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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1547

Cold-Welding Test Environment

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Preface

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Acknowledgment

Thanks are due Mr. R. L. Hammel of TRW for performing the experimental work reported herein, Messrs. J. Stephens, R. Bartera, and W. Owen for support during the Molsink test phase, Mr. D. T. Clift of AFRPL for providing the test equipments, Mr. T. Gindorf for his advice, Messrs. J. Schlue, D. Hess, and G. Ervin for their comments, and Mrs. W. Govett for preparing the report manuscript.

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Abstract

Spacecraft designers concerned with the development of excessive friction or cold-welding in mechanisms with moving parts operating in space vacuum for an extended period of time should consider cold-weld qualification tests. To establish requirements for effective test programs, a flight test was conducted and compared with ground test data from various facilities. Sixteen typical spacecraft material couples were mounted on an experimental research satellite (ERS-20), where a motor intermittently drove the spherical moving specimens across the faces of the fixed flat specimens in an oscillating motion. Friction coefficients were measured over a period of 14-month orbital time. Surface-to-surface sliding was found to be the controlling factor of generating friction in a vacuum environment. Friction appears to be independent of passive vacuum exposure time. Prelaunch and postlaunch tests identical to the flight test were performed in a TRW oil-diffusion-pumped ultrahigh vacuum (1.33×10^{-6} N/m^2) chamber. Only 50% of the resultant data agreed with the flight data owing to pump oil contamination. Subsequently, identical ground tests were run in the JPL Molsink, a unique ultrahigh vacuum facility, and a TRW ion-pumped vacuum chamber. The agreement (90%) between data from these tests and flight data established the adequacy of these test environments and facilities.

Cold-Welding Test Environment

I. Introduction

Spacecraft mechanisms with moving mechanical parts are frequently required to operate in the high vacuum of space for an extended period of time. A significant concern of a designer is the possibility of metal-to-metal cold-welding or significant increase in friction in areas where one surface slides or rolls over another. Lubrication is usually applied to avoid excessive friction, which precedes cold-welding. Naturally formed oxides tend to reduce friction and serve as lubricants. It has been found that surfaces stay lubricated in passive vacuum environment except where abrasion occurs due to surface rubbing. In some cases, lubrication cannot be used for fear of contaminating optical surfaces, which further increases the potential of cold-welding.

Although numerous studies have been done, the mechanism of cold-welding is still not well understood. A number of factors can affect the behavior of surfaces in vacuum. Load, degree of contamination, temperature, material properties, lubrication, and the molecular flux environment are important parameters. The lack of quantitative understanding of the interrelationship of these parameters makes it difficult to predict the friction behavior of a spacecraft mechanism operating in space. Consequently, ground testing to qualify spacecraft hardware with a potential cold-welding problem becomes a valuable means of gaining confidence in design adequacy.

II. Summary

A cold-welding program was initiated in 1969 to determine the proper test environment for qualifying spacecraft mechanisms. The specific objectives were:

(1) Determine if the JPL Molsink, a unique vacuum facility, can simulate space sufficiently well for performing cold-welding tests.

(2) Once the adequacy of Molsink is established, determine if the degree of sophistication characterized by the Molsink is necessary for adequate cold-welding tests; that is, identify the minimum environmental test requirements.

To achieve objective (1), a 10-day ground test was performed in the Molsink (Ref. 1) to provide a direct comparison with the in-space friction data (Refs. 2–5) previously acquired by the Air Force Rocket Propulsion Laboratory (AFRPL) Experimental Research Satellite No. 20 (ERS-20). The ground test used the same test material couples and equipments. The flight data were acquired over a 14-month period. Prelaunch test data were taken in a TRW oil-diffusion-pumped ultrahigh vacuum chamber (1.33×10^{-6} N/m^2). Additional postlaunch ground tests were conducted in a TRW oil-pumped chamber which included tests to evaluate the effects of ultraviolet radiation, inert gases, oxygen, water vapor, laboratory air, and controlled oil vapor contamination. Only 50% of the ground data agreed with the flight data. The Molsink adequacy was established by the good agreement (90%) between the Molsink and flight data.

Objective (2) was to determine if the degree of sophistication characterized by the Molsink was required. This was a very important question because Molsink is a unique research facility, costly to construct and operate. It is impractical to perform spacecraft mechanism testing in large quantities in this facility. Therefore, if a less sophisticated class of facilities could provide an adequate test environment, many of the problems of uniqueness, availability of facilities, and high cost could be eliminated for projects. Facilities considered appropriate for evaluation included chambers equivalent to the JPL facility in terms of cleanliness, but with slightly varied environments, e.g., a facility without a moltrap (a cryogenic inner chamber within the Molsink), higher sink temperature, different pressure levels, etc. While several vacuum chambers were under consideration, a cold-welding test on an electric contactor (Ref. 6) performed by AFRPL strongly indicated that an ion-pumped facility might be adequate. To verify its ability, a test (Ref. 7) was performed in a TRW ion-pumped vacuum chamber. The results showed that this type of facility could provide an adequate test environment. The facility was electronically pumped. The residual gases were ionized and then adsorbed by the chamber wall. Adsorption was enhanced by titanium sublimation pumping. Rough pumping was accomplished by cryogenic sorption pumps. Consequently, the danger of pump oil contamination was totally eliminated. Ion-pumped vacuum facilities can be found in most aerospace organizations. Thus, this research finding concludes that adequate cold-welding test environments exist wherever ion-pumped (no oil system) facilities are found.

