Eq. (1), instead of m_i. It is seen that the correlation provided by Eq. (1) is excellent at low and high flow rates but only fair at the intermediate values. The correlation on the whole is, however, greatly superior to that proposed in Ref. 1. Note that it is important to plot the data as shown and not as an effective force, F_i divided by the coefficient of m_i in Eq. (1), vs m_i, for the effect of wall curvature just mentioned depends strongly on the magnitude of the force. As pointed out earlier, the predicted magnitude of the interaction force is lower than the measured.

Consider next the effect of injection total pressure, or injectant nozzle diameter, on side force at a fixed injection rate. The injection momentum obviously depends on these variables, in fact, when the nozzle is choked the momentum depends directly on A_j as Eq. (3) shows. It is argued in Ref. 2 that it is only through this dependence that F_s is affected by A_j, i.e., that F_i is independent of this variable. In the experiments, CO_2 was introduced through various diameter ports and F_s measured. In Fig. 3 the measured F_s minus F_j or F_j^* is plotted as a function of mass flow. It is seen that there is no systematic dependence of F_i on d_i; on the contrary, except for the region around $m_i = 0.02$ lbm/sec, F_i is independent of d_i.

In summary, it is concluded that the analysis in Ref. 2 provides the basis for a good correlation of the experimental data of Ref. 1; in particular, the dependence of the side force on injectant molecular weight and injectant pressure is predicted correctly by the analysis. On the other hand, the magnitude of the predicted side force is low. A possible explanation for the discrepancy is that the experimental Mach number is too low for the blast wave theory, on which the analysis rests, to yield accurate quantitative results.

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Results of Ranger 1 Flight Friction Experiment

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An experiment to measure coefficients of friction in space was flown on the spacecraft Ranger 1 and 2, with the intent of making measurements under a vacuum better than can be obtained on earth under conditions of practical laboratory use. The apparatus, shown in Fig. 1, consisted essentially of 20 specimen disks mounted on a drive shaft, with four hemispherical specimen riders ($\frac{1}{8}$-in. diam) rubbing against each disk. The shaft was driven at 3 rpm by a sealed gear-motor. Each rider was held against a disk with a load of 0.3 lb provided by a calibrated coil spring; the frictional force was measured by the deflection of a leaf spring, supporting the rider, to which strain gages were attached. The strain gage output, telemetered to earth, indicated the coefficient of friction between rider and disk.

Two to four replicates of each rider-disk combination were used. The choice of materials was constrained to minimize magnetic materials in order to avoid interference with a magnetometer experiment aboard the spacecraft. A 5-μ-in. finish was specified for all metallic specimens. After final machining, disks and riders were cleaned with methyl ethyl ketone, dried, and thereafter touched only with plastic gloves.

Comparative tests in a laboratory vacuum of about 5×10^{-6} mm Hg were made on a duplicate of the flight apparatus. The disks and riders used for flight were run for 30 min in air during the final preflight spacecraft systems test. The experiment then was turned off and was turned on again by the spacecraft timer 6 hr after launch. Rangers 1 and 2 were intended to have elliptical orbits of very high apogee. Malfunction of the second stage of the launch vehicle resulted in these spacecraft being injected into low orbits. Thus, the vacuum desired for the experiment was not attained. The initial apogee for Ranger 1 was 504 km, the perigee 170 km; the corresponding pressures were about 7.8×10^{-9} mm Hg at apogee and 2.1×10^{-6} mm Hg at perigee.[1] The orbit of Ranger 2 was lower. Telemetry indicated that on both flights the experiment started in space as scheduled. From Ranger 1, telemetered friction data were received on a number of passes beginning about 13 hr after experiment start and continuing to a shutoff (believed due to normal rundown of the experiment batteries) at about 22 hr after experiment start. On Ranger 2 only a few pieces of telemetered friction data were received, and the spacecraft re-entered about 14 hr after experiment start.

