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:

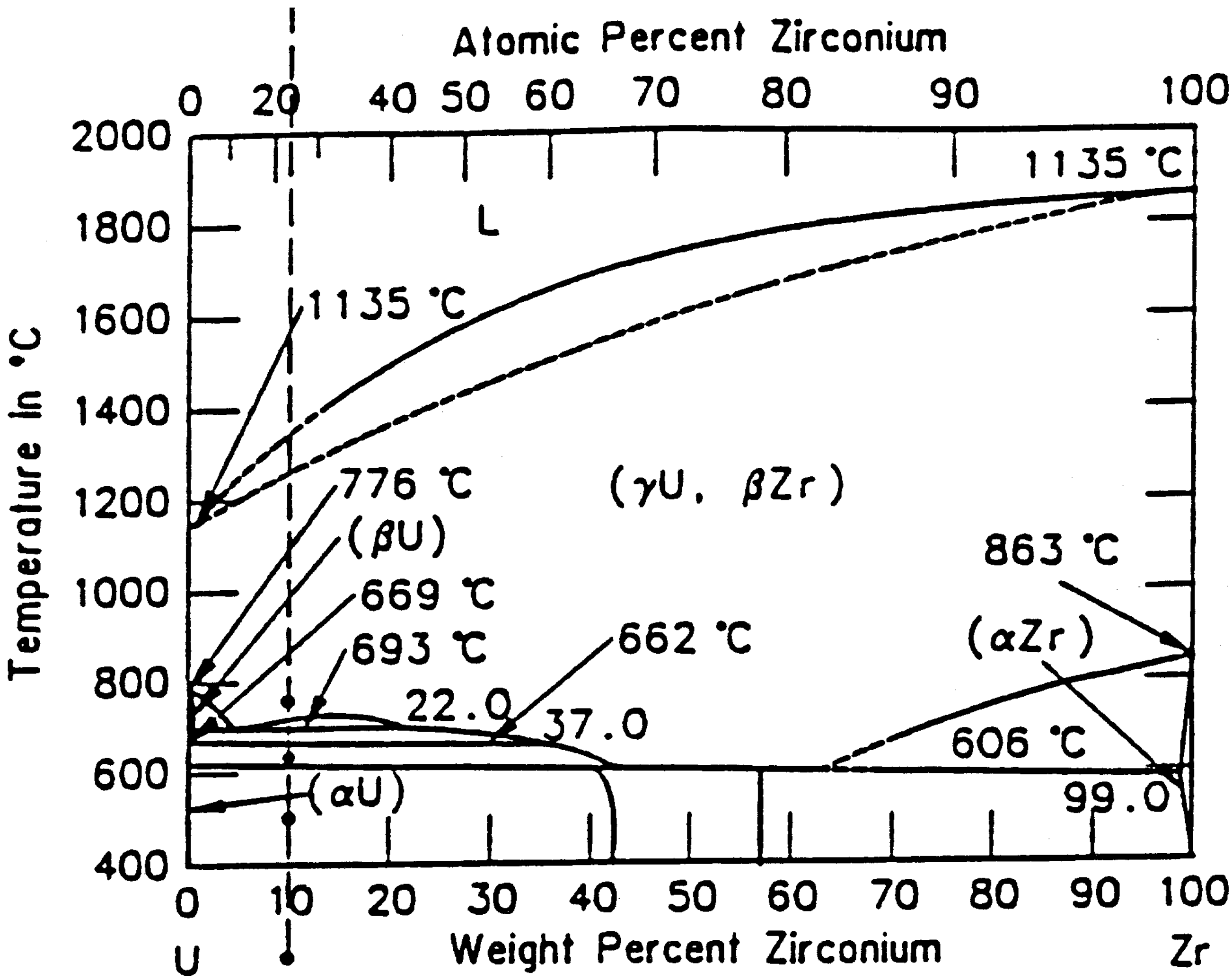
a.) it increases the solidus temperature. (figure)
b.) reduces interdiffusion between fuel and cladding

