Swelling, creep and embrittlement of D9 stainless steel cladding and duct irradiated in two FFTF driver fuel assemblies to high neutron exposures

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Questions frequently asked about D9 application to spallation, fusion and breeder reactors

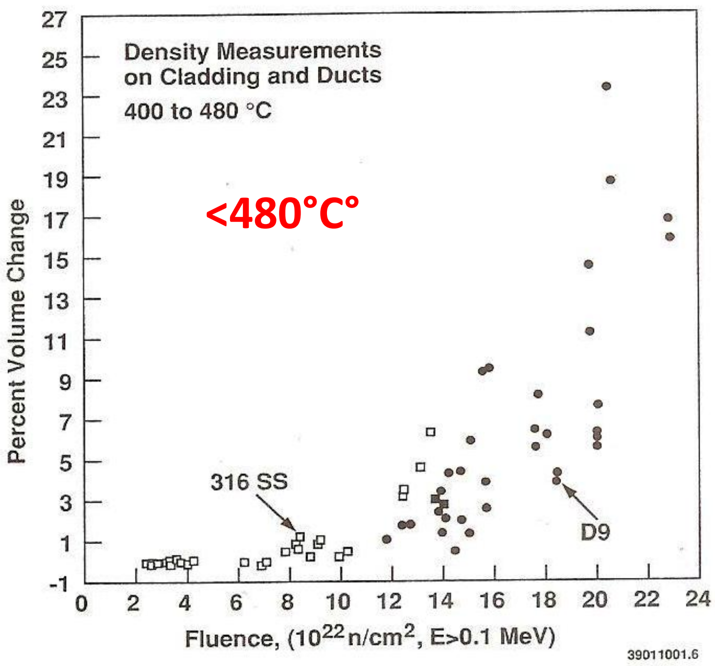
- There are a number of D9–type austenitic steels in various national programs ….. Can the various data bases be combined?
- How restrictive should the specification boundaries be for minor elements such as P, Si, C and especially the Ti/C ratio?
- If reproducibility of swelling behavior is important, what is the origin of the apparent scatter in swelling data base?
- For identical irradiation conditions, how reproducible is void swelling of any chosen steel?

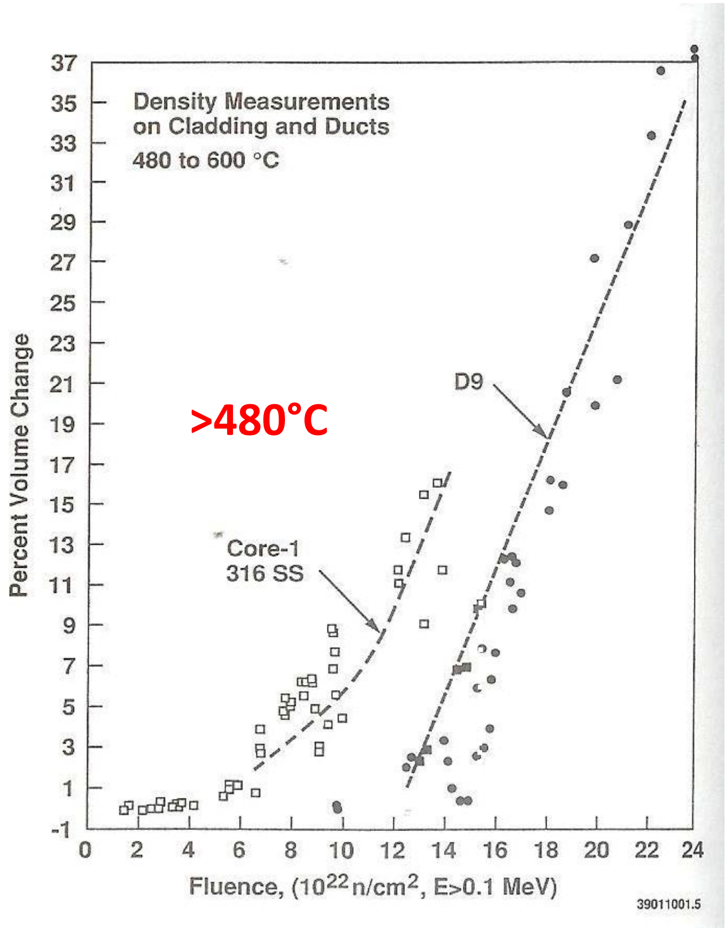
Comparison of volume changes observed in FFTF of CW 316 and CW D9 fuel cladding

Makenas et al., 1990

One heat of 316 SS and a number of heats of D9

Both duct and cladding data included from four driver fuel assemblies irradiated in FFTF.





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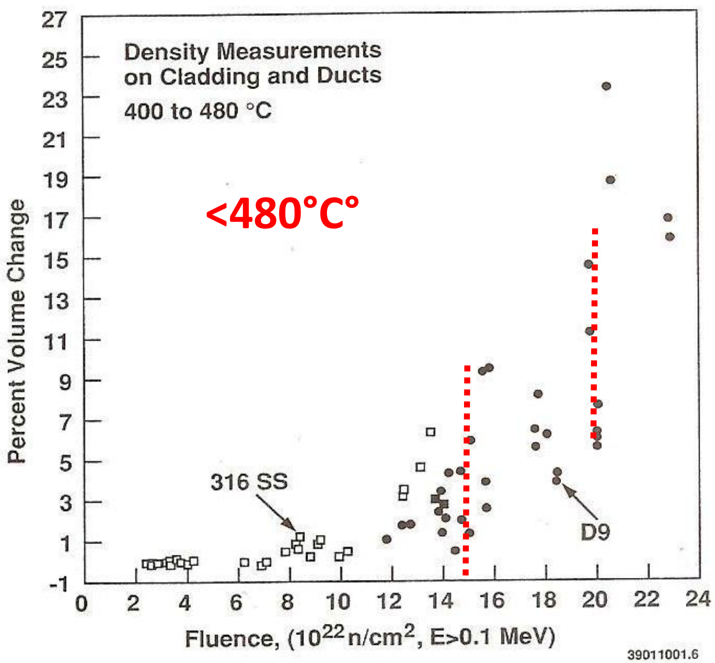

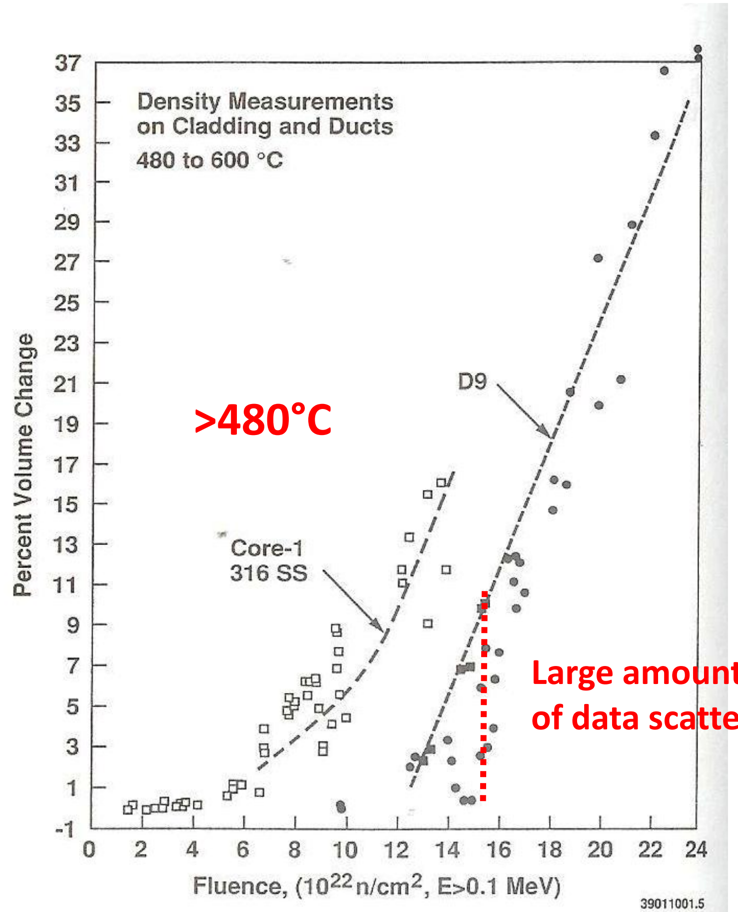

Is this really "inherent" scatter …. or is there additional information related to differences in composition, temperature, dose and dose rate?

Development and qualification of D9 stainless steel

- **The Ti-modified stainless steel designated D9 was developed for the U.S. fast reactor program to replace higher-swelling 316 stainless steel.**

- **This alloy was used to produce four subassemblies with 217 wire-wrapped fuel pins contained in a hexagonal duct.**

- **The cladding, wire, end caps and duct were all in the 20% cold-worked condition.**

- **This report focuses on the swelling and creep behavior of two subassemblies designated D9-2 and D9-4 which were irradiated in the FFTF fast reactor.**

- **Two different heats of D9 were used in these assemblies**.

Components destructively examined in this study

- **D9-2 assembly**

  Two near-adjacent fuel pins clad with D9-C1 heat

- **D9-4 assembly**

  1) Hexagonal duct (2 faces) made from D9-C1 heat

  2) Two adjacent fuel pins clad with different heats

  D9-C1 (standard levels of minor and tramp elements)

  D9-C1P (lower levels of "tramp" elements)

All other pins in these two assemblies were examined non-destructively by profilometry and length change.

Composition of two heats of D9 in wt%

	Cr	Ni	Mo	Mn	Ti	Si	Cu	V		
D9-C1	13.78	15.15	1.46	1.74	0.23	0.92	0.02	0.03		
D9-C1P	13.36	15.55	1.62	1.85	0.28	0.85	<0.01	<0.01		

	C	P	N	B	
D9-C1	0.052	0.009	0.005	0.001	
D9-C1P	0.045	0.002	0.002	<0.005	

The C1P heat also has lower levels of Nb, Ta, Al, As, Co and a slightly higher level of S.

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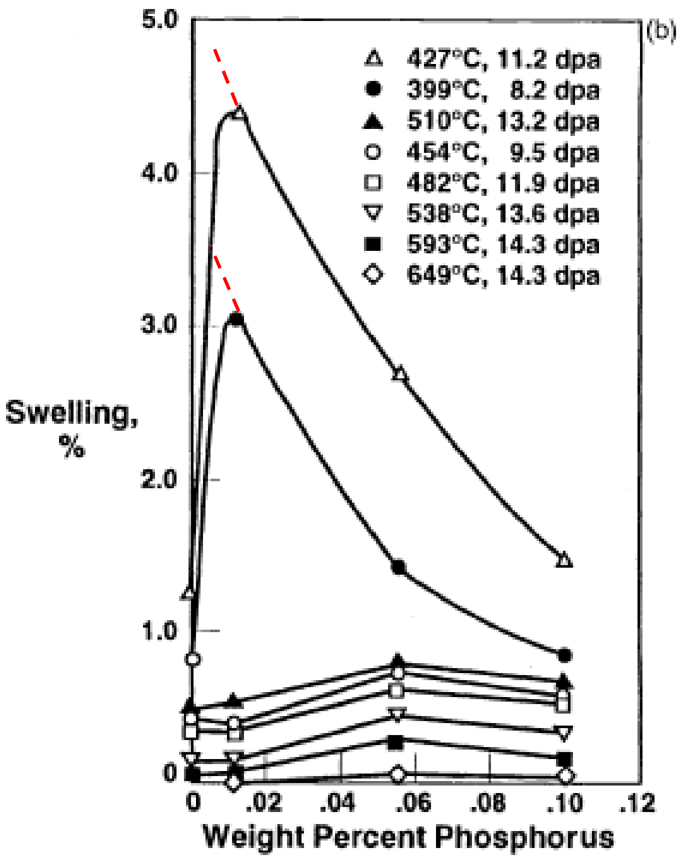
Specification P< 0.04 wt%

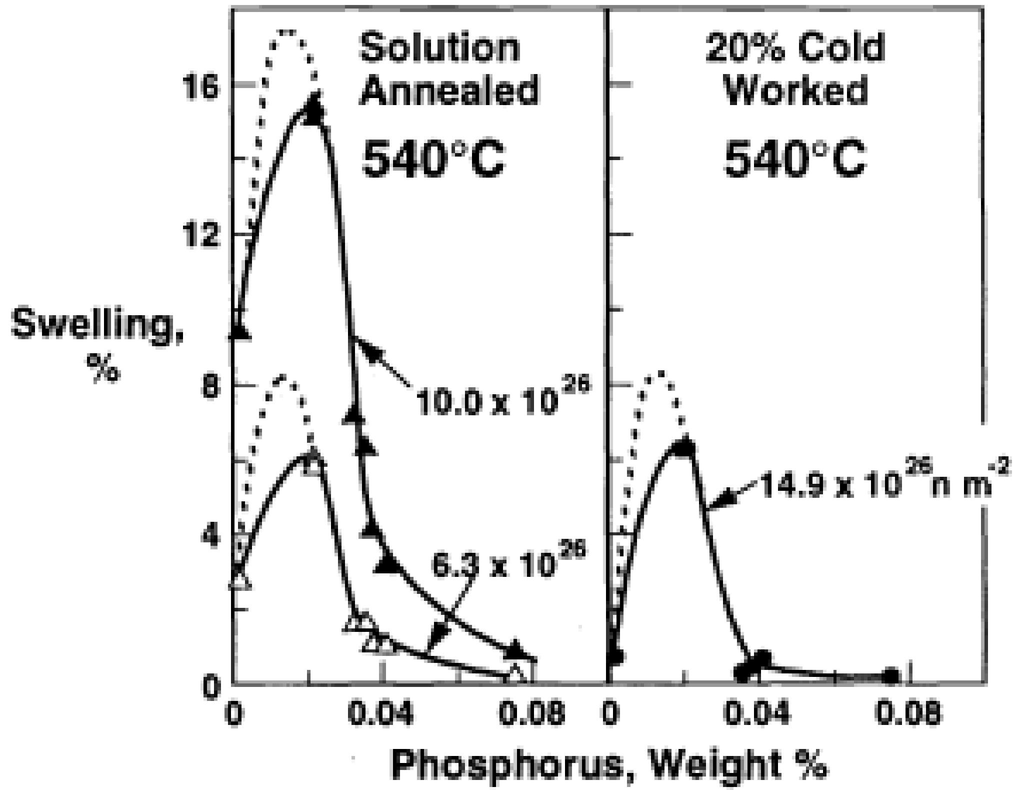
Per atom … P, Si and C are the most swelling-suppressive elements but their influence is often non-monotonic.

