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CLADDING DIMENSIONAL CHANGES IN MIXED OXIDE FUEL PINS

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CLADDING DIMENSIONAL CHANGES IN MIXED OXIDE FUEL PINS

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Several types of stainless steel (304, 316, 316-20% Cold Worked, and 316 Titanium stabilized 20% CW) (Figure 1) have been used as cladding for mixed oxide (U, Pu)O_2 fuel pins irradiated in EBR-II. All of the materials have performed satisfactorily in their respective experimental subassemblies but significant differences in swelling and inelastic strain behavior have been found at high fast fluences among the different materials and among different heats of the same material.

Cladding diameter increases were measured for 622 developmental and FFTF reference design fuel pins which were irradiated in 19 experimental subassemblies.(1) Fuel pin diameters were determined from multiangle axial trace profilometry measurements. The contribution of cladding swelling to the total diameter change was determined by immersion density measurements for 137 of these pins. Inelastic strain was assumed to be the difference between the percent total diameter change and 1/3 of the measured percent volume change. Figure 2 shows the range of temperature and fluence for which data are available.

Fuel pins clad with solution annealed type 304 stainless steel attained peak diameter changes of 6% at a maximum fast fluence ($E > 0.1$ MeV) of 12.7×10^{22} n/cm^2 (Figure 3b). Nearly all of this diameter change was due to swelling and not to irradiation or thermal creep. The observed cladding swelling was in excellent agreement with correlations derived from unfueled cladding data (Figure 4).(2)

Other developmental fuel pins were clad with solution annealed 316 material and irradiated to a peak fast fluence of 10×10^{22} n/cm^2. The maximum diameter change observed was 2.5% (Figure 3b). Swelling data are available only for lower fluence cases, but these results indicate that the majority of the diameter change is again due to cladding swelling. The observed swelling is also in agreement with correlations based on unfueled experiments.(3)

Five lots of type 316 20% CW stainless steel were used as cladding material in HEDL reference design tests: developmental lots, N, O and T and FFTF Core I lots, X and NICE. Fuel pins clad with N-lot attained a maximum diameter change of 2% at a peak fast fluence of 9.7 x 10^{22} n/cm^2 (Figure 3a). The peak diameter change generally occurred in the upper half of the fuel column and approximately 40% of this change was attributable to cladding swelling. The moderate amount of cladding swelling observed was again adequately described by swelling models developed from irradiated unfueled N-lot cladding (Figure 5)(4).

Twenty percent CW 316 T-lot was from the same heat of stainless steel as N-lot. O-lot was from a chemically similar heat with higher nitrogen content. The T-lot clad pins attained a maximum diameter change of 5% at a peak fast fluence of 12 x 10^{22} n/cm^2. O-lot pins behaved comparably with 7% diameter change at 14 x 10^{22} n/cm^2 (Figure 3a). The maximum diameter change generally occurred near the middle of the fuel column. Cladding swelling generally accounted for half or more of the total diameter change (Figure 6). Cladding swelling observed in T-lot and O-lot clad pins was greater than that seen in the N-lot clad pins at equivalent temperatures (Figure 5). It has been suggested(5) that temperature variations during irradiation can add additional increments of swelling beyond the expected values under isothermal conditions. Pins clad with O-lot and T-lot material experienced a significant temperature drop and several reconstitutions during their irradiation period which may account for the additional swelling.

Several experiments contained fuel pins clad with X and NICE lots which were obtained from a single heat of 316 20% CW FFTF Core 1 steel. At high fluence, for fuel pins irradiated in interior positions of a subassembly, the maximum diameter change usually occurred near the middle of the fuel column (Figure 7, 8). Fuel pins which were irradiated in the cooler corner or exterior positions exhibited the peak diameter change at a somewhat higher axial location (Figure 8). For fuel pins with low plenum pressures, roughly 90% of the diameter change was cladding swelling. Pins with higher plenum pressures showed significant inelastic strain in addition to cladding swelling. The highest exposure fuel pin experiment with Core 1 cladding was irradiated 18,000 hours to a peak fast fluence of 13.3 x 10^{22} n/cm^2. (Exposure in FFTF will be 7200 hours and 12.0 x 10^{22} n/cm^2). The fuel pins in this subassembly sustained diameter changes of nearly 10% (Figure 3a) without any deleterious performance such as cladding breach. Core 1 cladding lots have, in general, exhibited greater diameter change and greater swelling than previous lots of 20% CW 316 material for both unfueled and fuel pin experiments. However, attempts to predict fuel pin profiles based on data from unfueled Core 1 cladding experiments have not been entirely satisfactory (Figure 9).(6) When fuel pin cladding swelling data were compared to models derived from irradiated unfueled material, the maximum swelling occurred at lower temperatures and the magnitude of the swelling was lower for the fueled samples (Figure 10, 11) at temperatures above 500°C.

Fuel pins clad with titanium stabilized 20% CW 316 SS have previously been shown (7) to exhibit a swelling peak at the low temperature end of the fuel column. More recent results (Figure 12) have demonstrated that this behavior persists to peak fluences of at least 10.5×10^{22} n/cm^2. The maximum diameter changes are comparable to neighboring T-lot 20% CW 316 pins irradiated in the same subassembly.

Significant diameter changes have thus been observed in stainless steel clad fuel pins and these changes have been attributed to a combination of swelling and inelastic strain. Although differences in behavior among various cladding heats have been noted (Figure 13, 14), these experiments have not given rise to a strain limit for mixed oxide fuel pin cladding and indicate that similar pins will successfully achieve goal exposure in reactor systems such as FFTF.

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CLADDING DIMENSIONAL CHANGES

IN

MIXED OXIDE FUEL PINS

CLADDING MATERIALS

- 304 SOLUTION ANNEALED
- 316 SOLUTION ANNEALED
- 316 20% CW N, O, T-LOTS
- 316 20% CW CORE-I LOTS
- 316 20% CW Ti STABILIZED

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Figure 1.

