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by

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THERMAL CONDUCTIVITY OF URANIUM: EFFECTS OF PURITY AND MICROSTRUCTURE

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T. A. Sandenaw

ABSTRACT

Thermal conductivity curves for polycrystalline uranium are presented for the temperature range below 373 K. The curves are for specimens prepared by different fabrication procedures from material of known purity and hardness. Included is a curve for U/2wt% Mo alloy.

Different mechanisms appear to be influencing the thermal conductivity behavior of uranium in well-defined temperature regions: below 37-43 K, ~40 K to ~80 K, 80 K to ~280 K and from 280 K to the $\alpha \rightarrow \beta$ transformation temperature. Mechanisms responsible for results in one temperature region continue to exert a strong influence in the next higher temperature region. Impurities and initial microstructure seem to influence results at any starting temperature.

Evidence is presented for the possibility of imperfection ordering in uranium between ~40 K and ~280 K. It is postulated that the type of ordering is compatible with a martensite-like behavior and that all physical property results depend on the extent of a modification of the α -phase on cooling below ~280 K.

I. INTRODUCTION

The extremes in thermal conductivity values reported for polycrystalline α -phase uranium to 1957 have been shown in a survey by Smith.¹ He noted that there was a basic disagreement in the entire body of thermal conductivity data reported up to that time. His figures illustrated the scatter bands for different data groups. It was evident that at room temperature there was a discontinuity between low-temperature and high-temperature thermal conductivity values for α -phase uranium.

Babbitt et al.² noted that the high-temperature thermal conductivity of γ -phase extruded uranium increased as the tests were repeated and as the specimens were reheated a number of times. They considered that the changes in conductivity were real and probably resulted from alterations in crystal structure of the metal. They questioned the possibility of stabilizing the thermal conductivity within the α -phase region above room temperature.

The divergence in thermal conductivity values for uranium below 100 K has been shown in a recent

data compilation by Childs et al.³ The band of data widens considerably below 80 K and has a maximum width at about 15 K. The results obtained for low-temperature thermal conductivity of α -phase uranium by different investigators thus seem to depend upon whether measurements were started at ~4 K or at some higher temperature, if one disregards the effect of differing impurities in each specimen.

The apparent effect of a difference in texture of a specimen of uranium of reasonably high purity has been shown by the low-temperature thermal conductivity work of Hall and Lee.⁴ Their curves for "unannealed" and annealed specimens were widely separated in the temperature range below 100 K. The purity of uranium specimens used for thermal conductivity measurements has seldom been specified. Detailed tabulations of impurity elements present in their uranium specimens have only been given by Babbitt et al.² and Hall and Lee,⁴ and neither group of experimenters list the carbon content.

The data for the thermal conductivity of polycrystalline uranium specimens, as presented here, are for specimens produced by different fabricating techniques from material of known purity and hardness. The range of temperature measurements was between ~80 K and 373 K. The starting point of measurements would thus be at the temperature of the maximum in Young's modulus of α -phase uranium,⁵ and measurements would continue across what appeared from previous work to be a room-temperature discontinuity. It was hoped that results would answer some of the questions raised by Smith¹ regarding stability of results and roles of purity, structure, texture and unavoidable experimental factors. If the scatter bands are genuine, material differences such as purity, structure, and texture might be responsible for their width.

II. SPECIMEN DESCRIPTION

The uranium specimens subjected to thermal conductivity measurements were machined from rolled plate (parallel and perpendicular to rolling direction), cast plate, γ -phase extruded rod, swaged rod, and U/2wt% Mo alloy. The parallel direction of the rolled plate was taken as the direction of the last eight longitudinal passes. Final dimensions of specimens were: diameter, 6.35 mm; length, 88.9 mm.

The results of chemical and spectrochemical analysis of material sampled from the different specimens are shown in Table I. The results of metallographic analysis are shown in Table II. Listed are grain size, if measured, and diamond pyramid hardness. No metallurgical study was made of the U/2wt% Mo alloy.

