Thermal Analysis of Uranium Zirconium Hydride Fuel Using a Lead-bismuth Gap at LWR Operating Temperatures

By

Brendan M. Ensor

Submitted to the Department of Nuclear Science and Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Nuclear Science and Engineering

at the

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Abstract

Next generation nuclear technology calls for more advanced fuels to maximize the effectiveness of new designs. A fuel currently being studied for use in advanced light water reactors (LWRs) is uranium zirconium hydride (UZH), a fuel currently being used in the popular TRIGA research reactors. UZH is being considered because unlike the current fuel of choice, uranium dioxide, it is metal based and therefore better able to transfer the heat out of the fuel that is coming from fission. This can lead to lower operating temperatures which will reduce the amount of fission gas release to negligible quantities, eliminate cracking, and reduce the internal energy of the fuel. Furthermore, it is hoped the UZH will be better able to attain higher burnups, partly because of the presence of the strong moderator hydrogen, and thus will help better utilize resources and reduce the volume of nuclear waste produced. In order for UZH to be viable as a fuel it is recommended that the peak central temperature of the fuel be maintained below 650°C, at which point swelling due to void formation around the uranium atoms becomes a concern. In order to keep temperature below this level it has been proposed that lead-bismuth eutectic (LBE) be used as the gap material instead of helium. In order to ensure that the properties of UZH while using a LBE gap, specifically the thermal conductivity, do not degrade to the point of the fuel not being viable, an experiment was designed and put into the MIT research reactor. The initial results show a decreasing trend in thermal conductivity, albeit with much of this change considered to be because of the many thermal cycles the experiment underwent while in the reactor.

Thesis Supervisor: Gordon Kohse
Title: Principal Research Engineer
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Chapter 1

Introduction

1.1 Motivation

Nuclear power is entering a new era, faced with unique circumstances that call for the design of advanced nuclear reactors that depart from the technology used in the current reactor commercial power fleet. Every facet of older designs is being looked at to find every optimization possible in both performance and safety. One area being investigated is the choice of fuel for the reactor. A major performance parameter of fuel is the thermal conductivity of the material, which is a measure of how well the fuel transfers the heat from fission out to the cooling liquid. Currently, the fuel of choice is uranium dioxide (UO₂) with a helium filled gap. UO₂ has a fairly poor thermal conductivity of \(~3-4\) W/mK (Stehle, Assmann, & Wunderlich, 1975) and helium, as a gas, is also a poor conductor. Furthermore, because of the high operating temperatures of the fuel (peaking typically at \(~1450°C\)) there is a significant amount of fission gas release, fuel cracking from higher stresses, and higher internal energy of the fuel (Yacout, 2011).

Many different approaches are being used to address these issues. Two approaches of note are using a different fuel material that has better heat transfer properties and using a liquid, instead of gas, gap between the fuel and the cladding. Both techniques should limit the temperature in the fuel, particularly the peak fuel temperature, also known as the centerline temperature. Instead of these two materials, it has been proposed to use uranium zirconium hydride ((U, Zr)H₂) with a lead-bismuth eutectic (LBE) gap, a liquid, at reactor operating
temperatures (Terrani, 2010). The conductivity of the uranium zirconium hydride, \(-18\) W/mK, is substantially better than UO\(_2\), thus it could better transfer the fission heat out of the fuel and remain cooler (Olander, Greenspan, Garkisch, & Petrovic, 2009). Furthermore, LBE is significantly better at transferring heat than helium and should further help reducing centerline temperature (OECD/NEA Nuclear Science Committee, 2007). The combination of the two changes resulting in lower operating temperatures should reduce the amount of fission gas release to negligible quantities, eliminate cracking, and reduce the internal energy of the fuel (Olander, Greenspan, Garkisch, & Petrovic, 2009). In regards to safety, the UZH has a very high negative temperature coefficient of reactivity which is good for safety (Knief, 2008).

