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THE HEAT TRANSFER PROPERTIES OF STRUCTURAL ELEMENTS FOR SPACE INSTRUMENTS

by

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June 1962

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CHAPTER 1

INTRODUCTION

The primary concern of the investigations described in this report is the heat transfer properties of metallic surfaces in contact in a high vacuum environment. In order to determine possible design criterion for components that will be subjected to space environment it is essential to obtain knowledge of the temperature distribution of heat transfer across various contacting surfaces.

Extensive investigation into the thermal conductance of metallic surfaces in contact was undertaken earlier by the M.I.T. Heat Transfer Laboratory for the U.S. Atomic Energy Commission (Ref. 1). Considerable knowledge of the subject was learned from this reference and many of the basic considerations were extremely valuable in determining the approach to the high vacuum experiments. Work done by the General Electric Co. (Ref. 2) was also a valuable aid in experiments with filler materials in the latter stages of the tests.

When investigating the heat transfer between metallic surfaces, the three methods, convection, radiation, and conduction must all be considered. It is the intention here to show that metallic interface conduction is present in sufficient quantity to be the major factor. The work described in Ref. 1 treated composite conduction of metallic surfaces and fluids entrapped between surfaces as the primary method of heat transfer. However, their tests were conducted under atmospheric conditions and did not consider vacuum environments. In a high vacuum environment heat transfer by gaseous convection and gaseous conduction is considered to be negligible. This consideration is validated by vacuum theories (Ref. 3) and calculation of the mean free path of gas molecules entrapped in the metallic surfaces. The total thermal resistance of metallic surfaces in contact is the combination of the resistance offered by each method of transfer. Since heat transfer by gaseous convection is neglected, it remains to consider the radiation and metallic conduction transfer effects. The trapped gases in certain porous metals may be influenced by degassing procedures to the extent that reliability of recorded data can be increased.

Heat transfer due to radiation is easily calculated by the following standard approach.

$$\frac{q}{A} = \sigma\left(\frac{1}{\frac{2}{\epsilon} - 1}\right)(T_1^4 - T_2^4) \tag{1.1}$$

where

q = heat rate (Btu/hr)

A = heat transfer area (ft^2)

σ = Stefan-Boltzman constant = 0.172×10^{-8} ($Btu/hr/ft^2/°R^4$)

ϵ = normal emissivity

T = absolute temperature (°Rankine)

$$(T_1^4 - T_2^4) \cong 4T_m^3 \, \Delta t, \text{ where } \Delta t \text{ is small} \tag{1.2}$$

It then follows that the radiant conductance is

$$C_r = \frac{q}{A\Delta t} = 4\sigma \frac{1}{\left(\frac{2}{\epsilon} - 1\right)} T_m^3 \tag{1.3}$$

and, therefore the radiation resistance can be calculated.

$$R_r = \frac{1}{C_r} = \frac{(3.413)\,(144)\left(\frac{2}{\epsilon} - 1\right)}{4\sigma T_m^3} \; (°F/watt/in.^2) \tag{1.4}$$

Assuming ϵ is 0.5 for machined metal surfaces and that T_m is 530°R, the thermal resistance due to radiation is

$$R_r = 1440°F/watt/in.^2 \tag{1.5}$$

Since R_r shunts the conductive resistance, R_c, its affect in these tests will be shown to be negligible.

In contacting metals, heat is conducted through the numerous surface contact points of the materials. The amount of heat transferred is therefore dependent on both the material finish and the contact pressure. The following sections of this report describe the procedures used to determine the heat transfer by conduction. The test equipment and procedures used in examining the variable parameters are described in Chapter 2. Chapter 3 gives the results of the specimen metals and assemblies tested, and presents data plots illustrating the results. The conclusions drawn from this study are presented in Chapter 4.

CHAPTER 2

TEST EQUIPMENT AND PROCEDURES

2.1 General Considerations

The procedures described in this section were designed for the purpose of determining knowledge of heat transfer by conduction through contacting metals in a vacuum condition. Aluminum and beryllium test specimens of various machine finishes were investigated under a range of contact pressures, and with the insertion of several different filler materials between the contacting surfaces. Tests were also performed on bearing assembly configurations. All tests were performed in a vacuum chamber, where a pressure less than 3×10^{-6} Torr was maintained. Temperature readings on both sides of the contact surfaces were simultaneously recorded through thermocouples appropriately located in the specimen. Prior to testing, the specimens were placed in a vacuum oven for degassing purposes and held at 300°F and 2.5×10^{-2} Torr for at least 60 hours.

2.2 Test Equipment

The equipment used for this study, Fig. 1, consists of a vacuum chamber and its associated pumping system, a multichannel recorder, a fixture for holding the test item and varying the contact pressures, the cold plate apparatus, and appropriate thermocouples and controls. The water cooled plate is mounted in the chamber to dissipate heat passed through the item under test.

The holding fixture used to apply varying contact pressures, with a bearing assembly setup in position, is shown as Fig. 2. The arrangement for the testing of specimen blocks is similar to that shown for the bearing assembly. A pair of specimen blocks rest on the cold plate, with an insulating block directly above them. The insulating block has a cavity at its lower end to allow space for the 10-watt (nominal) heater to be in direct contact with the uppermost specimen. The variable compression force is applied through a horseshoe-shape force gauge mounted above the block. Figures 3 and 4 show the setup of the insulating block, heater, test specimens, and thermocouple leads. The force applied to the item being tested is varied by means of a gear driven screw powered by a

Fig. 1. Equipment setup for high-vacuum heat transfer investigations.