A specimen of Armco iron was chosen as a reference standard for monitoring the reproducibility of the thermal conductivity apparatus. This specimen was annealed at 773 K in a vacuum furnace to a diamond pyramid hardness of 160.4. Chemical and spectrochemical analysis showed the following impurities in the iron in ppm by mass: C, 60; Mn, 50-500; S, 13; Si, 30; Cu, 500; Ni, 80; Cr, <300; V, <100; Mo, 30; Co, <100; Ti, <30 and Zn, <500.

III. EXPERIMENTAL DETAILS

The thermal conductivity measurements were made in a double guard sleeve apparatus previously used with plutonium metal and described in detail.⁶

Thermal conductivity runs were made on the Armco iron specimen between those runs made with the different uranium specimens. This was done to ensure that there were no changes in thermocouple contact or output.

Each result obtained with each specimen was an equilibrium value. The heat sink was held at a fixed temperature until the thermal conductivity remained constant for at least 2 h. Each specimen was cycled between 80 K and 373 K two or three times to detect any effects of cycling.

Measurements of electrical resistivity were also made on each uranium specimen to determine the Lorenz number of each as a function of temperature.

IV. EXPERIMENTAL RESULTS

A. Armco Iron

The results for the thermal conductivity of Armco iron are shown by a log-log plot in Fig. 1. The data taken were analyzed statistically, and the 95% confidence limit for precision of results is shown for the temperature range between 80 K and 373 K. Results are compared with data of Hust and Sparks⁷ for electrolytic iron (1971), Hust et al.⁸ for Armco iron (1970) and Shanks et al.⁹ for Armco iron (1967). Purity of the Armco iron used for this study was higher than that investigated by Hust et al.,⁸ but not of the purity of the electrolytic iron used by Hust and Sparks.⁷ It should be noted that the curves for thermal conductivity vs temperature shown in Fig. 1 are at the lower edge of the band of data shown for iron in the recently published compilation of Childs et al.³

The calculated Lorenz numbers for the Armco iron measured in this study were $2.62 \times 10^{-8} \text{ V}^2 \text{ K}^{-2}$ at 273 K and $2.88 \times 10^{-8} \text{ V}^2 \text{ K}^{-2}$ at 373 K. This compares favorably with values of 2.69 and $2.84 \times 10^{-8} \text{ V}^2 \text{ K}^{-2}$ given by Shanks et al.⁹ for the same temperatures.

B. Uranium

The thermal conductivity vs temperature curves for the uranium specimens investigated in this study are shown in Fig. 2 for the temperature range 88 K to 373 K. The log-log plots in Fig. 2 also show data previously reported for uranium in the range 10 K to 300 K and included in the compilation of Childs et al.³ Also shown in Fig. 2 are high-temperature curves reported by Howl¹⁰ and Eriksen and Halg.¹¹

TABLE I
IMPURITY CONTENT OF URANIUM SPECIMENS

Element (ppm by mass)	Source of Specimens					
	<u>Rolled sheet, parallel (annealed)</u>	<u>Rolled sheet, perpendicular (not annealed)</u>	<u>Gamma- extruded rod</u>	<u>Swaged rod</u>	<u>As cast</u>	<u>U/2wt% Mo alloy</u>
C	310	320	445	660	390	95
Fe	70	80	>100	100	>100	170
Si	15	20	50	100	70	150
Ni	15	20	25	5	5	15
Al	2	2	20	20	15	2
Cu	2	3	15	10	10	2
Mg	2	2	2	5	4	-
Cr	4	5	7	8	4	8
Mn	3	4	3	5	5	3
Mo	-	-	-	-	-	2%

Li, Be and B all 0.1 ppm or less.

Na <1 ppm.

Co <5 ppm.

Ca and V <10 ppm.

TABLE II
GRAIN SIZE AND HARDNESS OF URANIUM SPECIMENS

Physical property	Source of Specimen					
	<u>Rolled sheet, parallel (annealed)</u>	<u>Rolled sheet, perpendicular (not annealed)</u>	<u>Gamma- extruded rod</u>	<u>Swaged rod</u>	<u>As cast</u>	<u>U/2wt% Mo alloy</u>
Grain size, mm	0.024	-	0.200	-	0.620	-
Hardness, D.P.H.	227	266	296	333	224	-

With one exception, the first measurement of the thermal conductivity of the five uranium specimens at -90 K gave values lower than were ever obtained again. First values at -90 K for the five specimens ranged between 14.2 and 15.5 W m⁻¹ K⁻¹. The first value (at -90 K) for the α -rolled specimen (cut parallel to the rolling direction and annealed) was reproducible for a period of 48 h. The final reproducible curve between 88 and 373 K for this specimen was the highest thermal conductivity curve of those determined.