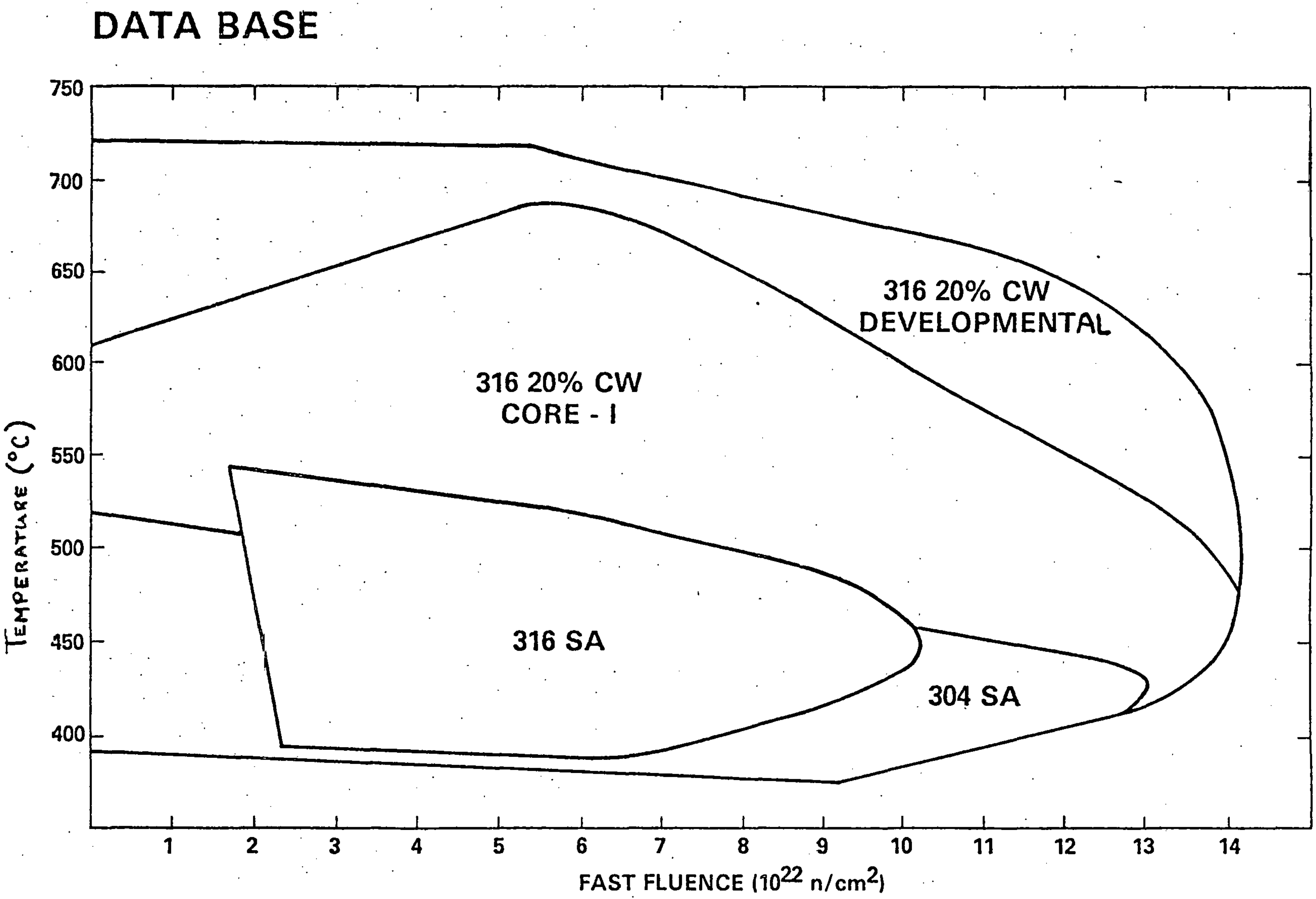

Figure 2. The range of temperature and fast fluence (E > 0.1 MeV) for which profilometry data are available. Several cladding types are shown. Note that at high cladding temperatures data is available only for 20% CW 316 material. The extent of the cladding density data base is similar to that shown for profilometry except that data for type 316 SA cladding are limited to fast fluences below 5 x 10^{22} n/cm^2 and data for Core I lots of 316 20% CW are limited to temperatures below 650°C. Temperature shown is time-averaged cladding midwall temperature.

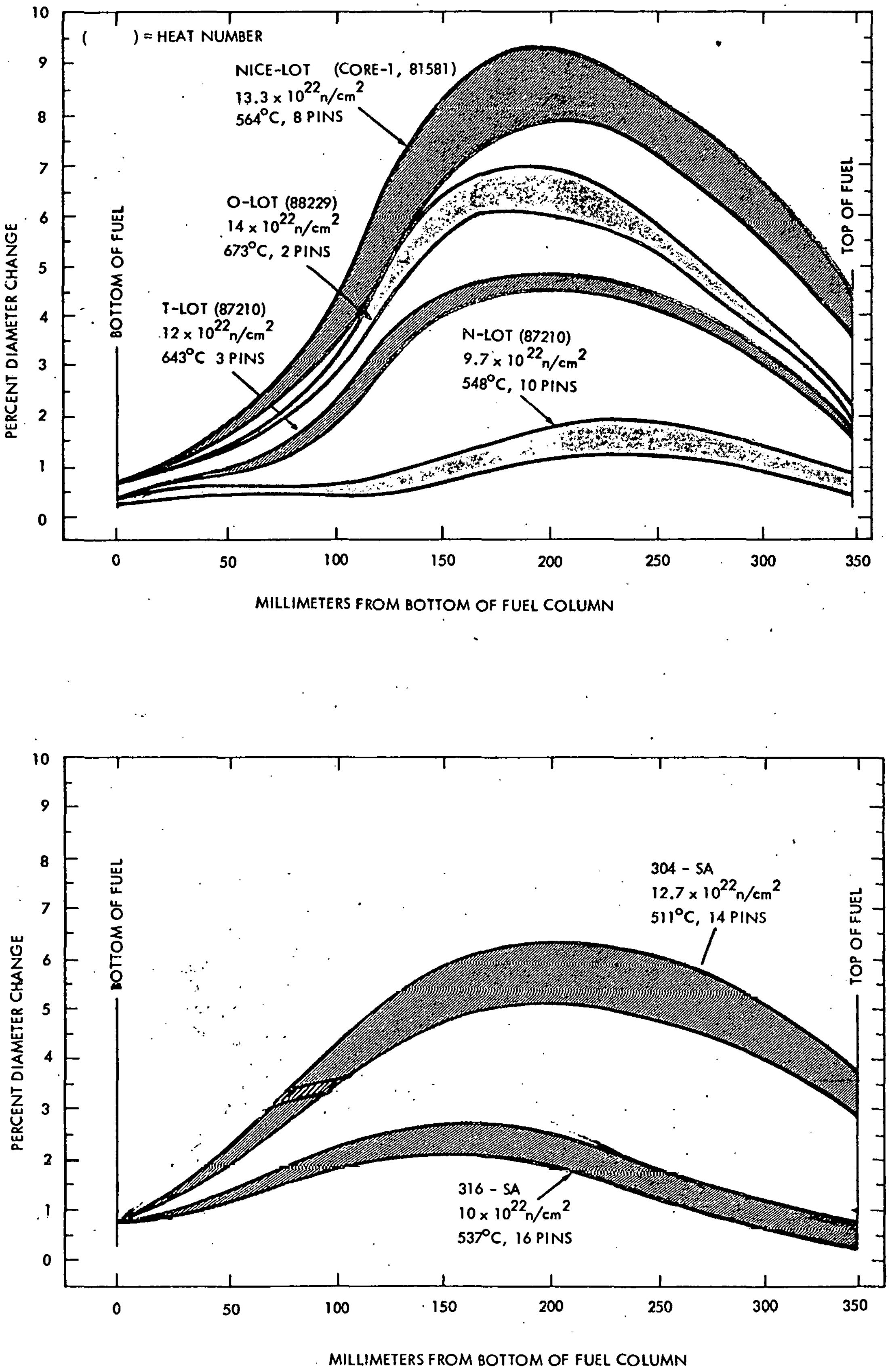

Figure 3. Diameter Measurements from Fuel Pins Clad With A) Various Lots of 316 20% Cold Worked Stainless Steel and B) 304 Solution Annealed, 316 Solution Annealed, and Titanium Stabilized 20% CW Cladding. Peak Fluences given (Middle of Fuel Column) Are For E > 0.1 MeV. Temperatures Given Are Peak End of Life Cladding Temperature at the Top of the Fuel Column. Bands Indicate the Range of the Data.