Tests have established the adequacy of an ion-pumped vacuum (1.33×10^{-6} N/m^2) for clean test items such as the friction module. The friction module does not produce oily, long chain hydrocarbons nor does it outgas excessively to make it difficult to maintain partial pressure at 1.33×10^{-6} N/m^2 or less at all times during test. Potential spacecraft test candidates such as science instruments are as clean as the friction module. Other spacecraft parts and test equipment in vacuum, including cables, potting compounds, etc., are required to be non-oil-producing and with low outgassing rate to avoid contaminating optics. In some cases, spacecraft parts are preconditioned. However, it is conceivable that some test items may outgas sufficiently or small leaks may develop in the vacuum system during test, causing the partial pressure to exceed 1.33×10^{-6} N/m^2 and thus rendering the test environment inadequate. Consequently, tests may have to be aborted. It is therefore advisable to determine the minimum acceptable test environment for all test items.

A test was performed in an ion-pumped vacuum which was modified by the controlled introduction of six gases: argon, carbon dioxide, methane, nitrogen, oxygen, and water, the common residual gas species in a vacuum system. Sliding friction data were taken under partial gas pressure ranging from 1.33×10^{-3} to 1.33×10^{-5} N/m^2 of each of the test gases. The data were compared to previous orbital, Molsink, and ion-pumped friction data. In two out of 16 material pairs (Co $\times$ Be, Co $\times$ WC), the maximum friction force attained appears controlled by the gas introduction. Selective influence of particular gas introductions was noted for two additional pairs (WC $\times$ Al_2O_3, Co $\times$ Ag). Other comparative data suggest the quantities and species used had little controlling influence on the frictional behavior of the remaining pairs.

It has been observed during tests that surface-to-surface sliding is the controlling factor of generating friction in a vacuum environment. Friction appears to be independent of passive vacuum exposure time. Therefore, a cold-welding test can be accelerated by using the mechanical sliding mission requirement of the mechanism as the primary control test parameter in simulation tests.

III. Approach

Through literature search and consultation with experimenters in the field, it was found that AFRPL has performed several cold-welding tests, including a flight test. By virtue of common objectives, a JPL–AFRPL joint research program was set up to determine the adequacy of test environment for cold-welding. JPL thus gained access to the AFRPL extensive flight and test background.

The approach of the program was to perform a series of tests to provide direct comparisons between ground test data and flight data. The flight data were secured over a one-year orbital time on satellite ERS 20. Active runs were made intermittently while the two friction modules produced reciprocating sliding motion between 16 pairs of frictional surfaces, each of a different material combination. The 10-day ground tests were designed to duplicate the flight experiment, except that the passive dwell-time between active runs was scaled down. The reduction of passive dwell-time was aimed at developing a valid method of accelerating a cold-welding test.

Because of the poor correlation between oil-pumped vacuum data and flight data acquired by TRW for AFRPL, the JPL Molsink was used for the next cold-welding test. As a result of the Molsink test success, a much less sophisticated ion-pumped vacuum facility was used to determine whether it can also provide an adequate test environment. Subsequently, a test was performed in a modified vacuum environment to determine how sensitive the ion-pumped vacuum environment was to residual gases caused by outgassing. The cold-welding program approach is shown in Fig. 1.

IV. Friction Module

Each friction module (Figs. 2–4) provides the mechanical structure to test eight specimen pairs. A self-contained dc drive motor and cam follower simultaneously drives eight moving specimens, which are individually mounted on the end of the compound flexure arms, across the faces of eight fixed specimens in an oscillating motion. Individual strain gage sensors for each test pair allow measuring a real-time analog force signal of both the drag and normal forces. Initial normal forces are set by adjustment of the individual moving sample holders at the end of their flexure arm. Adjustment of the fixed specimen alignment with respect to the moving arm is provided by adjustment nuts at the outboard edge of the fixed specimen support webs.

V. Test Materials

The primary criterion applied in the selection of the test material couples for the ERS 20 flight test was to provide a cross section of material combinations whose friction might be responsive to variations in the test environment. Four general classes were used:

(1) Metals and alloys.

(2) Thin film lubricants.

(3) Inorganic compounds.

(4) Polymers.

The 16 material couples are listed and defined in Table 1.

