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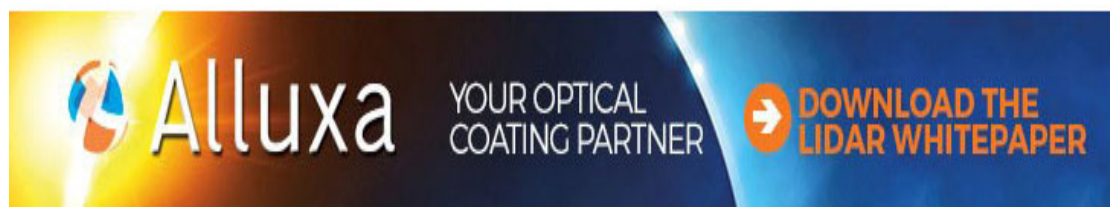
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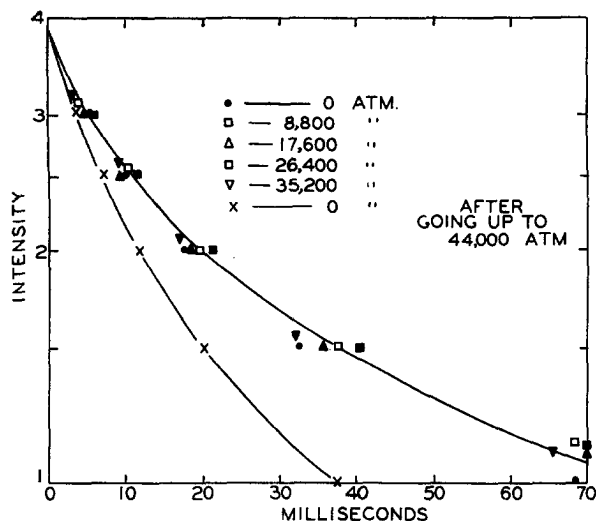


FIG. 6. Intensity vs pressure ZnS:Cu (1020).

Some measurements were also made on an hexagonal ZnS:Cu phosphor (BS No. 1022). Since the decay is

not a simple exponential, no characteristic time can be given, but decay curves are shown in Fig. 6. The rate of decay was substantially independent of pressure to 35 000 atmospheres. In the neighborhood of 40 000 atmospheres there was an apparent abrupt increase in the decay rate accompanied by a large decrease in intensity. The rate at high pressure was difficult to reproduce because of low intensity. This change of decay rate was irreversible, as the rate changed only slightly upon returning to one atmosphere pressure. X-ray powder patterns of the material before and after pressurizing showed that the hexagonal crystal had been converted substantially completely to the cubic (zincblende form). A pressure induced transition of this kind would be expected as the stable low-temperature form is cubic. Some measurements were attempted on another cubic ZnS:Cu sample, but intensities were too low for good data. There seemed to be a measurable increase in decay rate with pressure.

Low-Temperature Transport Properties of Commercial Metals and Alloys. II. Aluminums

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The thermal conductivity, electrical resistivity, Lorenz number, thermoelectric force, and thermoelectric power are given in the temperature range 4–120°K for ten aluminums and aluminum alloys: high-purity, 1100-F, 1100-O, 3003-F, 2024-T4, 5052-O, 5083-O, 5086-F, 5154-O, and 6063-T5. Four of the samples show a maximum in thermal conductivity, the others do not. For the four high-thermal conductivity samples the separate components in the electronic thermal resistivity are resolved; for the others, components in both the electronic and the lattice thermal resistivities are given. The residual electrical resistivities vary from 2.5×10^{-8} to 3.2×10^{-6} ohm cm. The Lorenz numbers for the high-conductivity samples fall considerably below the Sommerfeld value 2.44×10^{-8} watt-ohm/°K²; those for the low-conductivity samples are somewhat above the Sommerfeld value. The thermoelectric power of some of the alloys is positive with respect to the high-purity sample, for others it is negative. The various properties, methods of analysis, and separation of components are discussed in detail.

I. INTRODUCTION

DATA on thermal conductivity are necessary for the selection of suitable construction materials and prediction of operating characteristics of low-temperature apparatus used in research and industry. Values for commercial aluminum and its alloys are particularly important because of the widespread use of those metals in large-scale commercial and military storage and transport vessels. Measurements of the thermal conductivity of commercial metals and alloys that were reported in the literature prior to the spring of 1954 have been included in a comprehensive compilation.¹

¹ R. L. Powell and W. A. Blanpied, Natl. Bur. Standards Circ. No. 556 (U. S. Government Printing Office, Washington, D. C., 1954).

Previous reports on aluminum or its alloys include the work of de Nobel,² Andrews *et al.*,³ Powers *et al.*,⁴ and Rosenberg⁵ on pure aluminum; and the work of Mannchen,⁶ de Nobel,² and Powers *et al.*⁷ on aluminum alloys.

Some of the experimental results presented in this paper were reported in the Fifth (1957) International

² J. de Nobel, *Physica* **17**, 551 (1951).

³ Andrews, Webber, and Spohr, *Phys. Rev.* **84**, 994 (1951).

⁴ Powers, Schwartz, and Johnston, Technical Report 264-5, Cryogenics Laboratory, Ohio State University, 1951 (unpublished).

⁵ H. M. Rosenberg, *Phil. Trans. Roy. Soc. (London)* **A247**, 441 (1955).

⁶ W. Mannchen, *Z. Metallkunde* **23**, 193 (1931).

⁷ Powers, Ziegler, and Johnston, Technical Report 264-7, Cryogenics Laboratory, Ohio State University, 1951 (unpublished).

TABLE I. Physical and chemical specifications for aluminums and aluminum alloys.

