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Prepared for the U.S. Department of Energy
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DIMENSIONAL CHANGES IN FFTF AUSTENITIC CLADDING AND DUCTS

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ABSTRACT

As the standard cladding and duct material for the Fast Flux Test Facility driver fuel, 20% cold-worked 316 stainless steel has provided good service up to a fast fluence of 16 x 10^{22} n/cm^2 in extreme cases. The titanium-stabilized variant of 316 SS, called D9, has extended the useful life of the austenitic alloys by increasing the incubation fluence necessary for the onset of volumetric swelling. Duct flat-to-flat, length and bow, pin bundle distortion, fuel pin diameter and length, as well as cladding volumetric swelling have been examined for high fluence components representing both alloys. These data emphasize the importance of the swelling process, the superiority of D9, and the interrelation between deformations in the duct, bundle, and individual pins.

INTRODUCTION

The behavior of titanium-stabilized D9 alloy and 316 stainless steel (SS) in fueled tests has been compared previously for relatively low fluences achieved in both the Fast Flux Test Facility (FFTF) and EBR-II.[1,2] The use of D9 has extended the useful life of austenitic alloys in sodium-cooled fast reactors by increasing the incubation fluence necessary for volumetric swelling. This paper discusses some of the higher fluence dimensional change data (up to 25 x 10^{22} n/cm^2, E > 0.1 MeV) from an ever-increasing number of D9 ducts and fuel pins and reviews earlier data from 316 SS components. Radial, axial, and volumetric changes were considered as well as component bowing. All of the cladding data derive from actual fuel pins containing uranium/plutonium mixed-oxide in a 0.91-m (36-in.) fuel column. These wire-wrapped pins were uniformly 5.84 mm (0.230 in.) in diameter with cladding thickness of 0.38 mm (0.015 in.). All of the duct data were obtained from 3.18 mm (0.125 in.) thick ducts each containing a bundle of 217 fuel pins. These data continue to be used by various investigators as a way to validate materials performance correlations and as a complement to data from nonfueled irradiated materials.

As the standard cladding and duct material for the FFTF driver fuel, 20% cold-worked (CW) 316 SS has provided good service in cores with peak fast fluences of approximately 12 x 10^{22} n/cm^2. Selected assemblies have been allowed to run to as high as 16 x 10^{22} n/cm^2 although large numbers of such swelled assemblies could not be accommodated in a typical core because of refueling difficulties.

Cold-worked D9 alloy cladding and ducts have been used on a number of experimental assemblies in FFTF. The nominal compositions of 316 SS and D9 used in FFTF are compared in Table 1. The principal variation is of course in titanium, but other elements vary slightly also. Compositions for two cladding heats of D9 are given because the two subsets of cladding made from these heats behaved differently. None of the cladding/duct alloys currently on high exposure assemblies is from the high phosphorous/high boron variants of D9 which promise even greater reductions in radiation-induced dimensional increases. Although ferritic alloys have even better resistance to swelling, austenitic alloys are attractive because of their greater high temperature strength.

Table 1. D9 Composition.

	Ni	Cr	Mo	Si	Mn	Ti	C
AISI 316 (Nominal)	13.5	17.5	2.5	0.6	1.75	--	0.05
D9 (Early Cladding Heat)	15.2	13.8	1.46	0.92	1.74	0.23	0.052
D9 (Later Cladding Heat)	15.8	13.7	1.65	0.80	2.03	0.34	0.39
D9 (Duct Heat)	16.1	13.5	1.50	0.97	1.70	0.20	0.048

EXPERIMENTAL MEASUREMENTS

Fuel assemblies of interest were first removed from the FFTF core and cleaned of sodium coolant using a water wash. The dimensions of hexagonal ducts were then measured in the Core Component Measuring Machine[3] in the Interim Examination and Maintenance Cell at FFTF. This instrument measures radial distance and axial length as well as bow of an irradiated duct. Radial dimensions were measured every 2° around the duct circumference at selected axial positions resulting in flat-to-flat and corner-to-corner determinations accurate to 0.102 mm (0.004 in.). Length and bow measurements are judged to be accurate to 0.381 mm and 0.635 mm (0.015 in. and 0.025 in.) respectively. These postirradiation measurements agreed very well with in-situ duct length measurements made using the fuel handling machines in the FFTF core. Preirradiation duct dimensions were nominally 116.2 mm (4.575 in.) flat-to-flat and 3.1 m (121 in.) long. Bow was defined as a maximum deviation from a line joining the ends of a duct.

