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XI International Conference on
THERMAL CONDUCTIVITY

SEPTEMBER 28 – OCTOBER 1, 1971

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Eleventh International
THERMAL CONDUCTIVITY CONFERENCE

Albuquerque, New Mexico
September 28 - October 1, 1971
Western Skies Motor Hotel

CHAIRMEN:

R. U. Acton
P. Wagner
A. V. Houghton, III

SPONSORS:

Sandia Laboratories
Los Alamos Scientific Laboratories
University of New Mexico

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24

THE THERMAL CONDUCTIVITY CONFERENCE
GRATEFULLY ACKNOWLEDGES A NATIONAL
SCIENCE FOUNDATION GRANT FOR FOREIGN
TRAVEL.

Preface to the Eleventh International Conference on Thermal Conductivity

Despite the economic tremors which have affected the scientific and engineering communities in 1971, the program of 85 papers including contributions from 12 countries attest to the ever widening interest in the Thermal Conductivity Conference. The increased attendance from outside the United States has encouraged the sponsors to modify the Conference title to include the word "International", an addition which could have been made some years past with equal justification.

The format of the meeting planned for Albuquerque is a mixture of those items which we, the sponsors, have particularly appreciated in the past. Time for presentations has been lengthened in order to provide more discussion time and to give the session chairmen more leeway than they have had in the past. It had been hoped that we could have tandem sessions only—thus affording all attendees the opportunity of hearing all the papers. To this end we increased the meeting time to three and one-half days from the traditional three. From this standpoint, the large number of papers is a mixed blessing—while we are gratified at the response to the call for papers, we have been forced to schedule three sets of parallel sessions. We sincerely hope that the conflicts which are always extant in this situation will be minimal. One function which will be reinstituted at this meeting will be the informal evening session. The program at this session includes a limited agenda, informal presentations, and refreshments. Please come and have your say, it is more fun that way.

As in the past, the scope of the Conference includes a broad spectrum of topics related to the thermal conductivity area. We have several invited papers which we believe will excite as much interest in the general attendance as they have among the sponsors. By and large we have a high expectation for a profitable and enjoyable Conference and we wish to thank all those who have participated in making this a successful Conference.

Thermal Conductivity Conference History

The Conference had its beginning in 1961. In the fall of that year, a group of people from the USA and Canada, who were actively engaged in properties measurements, met to discuss their mutual problems and goals. From this small beginning, the Conference has grown in size until it is now international in scope and reputation. Twenty five of the scheduled 85 papers are from other than the USA. The Conference mailing list contains nearly a 1000 names and the attendance this year is expected to approach 150.

This year's Conference marks the beginning of its second decade. The Conference chairmen are dedicated to maintaining a truly "working group" atmosphere from which expert and novice alike may benefit.

The following is a list of Conference chairmen and sponsors.

DATE	CHAIRMEN	SPONSORS
Oct 1961	C. F. Lucks	Battelle Memorial Institute
Oct 1962	M. J. Laubitz	National Research Council (Canada)
Oct 1963	D. L. McElroy	Oak Ridge National Laboratory
Oct 1964	R. L. Rudkin	Naval Radiological Defense Laboratory
Oct 1965	J. D. Plunkett	University of Denver
Oct 1966	M. L. Minges G. L. Denman	Air Force Materials Laboratory
Nov 1967	D. R. Flynn B. A. Peavy	National Bureau of Standards
Oct 1968	C. Y. Ho R. E. Taylor	Thermophysical Properties Research Center Purdue University
Oct 1969	H. R. Shanks	Ames Laboratory and Office of Naval Research
Sept 1970	A. E. Wechsler R. P. Tye	Arthur D. Little, Inc Dynatech R/D Co
Sept 1971	R. U. Acton P. Wagner A. V. Houghton III	Sandia Laboratories Los Alamos Scientific Laboratories University of New Mexico

Registration

Registration for the Eleventh Thermal Conductivity Conference will be held in the main lobby of the Western Skies Hotel beginning at 7 p.m. Monday evening September 27, 1971. The \$45.00 registration fee includes the cost of one copy of the extended abstracts of the Conference and those meals described under Meals.

Meals

The Conference registration fee of \$45.00 includes the Tuesday and Thursday evening meals—Tuesday at the Barn Dinner Theatre and Thursday (the Banquet) at the Summit House atop Sandia Peak. Coffee and other refreshments will be furnished most of the time in the Sandia Room. Refreshments will also be furnished at the shirtsleeve session on Wednesday night. All other meals and refreshments are the personal responsibility of each attendee.

Technical Sessions

All single sessions and all invited papers will be given in the New Mexico Room. When there are dual sessions, the second session will be held in the Shalako Room.

Messages

A message board will be located at the registration desk. Conferees may be reached by calling (505) 299-4401.

Tours

No official tours have been planned. Both Sandia and Los Alamos Laboratories require a government security clearance for admittance. Tours of the University of New Mexico may be arranged on an individual basis with Prof. A. V. Houghton III.

These abstracts are informal. The authors are free to publish in the open literature. The contents herein may be referenced as a "private communication".

NAME	DAY	SESSION	NAME	DAY	SESSION
Abdinov, D. Sh.	Thursday	a.m., II	Martin, J. J.	Thursday	a.m., I
Achmedov, N. R.	Thursday	a.m., II		Thursday	a.m., I
Aliev, G. M.	Thursday	a.m., II	Martin, R.	Wednesday	p.m.
Ang, C. S.	Tuesday	p.m.	Matsumura, T.	Tuesday	a.m.
Ashworth, T.	Thursday	a.m., I	McElroy, D. L.	Tuesday	a.m., Invited
	Thursday, a.m.	a.m., I		Wednesday	a.m., I
Barsukov, V. F.	Thursday	a.m., II	McGaw, R.	Wednesday	a.m., I
Belskaya, E. A.	Friday	a.m.	Megerlin, F. E.	Thursday	a.m., II
Birkebak, R.	Wednesday	a.m., I	Mirkovich, V. V.	Friday	a.m.
Bowman, H. F.	Thursday	p.m., I	Moore, J. P.	Wednesday	a.m., I
Bury, P.	Wednesday	p.m.	Murphy, H. D.	Thursday	p.m., IV
Buyco, E. H.	Thursday	a.m., II	Nangia, K. K.	Tuesday	p.m., I
Buzbee, B. L.	Thursday	p.m., IV	Naum, R. G.	Thursday	p.m., III
Calza-Bini, A.	Thursday	a.m., I		Thursday	p.m., III
Chan, S. L.	Tuesday	p.m.	Null, M. R.	Friday	a.m.
Chen, S. H. P.	Wednesday	a.m., I	Ortiz, L.	Thursday	a.m., II
Chu, S.	Wednesday	a.m., II	Overton, W. C.	Wednesday	a.m., II
Ciminera, J. R.	Wednesday	a.m., II	Park, H. S.	Wednesday	p.m.
Cook, J. G.	Tuesday	a.m.	Patimo, C.	Thursday	a.m., I
Coumou, K. G.	Wednesday	a.m., I	Peletskii, V. E.	Friday	a.m.
Couper, J. R.	Thursday	p.m., III	Perelman, T. L.	Wednesday	a.m., II
Cremers, C. V.	Thursday	p.m., IV	Petri, F.	Wednesday	a.m., II
Deshpande, P. B.	Thursday	p.m., III	Piconi, C.	Thursday	a.m., I
Dixon, G. S.	Thursday	a.m., I	Powell, R.	Wednesday	a.m., I
Donaldson, A. B.	Wednesday	p.m.	Rechowicz, M.	Thursday	a.m., I
	Friday	a.m.	Remington, C. R.	Tuesday	p.m.
	Friday	a.m.		Tuesday	p.m.
Dorr, F. W., Jr.	Thursday	p.m., IV	Richter, J.	Friday	a.m.
Duggin, M. J.	Tuesday	p.m.	Riesbig, R. L.	Thursday	a.m., II
Dzhalilov, N. Z.	Thursday	a.m., II	Rogers, R. N.	Thursday	a.m., II
Endo, S.	Thursday	a.m., I	Rosenbaum, R.	Thursday	a.m., I
Evans, D. M.	Tuesday	a.m.		Thursday	a.m., II
Ferro, C.	Thursday	a.m., I	Sauer, H. J., Jr.	Tuesday	p.m.
French, B.	Tuesday	p.m.		Tuesday	p.m.
Fulkerson, W.	Thursday	a.m., II	Saxena, S. C.	Wednesday	a.m., I
Gdalevich, L. B.	Wednesday	a.m., II	Schimmel, W. P., Jr.	Wednesday	a.m., II
Green, D. B.	Wednesday	a.m., I		Wednesday	p.m.
Guevara, F. A.	Wednesday	p.m.	Schmidt, H. E.	Friday	a.m.
Hardee, H. C.	Thursday	p.m., III	Schriempf, J. T.	Friday	a.m.
Hayakawa, K.	Thursday	p.m., III	Shaffer, P. T. B.	Thursday	p.m., III
Hayden, R. W.	Friday	a.m.		Thursday	p.m., IV
Heckman, R. C.	Thursday	p.m., IV	Shashkov, A. G.	Thursday	a.m., II
	Thursday	p.m., IV	Shukis, F. A.	Thursday	a.m., II
	Friday	a.m.	Spinney, S. C.	Friday	a.m.
	Friday	a.m.	Stewart, W. S., Jr.,	Tuesday	p.m.
Heizer, G. A.	Tuesday	p.m.	Stornick, T. S.	Wednesday	p.m.
Houghton, A. V., III	Friday	a.m.	Stout, N. D.	Thursday	a.m., II
	Friday	a.m.	Taborek, J.	Tuesday	p.m.
Howard, J. F.	Wednesday	a.m., I	Tan, H. S.	Tuesday	p.m.
Huck, R. J.	Wednesday	p.m.	Taylor, R. E.	Tuesday	a.m.
Husid, B. M.	Wednesday	a.m., II	Thomson, R. K.	Thursday	a.m., II
Hwang, H. P.	Wednesday	a.m., II	Tufeu, R.	Wednesday	p.m.
Irie, T.	Thursday	a.m., I	Tye, R. P.	Tuesday	a.m.
Ishimoto, T.	Thursday	p.m., Invited		Wednesday	a.m., I
Johnson, E.	Wednesday	p.m.		Wednesday	a.m., I
	Wednesday	p.m.		Thursday	p.m., II
Johnson, K. W. R.	Tuesday	a.m.		Friday	a.m.
Johnson, R. L.	Thursday	a.m., I		Friday	a.m.
Jun, C. K.	Thursday	p.m., III	van der Aa, H. H. M.	Wednesday	a.m., I
	Thursday	p.m., III	van den Berg, M.	Friday	a.m.
Just, J.	Thursday	p.m., III	van der Hoek, L.	Friday	a.m.
Kahn, J. A.	Friday	a.m.	Van der Meer, P.	Tuesday	a.m.
	Friday	a.m.	Vasiliev, L. L.	Thursday	a.m., II
Kemme, J. E.	Wednesday	a.m., Invited	Venart, J. E. S.	Tuesday	p.m.
Kerrisk, J. F.	Tuesday	a.m.		Tuesday	p.m.
	Thursday	p.m., IV		Wednesday	p.m.
Kestin, J.	Wednesday	p.m.	Vodar, B.	Wednesday	p.m.
Kime, J. R.	Thursday	a.m., II	Wagner, P.	Thursday	p.m., IV
Kirihata, H.	Thursday	a.m., I	Watkins, J.	Wednesday	a.m., I
Kiyama, K.	Thursday	p.m., IV	Watson, J. T. R.	Wednesday	p.m.
Krzywoblocki, M. Z.	Wednesday	a.m., II	Weckesser, L. B.	Thursday	a.m., II
Laubitz, M. J.	Tuesday	a.m.	White, G. K.	Tuesday	a.m.
Lee, D. O.	Thursday	p.m., III	Wild, D.	Wednesday	p.m.
LeNeindre, B.	Wednesday	p.m.	Williams, R. K.	Thursday	a.m., II
Levitin, R. S.	Wednesday	a.m., II	Wilson, R. S.	Wednesday	a.m., II
Lin, T. Y.	Tuesday	p.m.	Wolf, M. W.	Thursday	a.m., I
Loomer, J. E.	Thursday	a.m., I	Yalamanchili, R. V. S.	Wednesday	a.m., II
Lozier, W. W.	Friday	a.m.		Wednesday	a.m., II
Lucks, C. F.	Thursday	a.m., I			
Luikov, A. V.	Thursday	a.m., II			
Magapu, V. K.	Tuesday	p.m.			
Mani, N.	Tuesday	p.m.			
Mar, R. W.	Thursday	a.m., II			

Tuesday, September 28, 1971

- 9:00 a.m.** **Welcome to the Eleventh Thermal Conductivity Conference**
Dr. J. E. McDonald, *Director of Material Sciences, Sandia Laboratories*
- 9:15 - 9:45 a.m.** By Invitation
D. L. McElroy, *Oak Ridge National Laboratory*
Thermal Conductivity Implications
- NEW MEXICO ROOM**
Experimental Results (A)
Session Chairman, Dr. P. Wagner
- 9:50 - 10:10 a.m.** R. E. Taylor, *Thermophysical Properties Research Center, Purdue University*
Thermophysical Properties of a Standard Tungsten Sample
- 10:15 - 10:35 a.m.** K. W. R. Johnson and J. F. Kerrisk, *Los Alamos Scientific Laboratory*
Thermal Diffusivity of Mo and W Between 20°C and 2000°C
- 10:40 - 11:00 a.m.** D. M. Evans, *Solar Div. H. I.*, and R. P. Tye, *Dynatech R/D Co.*
Prediction, Optimization, and Measurement of the Thermal Conductivity of an All-Metal-Insulation
- 11:05 - 11:25 a.m.** M. J. Laubitz and T. Matsumura, *National Research Council of Canada*
The High Temperature Properties of Cobalt
- 11:30 - 11:50 a.m.** G. K. White (read by M. J. Duggin), *National Standards Laboratory, Australia*
Lattice Conductivity and Lorenz Ratio for Chromium
- 11:55 - 12:15 p.m.** J. G. Cook and P. Van der Meer, *National Research Council of Canada*
The Thermal and Electrical Conductivity of Sodium from 40 K to 350 K
- LUNCH**
- Fluids and Related Topics
Session Chairman, Dr. M. J. Duggin
- 1:30 - 1:55 p.m.** K. K. Nangia and J. Taborek, *Heat Transfer Research, Inc*
Physical Properties of Liquids - Status of Present Knowledge and Importance in Design Methods for Heat Transfer and Fluid Flow
- 2:00 - 2:20 p.m.** N. Mani and J. E. S. Venart, *University of Calgary, Canada*
Fluid Thermal Conductivity Measurement Facility Using a Transient Hot-Wire Technique
- 2:25 - 2:40 p.m.** M. J. Duggin, *National Standards Laboratory, Australia*
The Thermal Conductivity and Lorenz Number of the Liquid In-Ga System
- 2:45 - 3:05 p.m.** C. S. Ang, H. S. Tan, and S. L. Chan, *University of Malaya,*
Heat Pulse Technique for Measurement of Thermal Diffusivity of Mercury
- 3:10 - 3:25 p.m.** V. K. Magapu and J. E. S. Venart, *University of Calgary, Canada*
Thermal Contact Conductance - Graphical Aids for Computation
- 3:30 - 3:45 p.m.** H. J. Sauer, Jr., C. R. Remington, W. S. Stewart, Jr., and T. Y. Lin, *University of Missouri*
Thermal Contact Conductance with Several Interstitial Materials
- 3:50 - 4:10 p.m.** H. J. Sauer, Jr., C. R. Remington, G. A. Heizer, *University of Missouri*
Thermal Conductance of Lubricant Films
- 4:15 - 4:35 p.m.** B. French, *Manned Spacecraft Center*
Thermal Lunar Dust Simulant
- BARN DINNER THEATER**

8 30 9 00 a.m. By Invitation
J E Kemme, *Los Alamos Scientific Laboratory*
The Heat Pipe at Los Alamos

NEW MEXICO ROOM

Session I Measurement Techniques
Session Chairman, Dr R. E. Taylor

9 05 9 20 a.m. D B Green and H H M Van der Aa, *Phillips Research Laboratories, Netherlands*
A Thermal Conductivity Apparatus Employing Heat Pipes

9 25 9 45 a.m. J P Moore and D. L. McElroy, *Oak Ridge National Laboratory*
A Guarded-Longitudinal-Heat-Flow Technique for Measurement of Thermal Conductivity, Electrical Resistivity, and Seebeck Coefficient Between 300 and 1000 K

9 50 10 05 a.m. R. Powell, *Royal Military College of Science, England*
The Advantages of Simultaneous Measurement of Thermal Conductivity and Thermoelectric Power

10 10 10 20 a.m. R. P. Tye, *Dynatech R/D Co.*
Measurements of Heat Transmission in Thermal Insulations Using the Guarded Hot Plate Method

10 25 10 40 a.m. J F Howard, K. G. Coumou, and R P Tye, *Dynatech R/D Co.*
A Rapid Direct Reading Instrument for Measuring the Thermal Conductivity of Thermal Insulations

10 45 11 00 a.m. R. Birkebak and J. Watkins, *University of Kentucky*
A General Method for Determining the Thermophysical Properties of Insulating Materials Using an Extension of the Line Heat Source Technique

11 05 - 11 20 a.m. R McGaw, *U. S. Army Cold Region Research and Engineering Laboratory*
The Use of the Cooling Curve in the Probe Conductivity Test

11 25 11 45 a.m. S H. P. Chen and S. C. Saxena, *University of Illinois*
An Evaluation of the Column Method for the Determination of Conductivity of Gases

SHALAKO ROOM

Session II Theory and Analysis
Session Chairman, Dr R. C. Heckman

9 05 9 20 a.m. M. Z. V. Krzywoblocki, *Michigan State University*
Heat Conduction in Turbulent Media Based Upon the Wave Mechanics

9 25 9 45 a.m. W C Overton, Jr., *Los Alamos Scientific Laboratory*
Analysis of Heat Pulse Propagation in Solid ³He

9 50 10 10 a.m. R. S. Wilson, *Northern Illinois University*
Correlation of Line Shapes of Impurity Reduced Absorption and Impurity Reduced Thermal Conductivity vs Temperature

10 15 10 35 a.m. S Chu and R. V S Yalamanchili, *Rock Island Arsenal*
Finite-Element Method Applied to Heat Conduction in Solids with Nonlinear Boundary Conditions

10 40 11 00 a.m. F. Petri, *Raytheon Co.*
Comparison of Automated Two Dimensional Transient Heat Conduction Methods

11 05 11 25 a.m. W. P. Schimmel, Jr., *Sandia Laboratories*
A Laplace Transform Method for Predicting Radiation Losses from a Laser Heated Foil

11 30 11 50 a.m. R. V. S. Yalamanchili, *Rock Island Arsenal*
Unsteady Heat Transfer Analysis for a Gun Barrel

11 55 - 12 15 p.m. H. P. Hwang and J. R. Ciminera, *IBM Corp*
A Transient Technique Employing Computer Aided Graphics to Measure Thermal Conductivity of Heat Sink Compounds

12 20 - 12 40 p.m. T. L. Perelman, R. S. Levitin, L. B. Gdalevich, and B. M. Husid, *BSSR Academy of Sciences, USSR*
Conjugated Unsteady-State Heat Transfer of a Plate in a Gas Flow

LUNCH

NEW MEXICO ROOM

Session III Gases
Session Chairman, Dr. R. L. Reisbig

1 00 1 20 p.m. J Kestin, *Brown University*
The Thermal Conductivity of Gases

1 25 1 45 p.m. J E. S. Venart, *University of Calgary, Canada*
Uncertainties in the Thermal Conductivity of Liquids and Dense Gases - Their Effect on Heat Transfer

1 50 - 2 10 p.m. R Martin and E Johnson, *University of Surrey, England*
Calculation of the Transport Coefficients for Dilute Gases Using an Iterative Solution of Boltzmann's Equation

2 15 - 2 35 p.m. J T R. Watson, *National Engineering Laboratory, Scotland*
The Viscosity and Thermal Conductivity Coefficients of the Rare Gases at Atmospheric Pressure in the Temperature Range 270 to 2000 K

2 40 - 3 00 p.m. F A Guevara, *Los Alamos Scientific Laboratory*
Determination of High Temperature Viscosities for H₂, He, Ar, N₂, Ne, Kr, and Xe and Calculation of the Corresponding Thermal Conductivities

3 05 3 20 p.m. D Wild and R. J Huck (read by E. Johnson), *University of Surrey, England*
Calculation of the Thermal Conductivity of Almost-Lorentzian Gas Mixtures

3 25 - 3 40 p.m. E. Johnson and D. Wild, *University of Surrey, England*
Thermal Transport in Binary Gas Mixtures with Disparate Masses

3 45 - 4 00 p.m. B LeNeindre, R Tufeu, P Bury, B. Vodar, *High Pressure Laboratory, C.N.R.S., France*
Experimental Results on the Thermal Conductivity of Carbon Dioxide and Steam in the Critical Region

4 05 - 4 25 p.m. H. S Park and T. S. Storvick, *University of Missouri - Columbia*
Thermal Transpiration Measurements and the Heat Conductivity of Hydrogen Chloride, Methyl Chloride and Methyl Fluoride

4 30 4 50 p.m. W. P. Schimmel, Jr., and A. B. Donaldson, *Sandia Laboratories*
Radiation Interaction Effect Upon Thermal Conductivity Measurements in an Absorbing-Emitting Gas

DINNER

NEW MEXICO ROOM

8 00 p.m. end Shirtsleeve Session Progress reports, open discussion time

NEW MEXICO ROOM

Session I Experimental Results (B)
Session Chairman, W. T. Engelke

- 8 30 - 8 45 a.m. J J Martin and M. W. Wolf, *Oklahoma State University*
Thermal Conductivity of Single Crystal ZnO
- 8 50 - 9 05 a.m. G S Dixon and J J Martin, *Oklahoma State University*
Thermal Conductivity of Single Crystal EuO
- 9 10 - 9 30 a.m. A Calza Bini, *National Committee for Nuclear Energy, Italy*
In-Pile Thermal Conductivity Measurements on Oxide Fuel for Fuel Reactors
- 9 35 - 9 55 a.m. C Ferro, C Patimo, and C Piconi, *National Committee for Nuclear Energy, Italy*
Thermal Diffusivity of Mixed ($\text{Th}_{1-x}\text{U}_x$) Oxides and Some Materials to be Used as Reference in the Range 650 to 2650 K
- 10 00 - 10 20 a.m. Ralph Rosenbaum, *Israel Institute of Technology*
Very Low Temperature Thermal Conductivity of Alkali Halides Crystals Containing the Hydroxide Ion
- 10 25 - 10 45 a.m. S Endo, H. Kirihata, and T. Irie, *Science University of Tokyo, Japan*
Thermal Conductivity and Seebeck Coefficient of Cadmium Indium Sulfide and Its Alloys with Cadmium Chromium Sulfide
- 10 50 - 11 05 a.m. T. Ashworth and L. R. Johnson, *South Dakota School of Mines and Technology*
Thermal Conductivity of Nylon From 4 to 350 K
- 11 10 - 11 25 a.m. T. Ashworth, J. E. Loomer, and M. Rechowicz, *South Dakota School of Mines and Technology*
Properties of Some Thermal Bonding Media
- 11 30 - 11 45 a.m. C F Lucks, *Columbus, Ohio*
ARMCO Iron - A Thermal Conductivity Reference Material and a New Thermal Conductivity Model

- 1 30 - 2 00 p.m. By Invitation
T. Ishimoto, *TRW Corp.*
Sensitivity Analysis

NEW MEXICO ROOM

Session III Topics in Multiphase Media
and Biological Applications
Session Chairman, Dr. R. K. Williams

- 2 05 - 2 25 p.m. R. G. Naum, C. K. Jun, and P. T. B. Shaffer, *Carborundum Co.*
Thermal Conductivity of Carbon-Carbon Composites as a Function of Temperature and Orientation
- 2 30 - 2 50 p.m. R. G. Naum, C. K. Jun, and P. T. B. Shaffer, *Carborundum Co.*
Thermal Conductivity of CVD, SiC and Composites
- 2 55 - 3 10 p.m. J. Just and H. F. Bowman, *Northeastern University*
Directional Thermal Conductivity of Textilite (Micarta) Between 4.2 and 100 K
- 3 15 - 3 35 p.m. P. B. Deshpande and J. R. Couper, *Howard University*
Effect of Particle Size, Shape, and Spatial Distribution on Thermal Conductivity of Suspensions
- 3 40 - 4 00 p.m. Kan-ichi Hayakawa, *Rutgers University*
Determining the Apparent Thermal Diffusivities of Viscous Food
- 4 05 - 4 25 p.m. H. C. Hardee and D. O. Lee, *Sandia Laboratories*
A Simple Conduction Model for Skin Burns Resulting From an Incident Heat Flux of Short Duration

SHALAKO ROOM

Session II Related Properties
Session Chairman, Dr. A. V. Houghton

- 8 30 - 8 45 a.m. Ralph Rosenbaum, *Israel Institute of Technology*
Very Low Temperature CMN Thermometry Techniques
- 8 50 - 9 10 a.m. R. L. Reisbig and R. K. Thomson, *University of Missouri*
Temperature Measurement in a Fluid Boundary Layer by Laser Interferometric Holography
- 9 15 - 9 35 a.m. R. W. Mar, *Sandia Laboratories*, and N. D. Stout, *LRL*
Enthalpy and Specific Heats of Various MB_4 and MB_{12} Compounds
- 9 40 - 10 00 a.m. E. H. Buyco, *Purdue University*
Spline Function Correlation of the Specific Heat of Liquid Metals: Sodium, Potassium and Mercury
- 10 05 - 10 20 a.m. L. Ortiz and R. N. Rogers, *Los Alamos Scientific Laboratory*
Simplified Technique for Emittance Measurement
- 10 25 - 10 45 a.m. F. E. Megerlin and F. A. Shukis, *Raytheon Co.*
The Effects of Thermal Conductivity on the Thermal Stresses in Ceramics
- 10 50 - 11 10 a.m. R. K. Williams and W. Fulkerson, *Oak Ridge National Laboratory*
Electrical Resistivity of High Purity Tungsten From 1100 to 2500 K
- 11 15 - 11 25 a.m. L. B. Weckesser and J. R. Kime, *Johns Hopkins University*
A Sensor for Measuring Convective Heat Transfer Coefficient
- 11 30 - 11 45 a.m. A. C. Anderson, *University of Illinois*
The Influence of Dislocation on Thermal Conductivity
- 11 50 - 12 10 p.m. G. M. Aliev, D. Sh. Abidinov, N. R. Achmedov, and N. Z. Dzhalilov, *Academy of Sciences of Azerbaidzhan, USSR*
Investigation of Thermal Conductivity of FeSe , Fe_2Se_3 , Fe_7Se_8 , Fe_3Se_4 , CrFe_2Se_4 , and NiFe_2Se_4 in the Temperature Range of 100 to 500 K
- 12 15 - 12 30 p.m. A. V. Luikov, A. G. Shashkov, V. F. Barsukov, and L. L. Vasiliev, *Byelorussian Academy of Sciences, USSR*
Thermophysical Properties of Some Filled Polymers in the Temperature Range 10 to 400 K

LUNCH

SHALAKO ROOM

Session IV Thermal Diffusivity (A)
Session Chairman, Dr. W. W. Lozier

- 2 05 - 2 25 p.m. B. L. Buzbee, F. W. Dorr, Jr., and P. Wagner, *Los Alamos Scientific Laboratory*
A Method for Simultaneous Determination of Thermal Conductivity and Thermal Diffusivity
- 2 30 - 2 45 p.m. J. F. Kerrisk, *Los Alamos Scientific Laboratory*
Steady State Approximation in Thermal Diffusivity Measurements on Heterogeneous Materials
- 2 50 - 3 10 p.m. R. C. Heckman, *Sandia Laboratories*
Finite Pulse Time Corrections for Flash Diffusivity Measurements
- 3 15 - 3 35 p.m. R. C. Heckman, *Sandia Laboratories*
The Analysis of Pulsed Thermal Diffusivity Measurement
- 3 40 - 4 00 p.m. H. D. Murphy, *Los Alamos Scientific Laboratory*
Flash Diffusivity in Cylindrical Coordinates
- 4 05 - 4 20 p.m. C. J. Cremers, *University of Kentucky*
Thermal Conductivity and Diffusivity of the Apollo 12 Lunar Fines at Landing Site Conditions
- 4 25 - 4 40 p.m. K. Koyama, *Gulf General Atomics*, and R. P. Tye, *Dynatech R/D Co.*
Thermal Conductivity of Some Irradiated Fuel Element Materials

BANQUET

Friday, October 1

NEW MEXICO ROOM

Experimental Results (C) and Thermal Diffusivity (B)

Session Chairman, R. U. Acton

- 8:30 - 8:50 a.m. R. P. Tye, R. W. Hayden, and S. C. Spinney, *Dynatech R/D Co.*
Thermal Conductivity of Eight Aerospace Metals and Alloys Over All or Part of the Temperature Range 90 to 1200 K
- 8:55 - 9:10 a.m. R. P. Tye, *Dynatech R/D Co.*
The Thermal and Electrical Conductivities of Some Copper Alloys at Elevated Temperatures
- 9:15 - 9:30 a.m. E. A. Belskaya and V. E. Peletskii, *Institute of High Temperature, USSR*
Thermal and Electric Conductivity of Porous Nickel
- 9:35 - 9:55 a.m. M. VandenBerg, L. VanderHoek, J. Richter, and H. E. Schmidt, *Euratom, Karlsruhe, Germany*
Observations on the Thermal Conductivity of Uranium-Plutonium Oxides
- 10:00 - 10:20 a.m. J. A. Kahn, R. C. Heckman, A. B. Donaldson, and A. V. Houghton III, *Sandia Laboratories*
Application of a Laser Barrier in Flash Thermal Diffusivity Studies of Insulative Materials (Experiment)
- 10:25 - 10:45 a.m. A. B. Donaldson, J. A. Kahn, R. C. Heckman, and A. V. Houghton III, *Sandia Laboratories*
Application of a Laser Barrier in Flash Thermal Diffusivity Studies of Insulative Materials (Theory)
- 10:50 - 11:10 a.m. M. R. Null, W. W. Lozier, and A. W. Moore, *Parma Technical Center, UCC*
Thermal Diffusivity and Thermal Conductivity of Pyrolytic Graphite From Room Temperature to 2700 K
- 11:15 - 11:30 a.m. J. T. Schriempf, *Naval Research Laboratory*
An Apparatus for the Measurement of the Temperature Dependence of the Thermal Diffusivity of a Single Specimen in Both the Solid and Liquid Phases
- 11:35 - 11:55 a.m. V. V. Mirkovich, *Dept. of Energy, Mines and Resources, Canada*
An Apparatus for Measurement of Thermal Diffusivity by Three Different Methods

TUESDAY

a.m.

X THERMOPHYSICAL PROPERTIES OF AFML-AGARD TUNGSTEN

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INTRODUCTION

The thermophysical properties of a sample cut from a bar of arc-cast tungsten were measured to 2800 K. Samples from this bar have been sent for physical property measurements to a number of laboratories throughout the North Atlantic Treaty Organization countries as part of an AGARD (Advisory Group for Aerospace Research and Development) program. The results from the various laboratories will be intercompared and analyzed.

The thermophysical properties measured at TPRC include normal spectral emittance, hemispherical total emittance, electrical resistivity, thermal conductivity and Lorenz function. The multi-property apparatus previously described [1,2]² was used for these measurements. The method involves heating the sample to high temperatures by passing a large electrical current through it. Emittances and electrical resistivities are determined under isothermal conditions and the thermal conductivity from temperature profiles.

RESULTS AND DISCUSSION

The electrical resistivity of the AFML-AGARD sample decreased appreciably upon heat-treatment in a high vacuum ($>10^{-6}$ torr). Noticeable grain growth also occurred upon heat-treatment and this was probably accompanied by some decrease in impurity content, although chemical analysis of the heat-treated material is not available as yet. The electrical resistivity data can be represented by the equation

$$\rho(\Omega m) = -3.7155 \times 10^{-8} + 2.70137 \times 10^{-10} T + 1.6214 \times 10^{-14} T^2$$
$$800 < T < 2800$$

The sample's surface characteristics were found to be unstable below about 1700 K. Apparently an oxide or nitride coating forms on the surface below this temperature in a vacuum of 10^{-7} torr and the coating is volatile at higher temperatures. This phenomenon was noted previously [3]. Attempts to get reproducible emittance (both spectral and total) data below 1700 K were not fruitful. However, reproducible emittance data at higher temperatures were obtained by heating the sample above 2300 K before taking measurements. In general the spectral and total hemispherical emittance data were comparable to that reported earlier for different tungsten samples [3].

Thermal conductivity (λ) values were computed using the spline program described previously [1] and also an expanded spline program in which temperature derivatives were computed for each data point in a profile, but the end points were not

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² Figures in brackets indicate the literature references at the end of this Abstract.

used in computing thermal conductivity values. This expanded spline procedure improves the computed conductivity values since the uncertainties in determining the derivatives near the ends of the profile are much greater than in the other regions.

The thermal conductivity data can be represented by

$$\lambda (\text{W m}^{-1} \text{C}^{-1}) = 1.1181 - 4.6469 \times 10^{-6} T - 2.09213 \times 10^{-8} T^2 \\ 1600 < T < 2800$$

The present results generally are greater than our previous results for samples from a different batch of tungsten [3] and also are greater than the recommended curve [4]. However all of these results can be included in a band $\pm 4\%$ wide, which is within the combined uncertainties.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support of Dr. M. Minges and Sgt. R. Byrum of Wright-Patterson Air Force Base. This program was sponsored by the Air Force Materials Laboratory.

REFERENCES

- [1] Taylor, R.E., Davis, F.E., Powell, R.W., and Kimbrough, W.D., Determination of Thermal and Electrical Conductivity, Emittance and Thomson Coefficient at High Temperatures by Direct Heating Methods, AFML-TR-69-277.
- [2] Taylor, R.E., Powell, R.W., Davis, F., and Nalbantyan, M., Evaluation of Direct Electrical Heating Methods, Thermal Conductivity--Proceedings of the Eighth Conference (Ed. C.Y. Ho and R. E. Taylor), 339-354, 1968.
- [3] Taylor, R.E., Kimbrough, W.D., and Powell, R.W., Thermophysical Properties of Tantalum, Tungsten and Tantalum-10 Tungsten at High Temperatures, Journal Less-Common Metals (in print).
- [4] Touloukian, Y.S., Powell, R.W., Ho, C.Y., and Klemens, P.G., Thermal Conductivity, Metallic Elements and Alloys, Volume 1 of Thermophysical Properties of Matter (1970), IFI/Plenum, New York-Washington.

X THERMAL DIFFUSIVITY OF MOLYBDENUM AND TUNGSTEN
BETWEEN 20°C AND 2000°C¹

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Previous measurements [1]² indicated that accurate thermal diffusivity measurements were possible at room temperature by the laser flash technique. Care was taken to optimize the laser beam uniformity, to minimize the effect of the sample holder, and to calibrate the detection instrumentation.

These concepts were embodied in the design of a high temperature (to 2700°C) thermal diffusivity apparatus. The system was tested by measuring the thermal diffusivity of 99.9% pure molybdenum and tungsten from 20 to 2000°C. The parameters investigated by these measurements were:

- (a) sample thickness - two different thicknesses
- (b) furnace atmosphere - argon, helium and vacuum
- (c) sample temperature rise detector - thermocouples and photomultiplier tube

Shown in Fig. 1 are the results of these measurements. The thermal diffusivities were corrected for heat losses by the method of Cape and Lehman [2] and for thermal expansion. Also shown are calculated thermal conductivities which are compared with TPRC recommended values [3].

References:

1. K. W. R. Johnson and J. F. Kerrisk, Tenth Thermal Conductivity Conference, Sept. 28-30, 1970, Newton, Mass.
2. J. A. Cape and G. W. Lehman, J. Appl. Phys. 34, 1909 (1963).
3. Y. S. Touloukian, et al., "Thermophysical Properties of Matter," Vol. 1, Plenum, New York, 1970.

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1. Work performed under the auspices of the U.S. Atomic Energy Commission.
 2. Figures in brackets indicate references at the end of this abstract.

Figure 1. Thermal diffusivity and conductivity of molybdenum and tungsten.

PREDICTION, OPTIMIZATION AND MEASUREMENT
OF THE THERMAL CONDUCTIVITY OF AN
ALL-METAL-INSULATION

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INTRODUCTION

A thermal model has been generated for predicting the equivalent thermal conductivity of an insulating material, constructed exclusively from stainless steel foil. A method was also devised for optimizing the performance of this material. A summary of these analytical results is presented, together with initial test results obtained from a guarded hot plate test of a representative sample of the material.

DISCUSSION

A thermal insulation, constructed entirely of stainless steel foil, has been devised. The configuration selected consists of layers of parallel sheets of metal foil spaced with relatively narrow, parallel strips of corrugated metal foil. The thermal model was constructed on the basis that the corrugated spacer convolution pitch (P) is dictated by the functional relationship $P = S/\sin \theta$, where S is the distance between parallel sheets (plate spacing) and θ is the apex angle of the convolution. Based on a series of simplifying assumptions, the equivalent thermal conductivity of this material ($\lambda_{eq.}$) is expressed by:

$$\lambda_{eq.} = \frac{2\delta W}{LS} \cdot \sin^2 \theta \lambda_M + \lambda_g + \epsilon_{1-2} h_R (S + \delta) \quad (1)$$

where δ is foil thickness, W spacer width, L spacer pitch, λ_M foil material thermal conductivity, λ_g interstitial gas thermal conductivity, ϵ_{1-2} net interchange factor for radiation and h_R the black body radiation heat transfer coefficient. Equation (1) is valid for any consistent set of units and assumes that the plate spacing is sufficiently close to preclude natural convection.

For this particular model, it may be shown that there is an optimum plate spacing, which balances radiation and metal conduction, to yield the minimum equivalent thermal conductivity:

$$S_{OPT} = \sqrt{\frac{2\delta W \sin^2 \theta \lambda_M}{L \epsilon_{1-2} h_R}} \quad (2)$$

A representative sample of this material was fabricated and the thermal conductivity was measured, utilizing a large guarded hot plate apparatus. The sample was constructed from .05 mm thickness AISI Type 304 stainless steel foil. The corrugated spacer strips had convolution apex angles of 60° , were approximately 20 mm wide and were spaced at a pitch distance of approximately 150 mm. Individual plate spacing was

about 6 mm and the package consisted of 8 such layers for a total thickness of about 50 mm. The overall sample was about 300 mm on the side, in plan view.