The main advantage of UZH is its higher thermal conductivity, however, if that were to decrease sufficiently as the fuel was subjected to more accumulated radiation, then the fuel would no longer be as competitive with other alternative fuel being studied – including uranium mononitride and uranium carbide (U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002). Furthermore, because UZH has a melting point much lower than UO\(_2\) (1800°C vs. 2800°C) (Olander, Greenspan, Garkisch, & Petrovic, 2009) (Stehle, Assmann, & Wunderlich, 1975), any decrease in the materials ability to transfer heat would be that much more significant. To test the thermal conductivity of the UZH with a LBE gap, an experiment is being conducted in MIT’s 6 MW research reactor (Terrani, 2010). The experiment, Hydrogen Fuel Irradiation (HYFI), is in the reactor core and will be subject to significant neutron fluence. Thermocouples are in place to measure the temperature at the center of the fuel and the clad and can be used to determine the thermal conductivity. This thesis will examine the results of the analysis of HYFI experiment and make a preliminary conclusion on how the thermal conductivity of UZH is affected by radiation typical of a power reactor core.
1.2 Uranium Zirconium Hydride fuel overview

UZH as a fuel has been used for decades and has been the subject of a fair amount of study, albeit much of the research has been done decades ago. It is currently the fuel of choice for the popular research reactor type called the Training, Research, Isotopes, General Atomics (TRIGA) (TRIGA Fuels, 2012). The NRC currently licenses 17 TRIGA reactors in the US (U.S. NRC, 2011), and there are many more located throughout the world (General Atomics, 2012). The fuel type was chosen due to its high negative temperature coefficient of reactivity because the goal of these reactors was to avoid any possible meltdown. This allowed the reactors to be used safely at college campuses for education and training purposes.

UZH was also used by NASA’s Systems for Nuclear Auxiliary Power (SNAP) program back in the late 50’s into the 60’s (Office of Nuclear Energy, Science & Technology, 1990). The program’s purpose was to provide nuclear power for spacecraft. The odd numbered SNAP reactors (3,5,7, etc.) were radioisotope thermoelectric generators (RTG) and powered many of the satellite and probe missions (Bennett, 2006). The even numbered SNAP reactors used UZH as a fuel to generate heat to use for electricity. The advantage of this reactor fuel was how compact it was. Having the strong moderator hydrogen built into the reactor lessened the need for extensive moderation or reflection (although these were still present) (Office of Nuclear Energy, Science & Technology, 1990).

While clearly UZH has a role in niche applications as a fuel, it has yet to expand into the realm of commercial power. Work sponsored by the US Department of Energy (DOE) Nuclear Energy Research Initiative (NERI) program has been done by Dr. Ehud Greenspan and Dr. Donald Olander of the University of California Berkeley, Dr. Neil Todreas of MIT, and Professor Yamawaki of the University of Tokyo. This work has led to the current HYFI.
experiment installed in the MIT reactor (Fission Reactor Analysis, 2012). The goal is to see if light water reactors (LWR) could benefit by using hydride fuels instead of UO₂. The advantages of UZH come primarily from the improved heat transfer and hope for higher burnup (Olander, Greenspan, Garkisch, & Petrovic, 2009). The benefits hoped to be achieved in addition to those listed in the previous section include:

- Improved economics
- Better utilization of resources
- Reduced proliferation risk
- Smaller amounts of waste
- Higher energy per core volume
- Longer core lifetime

The last two points can also lead to better capacity factors and higher power levels, or more compact cores (Terrani, 2010).

### 1.3 Thesis Objectives

The goal of this thesis is to determine how the thermal conductivity of the UZH fuel with the LBE bond varies during irradiation under typical light water reactor operating temperatures. The HYFI experiment is subjected to radiation typical of commercial power reactors and the goal is to see how the thermal conductivity changes as the radiation alters the atoms present in the fuel material. It is expected that there will be some redistribution of the hydrogen in the fuel as well, which could also alter how the fuel transfers heat.

