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COLD MOLECULAR WELDING STUDY IN ULTRA-HIGH VACUUM

FINAL REPORT
8 October 1964 - 17 December 1965

Contract No. NAS9-3623
Control No. PR 4183376

MRI Project No. 2817-E

For

NASA Manned Spacecraft Center
Structures and Mechanics Division
Mechanical and Landing Systems Branch
2101 Webster-Seabrook Road
Houston, Texas 77058

MRI
MIDWEST RESEARCH INSTITUTE
425 VOLKER BOULEVARD/KANSAS CITY MISSOURI 64110/AC 816 LO 1-0202

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by

C. E. Moeller
J. Bossert
M. Noland

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PREFACE

This program was conducted for the Mechanical and Landing Systems Branch, Structures and Mechanics Division, NASA Manned Spacecraft Center, with Mr. J. H. Kimzey as NASA's technical representative. At Midwest Research Institute, the program was directed by Mr. Vern Hopkins, Head, Materials Section.

Mr. C. E. Moeller, Project Leader was responsible for the over-all project activities. Mr. Joe Bossert directed the preparation of the specimens and operated the vacuum equipment during the test program with assistance from Mr. Dan Kos, Mr. Paul Mennemeyer, and Mr. Phil Tyrell. Mr. Frank Barker was responsible for the design, checkout, and maintenance of the electrical system. Dr. Paul Bryant, Dr. Paul F. Stablein, and Mr. Charles M. Gosselin contributed as consultants in vacuum technology and metallurgy.

Approved for:

MIDWEST RESEARCH INSTITUTE

Harold L. Stout

Harold L. Stout, Director
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19 November 1965

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SUMMARY

The degree of cold molecular welding was determined under static and dynamic conditions for 45 metal combinations in an ultra-high vacuum environment. The metals investigated were: 2014-T6 aluminum, Ti-6Al-4V titanium alloy, beryllium-copper, electrolytic grade copper, cobalt, 321 stainless steel, René 41, E52100 steel, and coin silver. Each of the nine metals was tested against themselves and each of the other metals. The test arrangement consisted of three pellets mounted in a rigid holder resting or being rotated on the top of a horizontal wear track. The pellets supported a weight of 9.2 lb. to create a contact pressure of 1,000 psi, based on projected area. The test surfaces were lapped and polished to less than 1 μin. rms finish. They were exposed to a chamber pressure of less than 5 x 10^{-10} torr before contact was made. During static and dynamic testing, the pressures were in the 10^{-9} torr range. The static test consisted of the coefficient of friction being measured at breakaway after stationary contact for 300 hr. at a temperature of 200°C. The dynamic test proceeded at a rotational velocity of 0.4 in/sec immediately after breakaway; it continued until the coefficient of friction exceeded 4.9 (limit of the test apparatus), the pellets wore excessively, or the time exceeded 100 hr.

The results of the investigations are compiled in several forms. A presentation of the data is first given as a ranking of the 45 metal combinations in order of increasing static coefficients of friction and a similar ranking of the dynamic coefficients of friction during short time testing (0 to 0.5 hr.). The second presentation is a tabulation of the coefficients of friction in a more convenient listing so that data of a particular metal combination can be readily located. The amount of pellet wear for each of the test combinations is given as a third set of data. These data indicate whether metal was transferred from or to the pellets. The frictional behaviors of four metal combinations were obtained in air; the values were all lower than the corresponding combinations in ultra-high vacuum. In air, all had moderately high initial dynamic coefficients which stabilized at lower values within a half hour.

A summary of the results of the 45 tests is presented in the following tabulation as a ranking of the metals based on average coefficients of friction. This Summary Table gives the general tendencies of various metals to cold weld.

SUMMARY TABLE

RANKING OF THE TENDENCY OF METALS TO COLD WELD IN ULTRA-HIGH VACUUM
AVERAGE COEFFICIENTS OF FRICTION

Static Breakaway* (after 300 hr. soak)		Dynamic Coefficient* (maximum value)	
Ti-6Al-4V Titanium	0.46	Cobalt	1.43
Beryllium-Copper	0.81	Ti-6Al-4V Titanium	1.59
321 Stainless Steel	0.86	Beryllium-Copper	2.36
René 41	0.86	2014-T6 Aluminum	2.52
Cobalt	0.89	321 Stainless Steel	2.53
Coin Silver	0.92	E52100 steel	2.86
Copper	1.03	Coin Silver	3.40
E52100 steel	1.06	René 41	3.63
2014-T6 Aluminum	1.21	Copper	3.80

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*Average values from metal combinations of specified metal with itself and the eight other metals.

This table is based only on the average coefficients of friction under the one set of parameters: controlled surface finish and flatness, specimen temperature 200°C, contact pressure 1,000 psi, chamber pressure less than 5×10^{-9} torr, and rotational velocity of 0.4 in/sec for the dynamic tests. Ranking of the tendency of the metals to cold weld was not possible on any other basis because of the wide variation of alloys, mutual solubilities, degrees of hardness, ultimate strengths, crystal structure, and other properties. The interaction of these properties and their influence on the behavior of the test surfaces prevented (1) the generation of any theoretical correlation to explain the various results, and (2) any prediction or grading of materials not tested on the program as to their cold welding tendencies.

I. INTRODUCTION

A potential problem area in the design of current and future NASA Manned Spacecraft is cold molecular welding between metal parts having relative motion while in the space environment. Numerous investigations have been conducted in the past on the adhesion, cohesion, cold welding friction, seizure, wear, and other related phenomena of two metals in contact. At the present, considerably more emphasis is being placed on studying the effect of two metals in contact when in a simulated space environment (ulra-high vacuum).

Cold molecular welding is generally referred to by most of the investigators as the adhesion or cohesion of two materials in contact at tmperatures significantly below the melting temperature of the materials. When a surface of one metal is in contact with another and moving relative to it, the coefficient of friction is a convenient measure of the degree of cold welding. When one metal slides smoothly over the other, the coefficient of friction is usually moderately low and relatively constant. When cold welding begins to occur on a microscopic scale, a stick-slip action begins to develop and the coefficient of friction becomes higher and more erratic. The degree of cold welding which can be tolerated in any system is dependent on the amount of energy which is available for creating relative motion between the two materials in contact and the amount of surface damage which can be permitted. Thus, a careful analysis must be made in any engineering application to establish the limits of cold welding.

This program was conducted to study and evaluate cold molecular welding of a variety of typical metals which are being used or considered for the Apollo mission. The coefficients of friction were determined for various metal combinations under specified conditions. Then, the metal combinations were ranked according to their likelihood of cold welding as indicated by their coefficients of friction. This rating of the 45 metal combinations is based on static breakaway friction after 300 hr. of contact and short-time dynamic conditions (during 0 to 0.5 hr.). In addition to the ultra-high vacuum tests for 45 metal combinations, the comparative effects of operation in air versus ultra-high vacuum were determined for four metal combinations.

The specific tasks undertaken to meet the objective of the program consisted of reviewing the scientific literature and research programs concerning cold welding and conducting an experimental program for generating data. The data reported by other investigators directly related to cold welding in ultra-high vacuum were examined for correlation with the data generated on this program. Results of the literature survey are given in the Appendix.

The experimental program consisted of developing test chambers and conducting the static and dynamic tests. The design of the test apparatus used the concept of three pellets resting or being rotated on an annular wear track, 2.3 in. dia. The three pellets, 0.0625 in. dia., were rigidly mounted in a holder and supported a 9.2-lb. weight; this weight produced a 1,000-psi contact pressure between the pellets and wear surface (based on projected area). The design incorporated heaters for maintaining the wear surfaces at approximately 200°C. The coefficient of friction was determined by measuring the torque necessary to rotate the pellets. The mechanism was enclosed in a stainless steel chamber and evacuated with an oil-free vacuum pumping system capable of maintaining pressures in the 10^{-9} and 10^{-10} torr region. Details of the equipment, specimen preparation, and testing procedures are given in Section IV, Experimental Program.

II. EXPERIMENTAL RESULTS

The experimental results of the testing program are based on the coefficient of friction measurements on static breakaway and dynamic rotation of the pellets on the wear track for the nine materials tested on themselves and each other. An additional set of data is obtained from observations of the wear of the pellets and the wear track surface and the relative manner of metal transfer. Prior the coefficient of friction data, the specimen description and chemical composition of the materials are given.

A. Description of Specimens

The specimens used in the testing program were made from materials whose compositions and physical properties are given in Tables I and II. The hardness values were measured on the ends of 1/4 in. dia. cylinders machined from the plates and bars with the same orientation as the pellet. All of the specimens were machined from rolled plates or rectangular bars; the test surface of the wear track was parallel to the face of the plate or bar. Each pellet of a given material was machined from the same plate or bar as the wear track of the material; the pellet was oriented with its axis perpendicular to the direction of rolling. Thus, the test surface of the pellet had elongated grains due to the rolling operation in the plane of the surface and not perpendicular to the surface. The wear track and pellet surfaces were lapped and polished to a finish of 1 μin. rms or less (described in Section IV). Generally the specimen materials were in the same heat-treat condition as is used in the Apollo program. Exceptions were E52100 steel which was tested in the spheroidized annealed condition, 2014 T6 aluminum, copper, and silver which were all softened somewhat by the bake-out temperature of 265°C.

TABLE I

COMPOSITION OF SPECIMEN MATERIALS

2014-T6 Aluminum (QQA 261)

Si	0.50 - 1.2
Fe	3.9 - 5.0
Mn	0.4 - 1.2
Mg	0.2 - 0.8
Cr	0.10
Zn	0.25
Ti	0.15

Ti-6Al-4V Titanium

C	0.027
Fe	0.09
N_2	0.014
Al	5.9
Va	3.9
H_2	0.004

Beryllium-Copper (QQC-530)

Be	1.85	Co	0.24
Fe	0.10	Zn	0.02
Al	0.05	Sn	0.01
Si	0.14	Pb	0.005
Ni	0.01	Cr	0.005
		Cu	Bal.

Copper, Electrolytic Grade

99.95 Cu - 0.04 Oxygen Typical
0.01 Total Other Impurities

Cobalt

Ni	0.3
Cu	0.005
Fe	0.0018
S	0.001
C	0.012
Co	Bal.

321 Stainless Steel

C	0.06	Ni	10.80
Mn	1.44	Cr	17.39
P	0.024	Mo	0.14
S	0.013	Other	0.59
Si	0.72	Fe	Bal.
Cu	0.08		

René 41

C	0.090	Co	11.25
S	0.005	Ti	3.15
Mn	0.04	Al	1.55
Si	0.10	B	0.008
Cr	18.83	Fe	1.35
Mo	9.75	Ni	Bal.

E52100 Steel

C	0.99
Mn	0.44
P	0.01
S	0.011
Si	0.30
Cr	1.40
Fe	Bal.

Coin Silver

Ag	90.71
Cu	Bal.
Cd	0.00[illegible]
Zn	<0.001
Sn	<0.001
Pb	<0.001
Fe	<0.001
Al	<0.001
Bi	<0.001

TABLE II

PROPERTIES OF SPECIMEN MATERIALS

	Material Hardness[a]		Ultimate Tensile Strength[b]	Yield Strength	Elongation	Crystal Structure
	As Procured	After Test				
2014-T6 Aluminum	R_B 85	R_B 47	68,000 psi	60,000 psi	7%	FCC
Ti-6Al-4V Titanium	R_c 32	R 34	142,400 psi	129,100 psi	14.5%	HCP with BCC Precipitate
Beryllium-Copper	R_c 38	R_c 43	205,800 psi	198,100 psi	4.5%	FCC with $BeCu_2$ Precipitate
Copper	R_B 40	R_B 25	45,000 psi	40,000 psi	20%	FCC
Cobalt	R_B 92	R_B 97	34,400 psi	-	-	HCP
321 Stainless Steel	R_B 81	R_B 83	81,400 psi	39,040 psi	53%	FCC
René 41	R_c 37	R_c 39	206,000 psi	154,000 psi	14%	FCC, Precipitate Hardened
E52100 Steel	R_B 90	R_B 97	-	-	-	BCC - Spheriodized
Coin Silver	R_B 73	R_B 62	50,000 psi	-	-	FCC with FCC Precipitate

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[a] Specimen hardness could not be determined after bake-out just prior to testing; changes of hardness values were generally caused by bake-out at 265°C and would not be further influenced by the subsequent testing at 200°C.

[b] Mechanical properties are for "Before Test" hardness condition; the materials which experienced a substantial reduction of hardness also had their mechanical properties degraded.

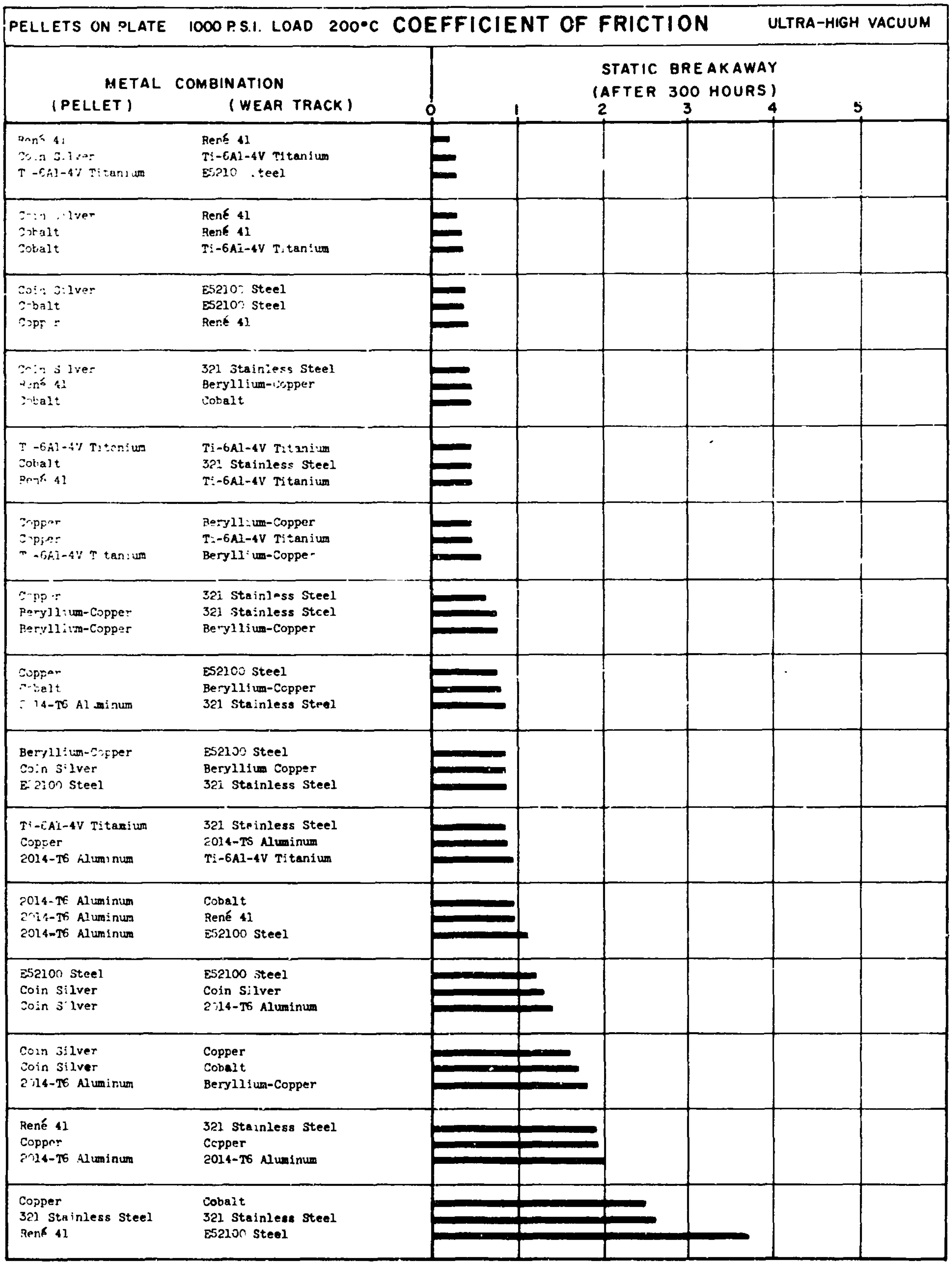
B. Coefficients of Friction

The coefficients of friction are used as an indication of the degree of cold welding for the metal combinations in the test program. The coefficient of friction was recorded at breakaway of the static test and continuously during the dynamic test. From these continuous recordings the coefficients of friction were obtained for various intervals of the dynamic test; i.e., 0 to 0.5 hr., 0.5 to 5.0 hr., and 5 to 100 hr. The coefficients for most metal combinations varied widely during the dynamic test. Maximum values occurred when the pellets dug into the wear track surface or cold-welding seizure was imminent. When sufficient torque was available to break the pellets free, they would tend to slip momentarily at low coefficient values. The resulting action of the pellets on the wear track was a random stick-slip behavior which caused an audible vibration in the test chamber.

1. Ranking of metal combinations: The tendency of various metal combinations to cold weld in a space environment at 200°C and a projected contact pressure of 1,000 psi is given in Figs. 1 and 2.

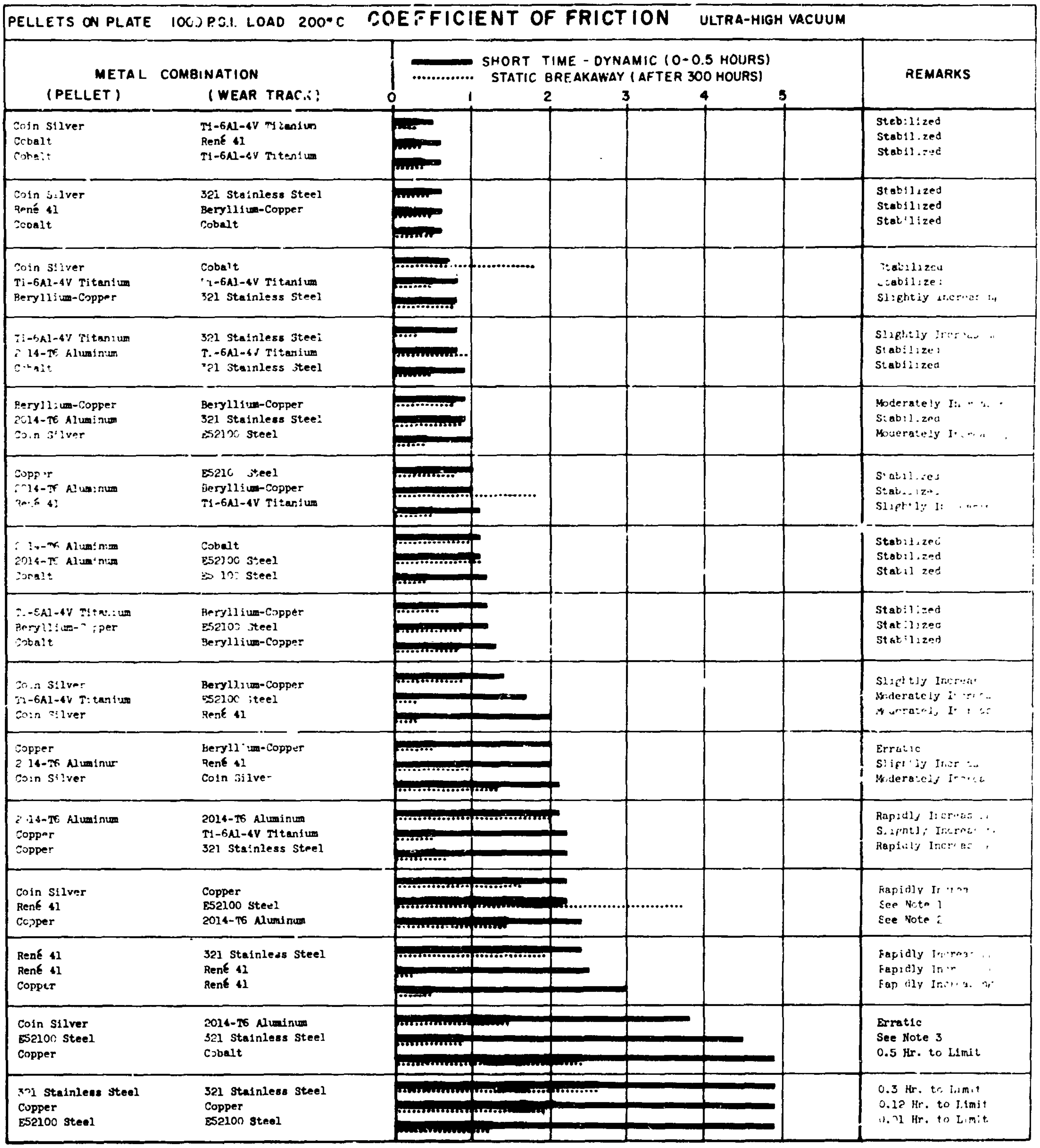
Static coefficients of friction are given in Fig. 1 for the pellets upon breakaway after 300 hr. of stationary contact in the ultra-high vacuum environment. This table indicates that René 41 on itself had the lowest static coefficient (0.20) but also René 41 on E52100 steel had the highest (3.70). The average static coefficient for René 41 (as shown in the Summary Table) is 0.86. Ti-6Al-4V titanium has the lowest average coefficient (0.46); a glance at the data for all the metal combinations involving Ti-6Al-4V titanium in Fig. 1 shows that its highest value is 0.95 (with aluminum), but most of the values are less than 0.5. The 2014-T6 aluminum has the highest average coefficient (1.21) because of the consistently high coefficients it has with itself and the other metals. Discussion of these results and those from the dynamic tests will be given in Section III, Discussion of Results.