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



Phase composition in mol% vs. temperature
for U-10%Zr fuel pin

T in °C	α	δ	β	γ
25	88 %	11 %	–	–
500	72	26	–	–
635	71	–	–	27 %
750	–	–	–	99

• -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

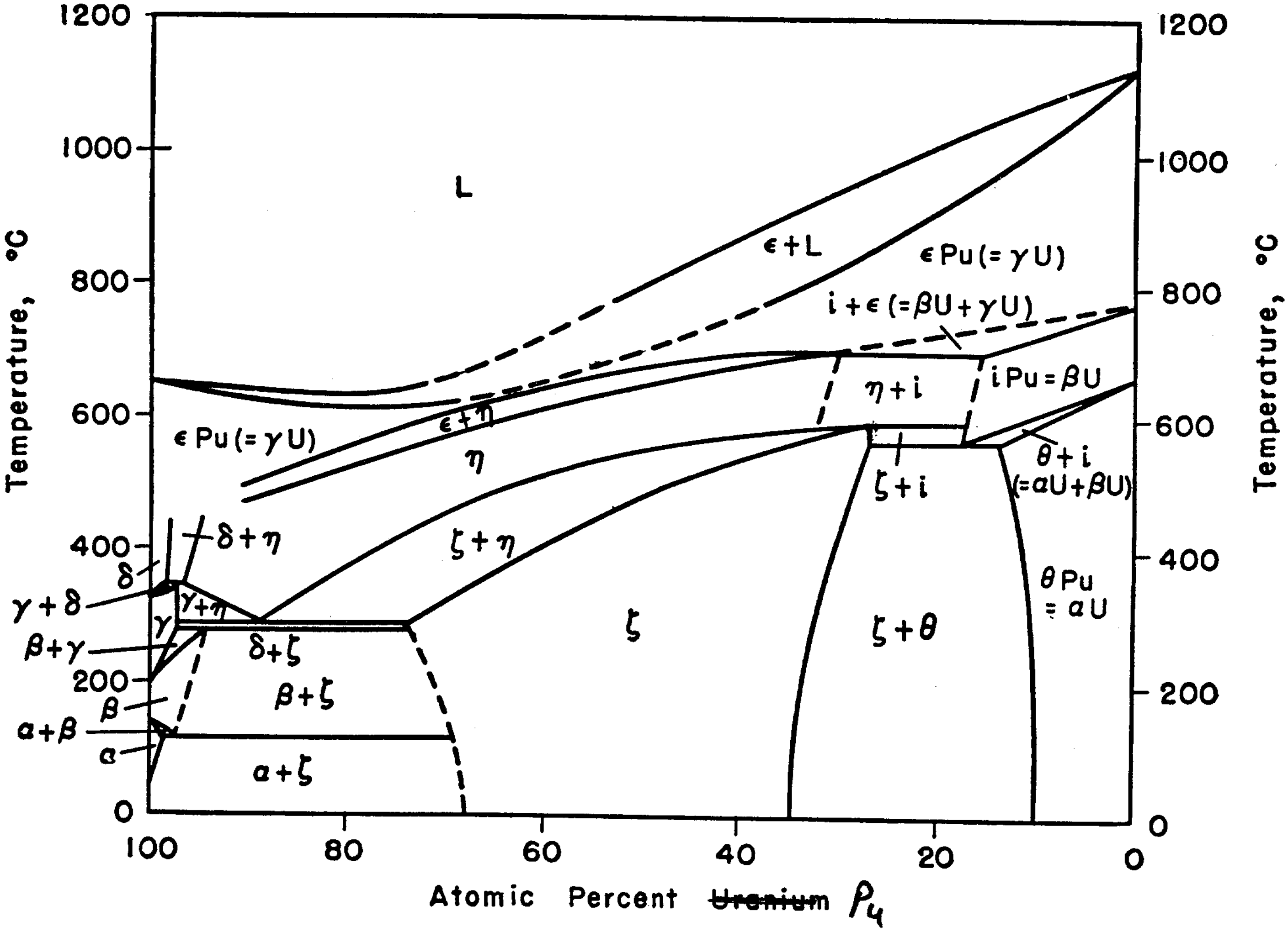


Fig. 12-12. The plutonium-uranium phase diagram.

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.