### 1.4 Thesis Organization
The thesis is organized into five chapters. The first chapter gives an overview of the project and UZH in general. The second chapter discusses the HYFI experimental setup and how the analysis of the results was done. The third chapter presents the results of the analysis and the fourth chapter enters into a discussion of meaning of the results. The final chapter provides concluding thoughts and discusses how the project will move forward.

Chapter 2

Methods

2.1 Experimental Setup

The HYFI experiment is installed in-core inside MIT’s 6 MW research reactor (MITR). A timeline of the experiments can be seen in Table 1.

Table 1- Timeline of the HYFI experiment capsules

<table>
<thead>
<tr>
<th>Capsule Position</th>
<th>Time in Core (2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>3/17 – 11/8: 17333 MWh</td>
</tr>
<tr>
<td>Middle</td>
<td>3/17 – 6/26: 8703 MWh</td>
</tr>
<tr>
<td>Upper</td>
<td>5/25 – 12/22: 14593 MWh</td>
</tr>
</tbody>
</table>

The MITR is capable of producing neutron fluxes similar to those found in a commercial reactor (Newton, Kazimi, & Pilat, 2007). It operates under atmospheric pressures and maintains an outlet temperature of around 50°C. However, experiments can, by installing different equipment, pressurize and heat up to commercial levels. Therefore, they are able to accurately simulate the environment inside the core of a commercial reactor. The HYFI experiment was designed so that the temperatures the clad was seeing were similar to what it would see in a light-water
commercial reactor, roughly 300°C. A diagram of the experiment can be seen in Figure 1. Additional views can be seen in Figures 2 and 3.

Figure 1- Schematics of (a) HYFI rig in axi-symmetric coordinate and (b) radial dimension in the fueled region (not to scale)
Sheath 1/16" TC welded to SS flange

SS304 flange
Zr flange
SS302 Spring
Eutectic Pb-Bi
Alumina spacer
Zircaloy tube
Hydride pellet
Alumina spacer
Zr cap

Figure 2- HYFi fuel rod axial view

Figure 3- 3D axial view of the HYFi experiment. (a) shows an individual capsule axial 3D view with the cover gas line (b) shows the stacking of the three titanium capsules in yellow, red, and green.
The experiment is set in an aluminum (alloy 6061) dummy element installed in the MITR core and designed to be the same size and have the same dimensions as the other elements in the core. Water flows in the element from the bottom (coming from the core water inlet) and is the source of heat removal for the experiment. A titanium outer capsule contains each sample fuel rod and was sized so as to provide for the proper temperatures for the clad and fuel. It also serves the purpose of providing experiment integrity and preventing a release of fission gases in case of clad or fuel failure. This also satisfies the requirement of the MITR for double encapsulation of fuelled experiments. In order to supply the correct temperatures, the titanium outer capsule was designed to be 8.445 mm thick in contact with a flow channel of width 11.413 mm. These precise dimensions were determined by running a thermal-hydraulic analysis of the experiment and to ensure correct temperatures for the clad and the fuel.

Inside of the titanium outer capsule is a layer of LBE, the clad, then an LBE gap, and finally the UZH fuel. The outer LBE gap was, again, sized to provide the clad with temperatures typical of a commercial LWR. This gap is 2.5 mm wide. The cladding material used is Zircaloy™ 4. The clad is 0.938 mm thick. Separating the clad from the fuel is a 125μm thick LBE gap. Finally, the fuel itself, UZH, has a radius of 4.752mm.

