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By Donald H. Buckley and Robert L. Johnson

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Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON
March 1959

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SUMMARY

The extreme temperatures anticipated for lubricated parts in advanced flight powerplants dictate the consideration of unconventional methods of lubrication such as solid lubricants and the reactive gases described in the present research. These halogen-containing "reactive" gases such as dichlorodifluoromethane, CF_2Cl_2, are among the most stable of organic molecules. The high "flash" temperatures generated at the contacting asperities as a result of frictional heat are sufficient to cause local decomposition of the halogen-containing gases. The active atoms thus released (e.g., chlorine) then react with the metal to be lubricated to form halides capable of effective lubrication. The presence of small amounts of a sulfur-containing gas (e.g., 1 percent sulfur hexafluoride, SF_6) was found to catalyze the formation of metal halides.

Friction and wear studies were made with a hemisphere (3/16-in. rad.) rider sliding in a circumferential path on the flat surface of a rotating disk ($2\frac{1}{2}$-in. diam.). The specimens of corrosion-resistant alloys were run in an atmosphere of the various gases with a load of 1200 grams, a sliding velocity of 120 feet per minute, and temperature from 75° to 1200° F.

An effective lubricant for ferritic materials (M-1 tool steel) was CF_2Cl_2, but significant corrosion occurred above 600° F. Corrosion evaluation in CF_2Cl_2 suggested a number of nickel- and cobalt-base alloys for additional lubrication study. Several combinations of gases and these metals were found to lubricate to 1200° F without excessive corrosion. The gases were CF_2Cl_2 plus 1 percent SF_6, monobromotrifluoromethane CF_3Br plus 1 percent SF_6, dibromodifluoromethane CF_2Br_2, iodotrifluoromethane, CF_3I, and I_2. Careful selection of metals and gas are necessary for successful lubrication over specific temperature ranges. Optimum combinations give friction coefficients as low as 0.05 without

excessive wear. An example of such a combination is a Stellite 98M2 rider on a Hastelloy C disk in CF_3Br plus 1 percent SF_6 at temperatures from 600° to 1200° F.

INTRODUCTION

The trends in aircraft, particularly missile designs, are placing demands on lubrication systems for use at extremely high temperatures. High-temperature lubrication problems are being encountered in the temperature range from 500° to 1000° F. The high temperature of 1000° F is beyond the limit at which organic liquids and grease lubricants are useful. There are, however, some gases that are thermally stable at these temperatures and may be useful as lubricants. Of these, the halogen-substituted methane gases are the most thermally stable. A number of these gaseous compounds have potential use in high-temperature lubrication problems.

In regard to the potential use of halogenated gases, a very important consideration must be the thermal stability of the gas. Several gases, such as CF_2Cl_2, CF_2Br_2, and CF_3Br, are stable in contact with metal surfaces at ambient temperatures of 1000° F. However, in a lubrication system where metals are in sliding contact, the flash temperatures generated at contacting asperities are extremely high. In work with effective boundary lubricants, temperatures as high as 600° C (1112° F) above ambient have been reported at the localized point of metal contact (ref. 1). These temperatures generated at the contacting surface are sufficient to rupture chemical bonds of gases adsorbed on the surface. Atoms of labile constituents of the gaseous molecule such as chlorine and bromine subsequently react at the hot spots of the sliding metal surface. The metallic halides formed then function on the surface as solid lubricants and are continuously reformed when needed. This mechanism is fundamentally the same as that for extreme pressure lubrication by reactive compounds used as additives to gear oils (refs. 2 to 4).

Lubrication with halogenated gases has presented a corrosion problem with ferritic materials at temperatures above 600° F (ref. 5). One method of reducing corrosion is the selection of materials that have good corrosion resistance in the gaseous atmosphere at high temperatures. Some nickel-base materials seem to offer such resistance. However, gaseous lubrication is selective and the proper gas must be used with a particular metal to form a film that has lubricating properties.

Experimental conditions in NACA research studies similar to those used herein (refs. 5 and 6) have shown that two chlorine atoms per molecule were necessary for effective lubrication. The removal of a single chlorine atom from the gaseous molecule was difficult to accomplish because of the extreme temperatures needed to rupture the chemical bond.

Furthermore, the addition of a small quantity of SF_6 will catalyze the decomposition of the gas and might give good lubrication with minimum corrosion.

The object of the research reported herein was to select materials that have resistance to corrosion, to study their lubrication with various gases and gas combinations, and to investigate their performance over a broad temperature range. The gases used were CF_2Cl_2, CF_3Br_2, CF_3Br, CF_3I, I_2, and SF_6. Experiments were made with iron-, cobalt-, and nickel-base materials sliding in an atmosphere of reactive gas from 75° to 1200° F. Friction, wear, and corrosion characteristics were noted. A 3/16-inch-radius hemispherically tipped rider under a load of 1200 grams contacted the flat surface of a rotating disk. The sliding velocity was 120 feet per minute.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is described in detail in reference 5 and is shown schematically in figure 1. The basic elements of the apparatus consist of a rotating-disk specimen ($2\frac{1}{2}$-in. diam.) and a hemispherically tipped rider specimen (3/16-in. rad.).

The rider specimen is stationary and in sliding contact with the rotating-disk specimen. The disk was rotated by means of an electric motor through a variable-speed transmission. Loads were applied to the rider specimen by means of a dead-weight system. The frictional force was measured directly by means of four strain gages mounted on a copper-beryllium dynamometer ring. The frictional force was continuously recorded on a strip-chart potentiometer. After the experiment the wear volume was calculated from the measured diameter of the wear area on the rider specimen.

The gaseous lubricants were introduced into a 2-liter Inconel pot, which (with its cover) enclosed the disk and rider specimen. The Inconel pot was heated by means of strip heaters mounted on the outer walls and concentric ring heaters in the base of the pot. The strip and ring heaters were controlled by individual Variac units. The temperature was measured by an Inconel-sheathed Chromel-Alumel thermocouple located along the side of the disk specimen and the temperatures were read from an indicating potentiometer. The temperatures were varied from 75° to 1200° F.

For corrosion studies, a 2-liter Pyrex jar and cover were used. The cover contained a Pyrex gas-dispersion tube. The metal test specimens were placed within the jar, which was contained in the Inconel test chamber of the friction apparatus. The gas admission and method of heating were the same as those employed in a friction and wear experiment.

The disk specimens used in test runs were: M-1 tool steel, Stellite 98M2, and Hastelloy C. The rider materials were: M-1 tool steel, K162B Kentanium, Stellite 21, Stellite 98M2, Inconel X, and $7\frac{1}{2}$-percent silicon-nickel. The compositions of these and other alloys used in the corrosion study are listed in table I.

Both rider and disk specimens were finish ground to 2 to 4 microinches. Before each run the rider and disk were given the same preparatory treatment. This treatment consisted of the following: (1) a thorough rinsing with acetone to remove oil and grease from the surface, (2) polishing with moist levigated alumina and a soft polishing cloth, (3) the specimens were thoroughly rinsed in tap water followed by distilled water, and (4) the specimens were rinsed with 95 percent ethyl alcohol and finally with acetone to remove any trace of water.

The gaseous lubricants used in this study were SF_6, CF_2Cl_2, CF_2Br_2, CF_3Br, CF_3I, and I_2. The physical and chemical properties of these gases are found in references 7 and 8. Details on the system of transfer of gas to the test chamber are presented in reference 6. The Inconel pot was purged for a 15-minute period prior to the actual starting of the run. In experimental tests in which temperatures other than room temperature were employed, the specimens were brought to temperature before the period of purge was initiated. The gas-flow rates and mixtures used in the purge were the same as those employed in the run. At the completion of the purge the run-in procedure was initiated. Measurements reported in reference 6 show that less than 0.5 percent oxygen was present in the test chamber during operation with CF_2Cl_2.

The run-in was started with an initial surface speed of 55 feet per minute and incremental loads of 200, 400, and 600 grams applied in 1-minute intervals. A 1200-gram load was then applied for a period of 2 minutes after which the surface speed was increased to 120 feet per minute. This speed was maintained for the duration of the 60-minute run.

The run-in procedure was found necessary as a result of some previous work with CF_2Cl_2, which showed that if the run was started with high load and speed, surface failure of the specimens was apt to occur. The high initial friction and wear can be attributed to the lack of sufficient time for the formation of a reaction film. As a result it was found that by reducing the speed and incremental loading, a reaction film could form, which markedly reduced the initial high friction and wear.

RESULTS AND DISCUSSION

Reference Data

Data obtained in reference 5 with M-1 tool steel rider and disk specimens in CF_2Cl_2 at various temperatures (from 75° to 1200° F) are presented in figure 2 for purposes of comparison. The low values of friction and wear are indicative of the effectiveness of iron chlorides as boundary lubricants. The progressive increase in wear observed at temperatures above 600° F can be attributed to a number of factors, one of the more important of which is corrosion.

The results of the addition of 1 percent SF_6 as a catalyst of CF_2Cl_2 in the lubrication of M-1 tool steel rider and disk specimens are shown in figure 3. The added SF_6 had two effects: (1) the wear was reduced somewhat at elevated temperatures and (2) the time needed for reaction-film formation at the onset of running was shortened. The first corrosion product at elevated temperatures was the same as with CF_2Cl_2 alone. Sulfur hexafluoride functions as a catalyst in that, upon its addition with CF_2Cl_2, a metallic sulfide forms rapidly and a subsequent substitution reaction takes place in which the metallic chloride is formed, releasing sulfur. The metallic sulfide catalyzes a rapid formation of the metallic chloride. The quantity of halide formed in this manner is $1\frac{1}{2}$ to 3 times that formed by the halogen gas itself. Analogous reactions with other compounds in lubrication studies are reported in references 4 and 9.

The lubrication of ferrous materials such as M-1 tool steel with CF_2Cl_2 or CF_2Cl_2 containing 1 percent SF_6 presents a corrosion problem at temperatures above 600° F. The reactive nature of ferrous and ferric chlorides, which are formed in lubrication with these gases, is well known. It should also be emphasized that M-1 tool steel is very susceptible to chemical attack.