The lowest thermal conductivity values at 200 K were found with both γ -phase extruded and swaged

rod material, but values at -90 K for the swaged rod were higher (after first cooling) than for other specimens examined and covered a narrow range between 18.3 and 18.8 W m⁻¹ K⁻¹.

The thermal conductivity vs temperature curve for "as cast" material had an entirely different slope than that for α -rolled uranium (cut parallel and annealed) or for γ -phase extruded and swaged rod metal. Values determined at ~370 K were between 32.2 and 33.8 W m⁻¹ K⁻¹ and were the lowest values found at this temperature for any of the specimens investigated.

Fig. 1. Iron specimens--thermal conductivity vs temperature.
 (a) Electrolytic-HS (J. G. Hust and L.L. Sparks⁷).
 (b) Armco-HPWI, 1 (a) (J. G. Hust, R. L. Powell, and D. H. Weitzel⁸).
 (c) Armco-SKD (H. R. Shanks, A. H. Klein, and G. C. Danielson⁹).
 (d) Armco (This report).

Fig. 2. Uranium specimens--thermal conductivity vs temperature.
 (a) HL and HL(a) (R. O. A. Hall and J. A. Lee⁴).
 (b) R (H. M. Rosenberg²⁷).
 (c) TWW (W. W. Tyler, A. C. Wilson, Jr., and G. J. Wolga¹⁹).
 (d) H (D. A. Howl¹⁰).
 (e) EH (V. O. Eriksen and W. Höggl¹¹).
 (f) α-rolled, parallel (a) (α-rolled, cut parallel, annealed).
 (g) as cast (as cast).
 (h) γ-ext. (γ-phase extruded).
 (i) SW. (swaged).
 (j) 2% Mo-U alloy (U/2wt% Mo alloy).

TABLE III
LORENZ NUMBER ($\times 10^8 \text{ V}^2 \text{ K}^{-2}$)

Temperature (K)	Source of Specimen					
	Rolled sheet, parallel (annealed)	Rolled sheet, perpendicular (not annealed)	Gamma extruded rod	Swaged rod	As cast	U/2wt% Mo alloy
80-90	2.58	2.28	2.25	2.69	2.50	1.88
190-200	2.61	2.47	2.52	2.51	2.48	2.46
273	3.02	2.93	2.95	2.90	2.92	2.87
370-373	3.42	3.31	3.38	3.28	3.28	3.28

A specimen cut from "unannealed" α -rolled uranium in a direction perpendicular to rolling direction had a very irreproducible behavior below room temperature, but values were extremely reproducible at 277 K and above and were comparable to those of "as cast" uranium.

The curves of Fig. 2 show a dependency upon the starting temperature of any set of measurements. The thermal conductivity values shown at -90 K, for the five uranium specimens measured, are much lower than values appearing on any of the curves for starts at 20 K and below. There is also a considerable difference in thermal conductivity values observed at 300-400 K for runs started at -20 K or -80 K and those started at room temperature and above. The values found on first measurement of the five uranium specimens in the range of 80-90 K could conceivably fall on curves of Howl¹⁰ and Eriksen and Hülgl¹¹ if they were projected down to -80 K at the same level of curvature as shown on Fig. 2.

The curves also appear to show the influence of purity and texture of the specimens over the entire temperature range. Hall and Lee⁴ show that the thermal conductivity of a very pure uranium sample is higher than anything previously reported in the temperature range between 5 K and 100 K, and that annealing more than doubles the value at the maximum (curves HL and HL(a), Fig. 2).

The Lorenz numbers (averaged values) calculated for the five uranium specimens and the U-Mo alloy at four widely separated temperatures are shown in Table III. It is remarkable that the Lorenz numbers for the U/2wt% Mo alloy are so close to those four of the uranium test specimens at temperatures of 200 K and above.

