Research reactor core conversion guidebook

Volume 4: Fuels (Appendices I-K)
APPENDIX I-1.1

SELECTED THERMAL PROPERTIES AND URANIUM DENSITY RELATIONS
FOR ALLOY, ALUMINIDE, OXIDE, AND SILICIDE FUELS

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ABSTRACT

This appendix presents data on the specific heat, thermal conductivity, and other properties of fuel meat materials commonly used, or considered for use, in research and test reactors. Also included are formulae relating the density of uranium in the fuel meat with the weight fraction of uranium and the volume fraction of the dispersed phase.

1.0 URANIUM DENSITY RELATIONS

In general, the density and weight fraction of uranium in fuel meat composed of aluminum, a dispersed phase, and voids can be written as:

\[ \rho_U = \frac{(1 - P) W_U}{\rho_{Al}} - a W_U \]

\[ W_U = \frac{\rho_U/\rho_{Al}}{1 - P + a \rho_U} \]  

where

\[ a = \frac{1}{W_D} \left( \frac{1}{\rho_{Al}} - \frac{1}{\rho_D} \right) \]

\[ P = \text{Porosity} = \frac{\text{Volume of Voids}}{\text{Volume of Solids + Volume of Voids}} \]

\[ W_U = \text{Weight Fraction of Uranium in the Fuel Meat} \]

\[ W_D = \text{Weight Fraction of Uranium in the Dispersed Phase} \]

\[ \rho_{Al} = \text{Density of Aluminum} = 2.7 \text{ g/cm}^3 \]

\[ \rho_D = \text{Density of the Dispersed Phase} \]

A useful formula in relating the terminology used by physicists and the terminology used by fuel fabricators is the relationship between the uranium density in the fuel meat and the volume fraction \( V_f^D \) of the dispersed phase:

\[ \rho_U = W_U \rho_D V_f^D \]
The derivation of these formulae is given below.

Volume Balance for Fuel Meat: \( V_m = V_D + V_{Al} + V_v \)

Divide by \( M_m \) (mass of meat): \( \frac{V_m}{M_m} = \frac{V_D}{M_m} + \frac{V_{Al}}{M_m} + \frac{V_v}{M_m} \)

Substitute: \( \frac{V_m}{M_m} = \frac{1}{\rho_m} \), \( \frac{V_D}{M_m} = \frac{V_D}{M_D} \frac{M_D}{M_m} = \frac{W_D}{\rho_D} \), \( \frac{V_{Al}}{M_m} = \frac{V_{Al}}{M_{Al}} \frac{M_{Al}}{M_m} = \frac{W_{Al}}{\rho_{Al}} \), and \( \frac{V_v}{M_m} = \frac{V_v}{V_m} \frac{V_m}{M_m} = \frac{P}{\rho_m} \)

to obtain:

\[
\frac{1 - P}{\rho_m} = \frac{W_D}{\rho_D} + \frac{1 - W_D}{\rho_{Al}} = \frac{1}{\rho_{Al}} - W_D \left( \frac{1}{\rho_{Al}} - \frac{1}{\rho_D} \right)
\]

Substitute: \( \rho_U = \frac{M_U}{V_m} \frac{M_m}{V_m} = \frac{W_U}{\rho_m} \) and \( W_U = W_D \)

to obtain:

\[
\frac{(1 - P) W_U}{\rho_U} = \frac{1}{\rho_{Al}} - W_U \left( \frac{1}{W_U} \left( \frac{1}{\rho_{Al}} - \frac{1}{\rho_D} \right) \right) = \frac{1}{\rho_{Al}} - a W_U
\]

Solve for \( \rho_U \):

\[
\rho_U = \frac{(1 - P) W_U}{\frac{1}{\rho_{Al}} - a W_U} \quad \text{which is Eq. (1)}
\]

Also:

\[
\rho_U = \frac{M_U}{V_m} = \frac{M_U}{M_D} \frac{M_D}{V_D} \frac{V_D}{V_m} = \frac{W_U}{\rho_D} \frac{V_D}{V_m} \quad \text{which is Eq. (3)}.
\]
2.0 THE URANIUM-ALUMINUM SYSTEM

The uranium-aluminum system\(^1\) (Fig. 1) contains three compounds - UAl\(_2\), UAl\(_3\), and UAl\(_4\) - which are formed during cooling down from the molten state. Some properties\(^2\) of these compounds are listed in Table 1:

Table 1. Some Properties of Uranium-Aluminum Compounds

<table>
<thead>
<tr>
<th>Compound</th>
<th>Density, g/cm(^3)</th>
<th>W(_{\text{U}})</th>
<th>Melting Point, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAl(_2)</td>
<td>8.1</td>
<td>0.813</td>
<td>1590</td>
</tr>
<tr>
<td>UAl(_3)</td>
<td>6.8</td>
<td>0.744</td>
<td>1350</td>
</tr>
<tr>
<td>UAl(_4)</td>
<td>6.1 (Theoretical)</td>
<td>0.685</td>
<td>730</td>
</tr>
<tr>
<td></td>
<td>5.7 ± 0.3 (Measured(^3))</td>
<td>0.640</td>
<td></td>
</tr>
</tbody>
</table>

*The compound UAl\(_4\) has a defect structure\(^3\) in which some of the uranium sites are unoccupied. The compound corresponds stoichiometrically to UAl\(_{4.9}\) (also referred to as U\(_{0.9}\)Al\(_4\)).

