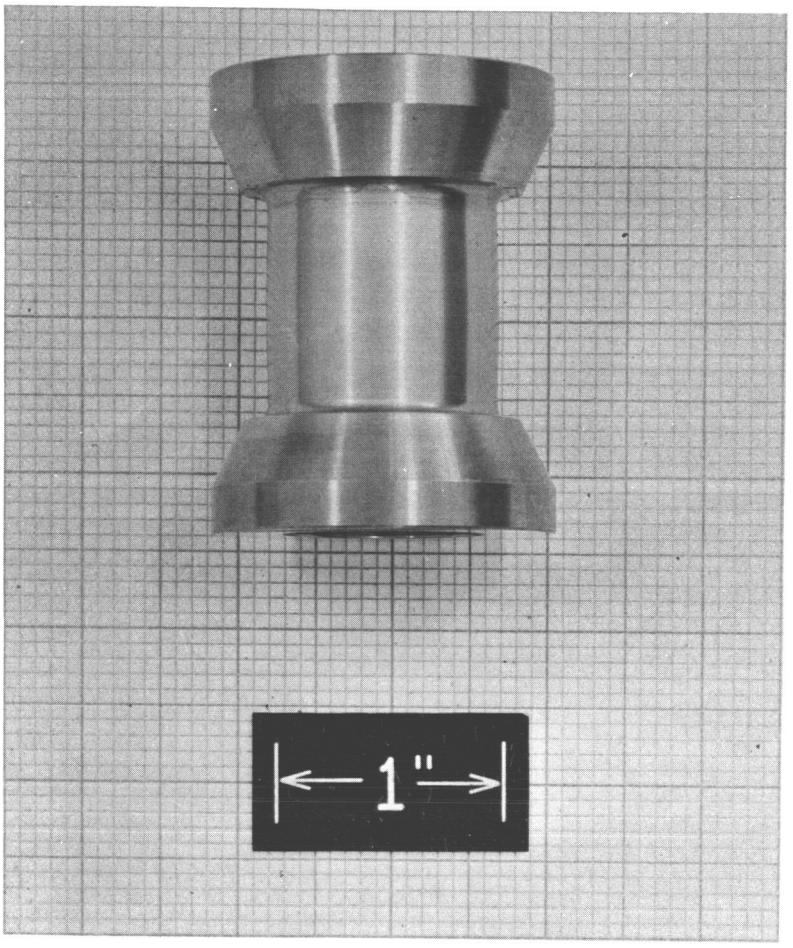
B5352-22

Figure 22. Carboloy 907 Compression Specimen (MCN 1036-G-3) After Being Tested at 800°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 607,000 psi and 1.9% Total Strain (1.47% Plastic Strain).



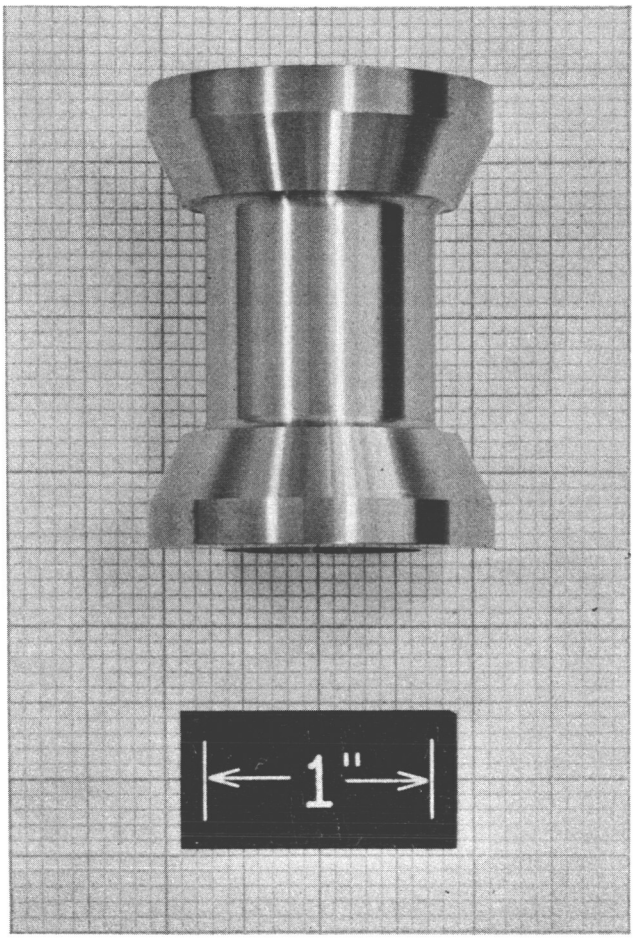
B5352-23

Figure 23. Carboloy 907 Compression Specimen (MCN 1036-G-7) After Being Tested at 1600°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 271,000 psi and 5% Total Strain (3.2% Plastic Strain).



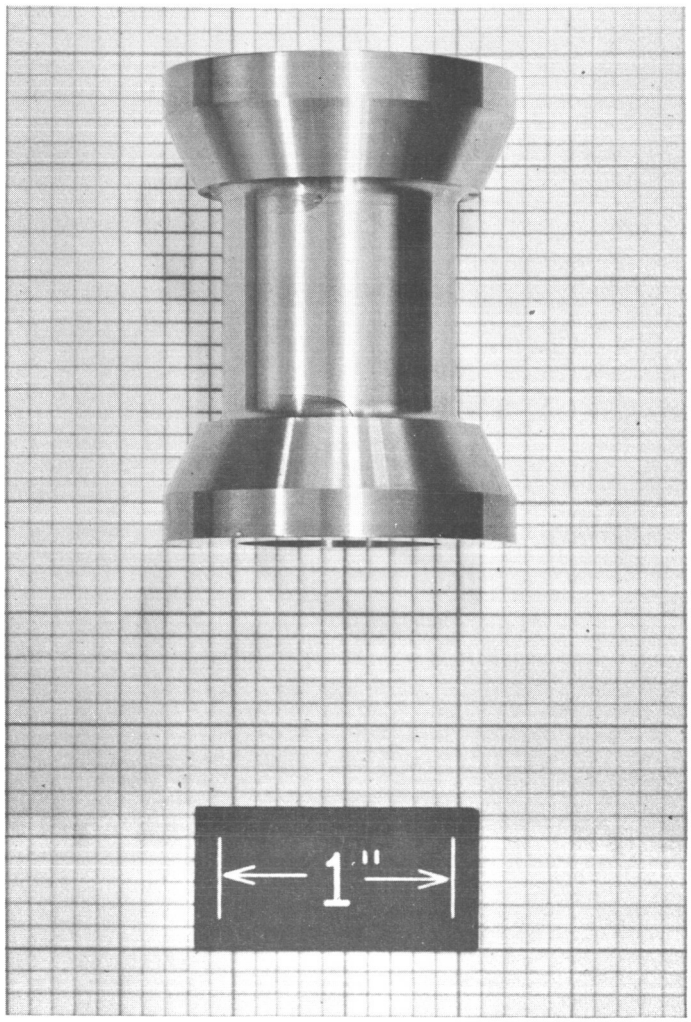
B5352-24

Figure 24. Carboloy 999 Compression Specimen (MCN 1035-G-7) After Being Tested at 1600°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 270,000 psi and 2% Total Strain (1.76% Plastic Strain).



B5352-25

Figure 25. Grade 7178 Compression Specimen (MCN 1046-G-10) After Being Tested at 1200°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 551,000 psi and 1.2% Total Strain (0.69% Plastic Strain).



B5352-26

Figure 26. Grade 7178 Compression Specimen (MCN 1046-G-2) After Being Tested at 800°F in a Vacuum of 10^{-6} Torr. Test was Terminated at 602,000 psi and 1.17% Total Strain (0.75% Plastic Strain).

APPENDICES

APPENDIX A

STRESS-STRAIN CURVES FOR CANDIDATE BEARING MATERIALS IN COMPRESSION

APPENDIX A

LIST OF ILLUSTRATIONS

Figure No.		Page No.
A-1	Stress Strain Curves for Star J in Compression.	65
A-2	Stress Strain Curves for Star J in Compression.	66
A-3	Stress Strain Curves for Stress Relieved Arc Cast Unalloyed Tungsten in Compression	67
A-4	Stress Strain Curves for Carboloy 907 in Compression. . . .	68
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A-6	Stress Strain Curves for Grade 7178 in Compression.	70
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A-10	Stress Strain Curves for TiC in Compression	74
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A-12	Stress Strain Curves for TiC+10%Mo in Compression	76
A-13	Stress Strain Curves for TiC+10%Cb in Compression	77

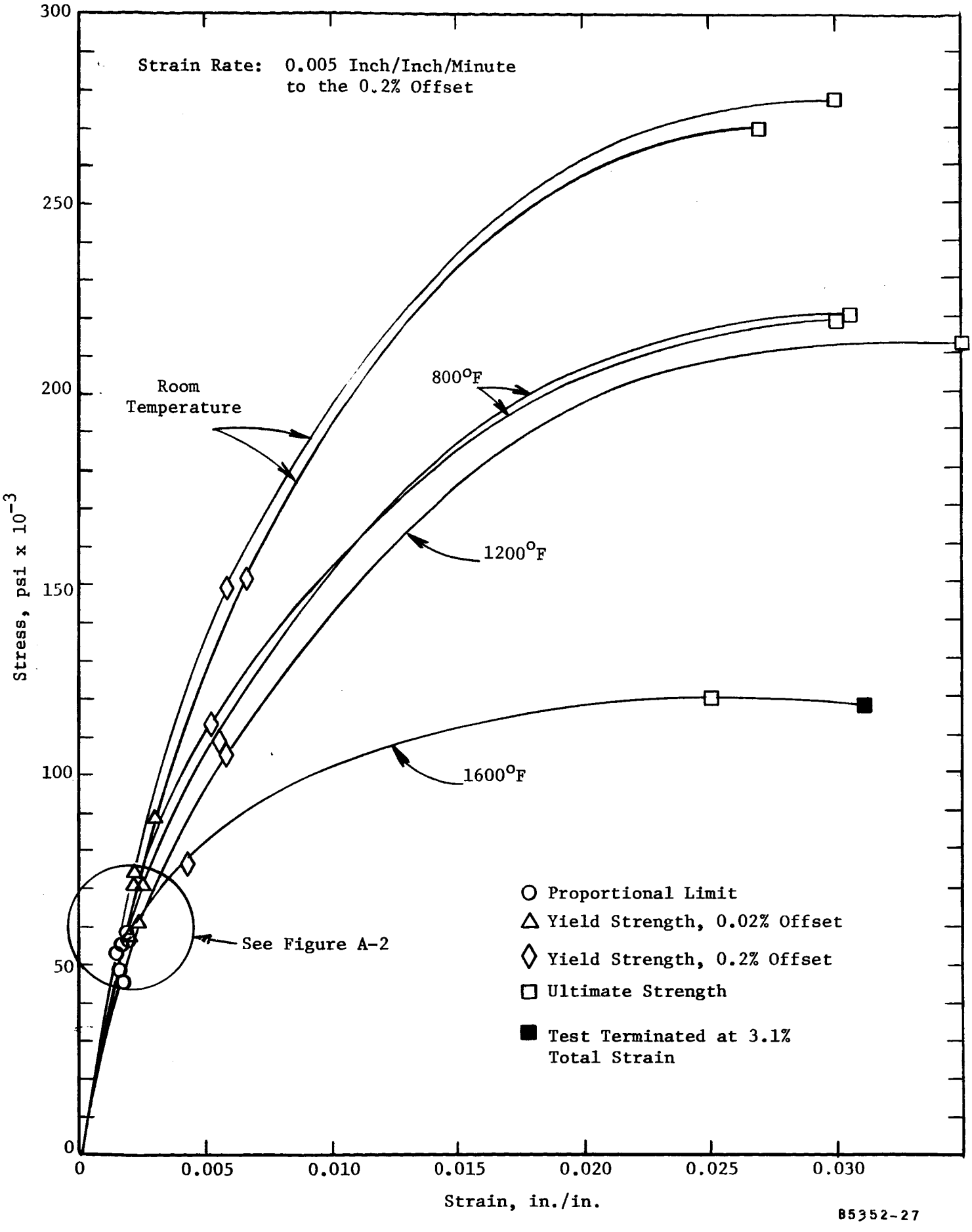


Figure A-1. Stress Strain Curves for As Cast Star J in Compression.

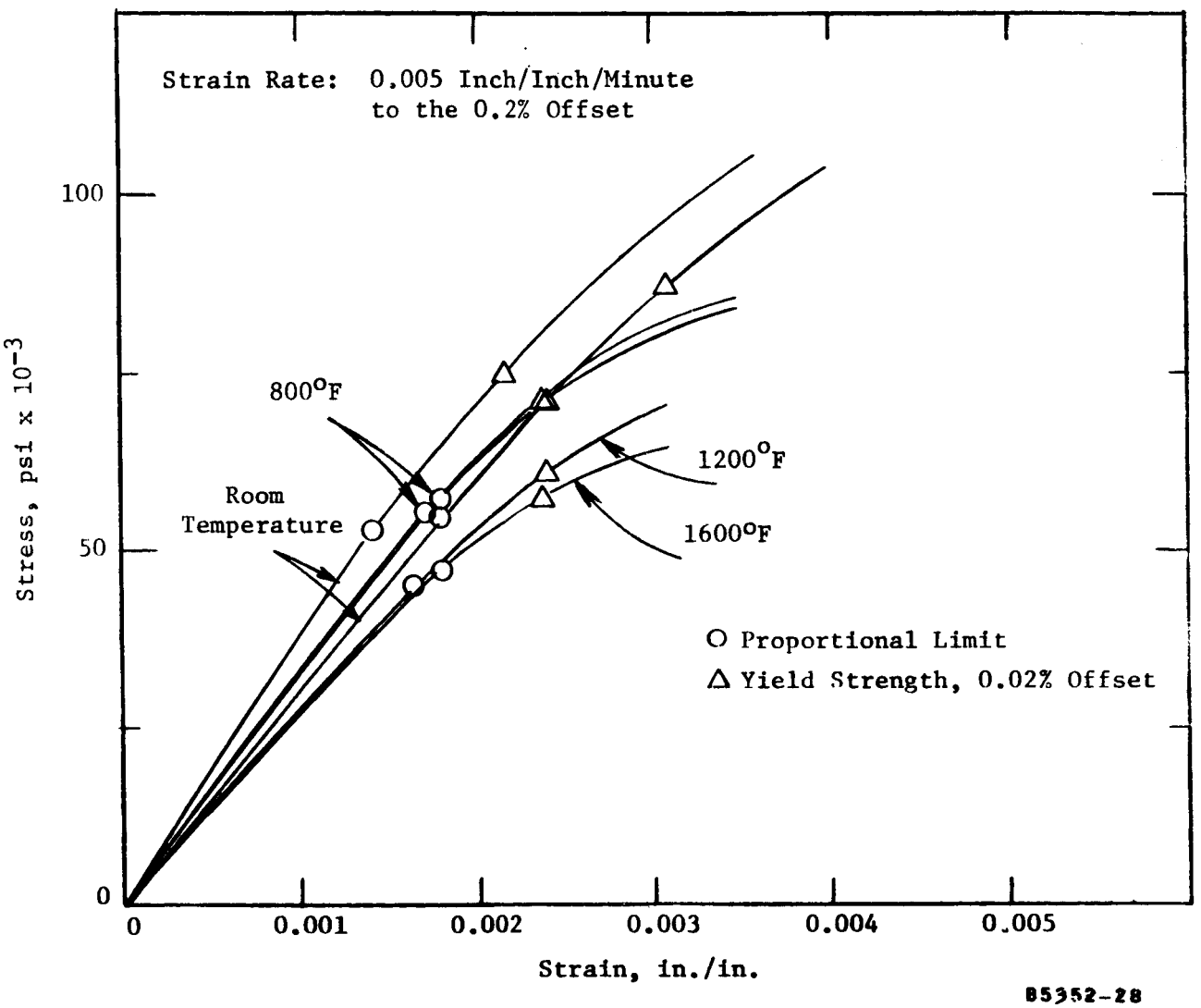


Figure A-2. Stress Strain Curves for As Cast Star J in Compression.

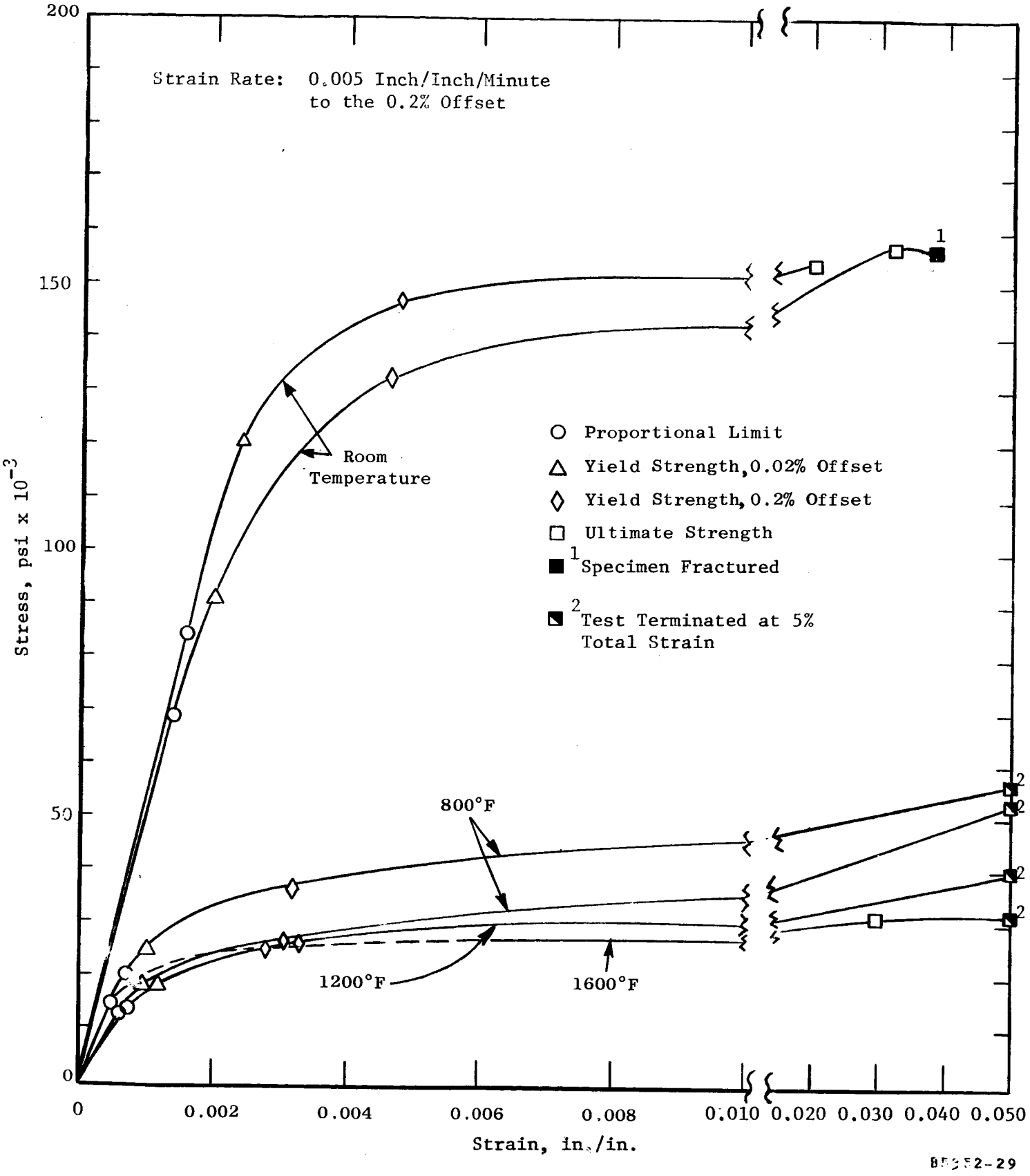


Figure A-3. Stress Strain Curves for Stress Relieved Arc Cast Unalloyed Tungsten in Compression.

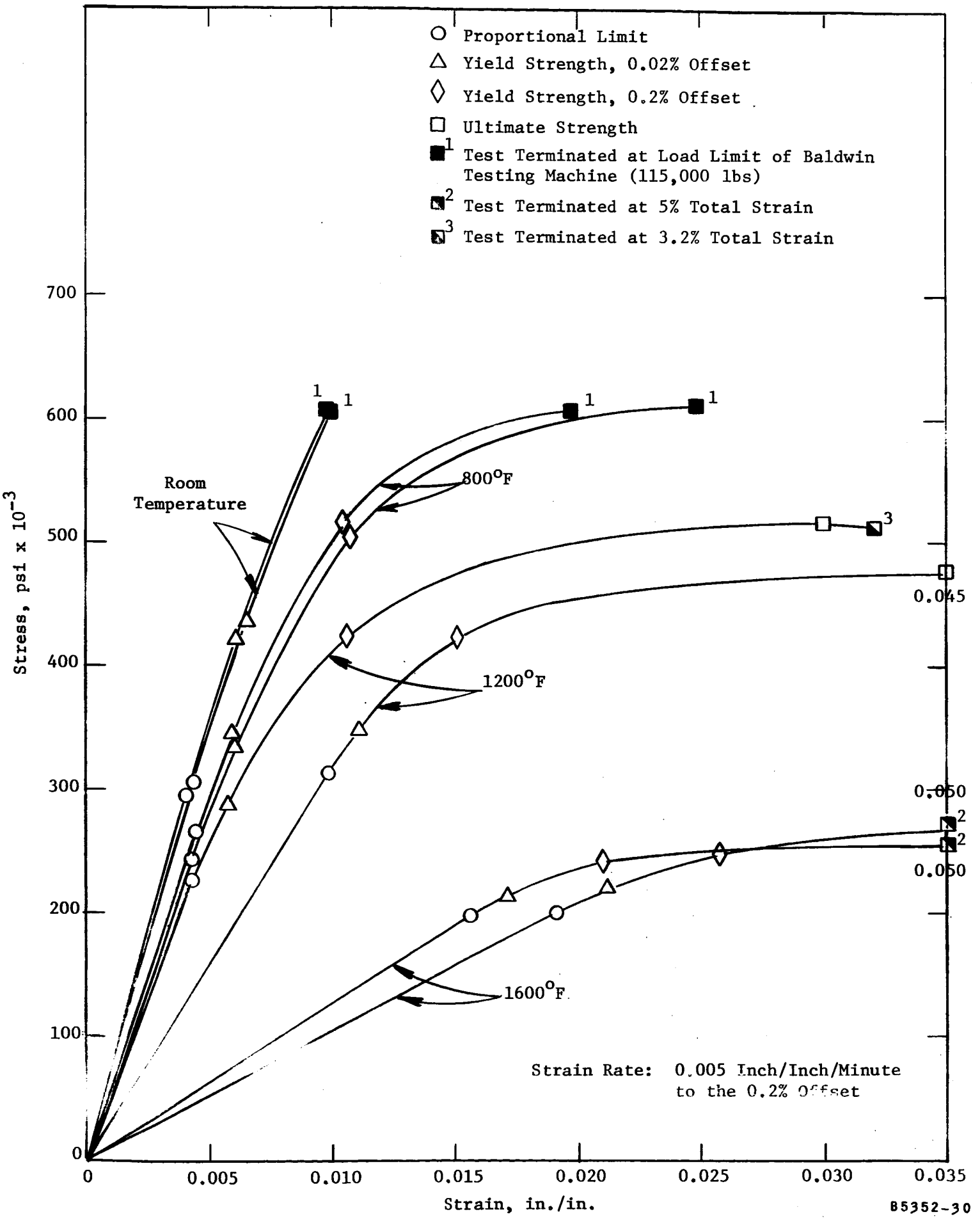


Figure A-4. Stress Strain Curves for Carboloy 907 in Compression.

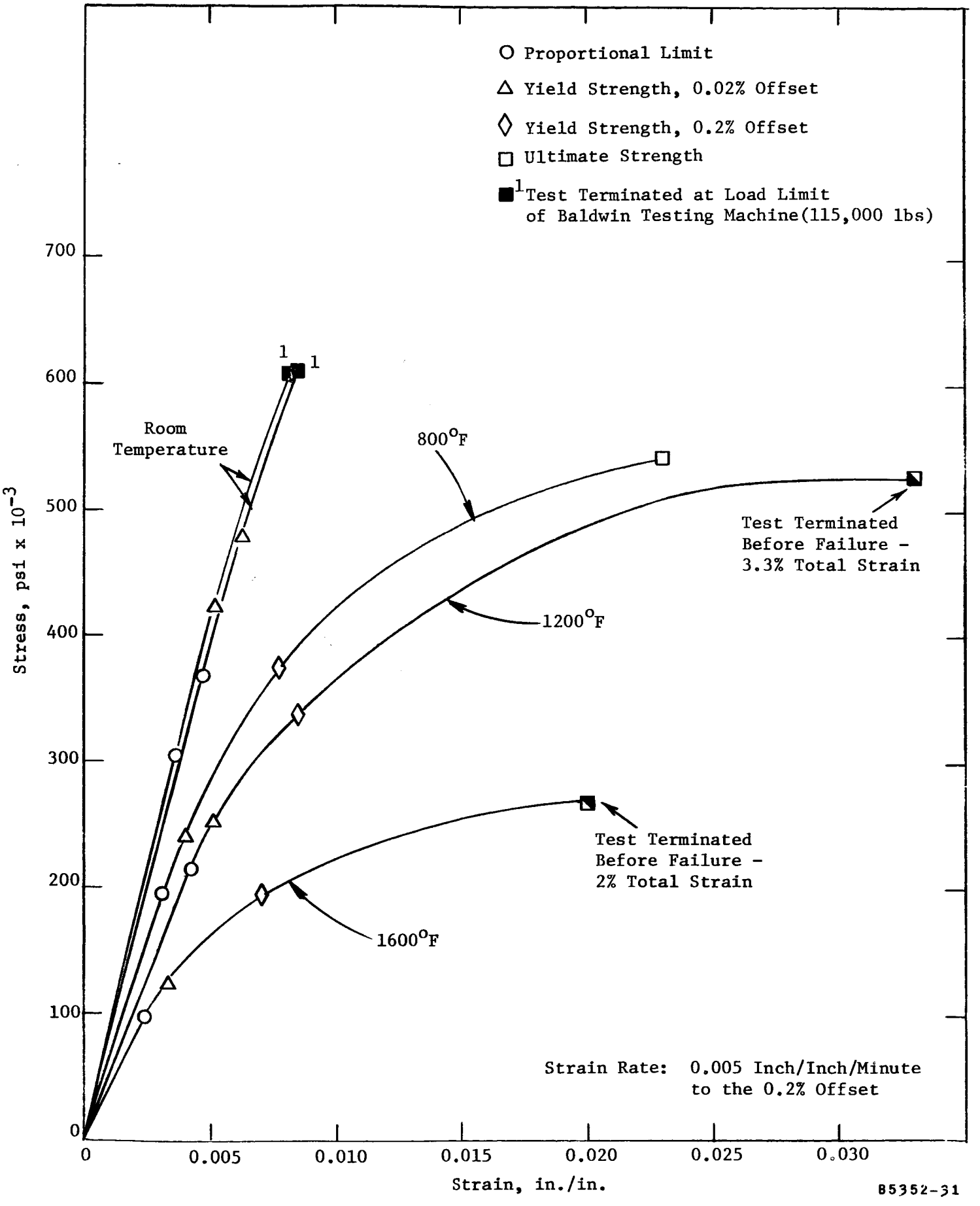


Figure A-5. Stress Strain Curves for Carboloy 999 in Compression.

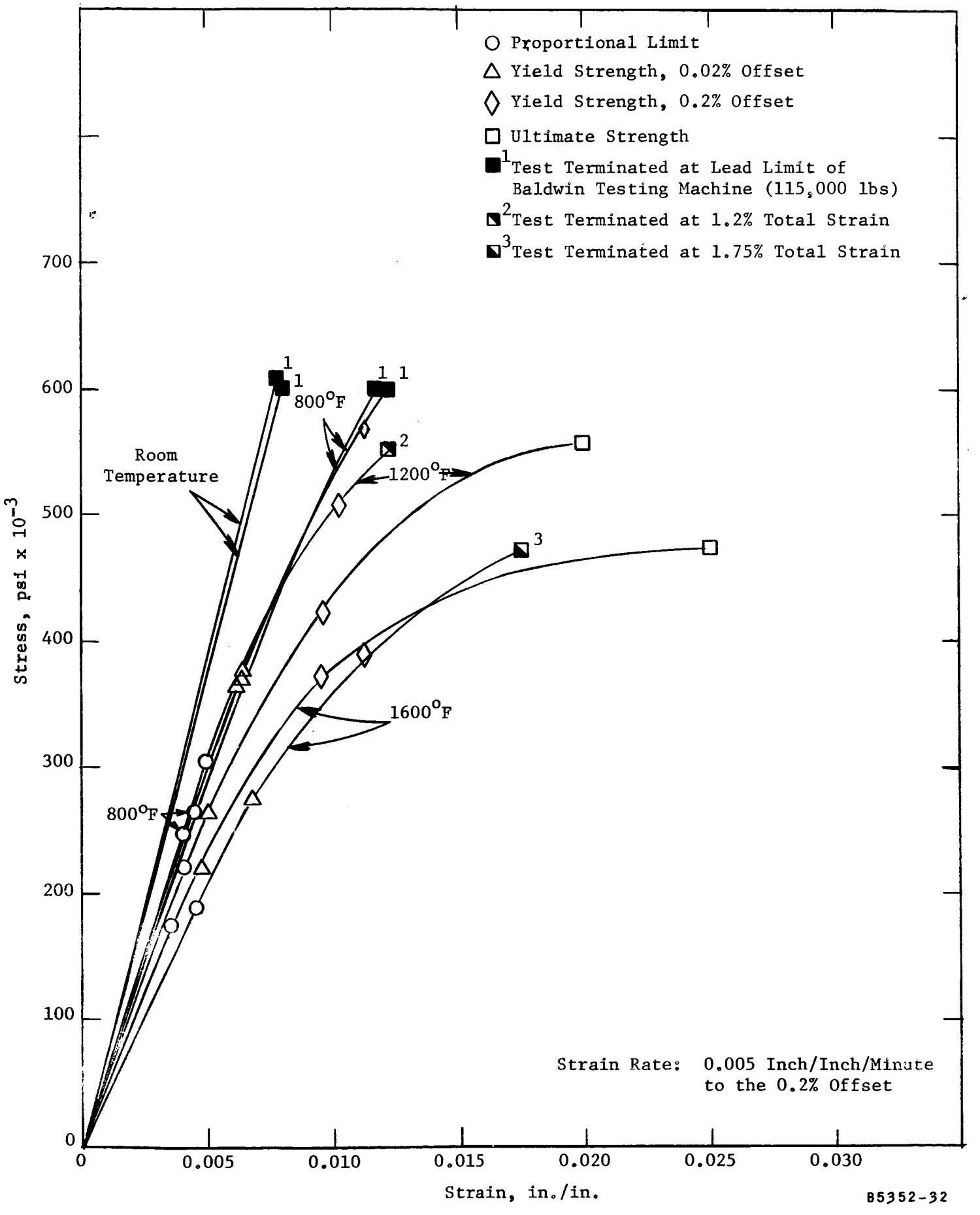


Figure A-6. Stress Strain Curves for Grade 7178 in Compression.