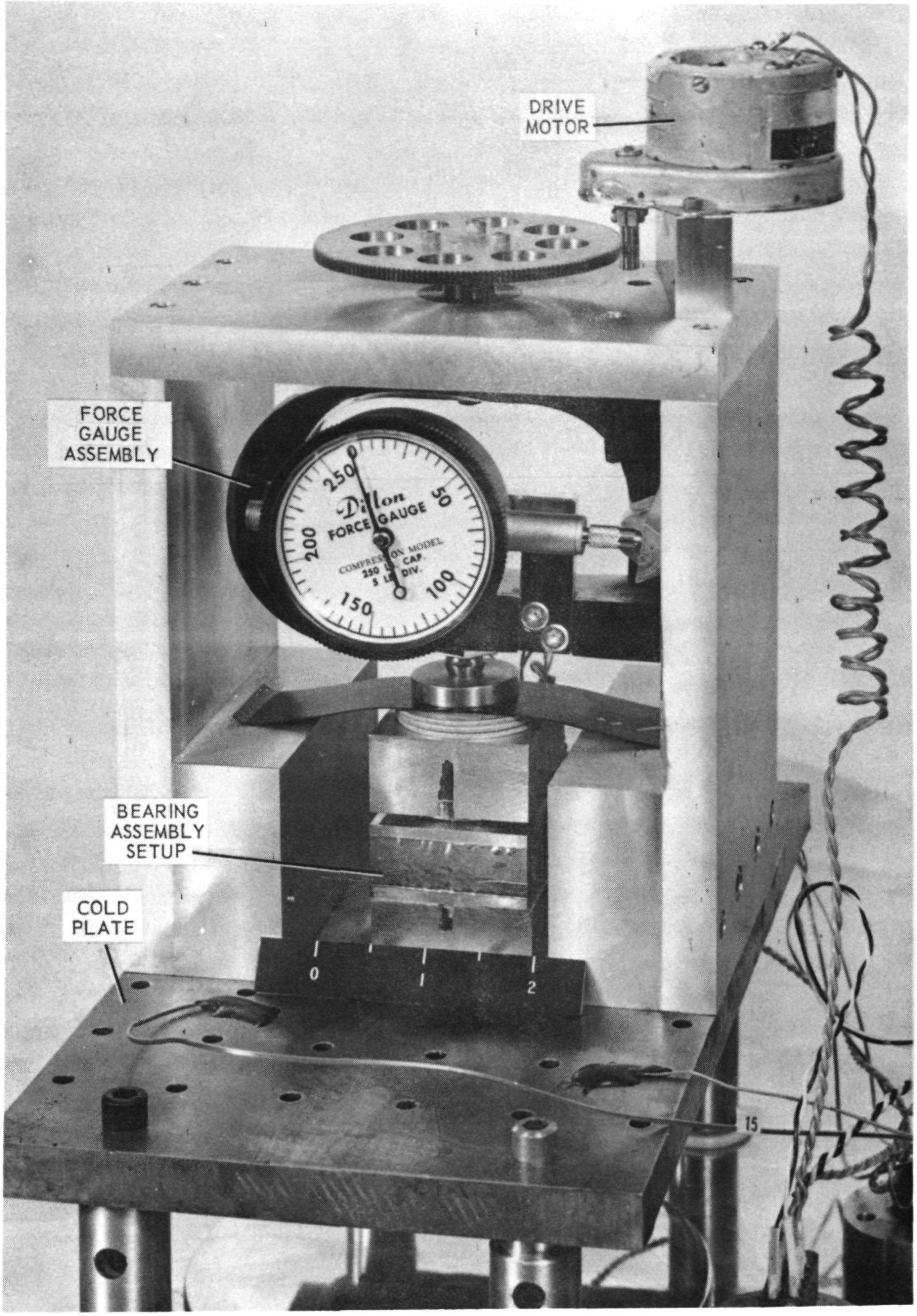

Fig. 2. Test fixture for application of varied contact pressures.

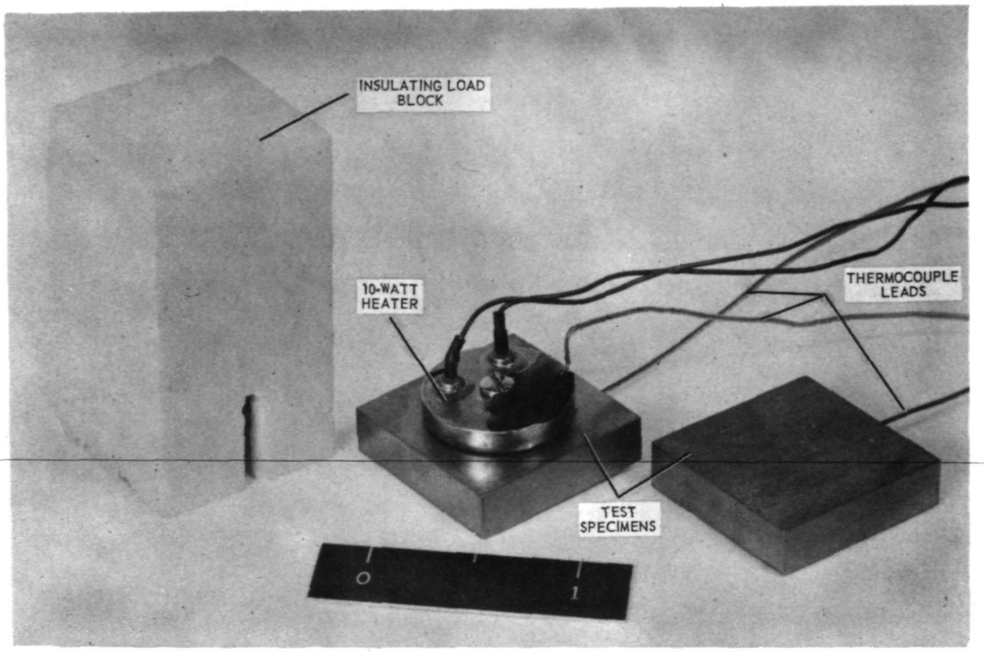

Fig. 3. Components used for testing of aluminum and beryllium specimens.