Corrosion Study

The poor corrosion resistance of M-1 tool steel at temperatures above 600° F prompted a corrosion study of various materials. The experiments were conducted in an atmosphere of CF_2Cl_2 with 1 percent SF_6 at temperatures of 75°, 600°, and 1200° F. Of the gases studied, this particular mixture of CF_2Cl_2 and SF_6 provided the most corrosive atmosphere. The results of this study are shown in table II. Of the materials investigated the nickel-base alloys, particularly $7\frac{1}{2}$ percent silicon-nickel, Inconel X, and Hastelloy C, showed the least corrosion. These materials showed no evidence of corrosion at 75° and 600° F. At 1200° F, $7\frac{1}{2}$ percent silicon-nickel and Inconel X showed the slight coloration of very thin chloride films: Hastelloy C showed some discoloration. The M-1 tool steel and 440-C stainless steel were the poorest materials reported under these environmental conditions. They exhibited heavy deposits and showed marked weight changes.

Alloy and Gas Combinations

Various nonferrous corrosion resistant alloys were explored as slider materials for lubrication by chlorine- and bromine-containing gases. Previous NACA solid-lubricant research studies (ref. 10) have shown that certain AX_2-type compounds (layer-lattice crystal structure) have good lubrication properties. The results of solid-lubricant studies were used as a guide in material selection for minimum friction and wear.

Runs were made with corrosion-resistant materials at 600° F (threshold of severe corrosion with M-1 tool steel) to establish alloy-gas combinations for detailed study. Two disk materials were used, nickel-base Hastelloy C and cobalt-base Rexalloy 33. The composition of Rexalloy 33 is similar to Haynes Stellite Star J, which has been considered by others for use in high-temperature bearings. This alloy (Rexalloy 33) does not possess as good resistance to corrosion as Hastelloy C, however, with CF_2Cl_2 the reaction product is cobalt chloride, $CoCl_2$, which was an effective solid lubricant in reference 10. A series of six rider specimens was used in combination with each of these two disk materials. The rider materials were: M-1 tool steel, K162B Kentanium, Stellite 21, Stellite 98M2, Inconel X, and $7\frac{1}{2}$ percent silicon-nickel. Friction and wear data (figs. 4 and 5) were obtained at 600° F with the various metal combinations in air, CF_2Cl_2 plus 1 percent SF_6 and CF_3Br plus 1 percent SF_6.

In CF_3Br plus 1 percent SF_6, two metal combinations showed significant reduction in friction and wear over results obtained in air (fig. 4). These metal combinations were M-1 tool steel on Hastelloy C and Stellite 98M2 on Hastelloy C. The cermet Kentanium K162B on Hastelloy C also gave much lower wear in CF_3Br plus 1 percent SF_6 than in air.

With CF_2Cl_2 plus 1 percent SF_6 as the lubricant, the best metal combination was a $7\frac{1}{2}$ percent silicon-nickel rider specimen in contact with a cobalt-base Rexalloy 33 disk (fig. 5). Of the metal combinations tested in the CF_2Cl_2 plus 1 percent SF_6, this particular combination showed the greatest reduction in friction and wear over reference runs made in air.

From the data presented in figures 4 and 5, the selectiveness of gas lubrication is readily seen. The effectiveness of a gas in reducing friction and wear depends on the metals with which it is used. In selecting materials for gas lubrication it is not sufficient to postulate the reaction product on only one of the slider metals although, as will be discussed later, one of the specimens may be of predominant importance.

Dichlorodifluoromethane Plus Sulfur Hexafluoride

The results obtained with some of the more effective alloy-gas combinations at 600° F indicated that these combinations should be studied over a broad temperature range. The data presented in figure 5 indicated that a $7\frac{1}{2}$ percent silicon-nickel rider in combination with Rexalloy 33 disk specimen was a good material combination in CF_2Cl_2 with 1 percent SF_6. These runs were repeated at various temperatures from 75° to 1200° F to indicate effectiveness of CF_2Cl_2 with 1 percent SF_6. The data are shown in figure 6. Friction was somewhat high at room temperature but was low (0.05) at 800° F. This extremely low friction coefficient indicates that molten surface films of reaction products may be present, as discussed for M-1 tool steel specimens in reference 5. The wear decreases rather rapidly from 75° to 800° F for $7\frac{1}{2}$ percent silicon-nickel on Rexalloy 33 (fig. 6); above 800° F the wear was relatively constant. This trend in wear was the reverse of that observed with M-1 tool steel (figs. 2 and 3). The disk specimen of Rexalloy 33 showed very little evidence of wear at 800° F (fig. 7). The presence of small agglomerates of condensed chlorides on the surface of the $7\frac{1}{2}$ percent silicon-nickel rider indicated the presence of a continuous surface film. Agglomerates of reaction products appear to have formed at the grain boundaries of the silicon nickel. The reaction mechanism involved has not been resolved but may include preferential reaction with silicon at the grain boundaries.

Dibromodifluoromethane

Although CF_2Br_2 was not used in the alloy-gas combinations at 600° F, the particular metal combinations that showed promise in CF_3Br with 1 percent SF_6 might be expected to be effectively lubricated by CF_2Br_2 because of the additional bromine. The data of figure 4 indicate that a good metal combination for lubrication with a bromine-containing gas would be Stellite 98M2 rider sliding against a Hastelloy C disk. This combination was run in CF_2Br_2 at various temperatures from 75° to 1200° F. The friction was within the range of what is considered effective boundary lubrication (0.20 or less)(fig. 8(a)). CF_2Br_2 boils at 76° F and the cylinder of gas had to be warmed slightly in a water bath to obtain the gas. In runs made at room temperature the gas may have condensed on the specimens, while at 200° F the CF_2Br_2 remained in the gaseous phase. The wear begins to increase above 600° F, which may be attributed to the limited corrosion resistance of Stellite 98M2 at elevated temperatures. The susceptibility of the rider to corrosion can have a pronounced effect on the wear. One method of reducing corrosion would be to reduce the bromine content in the lubricating gas from two atoms to one atom per molecule. This limits the quantity of halogen available for surface reaction. The optimum slider-material - gas combination for lubrication requires reactivity sufficient to give a protective surface film, but corrosive wear should not predominate.

Monobromotrifluoromethane Plus Sulfur Hexafluoride

Previous NACA data (ref. 5) involving similar experimental conditions have shown that one chlorine atom in a gas molecule is inadequate for effective boundary lubrication. The removal of a bromine atom from an analagous bromine-substituted gas molecule, however, is more easily achieved and thereby may provide effective lubrication. The benefits obtained with 1 percent SF_6 added to CF_2Cl_2, as described previously, suggest that the addition of SF_6 to CF_3Br might improve its lubrication characteristics.

A series of runs was made with Stellite 98M2 rider specimens sliding against Hastelloy C disks in an atmosphere of CF_3Br with 1 percent SF_6 at various temperatures up to 1200° F (fig. 8(b)). The friction values obtained at 1000° and 1200° F are higher than those obtained with either CF_3Br or SF_6 alone. This effect of the mixture giving increased friction bears further consideration. The wear decreased as the temperature was increased to 800° F. Above 800° F (to 1200° F) the wear was relatively constant.

The wear obtained with Stellite 98M2 rider specimens in sliding contact with Hastelloy C disks in CF_2Br_2 and in CF_3Br with 1 percent SF_6 is compared in figure 9. The wear shows opposing trends in the two gaseous atmospheres. The bromine content in CF_2Br_2 is such that the wear was constant to a temperature of 800° F, where corrosion begins to influence wear. The bromine made available in the decomposition of CF_3Br was sufficient for adequate lubrication at elevated temperatures without excessive corrosion, but wear was higher at temperatures below 800° F. Mixtures of CF_2Br_2 and CF_3Br may have merit for effective lubrication without objectionable corrosion over a greater temperature range. Figure 10 presents a photographic record of the appearance of the Stellite 98M2 rider and Hastelloy C disk specimens used in both CF_2Br_2 and CF_3Br with 1 percent SF_6 to temperatures of 1200° F. Corrosion was not severe at any temperature. At 1200° F, however, some corrosion products were observed but were not considered objectionable.

Iodotrifluoromethane

The encouraging results obtained with the bromine and chlorine substituted fluoromethanes as lubricants suggested that an analogous iodine compound might function in a similar manner. The gas CF_3I contains a single iodine atom and is one of the most stable iodine-containing organic molecules. This gas was tested for its thermal stability in contact with metal surfaces as well as for its ability to lubricate at temperatures of 70°, 600°, and 1000° F. In these experiments a $7\frac{1}{2}$ percent silicon-nickel rider specimen was in sliding contact with a Rexalloy 33 disk specimen. The friction and wear data obtained are presented in figure 11. The limited availability of the gaseous compound CF_3I restricted the number of experimental runs to three. The friction coefficient was nearly constant for the three temperatures investigated. The wear showed an increase at the higher temperatures (600° and 1000° F) reflecting the influence of corrosion.

Iodine

The increase in wear observed at 600° and 1000° F with CF_3I prompted a study with elemental iodine, I_2, to see if there existed a threshold level below which metals could be lubricated by iodine-containing gases without high-temperature corrosive wear. To obtain small quantities (approx. 200 parts per million) of iodine, argon gas was bubbled through an alcohol solution of iodine. With this source of iodine, friction and wear experiments were conducted at temperatures up to 1000° F. The alloy combination lubricated by iodine was $7\frac{1}{2}$ percent silicon-nickel rider sliding on a Rexalloy 33 disk. The data obtained are presented in figure 11. The data indicate that I_2 in small concentration is quite satisfactory in affording surface protection. X-ray diffraction examination of the surface film formed indicated that it was nickel iodide. The friction coefficient was less than 0.2 to a temperature of 800° F. At 1000° F the friction increases somewhat. The wear was low up to approximately 400° F where it began to increase. Reducing the iodine concentration in the gas should give lower wear at the higher temperatures. Although iodine provided effective lubrication, it does not appear to offer any advantages that cannot be obtained with a bromine- or chlorine-containing gas. Further, it is more difficult to obtain, expensive, and less stable than the comparable chlorine and bromine compounds.

