Specific Information on LMR Fuel

• Fuel suggested was U-Pu-Zr (actually started work in late 60's which showed excellant breeding performance)

• Metallic fuel demonstrated superior safety performance, partially related to high thermal k.

• Major research program started in 1984!

  - Zr picked as alloying element (up to 10%) because:

    a.) it increases the solidus temperature. (figure)
    b.) reduces interdiffusion between fuel and cladding

What About Burn-up?

• Early U-5Fs alloys, at high smear densities of 85 to 100%, only achieved burnup values of ≈ 30,000 MWd/tHM.

• When theory predicted gas bubbles would grow until they touched (at ≈ 30% swelling) designers increased the size of the gap volume to 30%, and increased the size of the gas plenum.

  B.U. ≈ 40,000 MWd
• 1970, used 304SS (later 316SS) for cladding

  B. U. reached 100,000 MW (this was later derated to 80,000 because the neutron fluence to the cladding was causing swelling of the clad.)

• There was little activity until 1985 when there was a series of tests to find an optimum value for Zr in a 3 component system.

  B.U now 185,000 MWd/tHM

U-Pu System

• Note Pu is only soluble up to:

  16% in $\alpha$U
  20% in $\beta$U
  100% in $\gamma$U

• Without alloying, "normal" U-Pu alloys are expected to behave the same dimensional instabilities as pure $\alpha$ U. In fact, the addition of Pu seems to accelerate the swelling and creep because Pu increases the diffusivity
How Can We Get Higher BU Fuel?

1.) Designing in a gas plenum (figure)
2.) More extensive alloying with Mo, Zr, Ti, or Nb to stabilize the $\gamma$ phase.
   (figure)

Note: the later technique also improves the chemical compatibility with the cladding.

- Also have found that adding small amounts of Si, Fe, or Al to the fissium alloy can reduce swelling. (figure)

- Important research in the last 2 decades has revealed that the theoretical work of the 60's stating that bubbles will link and release gas once the swelling exceeds 30 %.
  (2 figures)

<table>
<thead>
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<th>Fuel Cladding Interaction</th>
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<tr>
<td>1.) Mechanical</td>
</tr>
<tr>
<td>Fuel-Cladding Mechanical Interaction (FCMI)</td>
</tr>
</tbody>
</table>

- Arises from applied stress when the element is designed to restrain fuel swelling. This could result in plastic deformation of the cladding.
• Source of stress-swelling of metallic fuel due to fission gas bubbles or existing tears.

• This can be avoided by fabricating in a smear density of $\approx 75\%$ (which allows a free volume fuel swelling of $\approx 30\%$, see figure). At a $\Delta V$ of $\approx 30\%$, the porosity becomes interconnected and releases gas to plenum.

• The amount of cladding deformation depends on the strength of the cladding material and the amount of swelling in the cladding itself.

(2 figures)

note: $\sigma_y : HT9 > D9 > 316 SA > 304L SA$
Void Induced Swelling: HT9 $<$ D9 $<$ 316 SA $<$ 304L SA
### What About The Non Gaseous Fission Products?

<table>
<thead>
<tr>
<th>Element Group</th>
<th>Fission Yield/100 Fissions</th>
<th>Physical State</th>
<th>Average Molar Volume, cm³/mol</th>
<th>% Volume Change per % BUa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali (Cs, Rb)</td>
<td>22.2</td>
<td>Liquid, 70% in Na Bond</td>
<td>70</td>
<td>0.108</td>
</tr>
<tr>
<td>Alkaline Earth (Sr, Ba)</td>
<td>14.7</td>
<td>Solid and liquid</td>
<td>20</td>
<td>0.146</td>
</tr>
<tr>
<td>Rare Earth’s + Pd (Ce, Nd, etc.)</td>
<td>51.4</td>
<td>Solid, Precipitates</td>
<td>20</td>
<td>0.792</td>
</tr>
<tr>
<td>(Tc, Ru, Rh, Ag)</td>
<td>23.3</td>
<td>Solid, Precipitates</td>
<td>9</td>
<td>0.162</td>
</tr>
<tr>
<td>Total Non-Soluble Fission Products</td>
<td></td>
<td></td>
<td></td>
<td>1.208</td>
</tr>
</tbody>
</table>

a For a molar volume of 12.9 cm³/mol of U-19 Pu-10 Zr

#### Overall Contribution to Volume Changes

1.) Volume increase due to non-soluble fission products.  
   $1.2\% / \% BU$

2.) Volume decrease due to the fissioning of U and Pu.  
   $-0.2 \% / \% BU$

3.) Volume increase due to the increase of Zr, Mo, and Nb, which are soluble in the fuel matrix.  
   $+0.2 \% / \% BU$

(See Figure Relating Strain And Smear Density)
Chemical Interaction

Fuel Cladding Chemical Interaction

(FCCI)

Very complicated-

1.) At least 5 elements participate in the diffusion process

2.) Minor alloying elements, C, N, and O also play an important role

3.) Fission products play an important role.

Major problem is 2-fold:

1.) Degradation of cladding mechanical properties.

2.) Formation of low melting point compounds

-In the 1960's, it was determined that the 300 series stainless steels had adequate resistance to cladding attack from the U-Fs alloys

-However, the addition of Pu increased the attack & decreased the temperature at which melting was observed in the diffusion zone.
This led to the introduction of U-Pu-Zr alloys

(See Figure on Penetration)

• The formation of ZrOₓ or ZrNx appears to retard the inter diffusion.

(If fact, 300 series stainless steels which contain up to 600 ppm N were more resistant than the purer HT9 or D9 alloys which contain only ≈ 40-0 ppm N.)

• Another interesting note:

Older (1967) IFR fuels contained ≈500 ppm N, whereas newer fuel lots contain only ≈20 ppm N.

| Melting Temperatures of Diffusion Couples-300 to 700 hrs at temperature- °C |
|-------------------------------|-----|-----|-----|-----|
| Fuel                          | 304 | 316 | HT-9| D9 |
| U-8Pu-10Zr                    | >760| 790 | 740 | <750|
| U-19Pu-10Zr                   | >780| 790 | >780| >730|
| U-26Pu-10Zr                   | --- | <775| 650 | 650 |
| U-15Pu-11Zr                   | >800| >800| >800| >800|

Operation of IFR Fuel Element With Breached Cladding

Unlike the oxide fuels, metallic fuels are compatible with Na.