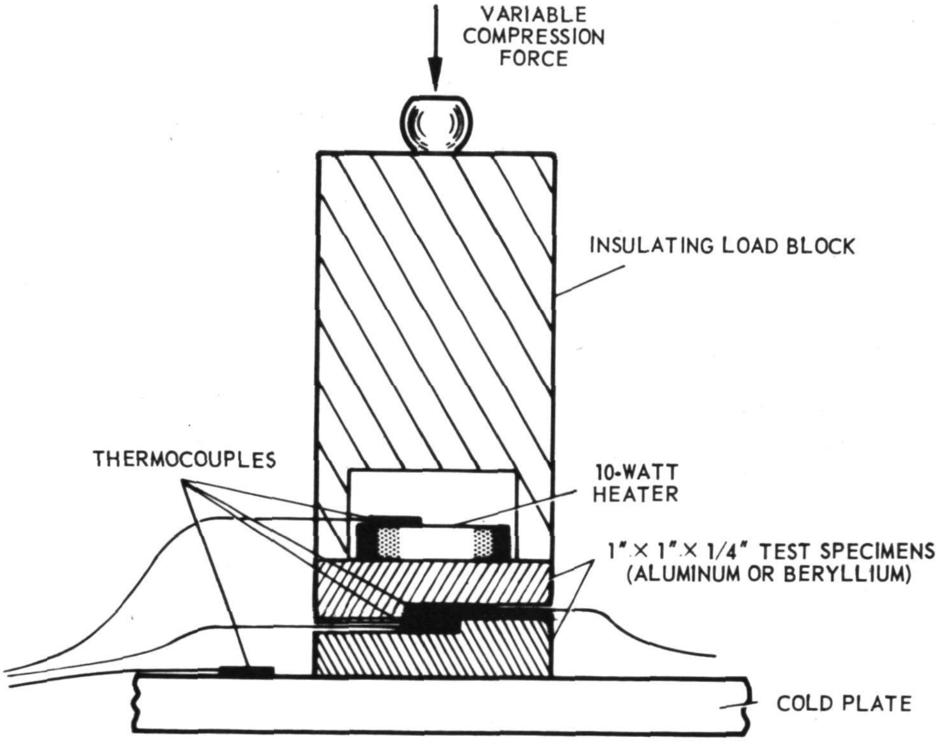

Fig. 4. Cross-section view of the arrangement used for testing aluminum and beryllium specimens.

small motor. The motor is controlled from a voltage source outside the vacuum chamber, and by observing the force gauge the applied load is adjusted to suit.

The setup for performing tests on bearing assemblies is similar to that of the specimen blocks, except as shown in Figs. 5 and 6. The bearing assembly is set in a stack of three aluminum blocks that form a variable preload loop. The lower block rests on the cold plate, the center block contains the bearing outer races and thermocouples, and pressure is applied through the top block to the bearing outer race. The heating element is located in the center of the bearing shaft, which is also instrumented with a thermocouple.

2.3 Test Procedures

Aluminum and beryllium specimens with nominal rms machine finishes of 125, 63, 32, 16 and 4 microinches were obtained for the tests. Four specimens of each finish and in both materials were used. Each specimen measured 1" × 1" × 1/4" and included a small hole near the machined surface for insertion of the thermocouples. These specimen blocks were tested in various combinations of each material and finish. Consideration was also given to the parallelism or perpendicularity of the machine finish cuts in the use of the 125 microinch specimens.

Each setup of specimen blocks was subjected to contact loads of 10, 40, 100 and 250 pounds. Continuous recordings were obtained on the recorder, data reduced, and the results plotted. Evacuation time varied from sixteen hours to several days. The varying lengths of evacuation time prior to starting the test did not appear to cause appreciable differences in the data.

Analysis of the early test data showed some scatter, which suggested some surface molecular gas effects. In order to reduce this condition the specimens were placed in a vacuum oven for degassing and then rechecked in the vacuum chamber. The degassing procedure proved to be effective and changes in the data were apparent.

Additional tests of the rough machine finish blocks were made with the insertion of several different filler materials between the contacting surfaces. Tests were made with a commercial flexible epoxy cement,* with foils of indium and lead, and with aluminum and gold leaf. The results of these tests were

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*Bacon Industries, Inc. Type FFA-5.

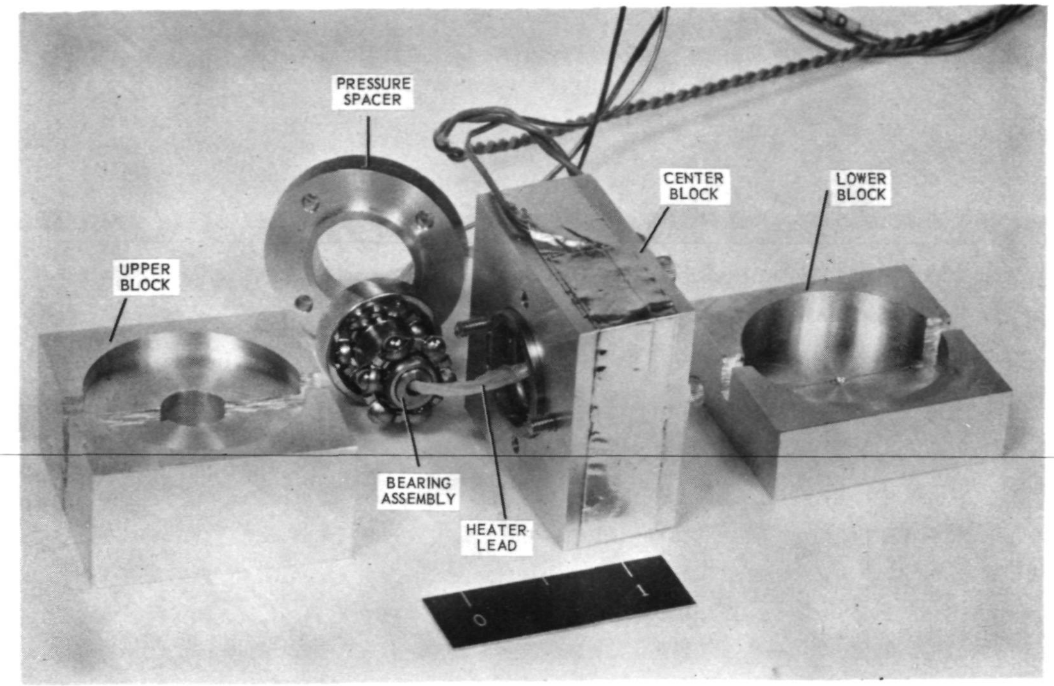

Fig. 5. Components used for testing bearing assemblies.