Fine gauge thermocouples were spot welded to each surface of the sample and the wires insulated from the metal surfaces by means of very thin Teflon tape. Each surface was covered with a 3 mm thick piece of silicone sponge rubber, of known thermal conductivity. The sample was then surrounded by a 150 mm wide annulus of a dense, fibrous, slightly compressible thermal insulation, having the same thickness as the sample. A similar thickness, 600 mm square piece of the same insulation was cut to form the other piece of a sample pair, for insertion into a guarded hot plate apparatus.

A flat 600 mm square heater, consisting of resistance wire wound uniformly on a central core, with thick, black oxide coated metal plates on either side, was sandwiched between the two sample pieces, with the test sample on the lower side. The heater consisted of two separate sections: an inner 300 mm diameter central measuring section, surrounded by a 150 mm wide annular guard section. The two sections were separated by a 2 mm air gap.

The composite stack was mounted between fluid cooled heat sinks, a separate heater with construction and instrumentation similar to the main heater, and a layer of thermal insulation. Slight pressure was applied to the plates to ensure uniform contact. The composite stack was surrounded by an outer cylindrical shroud over the approximate length of the combined sample. The interspace and surroundings were filled with a dry thermal insulating powder of very low thermal conductivity.

Measurements were taken at successively increasing temperatures, from approximately 50C to 250C. Following this the apparatus was dismantled and the sample pieces reversed in position. The experiment was repeated for this condition (heat flow up).

RESULTS AND CONCLUSIONS

A summary of test results is shown in Figure 1, together with the curve of equivalent thermal conductivity as a function of temperature, as predicted by eq. (1).

The sharp increase in thermal conductivity at the higher temperature levels for the "heat flow up" mode was investigated. Natural convection activity was precluded, based on present theory. Increased emissivity, due to material oxidation, is a possible explanation, but available data appears not to support this conclusion.

Fig. 1 Thermal Conductivity as Function of Mean Temperature

The High Temperature Properties of Cobalt

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Introduction

Few experimental results have been reported for the thermal conductivity of cobalt and in particular no data are available between 500 and 1000 K. In the present paper we report the results of measurements of the thermal conductivity λ , electrical resistivity ρ , and absolute thermoelectric power S of pure cobalt between 90 and 1250 K.

Specimen and apparatus

The specimen was a 5N pure Co purchased from Metals Research Ltd., Cambridge, England. A mass spectrographic analysis after the experiment showed the following major impurities: C 70 ppm, Ni 60 ppm, Fe 16 ppm, K 10 ppm, Na 7 ppm, and Al 3 ppm.

The specimen was annealed 4 hours at 1500 K in vacuum (5×10^{-6} Torr) and slowly cooled to room temperature. The residual resistivity ratio measured before and after the experiment was 140 and 120 K, respectively. Its density was 8.831 g cm^{-3} at 293 K.

Two experimental systems were employed in the measurements, the low temperature one operating between 80 and 370 K and high temperature one between 300 and 1250 K. Both systems were adequately described in previous papers^(1,2,3) and satisfactorily intercompared with systems in other laboratories⁴.

The specimen, nominally 2 cm in diameter and 20 cm long was first mounted in the high temperature system and its transport properties were measured between 300 and 1250 K in several cycles. After the high temperature experiment, the specimen was cut up, part of it being machined into the low temperature specimen, nominally 1 cm in diameter and 10 cm long, and another into a specimen used for a x ray diffraction analysis at room temperature. The latter showed that the specimen was in the α (h.c.p.) phase; no detectable amount of the high temperature β (f.c.c.) phase was observed, the limit of detectability being estimated at about 0.5%.

Results

The results obtained in the high and low temperature systems showed some small discrepancies in the overlap temperature region (300 to 370 K): The values of ρ , λ , and S measured in the high temperature system differed by 0.5%, -1.5% and -0.8% from those obtained in the low temperature ones. The estimated maximum error of the results obtained with the high temperature system varied with temperature from ± 0.2 to 0.5% for ρ , and from ± 1.3 to 1.5% for λ . The errors for the low temperature system are, on the average, 0.2% for ρ , and 0.6% for λ . The results for S are probably accurate to 5%, the major part of the possible error being not experimental, but arising from the uncertainty of the absolute thermoelectric power of the "standard" (Pt for the high temperature system and Cu for the low temperature system).

Smoothed experimental results for ρ , λ , and S are shown in Table 1. Note that in this experiment the α - β transformation occurred at about 700.5 K on heating and between 700.8 and 690 K on cooling.

Table 1. Electrical resistivity ρ , thermal conductivity λ , absolute thermoelectric power S and Wiedemann-Franz ratio of cobalt.

T K	ρ $\mu\Omega\text{-cm}$	λ W/cmK	S $\mu\text{V/K}$	$\frac{\lambda\rho}{L_o T}$	$\frac{\lambda\rho/T+S^2}{L_o}$
90	0.744	1.764	-7.49	0.597	0.599
100	0.939	1.643	-8.43	0.631	0.634
125	1.461	1.454	-10.97	0.696	0.701
150	2.018	1.341	-13.77	0.738	0.746
200	3.214	1.193	-19.75	0.785	0.801
250	4.527	1.084	-25.54	0.804	0.830
300	5.995	0.989	-30.82	0.809	0.848
350	7.657	0.905	-35.37	0.811	0.862
400	9.542	0.831	-39.22	0.812	0.875
500	14.118	0.715	-44.84	0.826	0.908
600	19.872	0.627	-47.78	0.850	0.943
700(α)	26.590	0.569	-48.05	0.884	0.979
701(β)	25.015	0.614	-42.56	0.897	0.971
800	32.056	0.578	-41.82	0.948	1.019
900	40.377	0.542	-39.60	0.995	1.059
1000	49.562	0.511	-35.88	1.037	1.090
1100	59.259	0.488	-30.69	1.076	1.114
1200	69.116	0.471	-24.00	1.110	1.133
1250	73.995	0.464	-20.10	1.125	1.142

References

- (1) Matsumura, T. and Laubitz, M.J. Can. J. Phys. 48, 1499 (1970).
- (2) Laubitz, M.J. Can. J. Phys. 45, 3677 (1967).
- (3) Laubitz, M.J. Can. J. Phys. 47, 2633 (1969).
- (4) Laubitz, M.J. and McElroy, D.L. Metrologia 7, 1 (1971).

LATTICE CONDUCTIVITY AND LORENZ RATIO OF CHROMIUM

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INTRODUCTION

In metals it is difficult to determine reliably the lattice conductivity $\lambda_g = \lambda_u$ at temperatures where phonon-phonon coupling is important ($T > \theta/5$) [1,2]². The Leibfried-Schlömann model (L-S) gives $\lambda_u \approx 360 \text{ aA} \theta^3 / \gamma^2 T$ which is about twice the value measured for cubic materials where λ_g is accessible. Available data show that λ_g in metals is not very different in magnitude from that in insulators provided differences in Debye temperature θ and Grüneisen γ are taken into account, i.e. a crude allowance for differences in lattice spectrum including anharmonicity. For example our preliminary results on Pt alloys near 100 K indicate $\lambda_g \approx 20 \times 10^2 / T \text{ W m}^{-1} \text{ K}^{-1}$, which is roughly similar to values for Ag and for KCl, all of which have similar θ values.

λ_g is relatively more important in transition elements than noble metals because of smaller electronic conductivity λ_e , the result of increased electron scattering. In chromium we expect λ_g to reach about $\frac{1}{2} \lambda_e$ at 100-150 K and neglect of λ_g leads to an apparent Lorenz ratio $L = \rho \lambda / T$, which is most implausible. Goff [3] has sought to explain this in terms of band structure but a credible estimate of λ_g given below leads to $L_e = \rho \lambda_e / T = \rho (\lambda - \lambda_g) / T$ which behaves quite normally.

CALCULATION AND DISCUSSION

Either by halving the magnitude of λ_u from L-S or using Steigmeier's alternative expression which replaces γ^2 by $(\gamma + \frac{1}{2})^2$, $\lambda_u \approx 170 \times 10^2 / T$ for chromium. This assumes $\theta = 480 \text{ K}$ and $\gamma = 1.3$; γ is calculated from thermal expansion well above the Neel temperature so as to get a true value of anharmonicity away from misleading effect of magnetostriction. At $T < 50 \text{ K}$, phonon-electron scattering is dominant and may be estimated from the electrical resistivity to be $\lambda_E \approx 10^2 \times 10^{-4} T^2$. Earlier experiments [4] on chromium samples of differing purity also lead to this magnitude. We calculated $W_g = 1/\lambda_g = W_E + W_u$ from this with three trial values of W_u , viz. $T/17\,000$, $T/14\,000$ and $T/11\,000$. Using our earlier data on pure chromium [4] below 100 K and that from ORNL above 100 K, we then calculated $\lambda_e = \lambda - \lambda_g$ and $L_e = \rho \lambda_e / T$. Choice of $14\,000/T$ leads to values $L_e(T)$ which in terms of T/θ are very similar to that for the noble metals, asymptotically approaching $L_0 = 2.445 \times 10^{-8}$ for $T > \theta$ (Figure 1). This

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² Figures in brackets indicate the literature references at the end of this Abstract.

result agrees with ORNL curve-filling procedure [2] and confirms that there is no gross anomaly in L_e which needs to be explained by strong inelastic scattering effects.

Figure 1. Lorenz number for chromium using alternative corrections for lattice conductivity

Assuming this choice of λ_G is correct, corresponding values for λ_e lead to an 'ideal' resistivity W_i , different from uncorrected values [4]. Thus at 300 K, $W_i \approx W_\infty \approx 2.0$ and at low temperatures $W_i = 17 (T/\theta)^2 W_\infty$.

REFERENCES

- [1] White, G.K., Proc. Eighth Conf. Thermal Conductivity, p.37, Plenum 1969.
- [2] Williams, R.K. and Fulkerson, W., *ibid*, p.389.
- [3] Goff, J.F., Phys.Rev. B1, 1351 (1970); *ibid.* B2, 3606 (1970).
- [4] Harper, A.F.A., Kemp, W.R.G., Klemens, P.G., Tainsh, R.J., and White, G.K., Phil.Mag. 2, 577 (1957); also Klemens, P.G., private communication.

The Thermal and Electrical Conductivity of Sodium
from 40 K to 360 K

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The thermal and electrical conductivity of three samples of sodium have been measured from 40 to 360 K. The apparatus and experimental procedure have been described in last year's thermal conductivity conference, together with some preliminary data. We now present our final data in smoothed form below. It is apparent that the thermal conductivity shows a minimum near 70 K, and that the Wiedemann-Franz ratio even at temperatures near 2θ is some 8% below unity. These two features may be explained by relatively strong inelastic electron-phonon and electron-electron interactions.

T	ρ_i	κ_i	L_i/L_o	T/ θ
40	0.1768	179.4	0.3246	0.262
50	0.3163	147.6	0.3822	0.328
60	0.4729	143.1	0.4616	0.393
70	0.6374	142.4	0.5306	0.459
80	0.8055	144.1	0.5938	0.525
100	1.145	147.2	0.6899	0.656
120	1.486	149.1	0.7558	0.787
140	1.830	150.1	0.8030	0.918
160	2.176	150.2	0.8360	1.049
180	2.529	149.9	0.8622	1.180
200	2.892	149.0	0.8820	1.311
240	3.652	146.0	0.9092	1.574
280	4.470	140.5	0.9178	1.836
320	5.360	134.0	0.9191	2.098
360	6.354	127.7	0.9223	2.361

The table gives the smoothed Na data: the temperature T(K), the ideal electrical resistivity ρ_i ($10^{-8}\Omega\text{m}$), the ideal thermal conductivity κ_i (W/MK), the reduced Wiedemann-Franz ratio

$$L_i/L_o = \kappa_i \rho_i / L_o T$$

and the reduced temperature T/ θ , with $\theta = 152.5$ K. The effect of the residual electrical resistivity ρ_o has been removed from both ρ and κ ; a lattice conductivity of $2.37/T$ has been subtracted from κ , and both ρ and κ have been corrected for thermal expansion of the sample geometry.

TUESDAY
p.m.

CONCLUSION

While certain liquids will probably for a long time remain to depend on direct measurements, the most urgent need exists for development of dependable predictive methods, covering at least similar liquid groups. The importance of predictive equations lies mainly in their use in computer programs, where reiterative loops require continuous updating of the values as function of the changing temperatures and mixture composition. This will require a massive new systematic data acquisition program which does not appear to be in sight.

Figure 1. Comparison of Measured and Predicted Values for Typical Industrial Liquids

REFERENCES

- [1] Grassmann, P., Straumann, W. and Jobst, W., "Progress in International Research on Thermodynamic and Transport Properties," ASME, Academic Press, New York, 1962
- [2] Weber, H. F., Weidemann's Ann. Phys. Chem. 10, 103 (1880)
- [3] Scheffey, W. J., "Thermal Conduction in Liquids," Project Squid Tech. Rept. PR-85-R, Princeton U, Princeton, N. J., Oct. 1958
- [4] Scheffey, W. J. and Johnson, E. F., J. Chem. Eng. Data 6, 245 (1961)
- [5] "AIChE Physical Property Estimation System, General Descriptive Manual," Arthur D. Little, Inc., Cambridge, Sept. 1965
- [6] Robbins, L. A. and Kingree, C. L., Proc. Am. Petrol. Inst. III, No. 42, 52 (1962)
- [7] Pachaiyappan, V., Ibrahim, S. H. and Kuloor, N. R., Chem. Engr., 74, No. 4, 150 (1967)
- [8] Standards of Tubular Exchanger Manufacturers Association, Tubular Exchanger Manufacturers Association, Inc., Fifth Ed. New York, 1968
- [9] Technical Data Book, Division of Refining, America Petroleum Institute (API), New York, 1966

FLUID THERMAL CONDUCTIVITY MEASUREMENT FACILITY USING A TRANSIENT HOT-WIRE TECHNIQUE

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INTRODUCTION

A computerized measurement facility utilizing an absolute transient hot-wire technique has been developed for fluid thermal conductivity determinations. The reliability of the apparatus has been established by radiation free measurements on toluene over its entire liquid range at atmospheric pressure. The versatility of the apparatus has been demonstrated by measurements on liquid and dense gaseous methane over wide ranges of pressure and temperature.

APPARATUS

The measurement facility utilizes an absolute transient hot-wire conductivity cell, made of an electrically heated fine platinum wire of 0.001" diameter immersed vertically in the fluid under consideration which is contained in a high pressure bomb. The high pressure system and the thermostat cover pressures from atmospheric to 700 bars and temperatures from 100 to 400°K. The detailed description of the facility and the measurement technique is given in [1]¹.

The apparatus to a first approximation simulates the behaviour of an infinite line source of constant heat generation in an extended medium. The response of the wire is monitored using a digital voltmeter under command from a digital computer at a rate of 40 readings per second. The computer is programmed to process the data immediately to provide readily the thermal conductivity results which are printed out on a teletype in a convenient format. By taking measurements at short times, 0.1 to 0.5 seconds, and subsequently extrapolating the result to zero time, errors caused by convection and radiation have been eliminated or greatly reduced. Additional reliability is obtained by statistically analyzing the digital data with the computer in the system.

RESULTS AND CONCLUSIONS

Measurements were carried out on toluene over its entire liquid range at atmospheric pressure. Although the liquid thermal conductivity, λ , exhibits a linear relationship with temperature in the range from -25 to 110°C, a substantial prefreezing anomaly [2] was observed below -25°C. Convection-free results were ensured by measurements at various power levels and time-lags. The consistency of these measurements corrected

¹Figures in brackets indicate the literature references at the end of this Abstract.

to 25°C was better than $\pm 0.5\%$ as indicated in the following figure.

Agreement with the "radiation-corrected" steady state measurements of Poltz [3] is within $\pm 0.5\%$.

Measurements were also performed on the liquid and dense gaseous methane in the temperature and pressure ranges mentioned above. The results are given in [1]. An enhancement of λ was observed as the temperature and density approach their critical values. A pre-freezing anomaly is suspected at low temperatures and higher densities in the vicinity of the triple point.

ACKNOWLEDGMENTS

This work was performed with the support of the National Research Council of Canada under Grant Number A-2788.

REFERENCES

- [1] Mani, N., Precise Determination of the Thermal Conductivity of Fluids Using Absolute Transient Hot-Wire Technique, Unpublished Ph.D. Thesis, Dept. of Mech. Engg., The University of Calgary (1971).
- [2] Venart, J. E. S. and Mani, N., Thermal Conductivity, Anomaly in Temperature Dependence for Liquids, *Cand. J. of Chem.*, 49, 2468 (1971).
- [3] Poltz, H. and Jugel, R., The Thermal Conductivity of Liquids - IV. Temperature Dependence of Thermal Conductivity, *Int. J. Heat Mass Transfer*, 10, 1975 (1967).

✓ THE THERMAL CONDUCTIVITY AND LORENZ NUMBER
OF A LIQUID INDIUM-GALLIUM ALLOY

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INTRODUCTION

Although measurements of the thermal conductivity, and hence of the Lorenz number L , of liquid metals are very inconsistent [1,2]², there is growing evidence [3,4,5] that for some liquid metals, especially in Groups III-V, L falls steadily away from the expected Sommerfeld value, L_0 , as temperature increases. This is surprising because these metals are free-electron-like in many of their solid properties, and simple theory suggests that they should behave similarly when liquid with $L = L_0$ at all temperatures.

My recent measurements on liquid In and Ga [5] show different deviations of L from L_0 at high temperatures (fig. 1). For Ga, L falls 16% below L_0 on melting and does not change with increasing temperature; for In, L rises sharply above L_0 by 12% on melting and then falls to 20% below L_0 as T increases to 845 K.

Figure 1. Lorenz Number

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² Figures in brackets indicate the literature references at the end of this Abstract.

The thermal conductivity of an approximately equiatomic In-Ga alloy has now been measured between 390 and 550 K with a maximum inaccuracy of 5%, using a guarded axial-flow apparatus with the alloy contained in an annular stainless-steel cell [5]. The electrical resistivity of the alloy was also measured with an inaccuracy of $\pm 1\%$ with an AC bridge and checked with a Mueller bridge.

RESULTS AND DISCUSSION

The temperature variation of L for the alloy is shown in figure 1: it is greater than L_0 at 390 K but has dropped to 18% below L_0 by about 550 K. Its behaviour is similar to, but more pronounced than, that of pure indium.

This high temperature behaviour of L for many group III-V metals contrasts with the situation in monovalent metals such as Na or K, for which $L \approx L_0$. It suggests that inelastic scattering of some sort must occur, due perhaps to electron-electron interaction or thermal broadening of the Fermi surface. An attempt by Rice [6] to develop a theory to describe this deviation quantitatively has not been successful.

It is hoped that measurements similar to those reported here will be made on other liquid metals and alloys and will show more clearly the factors determining the behaviour of L , so leading to a better understanding of this phenomenon.

ACKNOWLEDGMENTS

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REFERENCES

- [1] Powell, R.W., Ho, C.Y. and Liley, P.E., Thermal Conductivity of Selected Materials, NSRDS-NBS 8 (Washington: U.S. Govt Printing Office) 1966.
- [2] Ho, C.Y., Powell, R.W. and Liley, P.E., Thermal Conductivity of Selected Materials, Part 2, NSRDS-NBS 16 (Washington: U.S. Govt Printing Office) 1968.
- [3] Filippov, L.P., Int. J. Heat Mass Transfer 11, 331 (1968).
- [4] Yurchak, R.P. and Filippov, L.P., High Temp. 2, 628 (1964).
- [5] Duggin, M.J., Phys. Letters 29A, 470 (1969).
- [6] Rice, M.J., Phys. Rev. B2, 4800 (1970).

HEAT PULSE TECHNIQUE FOR MEASUREMENTS OF THERMAL DIFFUSIVITY OF MERCURY

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INTRODUCTION

The heat pulse technique for the measurement of thermal diffusivity reported by Parker et al [1] has been widely used on single-layer solid specimens, with great advantages of simplicity and reasonable accuracy. To apply this technique to measurements on a liquid or molten specimen contained in a cell with a transparent window for transmitting a heat pulse from an optical flash, it is found necessary in our work to solve the three-layer thermal diffusion problem. This arises because the layers of window and cell material, even though of poor thermal conductivity compared with the specimen, modify the transmitted temperature pulse to a considerable extent, and makes it inaccurate to treat this as a simple one-layer problem. The three-layer problem is solved analytically by Laplace transforms and the calculus of residues, and the solutions are specialised to the two- and one-layer cases for comparison.

figure 1
Transmitted Temperature Pulse

EXPERIMENT

Measurements from 150°K to 280°K are made on a 2 mm layer of mercury in an ebonite cell (of thermal diffusivity $\alpha = 10^{-7} \text{ m}^2 \text{ s}^{-1}$, and thickness 4.2 mm) with a glass window ($\alpha = 2.4 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$, and thickness 0.2 mm). The cell is secured to a cold finger inside a cryostat, with its temperature controlled to within a hundredth of a degree for periods of several minutes, and to within a millidegree for shorter periods — sufficient for our purpose since each measurement requires only about half a second. The transmitted temperature pulse is measured by a copper-constantan thermocouple embedded in the mercury-ebonite interface, and after low noise amplification stages, is displayed and photographed on an oscilloscope.

figure 2
Thermal Diffusivity of Mercury

RESULTS AND CONCLUSIONS

Computations from the one-, two- and three-layer solutions are shown in figure 1, from which it is seen that neglecting corrections for the effect of the window and the cell would incur errors of about 15% and 1% respectively. Figure 2 shows the uncorrected values of the thermal diffusivity of mercury deduced from experimental data by assuming a one-layer situation. These are compared with TPRC values deduced from selected data of thermal conductivity, specific heat and density. When corrections from the three-layer solution are applied to the measured values, the agreement is even better.

REFERENCES

- [1] Parker, W.J. et al, Flash Method of determining thermal diffusivity, heat capacity, and thermal conductivity, J. Appl. Phys. 32, 1679 (1961)

THERMAL CONTACT CONDUCTANCE -
GRAPHICAL AIDS FOR COMPUTATION *

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INTRODUCTION

Resistance to heat flow across contacting surfaces is termed as 'Thermal Contact Resistance'(TCR). If the radiation and convection modes of heat transfer are neglected, the inverse of TCR is the Thermal Contact Conductance (TCC).

A set of nomograms to determine the TCC of metallic contacts is proposed in this presentation. These facilitate quick estimates of TCC for single spherical wavy, and/or rough surfaces in contact. Values of surface parameters like the r.m.s. roughness, mean average slope of asperities, curvature of the waviness, and certain other standard properties of the contacting members and materials are required for making such estimates of TCC. The complete calculation can be expected using only the nomograms and a slide-rule, without recourse to any 'tables of values' or high speed computation facilities.

GENERAL APPROACH

The development of the charts is based on a modification of the available prediction theories [1,2]. The modification involves a correction for the estimated contact area in view of a phenomenological consideration of the following aspects:

- a) Mismatch of the asperities at the onset of contact.
- b) Instantaneous plastic yielding of the initial contacts asperities.
- c) Work hardening of the crushed asperities at later stages of contact.

* Work undertaken with the support of the Defence Research Board of Canada under Grant Number DRB 9535-39.

The effects of these phenomenae are incorporated in the empirically designed Nomograms by the adoption of two correction parameters, x and β .

The work hardening effect is estimated by x , the percentage reduction of contact area ratio with respect to the calculated one--at later stages of contact. This parameter is suggested to be a function of the mean separation distance, between the contacting surfaces, the estimated number of contact spots, and the work hardening characteristics of the materials.

Mismatch of asperities, and instantaneous plastic yielding effects, are estimated by β ; the percentage reduction of the mean separation distance w.r.t. the calculated one--at the onset of contact. This parameter is suggested to be a function of surface properties like R.M.S. roughness, Mean average slope, Autocorrelation distance, curvature of waviness, Hardness of the materials, and the coefficient of friction for the contacting surface asperities.

Estimation of x and β , is presently made using known values of TCC for the contact at two (moderate) contact pressures. The value for x has been empirically set at 20% in the nomograms.

Experimental work aimed at providing data based on which empirical relations for x and β may be derived, is presently being undertaken.

A computer program has also been formulated, which serves as an alternative to the Nomogram approach.

ACKNOWLEDGEMENTS

This work has been undertaken with the support of the Defence Research Board of Canada, under Grant Number DRB-9535-39.

REFERENCES

- [1] Yip, F. K. C., "Thermal Contact-Resistance", Ph.D. Thesis, Dept. of Mechanical Engineering, University of Calgary, 1969.
- [2] Mikic, B. B. and Rohsenov, W. M., "Thermal Contact Resistance", Report 4542-41, Contract No. NGR-22-009-D65, MIT, Sept. 1966.

THERMAL CONTACT CONDUCTANCE WITH SEVERAL INTERSTITIAL MATERIALS

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INTRODUCTION

The measurement and prediction of thermal contact conductance has received considerable attention in recent years. However, only a very limited amount of data on contact conductance with interstitial fillers are tabulated for ready use [1] [2]. The use of filler materials has the advantage of less sensitivity to loads and surface conditions and can serve to increase or decrease the thermal conductance of the junction. Results are reported on the thermal effect of several interstitial materials between metal specimens. Sets of cylindrical metal specimens of 6061-T6 aluminum, 2024-T4 aluminum, and 304 stainless steel were axially aligned and hydraulically loaded. Contact fillers were 20, 30, 40, and 50 mesh stainless steel screens, aluminum foil, 20 pound bond paper, and two silicone dielectric greases (heat sink compounds). All tests were conducted in air at atmospheric pressure. Apparent contact pressures ranged from 0.6 to 4.0 MN/m².

APPARATUS

The apparatus used for these tests is shown schematically in Figure 1. Test

Figure 1. Schematic of Experimental Apparatus

cylinders were 10.16 cm (4 in.) long and 2.54 cm (1 in.) in diameter. Four holes 1.77 cm deep were drilled in each specimen just large enough to accommodate 28-gauge copper-constantan thermocouples. Thermocouple leads were wrapped around the specimens and secured with epoxy. The interface

Figure 2. Experimental Results

surfaces were lathe cut, nominally flat, with surface roughness ranging from 5 to 35 μ in., rms. Surfaces were refined and cleaned with butyl alcohol prior to each series of tests. Glass wool (2.54 cm thick) was wrapped around the test column to minimize radial heat loss. Eight thermocouples were used to determine the radial heat flow.

RESULTS

The experimental results of these tests are presented as Figure 2. The dielectric greases, aluminum foil, and bond paper were tested between the 6061-T6 aluminum specimens. Results of bare interface tests with this alloy are shown and are about 20 percent lower than reported by Bloom [3]. The interstitial screens were 304 stainless steel of mesh 20, 30, 40, and 50 strands/inch and wire diameter of 0.01 inch. The screens were tested between both 2024-T4 aluminum and 304 stainless steel specimens. As can be seen from Figure 2, interstitial materials may significantly either increase or decrease the interface conductance over that of the base interface depending on the thermal characteristics of these interstitial materials. For interstitial screens, the thermal conductance increases with increasing mesh size and corresponding increase in the number of contact regions.

REFERENCES

- [1] Fletcher, L. S., Smuda, P. A., and Gyorog, D. A., Thermal Contact Resistance of Selected Low Conductance Interstitial Materials, AIAA Paper No. 63-31, 1968.
- [2] Anon, General Electric Heat Transfer and Fluid Flow Data Book, 1970.
- [3] Bloom, M. F., Thermal Contact Conductance in Vacuum Environment, Douglas Aircraft Co. Report SM-47700, December 13, 1964.

THERMAL CONTACT CONDUCTANCE OF LUBRICANT FILMS

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INTRODUCTION

Throughout the ages, one of man's most persistent problems has centered around the reduction and control of friction, and wear and heat. A lubricant film must be able to effectively dissipate the heat produced by friction. Little information has been generated on the thermal properties of lubricants. For this investigation, twelve series of tests were performed to evaluate the effect of apparent contact pressure and interface temperature level on the thermal conductance of four lubricants and the corresponding bare interfaces.

APPARATUS AND TEST PROCEDURE

A schematic of the test apparatus is shown as Figure 1. The test speci-

Figure 1. Schematic of Thermal Conductance Apparatus

mens were 10.16 cm (4 in.) long, 2.54 cm (1 in.) diameter cylinders of 304 stainless steel with the interfaces turned on a lathe. Each cylinder contained four thermocouples along the longitudinal axis at the center of the cylinder. The thermocouple holes were filled with a high thermal conductivity silicone heat sink compound. The thermocouple leads were wrapped around the test cylinders several times to minimize conduction error. A radiation shield was used to minimize radiation losses. In preliminary runs, a commercial heat meter was used to check the heat flows determined from the thermocouple readings and the thermal conductivity of the specimens. Agreement was always within five percent. Test runs were performed at two interface temperature levels, 38°C and 93° C; with ten of the twelve tests conducted in a vacuum environment of 0.5 mm Hg. Bare interface tests were also performed in air at atmospheric pressure.

RESULTS

The four lubricants tested were: a silicone spray lubricant, Molykote G grease, a lithium grease, and graphite grease. The test cylinders of 304 stainless steel were cleaned with alcohol and acetone between runs. The test cylinders had a surface roughness of 15-20 microinches rms. Figure 2 presents the results. The bare interface results are in agreement with

Figure 2. Thermal Conductance of Selected Lubricants

those of Brunot and Buckland [1], Fried [2], and Hargadon [3]. The thermal conductances of the four lubricants ranged from 1.6 to 15 $\text{kW m}^{-2}\text{C}^{-1}$ over the pressure range from .3 to 3 MN/m^2 . The maximum estimated errors in the thermal conductance measurements are 30 percent for the low temperature runs and 10 percent for the higher temperature tests.

REFERENCES

- [1] Brunot, A. W. and Buckland, F. F., Thermal Contact Resistance of Laminated and Machined Joints, Trans., ASME, Vol. 71, 1949.
- [2] Fried, E., Study of Thermal Contact Conductance, Final Report, NASA (M-RP-T), General Electric Document No. 64SD652, May 1, 1964.
- [3] Hargadon, J. M., Jr., Thermal Interface Conductance of Thermoelectric Generator Hardware, ASME Paper No. 66-WA/NE-2, 1966.

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THE HEAT PIPE AT LOS ALAMOS*

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INTRODUCTION

This presentation summarizes the findings of heat-pipe investigations at Los Alamos. A preface to the presentation and a list of pertinent references are given in this abstract.

MANNER OF OPERATION

A heat pipe achieves significant heat transfer by employing capillary forces to move the working fluid in a two-phase flow system. Although the size and shape of the system are rather arbitrary, its operation is best described in terms of a simple cylindrical structure consisting of a sealed tube with its interior lined with a thin wick network. The wick contains the liquid phase of the fluid and the remaining space contains the vapor phase. Each phase has a distinct flow path, and the paths have a common liquid-vapor interface which allows them to communicate in all parts of the system. When part of the system is heated and another part cooled, a countercurrent two-phase flow cycle is established, with mass addition and mass extraction. Evaporation and condensation occur wherever the liquid-vapor interface exists, but there is a net rate of evaporation in the heated section. The excess vapor flows to the cooled section where it condenses on the wick and releases its latent heat of evaporation. The heat is removed by conduction through the saturated wick and container wall to the cooling environment. The condensate is drawn into the wick and returned to the heated section to complete the flow cycle.

HEAT-TRANSFER LIMITATIONS

Because of its flow cycle, a heat pipe behaves like a structure of very high thermal conductance, but it possesses heat-transfer limitations imposed by sonic vapor flow, liquid entrainment, wicking ability, and boiling in the saturated wick. Also, it can possess chemical limitations, particularly when impurities are present in the system. If the volatility of the impurity is low, it can collect in the heated section and clog or corrode the wick, or change the properties of the working fluid. If its volatility is high, it can collect in the cooled section and reduce the area available for heat removal. The fundamental principles governing the physical and chemical limitations of heat pipes are discussed in the presentation, and methods are given for applying these principles to improve heat-pipe performance.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

REFERENCES

1. G. M. Grover, T. P. Cotter, and G. F. Erickson, "Structures of Very High Thermal Conductance," J. Appl. Phys. 35, 1990 (1964).
2. J. E. Deverall and J. E. Kemme, "High Thermal Conductance Devices Utilizing the Boiling of Lithium and Silver," Report LA-3211, Los Alamos Scientific Laboratory, 1965.
3. T. P. Cotter, "Theory of Heat Pipes," Report LA-3246-MS, 1965.
4. W. A. Ranken and J. E. Kemme, "Survey of Los Alamos and EURATOM Heat Pipe Investigations," IEEE Thermionic Conversion Specialist Conference, San Diego, 1965.
5. J. E. Kemme, "Heat Pipe Capability Experiments," Report LA-3585-MS, 1966.
6. J. E. Deverall and E. W. Salmi, "Orbital Heat Pipe Experiment," Report LA-3714, 1967.
7. T. P. Cotter, "Heat Pipe Startup Dynamics," IEEE Thermionic Conversion Specialist Conference, Palo Alto, 1967.
8. J. E. Kemme, "High Performance Heat Pipes," IEEE Thermionic Conversion Specialist Conference, Palo Alto, 1967.
9. J. E. Deverall, "The Effect of Vibration on Heat Pipe Performance," Report LA-3798, 1967.
10. J. E. Deverall, "Total Hemispherical Emissivity Measurements by the Heat Pipe Method," Report LA-3834-MS, April, 1968.
11. J. E. Kemme, "Ultimate Heat Pipe Performance," IEEE Transactions on Electron Devices, Vol. ED-16, No. 8, August, 1969.
12. J. E. Deverall, "Mercury as a Heat Pipe Fluid," Report LA-4300-MS, 1969.
13. J. E. Deverall, J. E. Kemme, and L. W. Florschuetz, "Sonic Limitations and Startup Problems of Heat Pipes," Report LA-4518, 1970.

Copies of these references can be obtained by writing to the authors at LASL.

A THERMAL CONDUCTIVITY APPARATUS EMPLOYING HEAT PIPES

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INTRODUCTION

Assemblies for the "rapid" determination of thermal conductivities in the ranges 10^{-3} to 10^{-7} W cm $^{-1}$ K $^{-1}$ and employing a minimum of control apparatus have been fabricated using heat pipes. The hot sides of existing and proposed versions have, at 900°C for example, spatial and temporal temperature gradients of less than 1°C cm $^{-1}$ and 1°C h $^{-1}$ respectively. These values are derived from the ability of an inert gas buffer to minimise pressure, and hence temperature, fluctuations of the working fluid in a heat pipe. A specific apparatus with such a gas-controlled isothermal chamber on the hot side and employing similar principles both for the maintenance of the cold-side temperature and the heat flux measurement, is described.

APPARATUS

A schematic of an existing apparatus, designed to operate with hot-side temperatures between 700°C and 1000°C and cold-side temperatures of 50°C to 250°C, is shown below.

Operation of the apparatus is effected by setting the pressure of the inert gas in the buffer space at a value corresponding to the vapour pressure of the working fluid (liquid sodium) at the desired hot side temperature.

The chamber C is then heated electrically until the sodium boils and the inert gas thus displaced from the chamber into the moving front section where an interface (heat front) between inert gas and sodium vapour develops. At this point, chamber C becomes virtually isothermal and any fluctuation or excess in the heat input is accommodated by such movement of the heat front in the moving front section, that is necessary to increase or reduce the heat dissipation area.

Heat passing through the insulation sample to the cold-side, which in this case consists of a baseplate and two coaxial cylinders forming vessels A and B, causes a suitable liquid in these vessels to boil. Vapour from the inner vessel A is condensed and collected and the heat flux thus determined from the measured boil-off rate. The equivalence of the boiling temperature of outer and inner vessel liquids permits the outer vessel B to be employed as a cold-side guard ring for the experimental sample.

Although small temperature gradients can occur in the baseplate as a consequence of differences in the baseplate-liquid heat transfer rates into vessels A and B; radial heat transfer between vessels via the baseplate can be eliminated by a correct design, as is indicated in the figure.

RESULTS AND CONCLUSIONS

By the correct choice of cold-side fluids, heat fluxes of 10^{-2} to 10 W cm^{-2} can be measured between two predetermined temperatures. In this way the thermal conductivities of both fibrous and multiple foil insulations have been obtained under various conditions and with a satisfactory degree of reproducibility.

Some limitations of the apparatus as well as its advantages are discussed, as are other possible applications of gas-controlled heat pipes in thermal conductivity assemblies.

A GUARDED-LONGITUDINAL-HEAT-FLOW TECHNIQUE FOR MEASUREMENT OF THERMAL
CONDUCTIVITY, ELECTRICAL RESISTIVITY, AND SEEBECK COEFFICIENT
BETWEEN 300 AND 1000 K*

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A guarded-longitudinal-heat-flow technique for measuring thermal conductivity (λ), electrical resistivity (ρ), and Seebeck coefficient on small (1×7 cm) cylindrical rods between 300 and 1000 K is described in detail. The technique was developed for studies of neutron irradiation effects on the thermal conductivity of graphites, and this imposed some design restrictions. We attempted to design specimen and guard heaters which would be isothermal and could be matched in temperature to minimize radial heat exchange in the heater regions. Small corrections were then made for radial heat exchange due to temperature mismatch between the specimen and guard cylinder.

An error analysis indicates a most probable determinate uncertainty in λ of $\pm 1.6\%$. Indeterminate errors are considered small on the basis of auxiliary tests and measurements on an Armco-iron standard. The ρ of our standard was measured and used to calculate λ following a procedure suggested by Fulkerson et al. [1], which should generate λ correct to within $\pm 1.5\%$. The λ of the standard was verified by λ measurements from 80 to 400 K in a low-temperature guarded-longitudinal apparatus [2] which has an uncertainty of $\pm 1.2\%$. Since the two approaches agree to within $\pm 0.2\%$ over the temperature range of overlap, we feel that the λ of our standard specimen is known to well within $\pm 1.5\%$. Data obtained using the high-temperature guarded-longitudinal apparatus agreed with the standard values to within the most probable uncertainty, except above 900 K where the values were too high by about 3%. The results were within $\pm 0.4\%$ of a smooth curve, indicating the technique precision.

*Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

REFERENCES

- [1] W. Fulkerson, J. P. Moore, and D. L. McElroy, J. Appl. Phys. 37(7), 2639-2653 (1966).
- [2] Called ORNL 2 by M. J. Laubitz and D. L. McElroy, "Precise Measurements of Thermal Conductivity at High Temperatures (100-1200 K)," Metrologia 7(1), 1-15 (1971).

