SECURITY MARKING

The classified or limited status of this report applies to each page, unless otherwise marked.
Separate page printouts MUST be marked accordingly.

U. S. NAVY

MARINE ENGINEERING LABORATORY

Annapolis, Md.

Dedicated To PROGRESS IN MARINE ENGINEERING

DEDICATED TO PROGRESS IN MARINE ENGINEERING

The Marine Engineering Laboratory is charged with the discovery of fundamental knowledge, the development of new and unique equipment to meet and anticipate new naval requirements, analysis of Fleet machinery failures, and evaluation of prototypes to insure high performance and reliability in the Fleet. Dedicated to progress in naval engineering, the Marine Engineering Laboratory contributes to the technical excellence and superiority of the Navy today - and tomorrow.

FOR OFFICIAL USE ONLY

Heat Transfer Between Solids

Assignment 75 125
MEL Research and Development Report 157/64
July 1965

By
R. P. Kolb

R. P. KOLB

Approved by:

H. R. BOROSON
Special Projects Division

ABSTRACT

In attempts to improve thermal performance of modules for thermoelectric generators an investigation based upon a program of experimentation in thermal conductance between plane solid surfaces in both dry and lubricated contact under pressure was conducted. Surface materials were Type 6061-T6 aluminum alloy and Type RS-70 unalloyed titanium. In some tests a 0.0027-inch mica layer was interposed between the metallic surfaces, with dry contact. Values of conductance were determined over a range of imposed pressures between 5 and 225 pounds per square inch (psi) in most cases, otherwise at a single pressure of approximately 100 psi.

Disparate results led to the conclusion that conductance may be related to the hardness as well as the roughness of the contacting surfaces.

Curves of conductance versus imposed pressure usually have a point of inflection at which they change from convex to concave upward, with rising pressure. It was established that the higher the value of surface roughness, the lower the pressure at which the point of inflection occurs. A lubricated-contact aluminum/aluminum joint showed a conductance at 100 psi, approximately six times the dry-contact value. A dry-contact joint with the specified mica layer interposed showed a conductance approximately 1/6 the original metal-to-metal value.

Results for a variety of surface material combinations are presented in a tabulation arranged for comparative study.

ADMINISTRATIVE INFORMATION

This work was performed under MEL In-House Independent Research Program (S-R011 01 01), Task 0401, Report Symbol BUSHIPS 3920-1.

TABLE OF CONTENTS

HEAT TRANSFER BETWEEN SOLIDS

1.0 INTRODUCTION

An investigation having as its basic objective the improvement of the thermal performance of modules for thermoelectric generators was initiated at this Laboratory during Fiscal Year 1961. Inasmuch as thermal conductance at the interfaces between surfaces in contact under pressure was an important factor in module performance, a program of experimentation was developed to enable a study of this factor. In order to carry on this program a contact-pressure loading apparatus was designed, constructed, and installed; and all of the study results stemmed from data obtained through the use of this apparatus and the test setup of which it was a part. This apparatus and the test setup have been described.[5,6,7,8]

During Fiscal Years 1961 and 1962, a series of contact-pressure tests were performed. Values of conductance were determined over a range of imposed pressures between 5 and 225 psi,*utilizing a single value of mean interface temperature (206 F), and a single value of surface finish approximating 10 rms microinches, for several surface material combinations used in the construction of thermoelectric generator modules. The majority of these conductance values were between the limits of 500 and 3000 Btu per (hr) (sq ft) (deg F). One of the several conclusions established was that an imposed pressure of at least 150 psi was required before a rapid increase of interface thermal conductance could be expected with increased pressure. Results obtained have been reported in detail.[8, 10] At the conclusion of the study in June 1962, it was recommended that further experimentation should be undertaken, using various mean interface temperatures, additional combinations of surface materials and finishes, and interfacial atmospheres other than air.

A new experimental study involving thermal conductance between solid surfaces in contact under pressure was initiated in July 1963 within the scope of a general investigation of interface phenomena. Tests similar to those made during Fiscal Years 1961 and 1962 were undertaken, using specially selected surface material combinations capable of yielding information of value to the general investigation.

2.0 THEORETICAL BASIS

Thermal conductance at the contact interface between surfaces under pressure is dependent upon several factors, the most apparent of which are: (a) the magnitude of the imposed pressure, (b) the mean interface temperature, (c) the degree of surface roughness, and (d) the physical properties of the material or materials involved. Less obvious (but

[5]Superscripts refer to similarly numbered entries in the Bibliography, Appendix A.

*Abbreviations used in this text are from the GPO Style Manual, 1959, unless otherwise noted.

not necessarily less important) factors include: (e) the surface electronic state, (f) the nature of the fluid filling the voids within the interface, and (g) the waviness (degree of approach to flatness) of the contacting surfaces. (This last factor is not to be confused with surface roughness which is a matter of finish rather than shape.) A complete and accurate determination of interface conductance depends upon a consideration of all of these factors simultaneously.