SUMMARY OF RESULTS

The boundary lubrication of various materials with halogen-containing gases was studied from 75° to 1200° F. The following results were obtained:

1. Corrosion-resistant alloys were lubricated effectively by reactive gases at temperatures from 75° to 1200° F. The best of materials and gas combinations with regard to friction, wear, and corrosion resistance varied with the temperature level. Thus, the optimum conditions for gas lubrication are highly selective.

2. Bromine-substituted gases were effective lubricants for nickel-base alloys (e.g., Hastelloy C). A good lubricant for Stellite 98M2 riders and Hastelloy C disks over the entire temperature range was CF_2Br_2. Especially effective from a wear standpoint at temperatures below 600° F was CF_2Br_2. Monobromotrifluoromethane plus SF_6 gave very low wear from 800° to 1200° F. Mixtures of the gases may have merit.

3. Chlorine-substituted gases were especially effective lubricants for cobalt-base alloys (e.g., Rexalloy 33).

4. The addition of SF_6 as a minor (1 percent by volume) constituent in gaseous mixtures with chlorine or bromine-substituted methane derivatives was generally beneficial. The additive improved the surface film formation properties of the other gases so that run-in at low temperature operation was less critical.

5. Iodine and an iodine-substituted gas were found to afford surface protection for a nickel alloy sliding on a cobalt alloy up to 1000° F. No advantage was gained, however, with the iodine-containing gas that cannot be obtained with a bromine- or chlorine-substituted gas.

6. Corrosion problems were practically eliminated by the use of various high-temperature alloys selected in preliminary corrosion studies with CF_2Cl_2. Bromine-substituted gases were not exceedingly corrosive to the alloys at temperatures to 1200° F.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 11, 1958

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TABLE I. - ALLOY COMPOSITIONS

Material	Source	Typical composition									Average hardness
		Fe	C	Si	Ni	Cr	Co	W	Mo	Other	
M-1 tool steel	Allegheny Ludlum Steel Corp.	86.0	0.80	0.30		4.0		1.50	8.50	V,Mn	Rockwell C-63
440-C stainless steel	Allegheny Ludlum Steel Corp.	78.5	1.1	1.0		17.0			.75	S,P,Mn	Rockwell C-54
"L" Nickel	International Nickel				99.4						Brinell 210
Cast Inconel		6.0		2.0	77.75	13.5				Cu,Mn	Brinell 175
Inconel S		8.40	.25	6.65	67.88	17.30					Rockwell B-93
Inconel X		5-9	.08	.50	70.0	15.0				Mn,S,Al,Cb	Rockwell C-29
$7\frac{1}{2}$ Percent Si-Ni				7.5	92						Rockwell C-33
"G" Nickel				4.5	94-95						Rockwell B-47
Hastelloy C	Haynes Stellite	6.0			52.0	17.0		5.0	19.0	Mn,Si	Rockwell C-23
Hastelloy R-235		10.0	.16	1.0	66.0	14-17	2.50		5.5	Mn,Al,Ti	Rockwell C-28
Multimet		30.0	.15	.50	20.0	21.0	20.0	2.0	3.0	N,Cb	Rockwell C-16
Stellite 21		.7	.22	.53	2.8	27.4	62.2	5.5		Mn	Rockwell C-30
Stellite 98M2		3.0	2.0	1.0	3.5	30.5	40.0	18.5		B,V	Rockwell C-52 to 57
Stellite Star J (Rexalloy 33)		3.0	2.4	1.0	2.5	32.0	43.0	17.0			Rockwell C-52 to 55
Molybdenum (arc cast)	Climax Molybdenum Corp.								99.+		Brinell 160-185
K-162B Kentanium	Kennametal Inc.				25.0				5.0	64.0 TiC; 6.0 CbC	
Titanium	NASA Stock		.2							98.4 Ti	Rockwell G-92

TABLE II. - CORROSION STUDY

[Gas mixture: CF_2Cl_2, 1.0 liter/min; SF_6, 0.01 liter/min]

Material	Corrosion resistance		
	Room temperature	600° F	1200° F
M-1 tool steel	Excellent[a]	Fair[b]	Poor[c]
440-C stainless steel		Fair	Poor
"L" Nickel		Good[d]	Fair
Cast Inconel		Good	Fair
Inconel S		Good	Fair
Inconel X		Excellent	Good
$7\frac{1}{2}$ Percent Si-Ni		Excellent	Good
"G" Nickel		Excellent	Good
Hastelloy C		Excellent	Good
Hastelloy R-235		Excellent	Good
Multimet		Good	Poor
Stellite 21		Good	Fair
Stellite 98M2		Excellent	Poor
Stellite Star J (Rexalloy 33)		Excellent	Poor
Molybdenum (arc cast)		Good	Poor
K-162B Kentanium		Good	Fair
Titanium		Fair	Poor

[a]No visible change.

[b]Tightly bonded layer.

[c]Profuse surface crystal growth.

[d]Surface coloration.

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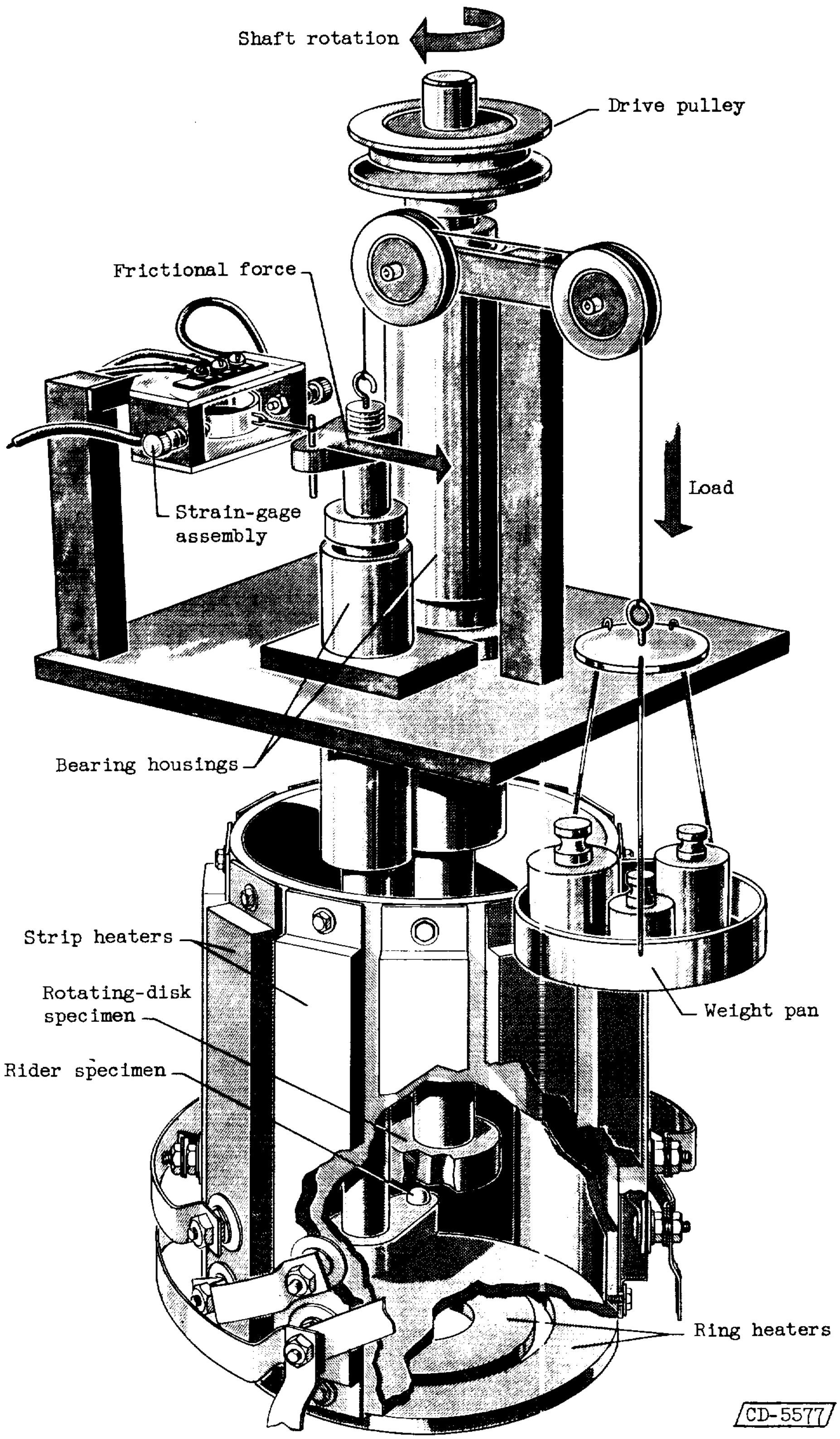


Figure 1. - Friction apparatus.