THE ADVANTAGES OF SIMULTANEOUS MEASUREMENT OF THERMAL CONDUCTIVITY AND THERMOELECTRIC POWER

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INTRODUCTION

While simultaneous electrical and thermal conductivity measurement has become a standard analytical tool, simultaneous thermoelectric power measurement as well is unusual in spite of minimal additions required to apparatus. This may be due to an undervaluation of thermoelectric power as a means of examining electron and phonon scattering mechanisms. This paper outlines links between current thermoelectric power and thermal conductivity work.

SURVEY

Most recent development in such use of thermoelectric power (S) is surveyed elsewhere [1]². Assuming S to be due to electron diffusion we have

$$S_d = \frac{\pi^2 k^2 T}{3e} \frac{\partial}{\partial E} (\ln \sigma)_{E_F} = \frac{\pi^2 k^2 T}{3e} \left[\frac{\partial (\ln p)}{\partial (\ln E)} + \frac{\partial (\ln A)}{\partial (\ln E)} \right]_{E_F} \quad (1a, b)$$

where derivatives are evaluated at the Fermi energy E_F , σ is the electrical conductivity, p the electronic mean free path and A the effective area of the Fermi surface. If the Fermi surface contacts the zone boundary the derivative of A can change sign, possibly changing the sign of S_d . At temperatures $\sim 0.1 \theta_D$ phonon-drag peaks may also change the sign of S if the large momentum reversal of an electron-phonon Umklapp process is present. U-processes become increasingly frozen out at low temperatures, explaining anomalies in λ for cadmium [2]. Only a fraction α of phonons contribute to phonon-drag, where $\alpha \sim W_{ge}/W_g$, (W_{ge} being the electron-scatter component of the total lattice thermal resistivity W_g); this relation can aid qualitative interpretation of phonon drag peaks in S [1].

For alloys the Nordheim-Gorter rule applies:-

$$S_d = \frac{\rho_1 S_1}{\rho_1 + \rho_2} + \frac{\rho_2 S_2}{\rho_1 + \rho_2} \quad (2)$$

suffices 1 and 2 indicating values for solvent and solute; ρ is the electrical resistivity. The resultant S_d is thus extremely sensitive to the relative amount of impurity present, in contrast to λ and σ which depend on the absolute impurity content. This is particularly useful with transition-metal impurities.

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²Figures in brackets indicate the literature references at the end of this Abstract.

Derivation of eq. (2) assumes Matthiessen's rule and the Wiedemann-Franz law; the effect on S of deviations from these is thus of interest, e.g. an electron-phonon contribution to ρ for an impure metal resulted in a deviation from Matthiessen's rule dependent on the ratio of S for the impure and pure metals [3]. The phonon-drag peak is usually reduced on alloying - one unusually small effect being explained by an unusually large W_{ge} indicating weak phonon-impurity scattering [4].

For transition and semi-metals with 2 groups of carriers a and b , a two-band expression applies [1]; a similar model involving S_a and S_b and Klemens' "method of moments" [5] explained the high Lorenz function L for chromium [6], while a 2-band spin-mixing model was used to interpret λ and S of nickel alloys [4]. Anomalies in L and S for transition metals can be due to a high value of $\partial[\ln N_d(E)]/\partial[\ln E]$, where $N_d(E)$ is the d-band density of states close to E_F . This derivative replaces $\partial(\ln p)/\partial(\ln E)$ in eq. (1b) and can determine S if s-d scattering is dominant. The resulting deviation [5] of L from the Sommerfeld value L_0 involves S^2 ; simultaneous measurement of σ , λ and S thus permitted analysis of conduction contributions in Ni_3Fe [7]. All three quantities appear in an analysis of phonon- and electron-electron-induced s-d transitions in transition metals [8].

Magnetic ordering and magnon effects both affect λ and S ; measurement of S might usefully augment recent work on the transport properties of Ag-Mn alloys [9].

REFERENCES

- [1] Powell, R.F., Recent Developments in the Use of The Thermoelectric Power of Metals and Alloys as a Research Tool, Contemporary Physics (to be published).
- [2] Bogaard, R. and Gerritsen, A.N., Thermal Conductivity of Cadmium and Cadmium-alloy crystals, Phys. Rev. B. 3 1808 (1971)
- [3] Rice, M.J. and Bunce, O. Anomalous Electron-phonon Resistivity of Metals containing Magnetic Impurities, Jnl. App. Phys. 41 1009 (1970)
- [4] Farrell, T. and Greig, D., The Thermoelectric Power of Nickel and Its Alloys, Jnl. Phys. C 3 138 (1970).
- [5] Klemens, P.G., Thermal Conductivity, Ed. R.P. Tye, Vol. I, 1969, Chapter 1.
- [6] Goff, J.F., Lorenz Number of Chromium, Phys. Rev. B. 1 1351 (1970).
- [7] Moore, J.P., Kollie, T.G., Graves, R.S., and McElroy, D.L., Thermal Transport Properties of Ordered and Disordered Ni_3Fe , Jnl. App. Phys. 42 3114 (1971).
- [8] Colquitt, L., Fankhauser, H.R., and Blatt, F.J., Effect of Phonon- and Electron-Electron-Induced s-d Transitions on the Thermopower of Transition Metals, Phys. Rev. B. 4 292 (1971)
- [9] Jhe, D., and Jericho, M.H., Low Temperature Transport Properties of Dilute Silver-Manganese Alloys, Phys. Rev. B. 3 147 (1971)

HEAT TRANSMISSION IN THERMAL INSULATIONS AT CRYOGENIC TEMPERATURES USING THE GUARDED HOT PLATE METHOD

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In the past great attention has been paid to the evaluation of heat transmission in thermal insulation materials used for the many specialised applications of aerospace. In general the results have been for the overall heat transmission factor based upon fixed hot and cold plates with a relatively large temperature difference across the material or system involved.

Recently, however, there has been a steady increase in the development of cryogenic bulk storage and transport facilities, particularly for liquid natural and other gases. For these applications the type and size of the facility is such that exotic forms of evacuated insulation are uneconomic or impractical. For the large thicknesses incorporated in the designs the thermal conductivity must be known over the whole temperature range and to be most meaningful the data should be obtained using small temperature differences.

Five commercially available material types have been evaluated by the guarded hot plate method according to ASTM C177 [1]² with current revisions. These include

- (i) a foamed glass having a density of 13.5 kg m^{-3} ,
- (ii) two different aged urethane foams having densities of 26.4 and 32 kg m^{-3} respectively,
- (iii) four different aged p.v.c. foams, two containing CO_2 having densities of 56.6 and 56.3 kg m^{-3} , one an open cell, the other a closed cell material and two containing the fluorocarbon refrigerant gas having densities of 30.9 and 54.8 kg m^{-3} , both essentially closed cell,
- (iv) a flexible glass fibre blanket having a density of 183.5 kg m^{-3} at 25.4 mm thickness,
- (v) three grades of exfoliated vermiculite having densities of 102.7 , 111.5 and 129.5 kg m^{-3} respectively.

The apparatus used was a model of the Dynatech TCFGM 200 mm diameter series guarded hot plate with heat flowing vertically. All measurements were made in an environment of dry nitrogen gas. Pre-dried Sant-o-cal powder was used as the insulation material packed into the interspaces and surrounds of the sample and cooled shroud. Liquid nitrogen was used as the fluid coolant with overall mean temperatures in the range 100 to 270K and water for measurements above 280K . Temperature differences were kept to the order of 30K and were never more than 60K or less than 15K across the approximate 25.4 mm thick samples. In all cases the temperature variations across individual plate surfaces were well within 0.3K and the system was monitored regularly for several hours to ensure that true equilibrium had been attained.

The results for the rigid cellular materials are shown in figure 1 and for the other materials in figure 2 which also contains two curves from figure 1 for reference.

For any one of the foams individual data points are within $\pm 2.5\%$ of the curve drawn through them. The urethanes behave identically and within experimental limits it is not possible to

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² Numbers refer to references listed at end.

differentiate between them. A clearly defined inflection is apparent in the range 240 to 260K and this is typical behaviour for foams containing a fluorocarbon and in the temperature range where the conductivity of the gas becomes pressure dependent [2]. Haskins and Hertz [3] present data for some urethane foams and, while the materials are not comparable, the present data are within the range of values obtained by them. However, they do not report any inflection in the curve, although the shape of their temperature dependence changes at about 230K. Closer examination of their data points would indicate that an inflection could exist.

The p.v.c. foams are significantly higher than the urethane counterparts at 300K but below 230K they are some 10 to 20% lower. At cryogenic temperatures, for the closed cell systems, the data are very similar, indicating that for the aged materials the effect of the gas is not significant. The higher density fluorocarbon containing foam again shows an inflection, whereas the lower density one does not. This can be explained qualitatively by assuming that the gas diffuses much faster from the latter material.

For the other materials, they are all higher in conductivity than the foamed plastics and little comparison with other data can be made. The present results for the glass foam are in very good agreement with data obtained in Germany [4] on a similar foam both in absolute value and relationship with temperature.

Prior to the guarded hot plate measurements a limited investigation of most of these materials was made at one or two mean temperatures in the range 250 to 300K in a Dynatech Rapid-k heat flow meter instrument according to the procedure ASTM C518-70 [5] using temperature differences in the range 15 to 30K depending upon the mean temperature. The results are given in Table 1 and show the excellent agreement between the two methods. This agreement tends to support a claim that the guarded hot plate measurements are accurate to +3%. Furthermore, it provides further evidence to support the heat meter method as being a truly reliable technique for evaluation of heat transmission in thermal insulations.

TABLE I
COMPARISON OF RESULTS OBTAINED ON SOME THERMAL INSULATIONS BY TWO METHODS

<u>MATERIAL</u>	<u>HEAT METER METHOD</u>		<u>GUARDED HOT PLATE METHOD</u>	
	at <u>260K</u>	at <u>300K</u>	at <u>260K</u>	at <u>300K</u>
FOAMGLASS	-	4.69	-	4.82
FOAMTHANE	2.49	2.62	[2.55]	2.59
URETHANE	2.52	2.58	[2.55]	2.62
PVC FOAM 281 SERIES	2.70	3.32	[2.68]	3.29
PVC FOAM 161 SERIES	2.83	3.69	[2.90]	3.72 and 3.77
KLEGECELL 33	2.68	3.25	2.62	3.28
KLEGECELL 55	2.52	2.78	2.51	2.82
ZONOLITE #2	-	6.8	-	6.95
[] values extrapolated from curve.				

REFERENCES

- [1] ASTM C177 (1963), Currently under revision, A.S.T.M. Stand., Philadelphia, U.S.A.
- [2] Dushman, S., in Vacuum Technique, John Wiley & Sons (N.Y.), 50, (1945).
- [3] Haskins, J. F., and Hertz, J. (1962) Adv. Cryogen. Engng., 7, 353.
- [4] Gerrish, R. W., Pittsburgh Corning, Private Communication.
- [5] ASTM C518 (1970), A.S.T.M. Stand., Philadelphia, U.S.A.

Fig 1 - Thermal conductivity of cellular plastic insulations

Fig 2 - Thermal conductivity of various thermal insulations

AN INSTRUMENT WITH DIRECT, DIGITAL READ-OUT OF THERMAL CONDUCTIVITY

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INTRODUCTION

The need in many industries for a simple quality control instrument to determine the thermal conductivity of insulating materials has prompted the development of a special heat flow meter apparatus designed and operated in accordance with ASTM C518 [1]² but with digital display of thermal conductivity. The instrument is designed to operate at a fixed set of sample hot and cold face temperatures which can be selected in the range -5°C to 120°C . Thus, the thermal equilibrium is disturbed only momentarily during the exchange of test specimens and a steady reading is obtained in five to ten minutes depending on the thickness and thermal diffusivity of the sample. Test samples must be 30 cm square by any thickness up to 5 cm, and have a thermal conductivity within the range 1.5 to $8.5 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$.

APPARATUS

The design of the test section is shown in Figure 1. Temperatures T_t and T_b are maintained at the selected values by controlled heaters overcoming the effect of the refrigerated heat sinks. Either heater temperature may be set from approximately -5°C to 120°C . The heaters are controlled by solid state proportional controllers within $\pm 0.15^{\circ}\text{C}$ of the set point.

The heat flux transducer with an approximate output of $0.25 \text{ mV per W m}^{-2}$ is 100 mm in diameter and is mounted in the center of a plate of equal thickness (about 3 mm) and made of the same material as the heat flux transducer. The entire assembly is mounted firmly against the lower heater surface plate.

The sample can be placed in the instrument quickly by lowering the bottom portion of the test section which is mounted on a movable frame. Upon release of the opening mechanism the sample is held firmly between the upper surface plate and the heat flow meter under a compressive load of about 15 kg to insure good thermal contact with the adjacent surfaces. The amount of travel of the movable frame is directly related to the sample thickness and is measured with a linear precision potentiometer.

The sample top and bottom temperatures are sensed by thermocouples located in the adjacent surfaces, T_1 and T_2 . The differential of these two temperatures is amplified along with the output of the heat flux transducer, using operational amplifiers (see Figure 2) in an analog computer module. The algebraic computations involving ΔX , heat flux, and ΔT are performed by computational modules. The output signal of the electronic calculator is displayed on a digital voltmeter. A calibration adjustment in the front panel allows the gain of the final amplifier to be adjusted in order to obtain the answer in the desired thermal conductivity units. The instrument is calibrated against an NBS fiberglass sample.

RESULTS AND CONCLUSIONS

Results obtained during the past half year have been in good agreement with thermal conductivity data determined by the guarded hot plate method and by the conventional heat flow meter method. Samples tested have been in the range 0.015 to $0.07 \text{ W m}^{-1} \text{ K}^{-1}$. The results are shown in Table 1.

Because the instrument is designed to test low conductivity materials only, the small error in the ΔT measurement by not having thermocouples in the sample itself is tolerable. Furthermore, the instrument is calibrated in this manner. A small inaccuracy in the assumed mean sample

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² Numbers in brackets refer to references listed at the end of the paper.

temperature exists, however, when testing materials of widely different thermal conductivity. This is because the small difference between T_2 and T_b (the latter being fixed) varies depending on the heat flux. Since the real ΔT (equal to $T_1 - T_2$) is used in the calculation of λ there is no loss of accuracy here.

Table I

Comparison of Results Using Different Instruments

Material Description	Thickness, mm	Thermal Conductivity, $10^2 \text{ W m}^{-1} \text{ K}^{-1}$		
		k-Matic	Rapid K	Guarded Hot Plate
An urethane foam 2 days old	31.1	1.90	1.94	-
An urethane foam over 1 year old	25.4	2.81	2.84	-
PVC foam sample #161	25.4	3.70	3.69	3.77
PVC foam sample # 55	25.4	2.78	2.78	2.82
A calcium silicate board	56.0	6.86	6.80	-
A combination perlite board, urethane foam and asbestos felt skin building board	41.0	3.45	3.37	-
A 32.2 Kg m ⁻³ dual density fibrous glass	19.0	3.52	3.64	-
A 24.8 Kg m ⁻³ dual density fibrous glass	28.6	3.58	3.60	-
A commercial foamglass	25.4	5.19	-	4.92
A 42 Kg m ⁻³ commercial polystyrene	25.4	1.91	1.94	-

REFERENCES

- ASTM C518-70, A.S.T.M. Stand., Philadelphia, U.S.A.

FIGURE 1 TEST SECTION SCHEMATIC

FIGURE 2 CALCULATOR BLOCK DIAGRAM

A General Method for Determining the Thermophysical Properties of Insulating Materials Using an Extension of the Line Heat Source Technique

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Introduction

The objective of this work was to develop the theory and its application for a better theoretical description of the commonly performed line heat source experiment. The new model accounts for the heater wire heat capacity which means that the entire early portion of the temperature history obtained for the experiment may be used to determine the sample thermal constants. The model also accounts for a contact resistance between the heater wire and sample. Our method uses a data fitting scheme which yields not only sample conductivity from the data but also sample heat capacity and a measure of the contact resistance. The data fitting scheme used also provides estimates of accuracies, and it has a more reliable subjectivity than have other methods used by previous investigators.

The disadvantages of our method is that it requires a large storage computer and a great deal of computer time and additional data (i.e., heater wire radius, heat capacity and conductivity).

Analytical Method

The solution to the differential equations describing a line heat source with contact resistance, heat capacity and finite sizes is [1]:

$$\Theta_m = E_1[\phi^2/4\tau] + \int_0^\infty e^{-U^2\tau} G(U) dU \quad (1)$$

where $\Theta_m = T_m/(\dot{Q}R^2/4\lambda_m)$, $\tau = \alpha_m t/R^2$ and T_m , λ_m , α_m are the temperature, thermal conductivity and diffusivity, respectively, of the medium, t = time, $\dot{Q}$ = heat generation per unit volume, $\phi = r/R$ and where R = wire radius and G is a function of thermal properties of the wire and medium and Bessel functions of the first and second kind.

A "better" asymptotic solution (better than $E_1(\phi^2/4\tau)$ used by many investigators) for large τ can be obtained by replacing all Bessel functions by the first few terms in their ascending series expansions and keeping only terms up through S^2 (Laplace transform variable) in the transform of Θ_m . The result is

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$$\begin{aligned} \Theta_m^* = & \ln \frac{4\tau}{\phi^2} - \gamma - \frac{1}{4\tau} \left[2 \left(\frac{\beta^2}{k} - 1 \right) \left(\ln \frac{4\tau}{\phi} - \gamma \right) + 2\eta\beta^2 + \frac{\beta^2}{2} - 1 - \phi^2 \right] \\ & + \frac{1}{(4\tau)^2} \left[b_7 - 2b_8(\ln 4\tau + \gamma - 1) + b_9 \left\{ 3(\ln 4\tau + \gamma)^2 - 6(\ln 4\tau + \gamma) \right. \right. \\ & \left. \left. - \frac{\pi^2}{2} \right\} \right] \text{ for large } \tau \end{aligned} \quad (2)$$

where b_7 , b_8 , and b_9 are explicit functions of α , β , η and φ . And $k = \lambda_m/\lambda_w$, $\beta = (\alpha_m/\alpha_w)^{1/2}$, $\lambda = \text{Euler's constant}$ and $\eta = \lambda_w/Rh$ where λ_w and $\alpha_w = \text{thermal conductivity and diffusivity of the wire, respectively}$ and $h = \text{contact conductance}$. T_1 and T_2 are asymptotic solutions to the Laplace transform of Θ_m for the case where terms of S and greater and greater than S , respectively, have been neglected. Notice in figure 1 that higher order asymptotic solutions are not necessarily better than the lower order ones. The conclusion is that the near equality of T_2 and Θ_m^* is no basis for assuming that either is the correct expression for Θ_m . A plot of Θ_m versus $\log \tau$ for various sets of parameters is shown in figure 2 where C is the ratio of the heat capacity of the wire to the medium. The results suggest the possibility of nondependence on the parameter k .

Acknowledgments

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Reference

- [1] Watkins, Jim A., "A General Method for Determining the Thermo-physical Properties of Insulating Materials Using an Extension of the Line Heat Source Technique," M.S. Thesis, Department of Mechanical Engineering, University of Kentucky, 1970.

Figure 1

Figure 2

THE USE OF THE COOLING CURVE IN THE PROBE CONDUCTIVITY TEST

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INTRODUCTION

The probe test can be a rapid and convenient method of measuring thermal conductivity, especially when one or more constituents of the test material would normally migrate under protracted heating. Because cooling data are generally considered to be less consistent than heating data, the test is typically performed utilizing only the heating portion for calculations. Unfortunately, this practice introduces elements of subjectivity which make it difficult to assess the true precision of the measurement. In particular, the operator is required to make judgments relative to the constancy of (1) ambient sample temperature or its drift rate, (2) contact resistance at the probe surface, (3) fluid distribution near the probe. Finally, there is always the question of whether the long-term slope of the heating relation has been reached during the test.

APPROACH and RESULTS

In this paper it is shown that proper utilization of the cooling portion of a test can provide a non-subjective check on each of these questions. The form of the cooling curve is illustrated both theoretically and experimentally, and two methods for calculating thermal conductivity from actual cooling data are presented.

CONCLUSIONS

Possible inconsistencies in cooling data are analyzed, leading to the conclusion that lack of precision in the control of ambient sample temperature may be a significant source of error in reported values of conductivity.

ACKNOWLEDGEMENTS

The author gratefully acknowledges a suggestion on the form of the cooling relation given to the author by Dr. James Beck at the 1970 Thermal Conductivity Conference. The analytical expression was found to have been published by Lachenbruch in 1957.

REFERENCES

Lachenbruch, Arthur H., A probe for measurement of thermal conductivity of frozen soils in place, Trans. Amer. Geophys. Union, Vol. 38, No. 5, Oct. 1957, pp. 691-697.

*
AN EVALUATION OF THE COLUMN METHOD FOR THE DETERMINATION
OF CONDUCTIVITY OF GASES

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Gandhi and Saxena [1] described, in detail, the design and fabrication of a conductivity column which can be used to measure thermal conductivity of gases up to as high as 3000°K. Here, we report our measurements on such a column for nitrogen (research grade 99.999% pure) to a maximum temperature of about 2500°K. Briefly, the column consists of a precision bore pyrex glass tube (internal diameter, 2b,: 0.8000 ± 0.0005 cm, nominal length: 105.5 cm) along the axis of which is stretched a tungsten wire. The cylindrical glass wall surface is maintained at a constant temperature by circulating water at 30.0 ± 0.02°C. The tungsten wire is heated to different temperatures by passing current from three power supplies connected in series. In our measurements reported here, the tungsten wires of three different diameters (2a) and of four different lengths (L) are used in the following combinations:

Set I	Set II	Set III	Set IV
L = 92.13 cm	L = 92.80 cm	L = 53.93 cm	L = 92.70 cm
2a = 0.3048 ± 0.0005 mm	2a = 0.5080 ± 0.0005 mm	2a = 0.5080 ± 0.0005 mm	2a = 0.2032 ± 0.0005 mm

The temperature of the wire is determined from its resistance on the basis of the following equation:

$$R_t = R_o (1 + At + Bt^2) \quad (1)$$

Here, R_t and R_o are the resistances of a given sample of wire at t and 0°C respectively. R_o is measured directly, while A and B are obtained by determining the resistance at the melting points of zinc (419.51°C) and aluminum (660.37°C).

A typical run consists in evacuating the conductivity column to 2×10^{-7} torr and then in determining the power Q_v required to heat the wire to different temperatures. Next, the test gas is transferred at the desired pressure, and measurements are repeated to determine the power Q_T necessary to heat the wire to various temperatures. Lipkea and Springer [2], Ganti, Sastri, and Saxena [3], and Ganti, Chen, and Saxena [4] experimentally examined the end heat transfer effects and found that the same are confined only over a length approximately equal to the diameter of the tube, as long as the Rayleigh number is smaller than a specified value. Saxena and Davis [5] also confirmed this by the theoretical calculations of the temperature profiles along the wire. In this analysis [5], convection effect is assumed to be negligibly small. Blais and Mann [6] have shown that the energy convected by free laminar convection in a sufficiently long column is negligible compared to the total energy fed to the wire. Thus, in the absence of temperature jump effect [7], a good

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estimate of the energy conducted through the gas, Q_H , is obtained from:

$$Q_H = Q_T - Q_V \quad (2)$$

plots of L/Q_H as a function of $1/P$ for various temperatures show that all the points up to the gas pressures of 10 cm of mercury lie on a linear plot; departures from the linearity are noticeable at higher pressures. The higher the temperature, the smaller the gas pressure at which convection appears. On the basis of equation (2), the gas conductivity, k , is calculated according to the relation:

$$k = \frac{\ln(b/a)}{2\pi L} \frac{dQ_H}{dR} \frac{dR}{dt} \quad (3)$$

A few sets of calculated k values as a function of the gas temperature, t , are listed in Table I. A good degree of agreement is exhibited in all the sets of values except those obtained from the data of set IV. The latter values are consistently higher, which confirms the presence of convection. This study thus clearly points out the need to select the gas pressure very carefully, and the important role it plays in determining conductivities from the column method. The k values obtained here are in good agreement with those available in the literature, and as soon as these calculations are completed and necessary corrections are applied, a detailed comparison with other data and with the theory will be in order.

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References

1. J. M. Gandhi and S. C. Saxena, Tenth Thermal Conductivity Conference, V 1, 1970.
2. W. H. Lipkea and G. S. Springer, Int. J. Heat Mass Transfer 11, 1341, 1968.
3. N. A. Ganti, V. M. K. Sastri, and S. C. Saxena, Dept. of Energy Engineering, University of Illinois at Chicago Circle, Technical Report TR-E 38, 38 pp., November 1970.
4. N. A. Ganti, S. H. P. Chen, and S. C. Saxena, Dept. of Energy Engineering, University of Illinois at Chicago Circle, Technical Report TR-E 42, 23 pp., July 1971.
5. S. C. Saxena and F. E. Davis, J. Phys. E: Scientific Instruments 4, 000, 1971.
6. N. C. Blais and J. B. Mann, J. Chem. Phys. 32, 1459, 1960.

TABLE I

Experimental values of the thermal conductivity of nitrogen as a function of temperature from various sets of data and at specified values of the gas pressure (cm of mercury).

t, °C	Set I		Set II	Set III	Set IV
	P = 11.0	P = 20.2	P = 10.05	P = 10.16	P = 73.9
200	36.8	37.0	36.8	36.9	36.6
400	47.4	47.2	47.2	47.0	46.9
600	59.2	59.0	58.2	58.2	58.2
800	68.1	67.9	67.1	67.9	74.1
1000	76.9	78.2	77.2	77.9	91.4
1200	82.6	85.2	-	84.3	111.2
1400	92.6	92.5	-	-	129.5
1600	-	-	-	-	171.1
1800	-	-	-	-	203.0
2000	-	-	-	-	260.7
2200	-	-	-	-	513.5

WEDNESDAY

a.m.

II

Heat Conduction in Turbulent Media Based Upon the Wave Mechanics

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Introduction

Using the wave mechanics theory of turbulence, recently developed by himself, the author presents the theory of the heat conduction in turbulent media applying the linear wave equation of Schroedinger.

Heat Conductivity Phenomenon

Assuming that the phenomenon of heat conduction is a natural phenomenon, one has to select the "natural" tool to describe--analytically--the phenomenon in question. As such one the writer has chosen the method of quantum field theory in statistical physics. The approach to the wave mechanics (and quantum) is based upon the famous theorem of John von Neumann related to the statistical formulation of the quantum mechanics. According to it, an explanation of the phenomena in media should be expressed in terms of complementary pairs of variables, each of which can be better defined only at the expense of corresponding loss in the degree of definition of the other. More than often the classical, deterministic causal mechanics uses the explanation in terms of "hidden variables (or parameters)" (Navier-Stokes equations belong to this category). As John von Neumann has proven, such an explanation is incompatible with certain qualitative fundamental postulates of the quantum mechanics. The interpretation of the quantum mechanics in the terms of the probability may lead to ambiguity due to the fact (considered to be a general principle) that each probability statement and approach arise from the incompleteness of one's knowledge. A quantum field theoretic method employs only the pair of (p,q) variables, and furnishes only probabilistic results and answers. After the explanation of basic fundamentals of the writer's approach to the phenomenon of the heat conduction in turbulent media, one may discuss more details of the formal nature. Since the definition of the "turbulent heat conduction" phenomena

refers to the "macroscopically" observable phenomena (and practically only to such ones) one may suggest in a speculative way some sort of a successful extension of the quantum theory to the domain of nuclear and particle dimensions. The definition of small scale properties of a system (quantum) is possible only as a result of interaction with large scale systems undergoing irreversible processes. In line with the above suggestion, quantum theoreticians propose that irreversible processes taking place in the large scale environment may also have to appear explicitly in the fundamental equations describing phenomena at the nuclear level. The only equation acceptable at the quantum level is the Schroedinger wave equation. Consequently, if the viscous medium is considered, the author proposes a probabilistic (by an iteration process) solution of the wave equation in which there are included viscous (undergoing irreversible processes) terms taken directly from the Navier-Stokes equation. This serves also towards another goal, i.e., towards the fulfillment of the correspondence principle (the laws of quantum physics must be so chosen that in the classical limit, where many quanta are involved, the quantum laws (and results) lead to the classical equations as an average). The Navier-Stokes equations contain in their entire system, the equation of energy, as well. Exactly, this equation is the primary analytical tool in the mathematical representation of the heat conduction phenomena in moving gaseous or liquid media. The way of achieving the geometric mapping of the turbulent phenomena in media in question was obtained by the writer by means of the hypothesis of linear superposition. The important step in the theory of the wave mechanical aspects of the turbulent media is the scale magnification from the quantum level to the macroscopic level of the classical, deterministic level. This is achieved by means of the association of the proper characteristic constants or variables appearing in the domains in question. Thus, the most characteristic quantum number, the Planck's constant, is associative with the Reynolds' number, one of the most characteristic variables on the macroscopic level of the deterministic, casual equations. Namely, the Planck number and the numerator in the Reynolds' number can be associated by means of a very simple operation. Consequently, a simple multiplication of the results by a ratio of the Reynolds' number factor (numerator) to the Planck constant transfers directly the results from the microscopic quantum domain to the macroscopic, deterministic, classical mechanics domain. The way in which the mean (average) values of variable functions have to be calculated, follows exactly fundamental principles and rules of the quantum mechanics.

ANALYSIS OF HEAT PULSE PROPAGATION IN SOLID ^3He ¹

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INTRODUCTION

The phenomenon of second sound in solids has been observed in single crystals of ^4He [1], ^3He [2], and, as incipient second sound, in NaF [3]. In solid ^3He heat pulses propagate diffusively for $T > 0.6$ K. Analysis of the arrival times of the slope and half-amplitude points of the temperature signal leads to the diffusivity. For very pure crystals umklapp processes dominate in this range. The analysis leads to values for the umklapp process relaxation time t_U . In the kinetic representation $\lambda = c_v v_D^2 t_U/3$, where c_v = heat capacity per cm^3 , v_D = mean Debye velocity. From this diffusive pulse propagation data we calculate λ vs T on the high-temperature side of the low-temperature anomalous curve. See dashed curve in figure 1.

In the range $0.4 < T < 0.58$ K (P-range of fig. 1) heat pulses propagate as distinct wave packets of highly-damped second sound. Normal process phonons are involved and they relax in a drifting coordinate frame (relaxation t_N) while umklapp processes are clamped to the lattice.

The microscopic theory of the second-sound phenomenon can be expressed in macroscopic terms [4] by suitable averaging. The approximation, valid at low temperatures, results in a third order differential equation involving t_N and t_U (or t_R , the overall resistive process relaxation time). It reduces to the ordinary diffusivity equation when t_N is very fast and $\partial^2 T / \partial t^2$ is ignored.

ANALYSIS

The analysis of the response to a delta-function type of heat pulse is a very complicated problem. We proceed by solving the differential equation for the plane wave case. This gives v_2 (second sound velocity) versus frequency. This dispersion relation contains t_N and t_U . Assuming parallel source and receiver planes, we determine the Green's function for adiabatic boundary conditions. Experimental arrangements of Ref. [2] are more-or-less consistent with the plane-wave assumption. The Fourier transform leads to an integral which we evaluate by summing residues. The result is a double series. A finite second-sound series with terms $(\cos \omega_n t + (\xi_n / \omega_n) \sin \omega_n t) \exp -\xi_n t$ is summed over a number

¹Work performed under the auspices of the U.S. Atomic Energy Commission.

of terms determined by the boundary conditions, t_N , and t_U . An infinite rapidly-convergent diffusive series with terms $(\cosh \Omega_m t + (\xi_m/\Omega_m) \sinh \Omega_m t) \exp -\xi_m t$ then starts. We sum these series by computer out to 110 terms in the range $0 < t < 4t_1$. Waveforms are similar to those observed experimentally.

To relate to the experimental data, we vary t_N and t_U until calculated pulse shapes have the same characteristics as the data. We compare: $t_{1/2}$ (half-amplitude point of first arrival), t_1 (peak of first arrival), t_2 (peak of second arrival—twice reflected packet). Velocity of packet propagation is $v_2 = L/(t_2 - t_1)$; L = separation of transmitter and receiver planes.

Having thus determined t_N, t_U corresponding to measured data, we calculate λ via the Guyer-Krumhansl [4] relation $c_v v_D^2 t(\text{effective})$, where $t(\text{effective})$ is given by

$$(t_N)/(1+s) + (t_U)/[(1+s)(t_U)(t_U^{-1})]$$

where $s = (t_N)/(t_U)$, $t_U^{-1} = \omega^2 T^n$, and $(t_{N,U})$ denotes average.

Using the method described above we find $1.0 < t_N < 2.3$ microseconds and obtain λ in the second sound region as plotted by triangles in figure 1. This is a factor of two lower than static λ as measured by Tomlinson [5]. Certain needed improvements in our computational and pulse-analysis technique are expected to lead to better agreement with the static data. The experimental value of v_2 is 165 m/sec in agreement with the lowest shear acoustic mode velocity divided by $\sqrt{3}$.

REFERENCES

- [1] Ackerman, C. C. and Guyer, R. A., Ann. Phys.(NY) 50, 128(1968).
- [2] Ackerman, C. C. and Overton, W. C., Phys. Rev. Letters 22, 764(1969).
- [3] McNelly, T. F., et al, Phys. Rev. Letters 24, 100(1970).
- [4] Guyer, R. A. and Krumhansl, J., Phys. Rev. 148, 766(1966).
- [5] Tomlinson, W. C., Phys. Rev. Letters 23, 1330(1969).

Figure 1. Comparison of computed from pulse analysis data with statically-measured thermal conductivity.

CORRELATION OF LINE SHAPES OF IMPURITY INDUCED ABSORPTION AND IMPURITY REDUCED THERMAL CONDUCTIVITY VS. TEMPERATURE

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INTRODUCTION

The lattice thermal conductivity for an ionic solid containing a single point defect is considered based on Kubo's theory of irreversible processes. In particular, the impurity induced thermal resistance is calculated through perturbation theory using the weak anharmonic coupling between the impurity and the lattice as perturbation parameter. In an attempt to correlate the optical properties such as absorption line widths and shifts with the thermal resistance, the appropriate heat current correlation function in the Kubo formula is formally expressed as a product of two single impurity phonon correlation functions. These have already been calculated by a new projection operator method due to Wilson, et. al. for the impurity infrared absorption problem. It is this approximation which leads almost directly to a single relation between the impurity induced thermal resistance and width and shift optical parameters as desired.

RESULTS AND CONCLUSIONS

The main result has the following form:

$$\chi_{ij} = \frac{t_i^2 \omega_I^2 v_i v_j e^{h\omega_I} e^{-h\omega_I} \gamma_i \gamma_j}{(2k_B T^2 v \gamma_i) (e^{h\beta\omega_I} - 1)^2}$$

where v_i , are the group velocities, ω_I is the impurity frequency, $\beta = 1/k_B T$, k_B is the Boltzmann constant, and T is the temperature. The quantities γ_i and γ_j are given as the real and imaginary parts of the following simple integral transform:

$$\gamma(\omega) = (1/t^2) \int_0^\infty \langle [\Gamma, \Gamma(t)] \rangle e^{-\omega t} dt$$

where Γ represents an arbitrary function of the bath coordinates which couples linearly to the impurity mode.

An alternate heuristic method is given based on recent theory of B. Deo, et. al.[1] and shown to be in a certain approximation a limiting form for the present more general result. In this way it is possible to make a more direct connection with some older kinetic theory results. Finally some recommendations are made for the possibility of treating the so-called resonance impurity absorption and its correlation to the appropriate thermal induced resistance through methods similar to those used here. A brief discussion of the possibility for similar behavior and correlations for molecular impurities in liquids is given with special reference to recent work of S.A. Rice, et. al. [2]

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REFERENCES

- 1 B. Deo and S. N. Bhera, Phys. Rev. 141, 735(1966).
- 2 W. L. Greer, J. A. Rice, and G. Morris, J. Chem. Phys. 52, 5622(1970).

FINITE-ELEMENT METHOD APPLIED TO HEAT CONDUCTION
IN SOLIDS WITH NONLINEAR BOUNDARY CONDITIONS - AN INDIRECT ITERATIVE APPROACH

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INTRODUCTION

In recent years, the use of the finite-element method to solve transient heat-conduction problems with linear boundary conditions has attracted considerable attention. Unfortunately, very little work has been done on the finite-element method for solid heat-conduction with nonlinear radiation-convection heat-flux boundary conditions. Richardson and Shum [1]¹ discussed the application of the finite-element method to solve heat-conduction problems involving nonlinear radiation boundary conditions. However, in their analysis, the contribution due to radiation and convection was calculated entirely on information available at one time-step earlier rather than on consideration of the variation of surface temperatures between each time-increment. The purpose of this investigation is to extend the finite-element method to heat conduction in solids with nonlinear boundary conditions so that surface temperature can be varied within each time-increment.

THEORETICAL ANALYSIS

The variational principles introduced by Gurtin [1], and applied by Wilson and Nickell [1] are used in this investigation. The details of derivation of the finite-element transient heat-conduction equations can be found in Reference [1]. The governing transient heat-conduction matrix equation for a complete finite-element system is given by:

$$([C] + \frac{\Delta t}{2} [K])\{\theta(t)\} = ([C] - \frac{\Delta t}{2} [K])\{\theta(t-\Delta t)\} + \{F\} \quad (1)$$

in which the specific heat matrix $[C]$, the conductivity matrix $[K]$, and the thermal force vector $\{F\}$ were defined in Reference [1].

In the consideration of the radiation-convection boundary condition, the following expression for surface heat-flux was assumed to be valid:

$$q = R(\theta_r^4 - \theta_c^4) + \lambda(\theta_c - \theta) \quad (2)$$

where R and λ are constants related to the effects of radiation and convection at the surface, respectively. The surface with temperature θ is exposed to radiation (θ_r) and convection (θ_c).

The inclusion of radiation-convection boundary conditions leads to the following form of the element thermal forces matrix:

¹Details of references cited throughout the paper can be found in the reference [1] mentioned at the end of the paper.

$$\{Q_m\} = \int_{S_m} (\theta_r^4 - \theta_c^4) * R_m \{d_m\} dS_m + \int_{S_m} (\theta_c - \theta) * H_m \{d_m\} dS_m \\ + \int_{V_m} \rho_m * \rho_m \langle b_m \rangle^T dV_m + \int_{S_m} \hat{Q}_i n_i \langle b_m \rangle^T dS_m \quad (3)$$

$$\text{and} \quad \{F\} = \sum_{m=1}^M \{Q_m\} \quad (4)$$

For the evaluation of the thermal force vector $\{F\}$ and the nodal temperature vector $\{\theta(t)\}$ in accordance with equations (3), (4), and (1), an iteration technique has to be used because $\{F\}$ depends upon the solution $\{\theta(t)\}$. An effective indirect-iterative technique given in References [1,2] was used to solve this system of equations. With this technique, the Gaussian elimination process is applied only once for each time-step.