Theoretical and experimental studies by various investigators have concentrated on those factors which can be controlled and which at the same time exert a predominant influence on conductance values, especially when these values are to be used in engineering design. Despite the existence of a substantial body of literature on interface thermal conductance, no consistent and comprehensive theory has as yet been advanced; however, much excellent published material in various study areas may, by synthesis, produce such a theory. A suitable mathematical model may provide the basis for a comprehensive theory.

Theoretical analyses [2,3,12] have dealt with the effects of imposed pressure, surface roughness, and interfacial fluids. The influence of other factors mentioned above should be studied in depth, looking toward the formulation of a comprehensive theory.

3.0 EXPERIMENTAL DETERMINATION OF THERMAL CONDUCTANCE

3.1 Apparatus and Test Setup. A sectional elevation of the contact-pressure loading apparatus which formed the central component of the test setup is shown in Figure 1. This apparatus has been described fully,[5,6] with accompanying illustrations. The primary feature of this apparatus is the arrangement of upper and lower pedestals between whose contact surfaces the interface is formed. These descriptions set forth the physical features of the pedestals, together with the arrangement of inserted thermocouples. Center is a point; it can't be "around" anything.

3.1.1 Since the inception of the project in Fiscal Year 1961, the pedestal materials utilized in the several test programs have included medium-carbon plain steel, Type 316 stainless steel, electrolytic tough-pitch copper, Armco ingot iron, Type 6061-T6 aluminum alloy, and titanium.

3.1.2 The test setup is illustrated in Figure 2 where the ensemble is shown mounted upon the table in the foreground. The contact-pressure loading apparatus, with baseplate and peripheral pedestal surfaces fully insulated, is at the left end of the table with the electrical heater controls adjacent to it. Wires from 18 thermocouples in the two contacting pedestals lead to the precision potentiometer at the right end of the table through a cold-junction device and a selector switch. Imposed pressure may be varied by changing the number of calibrated weights on the suspended platform which hangs from the yoke of the apparatus. A Variac in the main heater power-supply line enabled a continuous adjustment of the rate of heat input to the lower pedestal from baseplate source to maintain as nearly as possible a selected constant temperature at a particular thermocouple in the lowest row of the lower pedestal.