V. DISCUSSION OF RESULTS

The complexity of the thermal conductivity behavior of uranium below 373 K, as shown on Fig. 2, suggests that several mechanisms are operating. It appears that different mechanisms predominate in different temperature ranges, i.e., from 5 K to -80 K, 80 K and above, and 298 K and above. The data indicate that the mechanism which predominates in any one of these temperature ranges is also dependent upon the starting temperature of a particular series of thermal conductivity measurements.

Clues to the mechanisms operating in uranium are found in the similarities in two of the low-temperature physical properties of uranium and iron. Berlincourt¹² showed that the Hall coefficient of polycrystalline uranium was impurity sensitive and that it had a strong temperature dependence. The change in sign of Hall coefficient occurs in iron at -70 K as reported by Dheer¹³, or at -75 K as reported by Klaffky and Coleman.¹⁴ No change in sign was found for iron of low purity by Volkenshtein and Fedorov.¹⁵ The Young's modulus of each material increases on cooling below room temperature. While the Young's modulus of single-crystal α -iron is only slightly dependent upon temperature, it is highly dependent upon crystal orientation.¹⁶ The Young's modulus of polycrystalline uranium is very temperature dependent in the α -phase. A maximum at -80 K and a minimum at -37 K have been shown for uranium.⁵

A. Region Between 10 K and 80 K (Iron and Uranium)

Thermal conductivity values are most sensitive to the impurity content of either iron or uranium in the temperature range near and below that of the change of sign of Hall coefficient (Figs. 1 and 2). The highest thermal conductivity curve for iron below 80 K is shown by Childs et al.³ to be for iron

of the highest purity investigated. The highest thermal conductivity curve for uranium below -40 K was found by Hall and Lee⁴ for uranium which was probably of the highest purity of any uranium investigated at these low temperatures. Electron scattering by impurities appears to be the predominating influence on thermal conductivities of both iron and uranium at low temperatures. This appears to be the case below 37-43 K or the temperature of the reported α_0 - to α -phase transition in uranium.

A minimum in Young's modulus can indicate the start of a martensitic transformation.¹⁷ The extent of the martensite formed at 37-43 K could be influenced by impurity and defect concentration and cooling rate from room temperature. Stresses could be induced on cooling because of the anisotropic nature of the thermal expansion coefficient of the α -phase structure. Hall and Lee⁴ attribute the temperature dependence of thermal conductivity above -40 K to an increasing electronic conductivity with increasing temperature and a significant lattice contribution which is almost constant over the temperature range 40-100 K. This is also approximately the temperature range between the minimum and the maximum values of Young's modulus of uranium⁵. Therefore an increasing electronic conductivity between the α_0 - to α -phase transformation and -80 K could be indicative of an increasing degree of structural order, because the Young's modulus of some alloys is known to increase continuously with an increasing degree of order.¹⁸

A. Region Between 80 K and 280 K (Uranium)

There is a plausible explanation for the fact that all of the specimens investigated for this report showed a very similar low thermal conductivity (14.2 to $15.5 \text{ W m}^{-1} \text{ K}^{-1}$) on first cooling to -80 K. Initial values could be for unmodified α -phase material, as quenched with liquid nitrogen from room temperature. This possibility has been noted above. It is conceivable that the low temperature thermal conductivity vs temperature curve reported for uranium by Tyler et al.¹⁹ was also for α -phase material which was unaltered by cooling to below 20 K.

The importance of -80 K has been shown by the susceptibility study of Fournier²⁰ and in a resistivity study of Araj and Colvin.²¹ The latter experimenters observed a decrease in resistivity

on holding a lower purity uranium sample for 8 days in liquid nitrogen (-75 K). Some form of ordering at this temperature is indicated, although the mechanism could have been equivalent to tempering of a martensite.

Ordering is compatible with a martensitic transformation and may be required for a transformation to take place at a temperature as low as 37-43 K. The type of ordering which appears to have a maximum at 80 K could be modulation of the stacking faults remaining from the martensitic β $\rightarrow$ α -phase transformation. Christian and Swann²² have pointed out that the crystallographic structure of faults in metals can resemble that of other phases and that it has often been suggested that faults can nucleate and propagate martensitic transformations. It is speculated that the phenomena observed at approximately 37 K, 80 K, and 250-280 K in many physical property measurements are the consequences of a martensite-like behavior in uranium.

