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A. J. Lovell, G. L. Fox, W. H. Sutherland and S. L. Hecht
Westinghouse Hanford Company
P. O. Box 1970
Richland, Washington

The purpose of the Core Demonstration Experiment (CDE) is to demonstrate the capability of a mixed-oxide fuel system to achieve a three year life in a prototypic LMR heterogeneous reactor environment. The CDE assemblies are fabricated using wire-wrapped, large-diameter, advanced-oxide fuel and blanket pins with tempered martensitic HT9 cladding, wire wrap, and duct. The highest power fuel assembly operates with a Beginning of Life (BOL) peak linear pin power of 445 W/cm and a peak cladding temperature of 615C. The fuel and blanket assembly irradiation will start in FFTF Cycle 9 and continue for about 900 Equivalent Full Power Days (EFPD).

The successful utilization of the tempered martensitic HT9 alloy in an FFTF test assembly is fully anticipated. The low swelling, observed at intermediate neutron fluences and projected to higher fluences, together with reasonable creep behavior gives acceptable mechanical performance for fuel pins, blanket pins and ducts. Duct length increase, dilation and bow; plus fuel and blanket pin diameter increases remain within specified tolerances. In addition, stress rupture data from unirradiated HT9 imply cumulative damage fractions for the nominal fuel and blanket pins that are low.

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INTRODUCTION

The predicted performance of CDE assemblies (see Figure 1 for fuel and blanket) utilizing the tempered martensitic HT9 alloy as the duct and cladding material is discussed in the following paragraphs. The ferritic/martensitic steels have a high potential for Liquid Metal Reactor applications because of low swelling and creep characteristics. The tempered martensitic HT9 was selected as a fuel pin cladding and duct material for a high burnup fuel test in the Fast Flux Test Facility (FFTF). The test objective is to demonstrate the capability of a fuel system for use in a commercial-sized liquid metal reactor.

TEST CONFIGURATION

HT9 was selected as the cladding and duct material based on early observations that indicated no swelling after irradiation to fluences of 1.8×10^{23} n/cm^2 (E > 0.1 MeV) at temperatures of 538C.[1] In addition, the material exhibited good creep and tensile strength and ductility greater than 7% after irradiation to 1.0×10^{23} n/cm^2 (E > 0.1 MeV). The chemical compositions for the HT9 used in the duct and cladding fit well within the range of the commercially available HT9. Both the cladding and duct material are used in the normalized and tempered condition.

Ten fuel assemblies and six blanket assemblies comprise the CDE test. A partial core map for the beginning of FFTF Cycle 9A, Figure 2, shows the proposed placement of the CDE assemblies and CDE-related lead fuel tests with HT9 cladding. These tests are only included for reference since they have different burnups and operating conditions from CDE assemblies. Two of the blanket tests. ABA-1 and ABA-2, are orificed differently than the nominal CDE blankets so different temperature conditions are obtained.

Each CDE fuel assembly contains 169, 6.86-mm-diameter, advanced-oxide fuel pins fueled with 30% plutonium (Pu/Pu+U). The 91-cm-long annular fuel column (5.55-mm OD x 1.47-mm ID) has an average smeared density of 80% TD. At each end of the fuel column there is a 16.5-cm-long axial blanket column of depleted uranium oxide annular pellets with an average smeared density of 76% TD.

Each blanket assembly contains 91, 9.91-mm-diameter, depleted UO_2 blanket pins. The blanket pellets, which are solid, provide an average blanket pin smeared density of 89% TD, 124-cm-long.

FUEL TEST CONDITIONS

The composition of the fuel in this test has been adjusted to obtain a peak power of 445 W/cm; the liquid sodium coolant flow in the assembly has been adjusted to obtain a 615C peak cladding temperature. The anticipated beginning and end-of-life conditions in the assembly for the nominal pin are given in Table I.