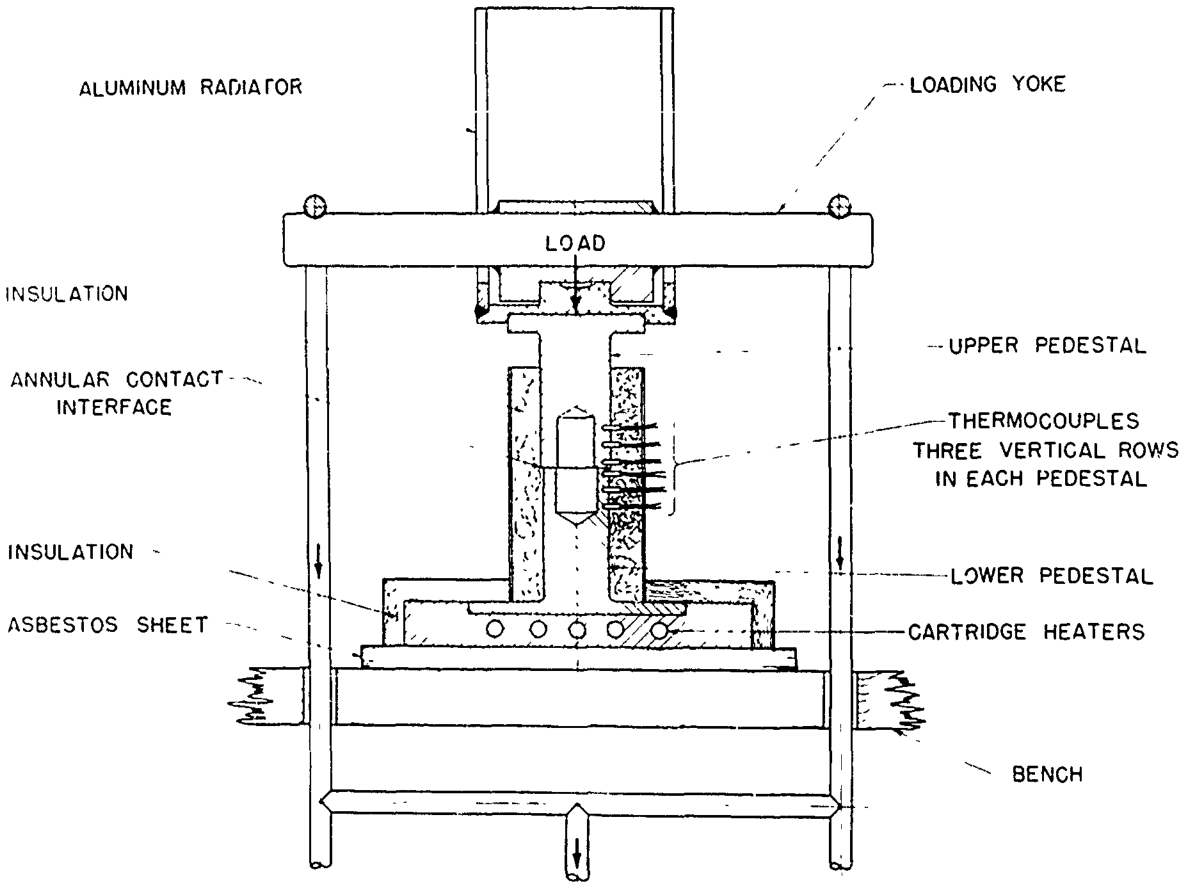

Figure 1
Sectional Elevation of MEL
Contact-Pressure Loading Apparatus

3.2 Experimental Plan.

3.2.1 Surface material selected for the current test program included Type 6061-T6 aluminum alloy, and Type RS-70 unalloyed titanium. Three different arrangements of aluminum alloy joints were tested. The first consisted of surfaces in direct dry contact, the second of surfaces in direct lubricated contact, and the third of surfaces in dry contact with an interposed mica layer. Titanium joints consisted of a pair of surfaces, first in direct dry contact, and second in dry contact with an interposed mica layer. The aluminum/aluminum lubricated-contact joint was tested at a single imposed pressure of 100 psi and the titanium/mica/titanium joint at a single pressure of 100.6 psi.

3.2.2 For each test, data were obtained using procedures similar to those previously described.[5,6] Data points for the full-range tests were established over a range of imposed pressures* between approximately 5 and 225 psi with point-to-point intervals not larger than 25 psi. The exact values of imposed pressure used for plotting results were dependent upon the weight of the particular upper pedestal in use, since this weight formed part of the total force applied at the interface.

3.2.3 In accordance with an original decision to simplify the experimental procedure, all tests were performed in ordinary atmosphere with heat dissipation from the apparatus radiator by natural convection. Pedestal contact surfaces were machined to the various values of finish, in terms of rms microinches, stated subsequently in this report; however, no consideration was given to possible surface waviness.

4.0 RESULTS

4.1 Procedures. For each test, procedures identical with those previously described [10] were used to compute results. Data were first used to plot temperature gradient lines (average observed temperature at thermocouple locations versus thermocouple distances from contact interface) for each pedestal of the pair, and the extension of these lines past the interface (zero distance) location on the graph enabled the determination of the temperature drop between the contacting surfaces. As before, the application of the indicated lower-pedestal temperature gradient in the equation for steady-state conduction effected a solution for the thermal flux entering the pedestal from the heat source. The heat flux crossing the interface between the pedestals was then determined by subtracting from the calculated input the computed loss of heat in a radial direction from the thermocouple zone within the lower pedestal, through the metal, the insulation, the jacket, and the air film to the surrounding atmosphere.

4.2 Values. The values of thermal conductance, h, as a function of apparent pressure are presented in this report for the several surface combinations tested. The curves portraying this relationship were derived from preliminary graphs of log-h versus log-pressure which had, in turn, been established by "fairing" through the several patterns of computed points.

---

* Throughout the descriptive portions of this report, the term "imposed pressure" has been used to denote the ratio of applied force to superficial surface contact area. This may be designated more precisely as "apparent pressure;" and this quantity is practically always smaller (and often much smaller) than the real surface contact pressure. The magnitude of the real pressure is a function of the roughness and waviness of the surfaces involved inasmuch as these factors determine the extent of the actual solid-to-solid contact at the interface.