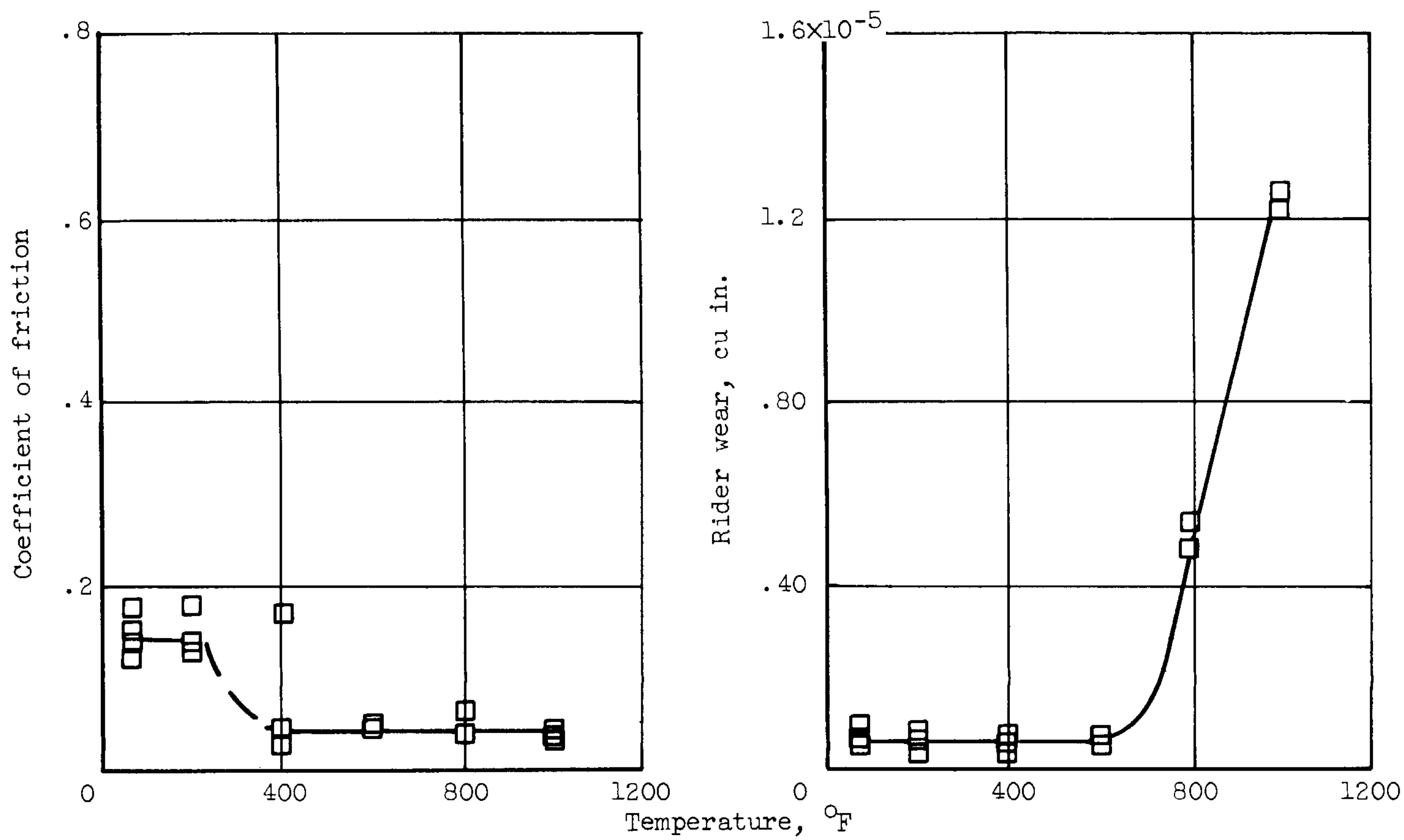


Figure 2. - Friction and wear of M-1 tool steel on M-1 tool steel. Gas, CF_2Cl_2; sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour.

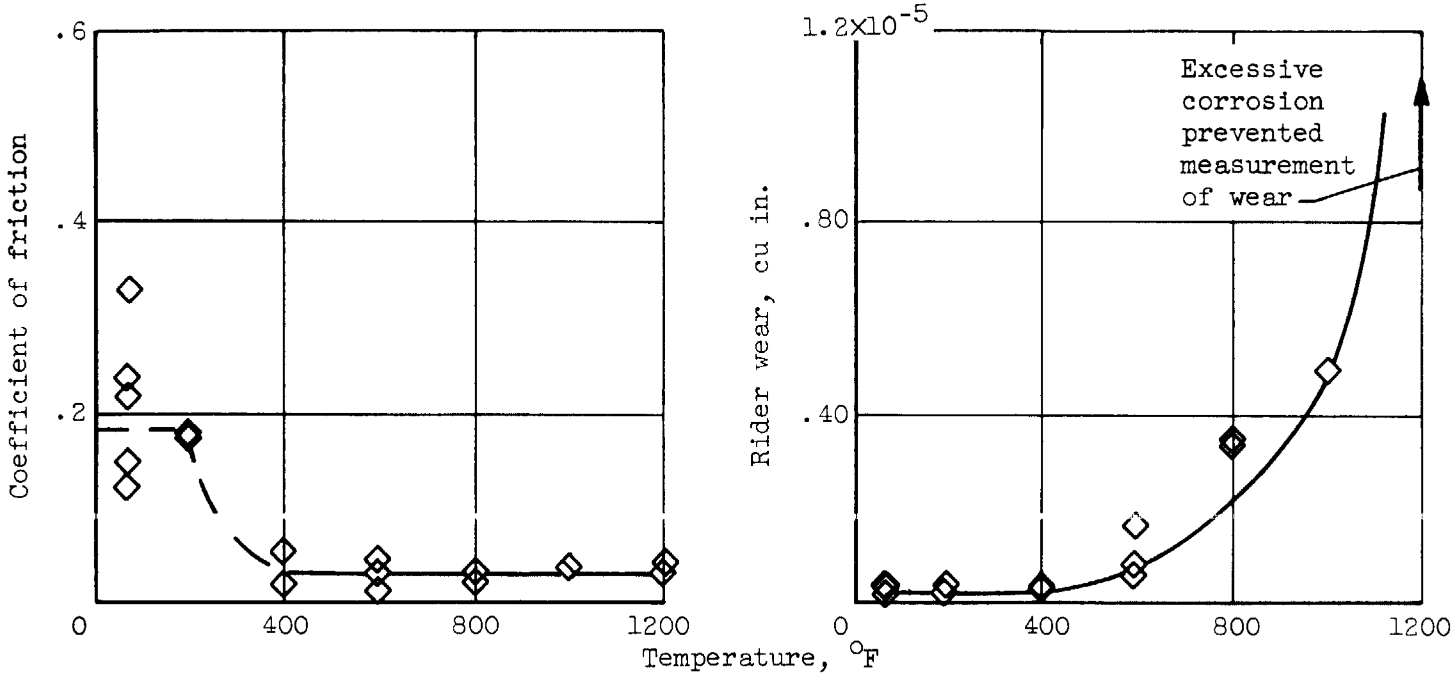
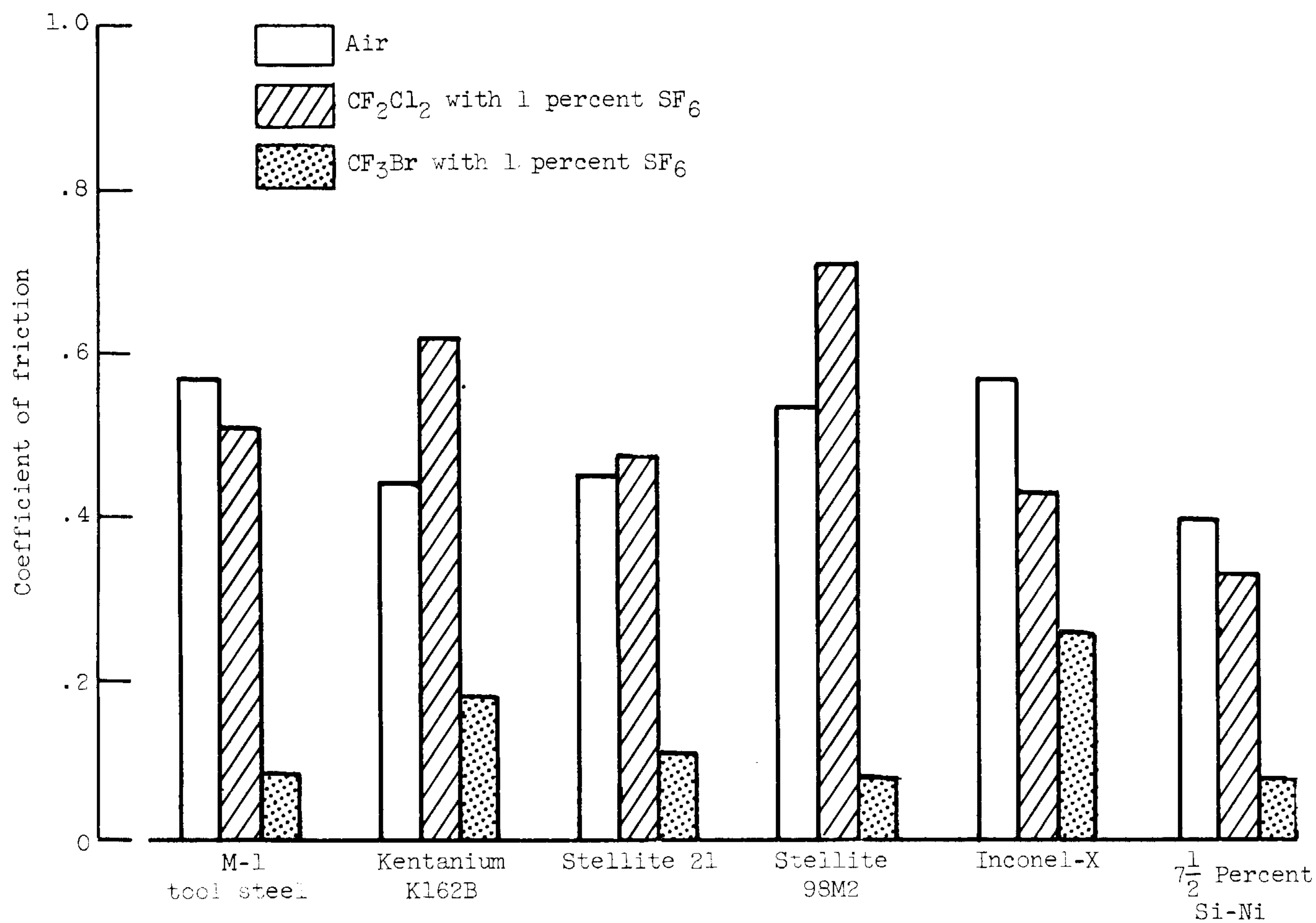
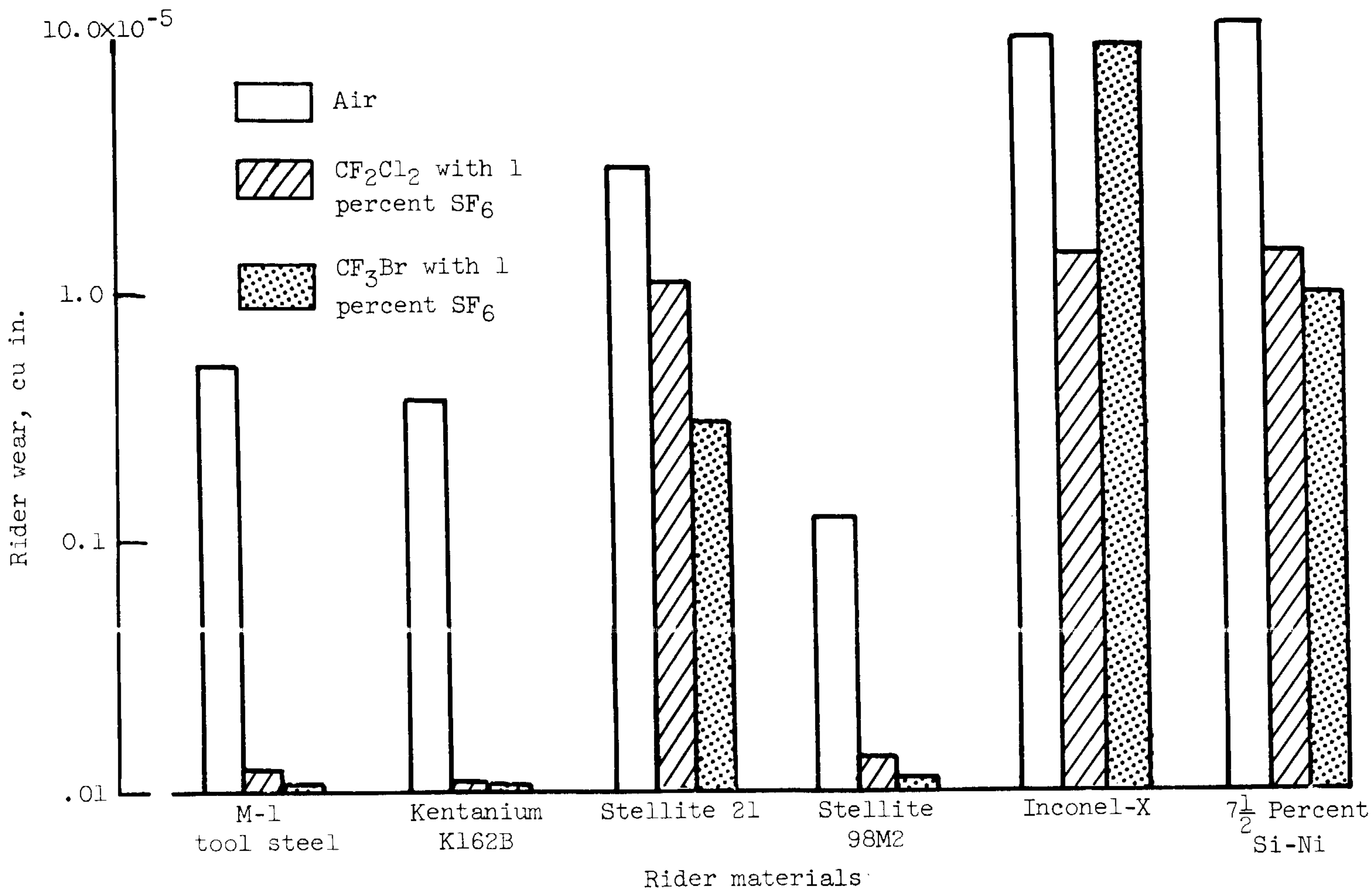


