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

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U-Pu System

- **Note Pu is only soluble up to:**

16% in αU
20% in βU
100% in γU

- **Without alloying, "normal" U-Pu alloys are expected to behave the same dimensional instabiliies as pure α 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 γ 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)**

Fuel Cladding Interaction

1.) Mechanical

Fuel-Cladding Mechanical Interaction

(FCMI)

- **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 ≈ 75% (which allows a free volume fuel swelling of ≈ 30%, see figure). At a ΔV of ≈ 30%, the porosity becomes interconnected and releases gas to plenum.

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• 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: σ_y :HT9>D9>316 SA>304L SA
Void Induced Swelling: HT9<D9<316 SA<304L SA

What About The Non Gaseous Fission Products?

Volume Change Due to Non Gaseous, Non Soluble Major Fission Products				
Element Group	**Fission Yield/100 Fissions**	**Physical State**	**Average Molar Volume, cm^3/mol**	**% Volume Change per % BU[a]**
Alkali (Cs, Rb)	**22.2**	**Liquid, 70% in Na Bond**	**70**	**0.108**
Alkaline Earth (Sr, Ba)	**14.7**	**Solid and liquid**	**20**	**0.146**
Rare Earth's + Pd (Ce, Nd, etc.)	**51.4**	**Solid, Precipitates**	**20**	**0.792**
(Tc,Ru, Rh, Ag)	**23.3**	**Solid, Precipitates**	**9**	**0.162**
Total Non-Soluble Fission Products				**1.208**

[a] For a molar volume of 12.9 cm^3/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.

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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 ZrO_X or ZrN_X 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.