Since UAl\(_2\) and UAl\(_3\) react with an excess of aluminum at moderate temperatures to form UAl\(_4\), the relative amounts of these compounds that are present in the fuel meat of a finished plate or tube is a function of the wt-% of the uranium and the fabrication processes and heat treatments that are utilized.

Fig. 1. Al-U Aluminum-Uranium
3.0 URANIUM-ALUMINUM ALLOY FUEL

For uranium-aluminum alloy fuel with less than ~25 wt-% U, the alloy is mostly aluminum and UA14. Above ~25 wt-% U, a considerable amount of metastable UA13 may be present. The amount of retained metastable UA13 increases with increasing uranium content and with increasing impurity content. If it is advantageous, the brittle UA14 phase can be suppressed in favor of the more ductile UA13 phase through the use of ternary additions such as silicon.

3.1 Uranium Density Relations for U-Al Alloy Fuel

The densities of UA13 and UA14, the corresponding weight fractions of uranium in each compound, and the value of the parameter a in Eq. (2) are:

<table>
<thead>
<tr>
<th>Uranium Compound</th>
<th>Density, g/cm³</th>
<th>W_U^D</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA13</td>
<td>6.8</td>
<td>0.744</td>
<td>0.300</td>
</tr>
<tr>
<td>UA14</td>
<td>5.7 ± 0.3</td>
<td>0.640</td>
<td>0.305</td>
</tr>
</tbody>
</table>

The relationships between the uranium density and the weight fraction of uranium in the fuel meat, and between the uranium density and the volume fraction of the uranium compound are:

\[
\rho_U = \frac{(1 - P) W_U}{0.370 - a W_U}
\]

\[
W_U = \frac{0.370 \rho_U}{(1 - P) + a \rho_U}
\]

\[
\rho_U = 5.1 V_{f UA13}
\]

\[
\rho_U = 3.7 V_{f UA14}
\]

3.2 Specific Heat of U-Al Alloy Fuel

The specific heat of U-Al alloy fuel meat depends on the relative amounts of its constituents and their respective specific heats. The specific heat of "pure" aluminum is given by:

\[
C_{p,Al} = 0.892 + 0.00046 T \quad J/g \cdot K, \quad T \text{ in °C}
\]

Measured specific heats for pure uranium-aluminum compounds such as UA13 and UA14 are not available. The best data available are calculated from specific heat data for uranium and aluminum employing Kopp's law and values of excess heat capacity. The data presented in Ref. 6 yield the following specific heats for UA13 and UA14:

\[
C_{p,UA13} = 0.329 + 0.00021 T \quad J/g \cdot K, \quad T \text{ in °C } (20-600 \degree C)
\]

\[
C_{p,UA14} = 0.473 + 0.00024 T \quad J/g \cdot K, \quad T \text{ in °C } (20-600 \degree C)
\]
Using $W_U^D = 0.744$ for fully-enriched $\text{UA}_3$ and $W_U^D = 0.640$ for fully-enriched $\text{UA}_4$:

$$C_p,\text{U-Al alloy} = (1.0 - \frac{W_U}{0.744}) C_{p,\text{Al}} + \frac{W_U}{0.744} C_{p,\text{UA}_3}$$

(100% $\text{UA}_3$)

$$= 0.892 + 0.00046 T - W_U (0.757 + 0.00034 T) \text{ J/g K, T in } ^\circ \text{C}$$

$$C_p,\text{U-Al alloy} = (1.0 - \frac{W_U}{0.640}) C_{p,\text{Al}} + \frac{W_U}{0.640} C_{p,\text{UA}_4}$$

(100% $\text{UA}_4$)

$$= 0.892 + 0.00046 T - W_U (0.655 + 0.00034 T) \text{ J/g K, T in } ^\circ \text{C}$$

Since most plate-type research reactor fuels contain < 25 wt-% U, the uranium compound in the fuel meat is mostly $\text{UA}_4$. At 25 wt-% U and 40°C, for example, specific heats for U-Al alloy calculated assuming 100% $\text{UA}_4$ and 100% $\text{UA}_3$ differ by less than 4%. In practice, only a small fraction of the uranium compound is likely to be $\text{UA}_3$.