USN MARINE ENGINEERING LABORATORY

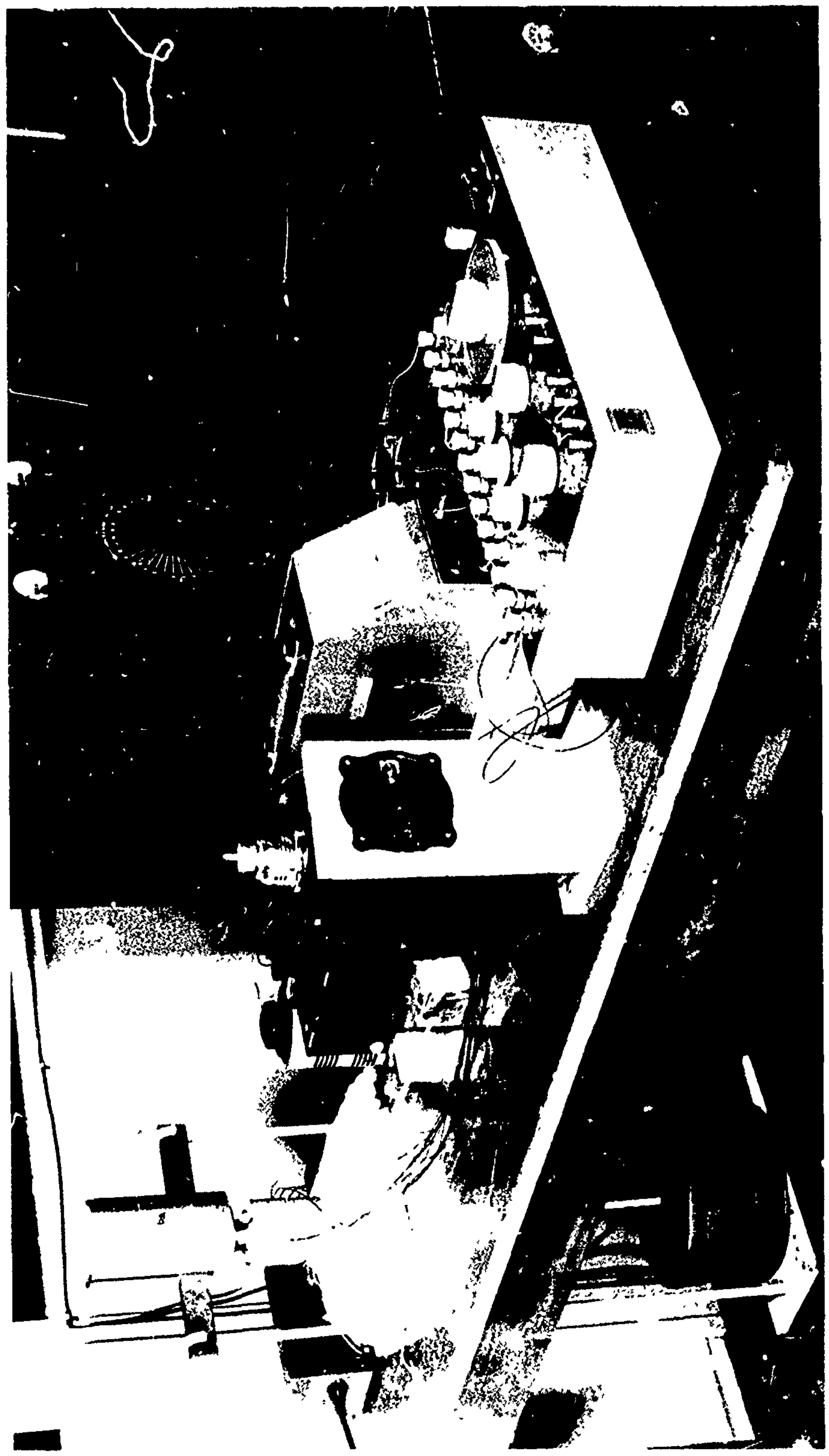

Figure 2 - Setup for the Determination of Interface Thermal Conductance Using the Pressure-Contact Loading Apparatus

4.2.1 The mica layer, which was interposed between the metallic bounding surfaces during some tests, took the form of a washer having suitable inner and outer diameters and a thickness of 0.0027 inch. In the computations for conductance, the thermal conductivity of mica transmitting heat normal to its natural cleavage planes was taken from an authoritative source to be 0.25 Btu per (hr) (ft) (deg. F). Curves showing the variation of thermal conductance with apparent pressure for the full-range dry-contact tests are portrayed in Figures 3 through 6.

4.2.2 At the single apparent pressure of 100.6 psi and a mean interface temperature of 206 F, the overall thermal conductance of the titanium/ mica/titanium joint was 520 Btu per (hr) (sq ft) (deg F), for the path between the enclosing metal surfaces. At the same apparent pressure and interface temperature, the value of conductance for each titanium/mica interface was 1910 Btu per (hr) (sq ft) (deg F). The metallic surfaces were finished to roughnesses of 4.2 and 5.4 rms microinches.

4.2.3 The lubricated-contact test of an aluminum/aluminum joint was performed after the metallic surfaces had been coated with the thinnest possible film of silicone grease. At the single apparent pressure of 100 psi and a mean interface temperature of 206 F, the thermal conductance was 19950 Btu per (hr) (sq ft) (deg F). The surfaces were finished to roughnesses of 15 and 17 rms microinches.

5.0 DISCUSSION

The final results portrayed in Figures 3 through 6 may be compared with those for similar tests with other surface material combinations, as previously shown in Figure 1 of the 1962 Progress Report[8] and Figure 4 of a later report of investigation.[10] Especially notable is the curve of Figure 3 which has an inflection at approximately 55 psi, whereas the curves for Tests 4, 8A, and 12A of Figure 1 of the Progress Report[8] have an inflection at approximately 125 psi. This shift of the inflection point toward a lower pressure is attributed to the rougher surface finish of the aluminum/aluminum joint as compared with the others cited above.

