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INVESTIGATION OF NEW METHODS FOR INCREASING THERMAL CONTACT CONDUCTANCE IN A VACUUM

by

S. P. Carfagno

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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ABSTRACT

The feasibility of two ideas for increasing thermal contact conductance were investigated. One idea was to flatten the tops of asperities on metal surfaces by passing a current pulse across the interface of a joint, while maintaining relative motion between the mating surfaces. The other idea was to overcome the restrictions of surface waviness by making one of the joint surfaces pliable; this took the form of a thin foil backed by a layer of paste.

Both methods were investigated initially by using electrical contact conductance measurements to indicate the quality of contact, but study of the pliable surface technique also included measurements of thermal contact conductance in a vacuum environment. The experimental findings did not support the feasibility of either idea.

A brief review of relevant topics and recommendations for further study are given. In particular, an idea for bonding joints with a metal or alloy capable of pressure-induced phase transformation is described.

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INVESTIGATION OF NEW METHODS FOR INCREASING THERMAL CONTACT CONDUCTANCE IN A VACUUM

SUMMARY

The purpose of this investigation was to evaluate the feasibility of increasing thermal contact conductance in a vacuum by flattening asperities and by the use of pliable surfaces.

The thermal conductance between surfaces at a joint is limited by the fact that the actual contact area is usually a very small fraction of the apparent area of the joint. On a micro-scale the surfaces are extremely rough, containing a distribution of protrusions or asperities; on a larger scale the surfaces are not perfectly flat, but have some waviness. Due to the waviness, certain regions of a joint may make no contact at all. In regions where contact is made, the contact area will consist mainly of a number of small spots where asperities on opposing faces touch one another.

The two methods investigated for increasing thermal conductance at a joint were aimed at producing smoother surfaces, by flattening the tips of asperities, and at overcoming the effect of waviness, by making one of the mating surfaces pliable.

The procedure investigated for flattening the tips of asperities was to pass a high current pulse through the interface between two metals. It was hoped that under proper conditions the tips of the surface asperities would melt and be flattened, a process we called plateauing.

Experiments were conducted with 1/8-in. and 1/4-in. diameter aluminum rods in contact with a polished aluminum surface and a polished stainless steel surface; in the latter case, some of the experiments were conducted with the parts in relative motion at the moment the current pulse was passed through the interface. It was estimated that the electrical energy dissipated in heating the interface was a few joules. In the static experiments the main effect of the pulse was to produce welds at a few small spots of the interface, usually accompanied by melting of the asperities over small areas surrounding the weld spots. When the parts were in motion relative to one another, there was, in addition, some scratching apparently caused by bits of resolidified aluminum caught in the interface.

The pliable surface technique was investigated by measuring, initially, the electrical contact conductance and, finally, the thermal contact conductance across the interfaces between thin metal foils (1 mil aluminum and 0.1 mil copper) and a wavy metal surface, under different

contact pressures. The results seemed to indicate that increasing the pressure behind the foil to approximately 100 lb/in^2 was sufficient to cause the foil to deform so as to contact the peaks of the asperities on the wavy surface, but large additional increases in pressure produced very little improvement of the contact.

The evidence of the experiments was generally negative regarding the feasibility of increasing thermal contact conductance by either the plateauing or the pliable surface techniques.

This report includes a short review of topics related to surface geometry, contact between metal surfaces, and methods of increasing thermal contact conductance.

An idea for increasing contact conductance by bonding the interface with an alloy which undergoes a pressure-induced phase transformation is described. Several recommendations for further investigation of the problem are also given.

1. INTRODUCTION

The purpose of this investigation was to study the feasibility of increasing thermal contact conductance across metal lap joints in a vacuum by (1) decreasing roughness by modifying asperities and (2) increasing uniformity of contact by making one of the joint surfaces pliable. With the aid of a review of surface geometry and other contact phenomena, different schemes for decreasing roughness and making a pliable surface were evaluated. Subsequently, the general outline of the experimental program was decided by a conference with NASA's technical project monitors. The findings of the review are given in Section 2, and the experimental investigations are reported in Sections 3 and 4.

During the preparatory investigation, the idea of bonding joints with an alloy which undergoes a pressure-induced phase transformation was generated and briefly investigated. The possibility of using this idea to increase thermal contact conductance is discussed in Appendix B.

Appendix C includes several recommended studies for solving problems associated with thermal contact conductance across joints in a vacuum environment.

2. SURVEY OF TOPICS RELEVANT TO THERMAL CONTACT CONDUCTANCE

2.1 Introduction

The purpose of this section is to provide a record of an examination of various aspects of the problem, of improving thermal contact conductance in a vacuum, with which we initiated this investigation. As we had already reviewed the literature in an earlier study [1]*, the following supplemental survey covers certain pertinent topics without attempting to give a complete account of the subject.

2.2 Properties of Surfaces and Interfaces

2.2.1 Topography

The properties of surfaces can be very different from those of the bulk material. The topography of real surfaces is very irregular and complicated. Coarsely finished surfaces, such as obtained by grinding or abrasion, have a topography consisting basically of a series of grooves. The cross section of the grooves is roughly that of a vee with a highly obtuse included angle. The hills and valleys of the grooves are themselves covered with smaller irregularities. Indirect evidence indicates that the included angle of the grooves becomes progressively more obtuse as the surfaces are made progressively more finely polished[2].

On an atomic scale the topography of surfaces can include sharp steps and steep slopes, but if one approximates the asperities with shapes such as cones, their slopes rarely exceed a few degrees.

Mechanical surface finishing operations cause structural changes in the surface layers. In the outermost layer the base crystal is broken into small fragments as a result of severe plastic deformation. Beneath the thin fragmented layer there is a much thicker layer of minor deformation, in which inhomogeneously distributed strains decrease rapidly with increasing distance from the surface. The elastic-plastic boundary of this layer has undulations associated with surface scratches. The thickness of the minor deformation layer is many times the depth of the scratches - as much as 50 times the depth of the scratches in soft metals. It may be on the order of 100 μm thick for a coarse finish and only a few microns thick for a fine polish.

* Numbers in brackets indicate items in the list of references.

If the finishing process involves use of abrasives, it is possible for fragments of the abrasive particles to become embedded in the surface. One study [3] indicated that a typical lapping operation can cause on the order of 10 particles/cm^2 to become embedded in the surface of a hardened steel.

Tabor [15] points out that even pure single crystals may have structurally complicated surfaces. Not only are the layers of atoms nearest the surface occupied less and less completely, but the addition of foreign molecules may produce unusual compounds and change the mobility and arrangement of the surface atoms.

2.2.2 Oxide Films

The oxide film that covers most metallic surfaces cannot be thought of as a uniform layer. Formation of the oxide layer probably begins at a number of isolated nuclei islands, growth occurring by spread of the islands both laterally and perpendicular to the surface and by formation of new nuclei. The resulting oxide layer is highly irregular, especially if the film forms at elevated temperature, when the outer layer may contain many protruding whiskers and blades.

Oxide films will fracture easily and allow metallic contact to occur if the oxide is hard and brittle and the underlying metal soft and ductile [11]. This is the case with indium and tin and to a lesser extent with lead and aluminum. Because of the softness of these metals, deformations are relatively large, and even the lightest loads are sufficient to break down oxide films. If the metal and its oxide have similar properties, as with copper and steel, the oxide will deform with the metal and may persist even under the heaviest loads. Roughening the surface facilitates breakdown of the oxide.

There is evidence that sliding of one metal surface over another allows strong junctions to form by rupturing the films of oxide and other contaminants which inhibit junction formation.

2.2.3 Conductance at Metallic Interfaces

In order for heat to be conducted across a metallic interface the metal-to-metal contacts must in effect constitute bonds. Adhesive bonds result when asperities on opposite faces of a junction between clean metals are pressed so close together that there is no distinction between atoms on one side or the other of the interface. Consequently, the forces between atoms at the interface are of the same nature as those

in the bulk metal. However, because of mismatching between the engaging crystal lattices the interface will almost certainly be weaker than the bulk material.

Experiments with steel surfaces [11] have shown that small tangential displacements at a joint can cause the electrical contact conductance to increase several hundredfold. This is explained as being a consequence of disruption of the oxide film and a growth of real contact area accompanied by a large increase in metal-to-metal contact. Increase in contact area and a strengthening of the junctions can also be caused by the application of a tangential stress while maintaining the normal load, accompanied only by micro-displacements of the specimens - without gross sliding. The effect of tangential displacements on thermal conductance at a joint is probably similar to, but of much smaller magnitude than the effect on electrical conductivity.

2.3 Contact Area and Stresses

When an indenter or an asperity penetrates a metal surface, most of the stress consists of a hydrostatic pressure which plays no part in producing plastic flow.

For a metal which does not work harden appreciably or one which has been fully work-hardened, it is found both theoretically and experimentally that the local yield pressure is about five times the critical shear strength

$$p_o = 5\ s_o \quad .$$

Since s_o is related to the tensile yield stress according to

$$s_o = Y_o/\sqrt{3} \quad ,$$

it follows that

$$p_o = 3\ Y_o \quad ,$$

which is the basic relation observed in hardness measurements. Consideration of the deformation of a flat surface by a spherical indenter has shown that the maximum shear stress occurs in the bulk material at a point below the surface such that the onset of plastic flow occurs when the mean pressure over the contact area has the value

$$p_m = 1.1\ Y_o \quad .$$

The extent of plastic deformation increases as the value of p_m is increased; and when p_m attains a value of the order of 3 Y_o, further increase in indentation produces little change in p_m. When this condition is attained, the deformation is regarded as being fully plastic. Since the penetration of a surface by the asperities on a mating surface is similar to the behavior of an indenter in a hardness test, it follows that the mean pressure, p_o, over all the areas of actual contact will be on the order of 3 Y_o. It follows that the total area of actual contact at an interface is given to a good approximation by

$$A_r = \frac{F}{p_o} \quad , \tag{2.1}$$

where F is the total load on the joint. If full plasticity is not attained at all the contact points, the mean pressure will be a little less than 3 Y_o. According to Eq. (2.1), the actual contact area is nearly proportional to the applied load and inversely proportional to the mean yield pressure, or effective hardness, of the softer of the two materials in contact. Furthermore, the above theory implies that the actual contact area is independent not only of the apparent area of the interface, but also of the smoothness and flatness of the surfaces.

The analysis of friction as due to adhesion at points of real contact is proportional to the normal load on a joint and is independent of the apparent area of the joint. When macroscopic sliding occurs, the frictional force is proportional to the normal load.

Although the above model has wide support, it is not universally accepted. In Ref. 10, for example, it is stated that the majority of experimental results have established that the area of real contact between surfaces pressed together is greater for smoother* surfaces. One of the possible sources of disagreement is the difficulty of measuring the actual contact area. It is frequently done indirectly, such as by making measurements of electrical conductance, a method which has a number of limitations. Surface irregularities can increase the local electric field strength to the extent that electrical conduction can occur by cold emission and the tunnel effect even at points where no direct contact exists. Furthermore, the relation between electrical conduction and contact area is complicated by the effects of variation in composition and the presence of oxides and adsorbed films at the surface.

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*See page 14 of Reference 10.

2.4 Theory of Solid-to-Solid Conductance

Several theories have been developed for the solid-to-solid conductance at a joint.

Assuming that the surfaces make contact at a number of isolated spots of equal size distributed uniformly over the interface, assuming that the separation of the contact spots is large compared to their size, and approximating the contact areas by circular areas of radius a, Cetinkale and Fishenden [23] showed that

$$h = 2\ n\ a\ \lambda_m \quad , \tag{2.2}$$

where n is the number of contact spots per unit area of the interface and λ_m is the harmonic mean value of the thermal conductivities of the two materials in contact: $\lambda_m = 2\ \lambda_1\ \lambda_2/(\lambda_1 + \lambda_2)$. Theories based on more complex models generally have the effect of replacing the factor 2 in Eq. (2.1) by a somewhat smaller number.

Combining Eqs. (2.1) and (2.2), and noting that the ratio of real to apparent area is $A_r/A_a = n\pi a^2$, we have

$$h = \frac{2\lambda_m}{\sqrt{\pi A_a}}\sqrt{\frac{nF}{P_o}} \quad . \tag{2.3}$$

This relation shows that the thermal contact conductance of a given joint is proportional to the square root of the total load on the joint; and, for a given load, it increases as the square root of the number of contact spots per unit interface area.

The above equation shows that, even without changing the actual contact area, the thermal contact conductance in a vacuum can be increased by increasing the number of contact spots. Thus, the greater the uniformity of contact over an interface, the greater the thermal conductance across it. Therefore, even if making surfaces smoother and flatter might not substantially increase the actual contact area, it is possible that these processes will cause a redistribution of microscopic contact areas conducive to a reduction of constriction resistance.

A number of workers have obtained results which support the general aspects of the above model. Williams [21], for example, prepared samples having between 1 and 48 wedge-shaped ridges cut into the surfaces. Pairing samples with the ridges on opposite faces crossed with each other, he formed joints with 1 to 1016 prospective contacts. Because of the

difficulty of obtaining coplanar ridges, the number of contacts were fewer than the prospective number of contacts. His measured thermal contact conductances were approximately proportional to $\sqrt{F}$ for a given sample (approximately fixed n) and were proportional to $n^{0.45}$ at fixed F, provided n was taken as the number of contacts confirmed by microscopic examination of the samples following the test.

Fried [22] found that the thermal contact conductance between stainless steel samples at a contact pressure of about 6900 kN/m^2 (1000 lb/in^2) increased from 800 $Wm^{-2}\,°C^{-1}$ for a sample with a very coarse finish to 30,000 $Wm^{-2}\,°C^{-1}$, almost 40 times greater, for a finely polished sample. These differences did not persist down to much lower contact pressures.

Miller [16] found that increasing the smoothness of the contacting surfaces caused the thermal conductance to increase. At high temperatures, however, the effect was not significant for soft metals such as aluminum.

2.5 Use of Interface Fillers and Surface Coatings to Increase Thermal Contact Conductance

A method of increasing thermal contact conductance is to fill the interfacial gap with a highly conductive material. Metals have been tried both as coatings on the mating surfaces and as foils placed between them. Grease and rubber have also been tried as interfacial fillers. A tabulation of references in which the effect of interstitial materials is discussed is given in Ref. 34. Some of the experiments that have been performed are discussed briefly below.

Getty and Tatro [17] investigated the effect of several greases, thermal putties, and copper, aluminum, and tin foils on the thermal contact conductance of aluminum samples 7.6 cm x 7.6 cm x 0.63 cm (3 in. x 3 in. x 1/4 in.), having three surface finishes ranging from 0.2 μm to 7.6 μm (8 μin. to 300 μin.) rms. The tests were conducted in a vacuum environment at contact pressures up to about 200 kN/m^2 (30 lb/in^2). Without fillers, the thermal contact conductance ranged approximately between 100 and 600 $Wm^{-2}\,°C^{-1}$; because of flatness deviations among the samples, the rougher samples had the higher thermal conductances. The foils produced some improvement; but much better results were produced by the thermal putties, the best of which yielded thermal conductances in excess of 12,000 $Wm^{-2}\,°C^{-1}$, more than an order of magnitude higher than the value without any filler.

Bloom [18] conducted experiments on aluminum samples, 5 cm in diameter by 2.5 cm high, with the interstices at the joint filled with

silicone oil and grease. The experiments were conducted in a vacuum environment at low mean interface temperatures: about -151°C (-240°F) for oil and -137°C (-215°F) for grease. Without filler, the thermal contact conductance increased from 3090 to 7840 Wm^{-2} $°C^{-1}$ (544 to 1380 Btu hr^{-1} ft^{-2} $°F^{-1}$) as the contact pressure was increased from 1768 to 6440 kN/m^2 (256 to 933 lb/in^2). With the fillers, the thermal contact conductance was relatively independent of contact pressure over the range between 300 and 5000 kN/m^2 (40 and 700 lb/in^2). With a grease-filled interface, the thermal contact conductance was approximately 19600 Wm^{-2} $°C^{-1}$ (3450 Btu hr^{-1} ft^{-2} $°F^{-1}$); and with an oil-filled interface, it was approximately 80000 Wm^{-2} $°C^{-1}$ (14,000 Btu hr^{-1} ft^{-2} $°F^{-1}$). Thus, the grease produced approximately a three-fold increase in thermal contact conductance and the oil produced a ten-fold increase.