### 3.3 Thermal Conductivity of U-Al Alloy Fuel

The thermal conductivity of U-Al alloy fuel meat decreases with increasing weight fraction of uranium$^{10}$ as shown in Fig. 2. A linear regression of the data points for the as-cast material yields the relation:

$$K = 2.17 - 2.76 W_U$$

$K$ = thermal conductivity of fuel meat, W/cm K

$W_U$ = weight fraction of uranium in the fuel meat.

Data presented in Fig. 3 for various uranium weight loadings in uranium-aluminum alloy fuel indicate only a small decrease in thermal conductivity with increasing temperature. Over the temperature ranges expected in research and test reactors, the thermal conductivity of U-Al alloy fuel meat can be assumed to be constant.

The thermal conductivity of a fuel plate can be calculated using:

$$\frac{t_{\text{plate}}}{K_{\text{plate}}} = \frac{t_{\text{meat}}}{K_{\text{meat}}} + \frac{2 t_{\text{clad}}}{K_{\text{clad}}}$$

(7)

where $t_{\text{plate}}$, $t_{\text{meat}}$, and $t_{\text{clad}}$ are the thicknesses of the plate, fuel meat, and cladding, respectively.

The thermal conductivity of 1100 Al cladding, for example, is 2.22 W/cm K. For U-Al alloy fuel meat containing 21 wt-% U with a thickness of 0.51 mm and 1100 Al cladding with a thickness of 0.38 mm, the thermal conductivity of the fuel plate would be 1.92 W/cm K.
4.0 UAl\textsubscript{x}-Al DISPERSION FUEL

The information presented in Section 2.0 on the uranium-aluminum system also applies to UAl\textsubscript{x}-Al dispersion fuel. The three broad steps in the manufacture of UAl\textsubscript{x}-Al dispersion fuel are production of the UAl\textsubscript{x} powder, fabrication of the UAl\textsubscript{x}-Al core compacts, and fabrication of the fuel plates.

Specified and typical properties\textsuperscript{11} of the UAl\textsubscript{x} powder and UAl\textsubscript{x}-Al core compacts that are used to manufacture finished fuel plates with uranium densities up to 1.7 g/cm\textsuperscript{3} for the Advanced Test Reactor (ATR) are shown in Table 2. Typical UAl\textsubscript{x} powder consists of about 6 wt-% UAl\textsubscript{2}, 61 wt-% UAl\textsubscript{3}, and 31 wt-% UAl\textsubscript{4}. During the hot rolling and annealing steps in fabricating fuel plates, almost all of the UAl\textsubscript{2} reacts with aluminum from the matrix to form UAl\textsubscript{3} and some of the UAl\textsubscript{3} reacts with aluminum to form UAl\textsubscript{4}. Thus, the core (fuel meat) of a finished plate contains UAl\textsubscript{3} and UAl\textsubscript{4} as the fuel compounds. The actual fractions of UAl\textsubscript{3} and UAl\textsubscript{4} in a finished plate will vary from manufacturer to manufacturer depending on the processes and heat treatments that are utilized in fabricating the powder, core compacts, and fuel plates.

In the following discussions, it is assumed that the UAl\textsubscript{x} in the fuel meat of finished fuel plates consists of 60 wt-% UAl\textsubscript{3} and 40 wt-% UAl\textsubscript{4}.

4.1 Uranium Density Relations for Aluminide Fuel

For UAl\textsubscript{x} in the meat of finished fuel plates that consists of 60 wt-% UAl\textsubscript{3} and 40 wt-% UAl\textsubscript{4}, the density of the UAl\textsubscript{x} is:

\[
\rho_{UAl_x} = W_{UAl_3} \rho_{UAl_3} + W_{UAl_4} \rho_{UAl_4}
\]

\[
= 0.6 (6.8) + 0.4 (5.7) = 6.4 \text{ g/cm}^3
\]

using the measured densities of UAl\textsubscript{3} and UAl\textsubscript{4} from Table 1. Additionally, the weighted value of x in UAl\textsubscript{x} (taking 4.9 aluminum atoms per uranium atom in UAl\textsubscript{4}) is about 3.8 and the uranium weight fraction (W\textsubscript{UD}) in the UAl\textsubscript{x} is about 0.70.