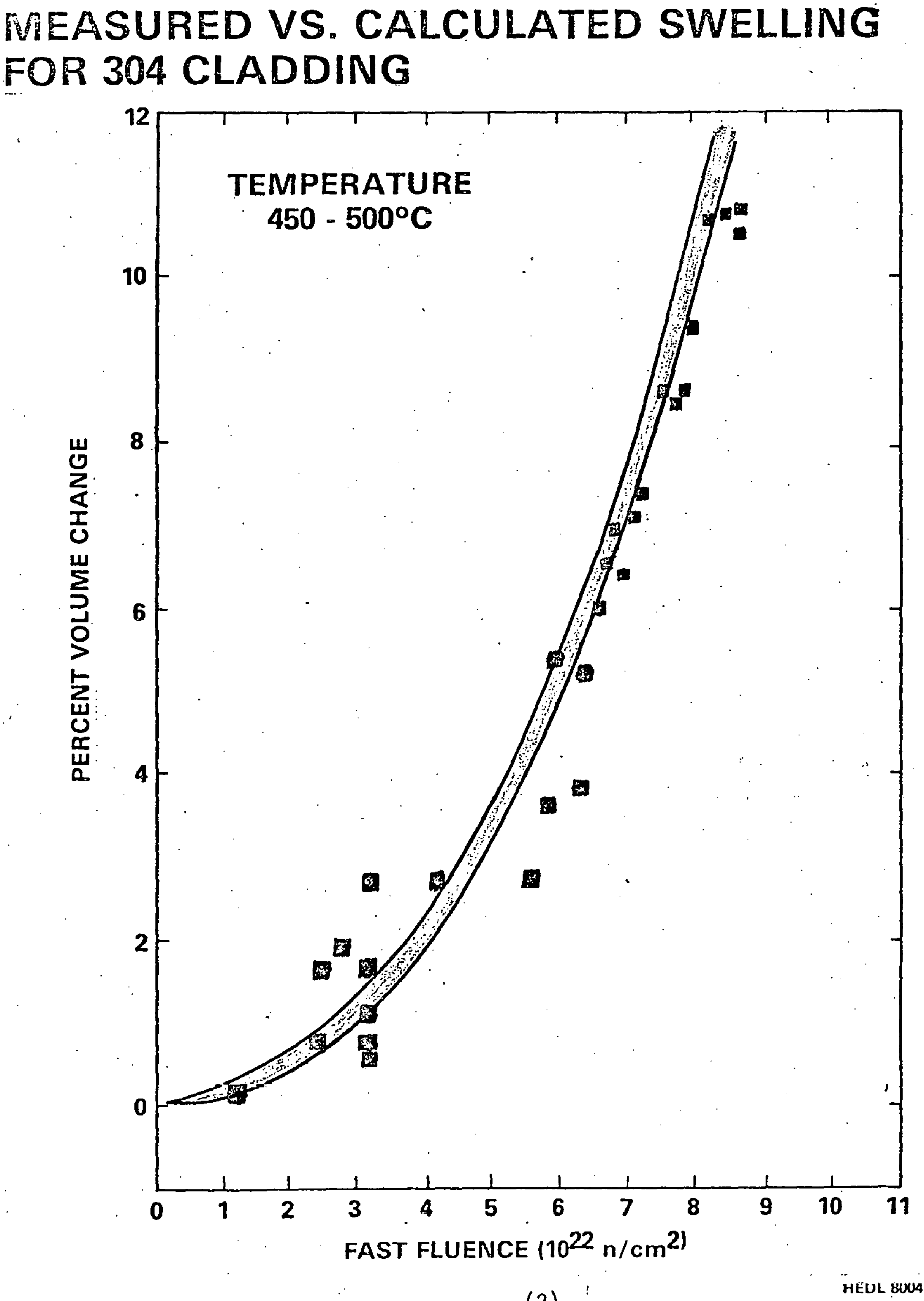

Figure 4. Measured vs. Calculated(2) Swelling for 304 Cladding Samples. The band is the predicted swelling for a temperature range of 450 to 500°C. The data points are fuel pin cladding samples with time averaged cladding midwall temperatures in the same range.

MEASURED VS PREDICTED SWELLING
316 20% CW DEVELOPMENTAL LOTS

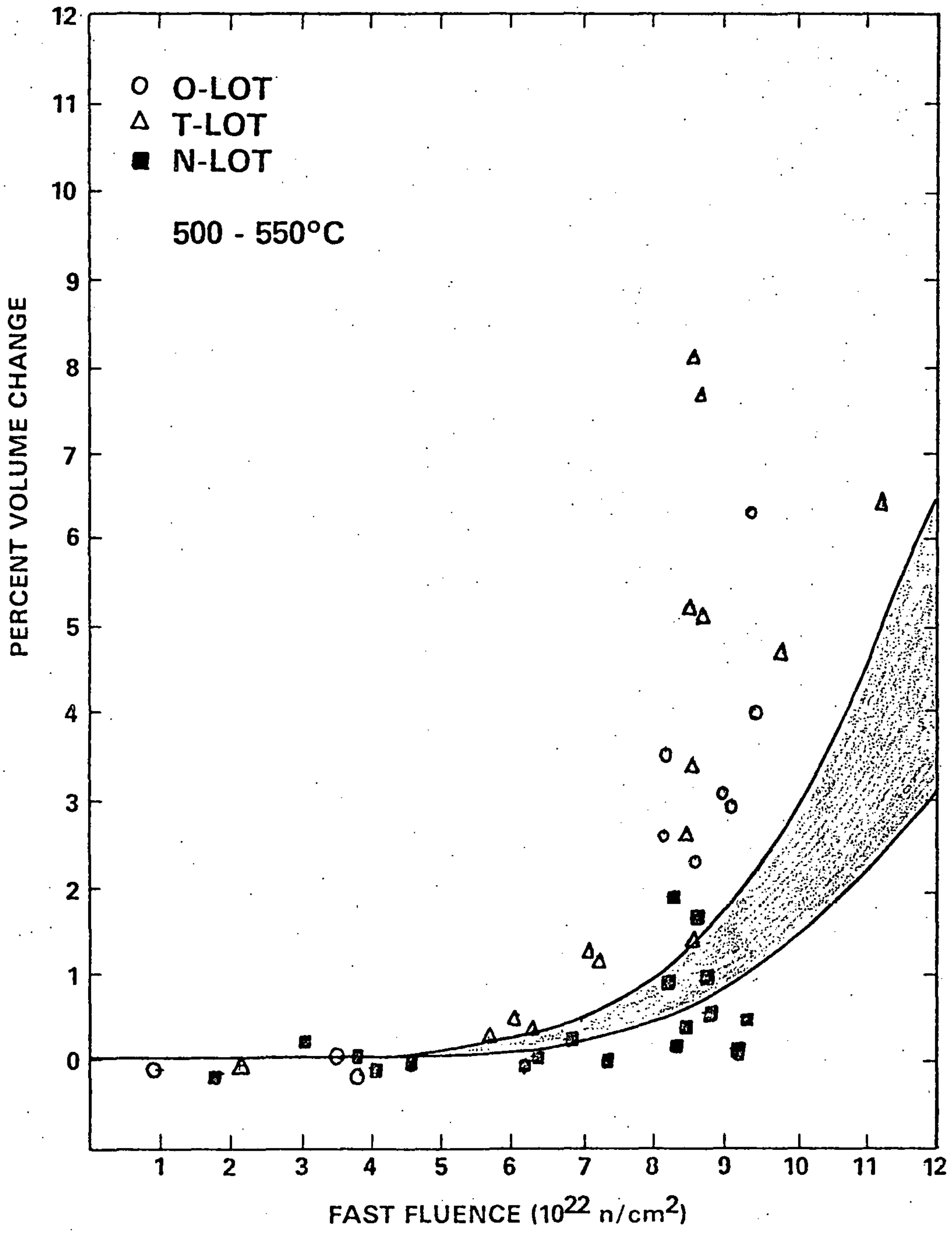

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Figure 5. Measured vs. Predicted Swelling for 316 20% CW Developmental Lots. The band indicates the predicted(4) swelling for a temperature range of 500 to 550°C. The points are data taken from fuel pin cladding samples with time averaged cladding midwall temperatures in the same range. N-lot cladding is in reasonable agreement with the correlation. T-lot and O-lot fuel pin cladding exhibit somewhat higher swelling