Table 1. Friction test materials

Class	Rider	Flat
1	440C SS	Boron nitride (NB)
1	Cobalt (Co)	Cobalt (Co)
1	Cobalt (Co)	Beryllium (Be)
1	Aluminum (Al)	Beryllium (Be)
2	Tungsten carbide (WC)	Gold plate (Au/52100)
2	440C SS	Burnished tungsten diselenide (WSe_2/17-4PH)
2	Cobalt (Co)	Silver plate (Ag/17-4PH)
2	440C SS	Burnished natural molybdenum disulfide (MoS_2/17-4PH)
2	440C SS	Burnished synthetic molybdenum disulfide (MoS_2/17-4PH)
3	Tungsten carbide (WC)	Tungsten carbide (WC)
3	440C SS	Tungsten carbide (WC)
3	Tungsten carbide	Aluminum oxide (bulk Al_2O_3)
3	440C SS	Boron nitride (BN)
3	Cobalt (Co)	Tungsten carbide (WC)
4	440C SS	15% glass-filled Teflon (PTFE)
4	440C SS	Polyimide (Vespel SP21)

VI. Test Facilities

A. TRW Oil-Diffusion-Pumped Vacuum Facility

The test vacuum facility consists of a double-wall ultrahigh vacuum chamber. The outer guard vacuum employs conventional O-ring seals. The 0.226-m^3 inner ultrahigh vacuum chamber utilizes copper shear seals. When the inner chamber is clean, dry, and empty, it is capable of operation at 1.33×10^{-8} N/m^2 measured with nude ion gages mounted within the chamber itself. The inner chamber and main trap regions have bakeout heaters mounted on the guard vacuum side. Likewise, traced copper cooling lines and cryogenic reservoirs are located