TABLE I

NOMINAL OPERATING CONDITIONS FOR THE TEST ASSEMBLY IN FFTF

Core Position	Row 2 (1202)
Total Assembly Fission Power (MWt)	5.88
Total Assembly Coolant Mass Flow Rate (kg/s)	22.5
Bundle Inlet Temperature (C)	360
BOL Bundle Average Outlet Temperature (C)	554
Peak Pin Deposited Power (W/cm)	445
Peak Flux (E>0.1 MeV), 10^{15} n/cm^2-s	3.2
Peak Burnup (MWd/kgM)	168
Equivalent Full Power Days in CDE	900

PREDICTED FUEL PIN PERFORMANCE

Performance of the assembly's peak fuel pin in the 169-pin bundle was evaluated with the SIEX3[2] and LIFE-4[3] design codes. SIEX3 is a gas loaded statistically based code which relies upon previous fuel pin experience for correlation of fuel pin behavior. LIFE-4 contains a capability for modeling fuel-cladding mechanical interaction. The analyses indicate that although peak cladding temperatures initially exceed 615C, temperature decrease (associated with power depletion) accompanies fuel burnup over the lifetime. The anticipated power depletion is shown in Figure 3; the resulting reduction in peak cladding temperature is also shown in Figure 3. The combination of low pressure and an open fuel-cladding gap in the fuel pin when the temperature is high, and decreased power when the gap closes plus decreased temperature when the pressure increases lead to a calculated creep strain as indicated in Figure 4, using SIEX3. The calculations indicate the largest diameter changes are in the center (X/L = .5) of the core indicating most of the strain results from irradiation induced creep. The calculations with LIFE-4 (Rev. 1) indicate the stresses are increased from FCMI but the resulting creep strains (see Figure 4) are still much smaller than a 2% guideline. Successful fuel test operation is anticipated due to the low creep strain prediction plus low predicted values for the cumulative damage fraction using the life fraction approach,[4-7] and rupture-life data from unirradiated HT9.

POROSITY ANALYSIS

The calculated diameter changes in the 169 fuel pin bundle result in a predicted bundle porosity that still has some clearance at the end of 1000 EFPD (see Table II).

TABLE II

POROSITY ANALYSIS

	0 EFPD	1000 EFPD
Bundle-Duct Clearance (mm)	0.64	0.24
Clearance Per Ring of Fuel Pins (mm)	0.09	0.04

BLANKET TEST CONDITIONS

The depleted uranium oxide used in the blanket pins will result in low power and temperature at the start of irradiation with increased power and temperatures at the end of irradiation. The calculated values are shown in Figure 5 for power and peak blanket cladding temperature. The blanket assemblies are orificed to avoid too low an outlet temperature at the start of irradiation, which could result in thermal striping when the assemblies are near higher temperature assemblies. The limit as to how low the starting outlet temperature can be coupled with the power buildup sets the allowable irradiation duration for a given blanket design.

PREDICTED BLANKET PIN PERFORMANCE

Performance of the blanket assemblies peak pin in the 91-pin bundle was evaluated with the SIEX3 code only. The analyses indicate that although the gas release from the blanket pellets is low the elevated temperature near the end of irradiation result in increased blanket pin diameter. The peak change occured at an axial position of $X/L = .5$. The change with time at $X/L = .5$ is shown in Figure 6. Successful blanket test operations are anticipated due to the predicted low creep strain plus predicted low values for the cumulative damage fraction. The calculated diameter changes in the 91-blanket-pin bundle will result in a predicted bundle clearance at the end-of-irradiation.

PREDICTED DUCT PERFORMANCE

One potential benefit of CDE to fast breeder technology is the demonstration of a significantly improved core restraint system performance. By replacing the moderate-swelling and creep austenitic duct alloys with low-swelling and creep HT9, significant gains in duct and hence subassembly lifetime are predicted.