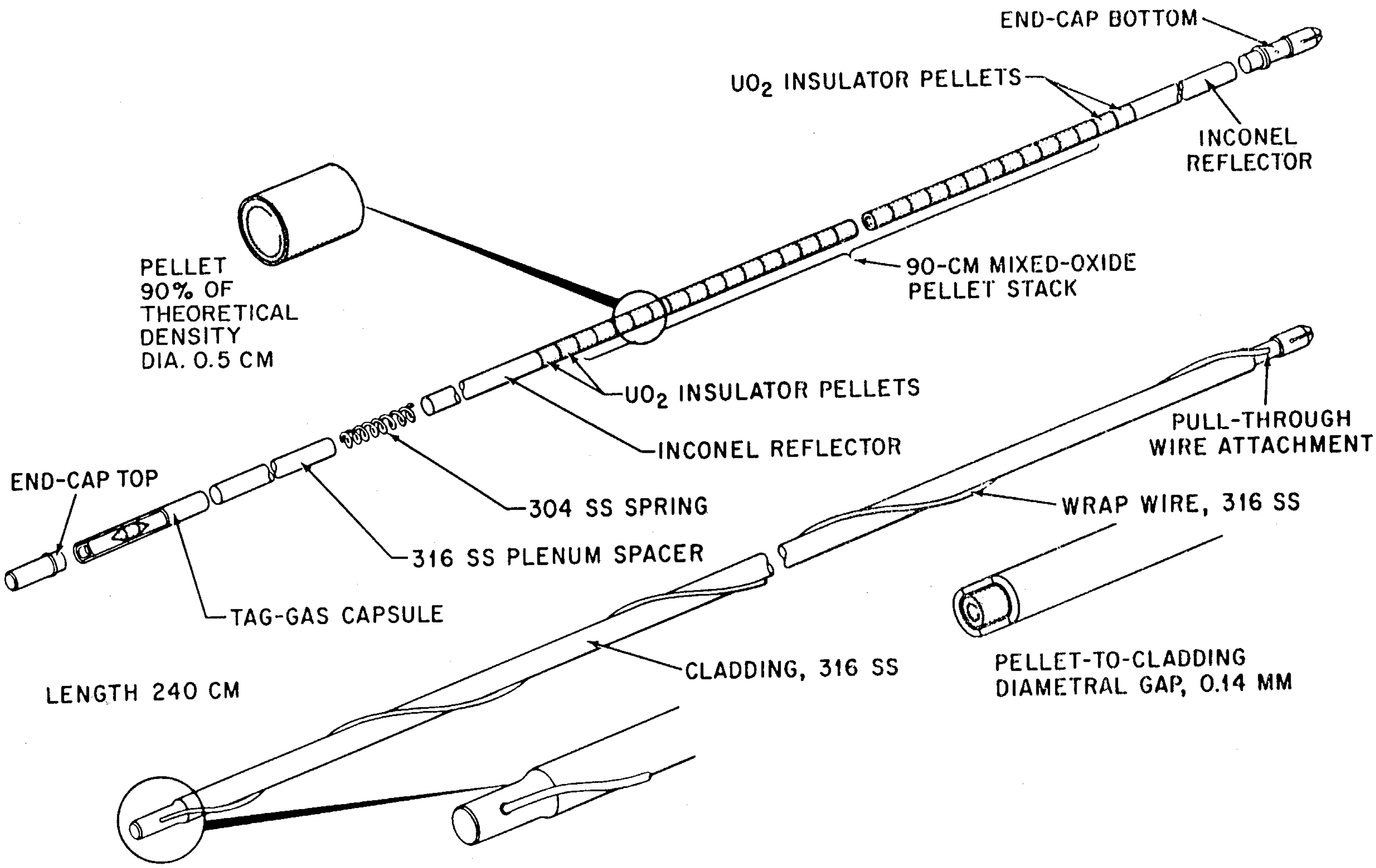
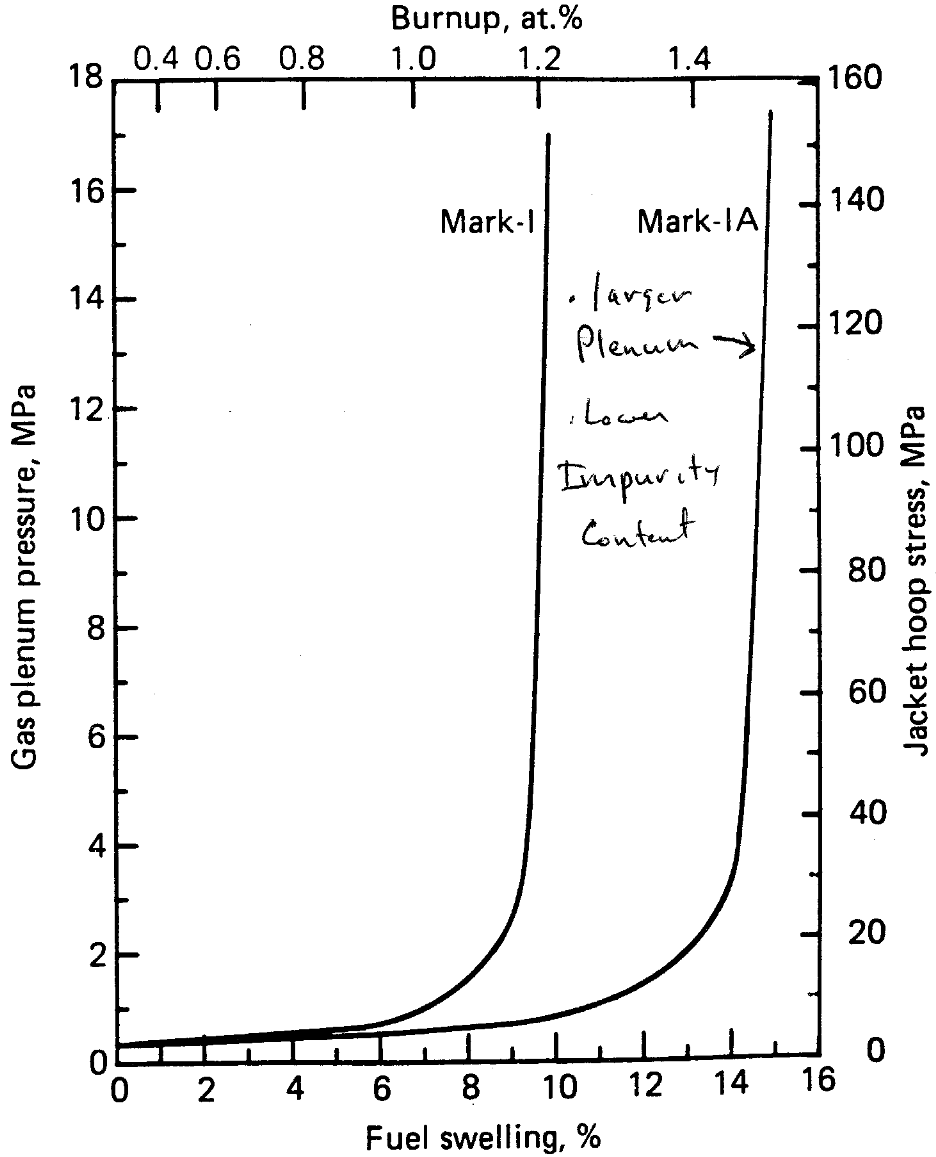


Fig. 10.2 Fuel pin of the Fast Test Reactor. (Courtesy C. Burgess, Hanford Engineering Development Laboratory.)