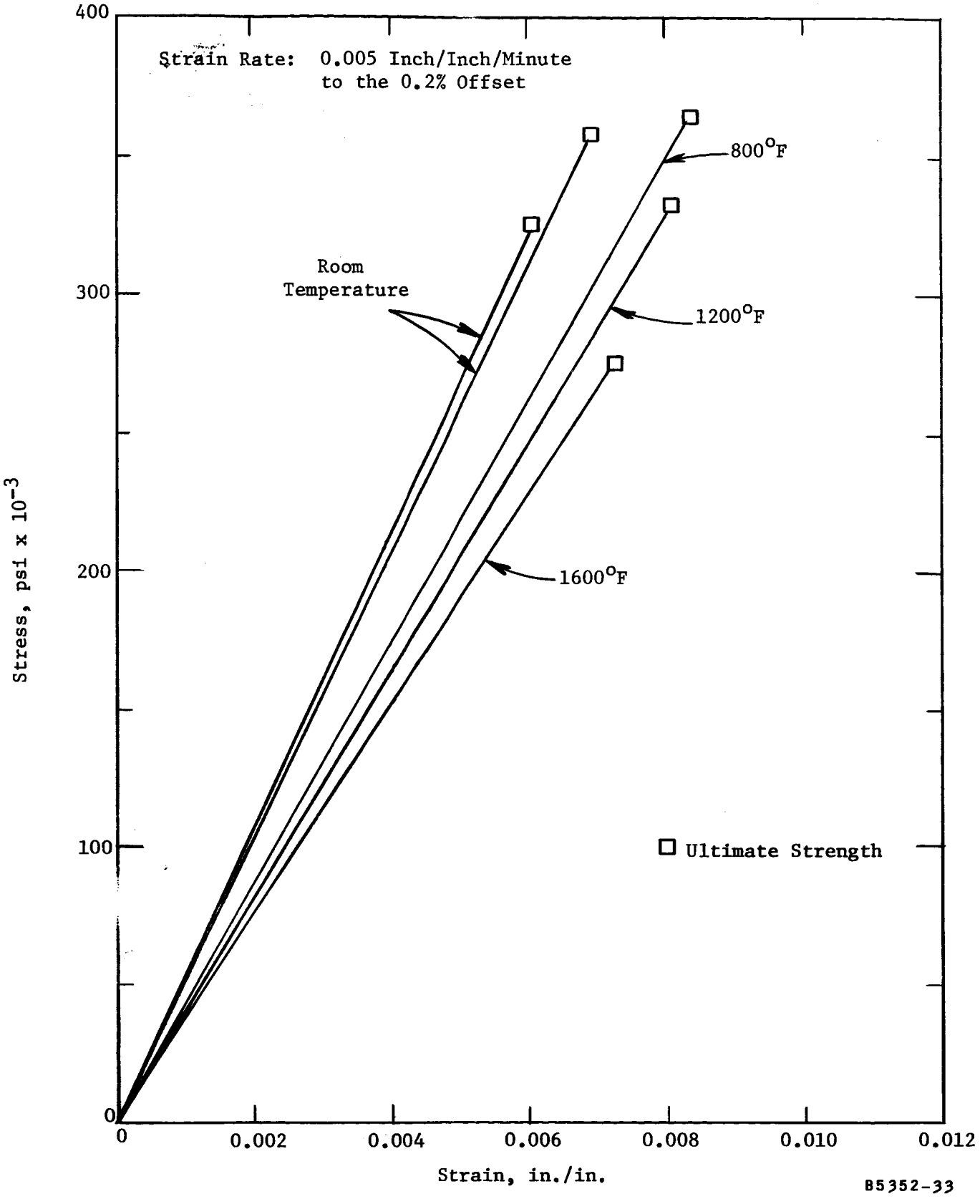


Figure A-7. Stress Strain Curves for Lucalox in Compression.

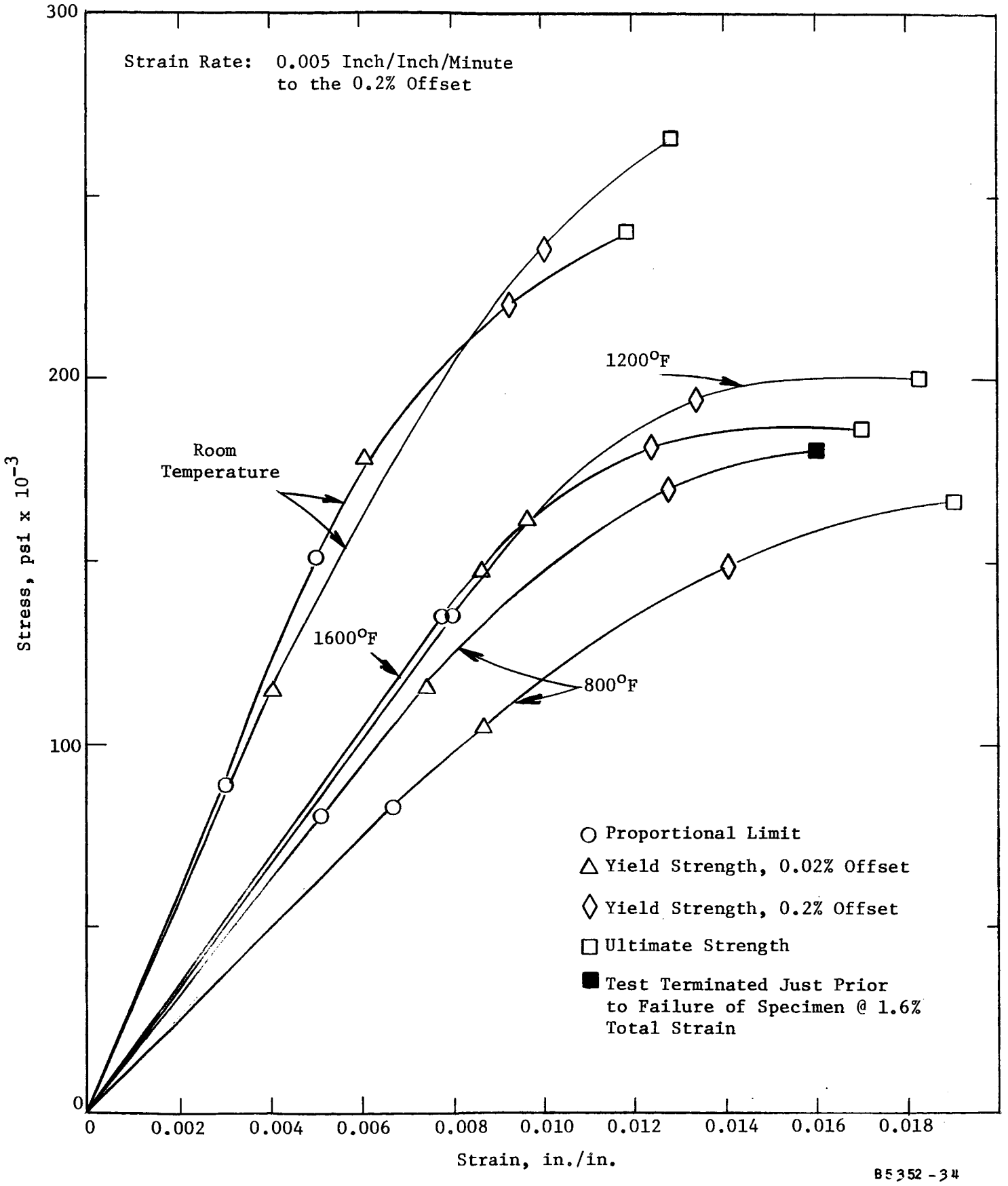


Figure A-8. Stress Strain Curves for Zircoa 1027 in Compression.

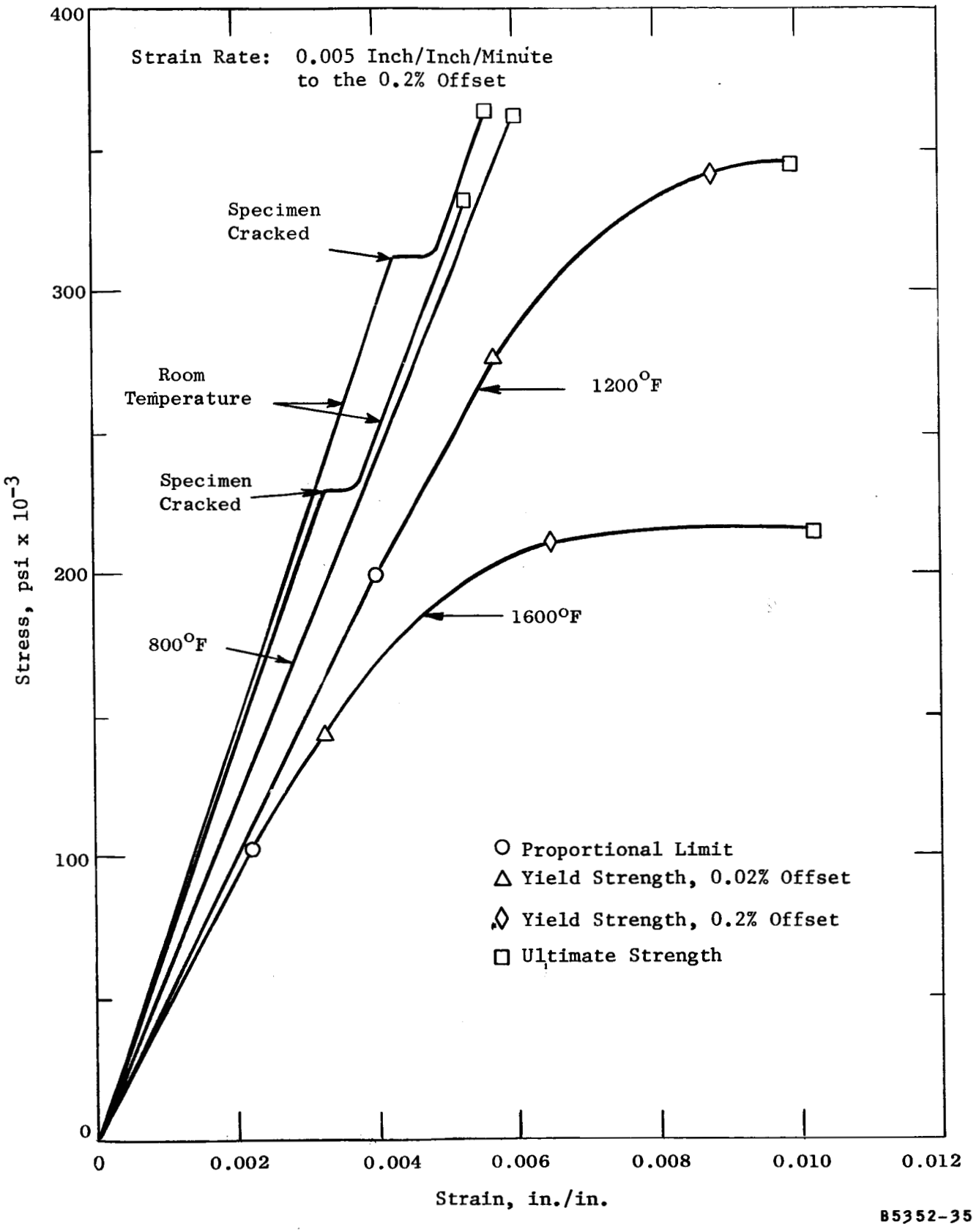


Figure A-9. Stress Strain Curves for TiB_2 in Compression.

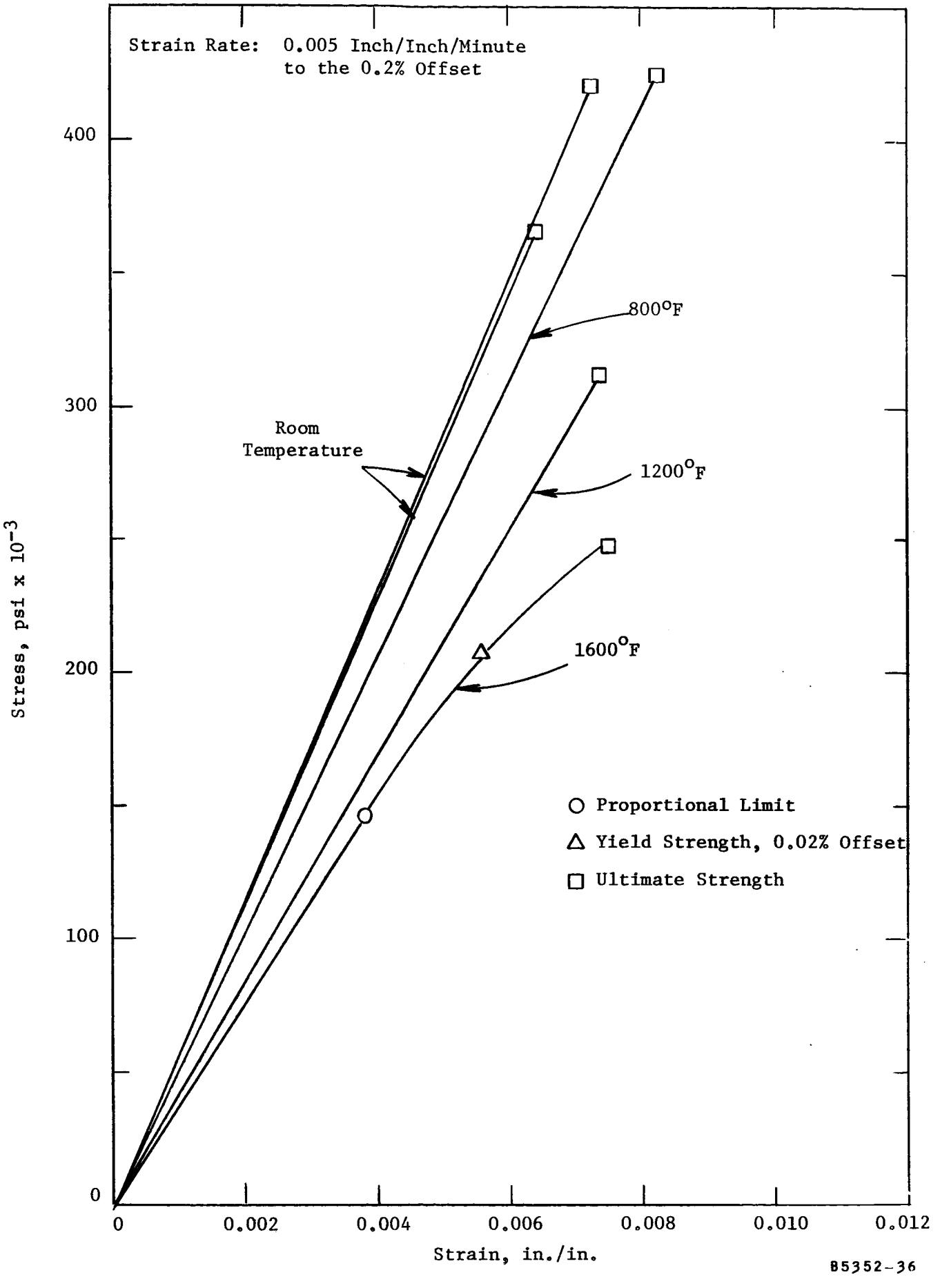


Figure A-10. Stress Strain Curves for TiC in Compression.

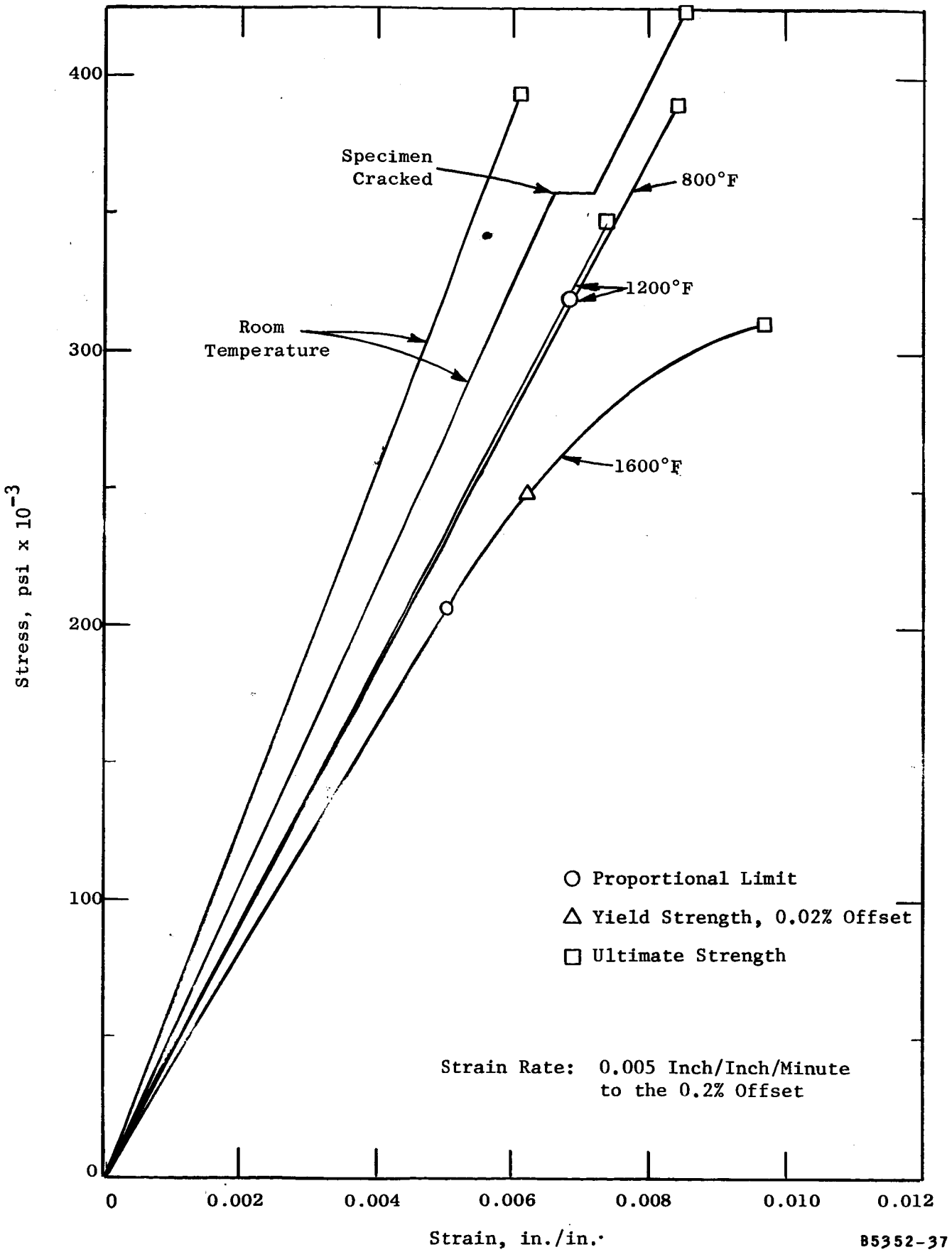


Figure A-11. Stress Strain Curves for TiC+5%W in Compression.

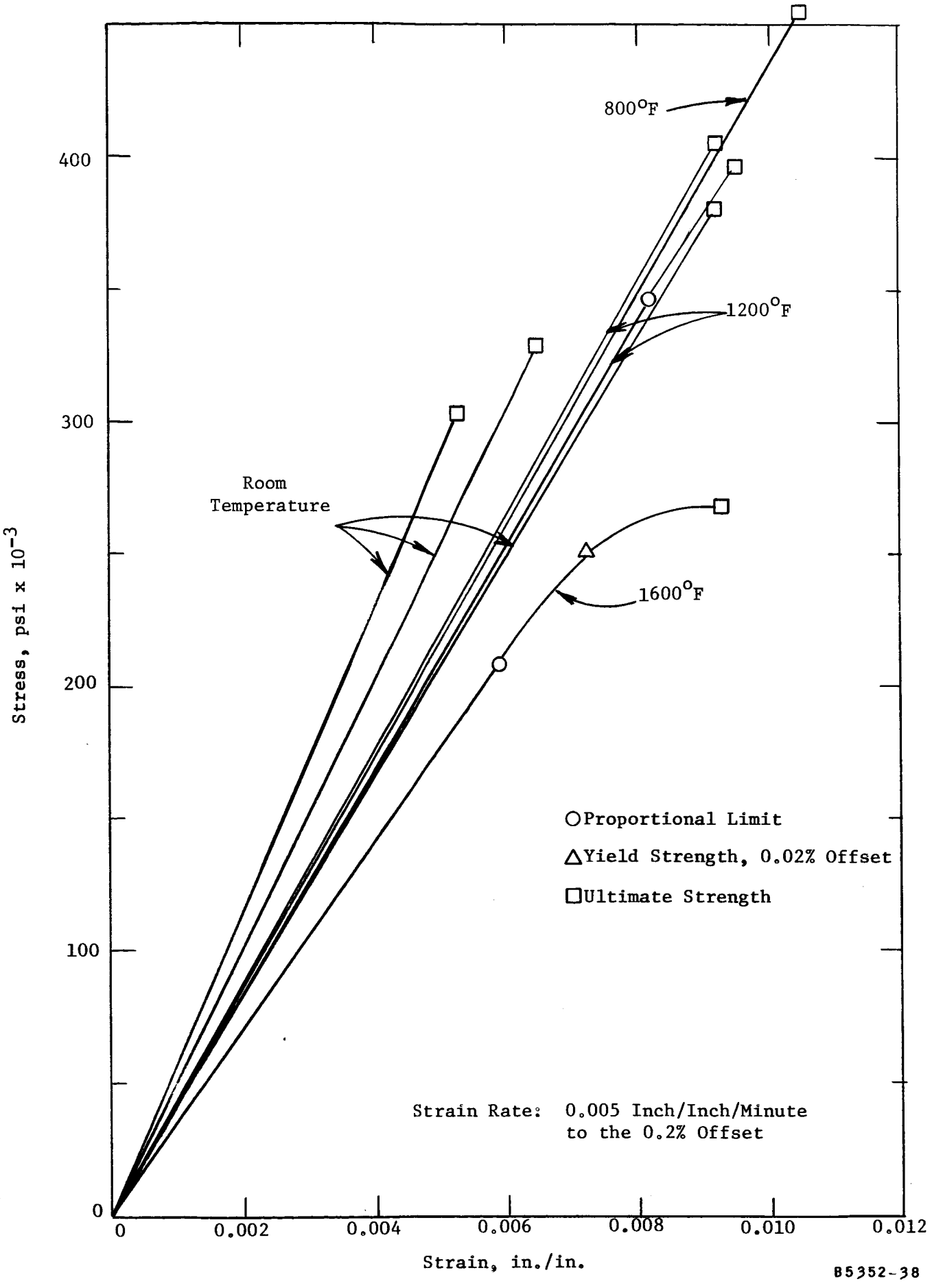


Figure A-12. Stress Strain Curves for TiC+10%Mo in Compression.

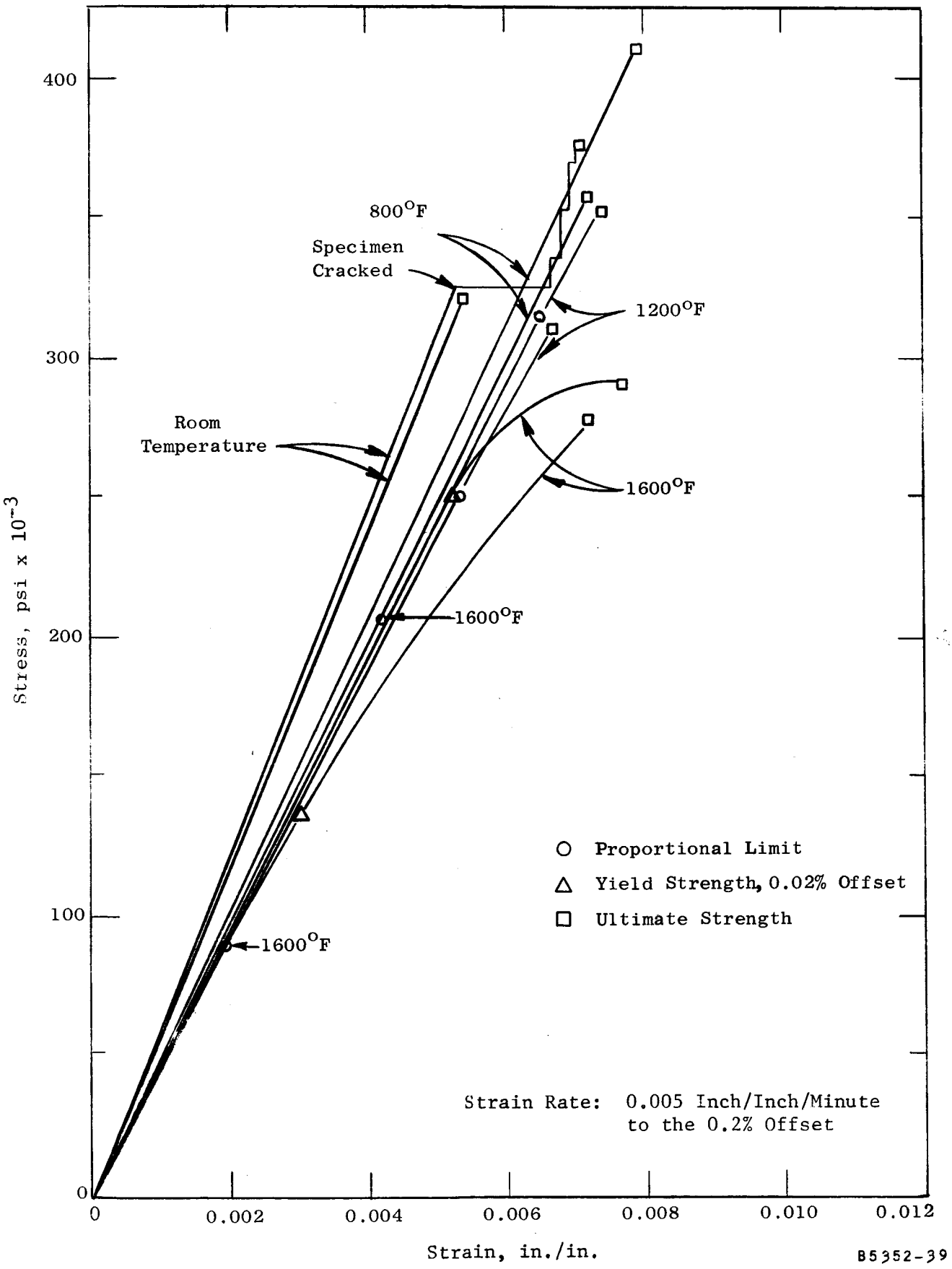


Figure A-13. Stress Strain Curves for TiC+10%Cb in Compression.