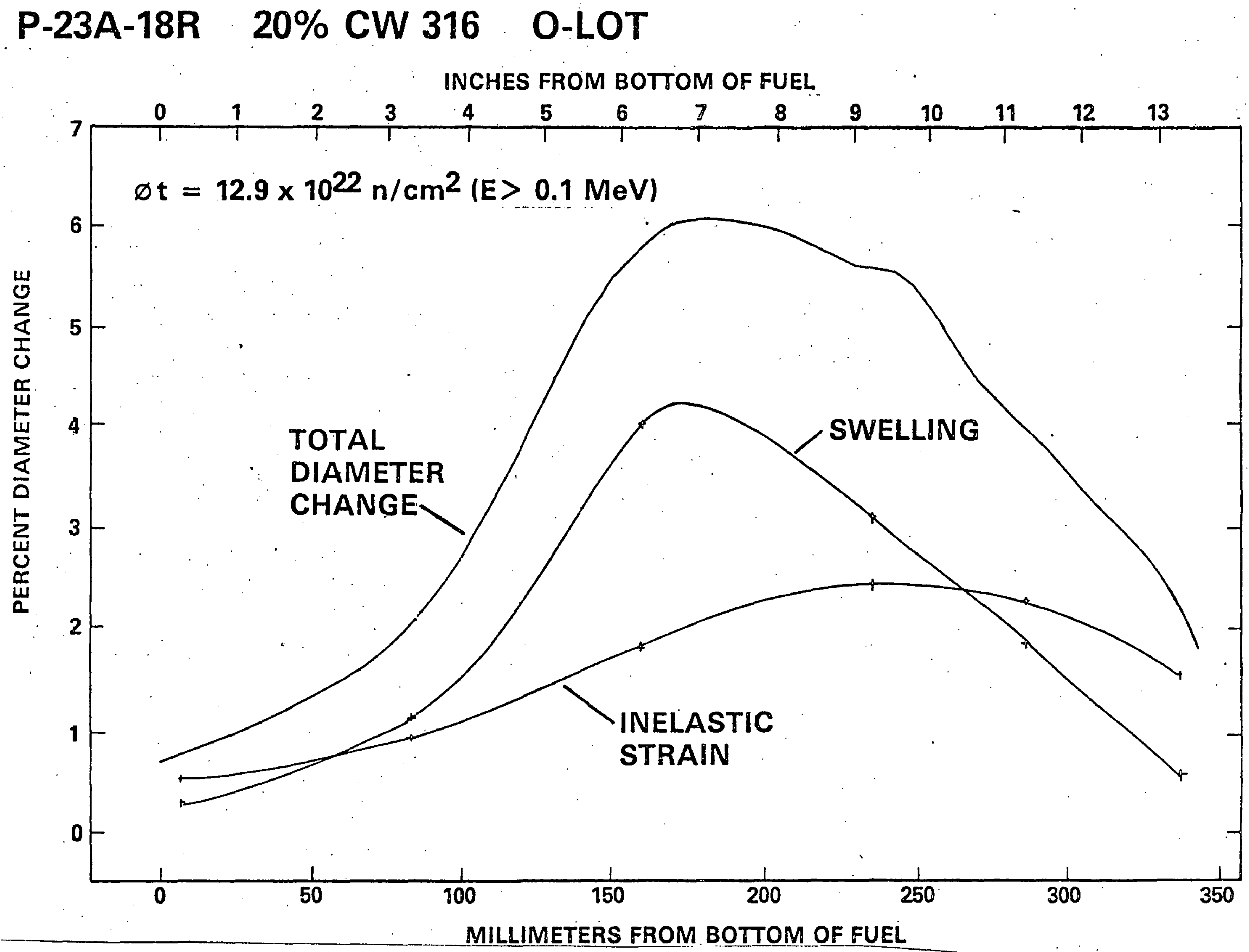

Figure 6. Cladding diameter change for fuel pin P-23A-18R. The contributions to the total diameter change of swelling and inelastic strain are also indicated.

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DIAMETER CHANGES FOR P-15 FUEL PINS

