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BEARING MATERIALS COMPATIBILITY
FOR
SPACE NUCLEAR AUXILIARY POWER SYSTEMS

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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BEARING MATERIALS COMPATIBILITY FOR SPACE NUCLEAR AUXILIARY POWER SYSTEMS

By

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ABSTRACT

A program to evaluate materials for suitability as exposed bearings on nuclear auxiliary power systems (SNAP Program) for space vehicles is reported in this document. Friction coefficients of material combinations in a 10^{-6} mm Hg vacuum at 1000°F for 200 hr were measured. Seven combinations found to have friction coefficients less than 0.50 are:

1) Graphite (National Carbon CDJ-83) - Haynes 90

2) Graphite (National Carbon CDJ-83) - Stellite No. 3

3) Graphite (National Carbon CDJ-83) - Al_2O_3 (sprayed)

4) Al_2O_3 (sprayed) - Cr_3C_2 (sprayed)

5) Al_2O_3 (sprayed) - TiC

6) Al_2O_3 (solid) - 3-F-12 (Deva Metal Corp.)

7) Al_2O_3 (solid) - 3-N-12 (Deva Metal Corp.)

I. INTRODUCTION

A. OBJECTIVES

Nuclear auxiliary power systems for space applications will be required to operate for long periods in the absence of an atmosphere, at high temperatures, and in a high radiation field. It will not be possible to lubricate moving parts in ways normally used for terrestrial applications and of course maintenance will not be possible. When the SNAP 2 (Systems for Nuclear Auxiliary Power) control program was started, a survey of the technology on bearings for high temperature vacuum use was made (see Appendix A). It was found that development of practical bearing materials and coatings for high temperature had been given some impetus, but information for both high temperature and vacuum was not available; therefore, a test program was initiated to simulate operating conditions and evaluate bearings under these conditions.

B. SCOPE

The urgency for information directly usable in SNAP bearing configurations dictated a straightforward approach in two phases. The first phase was aimed at screening likely materials and the second phase (not started at this time) will be to design actual bearing configurations and test them. For the screening phase, the following criteria were considered in the testing:

1) Sliding bearings - The actual duty cycle for SNAP equipment will be slow speed, intermittent operation, with long dwell periods. This duty is not suited to rolling bearings.

2) Pressure of 10^{-5} to 10^{-6} mm Hg - While space pressure is less than 10^{-10} mm Hg, the vacuum equipment available was limited to 10^{-6} mm Hg although 2×10^{-7} was attained during some of the testing. Equipment for operation at 10^{-9} mm Hg will be available for the second phase testing.

3) Temperatures to 1000°F - Temperatures of the reactor surface and coolant temperature will reach 1200°F, but bearing temperatures are not expected to exceed 1000°F.

4) Sliding velocity of 5 in./min - See 1 above.

5) Bearing load of 40 lb/in.^{2} - A relatively low pressure was used to enhance the possibility of success and to be consistent with efficient design practice.

6) The test duty cycle was made consistent with the actual bearing use so that a cycling rate of two cycles every two hours was employed.

7) The radiation environment was not simulated during these tests, as the materials tested were generally radiation-resistant types and the testing would have been severely complicated; hence, separate evaluations of the radiation effects on the materials are planned.

8) The surface finish of the sliding surfaces was specified to be 8 μ in. except where the type of material or machining operations prevented obtaining that finish.

9) The sliding surfaces were not specially prepared by electron bombardment or abrading but were taken "as machined" and cleaned of oils, greases, and normal dirt to simulate the actual condition of fabrication and use.

The second phase will involve evaluation of the most favorable materials on the bases of low friction coefficient, strength properties, expansion coefficient compatibility with the installation, machinability, radiation effects, and availability of the material. Sample bearings will then be operated in a vacuum furnace under simulated actual conditions to prove the selection.

II. SUMMARY OF RESULTS

A complete tabulation of the test results is shown in Table I with the friction coefficients observed at various phases of the test being shown. Table II lists the seven combinations which resulted in friction coefficients of less than 0.5 for testing through the seven days at 1000°F. Pertinent physical properties are also recorded. Table III shows the results of physical measurements on the bearing samples before and after the testing. Photographs of the test specimens after testing are in Appendix B.

TABLE I

FRICTION TEST MATERIALS AND TEST RESULTS

Test No.	Material Combinations					Observed Friction Coefficients											
	Small Rider Sample			Stationary Base Sample		Initially at Room Temp. and Pressure		After 10–20 hrs at 10^{-5}mm Hg and Room Temp.		After 24 hrs at 10^{-5}mm Hg and 600°F		After 24 hrs at 10^{-5}mm Hg and 1000°F		After 7 days at 10^{-5}mm Hg and 1000°F		Finally at Room Temp. and Pressure	
	Description	Sample Number		Description		Starting	Dynamic	Starting	Dynamic	Starting	Dynamic	Starting	Dynamic	Starting	Dynamic	Starting	Dynamic
I	Ni Base – Inconel X	30	33	Ni Base – Inconel X				Equipment shakedown test High friction samples used.									
II	WC – Kennametal K96	51	67	TiC – Kentanium K162B		†	.22	†	.65/.53	†	.68/.55	†	.64/.48	†	.78/.53	†	.71/.50
III	Co Base–Haynes Alloy #25	5	70	Co Base–Haynes Stellite #3		†	.63/.40	†	.61/.46	†	.82/.61	†	.94/.65	†	.63/.45	†	.71
IV	Cr_3C_2 on 316 SS - Linde LC-1A	64	55	Al_2O_3 on 316 SS - Linde LA-2		†	.18	†	.63/.55	†	.49	†	.43/.33	†	.37	†	.65
V	MoS_2 on 316 SS - Electrofilm	19	21	MoS_2 on 316 SS - Electrofilm		†	.21	†	.36	†	.81	Stopped because of excessive friction					
VI	MoS_2 on 316 SS Electrofilm	20	22	MoS_2 on 316 SS - Electrofilm		†	.20	Stopped because of excessive friction									
VII	MoS_2 on Ni Base Alloy Electrofilm on Inconel X	31	37	MoS_2 on Ni Base Alloy Electrofilm on Inconel X		†	.32	Stopped because of excessive friction									
VIII	MoS_2 on Co Base Alloy Electrofilm on Haynes #25	8	74	MoS_2 on Co Base Alloy Electrofilm on Haynes 3		†	19	Stopped because of excessive friction									
IX	Al_2O_3 on 316 SS - Linde LA-2	56	68	TiC - Kentanium K162B		†	.22	†	.33	†	.34	†	.25	†	.39	†	.89/.74
X	Graphite-Nat'l Carbon CDJ-83	39	71	Co Base-Haynes Stellite #3		†	18	†	.21	.27	.11	.21	.11	.47	.24	.29	.21
XI	Al_2O_3 Hot Pressed - Norton LA 687	10	48	SiC - Norton		†	.51	†	.88/.79	†	.69	†	.45/.23	†	.57/.27	†	.95/.74
XII	BN - Carborundum Co.	1	77	Cr_3C_2 - Firth CR2		37	.23	.39	37/ 30	53	42/ 33	.55	.40	.66	.47/.40	†	.23*
XIII	WC - Kennametal K96	52	49	SiC - Norton		†	.50	†	.42/.25	†	.79/.71	†	.57	†	.54	†	.47/.38
XIV	Al_2O_3 Hot Pressed - Norton LA 687	9	42	Graphite - National Carbon CDJ-83		19	.27/.21	†	.30/.22	.13	.05	.23	.20/.12	†	.09	†	.22
XV	Cr_3C_2 on 316 SS - Linde LC-1A	58	69	TiC - Kentanium K162B		†	.29	†	.42/.37	†	.48	.53	.39	.63	.43	†	.74
XVI	Al_2O_3 on 316 SS - Linde LA-2	57	72	Co Base-Haynes Stellite #3		†	.21	†	.45/.30	†	.90/.68	Stopped because of excessive friction					.85/.75
XVII	Al_2O_3 on 316 SS - Linde LA-2	16	85	Fe Base-Haynes Alloy #90		†	.16	†	16	†	.31/.26	Equipment failure after 8 hours at 600°F					
XVIII	Al_2O_3 on 316 SS - Linde LA-2	17	86	Fe Base-Haynes Alloy #90		†	.15	†	15	†	.29/.24	(Equipment failure at 800°F, .36/.30)				†	.75/.66
XIX	C-Graphite - Graphitar #16	98	61	Al_2O_3 Hot Pressed - Norton LA 687		†	.24/.20	(Special Test	Overnight at 10^{-5} and 500°F, Coefficient – .16 5 hrs at 500°F & N_2 atmosphere Coefficient = .10)								.29/.22
XX	C-Graphite - CDJ-83	90	87	Fe Base-Haynes Alloy #90		†	.20/.17	†	22	.19	.10	†	.05	†	.18		.17**
XXI	Al_2O_3 on 316 SS - Linde LA-2	18	43	Carbon CDJ-83		†	.14	.21	.15	(Temp raised to 1000° in one step)		†	.05	.06	.05	.17	.14
XXII	TiC - Kentanium K162B	79	97	Fired PbO coat on 304 SS		†	.18	†	.25	†	.07	Stopped because of excessive friction					
XXIII	Al_2O_3 on 316 SS - Linde LA-2	18	43	Carbon Graphite CDJ-83		†	.15	(Temp. to 1000°F in one step)				†	.05	†	.05	†	.20***
XXIV	Deva 3-N-12	105	62	Al_2O_3 Hot Pressed		†	.50/.43	.29	.23	.14	.12	.37	.21	.40	.30/.26	.48	.31
XXV	Deva 3-F-12	108	63	Al_2O_3 Hot Pressed		†	.30	†	.40	†	.26/.23	†	.21	†	.23	†	.26

*BN showed excessive wear

**A variation in test procedure was used in this test in that after 7 days at 1000°F, a 48 hour dwell period was added. After no operation for 48 hours and with a 10^{-6} mm Hg pressure at 1000°F, a starting friction of .27 was observed with a subsequent dynamic or running friction of .10.

***After 3 days at 1000°F and 10^{-6} to 10^{-7} mm Hg, Ion pump was turned "on" and the diffusion pump valve was closed for 3 days. No change in friction was noted.

†Means starting friction same as running friction

.XX/.XX←Average running friction
↑——Maximum running friction

.XX One number means running maximum was within .05 of average running friction

TABLE II

LOW FRICTION COMBINATIONS

Test No.		Friction Coefficient Maximum at Vacuum and 1000°F	Coefficient of Expansion (in./in./°F x 10^{-6})	Hardness Room Temperature	Room Temperature Strength (psi)	
					Compressive	Tensile
XX	C Graphite CDJ-83	.22	1.2	110 R_e	33,000	7,300
	Haynes No. 90		8.6 (32-1472°F)	60 R_c	-	60,000 (annealed)
XIV	(Hot Pressed) Al_2O_3 (or LA-2)	.23	(See test XXV & IX)			
	C Graphite (CDJ-83)		(See test XX)			
XXV	Deva 3-F-12	.23	6.6 (70°F)	36 R_b	30,000	13,000
	Al_2O_3 (Hot Pressed)		4.5 (77-1652°F)	9.-9.5 Mohs	450,000	-
IX	Al_2O_3 (LA-2)	.39	3.9 (70-1832°F)	1,000-1,200 (VPN) 300		
	TiC (K162B)		5.3	89 R_a	420,000	93,000
XXIV	Deva 3-N-12	.40	7.4 (Estimated for Pure Ni)	-	36,000	14,000
	Al_2O_3 (Hot Pressed)		(See test XXV)			
IV	Cr_3C_2 (LC-1A)	.49	6.4 (70-1800°F)	850 (VPN) 300	-	-
	Al_2O_3 (LA-2)		(See test IX)			
X	C Graphite (CDJ-83)	.47	(See test XX)			
	Haynes Stellite No. 3		7.3 (0-1100°F)	55 R_c	310,000	55,000

TABLE III

PHYSICAL DATA ON BEARING TEST SAMPLES

Test No.	Material	Sample Number	Surface Roughness (RMS μin.)		Weight Change (gm)	Dimensional Wear (in.)
			Before	After		
II	WC Kennametal K96	51	6	-	-	-
	TiC Kentanium K162B	67	6	25	*	0.0000
III	Co Base Haynes Alloy No. 25	5	-	-	-	-
	Co Base Haynes Alloy No. 3	70	4	9	-0.00180	0.0000
IV	Cr_3C_2 on 316 SS - Linde LC-1A	64	2	5	-	-
	Al_2O_3 on 316 SS - Linde LA-2	55	1.5	-	-	-
IX	Al_2O_3 on 316 SS - Linde LA-2	56	1.5	1.3	-0.00121	0.0000
	TiC - Kentanium K162B	68	6	6	*	0.0001
X	C Graphite - National Carbon CDJ-83	39	150	80	+0.00018	0.0004
	Co Base - Haynes Stellite No. 3	71	4	9	-0.00080	0.0000
XI	Al_2O_3 Hot Pressed - Norton LA-687	10	3	8	0.00000	0.0000
	SiC Norton	48	4	4	*	0.0000
XII	BN-Carborundum Co.	1	30	80	-0.11724	0.0092
	Cr_3C_2 - Firth CR2	77	8	10	*	-
XIII	WC Kennametal K96	52	5	2.5	-0.00078	0.0000
	SiC Norton	49	7	5	*	0.0001
XIV	Al_2O_3 Hot Pressed Norton LA-687	9	4	2	+0.00015	0.0000
	C Graphite - National Carbon CDJ-83	42	10	-	*	0.0004
XV	Cr_3C_2 on 316 SS - Linde LC-1A	58	2	2.5	-0.00008	0.0000
	TiC - Kentanium K162B	69	5	5.5	+0.00080	0.0000
XX	C Graphite - National Carbon CDJ-83	90	8	15	-0.01201	-0.0002
	Fe Base Haynes Alloy No. 90	87	-	7	+0.00040	+0.0002
XXI	Al_2O_3 on 316 SS - Linde LA-2	18	2	2	-0.02590	-0.0002
	C Graphite - National Carbon CDJ-83	43	8	8	-0.07870	-0.0002
XXIV	Deva 3-N-12 Deva-Metal Corp., Ridgewood, N.J.	105	85	80	-0.01070	+0.0009
	Al_2O_3 Hot Pressed Norton LA-687	62	6	6	+0.00090	+0.0001
XXV	Deva 3-F-12 Deva Metal Corp.	108	50	40	-0.02100	-0.0001
	Al_2O_3 Hot Pressed Norton LA-687	63	6	14	+0.00050	-0.0000

*The holddown clamps chipped corners on these samples so that weight change due to wear cannot be isolated.
-Data not available.

III. DISCUSSION

A. MATERIALS SELECTION

Because of the limited scope and time of the program, materials that showed good high temperature friction and wear characteristics under atmospheric conditions were selected. The selection was based on a literature survey of high temperature bearing friction tests, discussions with material suppliers and evaluation of their brochures, and recommendations of the metallurgical departments of the suppliers.

Where dry lubrication coatings were used, a control material of known high friction was used as the base metal so that failure of the coating would be obvious. Where flame sprayed coatings were used, a high temperature structural material was used for the base metal.

The general grouping, major constituents, and source of the materials selected for testing is listed below. Table I lists the material combinations tested to date:

Cobalt Base Alloys
- Haynes Alloy No. 25 - Co, Cr, Ni, W (Haynes Stellite Co.)
- Haynes Stellite No. 3 - Co, Cr, Ni, W, C, Fe (Haynes Stellite Co.)

Nickel Base Alloys
- Inconel X - (Control Material) Ni, Cr, Fe, Ti, Mn (International Nickel Co.)
- Deva Alloy (3-N-12) - Ni, C Graphite (Deva Metals Co.)

Refractory Materials
- Carbides -
  - Silicon Carbide - SiC (Norton Co.)
  - Tungsten Carbide - WC, Co (Kennametal Co., K96)
  - Chromium Carbide - Cr_3C_2, Ni, Flame Sprayed on 316 SS (Linde Co., LC-1A)
  - Titanium Carbide - TiC, Ni, Mo, CbC (Kennametal Inc., K162B)
- Nitrides -
  - Boron Nitride - BN (Carborundum Co.)
- Oxides -
  - Aluminum Oxide - Al_2O_3 Flame Sprayed (Linde Co., LA-2)
  - Aluminum Oxide - Solid Hot Pressed Al_2O_3 (Norton Co., LA-687)
  - Lead Oxide - Fired (Atomics International Lab)

Carbon - Carbon Graphite impregnated with proprietary constituents (National Carbon Co., CDJ-83)

Stainless Steel

316 SS (Control Material)

Lubricant Coating

Molybdenum Disulfide on 316 SS Base Metal MoS_2 (Electrofilm Corp.)

Iron Base Alloys

Haynes Alloy No. 90 - Fe, Cr, C (Haynes Stellite Co.)

Deva Alloy (3-F-12) - Fe, C (Deva Metal Corp.)

Ferro-Tic - Fe, TiC, Ni, Cr (Sintercast Co., S-45) (To be tested)

B. VARIATION OF FRICTION WITH TEST PHASES

A review of Table I will show a trend among the low-friction combinations as the tests progressed through the phases. With some exceptions the low-friction combinations displayed the following trends as displayed on Figure 1:

1) The friction coefficient rose when the vacuum was pulled.
2) The coefficient dropped as the temperature was raised to 600°F for 24 hr.
3) The coefficient dropped further when the temperature was held at 1000°F for an additional 24 hr.
4) The coefficient then rose slightly after 7 days at 1000°F and 10^{-6} mm Hg pressure.
5) Finally, the coefficient rose more when brought back to room conditions.

Figure 2 shows the effect on friction during the period of bringing the test to 1000°F at vacuum. The curve does not represent a specific test but is intended to show the general effect of imposing a change of conditions on the material combinations. The change of friction coefficient when one of the samples was carbon CDJ-83 was markedly different from the changes where carbon was not one of the materials.