Core restraint system analysis for the CDE core included core-wide single assembly analyses (COWAXS and COWDIL), ABADAN radial row analysis, and NUBOW3D (FFTF version) 30^o sector analysis for two sectors.[8-9]

An irradiation period of 1000 EFPD was evaluated based on nominal performance predictions. Resulting core restraint parameter predictions (after 1000 EFPD) are summarized in Table III:

TABLE III

Predicted Duct Performance at 1000 EFPD

Parameter	Maximum of Nominal Values: Fuel Assembly	Blanket Assembly	Limit
Duct Dilation (mm radial)	1.22	.660	1.8-2.54
Axial Growth (mm)	1.57	1.45	16.5-19.0
Permanent Bow (mm)	2.72	3.89	22.9
Peak Withdrawal Load (N)	3960	3300	12320

Core component bending moments were calculated to be considerably lower than those predicted for 316 and D9 assemblies. Calculated values of reactivity changes due to duct bow appear to show some improvement over that of current cores and provide negative feedback up to P/F ratios of 1.0.

Figure 7 shows the predicted duct dilation characteristics of central core CDE subassemblies, respectively. Figure 8 shows the dilation and bowing of a radial row of all HT9 subassemblies at shutdown after being irradiated (uniform burn) to 1000 EFPD. The CDE irradiation will have some 20% CW 316 in the radial rows that are removed in less than 1000 days.

Since all calculated duct performance parameters are well within these respective design limits, the CDE ducts are predicted to have lifetime of greater than 1000 EFPD, and provide significant improved performance over existing cores. Sufficient design margin appears to exist to support the design when taking material and environmental uncertainties into account.

CONCLUSIONS

The assemblage of large-diameter fuel pins clad with the tempered martensitic HT9 is expected to perform satisfactorily for an FFTF in-reactor irradiation period of 900 EFPD. Allowable limits for the HT9 duct will not be exceeded. The assemblage of tests in CDE are anticipated to also perform satisfactorily. The completion of the CDE test will qualify a three year fuel system for the LMR. The qualification will be valid for both a homogeneous or heterogeneous fuel and blanket array.

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FIGURE 1. CDE Fuel and Blanket Assemblies.