The dynamic coefficients of friction of the metal combinations are given in Fig. 2 for the initial period of rotation (0 to 0.5 hr.). The dynamic conditions consisted of rotation of the pellets over the wear track at a linear velocity of 0.4 in/sec. The metal combinations are ranked in the order of increasing coefficient, based on the maximum dynamic coefficients which occurred during the time interval. The last four combinations had values above 4.9, the limit of the test apparatus at the 1,000-psi contact pressure. These were then ranked on the basis of the time which they rotated before their coefficient exceeded the 4.9 limit. The E52100 steel rubbed on itself only two revolutions before its coefficient exceeded 4.9; yet there was no adhesion between the pellets and the wear track. The only combination which cold-welded in the sense that the pellets were bonded to the wear track was copper on copper; however, the pellets broke from the wear track when they were being removed from the pellet holder.



Data from single run with each metal combination.

Fig. 1 - Ranking of Metal Combinations Based on Static Breakaway Coefficients of Friction



METAL COMBINATION (PELLET)	(WEAR TRACK)	REMARKS
Coin Silver	Ti-6Al-4V Titanium	Stabilized
Cobalt	René 41	Stabilized
Cobalt	Ti-6Al-4V Titanium	Stabilized
Coin Silver	321 Stainless Steel	Stabilized
René 41	Beryllium-Copper	Stabilized
Cobalt	Cobalt	Stabilized
Coin Silver	Cobalt	Stabilized
Ti-6Al-4V Titanium	Ti-6Al-4V Titanium	Stabilized
Beryllium-Copper	321 Stainless Steel	Slightly Increasing
Ti-6Al-4V Titanium	321 Stainless Steel	Slightly Increasing
2014-T6 Aluminum	Ti-6Al-4V Titanium	Stabilized
Cobalt	321 Stainless Steel	Stabilized
Beryllium-Copper	Beryllium-Copper	Moderately Increasing
2014-T6 Aluminum	321 Stainless Steel	Stabilized
Coin Silver	E52100 Steel	Moderately Increasing
Copper	E52100 Steel	Stabilized
2014-T6 Aluminum	Beryllium-Copper	Stabilized
René 41	Ti-6Al-4V Titanium	Slightly Increasing
2014-T6 Aluminum	Cobalt	Stabilized
2014-T6 Aluminum	E52100 Steel	Stabilized
Cobalt	E52100 Steel	Stabilized
Ti-6Al-4V Titanium	Beryllium-Copper	Stabilized
Beryllium-Copper	E52100 Steel	Stabilized
Cobalt	Beryllium-Copper	Stabilized
Coin Silver	Beryllium-Copper	Slightly Increasing
Ti-6Al-4V Titanium	E52100 Steel	Moderately Increasing
Coin Silver	René 41	Moderately Increasing
Copper	Beryllium-Copper	Erratic
2014-T6 Aluminum	René 41	Slightly Increasing
Coin Silver	Coin Silver	Moderately Increasing
2014-T6 Aluminum	2014-T6 Aluminum	Rapidly Increasing
Copper	Ti-6Al-4V Titanium	Slightly Increasing
Copper	321 Stainless Steel	Rapidly Increasing
Coin Silver	Copper	Rapidly Increasing
René 41	E52100 Steel	See Note 1
Copper	2014-T6 Aluminum	See Note 2
René 41	321 Stainless Steel	Rapidly Increasing
René 41	René 41	Rapidly Increasing
Copper	René 41	Rapidly Increasing
Coin Silver	2014-T6 Aluminum	Erratic
E52100 Steel	321 Stainless Steel	See Note 3
Copper	Cobalt	0.5 Hr. to Limit
321 Stainless Steel	321 Stainless Steel	0.3 Hr. to Limit
Copper	Copper	0.12 Hr. to Limit
E52100 Steel	E52100 Steel	0.01 Hr. to Limit

Note 1 - Maximum at 2.4 at beginning and nearly the same for 4.3 hours until a sudden rise to 4.9.

Note 2 - Maximum at 2.2 at beginning, dropped to 0.2 to 1.5 within 1 hour, at 1.4 hours apparently debris caught pellet and stopped rotation, restarted and run for another half hour at 0.2 to 1.5 before next stoppage.

Note 3 - High friction at beginning, dropped in 3 hours to 0.2 to 0.5 and stable for next 30 hours, maximum increased to 4.9 in next 14 hours.

Data from single run with each metal combination.

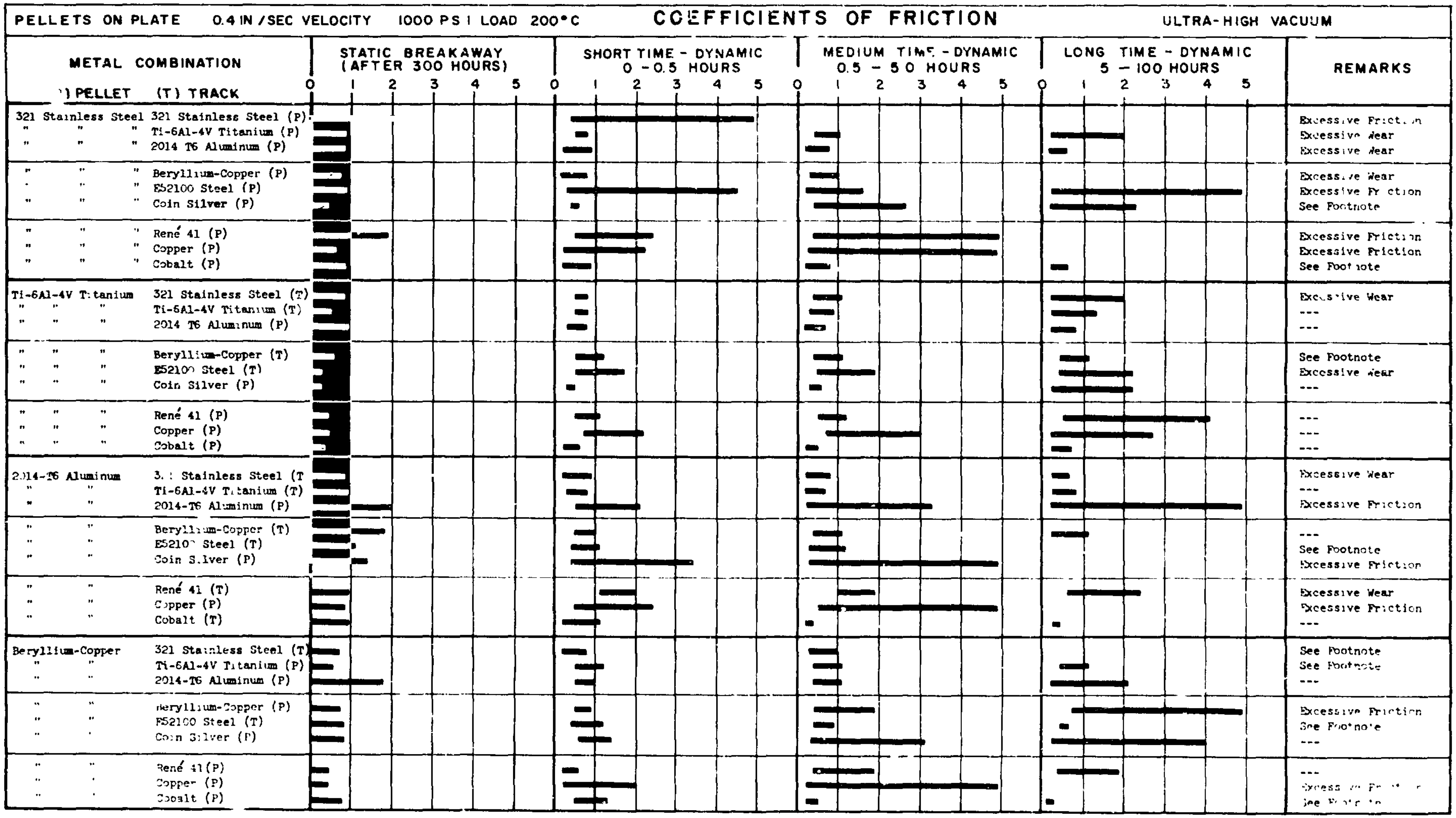
Fig. 2 - Ranking of Metal Combinations Based on Short-Time (0 to 0.5 hr.) Dynamic Coefficients of Friction

The static breakaway coefficient is also shown with the short-time dynamic test data in Fig. 2 so that the general correlation (and the few exceptions) between the two sets of data can be seen. Generally the static coefficients are less than the dynamic coefficients of the metal combinations.

In the Remarks column of Fig. 2, the notation, "stabilized," indicates that the coefficient of friction has stabilized during the first 0.5 hr. of dynamic testing. Throughout the remaining time, generally 100 hr., the coefficient did not change. The notation, "increasing," indicates that the coefficient was continuing the increase at the end of the 0 to 0.5 hr. period to a maximum value which occurred at some later time. Unusual frictional behavior is called out in a note at the bottom of the chart.

2. Tabulation of coefficients of friction: The static and dynamic coefficients of friction are presented in a more convenient form for easier access to the design engineer in Fig. 3 than in Figs. 1 and 2. Figure 3 includes the maximum and minimum values of the dynamic coefficients as well as additional data for medium and long time dynamic testing. Thus, the engineer can note the changes in the coefficients as a function of the duration of the test. As can be seen in Fig. 3, the data for all the metals tested against 321 stainless steel are given in bar graph form in one section, those for Ti-6Al-4V titanium in the next section, and so forth. In the second column of the material combination, the metal followed by (P) was the pellet metal of the common metal in the section, the one followed by (T) was the track.

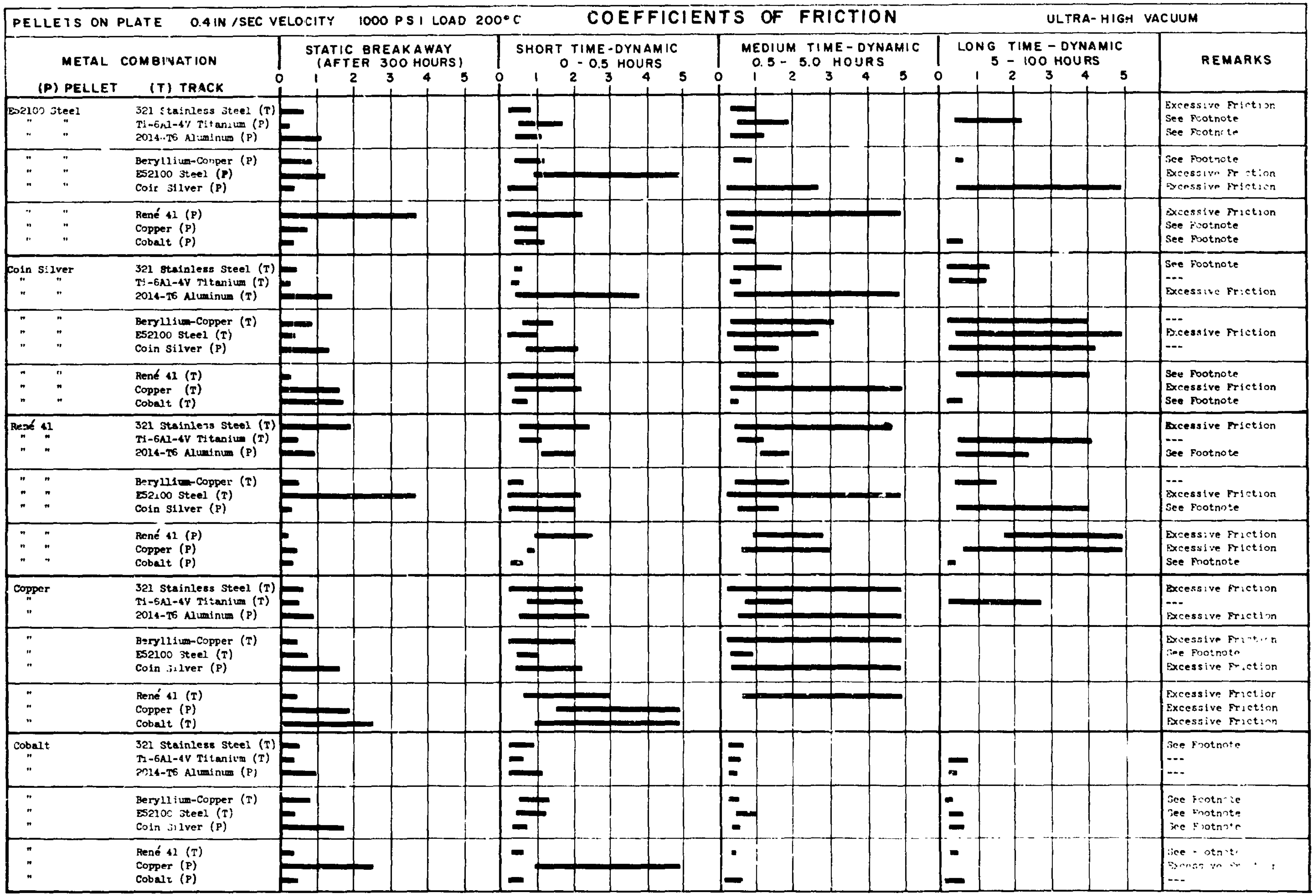
By the use of Fig. 3, the design engineer can readily locate the results of the studies for a particular metal combination which he may be considering in a design problem. The remarks column can give him a guide as to the reason for the termination of a test before the end of 100 hr. "Excessive friction" indicates that the coefficient of friction exceeded 4.9 and the apparatus was automatically stopped. "Excessive wear" indicates that the pellets wore away at a much higher rate than expected. When this wear was first encountered, the dynamic torque and the sound from the stick-slip action for the particular test was at moderate levels. Both abruptly dropped to a lower value and stayed at this lower value so the test was stopped. Upon examining the pellets later outside of the chamber, they were noted to have excessive wear and plastic deformation or smearings. Thus, the abrupt drop in torque was used as a signal to end the test. For a number of tests, this signal gave a false indication of excessive wear and so the "Remarks" column indicates a footnote to describe loss of contact between the test surfaces. Sufficient information had been obtained for these particular tests, so they were not rescheduled.



Note: Test ended when [illegible] and [illegible] significant [illegible]

Data from single run with each [illegible] combination.

Fig. 3 - Tabulation of Coefficients of Friction for all Metal Combinations



Note: Test ended when driving torque and sound decreased significantly, indicating loss of contact between test surfaces.

Data from single run with each metal combination.

Fig. 3 (Concluded)

3. Wear data: The wear data for the studies were collected after the pellets and wear track were removed from the apparatus (see Table III). An examination of all the pellet and wear track sets was made at one time since it allows an evaluation of the surfaces to be as comparative as possible. Measurement of the amount of pellet wear by itself could not be used for providing wear data because the wear tracks for many of the metals were deeply scored while the pellets were not appreciably worn. The degree of wear was judged on the combined effects of both the pellets and the wear track. Three degrees of wear were considered adequate in describing the results; the terms for these are "excessive," "moderate," and "slight." As previously indicated, "excessive" implies that the pellets wore down so that the pellet holder would be rubbing; furthermore, "excessive" is used if the pellets did not wear appreciably but the wear track had a deep or broad groove scored in it. The term "slight" was used during the examination to describe only slightly damaged wear track or worn pellets. The term "moderate" describes conditions between the two extremes.

The specimen hardness has an effect on the amount of wear or scoring, particularly if the wear track is softer than the pellets. The test procedure required a minimum bake-out temperature of the vacuum chamber of approximately 265°C for 4 to 5 hr. This temperature significantly reduced the hardness of silver, copper, and the 2014-T6 aluminum alloy from their original hardness values; i.e., R_B 73 to R_B 62, R_B 40 to R_B 25, and R_B 83 to R_B 47, respectively. The other materials were practically unaffected. Table III shows the relative hardness of the pellets and wear track and the direction the metal was transferred from the pellet to the wear track or vice versa.

4. Friction studies in air: A brief study was conducted to investigate the frictional behavior of selected metal combinations in ambient laboratory air. The parameters of the tests were the same as for the ultra-high vacuum tests; namely, contact pressure 1,000 psi, linear velocity 0.4 in/sec, and specimen temperature 200°C. The specimens were prepared and cleaned as in the other tests. They were not given the bake-out temperature cycle prior to testing but were given an hour of static testing before breakaway and the subsequent dynamic tests. The 2014-T6 aluminum alloy and Ti-6Al-4V alloy were rotated on 321 stainless steel for 5.5 hr., 321 stainless steel and cobalt on 321 stainless steel for 18 hr. The metal combinations and test results are given in Table IV. The surfaces generally showed slight to moderate wear. Comparison of the results of this study to those in ultra-high vacuum is given in Section III-B.

TABLE III

WEAR DATA FROM DYNAMIC FRICTION STUDIES IN ULTRA-HIGH VACUUM

Pellet (P)	Wear Track (T)	Metal Transfer	Pellet Hardness Relative to Wear Track
A. Metal Combinations Showing Slight Wear			
Coin silver	Cobalt	P to T	Softer
" "	René 41	"	"
" "	E52100 steel	"	"
Copper	" "	"	"
2014-T6 Al	René 41	"	"
" "	E52100 steel	"	"
Cobalt	Beryllium-copper	"	"
"	E52100 steel	"	Same
Beryllium-copper	Beryllium-copper	Indeterminate	"
René 41	" "	"	Softer
Cobalt	René 41	"	"
Beryllium-copper	321 stainless steel	P to T	Harder
B. Metal Combinations Showing Moderate Wear			
Coin silver	Ti-6Al-4V	P to T	Softer
" "	Beryllium-copper	"	"
" "	321 stainless steel	"	"
Copper	Cobalt	"	"
"	René 41	"	"
"	Ti-6Al-4V	"	"
2014-T6 Al	Cobalt	"	"
" "	Ti-6Al-4V	"	"
Ti-6Al-4V	Beryllium-copper	"	"
Coin silver	Copper	"	Harder
Beryllium-copper	E52100 steel	"	"
Copper	Beryllium-copper	Indeterminate	Softer
Cobalt	321 stainless steel	"	Harder
"	Cobalt	"	Same
René 41	René 41	"	"
Ti-6Al-4V	Ti-6Al-4V	"	"
E52100 steel	E52100 steel	"	"
René 41	Ti-6Al-4V	T to P	Harder
Cobalt	"	"	Softer

TABLE III (Concluded)

Pellet (P)	Wear Track (T)	Metal Transfer	Pellet Hardness Relative to Wear Track
C. Metal Combinations Showing Excessive Wear			
Copper	321 stainless steel	P to T	Softer
2014-T6 Al	Beryllium-copper	"	"
" "	321 stainless steel	"	"
Copper	2014-T6 Al	T to P	"
Coin silver	" "	"	Harder
René 41	E52100 steel	"	"
Ti-6Al-4V	" "	"	"
"	321 stainless steel	P to T	"
E52100 steel	" " "	"	"
René 41	" " "	Indeterminate	"
Coin silver	Coin silver	T to P	Same
Copper	Copper	Indeterminate	"
2014-T6 Al	2014-T6 Al	"	"
321 stainless steel	321 stainless steel	"	"

5. Typical test data: The results of the cold-welding tests are dependent on the documentation of the test parameters. Important parameters of each test of a metal combination consist of the condition of the pellet and wear track test surfaces, the variation of the coefficients of friction with time, the temperature of the wear track and the vacuum in the chamber. The data for these parameters were recorded as indicated in Testing Procedure, Section IV-D.