As shown in Figure 2, a short term drop in friction accompanied the initial pulling of vacuum due to outgassing, but then the friction rose and stabilized at a higher value. When the temperature was raised to 600°F, the friction for

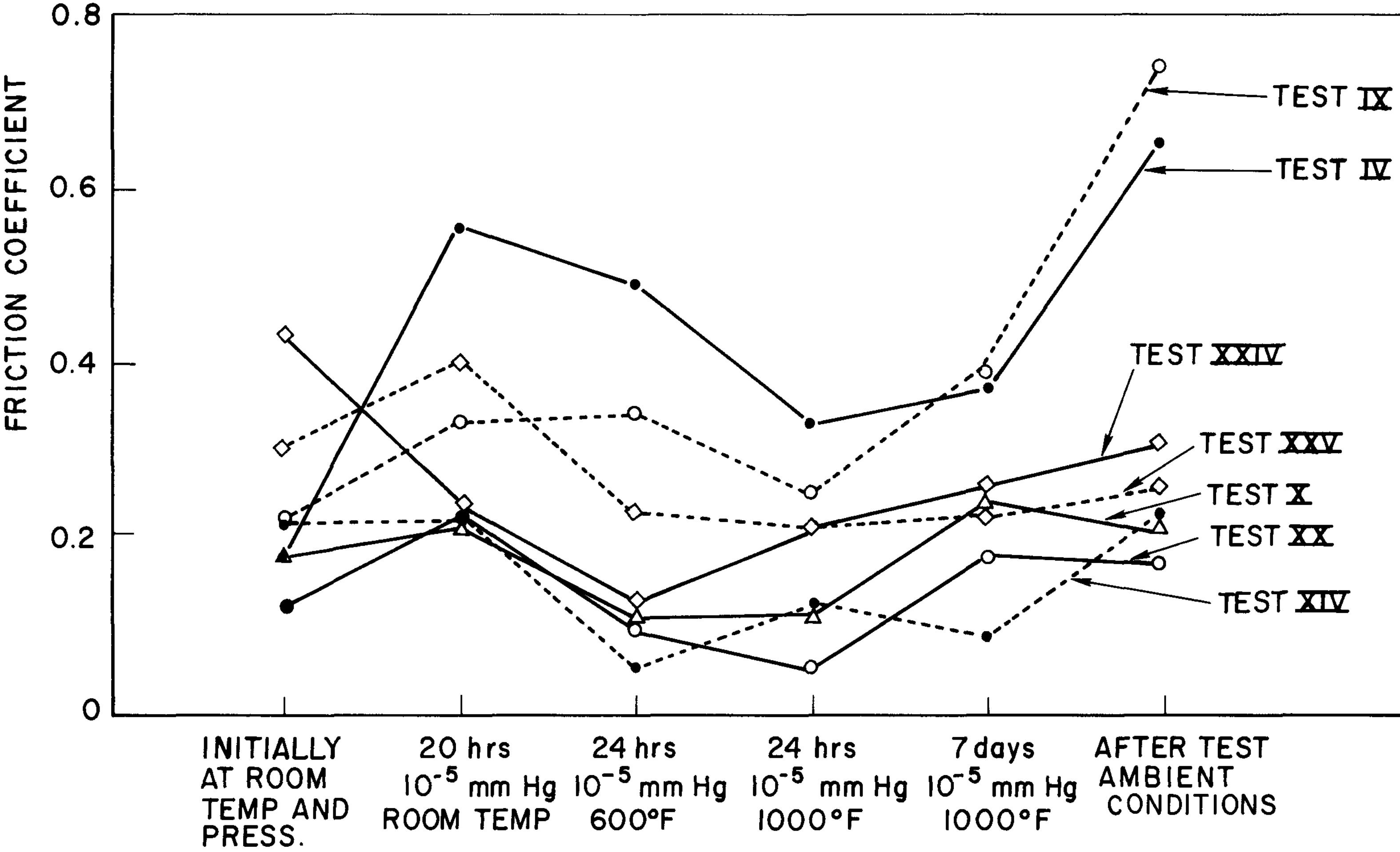

Figure 1. Typical Variation of Friction Coefficient with Temperature Increases

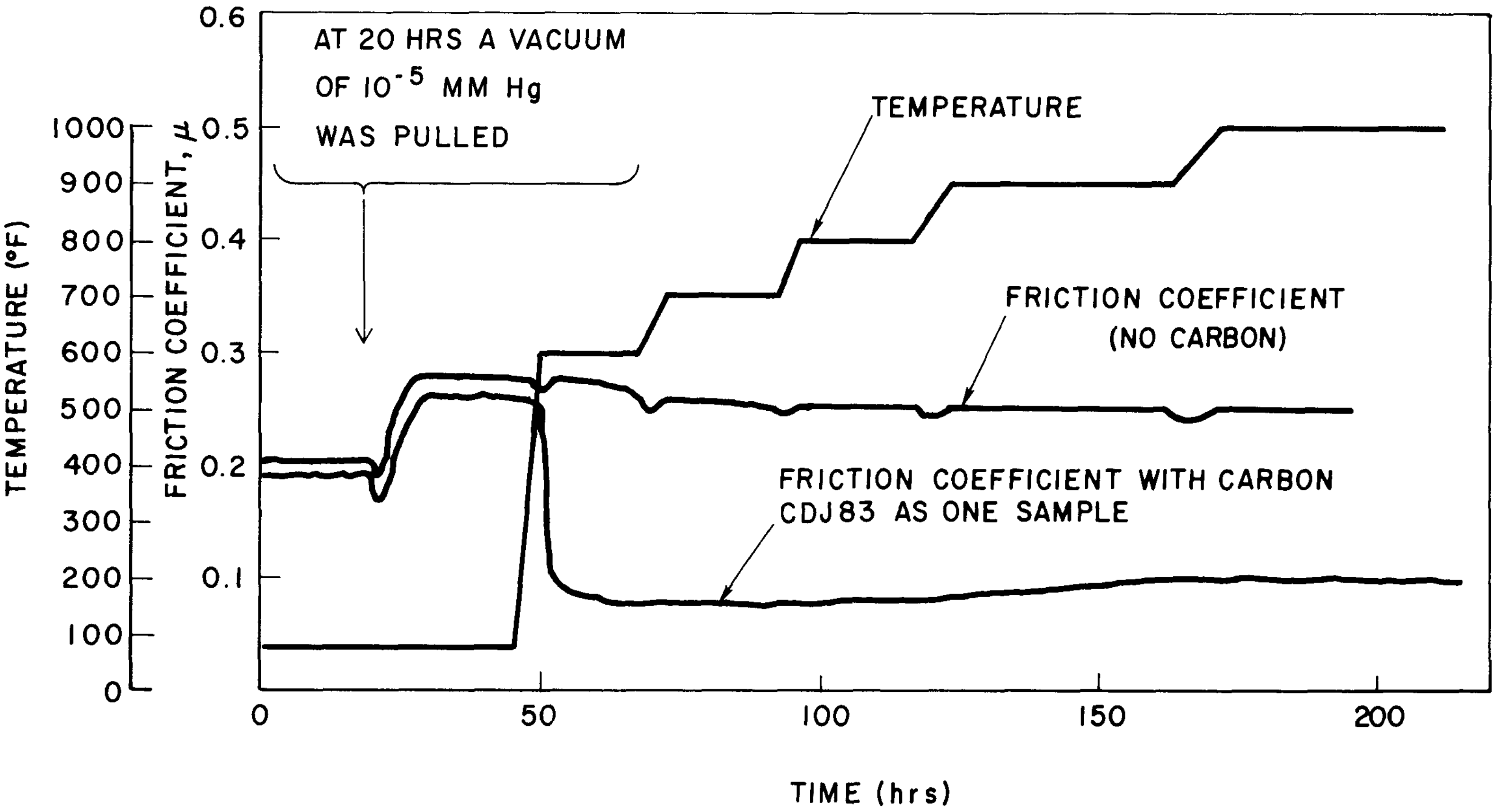

Figure 2. Change of Friction with Test Phase for Low Friction Combinations

combinations including carbon CDJ-83 dropped to a low level and changed very little as the temperature was stepped up to 1000°F. Combinations which did not include a carbon sample displayed a lesser drop when the temperature was raised to 600°F and then changed very little when stabilized between steps up to 1000°F. However, as each temperature change was made, a short term drop in friction was noted. This was probably caused by additional outgassing. The combinations involving carbon CDJ-83 did not display this sensitivity to temperature changes.

C. CHANGES IN PHYSICAL MEASUREMENTS

The changes in physical measurements during testing are shown in Table III. The usual test consists of 320 cycles of operation at 3.5 in. per cycle, or 1100 in. travel of the rides. (This is many times more travel than envisioned for the SNAP controls bearings.) It can be seen that graphite shows some wear along with an improvement of surface finish. The wear is not enough to affect performance in the SNAP installations.

The weight increase of the Al_2O_3 in tests XIV, XXIV, and XXV verifies the transfer of material observed in a microscopic observation of the samples after the test.

D. CONTACT WELDING

The original test procedure included a 16-hr period without any operational cycles to observe the effect of dwell periods. No appreciable effect was noted so that longer dwell periods were observed for later tests (see Table IV).

TABLE IV

EFFECT OF DWELL PERIODS ON FRICTION COEFFICIENT AT 1000°F AND 10^{-6} mm Hg PRESSURE

Test No.	Materials in Contact	Duration of Dwell Period	Starting Friction Coefficient	
			Before Dwell	After Dwell
XX	Graphite CDJ-83 on Haynes No. 90	48	0.16	0.27
XXI	Al_2O_3 on Graphite CDJ-83	48	0.04	0.14
XXIV	Deva 3-N-12 on Al_2O_3	72	0.34	0.48
XXV	Deva 3-F-12 on Al_2O_3	96	0.23	0.23

As can be seen, there is an appreciable increase in friction with a long dwell period in most cases. These results are inconclusive because very long periods are normally required to affect contact welding. Several devices envisioned for use on SNAP systems will have contacting surfaces that will be separated after long periods so that the mechanism of contact welding will be investigated in future tests.

E. VACUUM EFFECT ON FRICTION

Figure 3 shows the effect of lowering pressure on friction coefficients at 1000°F for three of the tests. It can be seen that the friction coefficient did not stabilize in the range of vacuum attained in the tests conducted. Testing at lower pressures to 10^{-9} mm Hg is planned to see if a stable level is reached.

F. SPECIAL TESTS

The hot pressed Al_2O_3 on graphite CDJ-83 of test XIV produced such favorable results that test XXI using flame sprayed Al_2O_3 instead of hot pressed Al_2O_3 was run. The same low friction resulted in the second test. The spray coat is more desirable from a fabrication viewpoint.

The question of diffusion pump oil contamination of the specimens prompted a re-run of the spray coat Al_2O_3 and graphite CDJ-83 specimens in test XXIII as follows:

1) The test chamber was brought to 1000°F and 1.6×10^{-7} mm Hg using the diffusion pump and N_2 baffle.

2) The 12-in. valve to the diffusion pump was closed and the ion pump was started so that the vacuum was held by the ion pump and N_2 baffle only.

3) Temperature of 1000°F and vacuum of 8×10^{-7} were held for three days with the diffusion pump valve closed.

The above procedure precluded back-streaming of pump oil during the three-day test and no change in friction coefficient from that observed with the diffusion pump was noted.

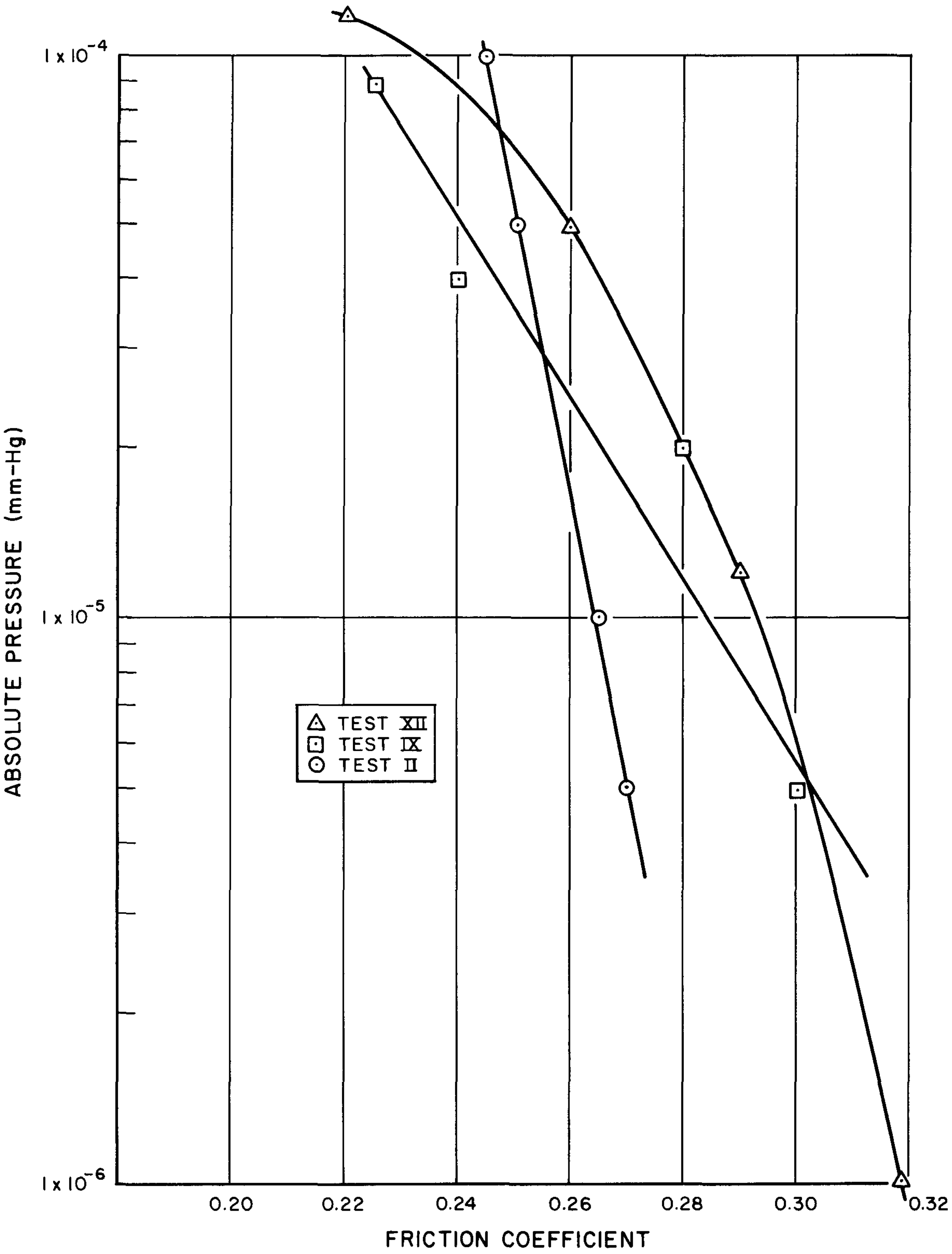

Figure 3. Friction Coefficient at 1000°F vs Absolute Pressure

G. DRY FILM LUBRICANTS

Tests V through VIII were run with MoS_2 dry film lubrication but early failures were experienced in vacuum with the temperature at only a few hundred degrees. Testing by other agencies has resulted in successes in this area so that further evaluation is planned.

IV. TESTING FACILITIES AND PROCEDURES

A. EQUIPMENT

The friction tests were conducted in an evacuated and heated cylindrical furnace. The rider sample was weighted against the base sample and was slid across the base by a motor outside the chamber. The motor moved a rod connected to the rider through a bellows seal. A ring force transducer was integral with the rod for friction force measurement.

Tests I through XV were run with the equipment shown in Figures 4, 5, and 6. The tests after XV were run with the same friction apparatus installed in a new vacuum furnace shown in Figure 8.

1. Friction Measurement

The stationary test sample (4 in. x 1.5 in. x 0.25 in.), or base, was clamped to an I-beam secured to the furnace. The rider sample (0.5 in. x 0.5 in. x 0.5 in.) was placed on the base and weighted through a yoke that rested in a groove on top of the rider as shown in Figures 5 and 6. The weight was suspended on the ends of the yoke about 2.5 in. below the rider in a cutout space in the I-beam web. The total load on the sample (the weight plus rod) was 11 lb.

The operating rod rested on the yoke but applied the force to the rider very close to the contact surface so that the turning moment from the applied force was negligible. The rod passed through a hole in a heat shield to the transducer and then through a bellows seal to the motor drive.

A ring-type force transducer integral with the rod was in a heat shielded portion of the vacuum chamber so that the operating temperature of the transducer was not exceeded. The force ring had a 10-lb force and a 0.015-in deflection rating. The deflections moved the transducer core and generated signals which were fed to a bridge balance and then to a paper chart recorder. Figure 7 is a photograph of a typical trace. Calibrations were made on the transducer after each test.

The rod was moved by a drive screw connected through a gear drive to a reversible electric motor. The rod speed (5 in./min) was set by a motor controller. Microswitches were set at the ends of travel to reverse and stop