Above and below the fuel are alumina spacers that separate the fuel from the LBE gap, apart from those spacers the fuel axially goes through the same gap, clad, gap, and then titanium sequence of materials. In the dummy element is room for three titanium capsules and each titanium capsule is separate and allows for individual removal and insertion of capsules. Each capsule contains five fuel pellets with the height of each fuel pellet being 1 cm for a total fuel height in each rodlet of 5 cm. The alumina spacers are each 0.5 cm height. The height of the clad is 7.5 cm. A total of four titanium capsules were made and can be inserted into the MITR.
The fuel pellets are sealed in the Zircaloy clad, which forms a tube with a cap at the bottom and a flange at the top. The flange at the top sits above stainless steel, alloy 302, springs which connect to the top alumina spacer and keep the pellets from moving. The tube contains LBE which fills down in the gap between the fuel and the Zircaloy clad/tube. Another flange sits on top of the Zircaloy flange and is made of stainless steel, alloy 304. The flange has a penetration for the K-type thermocouple that is inserted to measure the fuel centerline temperature. Another thermocouple is attached to the outside of the Zircaloy clad. These thermocouples send their data to a computer data acquisition system where the information is logged and recorded. This setup can be seen in Figure 2.

A helium cover gas is used to keep the pressure in the capsules above that of their surroundings. This pressure is to be maintained at 25 psig. This will allow any gas leaks to be out of the capsule and prevent water from leaking into the capsule. Each capsule has an isolated cover gas supply and the gas for that sample can be analyzed to determine how much fission gas is detectable, a rapid increase in the amount detected is indicative of clad failure. A view of the capsule with the cover gas tube can be seen in Figure 3a. Furthermore, an axial view of the entire experimental setup can be seen in Figure 3b. A picture of the fuel rod stack and aluminum dummy can be seen in Figure 4.

Figure 4- HYFI aluminum dummy element and titanium capsule
2.2 Analysis Method

The primary source of information for analysis was the temperature readings that came from the two thermocouples installed in each titanium capsule of the HYFI experiment. These readings, combined with the reactor power level and the inlet coolant temperature, provide enough information to be able to calculate the thermal conductivity of the fuel. The data acquisition software can provide high resolution of the changing parameters. However, a time step of 10 minutes was chosen for this analysis and still provides good resolution of the data. At each 10 minute interval the thermal conductivity was calculated and then plotted.

To calculate the thermal conductivity, the temperature difference between the clad and the fuel was used and can be seen in Equation 1,

\[ T_{\text{centerline}} = T_{\text{clad}} + \frac{q'_\text{fuel} + q'_\text{LBE, in} + q'_\text{Zr}}{2\pi K_{\text{Zr}}} \ln \frac{R_{\text{Cl}a}}{R_{\text{Cl}i}} + \frac{q'_\text{fuel} + q'_\text{LBE, in}}{2\pi K_{\text{LBE, in}}} \ln \frac{R_{\text{Cl}i}}{R_{\text{Po}}} + \frac{q'_\text{fuel}}{4\pi K_{\text{fuel}}} \]  

where \( T_{\text{centerline}} \) is the peak temperature in the fuel and was measured by the first of two thermocouples, \( T_{\text{clad}} \) is the temperature on the outside of the clad and is measured by the second of two thermocouples, \( q' \) is the linear heat rate generated by a given material from nuclear heating, \( k \) is the thermal conductivity of a given material, and \( R \) is the radius for various points in the radial geometry of the experiment.

The dimensions of the experiment and the thermal conductivities of the clad (Murabayashi, Tanaka, & Takahashi, 1975) and the LBE gap (OECD/NEA Nuclear Science Committee, 2007) are known, and \( q' \), the linear heat rate, can be calculated from the reactor power. The linear heat rate was calculated at startup of the experiment from Equation 1 because before irradiation the conductivity of the fuel was known (Yamanaka, et al., 2001). It should be
noted that there is some uncertainty in this value. It was then scaled linearly as power increases, and since power is known at every interval it could be calculated at each point. The calculated linear heat rates can be seen for various power levels in Table 2.