RESULTS AND CONCLUSIONS

A two-dimensional finite-element heat-conduction computer program [2] was prepared. This computer program can be used not only for arbitrary geometry (plane body with either rectangular or polar coordinates, axisymmetrical body), arbitrary initial conditions, orthotropic materials, and linear boundary conditions but also for nonlinear boundary conditions (radiation). For nonlinear boundary conditions, the computer program has provisions to run with only the information available at the beginning of each time-step, to iterate by successive substitution, or to iterate with any assigned weighted-average of data at the beginning of that time step plus the data at the end of the time step from the previous iteration. The various options for treatment of nonlinear boundary conditions permit the use of larger time steps while the results are being improved by iterations; these options also permit the obtaining of reasonable results at large times, even without iterations.

Numerical calculations included in References [1] and [2] are: (a) pure radiation at the surface of a semi-infinite solid, (b) a two-dimensional plane body subjected to radiation and convection boundary conditions, and (c) a multilayer hollow cylinder. This cylinder may be considered as a nuclear reactor or a gun tube with insulating material in the middle layer subjected to periodical heat input at the bore, and radiation and convection at both inner and outer surfaces. The numerical results of the first two problems are compared with the exact solution and with the results obtained by use of the probability method, respectively; excellent agreement has been found.

REFERENCES

- [1] Shih-Chi Chu and Rao V. S. Yalamanchili, "Application of the Finite-Element Method to Heat-Transfer Problems: Part I. Finite-Element Method Applied to Heat-Conduction Solids with Nonlinear Boundary Conditions," Research Directorate, U. S. Army Weapons Command Technical Report, RE-TR-71-37, AD726370, June 1971.
- [2] Rao V. S. Yalamanchili and Shih-Chi Chu, "Application of the Finite-Element Method to Heat-Transfer Problems: Part II. Transient Two-Dimensional Heat Transfer with Convection and Radiation Boundary Conditions," Research Directorate, U. S. Army Weapons Command Technical Report, RE-TR-71-41, AD726371, June 1971.

Comparisons of Automated Two Dimensional Transient Heat Conduction

Methods

by

F. Petri

Recently the use of the finite element method in two dimensional transient heat conduction problems has received considerable attention. In dealing with practical problems its chief advantage is the automatic formulation of problems, thus avoiding the laborious work of calculating conductances and capacitances for each node of a thermal network.

Another automated technique developed by the author is the use of a linear transformation to stretch an arbitrary shape into a rectangular shape. Assuming a body of the general shape shown in Figure 1a, the X location of the outer curve of the body is given by a continuous location $S(Y)$ while the inner curve is given by $b(Y)$. This body may be transformed to the rectangle shown in Figure 1b by the following transformation.

$$\xi = \frac{X - b}{S - b} = \frac{X - b}{\delta} \quad \delta = S - b \quad (1)$$

$$y = Y$$

The advantage of this transformation is that the transformed plane may be broken into a mesh which may be easily handled by the computer. This imposes the formal requirement that the first and second derivatives of $b(Y)$ and $s(Y)$ be continuous.

A comparison of this method, the finite element method, and the standard lumped parameter method (nodal network model) are given for some typical aerodynamically heated shapes shown in Figure 2. Temperature predictions of all three methods showed good agreement. However, the total computer times and labor required for input preparation were substantially

different. The finite element method and linear transform method require a minimum of input preparation. The finite element method program used considerably more computer time for the same mesh and time step. However, for very complex shapes with many discontinuities the linear transform method becomes limited by logic requirements.

Figure 1-Physical and Transformed Coordinate System

Figure Aerodynamically Heated Shapes Treated by Transformation
and finite element method

A Laplace Transform Method for Predicting
Radiation Losses from a Laser-Heated Foil

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The possibility of using a conventionally Q-switched laser as a source of intense electromagnetic radiation for inducing stress waves in solids has recently attracted a great deal of attention [1, 2]². The pressure generated by the deposited energy and the resulting stress pulse is limited by the radiation losses from the vaporized material. A complete description of the hydrodynamic process which takes place as a result of the deposited energy is a formidable task and beyond the scope of this analysis.

The present work considers an analytical solution for the linearized radiation losses from a thin irradiated foil which is attached to a semi-infinite substructure. The laser energy is assumed to be deposited uniformly over an extremely short time interval such that it is approximated by a uniform heat generation term in the foil. The solution is compared with a similar analytical solution for the case of an adiabatic boundary [3]. In both analyses the assumption of constant thermal properties is made. For the large range of temperatures and pressures encountered in a plasma, this assumption while not correct does afford some insight into the magnitude of radiation losses to expect in an actual situation.

An example problem to demonstrate the use of the analysis is considered. 100 J/cm² of laser energy are assumed to be deposited in a 1.0 μ m foil of aluminum attached to a slab of lucite assumed to be semi-infinite. The deposition period is taken to be 100 nsec. Taking into account the specific heat of the aluminum (assumed constant), this indicates a generation term of 4.0×10^{12} °K/sec. Figures 1 and 2 present results at 50 nsec and 100 nsec respectively for a range of values of the linearized radiation loss term. Results for the actual loss term determined by iteration are indicated in the figures by the dashed line. It is seen that for small deposition times, the radiation losses are small indicating the problem could be treated as an initial value problem with the initial temperature distribution in the foil being given by the characteristics of the particular laser being used. As the deposition time becomes large, however, the radiation losses become significant.

1. This work was supported by the United States Atomic Energy Commission.
2. Figures in brackets indicate references listed at the end of this abstract.

References

1. Skeen, C. H. and York, C. M., Appl. Phys. Lett. 12, 369 (1968).
2. Anderholm, N. C., APS Bulletin, Series 11, 13, Paper BK 9, 388 (1968).
3. Luikov, A. V., Analytical Heat Diffusion Theory, Academic Press, New York, 1968

UNSTEADY HEAT-TRANSFER ANALYSIS FOR A GUN BARREL

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INTRODUCTION

As the projectile moves ahead because of the high pressure gases created by burning propellant, the propellant gas will be set into motion starting from rest. Since the governing equations of fluid dynamics for many problems of interest are a system of nonlinear partial differential equations and are also dominated by real gas and nonequilibrium effects, no general solutions exist that allow arbitrary initial and boundary conditions. Therefore, examination of the flow field and subdivision of the overall problem by consideration of the dominant features only seems appropriate. The objective is to establish a capability to perform overall heat-transfer analysis for any given dimensions of the weapon and for specified propellant characteristics. Toward this goal, the propellant gas convective heat-transfer problem [1] is divided into five subproblems: 1) generation of thermochemical properties for any given propellant, 2) transient inviscid compressible flow, through the gun barrel (core flow), 3) transient viscous compressible flow on the bore surface (boundary layers), 4) unsteady heat diffusion through the multi-layer gun tube, 5) unsteady free convection and radiation outside the gun tube.

RESULTS AND DISCUSSION

With the use of the NASA-LEWIS (CEC-71) thermochemical program, chemical composition and adiabatic flame temperature properties are computed for any given propellant. Transport properties for a mixture of gases are calculated by use of pure gas properties, simple relationship such as Dalton's Law of partial pressures, and Sutherland's viscosity law.

The governing equations, i.e., continuity, momentum and energy of unsteady, inviscid and compressible flow are of the hyperbolic type. These are solved [2] by the method of characteristics. Pressure, density, temperature, and velocity distributions are obtained as a function of time. In general, in a fluid column a linear velocity gradient is found to be better than the uniform density approximation. For the first portion of bullet travel (approximately 20 per cent), neither of these assumptions is good. The uniform density assumption implies a linear velocity gradient even though the reverse is not necessarily true.

Analytical boundary layer analysis procedure was developed based on the transient compressible boundary layer momentum integral equation. Convective heat-transfer was evaluated by use of the Chilton-Colburn analogy between the energy transfer and the momentum transfer. Density variation across the boundary layer was taken into account by simplified Crocco relationship. Numerical schemes were laid for flows with linear velocity gradients and exponential wall shear laws by the method of characteristics. Theoretical predictions of convective heat-transfer coefficients are considerably lower than those of the experimental data. Some of these differences are attributable to the evaluation of thermal conductivity of gases at elevated temperatures (reference) and to difficulties associated with instrumentation. Calculations indicate that short-lived (less than one microsecond) peak heat fluxes of the order of 80,000 BTU/sec-ft² exist in a gun barrel. Fast response gauges are essential because of the rapidity with which this value is obtained and attenuated with time. The radiation contribution is estimated as negligible compared with the forced convective contribution. Under the assumption of a typical value of Reynolds number based on momentum thickness for laminar-turbulent transition at 300, turbulent regions can exist even before the bullet has traveled less than its initial distance from the breech.

The transient heat diffusion [3] through the multilayer gun tube walls is analyzed by the finite-element method. This analysis enables one to consider not only arbitrary geometry (plane body with either rectangular or polar coordinates, axisymmetrical body), arbitrary initial conditions, orthotropic materials, and linear boundary conditions, but also to consider nonlinear boundary conditions (radiation).

The unsteady, two-dimensional, free convection and radiation problem is formulated [1] to establish outer surface (gun tube) boundary conditions. The solution procedure is by finite-difference methods. Radiation and convection are of the same order of magnitude.

Appropriate interface boundary conditions between the problems are essential to enforce continuity. Requirement of iteration, because of the coupling between the problems, is not anticipated for reasonable time-step sizes. However, a strong interaction is expected between these problems if one attempts to solve these successively, once for each round of fire.

REFERENCES

- [1] Yalamanchili, Rao V.S., "Unsteady Heat Transfer Analysis for Chosen Ammunition and Gun," Research Directorate, U. S. Army Weapons Command Technical Report RE-TR-71-61, Aug 1971.
- [2] Yalamanchili, Rao V.S., "Transient Inviscid Compressible Flow Through the Gun Barrel," Proceedings of the XVII Army Mathematicians Conference, May 1971.
- [3] Yalamanchili, Rao V.S. and Shih-Chi Chu, "Application of the Finite-Element Method to Heat-Transfer Problems: Part II. Transient Two-Dimensional Heat Transfer with Convection and Radiation Boundary Conditions," Research Directorate, U. S. Army Weapons Command Technical Report, RE-TR-71-41, AD 726371.

A TRANSIENT TECHNIQUE EMPLOYING COMPUTER AIDED GRAPHICS TO MEASURE THERMAL CONDUCTIVITY OF HEAT SINK COMPOUNDS

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INTRODUCTION

A heat sink compound is a specially formulated paste used as a heat transfer medium with semiconductor devices. These compounds are also used to prevent electrical leakage under damp conditions. In electronic applications it is important to select a dielectric compound of high thermal conductivity.

This paper presents a technique to measure thermal conductivities of heat sink compounds.

THEORETICAL BACKGROUND

The measurement technique employed in this work uses the transient temperature response of a line heat source. An equation to calculate the thermal conductivity of a material has been obtained [1], [2], [3], as

$$\lambda = Q \ln(t_2 / t_1) / 4 \pi (T_2 - T_1) \quad (1)$$

where λ = the thermal conductivity, Q = the constant heat input,
 T_1 , T_2 = the temperatures of the line heat source at times t_1 and t_2
respectively.

APPARATUS

The apparatus to measure thermal conductivities of heat sink compounds is shown in Figure 1.

Figure 1 Schematic of Test Apparatus

A cylindrical plastic test tube contains a sample of the heat sink compound to be tested. A heater wire (30 ga. Nichrome alloy) is then embedded at the center of the test tube to simulate an axial line heat source. A DC power supply provides a constant heat rate to the heater wire. A thermocouple (40 ga. iron-constantan), welded to the heater wire, senses the transient temperature response due to sudden heat input. A computer controlled data acquisition system records data and performs data analysis. A peripheral X-Y recorder plots the test data automatically into graphic form.

The computer aided graphics technique is derived as follows: A straight line is theoretically expected to be shown on the plot of temperature vs. time on a semi-log scale. However, test data indicate a straight line occurring only within a certain time period. This is due to the effects of finite sizes of the heater wire and sample size. Therefore, the automatic data plotting technique is used to delineate this particular time period. Once a straight line is obtained by the computer graphics method, the thermal conductivity of the material is easily calculated by eq. (1).

CONCLUSIONS

The computer aided graphics technique simplifies test specimen design by reducing the sensitivity of the experiment variations of geometry. Secondly, the method is quicker than a steady state method (where time is required to reach equilibrium conditions). Finally, this method eliminates the problem of determining the exact thermocouple locations needed in a steady state method. This technique, therefore, when coupled with computerized data acquisition and plotting, provides a quick, simple, and accurate method for measuring thermal conductivities of heat sink compounds or similar potting materials.

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REFERENCES

- [1] Carslaw, H.S., and Jaeger, J.C., Conduction of Heat In Solids, Clarendon Press, Oxford 1947.
- [2] Scheiermacher, A.L.E.F., Wiedemann Annalen Physik, Volume 34.
- [3] Gale, E.H., Quick Determination of Thermal Conductivity of Potting Compounds by Transient Technique, National Electronic Packaging and Production Conference, New York City, 1964.

CONJUGATED UNSTEADY-STATE HEAT TRANSFER OF A PLATE IN A GAS FLOW

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Considered is conjugated (in the sense following [1-3]) unsteady-state heat transfer in a laminar boundary layer on a flat plate: a parallel compressible liquid flow with constant velocity u_∞ incoming an outer surface ($y=0$) of a plate of thickness h . Heat sources distributed throughout the plate are switched on at $t=0$. By simultaneous solution of equations of hydrodynamics, energy in a gas and of heat conduction in a body, the following temperature distribution in a boundary layer is obtained:

$$\rho \left[\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right] = \frac{\partial}{\partial y} \left[\mu \frac{\partial u}{\partial y} \right],$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0,$$

$$c_p \rho \left[\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right] = \frac{\partial}{\partial y} \left[\lambda \frac{\partial T}{\partial y} \right] + \mu \left[\frac{\partial u}{\partial y} \right]^2,$$

$$(u=v) \Big|_{y=0, x>0} = 0, \quad (v = \frac{\partial u}{\partial y} = \lambda \frac{\partial T}{\partial y}) \Big|_{y=0, x<0} = 0,$$

$$u \rightarrow U_\infty, \quad T(x, y, t) \rightarrow T_\infty \quad \text{at } y \rightarrow \infty,$$

$$T(x, y, 0) = T_e(x, y), \quad \frac{\partial T_e}{\partial y} \Big|_{y=0} = 0, \quad T_e \Big|_{y=\infty} = T_\infty,$$

$$c_p = \text{const}, \quad \text{Pr} = \text{const}, \quad \rho \mu = \text{const}$$

The equation of heat conduction in a body is

$$c_s \rho_s \frac{\partial T_s}{\partial t} = \lambda_s \left[\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} \right] + Q_0(x, y, t),$$

$$Q_0(x, y, t) = 0 \text{ at } t < 0; \quad \lambda_s \frac{\partial T_s}{\partial x} \Big|_{x=0} = \lambda_s \frac{\partial T_s}{\partial x} \Big|_{x=\infty} = 0;$$

$$\lambda_s \frac{\partial T_s}{\partial y} \Big|_{y=-h} = F_0(x, t) \text{ at } x > 0; \quad T_s(x, y, t) = T_\infty N(0) \text{ at } t < 0$$

Conjugation conditions are

$$\left. \begin{aligned} T &= T_s \\ \lambda \frac{\partial T}{\partial y} &= \lambda_s \frac{\partial T_s}{\partial y} \end{aligned} \right\} \text{ at } y=0, \quad x > 0.$$

For the whole plane of the flow an analytical solution is obtained for the problem of conjugated unsteady-state heat transfer of a plate in a gas flow for the case when the unsteady-state is due to the sources in the plate. Parameter R_e^+ is established taking into account the mutual thermal effect of a boundary layer and a body which permits subdivision of the unsteady-state heat transfer problem into two classes: a quasi-steady one and unsteady one. Temperature on the front edge of the plate is defined.

R E F E R E N C E S

- /1/ Luikov, A.V. and Perelman, T.L., On unsteady heat transfer between a body and a liquid flow around it. Collected papers "Heat and Mass Transfer of Bodies with Surrounding Gas Medium", Izd. "Nauka i Tekhnika", Minsk, pp.3-24 (1965).
- /2/ Luikov, A.V., Perelman, T.L., Levitin, R.S., Gdalevich, L.B., Heat transfer from a plate in compressible gas flow, Int. J. Heat Mass Transfer, 13, 1261-1270 (1970).
- /3/ Luikov, A.V., Perelman, T.L., Levitin, R.S., Gdalevich, Conjugated steady-state convective heat transfer of a plate in a gas flow, Doklady Akademii Nauk SSSR, 197, 1, 50-51 (1971).

WEDNESDAY
p.m.

THE THERMAL CONDUCTIVITY OF GASES

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INTRODUCTION

The paper analyzes our knowledge of the thermal conductivity of gases. In all cases, this is directly based on experiments. However, in the exceptional case of the monatomic gases (He, Ne, Ar, Kr and Xe), the Chapman-Enskog solution of the Boltzmann equation provides us with a sharp and reliable consistency test between thermal conductivity, k , and viscosity, μ . This is to the effect that the preceding two properties of any monatomic gas must satisfy the relation

$$\frac{k}{\mu c_v} = 2.5 f_k(T^*)/f_\mu(T^*) \quad , \quad (c_v = 1.5R) \quad , \quad (1)$$

provided that they have both been extrapolated to zero density. This relation is almost completely insensitive to the details of the molecular interaction, the latter being reflected merely in the correction factors $f_k(T^*)$ and $f_\mu(T^*)$. The ratio f_k/f_μ is almost exactly unity over a wide range of temperatures, $T = \epsilon T^*/k$, and the very small deviations from it can be calculated sufficiently accurately with any model of the inter-molecular force potential.

It is now interesting to select the most reliable values of viscosity and thermal conductivity and to determine whether they conform to theory.

COMPARISON

We have conducted extensive consistency tests for all monatomic gases [1] using our own results for viscosity and carefully correlated, "recommended" values for thermal conductivity [2]. The results of such comparisons can be tersely summarized by the statement that:

In the case of all monatomic gases the consistency test fails in the sense that deviations from the relation required by eq. (1) are contained within a band of +9% to -6%.

Given that the accuracy of our viscosity measurements ranges from 0.1% at room temperature to 0.3% at 700°C, it follows that the two sets of data are not consistent. Since the Chapman-Enskog theory cannot be seriously questioned, and since we take the view that our error estimates for viscosity are well-founded, we can only conclude that the published data on the thermal conductivity of monatomic gases are burdened with unaccounted for errors of the order of ±10% or so. A fortiori, the same would apply to measurements on more complex molecules. The preceding error is much higher than that reported for

the best measurements of thermal conductivity, and it seems necessary to identify the reason for its existence.

A SECOND COMPARISON

It is interesting to record here the results of another comparison. If the data of thermal conductivity are restricted to those measured by J. W. Haarman [3], the error band becomes drastically reduced and ranges from 0 to -0.9%. J. W. Haarman estimated his accuracy as one of 0.4% which combined with our error estimate of 0.3% at worst, admits an error band of $\pm 0.7\%$. Thus, with the exception of a few isolated cases, the two sets of data turn out to be consistent with the Chapman-Enskog theory.

POSSIBLE EXPLANATION

We express the view that the systematic, unaccounted for error in many investigations of thermal conductivity is introduced by the presence of natural convection. A critical reading of the relevant literature shows that many authors assume that natural convection sets in as a result of an instability expressed in the form of a critical Rayleigh number even in concentric-cylinder or hot-wire instruments. This, of course, is not the case, and at least a correction for convective transfer must be introduced. This view is supported by J. W. Haarman's work who used a transient method and who successfully eliminated the effects of natural convection from his apparatus.

REFERENCES

- [1] Kestin, J., Ro, S. T., and Wakeham, W., Physica (to be published).
- [2] Vargaftik, N. B., Fillipov, L. I., Tarzimanov, A. A., and Yurchak, R. P. "Thermal Conductivity of Gases and Liquids" (in Russian). Izd. Kom. Standartov, Moscow 1970.
- [3] Haarman, J. W., Thesis, Tech. Hogesch. Delft, 1969.

UNCERTAINTIES IN THE THERMAL CONDUCTIVITY OF
LIQUIDS AND DENSE GASES -
THEIR EFFECT ON HEAT TRANSFER*

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OUTLINE OF THE PROBLEM

Owing to uncertainties in numerical or estimated data for the thermal conductivity of fluids, heat transfer calculations may often be considerably in error. Sophisticated attempts to discern and attribute further fine detail to heat transfer mechanisms can often be masked by this data and force the designer to rely upon generalized correlations having about ± 20 percent reliability.

In most dimensional expressions for heat transfer coefficient, the exponent on the thermal conductivity varies between 0.5 and 1.0. Uncertainties in transfer coefficient, area, and/or surface temperature can therefore be between 0.5 to 1.0 as large as the uncertainty in the original conductivity data; ± 20 percent is not uncommon [1]+.

The situation is further confused by the fact that if we define thermal conductivity as a pure material property, not dependent upon measurement system peculiarities, we must, especially if dealing with hydrocarbon fluids even at room temperature, consider the effects of radiation since in the vicinity of the medium boundaries the effective thermal conductivity is often no property of the considered medium alone, but also a function of the distance from the boundaries, a function case--a function of the properties of the bounding media [2]. It can be said that the thermal conductivity of many liquids show a size effect which can be attributed to radiation.

The thermal conductivity of a fluid becomes infinite at the critical point [3] and carry over of this behaviour results in anomalous supercritical and subcritical characteristics which can cause substantial error in estimating thermal conductivity by empirical and/or theoretical means. Measurements of this behaviour are practically non-existent.

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+ Figures in brackets indicate the literature references at the end of this paper.

DISCUSSION

The above problems are discussed in the light of the available measurements for Methane, Water, Heavy Water, and a few other fluids. For liquid CH_4 the recent results of Mani[4] indicate that heat leak errors have caused previous workers to overestimate λ by between 5 to 18 percent below 200°K. Substantial carryover of critical behaviour is observed especially near phase change boundaries.

Water and Heavy Water are normally considered heavily absorbing fluids in the IR at room temperature. Most λ measurements show, below 250°C, reasonable agreement (within $\pm 2\%$). As the temperature is raised to the critical points the experimental deviation data for both fluids exhibit interesting differences--it is postulated that fluid radiation effects cause the experimental disagreements observed.

Recent radiation free measurements for toluene^[4] confirm the radiation free results reported by Poltz[2] and indicate as well a substantial pre-freezing anomaly.

RESULTS

The results of the discussions indicate:

(1) a need for the critical re-examination of existing thermal conductivity data.

(2) the need for comprehensive measurement and interpretive programmes, especially near fluid phase boundaries and the critical region for industrially important fluids.

(3) the need for the careful re-assessment of the mechanisms taking part in heat transfer measurements, even at low temperatures and especially when dealing with organic fluids.

REFERENCES

- [1] Venart, J.E.S., J. Chem. and Engg. Data, (1965), 10, 239.
- [2] Poltz, H., Int. J. Heat Mass Transfer, (1965), 8, 609.
- [3] Sengers, J. V. and Keyes, P. H., Phys. Rev. Letters, (1971), 26, 70.
- [4] Mani, N., Ph.D. Thesis, University of Calgary, 1971.

CALCULATION OF THE TRANSPORT COEFFICIENTS FOR DILUTE GASES USING AN ITERATIVE SOLUTION OF BOLTZMANN'S EQUATION

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INTRODUCTION

The second approximation to Boltzmann's equation for dilute gases is solved for several different potential models by using an iterative procedure. The first order perturbation function, ϕ , to the local Maxwellian distribution, $f^{(0)}$, is obtained as an infinite series, as are the various transport coefficients. Values for these coefficients have been calculated for several potential models and are compared with those obtained by the standard Chapman-Enskog method.

METHOD

The second approximation to Boltzmann's equation is written

$$-(\frac{5}{2} - \alpha V^2) \underline{V} \cdot \frac{\nabla T}{T} + 2\alpha \underline{V} \cdot \underline{V} : \nabla \underline{u} = -\phi(V) \int f^{(0)}(u) g b db d\epsilon d\underline{u} \\ + \xi \int f^{(0)}(u) \{ \phi(U') + \phi(V') - \phi(U) \} g b db d\epsilon d\underline{u} \quad (1)$$

where ξ is an ordering parameter to be set equal to unity at the end of the calculations.

Equation (1) may be written schematically as

$$X_{\underline{c}} = -\phi_{\underline{c}} L_0 + \xi L_1 \phi_{\underline{c}} \quad (2)$$

where $c(\eta)$ refers to the gradient term in temperature (flow velocity).

In order to perform the iterative procedure we must first expand ϕ in the infinite series

$$\phi_{\underline{c}}(V) = \sum_{n=0}^{\infty} \xi^n \phi_{\underline{c}}^{(n)}(V) \quad (3)$$

Then, on substituting equation (3) in equation (2) and equating powers of ξ , we obtain the following iterative relationships

$$X_{\underline{c}} = -\phi_{\underline{c}}^{(0)}(V) L_0, \quad \phi_{\underline{c}}^{(n)}(V) L_0 = L_1 \phi_{\underline{c}}^{(n-1)} \\ \text{for } n \geq 1. \quad (4)$$

Each $\phi_c^{(i)}(V)$ separately is required to satisfy the auxiliary conditions. This can be achieved by redefining $\phi_c^{(i)}(V)$ as follows

$$\bar{\phi}_c^{(i)}(V) \underline{V} \cdot \frac{\nabla T}{T} = \phi_c^{(i)}(V) \underline{V} \cdot \frac{\nabla T}{T} + \underline{\alpha}^{(i)} \cdot \underline{V} \quad (5)$$

where $\underline{\alpha}^{(i)}$ is to be determined from the second auxiliary condition.

Since the transport coefficients are determined from the flux equations, which contain ϕ , they too can be expanded as infinite series

$$\lambda = \sum_{n=0}^{\infty} \xi^n \lambda^{(n)} \quad \text{and} \quad \eta = \sum_{n=0}^{\infty} \xi^n \eta^{(n)} \quad (6)$$

The transport coefficients have been calculated for three different potential models using equation (6).

RESULTS

For the Maxwellian and Pseudo-Maxwellian models the $\bar{\phi}^{(i)}$'s, and hence $\lambda^{(i)}$'s and $\eta^{(i)}$'s, form an exact geometrical progression which can be summed and the analytical values for the transport coefficients are the same as obtained by the standard Chapman-Enskog method. In the case of the Rigid Sphere model the $\lambda^{(i)}$'s seem to approximate closely to a geometrical progression and, on assuming an exact geometrical progression, one obtains a value for the thermal conductivity which is about 95% of that obtained using the Chapman-Enskog method.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of their colleagues in the Physics Department. One of us (RM) would like to thank the Gas Council for a maintenance grant.

THE VISCOSITY AND THERMAL CONDUCTIVITY
COEFFICIENTS OF THE RARE GASES AT
ATMOSPHERIC PRESSURE IN THE
TEMPERATURE RANGE 270 to 2000 K

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INTRODUCTION

The experimental determination of the coefficient of thermal conductivity of gases is difficult at both moderate and high temperatures; measurements are relatively scarce and the agreement found between them is often poor. In general, the errors associated with the measurement of thermal conductivity are considerably larger than the errors associated with the measurement of the viscosity coefficient at the same temperature.

The results of the rigorous kinetic theory of the transport properties of dilute gases - the Chapman-Enskog solution of the Boltzmann equation - show that to a high order approximation the thermal conductivity and viscosity coefficients of the monatomic gases are linearly related and virtually independent of the form of the intermolecular force law. Assuming the validity of the Boltzmann equation to be established beyond any reasonable doubt [1], the kinetic theory provides a means whereby the thermal conductivity of the dilute monatomic gases may be derived to a higher accuracy than present experimental techniques allow. Previous attempts to examine the validity of the relationship between the thermal conductivity and viscosity coefficients have not been satisfactory, even allowing for the large uncertainties in the thermal conductivity data, the predicted agreement diminishing systematically above room temperature. The cause of the discrepancy is now believed to be understood and has been shown [2,3] to arise from a systematic error in the previously accepted values for the viscosity coefficient of dilute gases.

THE COEFFICIENTS OF VISCOSITY

Extensive measurements of the viscosity coefficient of dilute gases published in recent years differ systematically from the previously accepted values - produced mainly by workers in the 1930's - by up to 10 per cent at the highest temperature of measurement. The new data have been obtained for a number of gases, often over a wide range of temperatures, by two different experimental techniques, the oscillating disc and capillary flow viscometers. A complete reassessment [4] of the available data for a number of gases including the rare gases was recently undertaken at the National Engineering Laboratory and recommended values of viscosity produced.

The correlations were based almost entirely on the new experimental work though some of the more reliable older measurements below 300 K were also included. The equation used to correlate the selected data is of the same form as the rigorous kinetic theory expression for the viscosity coefficient, the collision integral and higher approximation terms being represented by a series of Chebyshev polynomials in the reciprocal of absolute temperature. The new experimental

¹Figures in brackets indicate the literature references at the end of this Abstract.

measurements are in good agreement with each other and with the correlated values up to 1100 K; above this temperature though some small systematic deviations in the data remain. The measure of corresponding states agreement found for the rare gases suggests however that the trend of the new data is close to the correct one and that the remaining uncertainties in the viscosity coefficient are of the order of 1 per cent at the highest temperatures.

THE COEFFICIENTS OF THERMAL CONDUCTIVITY

The correlation of the viscosity coefficients of the rare gases were used together with the higher order kinetic theory expression to derive values for the thermal conductivity coefficients [5]. The higher approximation term differs little from unity and is only weakly dependent on the form of the intermolecular potential. An empirical relation was used to represent the correction factor for the Lennard-Jones (6-12) potential; the magnitude of the correction factor for the (exp-6) or any other potential commonly used to represent the transport properties of these gases would differ by no more than 0.15 per cent from the values used. The combined uncertainties in the derived values due to quantum diffraction, density and other effects are unlikely to exceed the estimated uncertainties in the viscosity correlations by more than 2.0 at 270 K and 1.5 at 2000 K.

The derived thermal conductivity values were compared with recent experimental measurements and correlations. With a few exceptions the experimental data for helium agree with the recommended values to within the stated uncertainties in the data; the exceptions are mainly data or correlations based on data which are uncorrected for accommodation effects. For neon and argon the agreement is generally good, the experimental data lying within their combined uncertainties of the derived values. Comparatively few experimental data are available for krypton and xenon, however, and the agreement with the derived values is less satisfactory. The large scatter and the systematic trend in the data for these gases is attributed to their low thermal conductivities and the increased experimental difficulty of obtaining reliable data.

Evidence suggests that the remaining exceptions to the thermal conductivity/viscosity correlation are due largely to systematic errors in the measurement of thermal conductivity, in particular, the corrections for accommodation effects and parallel heat flows, and not to a failure in the kinetic theory of the transport properties of dilute gases.

REFERENCES

- [1] Barker, J. A. et al, An experimental test of the Boltzmann equation: argon, *Mol. Phys.* 20, 347 (1971)
- [2] Hanley, H. J. M. and Childs, G. E., Discrepancies between viscosity data for simple gases, *Science*, 159, 1114 (1968)
- [3] Guevara, F. A. et al, A critique on the high temperature viscosity measurements of Trautz and Zink, *J.Chem.Phys.*, to be published
- [4] Watson, J. T. R., A correlation of the viscosity of eleven gases, NEL Report, to be published
- [5] Watson, J. T. R., The viscosity and thermal conductivity of the rare gases from 270 to 2000 K, NEL Report No 488. East Kilbride, Glasgow: National Engineering Laboratory, October 1971.

DETERMINATION OF HIGH TEMPERATURE VISCOSITIES FOR HYDROGEN, HELIUM, ARGON, NITROGEN, NEON, KRYPTON, AND XENON AND CALCULATION OF THE CORRESPONDING THERMAL CONDUCTIVITIES*

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INTRODUCTION

Recently, measurements of the viscosity of several gases have been extended to 2100°K at Los Alamos by a capillary flow method [1], [2], [3], [4]. Another capillary method was also recently used by Dawe and Smith [5] to measure to 1600°K these same gases, except for hydrogen. Both sets of viscosities are in agreement to within experimental error and are higher than previously reported values. This is taken as verification of the conjecture which has been made for several years that established viscosity values were slightly low. In this paper, a brief review is given of the Los Alamos viscometer and the results obtained with it. Thermal conductivities for the monatomic gases are calculated from these results.

RESULTS

The ratios obtained in the Los Alamos measurements are converted to viscosities by selecting established values at 283°K. These values and the constants from a least squares fit of the previously unsmoothed ratios are shown in Table I. The form used by Dawe and Smith [5] to show the temperature dependency is used here. T is the temperature in °K.

$$\text{LOG}_{10} [\eta(T)/\eta_0] = A \text{ LOG}_{10} T + (B/T) + (C/T^2) + D \quad (1)$$

	η_0		A	B	C	D
H ₂	86.14 μ Poise		1.82694	1,423.29	-506,675	-6.02577
N ₂	170.6 " "		0.86151	355.925	-155,276	-2.40145
He	191.2 " "		0.37552	-322.566	82,538.7	-0.50171
Ar	215.7 ^(a) " "		1.02090	579.327	-245,396	-2.98884
Ne	304.5 " "		0.30976	-251.711	30,822.7	-0.34486
Kr	241.6 " "		0.60584	-28.3536	-5,138.98	-1.34056
Xe	220.6 " "		-0.06210	-873.681	277,679	1.25937

(a) This value is an improvement over the one used in Reference 1.

Table I. The reference viscosities and the coefficients for Equation (1)

* This work performed under the auspices of the U. S. Atomic Energy Commission.

Figure 1. Temperature dependency of viscosity.

Figure 2. Thermal conductivity vs. temperature.

The resulting values are compared with those of other workers in Figure 1. For the monatomic gases, the simple first approximation from Chapman-Enskog kinetic theory [9], $\lambda = (15/4)(R/M)\eta$, is used to calculate the thermal conductivities from the viscosities. These values are compared to the measurements of others in Figure 2. Saxena's measurements are stated to be accurate to $\pm 3\%$ so that while our predictions are slightly different, the values are in agreement within experimental error. The helium values of Blais and Mann [8] are 9% higher than ours at 2100°K. For nitrogen and hydrogen it was not possible to make a reliable thermal conductivity calculation from the existing theory.

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The Los Alamos work which underlies this report is due to the leadership of Dr. B. B. McInteer, the collaboration of W. E. Wageman and M. Goldblatt, the assistance in apparatus design of R. M. Potter and D. E. Armstrong, and the continued encouragement of Dr. E. S. Robinson.

REFERENCES

- [1] F. A. Guevara, B. B. McInteer, and W. E. Wageman, *Phys. Fluids* **12**, 2493 (1969).
- [2] M. Goldblatt, F. A. Guevara, and B. B. McInteer, *Phys. Fluids* **13**, 2873 (1970).
- [3] F. A. Guevara and Gary Stensland, *Phys. Fluids* **14**, 746 (1971).
- [4] M. Goldblatt and W. E. Wageman, *Phys. Fluids* **14**, 1024 (1971).
- [5] R. A. Dawe and E. B. Smith, *J. Chem. Phys.* **52**, 693 (1970).
- [6] M. Trautz and R. Zink, *Ann. Physik* **7**, 427 (1930).
- [7] V. K. Saxena and S. C. Saxena, *J. Chem. Phys.* **51**, 3361 (1969).
- [8] N. C. Blais and J. B. Mann, *J. Chem. Phys.* **32**, 1459 (1960).
- [9] J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, "Molecular Theory of Gases and Liquids" (John Wiley & Sons, Inc., New York, 1964).

THERMAL CONDUCTIVITIES OF ALMOST-LORENTZIAN GAS MIXTURES

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INTRODUCTION

The thermal conductivities of several binary rare gas mixtures are calculated using the Chapman-Enskog [1,2]¹ and Perturbed-Lorentzian methods [3]. The results obtained using the Lennard-Jones (6-12) potential are compared.

THEORY

In the Chapman-Enskog theory for a binary gas mixture the distribution functions f_i are written as

$$f_i = f_i^{(0)} (1 + \phi_i)$$

which represents an expansion about a local Maxwellian distribution function $f_i^{(0)}$. For thermal conductivity the relevant term in ϕ_i is $-\frac{A_i \cdot \nabla}{T^2} \ln T^2$. A_i is approximated by an expansion in terms of Sonine polynomials of the form

$$\underline{A}_i(N) = \underline{W}_i \sum_{\mu=0}^N a_{i\mu}(N) S_{3/2}^{(\mu)}(\underline{W}_i^2)$$

where $\underline{W}_i$ is the reduced peculiar velocity of molecules of species i . The thermal conductivity may be expressed in terms of the expansion coefficients a_{11} and a_{21} . The values of the coefficients $a_{i\mu}(N)$ depend on the number of terms N taken in the expansion and usually converge rapidly to their 'true' values.

However in the case of an almost-Lorentzian mixture, where $m_1 \gg m_2$ and $n_1 \gg n_2$, the coefficients $a_{2\mu}(N)$ for the light gas only converge slowly to their 'true' values and for this case Sandler and Mason [3] have devised the so called "Perturbed-Lorentzian method".

For a true Lorentzian gas [m_1/m_2 and $n_1/n_2 \rightarrow \infty$] the Boltzman equations are uncoupled and an exact solution for $\underline{A}_2$ is possible, enabling an explicit expression to be derived for the exact coefficients $a_{2\mu}^L(\infty)$ which would appear in an infinite series expansion in Sonine polynomials. The coefficients $a_{1\mu}(N)$ for this case converge satisfactorily

¹ Figures in brackets indicate the literature references at the end of this Abstract.

² The notation is the same as that used by Sandler and Mason [3].

and are the same as those of a pure gas of the heavy species whereas the $a_{2\mu}^L(N)$ show poor convergence to the limiting values $a_{2\mu}^L(\infty)$.