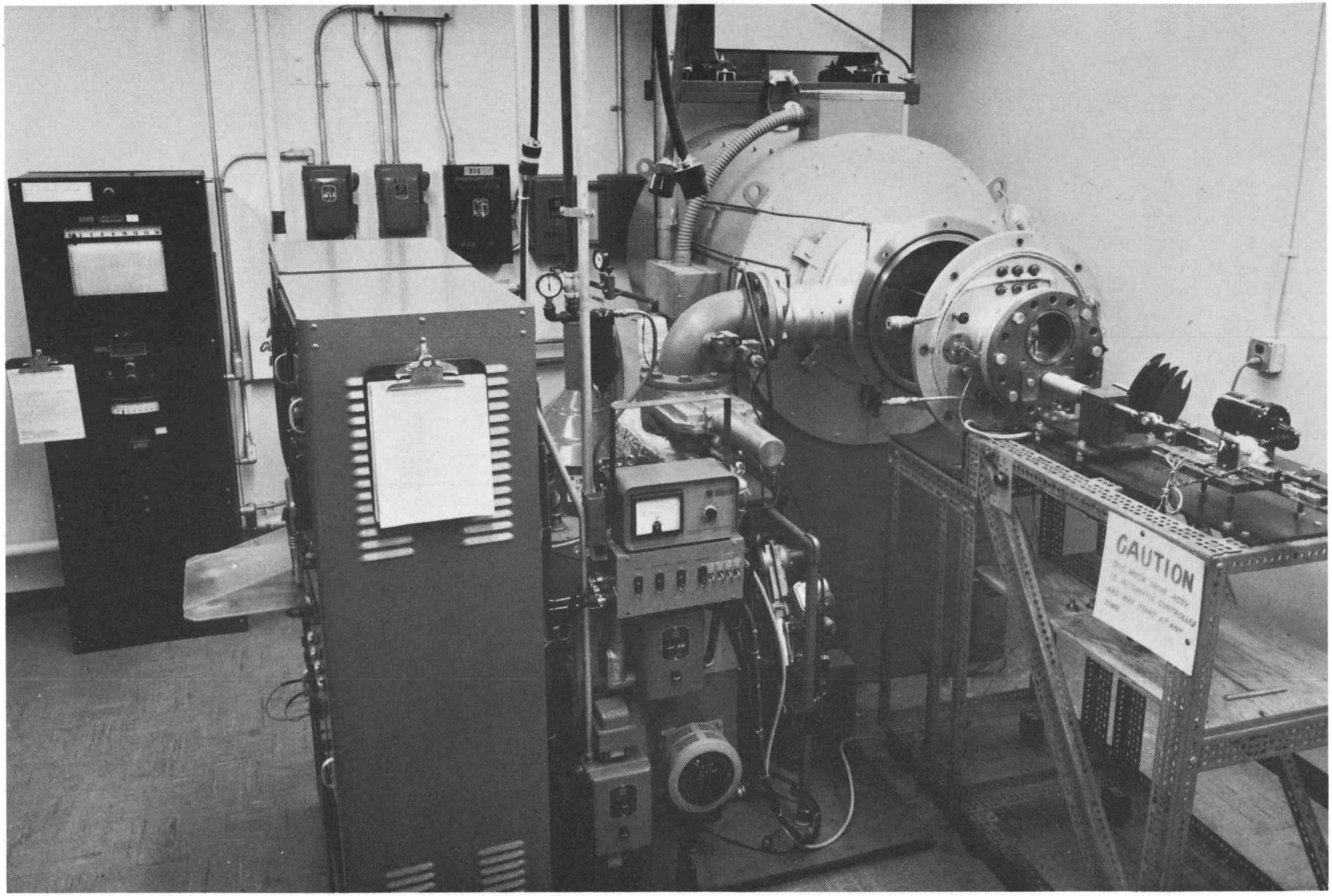

Figure 4. Friction Test Equipment - Tests I Through XV

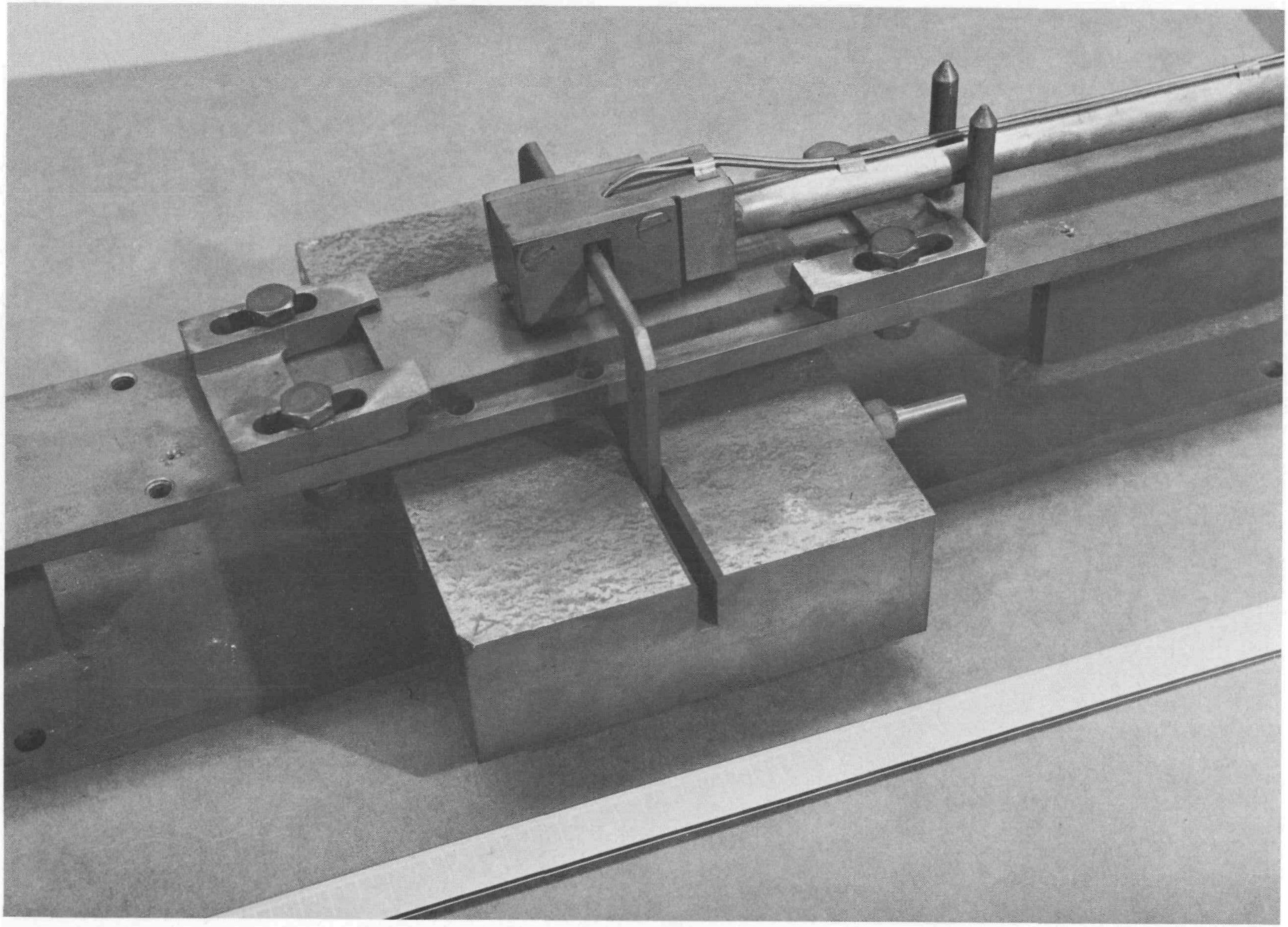

Figure 5. Friction Samples and Loading Yoke-Push Rod in Place

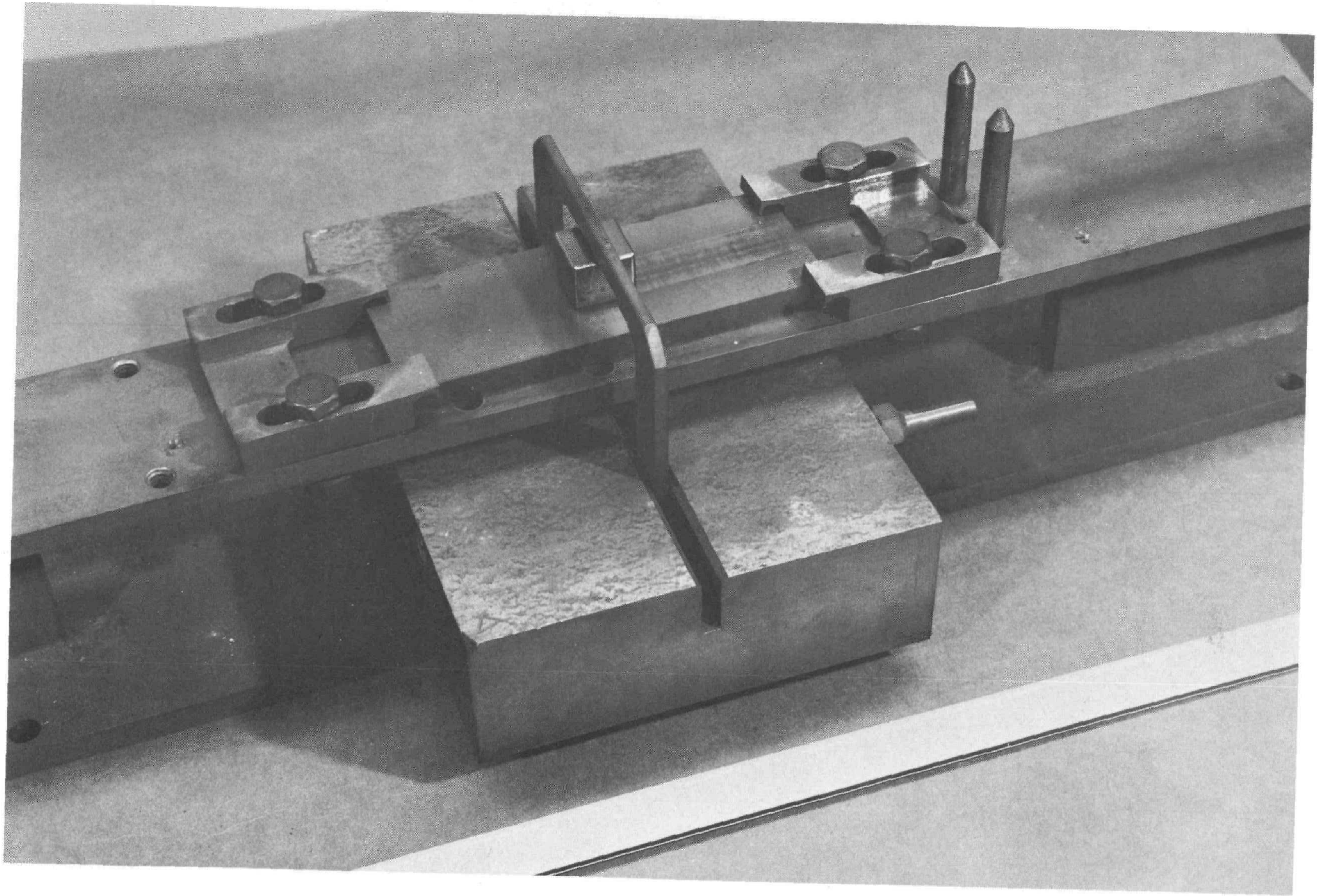

Figure 6. Friction Samples and Loading Yoke - Push Rod Raised

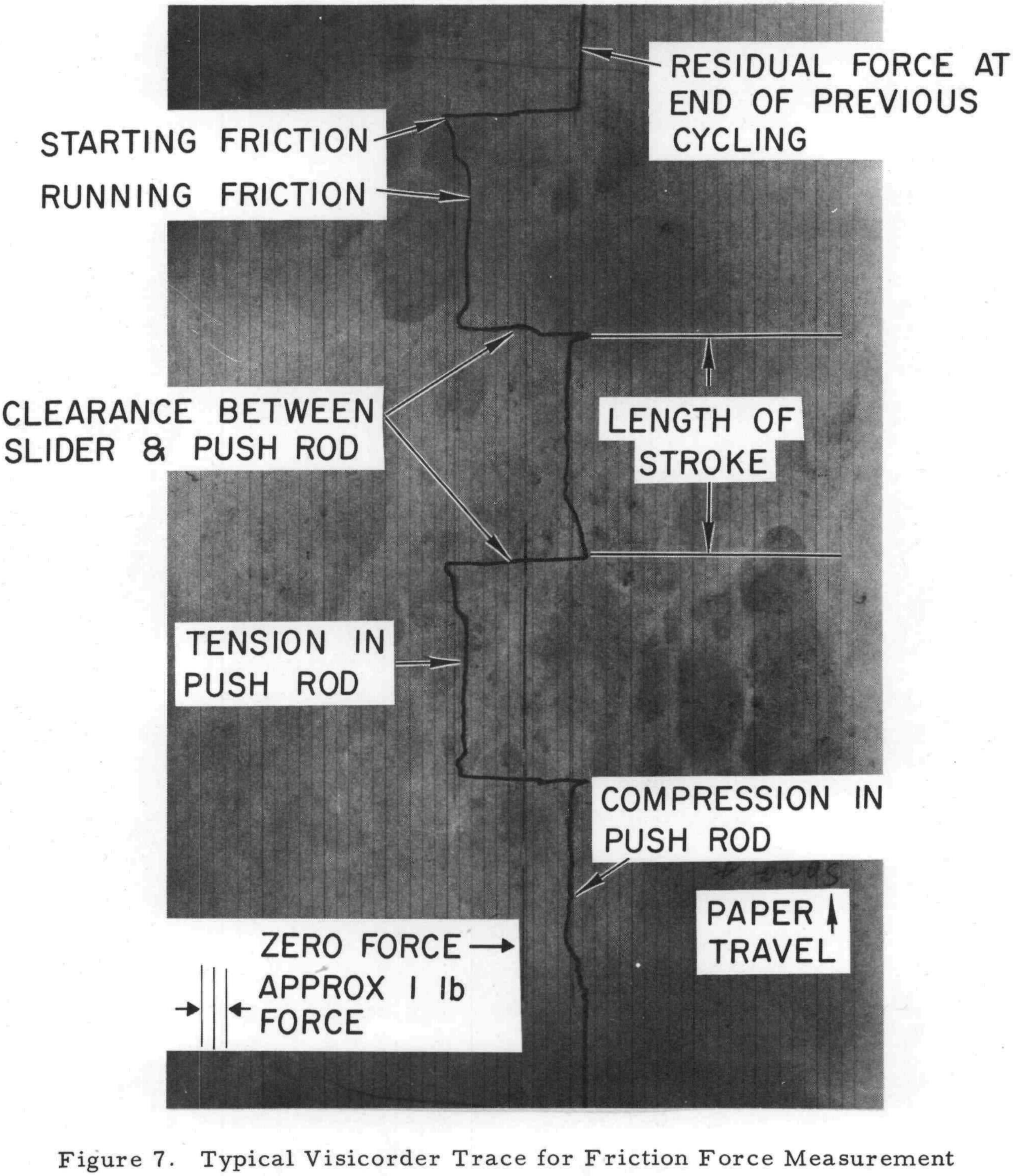

Figure 7. Typical Visicorder Trace for Friction Force Measurement

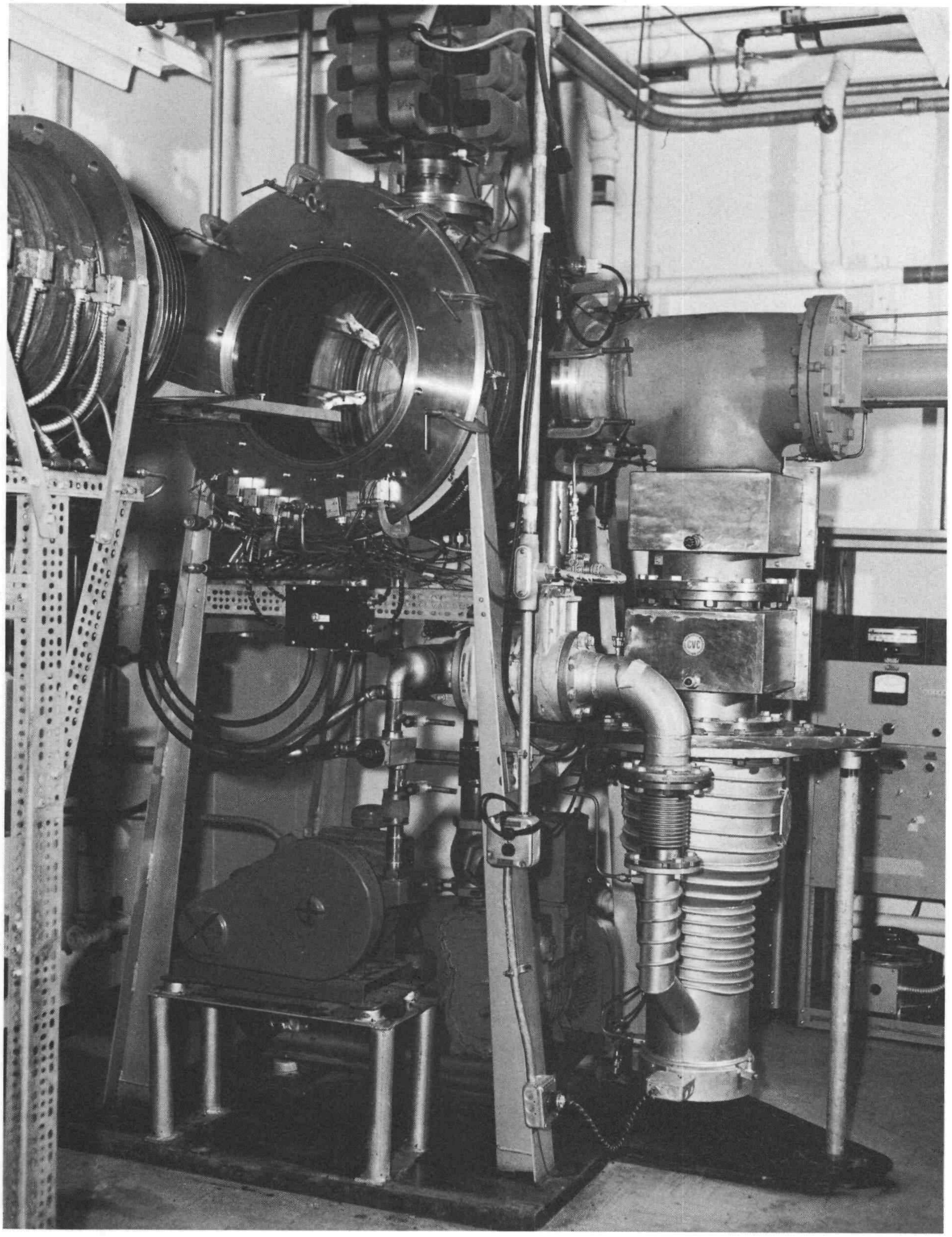

Figure 8. Vacuum Furnace for Tests XVI Through XXV

the motor during cycling. The switches were set for a stroke of 1.75 in. A timer setting controlled the time (2 hr) between cycles automatically but a switch for manual cycling was available. A counter recorded the number of cycles during a test.

Thermocouples sensed temperatures of the rider, base, and ring transducer. These temperatures were recorded by a recorder amplifier which also recorded elapsed time of testing. The following equipment was used:

Force Transducer - Crescent Engineering and Research Co., Model DVA-8-10

Transducer Bridge Balance - Crescent, Model 85-F

Force Recorder - Minneapolis Honeywell Visicorder, Model 906B

Drive Motor - Magnetic Amplifier Co., Spec. 720-133

Motor Speed Control - Magnetic Amplifier Co., Magne-Speed Control, Model MS-6500

Thermocouple Temperature Recorder - Foxboro Co., Model 9335AT

2. Vacuum Furnace

The furnace used for the first 15 tests is shown in Figure 4. The cylindrical chamber was 18-in. diameter x 54-in. long with an 18-in. diameter x 40 in. long usable space. The test chamber was heated to 1000°F while at vacuum by resistance heaters on the exterior of the test chamber.

Pressures as low as 1.5×10^{-6} mm Hg were achieved with a 6-in. diameter oil diffusion pump with a liquid nitrogen refrigerated inlet trap. Mechanical backing and roughing pumps were installed in series with the diffusion pump.

Vacuum sensing and readout in the low vacuum range (10^{-3} mm Hg) were provided by thermocouple and Pirani type gauges. In the high vacuum range (10^{-6} mm Hg), cold cathode and ionization type gauges were used.

The following equipment was used:

Furnace - Pacific Scientific Co., Type PNR 1824-V

Furnace Temperature Control and Recorder - Minneapolis Honeywell, Model No. 153R10-PS 142-KI-20

Mechanical Vacuum Backing Pump - W. M. Welch Scientific Co., Serial No. 11859-2

Mechanical Vacuum Roughing Pump - Kinney Manufacturing Corp., KD-30

Oil Diffusion Vacuum Pump - Consolidated Vacuum Corp., 6-in. Diameter, MCF 700

Cold Cathode Vacuum Gauge - Consolidated Electrodynamics Co., Type gph-100

Cold Cathode Sensing Tube - Consolidated, Type gph-001

Ionization Vacuum Gauge - Veeco Vacuum Corp., Type RG-75

Ionization Vacuum Control - Veeco, Type RG-31A

Vacuum Signal Amplifier - Kintel Corp., Model 114A

Vacuum Paper Chart Recorder - Esterline Angus Co., Serial No. 106776

The furnace used for tests after XV is shown in Figure 8. The cylindrical chamber is 30-in. diameter x 48-in. long with a usable space 18-in. diameter x 24-in. long. An instrumentation section 18-in. diameter x 18-in. long is also provided. This furnace has an internal infrared heating system capable of heating the test samples to 1000°F while the walls of the chamber are kept at ambient temperatures by a water cooling system on the exterior. The external walls are also fitted with heating strips. This heating and cooling arrangement allows the chamber walls to be outgassed at 750°F by the external heaters and then maintained at ambient temperature during testing to minimize the gas penetration through the chamber walls. The infrared system directs heat at the test samples with a minimum heat to other parts of the chamber.