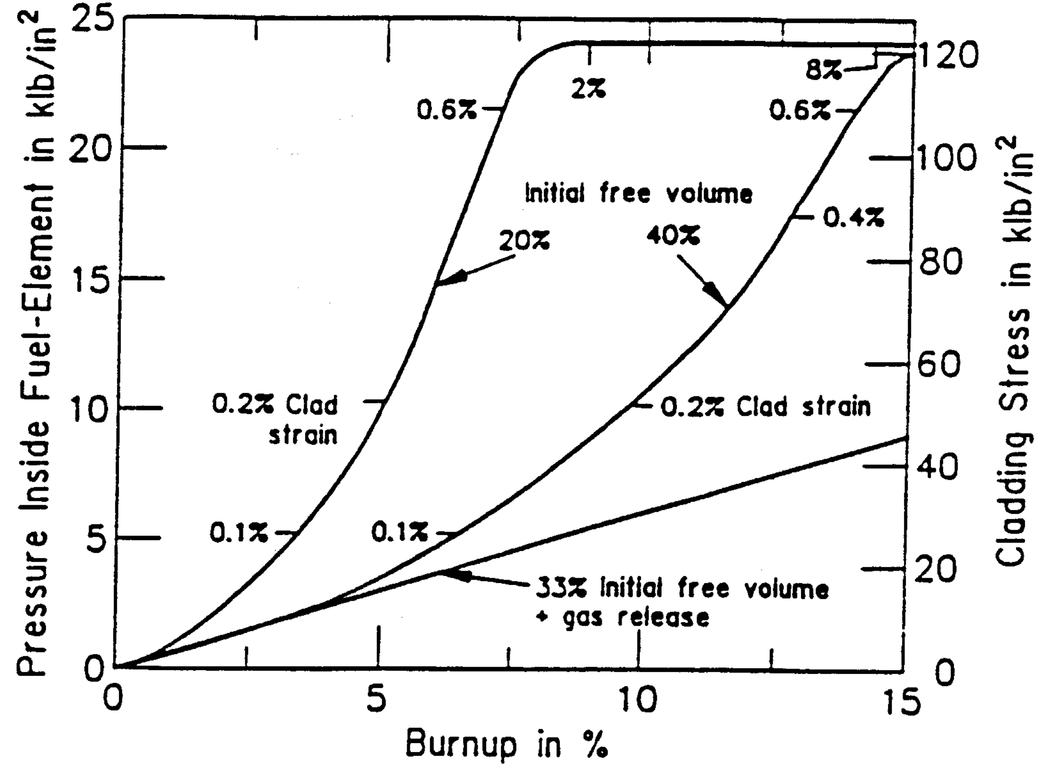
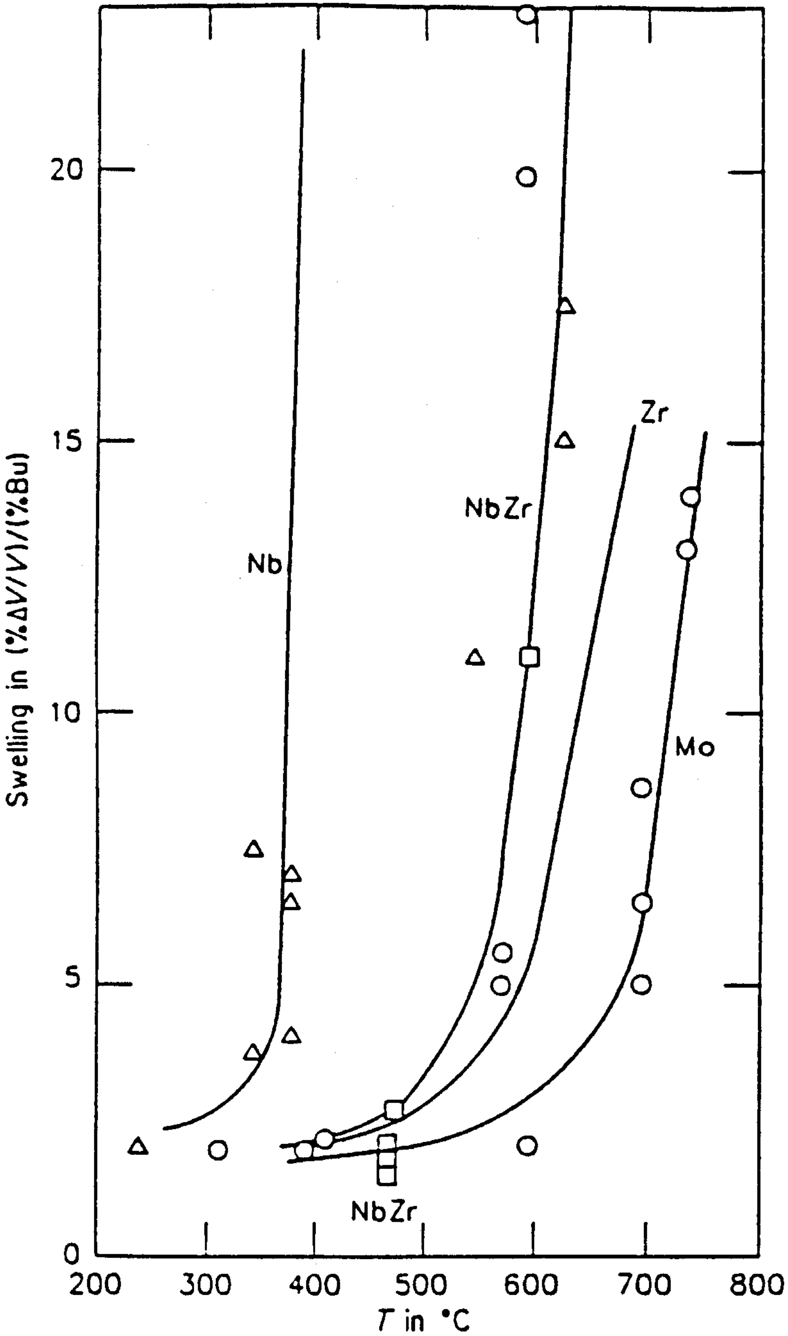
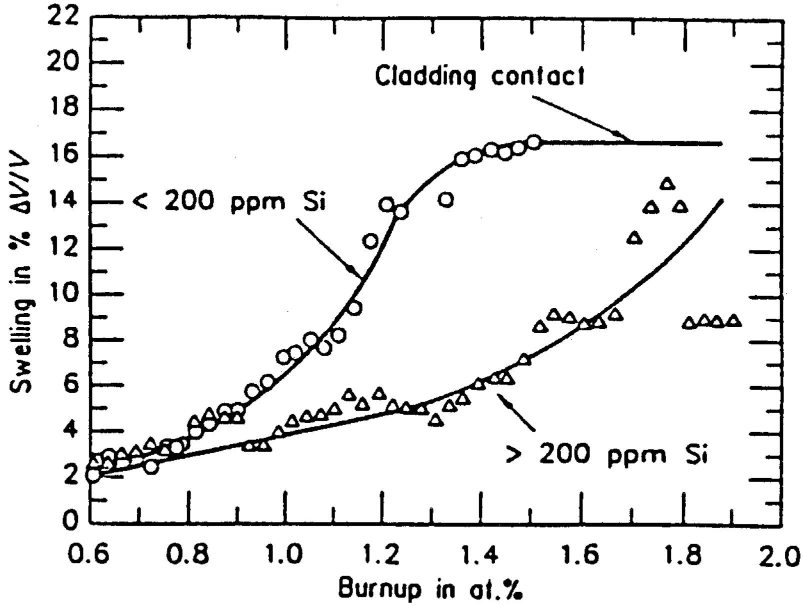


Fig. 1. Calculated gas plenum pressure and cladding hoop stress as a function of peak burnup for the Mark-I and -IA designs (Ref. 23).