For any binary gas mixture the coefficients $a_{i\mu}(N)$ may be determined from the coefficients $a_{1\mu}^L(N)$ by the equation

$$\underline{a}(N) = \{\underline{U} + \underline{P}(N)\} \underline{a}^L(N)$$

where $\underline{a}(N)$ is a column matrix formed from the coefficients $a_{1\mu}(N)$ and $a_{2\mu}(N)$, $\underline{U}$ is the unit matrix and $\underline{P}(N)$ is a matrix which describes the deviation of the gas from a true Lorentzian gas. The perturbed-Lorentzian approximation consists of substituting the coefficients $a_{2\mu}^L(\infty)$ for the slowly converging coefficients $a_{2\mu}^L(N)$. Sandler and Mason²⁴[3] have found that this leads to a better convergence for the coefficients $a_{2\mu}(N)$.

COMPUTATION

In order to calculate the collision integrals $\Omega^{(L,S)}$ and the coefficients $a_{2\mu}(\infty)$ collision cross-sections $Q^{(L)}$ had to be evaluated. These were calculated using methods proposed by O'Hara and Smith [4], [5]. The potential used in the calculations was the Lennard-Jones (6-12) potential.

Results will be presented for the calculation of the thermal conductivity of Xe-He, Kr-He and Ar-He mixtures.

ACKNOWLEDGMENTS

The authors wish to thank Professor E.A. Mason for suggesting this problem.

REFERENCES

- [1] S. Chapman and T.G. Cowling, "The Mathematical Theory of Non-Uniform Gases", Cambridge University Press, New York, 1952.
- [2] J.O. Hirschfelder, C.F. Curtiss and R.B. Bird, "Molecular Theory of Gases and Liquids," Wiley, New York, 1967.
- [3] S.I. Sandler and E.A. Mason, Physics of Fluids 12, 71 (1969).
- [4] H. O'Hara and F.J. Smith, J. Comp. Phys. 5, 328 (1970).
- [5] H. O'Hara and F.J. Smith, Comp. Phys. Comm. 2, 47 (1971).

ALTERNATIVE SOLUTION OF THE BOLTZMANN EQUATION
FOR DISPARATE MASS BINARY GASES: THERMAL FLUX PREDICTIONS

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INTRODUCTION

We investigate a new method of obtaining normal solutions to the Boltzmann equation which is expected to be more appropriate than the standard one for disparate mass binary gases. Predictions of the method for diffusion and thermal flux are presented.

APPROACH

The standard Chapman-Enskog method of solving the Boltzmann equation for a binary gas mixture is based on physical assumptions which are not expected to hold when the components have disparate masses [1,2]¹. Grad [2] has proposed an alternative method of solution, which we develop, explicitly aimed at overcoming this defect. The zero-order solutions are local Maxwellian distribution functions which can have independent flow velocities and temperatures. In a disparate-mass mixture, momentum of the components is expected to equilibrate much faster than temperature. Thus we choose zero-order solutions f_i^0 which have a common flow velocity $\underline{u}_0$ but different temperatures T_i . The first non-zero perturbations ϕ_i to the distribution functions have the form (in standard notation)¹

$$\phi_i = -\underline{A}_i \cdot \underline{\nabla} \ln T_i - \underline{B}_i : \underline{\nabla} \underline{u}_0 + \psi_i(V^2) + \underline{a} \cdot \underline{V} \quad , \quad (1)$$

where, in particular,

$$f_i^0 \left(\frac{5}{2} - \alpha_i V^2 \right) \underline{V} = \int f_i^0(V^2) f_i^0(U^2) [\underline{A}_i(\underline{V}') + \underline{A}_i(\underline{U}') - \underline{A}_i(\underline{V}) - \underline{A}_i(\underline{U})] \times \\ \times g_{ii} \, b \, db \, d\epsilon \, d\underline{U} \quad , \quad (2)$$

and $\underline{a}$ is found to be

$$\underline{a} = \frac{1}{nkT} \sum_{i=1,2} D_i \underline{\nabla} \ln T_i \quad ; \quad D_i \equiv \frac{m_i}{3} \int f_i^0 \underline{A}_i \cdot \underline{V} \, d\underline{V} \quad . \quad (3)$$

¹Figures in brackets indicate the literature references at the end of this Abstract.

RESULTS

The diffusion velocity $\bar{v}_1$ is given by

$$p p_1 \bar{v}_1 = - p_2 \frac{D_1}{T_1} \nabla T_1 + p_1 \frac{D_2}{T_2} \nabla T_2, \quad (4)$$

and similarly for $\bar{v}_2$. For thermal flux q one obtains

$$q = \frac{5}{2} \sum n_i k T_i \bar{v}_i - \lambda [\nabla T + (T_2 - T_1) \nabla \frac{n_1}{n}] - \kappa (\bar{v}_2 - \bar{v}_1), \quad (5)$$

$$\lambda_i = - \frac{k}{3} \int f_i^0 \left(\frac{5}{2} - \alpha_i v^2 \right) A_i \cdot v dv \quad (6)$$

$$\lambda = \sum \lambda_i + (\lambda_1 n_2 - \lambda_2 n_1) (\gamma/\delta); \quad \kappa = (\lambda_1 n_2 - \lambda_2 n_1) (\rho_1 \rho_2 p / \rho \delta) \quad (7)$$

$$\gamma = (- p_2 D_1 / T_1 + p_1 D_2 / T_2); \quad \delta = (n_2 p_2 D_1 / T_1 + n_1 p_1 D_2 / T_2) \quad (8)$$

Results obtained by this approach are in general simpler than those of the standard approach, since only single species collision integrals (here, D_i and λ_i) need be known. Comparison with experiment will be of interest.

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REFERENCES

- [1] B.B. Hamel, Phys. Fl. 9, 12 (1966)
- [2] H. Grad, in Rarefied Gas Dynamics, ed. F.M. Devienne (Pergamon Press, Inc., New York, 1960).

EXPERIMENTAL STUDIES OF THE THERMAL CONDUCTIVITY OF STEAM AND CARBON DIOXIDE IN THE CRITICAL REGION

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INTRODUCTION

The thermal conductivity coefficient of steam and carbon dioxide are reported in their critical regions. It is shown that the experimental data satisfy scaling laws.

APPARATUS

The concentric cylinder method without guard rings has been used for measuring the thermal conductivity of carbon dioxide and steam in the critical regions.¹ A tightened cell is used for steam to avoid the contact between the sample and the leads. The thickness of the layer is 0.2 mm. The temperature difference established across the layer is in general less than 0.1°C. Corrections have been made for the heat transfer by radiation, for parallel heat flow not conducted to the gas layer, for the location of thermocouples. The importance of convection is estimated. The accuracy is better than 10% for carbon dioxide and 6% for steam.

RESULTS

The anomalous thermal conductivity² is defined by $\Delta\lambda = \lambda - \lambda_{id}$ with $\lambda_{id} = \tilde{\lambda} + \lambda(0, T)$ and $\tilde{\lambda}$ excess of thermal conductivity outside the critical region, deduced from the high temperature data by,

$$\tilde{\lambda} = \lambda(\rho, T) - \lambda(0, T)$$

The scaling theories predict that the thermal conductivity at the critical isochore $\rho = \rho_c$ should diverge as

$$\Delta\lambda(\rho_c, T) = \Lambda \epsilon^\phi$$

with $\phi = -\gamma + V = -0.59 \pm 0.10$. To compare the anomalous thermal conductivity observed for different gases we plotted $\Delta\lambda/\lambda_c$ as a function of ϵ (Fig. 3). λ_c is the pseudo critical thermal conductivity.^c ($\lambda_c = \tilde{\lambda}(\rho_c) + \lambda(0, T_c)$).

¹B. Le Neindre
Thesis, University of Paris, 1969.

²J. V. Sengers
Transport Properties of Fluids near Critical Points, Technical Report No. 71074.
University of Maryland, 1970

Figure 1. The anomalous thermal conductivity $\Delta\lambda$ of CO_2

Figure 2. The anomalous thermal conductivity $\Delta\lambda$ of steam

Figure 3. $\Delta\lambda^* = \Delta\lambda/\lambda_0$ as a function of ϵ for carbon dioxide, steam, xenon

THERMAL TRANSPIRATION MEASUREMENTS AND THE
HEAT CONDUCTIVITY OF HYDROGEN CHLORIDE,
METHYL CHLORIDE AND METHYL FLUORIDE

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INTRODUCTION

Thermal transpiration measurements provide a source of data that can be used to compute the rotational collision numbers and the heat conductivity of polyatomic gases. The connection between these measurements and the transport properties is based on the kinetic theory procedures developed by Mason, Evans and Watson [1]¹ and recently modified by Annis, Malanauskas and Yun [2]. This "dusty gas" model has been shown to accurately describe the observed thermomolecular pressure difference as a function of the total pressure for each experimental temperature difference [3, 4]. This theory relates these experimental quantities to the rotational collision numbers and to the heat conductivity of the gases.

RESULTS AND CONCLUSIONS

The detailed results of the thermal transpiration experiments are reported by Park [5]. These data were used to determine the rotational relaxation numbers and the heat conductivity values for hydrogen chloride, methyl chloride and methyl fluoride that are reported in Table 1.

Temp K	Heat Conductivity $\lambda \times 10^{-2}$ ($\text{Wm}^{-1}\text{K}^{-1}$)							
	Hydrogen Chloride			Methyl Chloride			Methyl Fluoride	
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(c)
300	1.51	1.45	13.2	1.18	1.08	9.3		
350	1.83	1.71	13.6	1.56	1.42	13.7	2.46	3.7
400	2.05	1.96	13.9	1.90	1.74	18.1	3.12	2.6
450	2.39	2.39	23.1	2.31	2.22	12.8	3.86	2.0

- (a) This work
- (b) Obtained from Reference [6].
- (c) Rotation Collision Numbers Corrected for Resonant Exchange.

Table 1. Heat Conductivity and Rotational Collision Numbers for Polar Gases.

¹Figures in brackets indicate the literature reference at the end of this Abstract.

It is difficult to assess the experimental error of the reported heat conductivity. The previously reported data for hydrogen chloride and methyl chloride scatter and this contributes to the difference between the literature values and the values obtained in this work. The methyl fluoride values are probably accurate to $\pm 5\%$.

The rotation collision numbers are subject to errors which are tentatively assigned to be 20%. Very recent theoretical work by McCoy [7] and Loyalka [8] indicate that corrections should be made to the dusty gas model calculations to account for momentum accommodation at the capillary tube walls. The results reported here should be considered preliminary until this analysis has been completed.

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REFERENCES

- [1]. Mason, E. A., Evans, R. B., III and Watson, G. M., J. Chem. Phys., 38, 1808 (1963).
- [2]. Annis, B. K., Malanauskas, A. P. and Yun, J. Chem. Phys., 52, 1992 (1970).
- [3]. Healy, R. N. and Storvick, T. S., J. Chem. Phys., 50, 1419 (1969).
- [4]. Das Gupta, A. and Storvick, T. S., J. Chem. Phys., 52, 742 (1970).
- [5]. Park, H. S., "Rotational Collision Numbers of Polar Gases from Thermal Transpiration Measurements" M.S. Thesis, U. of Missouri-Columbia, June, 1971.
- [6]. Liley, P. E., "Thermal Conductivity of 46 Gases at Atmospheric Pressure", Proc. Fourth, Sym. on Thermophysical Properties, U. of Maryland, April, 1968 (ASME, New York 1968).
- [7]. McCoy, B. J., "Higher-Order Constitutive Equations in the Study of Thermal Transpiration", Presented at the 70th National A.I.Ch.E. Meeting, Aug. 29-Sept. 1, 1971, Atlantic City, New Jersey.
- [8]. Loyalka, S. K., "Kinetic Theory of Thermal Transpiration and Mechano-Caloric Effect-I", to appear, J. Chem. Phys., October, 1971.

Radiation Interaction Effect Upon Thermal
Conductivity Measurements in an Absorbing-Emitting Gas¹

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Recent advances in gaseous radiation heat transfer indicate that thermal conductivity measurements performed upon absorbing-emitting gases may be in error $[1]^2$. Experimenters customarily correct for the total net radiative transfer between surfaces but no attempt is made to characterize the non-linearity introduced into the temperature profile by gaseous radiation in the layer.

The present work utilizes an exponential wide-band model $[2]$ in conjunction with an experimental data correlation $[3]$ to arrive at a model for the gas vibration-rotation bands as a function of the optical path length. Results of the analysis are presented in Figures 1 and 2 for the $15\mu\text{m}$ and $4.3\mu\text{m}$ fundamental bands of CO_2 . The quantity indicated as q_0 is the sum of the radiative and conductive fluxes without interaction. The actual total flux which takes into account the radiation conduction interaction is denoted q in the Figures.

Figure 1 illustrates the effect of plate emittance upon the total heat transfer. One interesting fact observed from this figure is that for the large gas layer indicated (5 cm), the assumption of superposition is better for black surfaces ($\epsilon_1 = \epsilon_2 = 1.0$) than for perfectly reflecting surfaces ($\epsilon_1 = \epsilon_2 = 0$). For smaller layers, the interaction effect will decrease since the optical thickness decreases. In the optically thin limit, superposition is a correct assumption. The effect of pressure upon the total heat transfer is illustrated in Figure 2. As expected, once the gas absorption bands are fully pressure broadened, increasing the pressure results in no net change in the total flux.

1. This work was supported by the United States Atomic Energy Commission.
2. Figures in brackets indicate references listed at the end of this abstract.

References

1. Schimmel, W. P., et al, "Interferometric Study of Radiation-Conduction Interaction," Proceedings of the Fourth International Heat Transfer Conference, (1970).
2. Edwards, D. K., and Menard, W. A., "Comparison of Models for Correlation of Total Band Absorption," Appl. Optics, 3, p. 621-675, (1964).
3. Tien, C. L., and Lowder, J. E., "A Correlation for Total Bank Absorption of Radiating Gases," Int. Journal of Heat & Mass Transfer, 9, #7, p. 698-701, (1966).

THURSDAY

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Thermal Conductivity of Zinc Oxide

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ZnO is a hexagonal, wide band gap, piezoelectric semiconductor which has received considerable attention for acoustoelectric applications. Although its acoustic, electrical, and optical properties have been extensively studied, we are not aware of any thermal conductivity studies on ZnO. We have measured the thermal conductivities of two hydrothermally grown Li doped single crystals of ZnO that were purchased from Ventron. The heat flow was parallel to the "c" axis in one crystal and parallel to the "a" axis in the other. The electrical resistivities were $0.42 \Omega\text{cm}$ and approximately $10^6 \Omega\text{cm}$ for the "c" and "a" samples. This difference is the result of the doping, not of crystal anisotropy. The thermal conductivities were measured in a conventional steady state longitudinal heat flow apparatus from 4 to 300K.

The measured thermal conductivities did not show a significant anisotropy for the two crystallographic directions; this result is not surprising since the primitive unit cell is nearly isotropic. The thermal conductivities at liquid helium temperatures are nearly the same for the two samples which have considerably different electrical properties; this result indicates that electron phonon scattering is not important. We have analyzed the thermal conductivity data in terms of the Debye-Callaway model with a relaxation time that included boundary, dislocation, point defect and phonon-phonon scattering.

Thermal Conductivity of Single Crystal

Europium Monoxide

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The thermal conductivity of a single crystal of EuO oriented in the [100] direction has been measured from 4 to 200K with particular attention to the region of the Curie temperature, $T_C = 69K$. This same crystal was studied by Luthi, et al. [1] who found no anomalous ultrasonic attenuation above T_C . Our results indicate some anomalous scattering of thermal phonons in this region, but much less than that reported by Morris and Cason[2] in a sintered powder sample. Possible spin-phonon coupling mechanisms will be discussed.

[1] B. Luthi, T. J. Moran and R. J. Pollina, J. Phys. Chem. Solids 31, 1741 (1970).

[2] R. G. Morris and J. L. Cason, Jr., Helv. Phys. Acta. 41, 1045 (1968).

IN-PILE THERMAL CONDUCTIVITY MEASUREMENTS ON OXIDE FUELS FOR NUCLEAR REACTORS

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INTRODUCTION

The purpose of this work is the in-pile direct measurement of the thermal conductivity of ceramic nuclear fuels. The program foresees the irradiation of 8 samples, bearing 4 different types of fuel: UO_2 , pellets and vibrocompacted powder; UO_2 - PuO_2 , pellets and vibrocompacted powder (sol-gel). The reports deals with the results of the irradiation of the first 5 samples.

EXPERIMENT DESCRIPTION

The Zr-2 sheathed pins have two different geometries: 16.0 (mm) I.D. x 17.8 (mm) O.D. cans containing pelleted UO_2 with an enrichment of 8% (94% T.D.) and vibrocompacted UO_2 with an enrichment of 9% (85% T.D.); 13.18 (mm) I.D. x 15.66 (mm) O.D. cans containing mixed UO_2 - PuO_2 fuel with an enrichment of 4% (95% T.D. for pellets and 85% T.D. for vibrocompacted fuel). A WRe 5% - WRe 26% thermocouple is placed on the axis of the fuel pin, and Chromel-Alumel thermocouples are placed at 1 mm from the fuel surface.

The samples are placed in an irradiation device able to measure continuously, by means of an electric calorimetric system, the total power generated in the fuel pin.

The maximum burn-up reached is about 3,000 MWD/tonn.

RESULTS AND CONCLUSIONS

The values of integral conductivity between the surface and the centerline temperature are calculated according to the Robertson's formula. The fitting of the experimental data is done correlating the integral conductivity to the temperature by means of the thermal conductivity formula:

$$\lambda(T) = \frac{1}{B + CT} + DT^3 \quad (1)$$

The minimum temperature measured is $\sim 300^\circ\text{C}$, while the maximum temperatures are 1,900, 1,700 and 2,200 $^\circ\text{C}$ for the UO_2 pellets, UO_2 -vipac and UO_2 PuO_2 -pellets, respectively. A previous short-time irradiation experiment on UO_2 has given the values of the integral conductivity up to the melting point, obtained indirectly with post-irradiation measurements. The best fitting values of B, C and D are shown in Table 1; for the UO_2 samples, pellets and vipac, the experimental data include the results of short-time irradiation experiments.

Sample	B ($\text{W}^{-1} \text{ cm}^\circ\text{K}$)	C ($\text{W}^{-1} \text{ cm}$)	D ($\text{W cm}^{-1} \text{ }^\circ\text{K}^{-4}$)
UO_2 , pellets	2.5	.02848	1.2×10^{-12}
UO_2 , powder	46.5	$.1312 \times 10^{-5}$	9×10^{-13}
UO_2 - PuO_2 pellets	0	.02261	6×10^{-13}

Table 1 - B, C, D. Best-fitting values for various samples

Fig. 1 - Integral conductivity and thermal conductivity

In the figure 1.a) the integral thermal conductivity from 300°C to central temperature as a function of central temperature is shown; in figure 1.b) the corresponding thermal conductivity curves are shown. The dashed line represents the extrapolated trend.

× THERMAL DIFFUSIVITY OF THORIA-URANIA MIXED OXIDES AND SOME MATERIALS TO BE USED AS REFERENCE IN THE RANGE 650 + 2,650 °K

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INTRODUCTION

Some thermal diffusivity measurements on U-Th mixed oxides with a U content of 6, 10 and 100% have been performed to continue some studies already carried out in this field [1]¹. The materials, POCO-graphite and RVD-graphite obtained from AFML, were tested as reference materials. An attempt was made to correlate directly thermal diffusivity to the physical characteristics of the material used.

APPARATUS

The measurements were performed using the "flash" or "pulse" technique with an apparatus already described [1] and improved in order to reach higher temperatures [2]. The thermal diffusivity was calculated with Cowan's method [3], modified to take into account the radial heat losses and the laser pulse length [2 and 4]. The experiments were performed under Argon atmosphere at a pressure of ~10 torr, since this pressure has proved to be the best condition to avoid a high evaporation rate as well as high heat losses.

RESULTS AND CONCLUSIONS

Figs 1 and 2 show the mean values of the experimental results. All data were fitted with the equation having the form:

$$\alpha = \frac{1}{A+B \cdot T} \quad \alpha \left[\frac{\text{cm}^2 \cdot \text{sec}^{-1}}{\text{°K}} \right]$$

The following table shows the values of the constants.

¹ Figures in brackets indicate the literature references at the end of this abstract.

Reference	A	B	Oxides	A	B
POCO	1.6114	$4.4 \cdot 10^{-3}$	UO_2	58.536	$3.8 \cdot 10^{-2}$
RVD	3.3118	$4.4 \cdot 10^{-3}$	$(Th_{0.96}U_{0.04})O_2$	0.0559	$5.27 \cdot 10^{-2}$
(with grain)			$(Th_{0.90}U_{0.10})O_2$	12.5949	$4.92 \cdot 10^{-2}$

Figure 1

Figure 2

Thermal diffusivity (Comparison of mean values).

REFERENCES

- [1] C. Ferro, S. Moretti, C. Patimo, Thermal diffusivity and conductivity of sintered uranium thorium mixed oxides, Proc. 8th Conf. on Thermal Conductivity - Ed. by C.Y. Ho and R.E. Taylor, Plenum Press N.Y., pp. 815-822.
- [2] C. Ferro, C. Patimo, C. Piconi, Thermal properties of ceramic materials, CNEN RT/ING(70)23.
- [3] R.P. Cowan, Pulse method of measuring thermal diffusivity at high temperatures, J. Appl. Phys. 34, n° 4, pp. 926-927.
- [4] R.E. Taylor, J.A. Cape, Finite pulse time effects in the flash diffusivity technique, J. Appl. Phys., 5, n° 10 pp. 212-213.

THERMAL CONDUCTIVITY OF ALKALI HALIDE CRYSTALS
CONTAINING HYDROXIDE ION AT VERY LOW
TEMPERATURES

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Thermal conductivity measurements have been made on crystals of NaCl:NaOH, KCl:KOH, RbCl:RbOH, and KI:KOH between .09 to .35 K. Earlier thermal conductivity measurements on NaCl:NaOH give strong evidence for low lying energy levels of the hydroxide ion between .35 to .6 K.¹ Recent measurements on NaCl:NaOH indicate that no additional levels exist below .35 K and these measurements support a Devonshire type energy level scheme. The thermal conductivity data of KCl:KOH is surprising in that the conductivity is greatly depressed to the lowest temperature of .09 K. The data suggest a continuum of tunneling levels for KCl:KOH and does not support a Devonshire type energy scheme. Data of RbCl:RbOH suggest energy levels below .1 K. The KI:KOH data indicates a low lying level at .2 K or .5 cm⁻¹.

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¹ Rosenbaum, Ralph L, Chau, C. K., and Klein, M. V., Phys. Rev. 186, 852 (1969).

THERMAL CONDUCTIVITY OF CADMIUM INDIUM SULFIDE AND ITS ALLOYS WITH CADMIUM CHROMIUM SULFIDE

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INTRODUCTION

CdIn_2S_4 is known as a photoconductor [1]² and crystallizes in the cubic spinel structure having a lattice constant of $a = 10.797 \text{ \AA}$. However, the large single crystals appropriate to the electrical and the thermal measurements have not yet been obtained. Recently, we have succeeded in growing large single crystals of CdIn_2S_4 and have studied the electrical and the optical properties [2][3]. However, the thermal conductivity of CdIn_2S_4 has not yet been studied. In this paper a result of the measurement of the thermal conductivity of a single crystal of CdIn_2S_4 in the temperature range from 4 K to 300 K are presented.

CdCr_2S_4 is known as a magnetic semiconductor [4] and has the same crystal structure as that of CdIn_2S_4 . As it is interesting to study the transport properties of CdIn_2S_4 - CdCr_2S_4 system, the thermal conductivity of $\text{CdIn}_{2(1-x)}\text{Cr}_{2x}\text{S}_4$ ($x \leq 0.01$) has also been measured.

APPARATUS

The thermal conductivity was determined by mounting a sample in the form of a rod in a cryostat described previously [5], the temperature being determined by gold-cobalt versus copper thermocouples. Size of the sample was $2.96 \times 1.66 \times 16.5 \text{ mm}^3$.

RESULTS

Figure 1 shows the thermal conductivity of CdIn_2S_4 and $\text{CdIn}_{2(1-x)}\text{Cr}_{2x}\text{S}_4$ with $x = 0.01$ as a function of the temperature. The electronic contribution to the thermal conductivity can be neglected in most of the temperature range studied because of the high electrical resistivity of the samples. A dotted line in the figure is the theoretical curve computed for CdIn_2S_4 from Callaway's model using a relaxation time, τ , such as

$$\tau^{-1} = A \omega^4 + B \omega^2 T e^{-4/T} + C,$$

with $A = 1 \times 10^{-42} \text{ sec}^3$, $B = 3 \times 10^{-18} \text{ sec deg}^{-1}$, $b = 40 \text{ deg}$ and $C = 8.46 \times 10^5 \text{ sec}^{-1}$, where ω is the phonon angular frequency, T is the absolute temperature.

¹ Assistant Professor, Assistant, and graduate student, respectively.

² Figures in brackets indicate the literature references at the end of this abstract.

Figure 1. Thermal conductivity of CdIn_2S_4 and $\text{CdIn}_{1.98}\text{Cr}_{0.02}\text{S}_4$.

It is noted that substitution of chromium atoms for the indium atoms in CdIn_2S_4 by 1 % markedly influences the absolute values and the temperature dependency of the thermal conductivity in the low temperature region. The result may be interpreted by the scattering mechanism due to absorption and re-emission of the phonons between the energy levels of Cr^{3+} ions in an octahedral surrounding of S^{2-} ions [6].

REFERENCES

- [1] Koelmans, H. and Grimmeiss, H. G., *Physica* **25**, 1287 (1959)
- [2] Endo, S., Sudo, I. and Irie, T., *J. Phys. Soc. Japan* **29**, 519 (1970)
- [3] Endo, S., Sudo, I., Nakanishi, H. and Irie, T., *J. Phys. Soc. Japan*, to be published.
- [4] Baltzer, P. K., Lehman, H. W., and Robbins, M., *Phys. Rev. Letters* **15**, 493 (1965)
- [5] Nakanishi, H., Endo, S., and Irie, T., *Japan J. appl. Phys.* **8**, 443 (1969)
- [6] Slack, G. A. and Galginaitis, S., *Phys. Rev.* **133**, A253 (1964)

THERMAL CONDUCTIVITY OF NYLON FROM 4 TO 350 K

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INTRODUCTION

Thermal conductivity measurements have been carried out on two brands (Comco and Polypenco 101) of type 66 nylon in which the heat flow was along the direction of extrusion of the material. This data was sought because there is an absence of conductivity data on this important technical material in the range 20 K to 250 K and all the available data for above 250 K related to conduction perpendicular to the direction of extrusion of the sample.

EXPERIMENTAL

Absolute, linear-flow measurements were taken in an adiabatic vacuum cryostat. For the present work a shield was incorporated, around the sample, along which the temperature distribution was matched as closely as possible to that along the surface of the sample; this was achieved with the aid of a heater at the top of the shield and a differential thermocouple between the tops of the two components. Here the objective was to minimize the radiative losses from the sample. Our data is summarized in table I.

TABLE I. THERMAL CONDUCTIVITY OF NYLON

Temperature (K)	Thermal Conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)		
	Polypenco 101	Comco	Comco with Powder
340	0.668	0.682	
320	0.606	0.634	0.350
300	0.557	0.585	0.360
280	0.512	0.541	
260	0.478	0.502	
240	0.447	0.469	
220	0.415	0.440	0.350
200	0.390	0.412	0.340
180	0.367	0.391	0.337
160	0.347	0.364	0.334
140	0.330	0.343	0.334
120	0.310	0.324	0.313
100	0.291	0.303	0.298
80	0.266	0.275	0.271
60	0.229	0.237	
40	0.180	0.184	
20	0.095	0.096	
10	0.045	0.045	
4.5	0.015	0.015	

Below 20 K our data is in good agreement with other data. Indeed the conductivity is not a sensitive function of either type or manufacturer; a least squares fit in logarithmic space for all available data yielded

$$\lambda = 0.0019T^{1.30}w_m^{-1}K^{-1} \quad - - - - - (1)$$

with a root mean square deviation of less than 10%. Below 50 K there was no difference in the values of λ obtained with no heat supplied to the shield heater and with the supply to this heater controlled to match temperature distributions.

At higher temperatures the effects of radiation became evident; the apparent thermal conductivity of the sample increased by 8% and 55% at 100 K and 300 K respectively when control of the shield was dispensed with. These values agreed very closely with estimated radiation influence, and at 350 K the temperature derivative of λ was decreasing so it appeared that the shield, when controlled, was being effective in eliminating radiative effects. A marked increase in the slope of the conductivity-temperature curve was observed at the glass transition temperature (≈ 193 K).

In order to determine with greater certainty whether radiation effects had been eliminated, the measurements are being repeated with a radiation-preventative powder (50-50 mixture by weight of Cabosil and Aluminum powder) in the interspace between the sample and shield. It is apparent from this data (see table I) that equality of the temperatures at the top of the shield and the sample, and at their bases, is not a sufficient condition to prevent radiative heat transfers. The change in slope of conductivity at 193 K is now more evident, and it seems likely that λ is a decreasing function of temperature at 300 K and above, which is consistent with a decrease in the order within the sample as the melting point is approached.

CONCLUSIONS

At temperatures above 100 K the linear heat-flow method is unsuitable for measurements on poorly conducting samples unless a powder and controlled shield are employed; the complete suitability of this combination still has to be demonstrated. The insensitivity of the conductivity of nylon to the type and to the source of the sample and its simple relationship to temperature recommend this material for consideration as a secondary, low conductivity standard for the range below 20 K.

PROPERTIES OF SOME THERMAL BONDING MEDIA

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Large increases have been observed in the thermal conductance of metal-metal interfaces when a thin layer of grease (Apiezon N or T) is applied. However, as the temperature is lowered to the glass-transition temperature of the grease, the conductance drops abruptly by more than an order of magnitude. Measurements of the instantaneous thermal conductivity of N grease have been made in a linear heat-flow apparatus, but the conductivity turned out to be so low (less than $0.5 \text{ Wm}^{-1}\text{K}^{-1}$) that the radiation correction was excessive.

Measurements are being taken on Apiezon L, M, N and T greases in a simple unguarded plate apparatus. Edge effects are estimated from a numerical solution of the heat flow equation with the required boundary conditions. The accuracy of this process will be checked by comparison with results from a guarded plate system. Two types of unguarded apparatus are being used. In one the two outer heat sinks remain virtually equally spaced whilst in the second their separation is controlled, by the relative differential contraction of nylon and copper, to match the contraction of the grease as the temperature is lowered. Some differences in the performance of these two systems are being evaluated.

Data collected to date indicates that the thermal conductivities of these greases are around $0.1 \text{ Wm}^{-1}\text{K}^{-1}$ at room temperature and they drop by a factor of close to 10 below the glass-transition temperatures.

ARMCO IRON - A THERMAL CONDUCTIVITY REFERENCE MATERIAL
AND
A NEW THERMAL CONDUCTIVITY MODEL

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INTRODUCTION

Battelle's Columbus Laboratories and other laboratories have used Armco iron as a thermal conductivity reference material since 1934. The results of measurements involving a large number of laboratories and lots of Armco iron show the material to be a reliable thermal conductivity reference material over the temperature range 80-925 K. In the 0-80 K temperature range, measurements are limited to one laboratory [1]** and to one lot of material. The limited data in this range coupled with metallurgical observations suggest a new thermal conductivity model for iron and iron alloys.

RESULTS AND DISCUSSION

Recent literature usage has made the term "Armco iron" synonymous with iron made by the basic open-hearth process. One lot of such iron used in a round robin by seven laboratories is more specifically identified as "Armco Magnetic Ingot Iron for D-C Applications" [2]. Thermal conductivity measurements on 18 lots of Armco iron by about as many laboratories, using a wide range of measurement methods, yield data in the temperature range 80-925 K, having a standard deviation of 1.5 percent. The standard deviation increases to 7.1 percent for the 925-1275 K temperature range. Based on about 70 percent as many electrical resistivity measurements, the standard deviations for this property in the 80-925 K and 925-1275 K temperature ranges are 2.4 and 0.6 percent, respectively.

Plots of Lorenz ratio versus temperature have been used for at least three decades [1, 3, 4, 5, 6] in discussing factors contributing to the thermal conductivity of a metal. Breaking with tradition, a plot of thermal conductivity versus temperature divided by electrical

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**Figures in brackets indicate literature references at the end of this abstract.

resistivity for all available Armco-iron data over the temperature range 6-1275 K brings out the following in this correlation.

1. A linear relationship exists up to about 20 K, the normal boiling point of a liquid hydrogen.
2. Above 20 K, two nonlinear curves (depending upon specimen treatment) form which rejoin at about 77 K, the normal boiling point of liquid nitrogen.
3. From about 77 K to 925 K, the correlation is again linear with changes in slope at the Curie temperatures of two compounds.
4. In the temperature range 925-1275 K, the correlation is nonlinear.

For some time now metallurgists have been concerned with two forms of hydrogen in iron and steel, residual (generally considered molecular) and diffusible (considered atomic). Hill and Johnson [7] comment on the theories as to how molecular hydrogen is accommodated in iron and steel and state "...it (hydrogen) seems to have a severe grain-boundary weakening effect". To my knowledge there is no literature suggesting the presence of molecular nitrogen in iron and steel. The departure of the thermal conductivity versus temperature divided by electrical resistivity curve from a linear function at 20 K, coupled with the evidence of molecular hydrogen in iron, suggest a new thermal conductivity model for iron. The new model contains a gas phase and/or compounds in a semicontinuous manner in subgrain or grain boundaries in sufficient amount to influence the thermal and electrical properties of iron and steel.

ACKNOWLEDGMENTS

The permission of Battelle to publish Armco iron data generated at the Columbus Laboratories is very much appreciated. To the persons and laboratories participating in the round robin initiated in 1959, and the literally hundred or more present and former Battelle staff members who made measurements, gave literature guidance, and answered many questions, a sincere "thank you" for their cooperation and efforts. Special thanks are extended to my former associate H. W. Deem, with whom I shared the responsibilities of the Battelle-Columbus Physical Measurement Group for more than a decade; to W. H. Goldthwaite, Manager, Physics and Metallurgy Department, and his predecessor J. W. Chastain, Jr., for their condoning my extracurricular interest in thermal properties after relinquishing my responsibilities in that area; and to the late H. W. Russell for his introduction to thermal conductivity measurements in

1930 and who served for more than 35 years as a source of inspiration and guidance in many areas of physical measurement.

REFERENCES

- [1] Hust, J. G., "Thermal Conductivity Standard Reference Materials From 0 to 300 K - I, Armco Iron", Ninth Thermal Conductivity Conference, USAEC Conf. - 691002, 1970, pp 217-233.
- [2] Armco Magnetic Ingot Iron for D-C Applications, Armco Steel Corporation, Middletown, Ohio, Bulletin LE-168, 1968.
- [3] Powell, R. W., Proc. Royal Soc., Vol. 51, 1939, pp 407-417.
- [4] Shanks, H. R., Klein, A. H., and Danielson, G. C., Jour. Applied Physics, Vol. 38, 1967, pp 2885-2892.
- [5] Watson, T.W., Flynn, D. R., and Robinson, H. E., Jour. Res. U.S. Natl. Bur. Stds., Vol. 71C, 1967, pp 285-291.
- [6] Hust, J. G. and Clark, A. F., Materials Research and Standards, Vol. 11, 1971, pp 22-24.
- [7] Hill, M. L. and Johnson, E. W., Trans. Metallurgical Soc. AIME, Vol. 221, 1961, pp 622-629.

THURSDAY

a.m.

II

PRECISE CMN THERMOMETRY

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Numerous disagreements on very low temperature thermometry scales have motivated us to develop a precise and simple thermometry scheme for CMN. The scheme involves these techniques: a) Epibond 100A epoxy mixing chamber with an internal CMN chamber that contains: 1) susceptibility coils for the mutual inductance bridge wound directly onto the outside of the Epibond 100A mixing chamber, 2) copper wire brushes that externally connect the mixing chamber to a He^3 vapor pressure bulb, to carbon and germanium resistance thermometers, and to heaters; b) a Daybell type mutual inductance bridge¹ in which a second ratio transformer is used to cancel out small resistive voltages components arising from resistance losses internal to the CMN salt; and c) a He^3 vapor pressure bulb of 1 cm^3 volume which is coupled to the mixing chamber via copper brushes, but whose capillary filling tube is thermally isolated from components of the dilution refrigerator with a heater. The CMN is calibrated against the vapor pressure of He^3 from .6 to 1.1 K; the system works beautifully to .010 K and lower. CMN salts from Technion and Argonne National Laboratory have been compared with excellent agreement. The Technion CMN salt has been found contaminated with paramagnetic impurities that freeze out below 1 K; we have concluded that reliable calibrations of CMN salts can be made only below 1 K.

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¹Daybell, M, Rev. Sci. Instru. 38, 1412 (1967) .

TEMPERATURE MEASUREMENT IN A FLUID BOUNDARY LAYER BY LASER INTERFEROMETRIC HOLOGRAPHY

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INTRODUCTION

The application of laser systems to non-destructive testing have broadened constantly during the past decade. The application of laser holography to temperature detection in a gaseous media or its use to detect concentration gradients in a two component gas system has not been extensively investigated. It is the purpose of this paper to demonstrate the application of holography to the detection of temperature in a simple gaseous system in the neighborhood of a heated surface.

EXPERIMENTAL APPARATUS

The holographic interferometer shown in figure 1 was used to detect the temperature field in a free convection boundary layer caused by heating air about a vertical plate. The heated vertical plate was non-isothermal from its base to its upper edge. Experiments were conducted for four separate temperature distributions along the plate. The maximum plate temperature ranged from 200°F to 493°F. Photographs were taken of the fringe patterns as they were seen in the three dimensional holograms used to record the phenomenon. Temperature and boundary layer thickness information was then extracted from the two dimensional ordinary photographs.

RESULTS

The results of this study indicate that the holographic interferometer has great utility as a temperature detecting device. It's major advantages are: 1) remote sensing, 2) inexpensive compared to other interferometers, 3) records three dimensionally the events in the neighborhood of test surface, 4) precision components are not required, 5) dust-free environment is not required, 6) precision alignment is not essential, 7) the method can be used to detect live real time fringes.