Figure 3. - Friction and wear of M-1 tool steel on M-1 tool steel. Gas, CF_2Cl_2 with 1 percent SF_6; sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour.



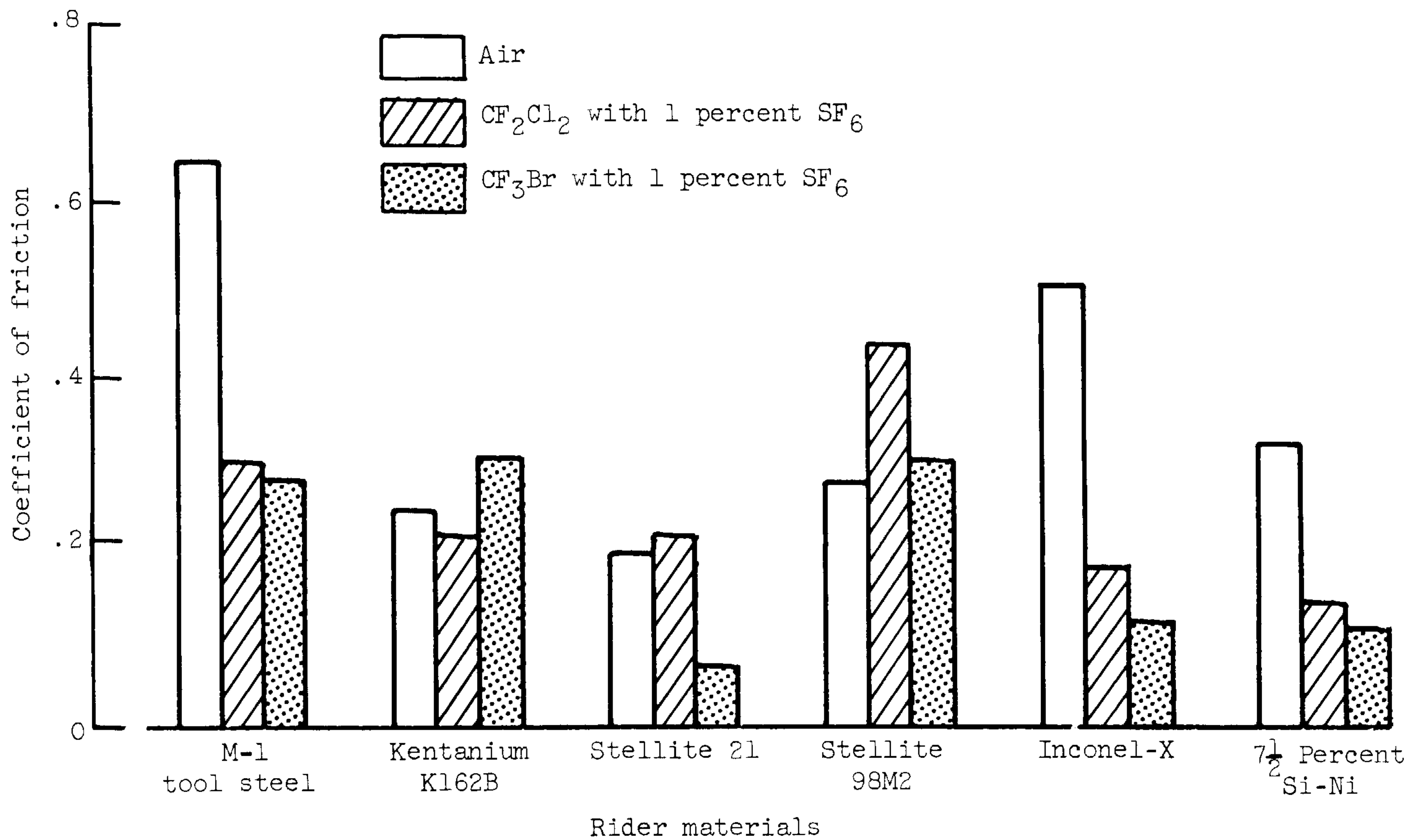
(a) Coefficient of friction. Hastelloy C disk.

Figure 4. - Effects of various rider materials on disks. Sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour; temperature, 600° F.