Sample	Composition ^a (weight percent)	Average grain size ^{b,c} mm		Hardness ^b Diamond point	
		Long.	Trans.	Long.	Trans.
Single crystal	Johnson-Matthey JM 340 99.995% pure (originally).	single crystal	
1100-F	Si, 0.13; Cu, Ga, Fe, Mg, V 0.1; Cr 0.02; Pb, Mn, Sn, Ti 0.01; Ca, Zr 0.001.	0.024×0.008	0.012	24	21
1100-O	Fe 0.41; Si 0.22; Cu, Ga, Mg, Mn 0.1; Cr; Pb, Ti, V, Zn 0.01; Ca, Zr 0.001; Bi 0.0001.	0.040×0.032	0.036	11	13
3003-F	Mn* 1.23; Fe 0.48; Si 0.15; Cu, Ga, Mg 0.1; Cr 0.02; Ga, Ti, V, Zn 0.01; Bi, Pb, Zr 0.001.	0.016×0.008	0.012	25	27
2024-T4	Cu* 4.58, Mg* 1.70; Ga, Fe, Mn*, Si, V, Zn 0.1; Cr 0.05; Sn, Ti 0.01; Ca, Ag, Zr 0.001.	0.080×0.052	0.048	66	66
5052-O	Mg* 2.46; Cr* 0.22; Cu, Ga, Fe, Mn, Si, Zn 0.1, Ti, V 0.01; Ca, Zr 0.001.	0.056×0.032	0.04	31	24
5083	Mg* 4.44; Mn* 0.7, Cr, Fe, Si 0.1; Cu 0.04.	0.74 ×0.21	0.54 ×0.14	21	20
5086	Mg* 4.10; Mn* 0.51; Fe 0.28, Cr, Si, Zn 0.1; Cu 0.07, Ti 0.02.	0.061×0.022	0.086×0.020	25	18
5154-O	Mg* 3.32; Cr* 0.21; Cu, Fe, Mn, Si 0.1; Ti, V, Zn, Zr 0.01; Ca, Pb 0.001.	0.036×0.028	0.032	40	33
6063-T5	Mg* 0.65, Si* 0.38; Ga, Fe, Mn 0.1; Cr, Cu, Ti, V, Zn 0.01; Ca, Pb, 0.001.	0.052×0.048	0.052	29	30

^a The analyses on 1100-F, 1100-O, 3003-F, 2024-T4, 5052-O, 5154-O, and 6063-T5 were performed by Herbert M. Ochs of Denver, Colorado. The analyses on 5083 and 5086 were supplied by R. D. Olleman of Kaiser Aluminum and Chemical Corporation. The elements marked with an asterisk* were deliberately added for alloying purposes, the other elements were incidental impurities.

^b The photomicrographs, grain size determinations, and hardness tests were performed by R. P. Reed and R. L. Greeson of this laboratory.

^c The 5083 and 5086 alloys were etched with a 49% CH₃OH, 49% H₂O, 2% HF solution; the 2024-T4 alloy, with Keller's dilute etch, HNO₃, HF, and HCl; and the rest, with a 4% HF solution.

Conference on Low Temperature Physics and Chemistry⁸ and the 1957 Cryogenic Engineering Conference.⁹ In addition to the thermal conductivity data obtained for practical applications, concurrent measurements were made on the electrical conductivity and thermoelectric force. Detailed analyses of the three properties help to clarify the general phenomena of electronic transport processes in aluminum and its alloys.

II. APPARATUS

A detailed description of the apparatus and measurement techniques has been previously published,¹⁰ and a summary description of the apparatus was included in the first article in this series.¹¹ The method of determining thermal conductivity by axial heat flow through a long cylindrical sample is used.

Since the previous publications, the apparatus has been modified to allow simultaneous measurements of electrical resistance and thermoelectric force. Wires of commercial purity copper magnet wire are connected electrically to the top and bottom thermocouple holders,

approximately seven inches apart. Electrical current leads are connected to the ends of the sample. The thermoelectric force of the sample rod relative to the commercial purity copper is determined by measuring the potential difference between the two copper wires when no electrical current is flowing through the sample. The temperatures of the two contact points are determined by the gold-cobalt *vs* copper thermocouples that are connected thermally, but not electrically, to the thermocouple holders. The electrical resistance of the sample is determined by measuring the potential drop across the same two wires when a measured current is flowing through the sample. The thermoelectric force is subtracted from the total potential drop to obtain the potential drop resulting from the electrical current. The calculated values for both the electrical resistance and thermoelectric force have a scatter of about 2%.

III. SAMPLE SPECIFICATIONS

Aluminums and aluminum alloys were selected that are most commonly utilized in the construction of low-temperature engineering equipment. For the same reason each sample was tested in the usual fabricated condition or with the standard anneal or heat treatment indicated. However, to help specify each sample more concretely, auxiliary measurements included the chemical analysis, grain size, and hardness. The specifications for each sample are included in Table I. The primary

⁸ *Low Temperature Physics and Chemistry*, edited by Joseph R. Dillinger (University of Wisconsin Press, Madison, Wisconsin, 1958), Paper XVI-1, p. 389.

⁹ *Proceedings of the 1957 Cryogenic Engineering Conference*, edited by K. D. Timmerhaus (University of Colorado, Boulder, Colorado, 1958), Paper G-6, p. 408.

¹⁰ Powell, Rogers, and Coffin, J. Research Natl. Bur. Standards 59, 349 (1957).