APPENDIX B

FRICTION AND WEAR DATA - HIGH VACUUM

FRICTION AND WEAR TEST PROGRAM

FRICTION AND WEAR TEST DATA FOR CARBOLOY 907 VS CARBOLOY 907 IN HIGH VACUUM

Test No. - 508H08B

Assembly No. - XX

Loading Arm No. - 4

Test Date - 4/29/66

Rider
Material - Carboloy 907
Specimen No. - 1036-E-15

Disc
Material - Carboloy 907
Specimen No. - 1036-F-7A

Test Temperature, °F - 806

Max. ΔT of Rider, °F - 141

Speed, SFM - 800

Test Duration, Min. - 60.00

Compressive Load, Lbs - 0.339 (H)

Compressive Stress, psi - 156,430

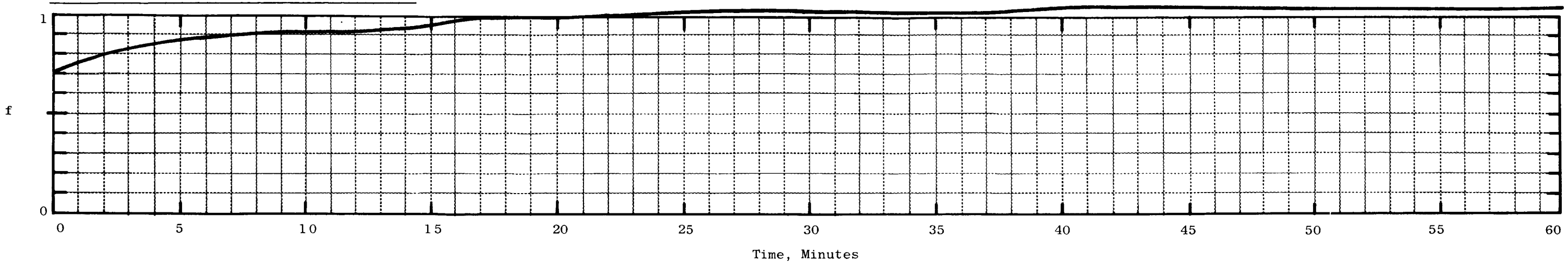
Load/Material UCS or 0.2%CYS -
Rider - 25%
Disc - 25%

Average Coefficient of Friction - 1.00

Chamber Pressure, Torr -
Start - 8.5×10^{-9}
Max. - 9.5×10^{-9}

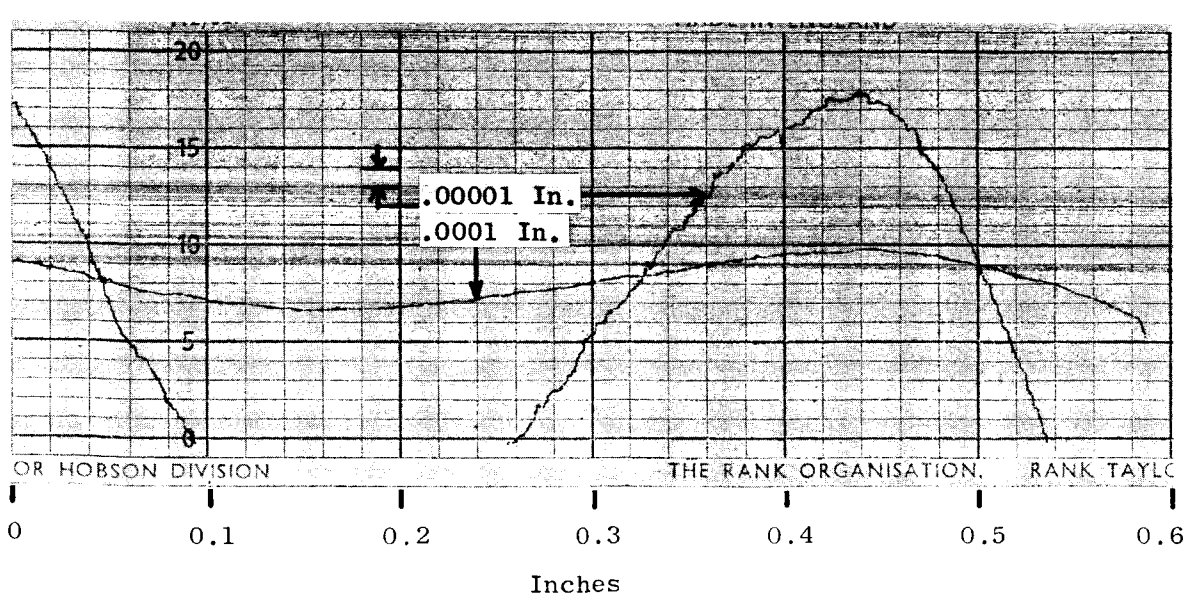
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



Wear Scar Dia., In. - 0.033

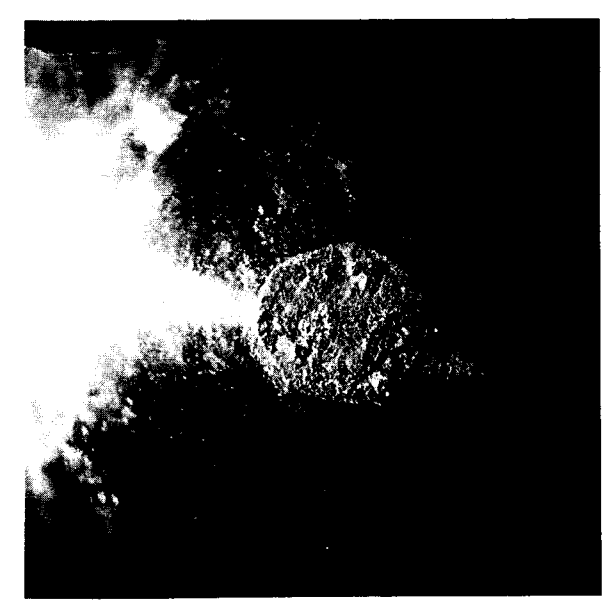
Weight, Gms -

Start -	3.5177
Finish -	3.5170
Change -	-0.0007

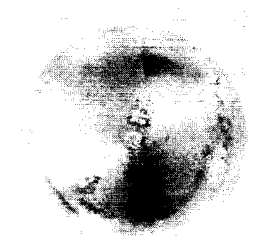
Material Density, Gms/Cm^3 -
14.684

Volume Change, Mm^3 -
-0.0477

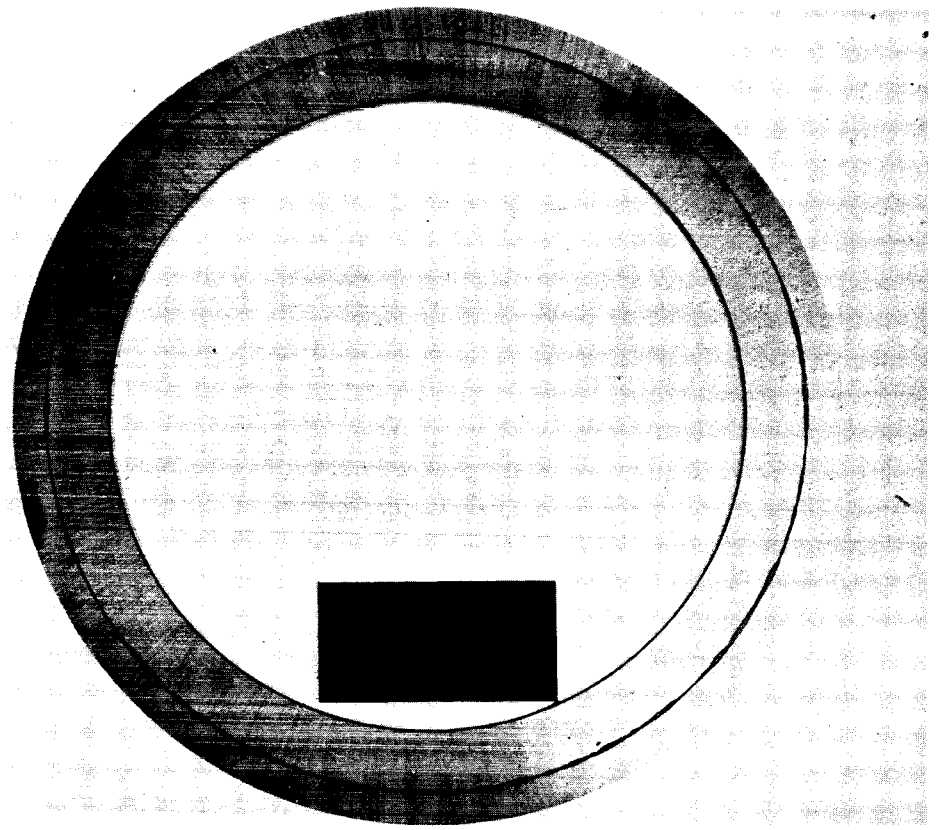
Wear Rate, In^3/10^{10}ft -
-0.59



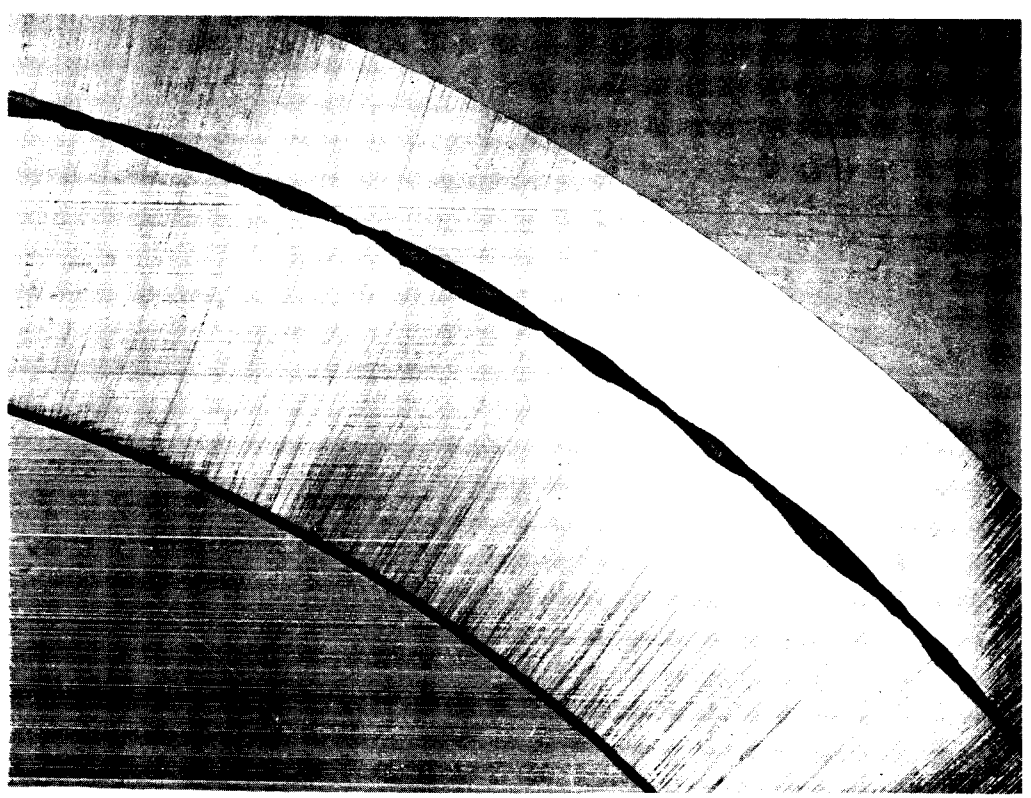
(C66081628) Mag.: 28.5X



(C660601114) Mag.: 5X



(C66060169) Mag.: 1X



(C66060189) Mag.: 5X

Initial Surface Finish, Avg. RMS - .5-1.5

Wear Scar Width, In. - 0.033

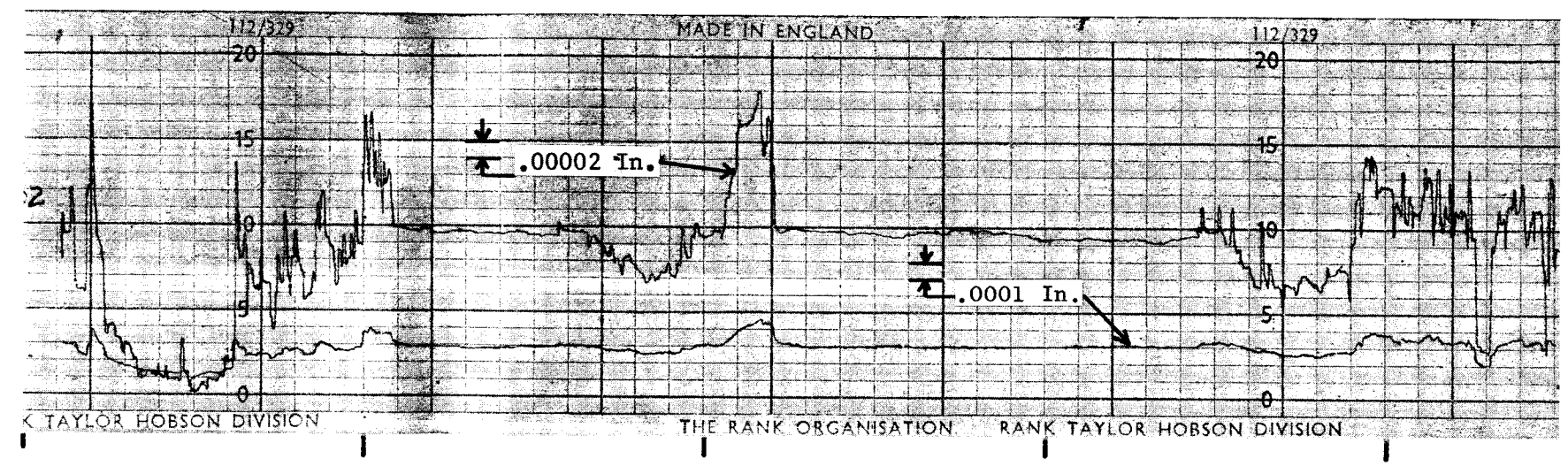
Weight, Gms /Cm^3 -
Start - 222.6713
Finish - 222.6690
Change - -0.0023

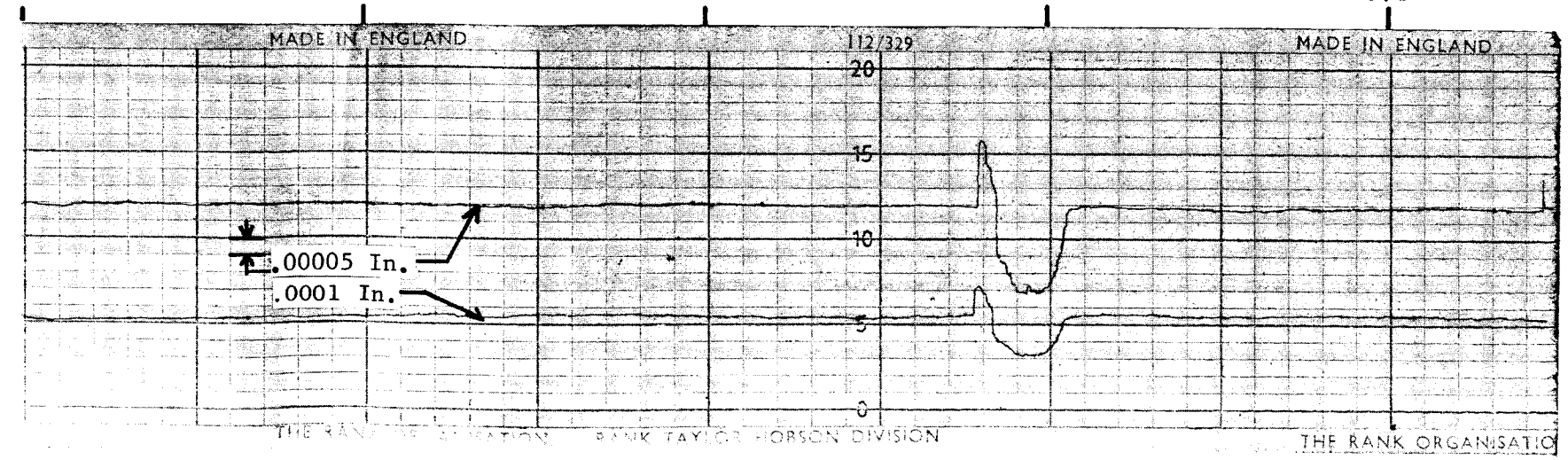
Material Density, Gms /Cm^3 - 14.684

Volume Change, Mm^3 - -0.157

Wear Rate, $In^3/10^{10}ft$ - -1.93

Post-Test Profilometer Trace - Circumferential at 90° CW from S/N





Post-Test Profilometer Trace - Radial at 90° CW from S/N

FRICTION AND WEAR TEST DATA FOR Mo-TZM ALLOY VS CARBOLOY 907 IN HIGH VACUUM

Test No. - 408K08B

Assembly No. - XX

Loading Arm No. - 2

Test Date - 4/30/66

Rider
Material - Mo-TZM
Specimen No. - 1037-E-24

Disc
Material - Carboloy 907
Specimen No. - 1036-F-8B

Test Temperature, °F - 800

Max. ΔT of Rider, °F - 12

Speed, SFM - 800

Test Duration, Min. - 60.00

Compressive Load, Lbs - 0.077(K)

Compressive Stress, psi - 82,810

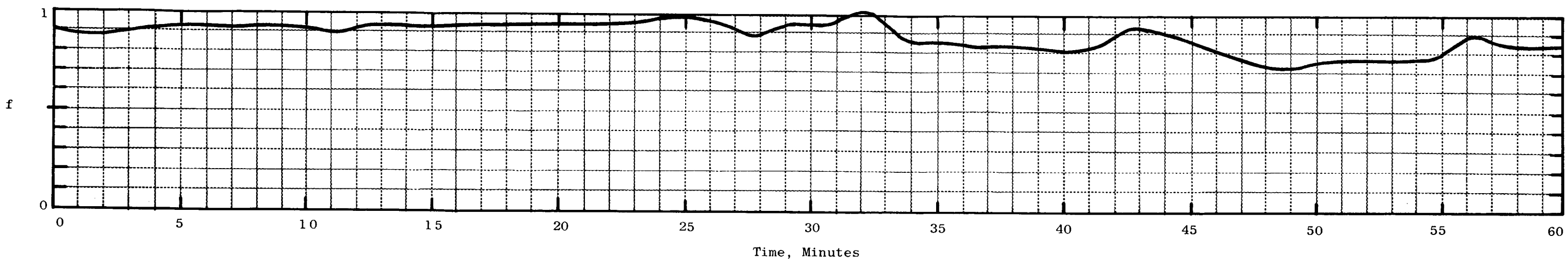
Load/Material UCS or 0.2%CYS -
Rider - 82%
Disc - 13%

Average Coefficient of Friction - 0.87

Chamber Pressure, Torr -
Start - 4.8×10^{-9}
Max. - 9.2×10^{-9}

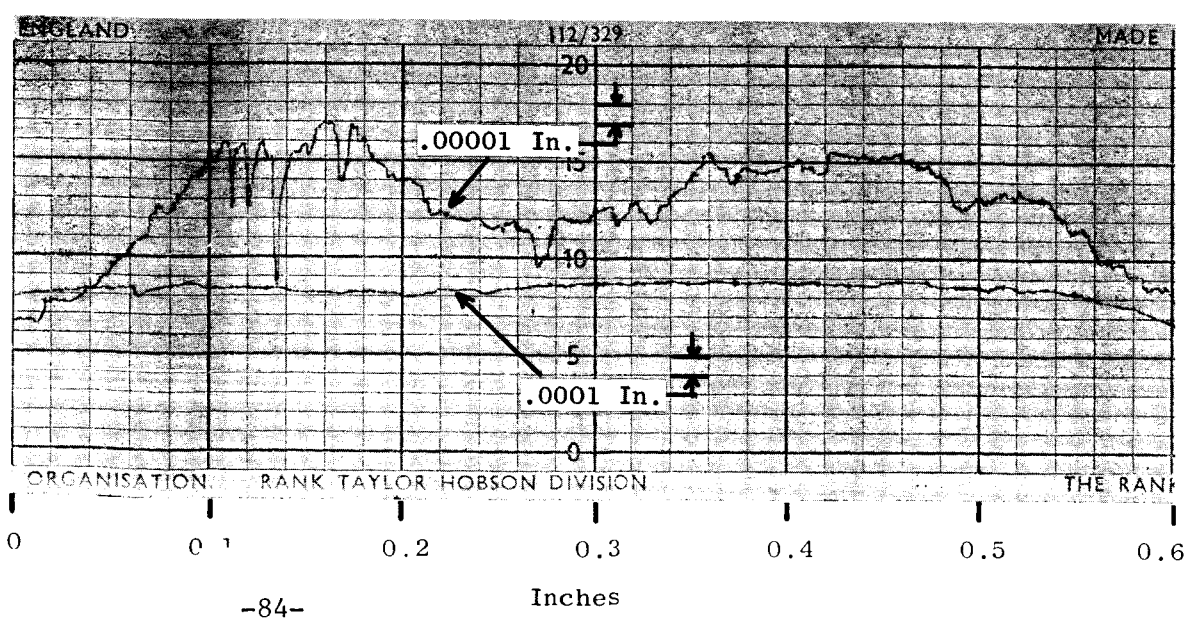
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



Wear Scar Dia., In. - 0.048

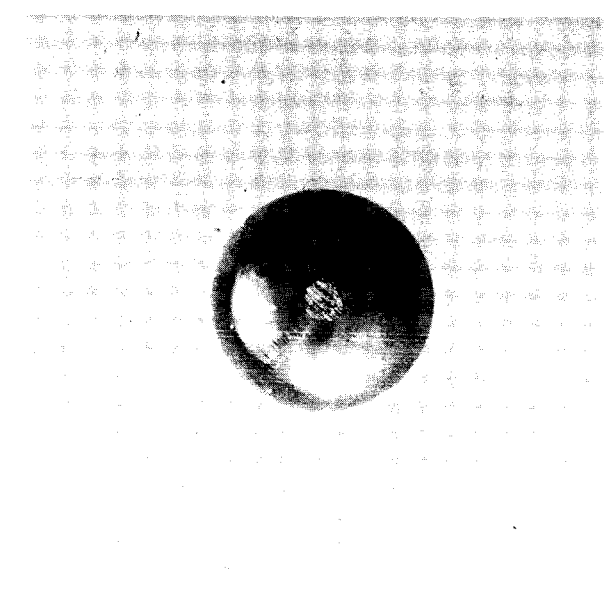
Weight, Gms -
Start - 2.4025
Finish - 2.4028
Change - +0.0003

Material Density, Gms/Cm^3 -
10.139

Volume Change, Mm^3 -
+0.0204 (1)

Wear Rate, In^3/10^{10}ft -
+0.202 (1)

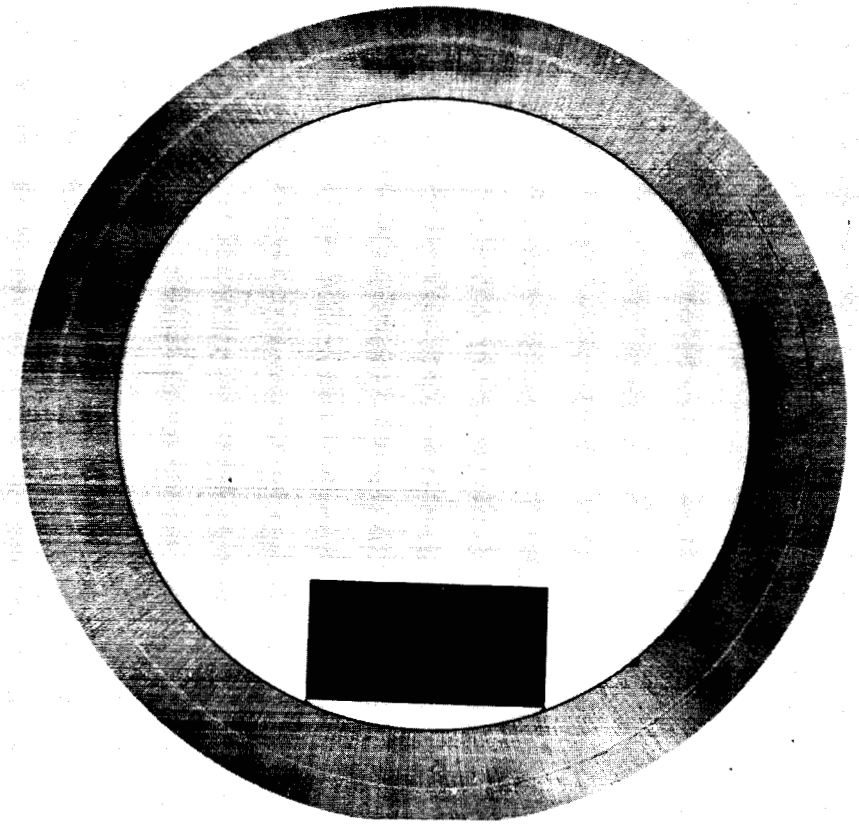
(C660[illegible]329) Mag.: 28.5X



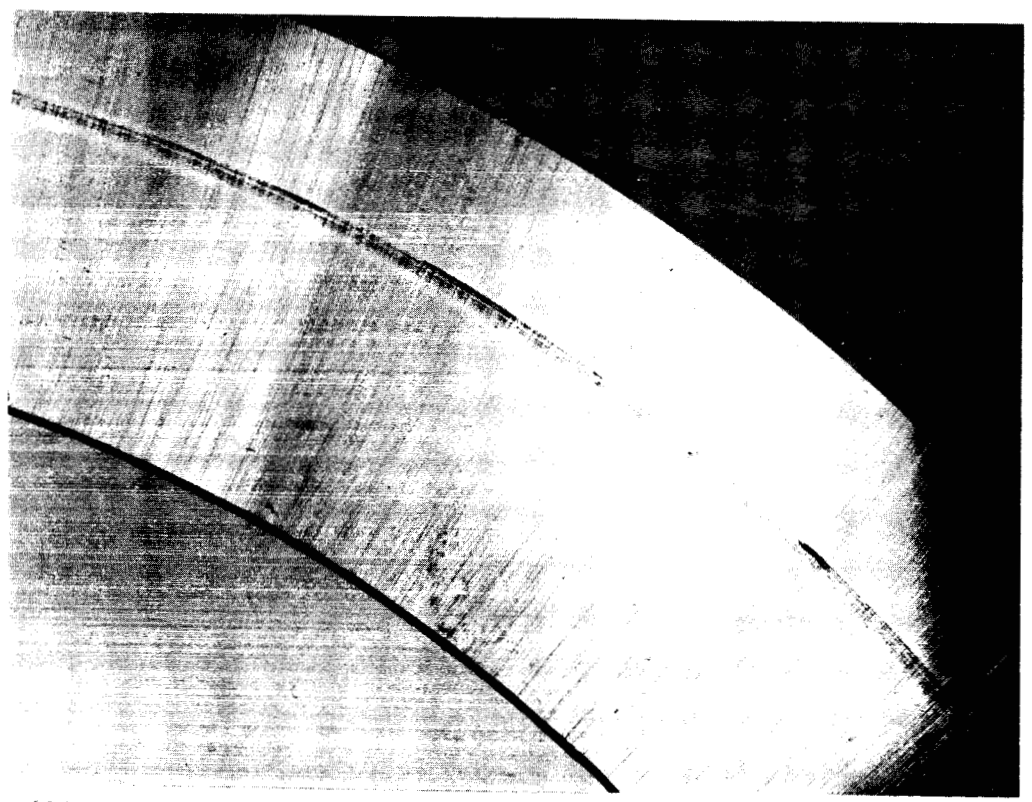
(C660601115) Mag.: 5X

WEAR - DISC

Test No. - 408K08B



(C66C60165) Mag.: 1X



(C66060192) Mag.: 5X

Initial Surface Finish, Avg. RMS - 0.5-1.5

Wear Scar Width, In. - 0.035

Weight, Gms /Cm^3 -
Start - 223.4918
Finish - 223.4918
Change - 0

Material Density, Gms /Cm^3 - 14.684

Volume Change, Mm^3 - 0

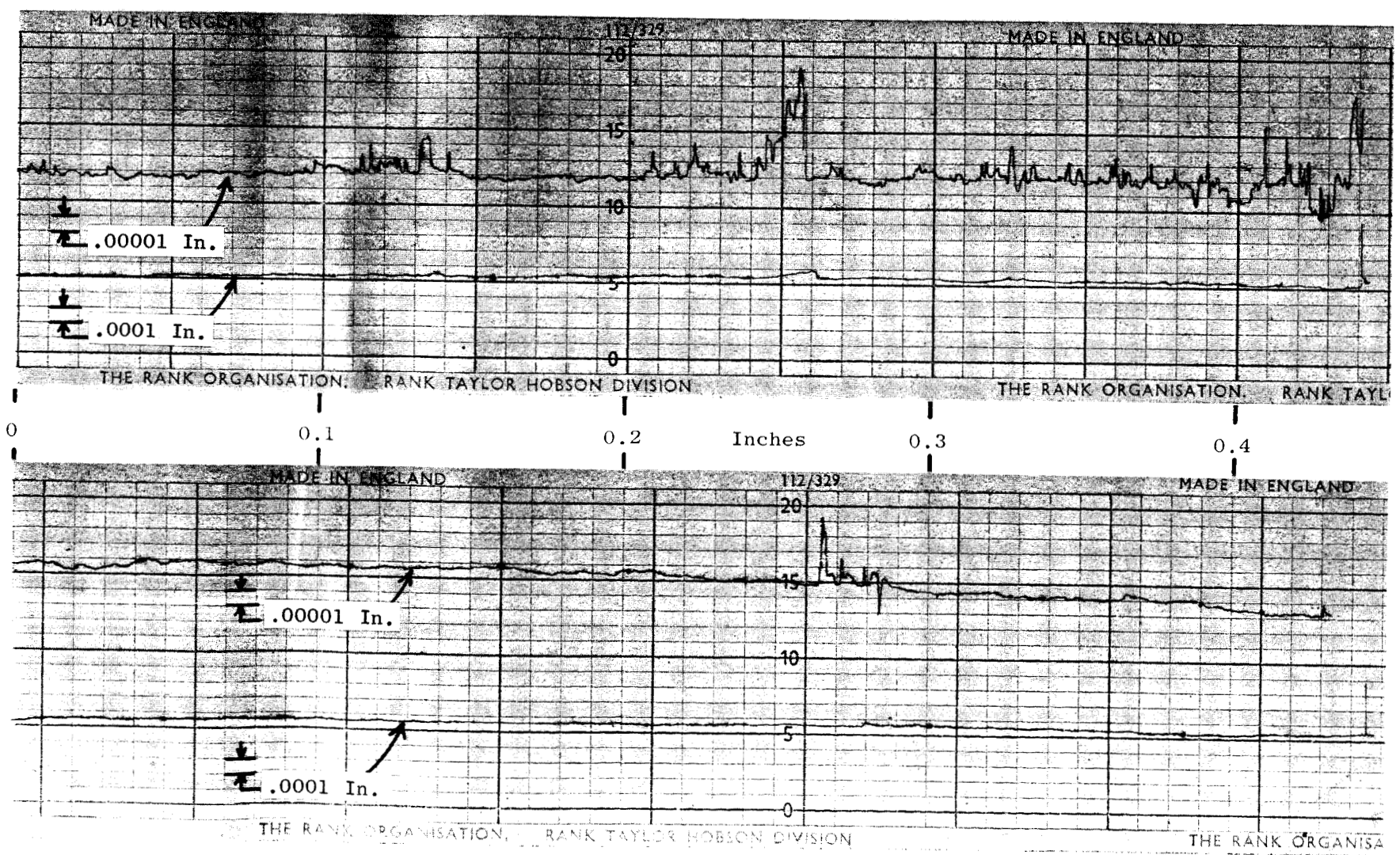
Wear Rate, $In^3/10^{10}ft$ - 0 (2)

Notes

(1) Calculated using properties of Carboloy 907

(2) Disc chipped

Post-Test Profilometer Trace - Circumferential at S/N



Post-Test Profilometer Trace - Radial at S/N

FRICTION AND WEAR TEST DATA FOR CARBOLOY 907 VS CARBOLOY 907 IN HIGH VACUUM

Test No. - 508K08A

Assembly No. - XX

Loading Arm No. - 3

Test Date - 4/30/66

Rider
Material - Carboloy 907
Specimen No. - 1036-E-16

Disc
Material - Carboloy 907
Specimen No. - 1036-F-9A

Test Temperature, °F - 800

Max. ΔT of Rider, °F - 23

Speed, SFM - 800

Test Duration, Min. - 60.00

Compressive Load, Lbs - 0.076(K)

Compressive Stress, psi - 94,921

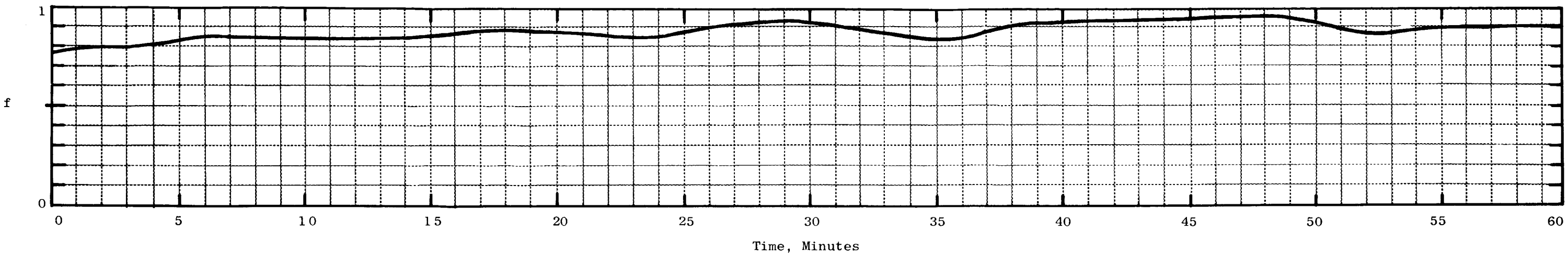
Load/Material UCS or 0.2%CYS -
Rider - 15%
Disc - 15%

Average Coefficient of Friction - 0.88

Chamber Pressure, Torr -
Start - 6.2×10^{-9}
Max. - 9.2×10^{-9}

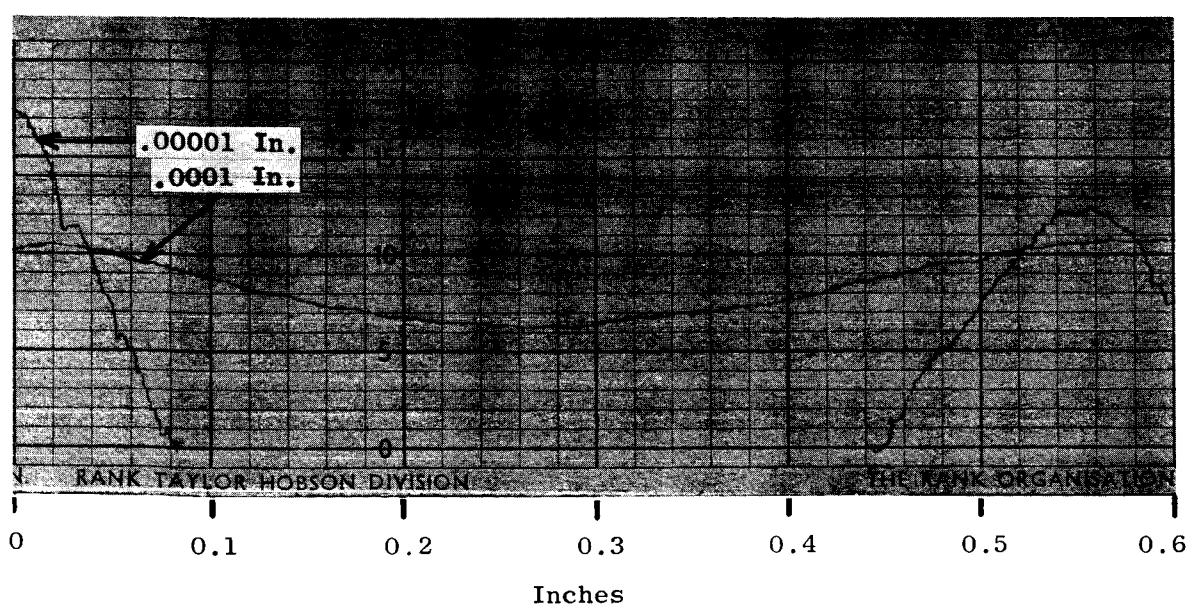
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