Past and present results for both single-pressure and full-range tests were compared at an apparent pressure of 100 psi. This comparison is set forth in Table 1 where the thermal conductance values for a number of selected surface combinations are recorded, each group being arranged in the order of increasing magnitude. Past results listed in Table 1 were reported originally in 1962.[8,10]

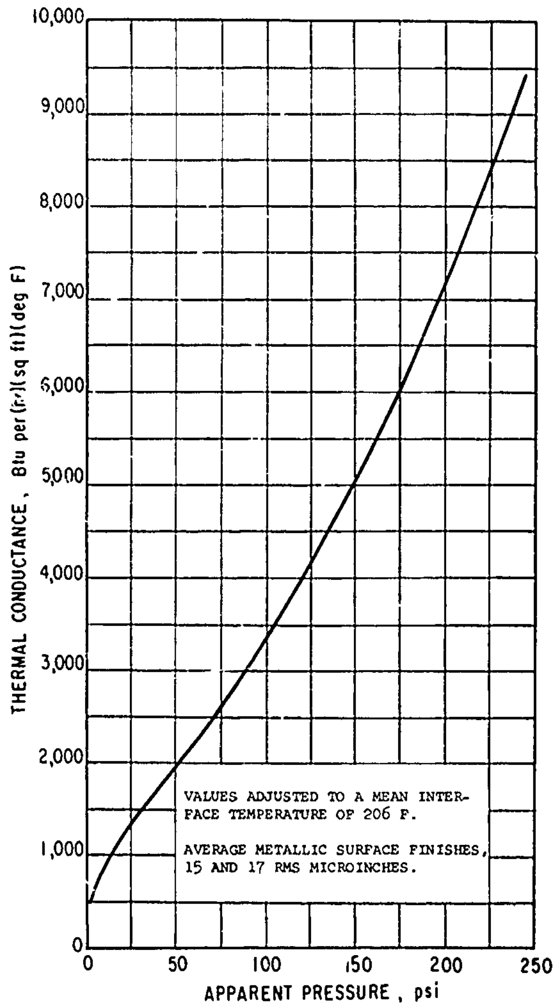

Figure 3

Variation of Thermal Conductance with Apparent Pressure for an Interface Having Type 6061-T6 Aluminum Surfaces in Dry Contact

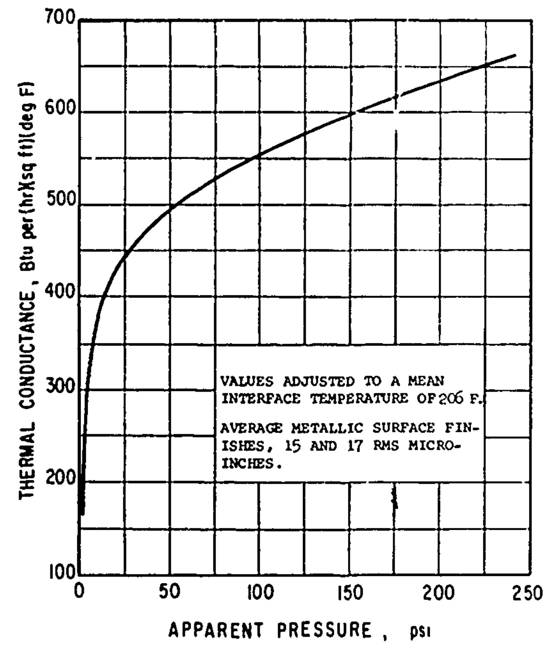

Figure 4

Variation of Thermal Conductance with Apparent Pressure for a Dry-Contact Joint Having Bounding Surfaces of Type 6061-T6 Aluminum and an Interposed Mica Layer

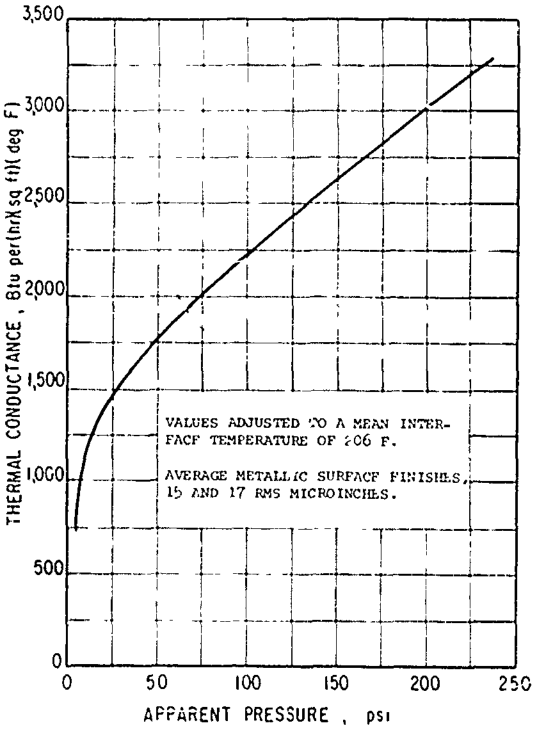

Figure 5

Variation of Thermal Conductance with Apparent Pressure for a Type 6061-T6 Aluminum/Mica Interface in Dry Contact