Influence of phosphorous on void swelling in EBR-II



Effect of P on swelling of annealed Fe-25Ni-15Cr

Garner and Kumar, 1987



Effect of P on swelling of Fe-16.2Cr-13.8Ni-2.5Mo-2.0Mn-1.5Si-0.2Ti-0.04C

Garner and Mitchell, 1992

Influence of phosphorous on void swelling of 316 SS in EBR-II

Garner and Mitchell, 1992

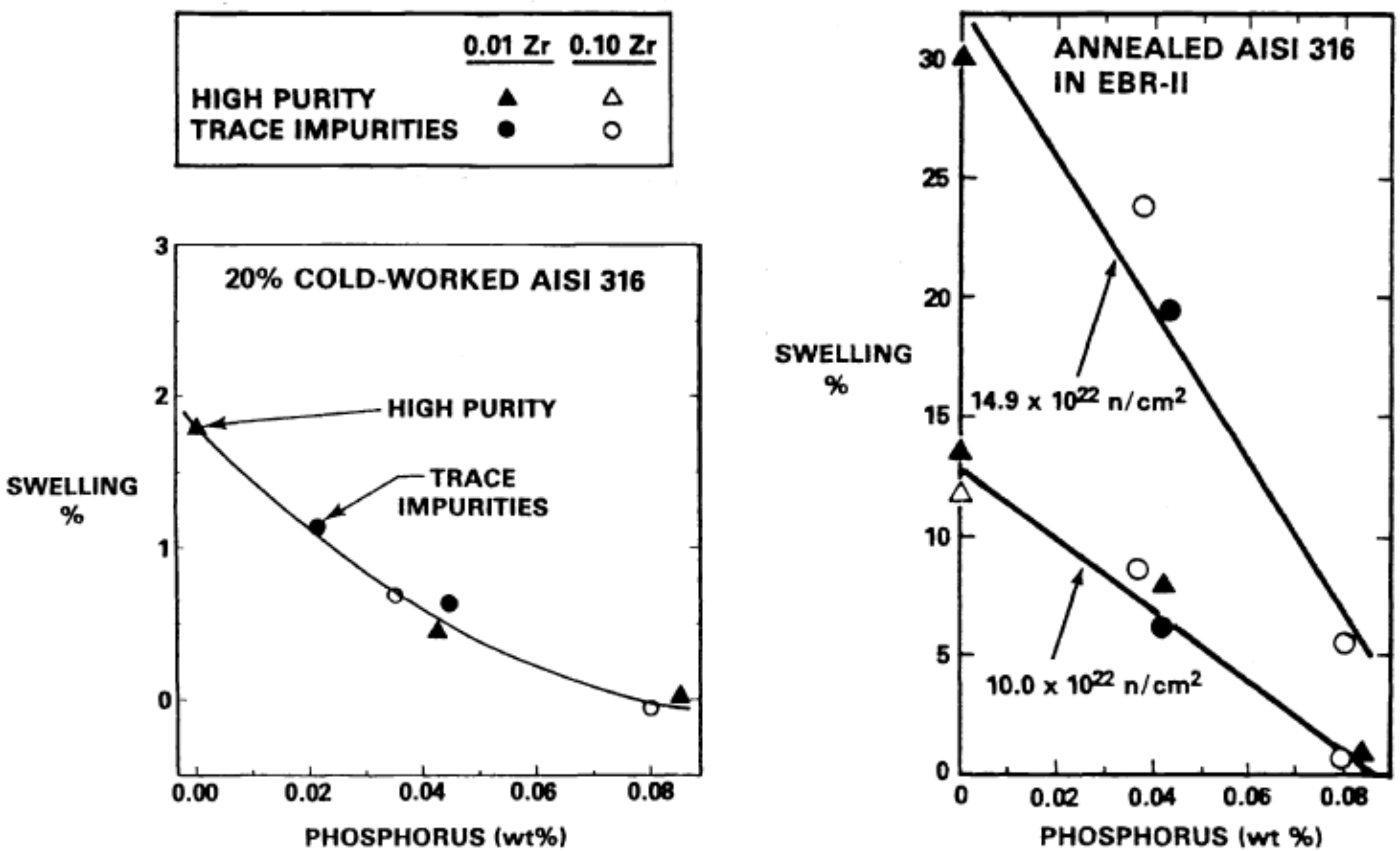
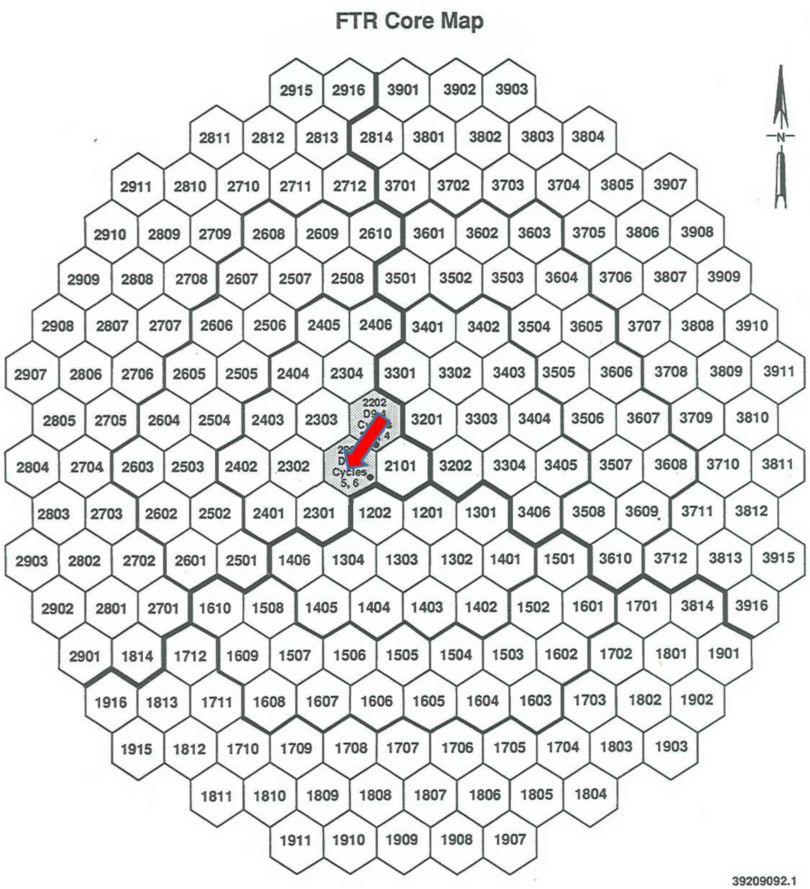
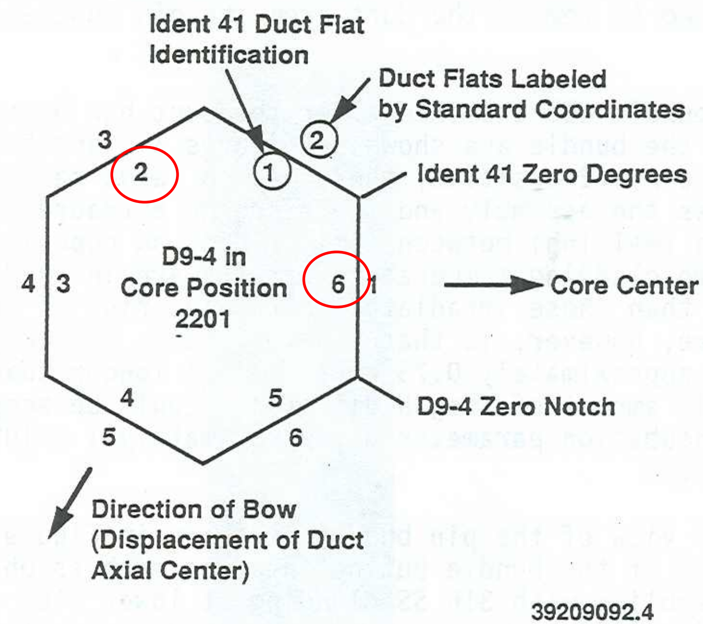


Figure 6-50. The relative influence of phosphorus, zirconium and trace impurities on the swelling of AISI 316: (left) 20% cold worked condition at 425 °C and 55 dpa, (right) annealed condition at 540 °C and 51 or 76 dpa (after Garner and Brager, 1988).

Irradiation of D9-4 in two positions in row 2





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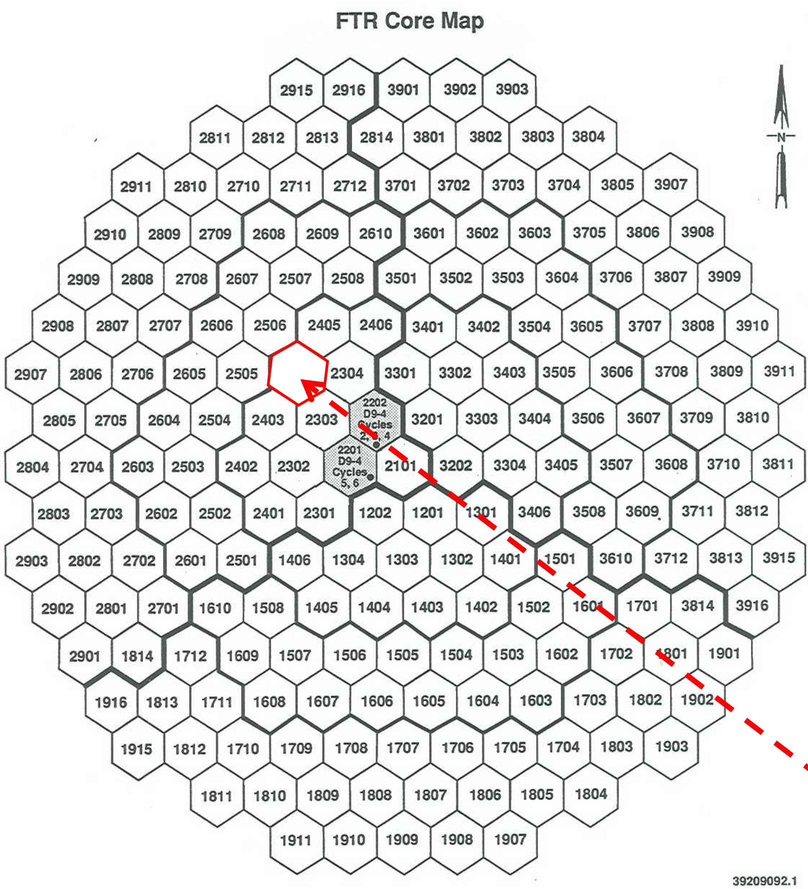
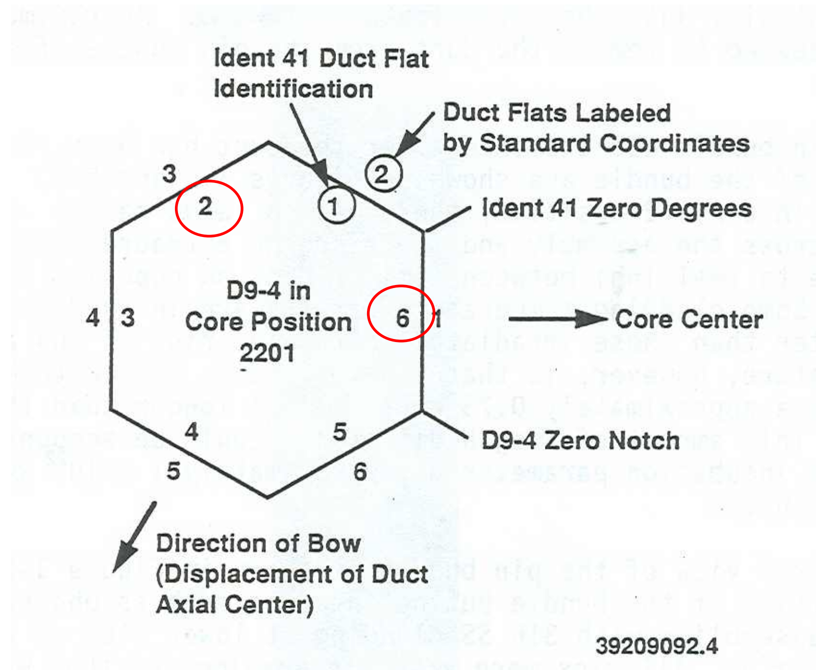




D9-2 was irradiated in only one position in row 4.

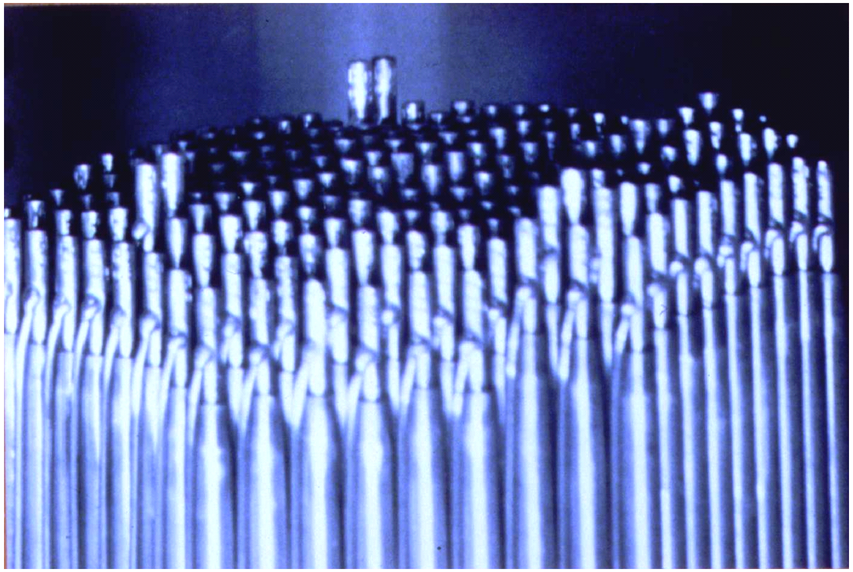
Irradiation conditions of D9 fueled assemblies

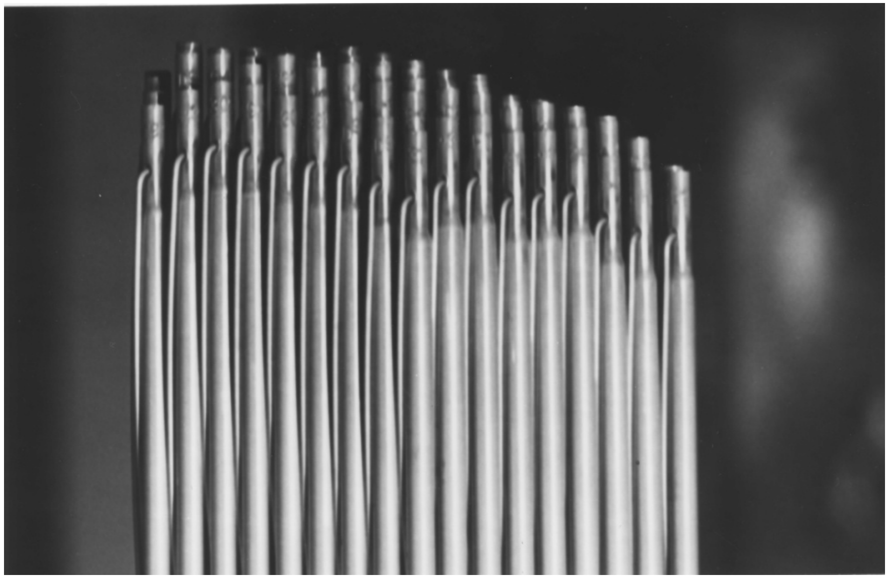
Assembly name	Location in FFTF	Maximum exposure 10^{22} n/cm^2 (E>0.1 MeV)	Maximum dpa
D9-4	No radial gradient Row 2	21.4	~92
D9-2	Radial flux gradient Row 4	25.3	~110

~4.3 dpa per 10^{22} n/cm^2 (E > 0.1 MeV)

Top of two D9 assemblies showing variable length increases in fuel pins

217 pin assemblies





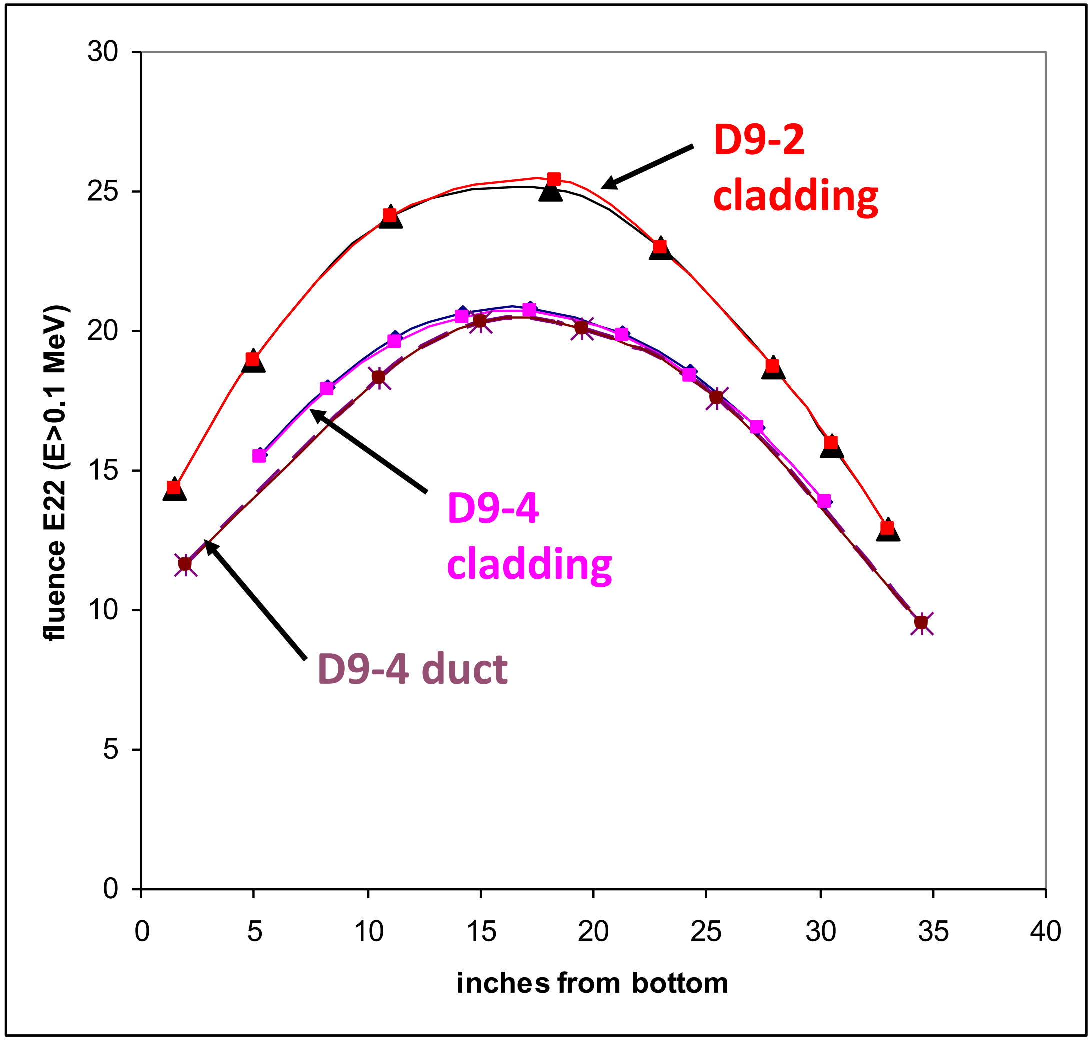
D9-4 assembly in Row 2 showing increased length change due to higher swelling of D9-C1P pins compared to D9-C1 pins

Difference is due primarily to the lower phosphorous level in D9-C1P.

D9-2 assembly in Row 4 showing higher swelling and length change of D9-C1 pins located closer to the core center

Difference is due primarily to the flux gradient across the assembly.

Fast neutron fluence (E > 0.1 MeV) experienced by two D9 assemblies in FFTF



D9-2 assembly spent more time in reactor and reached a higher fluence level than D9-4.

