

Specific Information on LMR Fuel

- ***Fuel suggested was U-Pu-Zr (actually started work in late 60's which showed excellent 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 U

20% in U

100% in U

- Without alloying, "normal" U-Pu alloys are expected to behave the same dimensional instabilities as pure 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 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 V 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: y :HT9>D9>316 SA>304L SA

Void Induced Swelling: HT9<D9<316 SA<304L SA

What About The Non Gaseous Fission Products?

<i>Volume Change Due to Non Gaseous, Non Soluble Major Fission Products</i>				
Element Group	Fission Yield/100 Fissions	Physical State	Average Molar Volume, cm³/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 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.**

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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.