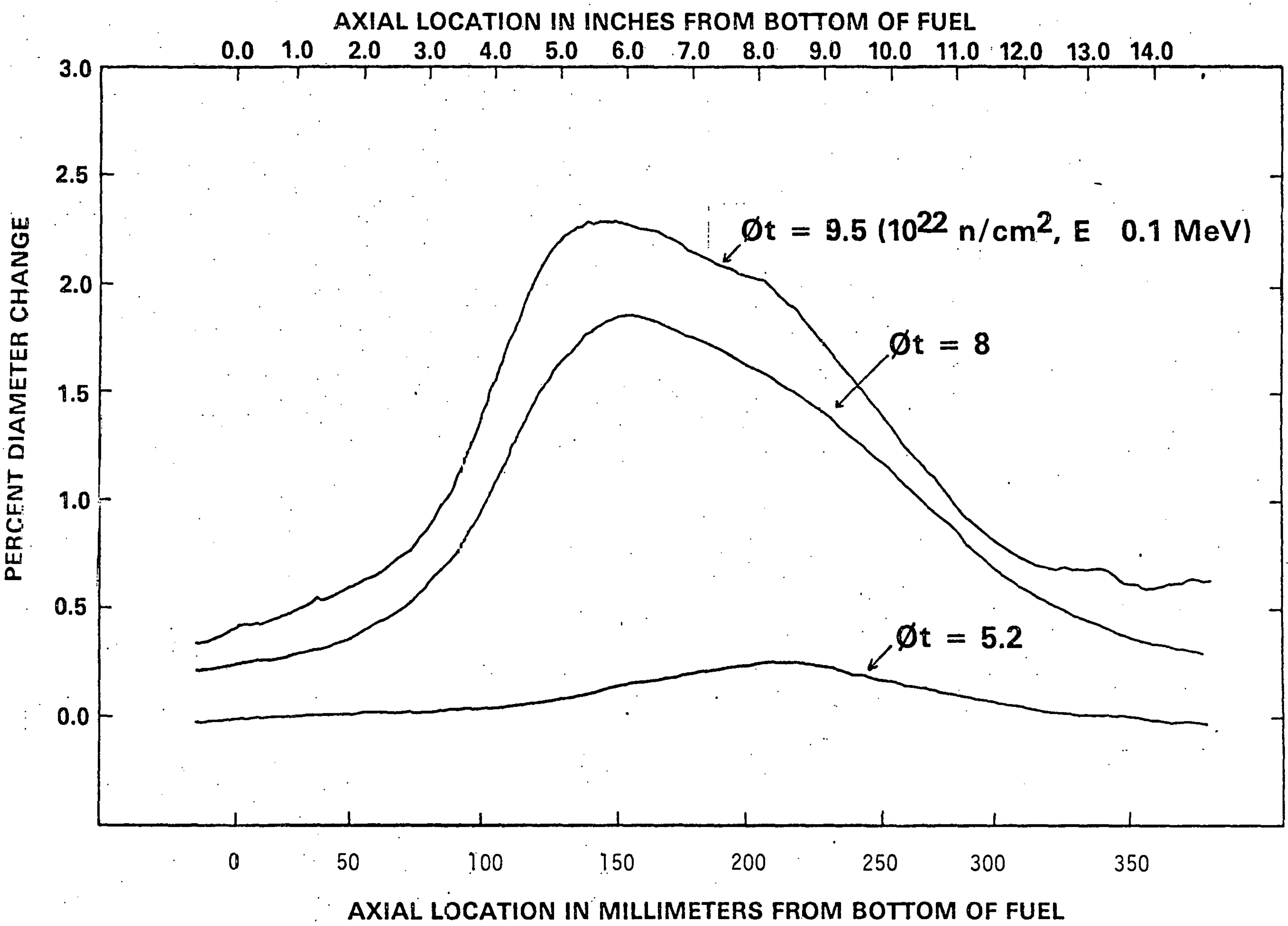

Figure 7. Diameter changes for P-15 Fuel Pins with increasing fluence. Each curve is an average of measurements from several fuel pins which were irradiated in interior positions of the subassembly. All pins were clad with Core I steel. The axial position of the peak diameter change has moved towards the bottom of the fuel column with increasing fluence.

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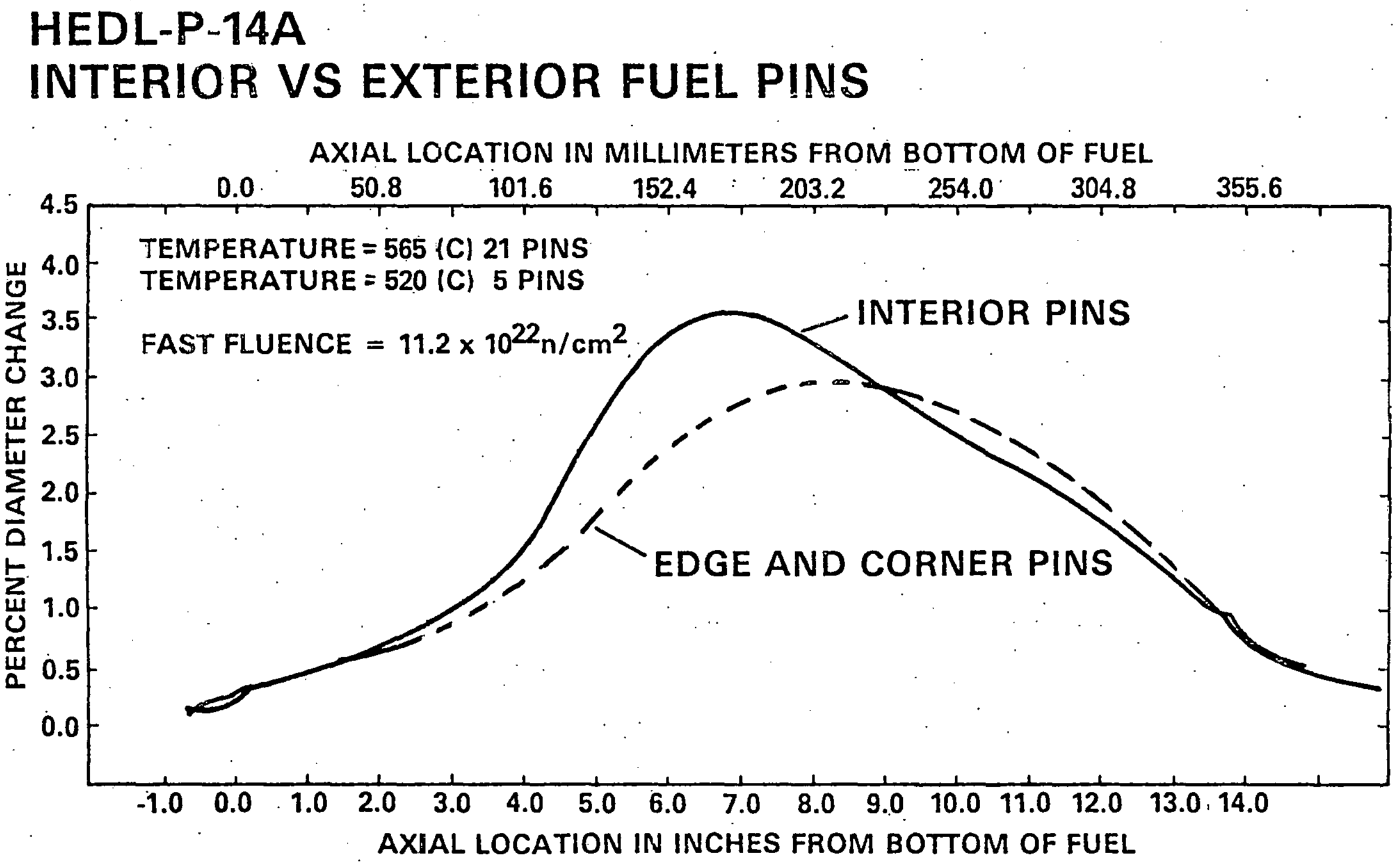

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Figure 8. Diameter changes for Fuel Pins Irradiated in exterior and interior positions in the HEDL-P-14A subassembly.

The cooler exterior pins showed a diameter peak at a higher axial location relative to the bottom of the fuel column. The major component of diameter change in the P-14A fuel pins was cladding swelling. The axial position of the peak diameter change reflects the different location of the peak swelling temperature (~500°C) in the two sets of pins.