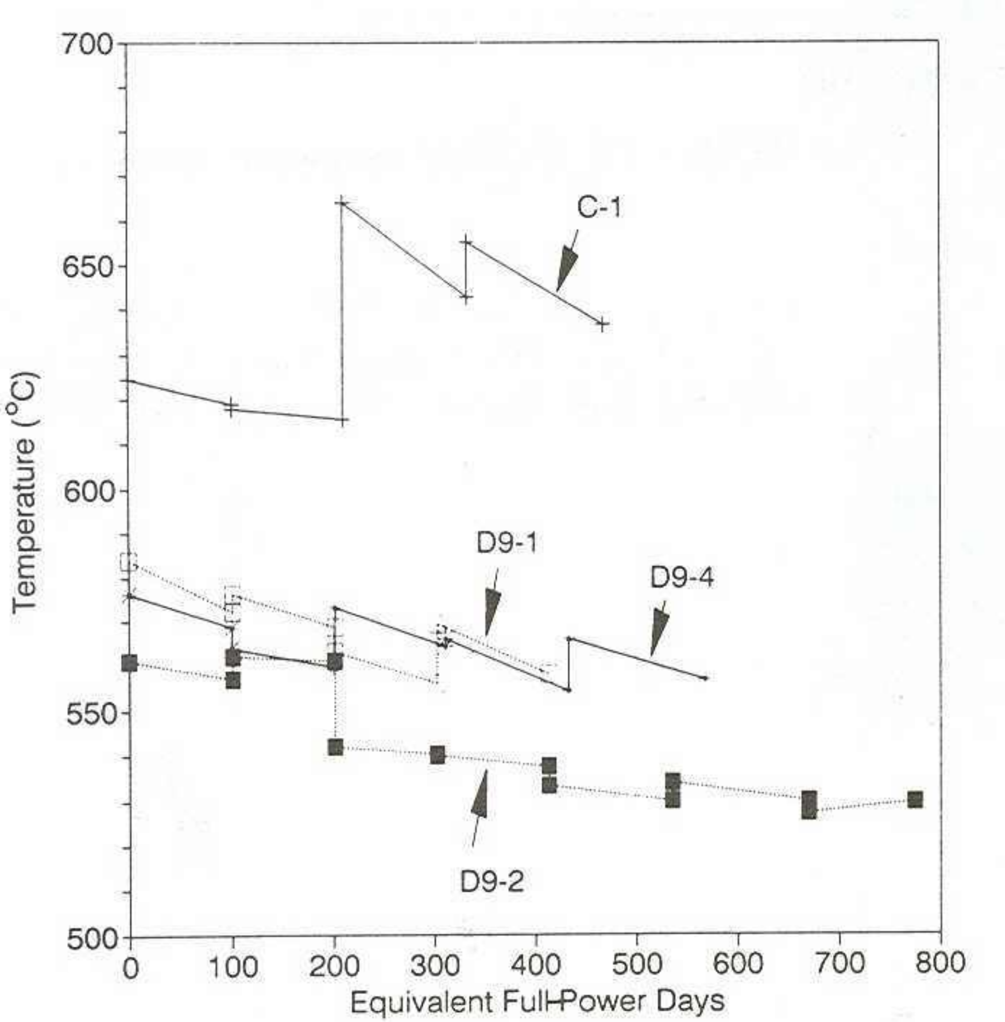
Each set of two pins experienced near-identical fluxes and temperatures.

Fluence and temperatures of the two duct faces are the same.

Fluence of duct faces and two chosen pin claddings in D9-4 were almost the same.

Temperature history of two assemblies in FFTF

Coolant outlet temperatures



Temperature during any one reactor cycle decreases with fuel burn-up.

Reactor flux was often raised at the beginning of each new cycle.

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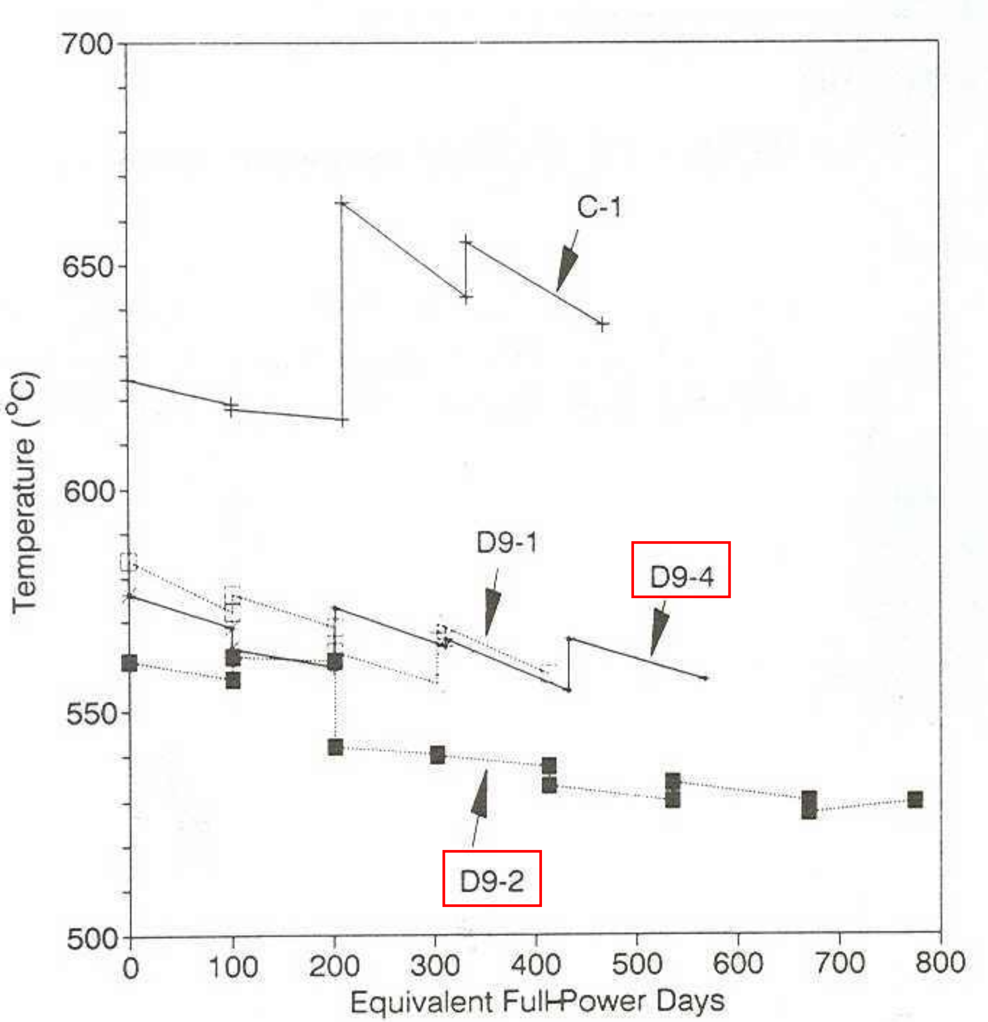
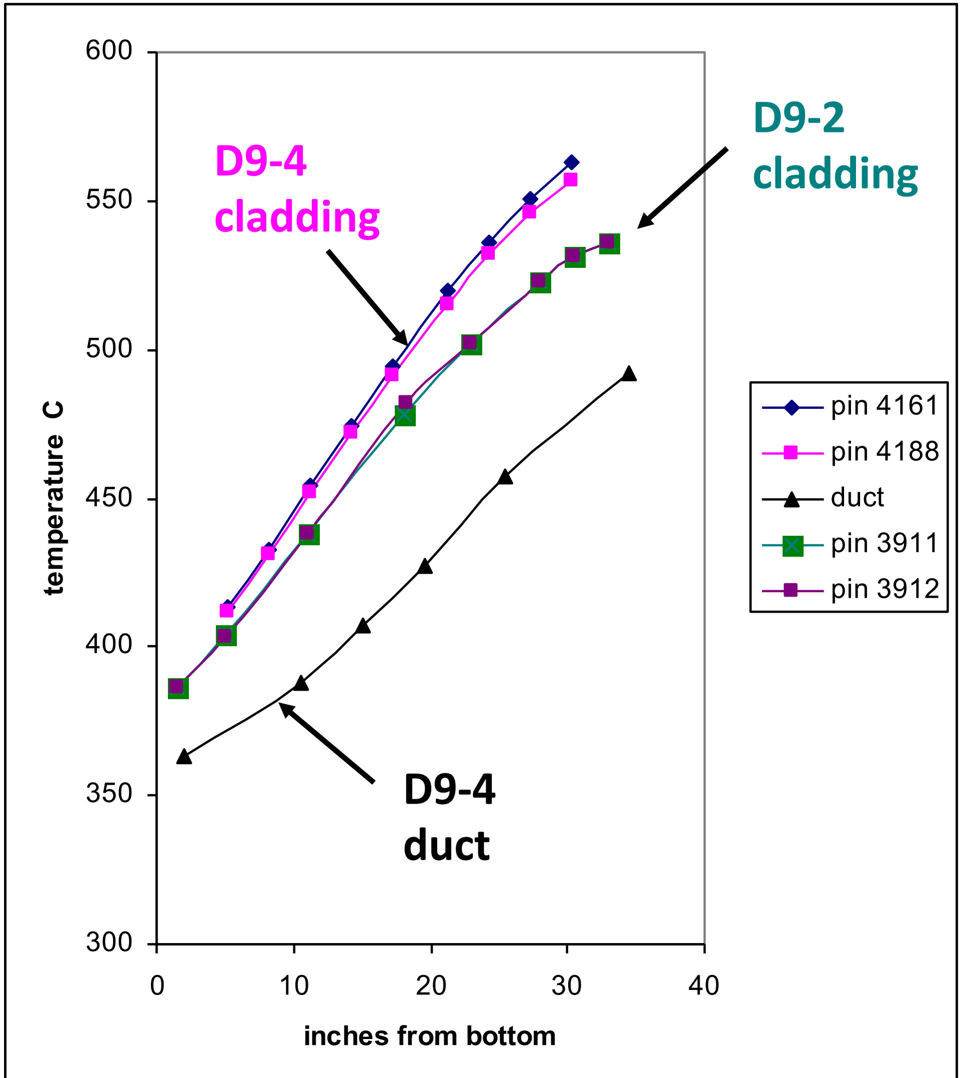


Temperature during any one reactor cycle decreases with fuel burn-up.

Reactor flux was often raised at the beginning of each new cycle.

D9-4 test operated at higher average temperatures than that of D9-2

Time-averaged mid-wall temperatures experienced by two D9 assemblies in FFTF

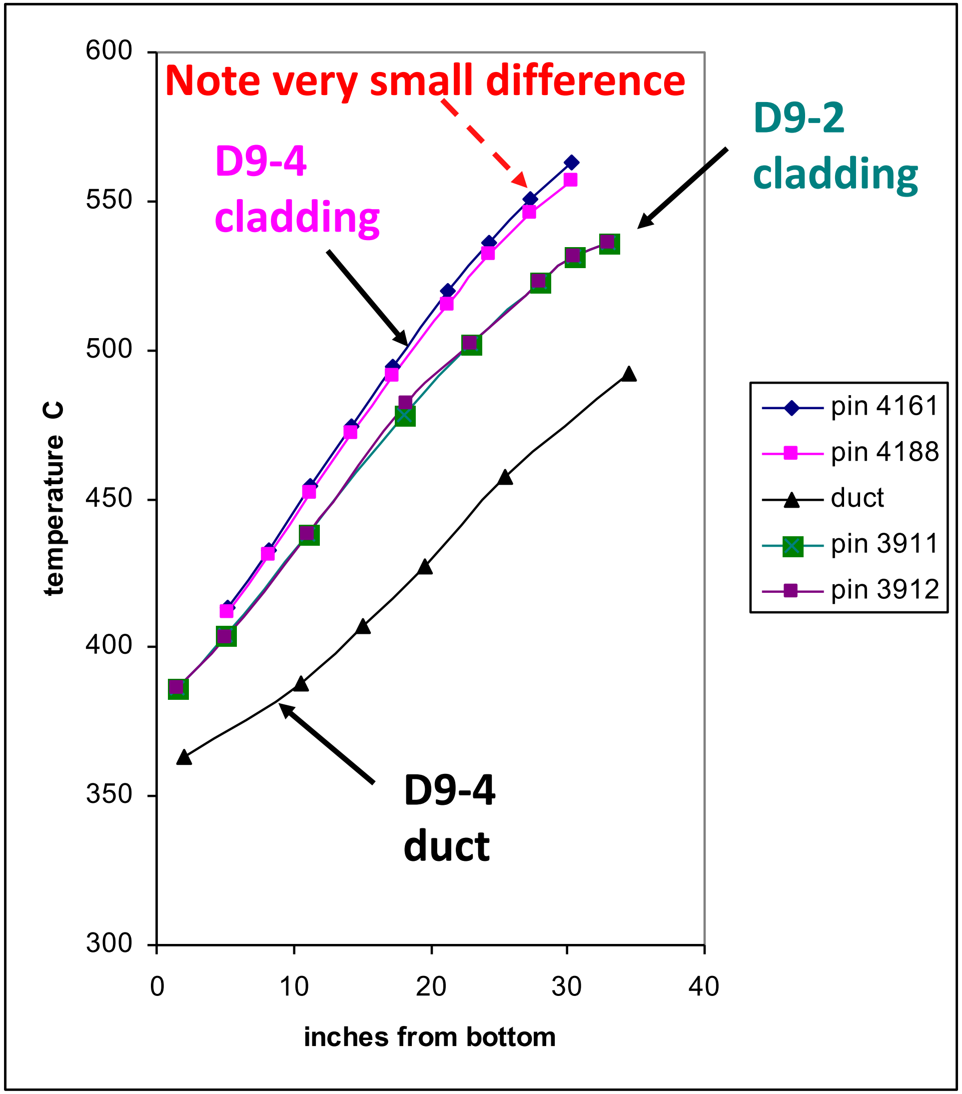


The D9-4 assembly operated at higher temperatures than did D9-2.

The D9-4 duct operated at lower temperatures than D9-4 cladding.

Temperature and neutron flux are the <u>most important variables</u> to determine the duration of the transient swelling regime.

Time-averaged mid-wall temperatures experienced by two D9 assemblies in FFTF



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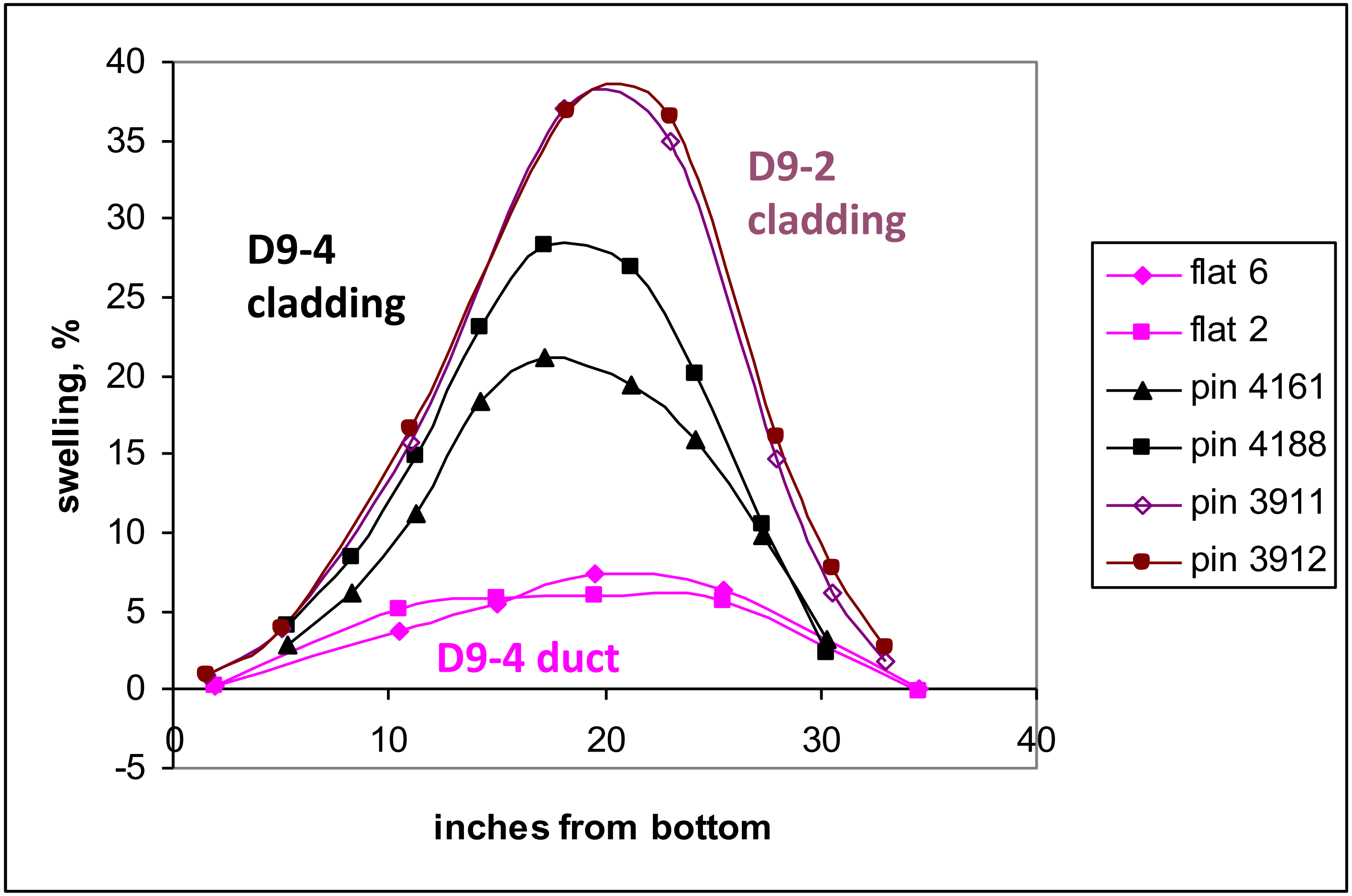
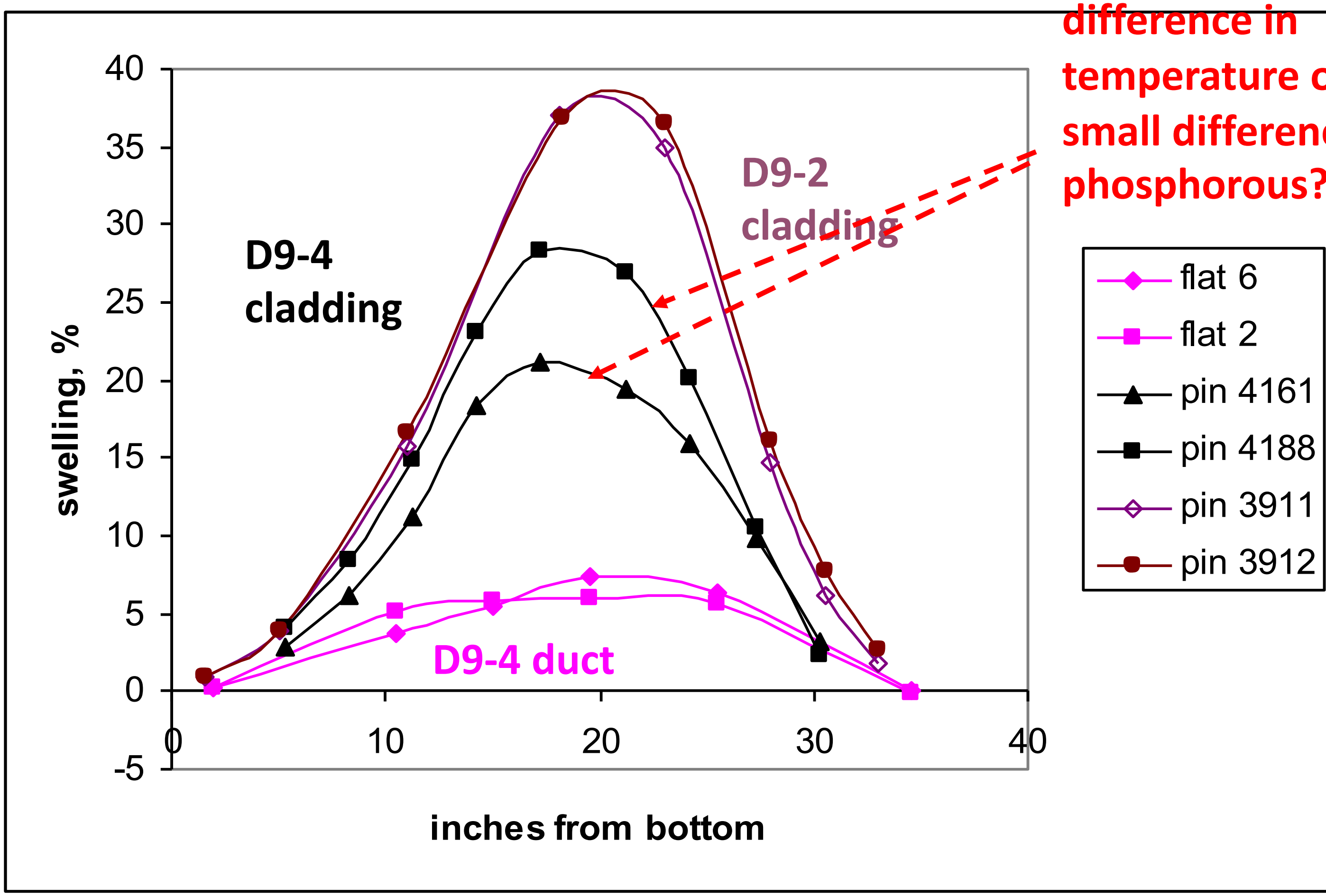
Swelling measured using density change for cladding and duct in two D9 assemblies



Swelling measured using density change for cladding and duct in two D9 assemblies

Result of the small difference in temperature or the small difference in phosphorous?