After removal of the duct from each individual assembly, the bundles of pins were inspected and individual pins were selected for detailed examination. Postirradiation axial and diametral dimensions of fuel pins were determined by either laser or contacting devices. Typically, diameter profiles were performed at several circumferential orientations. These data were compared to previously measured as-fabricated base values. Cladding volumetric void swelling (one component contributing to cladding and duct diameter change) was determined by immersion density measurement performed on defueled irradiated cladding rings sectioned from fuel pins or on samples machined from duct faces.

DUCT BEHAVIOR

Reference 4 emphasizes the importance of monitoring the dimensional changes of in-core ducts in that the life-limiting factor for the FFTF driver fuel systems was the deformation and increased withdrawal loads associated with duct swelling. It is also obvious that ducts cannot be allowed to grow indefinitely in length without hindering the operation of fuel handling machines.[a] The peak flat-to-flat dimensional increase observed in FFTF for 316 SS (20% CW) ducts occurred in an assembly irradiated to a fast fluence of 16 x 10^{22} n/cm^2 (E > 0.1 MeV).[1] The maximum dilation was approximately 7.6 mm (0.300 in.) at an axial position slightly above mid-core (Figure 1). Similar maximum deformation was not reached in D9 alloy ducts until a fluence of 24 x 10^{22} n/cm^2 with the peak dilation positioned slightly below mid-core. These highly deformed assemblies were irradiated in a core made up of primarily lower exposure assemblies; therefore, one should not infer that an entire core could be taken to these fluences with austenitic alloys.

In a number of high fluence ducts, the overall profile of duct deformation is superimposed over a regularly spaced series of localized strain peaks (Figure 2). These peaks do not occur at the same axial position for adjacent

[a]A rather complete history of the run-by-run core component performance and refueling behavior can be found in Reference 5.

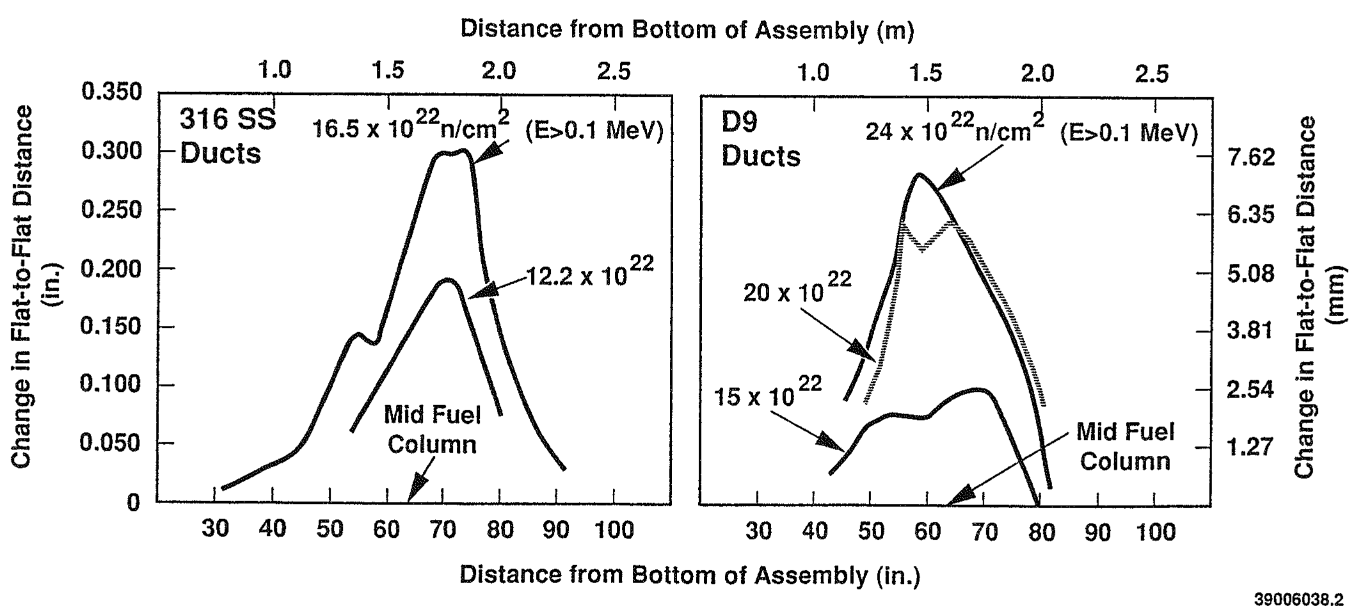

FIGURE 1. Peak Flat-to-Flat Dilation Observed in 316 SS and D9 Ducts Irradiated in FFTF. [Only the most deformed set of flats is shown for each. Unirradiated ducts were originally 116 mm (4.575 in.) across flats. Fuel columns were 0.91 m (36 in.)].