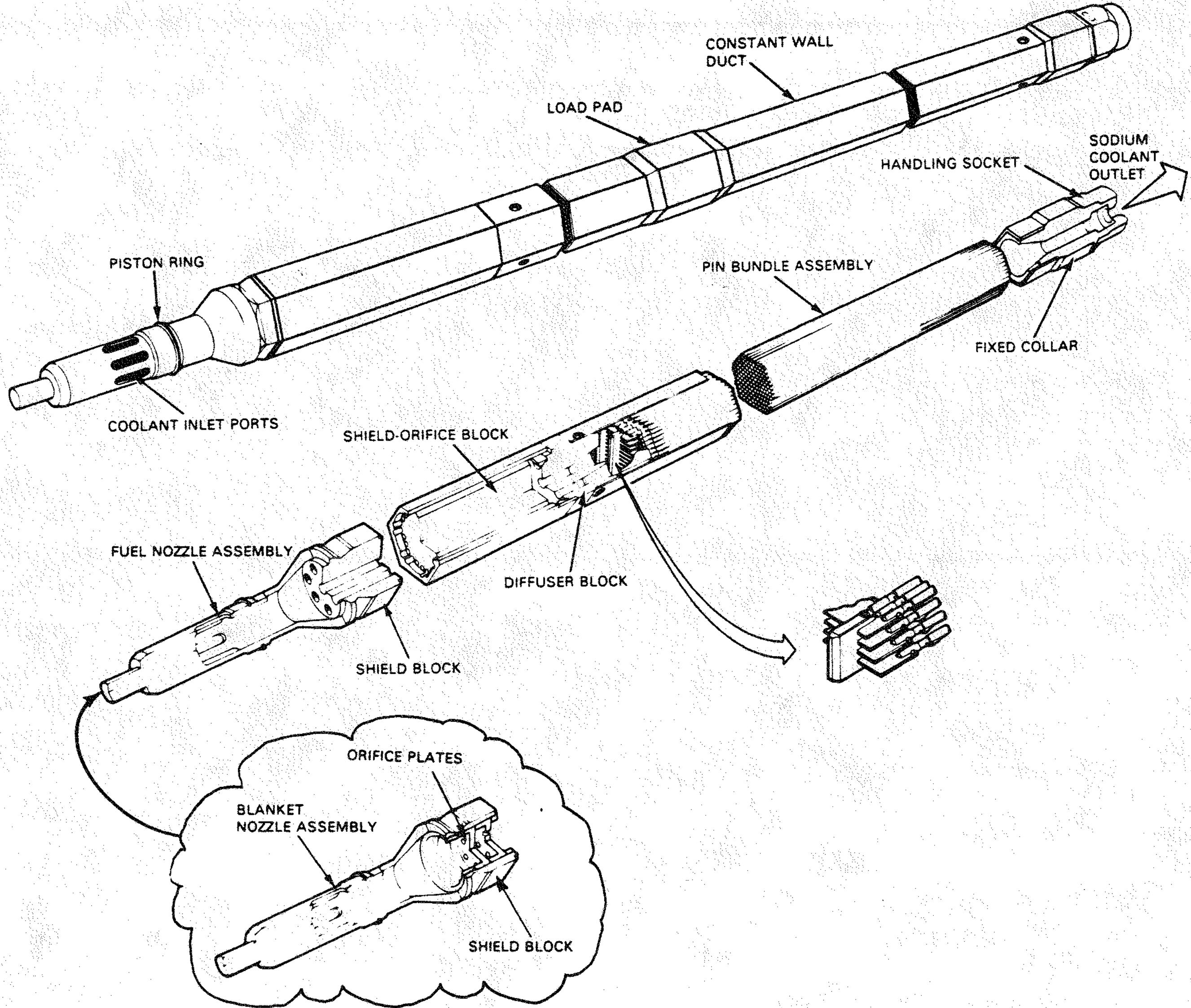

FIGURE 2. CDE Core Map.