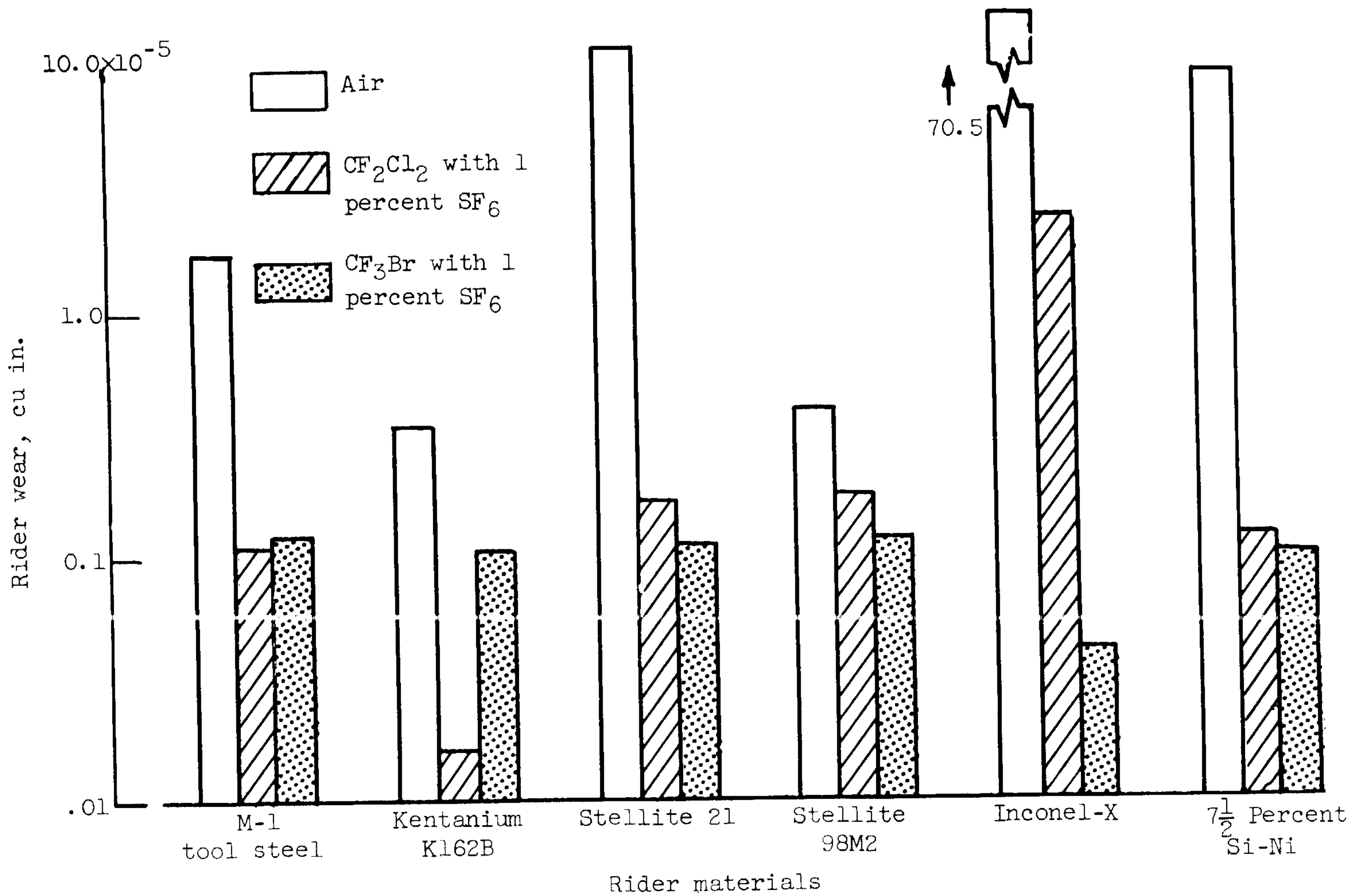
(b) Wear. Hastelloy C disk.

Figure 4. - Concluded. Effects of various rider materials on disks. Sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour; temperature, 600° F.



(a) Coefficient of friction. Rexalloy 33 disk.

Figure 5 - Effects of various rider materials on disks. Sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour; temperature, 600° F.



(b) Wear. Rexalloy 33 disk.

Figure 5. - Concluded. Effects of various rider materials on disks. Sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour; temperature, 600° F.

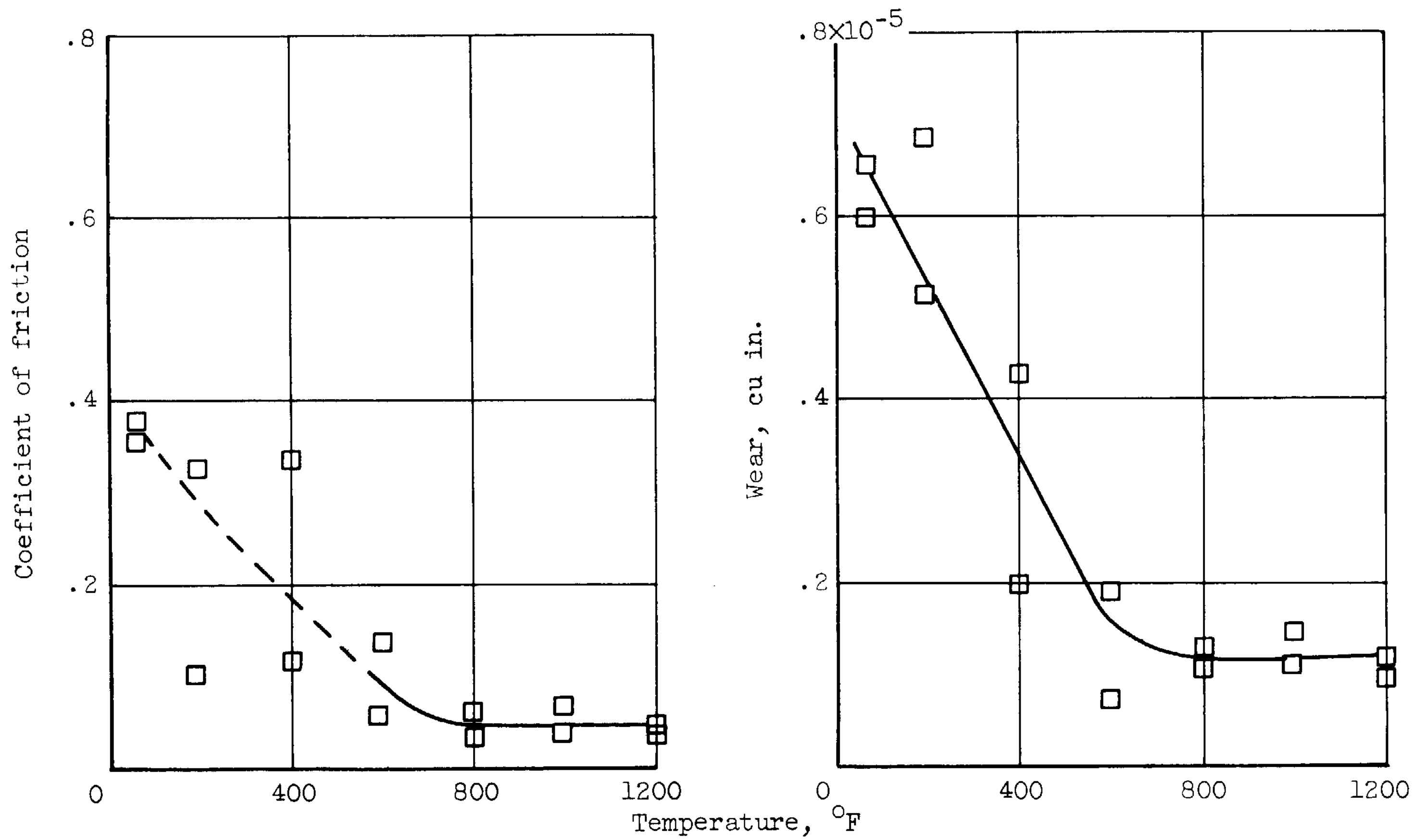


Figure 6. - Friction and wear of $7\frac{1}{2}$ percent Si-Ni on Rexalloy 33. Gas, CF_2Cl_2 with 1 percent SF_6; sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour.

