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CLADDING PROPERTIES UNDER SIMULATED FUEL PIN TRANSIENTS

By

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For presentation at the US-German Cladding Information Exchange in Germantown, MD during the week of October 13, 1975.

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Introduction

The design and licensing of Liquid Metal Fast Breeder Reactors (LMFBR) requires an extensive and basic understanding of fuel pin response to a wide range of off-normal events, which vary from the anticipated mild events to purely hypothetical conditions. These events may have been characterized as either loss-of-flow (LOF) or transient overpower (TOP).

During severe LOF or TOP transients the temperature of the fuel pin cladding is rapidly elevated above its steady state service temperature. To properly model the fuel pin transient behavior and to predict failure, the mechanical properties (specifically failure strength and ductility) of the cladding must be known under thermal and stress conditions encountered in transients. The temperature transient alters the strength, ductility and deformation behavior by causing recovery, recrystallization and annealing of the microstructure of the cold-worked and irradiated cladding. Since the extent of the property alteration is dependent upon time as well as temperature, it is imperative that the mechanical properties be determined under appropriate time/temperature conditions. Therefore, a sphcific testing program is underway at HEDL, utilizing a recently developed Fuel Cladding Transient

Tester (FCTT)(1-5) to generate the requisite mechanical property information on irradiated and unirradiated fast reactor fuel cladding under temperature ramp conditions.

In an LOF transient, cladding loading is from the plenum fission gas pressure, which is sufficiently low to produce cladding deformation and failure only at high temperatures above 2000°F. The failure behavior of low-fluence cladding ($1 \times 10^{22} n/cm^2$, $E > 0.1$ MeV) during high-temperature LOF transients has been characterized with the FCTT and is reported in Reference 2.

During a TOP event differential fuel-cladding thermal expansion, intragranular fission gas-induced fuel swelling, and transient release of the intergranular fission gases during an overpower transient generate local cladding loadings(3,5,6) sufficient to strain the cladding at lower temperatures. For example, the seven integral fuel pin TOP tests in the TREAT reactor, which are reported in Reference 5, failed at cladding temperatures from 1300 to 1800°F. Therefore, high gas pressures, which simulate the cladding loadings produced by fuel-cladding mechanical interaction, are employed in FCTT tests intended for TOP analyses. The effects of irradiation at 700 to 1000°F to fluence levels of $4 \times 10^{22} n/cm^2$, ($E > 0.1$ MeV) on cladding properties for TOP analyses is the subject of this paper.

Test Procedure

The simulated transient testing with the FCTT was accomplished by rapidly heating internally pressurized specimens of prototypic FTR 20% CW Type 316 stainless steel fuel pin cladding. Both unirradiated and irradiated specimens were maintained at a constant internal pressure while they were heated at ramp rates of 10F°/sec and 200F°/sec above the steady state irradiation temperature. Straining and/or failure occurred as the increasing temperature decreased the strength of the cladding. In addition to allowing different amounts of thermal recovery and annealing, the two heating rates also impose different cladding strain rates, as would occur in the various fuel pin transients.

Figure 1 schematically illustrates the testing approach employed with the FCTT. All transient tests were initiated from a temperature of 700°F, which was below the steady state irradiation temperature of the specimens. Specimen pressure and failure were indicated by a calibrated strain-gauge pressure transducer. Diametral strain and failure ductility were determined by micrometer measurements. Additional details of the experimental procedure are described in Reference 1.

Unirradiated Cladding Results

The failure strength and ductility of unirradiated 20% CW Type 316 stainless steel cladding are shown in Figures 2 through 4. The failure temperatures increased with decreasing internal pressure. The specimens heated at 200F°/sec are "stronger" than the 10F°/sec specimens because less thermal recovery of annealing of the cold-worked microstructure occurred. In Figures 3 and 4 the upper dashed lines give the diametral failure strain as a function of failure temperature. The solid curves describe the deformation preceeding failure at the various stress levels. Under the constant pressure test conditions, the majority of the deformation occurred during the last stages of the transient and the cladding strain rate increased rapidly as the failure temperature was approached. The diametral strain at 10F°/sec was greater than at 200F°/sec because of more time for recovery or annealing of the cladding cold-worked conditions. Additional information on the properties of unirradiated 20% CW Type 316 stainless steel cladding under transient conditions is available in Reference 1. A correlation of the transient failure strength with tensile, stress-rupture, and burst test results is available in Reference 7.