The vacuum was maintained at 1×10^{-7} mm Hg at 1000°F by a liquid nitrogen trapped, 16-in. diffusion pump. The system is being extended to achieve 10^{-9} mm Hg capabilities by addition of nitrogen and hydrogen cryogenic systems and an ion pump system. The furnace also has provisions for isolating the diffusion pump from the chamber by a 12-in. diameter pneumatic valve.

Vacuum sensing and readout is done with thermocouple gauges to the 10^{-3} mm Hg range and with ionization gauges for the lower pressure ranges.

The equipment used is listed below:

Furnace - Atomics International

Furnace Temperature Control and Recorder - Honeywell Y153-R10-PSH-(33)-185-III-(27)-A8

Mechanical Vacuum Roughing Pump - Kinney Manufacturing Co., Model KC-46

Mechanical Vacuum Backing Pump - W. M. Welch Scientific Co., Serial No. 3823-97

Oil Diffusion Vacuum Pump - NRC Equipment Corp., 16-in. diameter, H165P

Ion Pump - Ultec Corp., Series 327, 270 ℓ/sec

Diffusion Pump Shutoff Valve, 12-in. - Consolidated Vacuum Corp., VRA-123

Ionization Vacuum Gauge - Veeco Vacuum Corp., Type RG-75

Ionization Vacuum Control - Veeco, Type RG-31A

B. TEST PROCEDURE

A test procedure that measures the coefficient of friction of the specimens at high temperatures and vacuum while sliding was devised. The procedure includes stabilization without vacuum and then stabilization at several temperature levels with vacuum until 1000°F is reached. The 1000°F and vacuum is maintained for 1 week.

Cleaning of the specimen was done by washing in acetone, scrubbing with levigated alumina, washing in water, scrubbing with acetone, scrubbing with 95% ethyl alcohol, and then drying in room air.

During the testing, the rider was cycled on the base either manually or automatically. In the procedure below, "manual" cycles mean one back and forth movement on the base while "automatic" cycles denotes two back and forth movements every two hours. The testing environmental phases were:

1) Ambient pressure and temperature wear-in period of 24 hr to establish a reference friction level. For the first hour "manual" cycling was done two times every ten minutes, but was "automatic" cycling for the rest of the phase.
2) At ambient temperature, a minimum vacuum of 1×10^{-5} mm Hg was pulled and allowed to stabilize for about 24 hr with "automatic" cycling.
3) The temperature was then increased to 600°F in steps of 100°/hr with "manual" cycling at each step.
4) At 600°F and pressure less than 10^{-5} mm Hg, the samples were cycled automatically for 24 hr.

6) At 800°F and pressure less than 10^{-5} mm Hg, the samples were cycled automatically for 24 hr.

7) At 900°F and pressure less than 10^{-5} mm Hg, the samples were cycled automatically for 24 hr.

8) At 1000°F and pressure less than 10^{-5} mm Hg, the samples were cycled automatically for 7 days except that on the 5th day a 16-hr period of no cycling was imposed to evaluate long dwell periods.

9) With vacuum maintained, the temperature was dropped to 600°F. Nitrogen was then admitted to the test chamber until atmospheric pressure prevailed. (Use of N_2 instead of air facilitated more rapid and complete outgassing of the test rig on the subsequent runs.) The 600°F and N_2 at ambient pressure was held about 16 hr or overnight with "automatic" cycling.

10) The setup was turned off and allowed to cool for 24 hr to room temperature with "automatic" cycling.

11) At room pressure and temperature, final friction measurements were recorded.

The above procedure was intended to provide stabilization at several conditions on the way up to 1000°F. It was found that several of the steps did not produce significant changes so the procedure was revised. The revisions were; 20 cycles operation instead of 24 hr at ambient conditions, overnight operation at room temperature and vacuum instead of 24 hr, temperature increases of 200°F/hr instead of 100°F/hr, deletion of the 700°F and 900°F stabilization conditions, and incorporation of a 48-hr non-operating period after 7 days instead of 16 hr after 5 days at 1000°F.

Various special procedures were also worked out to investigate specific phenomena during the course of testing.

V. RECOMMENDATIONS

The program thus far has shown seven material combinations (see Table II) to have reasonably low friction coefficients for use in SNAP system design. These should be used, as applicable, in the design. This program should be continued as outlined below to expand and extend the findings.

A. FUTURE TESTING

The second phase testing outlined in Paragraph B, Section I, will be initiated but several areas of special testing will also be pursued.

A program to better understand and evaluate the contact welding observed during the dwell periods will be carried on. A test setup is being assembled to test several combinations at one time for much longer periods than the regular test. A means to keep the surfaces separated for a long cleaning period before being brought into contact has been devised.

Additional vacuum equipment will permit lowering the pressure to 10^{-9} mm Hg and the effect of these lower pressures on friction can be observed to determine if a point of stabilization is attained.

The additional equipment will also permit operation at very low pressures with the diffusion pump valve closed so that the back-streaming of oil can be eliminated.

Testing will be done to obtain maximum depletion of the graphite CDJ-83 impregnant by holding the samples already run at higher temperatures in vacuum for a longer period to drive out any volatile impregnant. If tests after the maximum depletion treatment still show a very low friction, the reliability of graphite CDJ-83 for use in SNAP systems will be assured.

The drive mechanisms for SNAP systems involve gearing so that findings here will be interpreted and extended to be made usable for gear design criteria.

APPENDIX A

LITERATURE SURVEY

Published papers dealing with dry bearing friction in the 1000°F range and/or in vacuum were reviewed. A few of the more pertinent papers reviewed are referenced at the end of this report with a short summary of the findings significant to this work.

The early vacuum work by Bowden and Hughes[1] showed a definite increase in friction when materials were cleaned and slid together in a vacuum at room temperatures. Later work by Bowden and Young[2] showed that high temperatures reduced the friction between metals in a vacuum. Figure 2 of this report shows the same tendencies. These papers and other findings were collected in a comprehensive book on friction by Bowden and Tabor[3] in 1950.

Friction and wear of graphite in a vacuum were found to be very unsatisfactory in work by Savage[4] but Bowden[5] notes conflicting reports on unpublished results of tests by Dr. Kenyon of Cambridge in which low coefficients have been observed with graphite on graphite, Au, Ag, Cu, Ta, Fe, and Ni.

The test results in Figure 1 show very low friction with graphite treated with a proprietary impregnant. However, a test with untreated graphite is planned.

Most bearing materials when put in actual use have oxides or contaminants on the surface, or compounds are formed at the interface during operation. This results in friction that is not necessarily a function of the base material alone but also of the interface materials. The friction increases during dwell periods as shown in Table IV may have been induced by interfacial reactions of the materials or contaminants. However, depending on which compounds are formed, the friction may increase or decrease. Bowden[5] displayed this effect by playing a stream of H_2S gas at the interface of a Mo bearing at 1000°C and observing the decreased friction as MoS_2 was formed.

A fair amount of work has been done on developing and testing materials and coatings for high temperature (not necessarily in a vacuum), but an accepted set of physical properties for high temperature bearing materials has not been developed. Coffin[6] points out that information is not readily available on many of the properties (solubility, alloying ability, etc.) affecting high temperature friction. High temperature friction characteristics were used as a basis for selection of materials tested for this report. Satisfactory friction properties of TiC on Al_2O_3 and C on Al_2O_3 at high temperature in a vacuum are shown in Table II. These same combinations produced reasonable coefficients at high temperature in air as observed by Rabinowicz.[7]

APPENDIX B

PHOTOS OF TEST SAMPLES AFTER TESTING

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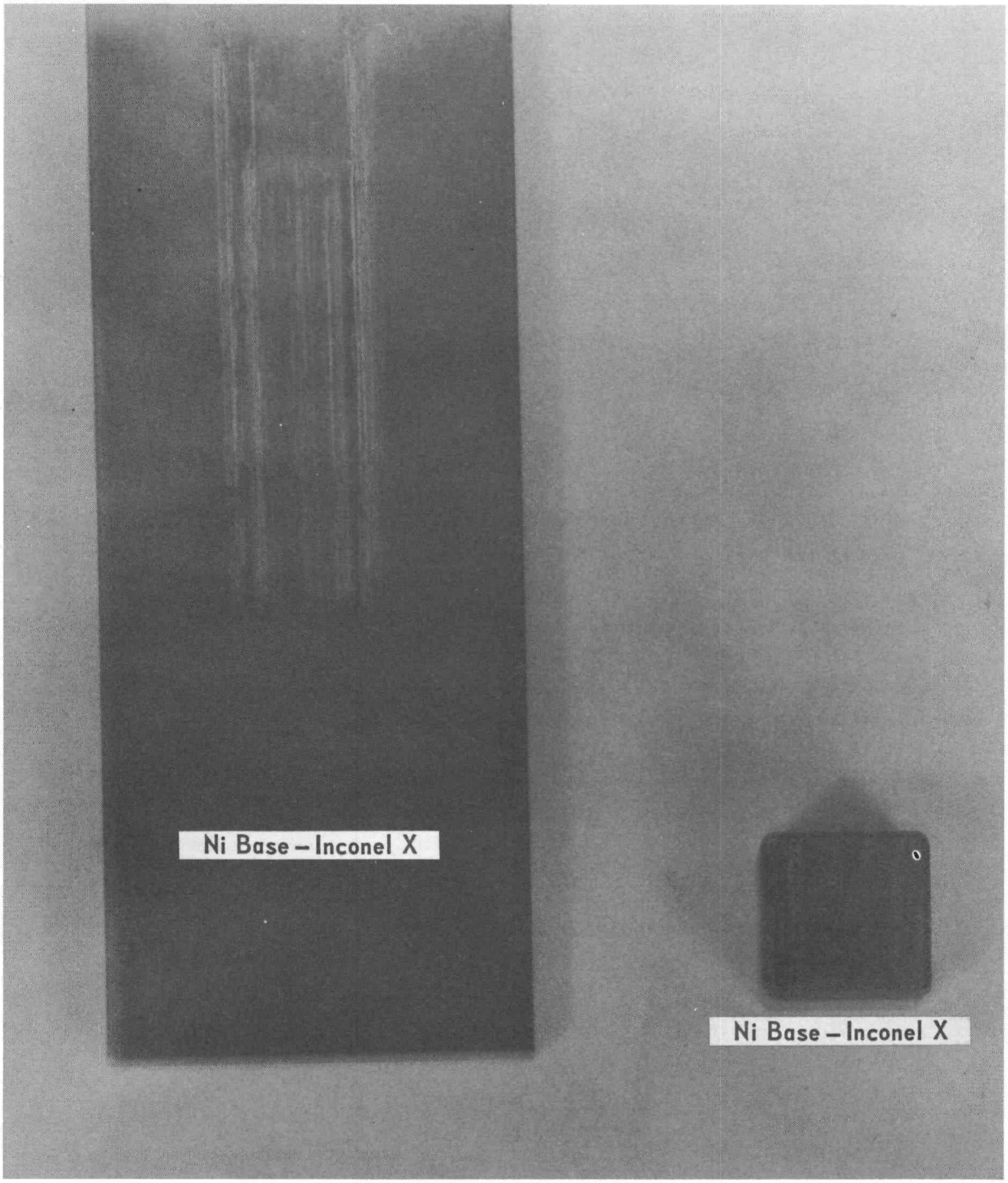