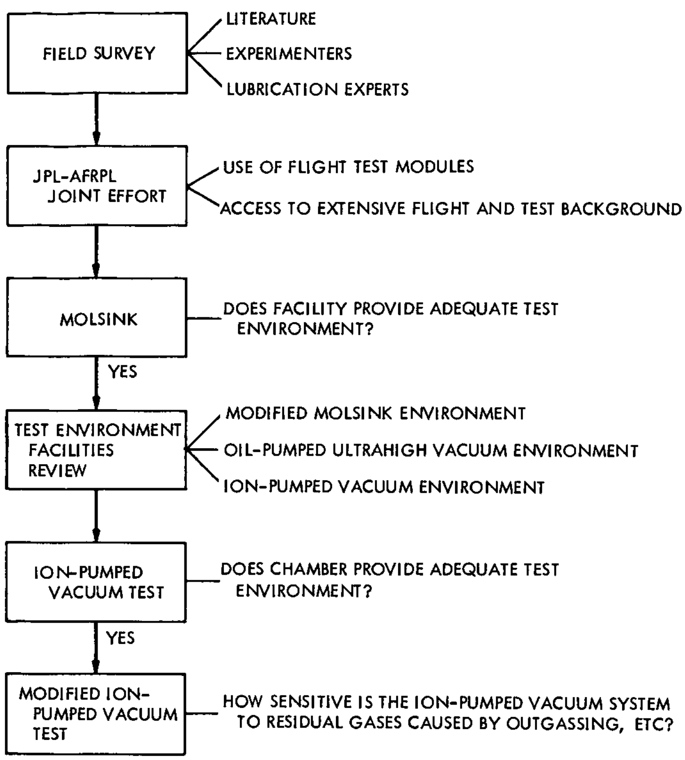

Fig. 1. Cold-welding program approach

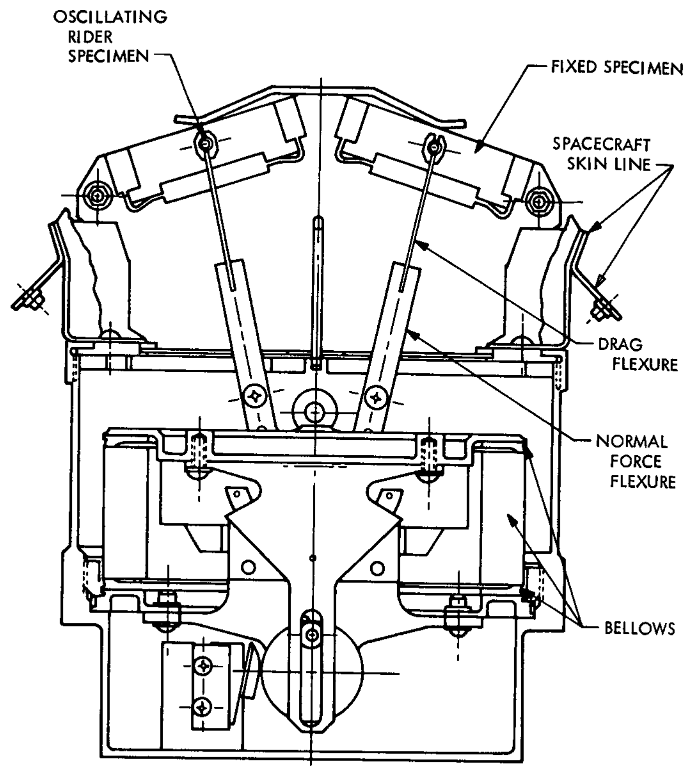

Fig. 2. Friction experiment, front cutaway view

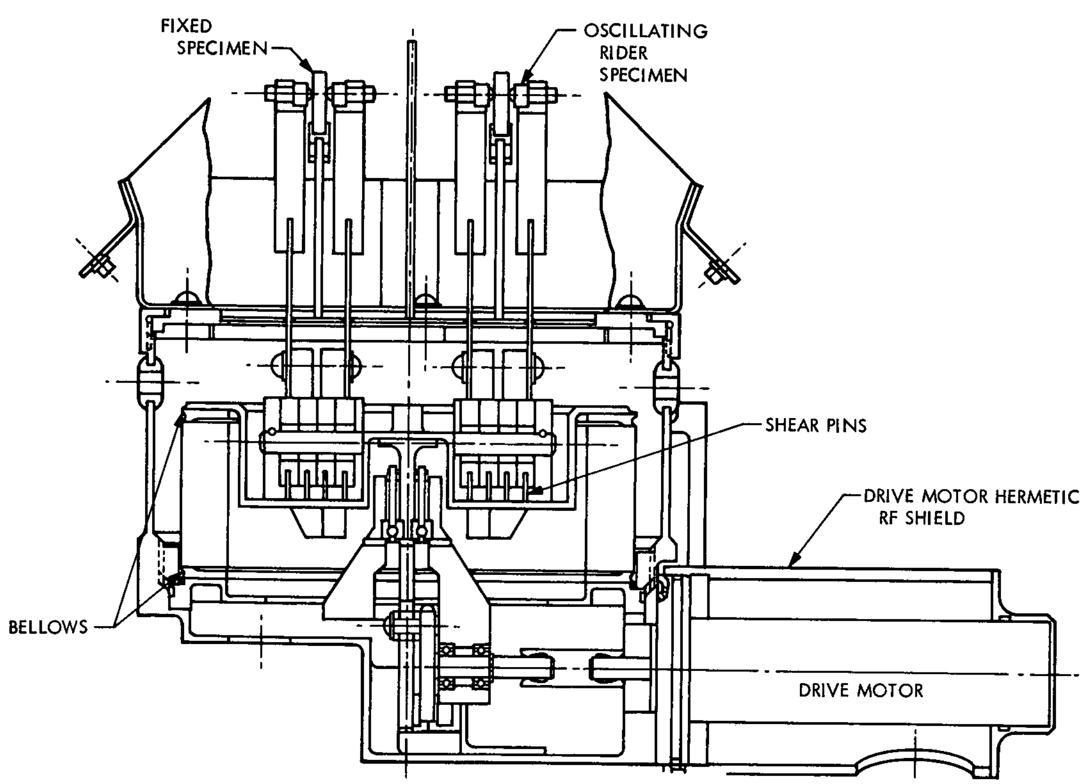

Fig. 3. Friction experiment, side cutaway view

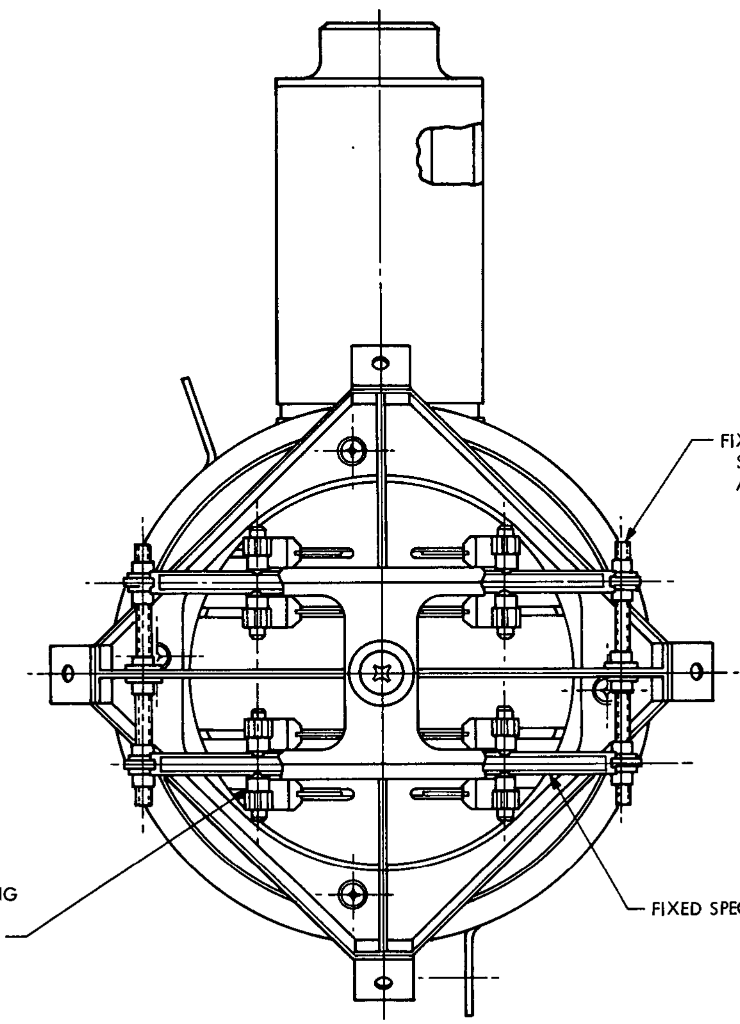

Fig. 4. Friction experiment, top view

on these surfaces. The design allows for differential bakeout up to 400°C and cooldown to liquid nitrogen temperatures.