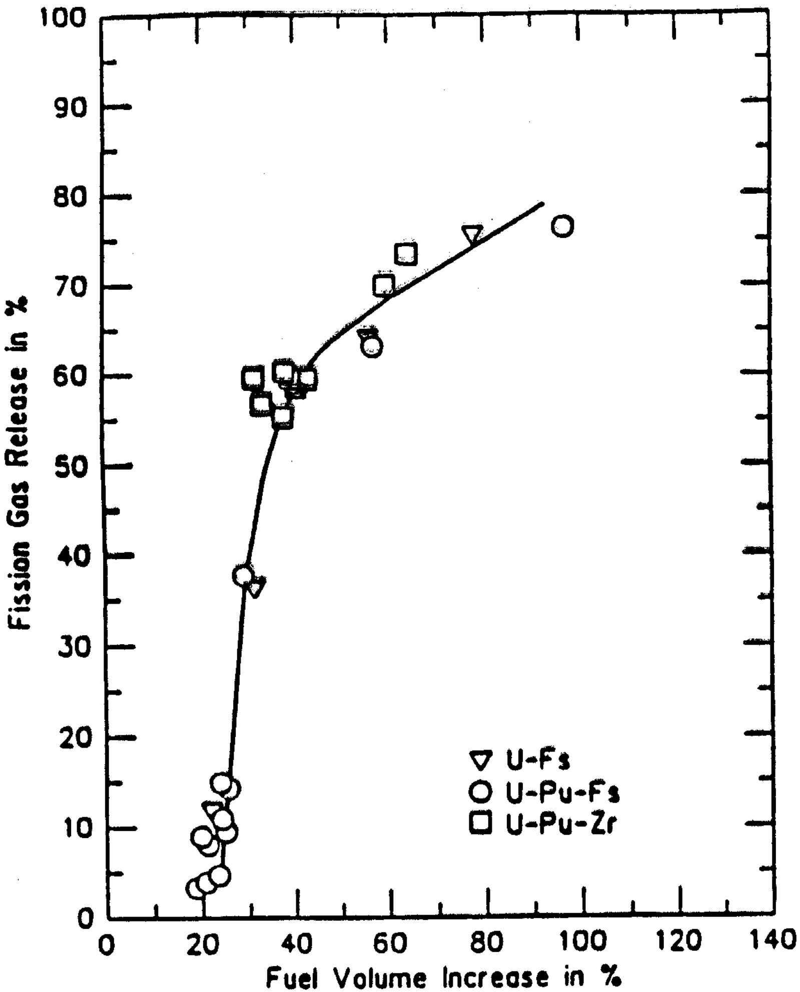
Swelling in (%ΔV/V)/(%Bu)
T in °C
Nb
NbZr
Zr
Mo
NbZr
0
5
10
15
20
200
300
400
500
600
700
800



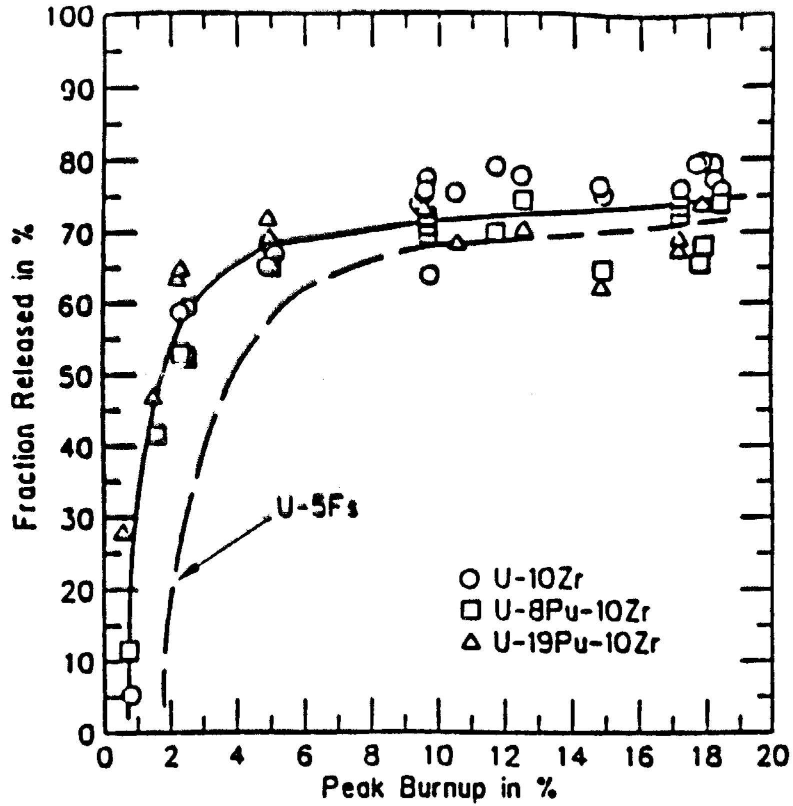
Swelling in % ΔV/V
Burnup in at.%
Cladding contact
< 200 ppm Si
> 200 ppm Si
0
2
4
6
8
10
12
14
16
18
20
22
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