Wear Scar Dia., In. - 0.031

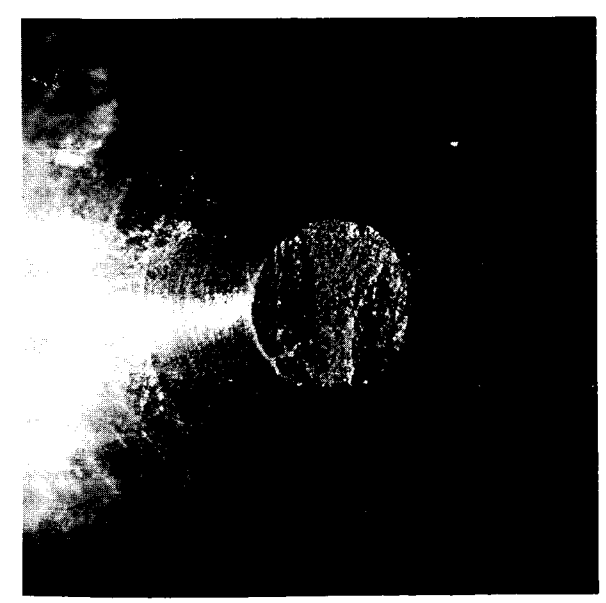
Weight, Gms -

Start -	3.5038
Finish -	3.5034
Change -	-0.0004

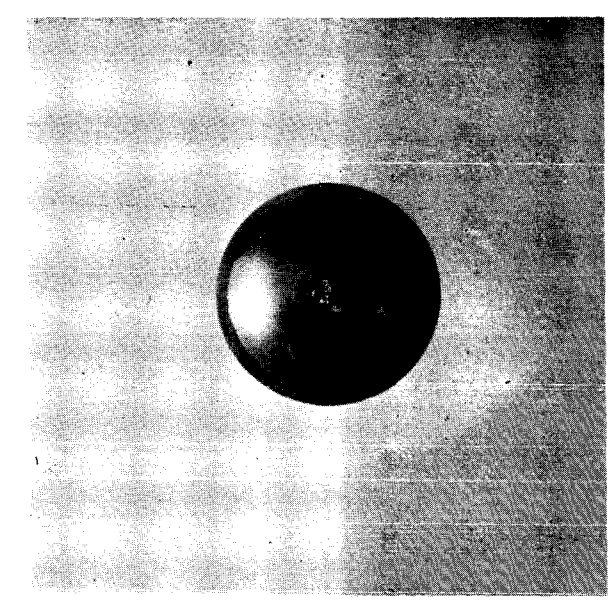
Material Density, Gms/Cm^3 -
14.684

Volume Change, Mm^3 -
-0.027

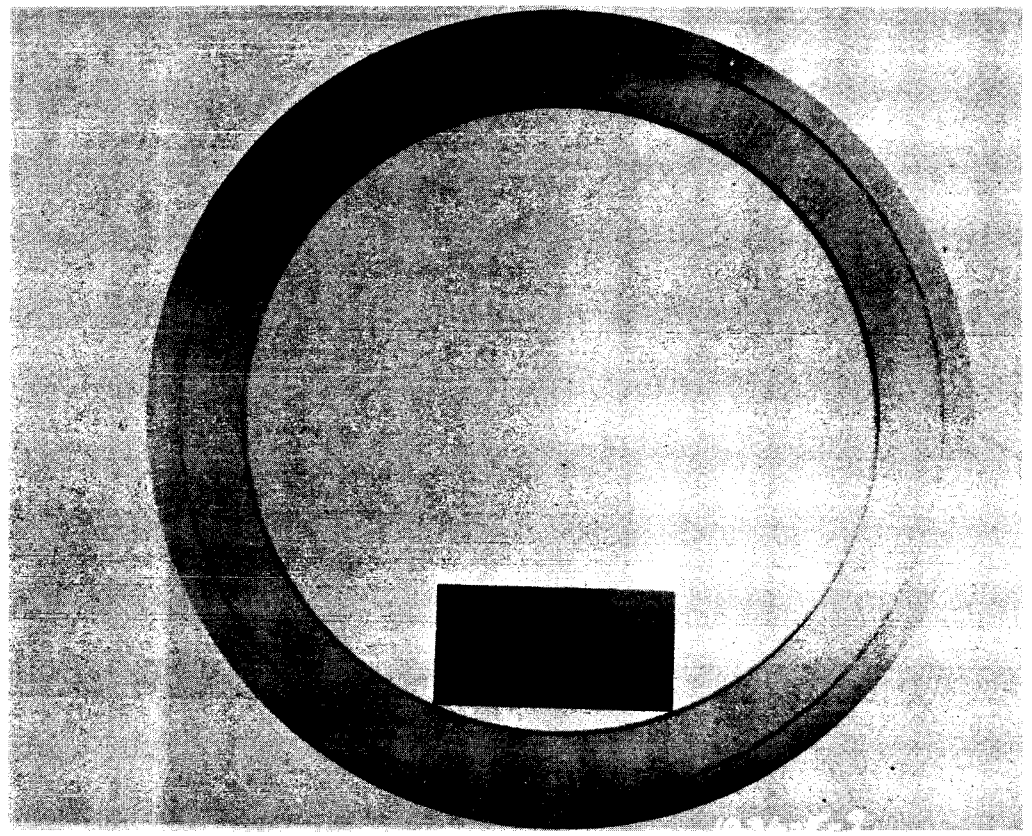
Wear Rate, In^3/10^{10}ft -
-0.30



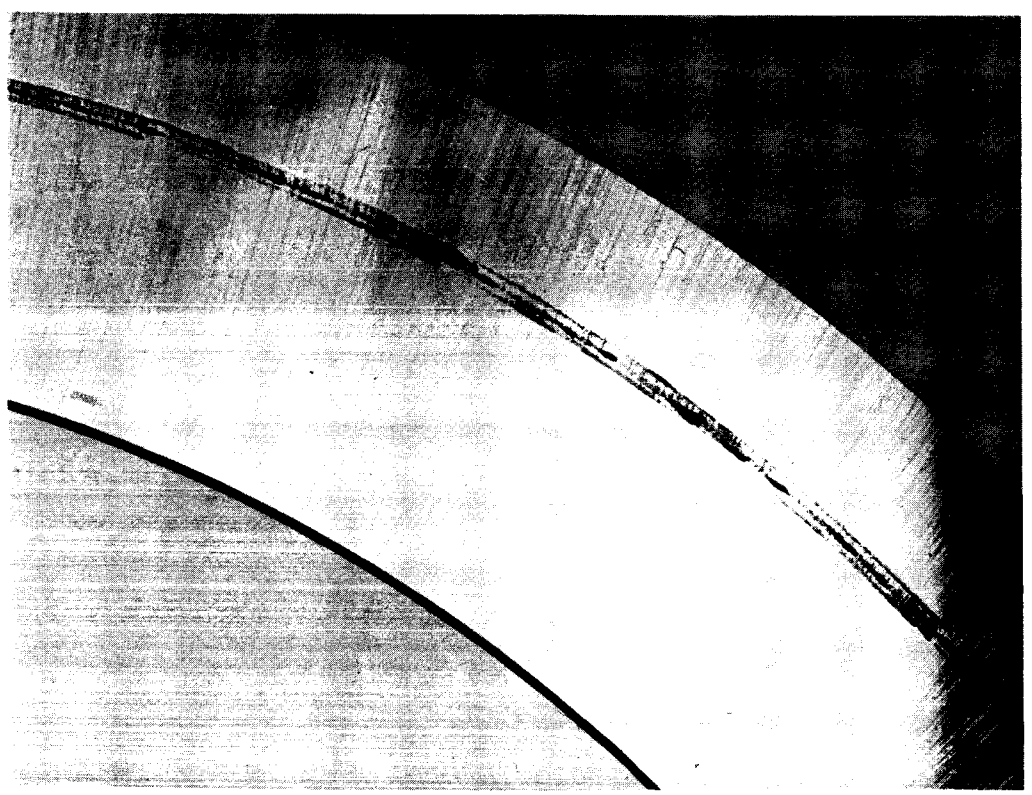
(C66081605) Mag.: 28.5X



(C660601112) Mag.: 5X



(C66060176) Mag.: 1X



(C66060190) Mag.: 5X

Initial Surface Finish, Avg. RMS - 0.5-1

Wear Scar Width, In. - 0.030

Weight, Gms /Cm^3 -

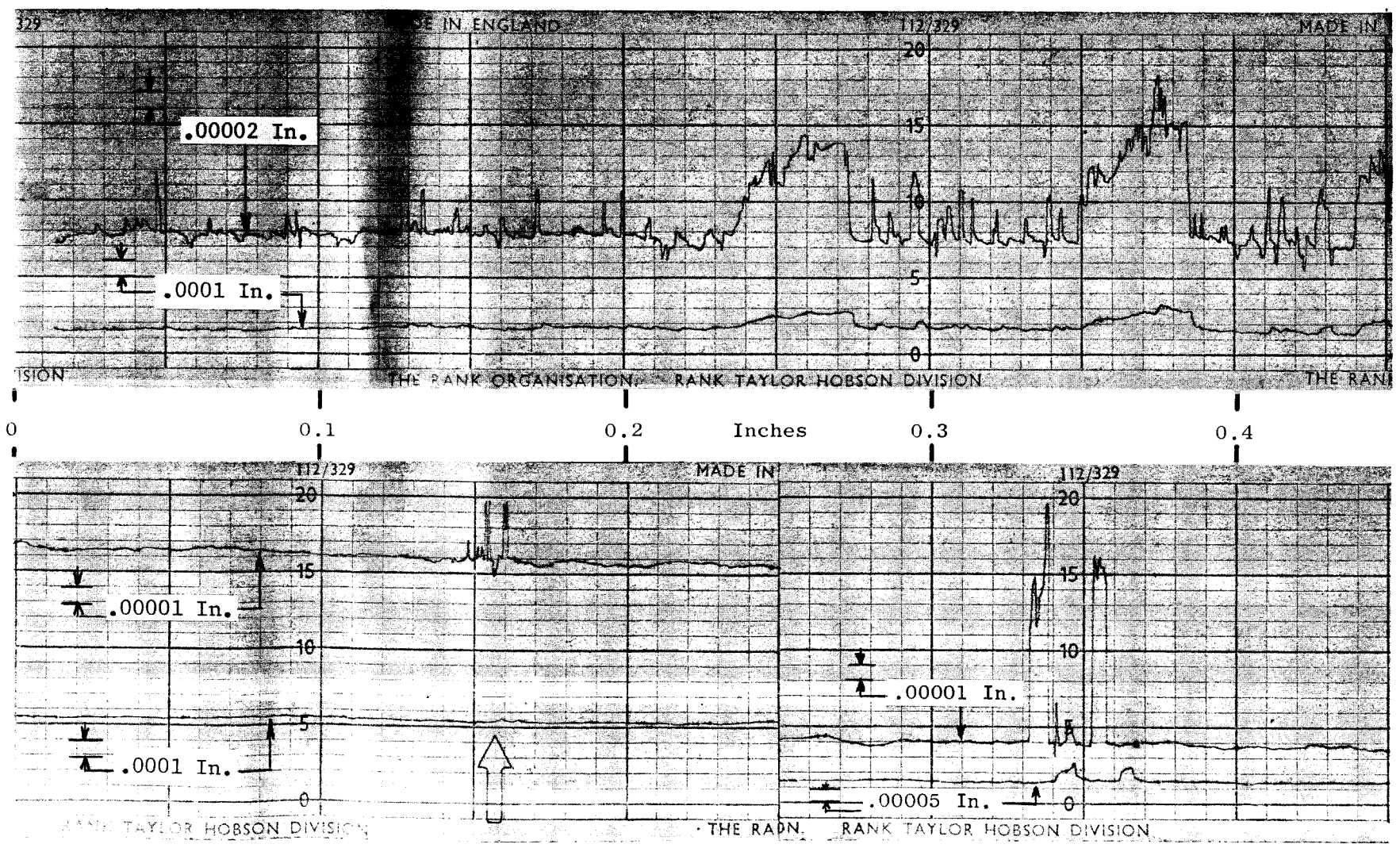
Start -	222.8831
Finish -	222.8827
Change -	-0.0004

Material Density, Gms /Cm^3 - 14.684

Volume Change, Mm^3 - -0.027

Wear Rate, $In^3/10^{10}ft$ - -0.30

Post-Test Profilometer Trace - Circumferential at 90° CW from S/N



Post-Test Profilometer Trace - Radial at 90° CW from S/N

FRICTION AND WEAR TEST DATA FOR CARBOLOY 907 VS CARBOLOY 907 IN HIGH VACUUM

Test No. - 500H08B

Assembly No. - XX

Loading Arm No. - 1

Test Date - 5/2/66

Rider
Material - Carboloy 907
Specimen No. - 1036-E-14

Disc
Material - Carboloy 907
Specimen No. - 1036-F-4A

Test Temperature, °F - 80

Max. ΔT of Rider, °F - 555

Speed, SFM - 800

Test Duration, Min. - 60.00

Compressive Load, Lbs - 1.26(H)

Compressive Stress, psi - 275,230

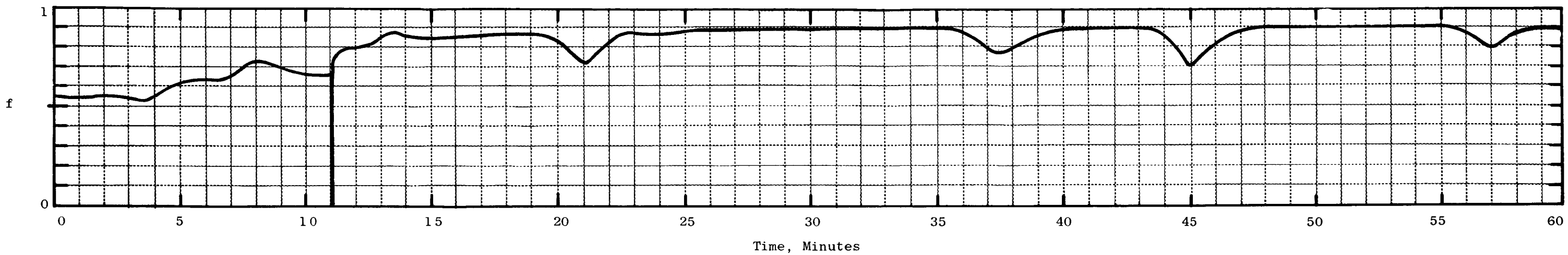
Load/Material UCS or 0.2%C4S -
Rider - 39%
Disc - 39%

Average Coefficient of Friction - 0.87

Chamber Pressure, Torr -
Start - 1.4×10^{-9}
Max. - 9.5×10^{-9}

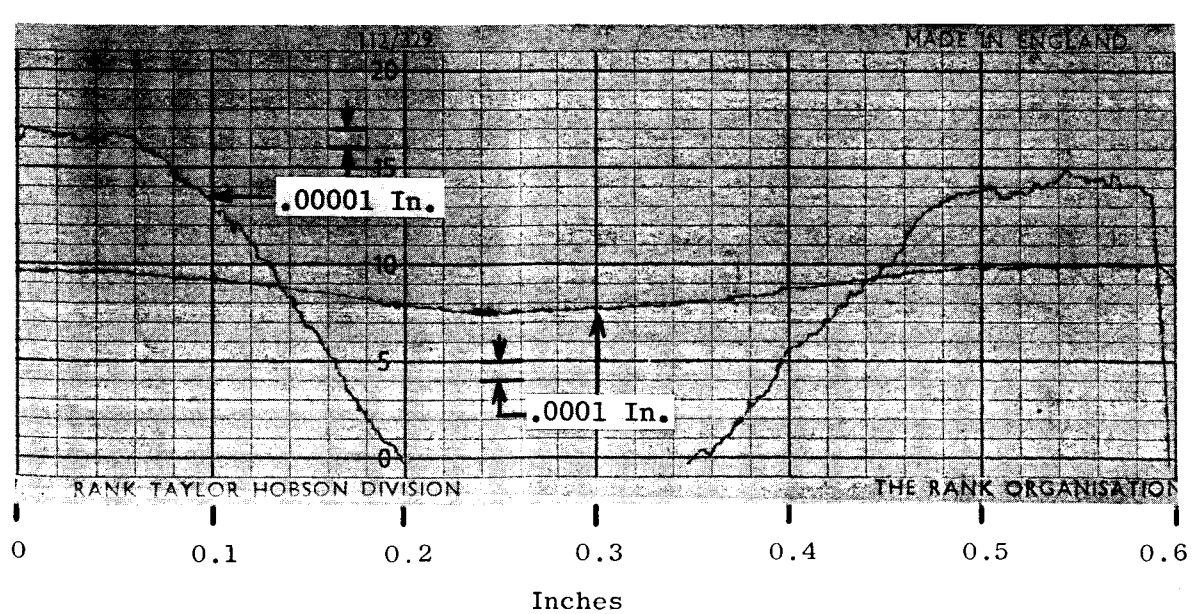
Remarks - Test conducted in two parts due to tester bearing failure. Pretest calibration and 10 minute run-in conducted before each part of test.

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



Wear Scar Dia., In. - 0.105

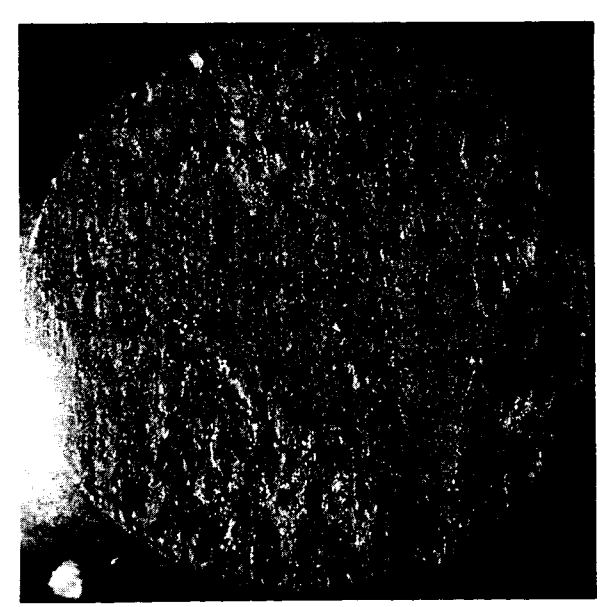
Weight, Gms -

Start -	3.5351
Finish -	3.5239
Change -	-0.0112

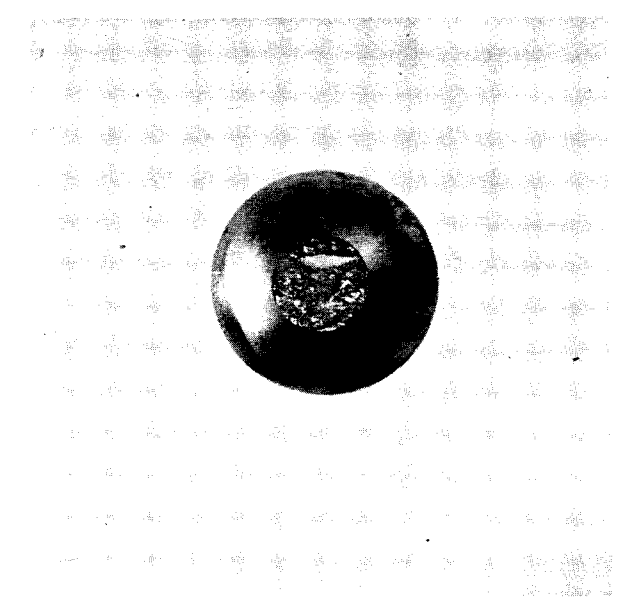
Material Density, Gms/Cm^3 -
14.684

Volume Change, Mm^3 -
-0.762

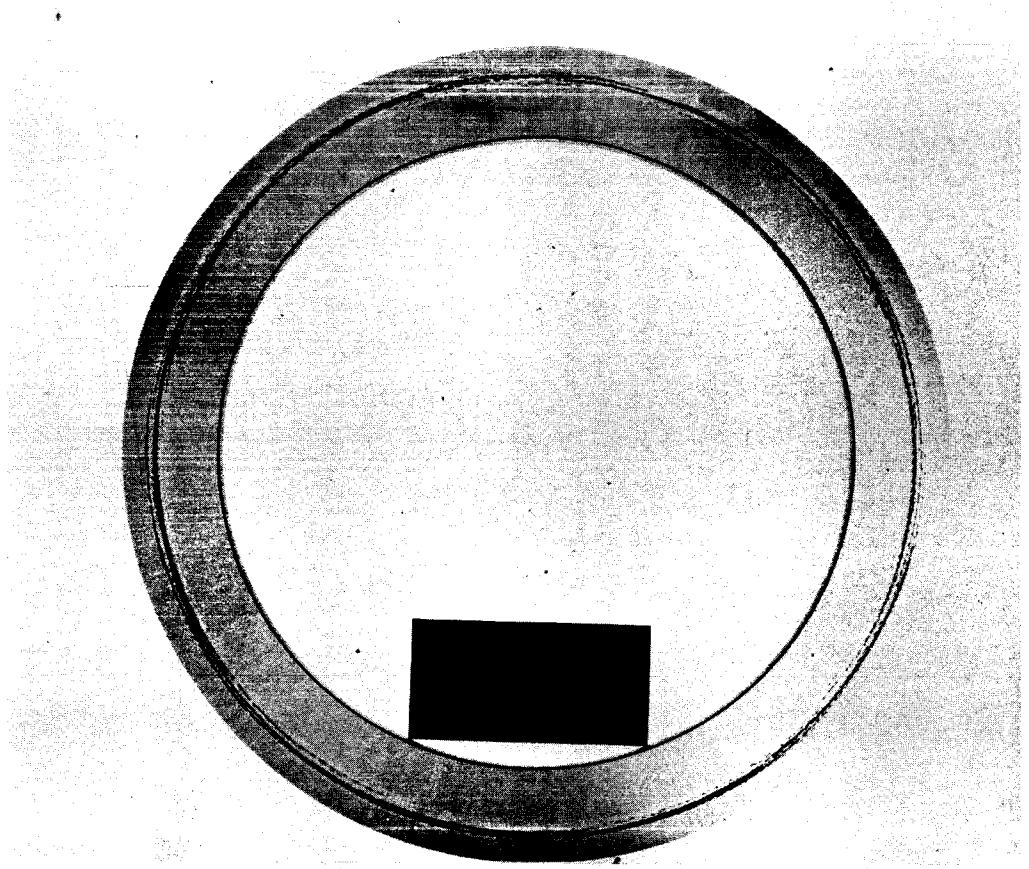
Wear Rate, In^3/10^{10}ft -
-9.53



(C66081631) Mag.: 28.5X



(C660601113) Mag.: 5X



(C66060177) Mag.: 1X

(C66060191) Mag.: 5X

Initial Surface Finish, Avg. RMS - 0.5-1

Wear Scar Width, In. - 0.105

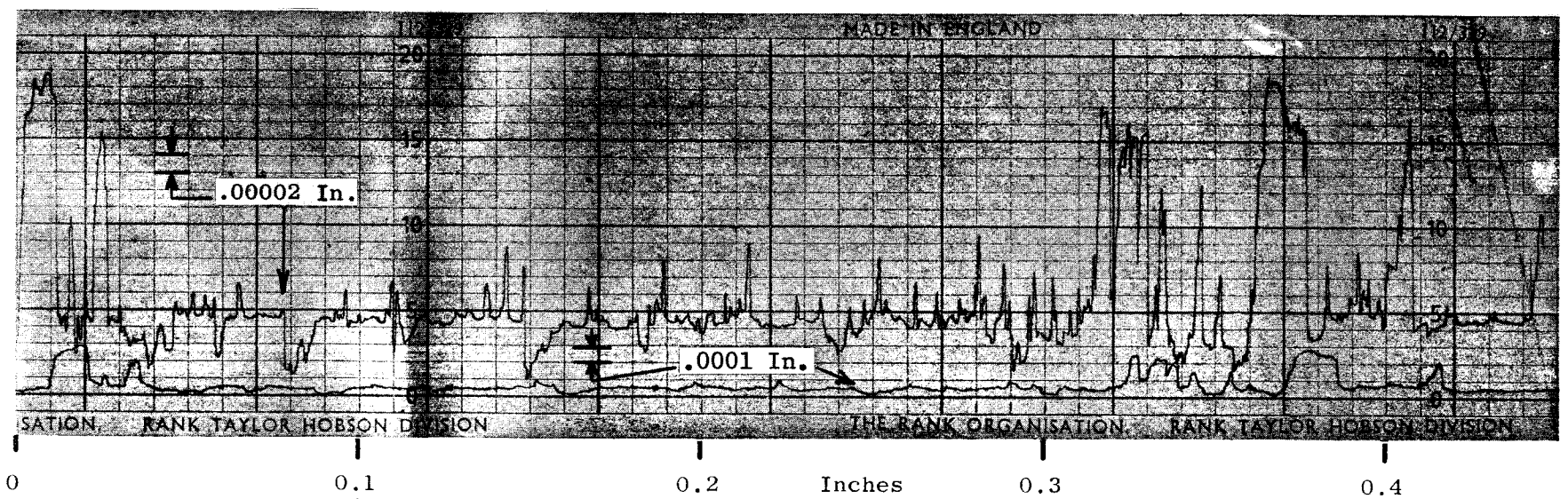
Weight, Gms /Cm^3 -
Start - 222.7879
Finish - 222.7881
Change - +0.0002

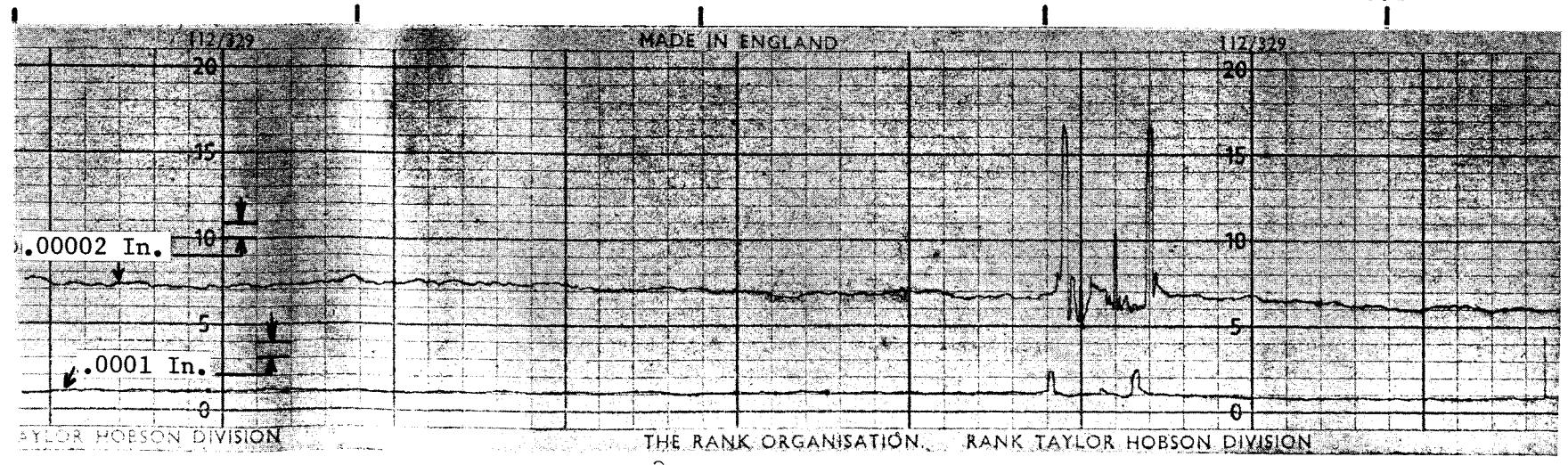
Material Density, Gms /Cm^3 - 14.684

Volume Change, Mm^3 - +.0136

Wear Rate, $In^3/10^{10}ft$ - +0.17

Post-Test Profilometer Trace - Circumferential at S/N





Post-Test Profilometer Trace - Radial at 90° CW from S/N

FRICTION AND WEAR TEST DATA FOR Mo-TZM ALLOY VS TiC+10%Cb IN HIGH VACUUM

Test No. - 604K08C

Assembly No. - XXI

Loading Arm No. - 3

Test Date - 5-10-66

Rider
Material - Mo-TZM Alloy
Specimen No. - 1037-E-25

Disc
Material - Tic + 10% Cb
Specimen No. - 1045-F-33

Test Temperature, °F - 410

Max. ΔT of Rider, °F - 55

Speed, SFM - 800

Test Duration, Min. - 60.00

Compressive Load, Lbs - 0.080(K)

Compressive Stress, psi - 84,800

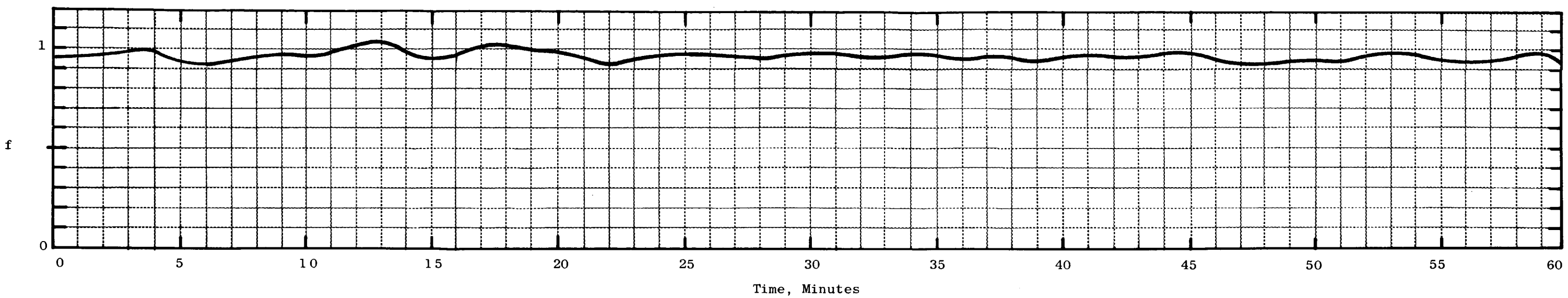
Load/Material UCS or 0.2%CYS -
Rider - 80%
Disc - 20%