The pumping system for this facility consists of two series oil-diffusion pumps which are extensively trapped. Figure 5 schematically shows the pumping system for the inner chamber. The trapping system consists of the dual-chevron trap design over the primary diffusion pump and the LN_2 flood trap of the right-angle elbow design. The diffusion pump oil used in the facility is DC 704.

B. JPL Molsink Facility

The Molsink facility at JPL (Fig. 6) was designed to provide a close simulation of the vacuum and cold sink of space for surface effects testing. Cryopumping is accomplished by a 2.44-m-diameter spherical molecular trap (moltrap) of wedge-fin configuration which was constructed of 0.041-cm-thick aluminum sheets that are spot-welded to the aluminum tubes. The tubes are cooled to below 14°K by helium supplied by a 1000-W helium refrigerator. The angles of the fins are such that their projections are tangent to a 25.4-cm sphere at the center of the moltrap, a configuration that has been shown to provide an order of magnitude capture improvement over a smooth-wall chamber when the test item gas load is from within the 25.4-cm spherical volume. It has been computed that only 4 of every 10,000 molecules of O_2, N_2, Ar, CO, and CO_2 emitted from a 25.4-cm spherical 300°K test item would restrike it.

Chemical pumping is accomplished by an electron-beam titanium sublimator mounted on the inner door of the chamber and used to coat nearly the entire moltrap at intervals during a test. This greatly increases the adsorption rate for H_2 and O_2.