Table 2- Linear heat rate for the three capsule locations based on a core average power level and an initial thermal conductivity of the UZH of 19 W/mK

<table>
<thead>
<tr>
<th></th>
<th>4.0 MW</th>
<th>5.0 MW</th>
<th>5.5 MW</th>
<th>5.9 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Capsule</td>
<td>21.80</td>
<td>27.25</td>
<td>29.98</td>
<td>32.16</td>
</tr>
<tr>
<td>Middle Capsule</td>
<td>29.07</td>
<td>31.90</td>
<td>35.09</td>
<td>37.64</td>
</tr>
<tr>
<td>Upper Capsule</td>
<td>19.85</td>
<td>24.81</td>
<td>27.29</td>
<td>29.27</td>
</tr>
</tbody>
</table>

Therefore, it was possible from this formula to calculate the thermal conductivity of the fuel. For simplification, the linear heat rates generated in the LBE and the zirconium from nuclear heating could be set to zero, as they are negligible when compared to the linear heat generation by the fuel.

The temperature in the clad was measured by a thermocouple attached to the outside of the metal, Figure 5.

Figure 5- Picture of a HYFI fuel rod showing the bonded clad thermocouple

There is some uncertainty in the clad temperature measurement because the attachment method does not maintain constant pressure and spacing between the clad and thermocouple. To correct for this, the temperature of the clad was calculated using Equation 2 by analyzing how heat would transfer from the outside cooling water to the clad.
This was then compared to the clad temperature being measured. To verify that this was accurate, the linear heat rate was also calculated by rearranging Equations 1 and 2 to solve for \( q'_{\text{fuel}} \). If the predicted and measured clad temperatures were equal and if the linear heat rates were equal, then the clad temperature was being measured correctly. It was assumed that at the beginning of the experiment the thermocouple was likely making good contact with the clad and the measured and predicted clad temperatures should be equal. However, in all 3 cases, they were not. Since the measured clad temperature was most likely accurate at this point in the experiment, blame for the difference would reside with the predicted value. Each step of the heat transfer process was then checked to ensure correct values were being used (see Figure 10 in the data section for aid visualizing the heat transfer process). As mentioned previously the thermal conductivity of Zircaloy-4 and the inner LBE gap were well known. There is some discrepancy in the literature regarding the thermal conductivity of titanium, ranging from 17 W/mK to 22 W/mK (Ermolaev, 1974) (Powell & Tye, 1961) (Haynes & Lide, 2010) with some recent agreement on a value of \(~20.6\) W/mK (and varying slightly based on temperature). Nevertheless, the difference was not enough to compensate entirely for the effect on the predicted clad temperature that was being seen. The heat transfer to the water was also ruled out as the issue, as even if the water was boiling at the surface of the experiment, the difference would not be made up. It was then left to the outer LBE gap. The outer LBE gap is much larger than the inner LBE gap and it was postulated that there could be some natural circulation of the LBE in this gap, increasing the heat transfer properties of the gap. Because of the density of the LBE and the fact

\[
T_{\text{clad}} = T_{\text{water}} + \frac{q'_{\text{fuel}} + q'_{\text{LBE,in}} + q'_{\text{Zr}} + q'_{\text{LBE,o}}}{2\pi K_{\text{LBE,o}}} \ln \frac{R_{\text{Cap,1}}}{R_{\text{Co}}} + \frac{q'_{\text{fuel}} + q'_{\text{LBE,in}} + q'_{\text{Zr}} + q'_{\text{LBE,o}} + q'_{\text{Ti}}}{2\pi K_{\text{Ti}}} \ln \frac{R_{\text{Cap,2}}}{R_{\text{Cap,1}}} + \frac{q'_{\text{fuel}} + q'_{\text{LBE,in}} + q'_{\text{Zr}} + q'_{\text{LBE,o}} + q'_{\text{Ti}}}{2\pi R_{\text{Cap,0}} h_{\text{w}}}
\]

[2]
that the outer gap is wide, 2.5 mm, natural circulation is possible. The natural circulation
increased the heat transfer of the LBE depending on the linear heat rate that was coming from the
nearby capsule. The higher the linear heat rate a capsule experiences, the larger the observed
‘effective’ thermal conductivity was in that capsule, which is in line with natural circulation
theory.