TABLE IV

FRICTION STUDIES IN AIR

Metal Combination	Coefficients of Friction: Static Breakaway (after 16 hr.)	Short Time (0 - 0.5 hr.)	Moderate Time (0.5 - 5 hr.)
2014 T6 Aluminum on 321 Stainless Steel	1.1	0.45 - 0.95	0.2 - 0.9
Cobalt on 321 Stainless Steel	0.27	0.37 - 0.70	0.25 - 0.45
Ti-6Al-4V Titanium on 321 Stainless Steel	0.58	0.7 - 1.5	0.5 - 1.1
321 Stainless Steel on 321 Stainless Steel	1.7	0.6 - 1.9	0.6 - 0.9

Typical test data from the investigations are given to provide background information for the user of the results. Typical photographs of the specimen surfaces before and after the tests are shown in Figs. 4 through 9. Figures 4, 5 and 6 are for metal combinations with moderate friction; the last three are for excessive friction. The top photograph in all the figures is the fringe pattern between the polished surface of the wear track and the bottom surface of a coated optical flat with a ± 0.000001 in. accuracy in flatness. The illumination was provided by a high-intensity sodium vapor lamp; thus, one fringe spacing is equivalent to approximately 12 μin. The parallel fringe pattern in the top photograph of Fig. 4 has 16 fringes which indicates that a foreign particle, approximately 0.0002 in. thick, was between the two surfaces at one edge to form a wedge-shaped space between them. The top group of three photographs is the fringe pattern of the ends of the three pellets mounted in the pellet holder as they support the optical flat. Thus, the three surfaces deviate from a common plane no more than 2-1/2 to 3 fringes or 30 to 36 μin . The middle group of photographs are the test surfaces of the pellets and wear track (at the same magnification) without the optical flat. The bottom group of photographs are the test surfaces after the dynamic tests. These show the type of scoring which took place between the surfaces of the wear track and the pellets. The close-up photographs were made with a camera attached to one side of a 40-power binocular microscope while the sodium lamp was placed over the other side.

Fig. 4 - Photographs of Test Surfaces of E52100 Wear Track and Beryllium-Copper Pellets: Top set shows surface flatness with an optical flat; middle set surfaces without optical flat; and bottom set - surfaces after dynamic tests (pellet diameter 0.06.5 in.)

Fig. 5 - Photographs of Test Surfaces of Beryllium-Copper Wear Track and Titanium Pellets: Top set shows surface flatness with an optical flat; middle set - surfaces without optical flat; and bottom set - surfaces after dynamic tests (pellet diameter 0.0625 in.)

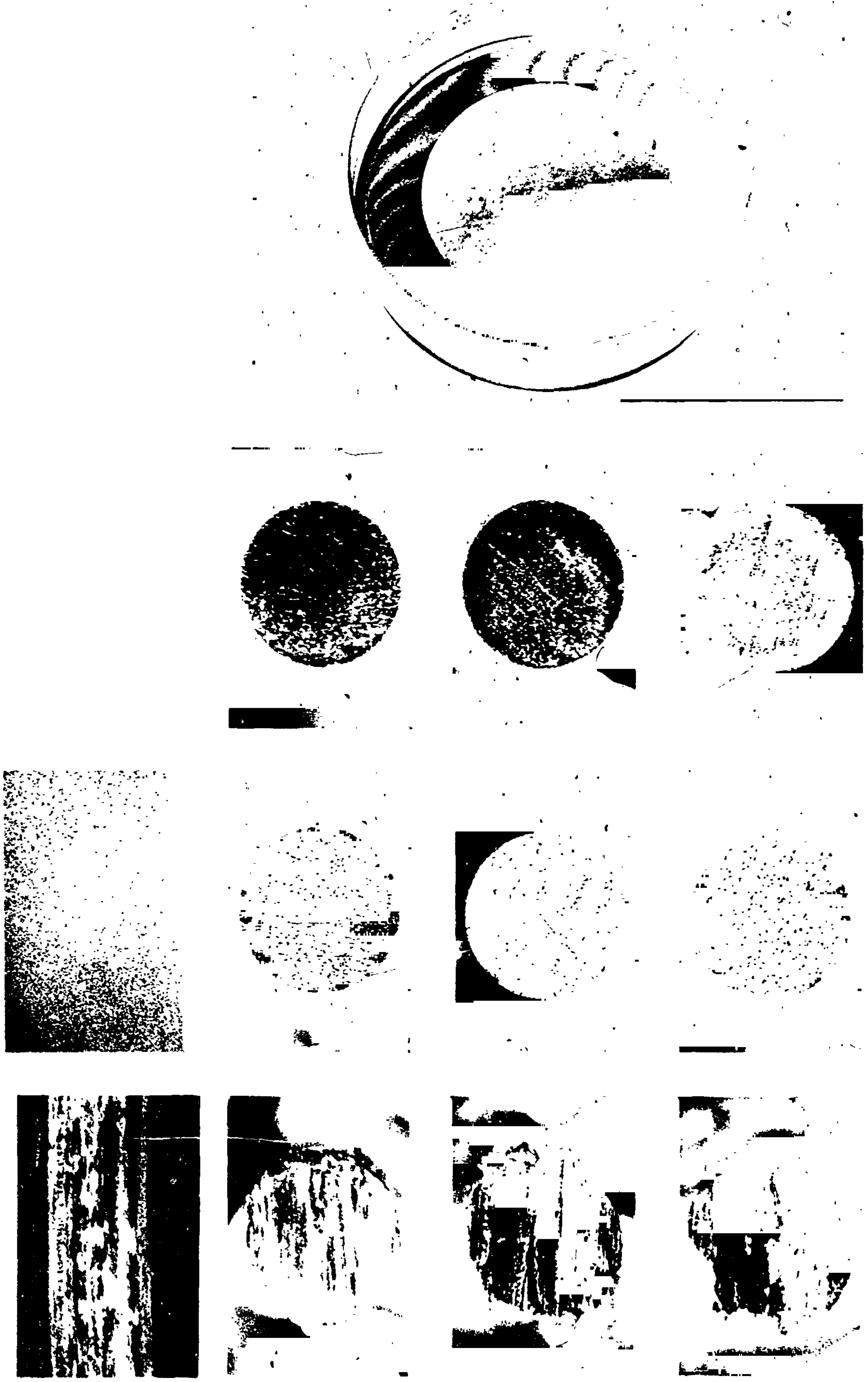


Fig. 6 - Photographs of Test Surfaces of SS321 Wear Track and Silver Pellets: Top set shows surface flatness with an optical flat; middle set - surfaces without optical flat; and bottom set - surfaces after dynamic tests (pellet diameter 0.0625 in.)

Fig. 7 - Photographs of Test Surfaces of E52100 Wear Track and René 41 Pellets: Top set shows surface flatness with an optical flat; middle set - surfaces without optical flat; and bottom set - surfaces after dynamic tests (pellet diameter 0.0625 in.)

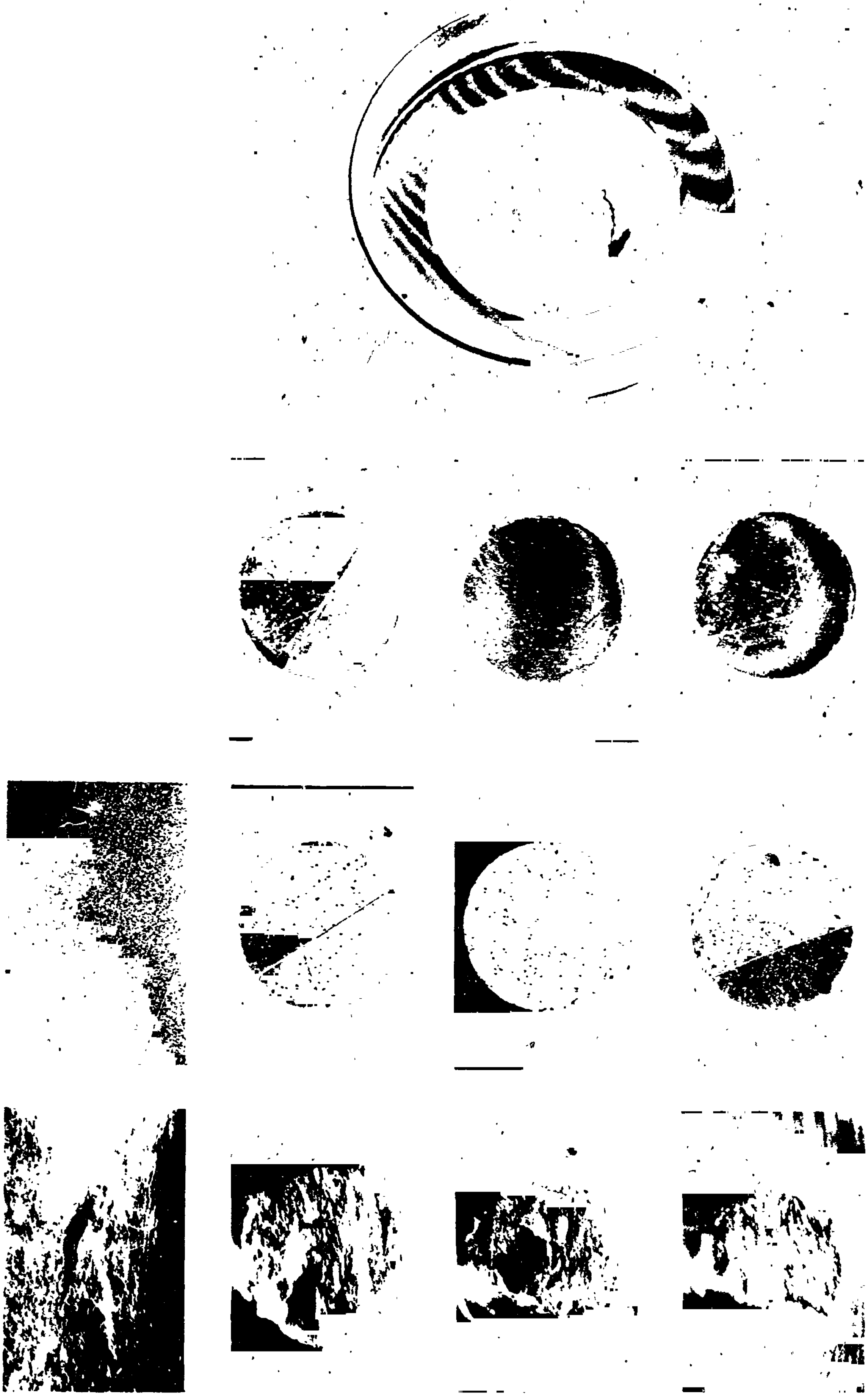


Fig. 8 - Photographs of Test Surfaces of Beryllium-Copper Wear Track and Copper Pellets: Top set shows surface flatness with an optical flat; middle set - surfaces without optical flat; and bottom set - surfaces after dynamic tests (pellet diameter 0.0625 in.)

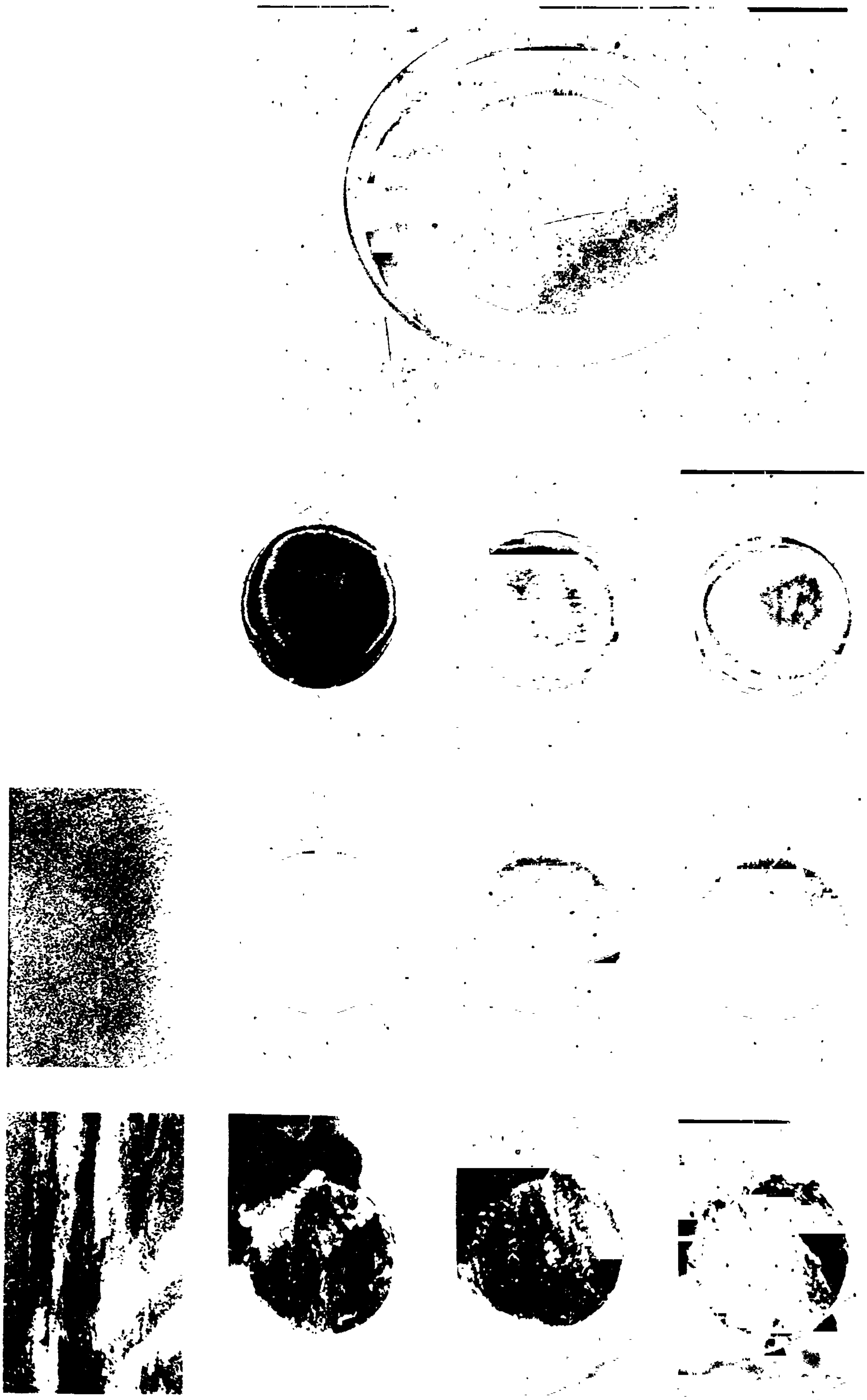


Fig. 9 - Photographs of Test Surfaces of Beryllium-Copper Wear Track and Beryllium-Copper Pellets: Top set shows surface flatness with an optical flat; middle set - surfaces without optical flat; and bottom set - surfaces after dynamic tests (pellet diameter 0.0625 in.)

The photographs of Fig. 4 show the results of rubbing beryllium-copper pellets on an E52100 steel wear track. The pellets were R_C 38-43 while the track was R_B 90-97. Examination of the entire wear track showed moderate wear with some transfer of the pellets to the wear track. The dynamic coefficient of friction had a maximum value of 1.2 but stabilized later within the range of 0.4 to 0.6.

Visual results of rubbing Ti-6Al-4V titanium pellets on a beryllium-copper wear track are shown in Fig. 5. The pellets were R_C 34 while the track was R_C 43. Moderate wear occurred with some pellet metal being transferred to the track; the coefficient of dynamic friction had a maximum value of 1.2 but stabilized later within the 0.4 to 1.1 range.

The results of rubbing silver pellets on 321 stainless steel can be seen in Fig. 6. Difficulty in polishing the surfaces to obtain a minimum amount of pits was encountered as indicated in the photograph of the pellets. The pellets were R_B 62, the track R_B 83. Moderate wear occurred with the transfer of the silver to the wear track; the coefficient reached a maximum of 1.7 but stabilized within the range of 0.2 to 1.3.

The wear of René 41 pellets (R_C 39) on E52100 steel (R_B 83) is indicated in Fig. 7. This combination had excessive wear with metal transfer from the wear track to the pellet surfaces. The coefficient increased steadily to 4.9 in 1.4 hr.

Figure 8 indicates the wear of copper pellets on beryllium-copper; hardness values are R_B 25 and R_C 43, respectively. The pellets appear as if they might have been welded to the wear track, but they were not bonded to it when the set was removed from the apparatus. The coefficient increased steadily to the 4.9 limit in 1.2 hr. of rotation.

Views are shown in Fig. 9 of beryllium-copper pellets after rubbing on the beryllium-copper wear track. This metal has a hardness of R_C 38. The combination had a slight amount of wear while it continually increased in friction; the 4.9 limit was reached in 28 hr.

Typical dynamic coefficients of friction (driving torque) records are shown in Figs. 10, 11 and 12. These records give the behavior of the friction for three types of friction observed in the program.