¹¹ Powell, Roder, and Rogers, J. Appl. Phys. 28, 1282 (1957).

additives to the aluminum were determined by chemical quantitative analysis; the minor impurities were determined by spectrographic analysis. The grain sizes in the longitudinal and transverse directions were obtained from 250 \times photomicrographs. Hardness measurements were made on plastic mounted specimens with a pyramid hardness testing machine using a one kilogram load for all samples, except the 2024-T4, 5052-O, and 6063-T5, where a five kilogram load was used. All of the commercial samples are wrought alloys.

A. Single Crystal, High-Purity

The rod was made from Johnson-Matthey stock by Horizons, Inc., Cleveland, Ohio. Apparently the crystal absorbed impurities during the crystallization or later during the fabrication at this laboratory because the residual electrical resistivity was not as low as one would expect from a crystal of 99.995% purity. The rod was supplied with about 3.68 mm diameter and was ground down to 3.66 mm at this laboratory. Chemical etching after the reduction in diameter indicated that the material was still a single crystal. After the last fabrication the rod was annealed in vacuum at about 400°C for two hours. The orientation of the single crystal was determined by Horizons, Inc. The [001] line was inclined 6° to the axis of the rod; the [011] line, 40°; and the [111] line, 50°.

B. Commercially-Pure Aluminum, 1100-F

This sample and all of the remaining alloys, except the 5083 and 5086, were supplied by R. L. Horst, Chemical Section, Sales Development Division, Aluminum Company of America. The rods of this and the following item, 1100-O, were turned down and drawn to the final diameter, 3.66 mm, from a flat sheet of about 1/2-in. thickness. Photomicrographs showed inclusions of Si primary crystals.¹² The sample was in the commercial "as fabricated" condition. The 1100 aluminums have good formability and corrosion resistance and are therefore used in tubing for liquid lines, machine fittings that are to be welded, and in shells for dewars.¹³

C. Commercially-Pure Aluminum, 1100-O

This sample had significantly more impurities than the 1100-F one. In addition to Si primary crystals, FeAl₃ inclusions were also observed. After fabrication the rod was annealed in vacuum for one hour at 350°C.

D. Alloy 3003-F

The sample rods of this alloy and all of the following items, except 6063-T5, were turned and then drawn

down to 3.66-mm diameter from oversized commercial rods supplied by the manufacturers. Photomicrographs showed inclusions of Si, MnAl₆, FeAl₃, and (MnFe)Al₆ peritectic. The measured sample was in the commercial "as fabricated" condition. The characteristics and uses of this alloy are quite similar to the ones for the 1100 alloys, except that the 3003 alloy has slightly greater structural strength.

E. Alloy 2024-T4

Inclusions of CuAl₂ and MnAl₆ were observed in this alloy. The added magnesium was in solid solution since up to 1.9 weight percent of magnesium is soluble in the alpha phase of aluminum.¹⁴ The commercial rod was supplied in the "T-4" condition, solution heat-treated. This alloy is noted for its high strength and is therefore used in structural members and in baffle plates within Dewars.

F. Alloy 5052-O

Inclusions of CrAl₇, Si, and possibly MnAl₆ were observed in this alloy. The main inclusion, however, was the extremely complex β phase of (MgAl) with an approximate composition of Mg₅Al₈.¹⁵ The sample was annealed in vacuum for one hour at 350°C after the last fabrication. The 5052 alloys have good corrosion resistance, high fatigue strength, and a moderate static strength. They are used in the inner and outer cylinders for fluid tanks and in tubing.

G. Alloy 5083-O

This sample and the 5086 alloy were supplied by R. D. Olleman, Kaiser Aluminum and Chemical Corporation. Photomicrographs showed inclusions of β phase (Mg₅Al₈), MnAl₆, and possibly Si, Mg₂Si, CrAl₇, and (FeMn)Al₆. The crystal grains were very large and also showed marked elongation even in the transverse direction. After fabrication the rod was annealed in vacuum for one hour at 350°C. Both 5083 and 5086 alloys are high-strength weldable magnesium-aluminums that are used for shells and structural members in Dewars.

H. Alloy 5086-F

Inclusions were observed of β phase (Mg₅Al₈), FeAl₃, MnAl₆, (MnFe)Al₆ and either Si or Mg₂Si. The crystal grains showed marked elongation even in the transverse direction. The sample was tested in the commercial "as fabricated" condition.

¹² Photomicrographs and discussions of inclusions in aluminum alloys are given by L. F. Mondolfo, *Metallography of Aluminum Alloys* (John Wiley & Sons, Inc., New York, 1943).

¹³ More lengthy and detailed discussions of the uses, fabrication techniques, heat treatments, phase diagrams and general properties of most aluminum alloys are included in the *Metals Handbook* (American Society for Metals, Cleveland, Ohio), 1948 edition, and in company product information books such as those published by Aluminum Company of America and Kaiser Aluminum and Chemical Sales, Inc.

¹⁴ Phase diagrams for many aluminum binary alloys are given in the extensive compilation and review by Max Hansen, *Constitution of Binary Alloys* (McGraw-Hill Book Company, Inc., New York, 1958), second edition. Diagrams for ternary alloys are given in references 12 and 13.

¹⁵ H. Perlitz, Chalmers Tekniska Högskolas Handlingar 50 (1946) reported the structure to be a complex face-centered cube with 1166 atoms to a unit cube. See also W. B. Pearson, *A Handbook of Lattice Spacings and Structures of Metals and Alloys* (Pergamon Press, New York, 1958).

I. Alloy 5154-0

This sample contained inclusions of β phase (Mg_2Al_3), CrAl_7 , and a small amount of FeAl_3 and MnAl_6 . After fabrication the rod was annealed in vacuum for one hour at 350°C . This alloy is quite similar in physical properties and uses to the 5083 and 5086 alloys except that it has somewhat less strength.