The thermal conductivity data was then plotted as a function of MWh to show long term
trends. Areas of rapid increase or decrease, attributed to startup and shutdown, were eliminated
so as to provide a smoother picture. The results of this analysis can be seen in the data section.

Chapter 3

Results

3.1 Data

Figure 6 shows the thermal conductivity for the capsules in from the start of the
experiment in March to the conclusion of this analysis in mid-December. The lower capsule, in
the longest, was in from March 17th to November 8th, when it failed due to a detection of fission
gas release. The middle capsule was also put in initially and was in from March 17th to June 26th,
when it also failed due to a fission gas release. Finally, the upper capsule was in from May 25th
to the end of the analysis on December 13th (it remained in until December 22nd beyond the range
of this analysis). Figure 7 corroborates the results of Figure 6 and shows how the centerline
temperature of the fuel capsules changes over time. Burnup values were calculated in ORIGEN
and are measured in megawatt-days per kilograms of heavy metal (MWd/kgHM).
**Figure 6**- Thermal conductivity of the 3 fuel capsules of the HYFI experiment in the MITR from mid-March to mid-December

**Figure 7**- Centerline temperatures of the HYFI capsules versus MWh
As was mentioned before, it was thought that the clad thermocouple was slightly off of the clad. The results of the corrective analysis for the lower capsule can be seen in Figure 8. As discussed in section 2.2, the corrective analysis entailed adjusting the outer LBE gap thermal conductivity until the predicted value from Equation 2 matched the temperature being measured by the thermocouple after initial insertion.

![Thermal Conductivity Graph](image)

**Figure 8**: Thermal conductivity of the lower capsule versus MWh with unadjusted values in red and fixed in blue.

A view of all three clad temperature corrected thermal conductivity graphs can be seen in Figure 9, with outer LBE thermal conductivities of 24, 47, and 18 W/mK used for the lower, middle, and upper capsules respectively. The derivation of these values is described above. As would be expected in natural circulation, a greater heat rate gives way to a larger amount of circulation, see chapter 4 for further discussion.
Figure 9- Thermal Conductivities with clad temperature fixes for all 3 capsules versus MWd/kgHM

A view of the typical temperature profile through a capsule can be seen in Figure 10. For Figure 10, it was assumed that the linear heat rate was approximately 30 W/mK and the inlet water temperature was approximately 40°C. These values are typical of the capsules. The middle capsule is located in a higher flux zone and thus sees a larger linear heat rate than either the upper or the lower capsules (see Table 2).
A summary of the materials and their thermal conductivities can be seen in Table 3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity $[\text{W/mK}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UZH (pre-irradiation)</td>
<td>$18 \pm 1$ (Yamanaka, et al., 2001)</td>
</tr>
<tr>
<td>LBE</td>
<td>$6.8543 \times 10^{-1} T$, with $T$ in Kelvin (OECD/NEA Nuclear Science Committee, 2007)</td>
</tr>
<tr>
<td>Zircaloy 4</td>
<td>15 (Murabayashi, Tanaka, &amp; Takahashi, 1975)</td>
</tr>
</tbody>
</table>
4.1 General Observations

Observing Figures 6 and 9 it appears that in all three capsule irradiations an initial rise to higher thermal conductivities was followed by a slow decrease in thermal conductivity over time. Notable about the decline was the fact that it was not a very steady decline, but instead had many discontinuities and jump changes to the thermal conductivity. These changes lined up with changes in power, primarily startups and shutdowns. It is hypothesized that the frequent thermal cycling and the stresses that comes with it are causing the changes. A notable observation of Figure’s 6 and 9 is the behavior of thermal conductivity of the upper capsule compared to the other two capsules. The first two capsules started at the same time, and the upper capsule came in later and thus different operating conditions and the timing and frequency of thermal cycles that the capsules experienced could explain this effect, although further investigation is merited to fully understand the difference.