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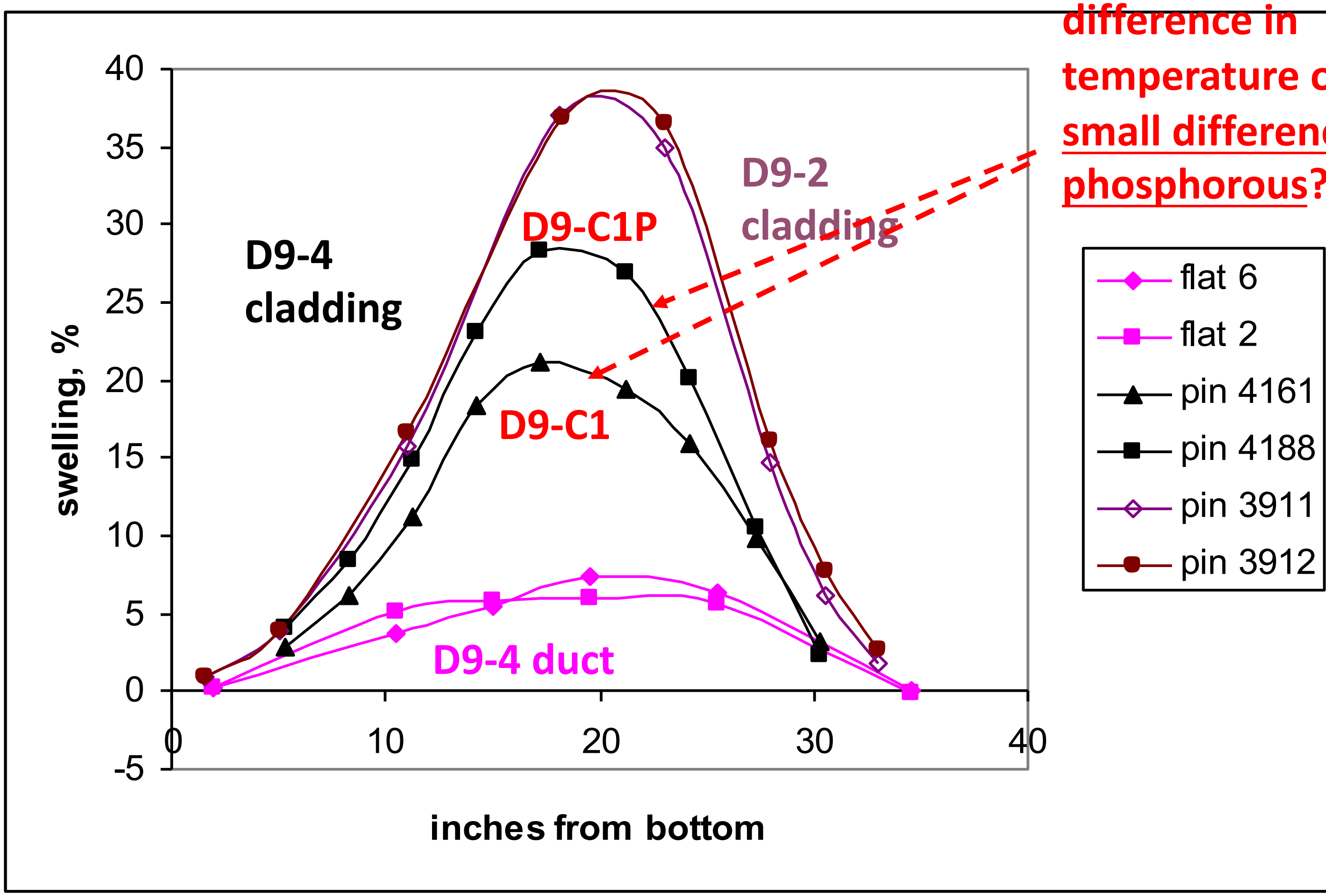

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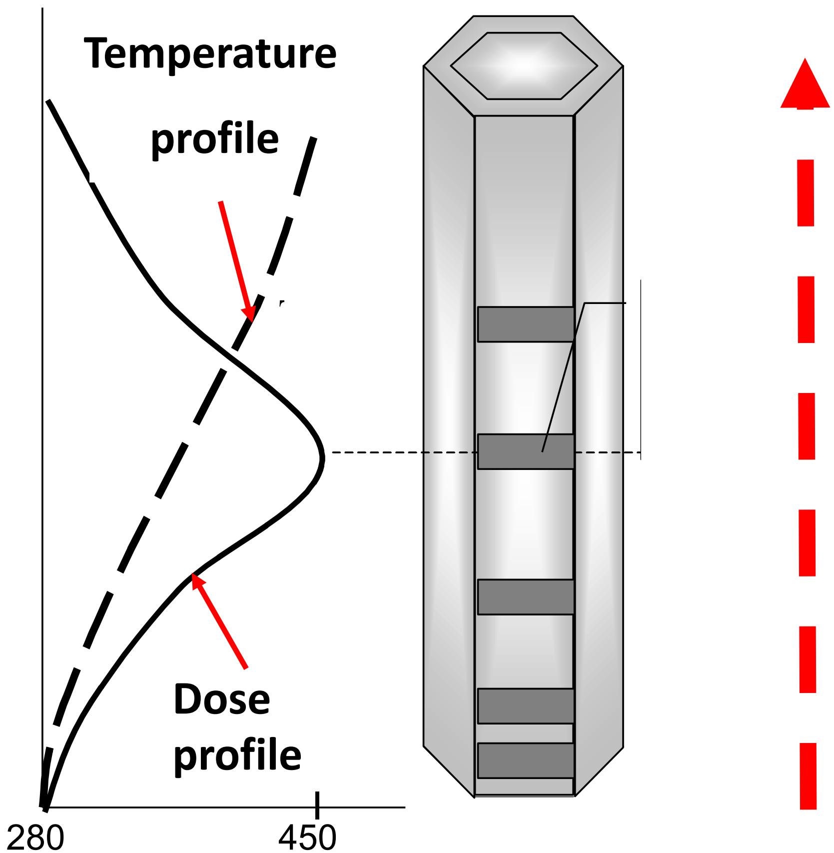
Flux-temperature relationships for irradiated through-core components



Plot swelling vs. dpa from bottom to top of component.

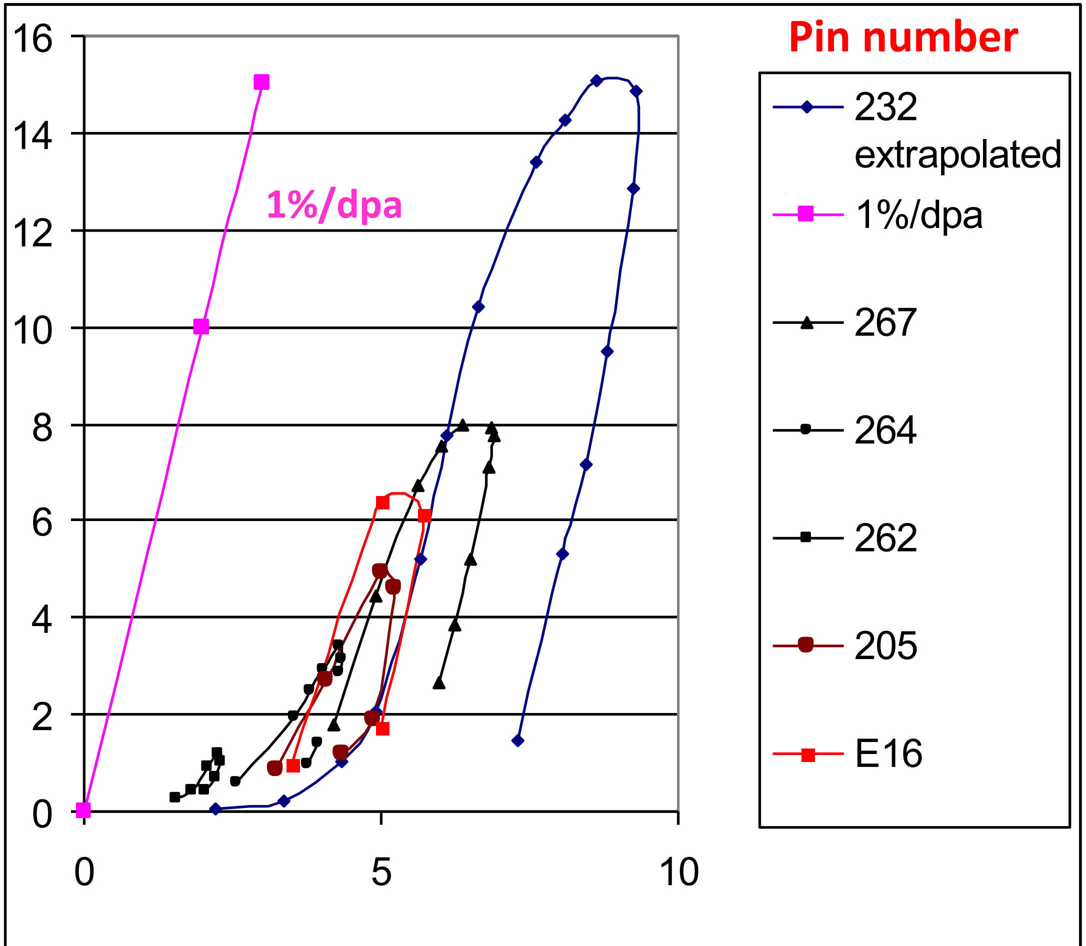
Swelling "loops" are produced!

Width of loop depends primarily on the temperature range of the component.

Long pressurized tubes of CW 316 at constant stress in EBR-II

Garner, 2014

Swelling, %



Swelling along various tubes as a function of dpa rate, temperature and stress level

Relatively low temperature range leads to "fat" loops

Long pressurized tubes of CW 316 at constant stress in EBR-II

Garner, 2014

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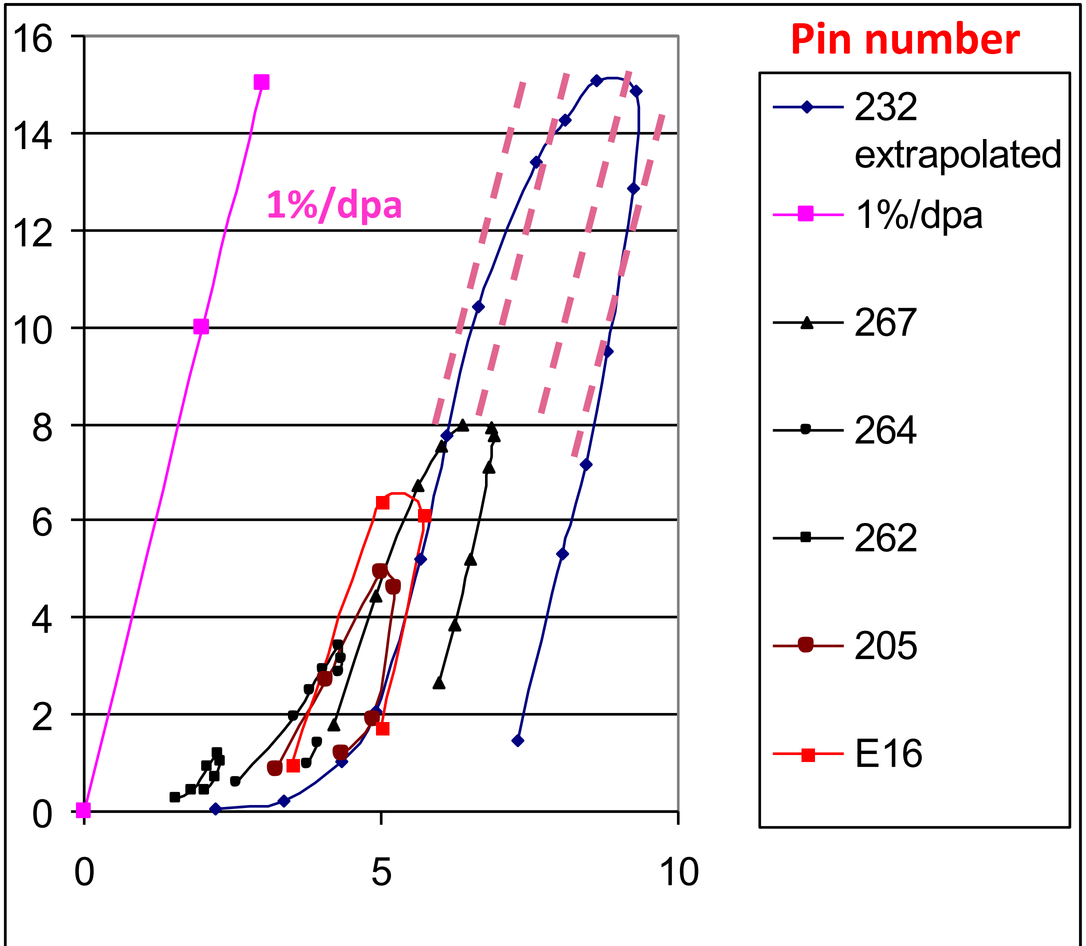


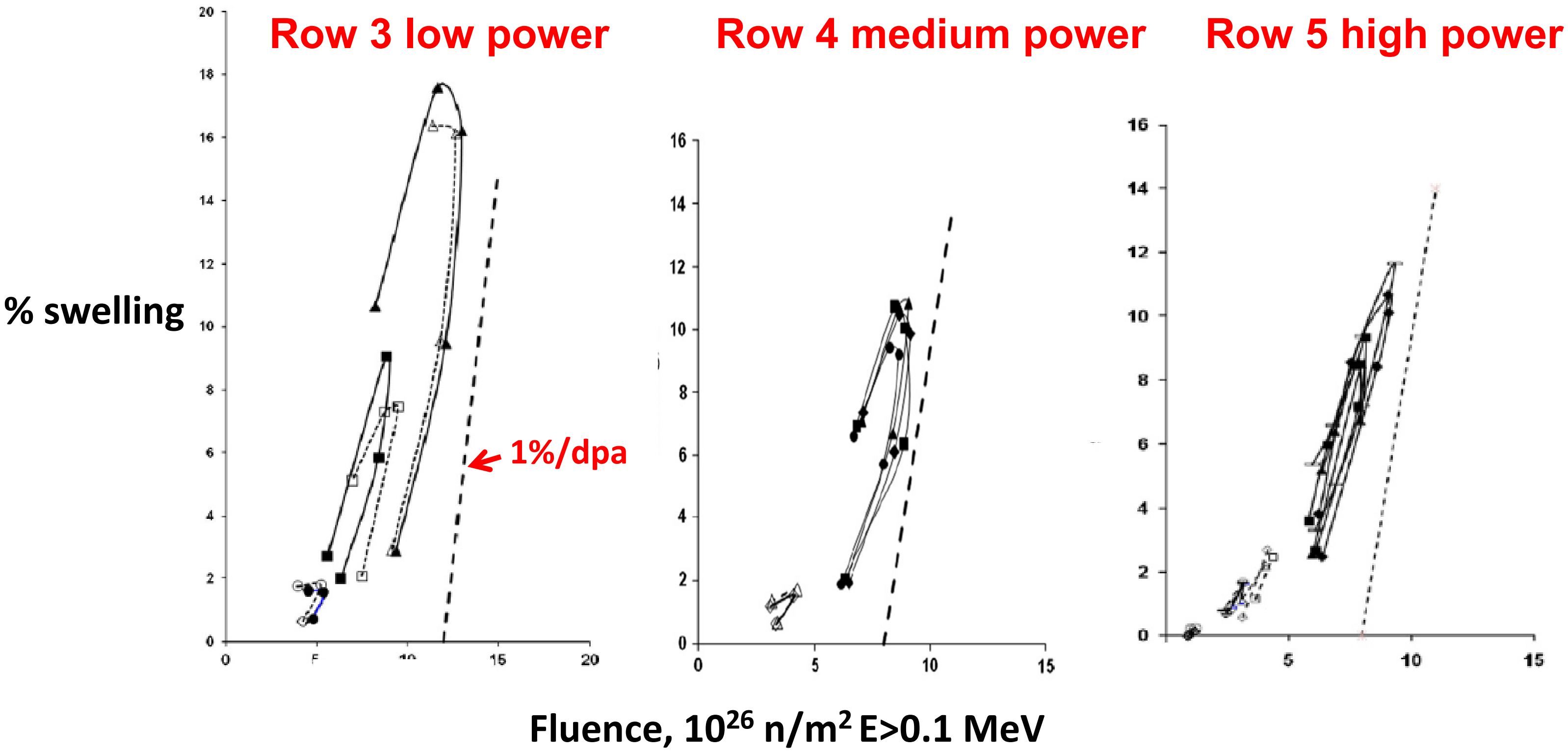
Swelling along various tubes as a function of dpa rate, temperature and stress level

Relatively low temperature range leads to "fat" loops.

