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THE EFFECTIVE THERMAL CONDUCTIVITY OF SHEARED PROTOTYPE LMFBR FUELS

S. D. Clinton
R. L. Cox

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S. D. Clinton

R. L. Cox

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FEBRUARY 1973

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THE EFFECTIVE THERMAL CONDUCTIVITY OF SHEARED PROTOTYPE LMFBR FUELS

S. D. Clinton and R. L. Cox

ABSTRACT

During the recovery of uranium and plutonium from irradiated LMFBR fuels by the mechanical shear-leach and aqueous Purex process, the volume of accumulated sheared fuel may be restricted by heat transfer limitations. The calculation of temperature gradients within a given volume of spent sheared fuels requires a knowledge of the effective thermal conductivity of the chopped fuel pieces. In this study, the effective thermal conductivities of 11 prototype systems were measured experimentally as a function of temperature. The experimental measurements were made at steady-state conditions using the technique of radial heat flow in a hollow cylinder. The prototype sheared systems ranged from metal-clad porcelain or unirradiated urania to empty stainless steel hulls in either an argon or air atmosphere. The measured thermal conductivities for each system could be correlated as an exponential function of temperature with an average deviation of only $\pm 4.1\%$ over the temperature range 200 to 1400°F. For stainless-steel-clad urania pellets that simulate sheared fuel from the LMFBR core region (0.305 in. diam by 1 in. long), the expression for the effective thermal conductivity was as follows:

$$k(\text{Btu/hr-ft-}^\circ\text{F}) = 0.109e^{0.00168T(^\circ\text{F})}$$

1. INTRODUCTION

The shear-leach process was developed at the Oak Ridge National Laboratory as an alternative head-end treatment to chemical decladding and subsequent fuel dissolution. The original objective of this process was to recover uranium and thorium from irradiated LWR (light water reactor) fuels. As the name of the process implies, the irradiated fuel assembly rods are chopped into short pieces (~1 in. long) by means of a mechanical shear. This operation exposes the fuel material and enables the fuel to be leached from the sheared cladding by a suitable dissolvent such as nitric acid.¹

Because of its proven reliability in both laboratory and commercial operations, the shear-leach process appears to be the leading contender as a head-end step for processing spent LMFBR (liquid metal fast breeder reactor) fuels. Because the LMFBR fuels will have a higher fuel burnup, a higher specific power, and a shorter decay period prior to reprocessing, the decay heat generation rates for proposed LMFBR fuel will be an order of magnitude higher than the rates experienced with LWR fuels.² For example, after a decay period of 30 days, sheared fuel rods from the Atomics International Follow-On Reactor core region will have a volumetric heat generation rate of approximately 20,000 Btu/hr-ft³. Consequently, the central temperature of a static volume of sheared LMFBR fuel would probably increase prior to contact of the fuel with the dissolver solution. In order to calculate the temperature rise within a volume of sheared fuel, it is necessary to know the effective thermal conductivity of the chopped fuel pieces.

In this study, the effective thermal conductivity across a cylindrical volume of sheared material was determined by measuring the heat flow and the corresponding steady-state radial temperature difference. Three different types of sheared material were evaluated: (1) stainless-steel-clad porcelain, (2) stainless-steel- and Zircaloy-2-clad unirradiated urania, and (3) empty stainless steel hulls. The clad porcelain was used as a possible stand-in fuel for urania-plutonia, while the clad urania pellets were studied to compare sheared geometries proposed for LMFBR and LWR fuels. The empty stainless steel hulls were investigated in order to determine the heat transfer characteristics of sheared cladding after dissolution of the nuclear fuel. The sheared material was measured in an atmosphere of either dry argon or air, and the log mean temperature of the cylindrical-sample volume was varied from 200 to 1400°F.

2. EXPERIMENTAL METHOD

The thermal conductivity data were obtained at steady-state conditions using the method of radial heat flow within a hollow cylinder. The upright

cylindrical sample container must be equipped with a central heater to provide a radial temperature gradient and with an outer furnace to maintain the sample at a particular temperature level. For a long hollow cylinder with angular symmetry and no axial temperature gradient, the expression for radial heat flow is;

$$Q = \frac{2\pi kL \Delta T}{\ln (R_2/R_1)} \quad , \quad (1)$$

where

Q = heat flow per unit time, Btu/hr,

k = effective thermal conductivity, Btu/hr-ft-°F,

L = axial length through which Q dissipates, ft,

R_1 = inner radius, in.,

R_2 = outer radius, in.,

ΔT = temperature difference between inner and outer radii, °F.