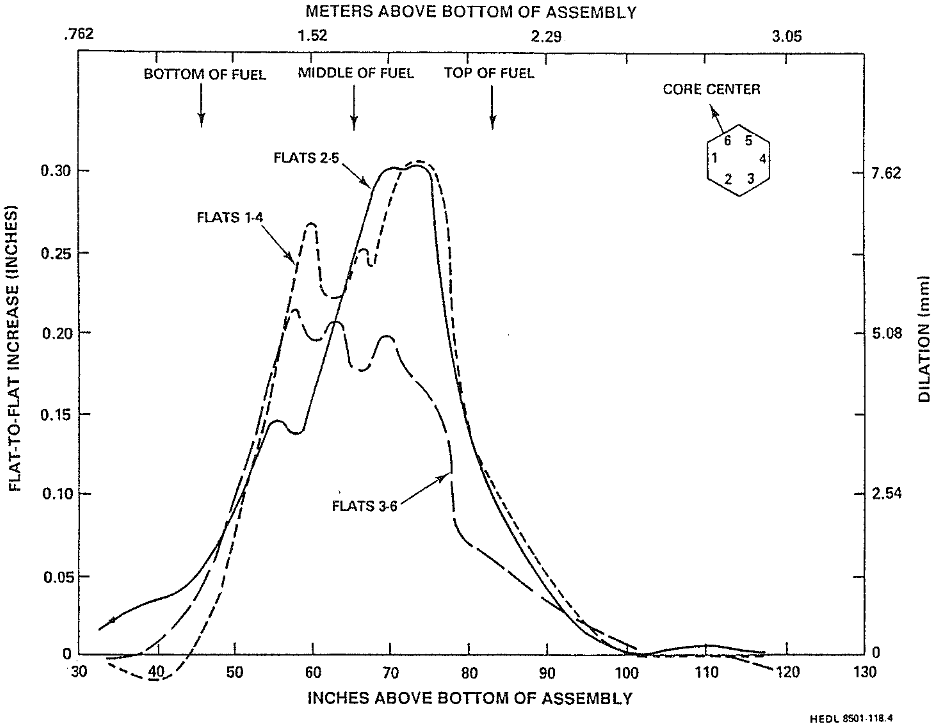

FIGURE 2. Flat-to-Flat Measurements for a Single Duct (316 SS at 16 x 10^{22} n/cm^2 peak fast fluence). Note local peaks in each trace.

duct faces. When the radial displacement data for each individual duct face are examined (as opposed to taking a flat-to-flat point of view) strains that spiral along the duct in a pitch of 305 mm (12 in.) are apparent. This is exactly the pitch of the wire wrap for the underlying pins and therefore the localized strains are taken as an indication of interaction between pin bundle and the duct. Plots of flat-to-flat dilation versus axial position thus show a local peak every 152 mm (6 in.).

Length changes of austenitic ducts measured after irradiation have been adequately covered in several papers.[4,5] These values have ranged from 15.7 mm (0.62 in.) in the case of 316 SS to 10.9 mm (0.43 in.) for D9 at the peak fluences of interest. The greatest observed residual bow was measured for an outer row (FFTF Row 6) 316 SS assembly which reached 9.7 mm (0.380 in.) at a fast fluence of 11 x 10^{22} n/cm^2. All assemblies to date have shown the trend of increasing residual bow with increasing distance from the radial core center (at a given fluence).

DEFORMATION OF THE PIN BUNDLE

After the duct is removed from an assembly, the condition of the intact bundle of pins is observed (Figure 3). In the case of very high fluence assemblies, a distinct waviness in the bundle was seen. The waviness corresponds to the permanent spiral deformation of individual pins. These strains are first observed at the point in life where the porosity of the bundle, i.e., the space remaining for pins and wires to swell into, is calculated to be zero in some directions. Pins must then move laterally and/or vertically to accommodate additional void swelling. Different swelling rates in wire versus cladding may also play a role.

The top of the bundle (Figures 4 and 5) also shows the effects of void swelling. For assemblies beyond the incubation fluence of swelling, the length of pins varies with the fluence gradient, with temperature and, in the case of D9 alloy, with cladding heat. Thus pins on the side facing core center will be longer than those on the opposite side; pins adjacent to the duct will not grow as much as more centralized pins; pins clad with different alloy heats will show remarkably different stature.