Chamber Pressure, Torr -
Start - 6.0×10^{-9}
Max. - 9.5×10^{-9}

Remarks -

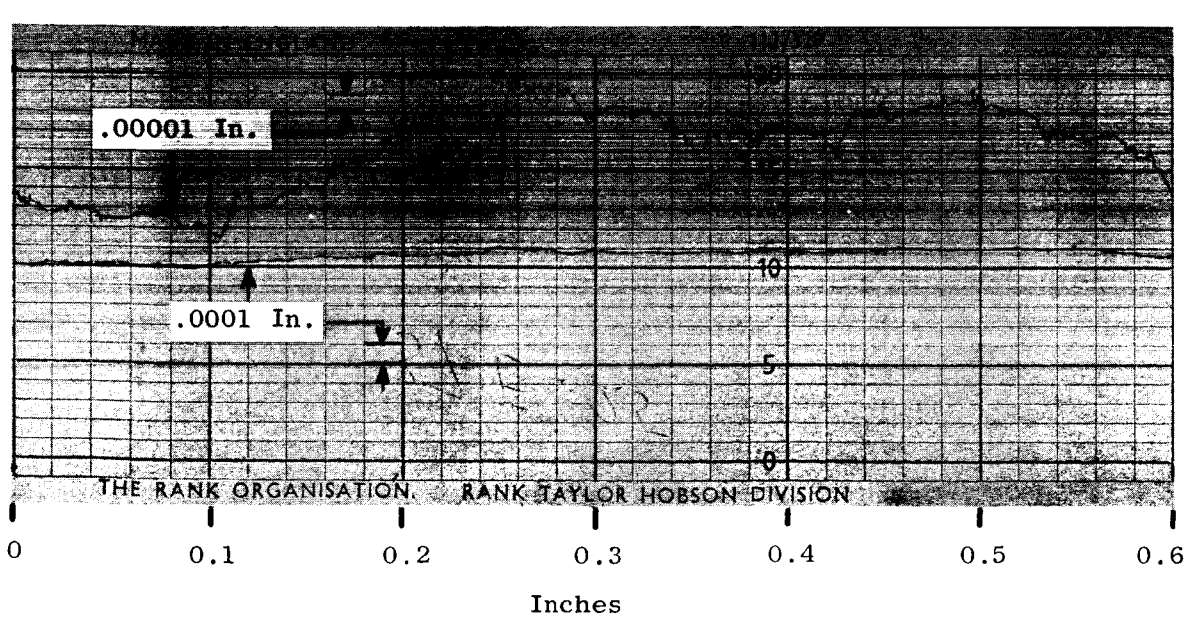
Change in Coefficient of Friction with Time -

Average Coefficient of Friction - 0.97



WEAR - RIDER

Initial Surface Finish -



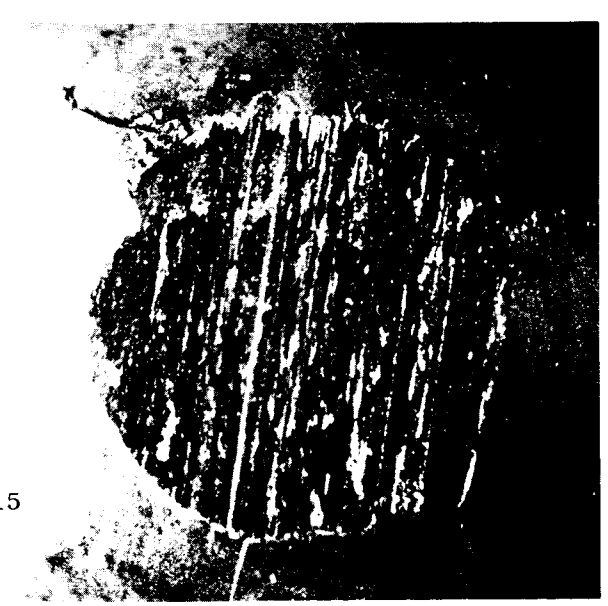
Wear Scar Dia., In. - 0.055

Weight, Gms -
Start - 2.3831
Finish - 2.3829
Change - 0.0002

Material Density, Gms/Cm^3 -
10.139

Volume Change, Mm^3 - -0.0197

Wear Rate, In^3/10^{10}ft - -0.215

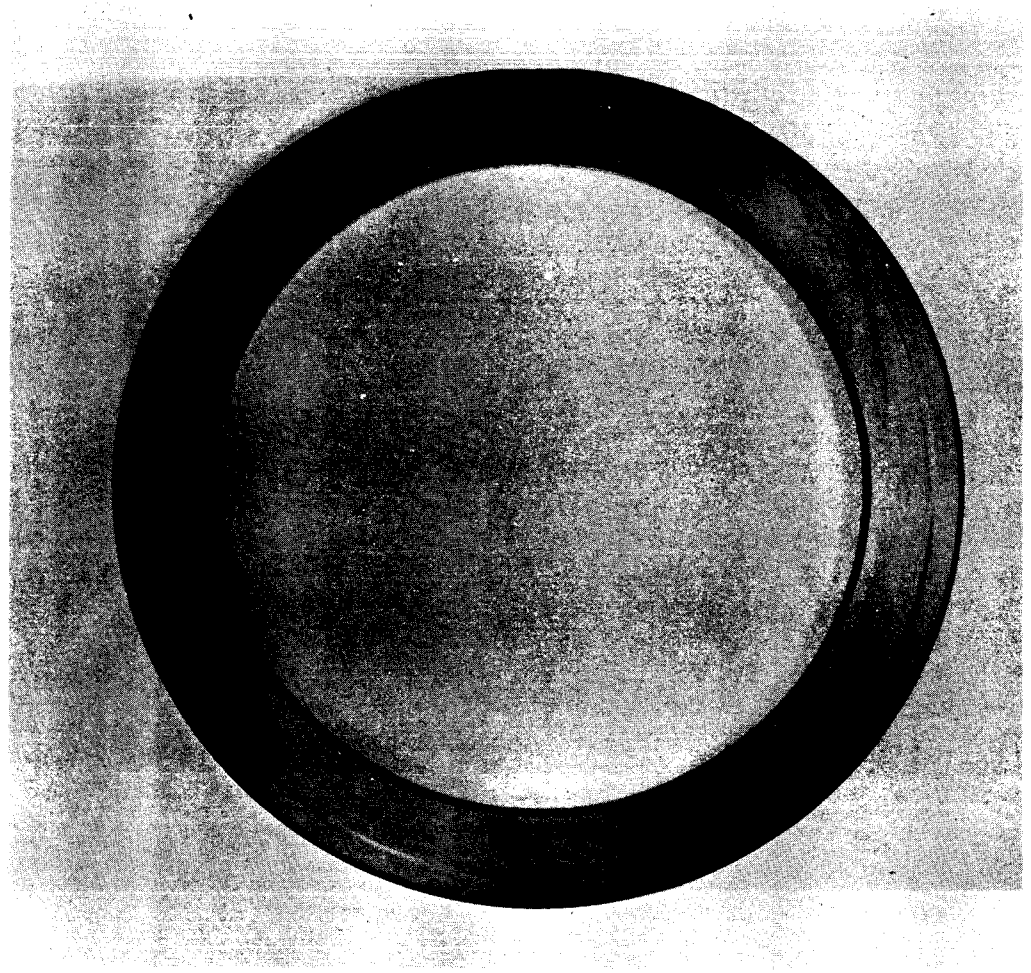


(C66111035) Mag.: 28.5X

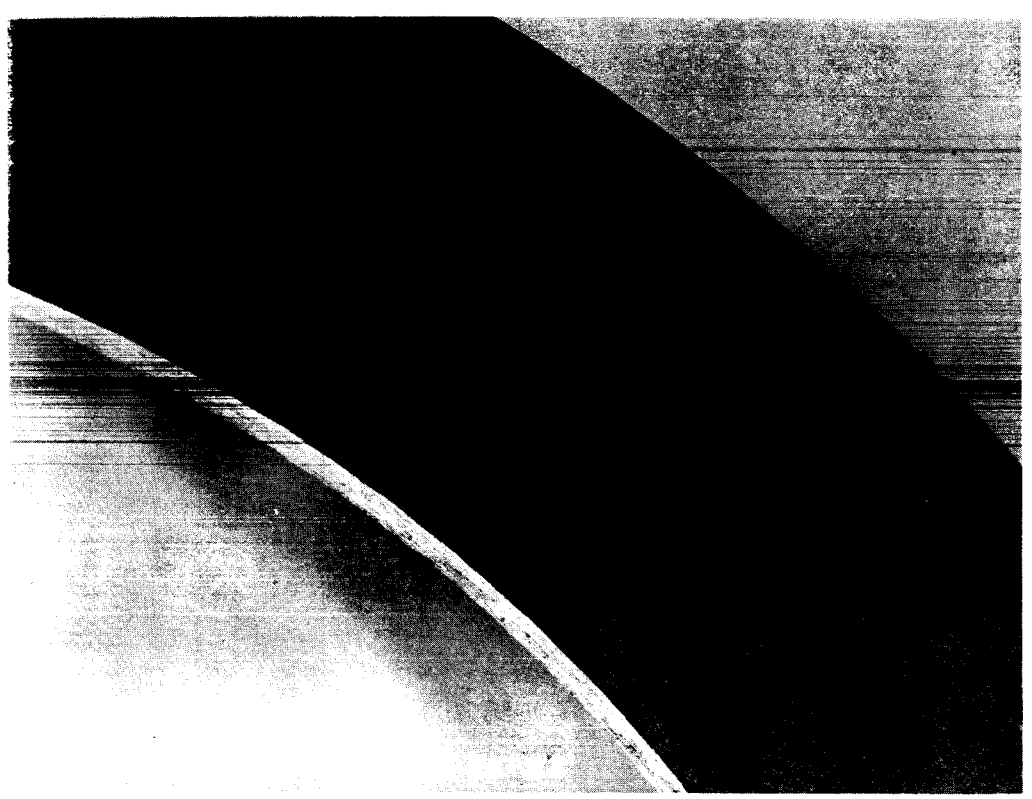
(C66111085) Mag.: 5X

WEAR - DISC

Test No. - 604K08C



(C66112329) Mag.: 1X



(C66112331) Mag.: 5X

Initial Surface Finish, Avg. RMS - 2.0 - 2.5

Wear Scar Width, In. - 0.032

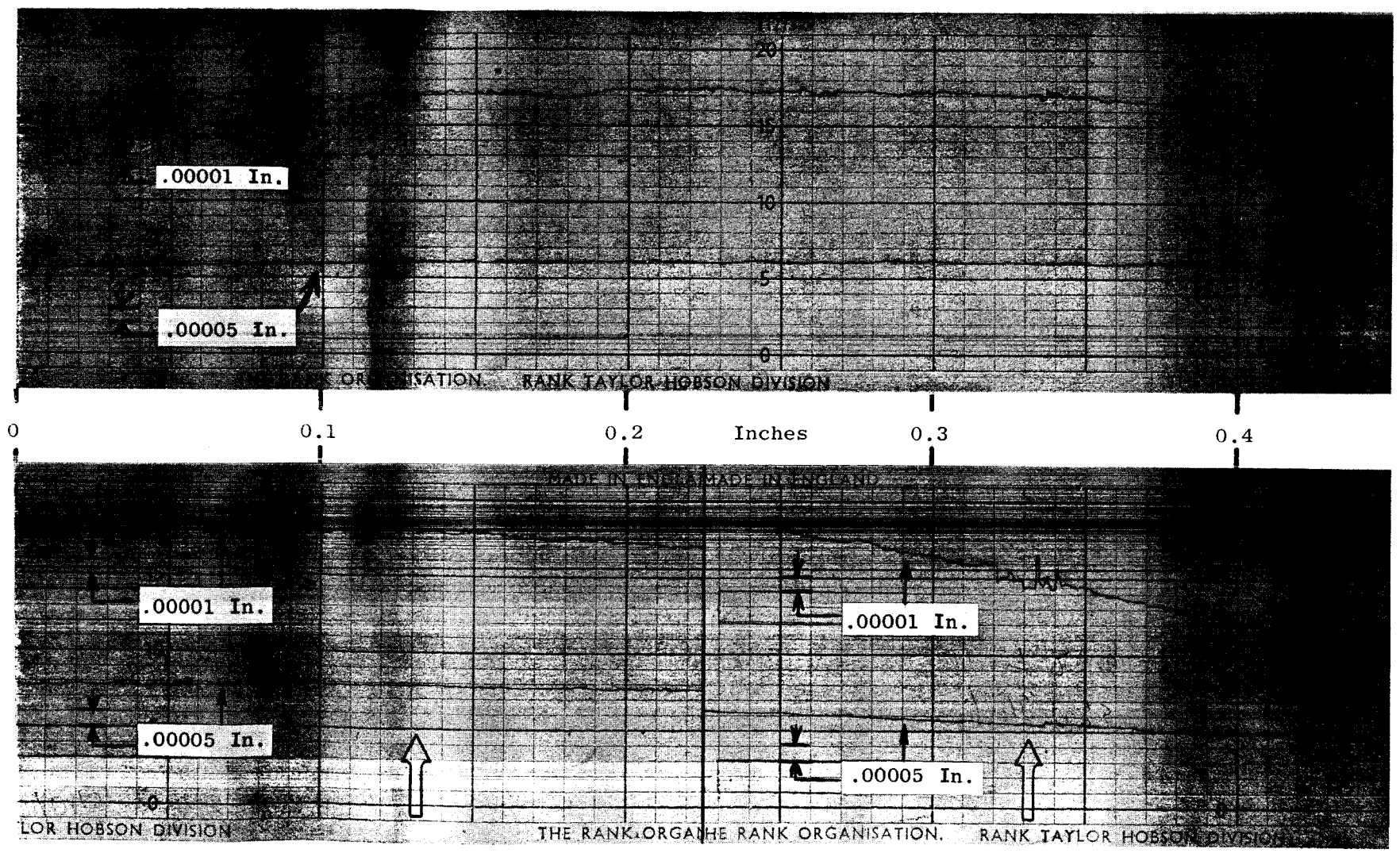
Weight, Gms /Cm^3 -
Start - 77.0778
Finish - 77.0776
Change - -0.0002

Material Density, Gms /Cm^3 - 5.239

Volume Change, Mm^3 - -0.038

Wear Rate, $In^3/10^{10}ft$ - -4.153

Post-Test Profilometer Trace - Circumferential at 0°



Post-Test Profilometer Trace - Radial at 0° Radial at 90°

FRICTION AND WEAR TEST DATA FOR GRADE 7178 VS Mo-TZM ALLOY IN HIGH VACUUM

Test No. - 208K08B

Assembly No. - XXI

Loading Arm No. - 2

Test Date - 5-12-66

Rider
Material - Grade 7178
Specimen No. - 1046-E-24

Disc
Material - Mo-TZM Alloy
Specimen No. - 1037-F-10

Test Temperature, °F - 800

Max. ΔT of Rider, °F - 23

Speed, SFM - 800

Test Duration, Min. - 13.60

Compressive Load, Lbs - 0.077(K)

Compressive Stress, psi - 82,580

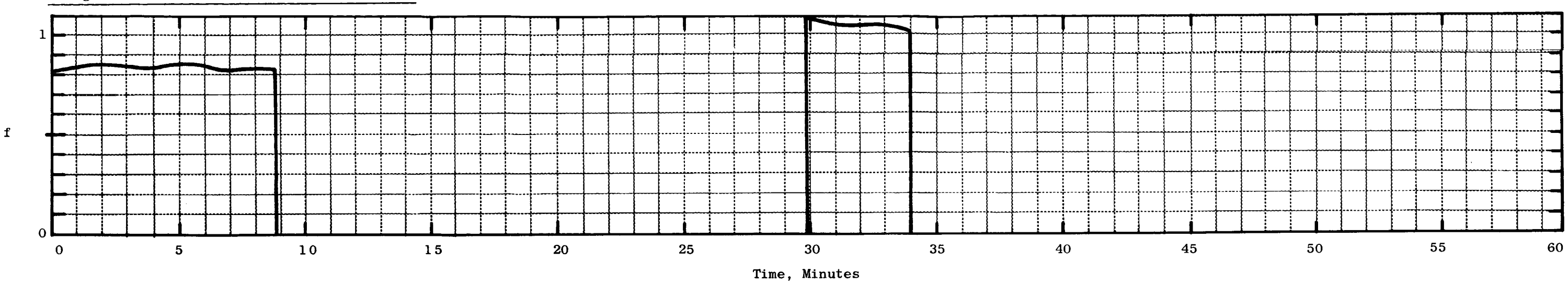
Load/Material UCS or 0.2%CYS -
Rider - 13%
Disc - 82%

Average Coefficient of Friction - 0.94

Chamber Pressure, Torr -
Start - 1.6×10^{-9}
Max. - 8.6×10^{-9}

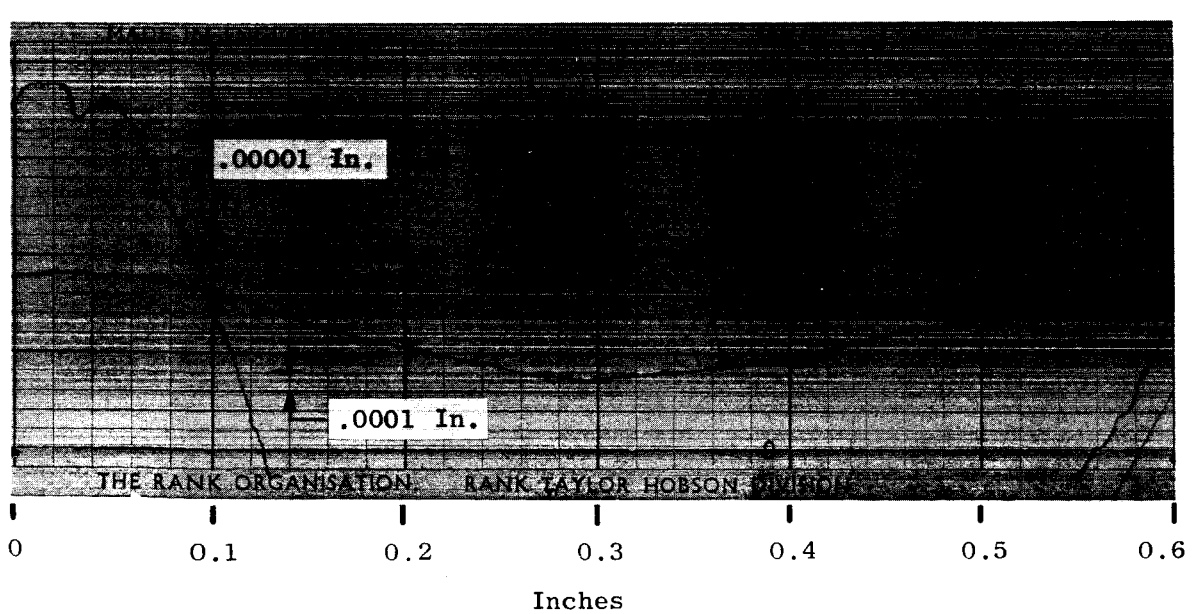
Remarks - Test aborted because vibrations caused fatigue failure of two load cell cables.

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



Wear Scar Dia., In. - 0.082

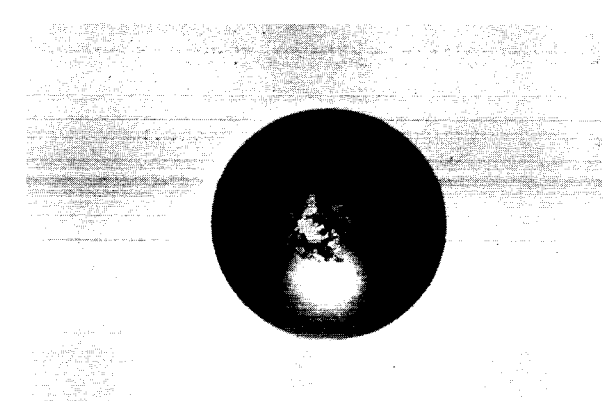
Weight, Gms. -
Start - 3.0991
Finish - 3.0968
Change - -0.0023

Material Density, Gms/Cm^3 - 14.301

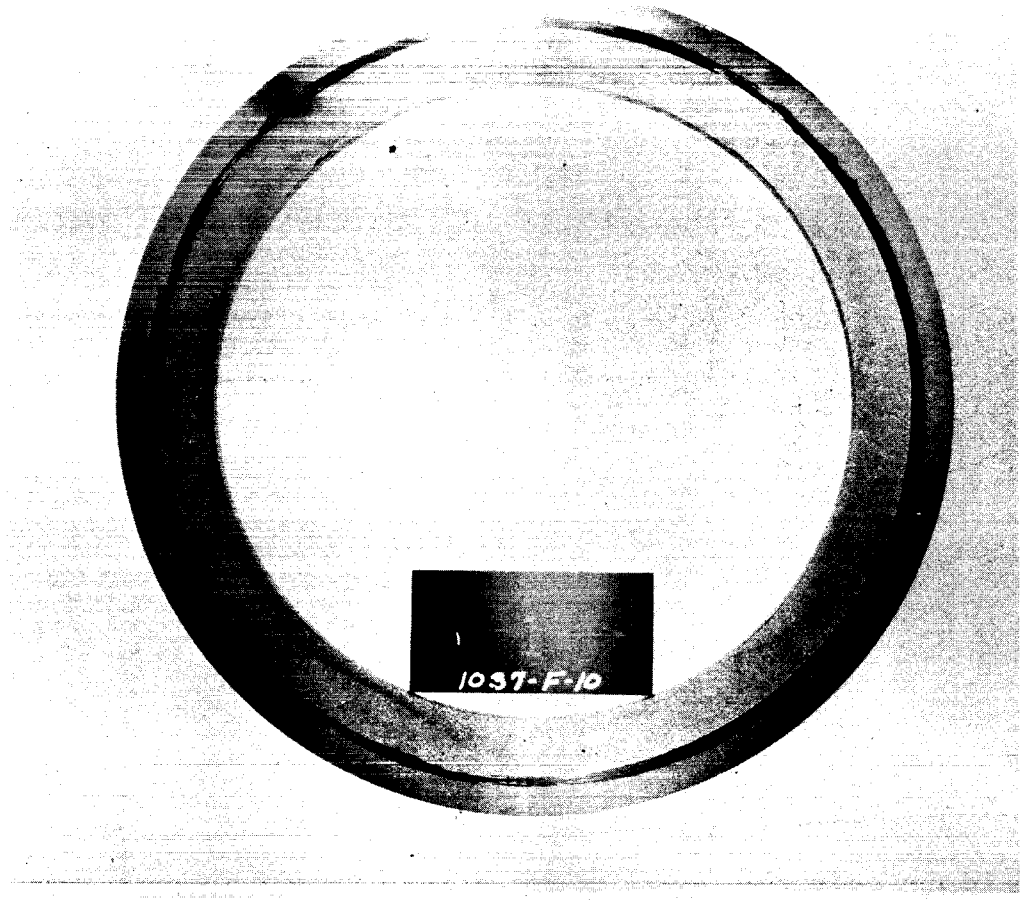
Volume Change, Mm^3 - -0.161

Wear Rate, In^3/10^{10}ft - -5.19

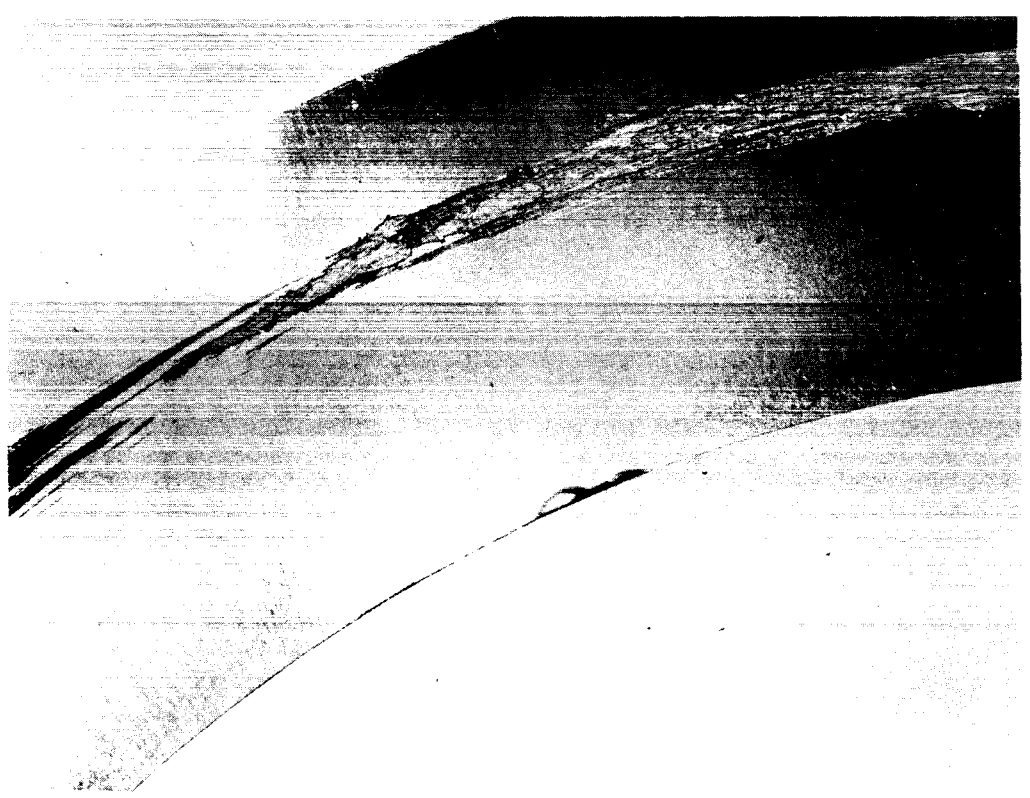
(C66111040) Mag.: 28.5X



(1046-E-24) Mag.: 5X



(1037-F-10) Mag.: 1X



(1037-F-10) Mag.: 5X

Initial Surface Finish, Avg. RMS - 1.0 - 2.5

Wear Scar Width, In. - 0.064

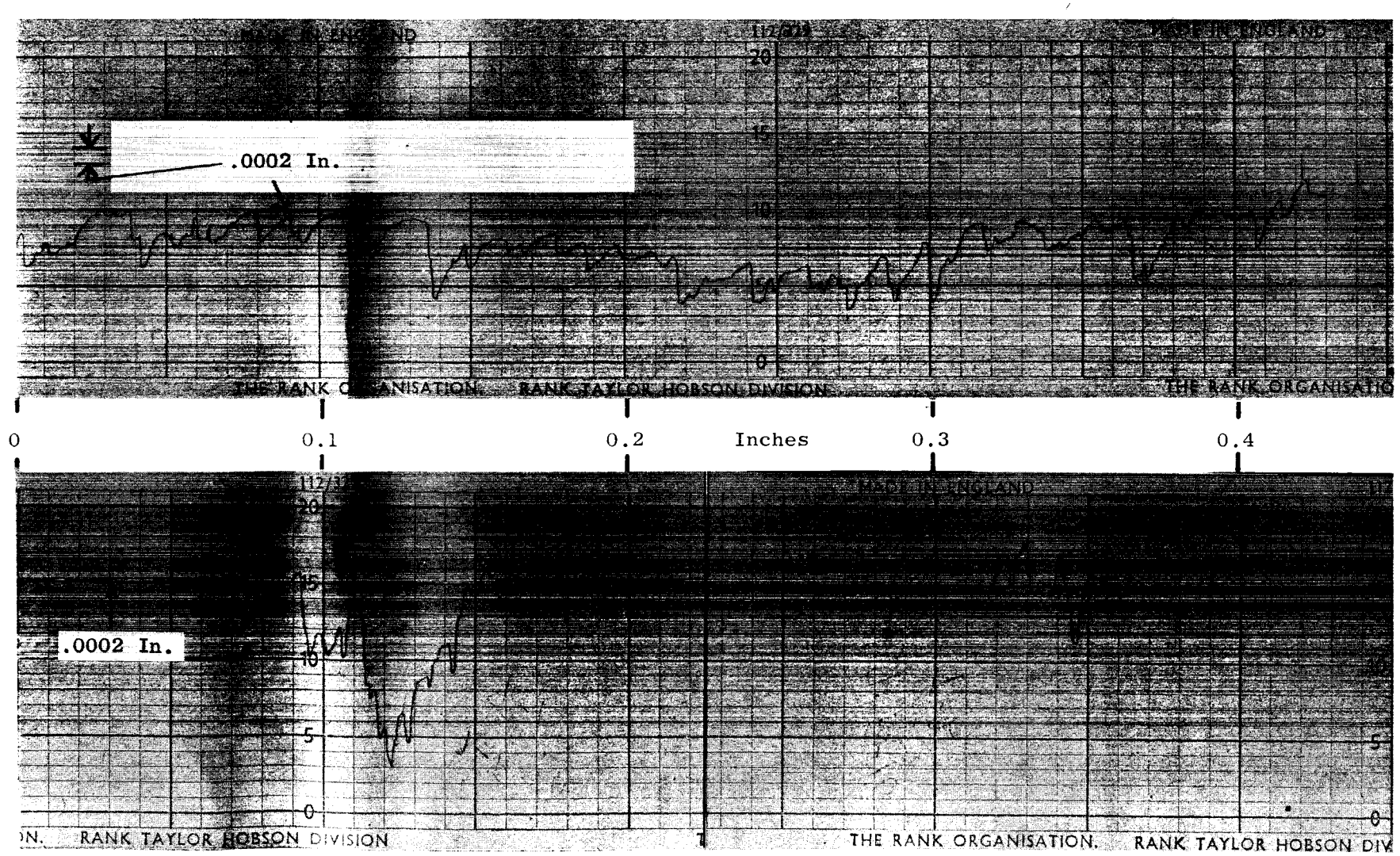
Weight, Gms /Cm^3 -
Start - 154.7079
Finish - 154.6702
Change - -0.0377

Material Density, Gms /Cm^3 - 10.139

Volume Change, Mm^3 - -3.718

Wear Rate, In^3/10^{10}ft - -120.07

Post-Test Profilometer Trace - Circumferential at 0°



Post-Test Profilometer Trace - Radial at 0° Radial at 90°

FRICTION AND WEAR TEST DATA FOR CARBOLOY 907 VS CARBOLOY 907 IN HIGH VACUUM

Test No. - 512708A

Assembly No. - XXI

Loading Arm No. - 1

Test Date - 5-17-66

Rider
Material - Carboloy 907
Specimen No. - 1036-E-17

Disc
Material - Carboloy 907
Specimen No. - 1036-F-11A

Test Temperature, °F - 1200

Max. ΔT of Rider, °F - 72

Speed, SFM - 800

Test Duration, Min. - 3.90

Compressive Load, Lbs - 2.58 (75%)

Compressive Stress, psi - 246,080

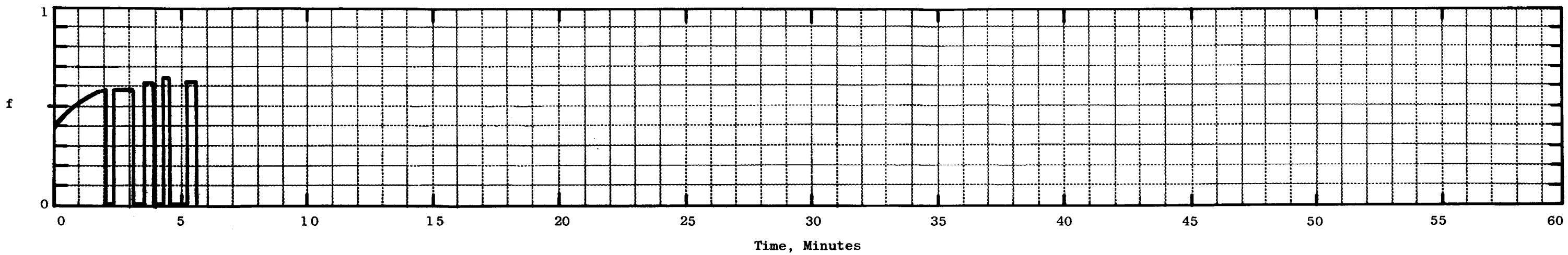
Load/Material UCS or 0.2%CYS -
Rider - 50%
Disc - 50%

Average Coefficient of Friction - 0.57

Chamber Pressure, Torr -
Start - 6.0×10^{-9}
Max. - 9.5×10^{-9}

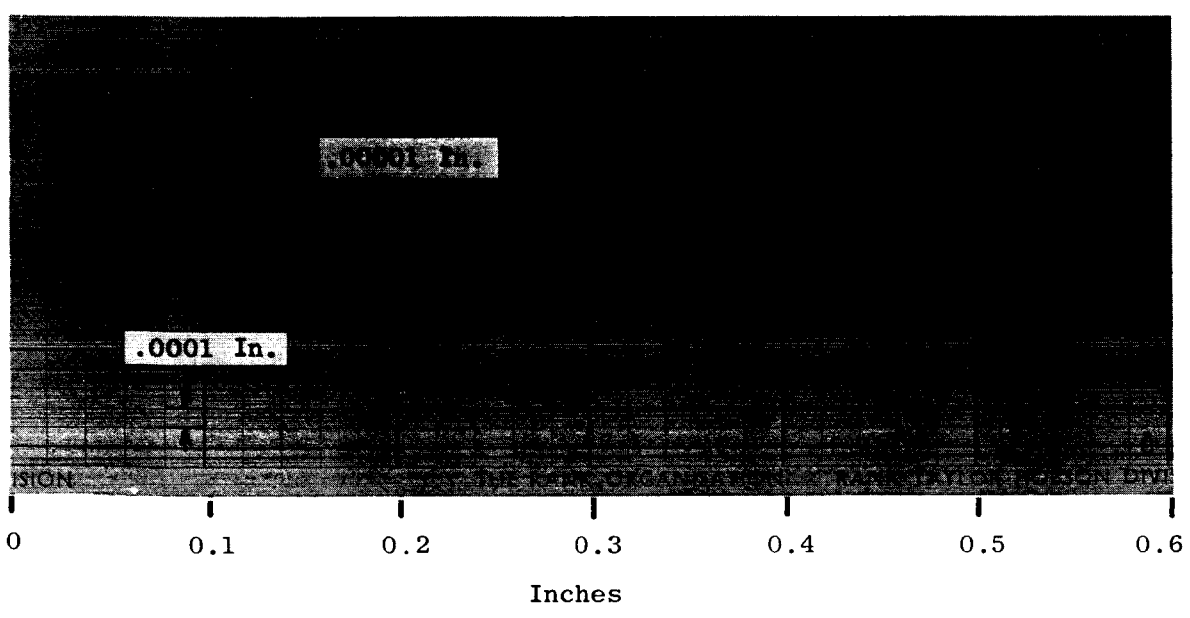
Remarks - Test terminated due to slippage of magnetic drive.