Substituting these values into Eq.(2), a value of "a" = 0.306 is obtained. The relationships between the uranium density and the weight fraction of uranium in the fuel meat, and between the uranium density and the volume fraction of the dispersed phase are then:

\[
\rho_U = \frac{(1 - P) W_U}{0.370 - 0.306 W_U} \quad W_U = \frac{0.370 \rho_U}{(1 - P) + 0.306 \rho_U}
\]

\[
\rho_U = 4.5 V_f UAl_x
\]

A plot\textsuperscript{11} of the fuel meat (core) density and porosity of uranium aluminide fuel for different uranium densities is shown in Fig. 4. The figure indicates that at constant core density, the porosity increases with increasing uranium loading. For calculational purposes, an average porosity of 7 vol-% is commonly used.
Table 2. Properties of Uranium Aluminide (UAl<sub>x</sub>) Powder and Core Compacts Used to Manufacture Fuel for the ATR Reactor (From Ref. 11).

<table>
<thead>
<tr>
<th>Power</th>
<th>Specified</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isotopic Composition:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>235U content</td>
<td>93.0 ± 1.0 wt%</td>
<td>93.19</td>
</tr>
<tr>
<td>238U content</td>
<td>6.0 ± 1.0 wt%</td>
<td>5.37</td>
</tr>
<tr>
<td>234U content</td>
<td>0.3 ± 0.2 wt%</td>
<td>0.44</td>
</tr>
<tr>
<td>1.2</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td><strong>Chemical Composition:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranium</td>
<td>69.0 ± 3.0 wt%</td>
<td>71.28</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.60 wt% maximum</td>
<td>0.25</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.18 wt% maximum</td>
<td>0.05</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.045 wt% maximum</td>
<td>0.032</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.020 wt% maximum</td>
<td>0.005</td>
</tr>
<tr>
<td>Nonvolatile matter</td>
<td>99.0 wt% minimum</td>
<td>99.9</td>
</tr>
<tr>
<td>Easily extracted fatty and oily matter</td>
<td>0.2 wt% maximum</td>
<td>0.09</td>
</tr>
<tr>
<td>EBC&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30 ppm maximum</td>
<td>&lt;6</td>
</tr>
<tr>
<td><strong>Physical Properties:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U.S. standard mesh</td>
<td>-100 +325 mesh</td>
<td>76.0</td>
</tr>
<tr>
<td>= 75% minimum</td>
<td>-325 mesh</td>
<td>24.0</td>
</tr>
<tr>
<td>= 25% maximum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystalline constituents - by x-ray diffraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% UAl&lt;sub&gt;3&lt;/sub&gt;, minimum</td>
<td>6% UAl&lt;sub&gt;2&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>no unalloyed U</td>
<td>63% UAl&lt;sub&gt;3&lt;/sub&gt;,</td>
<td></td>
</tr>
<tr>
<td>31% UAl&lt;sub&gt;4&lt;/sub&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Core Compact</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For ATR zone loaded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>core fuel loading, g 235U/cm&lt;sup&gt;3&lt;/sup&gt; core</td>
<td>1.00, 1.30, 1.60</td>
<td></td>
</tr>
<tr>
<td>(maximum) wt% UAl&lt;sub&gt;x&lt;/sub&gt;, in core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00 g 235U/cm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>46.4</td>
<td></td>
</tr>
<tr>
<td>1.30 g 235U/cm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>54.4</td>
<td></td>
</tr>
<tr>
<td>1.60 g 235U/cm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>62.8</td>
<td></td>
</tr>
<tr>
<td>Uranium concentration, U atom/cm&lt;sup&gt;3&lt;/sup&gt; of core (maximum)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00 g 235U/cm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>2.76 x 10&lt;sup&gt;21&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>1.30 g 235U/cm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>3.58 x 10&lt;sup&gt;21&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>1.60 g 235U/cm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>4.41 x 10&lt;sup&gt;21&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>EBC = equivalent boron content

<sup>b</sup>Either UAl<sub>2</sub> or UAl<sub>3</sub> reacts with an excess of aluminum at moderate temperatures to form UAl<sub>4</sub>. Thus, the finished fuel plate cores, ready for reactor use, contain UAl<sub>3</sub> and UAl<sub>4</sub> as the fuel compound. 11
Fig. 2. Thermal Conductivity of U-Al Alloy at 65°C (Ref. 10).

Fig. 3. Thermal Conductivity versus Temperature for Various Loadings (in Wt%U) of U-Al Alloy Fuel (Ref. 10).
Fig. 4. Core Density and Porosity of Uranium Aluminide Fuel Plates with Different Fuel Loadings (Ref. 11).
4.2 Specific Heat of Aluminide Fuel

Using Eqs. (5) and (6), the specific heat of UAlₓ that consists of 60 wt-% UAl₃ and 40 wt-% UAl₄ is given by:

\[ C_p \text{UAl}_x = W_{\text{UAl}_3} C_p \text{UAl}_3 + W_{\text{UAl}_4} C_p \text{UAl}_4 \]

\[ = 0.387 + 0.00022 T \quad \text{J/g K, T in °C} \]