FUEL PIN DIAMETER CHANGES

Peak diameter changes in pins from the highest fluence (16 x 10^{22} n/cm^2, E > 0.1 MeV) 316 SS clad driver assembly ranged from 0.43 mm to 0.71 mm (0.017 in. to 0.028 in.), i.e., a maximum change of about 12%. Similar pins at goal fluence from interior assemblies (13 x 10^{22} n/cm^2, E > 0.1 MeV) exhibited only 6% diameter change. Fuel pins with D9 cladding did not exceed 12% diameter change until fast fluences in excess of 20 x 10^{22} n/cm^2 were reached (Figure 6).

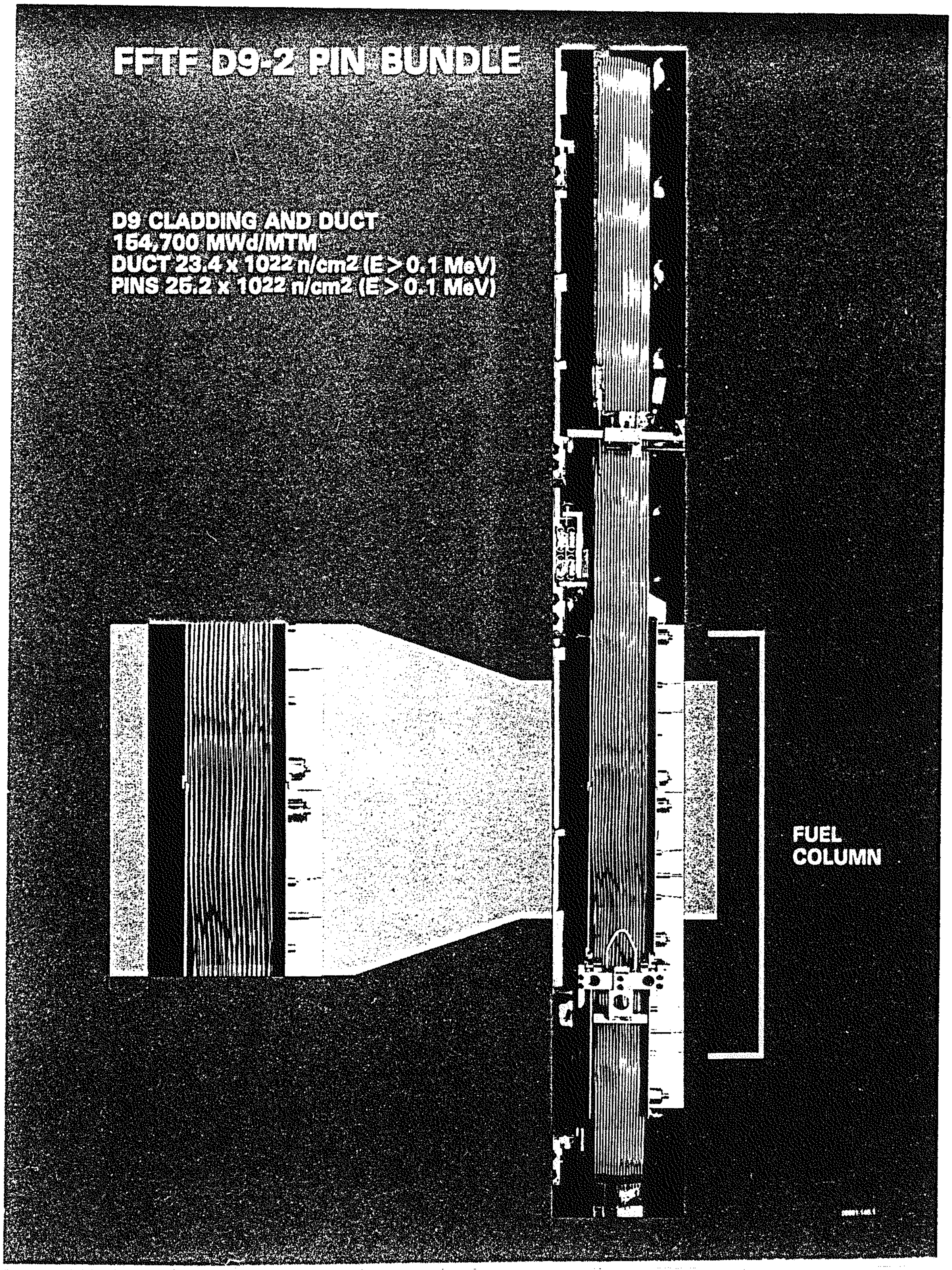

FIGURE 3. A Bundle of 217 D9 Clad Pins from a High Fluence Assembly.