From measurements in a vacuum environment, Fried [22] found that coating stainless steel with magnesium had an effect which increased with contact pressure. At pressures up to about 1000 kN/m^2 the effect was negligible, but with increasing pressure the coated sample attained increasingly higher conductance than the uncoated sample; and at a pressure of 7000 kN/m^2 the thermal contact conductance of the coated sample was approximately an order of magnitude higher than the uncoated sample. An aluminum coating was less effective than magnesium.

From measurements at atmospheric pressure, Miller [19, 20] found that thermal contact conductance could be increased by coating the base metals with a metal having a higher thermal conductivity and lower hardness. He also found that the conductance could be increased by placing at the interface a thin foil of a soft, highly conductive metal, the thickness of which he concluded should not exceed twice the average asperity height.

2.6 Metal Polishing

Two established methods of surface polishing that are pertinent to this study are described below. In addition, a method of reducing surface roughness suggested by the behavior of electrical switches is discussed.

Vibratory polishing [4, 5, 6, 7] is a relatively new polishing technique which is capable of producing surfaces of smoothness and flatness far superior to that possible by hand polishing. The method has been applied mainly to the final polishing of metallurgical specimens. The specimens are placed face down in a flat-bottomed bowl containing a polishing cloth or abrasive paper and an abrasive slurry. The bowl is caused to vibrate at the rate of 60 cycles/sec with a motion having both horizontal and vertical components. The motion results in relative

motion between the sample and abrasive, giving rise to the polishing action. The specimen moves a very short distance per cycle and appears to float smoothly on the slurry, riding along the periphery of the bowl. The polishing speed is affected by the weight on the specimen and the amplitude of vibration. It is best if the edge of the specimen can be chamfered to allow the abrasive to flow between the specimen face and the vibrating table. When applying the method to aluminum specimens it was found to be better to restrict the samples to a small area of the table - an area approximately 12.5 cm in diameter for 3.8-cm diameter samples. This polishing technique has the advantages that several samples can be processed at once, the equipment is relatively inexpensive, it is easy to operate and requires minimal attention.

Electrolytic polishing is accomplished by making a metal sample the anode in an electrolytic cell. The process has been described [8] as entailing *smoothing* or *macropolishing*, the removal of asperities or macroscopic irregularities, and *brightening* or *micropolishing*, the removal of the microscopic irregularities superimposed on the larger ones. Micropolishing is controlled by the formation of a thin film on the anode surfaces, and it precedes macropolishing. Macropolishing is controlled by the formation of a relatively thick viscous layer of reaction products around the anode. To explain the smoothing process it has been postulated that the layer is thin and has a high concentration gradient near the asperities and is thick and has a lower concentration gradient near the depressions, resulting in preferential dissolution of the asperities. An advantage of electropolishing compared to lapping methods is that a smooth surface is obtained without any work hardening.

Another method of decreasing surface roughness has been suggested by the observation that the electrical conductance of switches is considerably improved after being operated a number of times. A possible explanation is that the constriction of current through microscopic contact spots causes melting of the asperity tips; and the simultaneous rubbing of one switch surface over the other causes the molten asperity tips to flatten. This led to the idea that passing current pulses through an interface, under appropriate contact pressure and relative motion of the joint surfaces, might cause plateauing of asperities and increase the thermal conductance of joints made with parts whose surfaces had been thus prepared. It may be, however, that other phenomena are responsible for the observed improvement of electrical conductance. It is known, for example, that the sliding of one switch component over the other has the effect of breaking through oxide films and producing greater metal-to-metal contact. There is also a tendency for the tangential stresses at the interface to increase the size of contact spots. (See also Section 2.2.3).

The heating and other physical changes caused by the passage of electrical current through a junction have been discussed in Ref. 11.

Heating of a constriction by a steady current will accelerate the rate of creep, causing the junction to gradually increase in size and the resistance to drop. If large current pulses of short duration are passed through a junction there is little effect on resistance until the magnitude of the current pulse is increased to the point where the heating is sufficient to cause melting. Then the junction collapses and its resistance drops. After each such collapse, a current pulse of greater magnitude is needed to again cause melting and a recollapse of the junction. This is a consequence of the fact that, starting with a lower resistance, a larger current is needed to generate the heat required to reach the melting temperature. There is evidence that non-equilibrium conditions cause melting at the junction to occur at a temperature below the normal melting point. With increase in temperature both electrical and thermal resistances increase, such that a critical current is reached at which thermal conduction cannot cope with the increased ohmic heating; and the temperature will rise catastrophically until melting occurs.

3. PLATEAUING EXPERIMENTS

3.1 Introduction

The purpose of the plateauing experiments was to establish whether it is feasible to flatten, or *plateau*, asperities by melting them with pulses of electric current passed across the interface of a joint. It was thought that a suitable combination of contact pressure, relative motion at the interface, and pulse characteristics might cause the asperities to be flattened and, that such surface preparation would increase the thermal contact conductance across joints. Experiments were conducted both with and without relative motion between the mated surfaces. Examination of the treated surfaces under a microscope revealed no evidence that the method could be proved feasible.

Estimates of the feasibility of increasing contact area by flattening of asperities must take account of their typical shape. Surface analyses have shown that the base widths of asperities are usually greater than their height. The mean slope of their surface with respect to the mean plane of the interface is generally less than 10 deg. They represent somewhat gentle undulations which can be reasonably approximated by spherical or cylindrical surfaces. Profilometer traces may give the impression that asperities are cone- or wedge-like protrusions with steep walls, but this is an erroneous impression that arises because the magnification in the direction perpendicular to the interface is usually 10 to 50 times the magnification in the direction parallel to the interface. Therefore, plateauing was expected to increase contact area by a smaller factor than one might be led to expect from profilometer traces. We also considered that plateaued asperities on opposite sides of an interface might not make contact with their flat tops parallel, in which case plateauing would probably be of little benefit.

3.2 Description of the Electrical Pulses

The electrical pulse generator used in the experiments provided means of charging capacitors of 1, 2, or 10 μf to potentials up to 5 kv. Firing an ignitron caused the capacitor to be discharged through the load, which consisted of the impedance at the joint interface. All experiments reported herein were performed using the 10-μf capacitor charged to the maximum potential of 5 kv. Thus, the energy stored in the capacitor was 125 joules. To allow observation of the shape of the current pulse the circuit included an 0.05-ohm shunt resistor in series with the load.

By observing the voltage across the shunt, it was found that the discharge current had a period of approximately 24.5 μsec and that it decayed to zero in approximately three cycles. Since the shunt resistance was comparable to the initial resistance of the load - i.e., the resistance at the interface between the samples - and the load resistance decreased by a factor between 3 and 12 during the discharge, only a fraction of the energy stored in the capacitor was dissipated by melting asperities. The useful energy was further reduced by losses to other parts of the circuit, so that the energy dissipated at the interface may have been as little as 10 joules, or less.

3.3 Experiments with Aluminum/Aluminum Interface

Static experiments were performed with 3.2-mm and 6.4-mm (1.8-in. and 1/4-in.) diameter aluminum rods in contact with the flat, finely polished surface of an aluminum (6061-T6) cylinder, 3.8 cm (1.5 in.) in diameter. The end faces of the rods were polished with 240- and 600-grit cloth to produce samples having two patterns of parallel grooves on the surface. The polished ends of the rods were placed in contact with the finely polished aluminum surface and weighted to produce a light contact pressure: 220 kN/m^2 (32 lb/in^2) for the 3.2-mm rods and 55 kN/m^2 (8 lb/in^2) for the 6.4-mm rods. The experimental arrangement is shown in Figure 1, and test data are given in Table 1. A different area of the surface of the 1 1/2-in. diameter cylinder was used in each experiment; and each interface was subjected to a single capacitor discharge.

In all cases, passage of the current pulse through the interface caused welding at one or more small spots. For the 3.2-mm diameter rods, the cross-sectional area of the weld spots was about 1/30th of the interface area; and for the 6.4-mm diameter rods it was about 1/60th of the interface area. Surrounding the weld spots, there were usually small areas in which the ridges in the end faces of the rods appeared to have been melted by heat travelling radially outward from the weld spot. In these places the surface appeared smoother than the original surface. At the weld spots, or course, the surface had the rough shape caused by the fractures that occurred when the rods were separated from the aluminum cylinder.

The effect of the pulses is illustrated in Figure 2, which shows photomicrographs of the larger of two areas affected by a pulse passed through the interface between Samples 2 and 8. The black areas are where the weld formed by the pulse was fractured on separating the pieces. (Note that these areas are mirror images of one another in the two photographs.) Little else happened to the surface which was originally finely polished; other marks which appear in the left-hand photograph are scratches caused

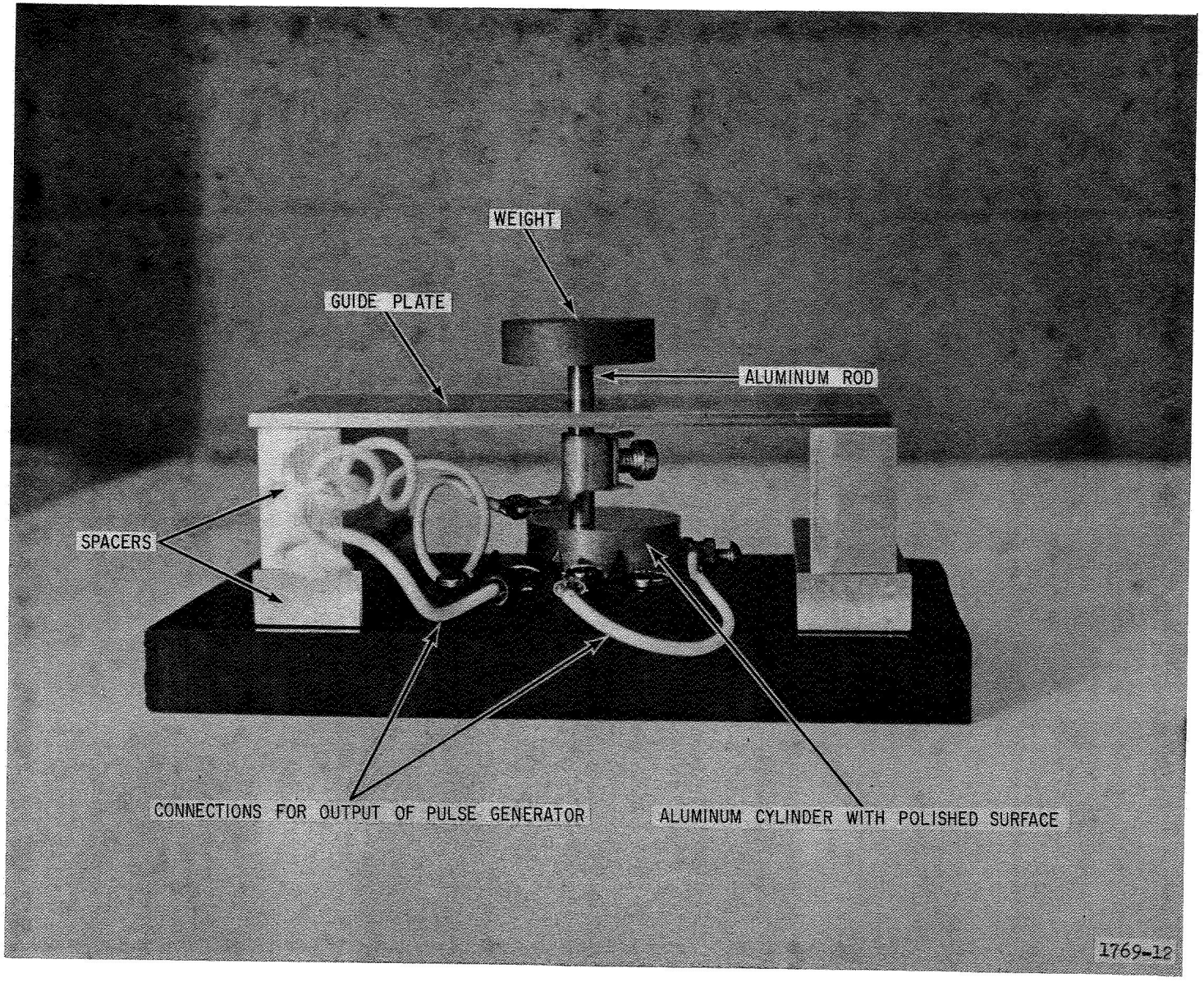
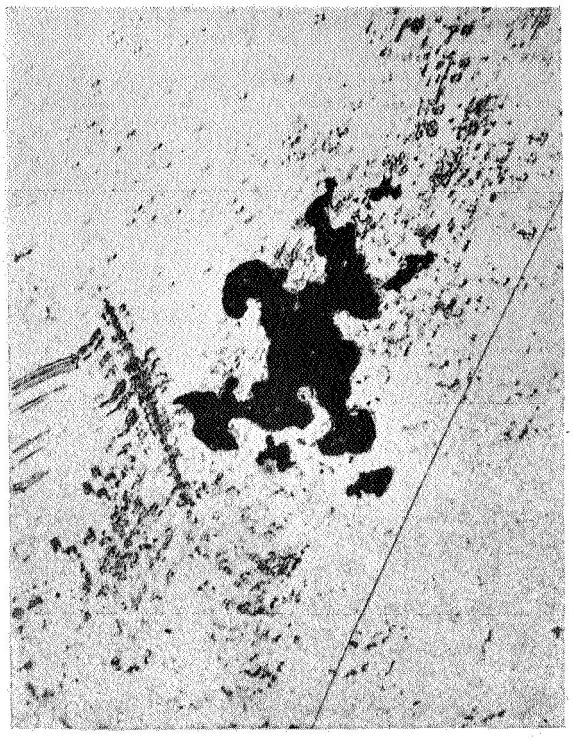


FIG. 1 . ARRANGEMENT FOR STATIC PLATEAUING EXPERIMENTS.



0.01 in.

Frame 94

Sample No. 2, 1 1/2-in. diam. al. cyl.

Original surface finished in vibratory polisher using 0.3 μ (Linde A) abrasive.

0.01 in.

Frame 102

Sample No. 8, 1/4-in. diam. al. rod.

Original surface polished with 600-grit paper.

FIG. 2 . PHOTOMICROGRAPH OF AREA AFFECTED BY PASSAGE OF ELECTRICAL PULSE THROUGH ALUMINUM/ALUMINUM INTERFACE.

Table 1

DATA FOR STATIC PLATEAUING EXPERIMENTS

Each rod was placed against a different area of the polished surface of an aluminum cylinder (Sample 2), as shown in Figure 1.

Exp. No.	Rod No.	Rod Diam. (mm)	Rod Diam. (in.)	Rod End Polished with Grit No.	Contact Pressure (kN/m^2)	Contact Pressure (lb/in^2)	Electrical Contact Resistance Before Pulsing (mΩ)	Electrical Contact Resistance After Pulsing (mΩ)
P1	7	6.4	1/4	240	55	8	----	----
P2	8	6.4	1/4	600	55	8	0.072	0.0050
P3	5	3.2	1/8	240	220	32	0.024	0.0092
P4	6	3.2	1/8	600	220	32	0.024	0.0082

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by subsequent handling. In the right-hand photograph, the light areas surrounding the black area are where the heating caused the asperities to melt. Outside the light areas are the parallel grooves produced by polishing.

Measurements of the electrical contact resistance at the joint, before and after pulsing, showed that the pulse caused the resistance to decrease by a factor of approximately 3 for the 3.2-mm rods and by a factor of 14 for one of the 6.4-mm rods. These reductions of electrical resistance probably reflect primarily the weld effect and should not be taken as representative of the potential contact improvement that can be achieved.

When we attempted experiments at contact pressures about twice those indicated above, most of the pulse energy seemed to be dissipated through arcing between various parts of the pulse generator. Apparently, the additional pressure reduced the electrical contact resistance at the joint to such an extent that too little energy was dissipated at the interface and the asperities were not heated sufficiently to melt.

3.4 Experiments with Aluminum/Stainless Steel Interface

Additional experiments were conducted with junctions between the end faces of 6.4-mm diameter aluminum rods and a polished stainless steel surface, with and without relative motion between them. The apparatus is shown in Figures 3, 4, and 5.

The size of the stainless steel plate was 5.1 cm x 10.6 cm x 1.9 cm thick (2 in. x 4 3/16 in. x 3/4 in.). The lapped surface used in the experiments had a maximum flatness deviation of 0.66 μm (26 μ in.) and a roughness of 0.010 to 0.013 μm (4 to 5 μ in.) rms. The ends of the 6.4-mm diameter aluminum rods were polished on 240-grit paper to produce a uniform series of approximately parallel scratches. The stainless steel plate was clamped in a vise attached to the table of a milling machine and aligned with its surface perpendicular to the spindle axis. Each rod sample was inserted through a collar in the spindle head so that one end face rested flat against the stainless steel plate. The contact pressure was varied between 45 and 166 kN/m^2 (6.5 and 24 lb/in^2) by placing weights over the top ends of the rods. The pressure on a rod was calculated from the measured weight of rod and added weights and the cross-sectional area of the rod.