The specific heat of UAlₓ-Al fuel meat is obtained by summing the specific heats of the UAlₓ and aluminum phases, weighted by their respective fractions:

\[ C_p, \text{UAl}_x-\text{Al} = (1.0 - W_U/0.7) C_p, \text{Al} + (W_U/0.7) C_p, \text{UAl}_x \]

\[ = C_p, \text{Al} + 1.43 W_U (C_p, \text{UAl}_x - C_p, \text{Al}) \]

\[ = 0.892 + 0.00046 T - W_U (0.722 + 0.00034 T) \quad \text{J/g K, T in °C} \]

4.3 Thermal Conductivity of Aluminide Fuel

Available data on the thermal conductivity of aluminide fuels (that are typical of those in reactor use) are limited to three data points (Ref. 6) calculated for ATR sample fuel plates using thermal diffusivity measurements (Ref. 10) at Battelle Northwest Laboratories on MTR-ETR type fuel plates. The data from Table II of Ref. 6 are reproduced in Table 3 below.

Table 3. Thermal Conductivity of ATR Sample Fuel Plates Calculated (Ref. 6) from Thermal Diffusivity Measurements (Battelle Northwest, Ref.10).

<table>
<thead>
<tr>
<th>Plate</th>
<th>Fuel</th>
<th>Thermal Diffusivity, cm²/s</th>
<th>Fuel Plate Density, g/cm³</th>
<th>Heat Capacity, J/g °C</th>
<th>Thermal Conductivity, W/cm K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25°C</td>
<td>600°C</td>
<td>25°C</td>
<td>600°C</td>
</tr>
<tr>
<td>P-1-1047</td>
<td>UAlₓ</td>
<td>0.32</td>
<td>0.25</td>
<td>2.953</td>
<td>2.830</td>
</tr>
<tr>
<td>P-1-1048</td>
<td>UAlₓ</td>
<td>0.38</td>
<td>0.33</td>
<td>2.980</td>
<td>2.855</td>
</tr>
<tr>
<td>P-5-576</td>
<td>UAlₓ</td>
<td>0.33</td>
<td>0.24</td>
<td>3.00</td>
<td>2.872</td>
</tr>
</tbody>
</table>

Thermal conductivities in Table 3 were obtained using the relation:

\[ K = \alpha \rho C_p \]

where K is the thermal conductivity, \( \alpha \) is the thermal diffusivity, \( \rho \) is the density of the plate, and \( C_p \) is the heat capacity.
The sample fuel plates in Table 3 had a thickness of 1.296 mm, with a 6061 Al cladding thickness of about 0.394 mm and an assumed fuel meat thickness of 0.508 mm. The fuel meat contained about 35.4 vol-% UAl\(_x\) (57.7 wt-% UAl\(_x\)) and had a porosity of about 6 vol-%. The matrix material was X8001 aluminum alloy and the uranium density in the fuel meat was about 1.6 g/cm\(^3\).

The thermal conductivity of the UAl\(_x\)-Al fuel meat can be calculated from the fuel plate data in Table 3 using the relation:

\[
\frac{t_{\text{plate}}}{K_{\text{plate}}} = \frac{t_{\text{meat}}}{K_{\text{meat}}} + \frac{2t_{\text{clad}}}{K_{\text{clad}}}
\]

where \(t_{\text{plate}}\), \(t_{\text{meat}}\), and \(t_{\text{clad}}\) are the thicknesses of the plate, fuel meat, and cladding, respectively. 6061 Al cladding has a thermal conductivity of 1.80 W/cm K and is essentially constant over the temperature range considered. The thermal conductivity of the UAl\(_x\)-Al fuel meat for the three fuel plates listed in Table 3 is then:

**Table 4. Calculated Thermal Conductivities of the UAl\(_x\)-Al Fuel Meat in the Three Sample Fuel Plates in Table 3.**

<table>
<thead>
<tr>
<th>Plate</th>
<th>Fuel Meat</th>
<th>Vol-% UAl(_x)</th>
<th>Percent Porosity</th>
<th>Thermal Conductivity of Fuel Meat, W/cm K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25°C</td>
</tr>
<tr>
<td>P-1-1047</td>
<td>UAl(_x)-Al</td>
<td>35.4</td>
<td>6</td>
<td>0.376</td>
</tr>
<tr>
<td>P-1-1048</td>
<td>UAl(_x)-Al</td>
<td>35.4</td>
<td>6</td>
<td>0.474</td>
</tr>
<tr>
<td>P-5-576</td>
<td>UAl(_x)-Al</td>
<td>35.4</td>
<td>6</td>
<td>0.378</td>
</tr>
</tbody>
</table>