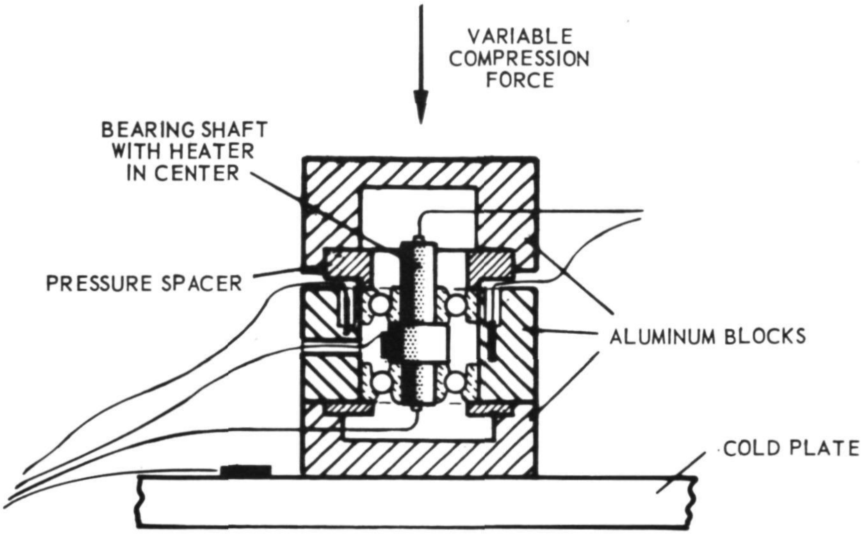

Fig. 6. Cross-section view of the arrangement used for testing bearing assemblies.

in some cases markedly superior to tests conducted without the use of filler materials, in particular the indium foil. The epoxy cement and lead foil provided some lowering of thermal resistance while the aluminum and gold did not provide any appreciable improvement.

As tests continued over a period of several weeks equipment and system deficiencies were adjusted or corrected with the result that the plotted data repeated at a rate indicating good reliability of the testing system. The results of several of the test series are shown in Chapter 3.

CHAPTER 3

TEST RESULTS

3.1 Aluminum and Beryllium Interface Results

The results of the metallic interface tests, plotting thermal resistance versus load pressure, are illustrated in Figs. 7, 8 and 9. These tests provide no specific information relating any given surface finish to thermal resistance. Only ranges of values, shown by the toned area in the figures, are obtainable for a given material and load. However, the data does show conclusively that conduction is the primary interface heat transfer mechanism.

Figure 7 shows the results of each of the material finishes for the aluminum specimens. A specimen pair of the rougher finish was tested with the finish machining cuts set both parallel and perpendicular to each other. The difference proved to be negligible. As can be seen in every test, an increasing load causes a lowering of thermal resistance. Figure 8 presents the results of the same aluminum specimens after degassing in a 300 °F vacuum oven, prior to their being replaced in the vacuum chamber for retesting. Comparison of Figs. 7 and 8 show that the degassing produces lower resistance when the specimens are subjected to the lower compression forces. However, when the contact pressure is upwards of 100 psi the fact that the specimen had been degassed has no marked effect on the thermal resistance.

Tests on beryllium specimens were made under the same conditions, including the degassing, as the aluminum specimens. Figure 9 shows these beryllium test results.

If more refined information were to be desired the test specimens would need to have considerably more depth so that more conclusive data as to thermal conductivity and temperature gradients could be obtained. More specific data would also be required as to the frequency and amplitude of the contacting surface irregularities (Ref. 1), the over-all flatness, and the waviness of the specimens.