The experimental data are given in Tables 2 and 3.

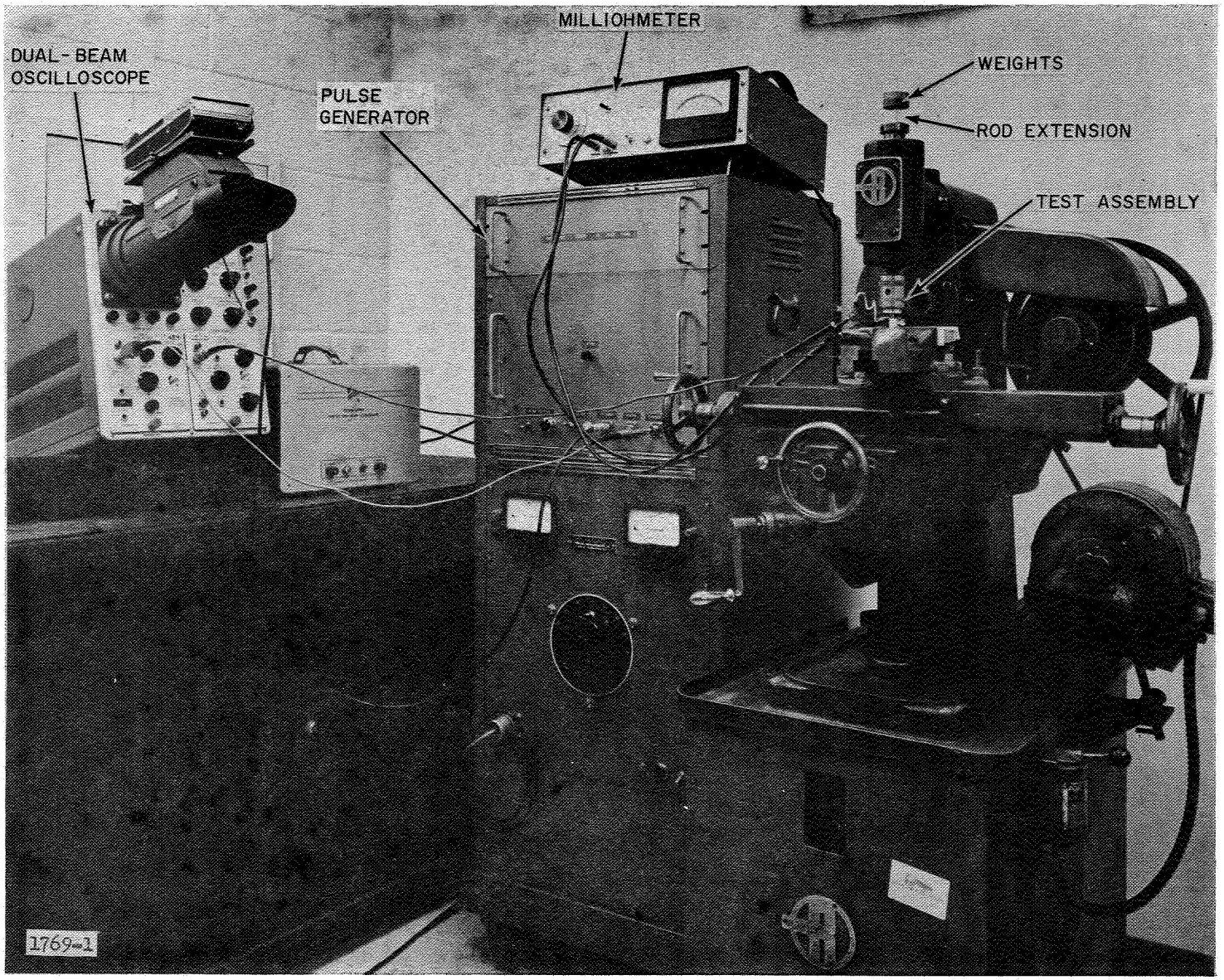

FIG. 3. APPARATUS FOR ASPERITY PLATEAUING EXPERIMENTS
See Fig. 4 for Detail of Test Assembly

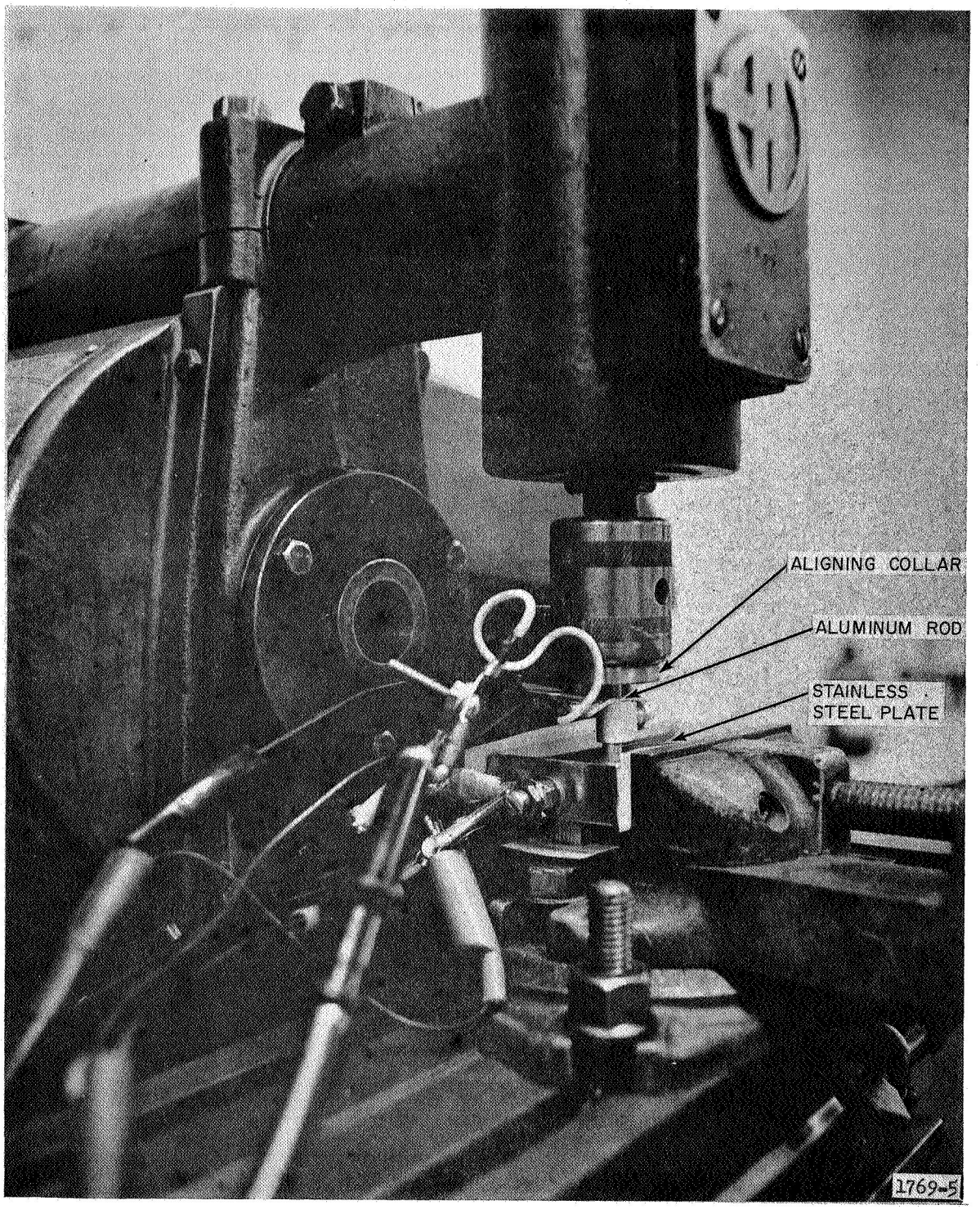

FIG. 4. DETAIL OF TEST ASSEMBLY FOR PLATEAUING EXPERIMENTS
See Fig. 5 for Cross-Section Diagram of Spindle Head Assembly.

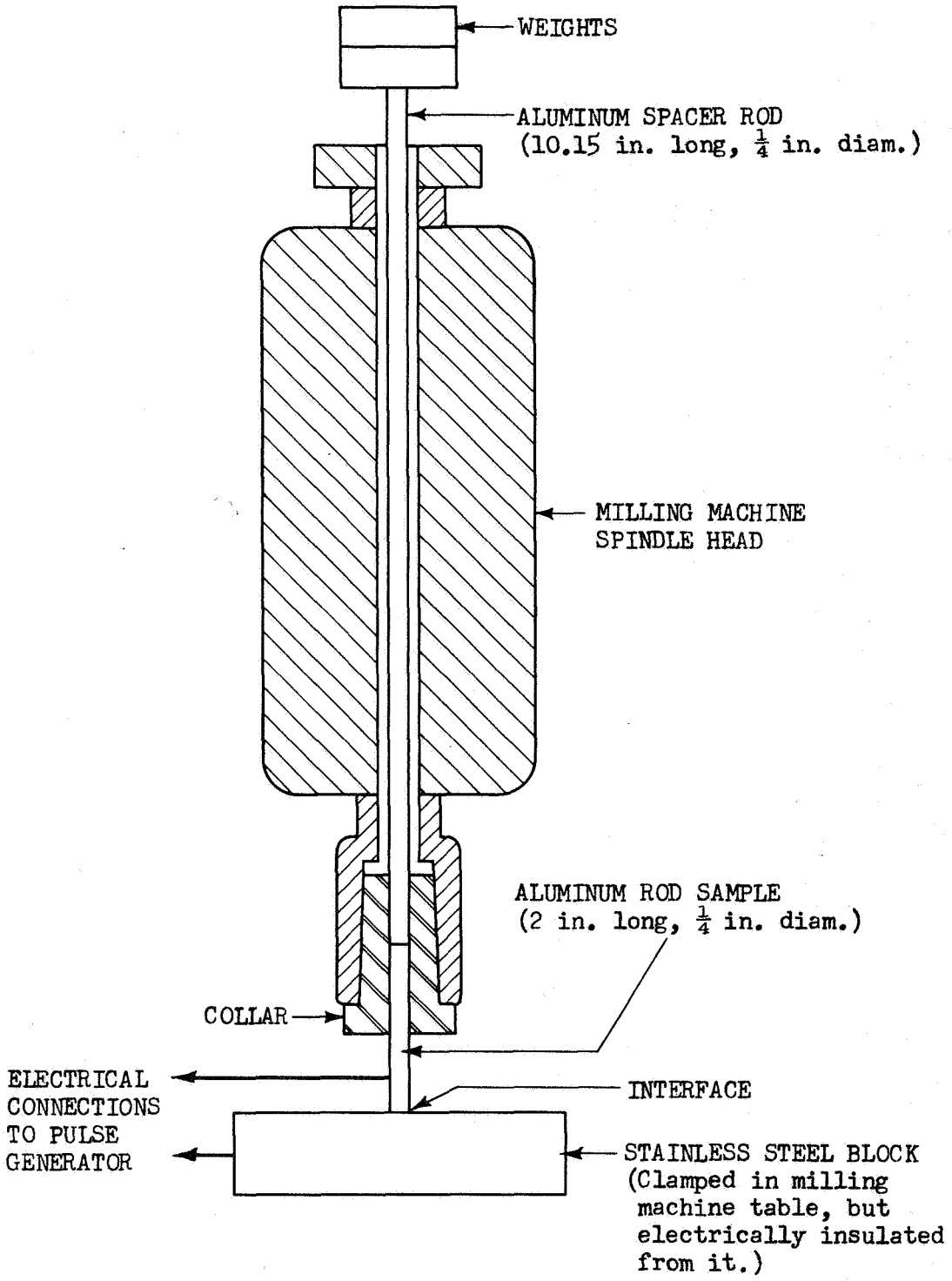

FIG. 5. ARRANGEMENT FOR PLATEAUING EXPERIMENTS WITH RELATIVE MOTION AT THE INTERFACE.

Table 2

DATA FOR STATIC PLATEAUING EXPERIMENTS WITH ALUMINUM/STAINLESS STEEL INTERFACE

Exp. No.	Rod No.	Capacitor Potential (C=10 μf) (kv)	Contact Pressure (kN/m^2)	Contact Pressure (lb/in^2)	Electrical Contact Resistance Before Pulsing (mΩ)	Electrical Contact Resistance After Pulsing (mΩ)	Amplitude of First Peak of Pulse V (volt)	Amplitude of First Peak of Pulse I (amp)	Approx. Energy in First Half Cycle (joules)
P5	11	5.0	45	6.5	10.4	3.4	a	a	---
P19	12	2.0	45	6.6	51	3.5	420	5,600	4.5
P20	13	2.0	85	12.3	53	5.0	340	5,600	2
P21	14	2.0	165	23.9	12	5.7	310	4,800	2
P22	15	5.0	165	23.9	38	3.6	>540[b]	10,800	---

Notes: a. Not measured.

b. First peak not visible because of high writing speed on oscilloscope.

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Table 3

DATA FOR PLATEAUING EXPERIMENTS WITH RELATIVE MOTION AT ALUMINUM/STAINLESS STEEL INTERFACE

Exp. No.	Rod No.	Capacitor Potential (C=10 μf) (kv)	Contact Pressure (kN/m^2)	Contact Pressure (lb/in^2)	Electrical Contact Resistance Before Pulsing (mΩ)	Electrical Contact Resistance After Pulsing (mΩ)	Velocity of Steel Plate (cm/sec)	Amplitude of First Peak of Pulse V (volt)	Amplitude of First Peak of Pulse I (amp)
P23	16	5.0	165	23.9	15	a	(1.0)[b]	a	a
P24	16	5.0	165	23.9	a	5.4	0.91	>560[c]	12,000
P25	17	5.0	165	23.9	6.2	1.43	0.94	>480[c]	12,000
P26	18	5.0	165	23.9	0.081	0.083	1.3	a	a

Notes: a. Not measured.

b. Not measured, but estimated to be approximately the same as in Experiments P24 and P25.

c. First peak missed because of fast writing speed.

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The current pulses were obtained from a 10-μf capacitor which was charged to potentials of 2 and 5 kv and discharged through the junctions between the aluminum rods and the stainless steel plate. The capacitor discharge produced a 43.5-kc current which decayed to practically zero amplitude within 2 or 3 cycles. Typical oscilloscope traces of the pulse are shown in Figure 6. The magnitude of the first current peak was on the order of 10^4 amp and the corresponding peak potential across the junction (in series with a 50-mΩ resistor) was a few hundred volts. With one exception, the contact resistances of the junctions, before the discharge, varied between 6 and 50 mΩ, depending on how well the parts were mated, but having little apparent relation to the contact pressures within the small range stated above. The contact resistances measured after the discharges varied between 1.4 and 4.7 mΩ. For the one exception, the contact resistance was 0.08 mΩ before and after the discharge.