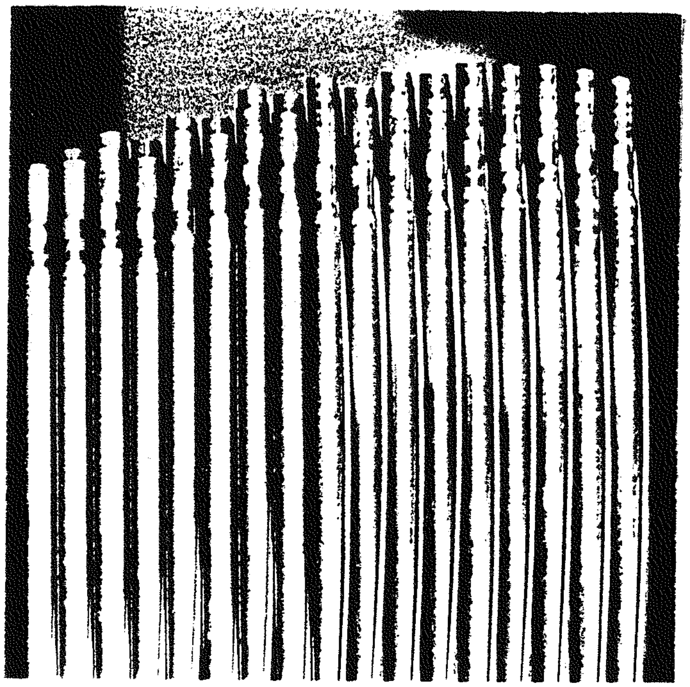

FIGURE 4. The Top of a Bundle of Irradiated 316 SS Clad Pins. Note the effects of temperature and fluence gradients.

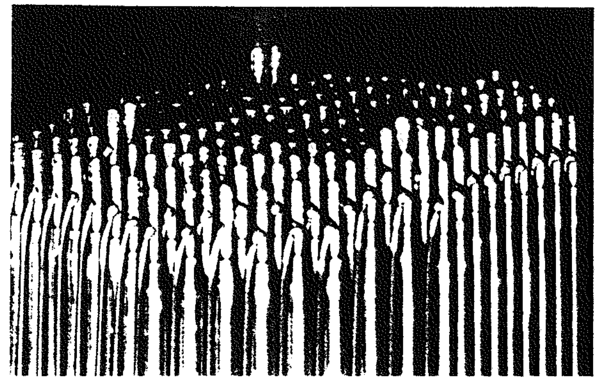

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FIGURE 5. Top of a Bundle of Irradiated Pins Clad with D9 Alloy. Note the varying length of pins due to differing alloy heats (fast fluence is 21 x 10^{22} n/cm^2).