All measured swelling levels lie on a separate 1%/dpa line after an incubation period that depends on flux and temperature.

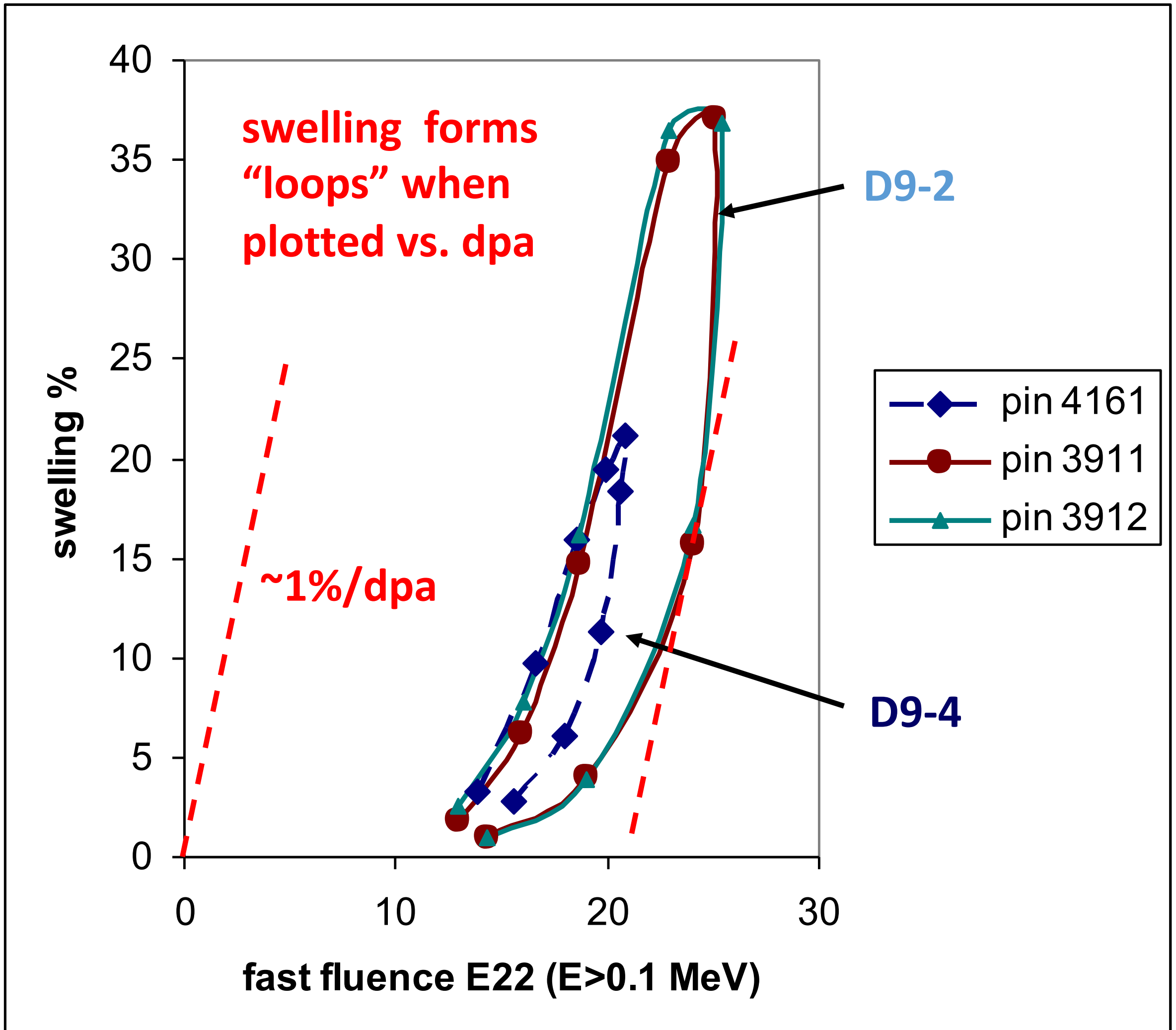
Swelling of annealed 304 stainless steel cladding in three fuel assemblies in in EBR-II

Garner, Makenas, Chastain, 2011



Swelling loops become thinner as the temperature range increases.

Swelling behavior of heat D9-C1 cladding in the two assemblies: another way to visualize the data



Higher fluence in D9-2 leads to higher overall swelling.

Higher temperatures in D9-4 lead to “narrower” loops.

High temperature “wall” defines shortest transient.

Loop and wall behavior is consistent with many other studies.

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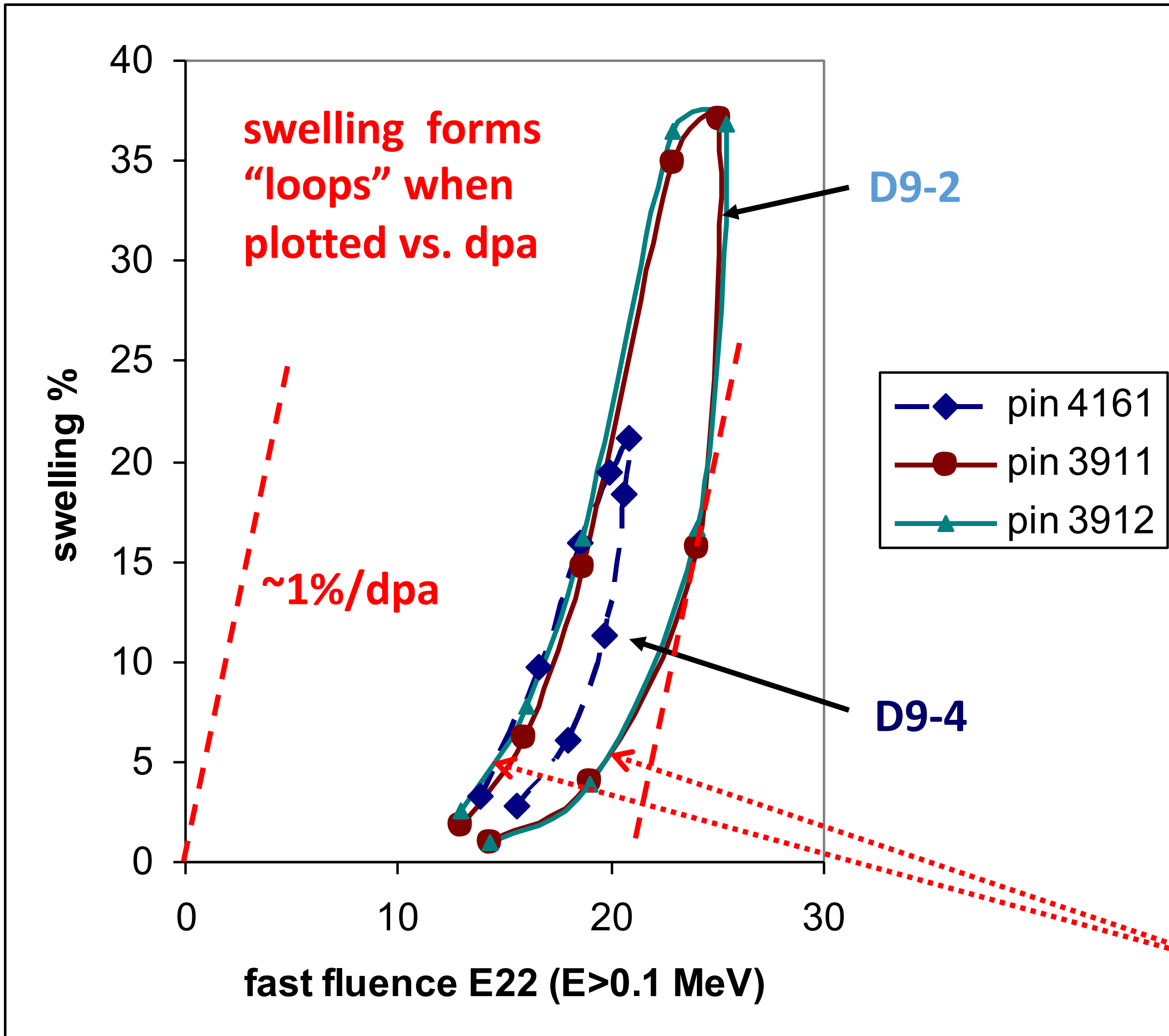


Higher fluence in D9-2 leads to higher overall swelling.

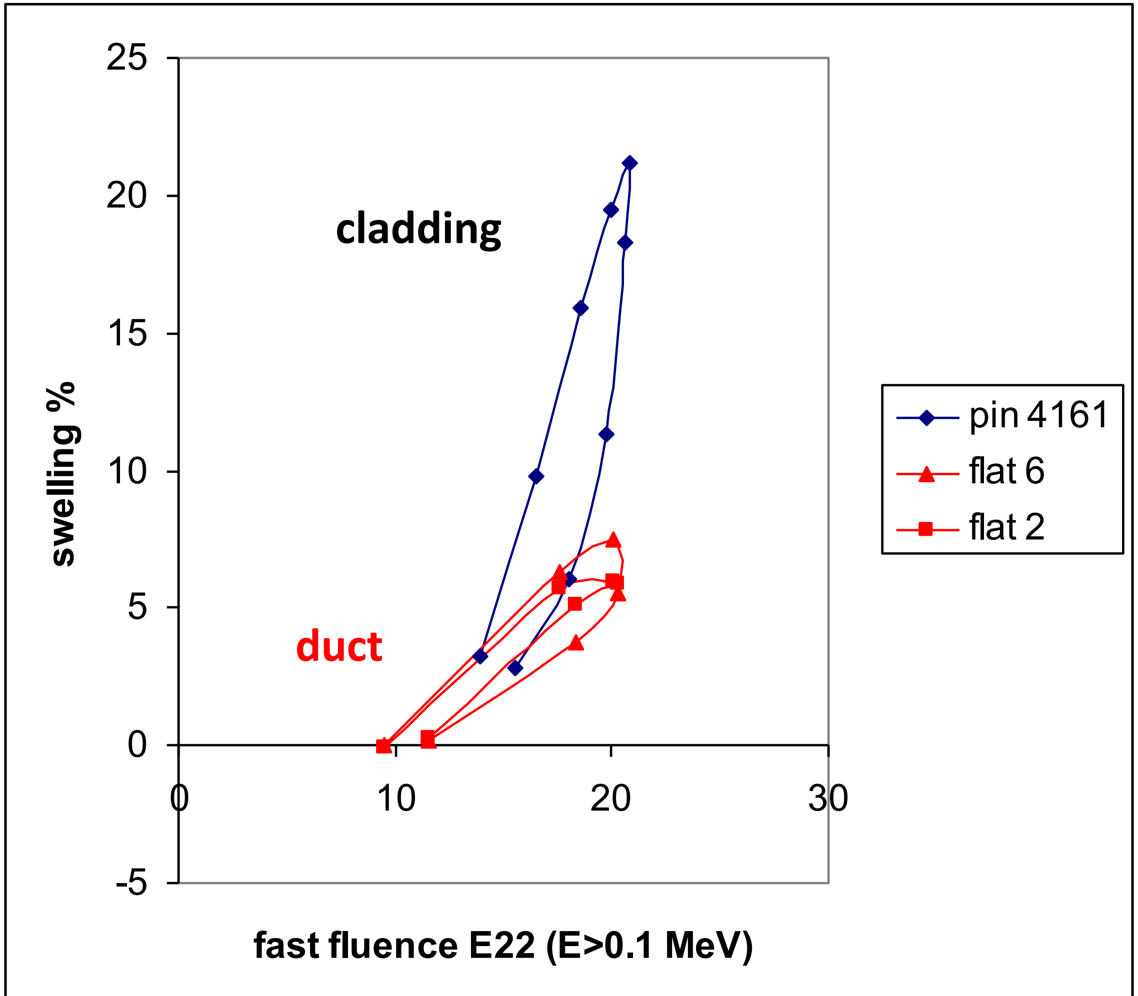
Higher temperatures in D9-4 lead to "narrower" loops.

High temperature "wall" defines shortest transient.

Loop and wall behavior is consistent with many other studies.

All temperatures between ~420 and ~540°C lie in the 1%/dpa regime …. and maybe even beyond.

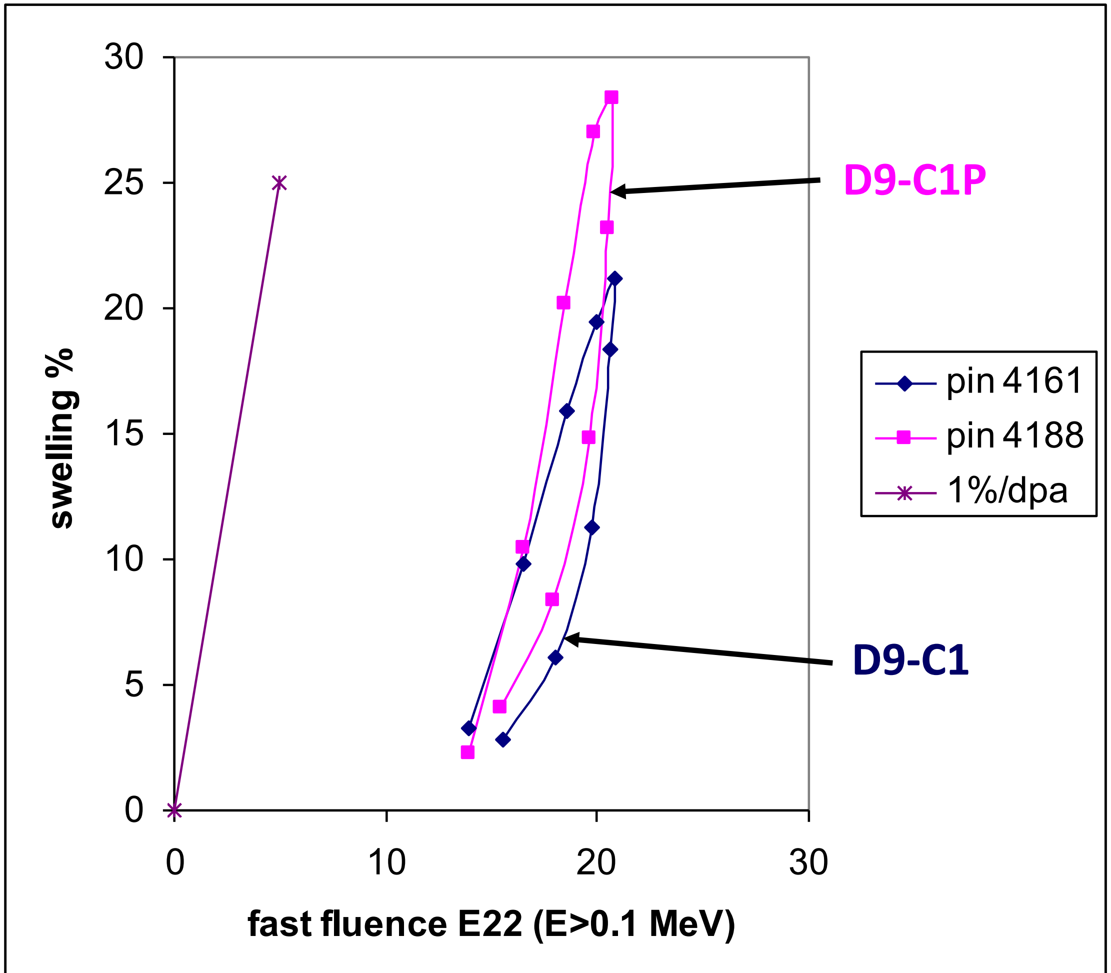
Comparison of swelling in D9-C1 cladding and duct in D9-4 assembly



Neutron fluences of cladding and duct are nearly identical.