By making the appropriate measurements, Eq. (1) can be used to calculate the effective thermal conductivity across the volume of the cylindrical sample.

To correct for any calibration discrepancies between the thermocouple wires, the temperature difference in Eq. (1) is derived from the following relationship:

$$\Delta T = \Delta T_{\text{data}} - \Delta T_{\text{iso}} \quad , \quad (2)$$

where

ΔT_{data} = temperature difference between inner and outer thermocouples when the central heater is energized, °F,

ΔT_{iso} = corresponding temperature difference when no power is generated in the central heater, °F.

The temperature differences ΔT_{data} and ΔT_{iso} should be measured when the sample is adjusted to the same average temperature. This correction for the radial temperature difference, ΔT , will also account partially for any axial heat flow within the cylindrical sample.³

2.1 Equipment and Procedure

2.1.1 Experimental Equipment

With the exception of the cylindrical sample container, the experimental equipment was essentially the same as that used by H. W. Godbee⁴ to measure the thermal conductivity of dry powders. A vertical cross section of the sample container is shown in Fig. 1. The sample container, which was fabricated from 304L stainless steel, has an inside diameter of 7 in. and a length of about 25 in. The radial heat flow from the platinum-wound central heater is controlled by a dc power supply. The outer furnace consists of three independently controlled heaters which surround the entire length of the sample container. Twelve thermocouple wells extend from the sample container cover into the 3-in.-long test region, and a single gas supply line extends from the top flange to the bottom of the sample container.

A horizontal cross section of the sample container is shown in Fig. 2 to indicate the thermocouple radial locations. The central heater is separated from the sample material by a 1-in.-diam stainless steel tube. Six thermocouple wells are tack-welded to the outside of the center tube, and six thermocouple wells are similarly attached to the inside of the sample container. The average radial distance between the inner and outer thermocouple junctions is assumed to be 2-3/4 in.

Figures 3 and 4 are photographs of the equipment associated with the cylindrical sample container. The outer furnace assembly, heater-control thermocouples, and container closure flange are shown in Fig. 3. Also identifiable at the flange closure are the container thermocouple wells

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Fig. 1. Vertical Cross Section of the Sample Container and Heaters.

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Fig. 2. Horizontal Cross Section of the Sample Container.

PHOTO 3674-72

Fig. 3. Photograph of the Outer Furnace Assembly and Sample Container Closure Flange.

PHOTO 3672-72

Fig. 4. Photograph of the Center Tube and Inner Thermocouple Wells.

and the central heater leads. Figure 4 shows the upper flange, the inner thermocouple wells, and the center tube after removal from the sample container.

2.1.2 Experimental Procedure

In the assembled condition, the sample container had a measured volume of 14.55 liters. The bulk density of a sample was found by dividing the weight of sheared pieces by the container volume. The particle density was determined by measuring the volume of water displaced by a known weight of the sheared material. The sample void fraction could then be estimated by subtracting the bulk-density-to-particle-density ratio from unity. Either argon or air was metered into the bottom of the sample container at the rate of 30 to 50 cc/min.

Thermal conductivity measurements of each of the sheared samples were obtained at about 200°F increments over the temperature range 200 to 1400°F. Measurements or readings were taken at each temperature level for two cases: (1) central heater "on", with sufficient power to give a temperature difference between the inner and outer thermocouples, ΔT_{data} , of 25 to 35°F; and (2) central heater "off", to determine ΔT_{iso} . To avoid the difficulty of trying to achieve the same average sample temperature for the measurement of both ΔT_{iso} and ΔT_{data} , the value of ΔT_{iso} was measured at the increasing temperature levels and plotted as a function of the log mean sample temperature, T . From the resulting graph, a value of ΔT_{iso} was obtained to correct ΔT_{data} according to Eq. (2) at the same log mean temperature.