Figure 9. Test I

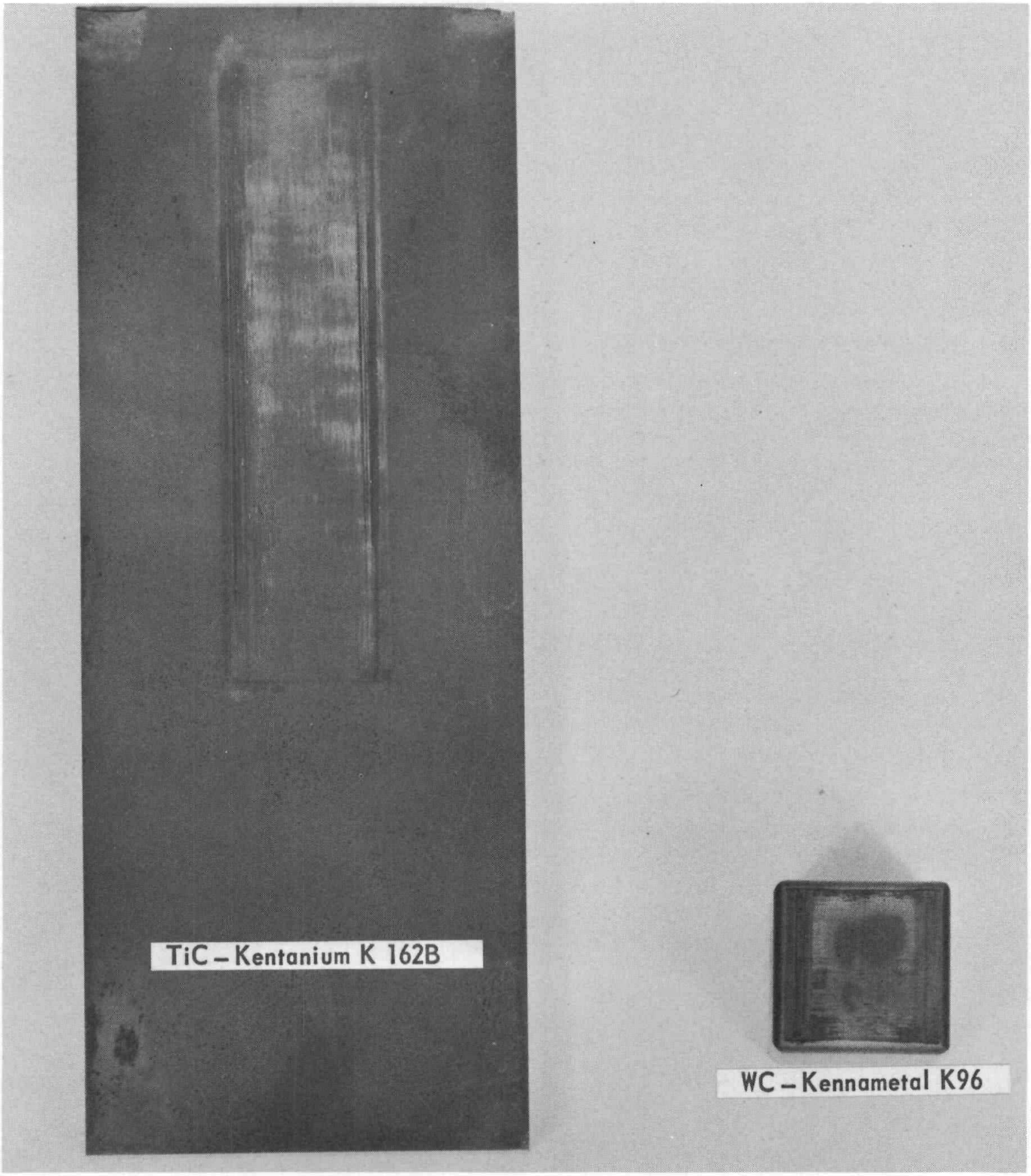

Figure 10. Test II

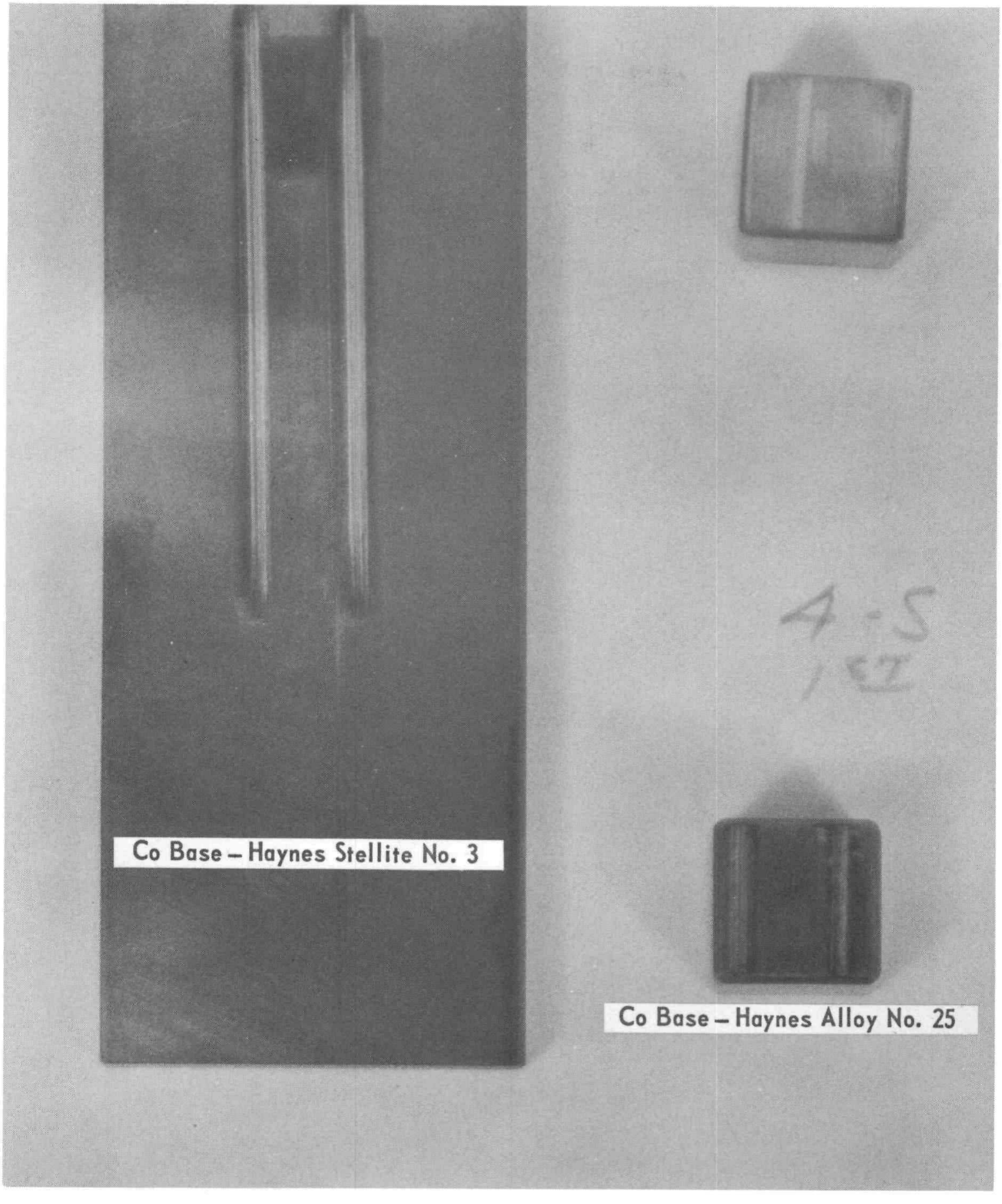

Figure 11. Test III

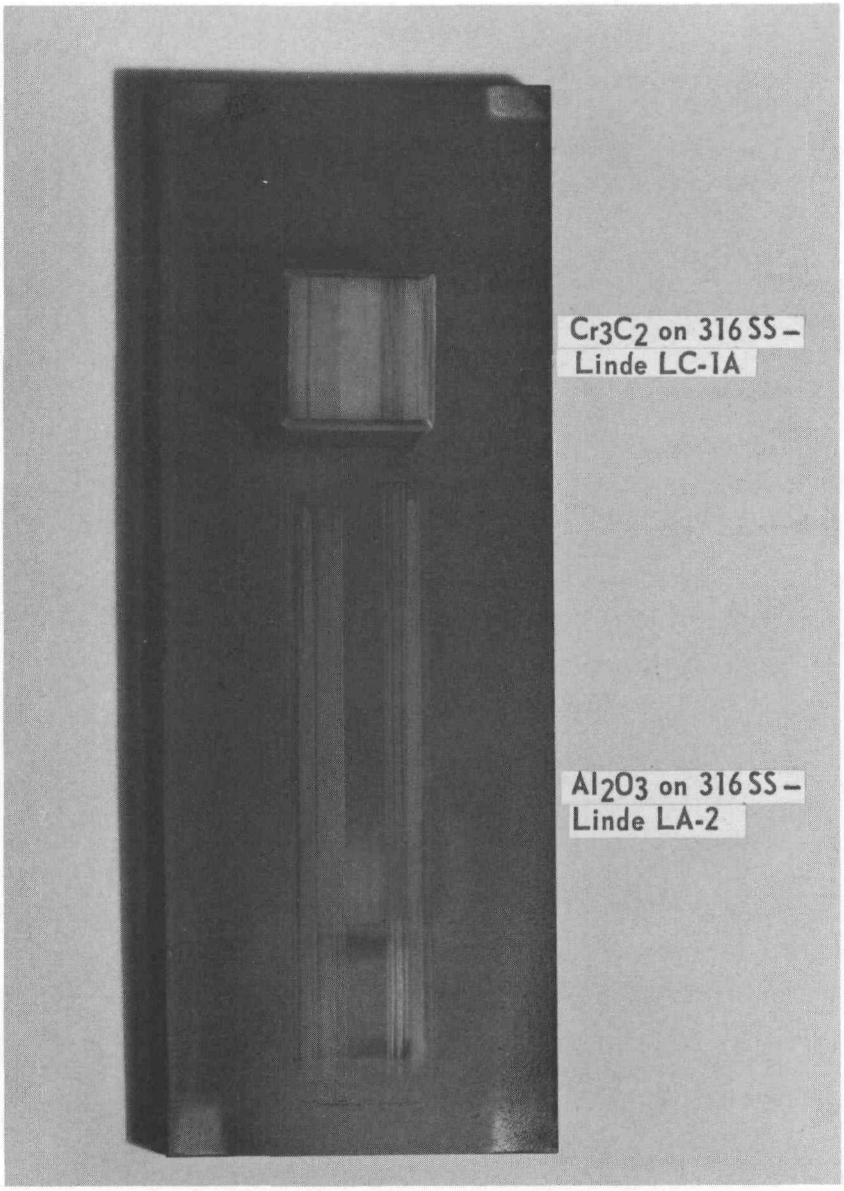

Figure 12. Test IV

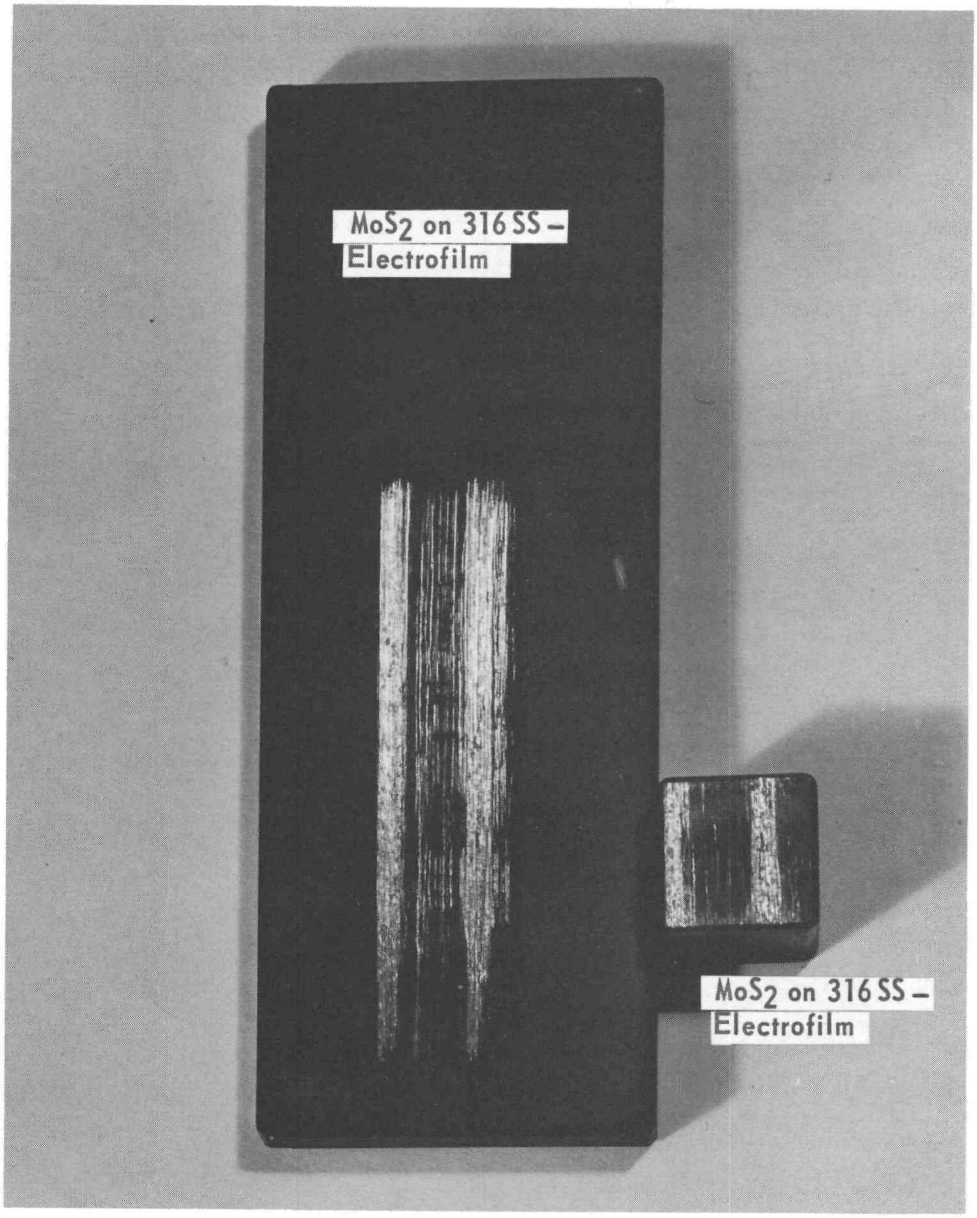

Figure 13. Test V

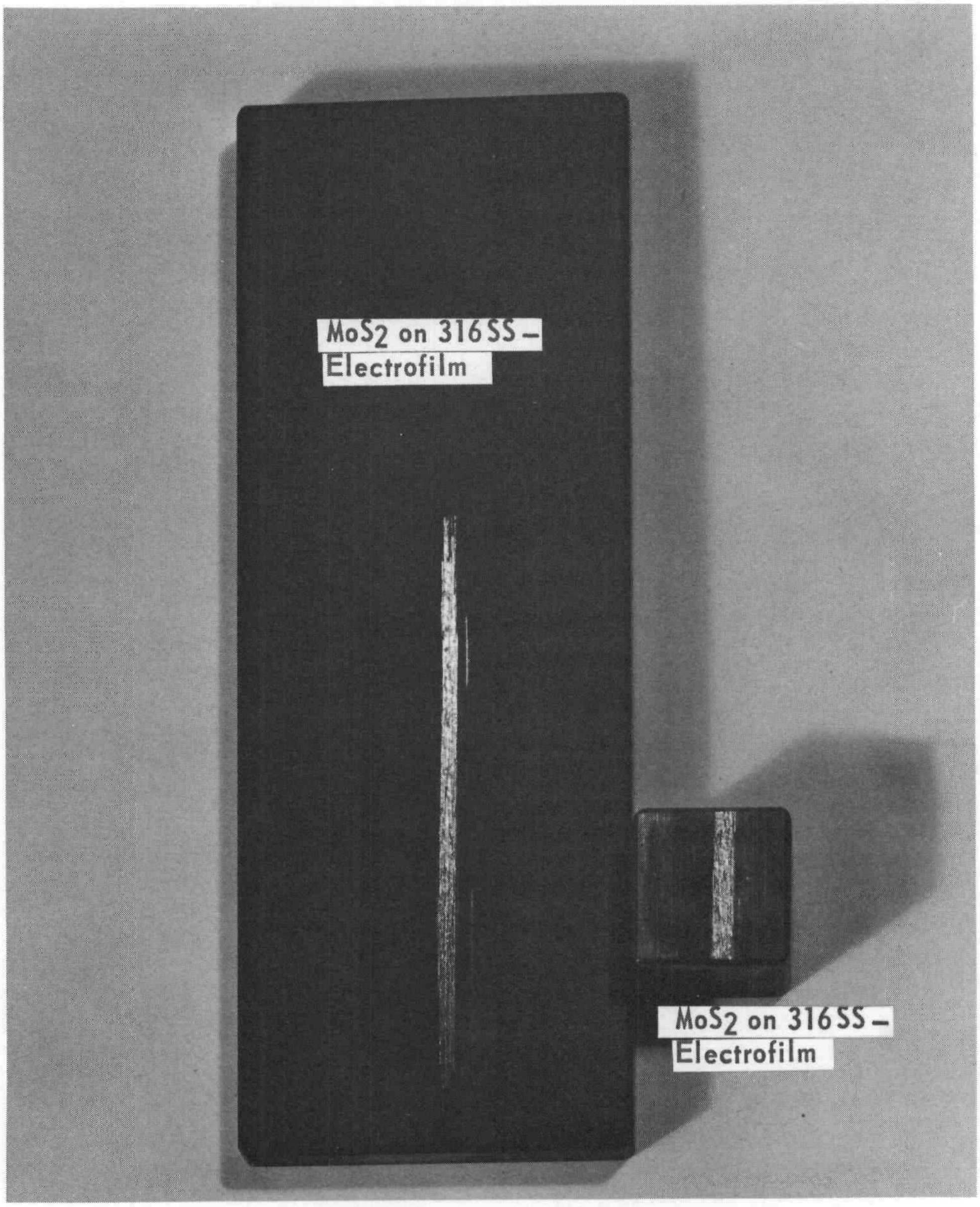

Figure 14. Test VI

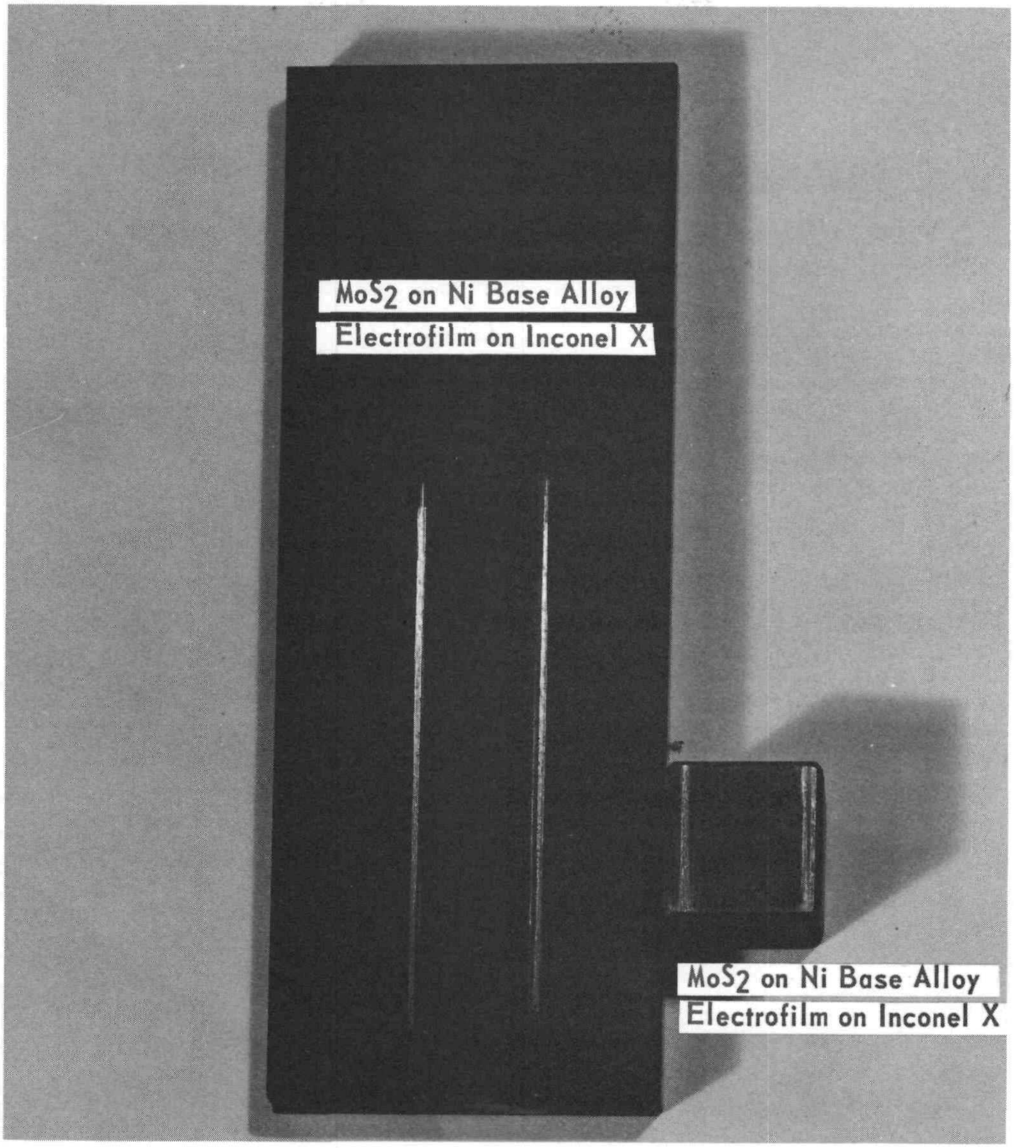

Figure 15. Test VII

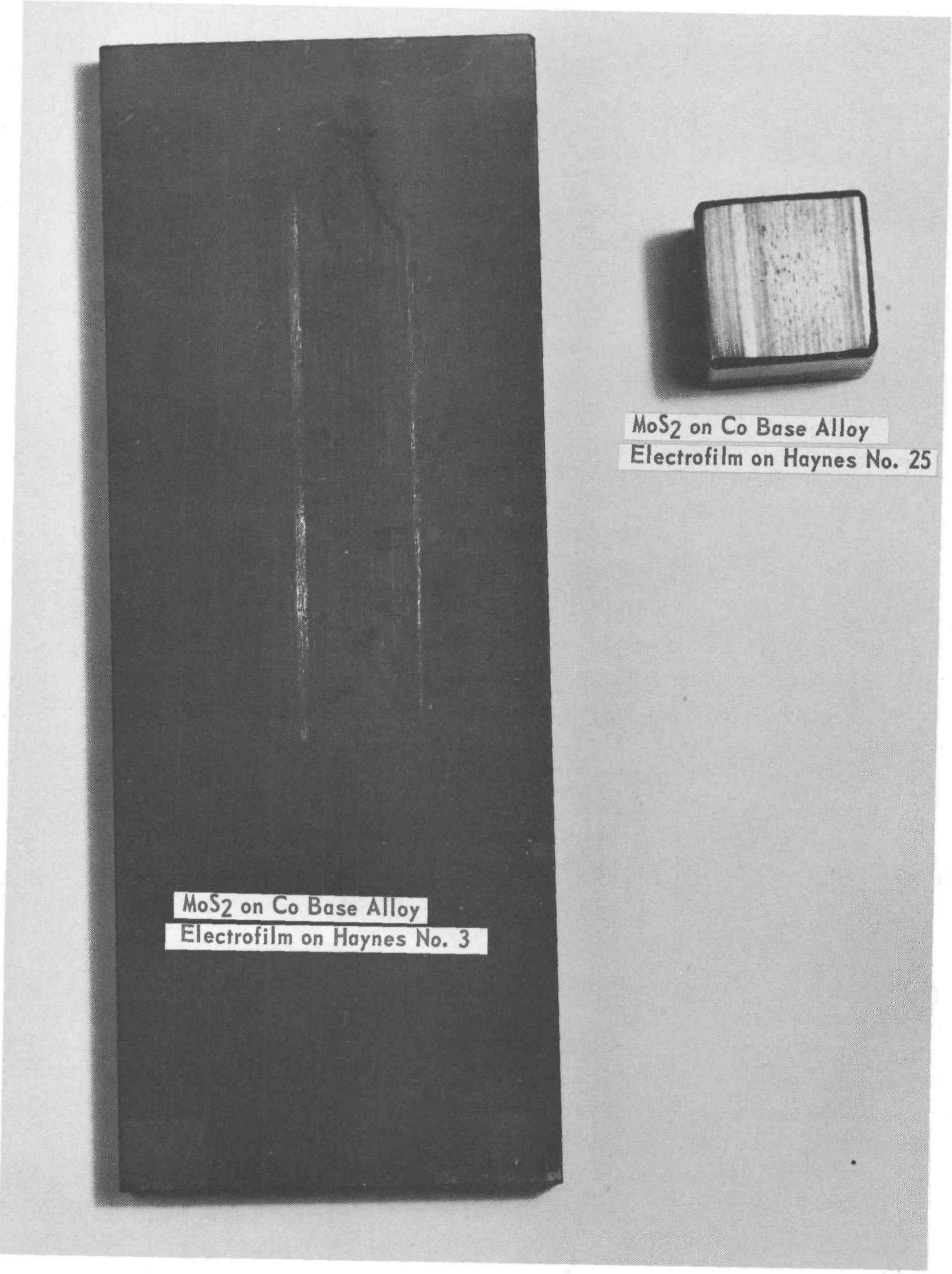

Figure 16. Test VIII

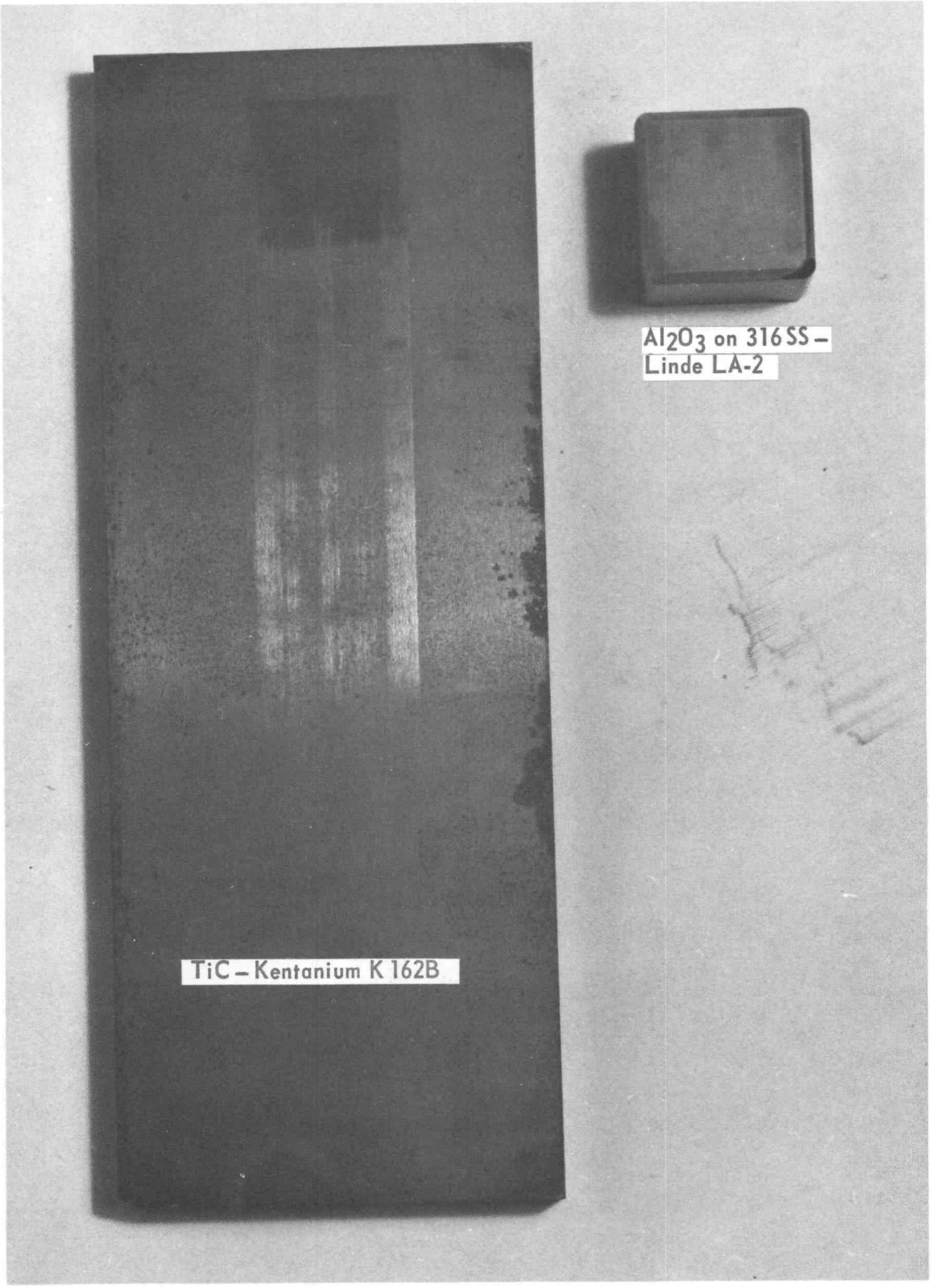

Figure 17. Test IX

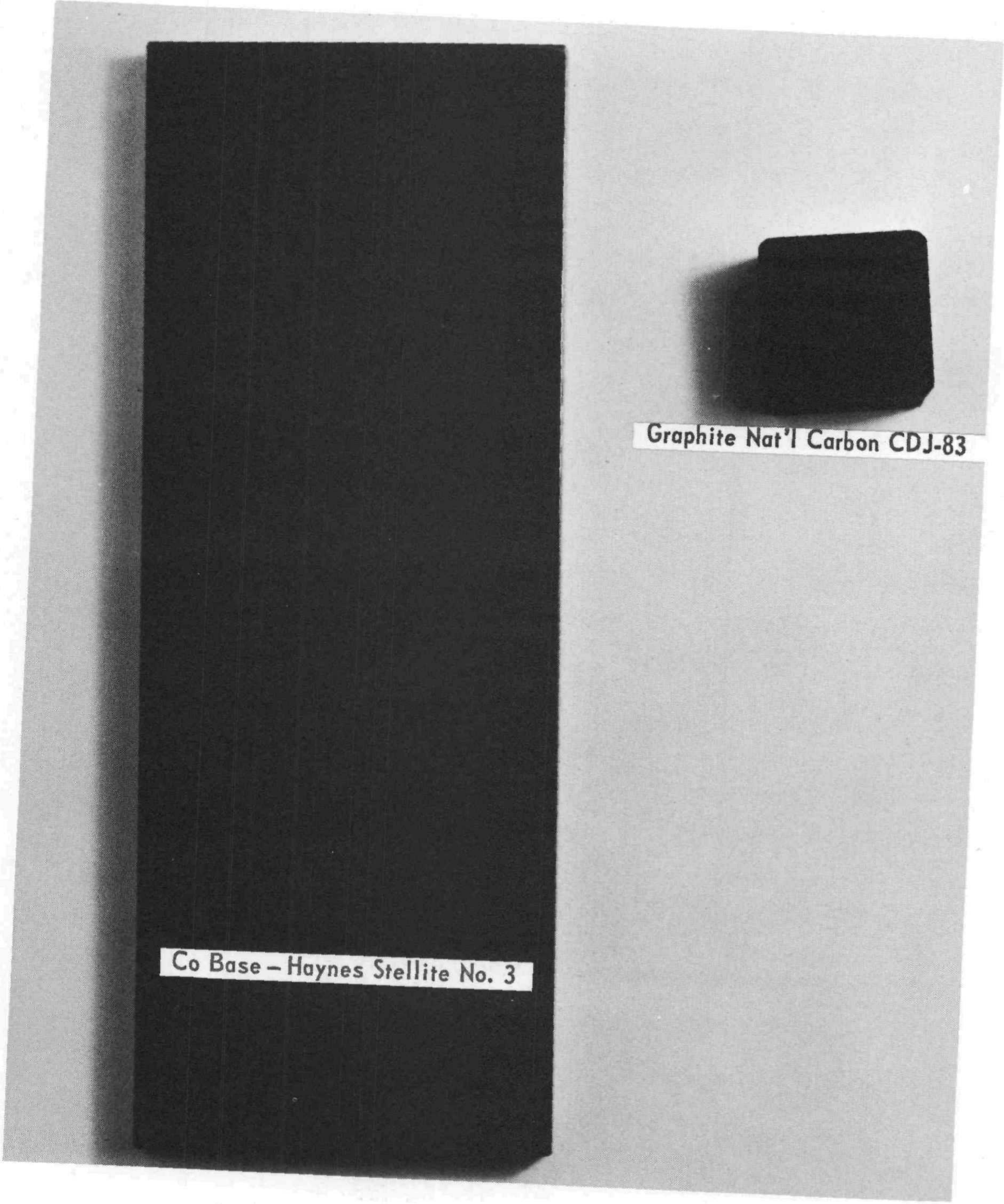

Figure 18. Test X

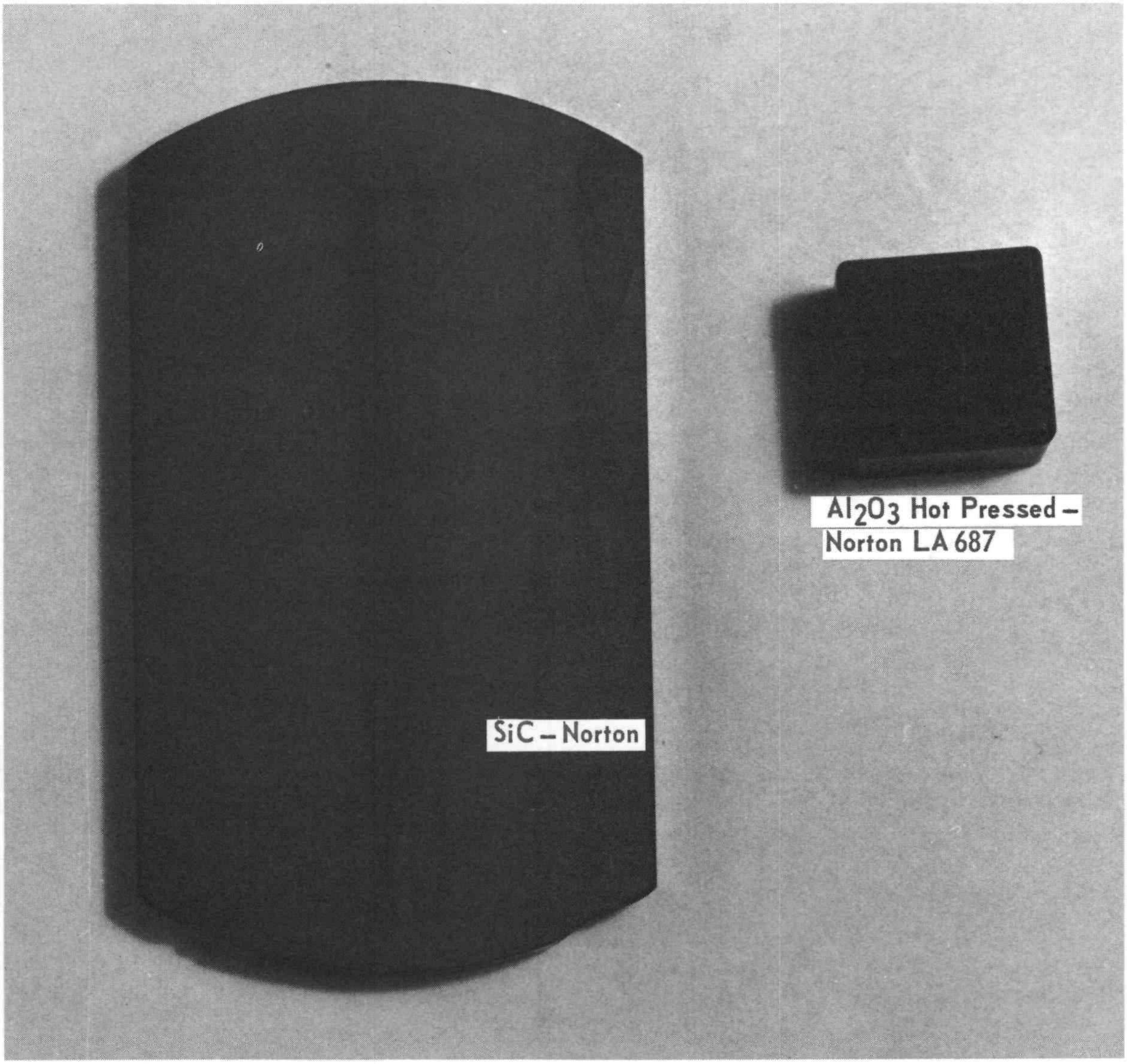

Figure 19. Test XI

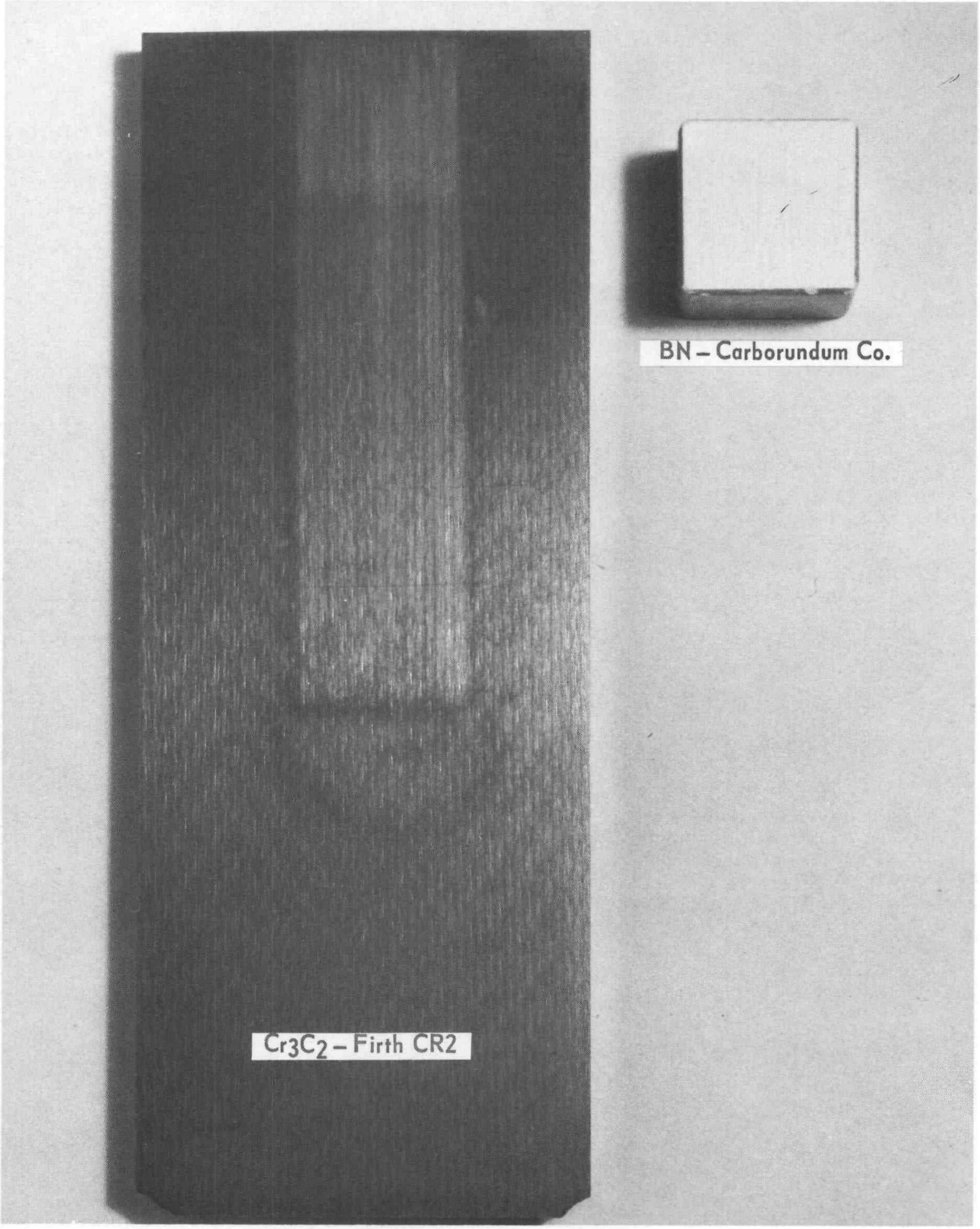

Figure 20. Test XII

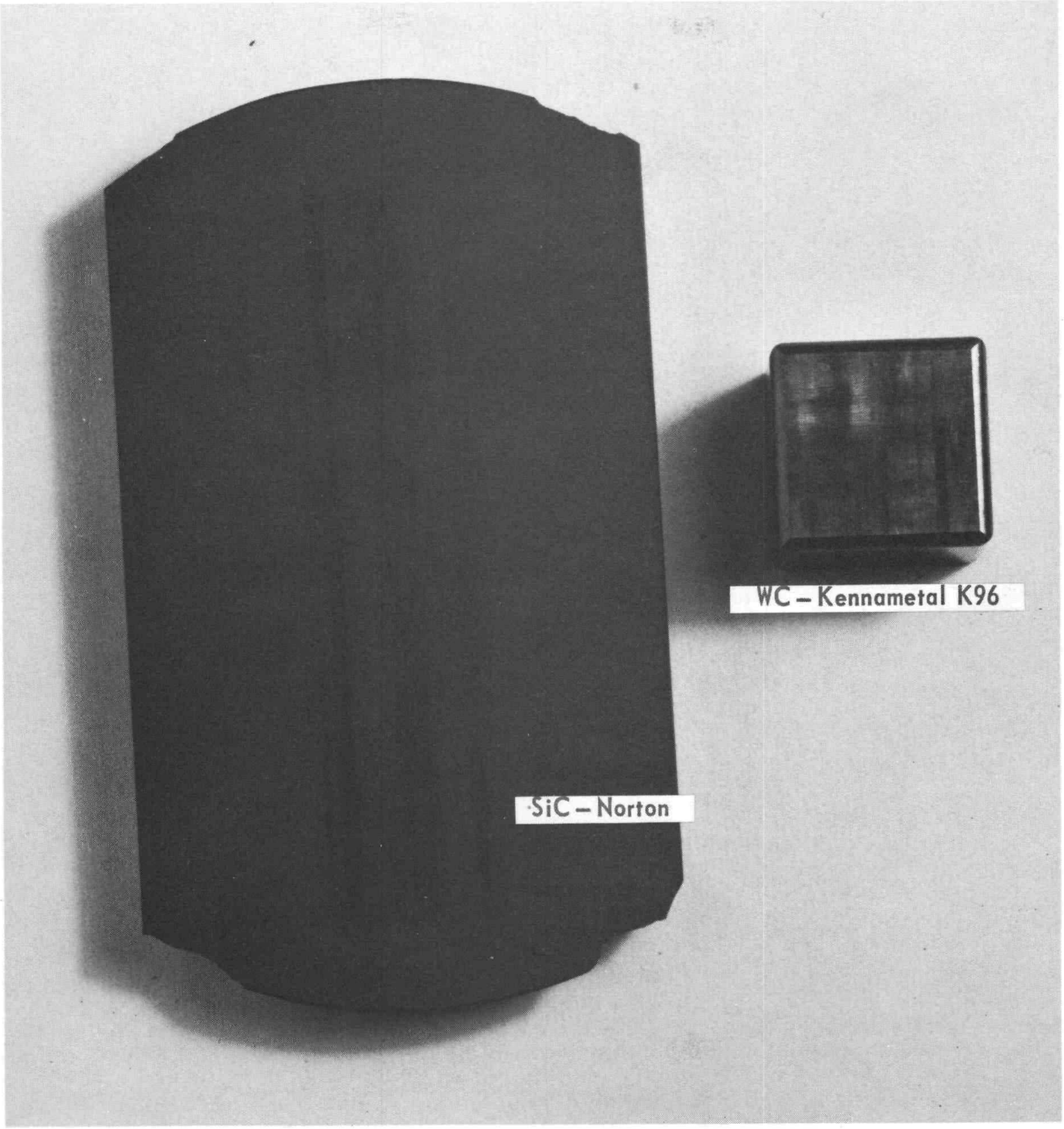

Figure 21. Test XIII

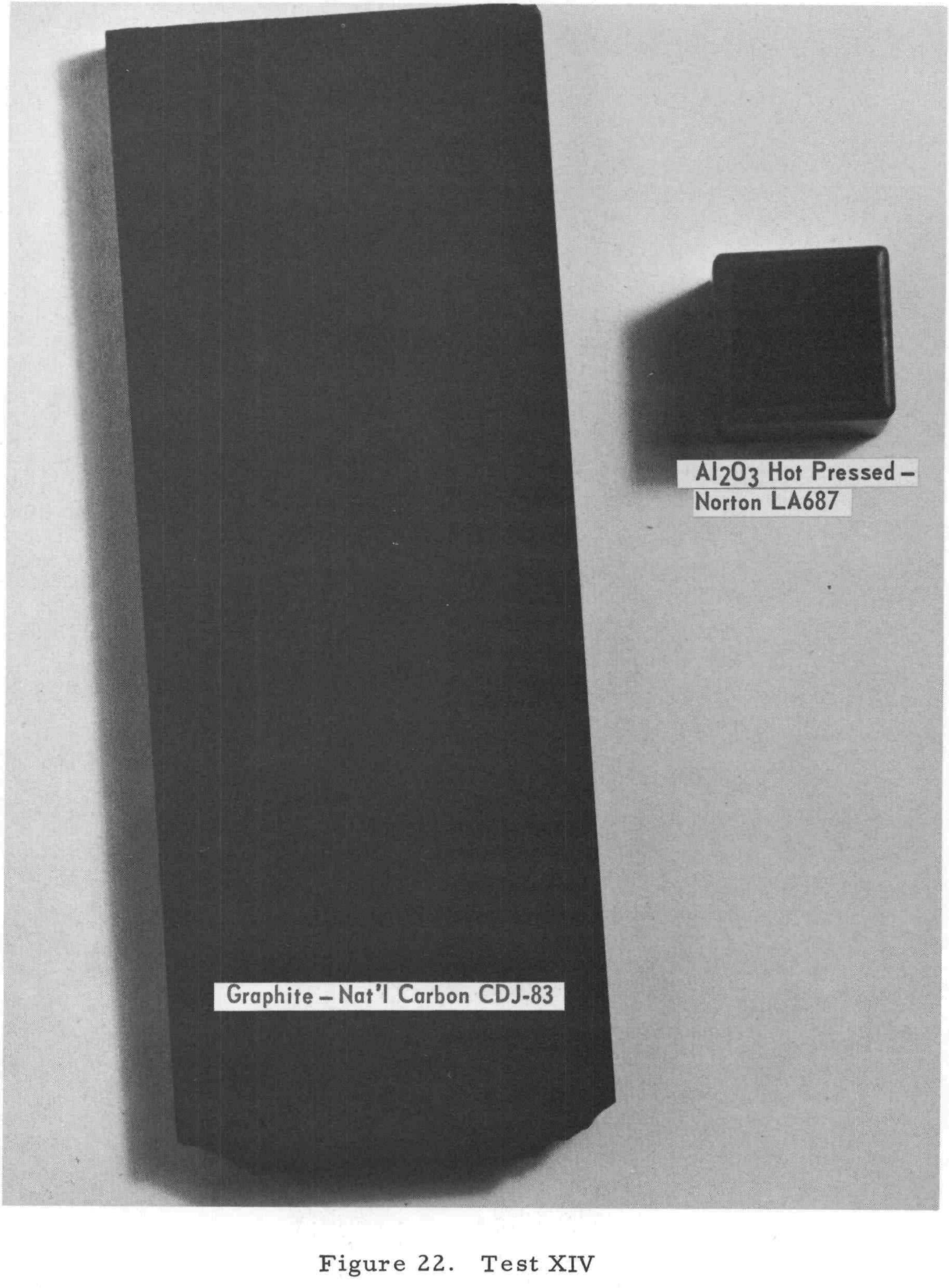

Figure 22. Test XIV

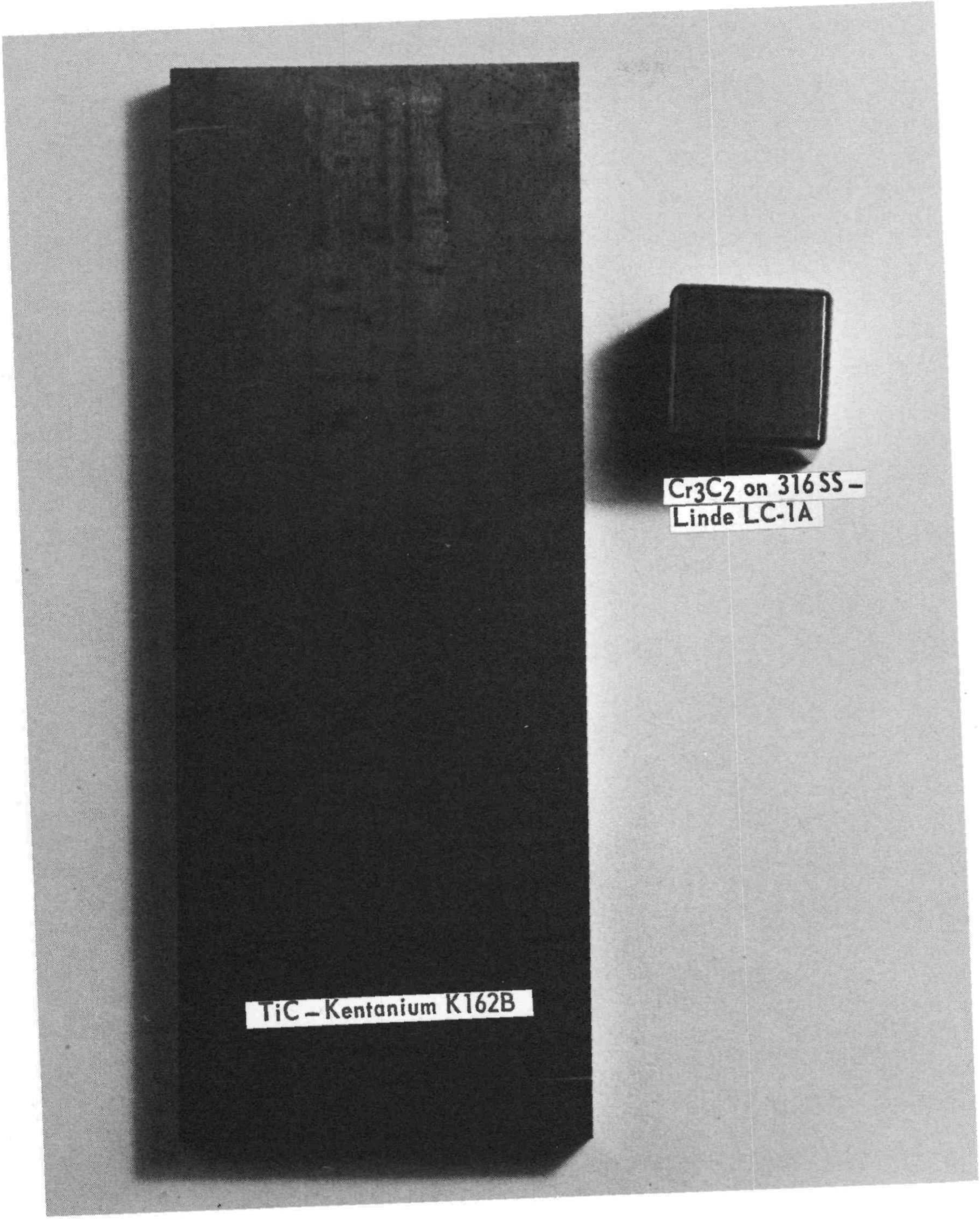

Figure 23. Test XV

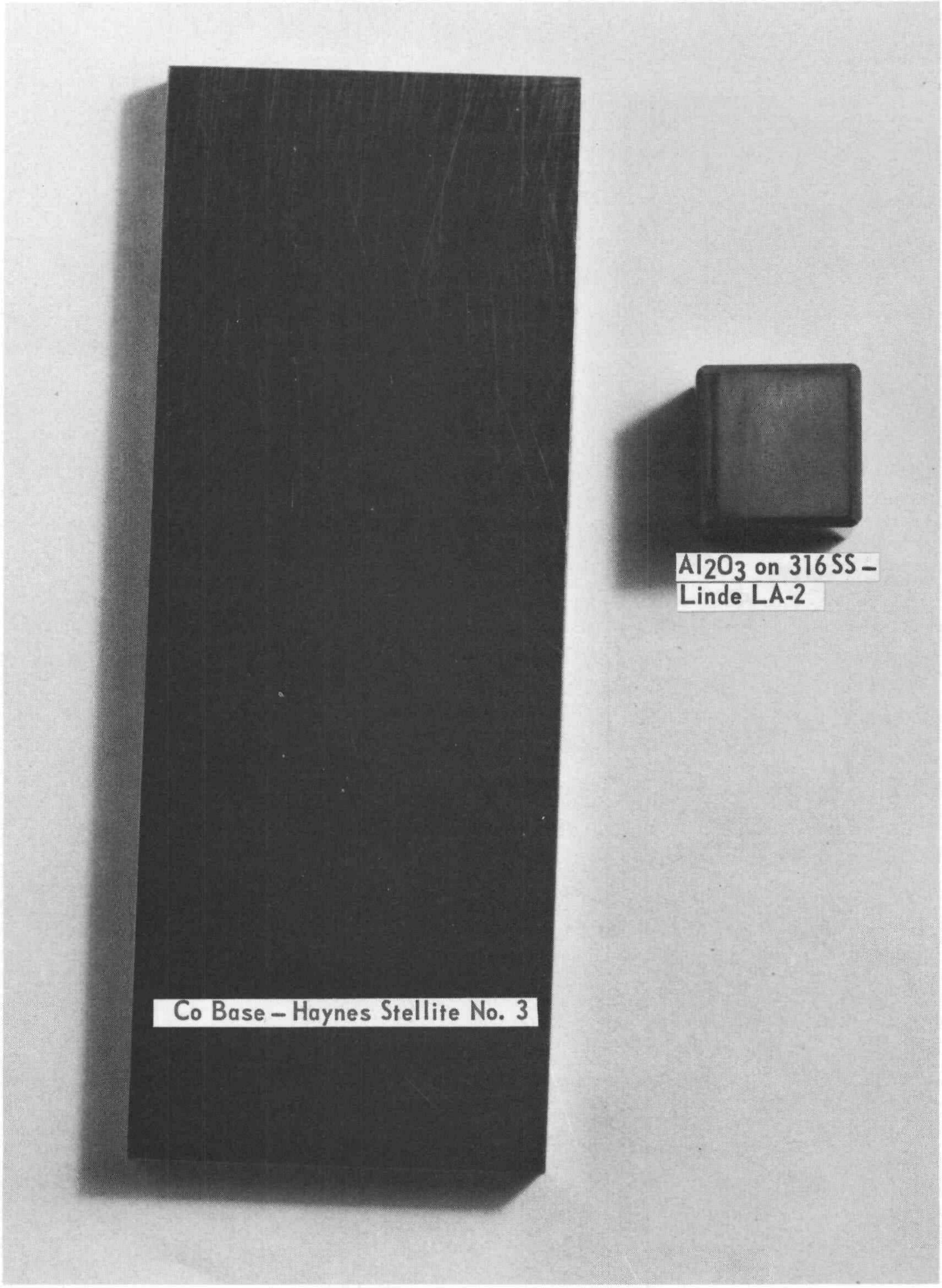

Figure 24. Test XVI

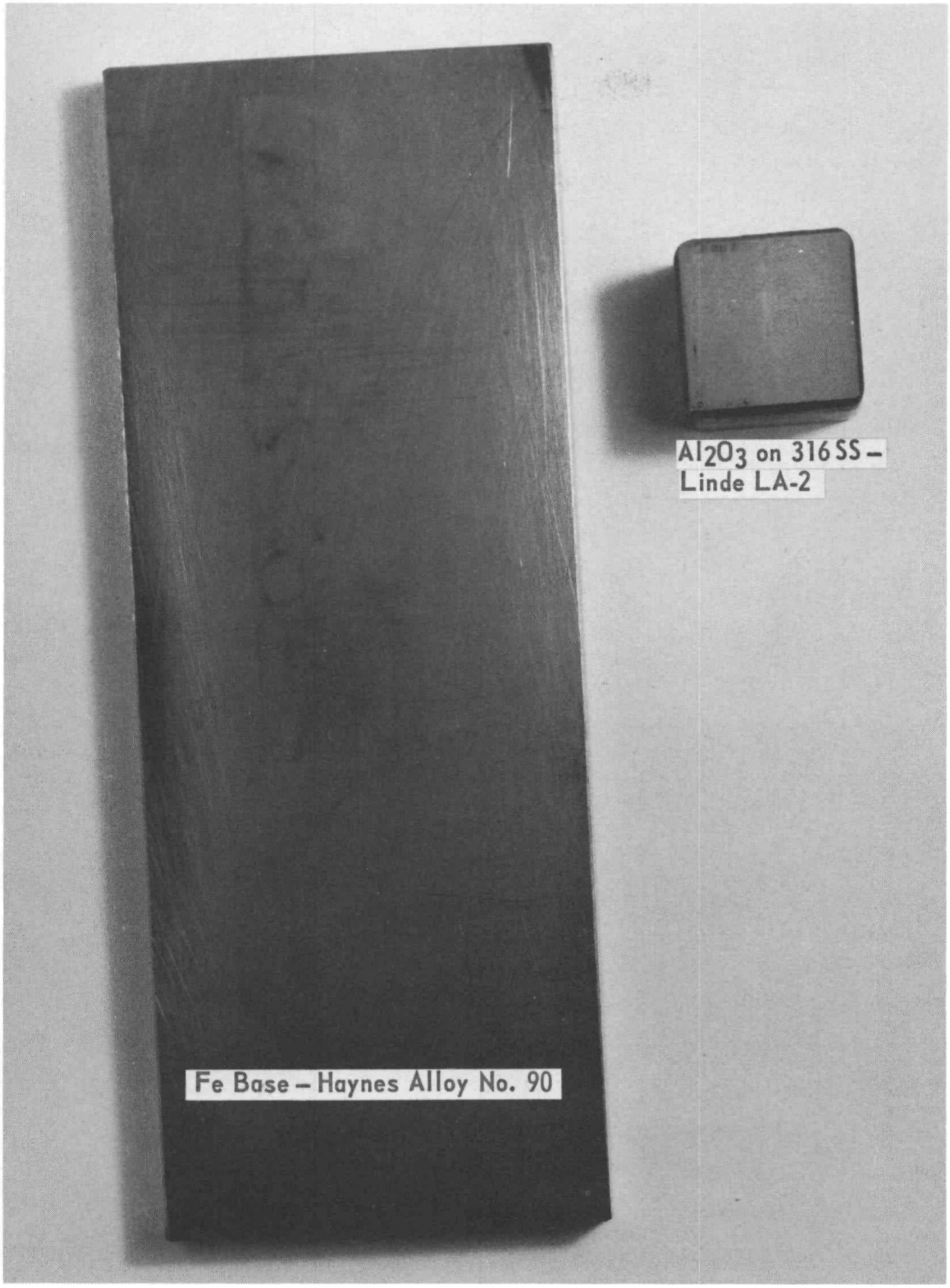

Figure 25. Test XVII

Figure 26. Test XVIII

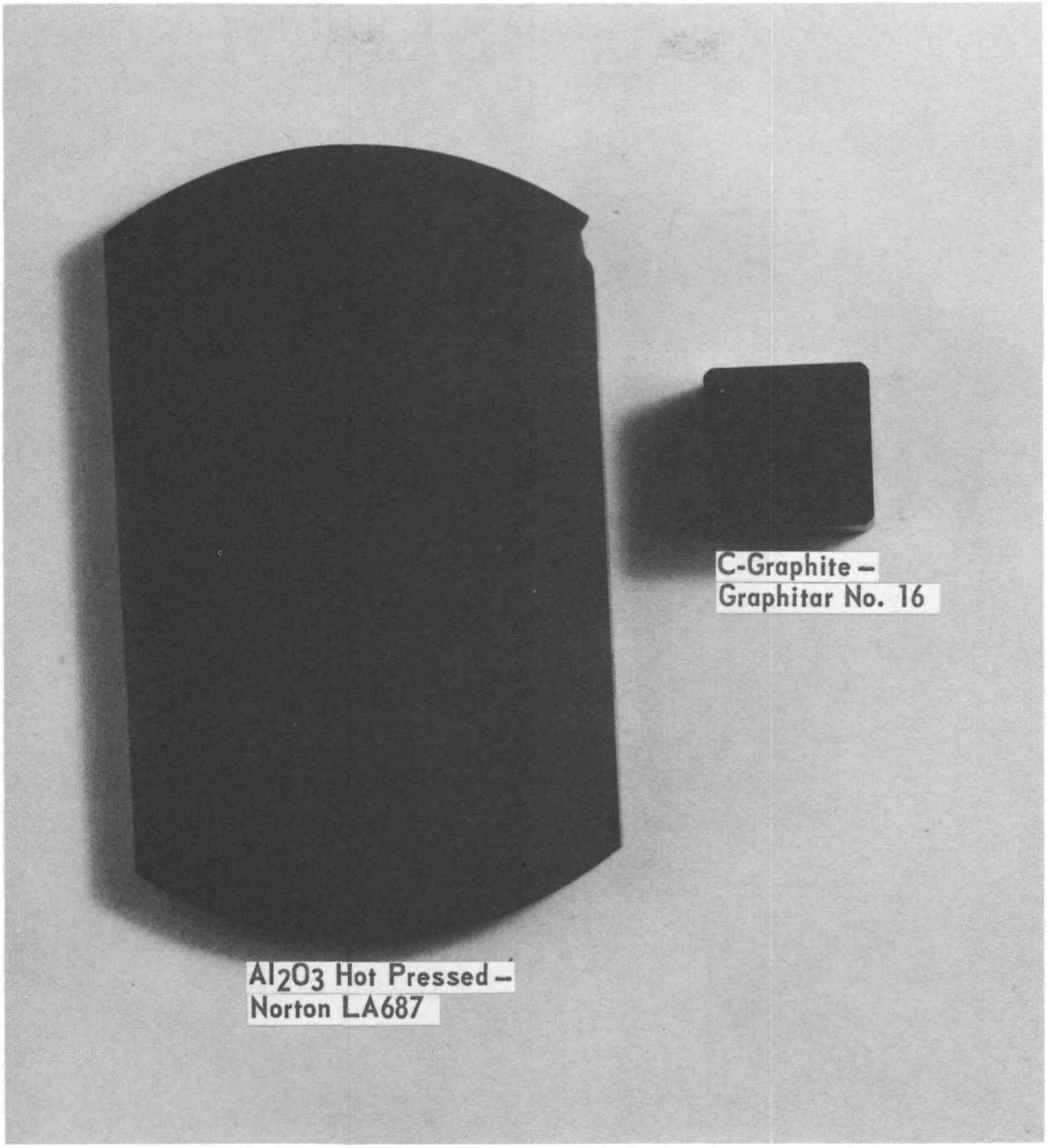

Figure 27. Test XIX

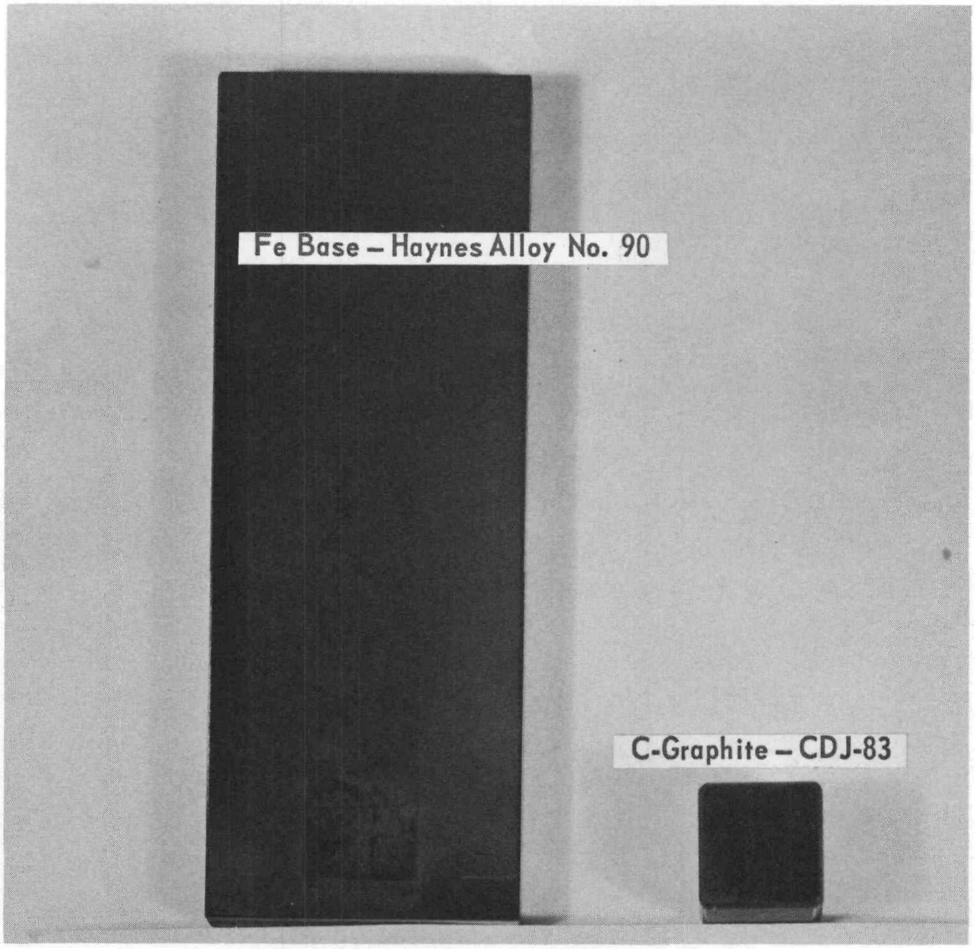

Figure 28. Test XX

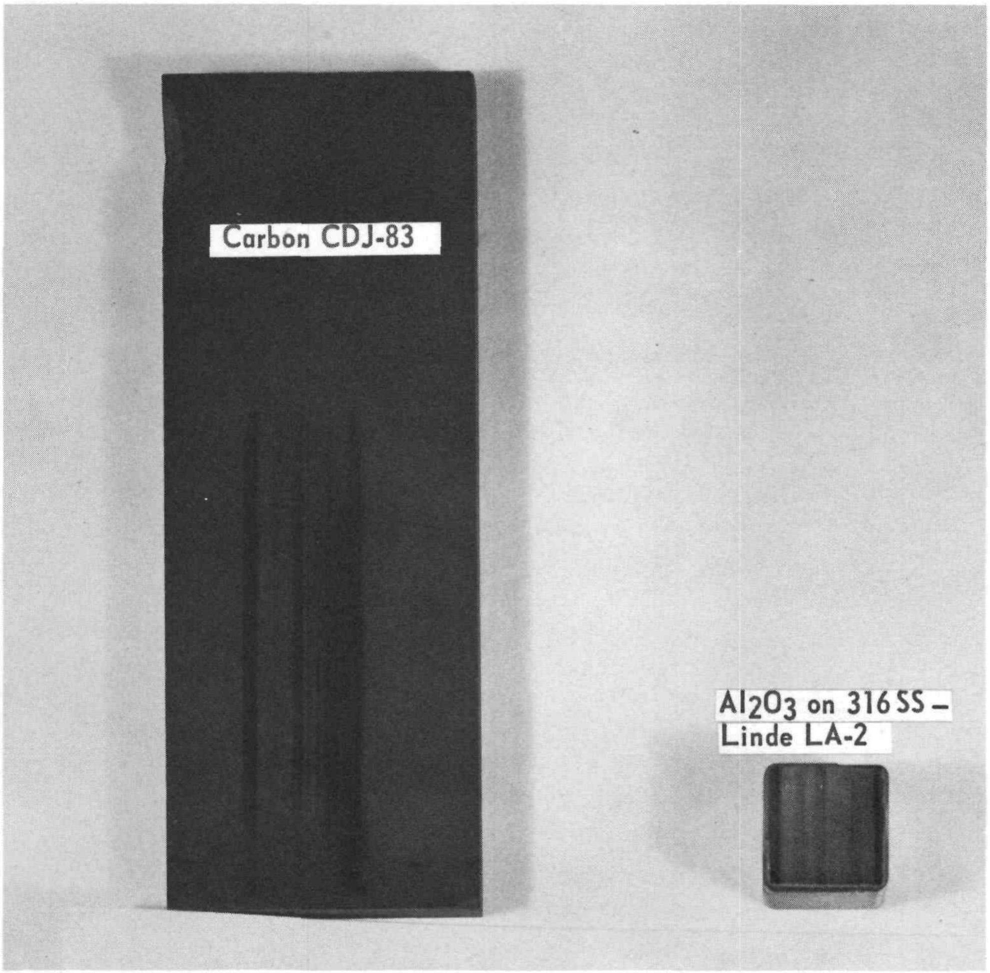

Figure 29. Test XXI and Test XXIII
(After completion of XXIII)

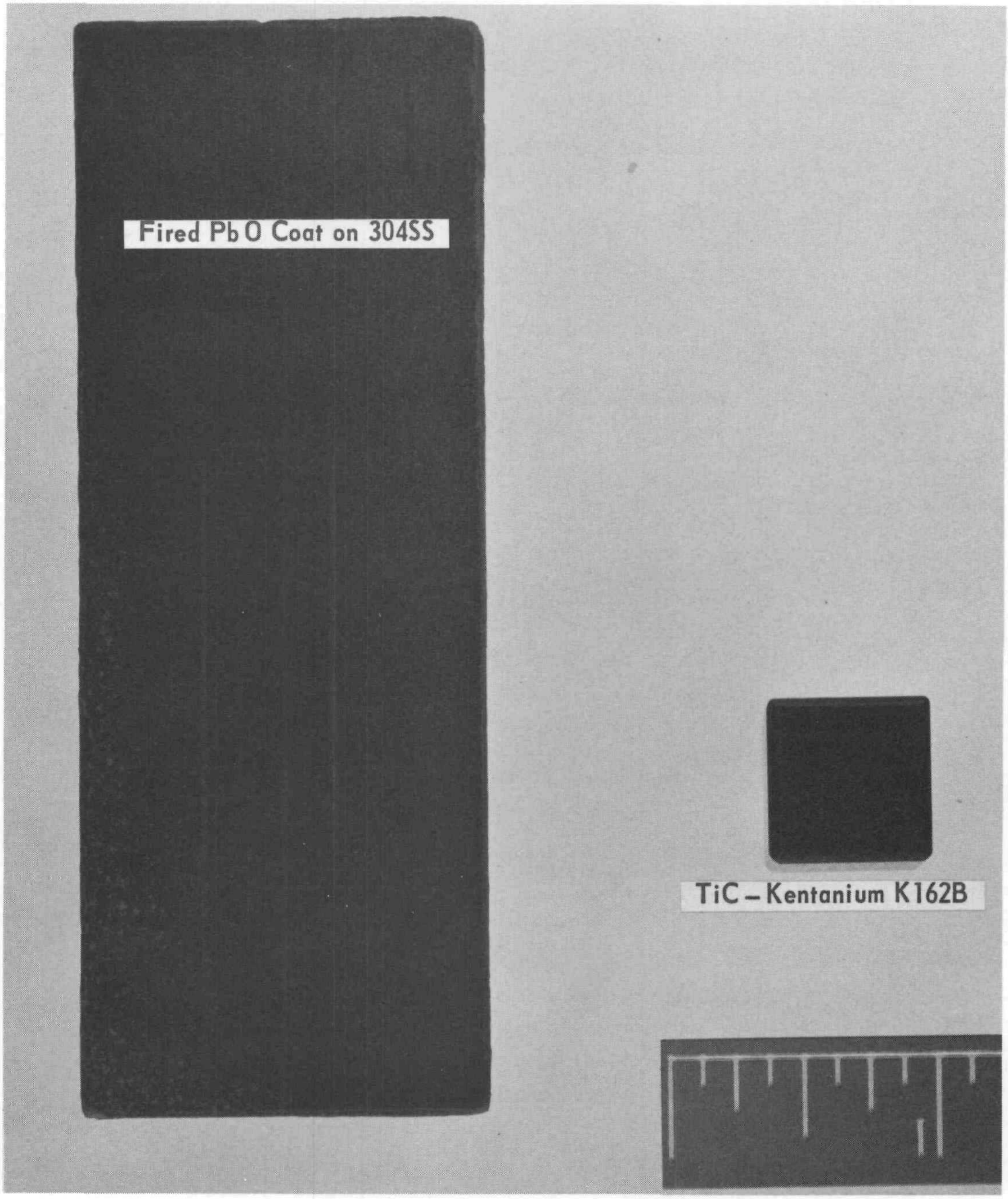

Figure 30. Test XXII

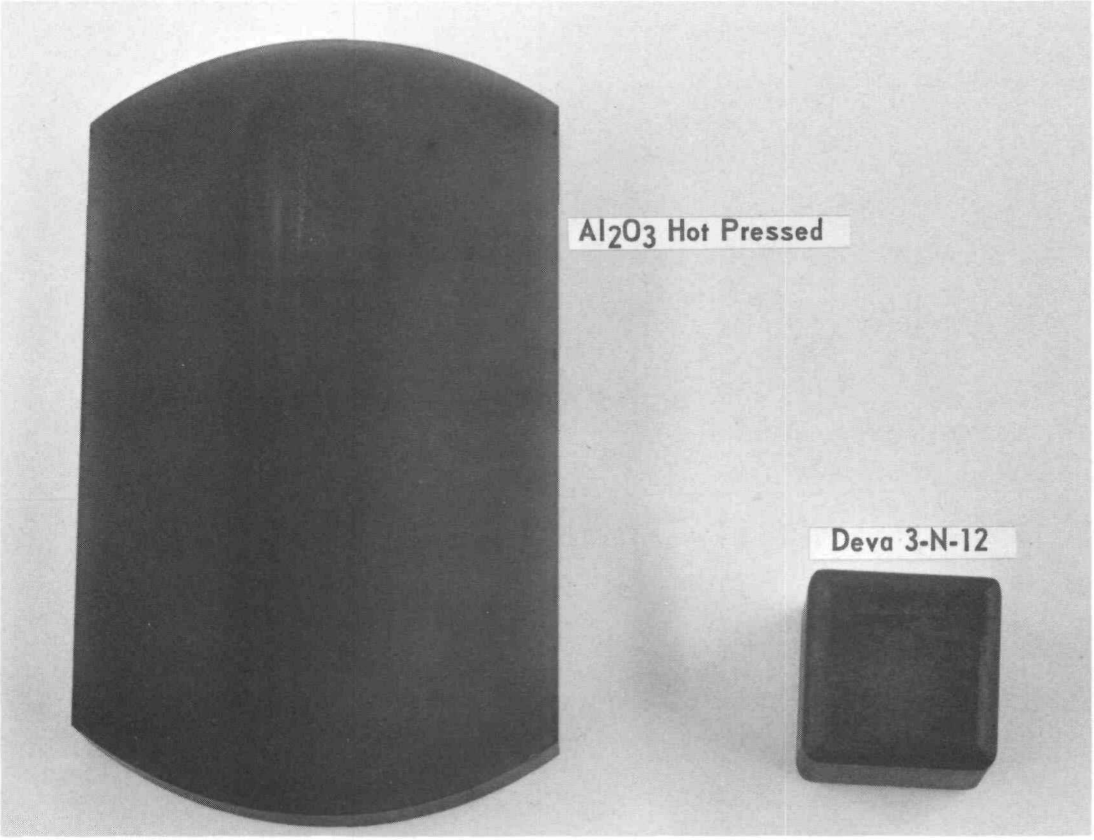

Figure 31. Test XXIV

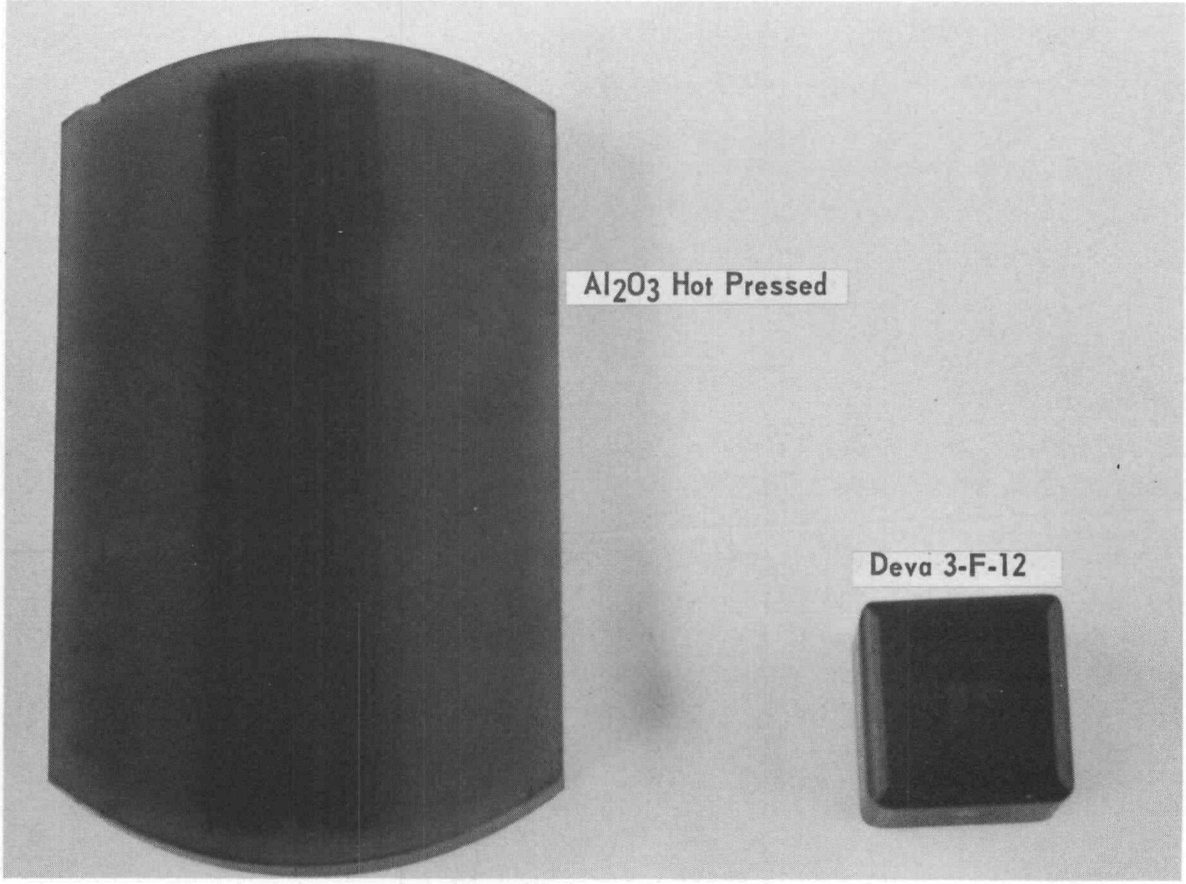

Figure 32. Test XXV

REFERENCES

1. F. P. Bowden and T. P. Hughes, Procedures of the Royal Society (LON), A172,263 (1939).