DIAMETER CHANGE HEDL-P-15-15A

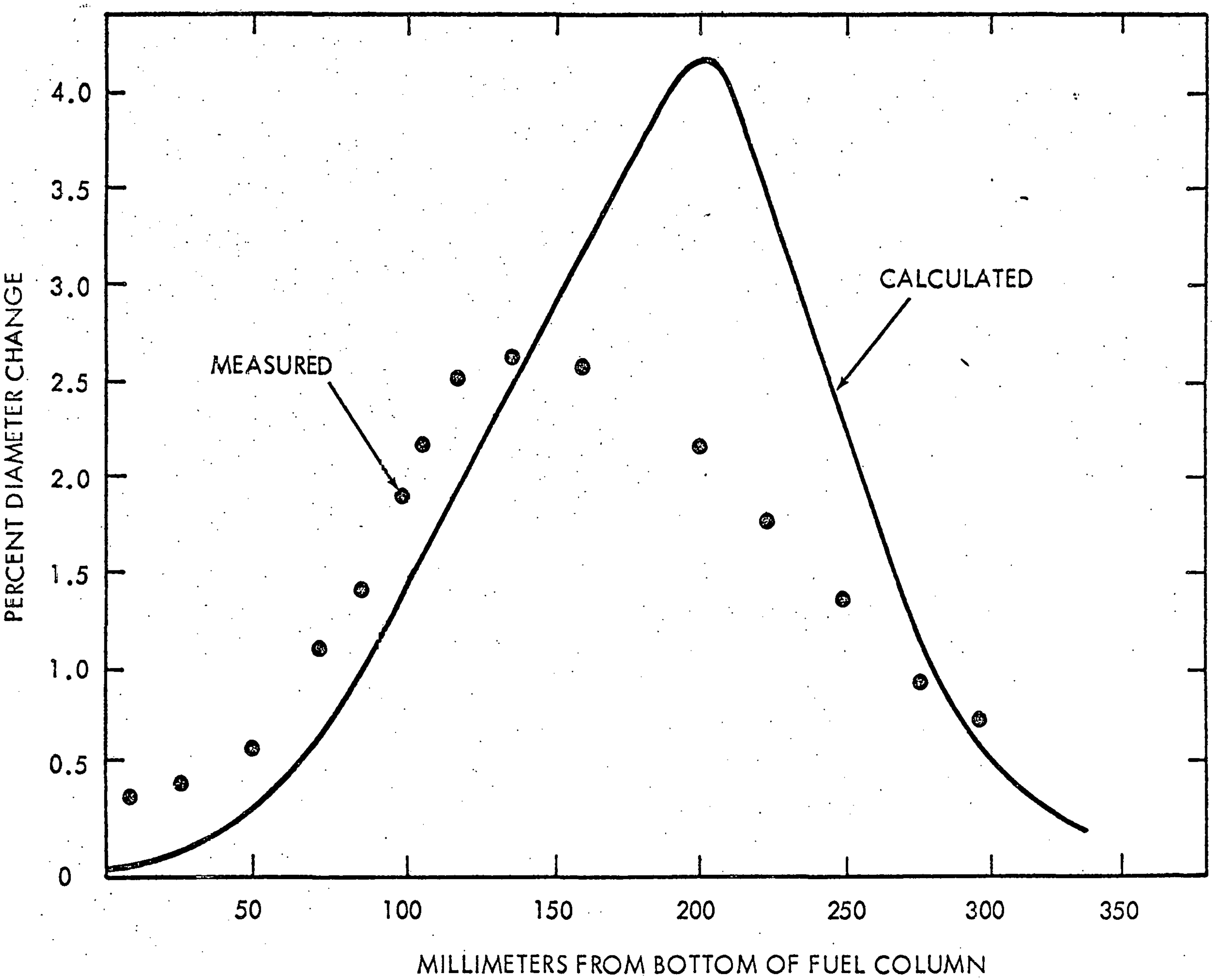

Figure 9. Measured vs. Calculated Diameter Profile for a fuel pin from the HEDL-P-15 subassembly. Calculations were performed using the HEDL computer code SIFAIL. Similar results were reported previously (6) for fuel pins from the HEDL-P-14A subassembly.

MEASURED VS CALCULATED SWELLING

20 % CW 316 SS CORE-1 CLADDING

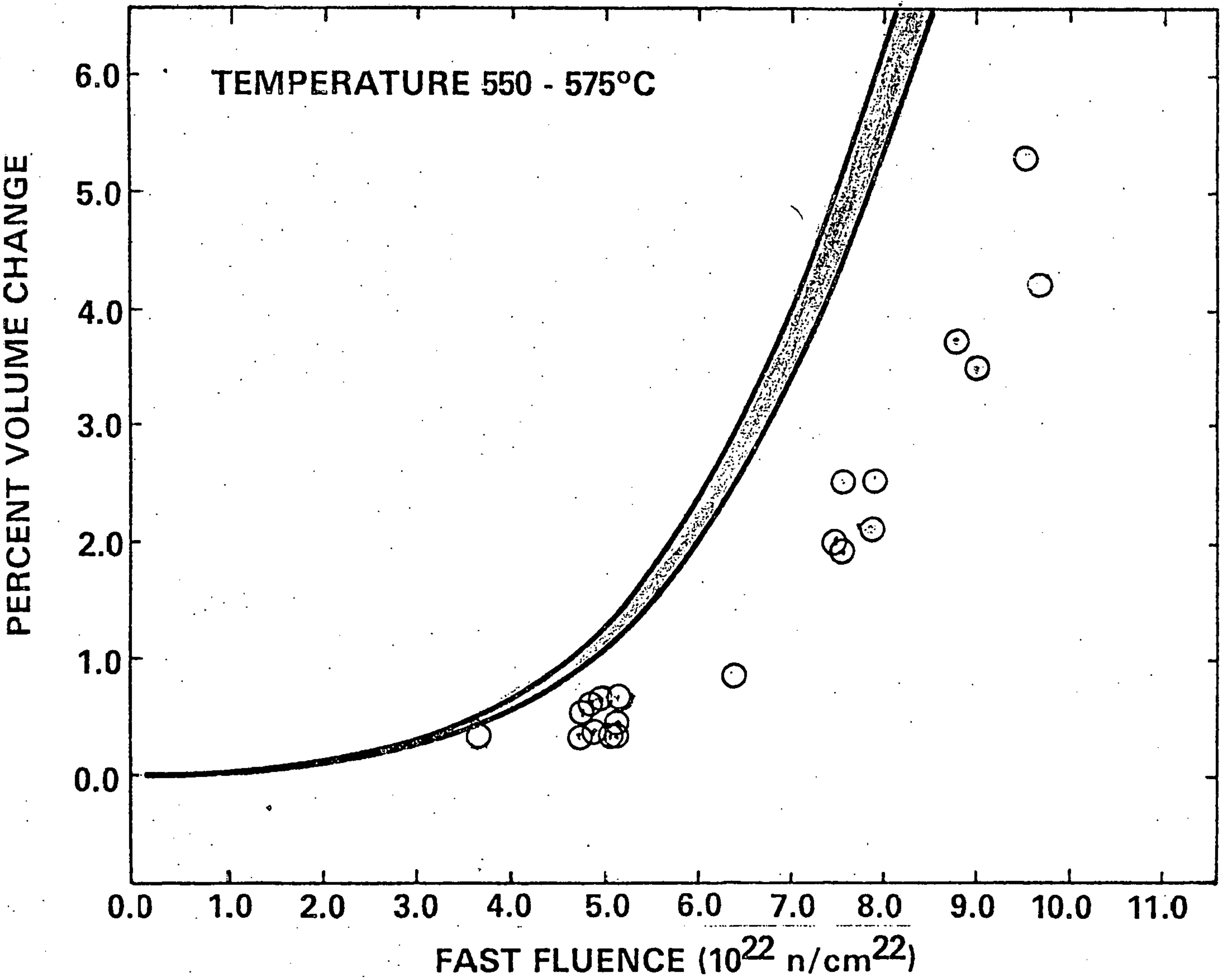

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Figure 10. Measured vs. Calculated (4) Swelling for Fuel Pins Clad with Core I steel. The curve is the predicted swelling for the temperature range 550-575°C. The points are fuel pin cladding samples with similar time averaged cladding midwall temperatures.