At each temperature level, the general procedure was as follows:

1. With the central heater "on", adjust the power input to the three outer-furnace heaters until a uniform axial temperature is attained.
2. Allow sufficient time for the system temperature to reach steady state.
3. Using a potentiometer, determine the emfs of the 12 inner and outer thermocouples located in the sample test region.

4. Record the voltage drop across the 3-in. section of central heater in the test region.
5. Record the voltage drop across a 0.005- Ω resistor to determine the current to the central heater.
6. Shut off the power supply to the central heater and repeat steps 2 and 3.

Although steady-state operation was achieved in shorter time periods, at least 24 hr was allowed to elapse between any two successive sets of readings.

The emf readings of the six inner radius and six outer radius thermocouples (Chromel-Alumel) were converted to the corresponding temperatures and averaged to determine a log mean sample temperature difference. In Eq. (1) the value of Q , the heat flow per unit time from the central heater, was calculated directly from the readings in steps 4 and 5. The geometric factor $\ln(R_2/R_1)/(2\pi L)$ was 1.0736 ft^{-1} in all of the experiments with $R_2 = 3.375 \text{ in.}$, $R_1 = 0.625 \text{ in.}$, and $L = 3 \text{ in.}$ The inner and outer radii values assume that the thermocouple junctions are positioned on the axes of the thermocouple wells.

2.2 Experimental Results

Thermal conductivity measurements for 11 different systems were obtained using various sheared materials in either an air or an argon atmosphere. The sheared materials can be separated into three general categories: (1) clad unirradiated urania, (2) clad porcelain, and (3) empty stainless steel hulls. The thermal conductivity data are tabulated as a function of temperature in the Appendix.

2.2.1 Clad Unirradiated Urania

The thermal conductivity results for the three unirradiated clad urania systems are shown in Fig. 5. The pellets in these systems had a density of

Fig. 5. Effective Thermal Conductivities of Sheared Stainless-Steel- and Zircaloy-2-Clad Unirradiated Urania.

10.35 g/cc and an oxygen-to-uranium atom ratio of 2,0005; all of them were sheared into 1-in. lengths. The cover gas for each of the three systems was argon.

The 304L stainless-steel-clad urania, which simulated sheared LMFBR blanket fuel, had a tubing diameter of 0.500 in., a wall thickness of 35 mils, and a void fraction of 0.65. The effective thermal conductivity of the simulated blanket material varied from about 0.17 to 1.6 Btu/hr-ft-°F over the temperature range 200 to 1400°F. As can be seen in Fig. 5, the conductivity characteristics of the simulated LWR fuel (Zircaloy-2-clad urania) were essentially identical to those of the simulated sheared LMFBR blanket material. The Zircaloy-2-clad urania had a tubing diameter of 0.562 in., a wall thickness of 35 mils, and a void fraction of 0.74. When a length-to-diameter ratio of about 2 was maintained during shearing, a considerable fraction of the urania was dislodged from the cladding. In all of the systems, the dislodged fragments were screened from the clad material and were thereby prohibited from falling into the sample container.

The simulated LMFBR core material (304L stainless-steel-clad urania) had an effective thermal conductivity of about 0.15 to 1.1 Btu/hr-ft-°F over the temperature range 200 to 1400°F. The stainless steel tubing had a diameter of 0.305 in. and a wall thickness of 15 mils; the sheared material (after removal of the fines) had a void fraction of 0.59.

2.2.2 Clad Porcelain

Porcelain pellets (Steatite L-3) were purchased from Clowes Ceramic, a division of Kearney National, Incorporated, to simulate urania-plutonia pellets proposed for the LMFBR core. The porcelain is composed primarily of magnesium silicate and has a room-temperature thermal conductivity of 1.5 Btu/hr-ft-°F, which is very close to that of sintered urania. The porcelain pellets were clad with 304L stainless steel tubing having an

outside diameter of 0.250 in. and a wall thickness of 15 mils. The steel-clad porcelain was sheared into both 0.5- and 1.0-in. lengths. After separation from the dislodged fines, the 0.5-in.-long clad porcelain and the 1.0-in.-long clad porcelain had void fractions of 0.52 and 0.57 respectively.