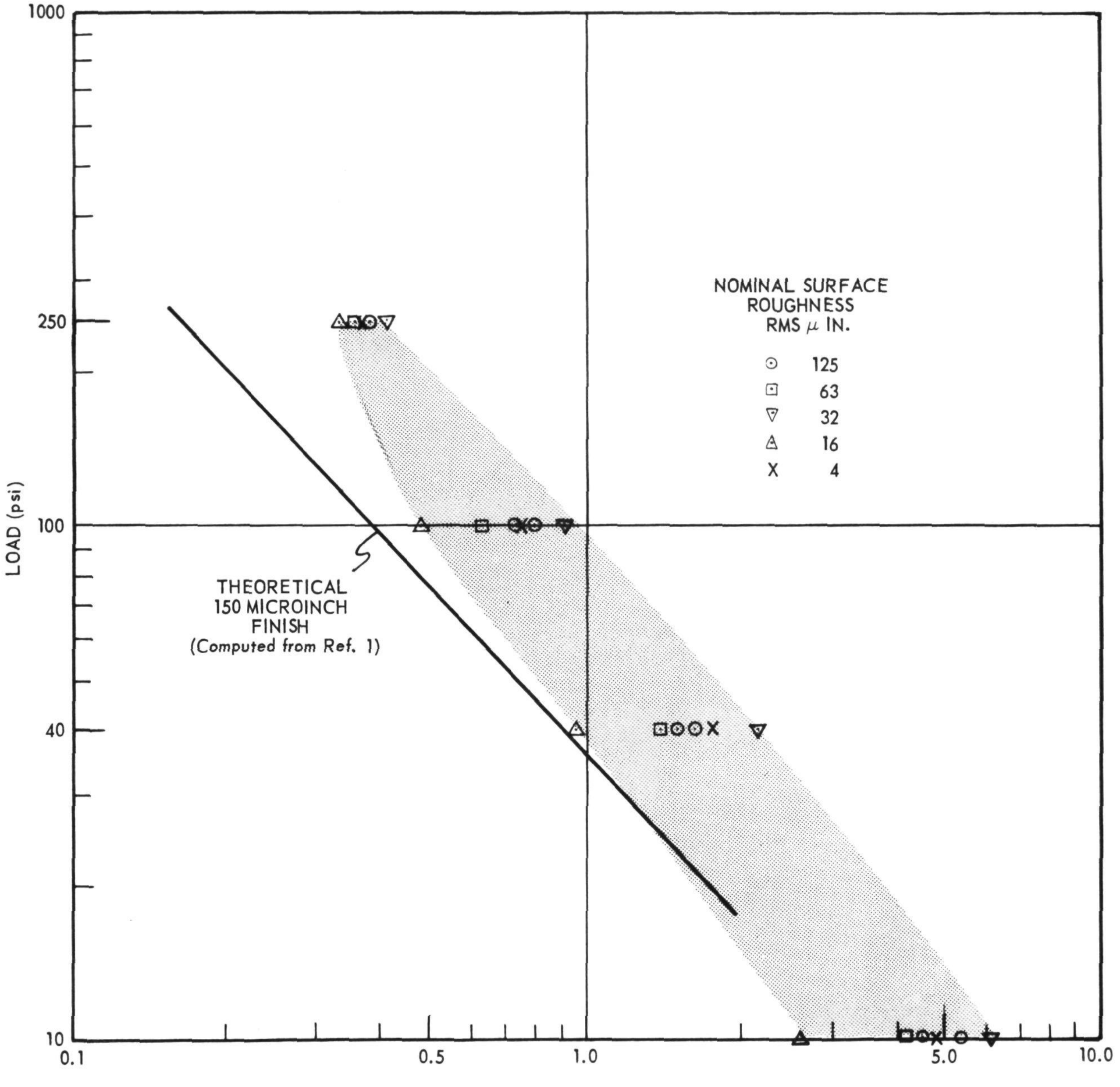

Fig. 7. Thermal resistances of metallic interfaces in a vacuum – aluminum specimens.

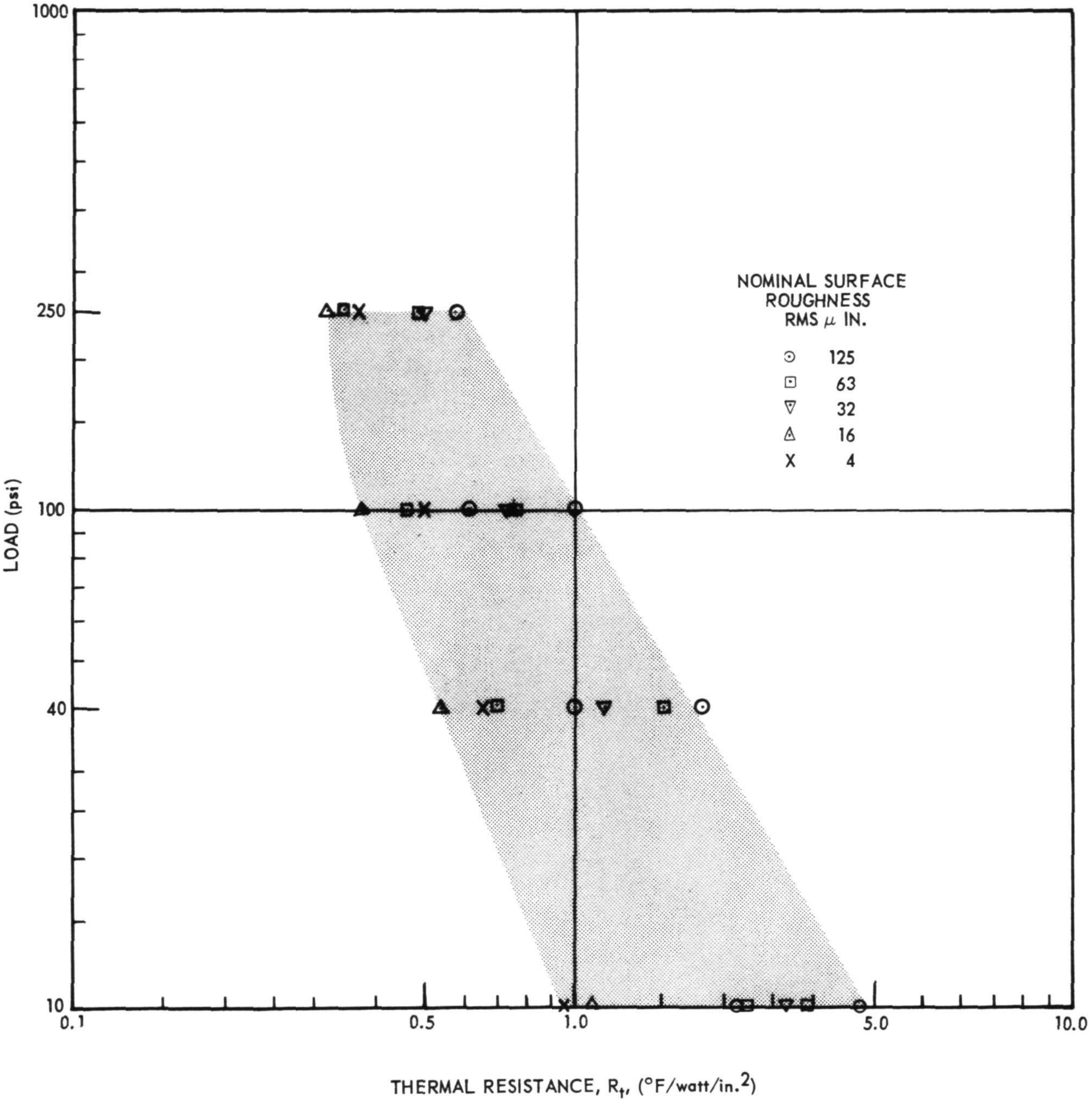

Fig. 8. Thermal resistances of metallic interfaces in a vacuum – aluminum specimens degassed.