J. Alloy 6063 T-5

This alloy containing deliberate small additions of magnesium and silicon was quite similar to the "J-51" alloy studied by Powers *et al.*⁴ The sample rod was turned down and drawn to the final diameter, 3.66 mm, from a flat sheet of about $\frac{1}{2}$ -in. thickness. Photomicrographs showed inclusions of Si primary crystals and small amounts of FeAl_3 and MnAl_6 . The magnesium was in solid solution. The plate was supplied in the "T-5" condition, precipitation heat-treated.¹³ This material is used for extrusions, tubing, and structural reinforcement on Dewar walls.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Thermal Conductivity

Several articles have been published recently that give summaries of the experimental and theoretical developments of the thermal conductivity of metals.¹⁶⁻¹⁸ Therefore, only a brief review is given here, enough to allow a discussion of the methods of analysis and separation of conductivity components.

Two principal mechanisms are responsible for the low-temperature transport of heat in a metal. The first and most important is the electronic thermal conduction, the transport of thermal energy by the motion of conduction electrons. The second is the lattice thermal conduction, the transport by directional cooperative quantized vibrations (phonons) of the interacting lattice ions. For the pure aluminums and the dilute alloys, the lattice thermal conductivity is insignificant compared to the electronic thermal conductivity. However, for the alloys with several percent of additives the decrease of electronic thermal conductivity makes the lattice contribution significant, though still small compared to the electronic contribution. The total conductivity λ is approximately the sum of the electronic conductivity λ_e and the lattice conductivity λ_g , that is,

$$\lambda = \lambda_e + \lambda_g. \quad (1)$$

The electronic thermal conductivity λ_e is predominant in all of the samples measured. There are two main scattering processes that limit this electronic conductivity. The first is the scattering of conduction electrons by thermal vibrations of the lattice, as represented by

the electron-phonon resistivity W_L a characteristic property for a given metal. This scattering is most important at intermediate and higher temperatures. The second process is the scattering of conduction electrons by imperfections (both impurity atoms and lattice defects), as represented by the electron-defect resistivity W_0 . This scattering is most important at the lower temperatures. The total electronic thermal resistivity W_e , defined as the reciprocal of the total electronic thermal conductivity λ_e is assumed to be the sum of the two resistivities W_L and W_0 plus a deviation term W_{L0} ; that is,

$$1/\lambda_e \equiv W_e = W_L + W_0 + W_{L0}. \quad (2)$$

The deviation term is given by an expression of the form¹⁹

$$W_{L0} = (\alpha W_L W_0 / \beta W_L + \gamma W_0), \quad (3)$$

where α , β , and γ are constants of order 1 and can be determined experimentally.

Both theoretical and experimental research have led to expressions for the magnitudes and temperature dependences of the electron-phonon and electron-defect resistivities:

$$\begin{aligned} W_L &= AT^n, & (n \approx 2 \text{ to } 3, T < 40^\circ\text{K}); \\ W_L &\approx \text{a constant}, & (\text{near room temperatures}); \\ W_0 &= B/T, & (\text{at all temperatures}). \end{aligned} \quad (4)$$

The constant A in the electron-phonon resistivity term is related to characteristic properties of the given metal; B in the electron-defect resistivity term is related to the amount of imperfections and residual electrical resistivity of the specific sample. Above 40°K the electron-phonon resistivity approaches a constant value, often labeled W_∞ . The methods of analysis and techniques for separation of electronic components are outlined in a previous paper.¹⁹

In several of the aluminum alloys the lattice thermal conductivity λ_g is also measurable and the separate scattering components may be resolved. Klemens²⁰ has recently given a survey of lattice thermal conductivity in dielectrics and metals. For the samples of aluminum alloys reported in this paper there are three main processes that limit the lattice conductivity. The first process is scattering of the lattice waves by conduction electrons, as represented by phonon-electron resistivity W_E ; the second is scattering by dislocations, the phonon-dislocation resistivity W_D , and the third is scattering by point imperfections, the phonon-point imperfection resistivity W_P . The first two processes will limit the lattice conductivity at the lower temperatures; the third, at higher temperatures.

The phonon-electron resistivity has approximately the same temperature dependence as the phonon-

¹⁶ P. G. Klemens, *Handbuch der Physik* (Springer-Verlag, Berlin, 1956), Vol. 14, pp. 198-281.

¹⁷ J. M. Ziman, *Nuovo cimento Suppl.* 7, 353 (1958).

¹⁸ H. Jones, *Handbuch der Physik* (Springer-Verlag, Berlin, 1956), Vol. 19, pp. 227-315.

¹⁹ Powell, Roder, and Hall, *Phys. Rev.* 115, 314 (1959).

²⁰ P. G. Klemens, *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1958), Vol. 7, pp. 1-98.