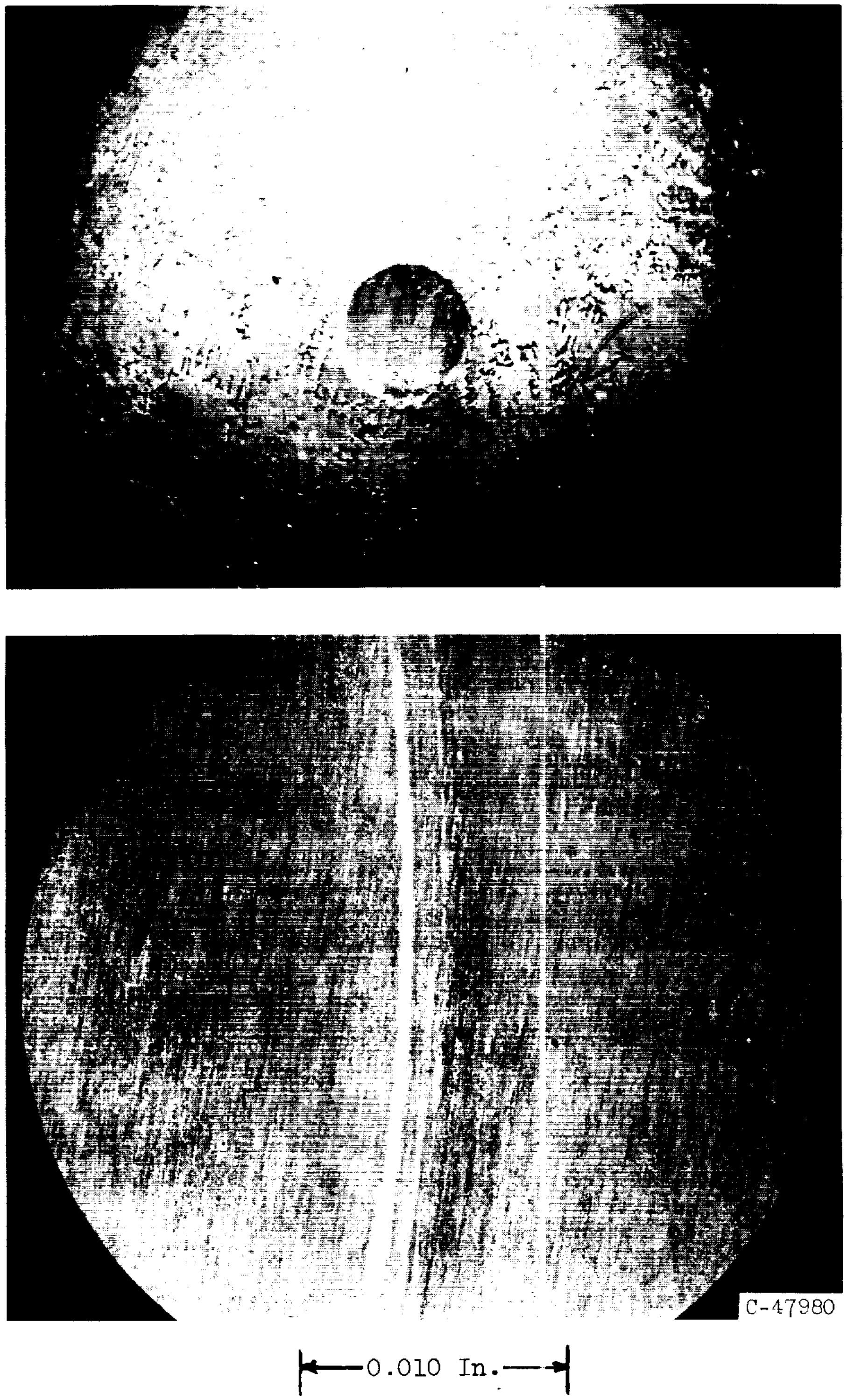
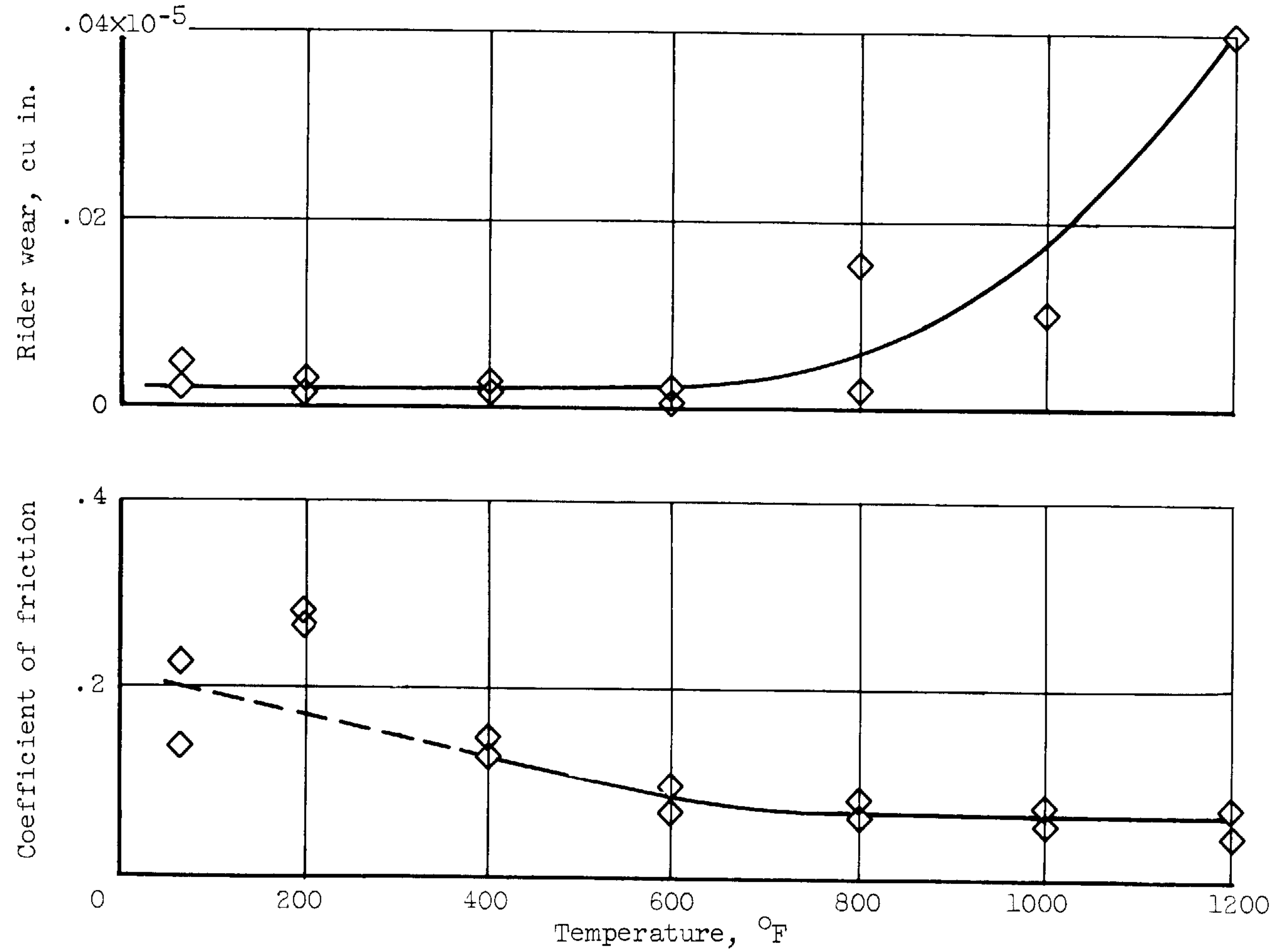
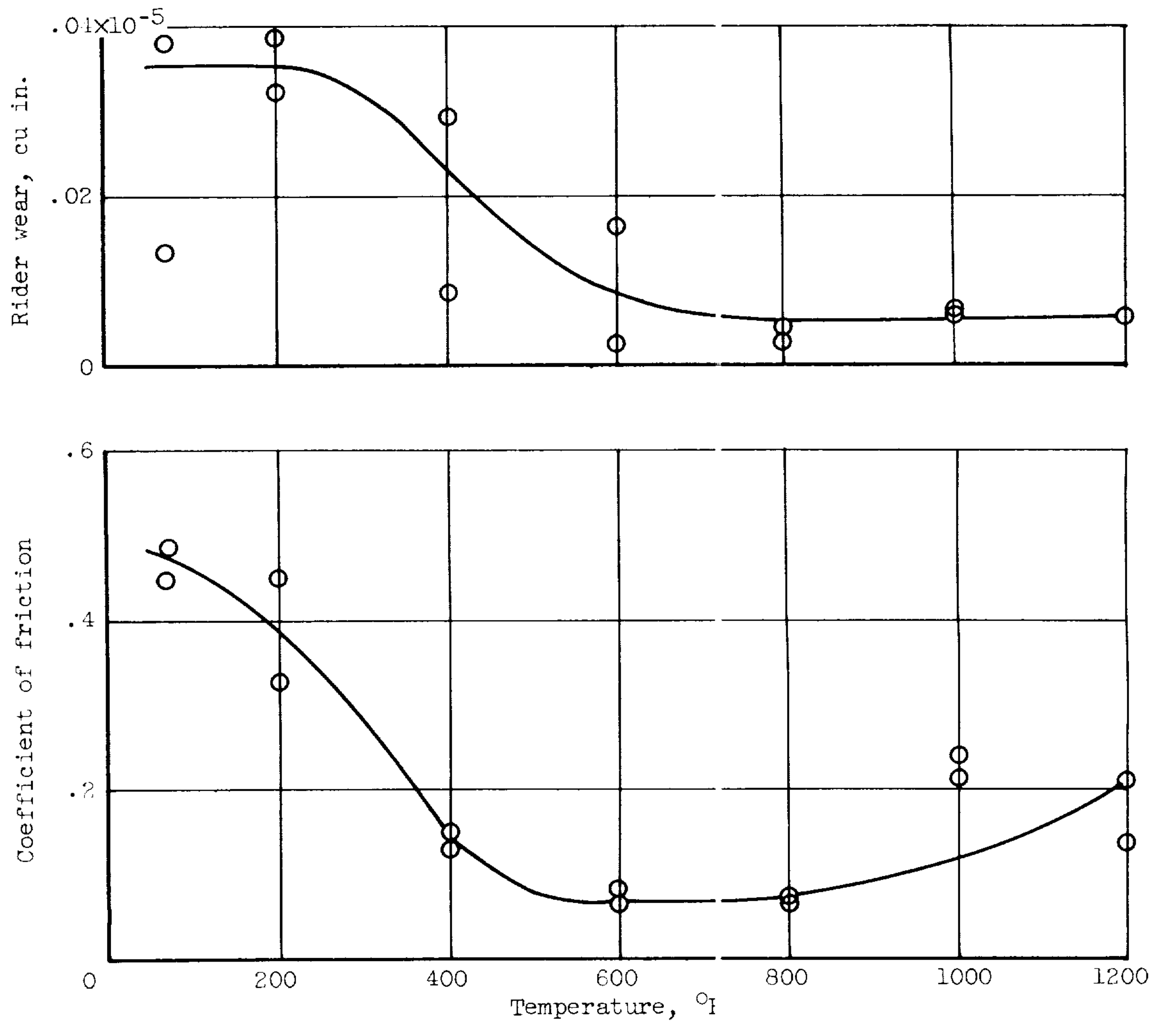


Figure 7. - Samples of 7 1/2 percent Si-Ni rider and Rexalloy 33 disk in CF_2Cl_2 with 1 percent SF_6 at 800 °F.



(a) Gas, CF_2Br_2.

Figure 8. - Friction and wear of Stellite 98M2 on Hastelloy C. Sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour.



(b) Gas, CF_3Br plus 1 percent SF_6.

Figure 8. - Concluded. Friction and wear of Stellite 98M2 on Hastelloy C. Sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour.