DYNAMIC COEFFICIENTS OF FRICTION
BERYLLIUM-COPPER ON BERYLLIUM-COPPER

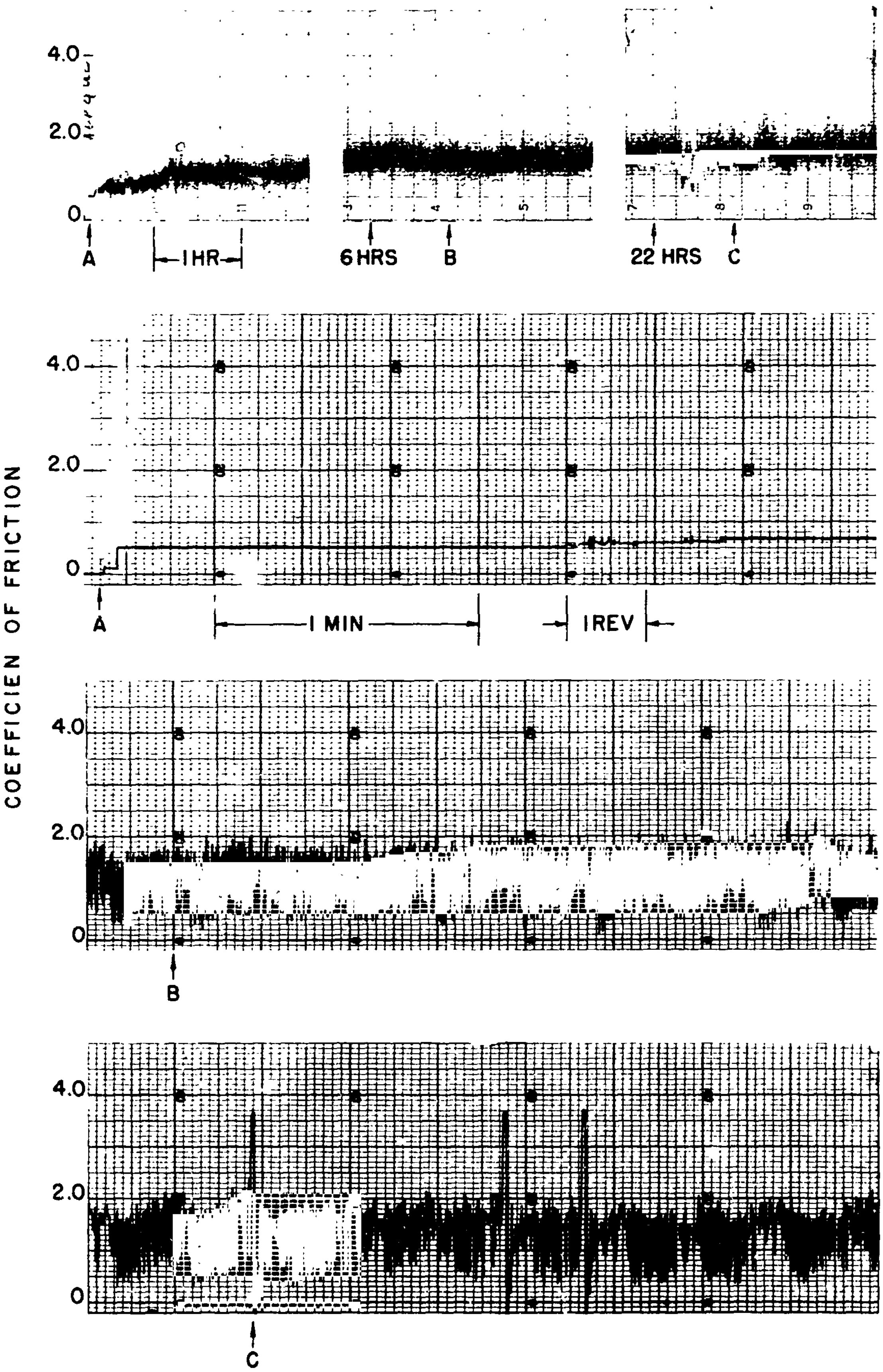


Fig. 10 - Dynamic Coefficients of Friction of Beryllium-Copper on Itself Showing Sliding Coefficients at A and Stick-Slip Coefficients at B and C With Two Types of Recordingss

DYNAMIC COEFFICIENTS OF FRICTION
RENE'41 ON RENE'41

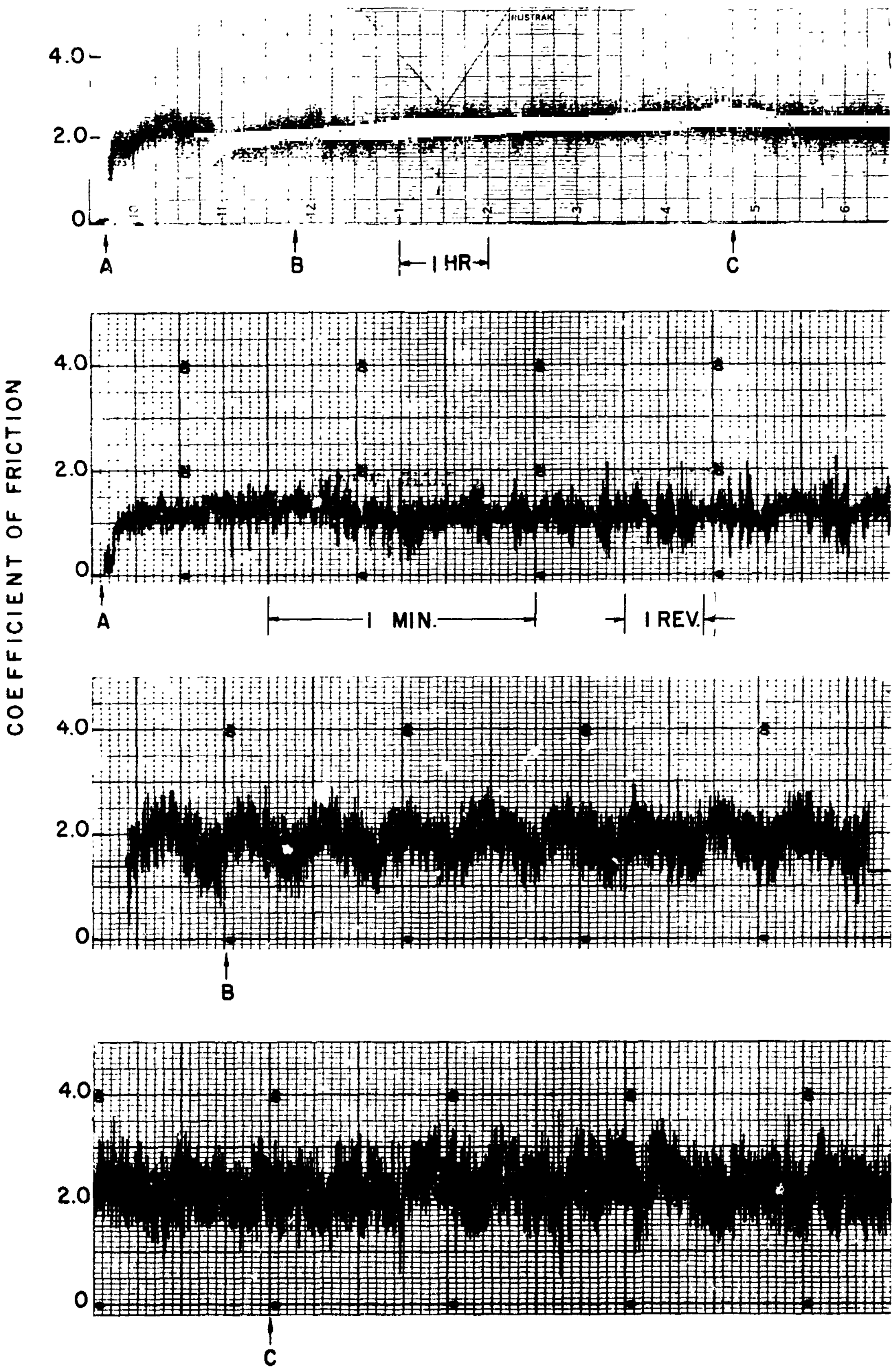


Fig. 11 - Dynamic Coefficients of Friction René 41 Rubbing on Itself Showing Stick-Slip Action Throughout the Test

The first type of dynamic friction was the sliding friction with nearly a constant coefficient which existed for varying lengths of time depending on the metal combination. Soon the sliding action changed to a mixture of partial sliding and stick-slipping. Finally the action was all stick-slip with large excursions between the minimum and maximum values; the maximum values eventually exceeded 4.9 which turned off the apparatus. The second type of dynamic friction observed in the tests was a stick-slip action with wide excursions from the beginning of rotation. Generally within a few hours, the friction became excessive and stopped the test. The third type had a moderately high coefficient at the beginning of the test but generally stabilized after a half-hour or so at low and relatively constant values.

Two recorders were simultaneously used. One recorded the general trend over a long time since it had a chart speed of 1 in/hr; the other produced records of the continuous friction values during 3-min. intervals about every 1/2 hr. of the test as a chart speed of 3 in/min was used.

In Fig. 10, the records of the dynamic coefficients of friction are shown for beryllium-copper rubbing on itself. (The recorded electrical signal is from the torque measuring sensor, but it is directly converted in terms of the coefficient of friction.) For about the first 4 min., the sliding action occurred with a coefficient of 0.5 to 0.6; slight stick-slipping action began and then gradually increased until the coefficients were varying from 0.4 to 1.9 at the end of 5 hr. and up to 4.9 at the end of 28 hr.

In Fig. 11 the records are given of the second type of friction in which René 41 was rubbing on itself. This combination had the stick-slip action from the beginning of rotation and increased until it had excessive friction (in 15 hr.).

In Fig. 12, the records are for cobalt rubbing on beryllium-copper; the behavior of this combination is an excellent example of the third type of friction. Initially, the coefficient had a maximum value of 1.3 but within 1/2 hr. it became stabilized within a range of 0.2 to 0.5 and remained approximately within this range the remainder of the test.

III. DISCUSSION OF RESULTS

The parameters investigated during the program represent conditions for applications in space environments which have metal-to-metal contacts with moderately high contact forces for a long period of time under static conditions and then followed by dynamic conditions. The data obtained in the program

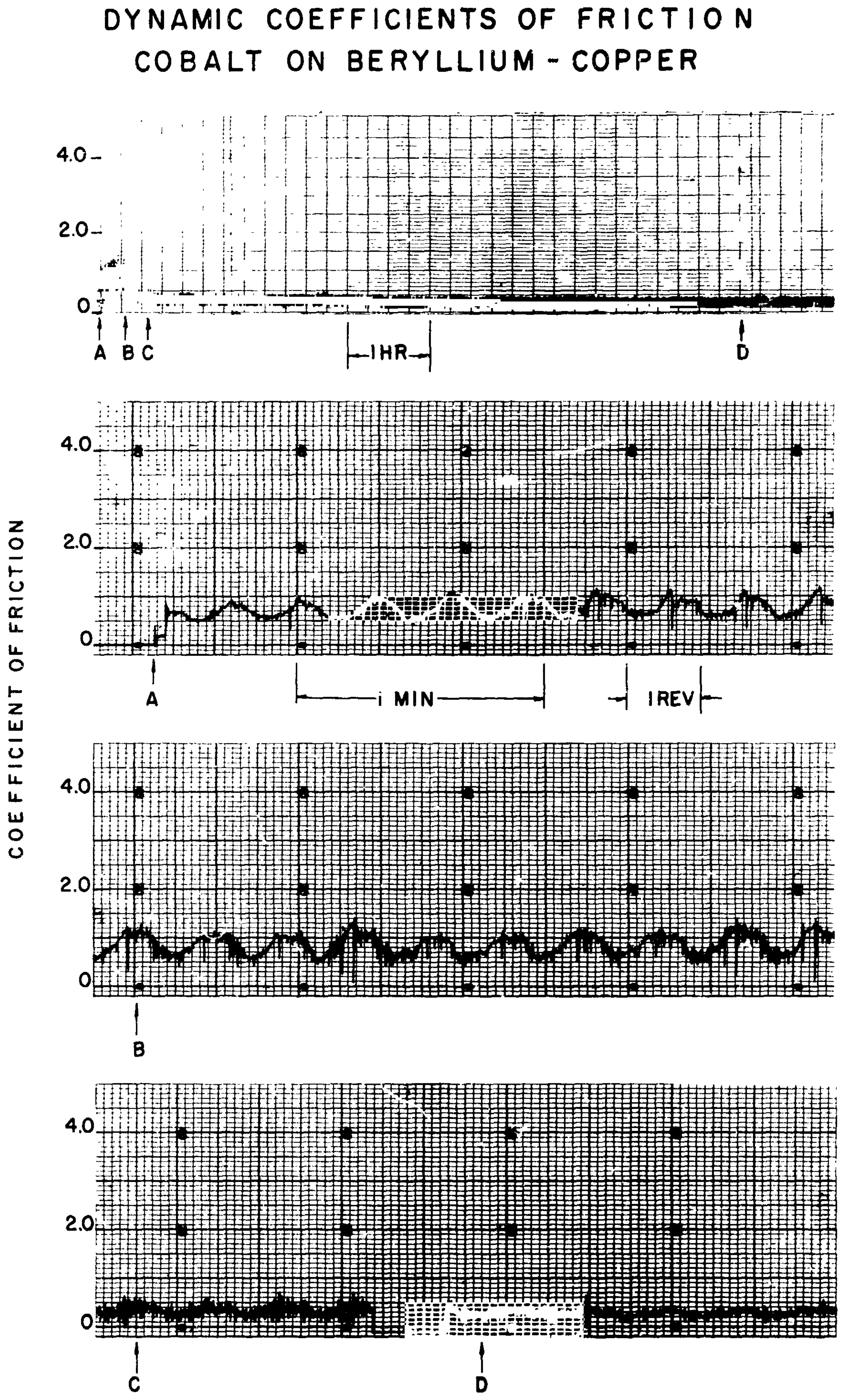


Fig. 12 - Dynamic Coefficients of Friction of Cobalt Rubbing on Beryllium-Copper

can be of value in such applications as well as in dynamic systems of low relative velocities as a guide in the selection of materials. However, the data should not be used as the basis of the final material selection because the data are from a single test. The reliability of the data is more certain if it is confirmed by duplicate tests or substantiated by other investigators. One task of the program was to survey the literature to determine if other investigators had studied the same material combinations in a manner which can be correlated with the MRI data. The results of the survey are presented below.

A. Correlation of Published Data and MRI Data

A comprehensive survey was made of the various research programs which have been or are currently studying cold molecular welding in ultra-high vacuum. Detailed results of the survey are given in the Appendix. The survey disclosed that only three groups of investigators have studied any of the metal combinations of the MRI program in vacuum with relative motion between the contacting surfaces so that coefficients of friction could be the defining term of cold welding. Hansen, Jones and Stephenson1/ investigated a number of metal combinations at room temperatures in a reciprocating motion with specimens machine-finished to 8 to 16 μin. rms finish. Their chamber pressure was in the 10^{-6} torr range and their load was approximately 3 or 6 psi. The highest coefficient of friction was 2.00 for a copper-copper combination at the end of 1 hr. of rubbing. Since the work was done in an environment of at least three orders of magnitude higher pressure than the MRI work and at a contact pressure of at least two orders less, correlation of results was not practical. However, copper was the only material in our tests which were stuck together at the end of the test.

The dynamic coefficient of friction of E52100 steel on itself and René 41 on itself were measured by Buckley, Swikert and Johnson2/ with a 3/16 in. spherical radius rider rubbing on a 2-1/2 in. dia. disk specimen at a surface speed of 390 ft/min (78 in/sec). A 1,000-gm. weight loaded the rider against the disk. Interpretations based on wear track widths of 0.030 to 0.075 in. as seen from their disk specimens, their final contact pressures at the end of 1 hr. were calculated to be within the range of 500 to 3,100 psi. The initial contact pressures were considerably higher as they began the tests with the 3/16 in. spherical radius. Specimen temperatures were not measured; the tests originally started at room temperatures. Their experiments were conducted at various pressures down to 2×10^{-7} torr which was created by liquid helium cryopumping. Oxygen was condensed on the cryopanels so no oxides would be formed on the E52100 steel test surfaces. Based on the probable amount of oxygen in their environment, their oxide producing atmosphere was possibly somewhat equivalent to our environment of 10^{-9} to 10^{-10} torr. They found a low initial coefficient (0.2) but it gradually increased to approximately 0.7 in 28 or 29 min. Apparently considerable scoring and galling then took place at that time as the coefficient jumped to between 4 and 5, and they called it mass welding of the specimens. Our data for this metal consisted of a static breakaway value of 1.2 and the friction becoming greater than 4.9 in approximately two revolutions (less than 1/2 min.). Buckley's data suggest that they had not broken through the oxide layer on the steel surfaces until about the 30th minute; whereupon the surfaces had atomic contact with the same results as we obtained.

Buckley, Swikert and Johnson also investigated a Ni-Cr alloy which had nearly the same composition and hardness as our René 41 material. At pressures in the 5 x 10^{-7} to 2 x 10^{-6} torr and under the same dynamic conditions as for the E52100 steel, their coefficient of friction was approximately 0.36 for the 1 hr. of rubbing. Our René 41-René 41 specimens had a friction range of 0.9 to 1.8 initially and increased to the range of 1.6 to 2.5 by the end of 0.5 hr. Then the friction stabilized within the range of 1.2 to 3.1 until it increased to 4.9 at the end of 15 hr. Apparently, the much higher coefficient of friction of our materials is because of the absence of an oxide layer; microscopic cold welding occurred at the interface and was either broken or sheared, causing the high values of friction.

Later, Buckley and Johnson[3/] conducted tests with a commercial nickel-chromium-aluminum alloy with their apparatus in ultra-high vacuum (10^{-9} torr). Their alloy was again very similar to René 41 with the exception of Fe, 5.0 per cent for their alloy, 1.35 per cent for our René 41. Their average coefficient is given as approximately 0.88, still considerably lower than our data.

In a study of cobalt rubbing on cobalt, Buckley and Johnson[4/] reported coefficients of friction of 0.45 and 0.55 in 10^{-9} torr vacuum when rider temperatures were about 200°C with a 1,000-gm. load. The coefficients were lower, about 0.3 for a second set of data, when the only apparent difference in their parameters was higher pressure (10^{-8} to 10^{-7} torr). The MRI data for cobalt on cobalt show a static breakaway coefficient of 0.47 and dynamic coefficients from 0.4 to 0.6 during the first 0.5 hr. Throughout the remainder of the 100 hr. of rubbing, the coefficient varied within 0.1 to 0.6. Thus, our data agree with those by Buckley and Johnson. During their investigations, they worked with copper on itself at 10^{-9} torr with a sliding velocity of 4.5 fpm or 0.9 in/sec. Our velocity was 0.4 in/sec. They had complete welding, presumably a coefficient of friction greater than 5.0, with a 1,000-gm. load; with a 500-gm. load, their average coefficient was 2.32 for 1 hr. of rubbing. The MRI data for copper on copper gave a static coefficient of 1.9 and during initial rubbing a coefficient of 1.5; within 7 min , the friction increased to greater than 4.9 and welding occurred. As in the case with cobalt-cobalt, our data are in general agreement with Buckley's and Johnson's data.

The only other data found in the literature with which our data can be compared is that of Kellogg.[5/]

In his work, Ti-6Al-4V was rubbed back and forth on itself at room temperature in a vacuum of 10^{-8} to 10^{-9} torr. The follower was moved in a 1/4-in. stroke with a constant velocity of approximately 5 in/min (0.08 in/sec) and a dwell time of about two to three times the moving time. An apparent contact pressure of 40 psi was used. The coefficient of friction measured was the static breakaway following each dwell cycle. Since the friction behavior of our specimens was usually a stick-slip action, our dynamic tests could be thought of as a series of rapidly repeating static tests. If this concept is acceptable, our maximum dynamic coefficients could be compared to Kellogg's data. His initial breakaway coefficient was 0.4 and continually increased to greater than 1.0 in seven cycles. Our static breakaway was 0.47 and the maximum values varied up to 0.8 within the first 0.5 hr. of rotation. During the remainder of the 100 hr. of rotation, the maximum increased gradually to 1.3. Although Kellogg's contact pressure was 1/25 of our contact pressure, the two sets of data have reasonable agreement.

As a result of these comparisons of an extremely limited number of like metal combinations, there is some substantiation of the MRI data.

B. Observations on MRI Data

The MRI data were studied from a number of aspects to determine if any trend could be found to permit prediction of the likelihood of cold welding of other metal combinations. Sikorski[6/] lists 10 properties of metals which influence their adhesion (and friction as well). These are (1) surface contamination, (2) crystal structure, (3) work hardening coefficient, (4) purity, (5) hardness, (6) elastic modulus, (7) melting point, (8) recrystallization temperature, (9) atomic radius, and (10) surface energy. Because of the overlapping effects of these properties, no correlation of our data has been possible with any one property with the one exception of cobalt; it has a hexagonal close-packed structure and has low friction which was reported by Ernst and Merchant in 1940.[7/] The low coefficients of friction for hexagonal close-packed materials, including cobalt, were confirmed in ultra-high vacuum by the recent work of Buckley and Johnson[4/] which has already been discussed. Thus, no guide has been set up to permit the prediction of the magnitude of cold welding of the metals of the MRI tests with other metals.

Some general trends have been found, however. The metal combinations tend to have lower static coefficients than the maximum dynamic coefficients in the short-time dynamic tests (as seen in Fig. 2). A strong correlation is also noted in Fig. 2 that for metal combinations with coefficients of 1.3 or less for the short-time dynamic tests, the coefficients become stablized within 0.5 hr. at lower values. For coefficients above 1.3 the friction does not stabilize but continues to increase, and eventually exceeds 4.9 in many combinations.