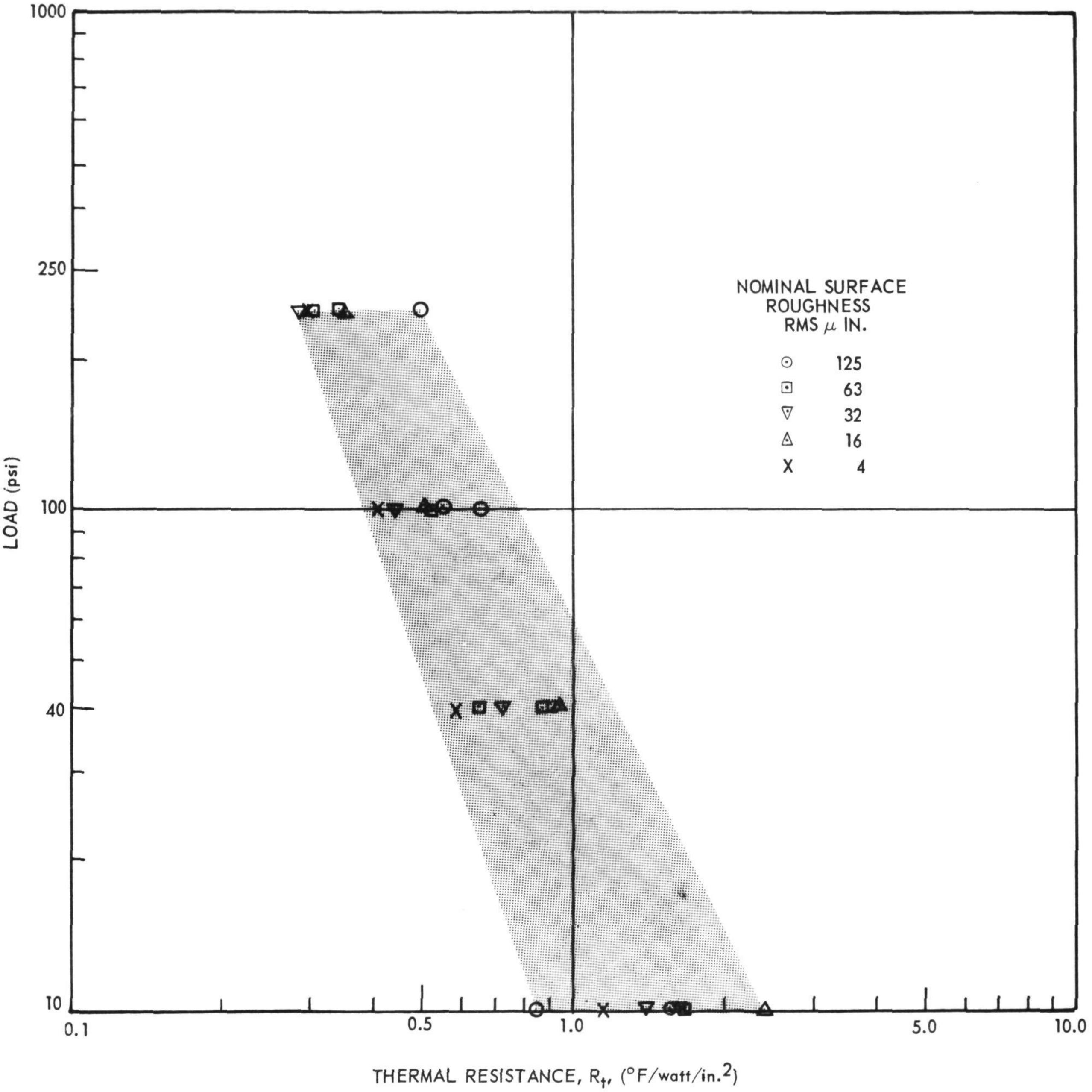

Fig. 9. Thermal resistances of metallic interfaces in a vacuum – beryllium specimens degassed.

3.2 Analysis of Potential Errors

Chapter 1 developed a reasonable value of the radiant thermal resistance of the interface, Eq. (1.5). This resistance is approximately three orders of magnitude higher than the test values, making the radiant heat transfer insignificant. Of particular concern in performing more complete tests of this nature would be the degree of flatness of the tested specimen. Other potential sources of error that are considered here are radiation to the chamber walls, conduction along the insulating load block and the certainty of thermocouple location.

Specimen-to-chamber radiation resistance is approximately:

$$R_r = \frac{(3.413)\,(144)\left(\frac{2}{\epsilon} - 1\right)}{4\,\sigma A\, T_m^3} \;(°\mathrm{F/watt}) \qquad (3.1)$$

Using an effective area of 3 in.^{2} and $\epsilon = 0.5$ at room temperature,

$$R_r = 480°\mathrm{F/watt} \qquad (3.2)$$

or about two and one-half orders of magnitude higher than test values, also insignificant.

Thermal conduction along the insulating load block is approximately:

$$R_c = \frac{(3.143)\,(144)\,(\Delta x)}{k A} \;(°\mathrm{F/watt}) \qquad (3.3)$$

Using an area of 1 in.^{2}, a heat path of 1.5 inches, and a k value of 3 Btu/hr ft^2 (°F/watt)

$$R_c = 245°\mathrm{F/watt} \qquad (3.4)$$

a value still too high to be considered.