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



Wear Scar Dia., In. - 0.013

Weight, Gms -
Start - 3.5159
Finish - 3.5155
Change - 0.0004

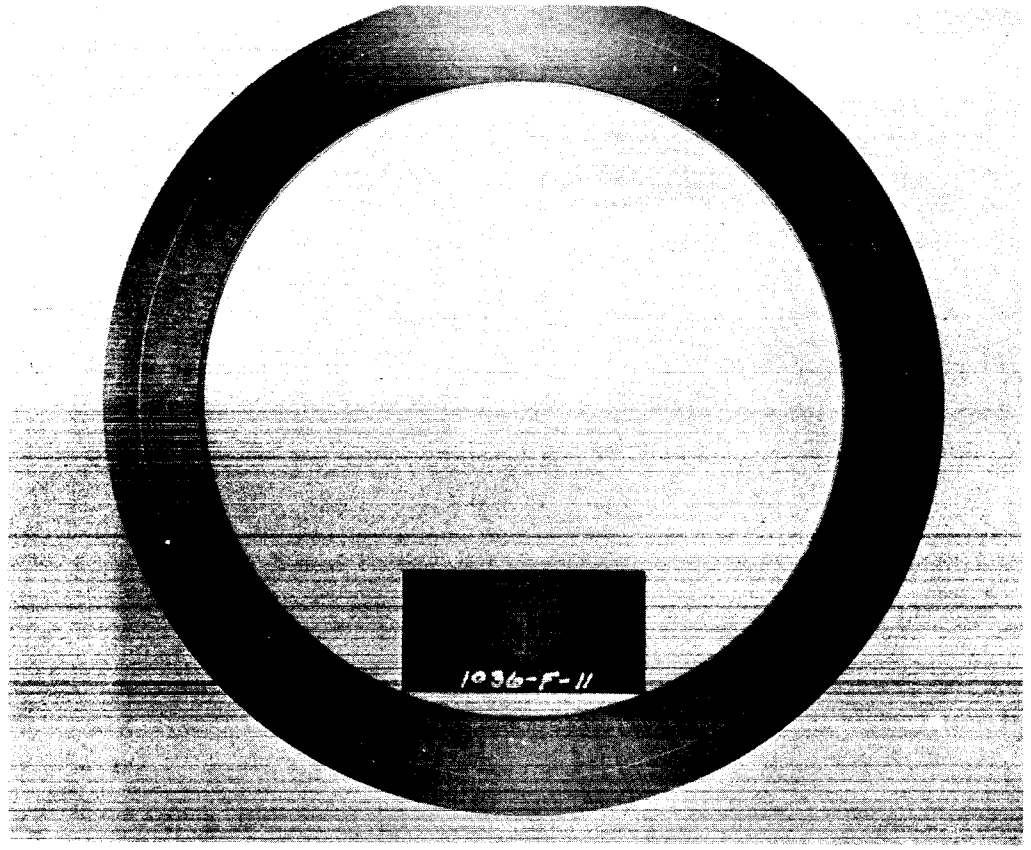
Material Density, Gms/Cm^3 - 14.684

Volume Change, Mm^3 - -0.028

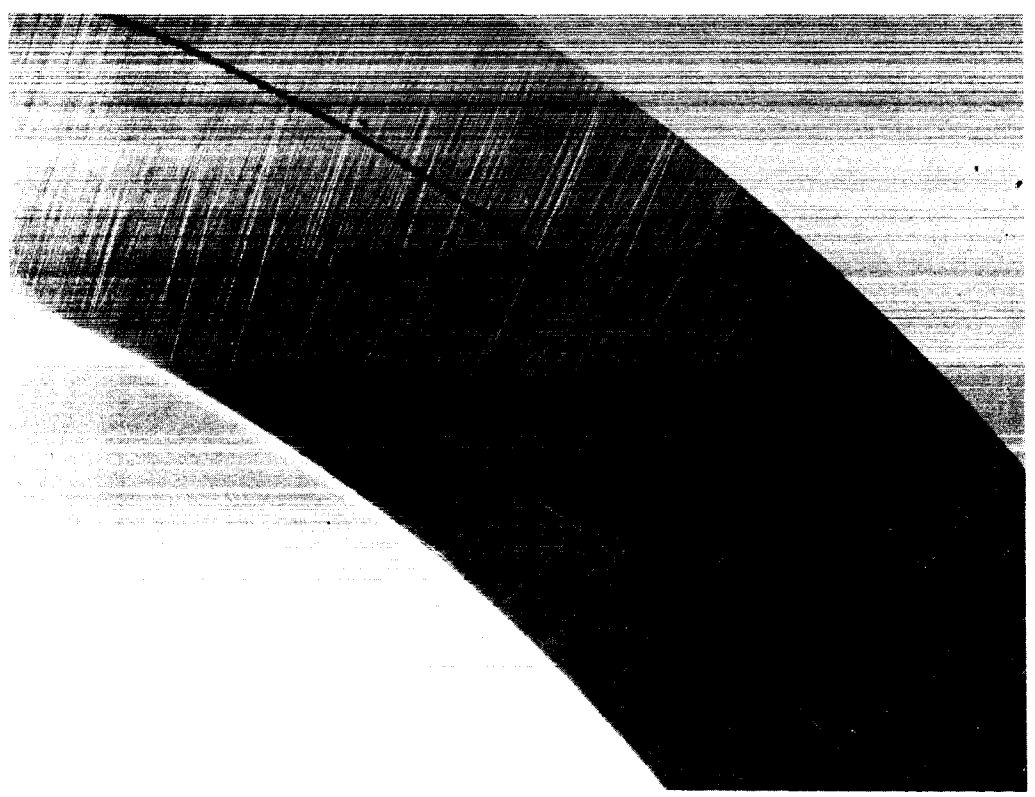
Wear Rate, In^3/10^{10}ft - -5.01

(C66111023) Mag.: 28.5X

(1036-E-17) Mag.: 5X



(1036-F-11) Mag.: 1X



(C66112332) Mag.: 5X

Initial Surface Finish, Avg. RMS - 0.5 - 1.5

Wear Scar Width, In. - 0.014

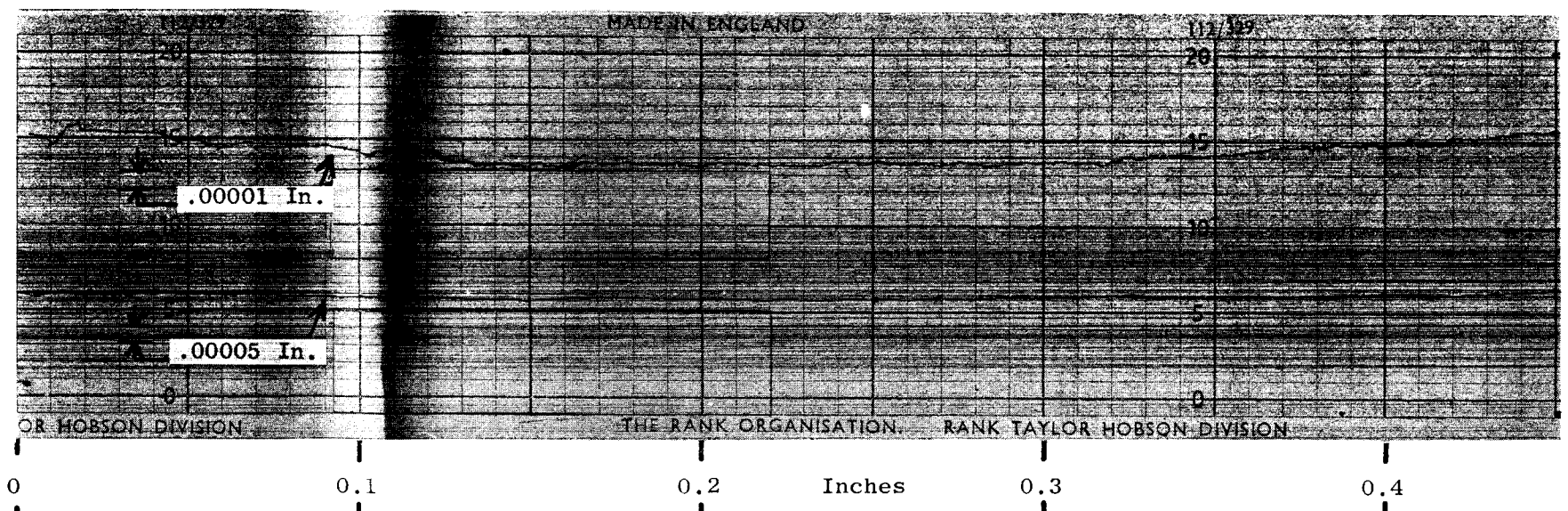
Weight, Gms /Cm^3 -
Start - 220.3611
Finish - 220.3579
Change - -0.0032

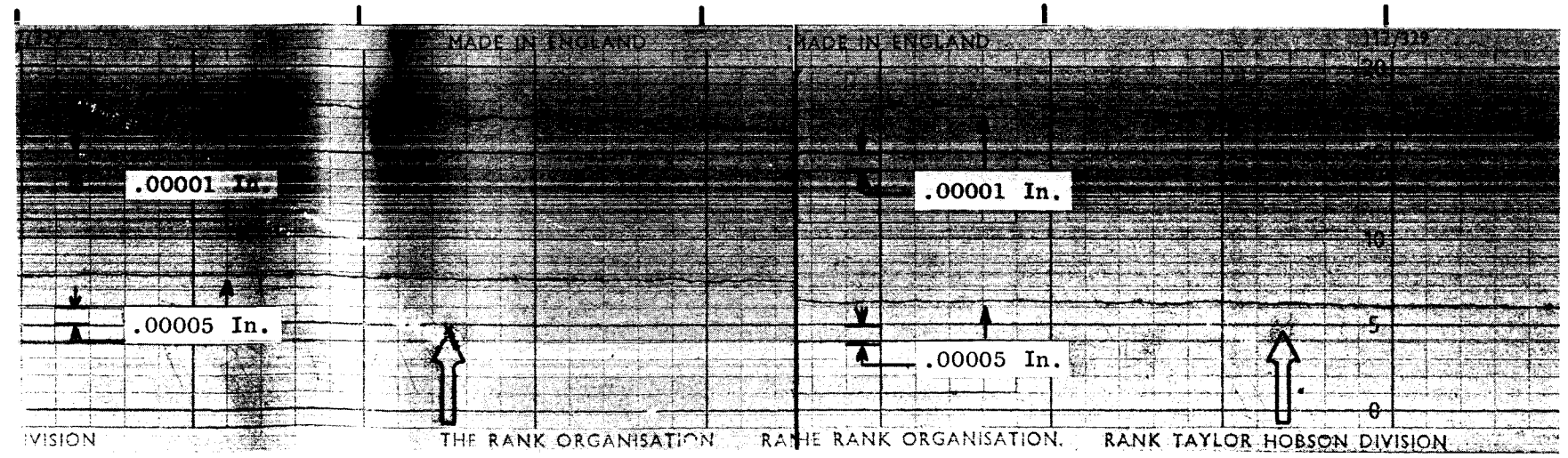
Material Density, Gms /Cm^3 - 14.684

Volume Change, Mm^3 - 0.218

Wear Rate, In^3/10^{10}ft - -40.1

Post-Test Profilometer Trace - Circumferential at 90°





Post-Test Profilometer Trace - Radial at 0° Radial at 90°

FRICTION AND WEAR TEST DATA FOR CARBOLOY 907 VS CARBOLOY 907 IN HIGH VACUUM

Test No. - 512H08A

Assembly No. - XXI

Loading Arm No. - 4

Test Date - 5-16-66

Rider
Material - Carboloy 907
Specimen No. - 1036-E-18

Disc
Material - Carboloy 907
Specimen No. - 1036-F-12

Test Temperature, °F - 1207

Max. ΔT of Rider, °F - 12

Speed, SFM - 800

Test Duration, Min. - 60.00

Compressive Load, Lbs - 0.119 (H)

Compressive Stress, psi - 88,260

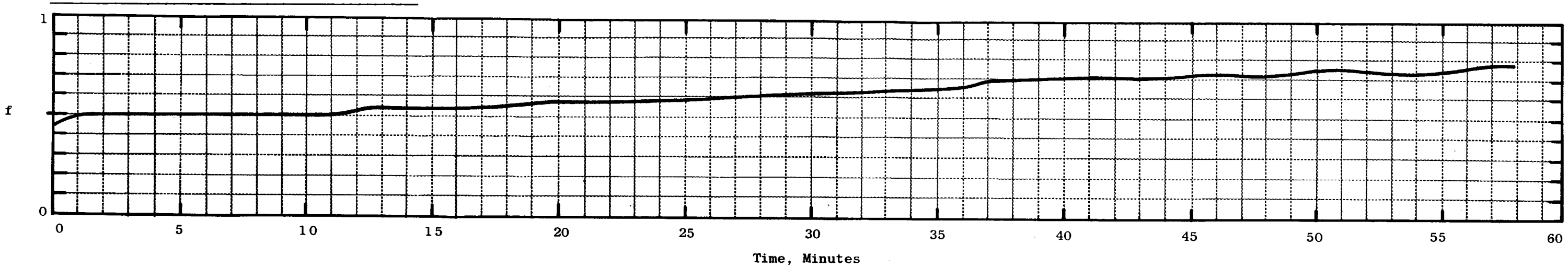
Load/Material UCS or 0.2%CYS -
Rider - 18%
Disc - 18%

Average Coefficient of Friction - 0.64

Chamber Pressure, Torr -
Start - 8.8×10^{-9}
Max. - 9.3×10^{-9}

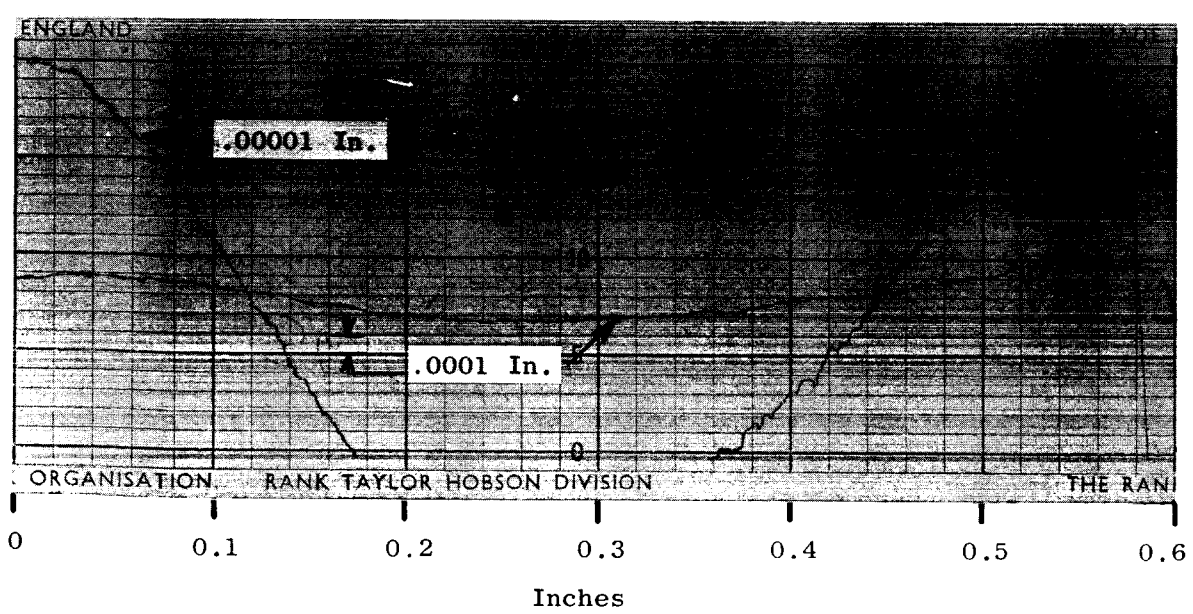
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



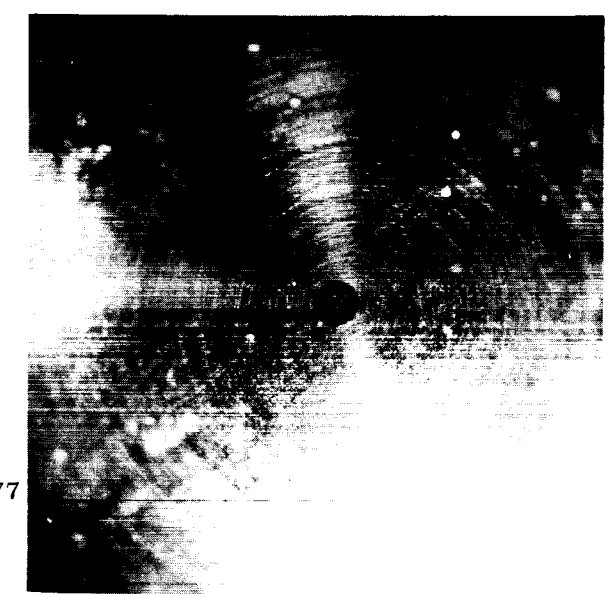
Wear Scar Dia., In. - 0.015

Weight, Gms -
Start - 3.5254
Finish - 3.5248
Change - -0.0006

Material Density, Gms/Cm^3 -
14.684

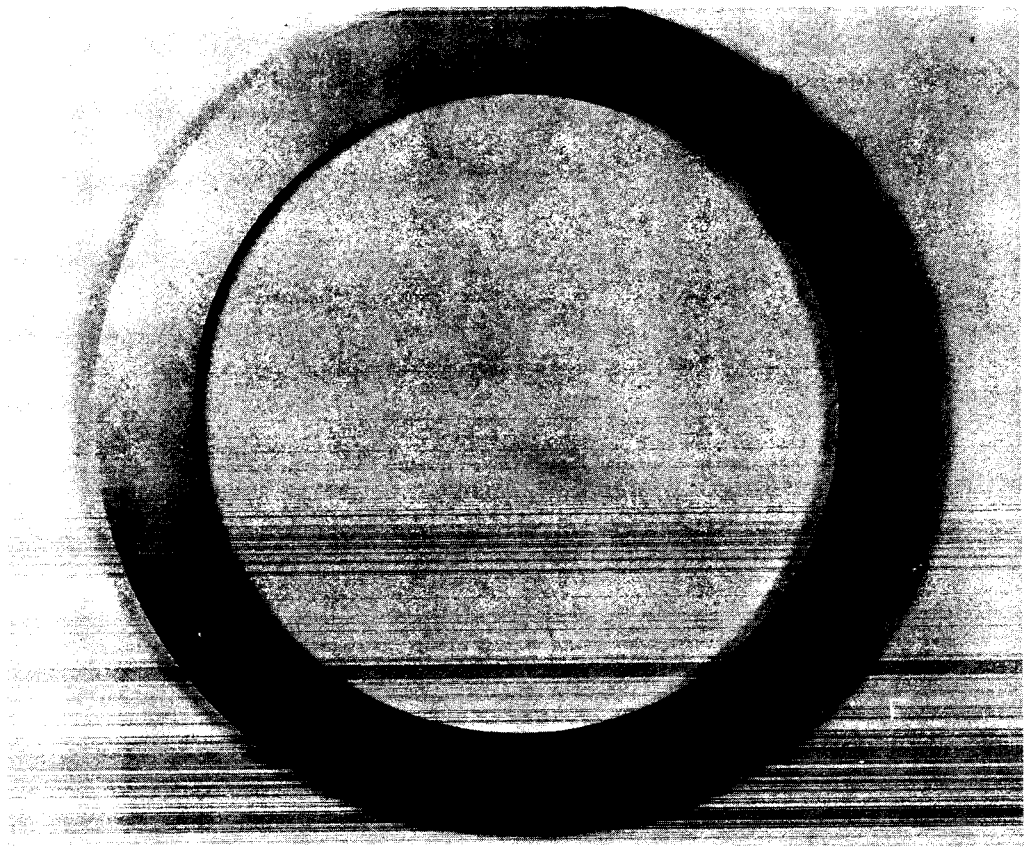
Volume Change, Mm^3 - -0.041

Wear Rate, $In^3/10^{10}ft$ - -0.477

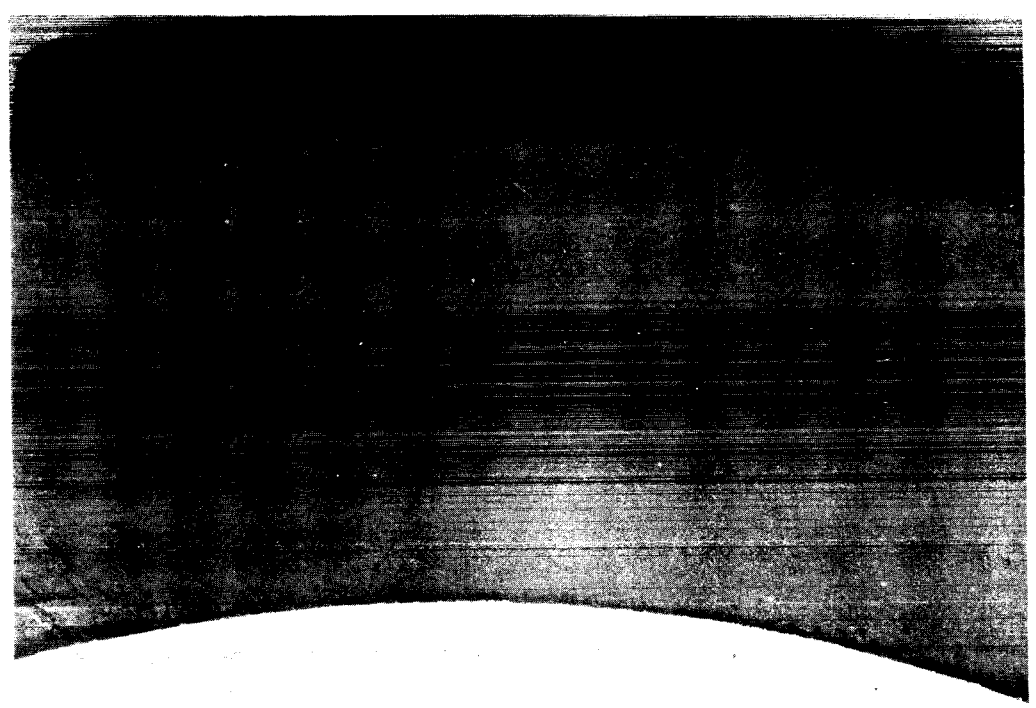


(C66111710) Mag.: 28.5X

(C66111708) Mag.: 5X



(C650813111) Mag.: 1X



(C65081344) Mag.: 5X

Initial Surface Finish, Avg. RMS - 0.5 - 2.0

Wear Scar Width, In. - 0.008

Weight, Gms /Cm^3 -

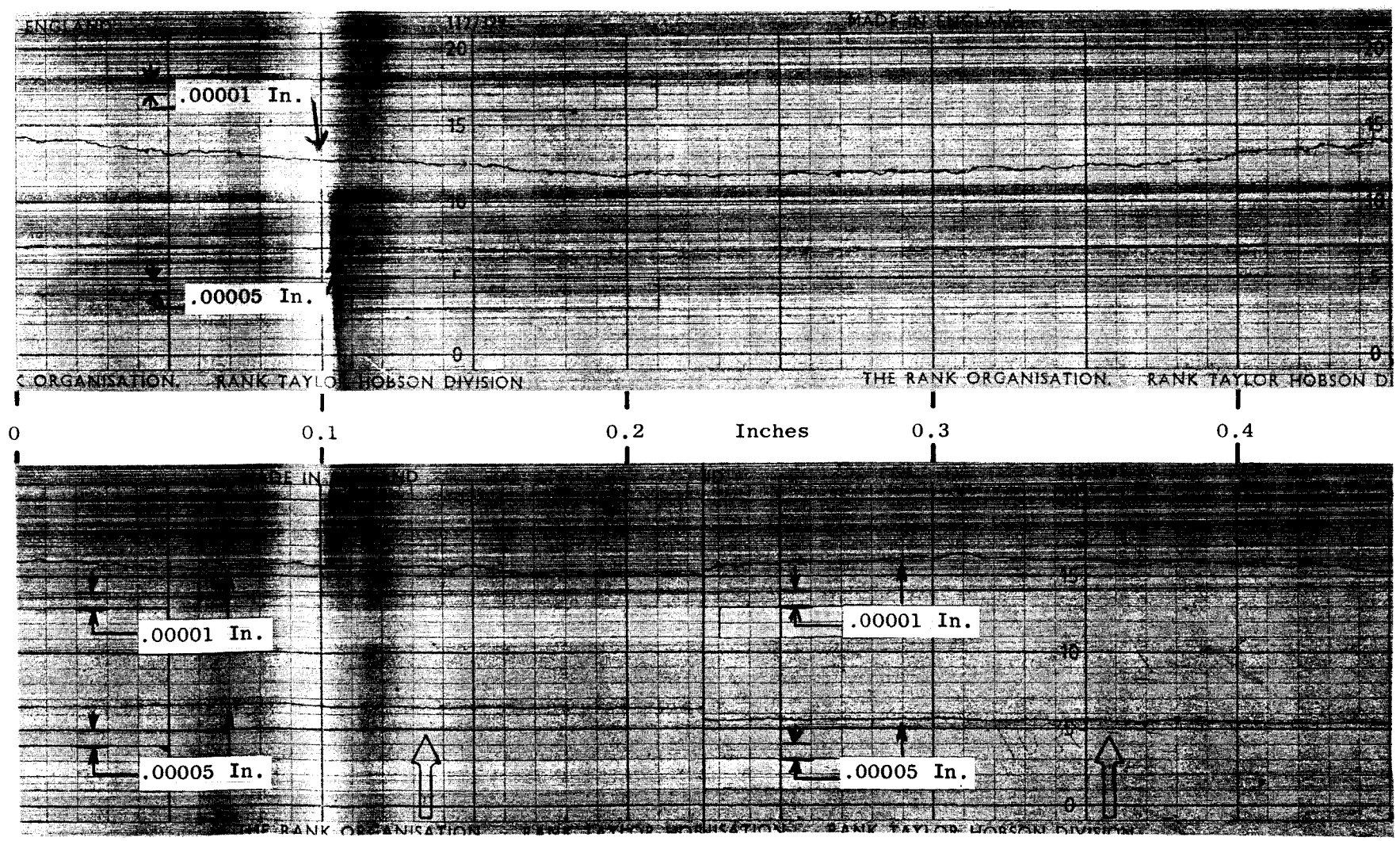
Start -	222.8212
Finish -	222.8197
Change -	-0.0015

Material Density, Gms /Cm^3 - 14.684

Volume Change, Mm^3 - -0.102

Wear Rate, $In^3/10^{10}ft$ - -1.19

Post-Test Profilometer Trace - Circumferential at 0°



Post-Test Profilometer Trace - Radial at 0°

Radial at 90°

APPENDIX C

FRICTION AND WEAR DATA - LIQUID POTASSIUM

FRICTION AND WEAR TEST PROGRAM

FRICTION AND WEAR TEST DATA FOR Mo-TZM ALLOY VS GRADE 7178 IN LIQUID POTASSIUM

Test No. - 104K10K

Assembly No. - KII

Loading Arm No. - 5

Test Date - 5-4-66

Rider
Material - MoTZM Alloy
Specimen No. - 1037-E-21

Disc
Material - Grade 7178
Specimen No. - 1046-F-23A

Test Temperature, °F - 408

Max. ΔT of Rider, °F - 10

Speed, SFM - 1000

Test Duration, Min. - 60.00

Compressive Load, Lbs. - 0.081(K)

Compressive Stress, psi. - 89,070

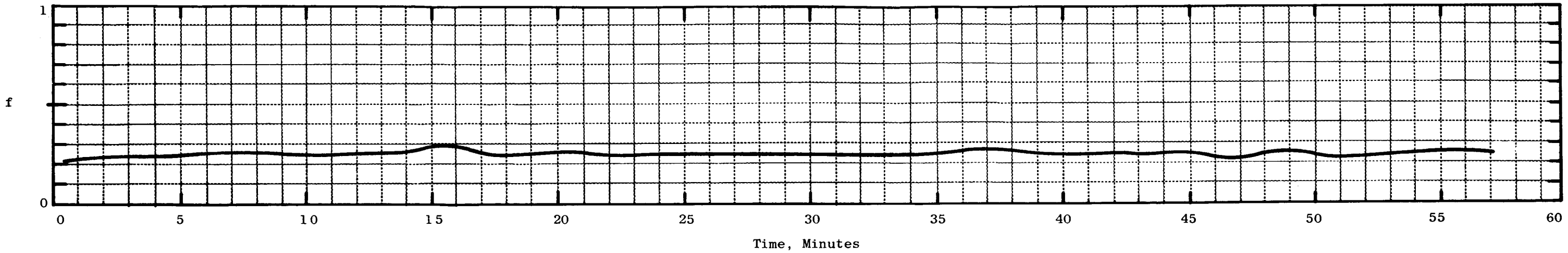
Load/Material UCS or 0.2%CYS -
Rider - 84%
Disc - 13%