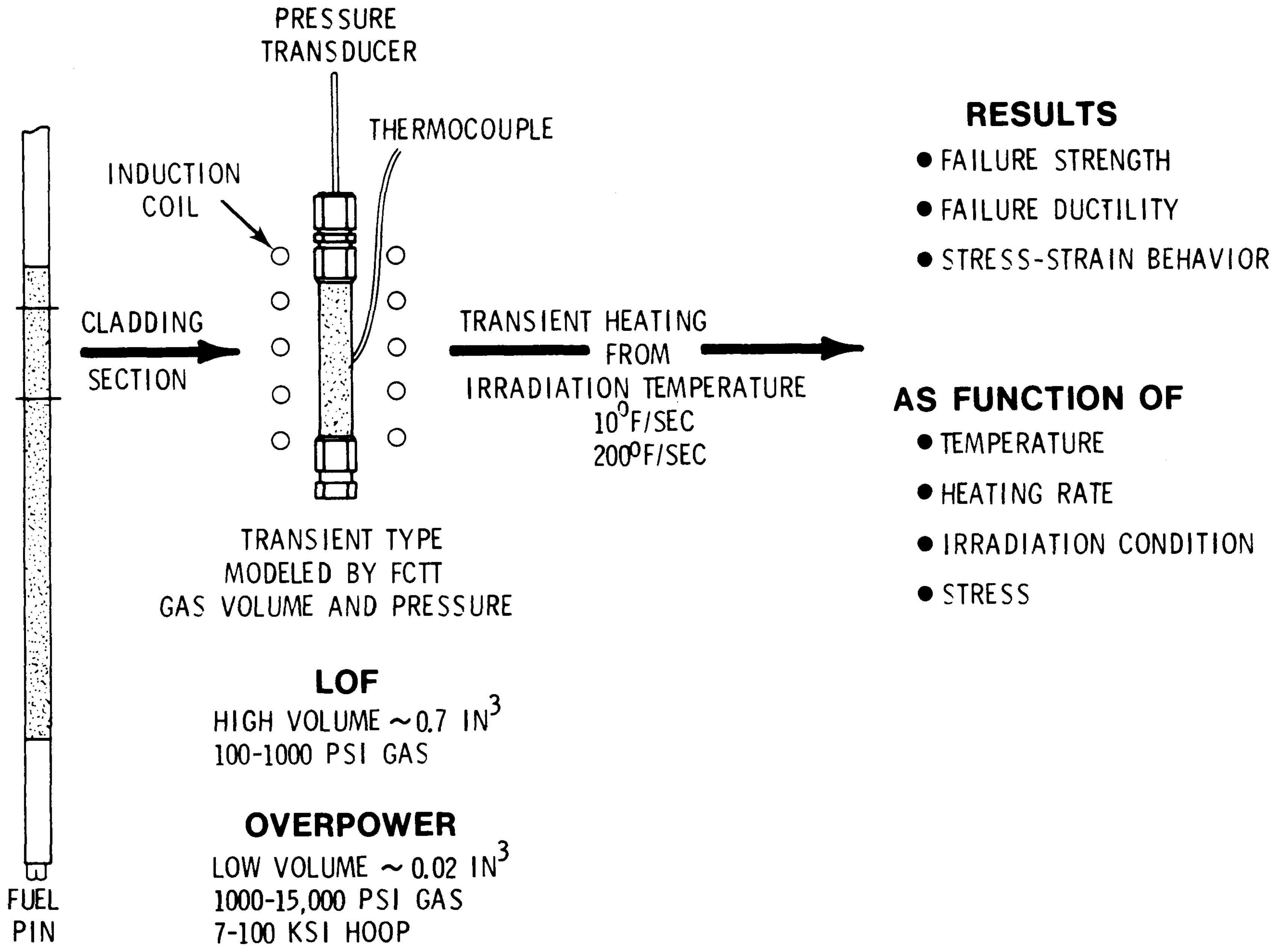

Figure 1. Testing Approach with Fuel Cladding Transient Tester (FCTT)