Probably the largest source of error, other than the lack of a surface profile plot, comes from the certainty of thermocouple location. Each thermocouple is placed in a hole parallel to the test interface and a nominal 0.062 inch from that surface. A correction to the measured thermal resistances is applied to approximate the metallic thermal resistances between the thermocouples. Using Eq. (3.3), a Δx of 0.125 in., an area of 1 in.^{2}, and k values (Ref. 4) of 1070 Btu/hr ft^2 (°F/in.) for the 6061 aluminum and 1160 Btu/hr ft^2 (°F/in.) for the QMV beryllium, these corrections become:

$$R_c = \frac{61.5}{k} \;°\mathrm{F/watt/in.}^2 \qquad (3.5)$$

$$R_c = 0.057°\mathrm{F/watt/in.}^2 \;(\text{Aluminum}) \qquad (3.6)$$

$$R_c = 0.053°\mathrm{F/watt/in.}^2 \;(\text{Beryllium}) \qquad (3.7)$$

3.3 Aluminum and Beryllium Interface Results with Filler Materials

In an effort to significantly modify the metallic interface thermal resistance tests were performed with various filler materials. These tests were made with a pair of 125 microinch finish aluminum blocks and 70 microinch finish beryllium blocks, with foil inserted between the contacting surfaces. The "dry" interface test, described in the previous section, was re-run as a comparison, and then filler materials of epoxy cement, 0.002 in. indium foil, aluminum and gold leaf, and 0.0015 in. lead foil were all checked under identical conditions. As can be seen from the plotted results, Fig. 10, the indium foil produced considerably lower thermal resistances. The lead foil showed a small amount of lowering, and the epoxy cement, while it did not vary with load pressure, also was of some improvement. The other filler materials made no significant differences.

As is to be expected, and as shown by the theoretical limit curve on the figure, there is a point beyond which the thermal resistance cannot be further lowered due to the resistance of the filler itself. The limiting thermal resistance of a filler material can be computed from Eq. (3.3), where for the case of indium foil Δx is 0.002 in., k is 174 Btu/hr ft^2 (°F/in.), and A is one square inch. Thus,

$$R_c \approx 0.006°F/watt/in.^2 \qquad (3.8)$$

3.4 Bearing Assembly Results

The thermal resistance of ball bearing assemblies was tested in a similar manner as the aluminum and beryllium block specimens. Tests were performed on Barden S36BX1 (0.25 I.D., 0.75 O.D.) and R3 bearing assemblies, and in spite of their size difference thermal resistances were quite similar. Because two bearings in parallel were used the data shown for these bearings is twice the actual measured resistance. Vacuum test data and data from prior tests run on a dry bearing at atmospheric pressure are shown for the Fafnir type B-543 bearing. While there is significant difference between these two plots, the vacuum data is suspect of some surface gas molecular effects at low load pressure. An additional test was run on a Kaydon KB-42 bearing and due to the many more balls produced a lower thermal resistance.

Except as noted all of the bearing tests were performed with dry bearings, a condition similar to the use of dry lubricants in ultrahigh vacuum environments. One test was run on the KB-42 bearing with the "as received" lubrication. The lower thermal resistance substantiates the trends of previous studies (Ref. 5) and suggests the application of filled lubricants in instrument bearings where the ambient pressure can be limited to the lubricant vapor pressure.

The results of these tests are shown in Fig. 11.

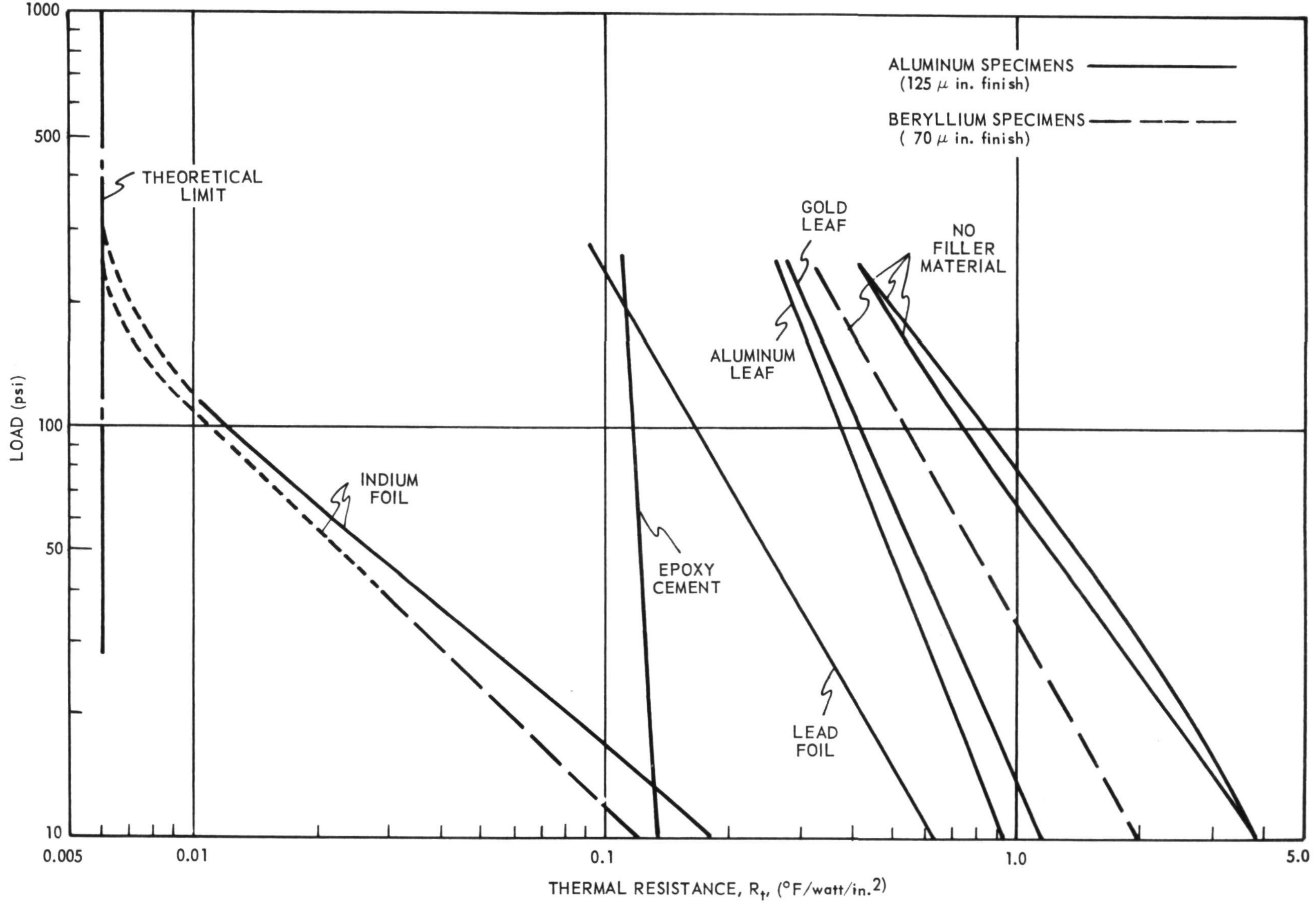

Fig. 10. Thermal resistances of metallic interface with various filler materials.