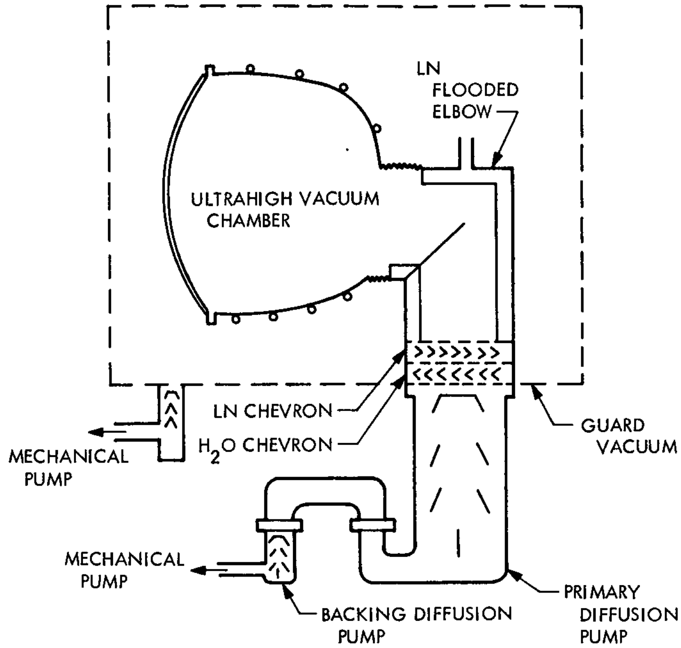

Fig. 5. Oil-pumped ultrahigh vacuum system

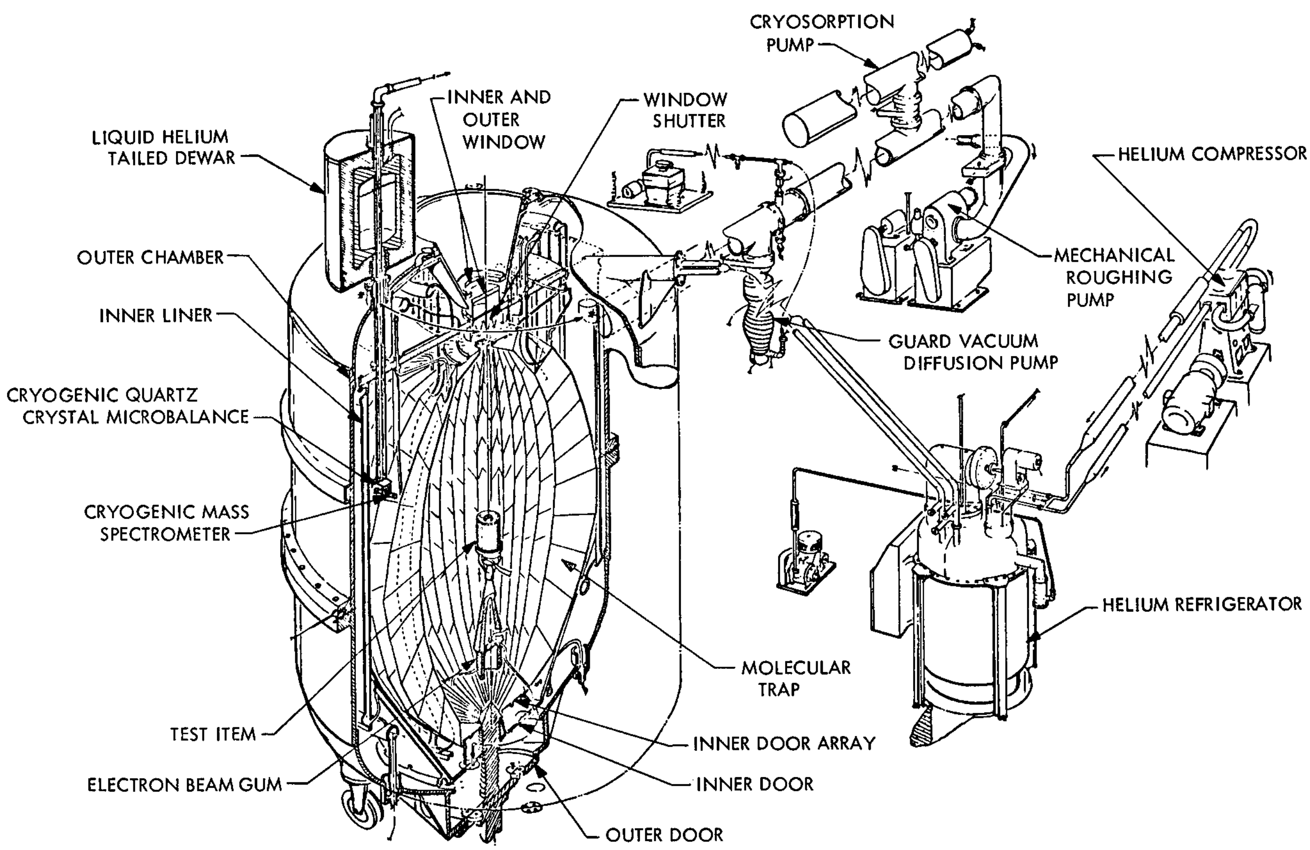

Fig. 6. Molsink facility

C. TRW Ion-Pumped Vacuum Facility

The test facility employed in this study was chosen as representative of ion-pumped ultrahigh vacuum systems commonly found throughout aerospace organizations. In particular, a room-temperature chamber wall provided the major view factor to the experimental apparatus and test surfaces. The facility and the test hardware are shown in Fig. 7. The facility consists of a double-ended horizontal test chamber 46 cm in diameter by 76 cm in length. The pumping system consists of a 400-liter/s ion pump and a titanium sublimation pump (TSP). Roughing the chamber from ambient pressure is accomplished by three sorption pumps. A sorption pump contains an extended surface porous structure which is cooled to liquid nitrogen temperature to condense the gas. These pumps are periodically rejuvenated by bakeout at elevated temperature. As can be seen in Fig. 7, numerous flanges on the test chamber permit the mounting of instrumentation and electrical and mechanical feedthroughs. This facility has been operated empty to less than 1.33×10^{-9} N/m^2.

Table 2 presents a comparison of test environmental parameters.

VII. Test Results

Friction represents a surface-sensitive property which may be influenced by variations in the environment of the facility employed. Comparison of the results for each material combination under each of the test conditions provides a basis for judging the adequacy of simulated environments. The orbital friction results further provide reference information for comparisons with other simulated test conditions.

The test results are presented in terms of coefficient of friction. The coefficient of friction μ_k is defined as the measured sliding force divided by the applied normal force between the sliding surfaces:

$$\mu_k = \frac{F_{\text{sliding}}}{F_{\text{normal}}} = \frac{F_s}{F_n}$$

The overall experimental accuracy for calculating a friction coefficient is estimated as ±10%.