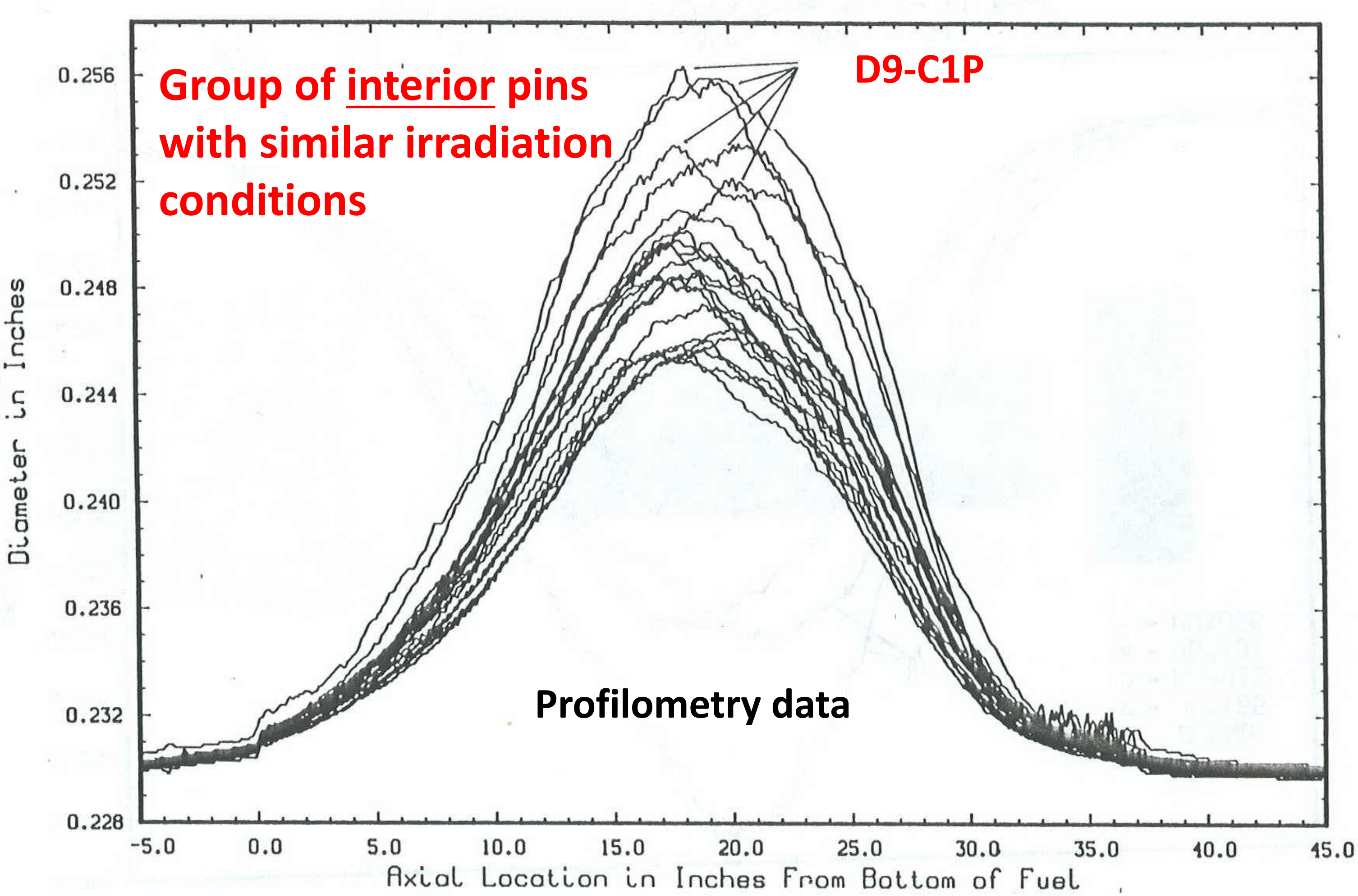
Lower swelling of duct faces is related primarily to their lower temperature.

Comparison of swelling of two cladding heats in D9-4 assembly



Difference is due primarily to the effect of lower phosphorus level to produce higher swelling and also a narrower loop.

In assembly D9-4 the pins with D9-C1P cladding swell more than pins with D9-C1



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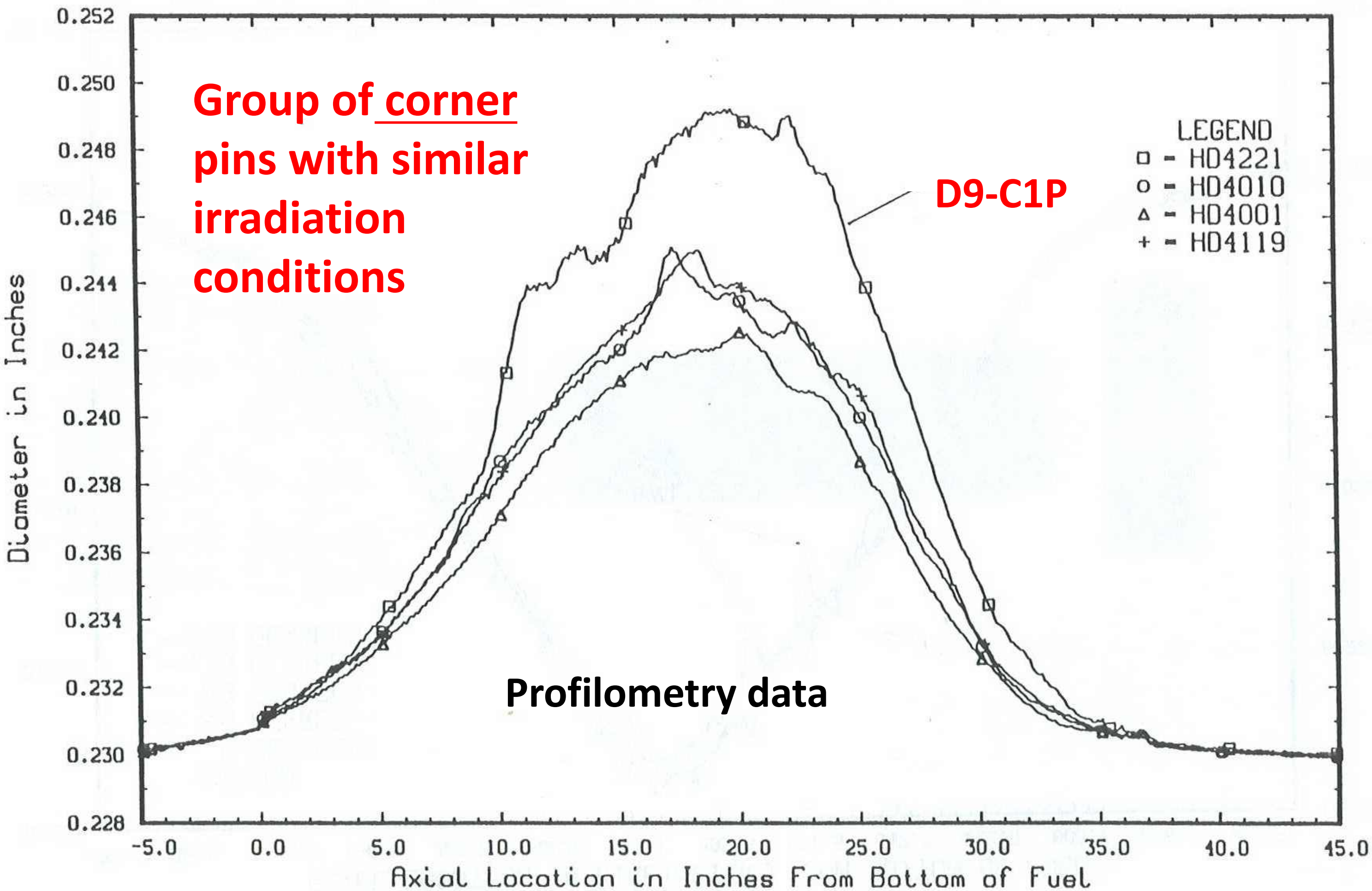
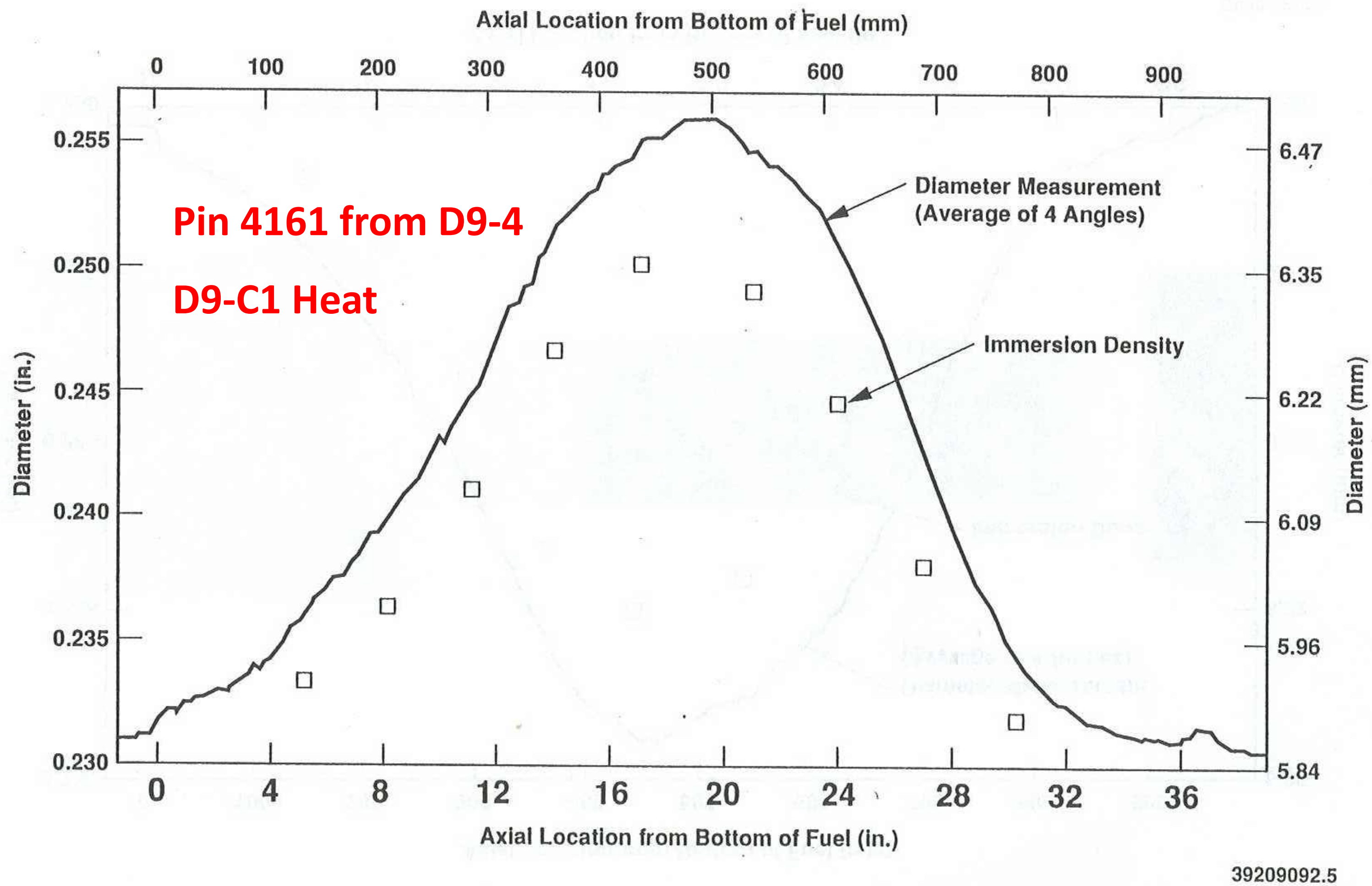


Most radial deformation arises from swelling and not creep



All pins exhibited this behavior.

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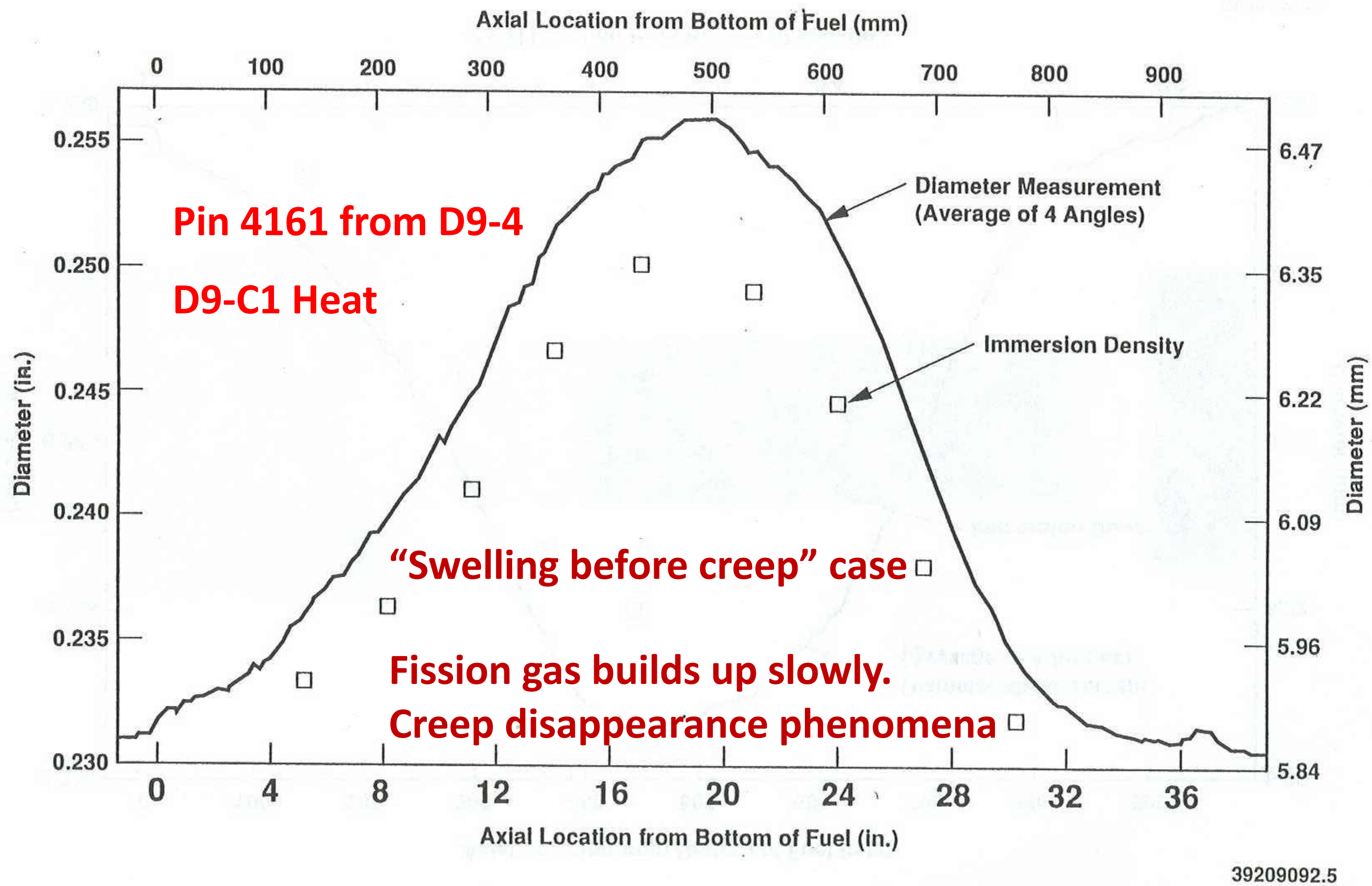
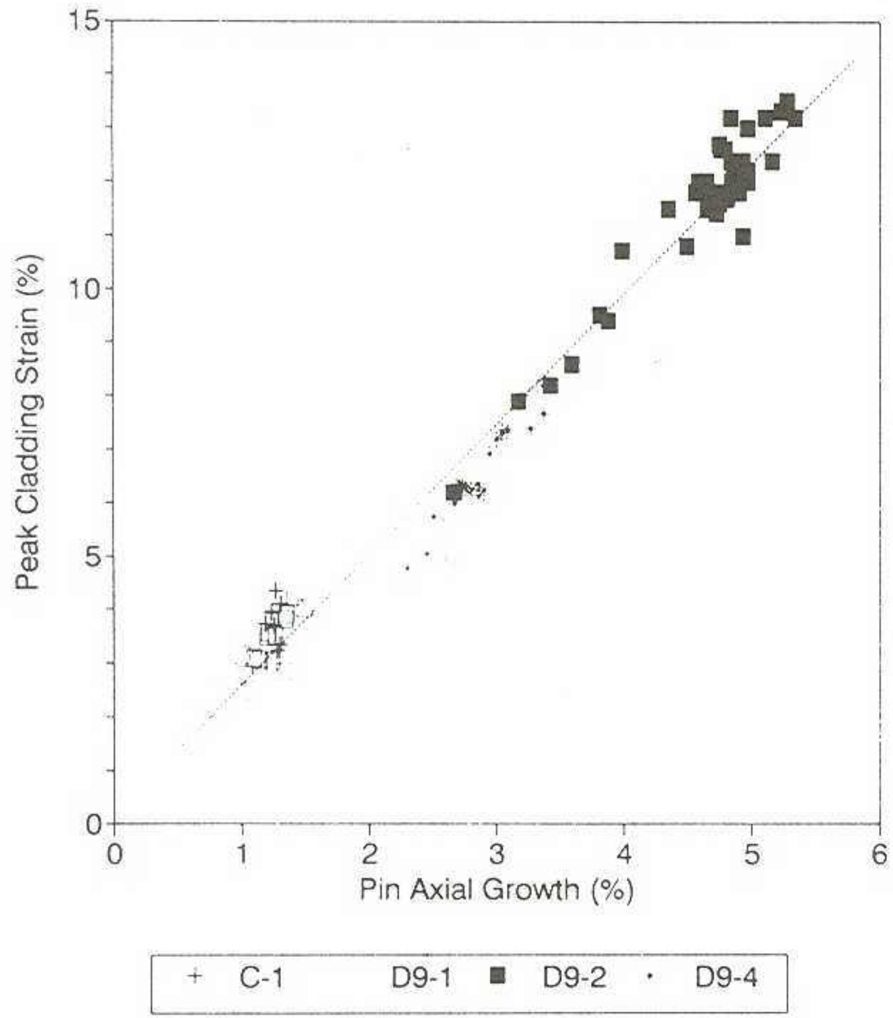


All pins exhibited this behavior.

Correlation between peak cladding diametral strain and axial growth



Length-averaged swelling leads to increase in pin length.