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a) Top view

b) Side view

Figure 1. Laser Interferometer Test Arrangement

ACKNOWLEDGEMENT

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✓
DETERMINATION OF THE HIGH-TEMPERATURE
ENTHALPIES OF SOME HIGH BORON COMPOUNDS

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INTRODUCTION

Boron forms binary compounds of compositions MB_2 , MB_4 , MB_6 and MB_{12} with a great number of elements. In general the borides are very refractory, extremely hard and brittle, have high thermal and electrical conductivities and have high enthalpies of fusion. These properties make them very attractive for numerous technological applications, particularly at elevated temperatures. However, very little thermodynamic data exist for the higher borides at temperatures above 800°K. In order to fill this need, a study of a few selected borides was carried out, and the high temperature enthalpies of ErB_{12} , UB_{12} , $Y_{.6}Zr_{.4}B_{12}$, and ErB_4 are reported in this presentation.

EXPERIMENTAL

The enthalpy measurements were made with a drop calorimeter consisting of a tungsten mesh furnace and a massive copper block calorimeter. The temperature rise of the copper block was measured with a quartz crystal thermometer with a precision of $\pm 1 \times 10^{-5}$ °K. A number of unique features of the apparatus reduced the uncertainties inherent in high temperature drop calorimetry. Large sample volume to surface ratios were used to reduce the effect of radiation losses during the drop.

The techniques used and various apparatus features helped to minimize the heat exchange between the calorimeter and the isothermal surroundings. The furnace and calorimeter were evacuated to at least 2×10^{-5} torr, and the resulting heat exchange coefficient was on the order of 4×10^{-6} deg/sec. for a one degree temperature difference. The amount of heat exchanged was further minimized by maximizing the rate of thermal equilibration between the sample and the calorimeter. This was accomplished by fitting the calorimeter with a sealable lid, which enabled the introduction of a heat exchange gas into the receiving well.

The heat exchange between the calorimeter and the isothermal wall was calculated in the usual manner by assuming Newtons cooling law [1]¹. To reduce the uncertainties in calculating the heat exchange, a calculational method was adopted which enables a unique heat exchange coefficient to be calculated for each run. All calculations were made with a CDC-6600 computer.

¹Figures in brackets indicate the literature references at the end of this abstract.

The compounds were all prepared by arc melting crystalline boron of 99.96% purity with the appropriate metal. All samples were shown to be single phase by X-ray diffraction. The compounds were contained in graphite crucibles which were borided to ensure against crucible-sample interactions.

RESULTS AND DISCUSSION

The enthalpies of $Y_{.6}Zr_{.4}B_{12}$, ErB_{12} , UB_{12} and ErB_4 were determined over the temperature range $1000^\circ - 2000^\circ C$. These dodecaborides were chosen because they, along with the previously investigated MgB_{12} [2] give representation over the entire periodic table. The dodecaboride enthalpies were all in close agreement with those predicted by assuming additivity. The ratio of the additive estimate to the experimental value was found to be 1.03-1.05 for all dodecaborides studied. This relationship was also observed for MgB_{12} [2]. Because such a wide range of dodecaborides has been shown to abide by the additivity law, it is reasonable to expect that the thermochemical data of all dodecaborides can be approximated by additivity.

A cursory glance at the data available for diborides [3] shows that they too can be approximated to within $\pm 5\%$ by the additivity law. It is therefore postulated that borides of the intermediate compositions (MB_4 and MB_6) behave similarly. Experimental verification is in part provided by the enthalpy measurements on ErB_4 , the additive to experimental ratio varying from 1.05 at $1000^\circ C$ to 1.07 at $2000^\circ C$.

It is therefore concluded that the enthalpies and specific heats of MB_2 , MB_4 , MB_6 and MB_{12} can be approximated to within 5-10% by assuming additivity.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to their colleagues who assisted in this investigation. Dr. William O. J. Boo (University of Mississippi) gave valuable assistance in refining and calibrating the calorimeter. Dr. Ray G. Bedford devised the calculational method and did much of the computer programming. Mr. Donald Helsper was instrumental in preparing the samples.

REFERENCES

- [1] Douglas, T. B. and King, E. G., in Experimental Thermodynamics Vol. I edited by McCullough, J. P. and Scott, D. W. (Plenum Press, New York, 1968).
- [2] Germaidze, M. E., Gel'd, P. V., and Letan, S. M., Zh. Prikl. Khim. 39, 1941 (1966).
- [3] JANAF Thermochemical Tables, (The Dow Chemical Company, Midland, Michigan).

SPLINE FUNCTION CORRELATION OF THE
SPECIFIC HEAT OF LIQUID METALS:
SODIUM, POTASSIUM, AND MERCURY

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INTRODUCTION

Experimental specific heat data reported in the literature for sodium, potassium, and mercury were analyzed and recommended values were generated for temperatures between 0°K to their melting points and beyond with the aid of an electronic computer using the spline fit technique.

A full-scale comprehensive program is underway at the Thermophysical Properties Research Center, Purdue University to collect, analyze, and generate standard reference data on thermophysical properties of solid, liquid, and gaseous substances. The work at TPRC has culminated in the publication of the handbook: "THERMOPHYSICAL PROPERTIES OF MATTER" by Plenum Press in 1970. The need for synthesizing existing knowledge on thermophysical properties of materials has long been recognized by such scientific organizations as: The International Council of Scientific Unions (ICSU), The National Standard Reference Data System (NSRDS), and the State System of Standard Reference Data (SSSRD). The dissemination of standard reference data to the ultimate users, the engineers and scientists is very essential for national progress.

CORRELATION OF SPECIFIC HEAT DATA

Recommended values for the specific heat of mercury were based on the experimental data reported by Busey and Gianque [1]², Douglas, Ball and Ginnings [4], and Smith and Walcott [12].

Specific heat data for potassium from which recommended values were generated were taken from measurements reported by Douglas et al. [5], Krier, Craig, and Wallace [8], Lien and Phillips [9] and Roberts [11].

The recommended specific heat values for sodium were selected from the investigations reported by Dauphine and McDonald [3], Gaumer and Heer [6], Ginnings, Douglas, and Ball [7], Martin [10] and Roberts [11].

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² Figures in brackets indicate the literature references at the end of this Abstract.

In this paper, the specific heats of sodium, potassium, and mercury have been correlated with an empirical spline function with the aid of a computer. The expressions used is in the form of a logarithmic cubic equation:

$$\ln C_p = A + B \ln T + C (\ln T)^2 + D (\ln T)^3. \quad (1)$$

This type of equation has been used successfully to correlate the data on the specific heat of aluminum [2] between zero to its melting temperature and beyond. To show its adaptability in correlating the data on the specific heat of other solids, the values for sodium, potassium, and mercury have been chosen because of their engineering importance.

RESULTS AND CONCLUSIONS

The recommended values generated by a spline function program are presented in Tables I, II, and III. The spline function equation represents the experimental data to within 5 per cent between 0°K up to melting points and beyond.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Busey, R. H. and Glauque, W. F., J. Am. Chem. Soc., 75, 806-9 (1953).
- [2] Buyco, E. H. and Davis, F. E. J. Chem. Eng. Data, 15, 518-23 (1970).
- [3] Dauphinee, T. M., MacDonald, D. K. C., and Preston--Thomas, H. Proc. Roy. Soc. (London), A 221, 267-76 (1954).
- [4] Douglas, T. B., Ball, A. F., and Ginnings, D. C., J. Res. Nat'l Bur. Stds., 46, 334-48 (1951).
- [5] Douglas, T. B., Ball, A. F., Ginnings, D. C. and Davis, W. D. J. Am. Chem. Soc., 74, 2472-8 (1952).
- [6] Gaumer, R. E. and Heer, C. U. Phys. Rev., 118, 955-7 (1960).
- [7] Ginnings, D. C., Douglas, T. B., and Ball, A. F., J. Res. Nat'l Bur. Stds., 45, 23-33 (1950).
- [8] Krier, C. A., Craig, R. S., and Wallace, C. A., J. Phys. Chem. 61, 522-9 (1957).
- [9] Lien, W. H. and Phillips, N. E., Phys. Rev. 133, A 1370-7 (1964).
- [10] Martin, D. L., Proc. Roy. Soc. (London), A 254, 434-43 (1960).
- [11] Roberts, L. M. Proc. Phys. Soc. (London), 70, 744-52 (1957).
- [12] Smith, P. L. and Wolcott, N. M., Phil. Mag. 1, 854-65, (1956).

SIMPLIFIED TECHNIQUE FOR EMITTANCE MEASUREMENT

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INTRODUCTION

The Perkin-Elmer Differential Scanning Calorimeter (DSC) [1,2] is designed to partition energy between two small sample supports in such a way that the two temperatures remain the same while the average temperature of the system is controlled. The quantity measured by the instrument is the difference in the amount of energy being supplied to the two supports. Any sample that causes an absorption or emission of energy from one of the supports will cause a corresponding signal proportional to the amount of energy. Energies on the order of a few millicalories per second can be measured, and 1/4-inch diameter discs can be used as samples. Since energy on the order of 10 millicalories per second is emitted from a nonmetallic 1/4-inch-diameter surface at 400°K, the instrument is well adapted to the measurement of emittances. Emittances have been measured with the instrument [3], but the procedure was laborious. The technique has been improved and simplified, and it is now possible accurately to measure an emittance within a few minutes at any temperature within the range of the instrument (-100-500°C).

PROCEDURE

The thermal emission of a surface is a sensitive function of the temperature of the surface, consequently emission can be used as a sensitive test for temperature identity. The temperature identity of the two supports of the DSC is set by "emission balancing." Discs of two identical materials, e.g., aluminum foil, are placed on the two supports with the instrument in the "standby" state. The recorder is zeroed, and the desired temperature is set on the instrument. The instrument is switched to any desired range, and the recorder is rezeroed by using the "differential temperature" (ΔT) control. When the recorder can be zeroed with the instrument on its most sensitive range, the two supports are very nearly at the same temperature.

In order to determine the emittance of a metal, replace the aluminum disc on the sample support with an identical size disc of the metal to be measured. Measure recorder deflection (in cm) on a suitable sensitivity range, and calculate emittance as follows:

$$\epsilon = \frac{SD + R_r}{W} . \quad (1)$$

S is a sensitivity factor for the instrument, calculated from the full-scale

width of the recorder and the range setting of the instrument, e.g., $S = 3.15 \times 10^{-4}$ cal/sec cm for a 10-inch, 10-mv recorder with the DSC on the 8 mcal/sec range. R_r is the emission of the reference surface at the specified temperature. For the 0.3167 cm² aluminum foil reference between 273 and 500 K, R_r can be calculated from the following expression:

$$R_r = 1.282 \times 10^{-3} - 9.019 \times 10^{-6}T + 3.307 \times 10^{-7}T^2 \text{ cal/sec.} \quad (2)$$

D is the recorder deflection measured in cm. W is the black body emission of a 0.3167 cm surface at the specified temperature, and it can be obtained between 273 and 500 K from the following expression:

$$W = 0.0208 - 1.57 \times 10^{-4}T + 3.31 \times 10^{-7}T^2 \text{ cal/sec.} \quad (3)$$

Measurements should be made with the cell holder assembly cover in place to prevent convection currents, and a slow flow (10-15 ml/min) of inert gas helps to prevent oxidation of metal surfaces during measurement.

In order to eliminate correction terms, nonmetals must be compared with nonmetal reference surfaces. Ideally, the reference surface should have nearly the same emittance as the surface to be measured. For making quick estimates, a heavily sooted aluminum disc can be used, assuming an emittance of 0.95. An aluminum surface with a 1-micron electrolytic oxide coating has an emittance of 0.3-0.4 at 400 K ($R_r = 0.004$ cal/sec), and a 5-micron coating has an emittance of 0.7 at 400 K ($R_r = 0.0077$ cal/sec). Other data can be obtained from reference [4]; however, reliable nonmetal reference surfaces are difficult to find. Using a suitable reference surface, the procedure for nonmetals is exactly the same as for metals.

ACKNOWLEDGMENT

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REFERENCES

- [1] M. J. O'Neill, The analysis of a Temperature-Controlled Scanning Calorimeter, *Anal. Chem.* 36, 1238 (1964).
- [2] E. S. Watson, M. J. O'Neill, J. Justin, and N. Brenner, A Differential Scanning Calorimeter for Quantitative Differential Thermal Analysis, *Anal. Chem.* 36, 1233 (1964).
- [3] R. N. Rogers and E. D. Morris, Jr., Determination of Emissivities with a Differential Scanning Calorimeter, *Anal. Chem.* 38, 410 (1966).
- [4] G. G. Gubareff, J. E. Janssen, and R. H. Torborg, Thermal Radiation Properties Survey, Honeywell Research Center, Minneapolis-Honeywell Regulator Co., Minneapolis, Minn., 1960.

The Effects of Thermal Conductivity on
the Thermal Stresses in Ceramics

by

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Thermal shock problems are common in brittle materials, especially for ceramics, under transient heating conditions. A well known example is the thermal shock susceptibility of radomes and ir domes of missiles or aircraft under aerodynamic heating in supersonic flight (Ref. (1) through (4)). Depending upon the thermal conductivity and/or diffusivity of the material under investigation one finds that for each heating (or cooling) condition a certain material thickness exists at which the stresses attain a maximum.

This paper contributes an analytical investigation of the thermal stress problem in brittle materials of axisymmetric shape. Realistic heating conditions are expressed analytically and the mathematical problem is formulated and solved in terms of the pertinent nondimensional parameters describing heat conduction and thermal stress. The solution allows a direct determination of the stress maximum. Thermal stresses are shown to always depend on the ratio of thermal conductivity to material thickness, among others, and decrease substantially if one avoids the ratio which would lead to maximum stress. For a missile radome design, for example, the results demonstrate the existence of a range of electromagnetic frequencies for which the thermal stresses reach a maximum and the radome may become structurally endangered.

REFERENCES

- (1) R. J. Joachim, and F. A. Shukis, "An Approximate Method for Calculation of Transient Heating and Temperature Distribution in Tip Region of Supersonic Radome," U.S. Air Force/Georgia Tech. Symposium on Electromagnetic Windows, Atlanta, Ga., June 1966.
- (2) M. P. Bleday and M. St. John, "Allowable Velocity Histories of Ceramic Radomes," AIAA paper No. 68-299, 9th AIAA/ASME Structures, Structural Dynamics and Materials Conference, Palm Springs, Calif., April 1968.
- (3) F. E. Megerlin, "Isotropic Pyrolytic Boron Nitride - A Prime Candidate for Hypersonic Missile Radomes," Proc. of the Tenth Annual Conf. on Thermal Conductivity, Boston, Mass., September 1970
- (4) F. E. Megerlin and L. Rayburn, "Thermal Shock of Infrared Domes During High Speed Missile Flight," Proc. Tenth Electromagnetic Window Symposium, Atlanta, Ga., July 1970.

ELECTRICAL RESISTIVITY OF HIGH-PURITY TUNGSTEN FROM 1100 TO 2500 K*

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The electrical resistivity of a zone-refined tungsten sample ($R_{273}/R_{4.2} = 9.6 \times 10^3$) was determined between 1100 and 2500 K. Most of the measurements were conducted in vacuum at indicated pressures which varied from 4×10^{-12} torr at 1100 K to 1×10^{-8} torr at 2500 K. Some auxiliary experiments were also performed in low (2 cm Hg) pressure argon and helium environments. The sample temperature was held constant to about 0.1 K during a measurement, and the maximum temperature gradient along the sample was about $2.2^\circ\text{C}/\text{cm}$. The scatter of the 48 data points taken in vacuum appears to be about $\pm 0.05\%$ and the results are in satisfactory (0.4%) agreement with our previous data [1] in the range (1100 to 1700 K) where the two studies overlap.

Sample temperatures were determined using calibrated, uninsulated $W_{97}Re_3:W_{75}Re_{25}$ thermocouples and a photoelectric optical pyrometer. The thermocouples shifted about 4 K after an initial 2500 K anneal and then remained stable for the balance of the vacuum experiments. The two types of temperature measurements agreed to about 7 K at 1700 K and 25 K at 2500 K; the final $\rho:T$ relationship will be obtained from the optical temperature measurements because thermionic emission effects were found to shift the thermocouple output.

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REFERENCE

- [1] J. P. Moore, R. S. Graves, W. Fulkerson, and D. L. McElroy, "The Physical Properties of Tungsten," V-G-1-V-G-35 in The 5th Conference on Thermal Conductivity, Held at Denver, Colorado, October 20, 21, and 22, 1965, Denver University, Department of Metallurgy, College of Engineering, Denver, Colorado, 1967. Volume 1 Sessions I, II, III; Volume 2 Sessions IV, V, VI.

Abstract

A Sensor for Measuring Convective Heat Transfer Coefficient

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A sensor has been developed capable of measuring heat flux and two wall temperatures simultaneously. This calorimeter-temperature (C-T) gauge has been studied both theoretically and experimentally to determine its capability to provide adequate data from which the convective heat transfer coefficient could be determined directly. The C-T gauge is simply a modification of the Gardon type calorimeter wherein provision has been made to measure sensing disk center and edge temperature in addition to heat flux.

Assuming that accurate measurements can be made of the three values mentioned above, an equation has been derived that defines the convective heat transfer coefficient in terms of these variables. The derivation makes use of the differential equation describing the steady-state heat transfer in the C-T gauge sensing disk. Solving this equation for disk temperature at any radius (r), substituting the solution into the integral equation describing the total heat transfer to the disk, and solving this second equation gives an expression in terms of the I_0 and I_1 Bessel functions

$$\frac{r_e}{2\sqrt{KS}} \frac{q_{ave}}{T_c - T_e} = Z = \frac{\sqrt{h} I_1(\beta r_e)}{I_0(\beta r_e) - 1} \quad (1)$$

where:

- q_{ave} = average heat flux to the disk,
- T_c and T_e = disk center and edge temperatures, respectively,
- r_e and S = disk edge radius and thickness, respectively,
- K = thermal conductivity of the disk material,
- h = convective heat transfer coefficient,
- β = $\sqrt{h/KS}$,
- Z = an intermediate function relating the two sides of Eq. (1).

As may be noted a value of h can be obtained directly from this equation for a given set of measured values of q_{ave} , T_c and T_e .

In an attempt to evaluate the accuracy of the above method, a leading edge model containing two C-T gauges was free jet tested in a Mach 2 flow. Three different total temperatures of 400, 550 and 700°F were applied with a total pressure of 120 psia. Because of the low total temperatures, an inadequate evaluation of the method resulted; however, the test results indicated that a basic assumption made in the derivation may be invalid. Therein, it was assumed that the heat flux measured by the C-T gauge (q_c) is an average of the heat flux experienced by the gauge sensing surface. For the low total temperature (T_t) cases of the test, the results show that the relation of q_c to q is dependent on T_t . Presently, it does not appear that any correlation can be made between the uniform heat flux applied during calibration by a radiant source and the convective heat flux experienced during fluid flow tests. This statement applies only to cases where the driving temperature is low compared to the temperatures experienced on the C-T gauge sensing disk. Further work is planned to evaluate the validity of the above assumption for high driving temperature convective environments.

The presentation will report on the C-T gauge design, the equation derived for use in computing h directly from gauge measurements, the experimental evaluation with low convective driving temperatures and any new findings subsequent to this abstract submittal.

THE INFLUENCE OF DISLOCATIONS ON THERMAL CONDUCTIVITY

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INTRODUCTION

Early estimates of the contribution of phonon scattering by dislocations to the thermal resistivity of LiF failed to agree with experiment by a factor of $\geq 10^2$ [1]¹. Although later calculations by Ohashi [2] improved this agreement, it was also suggested that the enhanced scattering may be caused by resonant motion of mobile dislocations. Evidence for the latter mechanism has been found in ultrasonic measurements [3]. In the present work the interaction of thermal phonons with both static and mobile dislocations was studied by measurements of thermal conductivity (0.04 - 0.8K) and ballistic phonon propagation (3.6K).

APPARATUS

The LiF crystals were oriented in the [110] direction and contained a 1 mm wide band of dislocations inserted in the [110] slip direction using the technique of Ref. [3]. Densities of dislocations were determined by etch-pit counts on appropriate cleaved surfaces. Edge dislocations predominated. The ballistic phonon techniques were similar to those of Ref. [4].

RESULTS

The thermal conductivity of the samples was reduced $\approx 50\%$ by insertion of the dislocations and was independent of the number of dislocations present. This was due to the preferential and strong scattering of phonons of the slow transverse mode alone, and was verified in the ballistic measurements where the three phonon modes could be identified by their time of flight.

¹Figures in brackets indicate the literature references at the end of this Abstract.

Only the low temperature (i.e. low frequency) tail of a resonance curve could be observed in the conductivity measurements, and this moved to higher temperatures with increasing doses of γ -irradiation. This irradiation produces point defects in LiF which pin the dislocations into shorter loop lengths and hence increase their resonance frequencies much like the shortening of a violin string. With sufficient irradiation the dislocations become immobile and the measured thermal conductance was found to return to the value obtained in the absence of dislocations. Hence, although the resonant scattering of phonons is very large, static scattering is found to be an order of magnitude weaker than that calculated by Ohashi [2]. The older theories [1] would therefore appear to give better agreement with the present results for the case of strain field scattering by sessile dislocations.

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REFERENCES

- [1] See, for example, P. Carruthers, Rev. Mod. Phys. 33, 92 (1961).
- [2] K. Ohashi, J. Phys. Soc. Japan 24, 437 (1968).
- [3] R. O. Schwenker and A. V. Granato, Phys. Rev. Letters 23, 918 (1969); J. Phys. Chem. Solids 31, 1869 (1970).
- [4] S. J. Rogers, Phys. Rev. B 3, 1440 (1971).

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Investigation of thermal conductivity of FeSe , Fe_2Se_3 , Fe_7Se_8 , Fe_3Se_4 , CrFe_2Se_4 , VFe_2Se_4 and NiFe_2Se_4 in the temperature range of 100 - 500° K.

The investigations were made of the thermal conductivity of FeSe , Fe_2Se_3 , Fe_7Se_8 , Fe_3Se_4 , CrFe_2Se_4 , VFe_2Se_4 , and NiFe_2Se_4 in the temperature range of 100-500°K. The thermal conductivity of these compounds up to 350°K has been found to be due to the vibrations of lattice atoms and to the electrons of conductivity. Above 350°K the bipolar thermoelectric diffusion becomes noticeable in the thermal conductivity of these compounds. It must be noted that the lattice thermal conductivity of these compounds increases slowly with temperature in all interval under the investigation

THERMOPHYSICAL PROPERTIES OF SOME FILLED POLYMERS
IN THE TEMPERATURE RANGE 10-400°K

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Filled polymers such as phenol-formaldehyde resin with fibre--glass, textolite, polystyrol and polyethylene with asbestos crumbles etc. have lately found wide use as constructional materials. They are used as pillers in reservoirs for storage and transportation of cryogenic liquids, reinforcement, heat protection coating, instrument cases. Knowledge of the effect of temperature, radiation as well as proportion of components on thermal conductivity, heat capacity and thermal diffusivity of these materials is very important for performing correct thermal engineering calculations.

The procedure for simultaneous determination of the relation between temperature and λ , C_p and α of solids in the temperature range 10-400°K when heating samples of the test material by constant heat flux under adiabatic conditions has been developed at the Heat and Mass Transfer Institute, Byelorussian Academy of Sciences. The theory of the method is considered in [1,2]. The present work contains the results of investigation of thermophysical properties of a number of filled and nonfilled polymers. In Fig.1 thermophysical coefficients of material made of woven fabric and epoxy-phenol resin versus temperature are plotted. In Fig.2 a plot of λ , C and α versus temperature for materials made of glass thread and epoxy-phenol resin is shown. Measurements were performed along two directions such as parallel to fibres and perpendicular to them. In Fig.3 λ , C , α of quasi-isotropic resin are given versus temperature. In Fig.4 are presented the temperature dependences of λ , C , α of textolite made of cotton fabric and phenol resin. Measurements were made in the

direction perpendicular to the layers. Phase transition zones are seen in the diagram which are caused by transitions of components from one state to another, in particular, at temperatures about 170°K alcohol freezes, and about 50°K the process of polymer glass-transition takes place.

REFERENCES

1. A.V. Luikoy, A.G. Shashkov, L.L. Vasiliev, Proc. 3d Symposium on Thermophysical Properties, March, 22-25, 1965, USA.
2. A.V. Luikov, L.L. Vasiliev, A.D. Shnyrev, V.F. Barsukov, A.A. Klebanovich, Experimental determination of thermophysical properties of polymer materials from 10 to 300°K , XIII International Congress of Refrigeration, Washington, D.C., 1971.

Fig.1 Plot of thermophysical coefficients for glass fabric on epoxy-phenolic resin basis.

Fig.2 Plot of thermophysical coefficients of anisotropic glass-thread material on epoxy-phenolic resin basis.

Fig.3 Plot of thermophysical coefficients of quasi-isotropic glass-thread material on phenol-formaldehyde resin basis.

Fig.4 Thermophysical coefficients plotted versus temperature for textolite.

THURSDAY

p.m.

III

APPLICATIONS OF SENSITIVITY ANALYSIS AND NETWORK CORRECTION

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INTRODUCTION

Sensitivity analysis has a number of applications in the design of a thermal control system. The analytical technique which has been developed into a computer program is based on the use of a lumped-parameter representation of the physical system. Thermal network correction represents in essence the solutions of the inverse problem with the physical system approximated by a lumped-parameter math-model. This analytical tool, which is presently undergoing refinements, appears to have a number of attractive applications.

The intent of this abstract is to indicate applications of sensitivity analysis in thermal control design and to indicate potential applications of network correction in order to reveal potential applications of these tools in other disciplines.

REVIEW OF BASIC EQUATIONS

Both sensitivity analysis and network correction are based on the use of a lumped-parameter math-model [1-3].² Sensitivity analysis as used here employs the set of steady state heat balance equations,

$$Q_i = \sum_{j=1}^p a_{ij} (T_i - T_j) + \sum_{j=1}^p \sigma b_{ij} (T_i^4 - T_j^4) \quad (1)$$

$$i = 1, 2, \dots, n$$

$$T_j = \text{boundary temperatures, } n < j \leq p$$

where Q_i = net heat input to the i th node, a_{ij} = coefficient for conduction and/or convection, b_{ij} = coefficient for radiation exchange, p = sum of n variable and $p - n$ boundary temperatures, σ = Stefan-Boltzmann constant, T = temperature.

The static sensitivity coefficients are found by a derivative operation on equation (1) in terms of Q_{kl} , a_{kl} , and T_k . For details refer to Reference [1].

Network correction uses the set of transient heat balance equations and a set of Kalman filtering equations tailored for thermal problems [2-3].

APPLICATIONS

Sensitivity analysis with the resultant use of sensitivity coefficients provides a means of identifying important parameters of a thermal mathematical model as well as yielding quantitative nodal temperature changes that are due to an

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²Numbers in brackets indicate the literature references at the end of this Abstract.

individual parameter value change or due to the sum of a number of parameter value changes. Because of the rather complex thermal interactions between nodes, identification of important parameters relative to a given node represents an important application of sensitivity analysis; simultaneously, a number of parametric runs can be eliminated because of the availability of quantitative temperature changes due to parametric perturbations.

Another important application of sensitivity analysis is the generation of temperature uncertainty of each node employed in a mathematical model due to inaccuracies in parameter values. Many of the inaccuracies are statistical-in-nature; as a result, deterministic temperature predictions based upon nominal parameter values must include a temperature uncertainty band.

The thermal network correction program provides a means of correcting a thermal mathematical model to reflect measured temperature data that are obtained from a thermal test. This means that simultaneous property measurements could be one application. In addition, the thermal network correction program provides a means of reducing a large thermal math-model to a smaller one containing only those nodes with measured temperature data.

CHARACTERISTICS OF COMPUTER PROGRAMS

The sensitivity analysis program called STEP (Sensitivity Temperature Error Program) can accommodate a math-model of about 200 nodes on a 65K core computer. Solution time varies with nodal size; a 46-node model requires about 2 minutes and a 204-node model requires about 27 minutes. Two subroutines of SINDA (Systems Improved Numerical Differencing Analyzer [4]) are used for thermal network correction. One subroutine KALØBS was developed for large networks by considering the equations singly and sequentially in time; the subroutine KALFIL considers the equations simultaneously but sequentially in time. The latter can accommodate about 90 variables including nodal temperatures on a 65 K core computer.

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REFERENCES

- [1] T. Ishimoto and J. T. Bevans, "Temperature Variance in Spacecraft Thermal Analysis," J. Spacecraft, Vol. 5, No. 11, November 1968.
- [2] T. Ishimoto, H. M. Pan, J. D. Gaski, and E. B. Stear, Final Report Development of Digital Computer Program for Thermal Network Correction, Phase I - Investigation/Feasibility Study, Report No. 1102-6001-RP-00, January 1969, Phase I - Addendum Report No. 11027-6001-RP-00, Addendum, June 1969, TRW Systems.
- [3] T. Ishimoto and H. M. Pan, "Thermal Network Correction Techniques," AIAA Paper No. 70-821, AIAA 5th Thermophysics Conference, Los Angeles, California, June 29 - July 1, 1970.
- [4] J. D. Gaski, L. C. Fink and T. Ishimoto, "SINDA Users Manual," Report No. 11027-6003-RO-00, September 1970, TRW Systems Group.

THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY OF CARBON-CARBON COMPOSITES AS A FUNCTION OF TEMPERATURE AND ORIENTATION

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INTRODUCTION

Thermal diffusivity and thermal conductivity were measured by the flash technique [1]¹ for a series of carbon-carbon composites at temperatures up to 1300°C. These samples are (1) carbon bonded carbon cloth, (2) carbon bonded graphite cloth, and (3) graphite bonded graphite cloth. Thermal diffusivity was measured both parallel and perpendicular to the fabric direction of each composite.

EXPERIMENTAL

The apparatus consist of the Korad K-1 laser system with a Nd laser, a graphite tube furnace, and the Tektronix Oscilloscope with a preamplifier and a Polaroid camera. The pulses have a maximum energy rated at 25 Joules and a nominal pulse duration of 500 microseconds. The thicknesses of samples were adjusted so that pulse-time corrections were not necessary. In order to minimize heat loss of radial conduction, the sample holder was designed to minimize contact between the sample and holder.

RESULTS

Thermal conductivity was calculated from thermal diffusivity and the results are shown in the Figures below.

THERMAL CONDUCTIVITY OF CARBON-CARBON COMPOSITES
(X DIRECTION IS PARALLEL TO THE FABRIC DIRECTION,
Z DIRECTION IS PERPENDICULAR TO THE FABRIC DIRECTION)

¹See references 1-5

A preferred crystallite orientation, along the fiber direction was observed by x-ray analysis, and is related to the higher thermal conductivities in the direction parallel to the fiber axes. It is strongest in the graphite bonded graphite cloth composite. The thermal conductivity of graphite bonded graphite cloth composite appears to follow a $1/T$ relation, which is a typical behavior [6-10] of graphites and of Umklapp thermal resistive processes in general. The thermal conductivities of carbon bonded carbon composite and carbon bonded graphite composite are much lower than that of graphite bonded graphite composite and the values increase with increasing temperature.

REFERENCES

- [1] Parker, W. J., Jenkins, R. J., Butler, C. P. and Abbott, G. L., "Flash Method of Determining Thermal Diffusivity, Heat Capacity and Thermal Conductivity", J. Appl. Phys. 32, 1679 (1961).
- [2] Cowan, R. D., "Pulse Method of Measuring Thermal Diffusivity at High Temperatures", J. Appl. Phys. 34, 926 (1963).
- [3] Cape, J. A. and Lehman, G. W., "Temperature and Finite Pulse-Time Effects in the Flash Method for Measuring Thermal Diffusivity", J. Appl. Phys. 34, 1909 (1963).
- [4] Larson, K. B. and Koyama, K., "Correction for Finite Pulse-Time Effects in Very Thin Samples Using the Flash Method of Measuring Thermal Diffusivity", J. Appl. Phys. 38, 465 (1967).
- [5] Branscomb, T. M. and Hunter, O., Jr., "Improved Thermal Diffusivity Method Applied to TiB_2 , ZrB_2 and HfB_2 from 200°-1300°C", J. Appl. Phys. 42, 2309 (1971).
- [6] Wagner, P. and Danelsberg, L. B., "The Thermal Conductivity of SX-5 Graphite", Carbon, 6, 373 (1968).
- [7] Taylor, R., Gilchrist, K. E. and Poston, L. J., "Thermal Conductivity of Polycrystalline Graphite", Carbon 6, 537 (1968).
- [8] Kelly, B. T., "Theory of the Effect of Crystallite Boundaries on the Principal Thermal Conductivities of Highly Oriented Graphite", Carbon 6, 71 (1968).
- [9] Wagner, P. and Danelsberg, L. B., "Some Thermal Properties of a Polyfurfuryl Alcohol Bonded Graphite", Carbon, 7, 273 (1969).
- [10] Lutcov, A. I., Volga, V. I. and Dymov, B. K., "Thermal Conductivity, Electric Resistivity and Specific Heat of Dense Graphite", Carbon 8, 753 (1970).

THERMAL CONDUCTIVITIES OF VAPOR DEPOSITED SILICON CARBIDE AND SILICON CARBIDE GRAPHITE COMPOSITE

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INTRODUCTION

Thermal diffusivities of CVD silicon carbide, graphite and SiC-graphite layer composite were measured by the flash technique [1]¹ and their thermal conductivities were calculated from these diffusivities at temperatures up to 1300°C.

EXPERIMENTAL

The apparatus consisted of the Korad K-1 laser system with a Nd laser, an Astro graphite tube furnace, and the Tektronix Oscilloscope with a preamplifier and a Polaroid camera. The pulses have a maximum energy of 25 Joules and a nominal pulse duration of 500 microseconds. The thicknesses of samples were adjusted so that pulse-time corrections were not necessary. In order to minimize heat loss of radial conduction, the sample holder was designed to minimize contact between the sample and holder.

The thermal conductivity of the graphite (1.58 g/cc) appears to follow a $1/T$ relation, and the values are lower than those of the dense graphite [2] (1.9 g/cc) and higher than those of the low dense graphite [2] (1.0 g/cc) over the entire temperature range of 100-1300°C.

The thermal conductivity of CVD SiC at room temperature compared well with the values of Price [3]. As would be expected the thermal conductivity and diffusivity of layered composite is not a single additive function but is more dependent on the phase having the lower conductivity in this case SiC. At high temperatures the thermal conductivity of this CVD SiC decreased less than that of Price. These data are all shown in the following Figures.

¹Parker, W. J., Jenkins, R. J., Butler, C. P., Abbott, G. L., "Flash Method of Determining Thermal Diffusivity, Heat Capacity and Thermal Conductivity", J. Appl. Phys. 32, 1679 (1961).

REFERENCES

- [1] Parker, W. J., Jenkins, R. J., Butler, C. P. and Abbott, G. L., "Flash Method of Determining Thermal Diffusivity, Heat Capacity and Thermal Conductivity", J. Appl. Phys. 32, 1679 (1961).
- [2] Lutcov, A. I., Volga, V. I. and Dymov, B. K., "Thermal Conductivity, Electric Resistivity and Specific Heat of Dense Graphites", Carbon 8, 753 (1970).
- [3] Price, R. J., "Structure and Properties of Pyrolytic Silicon Carbide", Ceramic Bulletin, 48, 859 (1969).

DIRECTIONAL THERMAL CONDUCTIVITY OF TEXTOLITE BETWEEN 4.2 AND 100 K

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INTRODUCTION

Our interest in determining the temperature and directional dependences of the thermal conductivity of textolite over a range of cryogenic temperatures originated from the need to know its effectiveness as a thermal insulator for heaters used in studies of the nature of pool boiling liquid helium and nitrogen. Textolite, in its many varied grades and specifications has found extensive application as a thermal insulation material at cryogenic temperatures.

APPARATUS

The samples were fabricated from the same stock of General Electric 1848 grade textolite having a medium weave cotton cloth base and a phenolic resin. The test samples were machined to dimensions of 0.351 ± 0.001 inch in diameter by 2.000 inches in length. Samples were taken both with and against the major orientation of the cotton fiber structure to determine the degree of anisotropy in the thermal conductivity, if any.

The thermal conductivity was measured by the differential technique in which the conductivity is expressed in terms of the axial heat flow P through a rod of cross sectional area A and of active length ℓ with ends fixed at temperatures T_1 and T_2 , as:

$$\lambda(T) = P\ell/A(T_1 - T_2) \quad (1)$$

This method yields $\lambda(T)$ directly when a small temperature gradient is imposed across the test section and the values of ΔT and P are recorded over a range of temperatures. The apparatus, consisting of a double can cryostat with a temperature controlled heat sink, has been described in detail [1]³ as have the experimental procedures and general considerations [2]. The temperature measurement instrumentation was modified somewhat over that previously reported. The temperature sensors used were high sensitivity germanium resistance thermometers ranging in resistance from 1100Ω at 4 K to 5Ω at 100 K. Whereas, the previously described system was truly a potentiometric system, the present system incorporated a Keithley 140 Precision Nanovolt DC Amplifier with a 50 megaohm input impedance and a Dana 5230 Digital Voltmeter for more efficient data acquisition. The large input impedance of the amplifier allowed retention of the accuracy in the temperature measurement.

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³Numbers in brackets designate references at the end of this abstract

RESULTS AND DISCUSSION

The experimental data is shown in figure 1. No directional dependence was observed as the contribution of the cotton weave base to the thermal conductivity is negligible. The curve between 30 and 55 K is extrapolated and is qualitatively consistent with data recently reported by Luikov, et al. [3] using a transient technique. The time required to establish thermal equilibrium was of the order of 2 to 10 hours. We are continuing our experiment to elucidate the phase transition region.

Figure 1. Thermal conductivity of 1848 Textolite parallel and perpendicular to the fiber base.

ACKNOWLEDGEMENTS

This work was supported by Northeastern University.

REFERENCES

- [1] Bowman, H.F., The Influence of Nuclear Radiation on Pool-Boiling Heat Transfer to Liquid Helium, Ph.D. Thesis, MIT, June 1968.
- [2] Bowman, H.F., Ziebold, T.O., and Smith, J.L., Low Temperature Thermal Conductivity of Copper Irradiated with Reactor Neutrons, Thermal Conductivity; Proceedings of the Eighth Conference, Edited by C.Y. Ho and R.E. Taylor, Plenum Press, New York, 1969, pgs. 175-184
- [3] Luikov, A.V. et al, Experimental Determination of Thermophysical Properties of Polymer Materials within 10 to 300 K, presented at I.I.R. Conference, Washington D.C., August 30 - September 3, 1971.(1.104)

EFFECT OF PARTICLE SIZE, SHAPE, AND SPATIAL
DISTRIBUTION ON THERMAL CONDUCTIVITY OF SUSPENSIONS

1

2

Pradeep B. Deshpande and James R. Couper

ABSTRACT

An experimental/theoretical study was undertaken to study the effect of particle size, shape, and spatial distribution on the thermal conductivity of suspensions.