TABLE II. Thermal conductivity of several aluminums and aluminum alloys.*

Sample	Single crystal						1100-F					1100-O	6063-T5
Temp. (°K)	λ_e^b watts cm °K	W_e^c (exptl.)	W_L^c	W_0^c	W_{L0}^c	W_e^c (calc.)	λ_e^b watts cm °K	W_e^c (exptl.)	W_0^c	W_{L0}^c	W_e^c (calc.)	λ_e watts cm °K	λ_e watts cm °K
4	3.58	0.279	0.0001	0.272	0.0001	0.272	0.554	1.80	1.75		1.75	0.459	0.351
6	5.42	0.184	0.0003	0.182	0.0002	0.183	0.823	1.21	1.17		1.17	0.688	0.522
8	7.22	0.138	0.0006	0.136	0.0004	0.137	1.107	0.903	0.875		0.876	0.918	0.697
10	8.95	0.112	0.0011	0.109	0.0008	0.111	1.395	0.717	0.700	0.001	0.702	1.145	0.868
14	11.8	0.0847	0.0027	0.0778	0.0019	0.0824	1.96	0.510	0.500	0.002	0.505	1.61	1.215
20	14.8	0.0676	0.0073	0.0545	0.0048	0.0666	2.70	0.370	0.350	0.005	0.362	2.28	1.70
24	15.8	0.0633	0.0120	0.0454	0.0059	0.0633	3.12	0.320	0.292	0.008	0.312	2.62	2.00
30	15.3	0.0654	0.0221	0.0363	0.0074	0.0658	3.58	0.279	0.233	0.014	0.269	3.04	2.35
40	12.0	0.0833	0.0482	0.0272	0.0079	0.0833	3.89	0.257	0.175	0.023	0.246	3.32	2.68
50	8.40*	0.119	0.090	0.0218	0.0073	0.119	3.78	0.264	0.140	0.030	0.260	3.31	2.76
60	6.02*	0.166	0.142	0.0182	0.0064	0.167	3.40	0.294	0.117	0.031	0.290	3.12	2.67
70	4.51	0.222	0.200	0.0156	0.0056	0.221	3.04*	0.329	0.100	0.030	0.330	2.83	2.52
80	3.70	0.270	0.251	0.0136	0.0050	0.270	2.74	0.365	0.087	0.028	0.366	2.57	2.34
100	2.88	0.347	0.332	0.0109	0.0040	0.347	2.38	0.420	0.070	0.024	0.426	2.27	2.13
120	2.57	0.389	0.377	0.0091	0.0034	0.389	2.23	0.448	0.058	0.020	0.455	2.12	2.06

* The equations for the separate terms are given in Eqs. (2), (3), and (4) in the text.

^b The asterisks indicate interpolated values.

^c W_e (exptl.) = $\lambda_e - 1$; W_L and W_0 are given by Eq. (4) in the text; W_{L0} by Eq. (3); and W_e (calc.) by Eq. (2). The constants used in the equations are: (a) For W_L at and below 60°K: $A = 2.03 \times 10^{-4}$, $n = 2.72$. (b) For W_0 : $B = 1.09 \pm 0.01$ for single crystal; $B = 7.00 \pm 0.05$ for 1100-F; $B = 8.38 \pm 0.05$ for 1100-O; $B = 11.23 \pm 0.12$ for 6063-T5. (c) For W_{L0} : $\alpha = \frac{1}{2}$, $\beta = 1$, $\gamma = 2$. All W are in units of cm °K/watt.

dislocation resistivity. Therefore, for one sample, the two scattering mechanisms may not be unambiguously separated. For annealed samples the two resistivities will be of about the same magnitude; for unannealed samples the dislocation resistivity will greatly outweigh the other. Below about 40°K the lattice conductivity can be represented by

$$1/\lambda_g \equiv W_g = W_D + W_E + W_P = (D+E)T^{-2} + P T; \quad (5)$$

above about 40°K the lattice conduction in these alloys can not be separated experimentally from the electronic conduction because the latter has a much greater magnitude.

The thermal conductivities of samples *a*, *b*, *c*, and *j* (Single crystal, 1100-F, 1100-O, and 6063-T5) are given

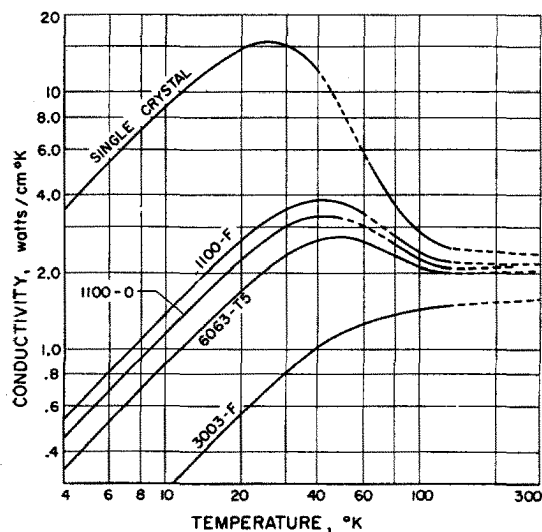


FIG. 1. Thermal conductivity of several aluminums and aluminum alloys. (The dashed parts of the curves indicate interpolated values.)

in Fig. 1 and Table II. The thermal conductivity of sample *d* (3003-F) is also given in Fig. 1 for comparison. The calculated values of the electron-defect resistivity, W_0 , and the deviation term, W_{L0} , are given in Table II for the single crystal and 1100-F samples. Curves for the calculated deviation term, W_{L0} , and the equivalent experimental term, $(W_e - W_L - W_0)$, are given in Fig. 2 for the same two samples. The values and graphs for the interaction terms for the other two samples are not given because the technique of separation of electric components is not applicable to alloys with more than about 1% additives or impurities.