Thermal conductivity measurements were obtained on the 0.5-in. material in both air and argon, whereas the 1.0-in. material was studied only in argon (see Fig. 6). In air, the effective thermal conductivity for the 0.5-in.-long clad porcelain increased from 0.20 Btu/hr-ft-°F at 200°F to 1.0 Btu/hr-ft-°F at 1400°F. When the atmosphere was changed to argon, the thermal conductivity varied from 0.14 Btu/hr-ft-°F to 0.9 Btu/hr-ft-°F over the same temperature range. The variation of effective thermal conductivity with temperature for the clad porcelain that had been sheared into 1-in. lengths was 0.11 Btu/hr-ft-°F to 0.7 Btu/hr-ft-°F.

2.2.3 Empty Stainless Steel Hulls

Two sizes of 304L stainless steel tubing (15-mil wall thickness) were sawed into 1.0-in. lengths in order to simulate sheared LMFBR cladding after dissolution of the nuclear fuel. Empty blanket hulls were simulated by 0.510-in.-diam tubing, and core hulls were simulated by 0.250-in.-diam tubing; the void fractions were 0.93 and 0.88 respectively.

Thermal conductivity measurements were determined in both air and argon for each size of empty hull (see Fig. 7). In air, the effective thermal conductivity for the 0.510-in.-diam hulls increased from 0.17 Btu/hr-ft-°F to 1.6 Btu/hr-ft-°F over the temperature range 200 to 1400°F; in argon, the conductivity varied from 0.13 Btu/hr-ft-°F to 1.6 Btu/hr-ft-°F. In air, the effective thermal conductivity for the 0.250-in.-diam hulls increased from 0.21 Btu/hr-ft-°F to 1.2 Btu/hr-ft-°F as the temperature increased from 200°F to 1400°F; in argon, the conductivity varied from 0.16 Btu/hr-ft-°F to 1.2 Btu/hr-ft-°F.

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Fig. 6. Effective Thermal Conductivities of Sheared Stainless-Steel-Clad Porcelain.

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Fig. 7. Effective Thermal Conductivities of Simulated Stainless Steel Hulls.

For comparison purposes a solid, 0.250-in.-diam 304L stainless steel rod was sheared into 1.0-in. lengths. The resulting sheared material had a void fraction of 0.50 and an effective thermal conductivity that increased from 0.31 Btu/hr-ft-°F at 200°F to about 1.6 Btu/hr-ft-°F at 1400°F (see Fig. 7).

2.3 Discussion of Results

For the 11 systems measured, the effective thermal conductivity data as a function of temperature appear to be reasonably consistent. For example, the thermal conductivity ratio of air to argon is about 1.5;⁵ consequently, when conduction is the principal mechanism for heat transfer, the effective thermal conductivity of a sheared material is higher in air than in argon. However, as the temperature of the sample increases and radiation becomes the controlling heat transfer mechanism, the influence of atmosphere on the effective thermal conductivity tends to disappear. Also, agreement of the data for Zircaloy-2-clad uranium and the data for the 0.5-in.-diam steel-clad uranium might be expected due to similar geometries and cladding thermal conductivities.

A theoretical treatment of the effective thermal conductivity data obtained in this study will be discussed in a later report by H. W. Godbee. The analysis should parallel a prior study in which Godbee developed a mathematical model for heat transfer in powders.⁴

Since the effective thermal conductivities of the sheared materials appear to increase as an exponential function of temperature, the experimental data were correlated on semilogarithmic graphs (see Figs. 8 - 10 in the Appendix). A least-squares line was calculated from the log k -vs- T data for each of the 11 systems studied, and the resulting least-squares equations are tabulated in Table 1. Although these equations have no theoretical significance, the relationships do permit the calculation of

Table 1, Equations to Predict Thermal Conductivity as
an Exponential Function of Temperature from 200 to 1400°F