The thermal conductivity data for UAl\(_x\)-Al fuel at 25°C are plotted in Fig. 8 (Section 6), which compares the thermal conductivities of U\(_3\)O\(_8\)-Al, U\(_3\)Si\(_2\)-Al, and U\(_3\)Si-Al fuel meats as a function of the volume percent of fuel dispersant plus voids. From the data in Fig. 7, we conclude that all four of these dispersion fuels have approximately the same thermal conductivity. Since the thermal conductivities of UAl\(_x\) and U\(_3\)Si\(_2\) and the metallurgical properties of UAl\(_x\)-Al fuel and U\(_3\)Si\(_2\)-Al fuel are very similar, we suggest that the measured thermal conductivity data for U\(_3\)Si\(_2\)-Al fuel be used for UAl\(_x\)-Al fuel as well.
5.0 U₃O₈-Al DISPERSION FUEL

5.1 Uranium Density Relations for Oxide Fuel

The density of the high-fired U₃O₈ used by the High Flux Isotope Reactor (HFIR) at ORNL is 8.22 g/cm³ and \( W_D^{U} = 0.846 \). Substituting these data into Eq. (2), one obtains \( a = 0.294 \). The relationships between the uranium density and the weight fraction of uranium in the fuel meat, and between the uranium density and the volume fraction of the dispersed phase are then:

\[
\rho_U = \frac{(1 - P) W_U}{0.370 - 0.294 W_U} \quad \quad W_U = \frac{0.370 \rho_U}{(1 - P) + 0.294 \rho_U}
\]

\[
\rho_U = 7.0 V_f U₃O₈
\]

The void content of U₃O₈-Al fuel meat depends on the concentration of U₃O₈ and to a lesser extent on the fuel meat thickness. The void content as a function of U₃O₈ concentration for plates with two fuel meat thicknesses fabricated by ORNL² are shown in Fig. 5. Appropriate values of \( P \) for use in the uranium density relations should be obtained from this figure or from similar data supplied by the fuel manufacturer.

5.2 Specific Heat of Oxide Fuel

Specific heat data¹³ for U₃O₈ in the temperature range from 0-300°C is represented approximately by the linear relationship:

\[
C_p, U₃O₈ = 0.27 + 0.00030 T \quad \text{J/g K, T in °C}
\]

If \( W_U \) is the uranium weight fraction and \( C_p, Al \) is the specific heat of aluminum [Eq.(4)], the specific heat of the U₃O₈-Al fuel meat is given by:

\[
C_p, U₃O₈-Al = (1 - W_U/0.848) C_p, Al + (W_U/0.848) C_p, U₃O₈
\]

\[
= 0.892 + 0.00046 T - W_U (0.734 + 0.00019 T) \quad \text{J/g K, T in °C}
\]

5.3 Thermal Conductivity of Oxide Fuel

Figure 6 shows a curve of measured¹⁴ thermal conductivity versus uranium loading for U₃O₈-Al dispersion material. For the lightly loaded dispersions, the decrease in conductivity with increasing volume fraction of U₃O₈ is linear, primarily due to the substitution of the low conductivity oxide (\( k ~ 0.3-0.5 \text{ W/m K} \))¹⁵ for aluminum. As more U₃O₈ is added, however, the thermal conductivity drops more dramatically. In the range of uranium loadings between 2.5 and 3.1 g/cm³, the thermal conductivity ranges from 30 to 12 W/m K.
Fig. 5. Void Content of U₃O₈-Al Fuel Meat versus Concentration of U₃O₈ and Fuel Meat Thickness

Fig. 6. Thermal conductivity of U₃O₈-Al core region depends significantly on the volume fraction of U₃O₈ + voids.
6.0 U₃Si₂-Al AND U₃Si-Al DISPERSION FUELS

The development and testing of uranium silicide fuels has been an international effort, involving national reduced enrichment programs, several commercial fuel fabricators, and several test reactor operators. Numerous results of this effort have been published previously. Some of the results are summarized in this section.

As with the uranium-aluminum system, the uranium-silicon system normally consists of a mixture of intermetallic compounds, or phases. The quantity of each phase present depends upon the composition and homogeneity of the alloy and on its heat treatment. Since the different phases behave differently under irradiation, knowledge of the phases to be expected in the fuel is necessary to correctly interpret test results and to prepare specifications. For this reason, a detailed discussion of the phases in the uranium-silicon system is presented in Appendix I-1.2 (Ref. 16). Further properties of uranium silicide fuels can be found in Refs. 17-19.

6.1 Uranium Density Relations for Silicide Fuels

The densities of the U₃Si₂ and U₃Si dispersants that were measured at ANL, the corresponding weight fractions of uranium in each dispersant, and the value of the parameter "a" in Eq.(2) are given below.