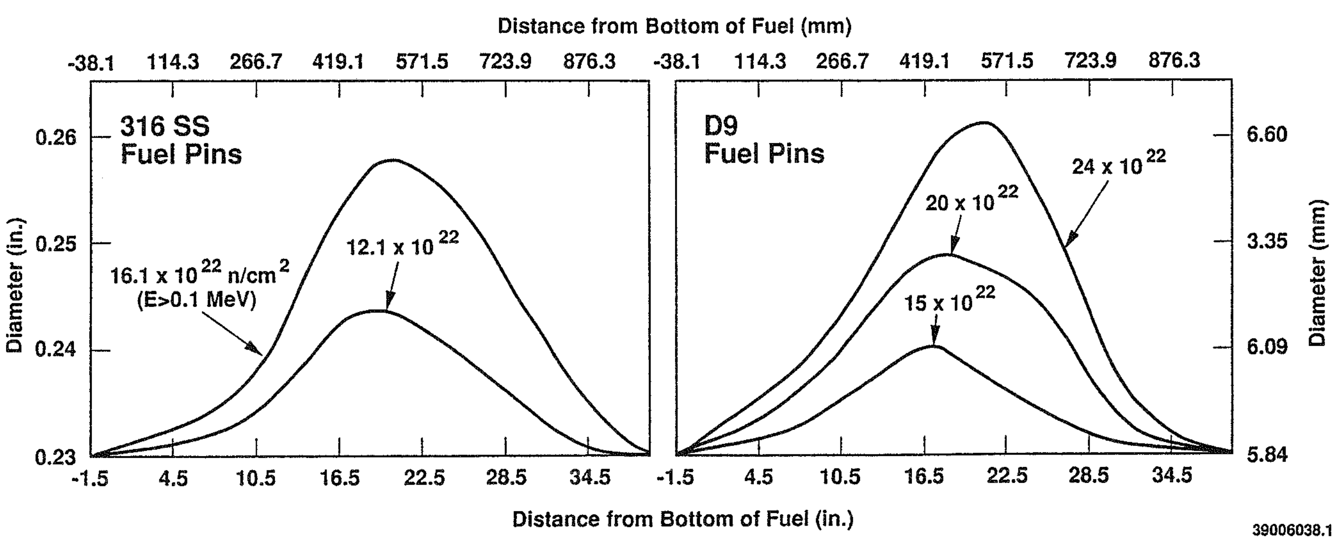


FIGURE 6. Diameter Measurements from CW 316 SS and CW D9 Clad Fuel Pins Irradiated in FFTF. [Unirradiated fuel pins were 5.8 mm (0.230 in.) in diameter. Each diameter profile shown is the average of four continuous traces made at different circumferential orientations.]

Driver pins irradiated on the periphery of the core for a similar time exhibited smaller diameter increases because of their lower overall fluence. However, these outer row driver pins showed the greatest variation in diameter from pin to pin because of the steep fluence gradients at the core extremity (Figure 7).

Most of the higher fluence pins showed some degree of ovality. An extreme case is shown in Figure 8. These asymmetrical deformations are thought to be related to pinch planes in the assembly where, as described above, bundle porosity is scarce.

FUEL PIN LENGTH CHANGES

Length changes of low smear density austenitic clad fuel pins are generally driven by the neutron-induced void swelling. Thus the observed increases in length (Figure 9) are a measure of the integrated swelling of the cladding tube as it experiences varying temperatures and fluences at different axial positions. Measured length increases have approached 50 mm (2 in.) and the use of lower swelling D9 has delayed the onset of significant length increase by about 6×10^{22} n/cm^2 fast fluence. The scatter in the data shown is attributable both to pins operating at different maximum temperatures and the use of different alloy heats as seen visually during examinations of the tops of intact bundles.

CLADDING SWELLING

Immersion density measurements have shown that in both the 316 SS and D9 cases, for the majority of ducts and fuel pins, most of the diameter change is due to void swelling and not to creep driven processes. It can be seen in Figure 10 that swelling of the austenitic alloys exhibits the classical behavior of neutron induced swelling i.e., an incubation period followed by a relatively linear increase in swelling with fluence. Type 316 SS and alloy D9 have reached 17% and 37% volume increase at their respective peak fluences of 14 and 24×10^{22} n/cm^2. When these volumetric measurements are compared on an integrated basis with pin length increases, the behavior is fairly isotropic. As intended, D9 exhibits a longer fluence incubation period at the higher temperatures than 316 SS. The D9 alloy in hand has not, however, fulfilled the promise of early overly optimistic swelling correlations. This is probably because these early correlations incorporated some data from non-D9 generic titanium-stabilized material. At lower temperatures the D9 data shows considerable scatter. This is partially due to the fact that the D9 data set incorporates more diverse heats of material than the 316 SS. However, the lower temperature data also includes much more duct material which is prone to more variations in cold work level than is cladding.