Sheared Material	Least-Squares Equation ^a
Stainless-steel-clad urania in argon, 0.500 in. diam x 1 in. long	$k = 0.119(e^{0.00186T})$
Zircaloy-2-clad urania in argon, 0.562 in. diam x 1 in. long	$k = 0.123(e^{0.00181T})$
Stainless-steel-clad urania in argon, 0.305 in. diam x 1 in. long	$k = 0.109(e^{0.00168T})$
Stainless-steel-clad porcelain in air, 0.250 in. diam x 0.5 in. long	$k = 0.158(e^{0.00130T})$
Stainless-steel-clad porcelain in argon, 0.250 in. diam x 0.5 in. long	$k = 0.100(e^{0.00155T})$
Stainless-steel-clad porcelain in argon, 0.250 in. diam x 1 in. long	$k = 0.081(e^{0.00155T})$
Solid stainless steel in argon, 0.250 in. diam x 1 in. long	$k = 0.236(e^{0.00132T})$
Empty stainless steel hulls in air, 0.510 in. diam x 1 in. long	$k = 0.118(e^{0.00189T})$
Empty stainless steel hulls in argon, 0.510 in. diam x 1 in. long	$k = 0.088(e^{0.00210T})$
Empty stainless steel hulls in air, 0.250 in. diam x 1 in. long	$k = 0.157(e^{0.00149T})$
Empty stainless steel hulls in argon, 0.250 in. diam x 1 in. long	$k = 0.116(e^{0.00168T})$

^a k = effective thermal conductivity, Btu/hr-ft-°F;
T = temperature, °F.

an effective, thermal conductivity across a volume of sheared material at any temperature within the 200 to 1400°F range. The average error between the 79 experimental conductivity values and the effective conductivities calculated by the least-squares equations is $\pm 4.1\%$.

Using essentially the same equipment, Godbee estimated an uncertainty in the measured conductivity values of approximately $\pm 10\%$.⁴ In Eq. (1), the maximum error is due to the variable $\ln(R_2/R_1)$, which is determined by the location of the inner and outer thermocouple junctions within the wells. No attempt was made to check the reproducibility of the data by refilling the annular sample container with the same sheared material. However, since the radial temperature difference was obtained from an average of six thermocouple pairs, the effect of packing variation across the annulus should be minimal.

3. CONCLUSIONS

The effective thermal conductivities for volumes of 11 prototype sheared systems were measured as a function of temperature over the range 200 to 1400°F. The prototype systems ranged from metal-clad unirradiated urania or porcelain to empty stainless steel hulls. An atmosphere of either air or argon was used. These particular volumes of chopped pieces were selected to simulate the different materials that would accumulate during operation of the shear-leach process in a LMFBR fuel reprocessing plant. If the volumetric heat generation rate and the effective thermal conductivity are known, a sheared fuel storage container can be designed to prevent excessive center-line temperatures. For each prototype system studied, an empirical equation was determined to predict the effective thermal conductivity as a function of temperature. The experimental data indicate the following general conclusions:

1. The effective thermal conductivities are essentially equal for sheared LMFBR blanket fuel and LWR fuel.

2. The effective thermal conductivity of prototype fuel apparently decreases as the sheared-length-to-diameter ratio increases from 2 to 4.
3. The effective thermal conductivities are very similar for both empty stainless steel hulls and clad urania.

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5. APPENDIX

The experimental data for the 11 prototype systems studied are tabulated in Table 2. Column (1) indicates the particular sheared prototype system; column (2) is the log mean sample temperature, T , in $^{\circ}\text{F}$; column (3) is the radial heat flow per unit time from the central heater, Q , in Btu/hr ; column (4) is the temperature difference between the inner and outer radii when the central heater is "on", ΔT_{data} , in $^{\circ}\text{F}$; column (5) is the temperature difference between the inner and outer radii when the central heater is "off", ΔT_{iso} , in $^{\circ}\text{F}$; column (6) is the effective thermal conductivity, k , in $\text{Btu/hr-ft-}^{\circ}\text{F}$ as calculated by Eqs. (1) and (2); column (7) is the effective thermal conductivity as predicted by the equations in Table 1; and column (8) is the percentage error between the predicted and experimental thermal conductivity values.

The experimental thermal conductivity data are plotted as a function of temperature in Figs. 8-10. The straight lines through the log k -vs- T data were determined by applying the method of least squares.