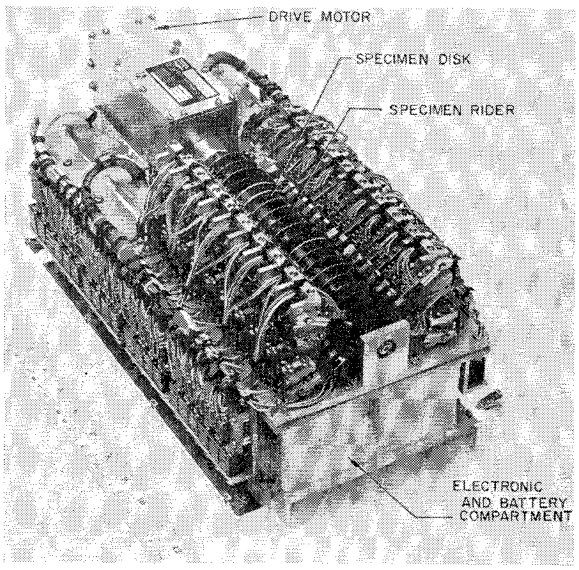

Fig. 1 Friction experiment assembly with temperature control surfaces removed.

Some noise was observed on the telemetered analog record. The "most probable" value of friction coefficient was read from the record and plotted vs time for each rider-disk combination. Figure 2 is typical data plot; dotted lines join points for each replicate. Comparisons of results in space, laboratory vacuum, and air are complicated by differences in running time. Because of the nonstandard orbit of Ranger 1, the flight data were obtained after considerably longer

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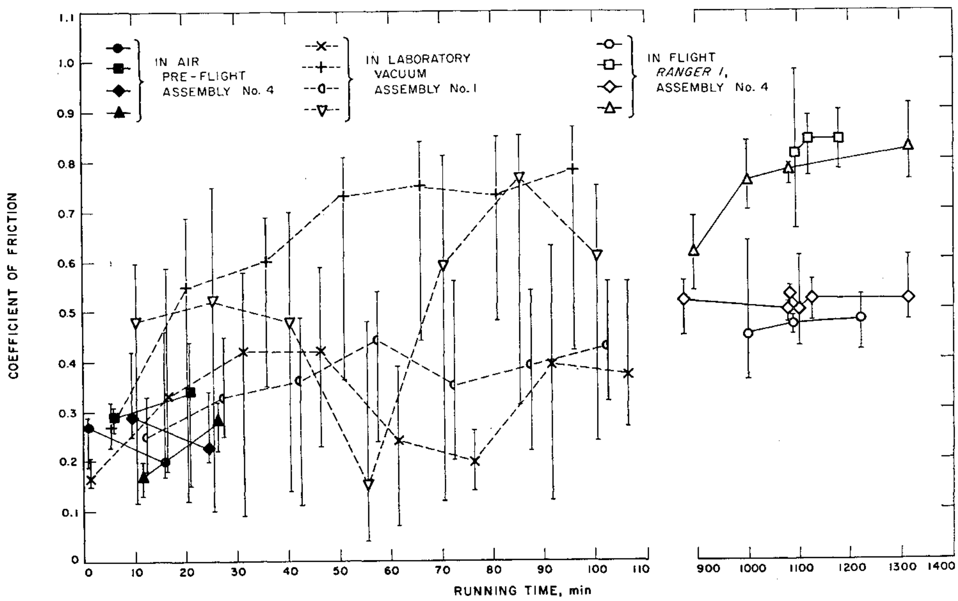

Fig. 2 Coefficient of friction vs time for A286 iron-base alloy on A286. Each point is shown at the most probable value. Vertical line through point indicates range during period of reading. Lines connecting points are only to identify readings made on same rider and disk.

running times than the anticipated 30 to 300 min. Ground data for comparison at the observed times are not available; it is planned to make such measurements and report them subsequently.

Results

The average of the "most probable" friction coefficient readings for each material combination is given in Fig. 3. Table 1 summarizes the results obtained for the various classes of materials. For metals running against metals, unlubricated, the friction coefficient averaged over all pairs was the same in space (0.5) as in laboratory vacuum; this compared with 0.3 in air. Some of the difference may be due to the shorter running times in air.