U-5Fs Alloy

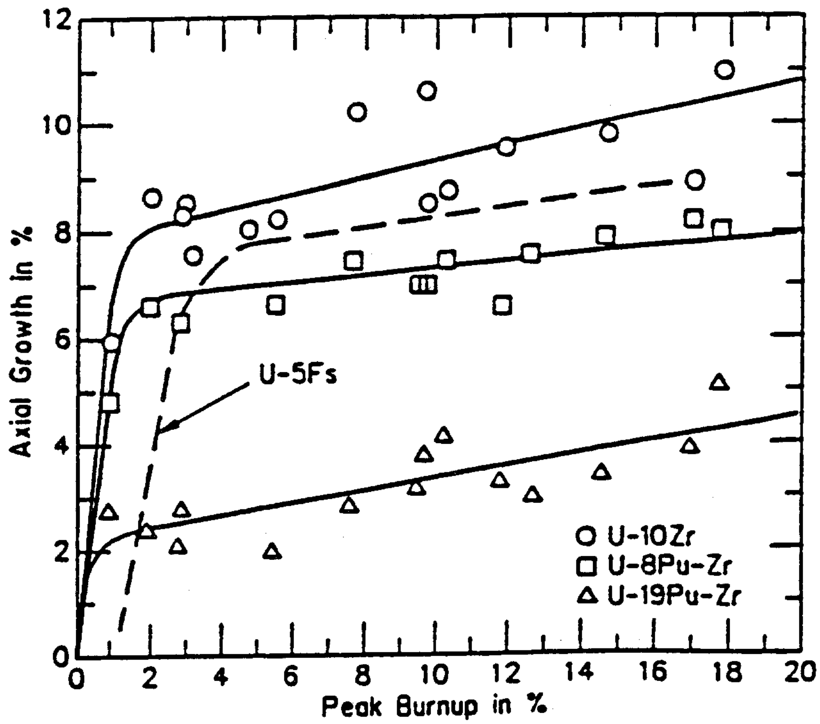
Na Logging



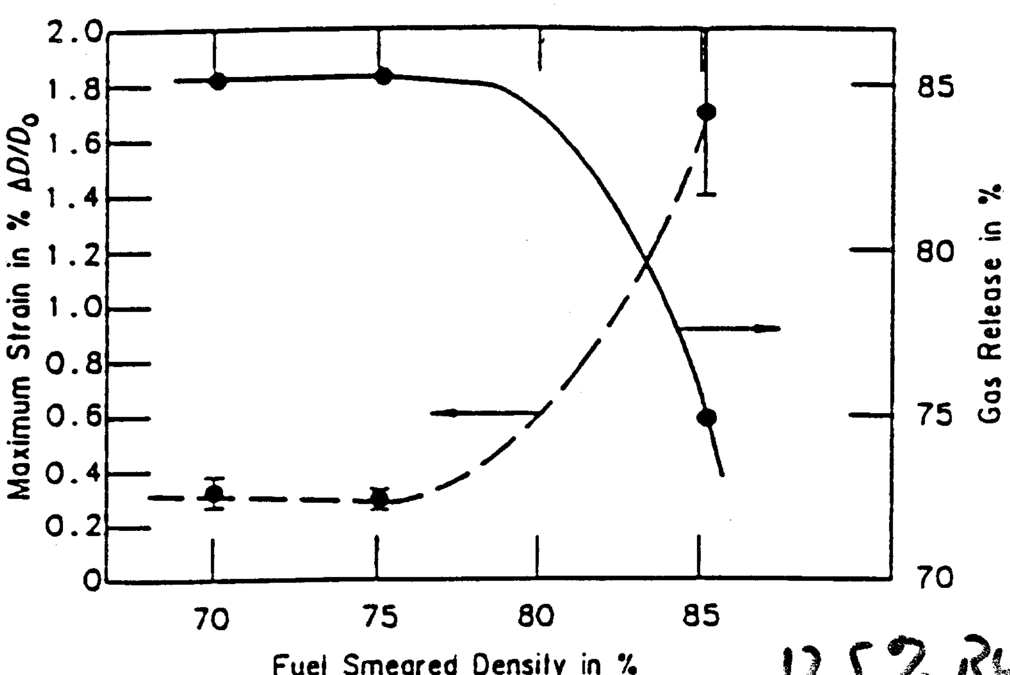
Fission Gas Release in %
Fuel Volume Increase in %
U-Fs
U-Pu-Fs
U-Pu-Zr



Fraction Released in %
Peak Burnup in %
U-5Fs
U-10Zr
U-8Pu-10Zr
U-19Pu-10Zr



Axial Growth in %
Peak Burnup in %
U-5Fs
U-10Zr
U-8Pu-Zr
U-19Pu-Zr
0
2
4
6
8
10
12
14
16
18
20



Maximum Strain in % ΔD/D$_0$
Gas Release in %
Fuel Smeared Density in %
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
70
75
80
85