Table 2. Comparison of Experimental and Predicted Effective Thermal Conductivity Values

(1) Prototype System	(2) T (°F)	(3) Q (Btu/hr)	(4) ΔT_{data} (°F)	(5) ΔT_{iso} (°F)	(6) Experimental k (Btu/hr-ft-°F)	(7) Predicted k (Btu/hr-ft-°F)	(8) Error (%)
Stainless-steel- clad urania in argon, 0.500 in. diam x 1 in. long	215.8	5.622	30.4	-4.4	0.173	0.178	-2.8
	418.2	11.026	37.1	-8.3	0.261	0.260	+0.5
	592.8	11.464	26.9	-10.0	0.334	0.360	-7.3
	720.2	17.783	32.2	-9.0	0.463	0.456	+1.6
	994.7	22.683	21.4	-4.9	0.926	0.761	+21.7
	1259.1	28.239	21.4	-3.6	1.214	1.246	-2.6
	1435.8	38.276	22.6	-3.3	1.589	1.733	-8.3
Zircaloy-2-clad urania in argon, 0.562 in. diam x 1 in. long	217.9	5.369	28.6	-5.2	0.170	0.182	-6.5
	396.0	8.389	27.5	-9.1	0.246	0.251	-1.9
	600.4	12.439	24.9	-10.5	0.378	0.364	+3.8
	806.3	15.759	19.5	-10.4	0.566	0.528	+7.2
	1006.5	25.011	23.2	-9.8	0.814	0.759	+7.3
	1207.1	33.287	24.0	-8.8	1.092	1.091	+0.1
	1413.7	37.616	19.6	-8.3	1.448	1.586	-8.6
Stainless-steel- clad urania in argon, 0.305 in. diam x 1 in. long	215.8	4.644	27.8	-6.3	0.146	0.156	-6.1
	395.5	7.750	27.4	-10.2	0.221	0.211	+5.0
	593.6	11.786	29.8	-11.4	0.307	0.294	+4.4
	806.4	14.531	25.0	-10.7	0.437	0.419	+4.3
	1019.8	23.760	39.7	-8.2	0.532	0.600	-11.3
	1223.6	31.778	31.8	-6.2	0.896	0.843	+6.2
	1394.8	35.878	28.8	-5.9	1.110	1.124	-1.2

Table 2 (continued)

(1) Prototype System	(2) T (°F)	(3) Q (Btu/hr)	(4) ΔT_{data} (°F)	(5) ΔT_{iso} (°F)	(6) Experimental k (Btu/hr-ft-°F)	(7) Predicted k (Btu/hr-ft-°F)	(8) Error (%)
Stainless-steel- clad porcelain in air, 0.250 in. diam x 0.5 in. long	187.0	5.403	26.4	-3.5	0.194	0.201	-3.3
	376.2	10.000	34.6	-7.2	0.257	0.257	0.0
	596.6	14.498	34.3	-9.6	0.355	0.342	+3.7
	823.5	18.812	34.3	-9.6	0.460	0.459	+0.2
	1034.8	20.817	28.4	-7.7	0.620	0.605	+2.5
	1234.3	25.017	28.4	-5.7	0.788	0.784	+0.6
	1448.2	32.530	31.4	-3.5	0.999	1.034	-3.4
Stainless-steel- clad porcelain in argon, 0.250 in. diam x 0.5 in. long	195.6	4.429	30.2	-5.7	0.133	0.136	-2.1
	371.5	6.767	29.1	-10.3	0.184	0.178	+3.6
	564.8	8.667	25.8	-13.2	0.238	0.240	-0.8
	823.4	15.331	33.8	-12.8	0.354	0.359	-1.4
	1004.5	18.766	32.2	-10.4	0.474	0.475	-0.3
	1208.0	21.068	25.8	-8.0	0.670	0.651	+2.9
	1409.4	29.043	28.8	-6.8	0.875	0.890	-1.7
Stainless-steel- clad porcelain in argon, 0.250 in. diam x 1 in. long	207.1	4.163	35.9	-4.2	0.112	0.111	+0.3
	376.4	8.244	51.1	-9.3	0.146	0.144	+1.4
	562.3	7.080	26.3	-13.7	0.190	0.193	-1.4
	797.4	8.842	20.0	-14.8	0.273	0.277	-1.5
	1020.1	17.692	35.3	-13.8	0.387	0.391	-0.9
	1225.0	29.426	46.5	-10.2	0.557	0.536	+3.9
	1448.9	43.346	53.3	-9.1	0.746	0.758	-1.6

Table 2 (continued)