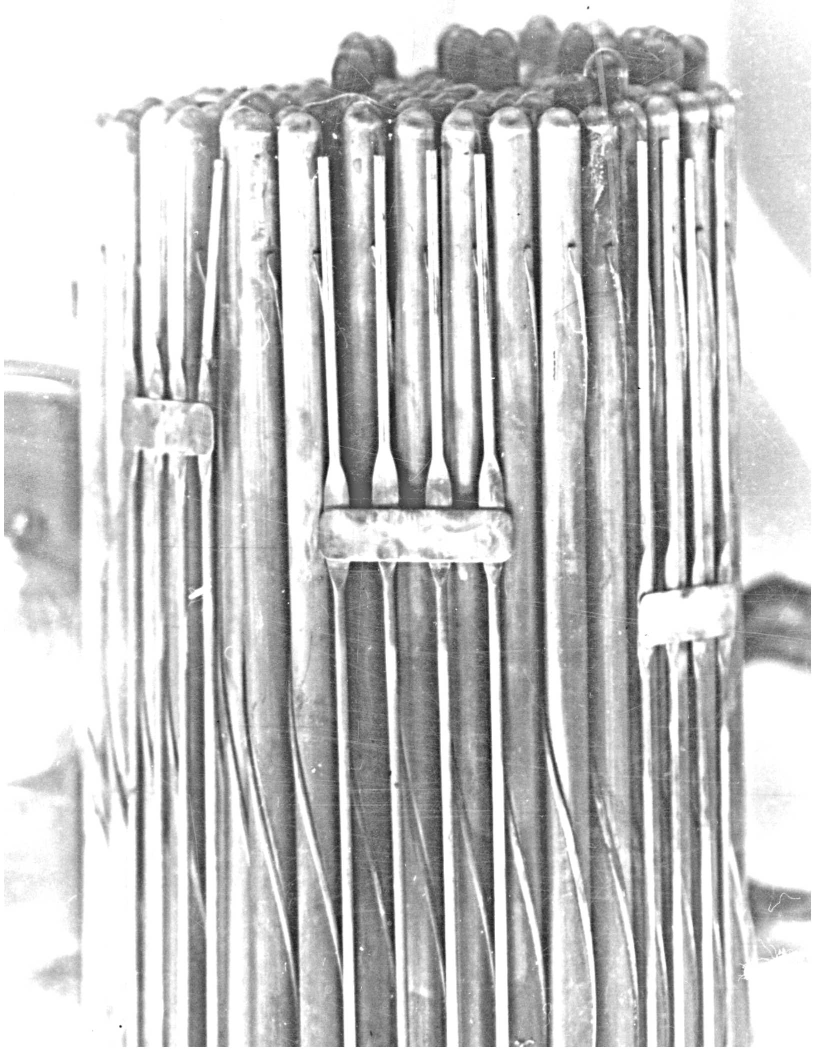
Length increase contains no creep contribution.

Length grows at ~40% the rate of peak radial strain.

Differences in composition, dpa rate and temperature do not affect this relationship!

Top end of fuel pin bundle in BN-600 with annealed EI-847 cladding

Porollo, Shulepin, Konobeev, Garner, 2008



Two heats of fuel pins

Both heats fell within specifications.

C(0.04-0.06); Mn(0.4-0.8); Si≤0.4; S≤0.010; P≤0.015; Cr(15.0-16.0); Ni(15.0-16.0); Mo(2.7- 3.2); Nb≤0.9; N≤0.025; B≤0.001; Co≤0.02; Cu≤0.05; Bi≤0.01; Pb≤0.001; Ti≤0.05, wt. %

Heat #1 was measured to be 0.10 ±0.015 wt. % Si and heat #2 had 0.18 ±0.011 wt% Si.

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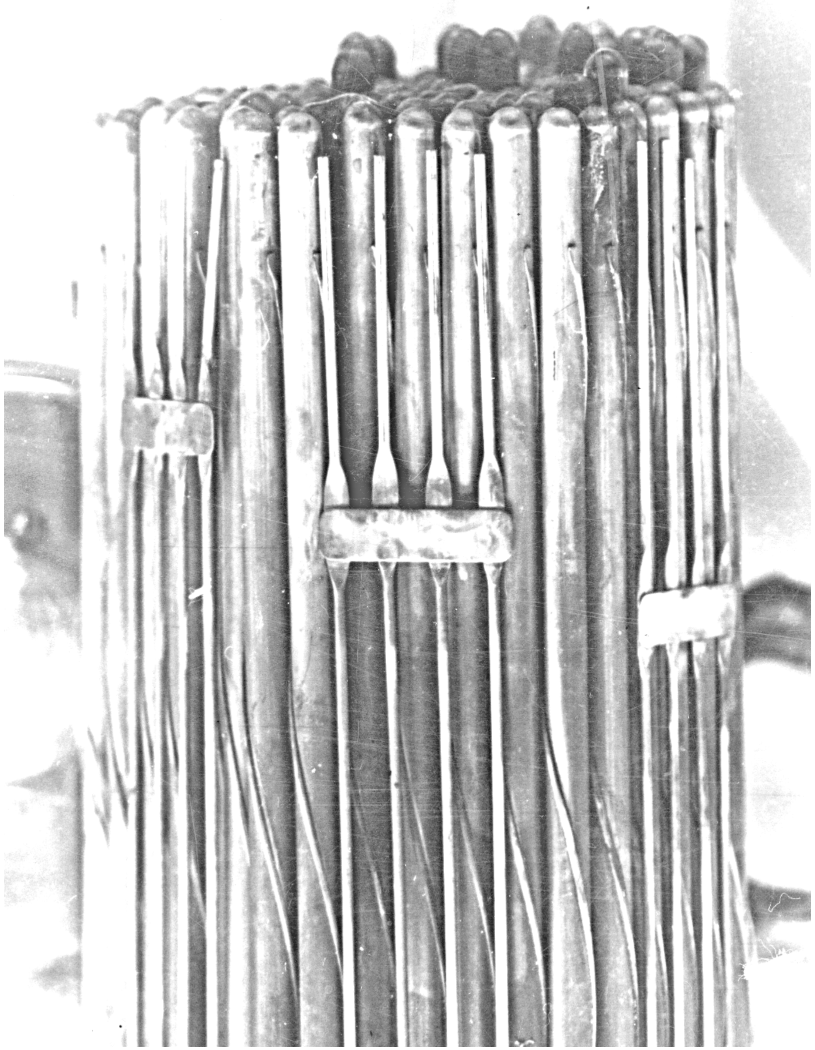

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Heat #1 was measured to be 0.10 ±0.015 wt. % Si and heat #2 had 0.18 ±0.011 wt% Si.

Lower silicon level caused increased swelling.

Remember that per atom, P, Si and C are the most swelling-suppressive elements.

Top end of fuel pin bundle in BN-600 with annealed EI-847 cladding

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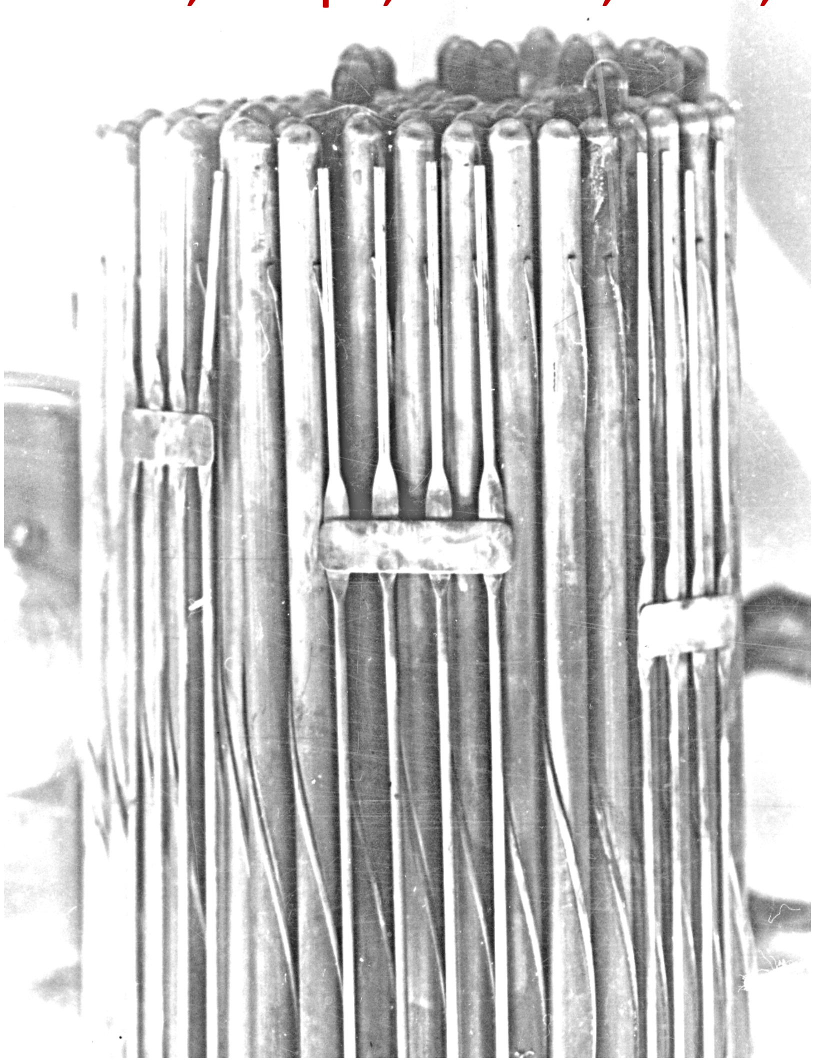
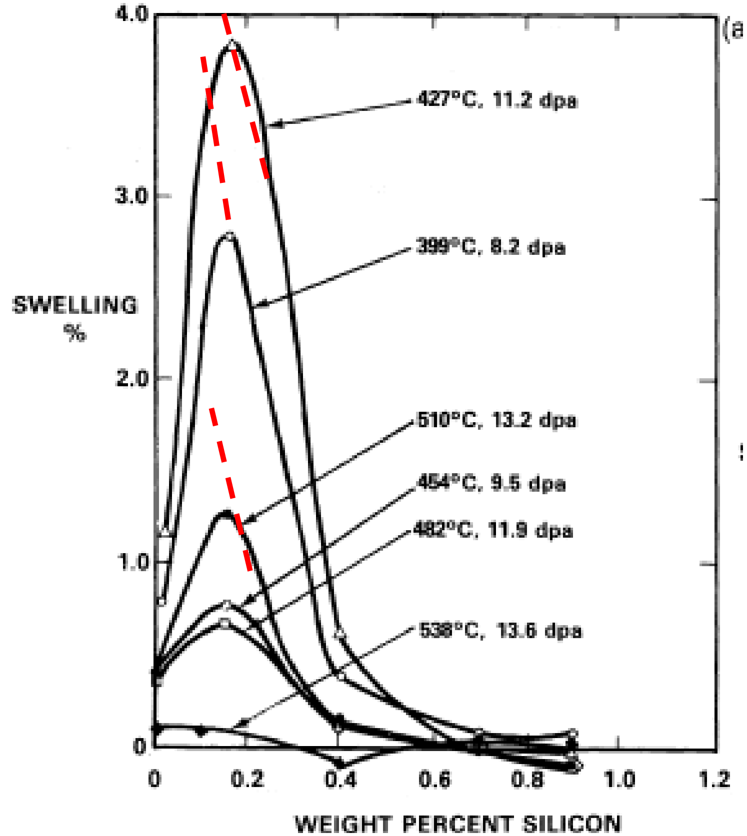


Garner and Kumar, 1987

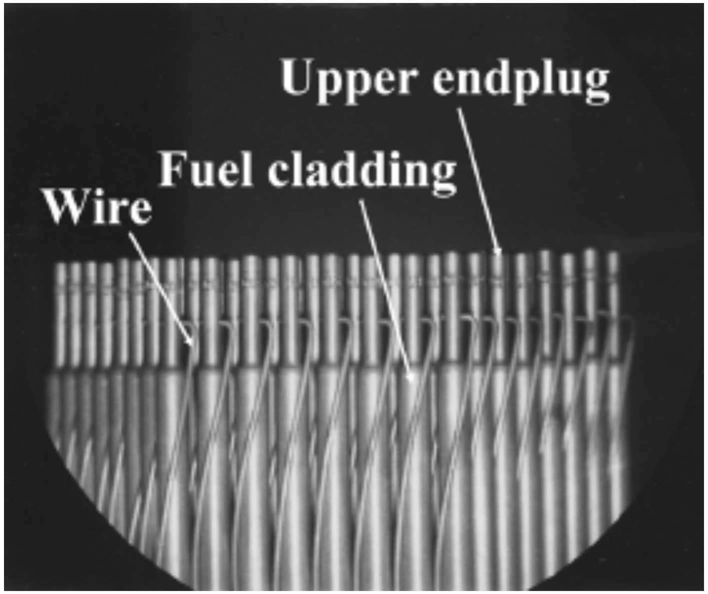


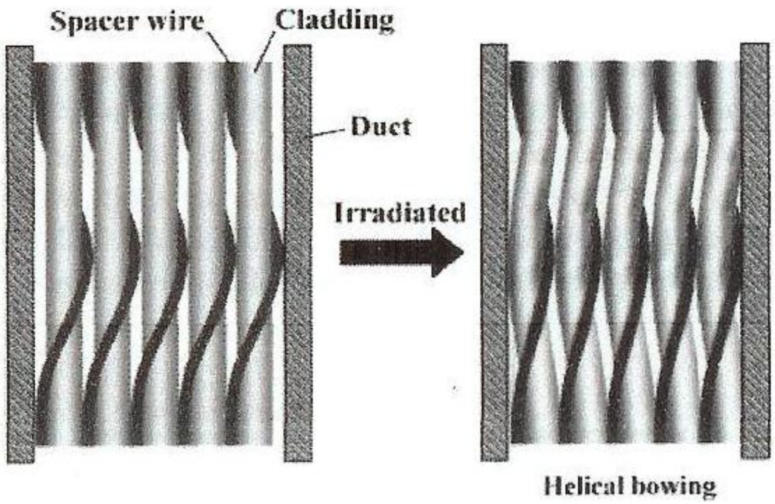
Effect of silicon on swelling of annealed Fe-25Ni-15Cr irradiated in EBR-II

Swelling behavior of FFTF fuel pins under constrained conditions by wire wrap

In presence of constraint the swelling strain is directed by irradiation creep toward unconstrained directions.

Constraints can be externally applied or arise internally from gradients in swelling.





Swelling behavior of FFTF fuel pins under constrained conditions by wire wrap

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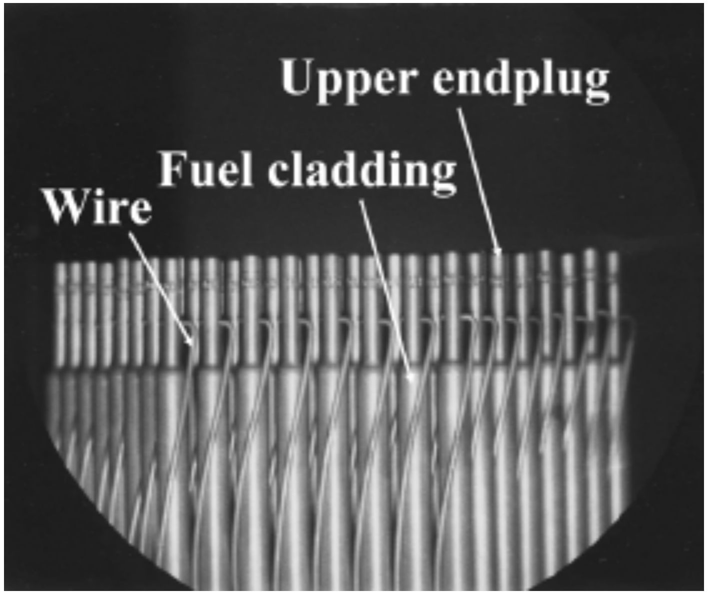
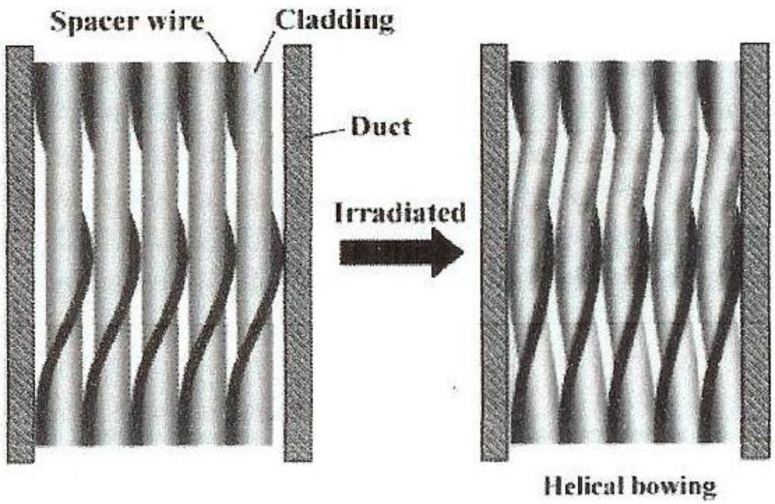
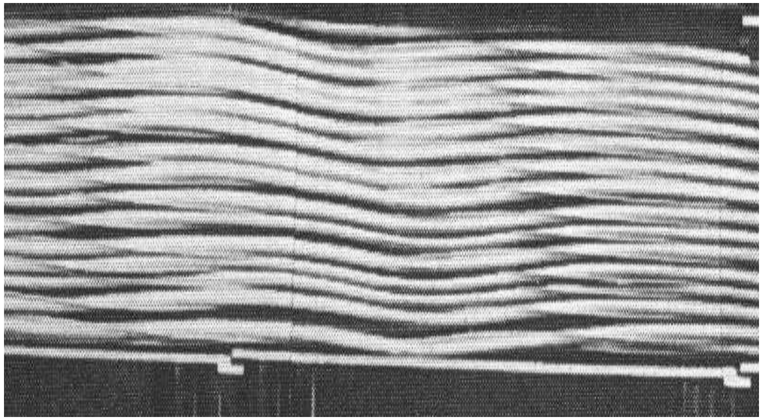
Constraints can be externally applied or arise internally from gradients in swelling.

Stresses generated by swelling or swelling gradients will <u>never</u> exceed the yield stress.