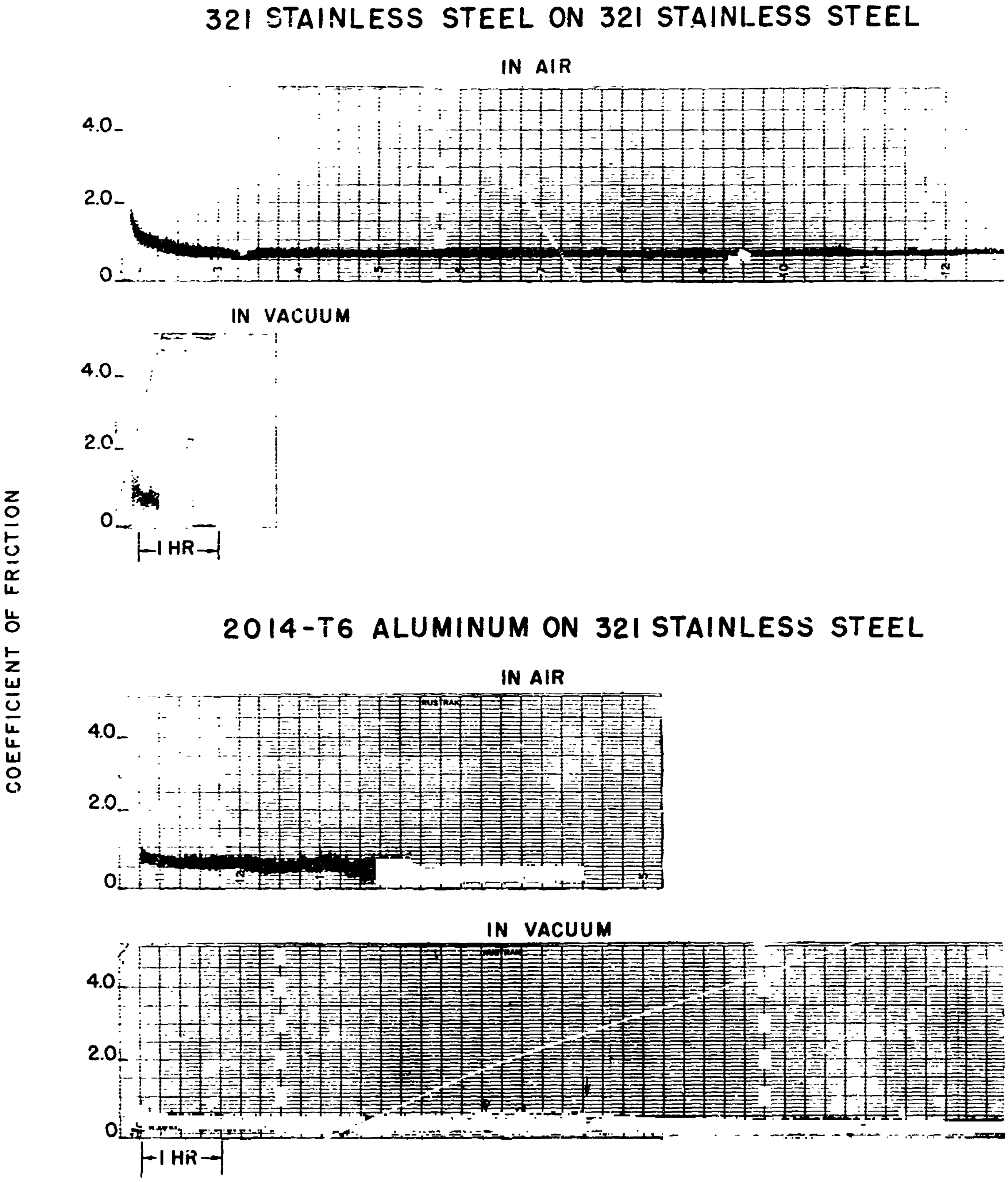
The four tests in air provide data to make a comparison of operation in air versus ultra-high vacuum. The coefficient of friction records for the metal combinations are given in Fig. 13 for both air and vacuum. These records show that Al-321 SS, Co-321 SS, and Ti-321 SS combinations have somewhat similar records and they all had moderate initial dynamic coefficients and then stabilized at lower values. The 321 SS - 321 SS combination had this same stabilizing behavior in air but not in vacuum where it developed excessive friction in 0.3 hr. The static breakaway coefficients were more than 50 per cent higher in vacuum than in air for all except Al-321 SS which had the opposite behavior. The cleansing action of ultra-high vacuum is probably the reason for the higher static breakaway coefficients except for the aluminum (2014-T6) surfaces where the durable oxide layer was a factor.

The comparison of the Al-321 SS combination in UHV to air tests is limited because the aluminum pellets in UHV had been heated (before testing) to 265°C for baking out of the chamber. They were softened to R_B 47 from this exposure; their shear strength was greatly reduced with a result of greater wear during the tests. However, even with the softer pellets, the wear of the aluminum was slight to moderate against cobalt, René 41, Ti-6Al-4V, and E52100 steel wear tracks. The air tests were conducted with the pellets being heated only to 200°C. They were slightly softened, from the original R_B 83 to within the range of R_B 75 to 80. Their wear was considerably less than for the UHV tests, test duration in air was 5.5 hr., in UHV 5.4 hr.

In relation to wear of the surfaces during the ultra-high vacuum, an obvious correlation (Table III) is that when the pellets are softer than the wear track, metal is transferred from the pellets to the track, particularly for metal combinations which show slight and moderate wear. For metal combinations showing excessive wear, this correlation was not found.

One of the controlled parameters of the tests was the surface conditions of the pellets and the wear track. The pellet surfaces were lapped and polished to provide a flatness to within three sodium light fringes (approximately 36 µin.) and to have a maximum of 10 per cent pit area. The ends of the pellets generally had a slight radius of curvature; the minimum radius was approximately 26 in. when three fringes occurred on the end of the pellets. The wear tracks were polished so that no more than three fringes occurred in any one radius.

The maximum Hertzian contact stress was calculated for a spherical rider on a flat plate and was 5,900 psi for the steel combination and 26 in. radius; other metal combinations would have different contact stresses because of different Young's modulus and Poisson's ratio. (These stresses can be considered only for the static tests.) Since the pellets generally had a flatness of less than three fringes, their radii of curvature were longer and thus the Herzian stresses would be generally less than the 5,900 psi value. The real stresses were considerably higher than the Hertzian stresses because the Hertzian calculations assume the unrealistic condition of perfectly smooth surfaces. Thus, the contact pressure of 1,000 psi based on projected area was


321 STAINLESS STEEL ON 321 STAINLESS STEEL

IN AIR

IN VACUUM

2014-T6 ALUMINUM ON 321 STAINLESS STEEL

IN AIR

IN VACUUM

Fig. 13 - Comparison of Coefficients of Friction in Air and Vacuum for 321 SS, 2014-T6 Aluminum, Cobalt, and Ti-6Al-4V Pellets on 321 SS

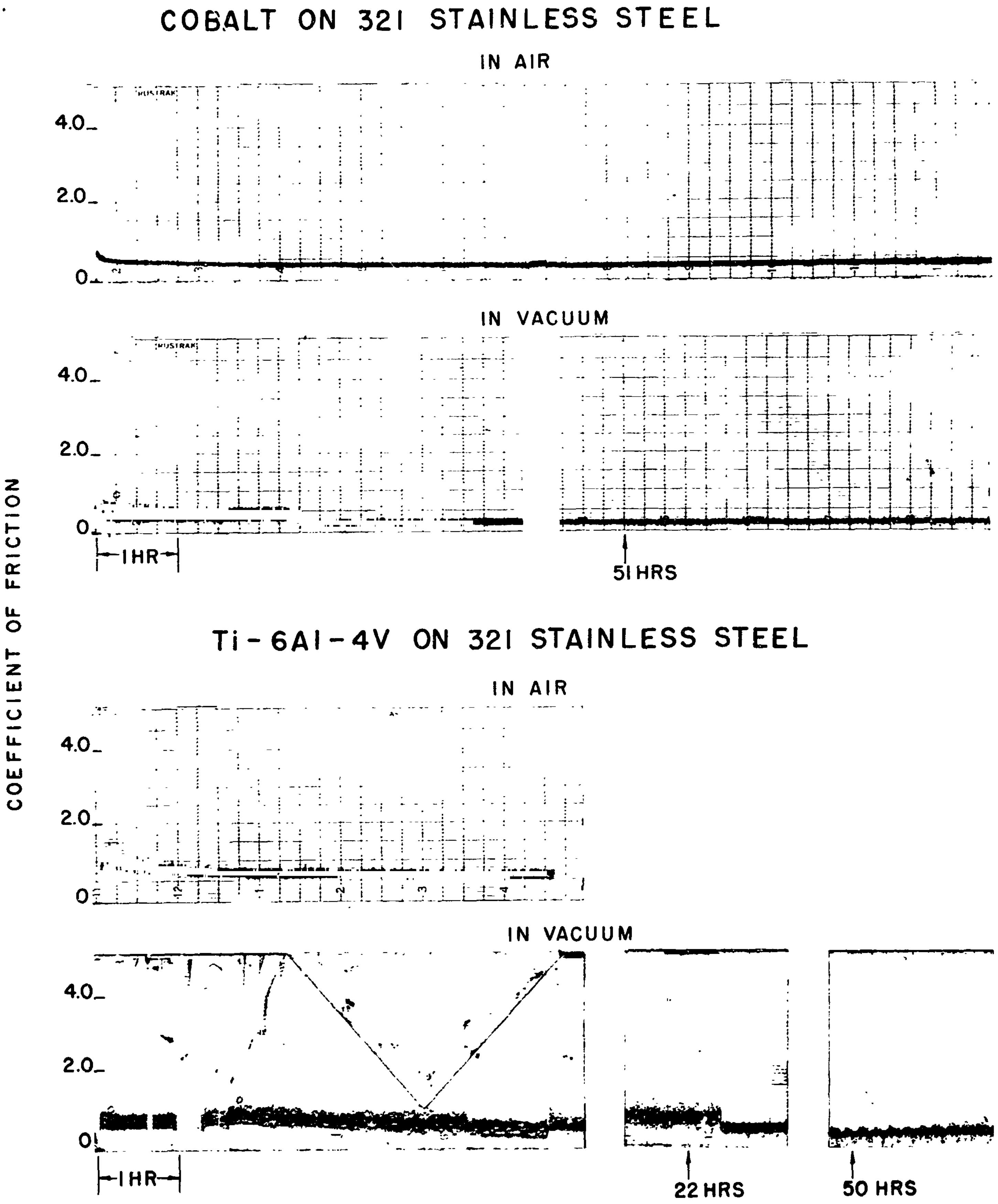


Fig. 13 (Concluded)

only a design parameter; the real contact pressures may have been and probably were in some cases that of the yield stresses of the particular metal combination.

The dynamic tests were conducted at one velocity, 0.4 in/sec. This velocity was so low that frictional heat did not influence the specimen temperatures. Buckley and Johnson[4] showed for cobalt on itself the coefficient of friction was constant until sliding velocity exceeded 250 in/sec and specimen temperatures exceeded 315°C. Subsequent tests showed that the specimen temperature and not the velocity caused a rise of friction.

IV. EXPERIMENTAL PROGRAM

The experimental program consisted of the design, fabrication, and checkout of the equipment, the development of a procedure for preparing the specimens and installing them in the apparatus, and the test program for the 45 metal combinations. The test program and its results have been discussed with the results in Section II, Experimental Results.

A. Equipment

The equipment used in this program consists of the nine ultra-high vacuum test stations and their control console as shown in Fig. 14. The test stations are mounted on insulation-covered tables so that a bake-out oven can be placed over the top of a station onto the table for baking out the station.

1. Test station description: The design of the test station is given in cross section in Fig. 15. The test chamber is basically a stainless steel 4-in. cross with two 4-in. flanges at top and bottom, one 5-in. flange and one 1-1/2-in. flange on opposite sides. Rotating motion is introduced into the top of the test chamber through a magnetic coupling which can transmit a maximum of 52 in-lb of torque.* The rotor is annealed low carbon steel and is supported by two stainless ball bearings, burnished with MoS_2. Torque measurements of the nine magnetic couplings by themselves with the chambers evacuated to 10^{-9} torr were approximately 0.2 in-lb although one had 0.5 in-lb. Since the maximum friction torque was no more than 1 per cent of the maximum torque capability and its effect is overshadowed by variations of specimen surface conditions, no corrections in the data were made. The drive system was a "Slo-Syn" synchronous motor with a planetary gear reduction to provide a 3.3 rpm output with a torque rating of 125 in-lb.

The drive shaft from the rotor of the magnetic coupling rotates the pellet holder through a yoke and pin connection as seen in Fig. 16. The flexible coupling restrains the radial travel of the pellet holder to within

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* The maximum torque is limited by a microswitch, calibrated at 52.0 ±1.5 in-lb.