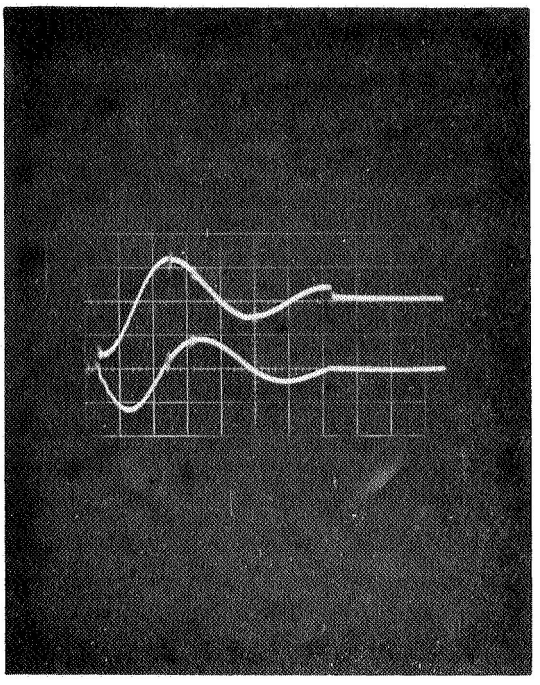
The energy dissipated through the junctions during the first half cycle of the discharge current was estimated to be a few joules, or about one-tenth the energy stored in the capacitor. It was estimated as follows. The values of V given in Tables 2 and 3 are the peak potential drops across the series combination of an 0.05-mΩ resistor and the electrical resistance, r, of the interface. (Actually, the load had an inductive component, but its effect was ignored for purposes of this approximation.) Although the value of interface resistance changed during the experiment, we assumed that the change during the first half cycle was small enough to be ignored in this calculation. By writing two expressions for the energy dissipated during a half cycle in the resistance r, we were able to compute values of r as well as of energy:

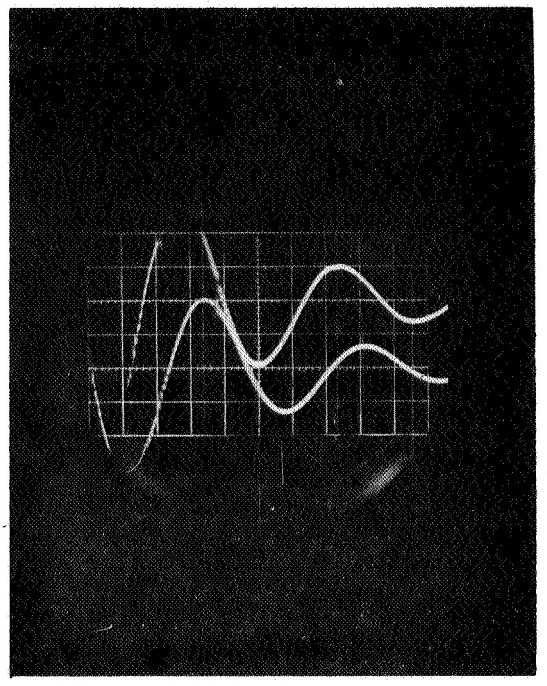
$$E = \frac{1}{4} I^2 r \tau,$$

$$E = \frac{1}{4} V \left(\frac{r}{r + 0.05}\right) I\tau,$$

where E = energy dissipated in resistance, r, during 1/2 cycle,
I = peak current through r,
V = peak potential across series combination of r and 0.05-Ω resistor,
τ = period of electrical pulse.

The reliability of this method of estimating E is supported by the fact that the values of r obtained from the above equations were intermediate between the values of electrical contact resistance before and after application of the pulse.





V = Potential across interface and 0.05-Ω resistor in series, 200 v/div.

I = Potential across 0.05-Ω resistor in series with interface, 200 v/div.

Exp. P21

No motion at interface. Capacitor charged to 2 kv.

Exp. P24

Speed of stainless steel plate = 0.36 in/sec. Capacitor charged to 5 kv.

FIG. 6. TYPICAL OSCILLOSCOPE TRACES OBTAINED BY DISCHARGING 10-μf CAPACITOR ACROSS ALUMINUM/STAINLESS STEEL INTERFACE.

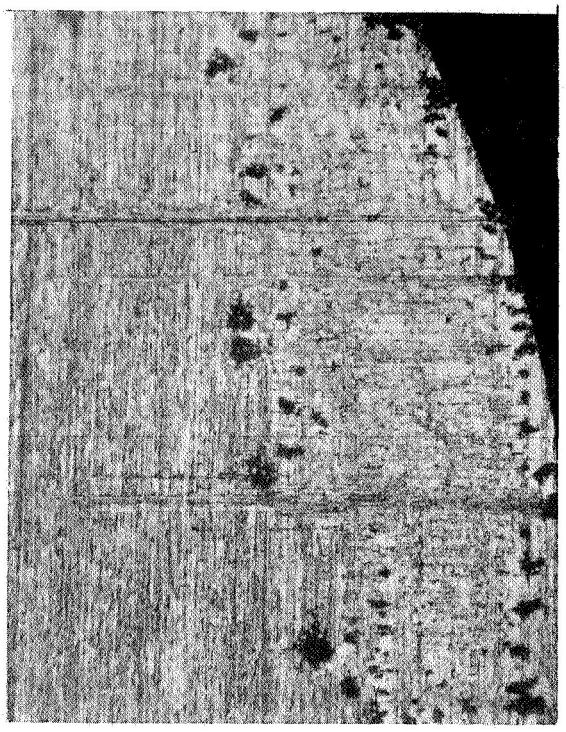
To produce relative motion at the junction, the milling machine table to which the steel plate was clamped was moved horizontally at a speed of about 1.0 cm/sec by turning the advancing wheel by hand. The rods were free to move up and down in the alignment collar to remain in contact with the plate at constant pressure even though the plate was not perfectly flat. When the stainless steel plate was set in motion, friction at the interface tended to move the bottom end of the rod with it. Because of the finite clearance in the aligning collar, the rod was tilted slightly from the perpendicular to the plate. Therefore, the contact was better near the leading edge of the rod; and in all the experiments involving relative motion between the rod and plate, the effects of the current pulse were confined to the area near the leading edge.

Examination of the affected surfaces under a microscope indicated that asperities on the aluminum surface melted at small scattered spots, and minute quantities of aluminum were deposited on the stainless steel surface at mating locations. There was some evidence that weak welds were produced in the static experiments, but it was difficult to ascertain this. After an experiment the electrical connections could be removed, and by lowering the milling machine table it was possible to lower the rod-plate assembly so that the rod was freed from the aligning collar. In one case, after this was done, it was noticed that the rod remained stuck to the plate. However, the force of attachment was so weak that, while removing the electrical connections and lowering the milling machine table, it was difficult to avoid breaking any bonds that might be present.

In the static experiments, it was noticed that less aluminum was deposited on the stainless steel plate when the contact pressure was increased. Apparently, increasing the contact pressure had the effect of improving the conditions for current flow so that there was less melting of aluminum. Within the range of contact pressures between 45 and 165 kN/m^2, however, there was no correlation of pressure with electrical contact resistance among the few samples tested.

Increasing the energy in the current pulse had the effect of increasing the total area of surface where melting or metal deposition occurred. This took place more by an enlargement of affected spots than by an increase in their number.

In experiments involving translatory motion of the stainless steel plate relative to the aluminum rods - in addition to the aforementioned misalignment effect which confined the affected areas to the vicinity of the leading edge of the rod - there resulted a scratching, primarily of the aluminum surfaces, apparently due to resolidified bits of aluminum melted by the current pulse. This is illustrated in Figure 7.



Sample 17

Exp. P25

FIG. 7. PHOTOMICROGRAPH SHOWING SCRATCHING CAUSED BY RELATIVE MOTION AT INTERFACE

- Photograph shows end of aluminum rod which was in contact with stainless steel plate.
- Black spots are areas where asperities melted when electric pulse was passed through the interface.
- Vertical scratches are due to polishing on 240-grit paper.
- Horizontal scratches were probably abraded by bits of resolidified aluminum as the stainless steel plate was moved to the left.

Such scratching did not occur when the stainless steel plate was moved relative to the aluminum rod in the absence of an electrical pulse. Therefore, the scratches were probably caused by the resolidified bits of metal deposited on the stainless steel surface or trapped in the interface. The fact that most such scratches trailed behind spots where melting had occurred further corroborates this veiw.

3.5 Conclusions

From these observations we conclude the following:

1. The contact pressure of the parts to be subjected to the pulse technique must be kept low; if the pressure is high enough to cause good electrical contact there may be insufficient heating of the asperities.

2. At low contact pressures, even with relatively flat surfaces, contact occurs at no more than a few points. Therefore, the pulses must be applied repeatedly to affect the entire interface. However, there is a limit to the expected benefit, because the increase in the number of contacts that will result from repeated pulsing will reduce the electrical contact resistance and tend to induce the trouble discussed in conclusion No. 1. Furthermore, repeated application of pulses will certainly increase the affected area, but it is difficult to see how it can produce uniform coverage of the interface.

3. For an aluminum/aluminum interface, without relative motion of the mated parts, the effect of the current pulse is to cause welding at the points of contact. This suggests that relative motion is essential It also suggests that the material out of which the reference surface is made should have a high melting point and not be easily wet by melted aluminum.

4. In small areas surrounding the welded spots, melting of the asperities produced a surface which appeared smoother than the original surface but rough compared to a well-polished surface.

5. The overall impression obtained from these experiments is that better results can be obtained by having relative motion at the interface, repeating the pulses, and choosing a better reference surface; but it does not seem encouraging that an acceptably smooth surface can be achieved by this method.

The experiments have revealed no evidence to support the feasibility of using electrical pulses to plateau asperities with the object of preparing surfaces that will have greater thermal contact conductance at a joint. For the most part, the surface areas affected by the pulses were made rougher than the original surface. Because of scratching caused by the resolidified metal, the introduction of relative motion at the interface during pulsing worsened, instead of improving conditions. It must be emphasized that the results are qualitative and applicable only within the narrow range of experimental parameters investigated. If one bears in mind that the application of the process would not justify an extremely costly procedure, however, there does not appear to be a reasonable hope that other experimental conditions would prove the method feasible.

4. PLIABLE SURFACE EXPERIMENTS

4.1 Introduction

Smoother surfaces tend to have more uniform distribution of contact spots within macro-contact areas; but the size and distribution of macro-contact areas are controlled by surface waviness, which prevents uniform contact over the entire interface. It is difficult to prepare surfaces free of waviness, and tremendous forces are required to produce reasonably uniform contact between wavy surfaces. Consideration of ways of overcoming waviness led to the idea of making at least one of the contacting surfaces pliable so that it could be made to conform to the shape of the mating surface.

The method chosen to produce a pliable surface, illustrated in Figure 8, was to use a thin metal foil backed by a paste or liquid-filled cavity. The intention was that applying pressure to the paste or liquid would force the foil to conform to the shape of the opposite member of the joint, thus producing uniform contact over the interface. It was felt that this might redistribute the contact areas in a way that decreases the constriction resistance, even if it did not result in increased area of actual contact for a given load. In an application, it would be necessary to anchor and seal the foil along its perimeter. Pressure would then be applied to the fluid behind the foil to force it to conform to the shape of the opposite member of the joint. In the test arrangement shown in Figure 8, an o-ring was used both to anchor the foil and to seal the fluid behind it.

Although our experiments did not support the feasibility of the pliable surface technique, it may nonetheless be useful to record an idea for attaching the foil to the rigid surface along its perimeter in any final application. Ultrasonic welding [14] is one of the methods that should be considered. This type of welding is a solid state bonding process as it permits joining without the application of heat, and the metals never reach their melting temperatures. High-frequency vibrations applied in the plane of the weld shatter the oxide and other contaminating layers covering the metal surfaces and reduce their yield strength so that only a small clamping force is necessary to bring the metals into intimate contact. Ultrasonic welding has been used to join thin foils to heavier sections, and ultrasonic ring welders have been used to hermetically seal volatile or explosive materials.

Computations (Appendix A) were made to estimate the foil thickness required in applying the pliable surface technique of improving

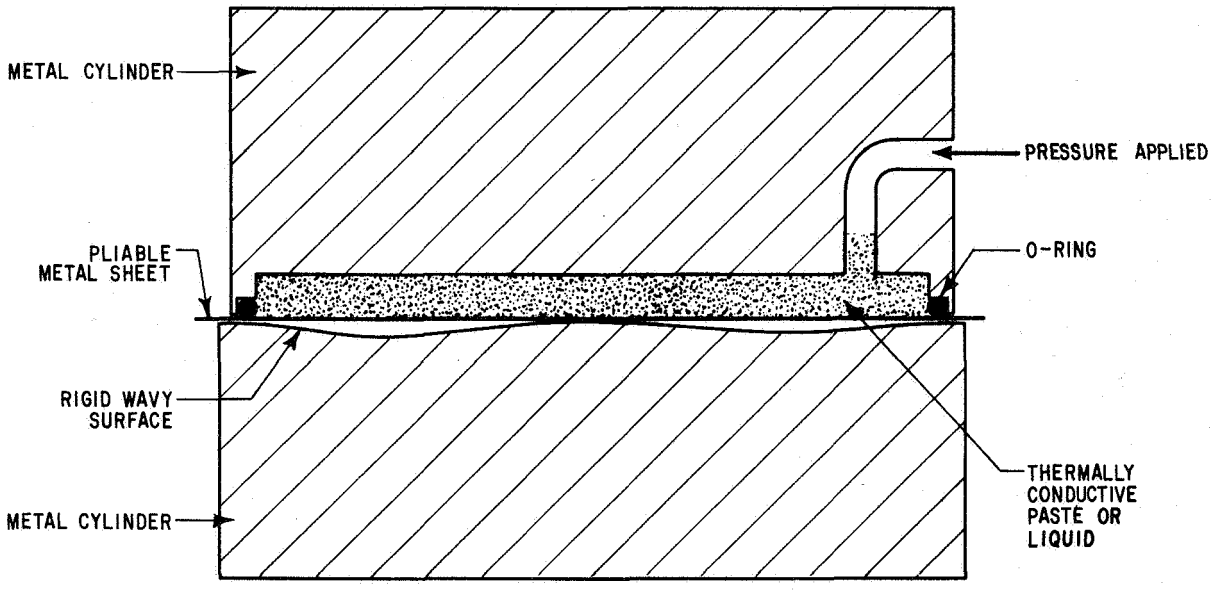


FIG. 8. SCHEME OF APPARATUS FOR INVESTIGATING THE USE OF A PLIABLE SURFACE TO INCREASE THE CONTACT CONDUCTANCE AT AN INTERFACE.

thermal contact conductance. Using classical plate theory and highly simplified mathematical models, it was estimated that a foil of 1 mil thickness should be able to touch the valleys of small surface waves under an applied pressure of 200 kN/m^2 (30 lb/in^2). When considering larger surface waves we found that only a negligible pressure was required to make the foil touch the bottoms of the waves. The required deflections for the large surface waves, however, are larger than the foil thickness, so that this result is subject to further investigation.

For the above method to be successful, the material used to fill the cavity should not introduce significant thermal resistance. Because of their high thermal conductivity and ability to make intimate contact with surfaces, liquid metals* such as mercury would be thermally superior to high vacuum grease. Experiments [13] have shown that the thermal contact conductance between pure mercury and a chromium or nickel surface is in the range 5 to 20 $Wm^{-2}\ °C^{-1}$, and it is considerably higher between mercury and a copper surface. These numbers may be compared with the values of contact conductance under moderate loads between aluminum surfaces, which are in the range 3000 to 30,000 $Wm^{-2}\ °C^{-1}$.

In our search for cavity fillers, we learned of a liquid metal alloy** which was advertised as having the ability to "wet" virtually anything and to make low resistance thermal contact to difficult materials including refractories, plastics, and metals. For thermal conductance, however, it might not be essential to have exceptionally good wetting. An analysis [12] of the experimental data of many workers led to the conclusion that nonwetting may impose a significant electrical resistance between a surface and a liquid metal, but it has a negligible effect on interfacial thermal resistance in nonboiling systems.

Of the liquid metals, mercury, with a melting point of -37.97°F, is the only one capable of functioning within most of the temperature range from -40°F to 140°F, as usually required for spacecraft applications. The liquid metal with the next higher melting point is the eutectic alloy of sodium and potassium (NaK), which melts at 12°F.

Although liquid metals and alloys have certain advantages, there are unfortunately a number of reasons why it might not be feasible to use them in a practical application. Some steels have good corrosion resistance to mercury and NaK, but aluminum has poor resistance [35]. For example, mercury amalgamates so readily with aluminum that it would destroy a thin foil.

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* The properties of liquid metals and their use as heat transfer media are described in Reference 32.

**"Wetalloy-232", developed by Victor King Laboratory, Los Altos, Calif.

Another shortcoming of some liquid metals, such as sodium and potassium, is their violent chemical interaction with water and oxygen.

A search for a suitable fluid or paste to fill the cavity behind the pliable surface revealed the following. A grease heavily filled with metallic oxides has a thermal conductivity about twice that of an unfilled grease and about 1/500th of the thermal conductivity of aluminum. Therefore, even if it were possible to reduce the thickness of the grease layer to 25 μm (0.001 in.), it would be thermally equivalent to 1.3 cm (0.5 in.) of aluminum. Considering, furthermore, that there would be some thermal resistance at the two interfaces between the grease layer and its metal boundaries, it is evident that a grease would not be a suitable filler for the cavity behind the pliable surface. Ordinary liquids are subject to the same objections. Only liquid metals seem to have sufficiently high thermal conductivity to meet the needs of the present application.