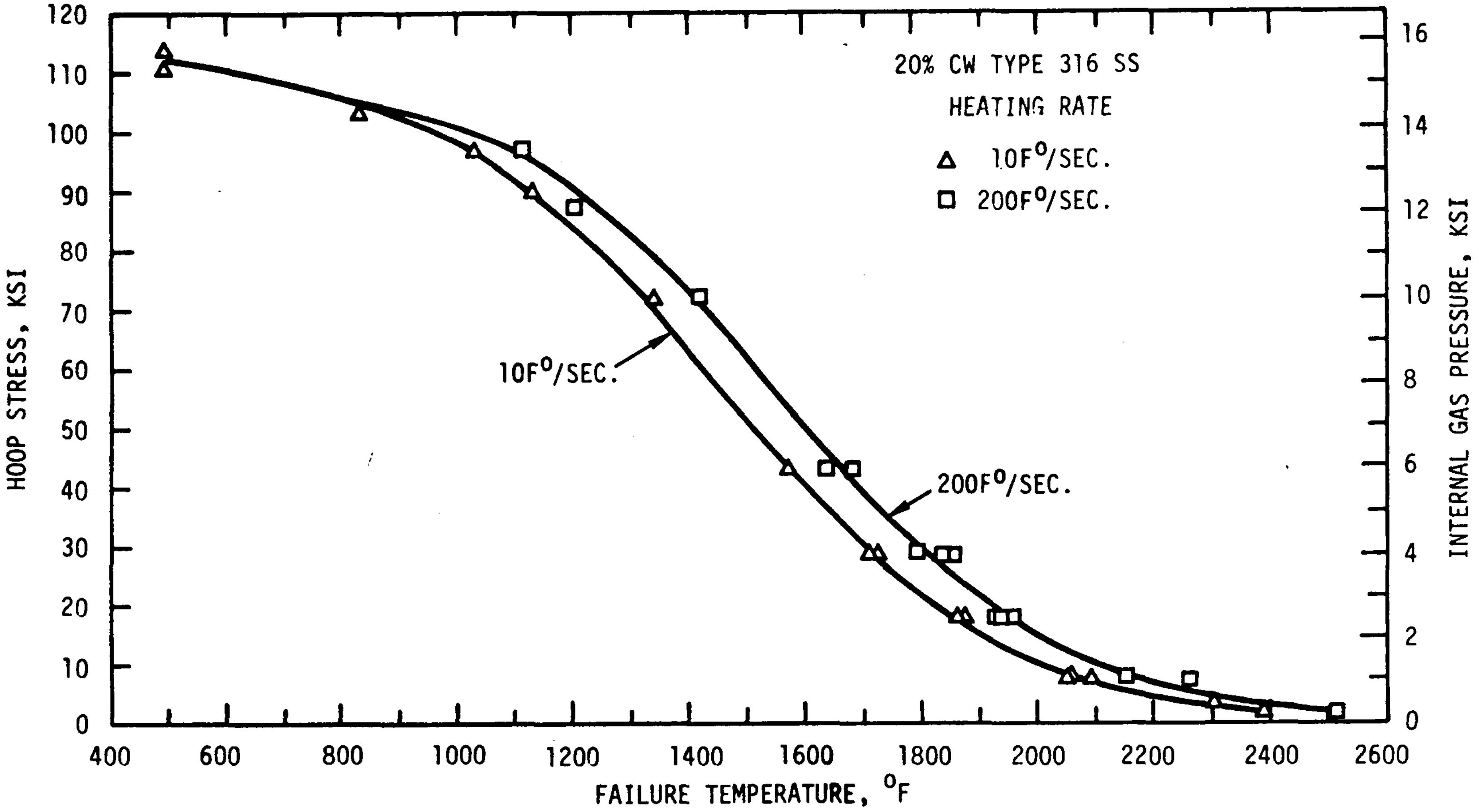

FIGURE 2. FAILURE TEMPERATURE OF FAST REACTOR CLADDING DURING TEMPERATURE TRANSIENTS