Several comments on the results can be given. The single crystal did not have a conductivity as expected,³ probably because of impurities absorbed during the melting and annealing. The 1100-O sample had a lower conductivity than the 1100-F sample, in spite of the annealing, because of the greater amount of chemical impurities in the original stock. The values for the 6063-T5 alloy are almost identical (in the overlapping temperature ranges) with the values obtained by Powers *et al.*⁴ for a J-51 alloy of similar composition. It should be specially noted that the temperature exponent in the electron-phonon term W_L is about 2.72 and not 2 as is often assumed. A similar exponent, 2.76, was obtained in our previous work on copper.¹⁹

The thermal conductivities of the alloy samples *d*, *e*, *f*, *g*, *h*, and *i* (3003-F, 2024-T4, 5052-O, 5083-O, 5086-F and 5154-O) are given in Fig. 3 and Table III. Below about 10°K the electron-imperfection resistivity is predominant in the electronic conductivity and the phonon-electron and -dislocation resistivities are predominant in the lattice conductivity. The separation of components for these low conductivity alloys can then be carried out in the following manner. A value for the electronic constant B , and a first approximation to the lattice constant $(D+E)$ may be obtained graphically

from a plot of (λ/T) vs T below 10°K . The resultant value for B is given in Table III and is used to estimate the electronic conductivities at all measured temperatures. However a small electron-phonon term must also be accounted for at the higher temperatures. The electronic conductivity is subtracted from the total conductivity to obtain the lattice conductivity contribution, λ_g , the values for which are given in Fig. 4.

It is seen that the lattice conductivity is about 10% or less of the total thermal conductivity. The values for the lattice constants, $(D+E)$ and P , obtained graphically from a plot of (λ_g/T) vs T^{-3} between 10 and 30°K , are given in Table III. The variation between this value of $(D+E)$ and the one obtained from the total conductivity by the method mentioned in the previous paragraph is about 5%. Theoretical values for the phonon-electron interaction resistivity W_E are not sufficiently accurate to allow a separation of the latter from the phonon-dislocation interaction resistivity W_D and thus obtain specific values for D and E . It is ex-

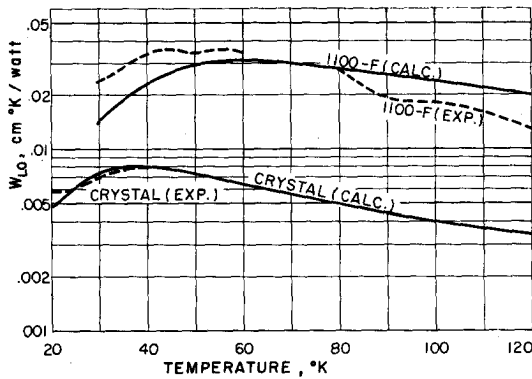


FIG. 2. Thermal resistivity deviation term W_{L0} . The term calculated from the theoretical Eq. (3) is given as a solid line; the equivalent experimental term is dashed.

pected, however, that the phonon-dislocation term is the larger of the two in all of the alloys reported here.

B. Electrical Conductivity

Several lengthy review articles or books on the subject have been published in recent years,^{17,18,21,22} so only very brief comments are given here. A discussion of the separation of components and scattering mechanisms for electrical conductivity would follow almost exactly the discussion given in Sec. A on the *electronic* thermal conductivity. The total electrical resistivity ρ is assumed to be the approximate sum of two separate resistivities, the intrinsic or electron-phonon resistivity ρ_L , and the residual or electron-imperfection resistivity ρ_0 . In other words, Matthiessen's rule for electrical resistivity is

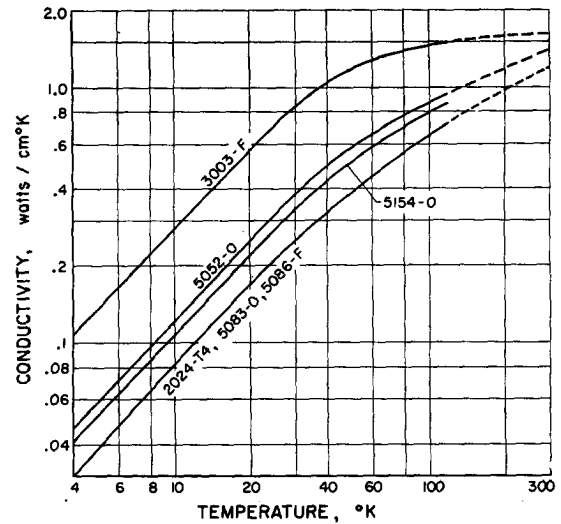


FIG. 3. Thermal conductivity of several aluminum alloys. (The dashed parts of the curves indicate interpolated values.) The values for the 2024-T4, 5083, and 5086 alloys are close enough together to be represented by one curve.

assumed to be approximately correct:

$$\rho \approx \rho_L + \rho_0. \quad (6)$$

The expressions for the temperature dependences of the intrinsic and residual terms have been found to be given approximately by

$$\begin{aligned} \rho_L &= \alpha T^n; \quad (n \approx 4 \text{ to } 5) \quad T < 40^\circ\text{K} \\ \rho_0 &= \beta \quad (\text{constant}). \end{aligned} \quad (7)$$

The electrical resistivities for seven of the samples are given in Fig. 5. Because of apparatus difficulties, values

TABLE III. Thermal conductivity of several aluminum alloys.*

Temp. (°K)	3003-F	2024-T4	5052-O	5083-O	5086-F	5154-O
4	0.107	0.0315	0.0452	...	0.0302	0.0412
6	0.163	0.0489	0.0698	0.0486	0.0469	0.0630
8	0.222	0.0661	0.0952	0.0669	0.0644	0.0857
10	0.282	0.0832	0.121	0.0852	0.0820	0.109
14	0.402	0.117	0.174	0.122	0.118	0.156
20	0.575	0.170	0.250	0.173	0.172	0.228
24	0.682	0.203	0.304	0.206	0.208	0.272
30	0.833	0.249	0.379	0.254	0.261	0.337
40	1.06	0.322	0.487	0.332	0.337	0.436
50	1.20	0.390	0.578	0.395	0.407	0.521
60	1.28	0.452	0.655	0.451	0.462	0.591
70	1.33	0.508	0.719	0.501	0.513	0.649
80	1.38	0.557	0.768	0.546	0.559	0.699
100	1.44	0.645	0.859	0.627	0.635	0.790
120	1.47	0.727	0.939	0.683	0.698	0.872
electronic constant B	39	135	94	141	141	101
lattice constants $(D+E) \times 10^{-3}$	3.5	8.3	6.7	6.0	8.7	10.0
lattice constant P	0.4	1.5	0.5	1.0	0.6	0.6

* The equations for the separate terms are given in Eqs. (1), (2), (4), and (5) in the text. The units for thermal conductivity are watts/cm² K.