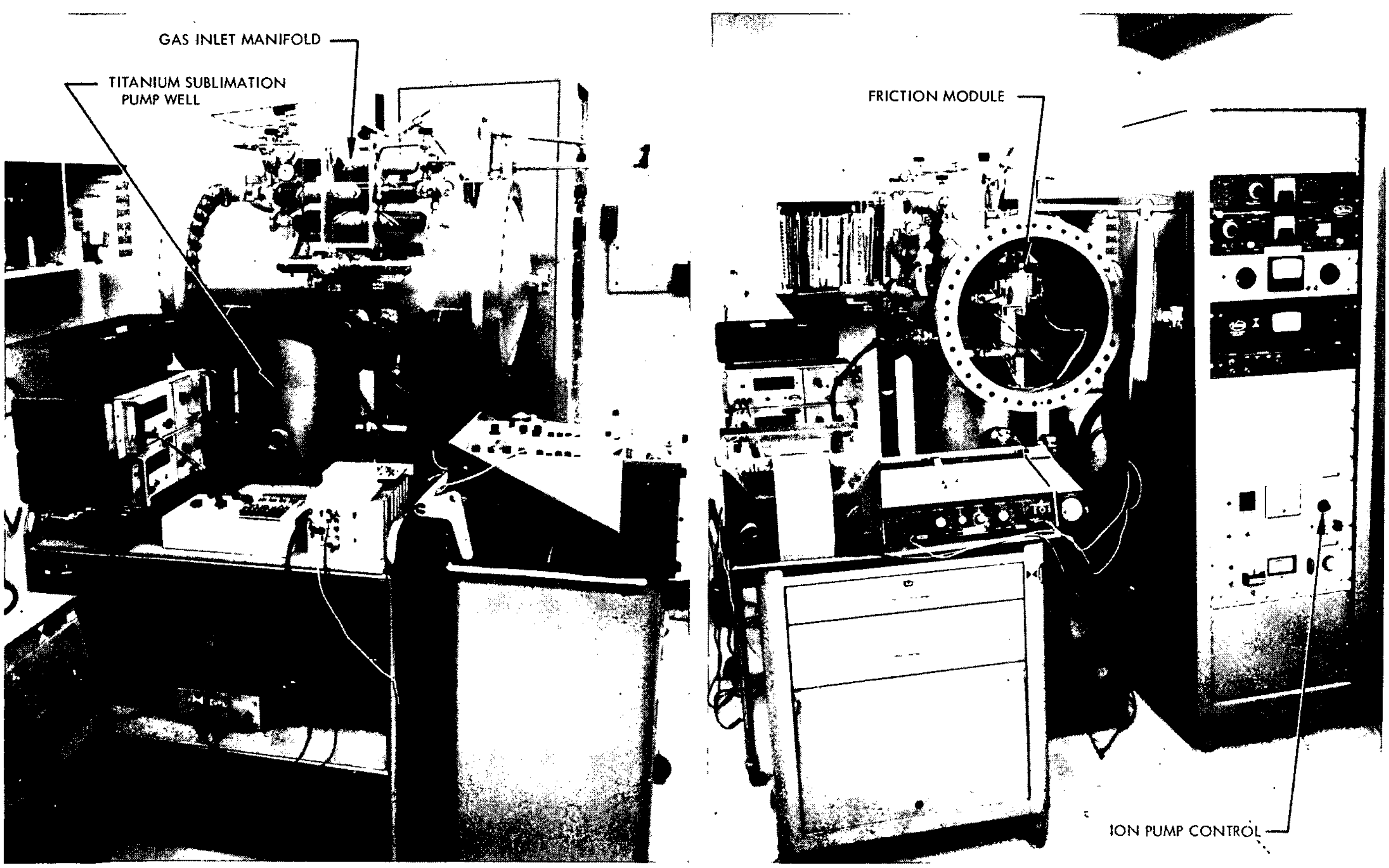

Fig. 7. Ion-pumped friction test facility

Table 2. Comparison of test environmental parameters

Test environmental parameters	TRW oil-pumped facility	Molsink facility	TRW ion-pumped facility	Modified TRW ion-pumped facility
1. Wall configuration	Smooth	Wedge fin	Smooth	Smooth
2. Wall temperature, °C	23	−259	23	23
3. Diffusion oil contamination	Some	None	None	None
4. Partial pressure, N/m^2	1.33×10^{-6}	1.33×10^{-6} to 1.33×10^{-9}	1.33×10^{-6}	1.33×10^{-3} to 1.33×10^{-6}
5. Test volume	0.23 m^3	2.44-m-diam spherical trap	46 × 76-cm cylindrical	46 × 76-cm cylindrical
6. Titanium sublimation pumping	None	Yes	Yes	Yes
7. Residual gas species	Long chain hydrocarbons, oil	He, Ne	N_2	A, CO_2, CH_4, N_2, H_2O, O_2

Summarized in Table 3 are typical coefficient of friction values for each test combination. Included in this summary are data taken in an oil-pumped ultrahigh vacuum. Comparison of this with the orbital data showed general agreement between seven combinations and disagreement of eight combinations; no definitive tests of one combination occurred.

By contrast, a comparison of molecular sink test data shows twelve combinations agree. The early wearout of synthetic MoS_2 in the flight test was the result of a nontypical sample. For three material combinations, no direct comparisons could be made. The lack of orbital data for one of these was due to the release of a shear pin during the flight test. Two combinations were not tested in the molecular sink tests because of inoperative strain gages.

The ion-pumped friction tests show good agreement between 14 of the 16 materials pairs. The lack of correlation in the synthetic MoS_2 test is attributable to the lack of significant test data in the flight test. The result is comparable to previous ground tests suggesting an abnormality in the flight test sample. The early wearout of the silver-coated sample in the ion-pumped test did not occur in any of the previous test series. Prior to wearout, the friction value appeared nominal.

With exception of the differences noted in the following paragraphs, none of the modified ion-pumped conditions produced a systematic difference in friction for any of the other test couples. Comparative behavior in orbital, molecular sink, or ion-pumped vacuum tests is generally good.

In two instances (Co × Be and Co × WC) the introduction of modifying gases into the ion-pumped vacuum appears to limit the development of the maximum friction force; however, neither couple shows a unique sensitivity to any of the particular modifying gases used. This suggests either physisorbed or impurity chemisorbed gases are involved in limiting the shear force development.

Two couples showed a unique decrease in friction when exposed to one or more specific modifying gases. The WC × Al_2O_3 shows a sensitivity to water vapor — a result previously found in Ref. 2. The Co × Ag following wearout shows a friction decrease when exposed to H_2O, O_2, or N_2. The specific influence noted is likely associated with the formation of nitrides and oxides of silver.