Several experimenters have observed slight changes in the physical properties of uranium at a temperature between 250 K and 280 K. Fournier²⁰ found that a slight dip in magnetic susceptibility of polycrystalline uranium ended at 280 K. Sze and Meaden²³ reported a thermoelectric power anomaly at 250 K, while Rosen²⁴ found that the longitudinal acoustical attenuation had a small hump centered at -250 K. Fisher and McSkimin²⁵ noted that the stiffness modulus, c_{11} , of uranium had a maximum value at 256 K. Sandenaw²⁶ reported that the dip in the C_p vs T curve of nominal high-purity polycrystalline ^{238}U ended at 250 K. He pointed out that such a dip in heat capacity was characteristic of a quenched martensite. The martensitic nature of iron is well established, and the similarities in Hall coefficient and Young's modulus behavior of iron and uranium at low temperatures have been discussed above.

C. Region Above 298 K (Uranium)

The results of measurements starting at room temperature and above must be for unmodified α -phase uranium. The relative positions of thermal conductivity vs temperature curves will be influenced by impurities and texture. The effects of impurities, principally carbon and iron, have been discussed by Howl.¹⁰ He found the highest thermal conductivity at 573 K and at 673 K for a C/Fe weight ratio of 2.3. The lowest values at these two temperatures

were found for C/Fe ratios of 1.5 and 4.0. The C/Fe ratios of the five uranium specimens investigated for this report were above 4.0, with the ratio for the swaged rod being 6.6.

Changes on thermal cycling above room temperature most probably result from alterations in crystal structure (texture) as suggested by Babbitt et al.² and which are due to anisotropy of the thermal expansion coefficient of the α -phase structure. It is conceivable that sufficient cycling above 298 K could lead to resulting curves approaching those of this research.

D. Uranium/2wt% Molybdenum Alloy

The U/2wt% Mo alloy showed a very low thermal conductivity at 80-90 K (Fig. 2), so that alloying element scattering must be playing an important role at this low temperature. The very rapid increase in thermal conductivity with rising temperatures suggests a changing role. At higher temperatures the alloying atoms enhance the thermal conductivity, as appears to be the case for α -phase uranium.

VI. SUMMARY

Impurities and initial texture seem to influence the results at any temperature for α -phase uranium, as evidenced by the different levels of reported thermal conductivity vs temperature curves.

It is suggested that different mechanisms are influencing the thermal conductivity behavior of polycrystalline uranium in four well-defined temperature regions. The span of these regions appear to be: below 37-43 K, 40 to 80 K, 80 to 280 K and from 280 K to the $\alpha \rightarrow \beta$ transformation temperature. Mechanisms responsible for the behavior in one temperature region continue to exist a strong influence into the next higher region.

The predominant effect on thermal conductivity below the 37-43 K transition temperature must be that of electron scattering by impurities, as is suggested by previous work.^{4,12} A martensitic transformation at 40 K, suggested as being induced by shear strain from cooling (or quenching) the anisotropic α -phase material, should change the conductivity mechanism. Thermal conductivity results above 40 K must be for modified α -phase uranium. An increasing electronic conductivity has been proposed to account for the temperature

dependence of thermal conductivity from 40 K to 100 K.⁴

Measurements started at 80 K indicate that an ordering mechanism is predominating. Texture, rather than purity, appears to be the important factor in thermal conductivity above 80 K. This can be explained if ordering at 80 K is through imperfections such as vacancies, interstitials, dislocations, or stacking faults. The latter type of ordering would be compatible with a martensitic transformation, and might be a prerequisite for such a transformation to occur. It is speculated that the temperature range between 250-280 K is the upper limit of a strain-induced defect ordering. This appears to be confirmed by published heat capacity measurements for uranium.²⁶

Results for thermal conductivity measurements starting only at room temperature and above must be for unmodified α -phase uranium. Anisotropy of the thermal expansion coefficient of the α -phase structure could account for effects of thermal cycling on texture, with changing texture responsible for the continuing changes in thermal conductivity above 298 K.