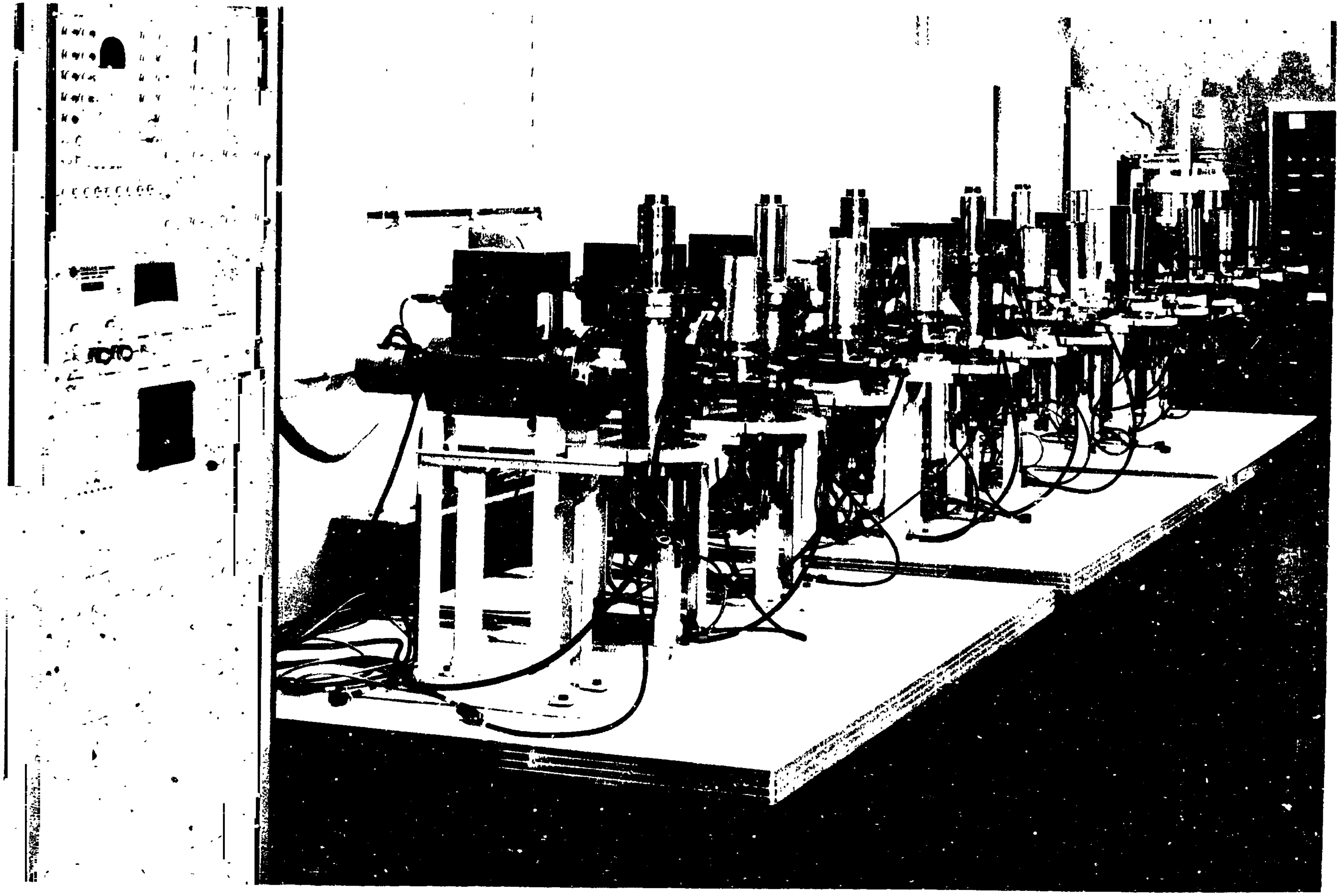

Fig. 14 - Nine Ultra-High Vacuum Test Stations and Control Console

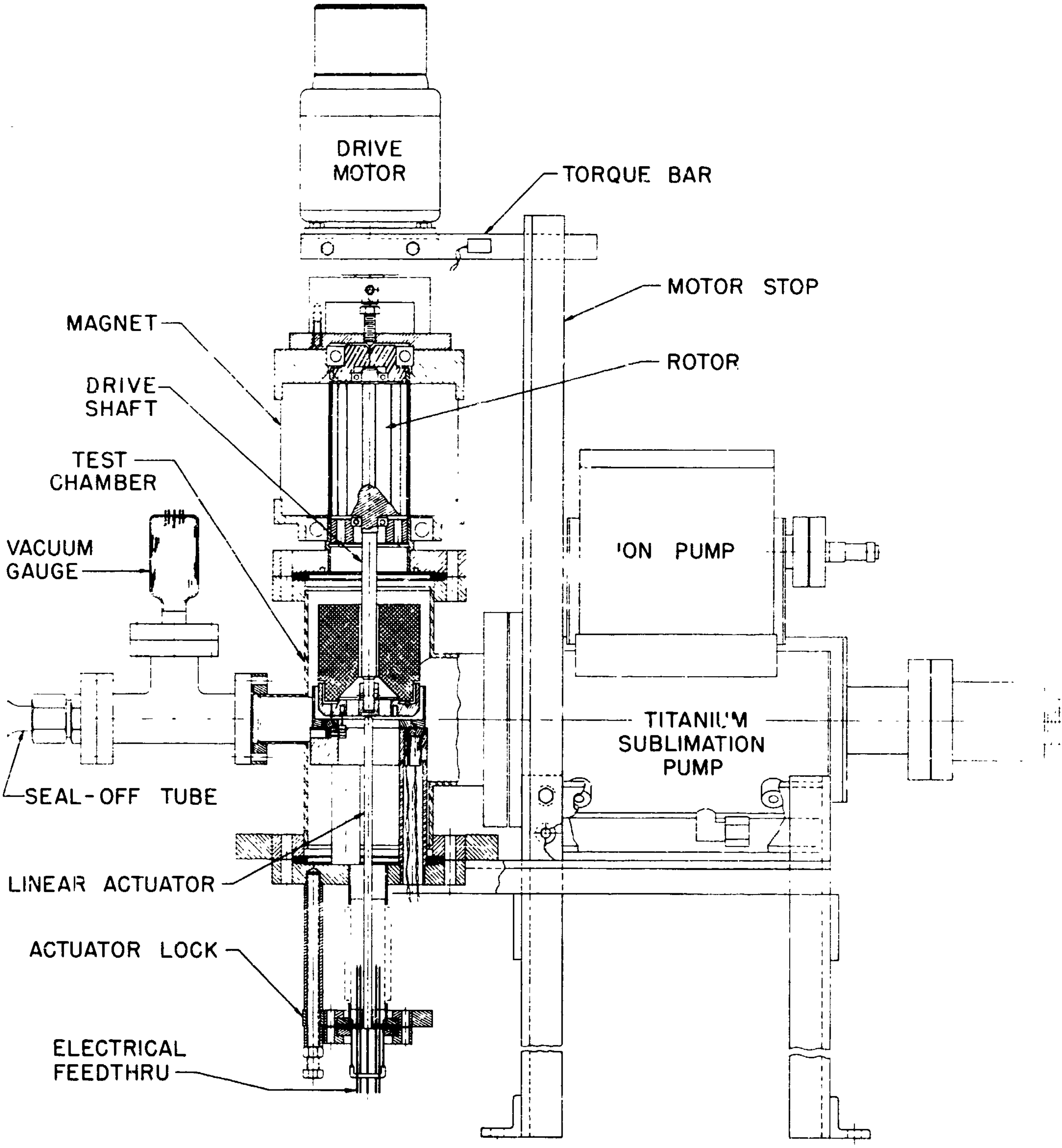

Fig. 15 - Ultra-High Vacuum Test Station

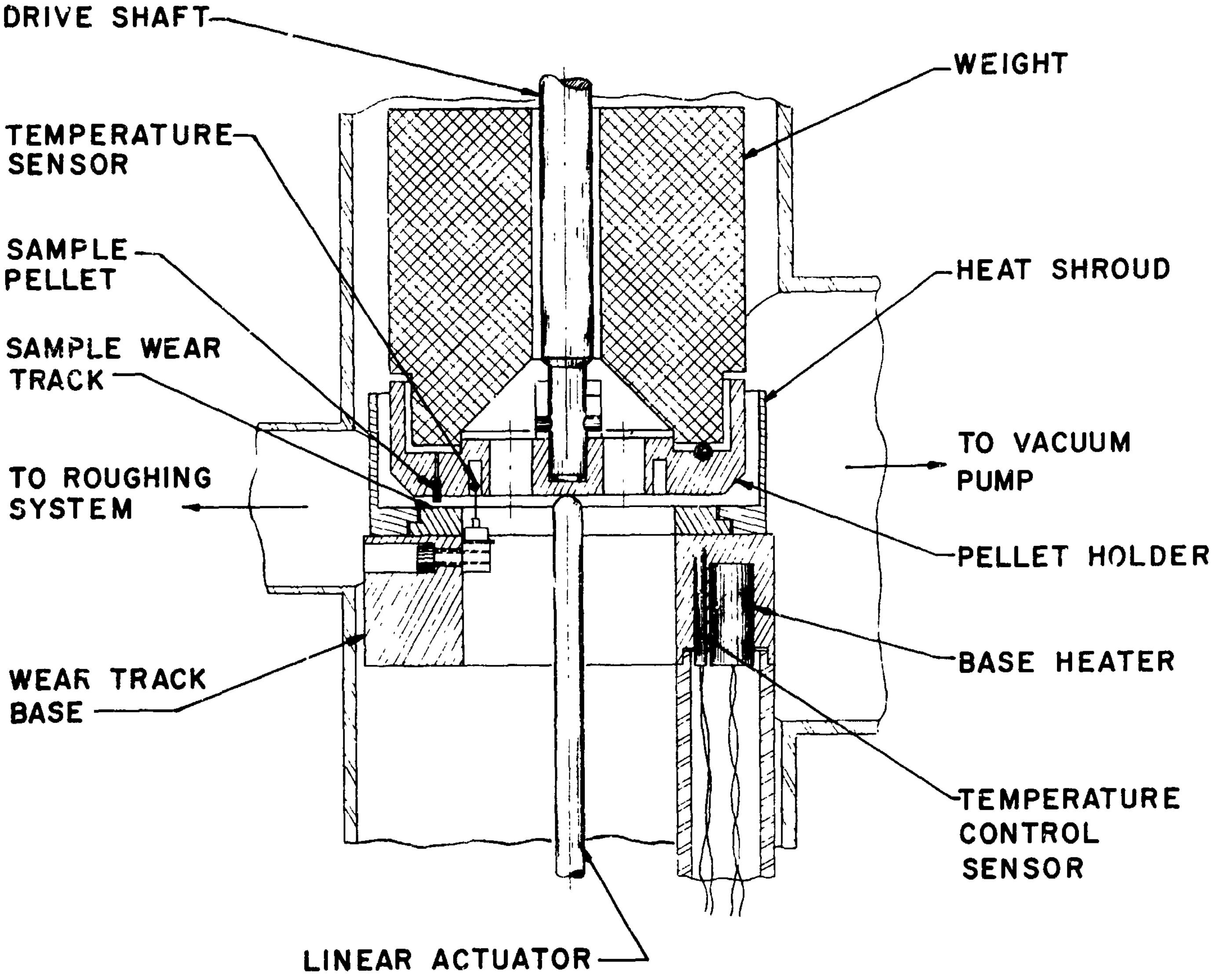

Fig. 16 - Ultra-High Vacuum Test Chamber Detail

±1/16-in. variations but allows the pellets to rotate on the track without restriction even though the holder may deviate several degrees from right angles with the drive shaft. The weight of the rotor and drive shaft has no effect on the specimen load.

The pellets are press-fitted into the pellet holder and are located at a 1.15 in. radius (120 degrees apart) to give a 0.4 in/sec linear velocity. A groove is machined into the underneath side of the pellet holder so that the holder surrounds a temperature sensor on three sides. Steady-state temperatures of the pellet holder can be estimated from the sensor's signals. The sensor is a single-crystal SiC thermistor encapsulated in a 0.050 in. dia. ceramic bead (commercially available from Carborundum Company). The pellet holder has a lip on its perimeter which is heated by radiation from the heat shroud of the wear track clamp. The shroud has a highly polished outer surface to minimize outward radiative heat loss. The pellet holder supports a weight of stainless steel, also with a polished surface to minimize heat losses. The pellet holder and the weight weighs 9.2 lb.; with three 1/16 in. dia pellets, an apparent contact pressure of 1,000 psi is obtained.

The wear track is clamped to a base with a two-piece clamp; the track is heated to the test temperature by three cartridge base heaters, inserted into the wear track base through tubes welded to the base at their top and at their bottom into the bottom 4-in. flange of the test chamber. Ambient pressure exists inside the tubes so that the cartridges operate in air. The wear track base is maintained at the desired temperature with the heaters being controlled by a second thermistor and a solid-state controller to within ±5°C.

The pellet holder and the pellets are held above the wear track during bake-out and until testing pressure and temperatures are attained by the end of the linear actuator rod brought into the vacuum chamber through bellows in the bottom 4-in. flange. The rod is then lowered and locked into a depressed position during the static and dynamic tests by the actuator lock, see Fig. 15. At the base of the linear actuator, an electrical feedthrough is used for connecting to the leads of the pellet holder temperature sensor.

2. Vacuum system: The vacuum system consisted of a combination ion and sublimation pump (Ultek Model 10-402 Boostivac Pump rated at 500 liters/sec at the 5-in. port) attached to the test chamber at the 5-in. flange. The test surfaces are well shielded from evaporated titanium of the sublimation pump. As shown in Figs. 14 and 15, a vacuum gauge (hot-filament ionization gauge, Varian Model UHV-12-KF) is positioned on a tee next to the test assembly. The test station is roughed out by an absorption pump and pumped during bake-out by a boostivac ion and sublimation pump. A 3/4-in. copper tube between the test chamber and roughing system is pinched off to seal the chamber after bake-out.

3. Instrument console: The nine test stations have their controls and measuring instruments in the console at the left of Fig. 14. At the top (not seen) are three high voltage power supplies for the ion pumps. The nine wear-track base-heater controllers and drive-motor controls can be seen at the

top of the photograph (Fig. 14). The next instrument from the top is Varian's Model 971-0003 vacuum gauge controller. The next panel below it contains the specimen temperature meter (for the SiC thermistors) and the vacuum gauge filament sustainers. The master power switch, vacuum gauge selector switch and sublimator pump filament selector switch are located in the next panel. The high-current power supplies with automatic cycling controls for the sublimation pumps are located in the bottom panel, the corner of which is visible in Fig. 14. An automatic emergency 110-v. AC power supply was connected to the system so that power failure would not disrupt the tests, particularly the dynamic tests.

4. Torque measurements: The torque measuring system is shown in Figs. 17 and 18. Initially, the pellets are held stationary to the wear track for the 300-hr. static tests. They are held from movement by the magnetic coupling shown to the left of Fig. 17. A restraining bar is clamped to the motor stop throughout the 300 hr. At the end of this period, a lever is placed on top of the clamped magnet and pulled with a hand-held force gauge (0 to 10-lb. range) after the clamp has been removed. This absolute torque measurement gives the coefficient of friction for static breakaway.

After the static breakaway torque is measured, the magnet with the clamping bar is replaced by the motorized magnet unit shown at the right of Fig. 17. A close-up view of the unit is shown in Fig. 18. The torque sensor consists of an LVDT (linear variable differential transformer) for measuring the displacements of a cantilevered flat spring. The spring is bolted to the base of the motor and restrains the motor at all times. The core for the LVDT is mounted at the end of the spring with a stiff coil spring to eliminate alignment problems. The fulcrum against which the flat spring is clamped is designed to allow angular movement of the spring. The entire system is calibrated with the force gauge and has an accuracy within ±3 per cent and a coefficient of friction sensitivity of ±0.15.

A microswitch is positioned in the system so that the power to the motor is cut when the frictional torque reaches 52 in-lb. If this switch were not used, the magnetic coupling would slip when the friction of the pellets became excessive. The motor is stopped to prevent chatter of the magnetic coupling and any subsequent damage to the test specimens.

B. Specimen Preparation

The specimens were prepared for the study by machining and grinding them to the proper dimensions. The pellets were press-fitted into the pellet holder and washers of the same material were glued down around them.

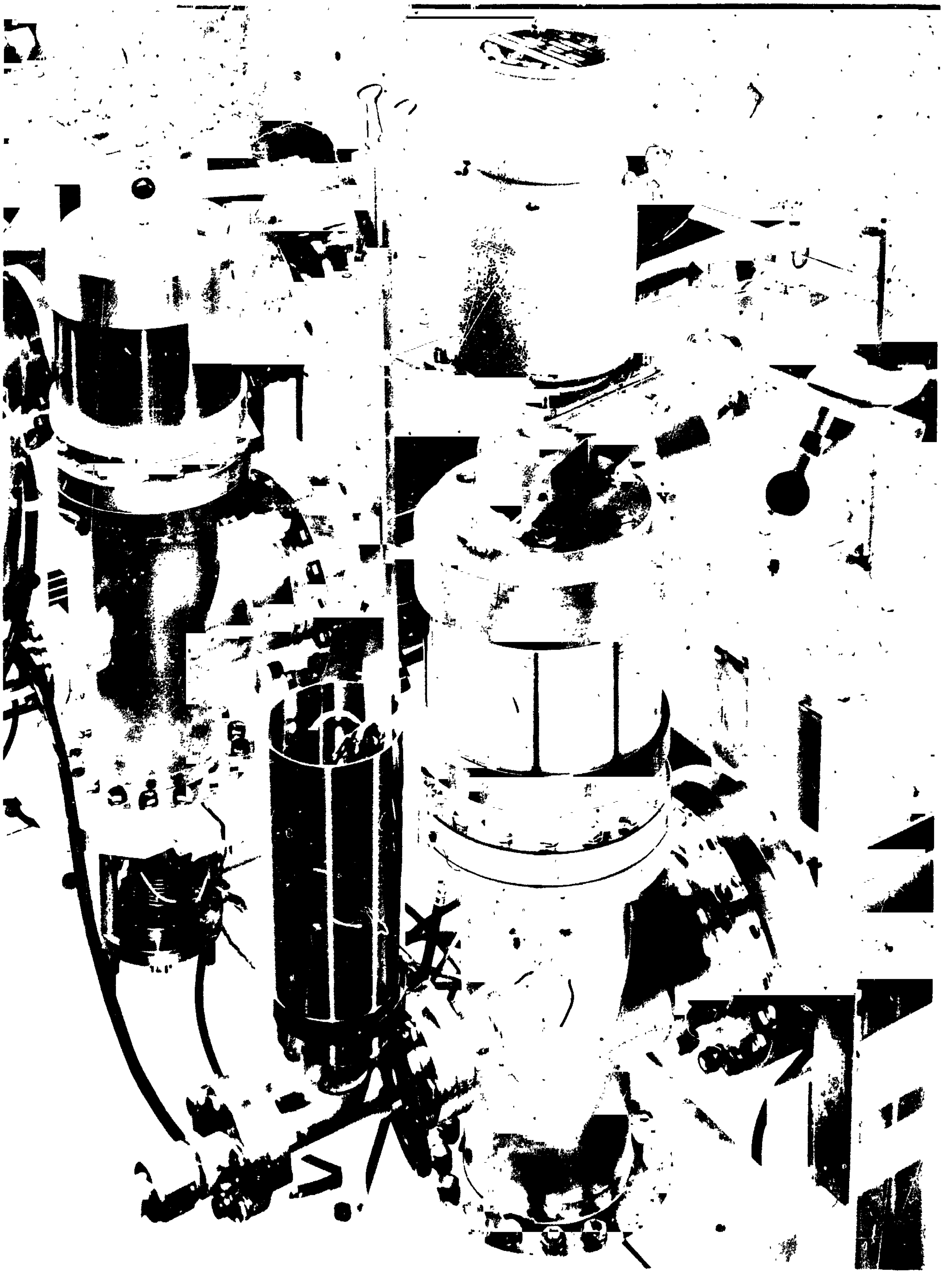

Fig. 17 - Two Types of Magnetic Coupling Units for Static and Dynamic Tests

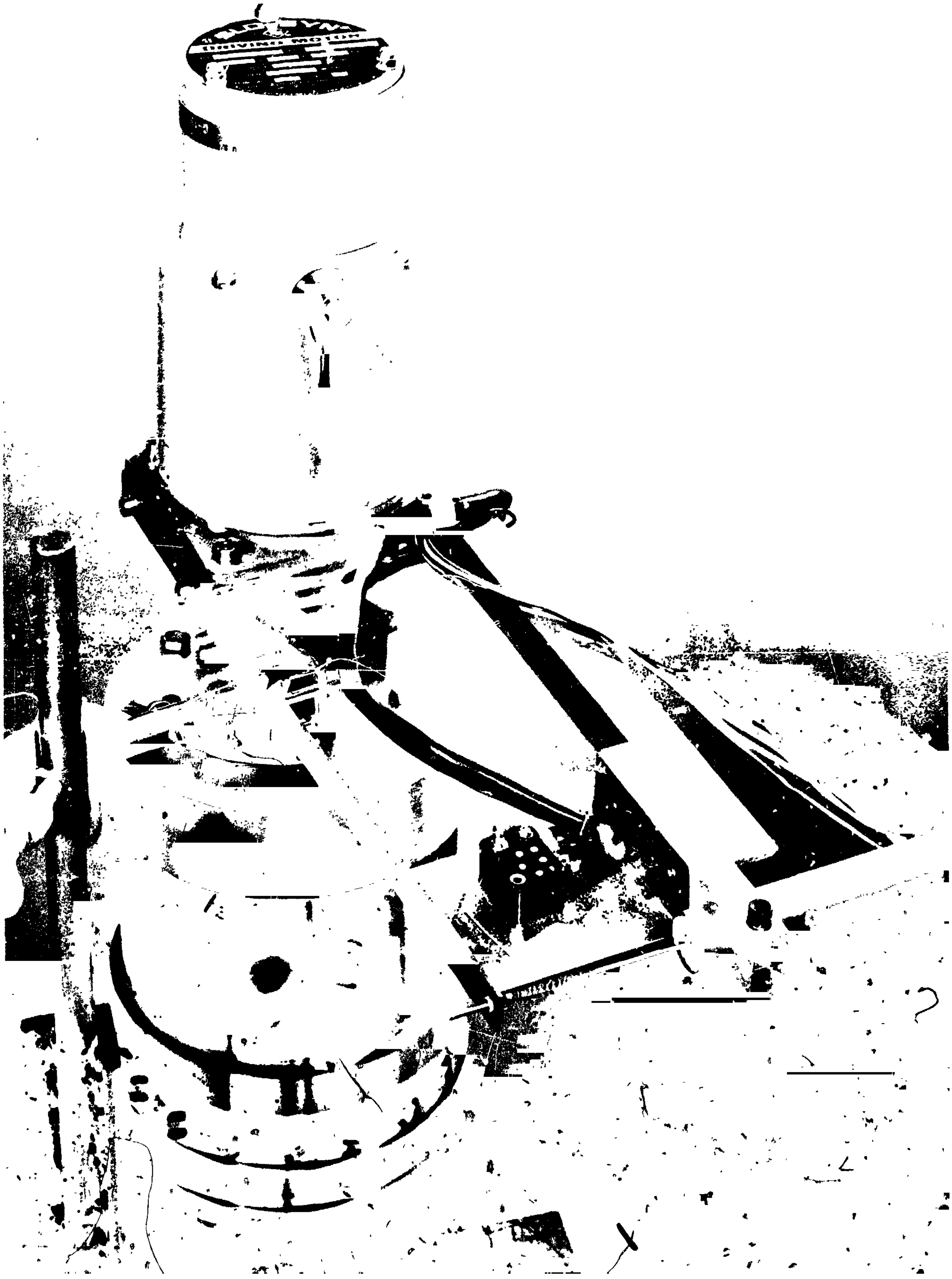

Fig. 18 - Detail of Motorized Magnetic Coupling with Torque Measuring Sensor

The wear surfaces of both the wear track and pellets were lapped flat and to a surface finish of 5 μin. rms. Then they were polished until pits and scratches were reduced to about 5 per cent or less and the surfaces were flat to within plus or minus three fringes of sodium light. (The wear track was not to have more than three fringes across any radius.) The washers were removed from around the pellets; all surfaces were then washed in methanol and air-dried. The specimens were next photographed and then cleaned in warm detergent solution in an ultrasonic cleaner, rinsed with deionized distilled water and then stored under anhydrous methanol until ready for installation in the test chamber. They were then dried in an oven at 75°C for 30 min. and placed in the station with clean forceps; the chamber was then sealed, ready for bake-out.

V. CONCLUSIONS

The following conclusions have been drawn from the results of this cold molecular welding study.

1. Very little correlation was found between the coefficients of friction (or tendency to cold-weld) and properties of the materials investigated. In one case however, our data confirm the observations of others, that a low coefficient of friction correlates with a hexagonal close-packed structure (cobalt).

2. Of the 45 tests, 42 metal combinations had greater maximum dynamic coefficients of friction than their static breakaway values; thus, greater force would be required for continual motion than for initial motion.

3. It was found in the results that 21 of the 45 metal combinations had maximum short-time dynamic coefficients of friction of greater than 1.3 and all of these combinations had increasing friction with time; 15 of the 21 exceeded 4.9. Of the remaining 24, 16 combinations had coefficients which became stable within the first half-hour and were below their initial values throughout the remainder of the dynamic tests.

4. For metal combinations with slight wear, metal was generally transferred from the pellets to the wear track when the pellets were softer than the wear track; when they were harder, metal transfer did not follow any particular pattern.

5. Comparative data for four metal combinations in ultra-high vacuum and air showed that static breakaway coefficients of friction in vacuum were more than 50 per cent higher than in air for three of the four combinations;

all combinations had moderate initial dynamic coefficients and then stabilized at lower values in air as did three of the four in vacuum, the fourth developed excessive friction within 0.3 hr.

6. Comparison of the MRI data with the appropriate data of like metal combinations from other investigators shows that good agreement was found for four metal combinations but poor agreement with two others.

VI. RECOMMENDATIONS

Some recommendations can be made as a result of the program.

1. Metal combinations not investigated in this program but used in the Apollo mission should be studied; these include such combinations as Inconel on Inconel, Inconel on Ti-6Al-4V, 4340 steel on Ti-6Al-4V and stainless steel on Inconel.

2. Different wear procedures should be studied, such as short-time dynamic tests followed by static tests and then followed by additional dynamic tests.

3. Duplicate or triplicate tests should be conducted to determine the reliability of the data from the tests of the current program and future programs.

4. Additional studies should be conducted to develop theories for predicting the cold-welding tendencies of space-oriented alloys in space environment and to obtain experimental verification of the theories.

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APPENDIX

COLD MOLECULAR WELDING IN A VACUUM - A SURVEY OF THE LITERATURE

I. INTRODUCTION

A literature search was conducted as part of the research effort under Contract No. NAS9-3623 to assess the current state of the art concerning cold molecular welding. The purpose of this search was to provide a knowledge of previous investigations and to incorporate this knowledge into the experimental studies conducted at MRI for NASA-Manned Spacecraft Center under Contract No. NAS9-3623.

The first problem encountered in a discussion of cold molecular welding is the proper definition of the term "cold welding." Kimzey[42/]* has defined it as the degree of "electrical forces which bind together the individual molecules when a vacuum or another process has cleaned a material adequately to give true molecular contact..." Most investigators avoid a direct definition of the term but it appears to be generally accepted that "cold welding" refers to the adhesion or cohesion of materials at temperatures significantly below the melting temperatures of the materials.