VIII. Conclusions

1. Both the ion-pumped vacuum facility and the Molsink are capable of producing a cold-welding vacuum environment equivalent to space.

2. Modified ion-pumped vacuum environment is acceptable for testing many material combinations. The addition of

Table 3. Comparison of orbital, postlaunch UHV, molecular sink, and ion-pumped vacuum results

Experiment designation	Material[a]	μ_k flight[b]	μ_k postlaunch[b]	Disagree	Agree	μ_k Molsink[b]	Disagree	Agree	μ_k ion-pumped vacuum[b]	Disagree	Agree	μ_k modified ion-pumped vacuum[b]	Disagree	Agree
A1	440C × BN	0.35 – 0.85	0.2 – 0.4	X		0.4 – 0.8		X	0.4 – 0.8		X	0.4 – 0.9		X
A2	440C × synthetic MoS_2	0.1 wearout	0.04	X		0.03	X		0.04	X		0.04	X	
A3	440C × WC	0.85	0.65	X		0.85		X	0.8		X	0.8		X
A4	440C × 17-4 PH	0.1 shear pin	0.9 – 1.1	–	–	1.2 – 1.6	–	–	1.0	–	–	1.4	–	–
A5	Co × Be	1.6 – 2.2	0.45	X		1.5 – 2.0		X	1.6 – 2.0		X	1.0	X	
A6	Co × Co	0.5	0.4		X	0.4		X	0.4		X	0.5		X
A7[c]	WC × Au	0.15 – 0.3	0.15 – 0.25		X	0.15 – 0.3		X	0.2		X	–	–	–
A8	440C × polyimide	0.2 – 0.3	0.27		X	0.26		X	0.2 – 0.3		X	0.2 – 0.3		X
B1	440C × WSe_2	0.04	0.05		X	0.04		X	0.04		X	0.05		X
B2	Co × Ag	0.2 – 0.4	0.2 – 0.4		X	0.2 – 0.4		X	0.3 – 0.4 wearout	X		0.5 – 1.0 wearout	X	
B3	WC × WC	0.75 – 1.2	0.55	X		No data	–	–	0.85 – 1.3		X	0.8 – 1.2		X
B4	WC × Al_2O_3	0.3 – 0.6	0.5		X	0.4 – 0.6		X	0.45 – 0.6		X	0.5 – 0.6		X
B5	Al × Be	0.25 – 0.9	0.35 – 0.65	X[d]		0.3 – 0.65	X[d]		0.4 – 0.65	X[d]		0.3 – 0.6	X[d]	
B6	Co × WC	0.3 – 1.6	0.65	X		No data	–	–	0.45 – 1.3		X	0.4 – 0.8	X	
B7	440C × PTFE	0.2	0.1	X		0.2		X	0.2		X	0.18		X
B8	440C × natural MoS_2	0.03 wearout	0.04		X	0.03 wearout		X	0.04		X	0.03		X

[a]See Section V for description.

[b]The coefficients of friction μ_k represent typical data obtained in each set of tests.

[c]In the modified ion-pumped vacuum, a new material was used: 440C × AFSL-15 (a composite lubricant of MoS_2 in Ta).

[d]Related to intermittent run effects noted only in orbital test.

trace amounts of a cross section of active gases including oxygen and light hydrocarbons suggests that for many material systems these species do not alter vacuum frictional behavior significantly. However, as previously noted, two material couples showed sensitivity to all gases and two others were sensitive to specific gases. This indicates that residual gases must be maintained at a very low level to avoid excessive molecular flux impinging upon test items.

3. Oil-pumped vacuum environment is not acceptable for cold-welding test even though some lubricated systems appeared insensitive to pump oil contamination. The presence of long chain hydrocarbons in pump oil is the primary factor in reducing unlubricated boundary layer sliding friction forces and invalidating the test results.

4. Accumulated mechanical sliding (mileage) was found to be the dominant factor in the development of friction between uncontaminated engineering surfaces. Passive dwell (nonsliding) had little if any effect on material couples tested.

5. No evidence of friction dependence on orbital altitude was found.

6. No universal conclusions from these tests regarding the influence of hardness, solubility, or crystal structure can be made. Generally, those materials having a high shear strength exhibit high coefficients of boundary layer friction.

IX. Recommendations

1. The cold-welding test technology and test criterion developed under this research program can be directly applied to all space missions.

2. The Molsink or an ion-pumped vacuum should be used for performing cold-welding tests.

3. Oil-pumped vacuum environment should not be used.

4. A cold-welding test should be accelerated by using the mechanical sliding mission requirement of the mechanism as the primary control test parameter in simulation tests. The rate of sliding should be the same as that required by the mission or higher.

5. Spacecraft assemblies with mechanical moving parts which are required to operate in space vacuum for an extended period of time should be cold-weld tested except:

(a) Those assemblies which have been flight-proven on previous spacecraft and retain basically unchanged mechanical design.

(b) Those assemblies which are hermetically sealed.

(c) Those assemblies which use special self-lubricating materials.

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