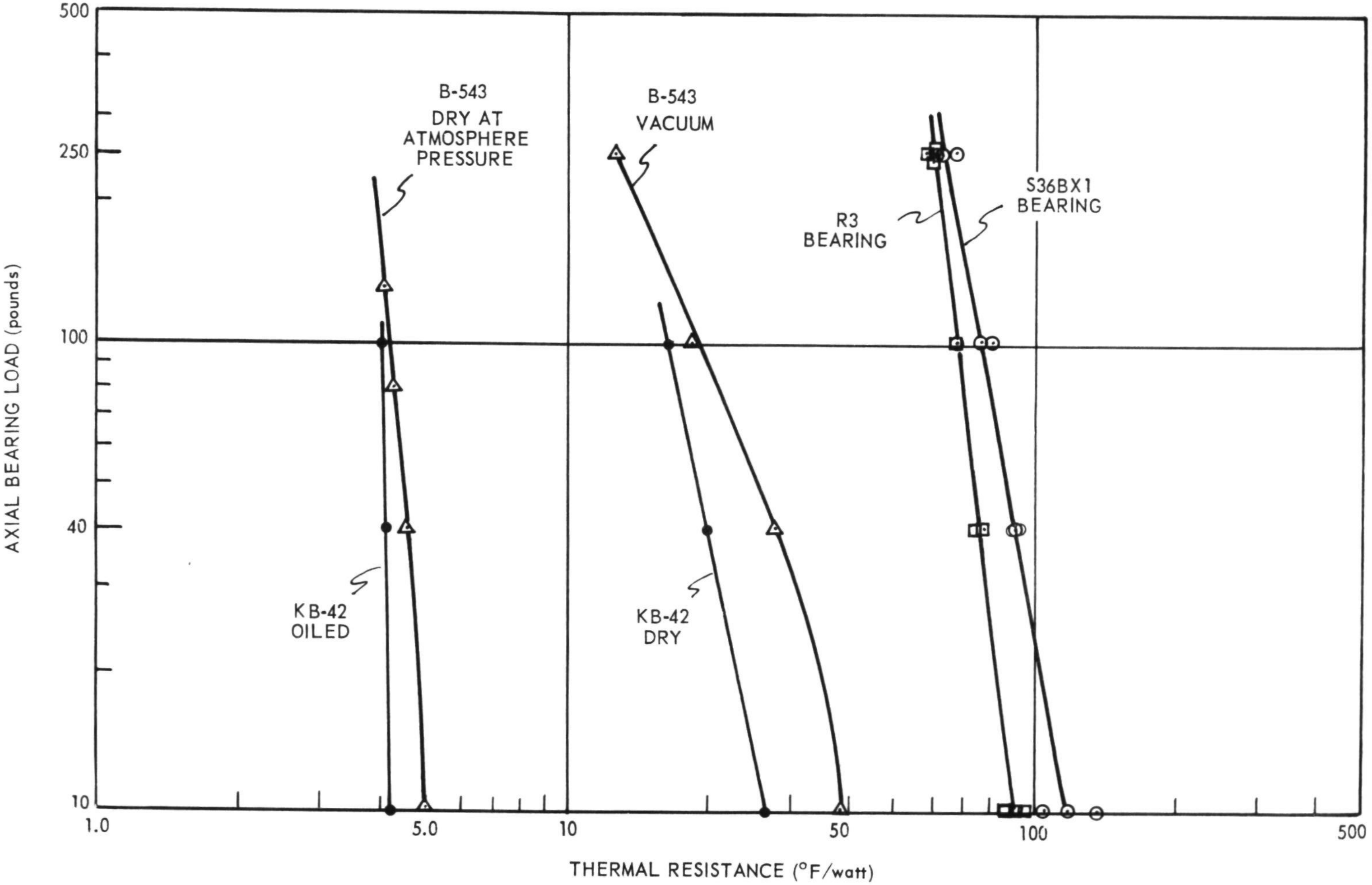

Fig. 11. Thermal resistances of bearing assemblies.

CHAPTER 4

CONCLUSIONS

The tests and data presented in this report, while not refined to the point of allowing analysis of the minute heat transfer mechanisms of metallic interfaces, have more than met the program objectives. The first objective was the establishment of techniques and procedures for high vacuum heat transfer measurements, and the second, the providing of useful data on the ranges of conductive thermal resistances to be expected for future design and test of more complex structures.

During the tests conducted over the period of investigation several factors proved to be of considerable significance. Reference 1 bases its work on the average number of contact points per square inch of a surface, and on the average area of the contacting points. On a macroscopic basis the bearing tests substantiate this thesis. The two smaller bearings, while of different sizes, each contain six balls and their thermal resistances are similar. The larger B-543 bearing containing more balls than the smaller bearings, produce a thermal resistance appropriately lower. The KB-42 bearing, with many more balls, resulted in even lower resistance.

It is reasonable to consider that perhaps the product of the number of contact points and the average size of the points, is nearly constant. This hypothesis then leads to the consideration that for any given load, regardless of the surface roughness, there would be a nearly constant thermal resistance. Varying surface roughnesses should yield different thermal resistances when a fluid is present at the interface, however in the absence of fluid the conduction is dependent upon the contact points alone.

As also seen from the data presented, significant reduction of interface resistance can be realized by the use of a filler material, effectively increasing the contact area. In fact, the tests with the indium foil, an extremely soft material, indicated sufficient compliance to completely fill the surface machine finish voids.

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