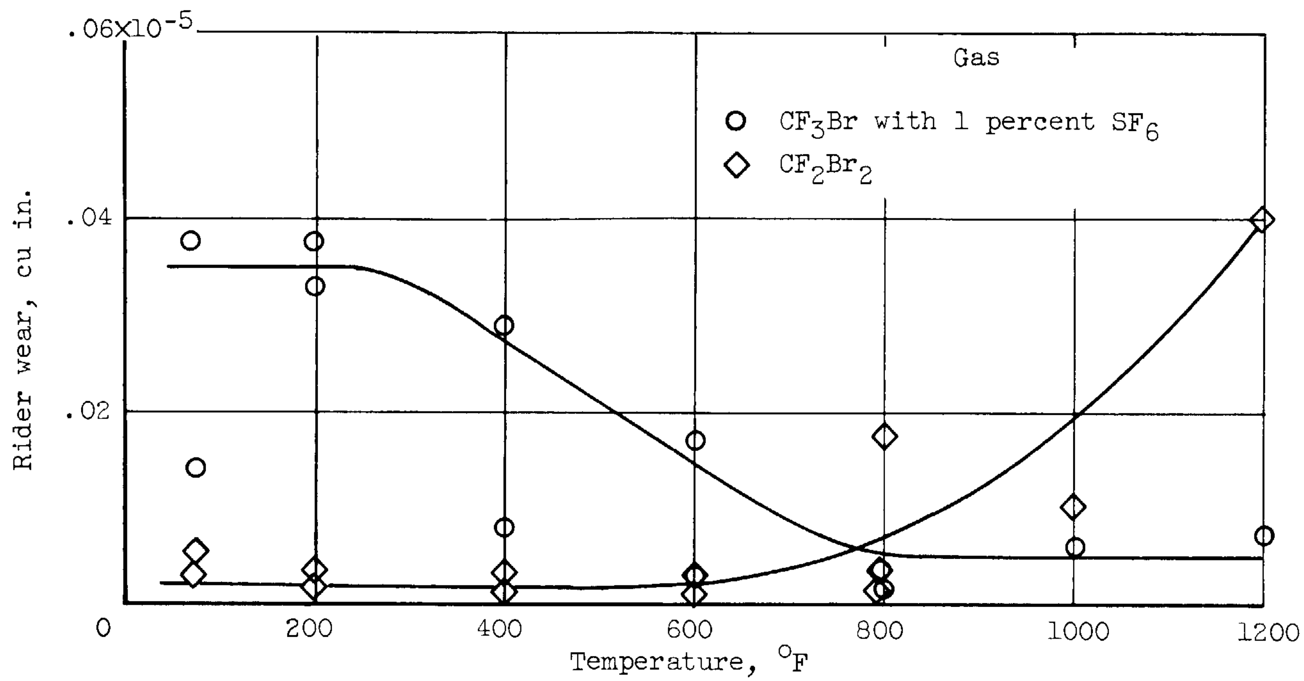
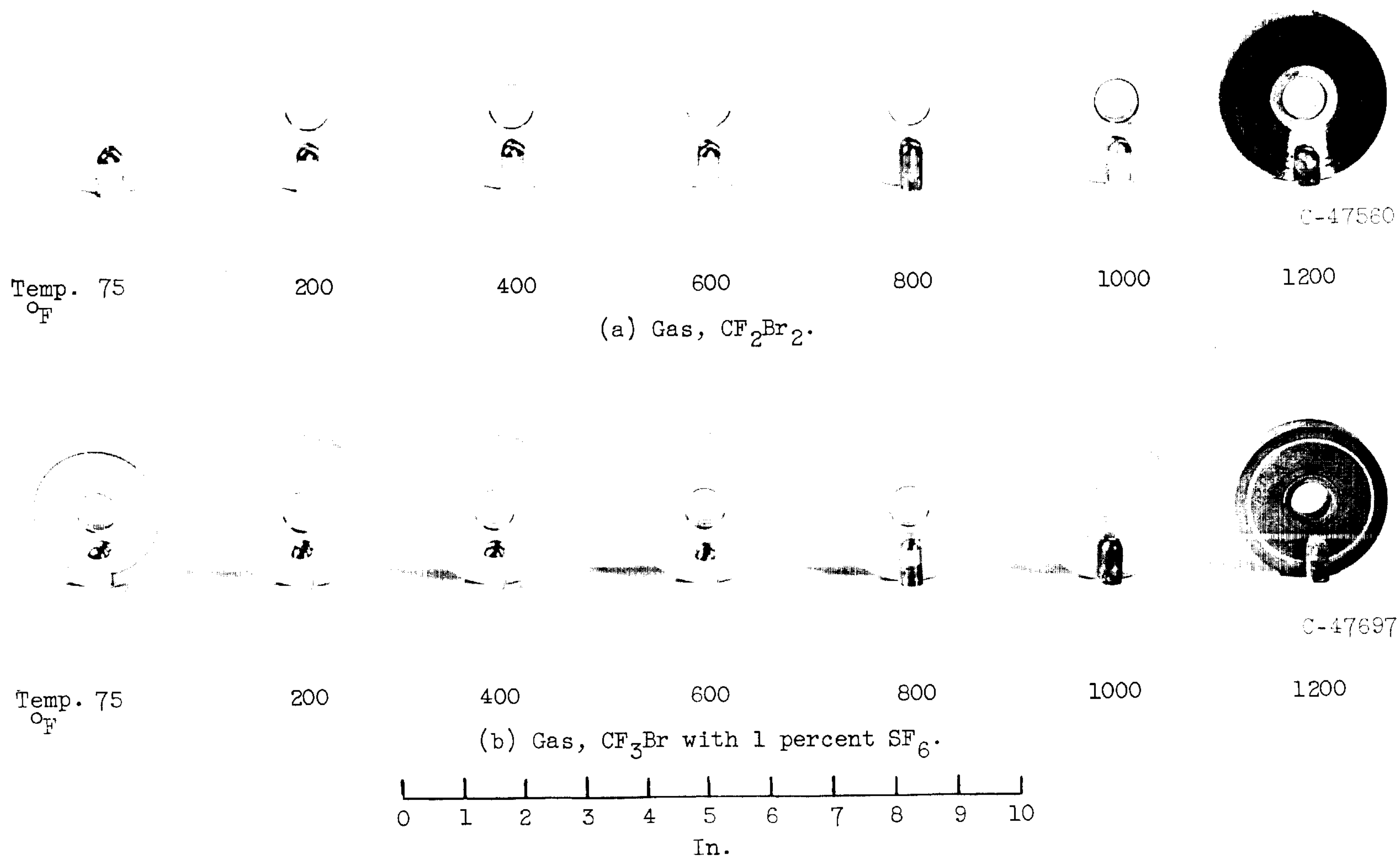


Figure 9. - Comparison of wear data for Stellite 98M2 rider on Hastelloy C disk. Sliding velocity, 120 feet per minute; load, 1200 grams; time, 1 hour.



(a) Gas, CF_2Br_2.

(b) Gas, CF_3Br with 1 percent SF_6.

Figure 10. - Samples of Stellite 98M2 riders and Hastelloy C disks after runs.

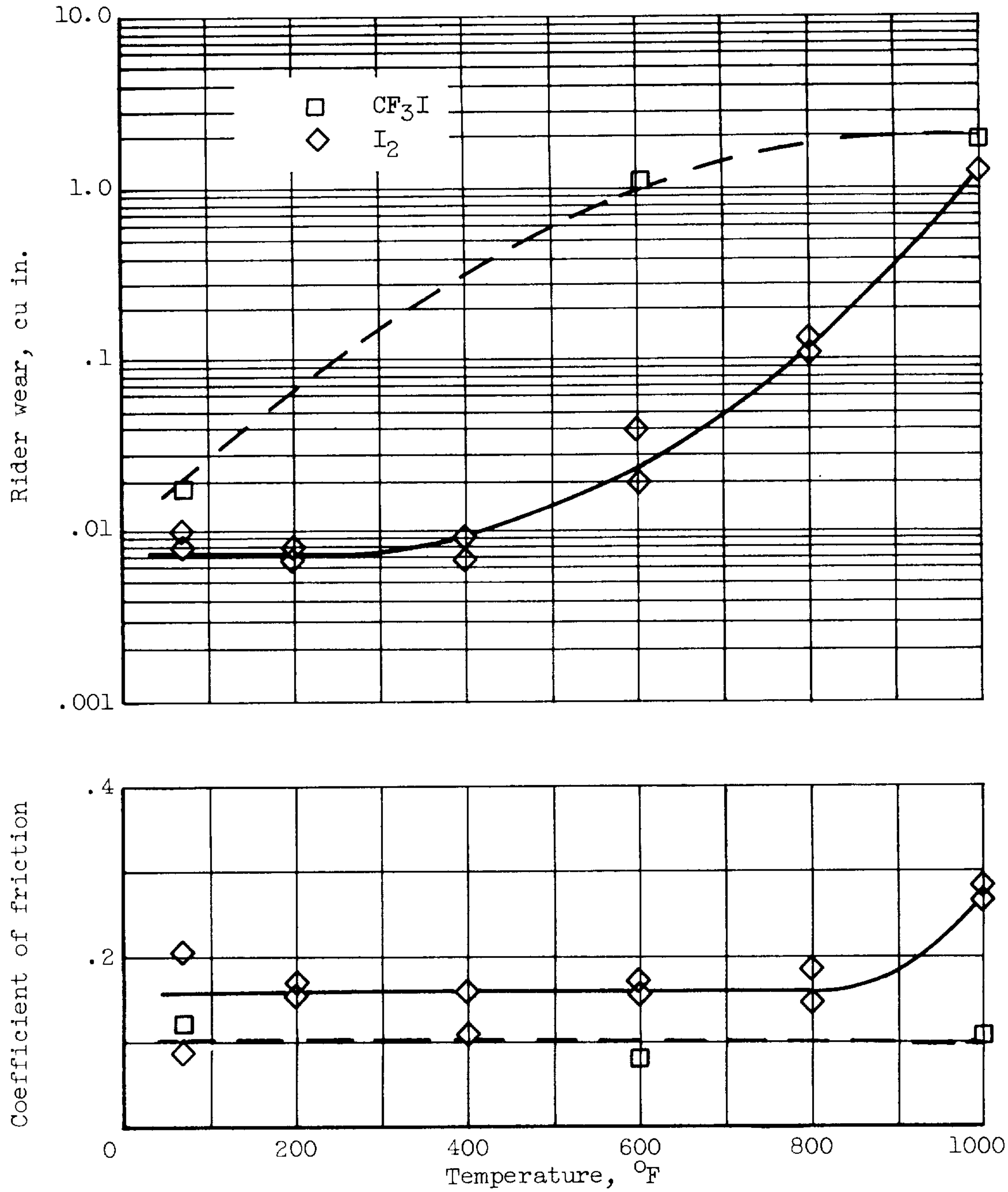


Figure 11. - Friction and wear of $7\frac{1}{2}$ percent Si-Ni rider sliding on Rexalloy 33 disk at various temperatures. Lubricants, CF_3I and I_2; sliding velocity, 120 feet per minute; load, 1200 grams; duration of test, 1 hour.