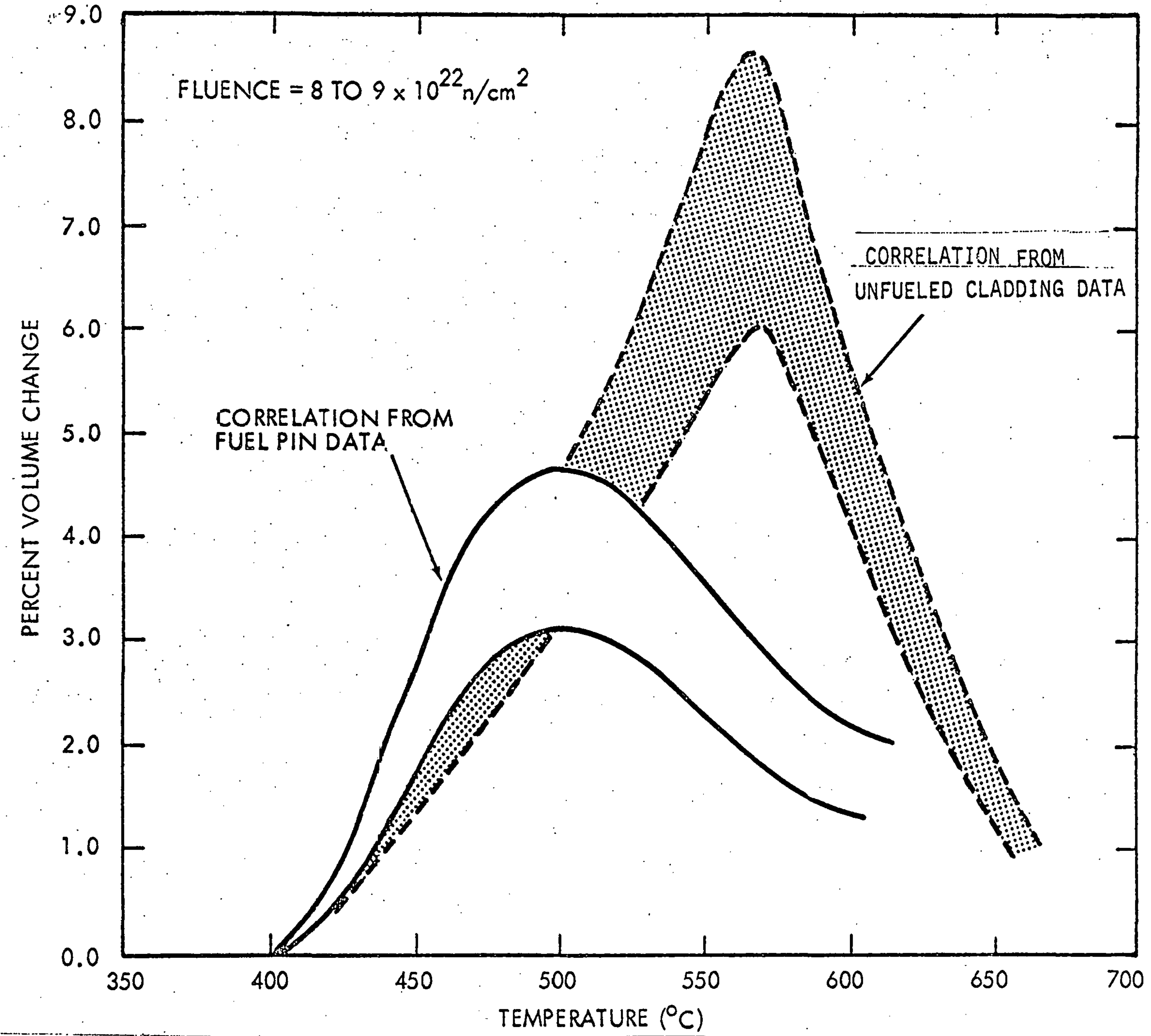

Figure 11. Cladding Swelling from unfueled experiments$^{(4)}$ and from fuel pins with Core I cladding. Bands indicate the results from one limited fluence range (8 to 9 x 10^{22} n/cm^2, E > 0.1 MeV). Similar results were found for other fluence ranges up to 11 x 10^{22} n/cm^2.

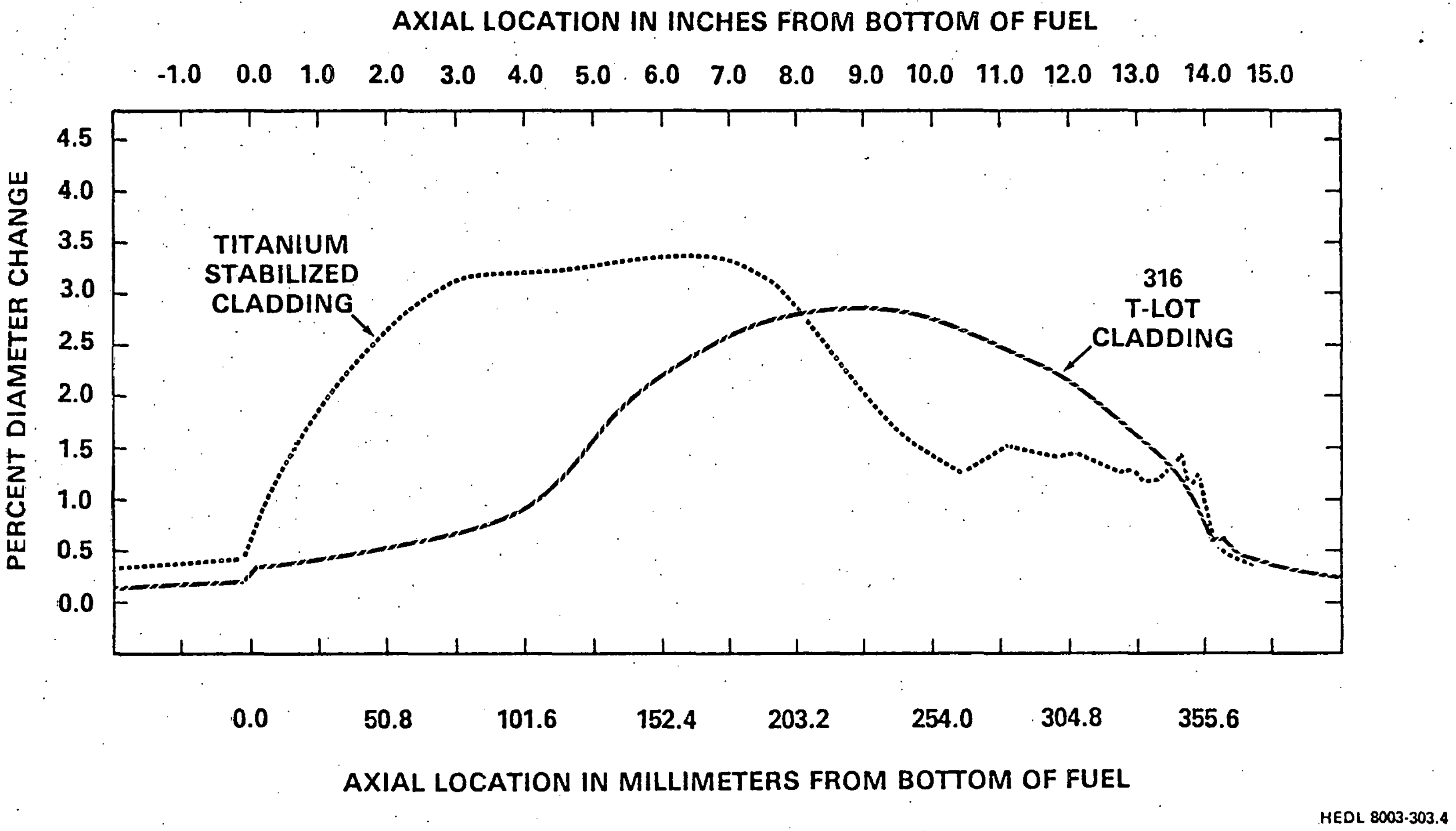

Figure 12. Diameter Measurements From A Fuel Pin Clad With Titanium Stabilized 20% CW 316 SS And From A Fuel Pin Clad With T Lot 20% CW 316 SS. These Pins Were Irradiated Side-By-Side In The HEDL P-23C Subassembly.