Some individual values of friction coefficient above 1.0 were observed. All of these involved copper-base alloys: nickel and aluminum vs copper in space and aluminum bronze vs aluminum bronze in laboratory vacuum. Four

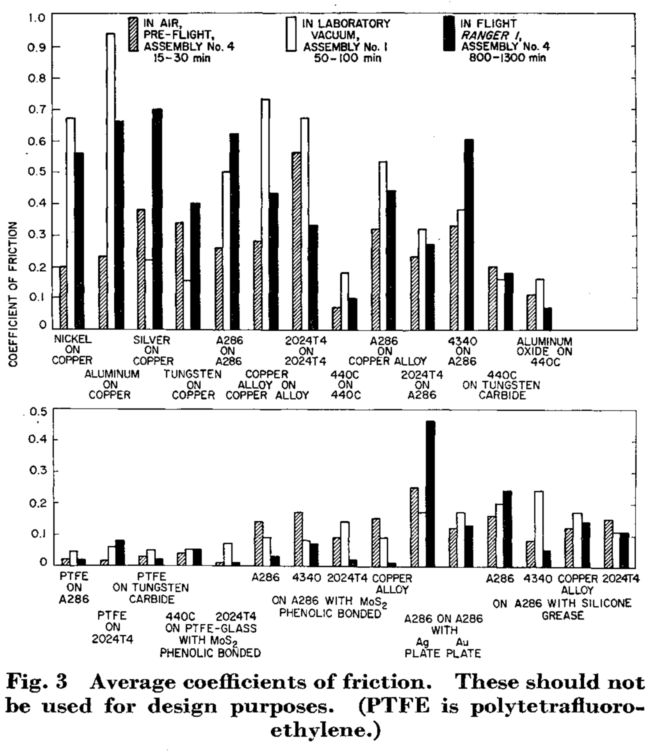

Fig. 3 Average coefficients of friction. These should not be used for design purposes. (PTFE is polytetrafluoroethylene.)

additional combinations showed occasional values above 0.8 in either space or laboratory vacuum: silver vs copper, 4340 steel and A286 vs A286 iron-base alloy, and 2024 vs 2024 aluminum-base alloy.

The copper disks and their unalloyed riders were selected to check the hypothesis that high-friction coefficient in vacuum is related to high mutual solid solubility.[2] Nickel has high solid solubility in copper, aluminum moderate solubility, silver low, and tungsten essentially none. Nickel and aluminum showed high friction against copper in vacuum with occasional very high values, silver showed moderate to high friction, and tungsten showed moderate values.

The solubility hypothesis is somewhat difficult to apply to multiphase engineering materials. It generally is accepted, however, that like materials sliding on each other tend to show higher friction than unlike. In this work, the like alloy pairs averaged 0.44 friction coefficient in vacuum and the unlike 0.42—not a significant difference. On the other hand, of the four pairs of like materials, three showed friction coefficient values above 0.8. Of the three unlike alloy pairs, only one (4340 steel vs A286 iron-base alloy) had values above 0.8.

For the unlubricated metallic materials, there was a definite trend toward low coefficient of friction in vacuum at high hardness. Combinations with at least one member of high hardness (440C martensitic stainless steel, tungsten) showed

Table 1 Summary of results

	Average coefficient of friction		
Materials combination and lubricant	In air, pre-flight, 15–30 min[a]	In laboratory vacuum, 50–100 min	In space, Ranger 1, 800–1300 min
Metal vs metal, unlubricated	0.29	0.48	0.48
Ceramic vs metal, unlubricated	0.16	0.16	0.12
Polytetrafluoroethylene vs metal or ceramic	0.02	0.05	0.04
Metal vs metal, molybdenum disulfide lubricant	0.14	0.10	0.04
Metal vs metal, metal film lubricant	0.18	0.17	0.30
Metal vs metal, grease lubricant	0.13	0.18	0.14

[a] Running time at 3 rpm.

low or moderate friction in vacuum; very high friction occurred only when both members were soft (copper and copper alloy, aluminum and aluminum alloy, silver, nickel), with the iron alloys of intermediate hardness (A286 and 4340) showing intermediate friction coefficients.

The ceramic vs metal combinations showed fairly low coefficients of friction, averaging 0.12 in space (Table 1). The harder member of each pair was, in these cases, extremely hard.

Combinations of metal vs metal with molybdenum disulfide lubricant and of polytetrafluoroethylene vs metal or ceramic gave the lowest coefficients, averaging 0.04 in space. Metal vs metal combinations with grease lubricant had somewhat higher friction. Metal vs metal with metal film lubricants averaged still higher friction; this may have been influenced by wearing away of the film. In all of the lubricated materials, the method of applying lubricant undoubtedly has an important effect.