Figure 6

Variation of Thermal Conductance with Apparent Pressure for an Interface Having Titanium Surfaces in Dry Contact

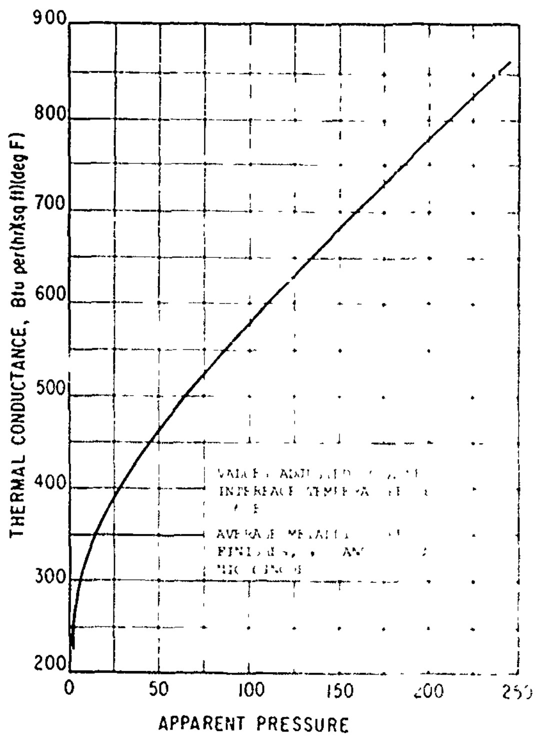

Table 1

Values of Thermal Conductance, in Btu per (Hr) (Sq Ft) (Deg F), at a Mean Interface Temperature of 206 F and an Apparent Pressure of 100 PSI For Various Surface Material Combinations

Group 1	
Metal-to-Metal (Dry Contact)	
Titanium/Titanium	577
Stainless Steel/Copper	1198
Stainless Steel/Stainless Steel	1275
Stainless Steel/Armco Ingot Iron	1480
Carbon Steel/Carbon Steel	1720
Aluminum/Stainless Steel	2080
Aluminum/Aluminum	3300
Group 2	
Metal-Mica-Metal (Dry Contact)	
Stainless Steel/Mica/Copper	520
Titanium/Mica/Titanium	520
Aluminum/Mica/Aluminum	554
Group 3	
Metal-to-Mica (Dry Contact)	
Stainless Steel/Mica	1905
Titanium/Mica	1910
Aluminum/Mica	2215
Group 4	
Metal-to-Metal (Lubricated Contact)	
Stainless Steel/Copper	2620
Aluminum/Stainless Steel	5480
Aluminum/Aluminum	19950

An inspection of Table 1 indicates that the metal-to-metal dry-contact joints (Group 1) presented an orderly progression of conductance values from titanium/titanium on the low end to aluminum/aluminum on the high end of the scale.

The overall conductance of dry-contact joints was substantially decreased when a 0.0027-inch mica layer was interposed between the metal surfaces (Table 1, Group 2). Although the conductance of this layer alone was comparatively high (1110 Btu per (hr) (sq ft) (deg F)), its presence resulted in a thermal circuit containing three resistances in series, with attendant reduction in overall conductance to a depreciated value which was nearly uniform regardless of the metallic surfaces involved.

The metal-to-mica interfaces (Group 3) exhibited fairly high conductance values as well as significant variations from the figures presented for the related metallic surfaces of Group 1. The conductance of titanium/mica was more than three times that of titanium/titantium whereas that of aluminum/mica was only 2/3 that of aluminum/aluminum. Analysis indicated that these peculiar conditions are related to surface roughness. In the titanium/mica joint, the titanium surface with a roughness of only 4.2 rms microinches contiguous to the very smooth (nonserrated) mica surface resulted in an interface having fewer voids and greater contact area than the titanium/titanium joint, with resulting higher conductance. In the aluminum/mica joint, the rougher aluminum surface (15 rms microinches) contained many voids filled with high-resistance air trapped behind the smooth contacting mica, whereas in the aluminum/aluminum joint, most of these voids were filled by interpenetration with the serrations of the two surfaces, the result being a higher conductance in the all-metallic joint.

Lubricated-contact joints were produced by coating each of the surfaces involved with the thinnest possible film of silicone grease which expelled the air from all voids and left these pockets filled with lubricant. A substantial increase in interface conductance resulted, as indicated by a comparison of the joints listed in Table 1, Group 4 with the related joints in Group 1. The relative increase in conductance was expecially pronounced in the case of surfaces having higher roughness values (e.g., aluminum/aluminum) where the voids are deeper and more numerous.

An extended study was made to determine a possible functional relationship between thermal conductance and various physical characteristics of contact surfaces and surface materials, using experimentally established information as a basis. The group of metal-to-metal dry-contact joints shown in Table 1, together with their stated values of conductance at the specified conditions of temperature and pressure, were used in this study. Physical characteristics investigated included the yield strength of the joint materials and the hardness and roughness of the contact surfaces. Other characteristics considered were determined to be unrelated to conductance.