<table>
<thead>
<tr>
<th>Silicide Dispersant</th>
<th>Measured</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wt-% Si</td>
<td>Density g/cm³</td>
<td>W U</td>
</tr>
<tr>
<td>U₃Si₂</td>
<td>7.5</td>
<td>12.2a</td>
<td>0.925</td>
</tr>
<tr>
<td>U₃Si</td>
<td>4.0</td>
<td>15.2b</td>
<td>0.960</td>
</tr>
</tbody>
</table>

a As-arc-cast.
b After heat treatment of 72 h at 800°C.

The relationships between the uranium density and the weight fraction of uranium in the fuel meat, and between the uranium density and the volume fraction of the dispersed phase are then:

\[
\rho_U = \frac{(1 - P) W_U}{0.370 - a W_U}
\]

\[
W_U = \frac{0.370 \rho_U}{(1 - P) + a \rho_U}
\]

with appropriate values of the parameter "a" for each dispersant.

\[
\rho_U = 11.3 V_f U₃Si₂
\]

\[
\rho_U = 14.6 V_f U₃Si
\]

Porosity remaining after fabrication of dispersion fuel meat provides space to accommodate the initial swelling of the fuel particles under irradiation. Data obtained at ANL from measurements on U₃Si₂ miniplates are plotted in Fig. 7. These data are well fit by the cubic function:

\[
V_P = 0.072 V_F - 0.275 V_F^2 + 1.32 V_F^3
\]
Fig. 7. Percent Porosity as a Function of the Volume Percent of $\text{U}_3\text{Si}_2$ in $\text{U}_3\text{Si}_2$-Al Fuel Matrix.
where \( V_P \) and \( V_F \) are the volume fractions of porosity and fuel dispersant in the meat, respectively. The amount of as-fabricated porosity increases significantly as the volume loading of fuel dispersant increases because it becomes more difficult for the matrix aluminum matrix to flow completely around all fuel particles, especially those in contact with one another.\(^{20}\)

It is important to note that the porosity in the fuel meat of fabricated fuel plates varies from fabricator to fabricator due to differences in manufacturing techniques in the aluminum alloys of the cladding. For example, consider the nominally identical \( \text{U}_3\text{Si}_2 \) fuel elements fabricated by B&W, CERCA, and NUKEM for irradiation testing in the Oak Ridge Research Reactor. The porosity content of the fuel cores produced by a given fabricator remained virtually constant, but there was a variation from fabricator to fabricator: 4 vol-% for CERCA, 7-8 vol-% for NUKEM, and 9-10 vol-% for B&W. Differences in material or fabrication parameters which might have contributed to the different amount of porosity include: (1) strength of the aluminum alloy used for frames and covers -- the CERCA alloy was by far the strongest while the B&W alloy was the weakest; (2) the rolling temperature -- 425°C for CERCA and NUKEM and ~500°C for B&W; (3) the amount of fines in the \( \text{U}_3\text{Si}_2 \) powder -- 40 wt-% for CERCA and 17-18 wt-% for NUKEM and B&W; (4) the rolling schedule, especially the amount of cold reduction; and (5) the relationship between the size of the compact and the size of the cavity in the frame.

### 6.2 Specific Heats of Silicide Fuels

The specific heats of \( \text{U}_3\text{Si}_2 \) and \( \text{U}_3\text{Si} \) as a function of temperature have been derived\(^{17}\) from plots of specific heat data\(^{21}\) for stoichiometric \( \text{U}_3\text{Si} \) and for a U-Si alloy at 6.1 wt-% Si:

\[
C_p, \text{U}_3\text{Si}_2 = 0.199 + 0.000104 T \quad \text{J/g K, T in °C}
\]
\[
C_p, \text{U}_3\text{Si} = 0.171 + 0.000019 T \quad \text{J/g K, T in °C}
\]

If \( W_U \) is the uranium weight fraction and \( C_p, \text{Al} \) is the specific heat of aluminum [Eq.(4)], the specific heats of \( \text{U}_3\text{Si}_2-\text{Al} \) and \( \text{U}_3\text{Si}-\text{Al} \) fuel meat are given by:

\[
C_p, \text{U}_3\text{Si}_2-\text{Al} = (1 - W_U/0.925) C_p, \text{Al} + (W_U/0.925) C_p, \text{U}_3\text{Si}_2
\]
\[= 0.892 + 0.00046 T - W_U (0.749 + 0.00038 T) \quad \text{J/g K, T in °C}
\]
\[
C_p, \text{U}_3\text{Si}-\text{Al} = (1 - W_U/0.960) C_p, \text{Al} + (W_U/0.960) C_p, \text{U}_3\text{Si}
\]
\[= 0.892 + 0.00046 T - W_U (0.751 + 0.00046 T) \quad \text{J/g K, T in °C}
\]