4.2 Cracks and Transient Effects

Physical cracking of the fuel can cause voids within the fuel that would decrease the thermal conductivity. This effect should be compensated somewhat by the presence of a LBE gap which should fill surface cracks and help alleviate the void problems. Unfortunately, LBE typically has a lower thermal conductivity than UZH fuel and it would be unable to reach voids
and cracks that are not on the surface. Another problem is the fact that on shutdown the LBE drops below its melting point and solidifies. LBE should not significantly contract or swell on solidification (OECD/NEA Nuclear Science Committee, 2007), but nevertheless the transient effects as the experiment heats up and any possible physical effects could affect thermal conductivity. The effect of the startup on thermal conductivity can clearly be seen in Figure 6, where after a startup the thermal conductivity rapidly rises to a steady state level. This can be attributed to a number of different competing factors, first there is the melting of the LBE, second there is a hydrogen migration in the fuel that is discussed more further in the following section, third there is the heat up of the structural materials, and finally there is the effect of the change in effective thermal conductivity of the outer LBE gap, discussed in later paragraphs.

During steady state operations there was typically little to no change in thermal conductivity.

4.3 Startup Changes- Hydrogen Migration

As mentioned, at the beginning of the radiation there is a large, relatively rapid rise in the thermal conductivity. This has to do with the migration of hydrogen within the UZH. The ratio of hydrogen to zirconium goes from 1.6 to -1.45 center of the fuel and -1.70 at the edges (Olander, Greenspan, Garkisch, & Petrovic, 2009). This is actually beneficial from a stress standpoint as the resulting migration stresses are sufficient to overcome temperature gradient stresses and should help prevent radial cracking.

The changing crystal structure of the UZH due to the hydrogen migration is a primary reason why an observed thermal conductivity rise is seen upon startup. Increased hydrogen concentration leads to increased thermal conductivity in metal hydrides (Ghafir, Batcha, & Raghavan, 2009). Therefore, at the center of the fuel where there is a less rapid transfer of heat,
the effect of decreased conductivity means that there is relatively little change in heat transfer, but at the edges, where there is an increased conductivity, the effect is more pronounced, leading to a higher overall conductivity.

4.4 Voids and Fission Gas Release

A limiting factor to the allowed temperature of the experiment was void formation in the fuel around the uranium atoms. This causes large swelling in the fuel and prevents use of a helium bond and was the primary motivation to use a LBE bond. It has been recommended to maintain the temperature below 650°C to prevent this effect from significantly altering the fuel and to reduce or eliminate fission gas release. A motivation for this experiment was to determine “the effect of released fission gas (if any) on the thermal effectiveness of the liquid metal bond in the fuel-cladding gap” (Olander, Greenspan, Garkisch, & Petrovic, 2009). The goal of this report was to give a first glimpse at the results. Monitoring the fission gas release by the fuel was an important aspect of the experiment. The first two fuel rods placed in the reactor were pulled out after fission gas release was detected. The rods were in the core for varying amounts of time and, as can be seen in Figure 7, both rods failed when a centerline temperature of ~560°C was reached. The cause of the failure is being investigated and will likely be determined by a Post-Irradiation Examination (PIE) of the failed rods by Idaho National Laboratory that will be done in the future.
4.5 Clad Temperature Discussion

An important aspect of the analysis was the outer LBE effective thermal conductivity. When the thermal conductivity was calculated strictly from clad and fuel temperatures (such as in Figure 6) this did not factor in, but for the corrective analysis for the clad thermocouples potentially being slightly off from the actual clad temperature, this became a crucial part of the calculation. The correction, as noted above, was done by calculating what the clad temperature should be at the beginning of the experiment from the linear heat rate and bulk water temperature values. This was then compared to what the thermocouple was actually reading for a clad temperature. Then by adjusting the outer LBE thermal conductivity, the clad temperatures were matched.