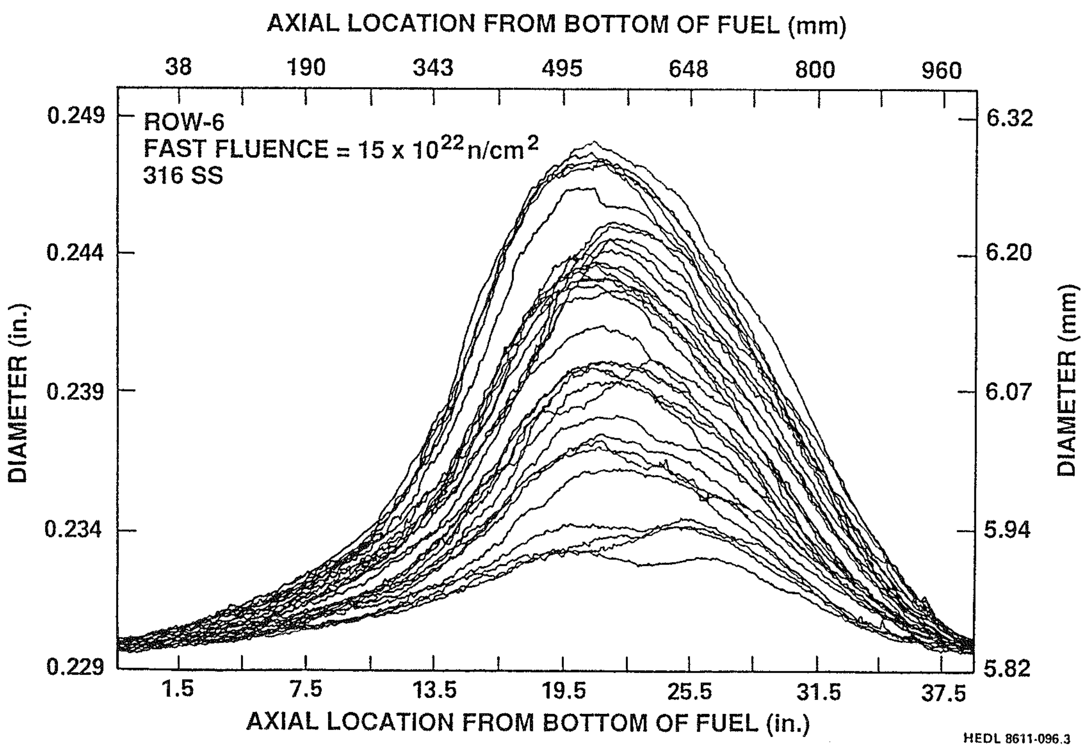
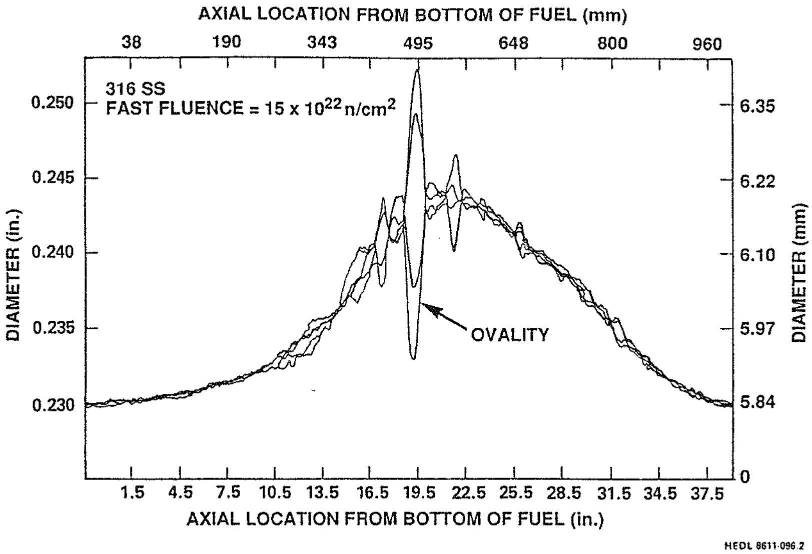


FIGURE 7. Diameter Measurements from a Large Number of Pins from the Same Subassembly. Each curve is the average of several traces each taken at a different circumferential orientation around a fuel pin. Data are from an outer row assembly.



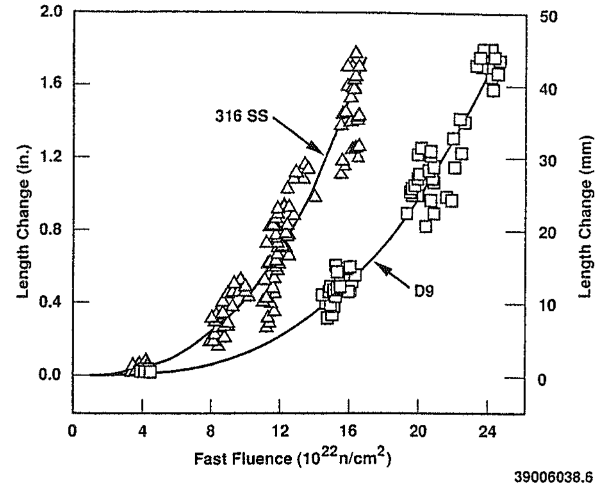
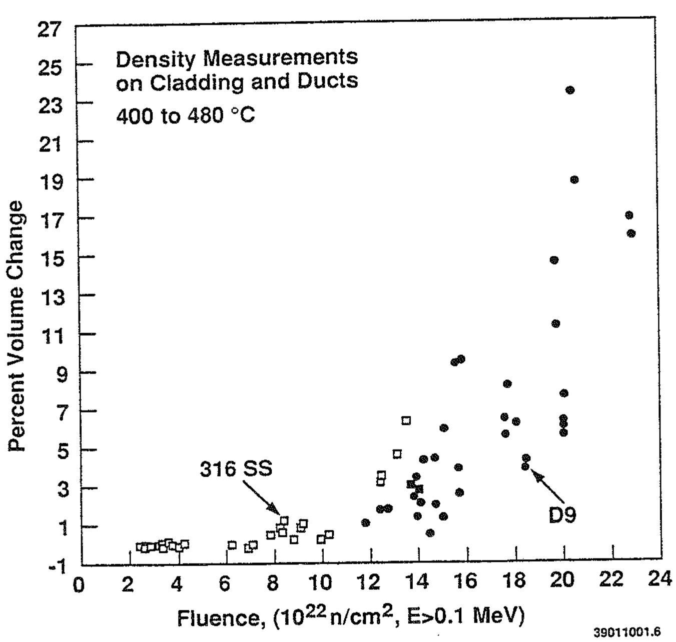