II. RESULTS OF THE LITERATURE SURVEY

The literature search to assess the current state of the art concerning cold molecular welding has resulted in a project library of the most pertinent publications and a comprehensive abstract file of over 200 references. The relevant publications in the project library have been reviewed in detail.

The literature clearly indicates that a study of cold welding under simulated space conditions requires:

1. A suitable environment of controlled temperature, load, and pressure (vacuum), and

2. A method of eliminating, controlling, and/or investigating surface contamination.

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* References refer to the Bibliography, p. 71.

The literature also indicated the lack of data concerning cold molecular welding under dynamic conditions, i.e., relative motion between the contacting surfaces. Only a few investigations, notably those of Buckley, Swikert, and Johnson,[9] Buckley and Johnson,[10,11] Winslow and McIntyre,[63] Bryant, Gosselin, and Longley[8,24] and Kellogg[39-41] were found which dealt with wear and friction or cold welding phenomena in ultra-high vacuum under dynamic conditions. Thus, the MRI program provides data under conditions for which only limited information exists in the literature. In addition to the above investigations, a limited amount of dynamic work was done by Hansen, Jones, and Stephenson[29] at a moderate vacuum (10^{-6} torr). The more severe vacuum conditions of the current program represent an area where data are required. Some notable adhesion and cohesion studies in ultra-high vacuum have been conducted by Ham,[27,28] Keller,[31-37] and Wells[61] but these investigations cannot be directly correlated to the dynamic studies as they were make-and-break-contact studies.

The investigations of interest to the MRI program are generally concerned with the determination of the conditions of temperature, load, and time under which adhesion or cohesion occurs between various metal surfaces in a vacuum. The results are usually listings of metal pairs which do or do not adhere or cohere under the specified conditions. The environmental conditions form only one of the two important criteria which appear to govern the occurrence of cold molecular welding. The second is the cleanliness of the contacting surfaces. Ham[27] states that "intermetallic cohesion or adhesion can occur easily only between clean, oxide-free metals." If the cold welding of metals in space is of interest, oxides and nitrides formed on the surface prior to launch are the principal sources of surface contamination. Such surfaces are self-cleaning in a perfect vacuum by one of several temperature-dependent processes. For most of the commonly used metals and alloys, however, a combination of elevated temperatures and long exposure times are required to remove oxide films. These times and temperatures can be estimated analytically. For example, one year in a perfect vacuum at over 100°C is required to remove a 100 Å thick oxide layer from 1018 steel, 4140 steel, and 52100 steel.[27] The corresponding temperature for removing a similar film from molybdenum is 1050°C. Under real conditions in space the required times and/or temperatures are even greater. Thus, Ham[27] concludes that "most metal surfaces exposed to the space environment are not likely to become clean in any reasonable period of time unless energetic electromagnetic irradiation accelerates the rate of removal of surface films." Of course, when relative motion exists between contacting surfaces, the oxide films can be mechanically ruptured revealing clean areas. If this occurs in a vacuum environment, the re-formation of the film would take place very slowly.

The cited investigations are summarized in the following paragraphs and tabulated in Tables A-I - A-XI. The investigations of Buckley, Swikert, and Johnson[9] at NASA-Lewis Research Center are concerned with the wear and friction characteristics of a number of materials, with and without lubrication, in a vacuum. Their publications of the early 1960's report experimental data concerning the friction, wear, and evaporation rates of several metals and lubricants under vacuum conditions of 10^{-7} mm. Hg. Although these particular investigations dealt largely with the effects of various lubrication methods on wear and friction in a vacuum, some data were collected for unlubricated metals. Their test parameters and metal combinations are summarized in Table A-I. Buckley and his colleagues concluded that a different wear mechanism prevailed in vacuum than was exhibited in air. In general, the wear in a vacuum was characterized by mass metal transfer. Some alloys demonstrated higher friction coefficients in vacuum (Ni-Cr alloy and Ni-bonded TiC-CbC) while others (notably 52100 steel) had lower friction coefficients in moderate vacuum. When liquid helium cryopumping was applied to eliminate O_2, the 52100 steel cold-welded in 33 min. Extensive evaporation rate data were generated in these studies to aid in the evaluation of lubricants for vacuum service.

The investigations of Buckley and Johnson[10] were extended, in 1964, to include the lubricating effects of the addition of sulfur to 52100, 440C stainless, and M-2 tool steels and the addition of aluminum to nickel-aluminum binary alloys. These experiments, which are summarized in Table A-II, were conducted in vacuum to 10^{-9} mm. Hg. It was found that the addition of 0.4 to 0.5 per cent sulfur to the steels appreciably reduced the welding tendency of the materials in vacuum. It was also found that 16.4 per cent aluminum in nickel resulted in an alloy exhibiting favorable vacuum wear and friction characteristics.

Buckley and Johnson[11] have also recently reported on friction and wear studies for 14 hexagonal metals in vacuum at temperatures to 850°F and sliding speeds to 2,000 fpm. The objective of these studies was to determine the effect of crystal transformation, slip systems, and lattice parameter on friction characteristics. The effect of alloy elements was also investigated. A summary of the experimental parameters is given in Table A-III. It was found that those metals with the largest interbasal planar spacing exhibited the lower coefficients of friction and a correlation between friction and lattice ratio was established for the hexagonal metals. Studies with single crystals of cobalt demonstrated that the crystal structure significantly influenced the friction, wear, and metal transfer characteristics in vacuum. Cobalt in the hexagonal form exhibited low friction and wear properties, whereas increased wear and complete welding were obtained at 900°F with crystal transformation to the face-centered cubic form. The hexagonal metals - titanium, zirconium, and hafnium - demonstrated higher wear and friction characteristics than cobalt, and beryllium showed relatively low friction properties. These observations were explained by the investigators in terms of the slip behavior of the various metals.

TABLE A-I

SUMMARY OF INVESTIGATIONS BY BUCKLEY, SWIKERT, AND JOHNSON[9]

Materials (in order tested)	52100 steel-52100 steel 440C-440C Cobalt-base alloy-Cobalt-base alloy Ni-Cr alloy-Ni-Cr alloy Ni-bonded TiC and CbC-Ni-bonded TiC and CbC (+ with lubricants + non-metals and coatings) (order not specified)
Vacuum range	10^{-6} to 10^{-7} torr + tests in air
Temperature range	75 to 1000°F
Load range	1,000 gm. (dead weight on lever) on 3/16 in. spherical radius rider
Sliding speed range	390 fpm
Adhered or cohered pairs	52100 steel-52100 steel with liquid helium cryopumping - 33 min. to seizure
Nonadhered or noncohered pairs	All others listed above (all times were 1 hr.)
Comments	Evaporation rates and wear and friction data presented. Specimens finish-ground and polished.

TABLE A-II

SUMMARY OF INVESTIGATIONS BY BUCKLEY AND JOHNSON[10]

Materials (in order tested)	52100 steel-52100 steel
	440C-440C
	M-2 tool steel-M-2 tool steel
	Sulfur modified 52100-sulfur modified 52100
	Sulfur modified 440C-sulfur modified 440C
	Sulfur modified M-2-sulfur modified M-2
	440C-sulfur modified 440C
	Electrolytic nickel-electrolytic nickel
	5.5% aluminum-nickel-5.5% aluminum-nickel
	13.3% aluminum nickel-13.3% aluminum-nickel
	16.4% aluminum-nickel-16.4% aluminum-nickel
	27.1% aluminum-nickel-27.1% aluminum-nickel
Vacuum range	10^{-9} torr
Temperature range	24°C (75°F)
Load range	1,000 gm. (dead weight on lever) on 3/16 in. spherical radius rider
Sliding speed range	75 to 1,960 fpm (most tests at 390 fpm)
Adhered or cohered pairs	52100 steel-52100 steel Electrolytic nickel-electrolytic nickel
Nonadhered or noncohered pairs	All others listed above (all times were 1 hr.)
Comments	Wear and coefficient of friction presented; specimen finish ground

TABLE A-III

SUMMARY OF INVESTIGATIONS BY BUCKLEY AND JOHNSON[11]

Materials (in order listed)	Cobalt-cobalt 25% moly-cobalt-25% moly-cobalt 2% moly-cobalt-2% moly-cobalt Titanium-titanium Titanium-tin alloys-titanium-tin alloys 10% oxygen-titanium-440C stainless Copper-copper Nickel-nickel Zirconium-zirconium Zirconium-440C stainless Beryllium-beryllium Beryllium-440C stainless Various rare earth metals on themselves Various rare earth metals on 440C stainless
Vacuum range	10^{-9} to 10^{-10} torr
Temperature range	75 to 850°F
Load range	250 to 1,000 gm. (dead weight on lever) on 3/16 in. spherical radius rider
Sliding speed range	4.5 to 2,000 fpm
Adhered or cohered pairs	Copper-copper at 1,000 gm., 1 hr. Nickel-nickel at 1,000 gm., 1 hr.
Nonadhered or noncohered pairs	All others listed above
Comments	Wear and friction correlated with lattice structure

The investigations of Buckley and Johnson are of particular interest because they are among the few studies that have been concerned with wear and friction, and hence cold molecular welding, under dynamic conditions in a vacuum. They provide data for direct correlation with the MRI data, although they are also directly concerned with vacuum lubrication materials and techniques.

Investigations were conducted in conjunction with the development of the SNAP in-flight reactor by Giles, Dewart, and Kellogg[25] and Kellogg[40,41] to evaluate bearing material compatibility in space. Various sliding couples using metals, carbon, ceramics, and lubricated specimens were studied in a vacuum of 10^{-9} torr. Sixty-seven material pairs were investigated by sliding square block specimens in contact in a vacuum chamber at temperatures to 1000°F and times to 3,000 hr. The results demonstrated the high friction, plowing, and seizure characteristics typical of sliding pairs in ultra-high vacuum. Contaminant films were found to reduce the coefficient of friction for metallic pairs. The scope of the experimental tests is outlined in Table A-IV.

The initial investigations of Ham[27] were intended to produce cohesion and adhesion data which would enable the designer of space hardware to select suitable metal combinations to either prohibit or enhance metallic adhesion depending upon the application. To eliminate surface cleaning problems, it was decided to repeatedly fracture and rejoin the specimens in a vacuum. This rendered the study applicable only to similar metal pairs. Data were obtained for OFHC copper, 1018 steel, and 52100 steel at various temperatures, times, joining stresses (loads), and degrees of contamination as outlined in Table A-V. Ham presents most of the data as "per cent cohesion" versus the product of time apart and environmental pressure while apart summed for all previous breaks ($\sum$Pt). Per cent cohesion is defined as the ratio of the average true cohesive stress to the average true virgin fracture stress. The product (Pt) is a measure of the contamination to which the fractured surfaces are exposed. As would be expected, the per cent cohesion of those metal pairs which did exhibit cohesion (copper-copper and 1018 steel-1018 steel) decreased with increased exposure. The cohesive stress values were also presented as a function of time with particular emphasis on the envelope formed by the maximum values. The latter showed an increase of per cent cohesion with temperature. Most of the stress data lie considerably below the maximum curve. Ham states that such points are caused by low compressive stress, short contact time, and/or high contamination.

Other general conclusions arrived at by Ham on the basis of this work were: load time is important only at higher temperatures; type 1018 and 52100 steels are self-cleaning at 500°C when exposed to a vacuum of 2 to 3 x 10^{-7} torr; work hardening as well as contamination contributes to the decrease in cohesion with repeated fracturing and rejoining.

TABLE A-IV

SUMMARY OF INVESTIGATIONS BY KELLOGG[40]

Materials (in order tested)	23 metal-metal combinations + other pairs involving non-metals; Ti-6Al-4V alloy against itself only combination on MRI program
Vacuum range	10^{-9} torr
Temperature range	75 to 1300°F
Load range	10 lb. on 0.25 sq. in.
Sliding speed	Average of 5 in/min (oscillatory)
Adhered or cohered pairs	Ti-6Al-4V alloy-Ti-6Al-4V alloy in 7 min. (75°F); coefficient increased to 1.0 (limit of apparatus)
Nonadhered or noncohered pairs	All others
Comments	Specimens separated during bakeout and until ultra-high vacuum was attained, slowly brought together

TABLE A-V

SUMMARY OF INVESTIGATIONS BY HAM[27]

Materials (in order tested)	OFHC copper-OFHC copper 1018 steel-1018 steel 52100 steel-52100 steel
Vacuum range	10^{-6} to 10^{-9} torr
Temperature range	25 to 500°C
Load range	0-90,000 psi (copper) 0-180,000 psi (1018 steel) 0-336,000 psi (52100 steel)
Adhered or cohered pairs	Copper-copper (65% max. at 25°C) 1018 steel-1018 steel (19% max. at 25°C) 52100 steel-52100 steel) ($>$ 400°C)
Nonadhered or noncohered pairs	52100 steel-52100 steel ($<$ 400°C)
Comments	Data plotted as per cent cohesion vs. $\sum Pt$ and maximum observed cohesive stress vs. temperature. Fracture-rejoin method used.

The above investigations by Ham were followed by additional work; the purpose of the follow-on work[28] was to obtain information concerning the adhesion of dissimilar metal pairs as well as cohesion of similar metal pairs. This necessitated extensive modification of the existing NRC facilities to permit cleaning of the specimens in a vacuum. This had not been done in the fracture-rejoin technique used previously. The cleaning method selected was wire brushing of the specimens in a vacuum by means of a small two-sided stainless steel brush activated by a rod through a flexible bellows.

A summary of the experiments conducted in this program is given in Table A-VI. The tests were all run at room temperature. They illustrate the effect of surface cleanliness since, in general, far less cohesion was observed in these tests than in the fracture-rejoin tests. The wire brush cleaning method was far from satisfactory. Several metal combinations were tested, some brushed in a vacuum and some merely exposed to 10^{-6} torr at 250°C, but cohesion occurred only for brushed soft copper pairs when slightly deformed. No adhesion or cohesion was observed for other conditions even when the surfaces were severely deformed by compression.

The investigations of Keller and associates[31-37] have been concerned with studies more fundamental and broader in scope than those of Ham. Keller begins with an attempt to describe the effect of surface composition and structure on the attractive forces present in adhesion.[31] He adopts the Bowden mechanism which requires that atomically clean surfaces must be contacted before adhesion can occur. He then assumes that the atomic model for surface energy is correct, i.e., that surface tension is due to the energy unbalance caused by an insufficient number of nearest neighbors for a surface atom. If two atomically clean surfaces of the same material were contacted with crystallographic orientations identical with respect to a continuous phase, an interface would be formed which would have a strength equal to that of the bulk materials. If such orientation did not exist, an interface similar to a grain boundary would be formed. Such adhesion would have a strength dependent upon the surface energy changes during formation.

Keller's initial experiments are outlined in Table A-VII. The specimens of pure metals were cleaned by argon ion bombardment. Loading was kept at only touch contact and adhesion was observed by physical sticking and microscopic examination. Adhesion was observed in the case of the aluminum-iron couple. This pair was selected because, at high temperatures, aluminum is capable of forming a solid solution with iron.

TABLE A-VI

SUMMARY OF INVESTIGATIONS BY HAM[28]

Materials (in order tested)	Soft copper-soft copper Soft 1018 steel-soft 1018 steel Soft 1018 steel-soft copper Soft 440C steel-soft copper Soft 41400 steel-soft copper Soft Cu-Be alloy-soft copper Soft titanium-soft copper Soft titanium-soft titanium
Vacuum range	10^{-8} to 10^{-9} torr
Temperature range	25°C
Load range	20-40,000 psi range
Adhered or cohered pairs	Soft copper-soft copper
Nonadhered or noncohered pairs	All other pairs listed above under Materials
Comments	Specimens wire brushed in a vacuum. It was stated that, except for copper, only a small fraction of the surface was effectively cleaned by this method. Material hardness was a parameter in these tests.

TABLE A-VII

SUMMARY OF INVESTIGATIONS BY KELLER[31]

Materials (in order tested)	Iron-germanium-iron Aluminum-iron Copper-molybdenum
Vacuum range	$< 10^{-8}$ torr
Temperature range	Room temperature
Load range	Very small
Adhered or cohered pairs	Aluminum-iron
Nonadhered or noncohered pairs	Iron-germanium-iron Copper-molybdenum
Comments	Specimens cleaned by vacuum exposure and ion bombardment.

These studies were followed by an extension of the experimental program to include other metal pairs and to provide a means of measuring adhesive force.[32] The results are outlined in Table A-VIII. Keller states that they suggest an adhesion mechanism which depends upon the surface physical chemistry rather than the mechanical nature of the contact area since all of the couples which exhibited adhesion form some type of intermediate phase. This denotes a negative free energy of bond formation which enables adhesion to occur.

The investigations conducted by Winslow and associates[62,63] at Hughes deal with the largest number of material couples. The objective of the program was the same as that of the NRC work, i.e., to produce data concerning the time and temperature conditions under which adhesion or cohesion of metals occurs in a vacuum. The data thus obtained are intended to provide information to facilitate the design of spacecraft.

The Hughes studies consist of both static and dynamic tests. The static tests were conducted in a vacuum of 5×10^{-9} torr for 6 hr. with the specimens separated, and the specimens were then placed in contact and loaded. Tests were conducted at 25°, 150°, 300° and 500°C for periods of 10, 100, 1,000,10,000 and 70,000 sec.; and the strength of the resulting static bond, if any, was measured. The results are outlined in Table A-IX.

The dynamic tests were conducted in the same fashion except that the load was smaller at first and increased for subsequent testing periods and, also, the upper member of the couple was oscillated ± 2° at a rate of three cycles per second. Hence, this manner of dynamic testing is somewhat different than that of Buckley and Johnson, Hansen, or the MRI method since it does not allow for the measurement of the coefficient of friction. It does, however, simulate the conditions existing at the interface between two surfaces with relative motion. The results, summarized in Table X, indicate that the motion enhanced cohesion and adhesion. All metal couples tested were found to bond under these more severe conditions.

A number of trends were noted in Winslow's and McIntyre's work. As was expected, the copper-copper pair was the easiest to cohere in both static and dynamic tests. In general, similar metal couples bonded more easily than dissimilar metals. In some cases couples bonded at low loads but not at high loads. This was attributed to rupture of the bond during elastic relaxation after the load had been removed, the forces available for such rupture being greater for higher loads. It was also observed that, whereas the 2014 aluminum alloy couples with itself and other metals were easily bonded (relative to other pairs) under static conditions, they were not so readily bonded under dynamic conditions. Winslow and McIntyre postulate that this may be caused by the aluminum oxide films which are more resistant to dynamic abrasion than the films of other metals and act as a barrier to dynamic bonding.

TABLE A-VIII

SUMMARY OF INVESTIGATIONS BY KELLER[32]

Materials (in order tested)	Iron-aluminum Silver-copper Nickel-copper Nickel-molybdenum Copper-molybdenum Silver-molybdenum Silver-iron Silver-nickel Germanium-germanium (order not specified)
Vacuum range	2×10^{-11} torr
Temperature range	Room temperature
Load range	Very small
Adhered or cohered pairs	Iron-aluminum Silver-copper Nickel-copper Nickel-molybdenum
Nonadhered or noncohered pairs	Copper-molybdenum Silver-molybdenum Silver-iron Silver-nickel Germauium-germanium
Comments	Specimens cleaned by vacuum exposure and argon ion bombardment. Numerical data not given.