12.5% B4

• 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

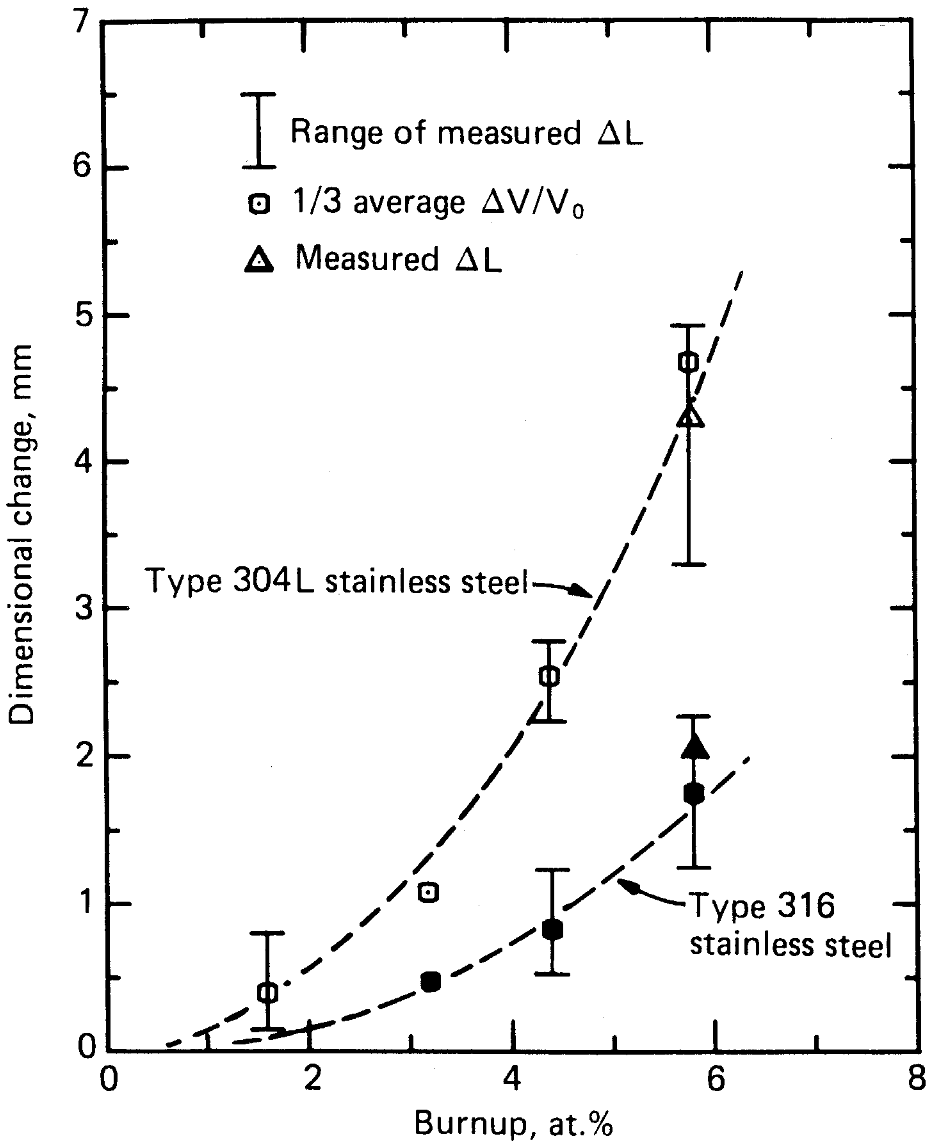
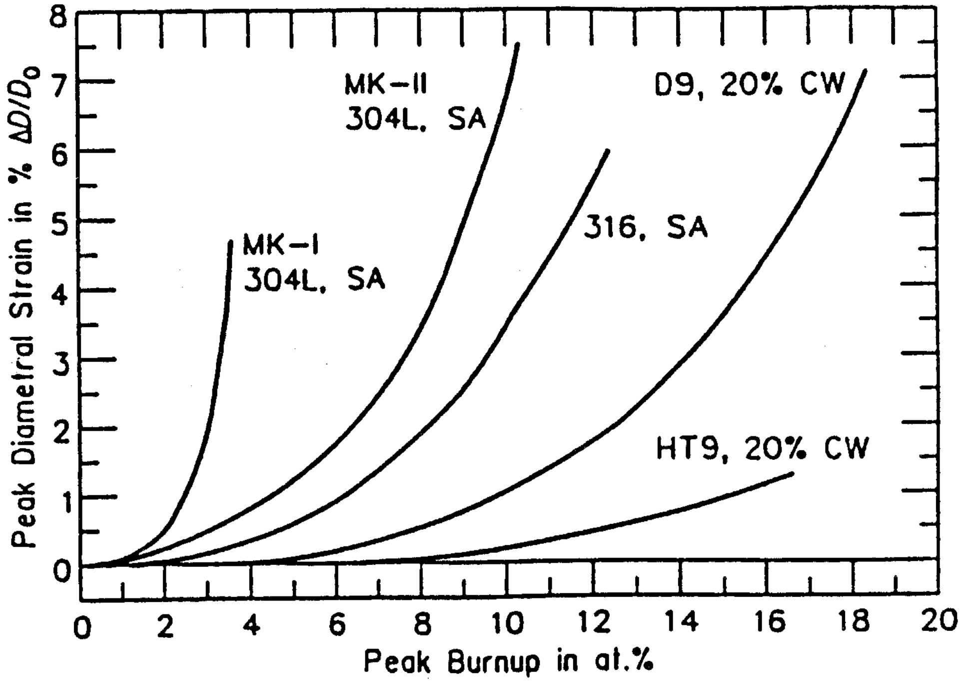


Fig. 7. Length changes compared to diameter changes for SA AISI Types 304L and 316 stainless steel-clad Mark-II elements as a function of peak burnup (Ref. 60).



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.)