²¹ D. K. C. MacDonald, *Handbuch der Physik* (Springer-Verlag, Berlin, 1956), Vol. 14, pp. 137-197.

²² A. N. Gerritsen *Handbuch der Physik* (Springer-Verlag, Berlin, 1956), Vol. 19, pp. 137-226.

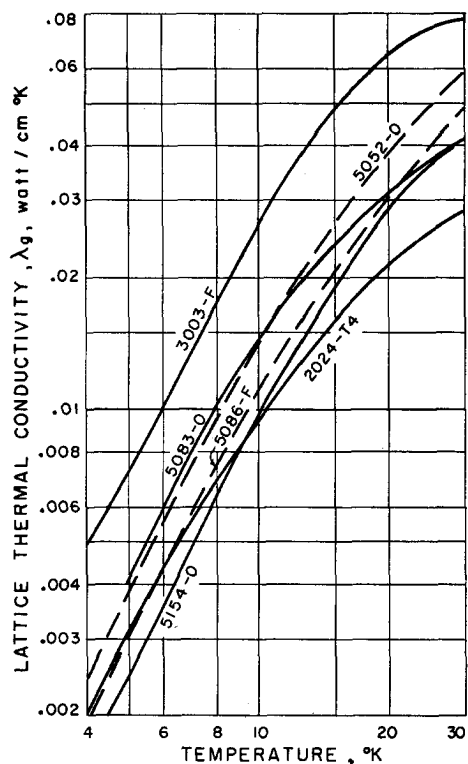


FIG. 4. Lattice thermal conductivity of several aluminum alloys. The values are obtained by subtracting the electronic term from the total thermal conductivity.

were not obtained for 1100-F, 3003-F, or 5083-O alloys. The intrinsic resistivity term ρ_L was found to vary approximately as $T^{4.2}$ rather than T^5 below 40°K. However, the exact temperature dependence of the

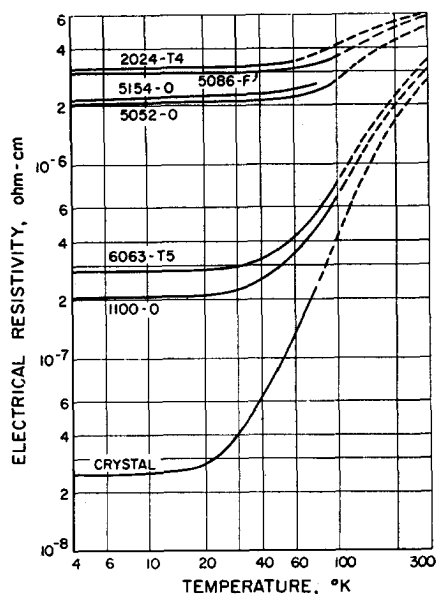


FIG. 5. Electrical resistivity of several aluminums and aluminum alloys. (The dashed parts of the curves indicate interpolated values.)

term will have to be determined in another more specialized and accurate apparatus.

C. Lorenz Ratio

The electrical resistivity may be compared to the electronic thermal resistivity by means of the Wiedemann-Franz-Lorenz law

$$\rho = LW_e T, \quad (8)$$

where L is the Lorenz number, assumed to be a fundamental constant given by the Sommerfeld value

$$L = (\pi^2/3)(k/e)^2 = 2.44 \times 10^{-8} (\text{watt-ohm}/^\circ\text{K}^2).$$

The Lorenz numbers given in Fig. 6 are slightly different in that they express the ratios of the electrical resistivities to the *total* thermal resistivities. However, the extrapolated values L_0 should represent ratios of electronic terms only because the lattice contribution to

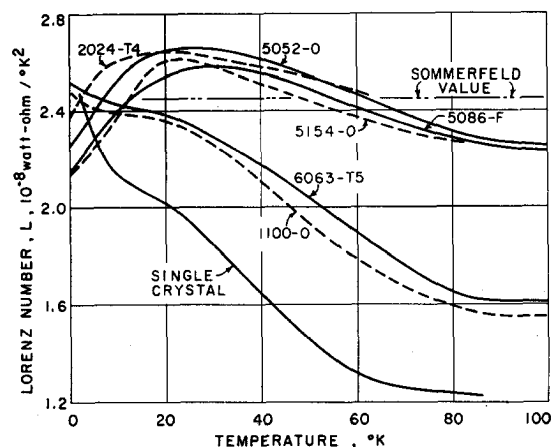


FIG. 6. Lorenz number of several aluminums and aluminum alloys. The Sommerfeld theoretical value is 2.44×10^{-8} watt-ohm/ $^\circ\text{K}^2$.

the total thermal conductivity is greatly reduced at the lowest temperatures. Most of the variations and errors are caused by the uncertainties in the electrical resistivity values.

It is seen that the Lorenz numbers for the high-conductivity samples extrapolate to approximately the Sommerfeld value at 0°K, but fall considerably below it at higher temperatures. The behavior of the low conductivity alloys is different: the extrapolated 0°K value is appreciably lower than the Sommerfeld value, the values between about 10 and 60°K are higher, but above 60°K the values are again lower.