### 6.3 Thermal Conductivity of Silicide Fuels\(^{17}\)

Both \( \text{U}_3\text{Si}_2 \) and \( \text{U}_3\text{Si} \) have a thermal conductivity of ~15 W/m K\(^{22}\). Values of the thermal conductivities of the fuel meat in unirradiated \( \text{U}_3\text{Si}_2-\text{Al} \) dispersion fuel plates, measured at 60°C, are listed in Table 5 and are plotted in Fig. 8.\(^{23}\) Most of the samples were cut from miniature fuel plates produced at ANL for use in out-of-pile studies. Two samples came from a full-sized plate from a lot of plates fabricated by CERCA for the ORR test elements. The porosities of these miniplates follows the trend discussed in Section 6.1 but are somewhat larger, owing, presumably, to the different shape of the fuel zone than in the miniplates fabricated for irradiation testing (cylindrical rather than rectangular compacts were used).
Table 5. Thermal Conductivities of U3Si2-Aluminum Dispersions

<table>
<thead>
<tr>
<th>Sample Identification</th>
<th>Fraction of Fuel -325 Mesh, wt-%</th>
<th>U3Si2 Volume1, Fraction, %</th>
<th>Porosity,2 vol-%</th>
<th>Thermal Conduct.of Dispersion at 60°C, W/m K</th>
<th>Temperature W/m K2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS148</td>
<td>15</td>
<td>13.7</td>
<td>1.9</td>
<td>181</td>
<td>0.148</td>
</tr>
<tr>
<td>CS106</td>
<td>15</td>
<td>32.3</td>
<td>6.0</td>
<td>78</td>
<td>0.029</td>
</tr>
<tr>
<td>CS140</td>
<td>0</td>
<td>39.4</td>
<td>9.2</td>
<td>40</td>
<td>0.014</td>
</tr>
<tr>
<td>CS141</td>
<td>15</td>
<td>37.0</td>
<td>9.3</td>
<td>48</td>
<td>5 x 10⁻⁴</td>
</tr>
<tr>
<td>CS142</td>
<td>25</td>
<td>39.1</td>
<td>9.5</td>
<td>40</td>
<td>0.017</td>
</tr>
<tr>
<td>CERCA #1</td>
<td>41.5</td>
<td>46.4</td>
<td>4.0</td>
<td>59</td>
<td>0.161</td>
</tr>
<tr>
<td>CERCA #2</td>
<td>41.5</td>
<td>46.4</td>
<td>4.0</td>
<td>59</td>
<td>0.076</td>
</tr>
<tr>
<td>CS143</td>
<td>15</td>
<td>46.4</td>
<td>15.4</td>
<td>13.9</td>
<td>0.010</td>
</tr>
</tbody>
</table>

1 Determined on the thermal conductivity specimens using a radiographic technique.
2 Average value for roll-bonded fuel plate.

In Fig. 8, the thermal conductivity decreased rapidly as the volume fraction of fuel plus porosity increases (and the volume fraction of aluminum matrix decreases), owing to the ~14 times larger thermal conductivity of aluminum than U3Si2. For very low volume loading of U3Si2, it would be expected that the thermal conductivity of the dispersion would be proportional to the amount of aluminum present, since the aluminum matrix should provide a continuous thermal path. Indeed, this is the case for sample CS148. At higher volume fractions of U3Si2 plus void, however, the aluminum ceases to be the continuous phase, and the thermal conductivity decreases more rapidly than the volume fraction of aluminum. At very high loadings the aluminum ceases to play a significant role, and the thermal conductivity approaches that of the fuel. It may even become lower than that of the fuel alone because of poor thermal contact between fuel particles. The microstructure of the meat, specifically the distribution of the voids, can significantly affect the thermal conductivity. It appears that thin planar regions in which voids are associated with fractured fuel particles are responsible for the large difference in thermal conductivity exhibited by the CERCA samples and sample CS143. The larger void content of the CS samples than measured in the miniplates fabricated for irradiation testing or in full-sized plates most likely indicated the presence of more such planar void regions. Therefore, it is believed that the thermal conductivity curve in Fig. 8 for U3Si2-Al fuel meat represents essentially a lower limit for the thermal conductivities of full-sized fuel plates.

The data for U3Si2-Al dispersions are virtually indistinguishable from those obtained in the same series of measurements for U3Si-Al dispersions. They are also quite similar to data obtained in other measurements of thermal conductivities of UAl1x-Al dispersions6 and U3O8-Al dispersions.14 The U3O8-Al data fall somewhat below the U3Si2-Al data, possibly because the friable nature of U3O8 leads to the formation of more planar void regions than are present in U3Si2-Al fuel.
Fig. 3. Thermal Conductivities of Uranium Silicide-, \( \text{U}_3\text{Si} \), and \( \text{UAI}_\text{x} \)-Aluminum Dispersion Fuels as a Function of Volume Fraction of Fuel Particles Plus Voids (Porosity).
REFERENCES