The yield strength of the "weaker," or "indented," material which has been cited by some investigators as a factor in interface conductance, was found to be of no significance for the range of test pressures utilized in the MEL program. Substantially higher imposed pressures would be needed to produce significant surface indentation, with consequent reduction of voids and increase of conductance. It appeared, however, that a relationship might exist between interface conductance and the hardness and roughness of the contact surfaces; a study would be required to evaluate this possibility.

6.0 CONCLUSIONS

The thermal conductance of a metal-to-metal interface in dry contact may be a unique function of the hardness and roughness of the respective surfaces.

Under the pressure and temperature conditions utilized during this experimental investigation, surface and material characteristics other than hardness and roughness have no significant influence upon interface conductance.

The presence of a thin (0.0027 inch) interposed layer of mica in an all-metallic dry-contact joint effectively reduced conductance values to a fairly low and nearly uniform level regardless of the kind of metal(s) composing the joint, or the characteristics of the surfaces. This was caused by the high thermal resistance of the mica and not by contact surface conditions.

The application of a film of lubricant to a wholly metallic interface resulted in a large increase in conductance, usually amounting to several times the dry-contact values. This effect is due to the virtual improvement of surface finish through the filling up of microscopic voids. Surfaces which are naturally susceptible to the occurrence of such voids (e.g., aluminum), or which have a roughness value on the "high side," show the greatest improvement. Lubrication will offset coarse surface finish.

If a dry-contact interface includes a smooth and impervious nonmetallic surface, such as that of mica, the contacting metallic surface should have the lowest possible roughness value to achieve optimum conductance.

The higher the roughness value of the contacting surfaces, the lower is the value of apparent pressure at which a rapid rise in interface conductance begins.

7.0 RECOMMENDATIONS

An investigation should be undertaken looking toward the formulation of a comprehensive theory to describe interface thermal transfer phenomena in terms of applicable parameters.

A program of experimentation covering a broad range of parametric variations suggested by the theoretical basis for this study should be accomplished as a part of any future studies. Laboratory apparatus of new and sophisticated design should be made available for such a program, and control of experimental procedures should be maintained to a high degree of precision.

Appendix A

BIBLIOGRAPHY

1 - Brunot, A. W., and Buckland, F. F., "Thermal Contact Resistance of Laminated and Machined Joints," Trans ASME, Vol. 71, 1949, p 253

2 - Cetinkale, T. N., and Fishenden, M., "Thermal Conductance of Metal Surfaces in Contact," International Conference on Heat Transfer, The Institution of Mechanical Engineers, London, 1951

3 - Fenech, H., and Rohsenow, W. M., "Prediction of Thermal Conductance of Metallic Surfaces in Contact," Jl of Heat Transfer (ASME), Feb 1963, p 19

4 - Kolb, R. P., "Thermoelectric Generator Design Study," NAVENGRXSTA Semiannual Progress Report, Fundamental Scientific Program, Jul-Dec 1960, pp.3-9

5 - Kolb, R. P., "Thermoelectric Generator Design Study," NAVENGRXSTA Semiannual Progress Report, Fundamental Scientific Program, Jan-Jun 1961, pp. 5-8

6 - Kolb, R. P., "Thermoelectric Generator Design Studies," NAVENGRXSTA R & D Rept 710513, 8 Aug 1961

7 - Kolb, R. P., "Thermoelectric Generator Design Study," NAVENGRXSTA Semiannual Progress Report, Fundamental Scientific Program, Jul-Dec 1961, pp. 8-13

8 - Kolb, R. P., "Thermoelectric Generator Design Study," NAVENGRXSTA Semiannual Progress Report, Fundamental Scientific Program, Jan-Jun 1962, pp. 5-9

9 - Kolb, R. P., "Thermoelectric Generator Design Study," NAVENGRXSTA Semiannual Progress Report, In-House Independent Research Program, Jul-Dec 1962, p. 5

10 - Kolb, R. P., "Thermoelectric Generator Design Study," NAVENGRXSTA R & D Rept 84 513, 5 Mar 1963

11 - Kolb, R. P., "Heat Transfer Phenomena Between Solids," MEL Semiannual Progress Report, In-House Independent Research Program, Jul-Dec 1963, pp. 5-9

12 - Rogers, G. F. C., "Heat Transfer at the Interface of Dissimilar Metals," International Jl of Heat and Mass Transfer, Vol. 2, 1961 p. 150

13 - Weills, N. D., and Ryder, E. A., "Thermal Resistance Measurements of Joints Formed Between Stationary Metal Surfaces," Trans ASME, Vol.71, 1949, p. 259

Security Classification Unclassified

DOCUMENT CONTROL DATA - R&D

(Security classification of title body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) U. S. Navy Marine Engineering Laboratory Annapolis, Md. 21402	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE

Heat Transfer Between Solids

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

5 AUTHOR(S) (Last name, first name, initial)

Kolb, Robert P.