Although unavoidable experimental factors may account for some of the great differences between thermal conductivity results reported by different experimentalists, it is believed that most differences are real and depend upon the specimen state at time of measurements.

REFERENCES

1. K. F. Smith, "The Thermal Conductivity of Uranium," Argonne National Laboratory report ANL-5700, Part A, Lemont, Illinois, April 1957.
2. J. D. Babbitt, T. M. Dauphinee, L. D. Armstrong, and W. Peria, "II, Thermal Conductivity of Uranium: A Preliminary Study," Atomic Energy of Canada Limited, Chalk River report CCR-438, Reprinted Chalk River, Ontario, July 1956.
3. G. E. Childs, L. J. Ericks, and R. L. Powell, "Thermal Conductivity of Solids at Room Temperature and Below," N.B.S. Monograph 131, U. S. Dept. of Commerce, National Bureau of Standards, Sept. 1973, p. 233.
4. R. O. A. Hall and J. A. Lee, J. Low Temp. Phys. 4, 415 (1971).
5. P. E. Armstrong, D. T. Eash, and J. E. Hockett, J. Nucl. Materials 45, 211 (1972/73).

6. T. A. Sandenaw and R. B. Gibney, J. Phys. Chem. Solids 6, 81 (1958).
7. J. G. Hust and L. L. Sparks, "Thermal Conductivity of Electrolytic Iron, SRM 734, from 4 to 300 K," N. B. S. Special Publ. 260-31, U. S. Dept. of Commerce, National Bureau of Standards, Nov. 1971.
8. J. G. Hust, R. L. Powell, and D. H. Weitzel, "Thermal Conductivity Standard Reference Materials from 4 to 300 K. I. Armco Iron: Including Apparatus Description and Error Analysis." J. Research, N. B. S. 74A, 673 (1970).
9. H. R. Shanks, A. H. Klein, and G. C. Danielson, J. Appl. Phys. 38, 2885 (1967).
10. D. A. Howl, J. Nucl. Materials 19, 9 (1966).
11. V. O. Eriksen and W. Halg, J. Nucl. Energy 1, 232 (1955).
12. T. G. Berlincourt, Phys. Rev. 114, 969 (1959).
13. P. N. Dheer, Phys. Rev. 156, 637 (1967).
14. R. W. Klaffky and R. V. Coleman, Phys. Rev. B, 10, 2915 (1974).
15. N. V. Volkenshtein and G. V. Fedorov. Sov. Phys.--JETP 11, 48 (1960).
16. M. C. Martin, J. Iron and Steel Inst. 209, 308 (1971).
17. H. Warlimont and L. Delaey, Progress in Materials Science Vol. 18, (Pergamon Press, Oxford, 1974) p. 117.
18. N. S. Stoloff and R. G. Davies, Progress in Materials Science, Vol. 13 (Pergamon Press, Oxford, 1966) p. 11.
19. W. W. Tyler, A. C. Wilson, Jr., and G. J. Wolga Trans. AIME, 197, 1238 (1953).
20. J. M. Fournier, C. R. Acad. Sci. (Paris) 271B, 1156 (1970).
21. S. Arajs and R. V. Colvin, J. Less-Common Metals 7, 54 (1964).
22. J. W. Christian and P. R. Swann, "Alloying Behaviour and Effects in Concentrated Solid Solutions," T. F. Massalski, Ed., (Gordon and Breach, New York, 1963) p. 179.
23. N. H. Sze and G. T. Meaden, "Plutonium 1970 and Other Actinides," W. N. Miner, Ed., Nuclear Metallurgy, Vol. 17, Part 2 (The Metallurgical Society, New York, 1970) p. 974.
24. M. Rosen, Phys. Lett. 28A, 438 (1968).
25. E. S. Fisher and H. J. McSkimin, Phys. Rev. 124, 67 (1961).
26. T. A. Sandenaw, "Impurity Effects on Low-Temperature Physical Properties of Uranium," Los Alamos Scientific Laboratory report LA-5721-MS (1974).
27. H. M. Rosenberg, Phil. Trans. Roy. Soc. London 247A, 441 (1955).