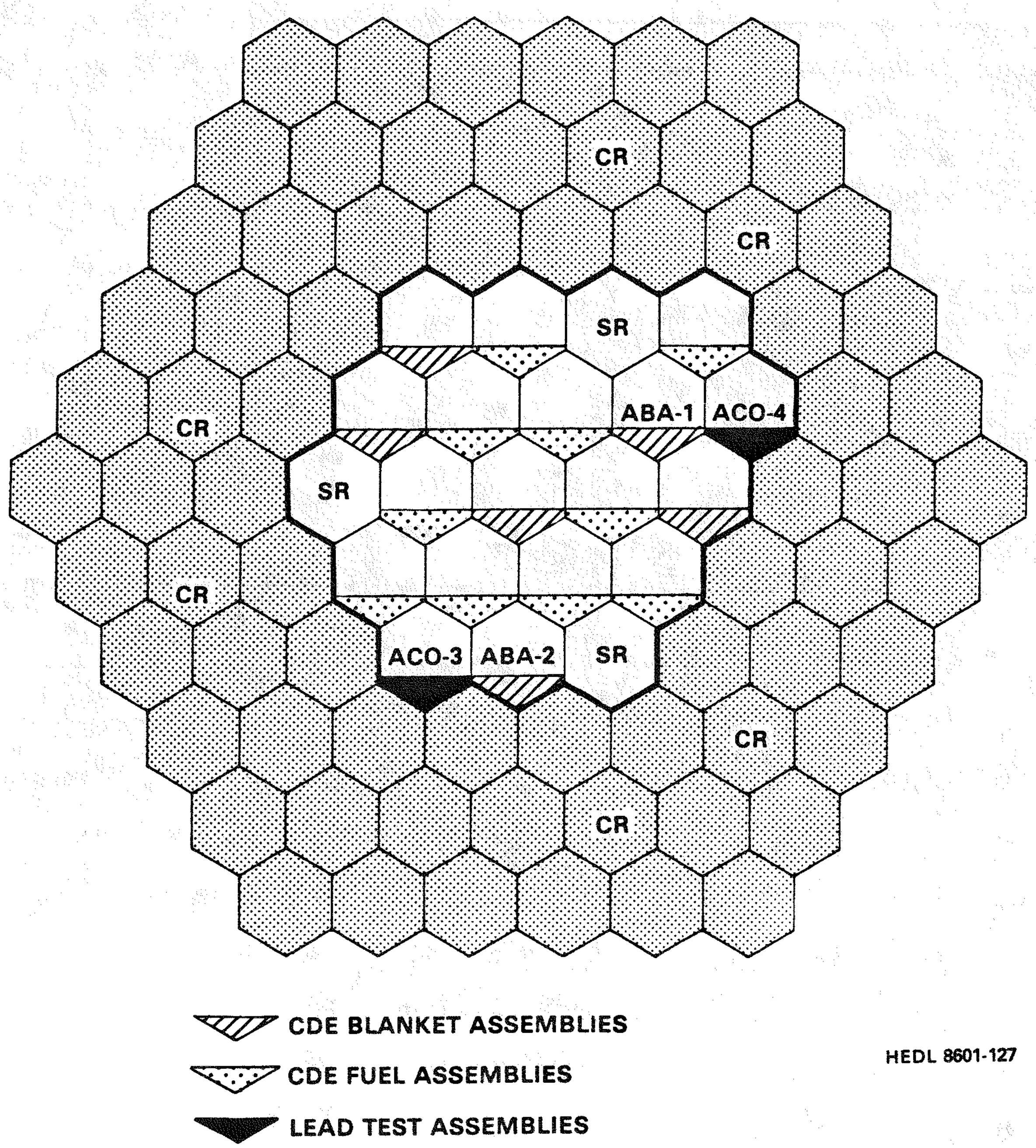

FIGURE 3. Fuel Pin Power and Temperature Depletion During the Test.

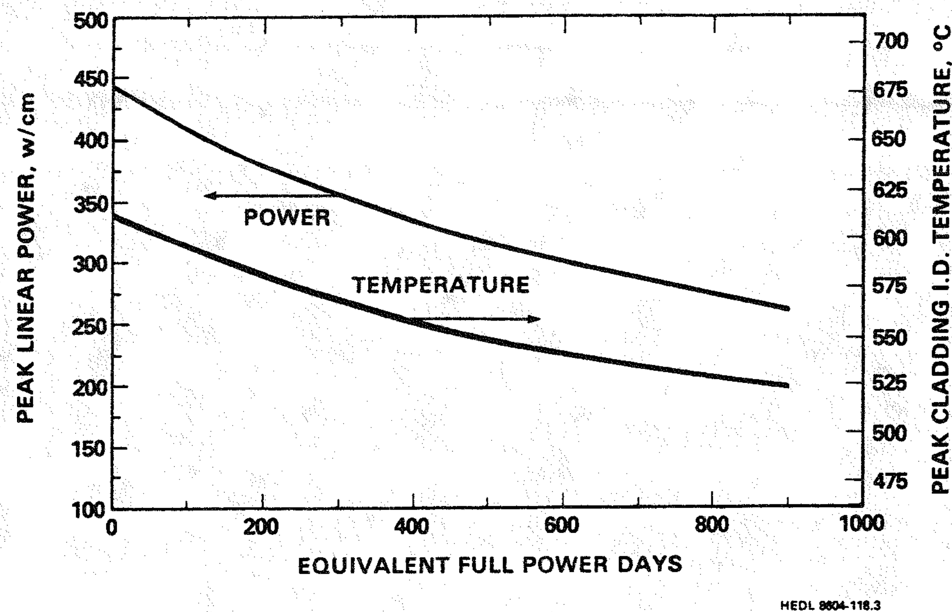

FIGURE 4. Calculated Fuel Pin Strain Using SIEX3 and LIFE-4.