Although the search for a fluid to meet the needs of the final application did not seem hopeful, it was easier to meet the needs of the feasibility study. We found that pieces of aluminum of the type used in the test fixture, including an aluminum foil, showed no perceptible damage after being exposed to mercury for more than two weeks at room temperature. Therefore, we decided to use mercury in the preliminary experiments involving electrical conductance measurements. To avoid the possibility of accidentally contaminating the complex thermal conductance column with mercury, however, thermal measurements under vacuum were made with a grease filling the cavity behind the foil.

4.2 Preliminary Pliable Surface Experiments

While preparations were being made for thermal contact conductance measurements under vacuum, various preliminary pliable surface experiments were performed using electrical conductance measurements to indicate the extent of contact between a thin metal foil and a wavy surface.

To increase the generality of the results and make them amenable to mathematical analysis, an effort was made to produce a surface of known waviness. Since the analysis given in Appendix A showed that greater pressure is required to make foils conform to the shape of small waves than to large waves, we aimed toward producing a surface having small waves; but this had to be compromised with the difficulty of machining such a surface. An attempt to grind a series of parallel, v-shaped grooves onto aluminum failed because the size of surface irregularities produced was comparable to the desired depth of

the grooves. Acceptable results were obtained with hardened steel, however, which is much easier to grind than aluminum. The steel sample (No. 10) was a cylinder 3.8 cm (1 1/2 in.) in diameter and approximately 1.9 cm (3/4 in.) long. Profilometer measurements showed that the parallel grooves machined onto the surface had the shape shown in Figure 9. The lack of symmetry was caused by difficulties experienced in dressing the edge of the grinding wheel used to cut the grooves.

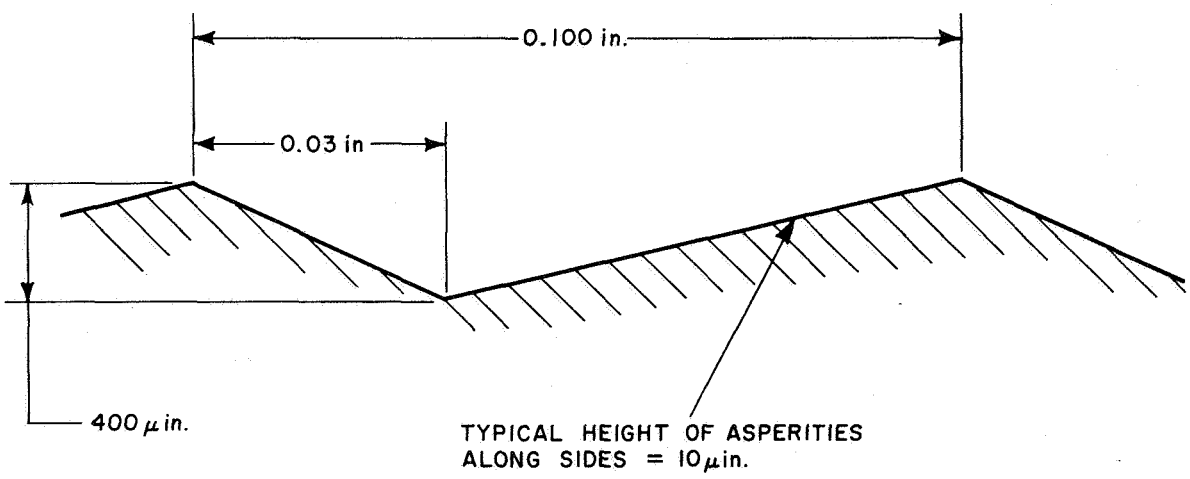

FIG. 9 . CROSS SECTION OF GROOVES IN WAVY SURFACE.

The apparatus used in some of the preliminary experiments is shown in Figures 10 and 11. The sample assembly shown corresponds to Figure 8. The lower sample is the steel cylinder with a wavy surface. The cavity in the upper cylinder was filled with mercury or an electrically conductive paste. When paste was used, the cavity was slightly overfilled with the paste before the foil was placed over it. The sample assembly was then clamped in the hydraulic press, and pressure was applied to the paste-filled cavity from a line connected through a regulator to a cylinder of compressed air. To fill the cavity with mercury instead of paste, the apparatus was first assembled as shown in Figure 10. The system, except for the pressure gage, was evacuated by connecting a vacuum pump to the side opening of the glass flask.

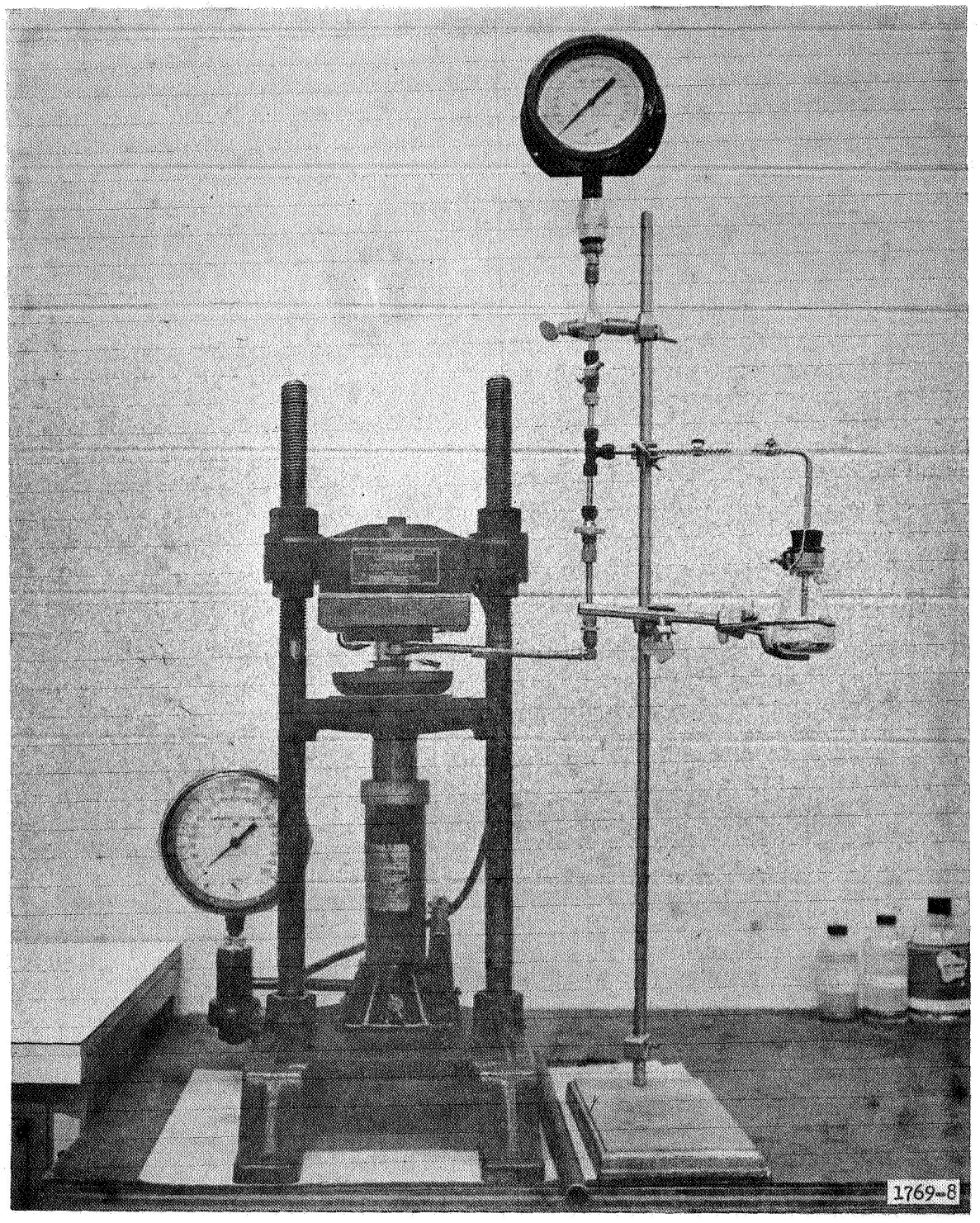

FIG. 10 . PHOTOGRAPH OF APPARATUS USED FOR PRELIMINARY PLIABLE SURFACE EXPERIMENTS (See Fig. 11 for detail of sample assembly.)

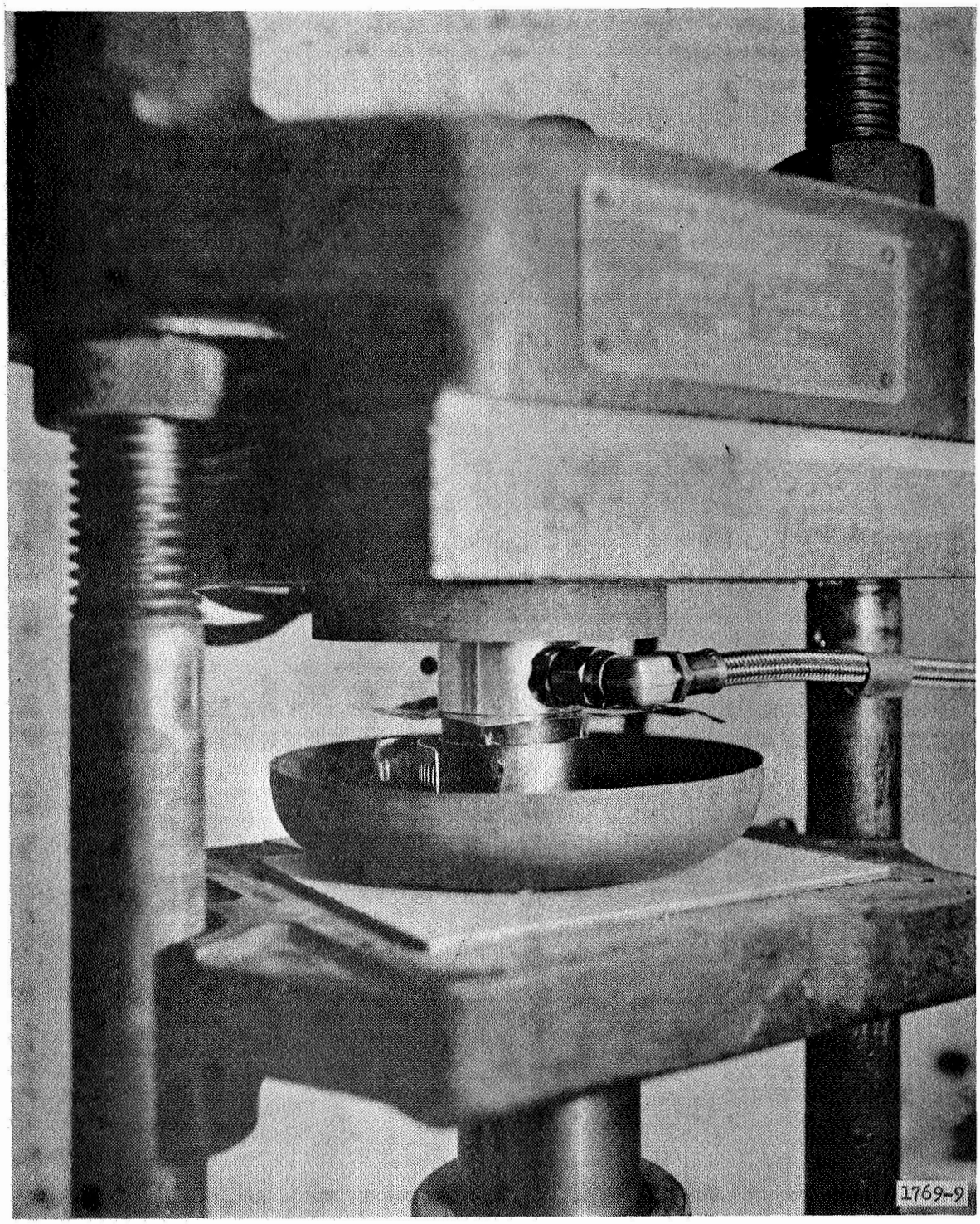

FIG. 11 . PHOTOGRAPH OF SAMPLE ARRANGEMENT USED FOR PRELIMINARY PLIABLE SURFACE EXPERIMENTS.

- The upper cylinder contained the mercury- or grease-filled cavity which could be pressurized.
- The lower cylinder had a surface of known waviness.
- The dish was used to catch mercury spilled when the samples were disassembled.
- A bakelite disc over the upper sample, and sheets of other insulating materials were used to isolate the assembly electrically from the hydraulic press.

Then the tube passing through the rubber stopper was pushed downward until its bottom end was in the pool of mercury inside the flask; and air was let into the flask to force the mercury into the previously evacuated system, including the cavity above the foil. The flask and the tube connected to it were then removed, and a cylinder of compressed air, with a regulator, was attached in its place.

Before the apparatus described above became available, a few experiments were conducted with the simpler arrangement shown in Figure 12.

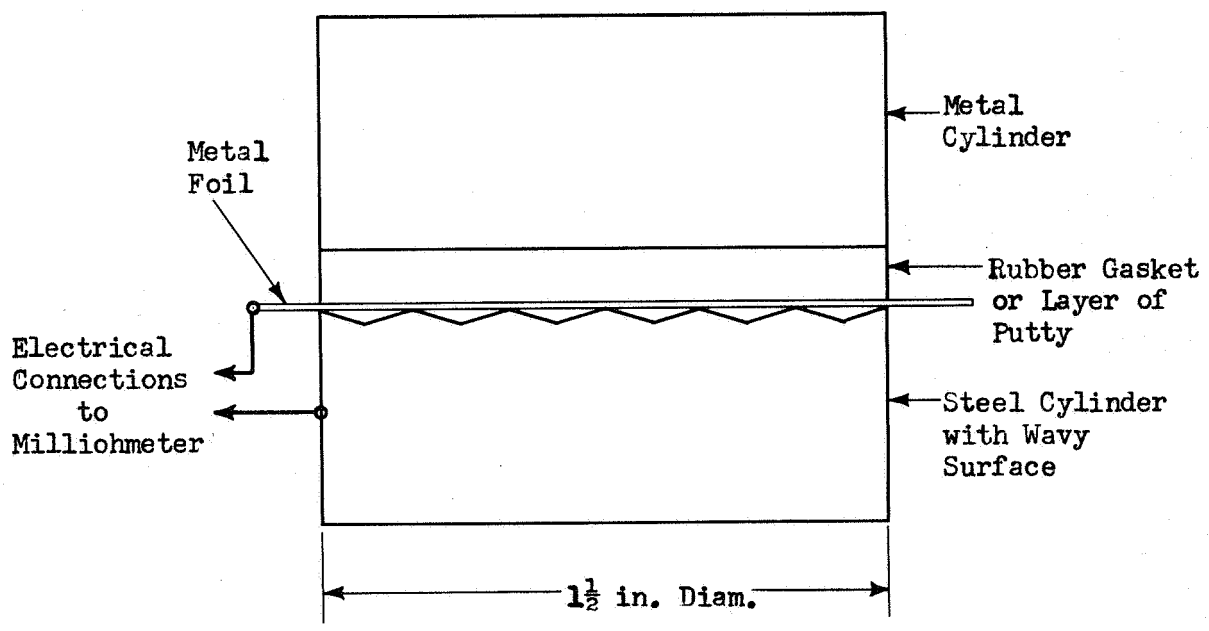

FIG. 12. ARRANGEMENT FOR MEASURING ELECTRICAL CONTACT RESISTANCE BETWEEN A METAL FOIL AND A METAL SURFACE.

A vertical clamping force was applied in a hydraulic press.

4.2.1 Experiments with Aluminum Foil

In all of the experiments described below, the aluminum foil was 25 μm (1 mil) thick, of the type sold in grocery stores for wrapping food. The interface of interest was always that between the foil and a steel cylinder with a wavy surface shaped as shown in Figure 9.

In one experiment, the arrangement was that shown in Figure 12, except that the upper aluminum cylinder was directly in contact with the aluminum foil. Without any compressive force, except the weight of the aluminum cylinder, the contact resistance was 36 mΩ. A compressive force of 1110 N (250 lb) was adequate to reduce the resistance to about half its original value. Increasing the force to 2700 N (600 lb) produced little further reduction in contact resistance. In this case the contact between the foil and the wavy surface was confined to the ridges of the grooves in the steel surface.