In the experimental work, a spectrophotometer was used to study the spatial distribution of solid particles in the two-phase system. The solid phase consisted of uranium-impregnated borosilicate glass particles. A gel composed of 85 volume % glycerol and 15 volume % benzyl alcohol was used as the liquid phase. The gelling agent was 1.5 weight % hydroxyethyl cellulose.

A beam of light of known intensity was passed through the two-phase system and the transmitted beam intensity was measured. From the data, the fraction of the light beam occupied by the solid phase, P_1 , was determined by solution of the Beer's Equation. Spatial distribution data on spherical and cylindrical particles of various sizes were obtained.

In the theoretical analysis, it was found that the random variable, P_1 was distributed according to the beta distribution. The two parameters of the beta distribution were determined from the experimental data, using the maximum likelihood method.

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Using the beta distribution model, the thermal conductivity of several suspensions was evaluated for the particle shapes and sizes considered in the study.

With large particles (cylindrical: 5-mm. diameter by 6-mm. long; spherical: 6-mm. diameter), the model predicted the two-phase thermal conductivity very well for low volume fraction solids ($f \leq 0.30$). The model was inadequate for high volume fraction solids.

With small particles (cylindrical: 3-mm. diameter by 4-mm. long; spherical: 5-mm., 4-mm., 3-mm. diameter), the predictability of the model was poor, indicating a strong dependence of particle size on the thermal conductivity of two-phase systems.

A statistical analysis of the results (large particle, $f \leq 0.30$) was made. The performance of the model under study was compared with several well-known models. When compared with experimental data, the predictability of the beta distribution model was better than those tested. It was also found that the thermal conductivity of the two-phase system was dependent to a lesser degree on the shape of the suspended particles.

Approximate time of presentation: 35 minutes including a few minutes for discussion.

DEVELOPMENT OF A PROCEDURE FOR DETERMINING APPARENT THERMAL DIFFUSIVITY OF VISCOUS LIQUID FOOD BY USING A CYLINDRICAL CELL¹

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INTRODUCTION

There are many procedures published for determining the thermal diffusivity of food or non-food material [1, 2,]². However, most of these procedures require expensive instrument and/or the large quantity of sample material. The present investigation is conducted to develop a new computational procedure for determining the apparent thermal diffusivity of viscous liquid food without these requirements.

APPROACH

The developed procedure utilizes a cylindrical test cell, which is made from a chrome plated copper tube and from two synthetic rubber stoppers. The dimensions of the copper tube are: outside diameter = 0.0127 m ($\frac{1}{2}$ in), inside diameter = 0.0111 m ($\frac{7}{16}$ in), and height = 0.0381 m ($\frac{3}{2}$ in). Slightly less than $4.1 \times 10^{-6} \text{ m}^3$ (0.25 in^3) of sample fluid is required to fill this cell. One copper-constantan thermocouple junction, which is made from guage No. 36 thermocouple wire, is permanently placed at each of the following four locations in the cell: i. The midpoint of its central axis. ii. The inside surface of the tube at a position located midway between its two open ends. iii. The food side surface of one rubber stopper at its center. iv. The food side surface of another stopper at its center.

Temperature history curves are determined at these four locations during a heating or cooling treatment of sample material, which is filled in the cell. These curves are used to estimate the thermal diffusivity of sample material. In this estimation an analytical solution for the Fourier's equation of heat conduction is also used. This solution was derived by assuming: i. Thermal diffusivity is temperature independent. ii. Initial temperature is uniformly equal to zero. iii. Temperatures on the side, top, and bottom surfaces of a cylinder vary arbitrarily with time and are all different although temperature

¹ This work was supported in part by U. S. Public Health Service Grant Nos. FD-00119-04 and 05A1 from the Food and Drug Administration.

² Figures in brackets indicates the literature references at the end of this abstract.

on any one surface is uniform. The solution was obtained through the application of Laplace transform, finite Hankel transform, and finite Fourier sine transform.

The diffusivity is determined through the following computational process. Theoretical temperature history curves at the center of the cell are calculated by using the analytical solution together with three experimental surface temperature history curves. In this calculation, a set of assumed thermal diffusivity values is used. For each assumed diffusivity value a sum of squares of differences between calculated and experimental temperatures at the center of the cell is evaluated. The best estimate of diffusivity is obtained by finding one diffusivity value which gives the minimum sum of squares. A set of Fortran IV programs is prepared for these calculations.

RESULTS AND DISCUSSIONS

The thermal diffusivities of the following materials were determined by the proposed procedure: egg yolk, thick egg albumin and thin egg albumin. Fresh shell eggs of various sizes, which were obtained at the Rutgers University Poultry Farm, were used for this determination. Temperature of each sample material changed from 5°C to 30°C during each experiment. There were no significant differences in diffusivities among various sizes of shell eggs and among the three egg components named above because of wide variations in the diffusivities determined. The averages of diffusivity values of yolk, thick albumin, and thin albumin are respectively equal to 1.00×10^{-7} (m²/s), 1.18×10^{-7} , and 1.30×10^{-7} .

Errors caused by slight variations in the position of thermocouple junctions were theoretically analyzed. This analysis reveals that these errors are partly responsible for the above stated wide variation in the diffusivity. Careful fabrication of the cell is suggested in order to utilize the proposed computational procedure. There are the following two advantages in the proposed procedures since time variable surface temperatures are utilized for determining diffusivity: i. Diffusivity can be determined without estimating a Biot number which is applicable to a heating or cooling treatment of sample material. ii. A constant temperature bath is not required.

REFERENCES

- [1] Tye, R. P. Editor. "Thermal Conductivity". Vol. 2 and 2. Academic Press. 1969.
- [2] Woodams, Edward E. and Nawrey, Joseph E. Literature values of thermal conductivities of foods. Food Technol. 22, 494 (1968).

A CONDUCTION MODEL FOR SKIN BURNS RESULTING
FROM A SHORT DURATION HEAT FLUX¹

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INTRODUCTION

Skin burns resulting from an incident surface heat flux of short duration (3 seconds) are analyzed with a conduction model which includes ablation of the skin. The amount of heat required to produce a third degree burn is predicted and the results are compared with experimental results in the literature and recent experimental results on test animals.

ANALYTICAL TECHNIQUE

When a heat flux is applied to the skin for an interval of time, a temperature profile is established through the skin. For a constant heat flux q at the surface and no ablation, the temperature rise in the skin at position X is for all times

$$\Delta T = T - T_i = \frac{2q\sqrt{\alpha}}{X} \left[\sqrt{t} \operatorname{ierfc} \frac{X}{2\sqrt{\alpha t}} - \sqrt{t - t_c} \operatorname{ierfc} \frac{X}{2\sqrt{\alpha(t - t_c)}} S_c(t) \right] \quad (1)$$

where $S_c(t)$ is the unit step function. The total heat deposited is

$$Q = t_c q \quad (2)$$

At the end of the heating pulse, the heat required to bring the skin to boiling is 0.1567 MJ/m^2 and is sufficient to produce a $\Delta T = 11^\circ\text{C}$ at the base of the derma. Hardy, et al [1]², have shown that a $\Delta T = 8^\circ\text{C}$, which corresponds to 0.125 MJ/m^2 in 3 seconds, is sufficient to cause thermal injury to the skin. Any Q greater than 0.1567 MJ/m^2 would cause boiling to occur at the skin surface, and thus little additional heat would be deposited in depth.

At higher heat fluxes where boiling occurs, the absorbed heat and the exposure time are, respectively,

$$Q = 207.6 \times 10^7 \frac{\xi}{q} \quad (3)$$

$$t = \frac{2.27 \times 10^{10}}{q^2} \left[(4 - \xi) - 47.6 \ln \frac{47.6 - \xi}{43.6} \right] \quad (4)$$

Equations (2) and (3) can then be plotted (fig. 1) for the absorbed heat resulting from constant heat fluxes applied for 3 seconds.

¹This work was supported by the United States Atomic Energy Commission.

²Figures in brackets indicate the literature references at the end of this abstract.

Figure 1. Absorbed Heat for Heat Fluxes Applied Over 3 Seconds

RESULTS AND CONCLUSIONS

The results of this model is given in table 1 and is compared with animal test data and data from the literature.

Source	$Q, J/m^2$
Theoretical	1.25×10^5
Maximum Possible Absorbed Heat from figure 1	2.16×10^5
Measure in Swine Test [2]	1.02×10^5
Büttner [3]	2.27×10^5
Perkins, et al [4]	4.98×10^5
Mitchell [5]	8.75×10^5

Table 1. Absorbed Heat for Third Degree Burn

Many researchers have felt that the degree of burn could be correlated to the amount of heat absorbed. This correlation may be in error if one assumes that the integral of the incident heat flux is equal to the heat absorbed in depth. This assumption is valid only until the surface of the skin reaches phase change temperature.

REFERENCES

- [1] Hardy, J. D., Woell, H. C., and Goodell, H., Pain Sensations and Reactions, Williams & Wilkins, Baltimore, 1952, pp. 87-122.
- [2] Hardee, H. C. and Lee, D. O., Unpublished Report, Sandia Laboratories.
- [3] Büttner, K., "Conflagration Heat," German Aviation Medicine, Vol. II, Chapter XIII-A, Department of the Air Force, pp. 1167-1187.
- [4] Perkins, J. B., Pearse, H. C., Kingsley, H. D., The University of Rochester, UR217, December 1952.
- [5] Mitchell, H. H., Rand Report, RM-1149, October 12, 1953.

THURSDAY

p.m.

IV

✓ A METHOD FOR THE SIMULTANEOUS DETERMINATION OF THE HIGH TEMPERATURE
THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY*

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Historically the interest in this technique arose when the use of ZrC-graphite composites was actively pursued by materials scientists working on the nuclear rocket project. Previous to this time the interest had centered around the use of graphite for structural and fuel-bearing materials. Measurements on graphite of thermal conductivity (λ) and thermal diffusivity (α) from room temperature to about 3000 K have been made by different methods and have been found to be in reasonable agreement. For a homogeneous material, $\lambda = \alpha \rho C_p$ where ρ is the density and C_p is the specific heat. ρC_p is the volumetric heat capacity and when, in a two component system, this product differs for the two components, the relation between λ and α is no longer clearly defined. For the composites in question, ρC_p (graphite) = 1.62 joules/cc-K and ρC_p (ZrC) = 2.5 joules/cc-K at room temperature. The question to be answered then is what is the corresponding value for λ when the more conveniently measured α is determined.

Past measurements of λ on graphite have been made using a steady-state radial heat flow technique.¹ This method should be applicable to the composites system and it was felt that the identical experimental system could be used for λ and α if a temperature transient could be generated whose mechanism was controlled by the thermal properties of the specimen in question. Since an automatic pyrometer was available with this equipment, it was decided that cooling curves could be generated which would fulfill our requirements, and a test experiment was run using a known graphite.

The existing physical system can be approximated by a disc of zero thickness with a maximum temperature at the center and the boundary condition at the outer edge given by the radiation heat loss term. The experimental transient cooling profile for the sample was determined by measuring $\partial T / \partial t$ at the center of the rod and at a point R_1 where R is the cylinder radius and $0 < R_1 < R$. This was done with the automatic pyrometer. Next the cooling was simulated on the CDC 6600 computer by solving a set of finite difference equations.**

* This work was performed under the auspices of the U.S. Atomic Energy Commission.

** For a complete description see "A Method for Numerical Determination of Thermal Conductivity", B. L. Buzbee and F. W. Dorr, Los Alamos Scientific Laboratory Report LA-4485 (1970).

The procedure has been applied successfully to a test case modeled on graphite experimental data. One feature of the method is that it automatically indicates whether the experimental data are accurate enough for the computational results to be meaningful. No solution was obtained when the procedure was applied to the graphite laboratory data, probably because of both experimental inaccuracies and because the computational model does not adequately describe the laboratory experiment.

The results of the test case indicate that the method could be very useful for similar problems with sufficiently accurate input data.

1. Wagner, P. and Dauelsberg, L. B., Carbon 5 271 (1967), *ibid* 6 373 (1968), *ibid* 7 273 (1969). Wagner, P., Brit. J. Appl. Phys. 2 293 (1969).

THE STEADY-STATE APPROXIMATION IN THERMAL DIFFUSIVITY MEASUREMENTS ON HETEROGENEOUS MATERIALS¹

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In thermal diffusivity measurements on heterogeneous or porous materials it is usually assumed that the thermal diffusivity, α , is related to the steady state thermal conductivity λ , specific heat c , and density d by the relation which holds for homogeneous materials,

$$\alpha = \lambda/dc. \quad (1)$$

This work shows that for two model heterogeneous materials examined this assumption is valid in the limit as a steady state of heat transfer is approached. The validity of this approximation for a particular problem can be determined from these results.

Two model heterogeneous materials frequently used are (1) spheres of one material imbedded in a matrix of a second, and (2) a two phase material composed of roughly spherical particles with neither phase continuous. The steady state thermal conductivity of both model materials has been calculated in terms of the individual phase properties[1]². For model (1)

$$\lambda_H = \lambda_1 \left[\frac{\lambda_2 (1 + 2 V_2) + 2 \lambda_1 V_1}{\lambda_1 (2 + V_2) + \lambda_2 V_1} \right], \quad (2)$$

where subscript 1 refers to the matrix and 2 to the spherical inclusions and V is the volume fraction. For model (2)

$$V_1 \left[\frac{\lambda_H - \lambda_1}{2\lambda + \lambda_1} \right] + V_2 \left[\frac{\lambda_H - \lambda_2}{2\lambda + \lambda_2} \right] = 0, \quad (3)$$

where subscripts 1 and 2 refer to the two equivalent phases. In both eqs (2) and (3), λ_H refers to the heterogeneous material conductivity. A single model [2] has been used to obtain both steady state results. It consists of a sphere of radius a_i and properties λ_i , d_i and c_i , surrounded by a spherical shell of radius a_o and properties λ_o , d_o , and c_o , which in turn is surrounded by an equivalent matrix whose properties represent the unknown heterogeneous material properties λ_H , d_H , and c_H . When $\gamma = (a_i/a_o)^3 = V_i$, model (1) is obtained; while if $\gamma = 1$, model (2) is obtained.

¹Work performed under the auspices of the U.S. Atomic Energy Commission.

²Figures in brackets indicate references at the end of this abstract.

To learn something of the apparent thermal diffusivity of these model materials, an unsteady state heat transfer problem must be used. Consider a two shell spherical particle, with the properties just defined, imbedded in a matrix whose properties are to be determined so that the entire material appears homogeneous. Far from the particle the temperature varies periodically, i. e. ,

$$\lim_{x \rightarrow \infty} T_H = A \exp [i(kx - \omega t)], \quad (4)$$

where complex notation has been used, and x is distance, T is temperature, t is time, ω is frequency, k is a wave vector, and A is a constant. Three solutions are required: T_i in the inner sphere, T_o in the outer spherical shell, and T_H in the matrix. As in any multiregion problem, the three solutions are interrelated by matching temperature and heat flux at the surfaces $r = a_i$ and $r = a_o$, where r is the radius measured from the center of the particle. The criterion for homogeneity is established by forcing the solution T_H , which is a function of the unknown properties λ_H , d_H , and c_H , as well as the properties of regions i and o , to look like a solution for a completely homogeneous material, i. e. , to look like a plane wave for this problem. This requires certain relations to exist between the properties of regions H , i , and o . In the limit that the frequency ω is low or a_i and a_o are small, that is the long wavelength limit, these relations can be simply expressed. For model (1) we find eq (2) is required, along with

$$d_H c_H = V_1 d_1 c_1 + V_2 d_2 c_2, \quad (5)$$

which is merely the equilibrium definition of the specific heat. Similarly for model (2) eqs (3) and (5) result. These results are valid in the long wavelength limit, which can be expressed quantitatively for the two model materials. For model (1) we have

$$\alpha_1/\omega = (\ell_1/2\pi)^2 \gg a_2^2 \quad (6)$$

$$\alpha_H/\omega = (\ell_H/2\pi)^2 \gg (a_2/V_2^{1/3})^2, \quad (7)$$

while for model (2) we have

$$\alpha_H/\omega = (\ell_H/2\pi)^2 \gg a_1^2 \text{ and } a_2^2. \quad (8)$$

The quantity ℓ defined in eqs (6) through (8) is a thermal wavelength associated with the problem [3].

One interesting sidelight of these results is that even though one starts with α as a characteristic constant of the individual phases, the resulting relations are between λ and dc , the volumetric heat capacity. This comes about through the matching of heat flux at the phase boundaries, which introduces λ independently into the problem. Thus even in the limit as the steady state is approached, α is not a characteristic constant of a heterogeneous material.

References

- [1] For model (1) see J. C. Maxwell, A Treatise on Electricity and Magnetism, 3rd edition, Vol. I, Oxford Univ. Press, Oxford (1892) p. 435; for model (2) see R. Landauer, J. Appl. Phys. 33, 779 (1952).
- [2] Z. Hashin, J. Composite Materials 2, 284 (1968).
- [3] J. Kerrisk, J. Appl. Phys. 42, 267 (1971).

Finite Pulse Time Corrections for Flash Thermal Diffusivity Measurements¹

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Measurements of thermal diffusivities by the pulsed technique involve the deposition of a pulse of energy on the front face of a flat thin sample and the recording of the temperature excursion as a function of time of the rear face[1]². The thermal diffusivity (α) is typically deduced from the time at which the temperature reaches one half of its final equilibrium value ($t_{1/2}$) through the relation $\alpha = 1.37 d^2 / (\pi^2 t_{1/2})^3$. This relation applies for instantaneous planar pulses, one dimensional heat flow and no heat losses. It is often the case that the actual duration of the pulse is not instantaneous but in fact may be comparable to diffusion time of heat through the sample, with the consequence that the temperature excursion at the rear face is retarded and altered in shape. In this event the foregoing relation does not yield the correct value for the diffusivity. It has been recognized by several authors [2,3,4] that it is possible to correct for this effect if the pulse shape and duration are known and they have provided correction factors for several types of pulses. Typically pulses, from whatever sources may be used, may be fit approximately by triangles, the positions of whose apices are adjustable in time to coincide with maximum of the actual pulse. Correction factors for a series of these pulses have been calculated using a Greens function method. They are given (see Table I) in the form of ratios of true values of diffusivities to values obtained ignoring pulse width effects and as functions of the ratio of the pulse width to $t_{1/2}$. The parameter b is the ratio of the time of occurrence of the triangle apex to the pulse width, x .

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1. This work was supported by the United States Atomic Energy Commission.
 2. Figures in brackets indicate literature references.
 3. d is the sample thickness.
 - [1] W. J. Parker, et al., J. Appl. Phys. 32, 1679 (1961).
 - [2] J. A. Cape and G. W. Lehman, J. Appl. Phys. 34, 1909 (1963).
 - [3] R. E. Taylor and J. A. Cape, Appl. Phys. Letters 5, 212 (1964).
 - [4] K. B. Larson and K. J. Koyama, J. Appl. Phys. 38, 465 (1967).

PULSE WIDTH CORRECTION FACTORS. TRIANGULAR PULSE

$b = 0.0$ $\tau/t_{\frac{1}{2}} \quad \alpha/\alpha'$	$b = .05$ $\tau/t_{\frac{1}{2}} \quad \alpha/\alpha'$	$b = .10$ $\tau/t_{\frac{1}{2}} \quad \alpha/\alpha'$	$b = .15$ $\tau/t_{\frac{1}{2}} \quad \alpha/\alpha'$	$b = .20$ $\tau/t_{\frac{1}{2}} \quad \alpha/\alpha'$
.036 1.012	.036 1.013	.036 1.013	.036 1.014	.036 1.015
.071 1.024	.071 1.026	.071 1.027	.071 1.028	.071 1.029
.108 1.038	.108 1.039	.108 1.041	.108 1.043	.107 1.045
.139 1.049	.139 1.051	.139 1.054	.138 1.056	.138 1.059
.172 1.061	.171 1.065	.171 1.068	.170 1.071	.170 1.074
.225 1.083	.224 1.087	.223 1.091	.222 1.095	.221 1.099
.266 1.100	.264 1.105	.263 1.109	.262 1.114	.261 1.119
.324 1.126	.323 1.131	.321 1.137	.319 1.143	.318 1.149
.356 1.140	.354 1.146	.352 1.153	.350 1.159	.348 1.166
.394 1.158	.392 1.165	.389 1.173	.387 1.180	.384 1.187
.441 1.181	.438 1.190	.435 1.198	.432 1.207	.429 1.215
.501 1.213	.497 1.223	.494 1.233	.490 1.242	.486 1.252
.580 1.258	.575 1.270	.570 1.281	.565 1.293	.560 1.305
.629 1.289	.623 1.301	.617 1.314	.611 1.327	.605 1.340
.688 1.327	.680 1.341	.673 1.355	.666 1.370	.659 1.384
.758 1.376	.749 1.392	.740 1.409	.732 1.425	.723 1.442
.844 1.442	.833 1.461	.822 1.480	.811 1.499	.801 1.519
.952 1.533	.938 1.556	.924 1.579	.911 1.602	.898 1.626
1.096 1.665	1.077 1.695	1.058 1.724	1.040 1.755	1.022 1.785
1.187 1.756	1.164 1.791	1.142 1.826	1.121 1.860	1.100 1.896
1.298 1.875	1.270 1.916	1.243 1.957	1.217 1.999	1.192 2.041
1.434 2.036	1.399 2.087	1.366 2.137	1.355 2.187	1.304 2.239
1.608 2.270	1.564 2.334	1.522 2.398	1.482 2.462	1.443 2.528
1.715 2.433	1.664 2.506	1.617 2.580	1.571 2.655	1.527 2.731
1.840 2.645	1.781 2.732	1.726 2.819	1.674 2.908	1.623 2.998
1.988 2.938	1.919 3.043	1.855 3.148	1.794 3.255	1.735 3.365
2.165 3.371	2.084 3.502	2.008 3.635	1.936 3.771	1.867 3.910
2.247 3.609	2.160 3.755	2.078 3.903	2.000 4.055	1.926 4.210
2.336 3.906	2.242 4.070	2.153 4.237	2.070 4.409	1.990 4.585
2.433 4.286	2.330 4.474	2.235 4.666	2.145 4.862	2.059 5.064
2.538 4.793	2.427 5.012	2.323 5.236	2.226 5.466	2.134 5.702
2.653 5.502	2.532 5.765	2.420 6.034	2.314 6.309	2.214 6.594

The Analysis of Pulsed Thermal Diffusivity Measurements¹

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Measurements of thermal diffusivities by the pulsed technique involve the deposition of a pulse of energy on the front face of a flat thin sample and the recording of the temperature excursion vs time of the rear face. The extraction of the thermal diffusivity from this record is accomplished, in effect, by selecting values for the diffusivity and other parameters (i.e., heat loss parameters) which when entered into the analagous heat conduction problem cause the theoretical and experimental temperature vs time curves to coincide. This paper reports on calculations which provide a number of techniques by which this selection can be made and applies to the case of an instantaneous planar pulse, one-dimensional heat flow and radiant or convective losses at both faces.

The analysis, which starts with the solutions to the heat diffusion problem given by Watt[1]², has yielded non-dimensional times³ ($\pi^2 \alpha t / d^2$) and/or temperatures (T/T_∞) or values of derivatives of the temperature-time function for the following events: time of maximum curvature of T vs t , time of maximum slope, time and temperature at maximum temperature, the times at which the temperature equals .1 through .9 of its maximum value and the temperatures at⁴ (3, 4, 5, 6, 7, 8, 9, 10) $\times t_{\frac{1}{2}}$. From tables of these values it is possible to reduce experimental data and obtain diffusivities in a variety of ways, some of which have distinct advantages in certain situations. For instance, the events of maximum curvature and maximum slope occur very early in time and are consequently much less sensitive to heat losses than is $t_{\frac{1}{2}}$ which is the event commonly used to determine diffusivities. Likewise, two-dimensional effects arising from losses at the sample edges are smallest at early times. The use of several reduction techniques, in itself, is advantageous since it tests the coincidence of the experimental and theoretical temperature vs time curves at a number of points and thereby provides verification that boundary and initial conditions have been satisfactorily met.

Table I gives some representative results of the calculations. L_1 and L_2 are the heat loss parameters for the front and rear faces, respectively.

1. This work was supported by the United States Atomic Energy Commission.
 2. Figures in brackets indicate literature references.
 3. α , thermal diffusivity; t , time; d , thickness; T , excess temperature; T_∞ , excess (equilibrium) temperature at infinite time in the absence of losses.
 4. Certain of these parameters correspond to those of R. D. Cowen[2], $t_{\frac{1}{2}}$, non-dimensional time for T equal to $\frac{1}{2}$ of its maximum value.
- [1] D. A. Watt, Brit. J. Appl. Phys. 17, 231 (1966).
[2] R. D. Cowen, J. Appl. Phys. 34, 926 (1963).

L_1	L_2/L_1	$t(T_{max})$	$t(T_{max})$	t_2	$t(T_{max})$	T_{max}	$T(5t_2)$	$T(10t_2)$
.00	0.00	.4466	.9056	1.3698	"	1.000	--	--
.05	0.00	.4459	.9015	1.3371	5.9761	.9578	.9568	.9277
.05	.30	.4457	.9002	1.3292	5.7051	.9469	.9449	.9071
.05	1.00	.4452	.8974	1.3124	5.2661	.9236	.9183	.8620
.10	0.00	.4452	.8975	1.3132	5.2897	.9245	.9194	.8644
.10	.30	.4448	.8951	1.2999	5.0106	.9056	.8972	.8273
.10	1.00	.4439	.8897	1.2727	4.5687	.8662	.8495	.7506
.20	0.00	.4439	.8899	1.2750	4.6134	.8687	.8532	.7582
.20	.30	.4432	.8855	1.2534	4.3214	.8372	.8140	.6988
.20	1.00	.4414	.8752	1.2119	3.8781	.7747	.7352	.5819
.30	0.00	.4427	.8828	1.2442	4.2266	.8221	.7962	.6729
.30	.30	.4415	.8761	1.2162	3.9252	.7807	.7434	.5948
.30	1.00	.4389	.8618	1.1648	3.4832	.7021	.6438	.4616
.40	0.00	.4415	.8761	1.2181	3.9589	.7816	.7465	.6029
.40	.30	.4400	.8675	1.1850	3.6489	.7322	.6828	.5134
.40	1.00	.4366	.8495	1.1263	3.2099	.6420	.5690	.3728
.50	0.00	.4403	.8697	1.1954	3.7562	.7459	.7027	.5447
.50	.30	.4384	.8593	1.1578	3.4388	.6897	.6300	.4472
.50	1.00	.4343	.8381	1.0936	3.0041	.5910	.5067	.3056
.60	0.00	.4392	.8636	1.1754	3.5947	.7139	.6638	.4956
.60	.30	.4369	.8515	1.1339	3.2709	.6521	.5837	.3928
.60	1.00	.4322	.8274	1.0652	2.8404	.5470	.4543	.2538
.80	0.00	.4370	.8524	1.1412	3.3492	.6585	.5975	.4179
.80	.30	.4341	.8371	1.0932	3.0128	.5878	.5061	.3091
.80	1.00	.4280	.8081	1.0181	2.5926	.4747	.3711	.1807
1.00	0.00	.4349	.8422	1.1129	3.1673	.6120	.5433	.3595
1.00	.30	.4313	.8241	1.0594	2.8205	.5346	.4439	.2487
1.00	1.00	.4242	.7910	.9800	2.4104	.4175	.3088	.1332
1.50	0.00	.4301	.8203	1.0584	2.8601	.5219	.4429	.2635
1.50	.30	.4251	.7961	.9943	2.4919	.4340	.3324	.1555
1.50	1.00	.4155	.7556	.9090	2.1065	.3158	.2071	.0697
2.00	0.00	.4259	.8024	1.0187	2.6631	.4560	.3739	.2064
2.00	.30	.4195	.7730	.9465	2.2780	.3627	.2592	.1049
2.00	1.00	.4080	.7276	.8587	1.9141	.2492	.1480	.0411
2.50	0.00	.4221	.7873	.9881	2.5241	.4054	.3236	.1691
2.50	.30	.4145	.7536	.9093	2.1241	.3094	.2083	.0747
2.50	1.00	.4014	.7049	.8206	1.7791	.2025	.1108	.0264
3.00	0.00	.4187	.7744	.9635	2.4195	.3651	.2854	.1431
3.00	.30	.4100	.7369	.8791	2.0067	.2681	.1712	.0554
3.00	1.00	.3956	.6859	.7905	1.6782	.1683	.0859	.0181
4.00	0.00	.4127	.7536	.9263	2.2720	.3048	.2311	.1095
4.00	.30	.4020	.7096	.8325	1.8369	.2085	.1218	.0334
4.00	1.00	.3857	.6558	.7453	1.5360	.1220	.0559	.0098
5.00	0.00	.4078	.7374	.8992	2.1723	.2617	.1944	.0888
5.00	.30	.3953	.6879	.7978	1.7182	.1678	.0912	.0219
5.00	1.00	.3776	.6328	.7128	1.4398	.0928	.0392	.0060
6.00	0.00	.4036	.7245	.8786	2.1001	.2293	.1678	.0749
6.00	.30	.3895	.6701	.7705	1.6295	.1385	.0708	.0153
6.00	1.00	.3708	.6146	.6878	1.3697	.0730	.0291	.0040
8.00	0.00	.3968	.7049	.8490	2.0021	.1839	.1321	.0572
8.00	.30	.3798	.6424	.7300	1.5040	.0996	.0463	.0084
8.00	1.00	.3599	.5875	.6520	1.2741	.0488	.0178	.0022
10.00	0.00	.3916	.6908	.8287	1.9387	.1535	.1090	.0464
10.00	.30	.3722	.6217	.7008	1.4184	.0755	.0326	.0053
10.00	1.00	.3517	.5681	.6276	1.2114	.0349	.0121	.0013
15.00	0.00	.3825	.6684	.7978	1.8486	.1085	.0761	.0317
15.00	.30	.3581	.5864	.6532	1.2870	.0434	.0167	.0022
15.00	1.00	.3375	.5371	.5897	1.1208	.0182	.0059	.0006
20.00	0.00	.3768	.6552	.7804	1.8005	.0840	.0585	.0242
20.00	.30	.3485	.5638	.6243	1.2109	.0283	.0101	.0012
20.00	1.00	.3285	.5188	.5679	1.0718	.0112	.0035	.0003

FLASH DIFFUSIVITY IN CYLINDRICAL COORDINATES

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INTRODUCTION

The flash-diffusivity technique, first described by Parker et al [1]¹ is extended to cylindrical coordinates. This is particularly advantageous in the determination of the thermal diffusivity of nuclear-reactor fuel elements for which specimens are easily fabricated as long, hollow cylinders.

APPARATUS

The apparatus is shown in Fig. 1. The thermocouple-probe is cradled in the adapter, which is secured to the specimen with a binding screw. The thermocouple consists of a shielded, twisted pair of 0.025-cm-diam. chromel-alumel wires, whose ends have been electrochemically etched to very sharp points. These points are spring-loaded against the inner diameter of the specimen so that the thermocouple junction is actually made through the specimen. The specimen-thermocouple assembly is positioned inside a helically wound flash lamp. When the flash lamp is discharged the subsequent thermal response at the inner radius of the specimen is monitored and recorded with an oscilloscope equipped with a Polaroid camera.

For the ideal case of one-dimensional radial heat flow with no losses and negligibly short flash duration, the thermal diffusivity can be determined as:

$$\alpha = u_{1/2} (b - a)^2 / t_{1/2} , \quad (1)$$

where α is the thermal diffusivity, b and a are the outer and inner radii and $t_{1/2}$ is the time required for the inner radius to attain one-half its maximum temperature. For flat (slab-geometry) specimens, $u_{1/2}$ is constant and is given as 0.139 [1]. For cylindrical specimens, this parameter is a relatively weak function of the ratio of the outer-to-inner radius, as shown on Fig. 2.

EFFECTS OF FINITE PULSE TIME

Larson and Koyama [2] have proposed that the pulse shape of a xenon flash tube can be represented as:

$$\phi(t)/\phi_{\max} = (t/t_p) \exp(1 - t/t_p) \quad (2)$$

where $\phi(t)$ is the output amplitude at time, t ; $\phi_{\max}$ is the maximum amplitude; and t_p is the time required to attain $\phi_{\max}$. Figure 3 compares Eq. (2) with three experimental pulses obtained with the power supplier conditions

¹ References appear at the end of this abstract.

² These results were arrived at independently by the writer and D. Klein, IASL summer employee, 1966 (unpublished).

as shown. These pulses were obtained with a type IN2175 photodiode (Texas Instruments). The flash tube used is a xenon-filled, General Electric Model 524, powered with a Hughes Model 260 laser power supply. As can be seen, Eq. (2) represents the pulse shape quite well, and thus the results of Larson and Koyama are applicable with considerable accuracy. Finite pulse time effects are incorporated by multiplying the right-hand side of Eq. (1) by a "correction" factor, C, which is presented in Fig. 4. Figure 4 is simply a recasting into a different form of the original results of Larson and Koyama [2].

REFERENCES

1. Parker, W. J. et al, J. Appl. Phys. 32, 1679 (1961).
2. Larson, K. B. and Koyama, K., J. Appl. Phys. 38, 465 (1967).

Fig. 1. Schematic of Apparatus

Fig. 2. The Parameter $\omega_{1/2}$

Fig. 3. Relative Flash Lamp Output

Fig. 4. "Correction" Factors for Finite Pulse Time Effects

THERMAL CONDUCTIVITY AND DIFFUSIVITY OF THE APOLLO 12 LUNAR FINES AT LANDING SITE CONDITIONS

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INTRODUCTION

The design of lunar systems from a thermal point of view and the calculation of lunar heat flow both require an accurate knowledge of the thermophysical properties of the lunar regolith, which consists primarily of fine material. The present paper reports a set of measurements of one of these properties, the thermal conductivity, for the returned Apollo 12 fines and the subsequent calculations of a second property, the thermal diffusivity. These properties are determined over the range of temperatures experienced by the lunar surface layer and for a density corresponding to the density of the returned core-tube sample, which should be close to the true density just below the lunar surface.

APPARATUS

The thermal conductivity was measured over the temperature of 104-425K by a modified line heat-source technique described by Cremers [1]². The test cell, which held 5-8 grams of material, depending on the sample density, was mounted in a thermal environmental chamber which permitted ambient temperature control from 100K to 600K. This in turn was suspended in a vacuum chamber in which the pressure was held at about 10^{-6} torr, well below the level at which gaseous effects are important.

RESULTS AND CONCLUSIONS

The effective thermal conductivity of the Apollo 12 fines was measured for a density of 1970 kg/m^3 which is the same as the density of the material in the returned core-tube sample. The data are shown in figure 1. Also shown is a least-squares curve fitted through the data according to the relation

$$\lambda = A + BT^3 \quad (1)$$

This temperature dependence of the conductivity of powdered evacuated dielectrics is predicted by elementary theory and fits the data fairly well. These data also show a similar temperature dependence. The physical interpretation of equation (1) is that the effective conductivity of a porous evacuated dielectric material is made up of an approximately constant component representing solid conduction plus a term proportional to temperature cubed representing internal radiative transfer.

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² Figures in brackets indicate literature references at the end of this abstract.

The thermal diffusivity $\alpha = \lambda/\rho c$ is calculated using the specific heat data of Robie, et al. [2]. This data was taken on the Apollo 11 sample but because of the chemical similarity of the samples it should represent the Apollo 12 sample fairly well. The diffusivity obtained from combining Robie's data with the least-squares conductivity curve of figure 1 is also shown in that figure.

Figure 1. Thermal Conductivity and Diffusivity

ACKNOWLEDGEMENTS

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REFERENCES

1. Cremers, G.J., Thermal Conductivity Cell for Small Powdered Samples, to be published in Rev. Sci. Inst.
2. Robie, R.A., Hemingway, B.S. and Wilson, W.H., Specific Heats of Lunar Surface Material from 90 to 350K, Proc. Apollo 11 Lunar Sci. Conf., Pergamon Press, New York, 2361 (1970).

THE THERMAL CONDUCTIVITY OF SOME UNIRRADIATED HTGR FUEL ELEMENT MATERIALS

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INTRODUCTION

The thermal conductivity of some typical production pieces of HTGR fuel element materials consisting of coated particles bonded in a porous graphite matrix has been measured over the approximate temperature range 400 to 1200°K using a modified cut bar technique, and 1000 to 1400°K using a direct heating method^{1,2}. This work was carried out to develop a technique both to measure the thermal conductivity of short small-diameter specimens in the "as-received" condition in a non-destructive manner and which, in addition, could be adaptable for measurements of irradiated specimens remotely in the hot cell.

DETAILS OF SAMPLE

The fuel elements were made by hot injecting a graphite flake-pitch mixture into a die containing the fuel particles. The green elements were then slowly carbonized at 850°C and finally heat treated at 1800°C to form solid right circular cylinders 5 cm long. The shorter specimens 1 through 6 were cut from these with a diamond wheel; a full length element was used for Sample 7. The surfaces of the parallel faces were prepared as good as possible; however, due to the form of the material some small imperfections and holes were present. The apparent matrix macroporosity of the fuel elements in this series ranged from 14 to 39%. Details of the description, dimensions, weight, and derived density of each are given in Table I.

Table I
Details of Test Samples

<u>Sample</u>	<u>Dimensions, mm</u>	<u>Weight, gm</u>	<u>Density, Kgm⁻³</u>
1	12.44 dia. 12.47 long	2.77	1835
2	12.44 dia. 25.14 long	5.99	1962
3	12.42 dia. 23.20 long	5.34	1900
4	12.43 dia. 19.13 long	4.53	1955
5	12.42 dia. 28.08 long	7.04	2060
6	12.43 dia. 19.25 long	4.52	1935
7	12.50 dia. 49.45 long	12.34	2022

EXPERIMENTAL DETAILS

Any technique used had to be such that it was compatible with small diameter samples which were relatively short. In addition, due to the nature of the material and because subsequently the technique would have to be used on similar samples in an irradiated state, it was desirable little machining of samples was to be made and certainly that no holes or grooves could be cut in the sample.

¹ Head, Thermophysical Properties Group, and Manager, Measurements Laboratory respectively.