6 REPORT DATE	7a TOTAL NO OF PAGES	7b NO OF REFS
July 1965	12	13

8a CONTRACT OR GRANT NO	9a ORIGINATOR'S REPORT NUMBER(S) 157/64
b PROJECT NO S-R011 01 01 Task 0401 c d	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) Assigt 75 125

10 AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	NAVSHIPS

13 ABSTRACT In attempts to improve thermal performance of modules for thermoelectric generators an investigation based upon a program of experimentation in thermal conductance between plane solid surfaces in both dry and lubricated contact under pressure was conducted. Surface materials were Type 6061-T6 aluminum alloy and Type RS-70 unalloyed titanium. In some tests a 0.0027-inch mica layer was interposed between the metallic surfaces, with dry contact. Values of conductance were determined over a range of imposed pressures between 5 and 225 pounds per square inch (psi) in most cases, otherwise at a single pressure of approximately 100 psi. Disparate results led to the conclusion that conductance may be related to the hardness as well as the roughness of the contacting surfaces. Curves of conductance versus imposed pressure usually have a point of inflection at which they change from convex to concave upward, with the rising pressure. It was established that the higher the value of surface roughness, the lower the pressure at which the point of inflection occurs. A lubricated-contact aluminum/aluminum joint showed a conductance at 100 psi, approximately six times the dry-contact value. A dry-contact joint with the specified mica layer interposed showed a conductance approximately 1/6 the original metal-to-metal value. Results for a variety of surface material combinations are presented in a tabulation arranged for comparative study.

(Author)

DD FORM 1 JAN 64 1473

Unclassified

Security Classification

Security Classification Unclassified

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Thermoelectric generators Thermal conductance Heat transfer Generator modules						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

DD FORM 1 JAN 64 1473 (BACK)

Unclassified
Security Classification

Navy Marine Engineering Laboratory Report 157/64
HEAT TRANSFER BETWEEN SOLIDS, by R. P. Kolb. July 1965. 12pp. Figs. UNCLASSIFIED

In attempts to improve thermal performance of modules for thermoelectric generators an investigation based upon a program of experimentation in thermal conductance between plane solid surfaces in both dry and lubricated contact under pressure was conducted. Surface materials were Type 6061-T6 aluminum alloy and Type RS-70 unalloyed titanium. In some tests a 0.0027-inch mica layer was interposed between the metallic surfaces, with dry contact. (over)

1. Solids-Heat transfer
2. Solids-Surfaces
3. Generators-Heat transfer
I. Kolb, R. P.
II. Title

UNCLASSIFIED

Values of conductance were determined over a range of imposed pressures between 5 and 225 pounds per square inch (psi) in most cases, otherwise at a single pressure of approximately 100 psi. Disparate results led to the conclusion that conductance may be related to the hardness as well as the roughness of the contacting surfaces. Curves of conductance versus imposed pressure usually have a point of inflection at which they change from convex to concave upward, with rising pressure. It was established that the higher the value of surface roughness, the lower the pressure at which the point of inflection occurs. A lubricated-contact aluminum/aluminum joint showed a conductance at 100 psi, approximately six times the dry-contact value. A dry-contact joint with the specified mica layer interposed showed a conductance approximately 1/6 the original metal-to-metal value. Results for a variety of surface material combinations are presented in a tabulation arranged for comparative study.

Navy Marine Engineering Laboratory Report 157/64
HEAT TRANSFER BETWEEN SOLIDS, by R. P. Kolb. July 1965. 12 pp. Figs. UNCLASSIFIED

In attempts to improve thermal performance of modules for thermoelectric generators an investigation based upon a program of experimentation in thermal conductance between plane solid surfaces in both dry and lubricated contact under pressure was conducted. Surface materials were Type 6061-T6 aluminum alloy and Type RS-70 unalloyed titanium. In some tests a 0.0027-inch mica layer was interposed between the metallic surfaces, with dry contact. (over)

1. Solids-Heat transfer
2. Solids-Surfaces
3. Generators-Heat transfer
I. Kolb, R. P.
II. Title

UNCLASSIFIED

Values of conductance were determined over a range of imposed pressures between 5 and 225 pounds per square inch (psi) in most cases, otherwise at a single pressure of approximately 100 psi. Disparate results led to the conclusion that conductance may be related to the hardness as well as the roughness of the contacting surfaces. Curves of conductance versus imposed pressure usually have a point of inflection at which they change from convex to concave upward, with rising pressure. It was established that the higher the value of surface roughness, the lower the pressure at which the point of inflection occurs. A lubricated-contact aluminum/aluminum joint showed a conductance at 100 psi, approximately six times the dry-contact value. A dry-contact joint with the specified mica layer interposed showed a conductance approximately 1/6 the original metal-to-metal value. Results for a variety of surface material combinations are presented in a tabulation arranged for comparative study.