In another experiment, the foil was backed by a layer of putty, as shown in Figure 12. The initial contact resistance under a small compressive force was 23 mΩ. Increasing the pressure to about 1400 kN/m^2 (200 lb/in^2) reduced the contact resistance to 9 mΩ. Further increase in pressure to about 14,000 kN/m^2 (2000 lb/in^2) produced extremely little further reduction in contact resistance. It is possible that the foil conformed to the shape of the mating surface when the pressure was 1400 kN/m^2 (200 lb/in^2), and increasing the pressure caused negligible improvement in contact. Similar results were obtained when pressure was applied to the foil through a sheet of fluoro-silicone rubber, 2.4 mm (3/32 in.) thick.

All of the foils which were pressed against the grooved surface with pressures exceeding approximately 3500 kN/m^2 (500 lb/in^2) had a permanent pattern of lines engraved in them: heavy lines corresponding to the ridges of the grooves and finer parallel lines corresponding to smaller machine marks along the sides of the grooves.

Two additional experiments were conducted with the apparatus shown in Figure 10, pressure being applied to the foil through mercury filling the cavity behind it. In both cases, the foil was oriented so that the direction in which it had been rolled (during manufacture) was perpendicular to the grooves. The side of the foil facing the grooved steel surface was in one case the shiny side and, in the other case, the dull side. The sample assembly was clamped in the hydraulic pressure with a force which was maintained constant. With the dull side of the foil in contact with the steel surface, the contact resistance was

initially about 11 mΩ; and it remained approximately constant as the pressure on the foil was increased to 2000 kN/m^2 (300 lb/in^2). With the shiny side in contact with the steel surface, the initial contact resistance was 22 mΩ. It decreased to 7 mΩ as the pressure was increased to 700 kN/m^2 (100 lb/in^2), and it remained constant as the pressure was increased further to 3280 kN/m^2 (475 lb/in^2).

4.2.1 (a) Conclusions

The conforming of a foil to a wavy surface seems to occur in two stages: first the foil comes into contact with the tips of asperities, then it makes more intimate contact with these asperities. A pressure on the order of 700 kN/m^2 (100 lb/in^2) seems to be adequate to cause a 25-μm(1-mil) thick aluminum foil to come into contact with the tips of asperities on grooves representative of typical surface waviness. Much higher pressure is required to cause better contact in the second stage, because this requires that the foil make sharper bends and that the asperities penetrate the foil to some extent. The electrical contact resistance is decreased by a small factor (about 3) during the first stage; but very little change occurs during the second stage, even when the pressure is increased by an order of magnitude.

4.2.2 Experiments with Copper Foil

Two experiments were conducted with a copper foil, 2.5 μm (0.1 mil) thick. The first experiment was conducted with the arrangement shown in Figure 12, using a sheet of rubber to transfer pressure to the foil. At a pressure of 145 kN/m^2 (21 lb/in^2) the contact resistance was 96 mΩ. This decreased to 24 mΩ as the pressure was increased to 965 kN/m^2 (140 lb/in^2), and increasing the pressure to 7240 kN/m^2 (1050 lb/in^2) produced very little further change in resistance. In fact, the last increase in pressure (from 4800 to 7240 kN/m^2) caused a 10 percent increase in contact resistance. Apparently, this was caused by a tearing of the foil along an approximately circular line having a diameter equal to three-fourths of the sample diameter, which is shown in Figure 13. The wrinkles seen in Figure 13 were probably caused by contraction of the rubber sheet upon release of the pressure on it.

The second experiment was performed with the arrangement shown in Figures 10 and 11, using an electrically conductive paste* in the cavity behind the foil. There were some uncertainties in the measurements because of difficulties in connecting the milliohmeter lead to the foil. However, discarding doubtful measurements, the initial contact resistance - without any pressure applied to the paste - was 56 mΩ. After increasing the pressure to 3500 kN/m^2 (500 lb/in^2) and releasing it, the contact

*Eccoshield VY, manufactured by Emerson & Cuming, Inc., Canton, Mass.

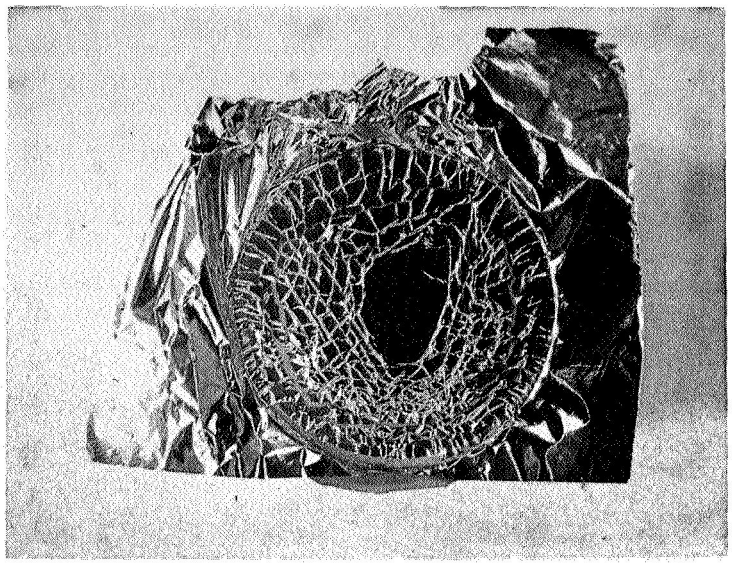

FIG. 13 . APPEARANCE OF A COPPER FOIL AFTER BEING PRESSED AGAINST A GROOVED STEEL SURFACE.

- The test arrangement was that shown in Fig. 12, using a rubber gasket.
- The maximum pressure applied was 1050 lb/in^2.

resistance was 17 mΩ. The resistance at intermediate pressures was uncertain because of the problem mentioned above. After the experiment, the foil did not have any of the type of wrinkles found in the rubber-backed foil. Also, there were no engraved markings caused by contact with the grooves, such as were formed on the aluminum foils. The absence of engravings may have been due to the pliability of the exceptionally thin foil.

4.3 Measurements of Thermal Contact Conductance of Pliable-Surface Sample

4.3.1 Procedure and Results

Following the preliminary pliable-surface experiments discussed in Section 4.2, thermal contact conductance measurements were made under vacuum using the 2.5-μm (0.1-mil) copper foil, which was considered to be the most suitable of the available foils for making a pliable surface. The sample consisted of two cylinders of 6061-T6 aluminum, each 3.8 cm (1.5 in) in diameter and approximately 1.9 cm (0.75 in.) long. One of the cylinders had a wavy surface on one end; the mating end of the other cylinder was closed by the copper foil backed by a thin layer of paste which could be pressurized to force the foil against the wavy surface.

The thermal conductance apparatus, borrowed from NASA, is described in Ref. 9 and shown in Figure 14. The vacuum system was provided by FIRL.

Preparation of a sample involved several problems: It was difficult to machine a wavy surface of simple, known geometry onto aluminum, which we wished to use instead of steel. The arrangement (Figure 10) which had been used in preliminary experiments was too bulky to fit into the limited space available in the thermal conductance column. Space limitations also required that the sample be pre-assembled before insertion into the column; but any provision for pre-assembly had to be such as to shunt a negligible amount of heat flux from the main path through the sample interface. There was very little space available for the tube connecting the cavity behind the foil to a source of compressed air, and the entire arrangement had to be leak tight.

The sample arrangement shown in Figure 15 overcame all of the above problems adequately for the purposes of these tests. The problem of producing a wavy surface in aluminum was solved by impressing the shape machined into the steel sample (Figure 9) onto the face of an aluminum cylinder, using a physical testing machine. The pressure required to produce the plastic deformation of the aluminum surface (6061-T6) was approximately 400,000 kN/m^2 (60,000 lb/in^2). To avoid the risk of

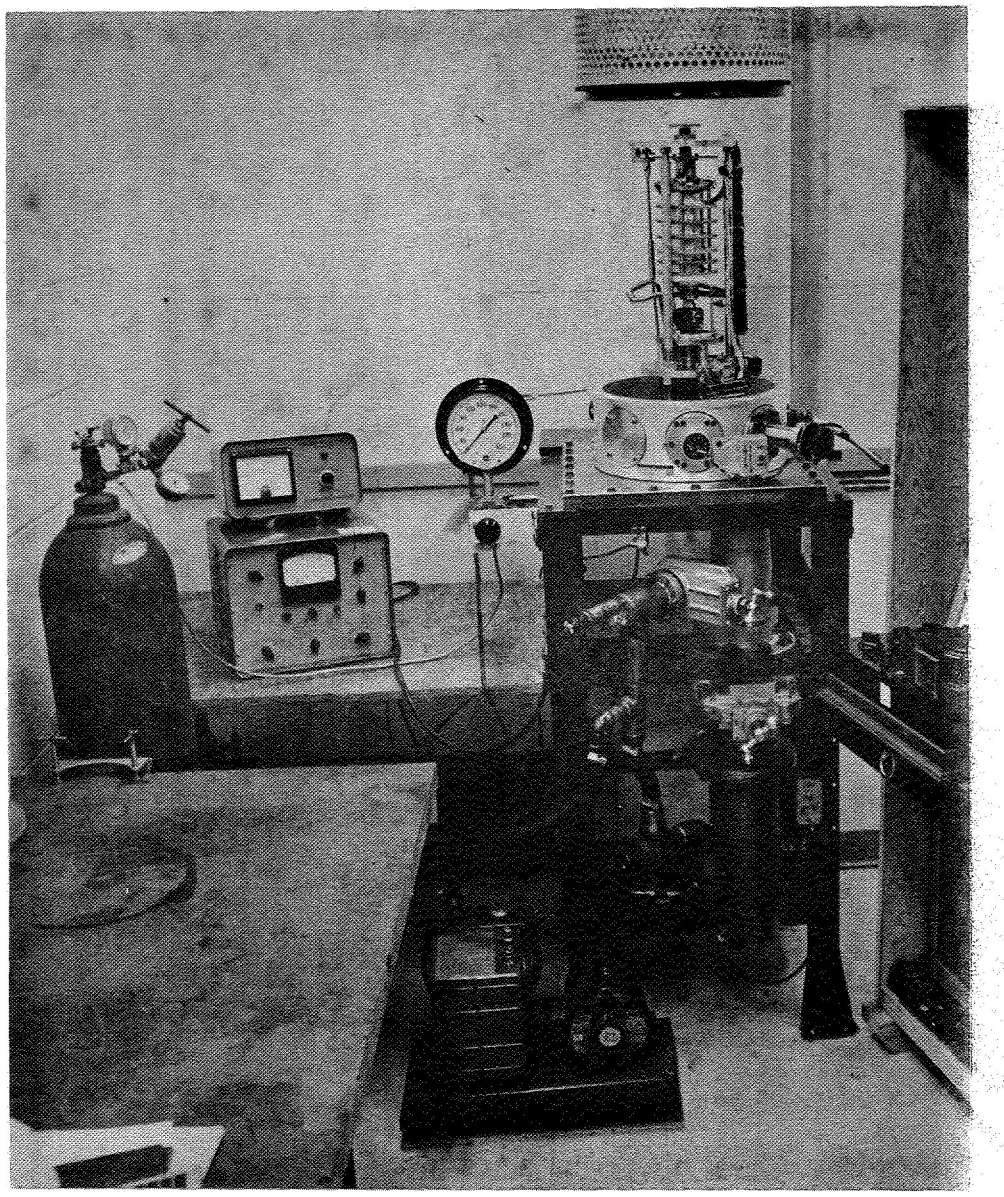

FIG. 14. APPARATUS FOR MEASURING THERMAL CONTACT CONDUCTANCE IN A VACUUM.

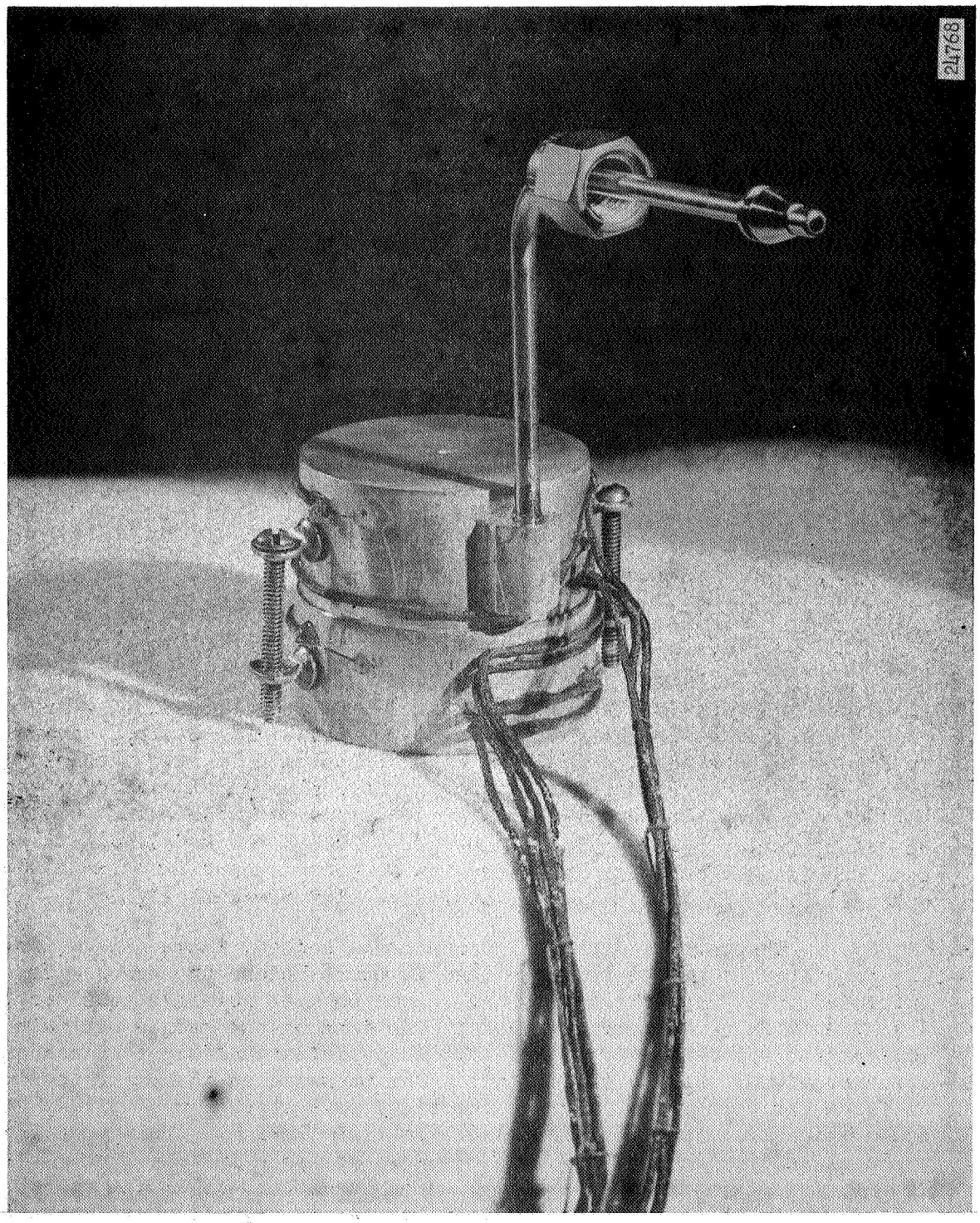

FIG. 15. SAMPLE USED FOR THERMAL CONTACT CONDUCTANCE MEASUREMENTS.

See Fig. 8 for Schematic Cross Section of Arrangement and Fig. 16 for Actual Cross Section of Upper Half.

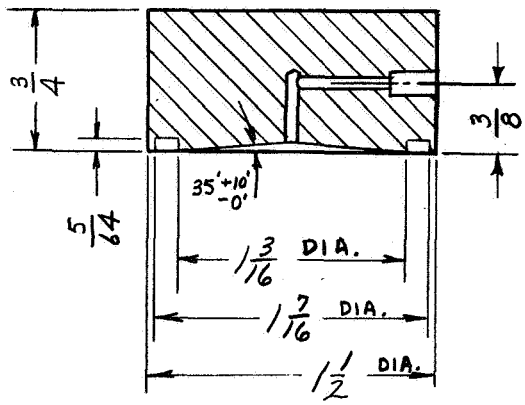

FIG. 16. CROSS SECTION OF SAMPLE WITH CAVITY FOR PASTE OR LIQUID

accidentally contaminating the apparatus with mercury, we used a thermally conductive grease* in the cavity behind the foil. The cavity, shown in Figure 16, was made as small as possible to minimize its thermal resistance. Four copper-constantan thermocouples were mounted in each half of the sample assembly, with the junctions near the axis, at distances of 0.152, 0.510, 1.020, 1.520 cm (0.060, 0.200, 0.400 and 0.600 in.) from the interface. They were cemented with an epoxy cement into radial holes, 0.76 mm (0.030 in.) in diameter, staggered circumferentially.