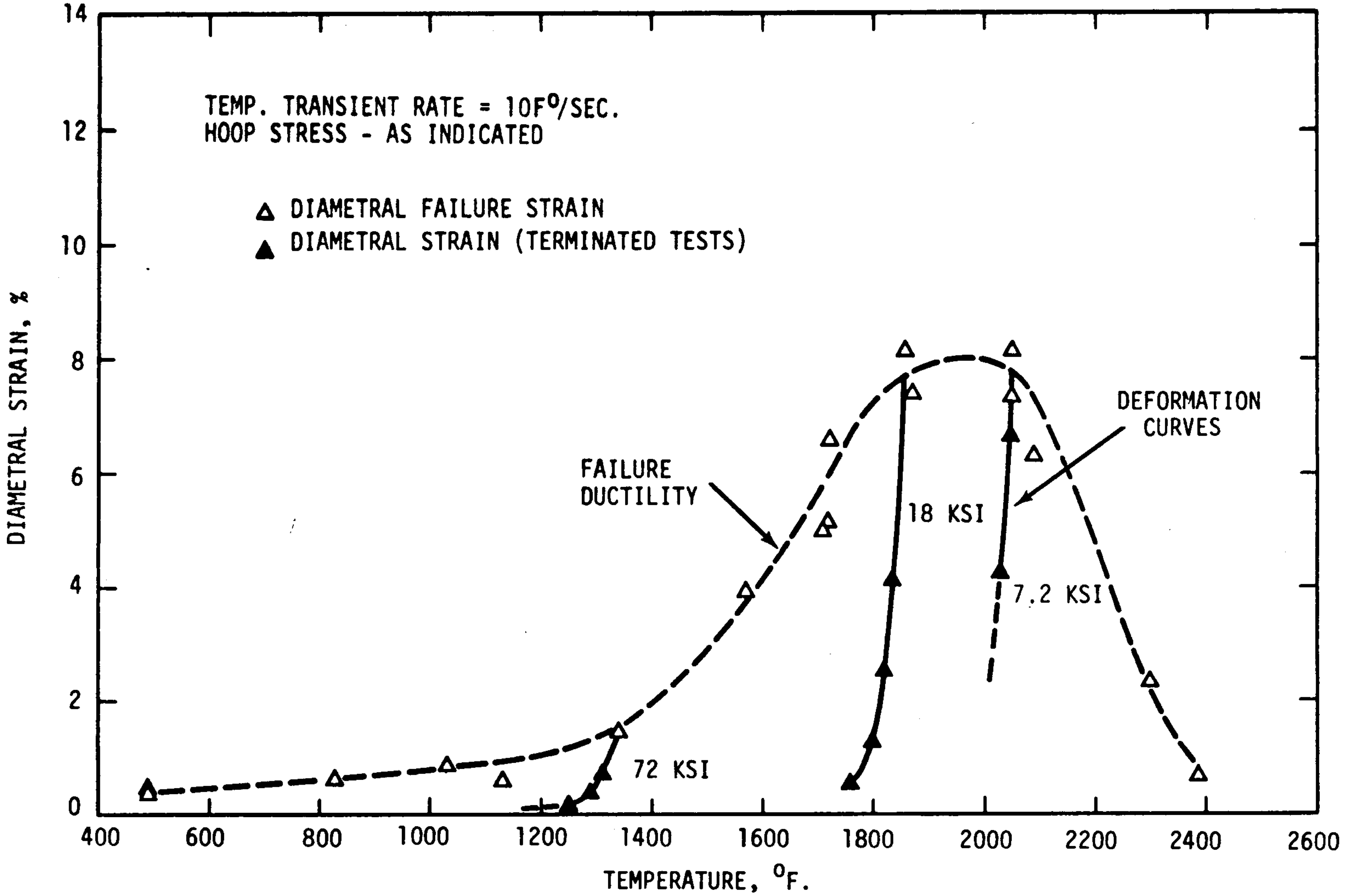

FIGURE 3. DEFORMATION AND DUCTILITY OF FAST REACTOR CLADDING TRANSIENT TESTED AT 10F°/SEC.