Friction tests were run with a cylinder sliding on a wire in a vacuum tube. Electric current through the wire and electron bombardment of the slider were used to outgas the specimens. Tests of Ni on W and Cu on Cu showed an initial coefficient of 0.5 but this increased to 4.5 and 6.0 when outgassed and held in a vacuum. Friction measurements were at room temperature.

2. F. P. Bowden and J. E. Young, Nature, Vol 164, page 1089 (1949).

Measurement of friction in a vacuum tube after degassing by high frequency induction heating showed a change of friction coefficient from 1.4 to 9 for Ni at room temperature. The friction of Ni surfaces thoroughly degassed was observed to decrease very little at low temperatures but considerably at high temperatures. The small change at low temperatures is explained as resulting from junction area changes being balanced by shear strength changes to effect a negligible net change. At high temperatures, however, a marked thermal softening of the metal occurs.

3. F. P. Bowden and D. Tabor, The Friction and Lubrication of Solids, Oxford Clarendon Press (1950).

This book is a collection of the experimental researches carried out by the writers and their collaborators and colleagues. The coverage is broad and the material is well referenced so that it serves as a bibliography on friction to the time of writing.

The authors develop a two-term metallic frictional resistance formula consisting of a shearing and a plowing term. One term describes the shearing of metallic junctions while the second describes the displacement of the softer metal as the harder metal plows into it. This theory is used by the authors and other writers as a basis for explanation of friction phenomena.

4. R. Savage, Journal Applied Physics, Vol 19, page 1 (1948).

Friction and wear tests at high vacuum with graphite showed excessive wear and high friction. The fine wear powder was superactivated carbon. Organic vapors or water vapor admitted to the vacuum reduced the friction and wear. It is suggested that graphite lubrication is a result of the adsorbed layers instead of slipping of the lamellae as earlier theorized.

5. F. P. Bowden, "Procedures of Symposium on Friction and Wear," R. Davies, page 84 (1959).

High speed friction of a soft material sliding across a hard one can cause wear or polishing of the hard material as with steel moved across a diamond bullet-shaped specimen.

The work of Dr. Kenyon was pointed out. He found that C graphite on C graphite at high temperature and outgassed gave a low friction

coefficient (0.2). Also he found that the friction of C graphite on Ag, Au, and Cu in vacuum dropped with temperature increases until the metal melted. However, with Ta, Fe, Ni and steel the friction dropped with temperature increases until about 1000°F was reached and then the friction rose sharply. The latter metals are known to react chemically with graphite to form a metal carbide.