The assembled thermal conductance column, including the sample, was permitted to outgas for more than 24 hours before the tests were initiated. The pressure within the vacuum chamber remained equal to 4×10^{-5} mm Hg throughout the tests. The load on the sample was maintained constant at approximately 4030 N (906 lb), yielding an apparent contact pressure of 3530 kN/m^2 (512 lb/in^2). The pressure on the paste tending to force the copper foil against the rigid wavy surface was varied between atmospheric pressure and 1140 kN/m^2 (165 lb/in^2). This pressure was applied over an area having a diameter of approximately 3 cm (1 3/16 in.), so that the maximum load applied to the foil was approximately 810 N (182 lb). It was found that barely any adjustment of the bellows pressure was needed to maintain a constant load on the column when the paste pressure was varied.

*Dow-Corning 304 silicone heat-sink compound.

The heating and cooling rates at opposite ends of the column were adjusted to maintain the sample interface at approximetely 24°C (75°F). Erratic behavior of the control circuits on the 6 guard heaters intended to prevent radial heat losses prevented their use. Therefore, the upper part of the sample, which was closer to the heated end of the column, had a larger axial heat flux than the lower part of the sample. The heat flux, q, used to compute the thermal contact conductance was taken as the mean of the fluxes through the two halves of the sample.

The thermal contact conductance was computed with the formula

$$h = q/\Delta T \ ,$$

where ΔT, the temperature drop across the interface, was determined by the usual procedure of extrapolating the temperature gradient in each half of the sample to the interface,which we did mathematically.

One thermocouple in each sample was inoperative (in one case because of a broken lead, in the other case because of trouble in the associated circuitry) and the sample thermocouple nearest the interface with the heat sink gave low readings which were not useful in computing the temperature gradient, which appeared to change rapidly with distance in the vicinity of the heat sink. Fortunately, in each sample the two thermocouples closest to the interface between foil and wavy surface functioned normally, yielding measurements from which the temperature gradients were computed. Although the use of 2, instead of 3 or 4, temperatures in computing the temperature gradient reduced the accuracy, it remained adequate for these experiments.

The temperatures within the sample were measured three or four times at each setting of the pressure in the paste-filled cavity, always in the same sequence, and a value of h was computed for each set of temperature measurements. Since the values of h at a given pressure did not show a trend, their average was used as the representative value.

The results, which are plotted in Figure 17, are somewhat difficult to interpret. The apparent tendency of the thermal contact conductance to decrease as the paste pressure was increased, although a slight effect, is opposite to the effect that had been anticipated. Also, the point at 267 kN/m^2 (38.7 lb/in^2) does not fall in line with the remaining points; but since it represents the average of 5 sets of measurements which did not exhibit any peculiarities, no reason could be found for discarding it. Actually, the slight change indicated by the curve in Figure 17 is comparable to the variations among individual values of h at a given pressure, and it is therefore not certain that the apparent trend is real. What can be said is that increasing the paste pressure up to 1140 kN/m^2 (165 lb/in^2) had very little influence on the thermal contact

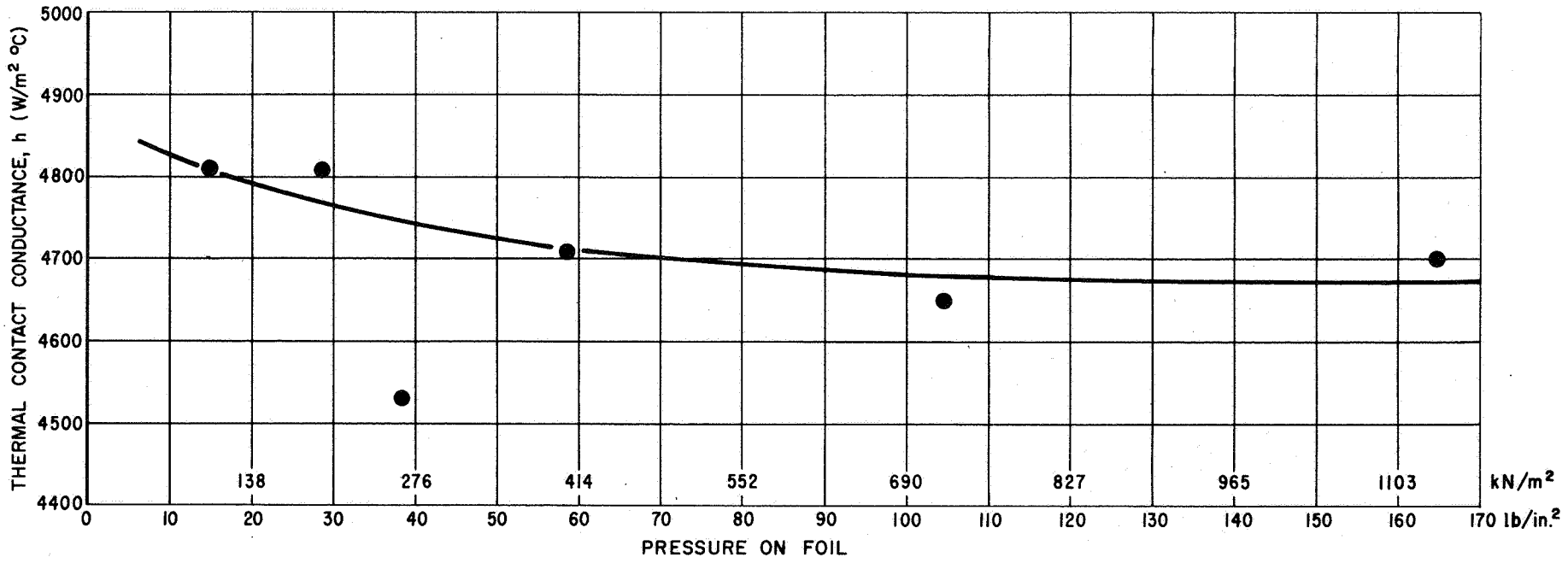

FIG. 17. THERMAL CONTACT CONDUCTANCE AS FUNCTION OF PRESSURE ON FOIL

conductance. A discussion of possible experimental difficulties, none of which could be verified, follows later in this section.

Following the tests at 1140 kN/m^2, the pressure on the paste was returned to atmospheric pressure, and the temperatures within the sample were remeasured. Unfortunately, after one set of measurements, a set screw on the shaft of the thermocouple selector switch within the vacuum chamber became loose, making it impossible to proceed with further measurements. The single value of h obtained from this set of measurements was the same as the average value obtained from the immediately preceding tests at 1140 kN/m^2. It is possible that friction, between the paste and the walls of that portion of the tube (Figure 15) which contained paste, prevented the interface conditions from changing significantly after the pressure was decreased. However, in view of the fact that only one measurement was made after reducing the pressure, a reliable interpretation of the observation is not possible.

At the end of the experiments, the sample was disassembled and examined carefully. No evidence of malfunction was observed. The foil had remained intact, and the paste had remained sealed in the cavity behind it. By applying a small pressure to the tube connected to the paste cavity and observing that this caused paste within the tube to flow into the cavity, we verified that there was no blockage which might have prevented transmission of the applied pressure to the cavity. Our thought that the interface between paste and air within the tube was far enough from the cavity to prevent compressed air from entering the cavity was verified when the foil was removed, as we then observed no evidence of air having entered the cavity. In short, nothing was observed that would cast doubt on the validity of the experiments.

Our values of thermal contact conductance, all of which were close to 4700 $Wm^{-2}\ °C^{-1}$, may be compared with values in the vicinity of 3000 $Wm^{-2}\ °C^{-1}$ obtained by Cunnington [31] for samples of 6061-T4 aluminum at apparent contact pressures of about 600 kN/m^2 (90 lb/in^2). The presence of a paste-filled cavity in our arrangement tended to decrease the thermal contact conductance. This was partly compensated by the small but unavoidable, direct contact between the two samples and the foil along the outer edge of the interface. In view of these differences and the many experimental difficulties experienced in the present tests, it is encouraging that our values of conductance are comparable to values reported by others.

4.3.2 Conclusions

The above results do not support the feasibility of the pliable surface technique for increasing thermal contact conductance. Foils of other materials on hand (0.001-in. thick aluminum and 0.012-in. thick indium) would be expected to be even less effective than the 2.5-μm (0.0001-in.) thick copper foil which was tested. Because of the difficulties of applying the pliable surface technique it would have to be superior to other methods of increasing thermal contact conductance in order for its use to be justified. For example, the use of thin indium foil at an interface has been shown to be capable of increasing the thermal contact conductance by an order of magnitude in a vacuum environment, it can be concluded that our pliable surface arrangement is much less effective than the use of a thin foil alone. Improvements of the pliable surface technique are likely to be achieved only with considerable effort, but in any case it is doubtful that superiority over other techniques can be achieved.

As presently conceived, the pliable surface technique involves the introduction of a layer of a paste or liquid (in the cavity behind the foil), which has lower thermal conductivity than the material it replaces, and the addition of two interfaces (the boundaries of the paste- or liquid-filled layer) which add to the thermal resistance. Thus, the pliable surface must effect a reduction of thermal contact resistance at the interface with the wavy surface simply to achieve parity with the usual joint interface. The preliminary experiments provided evidence that a practical pressure is adequate to cause a thin foil to conform to the envelope of the small-scale asperities of a wavy surface, but that beyond this it is difficult to increase the area of actual contact, even with application of quite high pressures. The situation can be alleviated by making the surfaces smoother, but it is doubtful that the requisite improvement can be achieved without unreasonable effort.

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A P P E N D I C E S

APPENDIX A

ESTIMATION OF PLIABLE SURFACE REQUIREMENTS*

The object of the following computations was to determine whether ordinary foils can be made to conform to the shape of a wavy surface with the application of reasonable pressure. For reference purposes, we thought that it would be possible to design a pliable surface of 1-mil thick aluminum foil, say, if the computations showed that it would deform adequately under a pressure of about 100 lb/in^2. Based on information in the literature [33]. The following wavelengths and amplitudes were taken to represent the smallest and largest waves that might be encountered in the geometry of metal surfaces:

	Amplitude (μ in.)	Wavelength (in.)
Minimum	80	0.04
Maximum	1600	0.4

The asperities associated with surface roughness were not considered.

A given surface may have waves which are corrugated or spherical in nature, depending upon the method of fabrication. As a foil is pressed against a surface it tends to come in contact first with the peaks and then gradually with the valleys. A reasonably close approximation of the behavior would have to consider the overall foil, with representative boundary conditions at its periphery, and follow the motion as the pressure on the foil is gradually increased, taking into account the kinematic constraints for a given surface pattern. We simplified the model by considering an isolated portion of the foil over a single surface wave and neglecting its interaction with the remainder of the foil. We considered isolated foil sections which are either circular for spherical waves or rectangular for corrugated waves. The behavior for both fixed and simply supported boundary conditions was considered. Classical plate theory was assumed, which is valid only for plate deflections which are small compared to the plate thickness.

Based on the calculations (see below) made with the highly simplified mathematical models which we considered, we estimated that a foil of 1 mil thickness should be able to touch the valleys of the smallest surface waves under an applied pressure of 30 lb/in^2. When considering the larger surface waves, we found that, based on classical plate theory, only a negligible pressure was required to have the plate touch the bottom. The required deflections for the large surface waves, however, are larger than the foil thickness, so that this result is subject to further

*This analysis was conducted by L. Berkowitz.

investigation, possibly using Von Karman large deflection plate theory as discussed in Ref. 24. Stresses in all cases were found to be within the yield strength.

The calculations described above are adequate to indicate the feasibility of using foils. Further insight into the behavior of foils pressed against wavy surfaces could be gained by the following analyses:

1. Behavior of a foil section over large surface waves using large deflection plate theory.

2. Behavior of the entire foil, due consideration being given to the boundary conditions at the foil periphery for several wave patterns.

3. Deformations of the asperities on the mating surfaces. Because of the sharp peaks it is anticipated that plastic flow would have to be considered.

Simply Supported Edge

Computations for Spherical Wave

The foil is considered to be a circular plate of radius, a, with simply supported edges. Then, from Roark [25], Table X, Case-1, the maximum deflection at the center is

$$y_o = \frac{3W\,(m - 1)(5m + 1)a^2}{16\,\pi\,E\,m^2\,t^2} \tag{1}$$

where m = 1/Poisson's ratio,

a = radius of plate, (in),

t = plate thickness, (in),

$W = \pi\,a^2\,p$, (lb); p = pressure on plate, (lb/in^2),

E = modulus of elasticity, (lb/in^2),

y_o = deflection at center, (in).

The maximum stress is given by,

$$\sigma_r = \sigma_t = \frac{3W}{8\,\pi\,mt^2}\,(3m + 1) \tag{2}$$

Assume values of E and ν representative of aluminum:

$$E = 10^7 \text{ lb/in}^2$$
$$\nu = 0.333, \; m = 3.$$

Then, for aluminum

$$y_o = 0.667 \times 10^{-7} \frac{pa^2}{t^3} \quad , \tag{3}$$

and for most materials,

$$\sigma_r = \sigma_t = \frac{1.25 \; pa^2}{t^2} \tag{4}$$

If $y_o = t$, then from (3),

$$y_o = t = 0.01606 \; a(p)^{1/4} \quad . \tag{3a}$$

Consider the spherical wave of minimum wavelength and depth,

$$a = 0.02 \text{ in.}, \quad y_o = 0.8 \times 10^{-4} \text{ in.}$$

Letting t = .001 in., and using Eq. (3), we find

$$p_{reqd} = \frac{(10^{-3})^3 \times 0.8 \times 10^{-4}}{0.667 \times 10^{-7} \times (0.02)^4} = 7.51 \text{ lb/in}^2 \text{ .,}$$

and Eq. (4) gives us

$$\sigma_r = 1.25 \times 7.51 \times \left(\frac{0.02}{0.001}\right)^2 = 3760 \text{ lb/in}^2 \quad .$$

Now, consider a spherical wave of maximum wavelength and depth:

$$a = 0.2 \text{ in.}, \quad y_o = 0.0016 \text{ in.}$$

Again letting t = 0.001 in., Eqs. (3) and (4) give us

$$p_{reqd} = \frac{0.0016 \times 10^{-9}}{0.667 \times 10^{-7} \times 16 \times 10^{-4}} = 0.015 \text{ lb/in}^2,$$

$$\sigma_r = \frac{1.25 \times 0.015 \times 0.04}{10^{-6}} = 750 \text{ lb/in}^2 \quad .$$

Note that the deflection is greater than the foil thickness; hence the computed pressure and stress based on the above formulas are inaccurate. But, even allowing a large margin for error, it seems reasonable to expect that the pressure required to produce the assumed deflection will be low.

Since the minimum surface wave seems to determine the plate design, assume that the available pressure is 50 lb/in^2, $y_o = 0.8 \times 10^{-4}$ in., and a = 0.02 in. Then, from Eq. (3):

$$t^3 = \frac{0.667 \times 10^{-7} \times 50 \times 16 \times 10^{-8}}{0.8 \times 10^{-4}} = 6.67 \times 10^{-9},$$

$$t = 0.00188 \text{ in.}$$

If t = 0.002 in., the required pressure is

$$p_{reqd} = \frac{0.8 \times 10^{-4} \times 8 \times 10^{-9}}{0.667 \times 10^{-7} \times 16 \times 10^{-8}} = 60 \text{ lb/in}^2,$$

and the resulting maximum stress is

$$\sigma_r = 1.25 \times 60 \times \frac{4 \times 10^{-4}}{4 \times 10^{-6}} = 7500 \text{ lb/in}^2.$$

Clamped Edge

From Ref. 26, pages 60 and 61, for a circular plate with clamped edges

$$y_o = \frac{pa^4}{64D}, \quad D = \frac{Et^3}{12(1 - \nu^2)}$$

$$\sigma_{max} = 0.75\, p \frac{a^2}{t^2} \text{ (at edges).}$$

Again taking $E = 10^7$ lb/in^2, and $\nu = 0.333$, we have

$$D = \frac{10^7 \times t^3}{12(1 - 0.111)} = 9.36 \times 10^5\, t^3$$

$$y_o = 0.167 \times 10^{-7} \frac{pa^4}{t^3}$$

Consider a minimum surface wave:

$$a = 2 \times 10^{-2} \text{ in.}, \quad y_o = 0.8 \times 10^{-4} \text{ in.},$$

and let $t = 10^{-3}$ in. Then

$$p_{reqd} = \frac{0.8 \times 10^{-4} \times 10^{-9}}{0.167 \times 10^{-7} \times 16 \times 10^{-8}} = 30 \text{ lb/in}^2 ,$$

and

$$\sigma_{max} = 0.75 \times 30 \times 400 = 9000 \text{ lb/in}^2 .$$

Computation for Cylindrical Wave

Consider a rectangular strip of width, $b = 2a$, and length, $\ell = 4b$, and assume all edges are fixed. From Roark [25], Table X, Case 41:

$$y_o = \frac{0.0284 \, pb^4}{Et^3 \, (1 + 1.056 \, \alpha^5)}$$

where $$\alpha = \frac{b}{a} = 1/4, \; \alpha^5 \approx 0 .$$

Again considering a surface wave of minimum wavelength and depth

$$b = 0.4 \text{ in.}, \quad y_o = 0.8 \times 10^{-4} \text{ in.},$$

and taking $$t = 10^{-3} \text{ in.}, \quad E = 10^7 \text{ lb/in}^2 ,$$

we have

$$y_o = \frac{0.0284 \, pb^4}{10^7 \times t^3} = 0.0284 \times 16 \times 10^{-7} \frac{pa^4}{t^3} ,$$

$$y_o = 0.454 \times 10^{-7} \frac{pa^4}{t^3} .$$

Comparing the above formula with Eq. (3), corresponding to a circular section of radius a, it is apparent that a long rectangular plate of width 2a is more flexible than a circular plate of diameter 2a.