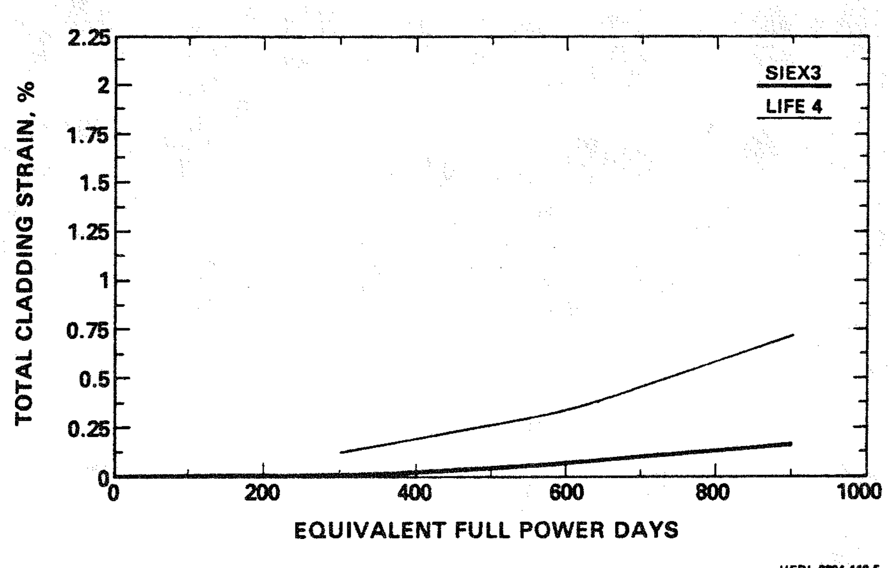

FIGURE 5. Blanket Pin Power and Temperature Increase During the Test.

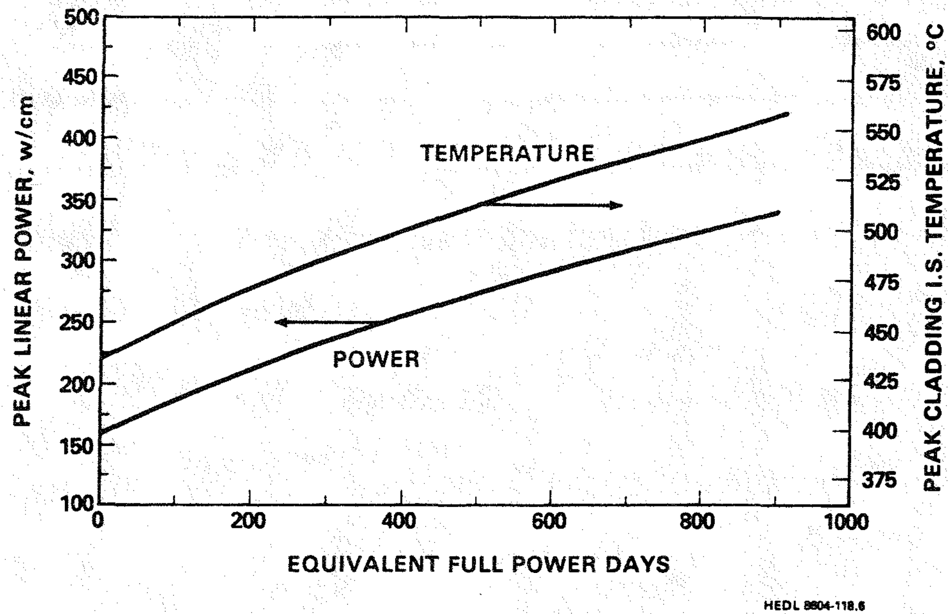

FIGURE 6. Calculated Blanket Cladding Strain Using SIEX3.