Kohler²³ showed that the Lorenz number should be constant if the conduction electrons were scattered elastically. That condition is approximately true at high temperatures and at very low temperatures where the residual term is predominant in the electrical resistivity. At intermediate temperatures the condition

²³ M. Kohler, Ann. Physik 40, 601 (1941).

of elasticity no longer holds and the Lorenz number decreases considerably from the Sommerfeld value (if the lattice thermal conductivity is negligible). Any significant amount of lattice thermal conductivity will raise the Lorenz number above the value it would have had if only the electronic term in the thermal conductivity were considered.

Nearly all of the variations observed in the Lorenz numbers plotted in Fig. 6 can be explained, at least qualitatively, by the foregoing arguments. However, we do not have any reasonable explanation for the decrease of the Lorenz number below the Sommerfeld value for the low conductivity alloys in the temperature range below 10°K.

D. Thermoelectric Force and Power

There is comparatively very little literature on the thermoelectric forces for pure metals or for alloys not

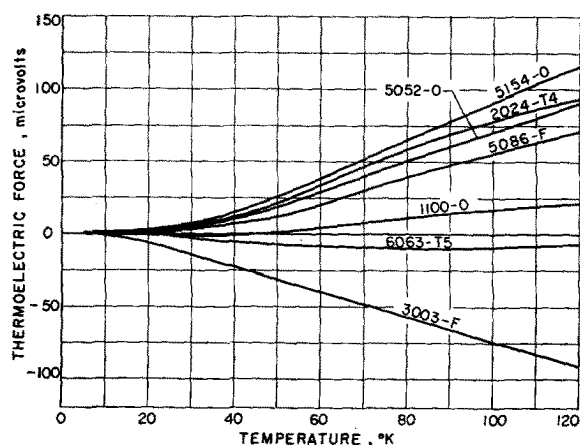


FIG. 7. Thermoelectric force of the aluminum alloys with respect to the high-purity sample. The low-temperature reference junction is 4°K.

suitable as thermocouple elements. Both the quantitative and qualitative predictions of the standard theory for simple metals as outlined by Wilson²⁴ are in serious error. More recent general theoretical discussions of thermoelectric power have been given by Domenicali,²⁵ Domenicali and Otter,²⁶ ter Haar and Neaves,²⁷ Sondheimer,²⁸ and MacDonald.²⁹ Considerable improvement

²⁴ A. H. Wilson, *Theory of Metals* (Cambridge University Press, Cambridge, 1953), second edition.

²⁵ C. A. Domenicali, *Revs. Modern Phys.* **26**, 237 (1954).

²⁶ C. A. Domenicali and F. A. Otter, *Phys. Rev.* **95**, 1134 (1954).

²⁷ D. ter Haar and A. Neaves, *Proc. Roy. Soc. (London)* **A228**, 568 (1955).

²⁸ E. H. Sondheimer, *Proc. Roy. Soc. (London)* **A234**, 391 (1956).

²⁹ D. K. C. MacDonald, *Z. Phys. Chem.* **16**, 310 (1958).

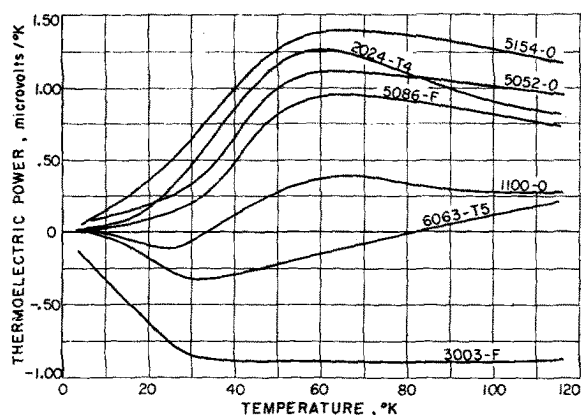


FIG. 8. Thermoelectric power of the aluminum alloys with respect to the high-purity sample.

in the agreement between theoretical predictions and experimental measurements will probably be brought about by advances along two separate lines: (1) refinements in the "phonon-drag" concepts introduced by Gurevich³⁰ and recently calculated in detail by Bailyn,³¹ and (2) progress in two-band model calculations as they pertain to aluminum and similar metals.^{24,32}

For seven of the alloys the thermoelectric forces and powers with respect to the pure sample are given in Figs. 7 and 8, respectively. Crussard³³ has made measurements at high temperatures on several controlled alloys of aluminum and his work was discussed theoretically by Galt³⁴ and Friedel.³⁵ Our results are difficult to interpret because of the simultaneous presence in the samples of physical imperfections and several types of chemical impurities. However, they are in rough qualitative agreement with Crussard's results: the alloy with an appreciable amount of Mn (3003-F) shows the largest negative thermoelectric power and the alloys with Mg have a positive thermoelectric power.

V. ACKNOWLEDGMENTS

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³⁰ L. Gurevich, *J. Physics (Moscow)* **9**, 477 (1945).

³¹ M. Bailyn, *Phys. Rev.* **112**, 1587 (1958).

³² E. J. Moore, *Australian J. Phys.* **11**, 235 (1958).

³³ C. Crussard, *Report on a Conference on Strength of Solids* held at H. H. Wills Physical Laboratory, July 7-9, 1947 (London, Physical Society, 1948), p. 119.

³⁴ J. K. Galt, *Phil. Mag.* **40**, 309 (1949).

³⁵ J. Friedel, *J. Phys. Rad.* **14**, 561 (1953).