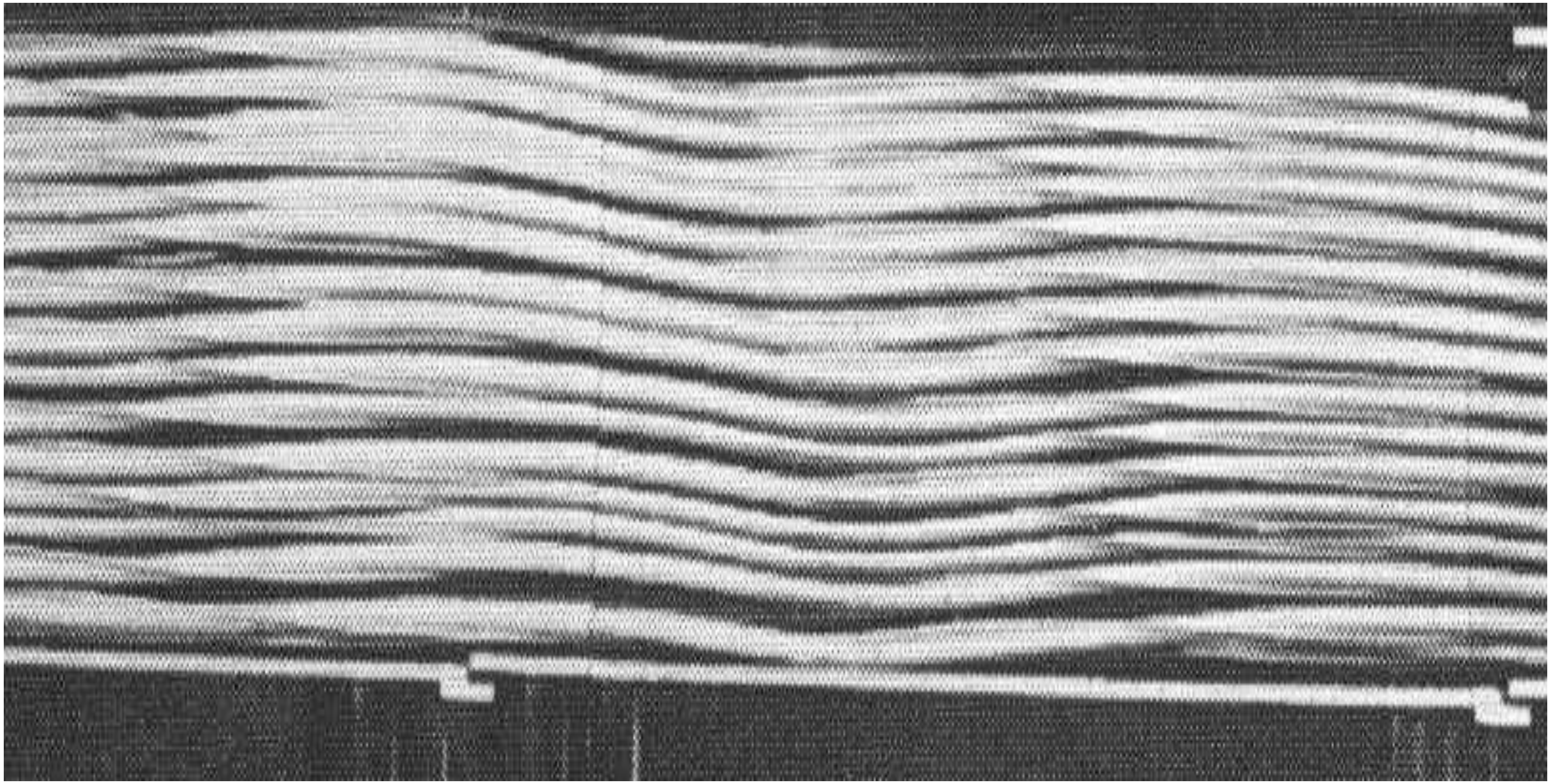




~40% maximum swelling in D9-2

Swelling-creep interaction of clad with with wire wrap to produce spiral pins in FFTF

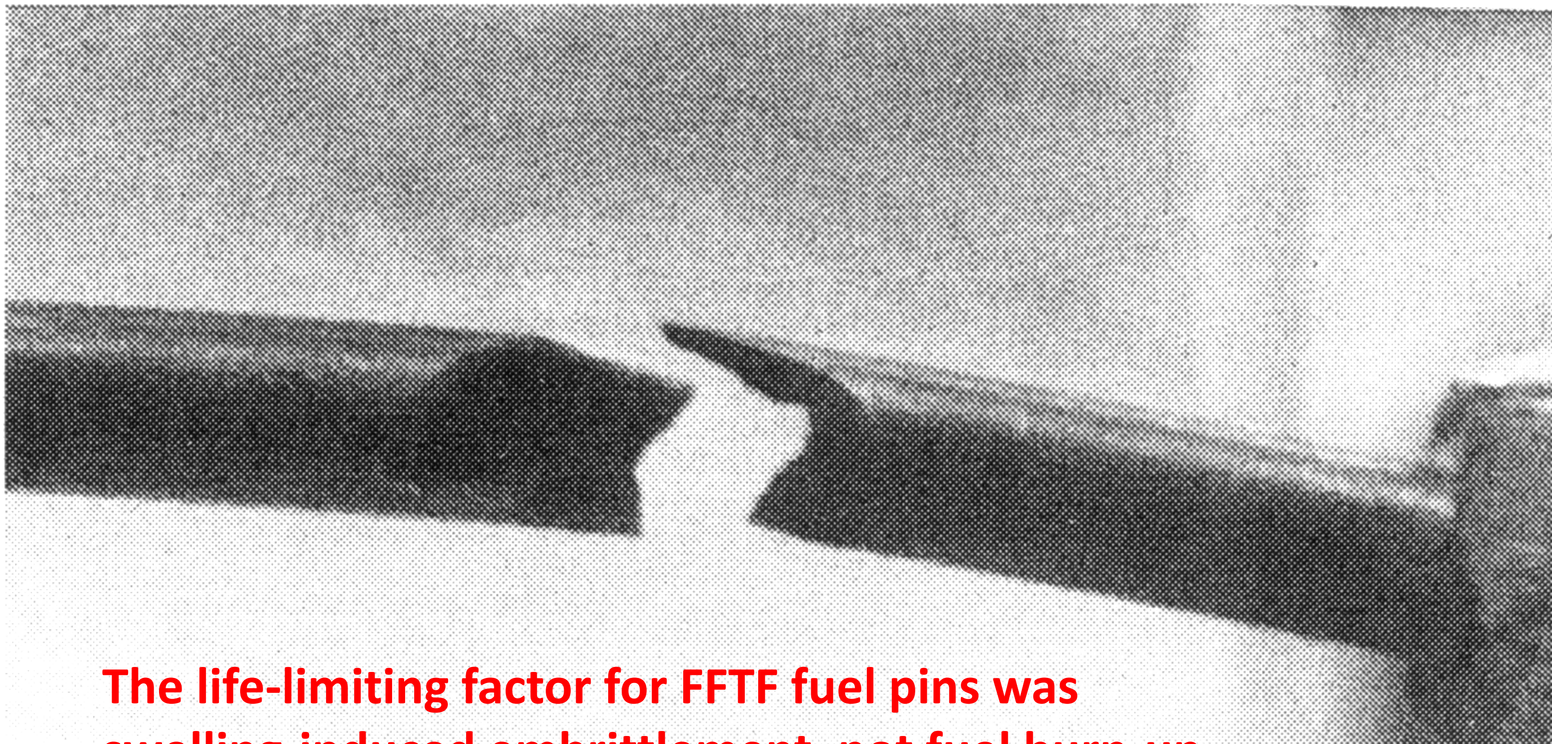
D9-2 assembly



No pin failures were observed even for such large deformation.

Out-of-reactor failure of D9-2 fuel pin after irradiation in FFTF to ~110 dpa

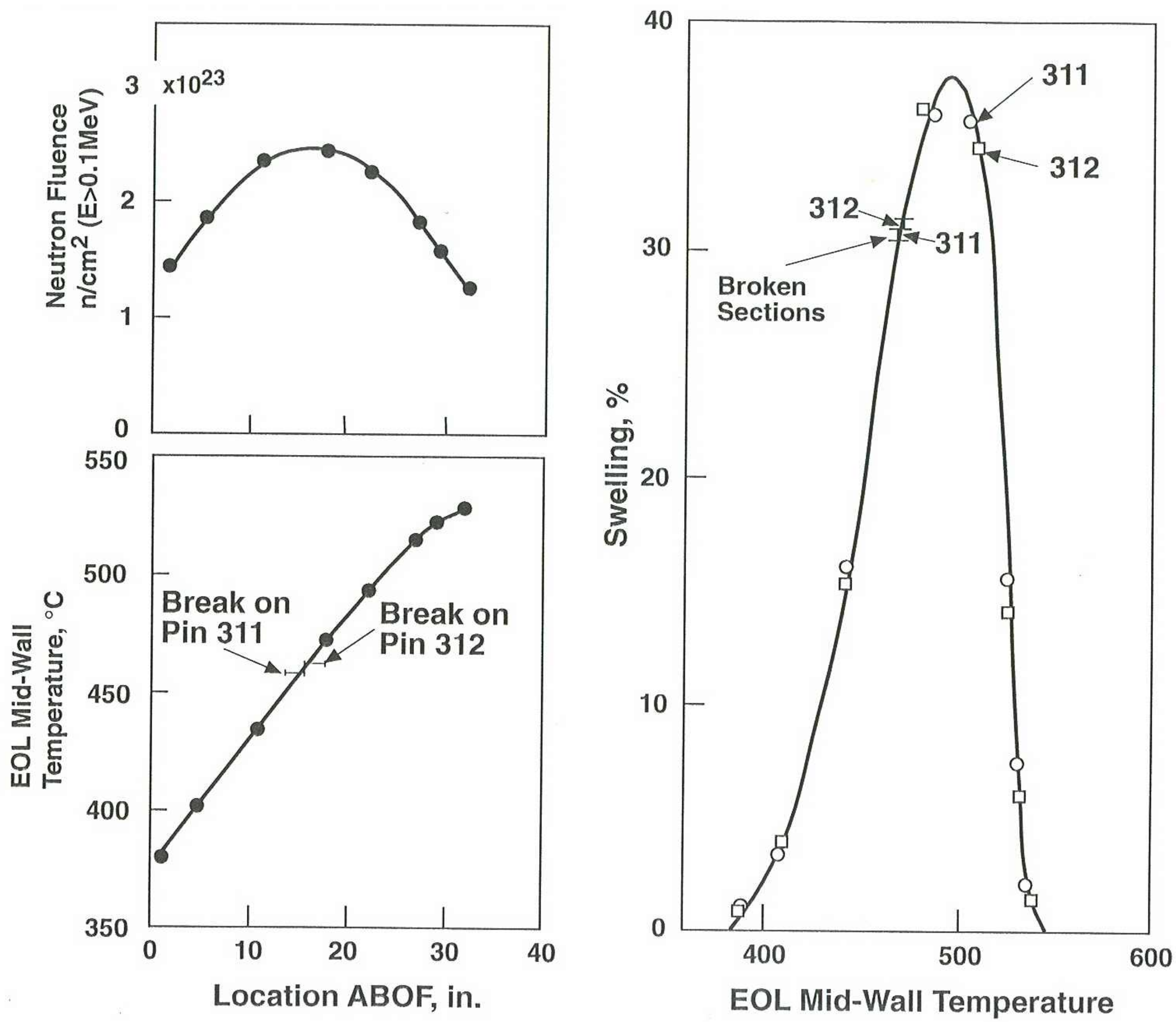
Makenas et al., 1990



The life-limiting factor for FFTF fuel pins was swelling-induced embrittlement, not fuel burn-up.

Two fuel pins were broken upon receiving minor physical insults from the manipulator. There was ~30% swelling at the failure points.

Void-induced embrittlement of two sibling fuel pins in D9-2 assembly



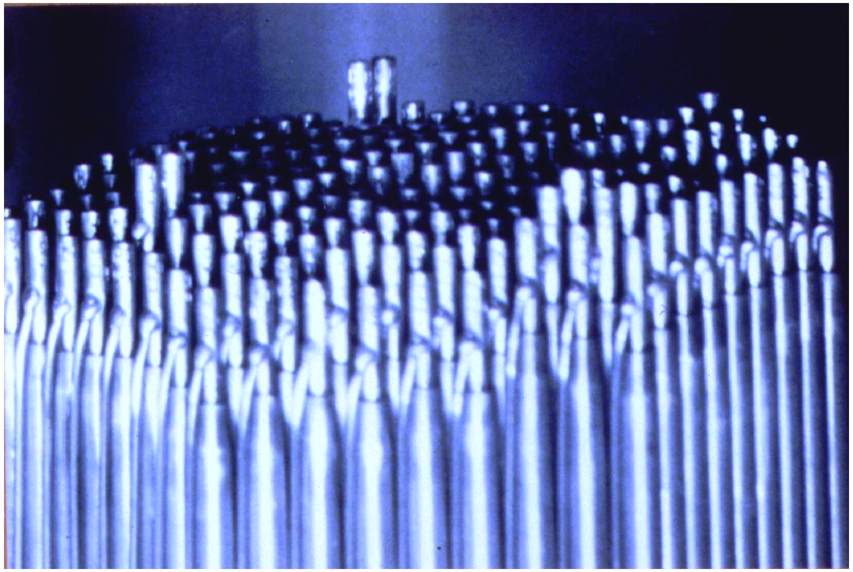
Different physical insult to produce failure in each pin

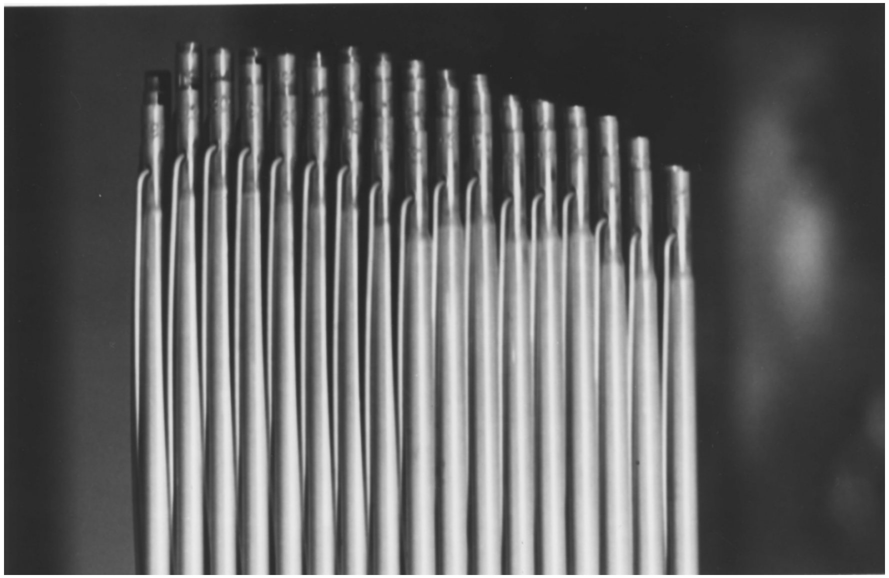
Failure occurred at the same position and swelling level.

The D9-2 duct also showed evidence of cracking during milling of test specimens.

Top of two D9 assemblies showing variable length increases in fuel pins

217 pin assemblies





D9-4 assembly in Row 2 showing increased length change due to higher swelling of D9-C1P pins compared to D9-C1 pins

Difference is due primarily to the lower phosphorous level in D9-C1P.

D9-2 assembly in Row 4 showing higher swelling and length change of D9-C1 pins located closer to the core center

Difference is due primarily to the flux gradient across the assembly.

Conclusions

- **Various D9 heats are more resistant to swelling than AISI 316 heats.**
- **Minor variability in composition of D9 leads to significant differences in swelling behavior.**
- **Variations in phosphorus are especially important.**
- **It is necessary to define both upper and lower limits of composition specifications for uniformity of response.**

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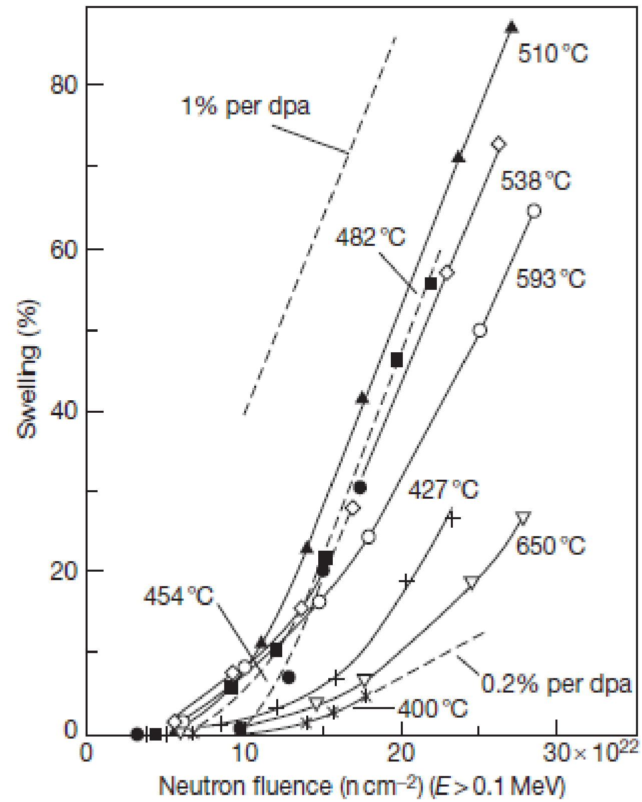
- Post-transient swelling rate is ~1%/dpa over a wide range of temperatures, at least 420 to 540°C ….. probably even more!
- High swelling leads to large axial growth of pins and development of spiral ovality.
- **While high swelling does not lead to direct in-reactor failures, post-irradiation examination shows severe embrittlement during examination.**
- **Embrittlement is very sensitive to the temperature when the physical insult is experienced.**
- **Root causes are martensite instability arising from segregation at void surfaces and stress concentration between voids.**

A broader set of conclusions



There are two kinds of swelling experiments.

Well-controlled minimum variable experiments

Real-life complex-history devices, i.e. fuel assemblies

Void swelling exhibits a smaller than imagined amount of "inherent" data scatter.

Most "scatter" is just information that you do not recognize.

"Scatter" arises first from the strong sensitivity of swelling to very minor variations in composition and especially to thermal-mechanical processing.

Additionally, swelling is very sensitive to details of temperature history and neutron flux-spectrum.