The coefficients in space were not systematically different from those in laboratory vacuum (Table 1). It is possible that the pressure difference between the space and laboratory vacuums achieved was too small to bring out a difference in friction behavior. It also is possible that a difference in behavior was masked by differences between experiment assemblies. (The same assembly was not used in laboratory vacuum as in space, because it was desired to fly unworn disks and riders.) A more complete account of this work will be published at a later date.[3]

Conclusions

1) An experiment for measuring the coefficient of sliding friction for a number of material combinations was flown on the spacecraft Ranger 1 and 2. The apparatus functioned in space as designed, on both flights. Although the orbits attained were different from those planned, meaningful data were obtained from Ranger 1.

2) Under the conditions of the experiment (including vacuums of 8×10^{-9} to 3×10^{-6} mm Hg), polytetrafluoroethylene sliding against metals and ceramics, as well as metals sliding on metals with a molybdenum disulfide lubricant, appeared to have very low coefficients of friction, averaging 0.04. Ceramics sliding against metals, unlubricated, and metals sliding on metals with grease or gold-plate lubrication showed intermediate values, averaging 0.13. Unlubricated metals sliding on metals showed moderately high coefficients, averaging about 0.5; with some pairs, values above 1.0 were observed.

3) For unlubricated metals sliding against metals or ceramics, the friction coefficient tended to be low when at least one member of each pair was of high hardness.

4) The data were not inconsistent with the hypothesis that high coefficient of sliding friction between metals in vacuum can be correlated with high mutual solubility of the materials.

5) The friction coefficients measured in space, with exposure to vacuums of 8×10^{-9} to 2×10^{-6} mm Hg, were not, in general, systematically different from those measured in the laboratory at a vacuum of 5×10^{-6} to 1×10^{-5} mm Hg. For unlubricated metallic materials, the friction coefficients observed in vacuum generally were higher than those measured in air at shorter running times.

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Effect of Additives on Formation of Spherical Detonation Waves in Hydrogen-Oxygen Mixtures

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This paper deals with the initiation, by means of exploding wires, of spherical detonation in a gaseous mixture consiting of 62 mole % of hydrogen and 38 mole % of oxygen. The minimum electrical energy, stored in the condenser of the initiator circuit, needed for initiation of detonation is $E_i = 10.5 \pm 0.3$ joules, in agreement with results reported in the literature. The effect of up to 5% of various gases, added to this hydrogen-oxygen mixture, on E_i is studied. It is found that, while some gases inhibit the formation of detonation ($E_i > 10.5$ joule), others promote it ($E_i < 10.5$ joule). Of the additives studied in this program, the best inhibitor is isobutene; transbutene-2, propylene, and pentacarbonyl iron are also quite effective. The results are compared and contrasted with the related flame-inhibition experience. A mechanism is suggested to account for the inhibition.

Introduction

ACCIDENTAL spilling of large amounts of liquid hydrogen and liquid oxygen, such as might occur in either ground or flight use of rockets, resulting in rapid evaporation of the two liquids, presents a gas-phase detonation hazard. The aim of this work has been a quantitative study of the possible desensitizing agents by determination of the critical energy necessary for initiation of detonation, first in a pure hydrogen-oxygen mixture and then, in the same mixture, containing small amounts of various gaseous additives.

Initiation of detonation in gaseous mixtures of hydrogen and oxygen confined in tubes has been investigated extensively for many years.[1] The recent work has shown quite conclusively that the process of transition of a flame to detonation depends essentially on hydrodynamic interactions of the gas with the confining walls.[2–4] Therefore, if the length of the tube and the conditions of confinement are adequate, the minimum energy that must be supplied externally for initiation of detonation is not necessarily larger than that needed to establish a slow flame, which is usually only a fraction of a millijoule. On the other hand, the amount of energy needed to initiate a (spherical) detonation wave purely in the gas phase, without the benefit of interacting solid surfaces, is many orders of magnitude higher.[5–9] Litchfield[8] found that, if such a detonation wave is initiated by means of an exploding wire, the critical energy needed for initiation in the stoichiometric hydrogen-oxygen mixture, initially at 1 atm, is 13 joules. The critical energy obtained with other ignition sources is even higher.[6, 8]

Experimental Procedure

The apparatus used was fashioned after the one described by Litchfield.[8] The reaction was initiated in the center of a stainless-steel bomb, 19.2 cm in diameter, by explosion of a copper wire, 1-cm long, and 0.079-mm thick. The wire

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