(1) Prototype System	(2) T (°F)	(3) Q (Btu/hr)	(4) ΔT_{data} (°F)	(5) ΔT_{iso} (°F)	(6) Experimental k (Btu/hr-ft-°F)	(7) Predicted k (Btu/hr-ft-°F)	(8) Error (%)
Solid stainless steel rods in argon, 0.250 in. diam x 1 in. long	207.2	10.426	31.1	-1.9	0.339	0.310	+9.3
	259.6	12.142	37.2	-2.8	0.326	0.333	-2.0
	379.8	12.109	26.0	-4.9	0.420	0.390	+7.7
	568.2	15.648	28.4	-7.7	0.465	0.501	-7.1
	679.7	22.909	36.2	-8.5	0.550	0.580	-5.2
	830.7	28.155	37.4	-8.7	0.656	0.709	-7.4
	1005.4	27.431	26.4	-7.9	0.859	0.894	-3.9
	1199.4	36.227	26.3	-7.0	1.167	1.155	+1.0
	1413.7	50.325	25.6	-6.5	1.682	1.535	+9.6
Empty stainless steel hulls in air, 0.510 in. diam x 1 in. long	214.4	4.973	27.4	-5.3	0.163	0.178	-8.2
	399.5	8.828	29.5	-8.4	0.250	0.252	-0.7
	598.8	11.497	22.7	-9.2	0.386	0.367	+5.3
	800.3	15.902	20.5	-9.0	0.579	0.537	+7.7
	999.7	26.242	26.3	-7.6	0.831	0.783	+6.2
	1196.9	35.736	26.9	-6.3	1.123	1.136	-1.1
	1399.4	40.655	22.9	-5.6	1.533	1.665	-7.9
Empty stainless steel hulls in argon, 0.510 in. diam x 1 in. long	218.2	5.111	35.0	-6.5	0.132	0.140	-5.3
	400.8	8.120	32.6	-9.8	0.206	0.205	+0.4
	602.4	12.373	30.2	-10.5	0.326	0.313	+4.1
	804.7	15.740	25.8	-8.3	0.495	0.480	+3.2
	1010.1	26.658	31.7	-6.6	0.748	0.739	+1.2
	1200.2	34.744	28.1	-5.0	1.128	1.103	+2.3
	1397.7	40.821	23.7	-4.0	1.580	1.671	-5.4

Table 2 (continued)

(1) Prototype System	(2) T (°F)	(3) Q (Btu/hr)	(4) ΔT_{data} (°F)	(5) ΔT_{iso} (°F)	(6) Experimental k (Btu/hr-ft-°F)	(7) Predicted k (Btu/hr-ft-°F)	(8) Error (%)
Empty stainless steel hulls in air, 0.250 in. diam x 1 in. long	207.9	4.856	22.7	-4.3	0.193	0.214	-9.5
	401.7	8.460	24.3	-8.0	0.281	0.286	-1.5
	602.5	11.657	19.1	-8.9	0.447	0.386	+15.8
	808.5	15.389	21.5	-8.9	0.544	0.524	+3.7
	1012.8	26.017	31.1	-7.9	0.717	0.712	+0.7
	1201.2	33.979	33.7	-6.2	0.914	0.943	-3.1
	1402.3	41.436	31.3	-5.2	1.220	1.273	-4.2
Empty stainless steel hulls in argon, 0.250 in. diam x 1 in. long	216.9	5.132	29.6	-5.0	0.159	0.167	-4.8
	394.4	8.050	29.4	-7.9	0.232	0.225	+2.8
	601.2	12.237	31.3	-8.5	0.330	0.319	+3.5
	799.6	15.862	30.2	-7.8	0.448	0.445	+0.8
	1009.5	26.451	38.9	-6.5	0.626	0.632	-1.0
	1206.5	33.409	34.9	-5.4	0.890	0.880	+1.2
	1407.6	38.680	29.6	-4.9	1.206	1.233	-2.2

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Fig. 8. Least-Squares Thermal Conductivity Correlations for Sheared Metal-Clad Urania.

Fig. 9. Least-Squares Thermal Conductivity Correlations for Sheared Steel-Clad Porcelain.

Fig. 10. Least-Squares Thermal Conductivity Correlations for Simulated Empty Steel Hulls.

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