The comparative cut-bar method was chosen using Pyroceram 9606 reference materials of the appropriate diameter. Each reference material was 51 mm long and had three holes approximately 1.3 mm diameter drilled to the center over the central section some 43 mm total distance apart. In addition a fine groove approximately 0.3 mm wide and deep was cut across the flat polished surface of each which was to be in contact with the sample. Fine gauge platinum 10% rhodium/platinum thermocouples were fitted tightly into the holes and into the grooves. Some pressure was applied to the upper end of the sample stack to align the samples and help reduce contact resistances. All measurements were carried out in an atmosphere of helium gas at 1 atmosphere.

Measurements were undertaken on a sample of Pyroceram 9606 to check the technique. The sample was the same diameter as the test samples and 51 mm long. It had grooves cut across each surface and three holes were drilled to the center as for the reference materials. As a further check, Sample 7 was measured by a direct heating method [1,2]² in which the power was calculated from voltage and current measurements and the radial temperature difference measured between the central axis and the surface by optical pyrometry. The pyrometer sight hole was placed in the sample in the green state before the fuel element was hardened by the baking and heat treatment.

RESULTS

The results for the seven samples obtained from smooth curves drawn through the experimental points are given in Table II. The first six samples were measured by the comparative cut bar method. Each experimental point for the first six samples was derived as the mean value from the heat flows calculated from the appropriate temperature difference in the top and bottom reference material. The individual values for each reference material usually differed by an amount of the order of 8 to 20% but was in no case greater than 22%. The results for the last sample obtained by the direct heating method is in fair agreement with the other results in the overlapping temperature region.

Table II

Thermal Conductivity of Some Unirradiated Fuel Element Materials

Temperature, °K	Thermal Conductivity, W m ⁻¹ K ⁻¹						
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
400	6.1	7.1	7.35	7.85	9.75	7.7	-
600	6.2	6.8	7.2	7.6	9.95	7.45	-
800	6.15	6.55	7.0	7.35	9.8	7.2	-
1000	6.05	6.25	6.8	7.1	9.6	6.95	7.25
1200	5.95	6.0	6.65	6.9	-	6.7	7.6
800 cooling	6.2	-	7.0	7.3	-	7.15	-
1300	-	-	-	-	-	-	7.75
1400	-	-	-	-	-	-	7.95

The measurements undertaken on the Pyroceram 9606 sample, when compared to accepted values for the material, gave values which were some 10% low at approximately 400°K, 8% low at 700°K, and 5% low at 1000°K.

These measurements indicate that the modified cut bar method can be used for this type of material without making any alterations such as drilling of thermocouple holes. The technique is capable of attaining an accuracy of the order of $\pm 10\%$ and has the potential of being applicable to measurements of irradiated fuel elements in the hot cell.

ACKNOWLEDGEMENTS

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REFERENCES

- (1) Angell, M. F., Phys. Rev., **33**, 421-432 (1911).
- (2) Powell, R. W., and Schofield, F. H., Proc. Phys. Soc. Lond., **51**, 153 (1939).

² Numbers and brackets refer to references at end of paper.

FRIDAY
a.m.

THE THERMAL CONDUCTIVITY OF EIGHT AEROSPACE METALS AND ALLOYS

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In association with the requirement for reliable design data for materials used in conjunction with nuclear energy applications, thermal conductivity determinations have been carried out over all or parts of the approximate temperature range 100 to 1200K on eight metals. In all, eight samples of each material in its appropriate commercial form were studied in order to obtain sufficient data to provide a valid statistical curve for the thermal conductivity behaviour.

The eight materials and the temperature range studied were as follows:

1. A hot pressed beryllium approximately 98.4% pure, 90 to 600K
2. A titanium alloy containing 5% Al and 2.5% Sn, 90 to 600K
3. An Inconel 718 in the unannealed condition, 90 to 1200K
4. An iron based superalloy A 286, 90 to 700K
5. A Molybdenum TZM alloy containing approximately 0.5 Ti, 90 to 1200K.
6. A 304 Stainless Steel, 100 to 1100K
7. A 301 Stainless Steel, 100 to 700K
8. A T6061 aluminum alloy, 100 to 600K

The materials were supplied in rod form except for the 301 Stainless which was in sheet form and this was fabricated into rod form using special end pieces. Determinations were made by the axial rod method [1]² and, in all, three different apparatus were used. In addition, electrical resistivity measurements were carried out over the required temperature range, plus determinations at 4.2K to help characterise the materials.

The thermal conductivity instruments used were checked out using both a high purity copper for the temperature range 100 to 600K and Armco Iron for the range 100 to 1100K. The latter material was a piece cut from the original Powell 1934 iron [2] and which had been in use as a reference material for many years.

Results will be presented for each material both individually and collectively and compared when possible with other results. The present results verify the claim that an accuracy of ± 2 to $\pm 4\%$ is possible with the instruments as designed and operated and for the conductivity range covered. The results may be summarized as follows:

1. The hot-pressed beryllium consisted of two distinct "lots", one having a resistivity ratio between 293 and 4.2K of 6.6, and the other 4.6. The former material exhibited a maximum in λ at approximately 118K with a value of $330 \text{ W m}^{-1} \text{ K}^{-1}$ and the latter at 140K with a value of $260 \text{ W m}^{-1} \text{ K}^{-1}$. Within the two lots differences in the values of λ and ρ from the means are due to slight compositional differences. Above 300K the relative differences are slight and the values are in good agreement with those reported previously [1,3] for this material.
2. The titanium alloy showed very small variations in electrical resistivity and all thermal conductivity values were well within 4% of a mean line drawn through the experimental points. The values are in excellent agreement over the range 100 to 300K with those of Hust et al [4] for the same nominal composition and in good agreement above 300K with published data for similar alloys [5,6].
3. For the Inconel 718 all data points were within $\pm 3\%$ of a mean line drawn through them and the material was very reproducible in terms of ρ . Over the range 100 to 300K the results for λ are again in excellent agreement with Hust et al [4].

¹ Manager, Measurements Laboratory, Engineering Aide and Project Manager, respectively.

² Numbers in parenthesis refer to references at end of paper.

4. The A 286 alloy appeared to be a material which is very reproducible in its thermal and electrical transport properties.

5. The TZM Molybdenum alloy increases from approximately $102 \text{ W m}^{-1} \text{ K}^{-1}$ at 100K to a clearly defined maximum of approximately $119 \text{ W m}^{-1} \text{ K}^{-1}$ at 340K and then continues to decrease to $108 \text{ W m}^{-1} \text{ K}^{-1}$ at 1100K. All experimental points were well within $\pm 2\%$ of a mean curve.

6. The 304 stainless steel was very uniform in properties and the mean thermal conductivity curve obtained can be compared with the TPRC recommended curve for this type of material [7]. Over the range 100 to 500K the differences between the curves are between 1 and 2% while up to 1100K the differences are less than 3%.

7. Both the 301 stainless steel and the aluminum alloy were reproducible but were found to be unstable in their original "as supplied state" at temperatures slightly above those required of the original programme. Results will be presented to indicate the changes obtained on heat treatment. In both cases the value of the derived Lorenz Numbers were found to remain unchanged after heating.

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REFERENCES

1. Tye, R. P. and Quinn, J. E. (1964) Proc. 4th Symposium on Thermophysical Properties. A.S.M.E., New York, pp. 144-149.
2. Powell, R. W. (1934) Proc. Phys. Soc. 46, 659.
3. Tye, R. P. and Brazel, J. P. (1970) Rev. Int. Hautes. Temper. et Refract., 7, 326.
4. Hust, J. G., Powell, R. L. and Weitzel, D. H. (1969), NBS Report - 9732, p. 188.
5. Powell, R. W. and Tye, R. P. (1960) J. Less. Common Metals, 3, 226.
6. Deem, H. W., Wood, W. D., and Lucks, C. F. (1958) Trans. Metall. Soc. AIME, 212, 520.
7. Thermophysical Properties of Matter, Volume 1, Eds. Touloukian, Y. S., Powell, R. W., Ho, C. Y., and Klemens, P. G., Plenum Press, New York, 1970.

THE THERMAL AND ELECTRICAL CONDUCTIVITY OF SOME COPPER ALLOYS AT ELEVATED TEMPERATURES

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A considerable amount of experimental work has been carried out upon various copper alloy systems [1, 2, 3]² but in general the temperature range covered has been limited to below 600 to 700K. As a result of their rather thorough investigation of thermal conductivity and electrical resistivity on a large number of alloys some forty years ago, Smith and Palmer [1] proposed the following empirical equation for the approximate range 300 to 600K.

$$\lambda = 2.39 \times 10^{-8} \frac{T}{\rho} + 7.5$$

as a means of calculating thermal conductivity, λ , $\text{W m}^{-1} \text{K}^{-1}$, from the much more easily measured electrical resistivity, ρ , Ωm , at an absolute temperature T , K. The accuracy was surprisingly good, being well within $\pm 5\%$, except for alloys containing a considerable amount of manganese. This latter fact was confirmed by the results of Gupta and Bannerjee [2] which indicated that for manganese contents in excess of 5% the differences between λ measured and derived could be up to the order of 15%.

Very few determinations have been made on any copper systems at temperatures much in excess of 700K. Recently Willett [4] undertook studies on a number of copper-nickel alloys to approximately 1000K including a study on the effects of heat treatment and quenching. At temperatures in excess of 800K one of these alloys, a nominal 90-10 cupro-nickel (706) alloy, gave indications of a small maximum in λ which the author attributed to the effect of the relatively high iron content which could be in or out of solution. However, it was unfortunate that measurements of ρ were included since there could be uncertainties in the thermal conductivity measurements due to contamination and uncertain heat losses. Furthermore the absence of values of ρ did not allow one to investigate the behaviour of the Lorenz Number or the possible validity of the Smith-Palmer equation at higher temperatures.

During the course of some studies on metals and alloys the present author has had an opportunity to measure some alloys up in the range 1000 to 1200K. Two of these alloys were varieties of Inconel, a high nickel content aluminum bronze, and the other three were copper alloyed with the order of 1 to 2% of beryllium plus a little cobalt. The determination of λ and ρ were carried out by an axial rod method which has been described in detail [5]. Measurements were taken both on heating and cooling both to check that contamination had not occurred and since it was expected that the properties of the copper beryllium alloys would be affected by heat treatment.

The results obtained for the various alloys in their final stabilized condition are summarized in Table I. They indicate clearly that the thermal conductivity increases to a clearly defined maximum and then decreases sharply on further increase of temperature. At temperatures close to the position of the maximum the electrical resistivity exhibits a marked increase in rate of rise with temperature and this is maintained up to the limit of the measurements. In consequence therefore, the derived Lorenz Number remains approximately constant. The temperature at which these changes are apparent coincide with known metallurgical changes in the respective materials. Cone [6] made thermal conductivity determinations on a copper alloy containing 2.75% Be. His results indicated that a maximum occurred at approximately 623K. However, the author did not include electrical resistivity measurements.

Manager, Measurements Laboratory.

² Numbers in parentheses refer to references at end of paper.

Table I

Thermal Conductivity, λ , $\text{W m}^{-1} \text{K}^{-1}$, Electrical Resistivity, ρ , $10^8 \Omega \text{m}$
and Derived Lorenz Number, L , $10^8 \text{V}^2 \text{K}^{-2}$

Temperature K	Standard Incramet			Special Incramet			Alloy 10			Alloy 10-52			Alloy 25		
	λ	ρ	L	λ	ρ	L	λ	ρ	L	λ	ρ	L	λ	ρ	L
298	-	19.4	-	-	18.2	-	-	3.48	-	-	3.26	-	-	6.7	-
373	49.0	20.5	2.69	52.5	18.9	2.66	228	3.98	2.43	237	3.88	2.46	125.5	7.8	2.63
473	57.5	21.7	2.64	60.5	19.9	2.55	245	4.78	2.46	253.5	4.62	2.48	141	8.68	2.59
573	65.8	23.0	2.68	68.0	21.2	2.52	254	5.58	2.47	266	5.37	2.49	153.5	9.6	2.57
673	72.8	24.3	2.63	74.0	22.6	2.49	263	6.34	2.48	274.5	6.17	2.52	163.5	10.5	2.55
773	77.5	25.8	2.59	77.5	24.2	2.43	268	7.18	2.49	282	7.08	2.58	166	11.7	2.51
873	80.0	27.6	2.53	80.5	26.3	2.43	273	7.94	2.48	-	-	-	150	14.6	2.51
973	80.0	30.1	2.48	80.0	29.6	2.43	271	8.96	2.50	-	-	-	143.5	17.1	2.52
1073	78.0	34.2	2.48	76.0	34.2	2.42	245	11.02	2.51	-	-	-	140.0	19.0	2.48
1173	73.5	39.6	2.48	72.0	39.9	2.45	-	-	-	-	-	-	-	-	-

If the present value of ρ for the various alloys are used in conjunction with the Smith-Palmer relationship it is found that the derived λ values are well within 5% of the measured ones for the copper-beryllium materials and within 6% for the Standard Incramet and 8% for the Special Incramet. Furthermore, the equation predicts exactly the shape and form of the relationship of λ versus T . While it is obvious that more copper alloys need to be studied at elevated temperatures, the present works indicate that the Smith-Palmer equation is probably valid over a much wider temperature than previous experience has shown.

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REFERENCES

1. Smith, C. S. and Palmer, E. W. (1935) Trans. Amer. Inst. Min. Metall. Engrs. 117, 225.
2. Gupta, M. K. and Bennerjee, T. (1962) Nat. Metall. Lab. Tech. J., 4, 12.
3. Powell, R. W. (1965) Int. J. Heat Mass Transfer, 8, 1033.
4. Willett, R. E. (1968) J. Materials, 3, 744.
5. Tye, R. P. and Quinn, J. E. (1968) Proc. 4th Symposium on Thermophysical Properties, A.S.M.E. New York, pp. 144-149.
6. Cone, E. F. (1933) Trans. Am. Foundrymens Assoc., 41, 330.

Summary of the report to the XI Conference on Thermal
Conductivity in Albuquerque, New Mexico, USA

THERMAL AND ELECTRIC CONDUCTIVITY OF POROUS NICKEL

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The possibilities of making theoretical predictions in evaluating the generalized conductivity of a porous material are limited, especially so, in a wide porosity range. The present paper aims at revealing the effect of porosity upon the transport properties of a sintered metal such as nickel.

The materials were obtained by pressing nickel powder not less than 99.7 per cent pure. Samples were prepared from four different powders having the grain size of 2.5, 1.2, 0.8 and less than 0.5 microns. All samples were obtained in a reduction medium at the same sintering temperature.

Thermal conductivity was studied with the aid of the stationary technique of radial heat flux from an inner core heater. The samples were shaped as washers 30 mm high and having the inner diameter of 10 mm and the outer diameter of 40 mm. The whole set was 380 mm high.

Temperature measurements were carried out by means of chromel-alumel thermocouples, three of which were placed in axial channels at a radius of 6.5 mm, and the other three at a radius of 19 mm, as measured from the sample axis. The heat flux was found from electric energy evolved on the work-

ing portion of the heater, with consideration for its linear expansion.

Thermal conductivity was measured in an argon atmosphere at a pressure somewhat higher than the atmospheric one. The measurements were carried out in the temperature range of from 400 to 1,200°K. The maximum experimental temperature did not exceed the sintering temperature of the samples. The maximum error in individual measurements was 15 to 6 per cent, for dense and porous samples, respectively. The limit error in the averaged data on thermal conductivity did not exceed 10 per cent.

Electric conductivity was measured with the aid of a potentiometer. The error was two per cent. All the necessary geometrical dimensions were measured with the aid of a microscope prior to and after the experiment.

Thermal and electric conductivity values were calculated and related to total porosity measured after the experiments. The thermal conductivity measurements were carried out in 12 samples, the electric conductivity ones - in 28 samples. The investigated porosity range was 19-63 per cent.

The experimental data obtained were checked as to their agreement with calculation formulae suggested by various authors.

For finding the generalized porosity dependence of thermal and electric conductivity use was made of smoothed values obtained from the temperature dependence curves.

The porosity dependence for the chosen isotherms was

selected by the method of least squares.

The isotherms obtained were processed in generalized coordinates $\sigma/\sigma_0; \lambda/\lambda_0 = f(P)$, where σ_0, λ_0 were found by the extrapolation of an appropriate isotherm for zero porosity. The maximum divergence of all the plotted isotherms in the generalized coordinates relative the single smoothing curve did not exceed ± 15 per cent. When processing the experimental data, special attention was paid to a sound choice of the conductivity value of the material of the matrix (σ_0, λ_0). To this effect, the results of direct extrapolation of the experimental data for zero porosity were compared with the calculated values of these quantities obtained on the basis of the single generalized dependence. Serving as the criterion of applicability of the generalized dependence was, first, the minimum divergence between the experimental and calculated values of σ_0 and λ_0 for all isotherms and, second, the minimum divergence of this dependence from the isotherms themselves.

Of the models considered, the most optimum one for describing the porosity dependence of thermal and electric conductivity of porous nickel in generalized coordinates within the investigated temperature interval in a wide porosity range is the dependence found by V.V.Skorokhod^I.

Part of the results obtained is presented in the Table.

P%	0	10	20	30	40	50	60	70	80	90	100
$\tilde{\sigma}/\tilde{\sigma}_0; \lambda/\lambda_0 [1]$	I 0,847	0,687	0,525	0,368	0,222	0,140	0,059	0,033	0,008	0,000	
$\tilde{\sigma}/\tilde{\sigma}_0$ (2201) (T=290°K)	I 0,843*	0,656	0,470	0,344	0,238	0,156	0,085	0,035*	0,0082*		0,000
λ/λ_0 (4101) (T=300°K)	I 0,850*	0,690	0,517	0,345	0,224	0,144	0,069	0,034*	0,0085*		0,000

Note: * - extrapolated data;

Reference: ^I - V.V.Skorokhod, Inzhenerno-Fizicheskii Zhurnal,
vol.II, No.8, 51, 1959.

Тезисы доклада на XI конференции по теплопроводности
в США.

ТЕПЛО- И ЭЛЕКТРОПРОВОДНОСТЬ ПОРИСТОГО НИКЕЛЯ.

Э.А.Бельская, В.Э.Пелецкий

Возможности теоретического прогноза в оценках величины обобщенной проводимости пористого материала ограничены, особенно в широком диапазоне пористостей. Целью данной работы было выяснение влияния пористости на свойства переноса спеченного металла на примере никеля.

Материалы были получены прессованием из порошка никеля, чистота которого была не хуже, чем 99,7%. Образцы изготавливались из порошков четырех серий, имеющих размер крупинок 2,5; 1,2; 0,8 и меньше 0,5 мк. Все образцы были получены в восстановительной среде при одной температуре спекания.

Теплопроводность исследовалась стационарным методом радиального потока тепла от внутреннего стержневого нагревателя. Образцы имели вид шайб высотой 30 мм и диаметром $d_{\text{внзр}} = 10$ мм и $d_{\text{нар}} = 40$ мм. Общая высота набора составляла 380 мм.

Температурные измерения проводились хромель-алюмелевыми термопарами, три из которых размещались в осевых каналах на радиусе 6,5 мм, три других на радиусе 19 мм от оси образца. Тепловой поток определялся по электрической мощности, выделенной на рабочем участке нагревателя, при этом учитывалось его линейное расширение.

Измерение теплопроводности проводилось в атмосфере аргона при давлении несколько выше атмосферного. Исследования про-

водились в интервале температур 400 – 1200°K. Максимальная температура опытов не превышала температуры спекания образцов. Максимальная ошибка отдельных измерений составляла величины $15 \div 6 \%$, соответственно для плотных и пористых образцов. Предельная ошибка осредненных данных по теплопроводности не превышала 10%.

Для измерения ~~ж~~электропроводности был использован потенциометрический метод. Погрешность определения электропроводности составляла величину 2%. Все необходимые геометрические размеры определялись на микроскопе до и после опытов.

Значения тепло- и электропроводности рассчитывались и относились к общей пористости, измеренной после опытов. Измерение теплопроводности было проведено на 12 образцах, электропроводности – на 28. Исследованный диапазон пористости составлял 19–63%.

Была проведена проверка согласования полученных опытных данных с расчетными формулами, предложенными различными авторами.

Для нахождения обобщенной зависимости тепло- и электропроводности от пористости использовались сглаженные значения, полученные из кривых температурной зависимости.

Для выбранных изотерм зависимость от пористости подбиралась методом наименьших квадратов.

Полученные изотермы обрабатывались в обобщенных координатах $\sigma/\sigma_c; \lambda/\lambda_c = f(P)$, где σ_c, λ_c – находилось экстраполяцией соответствующей изотермы на нулевую пористость. Максимальное расхождение всех построенных изотерм в обобщенных координатах относительно единой сглаживающей кривой не превышало $\pm 15\%$.

При обработке опытных данных особое внимание было уделено обоснованному выбору величины проводимости материала матрицы ($\bar{\sigma}_c$, λ_0). С этой целью результаты прямой экстраполяции экспериментальных данных на нулевую пористость сравнивались с расчетными значениями этих величин, полученными на основе единой обобщенной зависимости. Критерием применимости обобщенной зависимости было, во-первых, минимальное расхождение между экспериментальными и расчетными значениями $\bar{\sigma}_c$ и λ_0 для всех изотерм и, во-вторых, минимальное отклонение этой зависимости от самих изотерм.

Среди рассмотренных моделей наиболее оптимальной для описания зависимости в обобщенных координатах тепло- и электропроводности пористого никеля в исследованном интервале температур в широком диапазоне пористостей является зависимость В.В. Скорохода [1].

Часть полученных результатов приведена в таблице.

P %	0	10	20	30	40	50	60	70	80	90	100
$\bar{\sigma}/\bar{\sigma}_c; \lambda/\lambda_0$	1	0,847	0,687	0,525	0,368	0,222	0,140	0,059	0,033	0,008	0,000
$\bar{\sigma}/\bar{\sigma}_c$ ($T=290^\circ\text{K}$)	1	0,843*	0,656	0,470	0,344	0,238	0,156	0,085	0,035*	0,0082*	0,000
λ/λ_0 (экс.) ($T=290^\circ\text{K}$)	1	0,850*	0,690	0,517	0,345	0,224	0,144	0,069	0,034*	0,0085*	0,000

Примечание: * - экстраполированные данные.

[1] - Скороход В.В., ИФЗ П, № 8,51, 1959.

Observations on the Thermal Conductivity of Uranium-Plutonium Oxides

by Max v.d.Berg, Lendaert v.d.hoek, Joseph Richter and Hans E. Schmidt

Thermal Conductivity and thermal diffusivity of Plutonium- and Uranium-Plutonium mixed oxides of various U/Pu- and U/Pu-ratios was measured at temperatures between ambient and 1800°C. The results are discussed and compared with those of other investigators.

An analysis linking the high temperature heat capacity to the thermal conductivity of uranium dioxide has been applied to the above results and an estimation of the conductivity variation up to the melting point was carried out.

The particular variation of the conductivity of mixed oxides with Pu-content at temperatures below 1000°C is explained by the presence of magnetic phonon scattering centers which gradually disappear with increasing plutonium concentration.

The results of conductivity and diffusivity measurements on mixed oxides with simulated fission product additives representing burn-ups of 2, 6 and 16 at-% seem to confirm the hypothesis, that the change in overall stoichiometry is the predominant factor which determines the effect of solid fission products on the thermal conductivity of mixed oxide fuel at elevated temperatures.

The room-temperature thermal conductivity of Pu-rich mixed oxides, which are freshly prepared or annealed decreases gradually with storage time as a consequence of the presence of self-irradiation induced defects. In the case of PuO₂, saturation occurs after about 200 days. Most of the defects are annealed out around 400°C.

APPLICATION OF A LASER BARRIER IN FLASH THERMAL
DIFFUSIVITY STUDIES OF INSULATIVE MATERIALS, EXPERIMENT^{*}

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Measurement of thermal diffusivity by the flash method entails the deposition of energy onto the front surface of a specimen and the measurement and analysis of the consequent rear surface temperature excursion. In materials of low diffusivity, e.g., insulators, difficulties in the use of the method are frequently encountered. The rear surface pulse may be very weak due to extensive heat losses resulting in large uncertainties in the measurement. Increased energy deposition in the front surface does not necessarily resolve the problem, leading only to material blowoff. Thinner samples may also be unsatisfactory because of shine-through. To overcome these difficulties, a technique has been devised in which a thin slab barrier of high conductivity material is placed in intimate contact with the front face of the insulator. A relatively large amount of energy can then be deposited in the barrier and allowed to diffuse slowly into the insulator. The rear surface temperature response of this system is recorded and subsequently analyzed using a theory which assumes infinite conductivity in the barrier, one dimensional heat flow and (linearized) radiant heat losses at the surfaces.¹ Results have been obtained for several types of fibrous carbon insulations at temperatures up to 2800°K. Agreement with equivalent data obtained by other techniques is good.

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¹A. B. Donaldson, et al., XI International Conference on Thermal Conductivity 1971.

APPLICATION OF A LASER BARRIER IN FLASH THERMAL DIFFUSIVITY STUDIES OF INSULATIVE MATERIALS, THEORY¹

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A mathematical analysis of transient one-dimensional heat conduction in a two-layer composite was performed for the purpose of reducing data from the laser barrier diffusivity experiment. The assumptions made in the analysis are (a) infinite barrier conductivity, i.e., uniform temperature throughout barrier, (b) intimate thermal contact between barrier and insulator, (c) linearized radiant heat losses at both external surfaces, and (d) constant thermal properties over the range of temperature excursions. The solution is obtained by the method of Laplace transforms, and the temperature profile through the insulator is

$$\frac{T_1(\xi, t) - T_i}{Q/\rho_2 c_2 b} = R \sum_{n=1}^{\infty} \left\{ \left[\beta_n \cos(\beta_n \xi) + N_1 \sin(\beta_n \xi) \right] e^{-\beta_n^2 \tau} / \right. \\ \left. \left\{ \sin(\beta_n) \left[1 + \frac{N_1 + N_2 - 2R\beta_n^2}{2} + N_1 R \right] + \right. \right. \\ \left. \left. \cos(\beta_n) \left[\frac{\beta_n}{2} - \frac{N_1 + (1 + N_1)(N_2 - R\beta_n^2)}{2\beta_n} + R\beta_n \right] \right\} \right\}$$

where the eigenvalues, β_n , are defined by the eigenequation

$$\tan(\beta_n) + \frac{\left[\beta_n N_1 + \beta_n (N_2 - R\beta_n^2) \right]}{\left[-\beta_n^2 + N_1 (N_2 - R\beta_n^2) \right]} = 0$$

and

- T = temperature
- Q = total energy deposited by laser pulse
- ρc = volumetric heat capacity
- a = insulator thickness
- b = barrier thickness
- R = heat capacity ratio of barrier to insulator
($= \rho_2 c_2 b / \rho_1 c_1 a$)

¹This work was supported by the United States Atomic Energy Commission.

ξ = dimensionless position ($= x/a$)
 τ = Fourier number ($= \alpha t/a^2$)
 α = thermal diffusivity
 N_1 = insulator heat loss term ($= h_1 a/k$)
 N_2 = barrier heat loss term ($= h_2 a/k$)
 k = insulator thermal conductivity
 h = coefficient of linear heat loss

subscript

1 = insulator
 2 = barrier
 i = initial condition

For the special case of adiabatic boundaries ($N_1 = N_2 = 0$), the leading term $R/(R + 1)$ must also be included in the solution.

The experimental data will consist of the temperature history at the back surface of the insulator. Data reduction then is simply some process of finding the diffusivity and heat loss terms for which the theoretical backside temperature history and the data match; the value of diffusivity is the desired result. For the idealized case of no surface heat loss, the general procedure for one-layer data reduction can be applied, that is, correlation in terms of time required to achieve 50 percent of the maximum temperature. However, now the correlation must include R . A plot of this correlation is shown in figure 1.

Figure 1. Time to 50% of Maximum Temperature as a Function of R

X THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE FROM 300 to 2700°K

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INTRODUCTION

The thermal diffusivity of pyrolytic graphite has been measured in argon gas along directions perpendicular and parallel to the plane of deposition over the temperature range 1500 to 2700K by using a carbon arc image furnace and a cyclic phase shift method, and at room temperature by using a "laser flash method." Measurements were made upon three pyrolytic graphite materials derived from the same regeneratively nucleated deposit; the properties are given in Table I.

<u>Material</u>	<u>Bulk Density</u> (10 ³ kg m ⁻³)	<u>c-Axis</u> <u>Misalignment</u> ^a (degree)
As-deposited at 2200C	~ 2.18-2.19	~ 45
Annealed > 3200C	~ 2.25	~ 5
Stress-annealed > 3000C	~ 2.25	~ 0.4

^a Full width of rocking curve at half maximum (002 line).

Table 1. Properties of Pyrolytic Graphite Materials

METHOD OF MEASUREMENT

The phase shift method for measurement of thermal diffusivity has been described [1]³. The results have been corrected for effects of axial and radial losses by extrapolating to zero thickness the values of thermal diffusivity obtained from a series of specimens differing only in thickness. The values of thermal diffusivity were multiplied by the specific heat [2] and the density to obtain values of the thermal conductivity (Table II).

RESULTS

The $\lambda_{\parallel}$ values of thermal conductivity for the annealed and stress-annealed materials show the following features above 1500K; (1) they are the same within the experimental error, (2) they are 25 to 40 percent higher than the values for the as-deposited material, and (3) they follow a T^{-1} relation. The values of $\lambda_{\perp}$ for the as-deposited material follow a T^{-1} relation from 1500 to 1900K and increase rapidly above 1900K. The $\lambda_{\perp}$ values for the annealed and stress-annealed materials show the following features above 1500K: (1) they are the same, (2) they are 50 to 150 percent higher than the values for the as-deposited material, and (3) they decrease much

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3 Figures in brackets indicate the literature references at the end of this Abstract.

"slower" with increasing temperature than the T^{-1} relation.

Table II shows also calculated values of the thermal conductivity (λ_c and λ_{ab}) along the principal axes of the graphite crystallites, based upon the observed degree of misalignment and assuming zero porosity and thermal contact resistance [3]. The calculated values of λ_{ab} for all three materials are in satisfactory agreement above 1500K. Values of λ_c were obtained only from the stress-annealed deposit and these were unchanged from λ_l ; the as-deposited and the annealed materials gave absurd negative values for λ_c . The values of λ_l and λ_{ab} for the annealed and stress-annealed materials are in satisfactory agreement with the results of Taylor [4]. The values of λ_l and λ_c are close to Taylor's at room temperature; however, above 1500K, our values are approximately double the values indicated by Taylor's measurements. A lattice-vibrational analysis of the values of thermal conductivity, similar to that made by Taylor [4], assuming that the thermal conductivities λ_a and λ_c are due, respectively, to in-plane and out-of-plane vibrational modes, gives values for the phonon mean-free path L_c along the c-axis which approach a value near the sublimation temperature (3800K) that is very close to the layer-plane spacing; the corresponding value of L_{ab} is much larger than the spacing between atoms in the ab-plane.

Material	Temperature (K)	Diffusivity α_l ($10^{-4} m^2 s^{-1}$)	Conductivity λ_l ($W m^{-1} K^{-1}$)	Conductivity λ_c ($W m^{-1} K^{-1}$)	Diffusivity $\alpha_{ }$ ($10^{-4} m^2 s^{-1}$)	Conductivity $\lambda_{ }$ ($W m^{-1} K^{-1}$)	Conductivity λ_{ab} ($W m^{-1} K^{-1}$)
As-deposited	300	0.0150	2.39	-	1.94	306	440
Annealed	300	0.0424	1.87	-	11.35*	1840*	1850*
Stress-annealed	300	0.0540	8.67	8.58	9.54**	1550**	1550**
As-deposited	1500	0.00380	1.58	-	0.503	211	302
Annealed	1500	0.00786	3.37	-	0.729	313	315
Stress-annealed	1500	0.00789	3.40	3.37	0.692	298	298
As-deposited	1900	0.00285	1.23	-	0.425	184	264
Annealed	1900	0.00726	3.22	-	0.598	265	267
Stress-annealed	1900	0.00702	3.12	3.10	0.575	255	255
As-deposited	2300	0.00296	1.30	-	0.368	162	233
Annealed	2300	0.00666	3.01	-	0.462	209	210
Stress-annealed	2300	0.00626	2.84	2.83	0.448	203	203
As-deposited	2700	0.00407	1.81	-	0.323	144	207
Annealed	2700	0.00609	2.80	-	0.378	173	174
Stress-annealed	2700	0.00619	2.84	2.83	0.401	184	184

Note: Subscripts l and $||$ indicate values measured, respectively, perpendicular and parallel to the deposition plane, subscripts c and ab indicate corrections for crystallite misalignment to give values, respectively, parallel and perpendicular to the c-axis of the crystallite.

* See **.

** This value is probably too small because the thickness of the sample was too small to eliminate errors of pulse duration and transit time, and the value should probably be as large as *.

Table II. Thermal Conductivity and Thermal Diffusivity

REFERENCES

- [1] Null, M.R., and Lozier, W.W., Measurement of Thermal Diffusivity by the Phase Shift Method, Proc. 8th Conf. on Thermal Conductivity, ed. by C.Y. Ho and R.E. Taylor, Plenum Press, New York (1969), pp 837-856.
- [2] Spence, G. B., Survey and Analytical Representation of the Measurements of the Specific Heat of Graphite, WADD Technical Report 61-72, Vol. XLI, November (1963).
- [3] Kelly, B. T., The Thermal Conductivity of Graphite, Chemistry and Physics of Carbon, Vol. 5, ed. by P. L. Walker, Jr., Marcel Dekker, Inc., New York (1969), pp 119-215.
- [4] Taylor, R. E., The Thermal Conductivity of Pyrolytic Graphite, Phil. Mag. 13, 157 (1966).

AN APPARATUS FOR THE MEASUREMENT OF THE TEMPERATURE
DEPENDENCE OF THE THERMAL DIFFUSIVITY OF A SINGLE
SPECIMEN IN BOTH THE SOLID AND LIQUID PHASES

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The laser pulse method of measuring thermal diffusivity, in which a single laser pulse provides a short heat input to one face of a thin, flat specimen while the temperature response of the opposite face is monitored, provides a relatively direct way of obtaining thermal diffusivity measurements of modest accuracy in solid materials over a wide range of temperatures. In the present work this technique is applied to the determination of the thermal diffusivity of metallic systems by making measurements of the temperature response of a specimen to a laser pulse at temperatures up to and beyond the melting point.

The specimen geometry was chosen to be a disc with dimensions of the order of 1 cm diameter by 1 mm thick. Measurements in the solid state are carried out in the usual fashion. Once the specimen has melted, however, there are two major problems: (1) the interaction of the laser radiation with the material may cause significant mass motion to take place, and (2) the specimen chamber may cause serious heat losses which are difficult to estimate in a reliable way.

A high speed (about 10^4 frames per second) motion picture study was made of the surface of mercury which was exposed to a pulse of 1.06 μm wavelength with a width at half-maximum of about 150 μs and an energy of about 20J distributed over an area of about 3 cm^2 . These motion pictures, which will be presented, show that serious rippling of the surface occurs within a few tenths of a millisecond of the laser pulse and that the motion persists for times of the order of tenths of seconds. This motion can be effectively quenched, however, by placing a quartz plate on top of the mercury.

The effect of heat losses through the specimen chamber is being studied by performing calibration measurements on systems with well-known diffusivities. Preliminary data on lead up to 500 C indicate that such losses, if not taken into account in the data

processing, would produce diffusivity values as much as 25% too large. Current efforts both to reduce these losses by the appropriate design of the specimen chamber and to calculate their magnitude will be discussed.

AN APPARATUS FOR MEASUREMENT OF THERMAL DIFFUSIVITY BY THREE DIFFERENT METHODS

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INTRODUCTION

In principle, any theoretical model can be used as a basis for construction of a measuring apparatus if the mathematical boundary conditions can be experimentally satisfied. The selection of the model will depend, however, on the nature of the material on which the measurement is to be performed. In the case of coarse-grained minerals and natural rock and in order to integrate the contributions of individual grains towards the over-all thermal diffusivity of the specimen, the size of the sample has to be appreciably larger than that for a homogeneous and amorphous material. Furthermore, if the thermal diffusivity of the material were low, the attenuation of the linear-flow heat wave would be so rapid that the thickness of the specimen would have to be impractically small. The ratio of surface to volume and, consequently, the attenuation of a heat wave are lowest in a sphere. However, preparation of spherical rock samples and the construction of an apparatus capable of satisfying such boundary conditions would be rather difficult. Therefore, models based only on the concept of an infinite cylinder are considered in this analysis.

THEORY

Mathematical solutions¹ for the following three models of heat flow were obtained:

- (1) *Initial temperature is zero. Surface temperature is a linear function of time.* Temperatures are measured at the centre of the specimen and at a point near the surface. With constant-rate heating of the surface, the temperature differential is plotted until it reaches the maximum. An equation derived for this model relates the increase in the dimensionless temperature differential to a dimensionless factor which includes thermal diffusivity, time, and the diameter of the cylinder.
- (2) *Zero surface flux.* At time zero, a quantity of heat is uniformly absorbed within a small depth under the surface. With no further heat exchange taking place at the surface, the temperature rise at the centre

¹Submitted for publication in the proceedings of the Third International Conference on Thermal Analysis, Davos, Switzerland, 1971.

of the cylinder is recorded until it reaches the maximum. The equation relates the increase in dimensionless temperature at the centre of the cylinder to a dimensionless factor which includes thermal diffusivity, time, and radius of the cylinder.

(3) *Surface temperature a harmonic function of time.* A sinusoidal type of heat wave is imposed on the surface of the cylinder. Temperatures are measured at the centre and at a point near the surface and are simultaneously plotted against time. In the equation derived for this model, the time interval needed for the heat wave to penetrate from the near surface measuring point to the centre is related to thermal diffusivity, to time of one heat wave, and to the radius of the cylinder.

APPARATUS, RESULTS, AND CONCLUSIONS

In the experimental configuration, the sample, a cylinder 1 inch in diameter and 1 inch high, is stacked between cylindrical insulators of similar size. The column thus formed is surrounded by two tungsten wire heaters and by heat shields and is contained in vacuum. Measurements of thermal diffusivity were made on Pyroceram 9606 and on a 95% dense, polycrystalline alumina, using Models 1 and 3. Agreement with the published data is very good. It was discovered that, for measurements to be performed in Model 2, some additional instrumentation was required.

It has been concluded that the theoretical boundary conditions of Models 1 and 3 have been experimentally satisfied and that the condition for Model 2 can be also satisfied by some minor changes in the instrumentation. Furthermore, the accuracy of the measurements is inherently greater than that obtained by other methods because of the cylindrical symmetry of the models and the ease of checking results by repeating the measurement in a different model.