Compounds formed at the interface of bearings can give low friction results if the compound is soft and has low shear strength. H_2S gas on Mo bearing surfaces at 1000°C produced MoS_2 with resulting low friction.

6. L. R. Coffin, "Procedures of Symposium on Friction and Wear 1957," page 36, R. Davies (1959).

This paper studies the metallurgical aspects of friction and wear and poses two modes of sliding. One is "sliding by shear" of the interface material and not the base metals. The other is "sliding by welding" or separation of contact inside the base metal. Sliding by shear gives the lowest friction and wear.

Interface materials depend on solubility of the mating materials, position of the material couple on the periodic table, alloying ability of the couple elements, the work of adhesion of couple elements, and the contact angle while the base metal properties are usually well defined.

For high temperature it is difficult to find combinations that slide by shear at the interface because high temperatures increase adhesion and decrease strength of the base metals.

7. E. Rabinowicz, WADC-TR-59-603 (1960).

High temperature tests in air on three groups of materials at a speed of 3 cm/sec and temperature of 1200°F resulted as follows:

Hard Oxides, Borides, and Carbides:	
Al_2O_3 on Al_2O_3	Coefficient = 0.8
TiC on Al_2O_3	Coefficient = 0.4
Al_2O_3 on SiC	Coefficient = 0.5
TiC on SiC	Coefficient = 0.5
B_4C on Al_2O_3	Coefficient = 0.5
C Graphite:	
C on Al_2O_3	Coefficient = 0.05
C on C	Coefficient = *
*(varied according to finish 0.05 to 0.25)	
Carbide:	
Carballoy 330 on Carballoy 330	Coefficient = 0.7