Average Coefficient of Friction - 0.25

Chamber Pressure
Pre-Test, Torr - 1.4×10^{-6}
Cover Pressure, Psig - 15.2

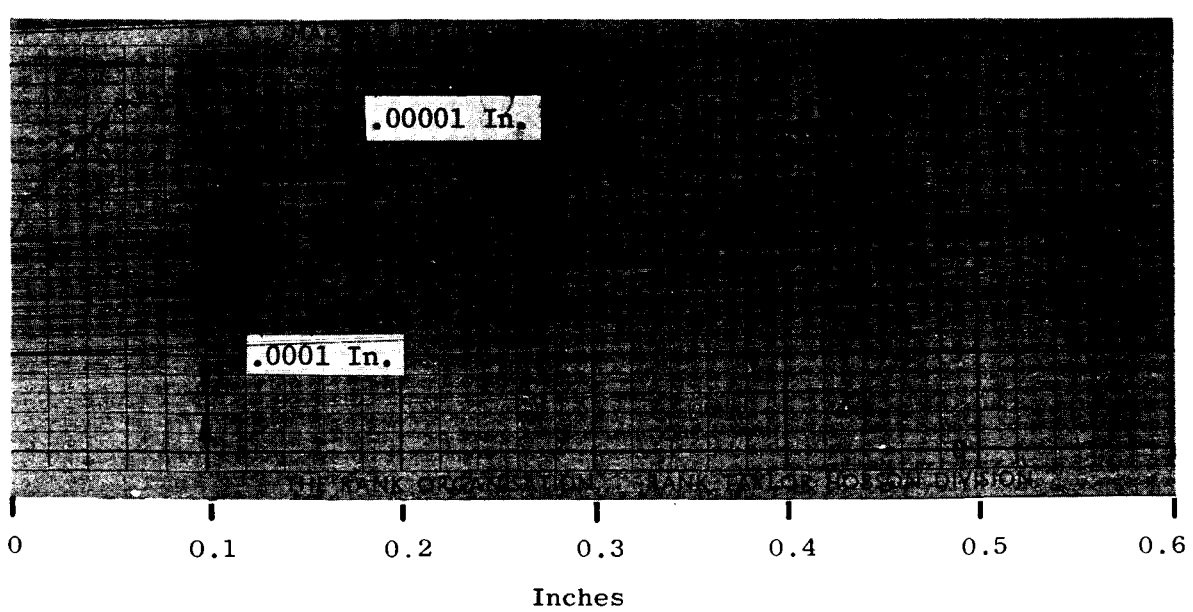
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



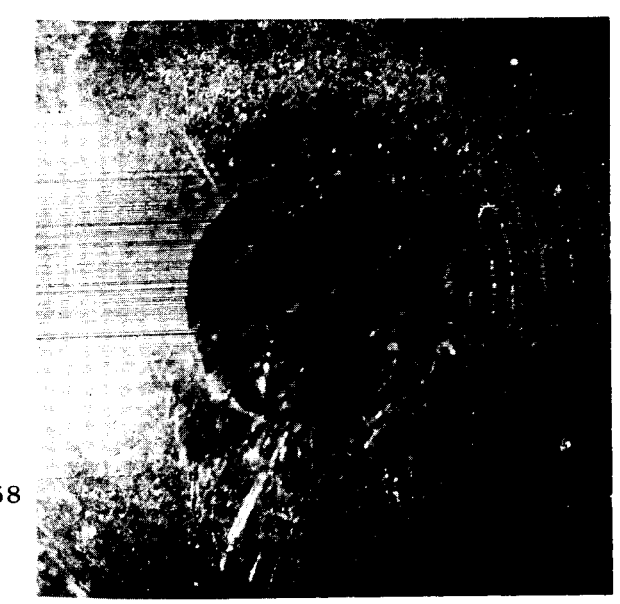
Wear Scar Dia., In. - 0.030

Weight, Gms. -
Start - 2.3806
Finish - 2.3803
Change - 0.0003

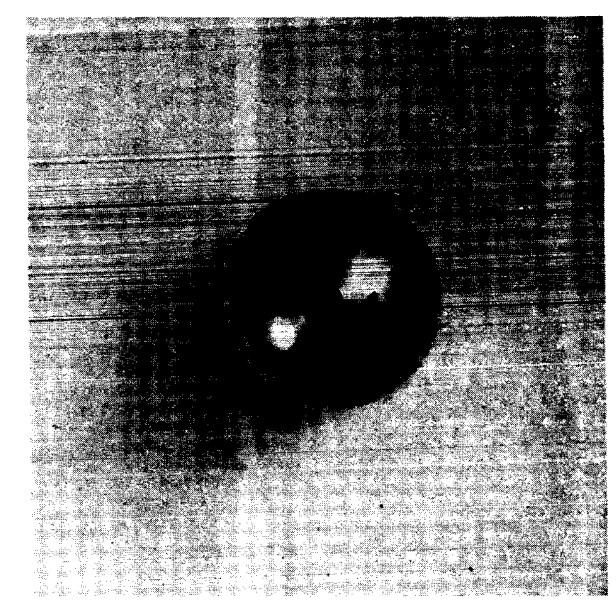
Material Density, Gms/Cm^3 -
10.139

Volume Change, Mm^3 - -0.030

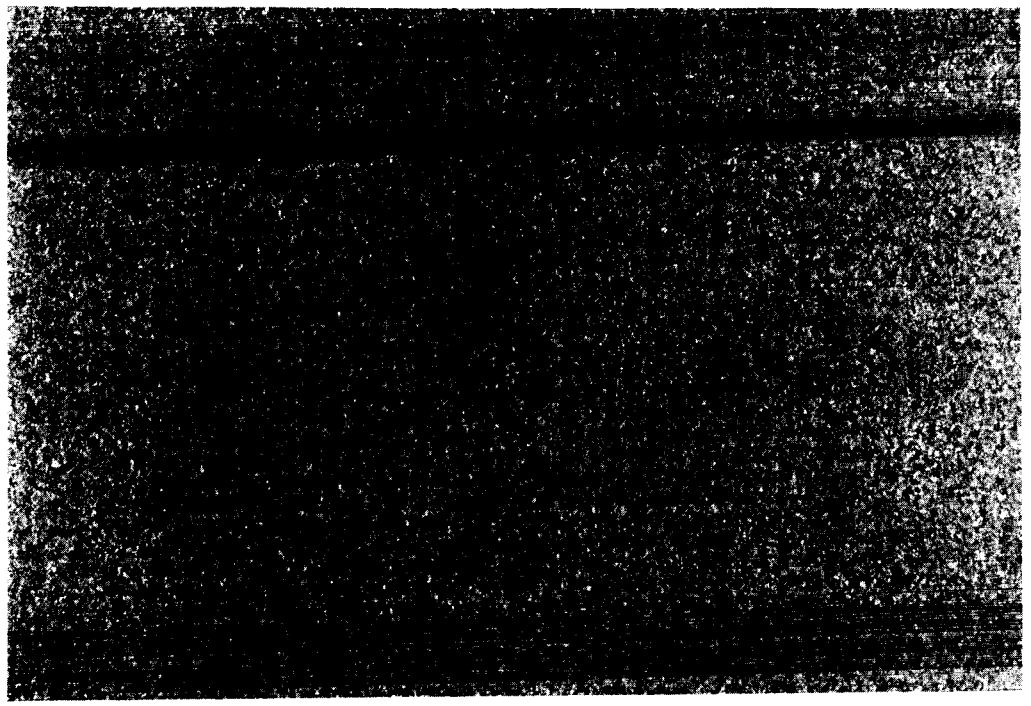
Wear Rate, In^3/10^{10}ft - -0.258



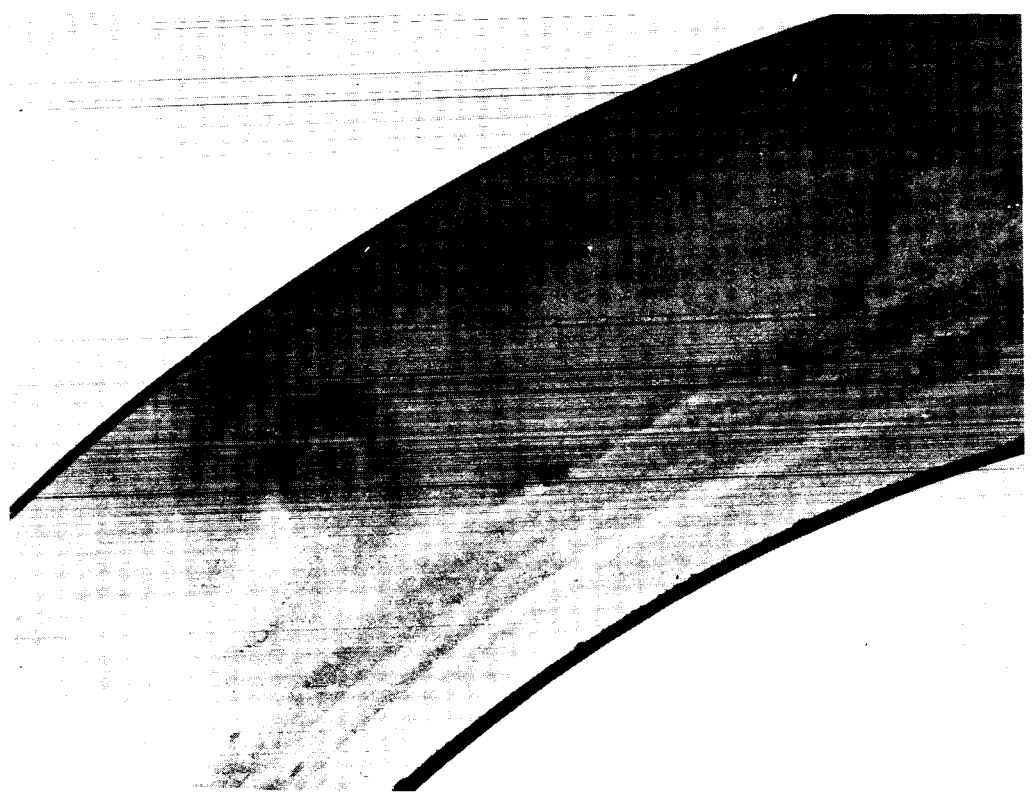
(C66111033) Mag.: 46.2X



(1037-E-21) Mag.: 5X



(C66112327) Mag.: 46.2X



(1046-F-23) Mag.: 5X

Initial Surface Finish, Avg. RMS - 3-5

Wear Scar Width, In. - 0.020

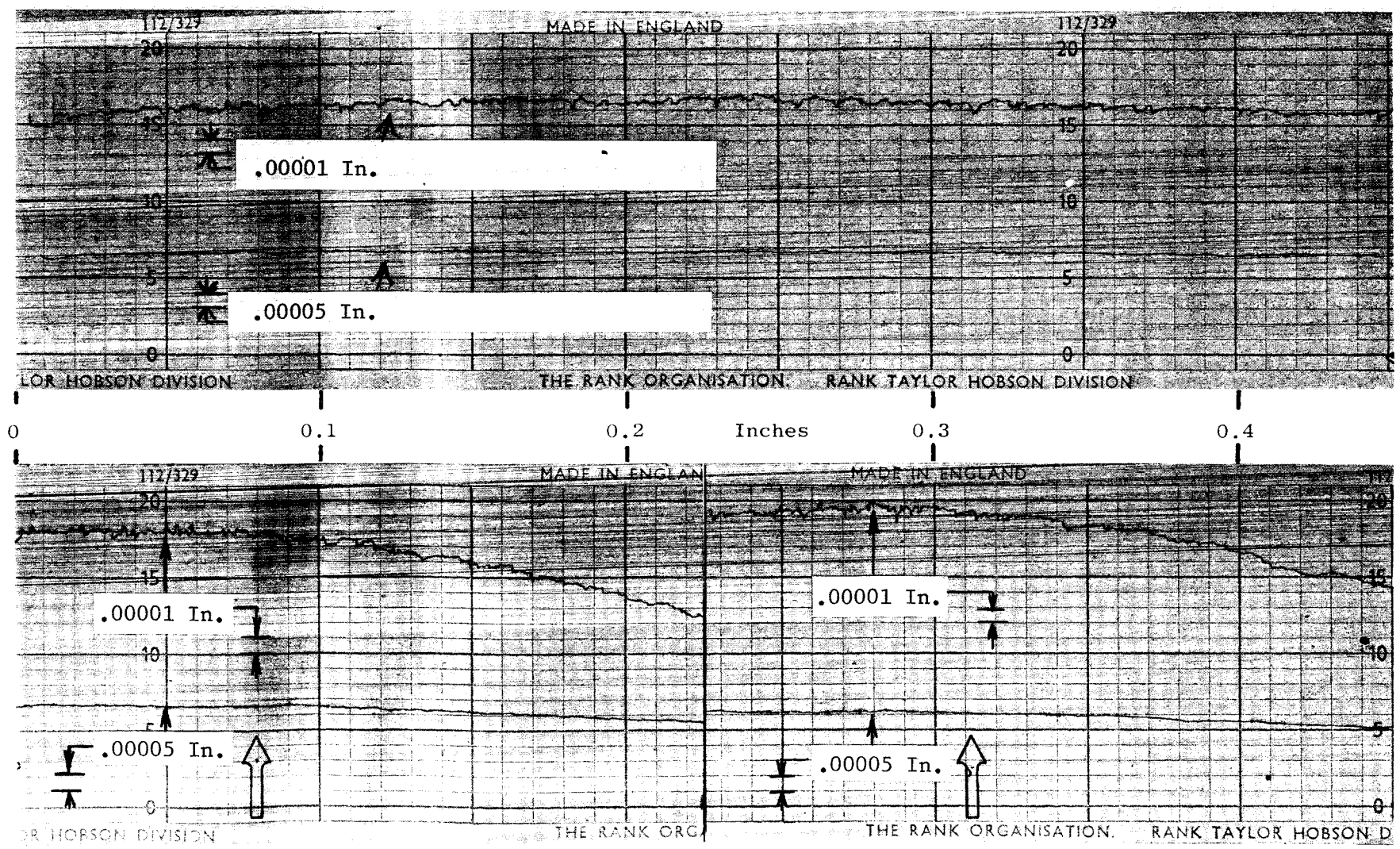
Weight, Gms./Cm^3 -
Start - 220.8020
Finish - 220.7818
Change - -0.0202

Material Density, Gms./Cm^3 - 14.301

Volume Change, Mm^3 - -1.412

Wear Rate, $In^3/10^{10}ft$ - -12.3

Post-Test Profilometer Trace - Circumferential at 90°



Post-Test Profilometer Trace - Radial at 0° Radial at 90°

FRICTION AND WEAR TEST DATA FOR GRADE 7178 VS GRADE 7178 IN LIQUID POTASSIUM

Test No. - 304H10K

Assembly No. - KII

Loading Arm No. - 6

Test Date - 5-20-66

Rider
Material - Grade 7178
Specimen No. - 1046-E-25

Disc
Material - Grade 7178
Specimen No. - 1046-F-24A

Test Temperature, ^{o}F - 394

Max. ΔT of Rider, ^{o}F - 36

Speed, SFM - 1000

Test Duration, Min. - 60.00

Compressive Load, Lbs. - 0.829(H)

Compressive Stress, psi. - 224,040

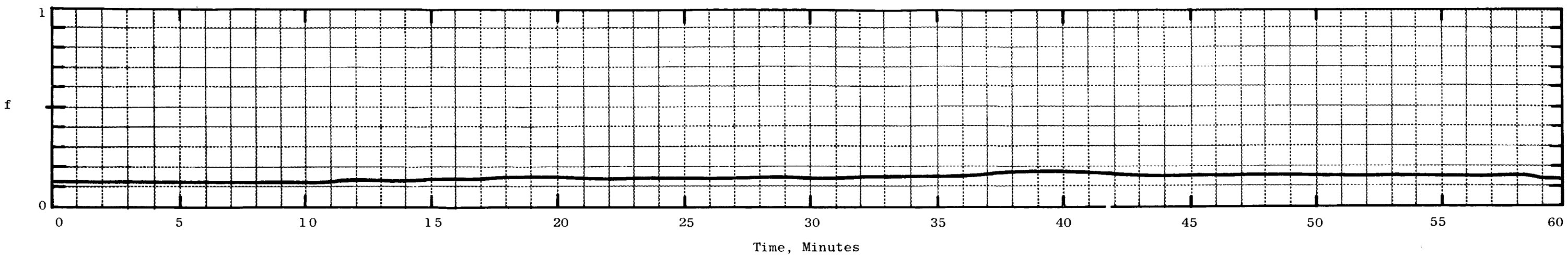
Load/Material UCS or 0.2%CYS -
Rider - 33%
Disc - 33%

Average Coefficient of Friction - 0.15

Chamber Pressure
Pre-Test, Torr - 5.0×10^{-4}
Cover Pressure, Psig - 15.1

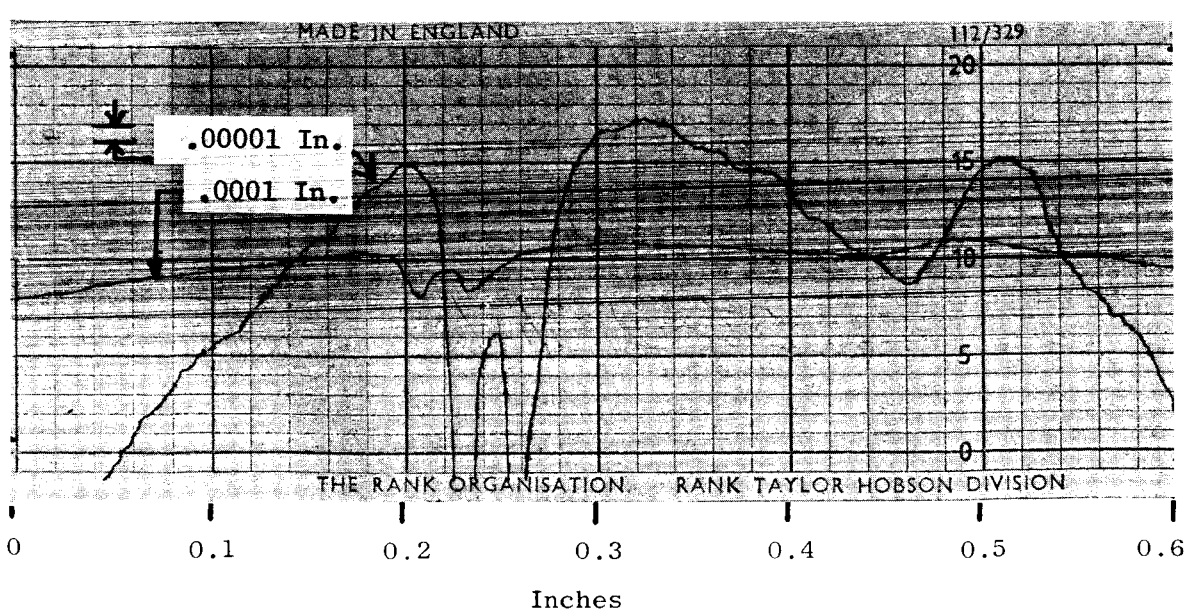
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



Wear Scar Dia., In. - 0.020

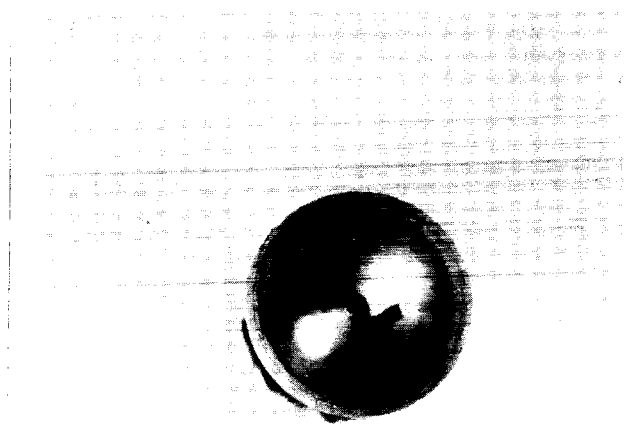
Weight, Gms. -
Start - 3.0827
Finish - 3.0825
Change - 0.0002

Material Density, $Gms./Cm^3$ -
14.301

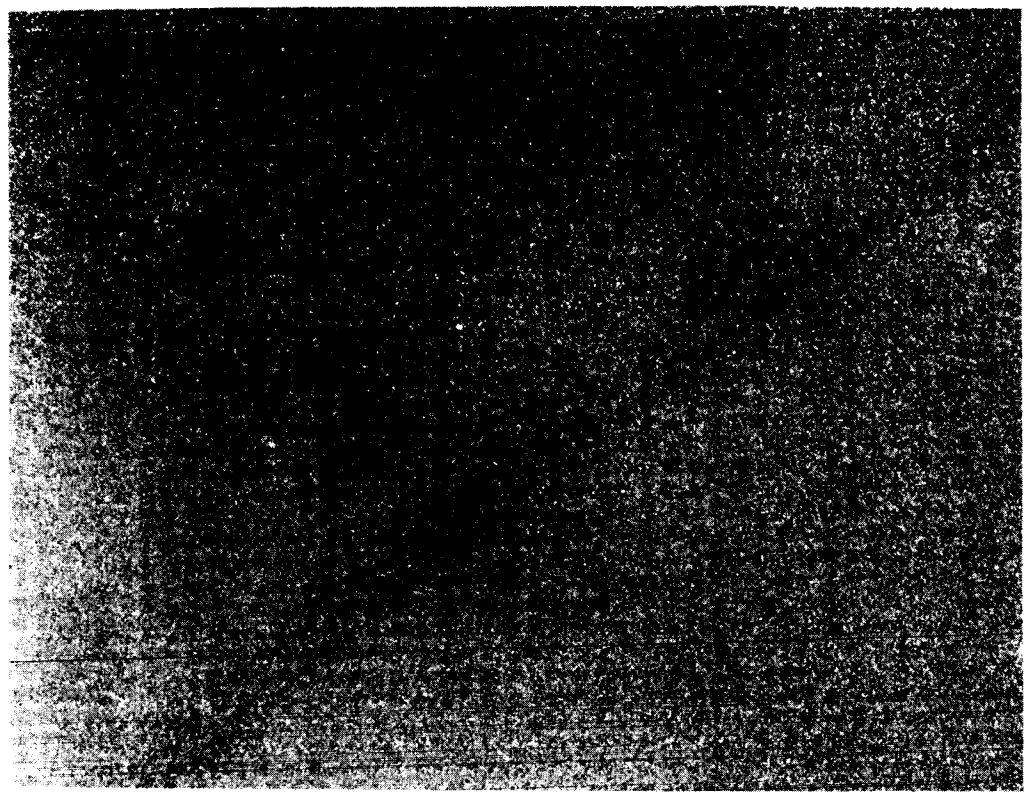
Volume Change, Mm^3 - -0.014

Wear Rate, $In^3/10^{10}ft$ - -0.141

(C66111060) Mag.: 46.2X



(C66111095) Mag.: 5X



(C66111056) Mag.: 46.2X

(1046-F-24) Mag.: 5X

Initial Surface Finish, Avg. RMS - 3.5 - 5.0

Wear Scar Width, In. - 0.016

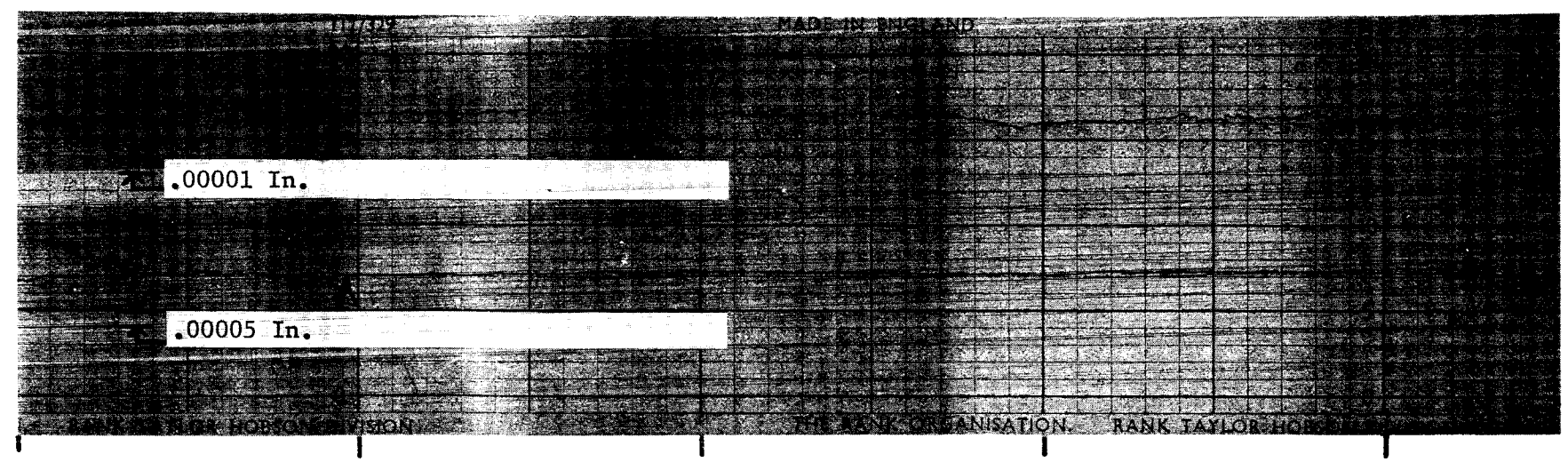
Weight, Gms./Cm^3 -
Start - 219.0356
Finish - 219.0244
Change - -0.0112

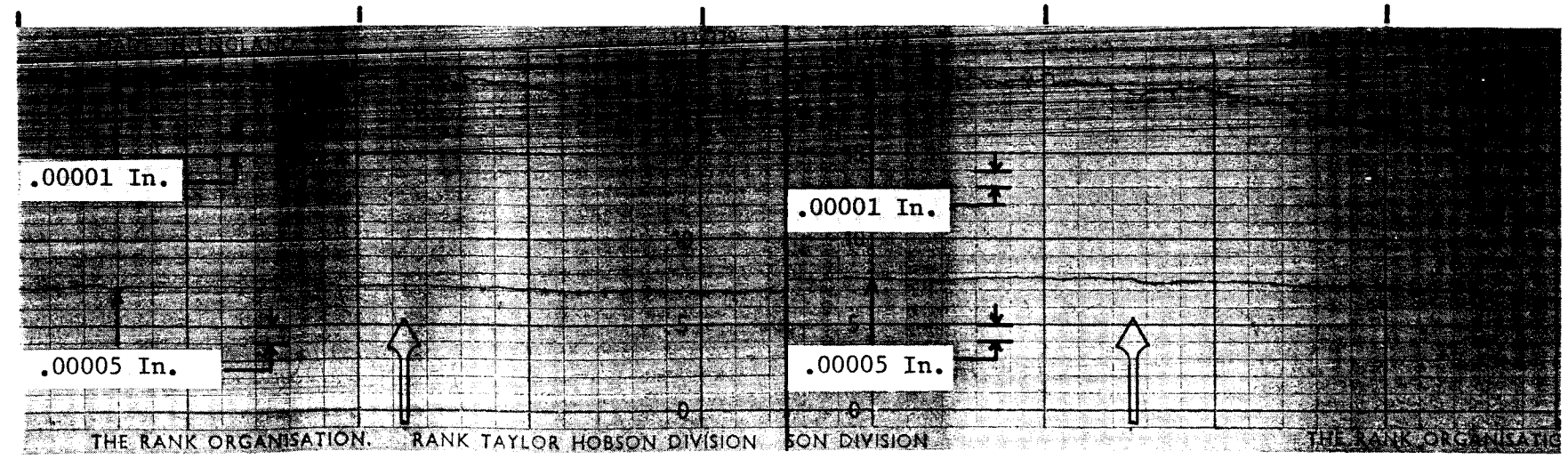
Material Density, Gms./Cm^3 - 14.301

Volume Change, Mm^3 - -0.783

Wear Rate, $In^3/10^{10}ft$ - -7.87

Post-Test Profilometer Trace - Circumferential at 0°





Post-Test Profilometer Trace - Radial at 0°

Radial at 90°

FRICTION AND WEAR TEST DATA FOR TiC + 10%Cb VS TiC +10%Cb IN LIQUID POTASSIUM

Test No. - 704H10K

Assembly No. - KIII

Loading Arm No. - 5

Test Date - 7-12-66

Rider
Material - TiC + 10%Cb
Specimen No. - 1045-E-27

Disc
Material - TiC + 10%Cb
Specimen No. - 1045-F-37A

Test Temperature, °F - 396

Max. ΔT of Rider, °F - 32

Speed, SFM - 1000

Test Duration, Min. - 60.00

Compressive Load, Lbs. - 2.81(H)

Compressive Stress, psi. - 299,960

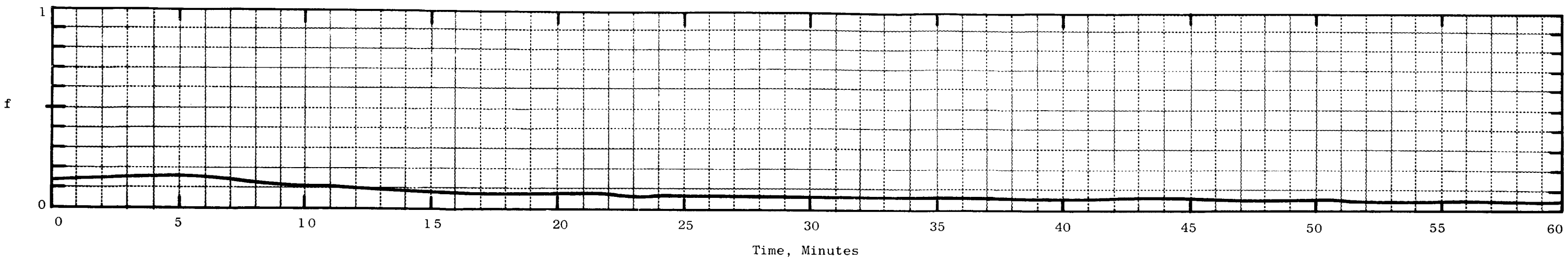
Load/Material UCS or 0.2%CYS -
Rider - 75%
Disc - 75%