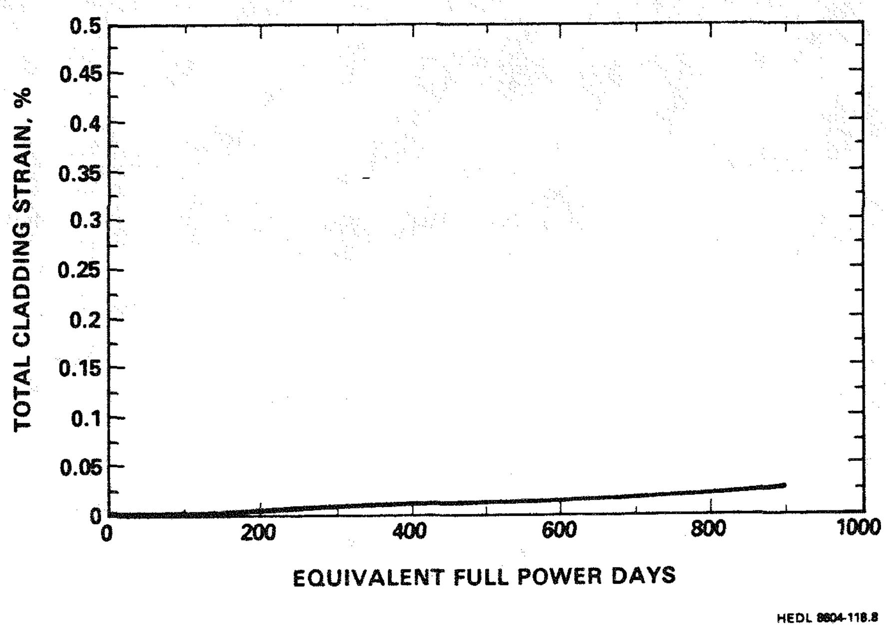

FIGURE 7. Calculated Assembly Duct Dilation for CDE Fuel and Blanket.

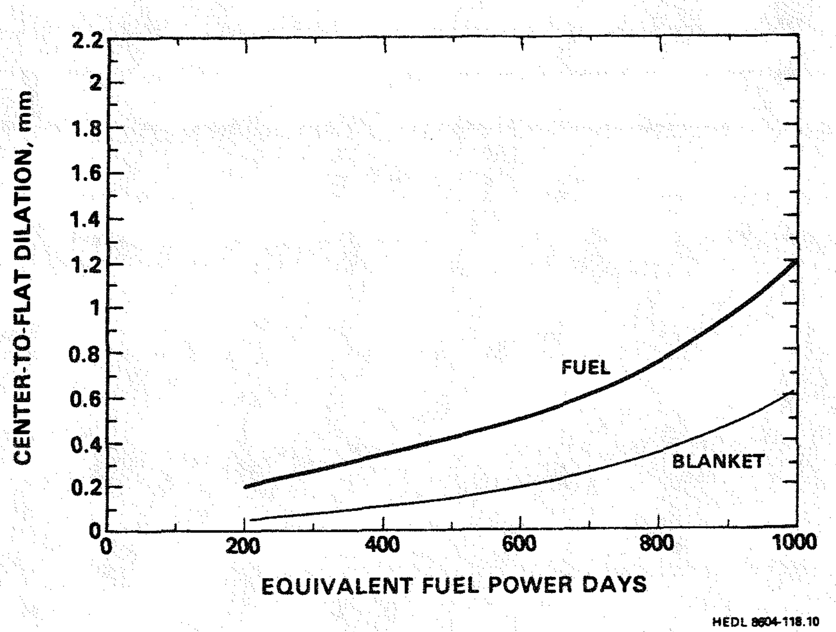

FIGURE 8. Residual Deformation After 1000 EFPD Irradiation (Deformation is Exaggerated).