FIGURE 8. Diameter Measurement from a Single Pin. Each curve is a diameter trace taken at a different circumferential orientation.

FIGURE 9. Length Changes Measured for 316 SS and D9 Clad Fuel Pins from FFTF Assemblies. [Unirradiated pins were approximately 2.4 m (93 in.) long.]



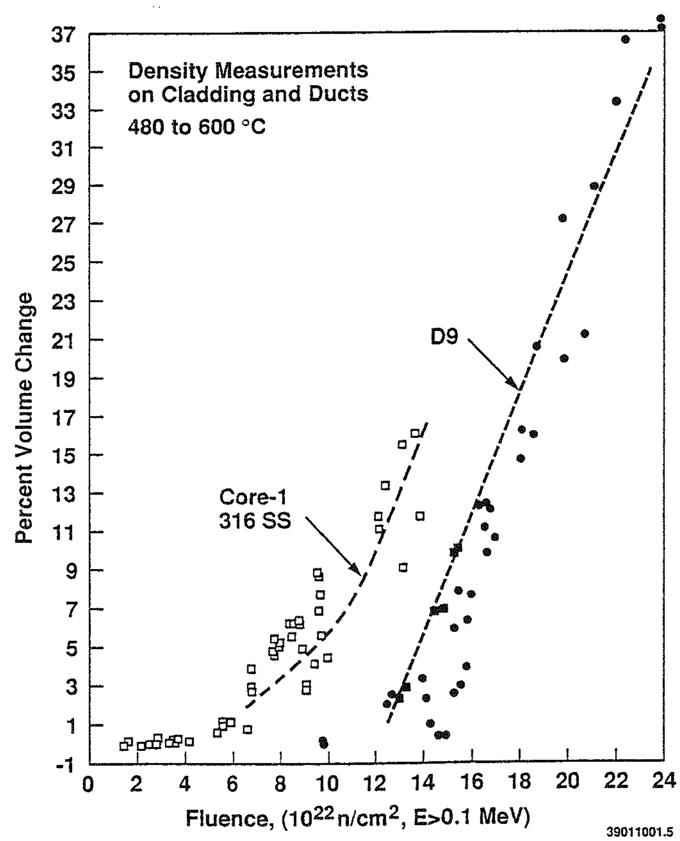


FIGURE 10. Cladding Swelling in D9 and 316 SS. Each point represents a sample taken from an actual fuel pin or duct. Temperatures are time averaged.

DISCUSSION AND CONCLUSION

The life-limiting factor in the FFTF driver fuel system proved to be the expansion of and interference between austenitic ducts. Studies at other facilities[6] have suggested that bundle-duct interference can also, in some cases, be a life limiter in fast reactors. Highly swelled austenitic fuel pins also tend toward increasingly brittle behavior with higher fluence[7,8] (a fact observed by the authors). Nonetheless, the use of cold-worked 316 SS as a cladding and duct material has allowed FFTF to attain and exceed its design goals in flawless fashion. Dimensional increases have been notable (up to 7.6 mm increase in duct flat-to-flat and nearly 50 mm increase in pin length) but not unexpected. The deformation of irradiated ducts, the shape and porosity of the pin bundles, the shape and ovality of individual pins are all interrelated. They are also simultaneously related to irradiation conditions and material swelling and creep rates (with all the various temperature dependencies). The use of a related austenitic alloy, D9, has allowed the fluence goals and expectations set for 316 SS to be significantly exceeded (to fast fluences greater than 17 x 10^{22} n/cm^2 in recent design cases).

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