Average Coefficient of Friction - 0.07

Chamber Pressure
Pre-Test, Torr - 2.0×10^{-7}
Cover Pressure, Psig - 15.1

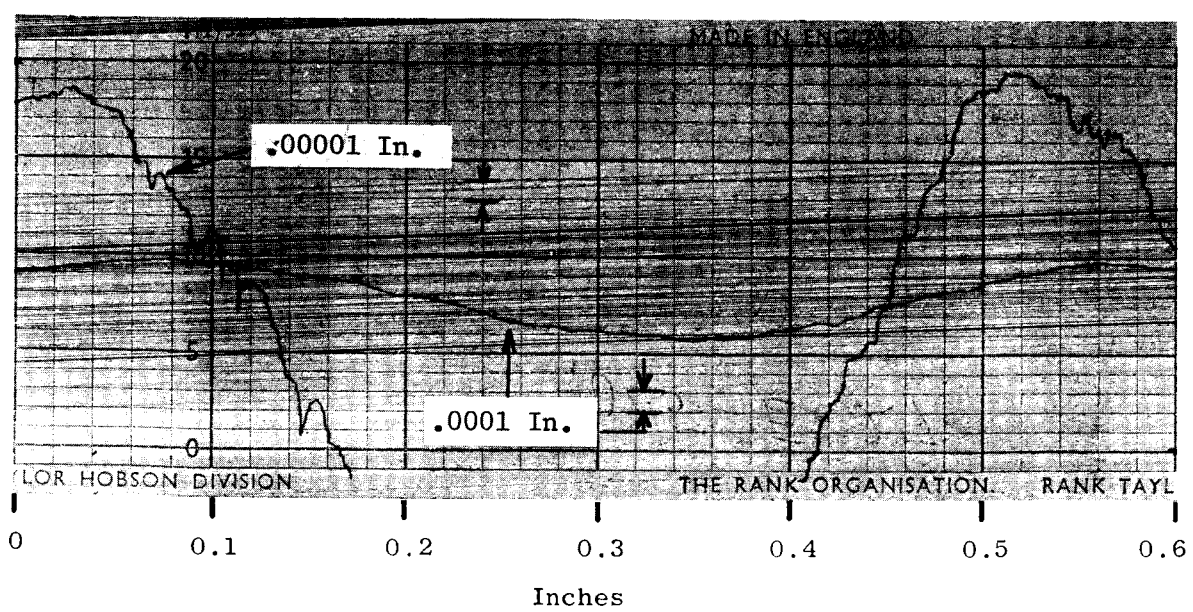
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



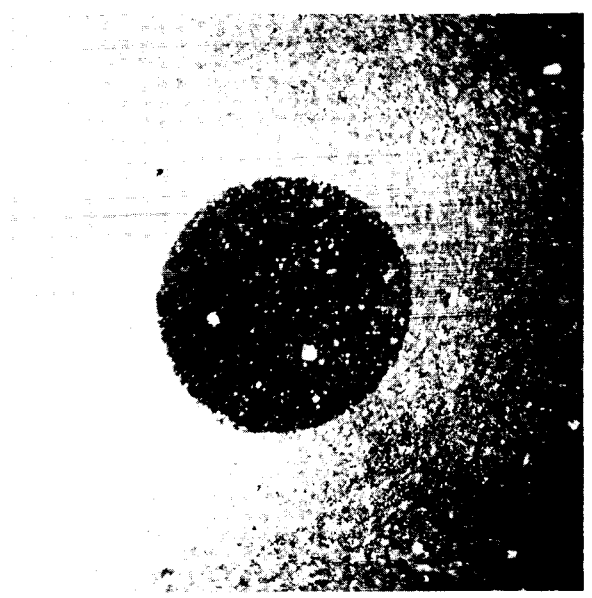
Wear Scar Dia., In. - 0.030

Weight, Gms. -
Start - 1.1064
Finish - 1.1060
Change - -0.0004

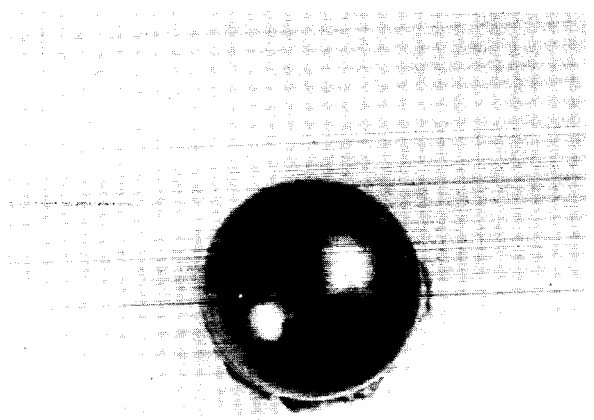
Material Density, Gms/Cm^3 -
5.239

Volume Change, Mm^3 - -0.076

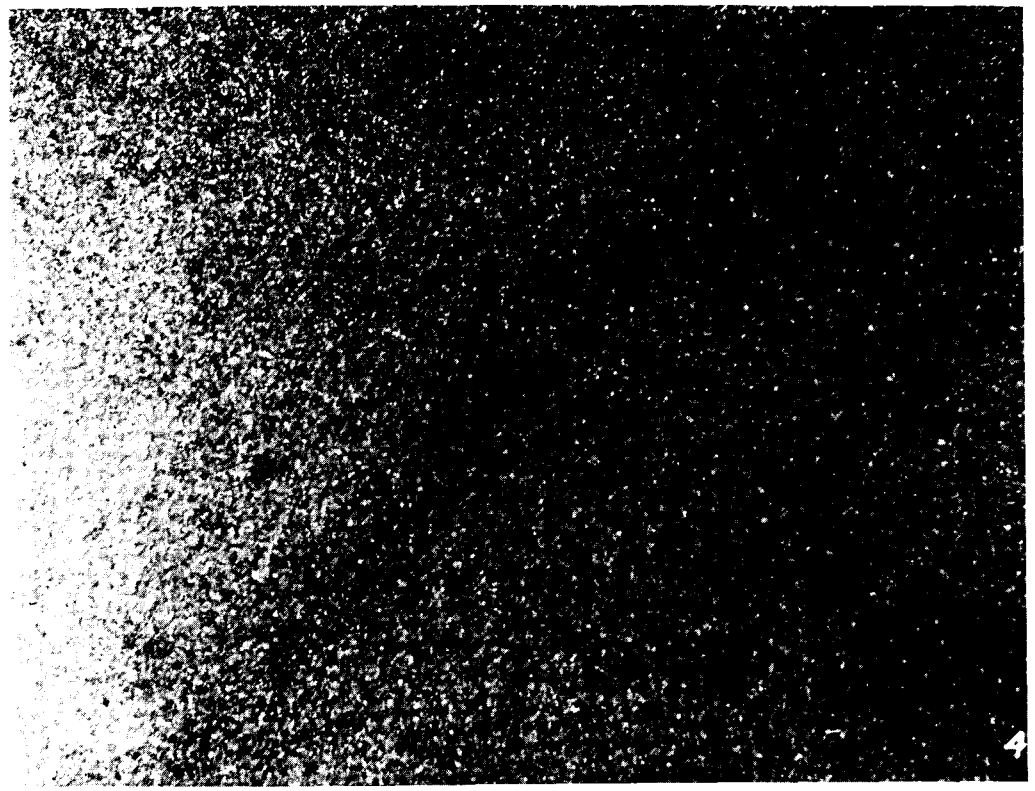
Wear Rate, In^3/10^{10}ft - -0.774



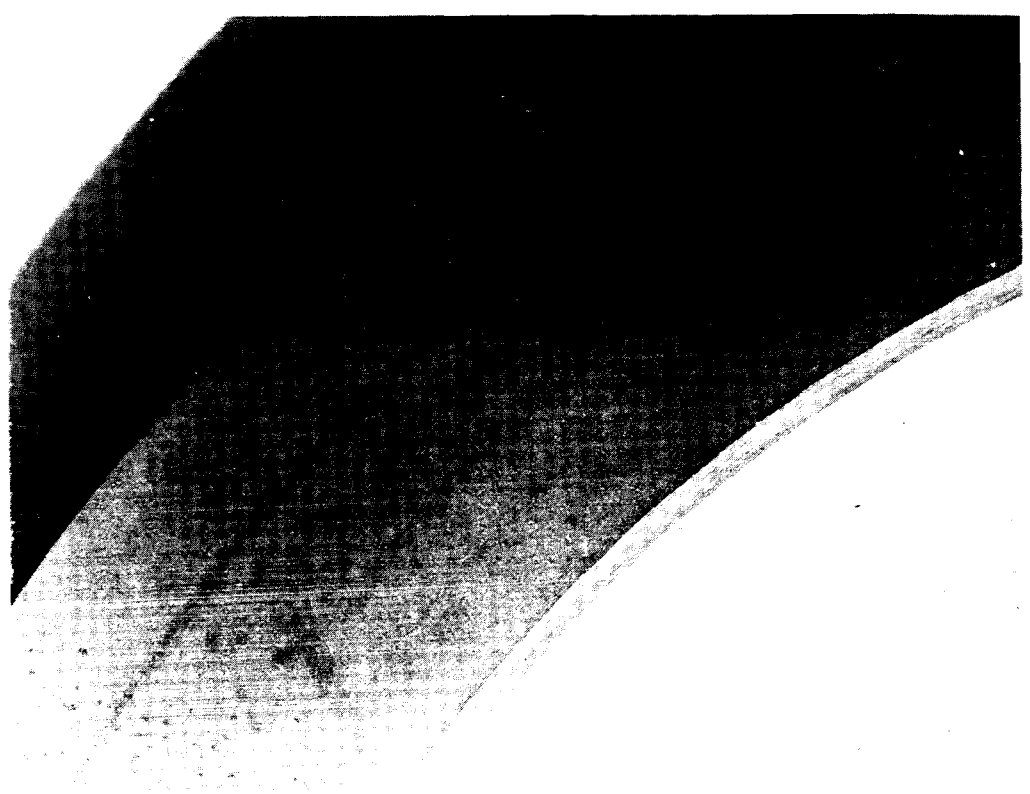
(C66111026) Mag.: 46.2X



(C66111083) Mag.: 5X



(C66111061) Mag.: 46.2X



(C66111063) Mag.: 5X

Initial Surface Finish, Avg. RMS - 1.5 - 2.0

Wear Scar Width, In. - 0.020

Weight, Gms./Cm^3 -

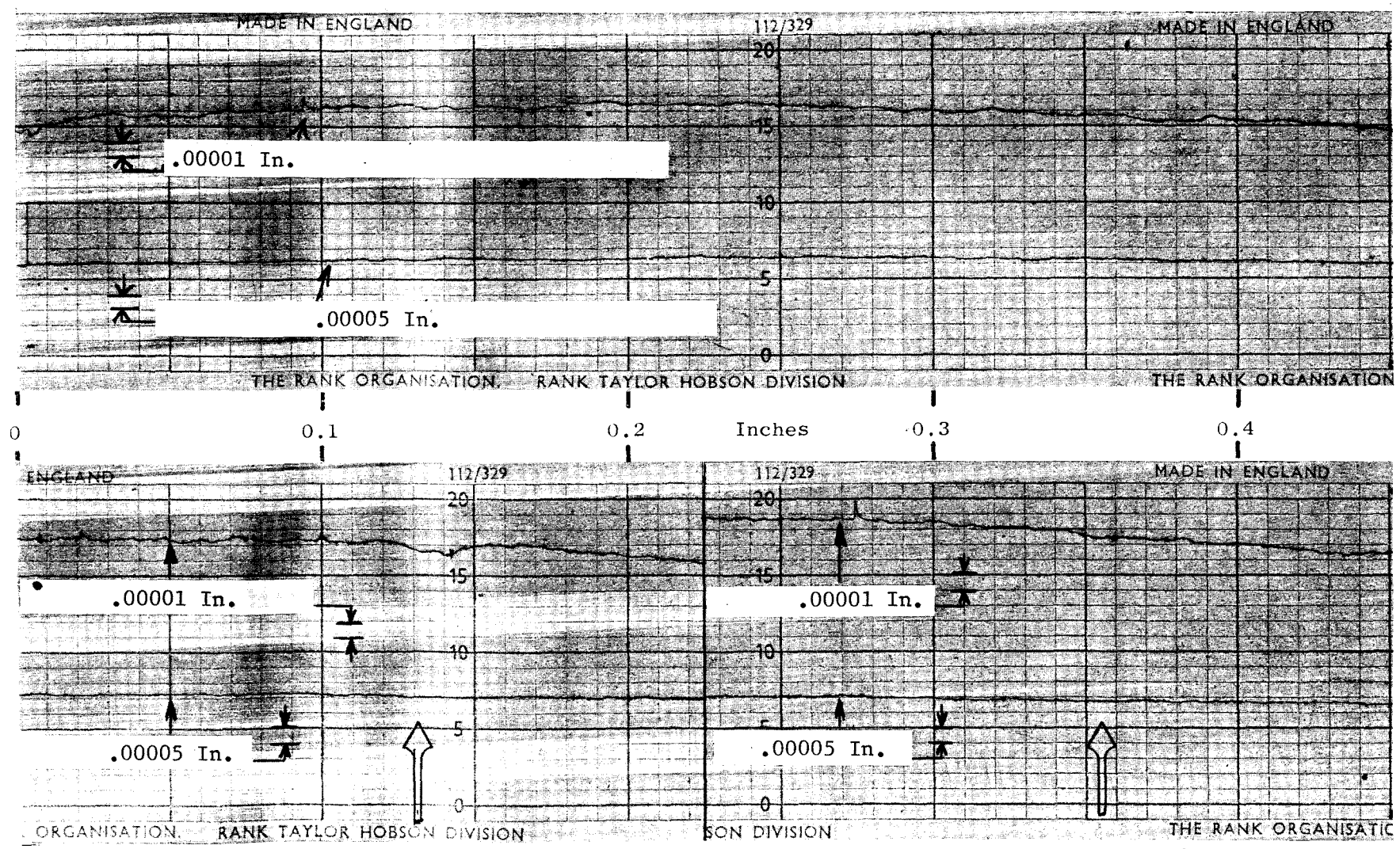
Start -	77.3439
Finish -	77.3436
Change -	-0.0003

Material Density, Gms./Cm^3 - 5.239

Volume Change, Mm^3 - -0.057

Wear Rate, $In^3/10^{10}ft$ - -0.580

Post-Test Profilometer Trace - Circumferential at 90°



Post-Test Profilometer Trace - Radial at 0° Radial at 90°

FRICTION AND WEAR TEST DATA FOR GRADE 7178 VS GRADE 7178 IN LIQUID POTASSIUM

Test No. - 308H10K

Assembly No. - KIII

Loading Arm No. - 6

Test Date - 7-12-66

Rider
Material - Grade 7178
Specimen No. - 1046-E-26

Disc
Material - Grade 7178
Specimen No. - 1046-F-26A

Test Temperature, ^{o}F - 784

Max. ΔT of Rider, ^{o}F - 69

Speed, SFM - 1000

Test Duration, Min. - 60.00

Compressive Load, Lbs. - 2.91(H)

Compressive Stress, psi. - 317,170

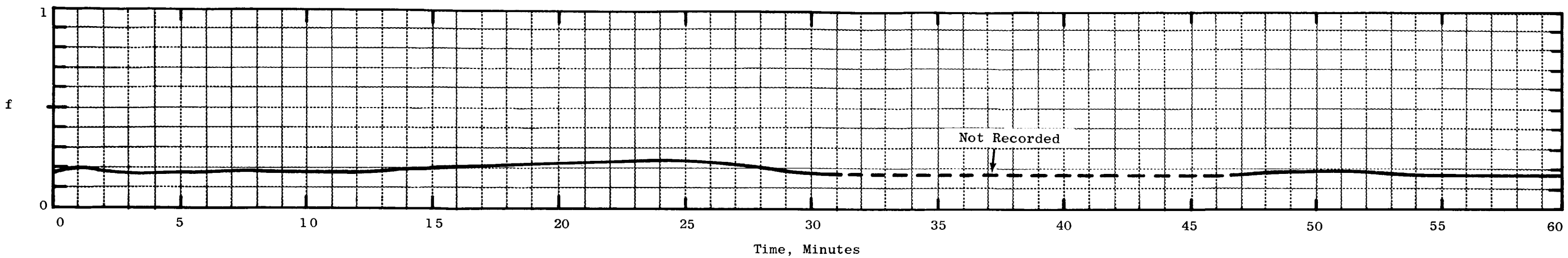
Load/Material UCS or 0.2%CYS -
Rider - 50%
Disc - 50%

Average Coefficient of Friction - 0.18

Chamber Pressure
Pre-Test, Torr - 2.0×10^{-7}
Cover Pressure, Psig - 15.0

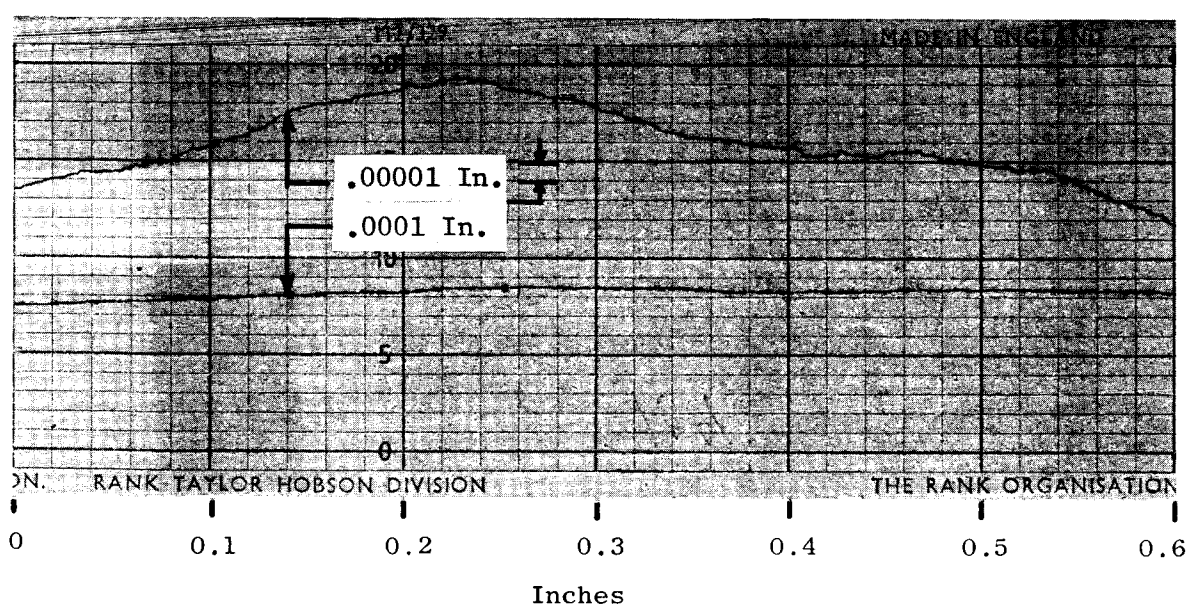
Remarks -

Change in Coefficient of Friction with Time -



WEAR - RIDER

Initial Surface Finish -



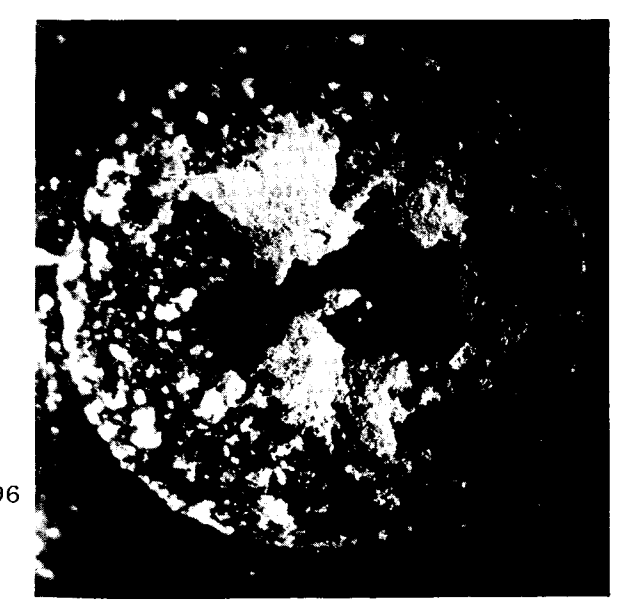
Wear Scar Dia., In. - 0.060

Weight, Gms. -
Start - 3.0946
Finish - 3.0939
Change - -0.0007

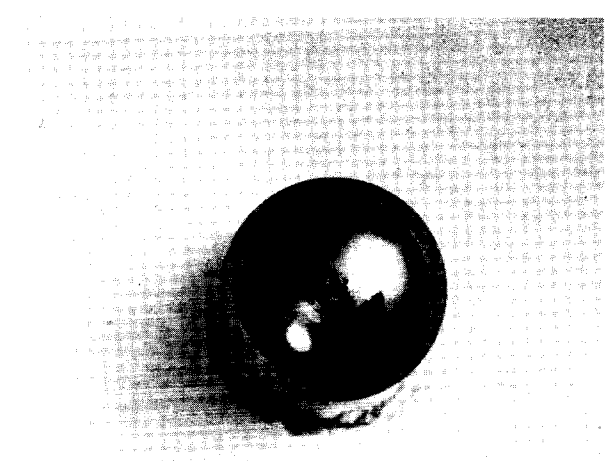
Material Density, Gms/Cm^3 -
14.301

Volume Change, Mm^3 - -0.049

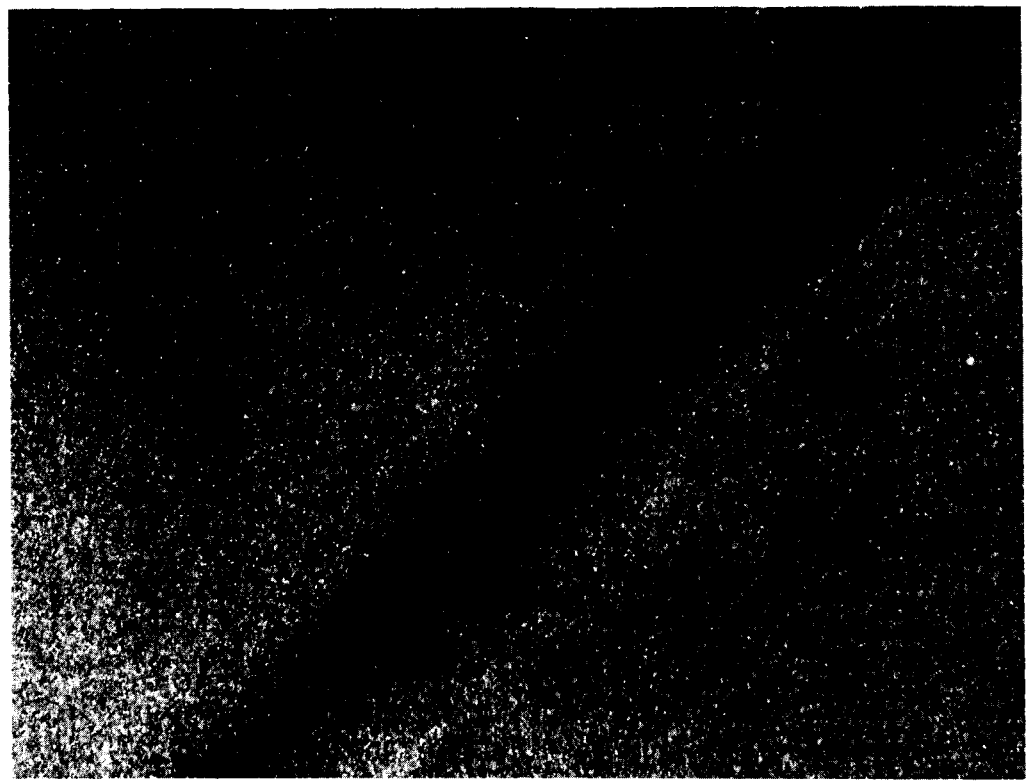
Wear Rate, $In^3/10^{10}ft$ - -0.496



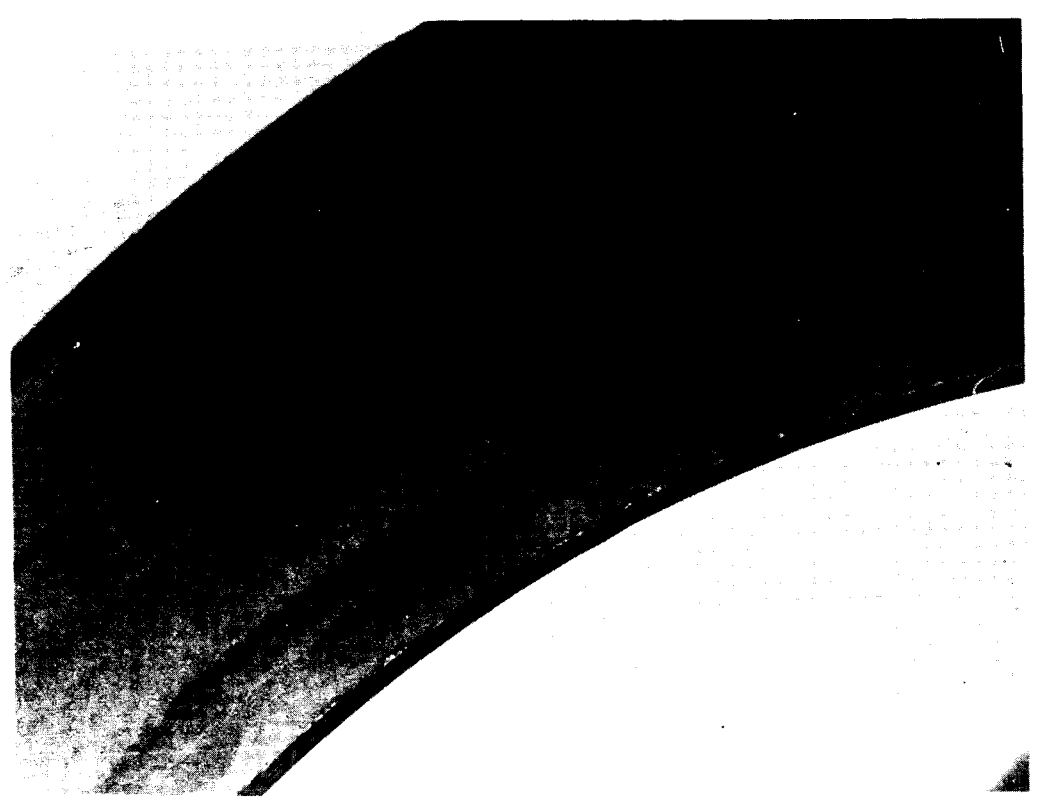
(C66111025) Mag.: 46.2X



(C66111087) Mag.: 5X



(C66111042) Mag.: 43.2X



(C6611078) Mag.: 5X

Initial Surface Finish, Avg. RMS - 2.0-4.5

Wear Scar Width, In. - 0.012

Weight, Gms./Cm^3 -
Start - 220.2614
Finish - 220.2469
Change - -0.0145

Material Density, Gms./Cm^3 - 14.301

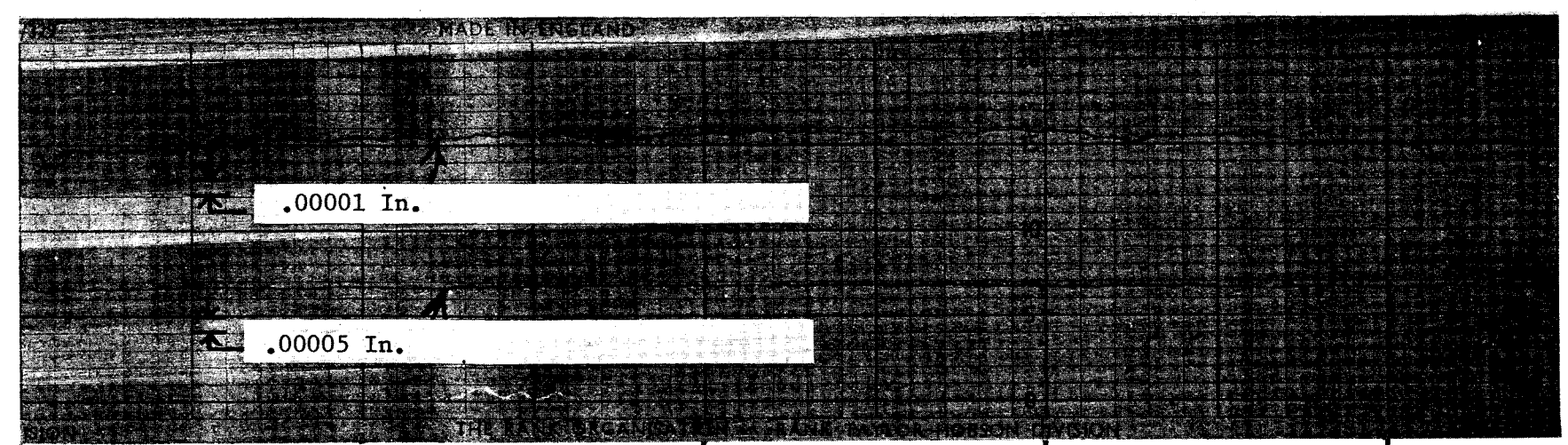
Volume Change, Mm^3 - -1.01 See Note 1

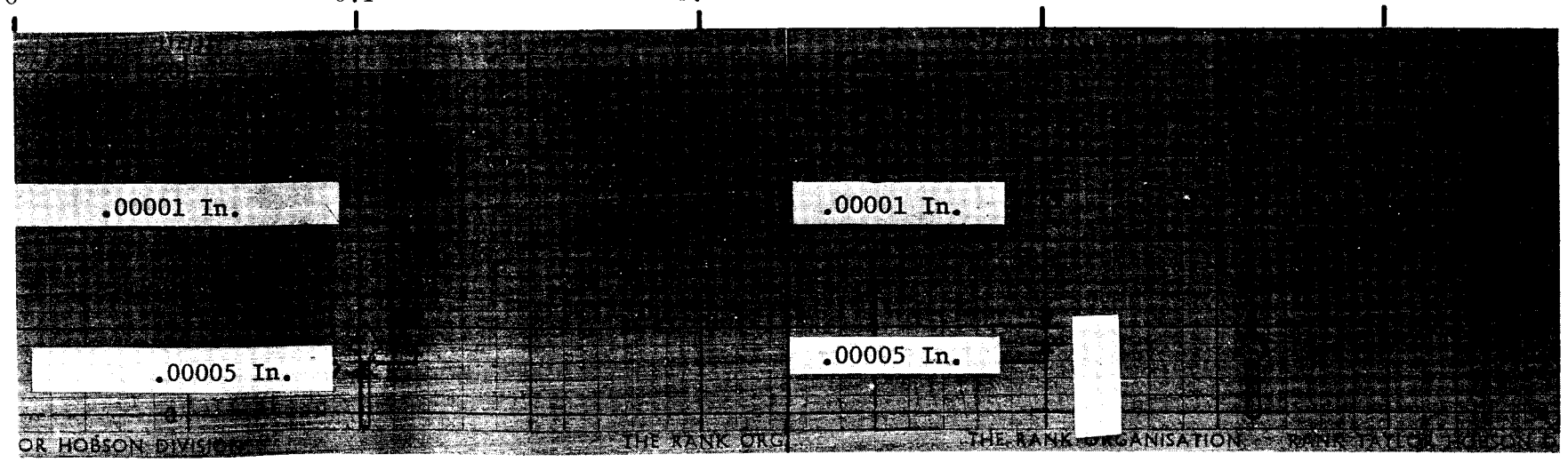
Wear Rate, In^3/10^{10}ft - -10.3 See Note 1

Notes:

1. Specimen chipped

Post-Test Profilometer Trace - Circumferential at 0°





Post-Test Profilometer Trace - Radial at 0° Radial at 90°

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