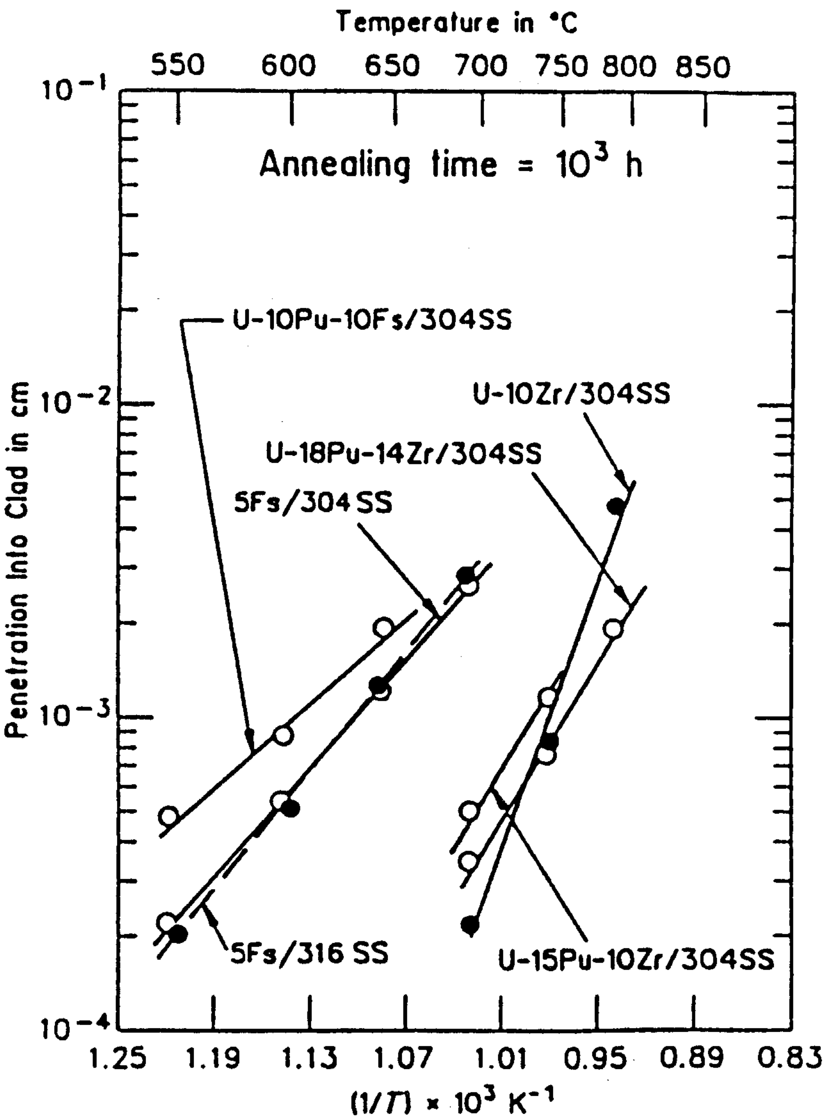
- **Another interesting note:**

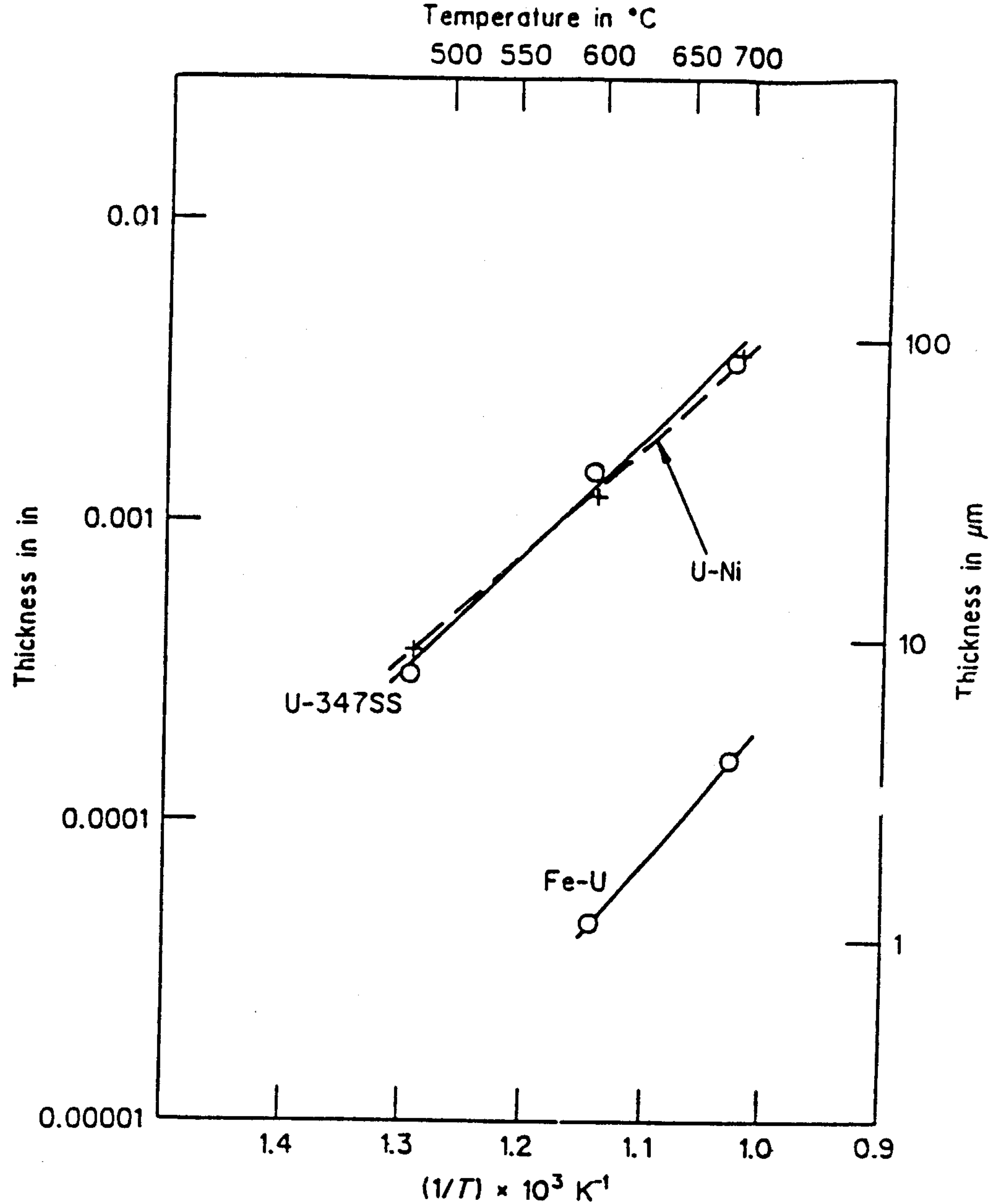
Older (1967) IFR fuels contained ≈500 ppm N, whereas newer fuel lots contain only ≈20 ppm N.

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.


Temperature in °C
550
600
650
700
750
800
850
Annealing time = 10^3 h
U-10Pu-10Fs/304SS
U-10Zr/304SS
U-18Pu-14Zr/304SS
5Fs/304 SS
5Fs/316 SS
U-15Pu-10Zr/304SS
Penetration into Clad in cm
10^-1
10^-2
10^-3
10^-4
1.25
1.19
1.13
1.07
1.01
0.95
0.89
0.83
(1/T) × 10^3 K^-1


Temperature in °C
500
550
600
650
700
0.01
0.001
0.0001
0.00001
Thickness in in
Thickness in μm
100
10
1
U-Ni
U-347SS
Fe-U
1.4
1.3
1.2
1.1
1.0
0.9
(1/T) × 10^3 K^-1