APPENDIX B

PRESSURE-INDUCED PHASE TRANSFORMATION IN INTERFACE BONDING MATERIALS*

The true metal-to-metal contact area of two metal plates bolted together in a conventional manner is quite small - on the order of a few percent of the apparent contact area. In a vacuum, conduction of heat between two plates bolted together depends essentially entirely on the actual metal-to-metal contact, as the voids between the contacts will be acting as excellent insulators. In order to improve heat transfer under such conditions it was suggested to consider bonding the interface with a metal that undergoes a phase transition in the temperature and pressure range of the bolting operation. A foil made of the metal could be placed between the two plates to be joined; and, upon application of pressure through tightening the bolts, the foil may undergo the phase transformation. During the transformation, increased plasticity would exist and thus the bonding material would readily flow and increase the contact area. If the bonding material were brittle, the joint could be readily broken, thus meeting the requirement for this capability in the contemplated application. The results of a brief exploratory study on the possible existence of such a metal are reported below.

There are many metals in elemental form and metal alloys which undergo phase transformation upon application of pressure. However, the pressures are usually relatively high - on the order of 150,000 to 500,000 lb/in^2. This is considerably above the yield strength of many soft metals which may be considered as bonding materials, and thus it might be expected that the material may yield and flow before the transformation pressure is reached. A further problem is the actual production of the high pressures needed to cause a phase transformation. However, on a microscopic scale the real pressure reached between local asperities of the two plates may be easily as high as 100 times the pressure based on the apparent contact area; and, if the bonding material surrounding the local contact points does not flow due to friction, cold work or mechanical restraint, suitable transformation pressures may be reached.

For the purposes of the present exploratory study metals which exhibit phase transformations up to approximately 30 kilobars (1 kilobar is equivalent to 14,500 psi) and in the temperature range -40°F to +140°F were sought. The pressure range was determined from Table B1.

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*This section is based on a memo written by Dr. J. Hanafee on his preliminary investigation of a suggestion by Dr. J. Meakin.

Table B1

CONTACT PRESSURES IN BOLTED JOINTS

Apparent Contact Area (in^2)	Bolt Material	Load (lb)	% Real Contact Area (%)	Real Contact Pressure (lb/in^2)	Real Contact Pressure (kilobars)
3	Aluminum	1,500	1	50,000	3.4
			5	10,000	0.7
3	Steel	15,000	1	500,000	34.5
			5	100,000	6.9

Several types of transformation may occur upon application of a confining pressure. Five elements are known to go from solid to liquid, i.e., their melting points decrease with increasing pressure, and the transformation pressure of two of these elements, gallium and bismuth, are in the approximate range of the prescribed pressures and temperatures. The transformation of the foil material to liquid would be extremely helpful in increasing the contact area.

A second type of transformation which may occur upon application of pressure is a solid going to solid-plus-liquid. Such a transformation would be nearly as effective as a solid-to-liquid transformation in increasing contact area. Unfortunately, few pressure-temperature-composition phase diagrams are available. However, from (1) one atmosphere phase diagrams, (2) pressure-temperature diagrams of the elements, and (3) exploratory studies by P. W. Bridgman [27, 28, 29, 30] there appear to be several possible binary systems which may be utilized as bonding material. A particularly promising system is bismuth-antimony. The melting temperature of both of these elements decreases with increasing pressure and both elements exhibit complete natural solubility. Other likely successful systems of this type consist of one of the elements whose melting temperature decreases with pressure, and a second element which (1) forms a low melting point phase with the first element, or (2) is soluble in the first element. Several such alloy systems do exist, e.g., bismuth-lead, bismuth-cadium; however, the solidus surface has not been determined as a function of pressure.

A third type of pressure-induced transformation which may make suitable bonding material is a solid-to-solid transformation. The increased plasticity during the transformation would not be as large as in the case of the transformations involving liquid; but if the high pressure phase were retained upon release of pressure, and if the high pressure phase were brittle, it would probably be easier to rupture a joint made with this type of system than one made with the types of systems

involving melting. Most of the known solid-to-solid transformations occur at relatively high pressures although a few possible alloys have been found. One such alloy is Bi-35 Pb for which Bridgman [30] reports a new phase occurring at approximately 10 kilobars which is retained to one atmosphere.

In conclusion, there exist metals and metal alloys which exhibit the desired phase transformations in the approximate temperature and pressure range of the bolting operation. Further study may take two avenues. (1) Ascertain the feasibility of a gasket performing in the desired manner by selecting one of the best materials, without regard to the exact pressure and temperature to be used in the actual bolting operation, and compressing it between two aluminum plates similar to the action in a bolting operation. Then determine the percentage of contact area by a suitable test. (2) Develop an alloy which would exhibit the desired transformations at suitable temperatures and pressures, and determine the plastic flow characteristics of the alloy during such transformations under the more ideal conditions of a hydrostatic pressure.

APPENDIX C

RECOMMENDATIONS FOR FURTHER INVESTIGATION

For spacecraft applications there is a need both for increasing the thermal conductance at the interfaces of certain joints and for increasing the predictability of the thermal performance of such joints. A review of the literature indicates that, while much experimental and analytical effort has been devoted to the problem, it is still not generally feasible to make a reliable computation of the thermal conductance of a joint. One of the basic problems is that the manufacturing process leads to wide variations in the physical properties of joints which are meant to be identical. Furthermore, it has been found that appreciable contact occurs only in the immediate vicinity of bolts and rivets. Elsewhere, the plates tend to separate. Thus, not only is the actual contact area a small fraction of the macroscopic contact area, but macroscopic contact itself occurs over a small fraction of the apparent contact area. It appears, in other words, that thermal conductance across joints may be limited as much, if not more, by joint design as by surface geometry.

Based on the above point of view, it is thought that the following steps hold considerable promise for achieving the objectives of increased thermal contact conductance and more accurate computational procedures.

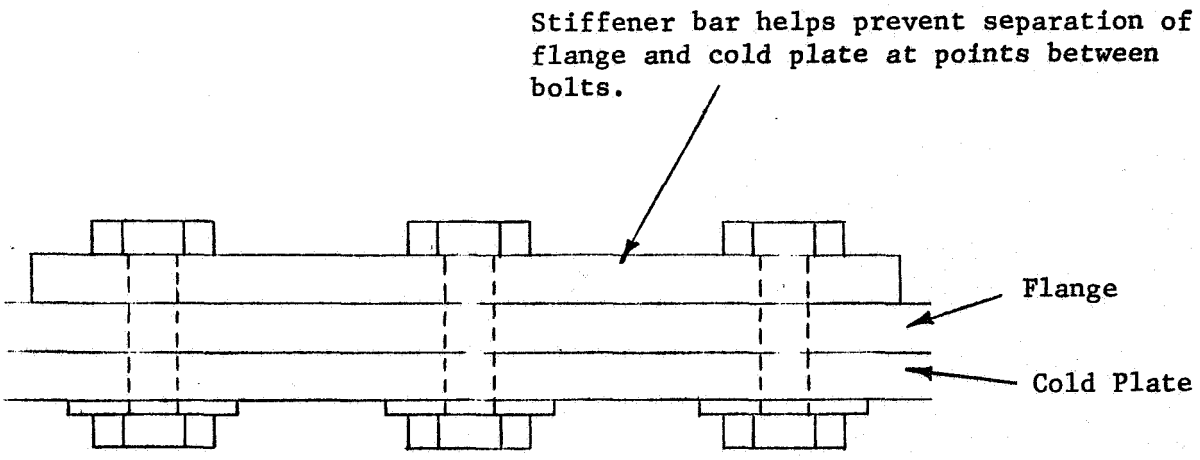
1. Conduct sophisticated analysis of joint design with the objective of producing uniform contact pressure over the entire interface area. This would have the effect of increasing the thermal conductance and improving the uniformity among joints.

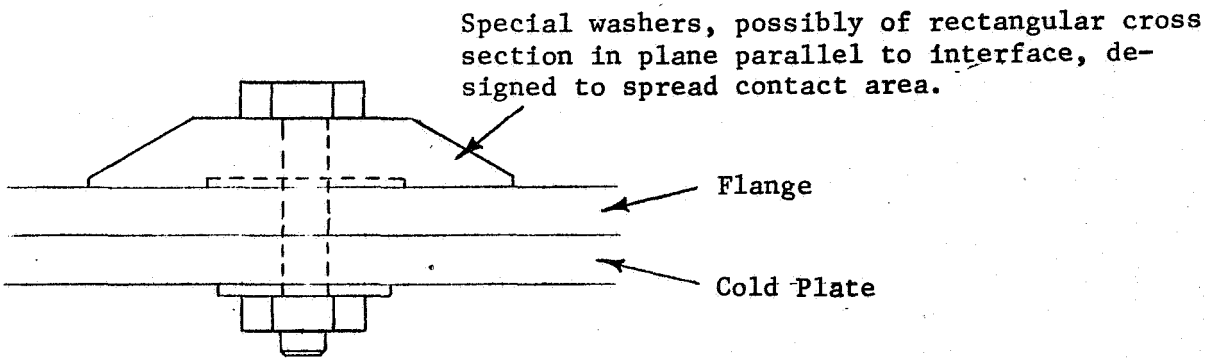
2. Investigate novel flange designs and techniques for fastening component boxes to cold plates. Some ideas are shown in Figure C1.

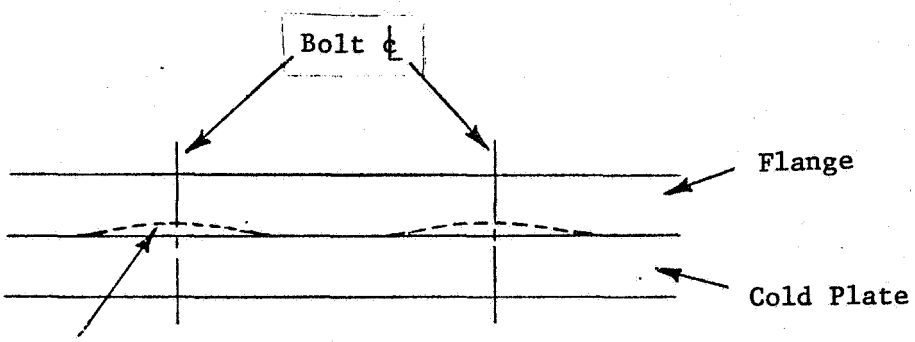
3. Examine manufacturing methods to find ways of increasing the uniformity of finished joints. This should include investigation of surface contamination during manufacture and cleaning procedures prior to assembly.

4. Investigate the possibility of elastic fillers capable of maintaining contact at an interface in spite of creep, thermal strains, and other factors which cause non-elastic fillers to lose contact.

5. Evaluate computational methods by comparison of predicted and actual thermal properties of joints.



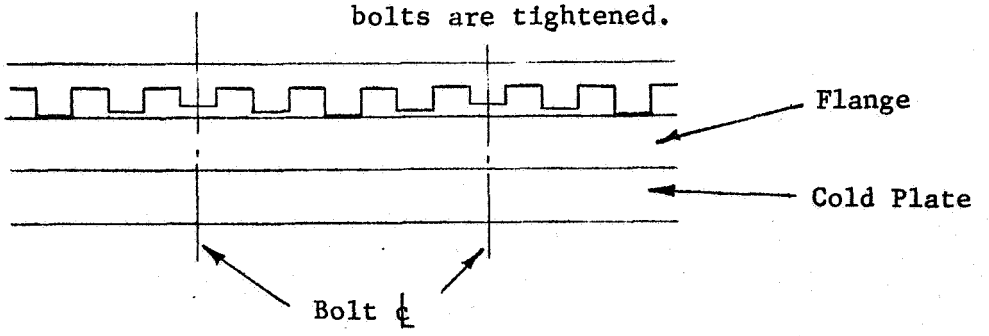


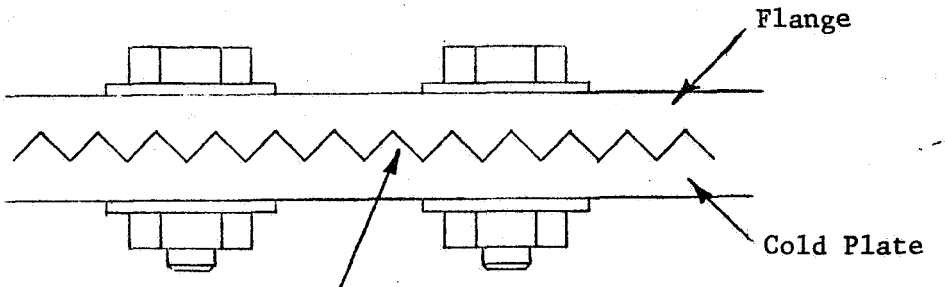


Surface contoured so uniform contact pressure results after bolts are tightened. Shape of contour, which may be two-dimensional, is to be determined by stress analysis.

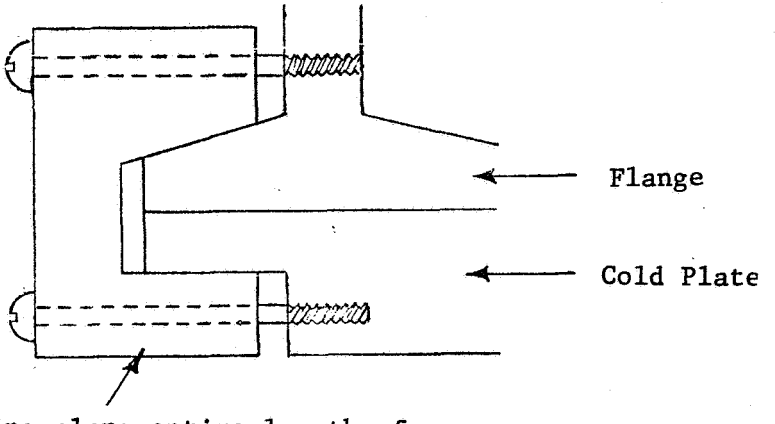
Figure C1 Joint Designs

Rack with teeth of variable lengths, so chosen that uniform contact pressure results when bolts are tightened.





Zig-zagged interface has effect of increasing contact area without reducing the contact pressure.



Wedged clamp running along entire length of flange edge produces more uniform contact pressure over interface. The wedge also produces a mechanical advantage between the screw tension and the normal clamping force on the interface.

Figure C1 (Cont.)

Further thought should also be given to improved methods of using thermally conductive pastes. As previously discussed, the pliable surface technique entails the introduction of two additional interfaces and the effective replacement of some metal by a paste. Because the paste is less conductive than the metal and because it may not perfectly fill the spaces in the microstructure of the cavity walls, the introduction of a paste-filled cavity tends to lower thermal conductance across a joint. Consequently, the scheme must produce some reduction of the constriction resistance at the interface just to prevent the thermal conductance from being lower than it is in a normal joint. This aspect of the problem leads one to consider a modification of the interface filler technique which may be more likely to provide a solution. If a practical way can be found of sealing the joint interface at its boundaries, then the interface void could itself be filled with a pressurized paste. In this case there would be no tendency toward a decrease in thermal conductance to be counteracted, and the full potential of the procedure would be effective in increasing conductance.