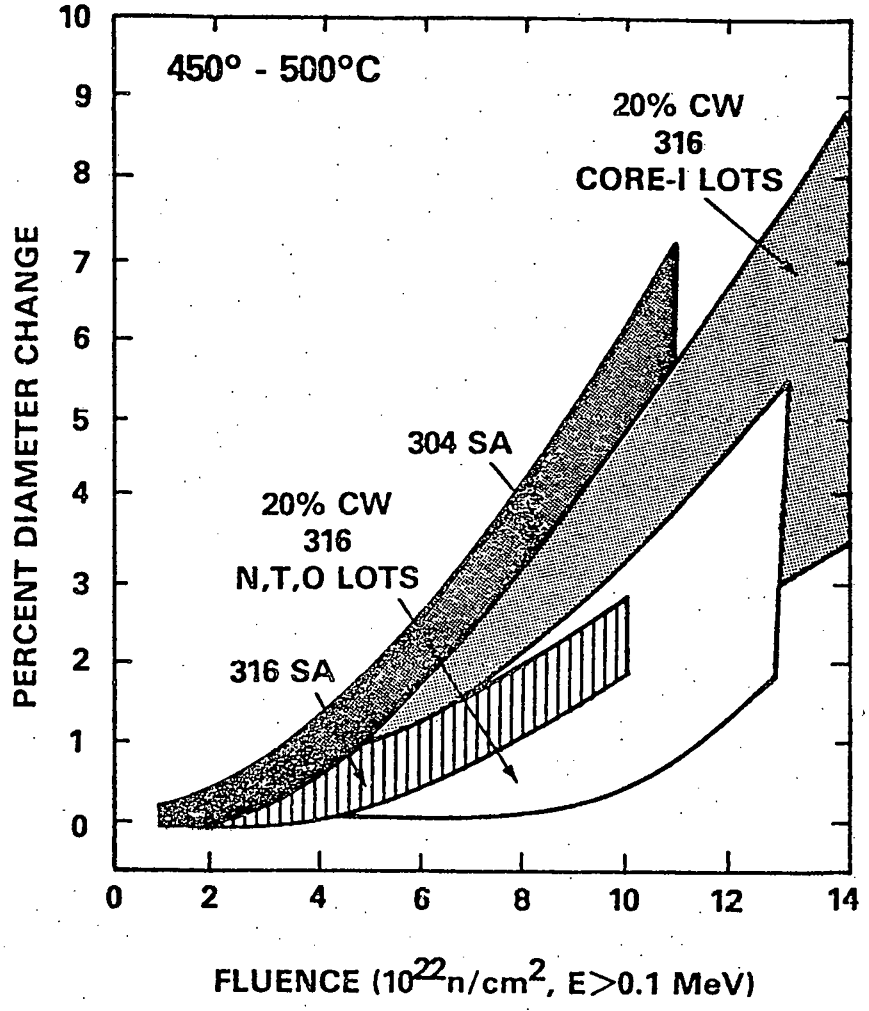

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Figure 13. Cladding Total Diameter Change For Various Materials As A Function Of Fast Fluence. Only Data From Cladding Irradiated At Temperatures Between 450 and 550°C Are Shown.

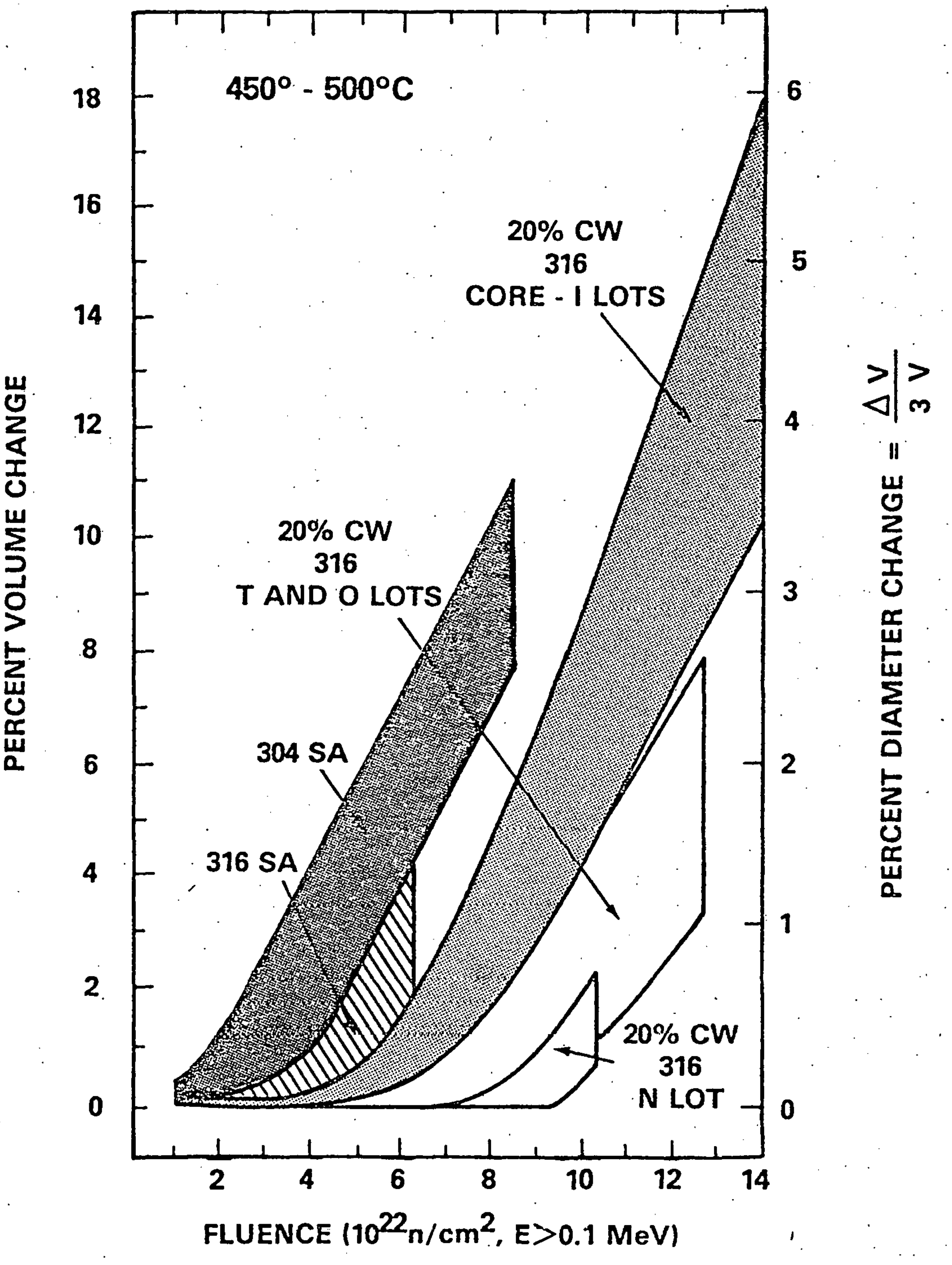

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Figure 14. Fuel Pin Cladding Swelling Data Vs. Fast Fluence For 450°C to 500°C For Various Materials.