While it is possible that errors in the assumed thermal conductivity for titanium could cause the difference, this was not considered to be likely since the difference in the possible thermal conductivities of titanium was not large enough to significantly alter the clad temperature. Furthermore, it seemed very possible that with the size of the outer gap (as can be seen in Figure 10) that some natural circulation would be occurring. Thus by altering the thermal conductivity of the LBE to match the actual and calculated clad temperatures at the beginning of life of the experiment (when it would be less likely that thermal stresses had moved the thermocouple far off of the clad) the effect of the increased heat removal during natural circulation could be extrapolated. Then using the same thermal conductivity for the rest of the experiment, a different thermal conductivity of UZH could be found using the new clad temperature. This is what is seen in Figure 9. The more ‘noisy’ data can be attributed to the fact that the calculation relies on a clad temperature that was calculated from the bulk water temperature and the linear heat rate. Thus variations or immediate changes in power would
promptly show up in the calculations for the clad temperature but due to transient thermal changes would take longer to show up in the actual clad.

4.6 Local Power Variation

Reactor power at the MITR is controlled primarily by raising six stainless steel “shim” blades (impregnated with boron). As these blades are withdrawn from the reactor core the axial power shape changes. As such, the local power at the experiment also varies over a reactor fuel cycle. Generally speaking, the axial peak decreases over an operating cycle and higher regions see an increase in flux. Since only reactor average power is used in calculation of the linear heat rate, the effect of these local axial changes is not taken into consideration. The lower capsule would be least affected by these changes and the higher capsule the most affected. Observed data, as seen in Table 4, shows that this effect alters temperature by only a few degrees for the lower capsule and possibly as high as 15 degrees for the upper capsule. Routine heat up, derived from constant shim bank height after startup at a high bank position, accounts for about \( \sim 10 \) degrees for each capsule.

<table>
<thead>
<tr>
<th>Date</th>
<th>Power Level</th>
<th>Lower Capsule</th>
<th>Middle Capsule</th>
<th>Upper Capsule</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/28/11, 2100, SBH @ 11.48 in, 5 MW</td>
<td>--</td>
<td>441°C</td>
<td>464°C</td>
<td>--</td>
</tr>
<tr>
<td>3/29/11, 1146, SBH @ 14.34 in, 5 MW</td>
<td>--</td>
<td>455°C</td>
<td>488°C</td>
<td>--</td>
</tr>
<tr>
<td>Change minus heat up effect</td>
<td>+4°C</td>
<td>+14°C</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>6/15/11, 0320, SBH @ 1300, 5.5MW</td>
<td>--</td>
<td>--</td>
<td>451°C</td>
<td>--</td>
</tr>
<tr>
<td>6/15/11, 0910, SBH @ 1600, 5.5 MW</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>476°C</td>
</tr>
<tr>
<td>Change minus heat up effect</td>
<td>--</td>
<td>--</td>
<td>+15°C</td>
<td>--</td>
</tr>
</tbody>
</table>
Chapter 5

Conclusions and Recommendations

5.1 Conclusion

The initial results from the HYFI experiment show that uranium zirconium hydride with a lead-bismuth eutectic gap has a decreasing thermal conductivity as it is irradiated, with the HYFI experiment showing a maximum of a 33% decrease in thermal conductivity. Figures 6 and 9 illustrate this effect. However, much of the decreases in the thermal conductivity come following thermal cycles of the system, and thus in a stable commercial power reactor scenario, the decrease would not be as large. Therefore, UZH is still a viable fuel for future commercial light water reactor use. Future experiments using a thermocouple capable of measuring thermal conductivity and a PIE at INL should shine more light on how the thermal conductivity changes over time. The issue of accurately measuring the clad temperature and the effect of the naturally circulating LBE should also be taken into account when observing the thermal conductivity presented here.

It is recommended that future experiments have a means of either directly measuring thermal conductivity, or if not, have a means to accurately measure local power. Furthermore, when using a larger gap size with LBE the effects of natural circulation should be investigated to determine how much circulation happens and what the effect of this circulation is on thermal conductivity.
Bibliography