TABLE A-IX

SUMMARY OF INVESTIGATIONS BY WINSLOW, HORWITZ, AND MCINTYRE[62]

(Static Tests)

Materials (in order tested)	Copper-copper 2014-T6 Al-2014-T6 Al 2014-T6 Al-304 Steel 2014-T6 Al-A286 Steel 2014-T6 Al-René 41 2014-T6 Al-Ti-6Al-4V 304 Steel-304 Steel 304 Steel-A286 Steel Ti-6Al-4V-304 Steel 304 Steel-René 41 Ti-6Al-4V-Ti-6Al-4V René 41-Ti-6Al-4V A286 Steel-A286 Steel René 41-René 41 A286 Steel-René 41 17-4PH Steel-17-4PH Steel
Vacuum range	5 x 10^{-9} torr
Temperature range	25 - 500°C
Load range	0-100,000 psi
Adhered or cohered pairs	Copper-copper (500°C) Copper-copper (300°C after 70,000 sec.) 2014-T6 Al-2014-T6 Al (300°C after 70,000 sec.) 2014-T6 Al-304 Steel (300°C after 70,000 sec.) 2014-T6-304 Steel (400°C after 500 sec.) 2014-T6-A286 (300°C after 10,000 sec.) 2014-T6 Al-René 41 (300°C after 70,000 sec.) 2014-T6 Al-Ti-6 Al-4V (300°C after 70,000 sec.)
Nonadhered or noncohered pairs	All others listed above at temperatures to 500°C, times to 70,000 sec., and various loads.
Comments	Specimens were cleaned by exposure at the test temperature (25°C to 500°C) to a vacuum of 5 x 10^{-9} torr for at least 6 hr. Most severe tests were conducted first.

TABLE A-X

SUMMARY OF INVESTIGATIONS BY WINSLOW AND MCINTYRE[63]

(Dynamic Tests)

Materials (in order tested)	A286 Steel-A286 steel 304 Steel-304 steel 2014-T6-2014-T6 René 41-René 41 Ti-6Al-4V-Ti-6Al-4V 304 Steel-2014-T6 304 Steel-René 41 2014-T6-René 41 2014-T6-A286 steel 2014-T6-Ti-6Al-4V
Vacuum range	5 x 10^{-9} torr
Temperature range	25 to 300°C
Load range	Variable
Adhered or cohered pairs	All of the pairs listed above at temperatures of 300°C or below and load times of 10 sec. with the exception of Ti-6Al-4V vs. Ti-6Al-4V which bonded at 25°C with a dynamic test of 300 sec. which included a static load.
Nonadhered or noncohered pairs	None
Comments	Data presented compares bond strength with load. Cleaning procedure same as static tests.

Conversely, the ease with which they bond under static conditions might be due to diffusion of the oxide into the metal thus removing the surface film. The Hughes data were used to develop recommended criteria for selecting materials which are to be in contact in space.

A study of surface friction and wear under vacuum conditions was conducted in 1958 by Hansen, Jones, and Stephenson[29] at Litton Industries and is summarized in Table A-XI. These investigations were begun with a study of the nature of an individual frictional contact. A copper point sliding on a copper plane was used to determine the friction coefficient under conditions where the applied load pressure was equal to the yield point of the material. These tests indicated the existence of two distinct modes of sliding; first a mode characterized by an extremely low coefficient of friction and an almost total absence of wear and distortion of the plane surface; and, second, a mode characterized by a very high friction coefficient and rapid destruction of both the plane and the point. The latter mode was found to be the only one occurring when the sliding surfaces are clean of contaminants. The first mode required the presence of at least a monomolecular film of lubricant. Based upon this concept, of two distinct types of contact, a relation between the gross friction coefficient and the relative areas engaged in the two types of contact was developed and found to agree with observation.

The friction characteristics of numerous material pairs were investigated in air and in "immediate" vacuum, i.e., conditions where the specimens were not subjected to long periods of outgassing. The measurements were made under various conditions of load, time, and degree of vacuum; the lowest pressure was 10^{-6} torr. The specimens were cleaned to remove soluble contaminants but not bonded contaminants or oxides. The tests were conducted by measuring the tangential force developed between two blocks which are pressed together by a contact pressure of either 7.7 or 14.7 lb. per 2.6 sq. in. of projected surface and slowly reciprocated with a 1/4-in. stroke. A limited number of tests were also conducted on specimens subjected to longer periods of outgassing. The resulting data would be of particular interest for correlating with the MRI data if the work had been done in ultra-high vacuum or with apparent contact pressures of approximately 1,000 psi.

No evidence of fundamental relationships was observed in the Litton studies. However, several trends were noted. It was found that, in general, when dissimilar metals were being tested the softer material transferred to the harder material, thus masking the effects of the tests on the harder material. Hence, tests on similar couples would be more valuable in establishing fundamental relationships. It was also observed that, under good vacuum conditions, the wear products consisted of particles torn from the surfaces.

TABLE A-XI

SUMMARY OF INVESTIGATIONS BY HANSEN, JONES AND STEPHENSON[29]

Materials (in order tested)	99% Al-99% Al 2024-T4 Al-2024-T4 Al Beryllium cu-beryllium cu Brass-brass Copper-copper 304 Steel-304 steel 52100 Steel-52100 steel 304 Steel-2024-T4 Al	Brass-304 steel Brass-beryllium copper Copper-52100 steel Cadmium plate-cadmium plate Chrome plate-chrome plate Nickel plate-nickel plate Silver plate-silver plate
Vacuum range	10^{-5} to 10^{-6} torr	
Temperature range	25°C	
Load range	7.7 and 14.7 lb. on 2.6 sq. in. contact surface	
Sliding speed range	1/4 in. reciprocal stroke	
Adhered or cohered pairs	None	
Nonadhered or noncohered pairs	All pairs tested (durations to 60 min.)	
Comments	Coefficient of friction data generated in air and vacuum.	

Due to work hardening, these particles were harder than the base materials. In such cases the friction would be expected to increase as these particles are dragged through portions of the surface. The tests conducted on 52100 steel-52100 steel were found to suggest a speculative explanation for the trends of the friction coefficients under the three test conditions, i.e., air, "immediate" vacuum, and long-term outgassing. The Litton studies indicate that in air it appears that the friction forces are most strongly affected by abundant formation of oxides which apparently minimize actual metal-to-metal contacts. Under immediate vacuum the quantity of oxides is reduced and a certain amount of metal-to-metal contact occurs, but the outgassing of the surfaces now tends to cause the friction to remain relatively low. Under conditions of more thorough outgassing the metal-to-metal contact is enhanced and the friction forces increase.

The experimental phases of the Northrop studies by Wells[61] have not been reported. The only information presently available concerns the development of the experimental apparatus. The program was initiated to study adhesion and cohesion in much the same manner as the work discussed above but with special emphasis on possible applications of cold welding to metal joining. The Northrop studies will involve static contact only and are expected to be conducted at 10^{-10} torr with the aid of liquid nitrogen cooling.

Cold welding studies under vacuum conditions have also been studied by Bryant, Cosselin, and Longley at MRI.[8,24] They found that when molecularly smooth cleaved crystals are permitted to reheal, cold welding occurs due to the large contact area which is reformed at normal atomic lattice spacings. They further conclude that when structural metals with polished or original surfaces make touch contact after exposure to simulated space environments, cold welding does not occur. However, when structural materials are contacted and vibrated under a 250 psi normal load, cold welding occurs under vacuum to a greater extent than at atmospheric pressure. The metals used in these studies were 2020-T6 aluminum, titanium (6 Al-4V) and 301 stainless steel.

A subcommittee of the ASTM has been recently formed to collect and correlate significant data produced by various investigators in the field of adhesion and cohesion under vacuum conditions. This group, headed by D. V. Keller, Jr., of the Syracuse University Research Institute, is the Subcommittee 6 of the Materials Section VI, ASTM Committee E21, and is concerned with the subject "Adhesion of Materials in the Space Environment."[38] Their activities should be of particular interest to future programs in this area.

The studies outlined above demonstrate the importance of surface conditions and surface contamination in achieving cold welding between two metal surfaces. It is extremely difficult to obtain and maintain a clean oxide-free surface. Some investigators argue, however, that such surfaces do not represent the actual metal surfaces in space. When a vehicle is launched, the components usually have an oxide layer. It is known that removal of this layer in a space vacuum requires long times and elevated temperatures unless some mechanical means exists for rupturing the oxide. If the latter occurs, the low partial pressures of space will greatly decelerate the rate at which a new oxide or contaminant layer forms on the clean metal surfaces. Thus, a clean metal surface in space will most likely exist where mechanical friction and relative motion between contacting pairs occurs. The MRI data generated under Contract No. NAS9-3623 represent a significant contribution to the present state of the art concerning the phenomena of cold molecular welding since it simulates conditions of relative motion between contacting metal surfaces in space. As mentioned above, only a limited amount of data had been previously generated in this area.

III. GENERAL LITERATURE CONCERNING SURFACE PHENOMENA RELATED TO COLD WELDING

The information obtained from the other references reviewed in the literature search generally parallels that of the publications referred to in Section II. These additional references describe studies conducted in areas related to cold molecular welding in a vacuum, e.g., adhesion and cohesion in air, friction, wear, and other phenomena all of which depend upon the conditions at an interface. The literature which was reviewed in detail as part of the literature search is listed in the Bibliography.

As has already been pointed out, surface contamination has a great effect on cold welding. The friction of clean surfaces was studied by Bowden and Hughes in 1939[5/] at pressures below 10^{-6} torr; the adsorbed film of oxygen and other contaminants were removed from the test surfaces by ion bombardment. Immediately upon cooling, the coefficients of friction for nickel on tungsten and copper on copper were between 4.5 and 6. When a trace of oxygen was admitted, the coefficient dropped to 1 or less while pure hydrogen or pure nitrogen had little effect on the friction of clean metal surfaces. Bowden and Young[7/] subsequently conducted the same experiment but with improvements so that the slider could be dragged along the fixed surface and with higher loads, about 15 gm. instead of less than 1 gm. Degassing and surface cleaning was accomplished by heating in vacuum to 1000°C by induction heating. Their results confirmed the earlier work. These results support the view that surface oxides and other contaminants prevent the formation of metallic junctions at the interface which would occur with clean surfaces to cause cold welding. Bowden and Rowe[6/] in the same general type of investigations measured adhesive forces in addition to frictional forces. They were concerned with the adhesion between hard metal surfaces cleaned by heating at pressures of 10^{-6} torr and later 10^{-8} torr. The hard metals had low adhesive values even for clean surfaces; the low values were attributed to the elastic recovery of the surfaces upon removal of the load as had been earlier reported by McFarlane and Tabor.[47,48] Contamination was found not to be an important factor in adhesion for pure normal loading. However, adhesion was increased significantly if a tangential load was applied to cause a growth of real contact area; contamination became a large factor in this latter case. When the metals were heated in vacuum to temperatures high enough to anneal the asperities of the surfaces, very large adhesions were recorded for pure normal loading.

Theoretical and experimental studies on mechanism of metallic friction, friction and surface damage of sliding metals, area of contact between solids, effects of contaminant films on friction of clean surfaces and other related topics prior to 1953 were described by Bowden and Tabor;[64] a continuation of various investigations to 1963 was given in their subsequent volume.[65] Much of their discussion is pertinent to cold welding studies.

The work of Anderson[1-3] was largely intended to experimentally test the adhesion theory of friction proposed by Bowden and Rowe[6] and to develop methods for thermocompression bonding of wire leads to brittle nonmetals. They showed the effects of shear strains on the structure of metal surfaces and substrates after adhesion. These shear strains are generally necessary for adhesion as they are very effective in removing surface oxides; they roughen the surface, increase the amount of atomic contact, and produce a work-hardened zone near the common interface, all of which increases the adhesion strength of the joint.

The investigations of Burton, Russell and Ku[12] were concerned with static and dynamic coefficients of friction of metal surfaces cleaned by hydrogen bake-out and other means at temperatures -250° to 25°C. A spherical radius was rubbed on internal surfaces of a cylinder in a helium atmosphere. The coefficients had virtually no change throughout the temperature range. Later Burton, Russell, and Ku[13] studied friction of lead-plated tool steels and effects of oxide coatings on copper under the same conditions. Burton, Brown, and Ku[14,15] conducted friction and wear characteristics of oscillating, plain journal, and self-aligning bearings over the range -90 to 1750°F at pressures ranging from 10^{-6} to 10^{-3} torr. They studied cermets and high temperature metal alloys with the test surfaces subjected to rotating motion under normal loading from 1,500 to 15,000 psi and at temperatures up to 2000°F. The tendency toward adhesion, gross seizure, and severe surface roughening was much less for the cermets than for the metal alloys.

An experimental study of the role of oxidation in inhibiting metallic interaction between metal surfaces sliding at high speeds (up to 260 in/sec) was conducted by Cocks.[17] At light loads, the metal surfaces were severely torn; but at higher loads, the tearing became less severe. Above a certain load which depended on the speed, tearing was almost eliminated from at least one of the surfaces. Surface protection was attributed to surface oxidation from the generated heat of friction. Friction and wear were also studied. Cocks[18] later investigated the effects of wedge-shaped wear particles on friction and sliding action of flat plates.

The influence of surface activity on friction and surface damage was studied by Feng.[22,23] Included in his investigations were the effects of gases and liquids in the lubricating fluids on lubrication and surface damage. The nature of surface damage that occurs at the surfaces of solids in sliding contact is highly dependent on the interaction between the surfaces and the environment.

A series of metals were tested in air by Goodzeit[26] to determine metal combinations which would make good bearing metals immune to strong welded junctions during operation. The work resulted in the establishment of a method for predicting metal combination performance; however, the work was generally limited to pure metals and did not include alloys.

Keller[34,35] presented a broad definition of adhesion between solid metals and discussed it in order to permit a better understanding of the vast amount of metallic adhesion data being published currently. An interesting result of this definition is that there appears to be a real relationship between adhesion phenomena and the processes of friction, cold welding, sintering, grain boundaries, strength and fatigue. A number of experimental techniques were discussed and analyzed with respect to the increasing knowledge of adhesion phenomena.

In addition to Keller's earlier work, he presented an examination of the classical statistical theories of surfaces with particular emphasis on the metallic state.[36] The statistical, or thermodynamic approach was then compared to a simple atomic model which was developed on the basis of some of the more recent experimental data. The atomic model was studied for consistency with such well established phenomena as surface energy and its variation with crystallographic orientation, adsorption, grain boundary formation and certain diffusion bonding systems. The statistical view of surfaces establishes the exact total energy function for various surface reactions which include only the initial and final states of the equilibrium system, while the atomic model permits a mechanistic picture of the nonequilibrium interface. Although the latter is consistent with the more formal approach, Keller points out that the intermediate energy values which are evident from the atomic model may be more difficult to attain.

A theoretical and experimental investigation of adhesion was made by Ling[43] in which he showed that the coefficient of adhesion is related to two important parameters: activation energy of the process and a time exponent, both of which are dependent on the degree of cleanliness of the test surfaces. Later, he postulated a mechanism of metal adhesion[44] and conducted experiments to confirm the validity of his theory. One of his earlier experiments showed that adhesion could occur without shear strains.[45]

Work in 1948 by Moore[49] was concerned with the deformation of metals in static and in sliding contact. When a groove was made by sliding a hemispherical slider over a copper surface, there was sufficient surface damage to obliterate completely the surface irregularities. In the presence of a lubricant, similar effects were observed, though on a reduced scale. The tops of the asperities were wiped away, showing that there was considerable interaction between the metal surfaces through the lubricant film. A detailed examination of the surface damage produced during sliding showed that metallic junctions were formed and sheared during the sliding process. These junctions were formed even when the sliding speeds were so small that the temperature rise due to frictional heating was negligible. Moore suggested that the junctions were produced by cold welding of the surfaces as a result of the high localized pressures developed at the points of real contact. These junctions were often strong enough to rupture the stronger of the two sliding metals. Although a lubricant reduces the amount of intimate metallic contact, the investigations showed that metallic junctions were formed through the lubricant film by an essentially similar mechanism. These observations provided graphic evidence for the view that the frictional force for both clean and lubricated surfaces are due mainly to the shearing of metallic junctions formed by cold welding at the points of intimate contact.

The influence of surface energy on friction and wear phenomena was studied by Rabinowicz.[50-53] He found qualitatively that high friction coefficients were found for sliding materials with high surface energy/hardness ratios and conversely. This relationship could not be tested quantitatively because the derived expression contained parameters which could not be independently controlled. However, in the wear field, it was possible to derive an expression for the size of loose wear particles which could be readily tested; namely, that the average size of loose wear particles is proportional to the surface energy/hardness ratio, the dimensional constant of proportionality being 60,000. Experiments with 15 different materials showed the validity of this expression. Another phenomenon, adhesion, which also seems to be governed by the surface energy considerations, was discussed in qualitative terms.

Later Rabinowicz and Imai[51] measured the coefficients of friction as a function of temperature using surfaces covered with metals having low melting points. The temperature effect on the coefficients with wetting metals was shown to be significant but essentially insignificant for the nonwetting metals.

Sikorski[56] compared the coefficients of adhesion as obtained by a twist-compression bonding method with the following properties of metals: crystal structure, hardness, surface energy, elastic modulus, work-hardening properties, recrystallization temperature, purity, and atomic volume. Conclusions were reached regarding the desirable characteristics of metals or combinations of metals, for antifriction applications. Sikorski[57] subsequently made a study of adhesion and friction coefficients with the same general method. His results showed that high friction between metals is usually accompanied by large adhesion, thus fully supporting the adhesion theory of friction. Two aspects of adhesion were considered in the discussion of factors that influence it, namely mechanical and physicochemical. The mechanical aspect was related to the properties of metals and their oxides which affect the size and cleanliness of the real areas of contact between two metal specimens subjected to the action of normal and tangential forces. The physicochemical aspect of adhesion, in turn, involved properties that determine whether adhesion will or will not take place under given experimental conditions. In a study of the adhesion of rare earth metals, Sikorski and Courtney-Pratt[58] proposed to apply an atomic "size factor" criterion to the prediction of adhesion properties of dissimilar metals and provided an illustration in terms of adhesion of iron to the rare earth metals.

Semenov[54,55] reported on a cold welding technique for studying seizure. He described sliding friction experiments of various types and experiments in which the amount of deformation required to cold weld two metal specimens was measured. He indicated such methods have been used to study the effect on seizure processes of the experimental conditions and of many factors in the constitution of the specimens and their surface layers. The nature of seizure and the related phenomena of interatomic force, recrystallization, diffusion and plasticity were also described qualitatively. He advanced the hypothesis that surface atoms must in general overcome an energy barrier before seizure can proceed.

Chapters of several books on adhesion[66-68] have appropriate discussions on the surface phenomena related to cold welding. Eley and Tabor[21] present the fundamentals of adhesive joints in general while Tabor[59] reviews friction and adhesion between metals and other solids.

Debye[20] gave an outstanding theoretical paper on the interatomic and intermolecular forces in adhesion and cohesion at the General Motors Symposium on Adhesion and Cohesion in 1961. An understanding of these forces can give insight into the mechanism of adhesion and friction.

IV. TECHNIQUES OF THE LITERATURE SEARCH

The literature search to assess the state of knowledge concerning cold molecular welding phenomena commenced with the preparation of a list of pertinent subject headings. This list was used in a search of related technical journals, and various abstracts and indexes.

The subject headings were:

Adhesion
Cohesion
Cold Welding
Diffusion Bonding/Welding
Friction Bonding/Welding
Friction
Fusion Bonding
Pressure Bonding/Welding
Seizure
Solid-State Bonding
Wear
Welding

The sources were:

Applied Science and Technology Index, 1958 to date.
British Technical Index, Vol. 3, No. 6, 1964.
Chemical Abstracts, 1960 to date.
Consolidated Translation Survey, 1963-1964.
Engineering Index, 1958 to date.
Science Abstracts (Sec. A, Physics), 1961-1963.
Battelle Technical Review, abstracts, 1960-1964.
Wear, abstracts, 1957 to date.
Current Contents, 1964 to date.
Referrals to recent current work, 1964-1965.

Also, a literature search was conducted through the Technical Abstract Bulletin (ASTIA) and a listing of research projects in the area of cold welding was obtained from the Science Information Exchange.

In addition to the search of direct literature sources, over 20 individuals, firms, and institutions who were, or are currently, engaged in related investigations were contacted.

These sources provided information from which a comprehensive listing of publications was obtained. Some of these were regarded as not applicable to the subject investigation and were eliminated. Abstracts were obtained or written for others. Copies of the publications which appeared to be of sufficient interest were obtained.

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