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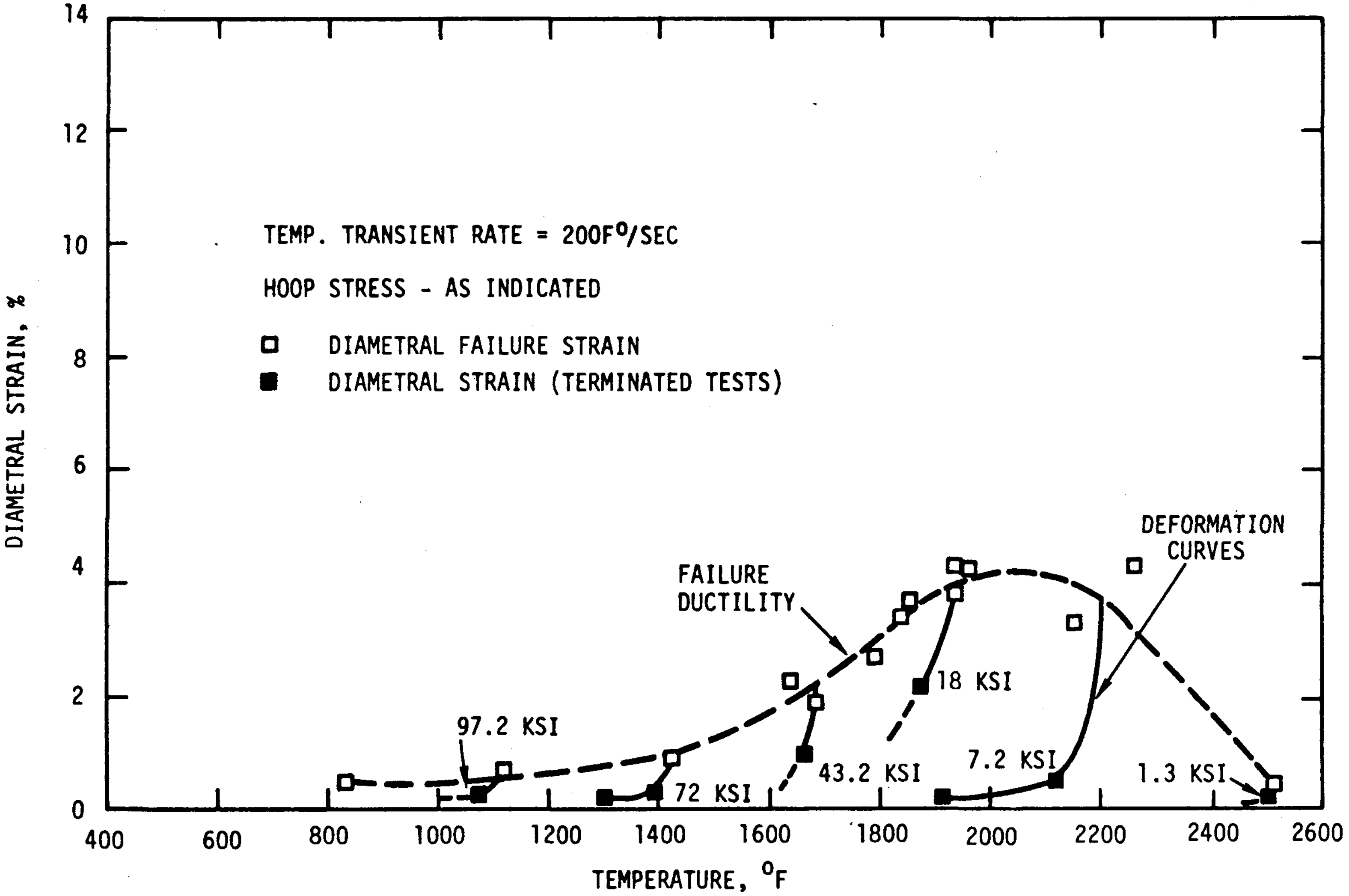

FIGURE 4. DEFORMATION AND DUCTILITY OF FAST REACTOR CLADDING TRANSIENT TESTED AT 200F°/SEC.

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Irradiated Cladding Results

Irradiated specimens were tested from HEDL mixed oxide (75% U, 25% Pu)O_2 fuel pins NUMEC F, PNL-10, and PNL-11, which were irradiated in EBR-II at 8 to 12 kW/ft with cladding temperatures of 700 to 1000°F. The maximum cladding fluences were 4 x 10^{22}n/cm^2, (E > 0.1 MeV) and the burnup levels were 30,000 to 50,000 MWd/MTM.

The irradiated fuel pin cladding results may be characterized as exhibiting reduced ductility, and failing at lower temperatures during the transient, than did the unirradiated cladding material. A comparison of data for the unirradiated and irradiated cladding is shown in Figures 5 through 7. Under the constant-pressure FCTT test conditions, a decrease in the failure temperature for an irradiated specimen, relative to the unirradiated specimen, implies that the load-bearing capability or failure strength is reduced. The ductility in Figures 6 and 7 is lowest in the temperature region from 1000 to 1600°F. At 10F°/sec the minimum values were 0.1 to 0.2%, while at 200F°/sec the minimum was 0.25%. Specimens for which inner or outer surface wastage had been identified are noted in the figures.

An increase in the neutron fluence results in a decrease in both the failure strain and temperature. Figure 8 shows the general trend of decreasing failure strain with increasing fluence. The failure temperatures for the same specimens also decrease with fluence as illustrated in Figure 9. Thus the reduction in ductility due to fluence is compounded with the inherent ductility reduction of unirradiated material as the failure temperature is decreased (see Figures 3 and 4). Therefore, the strain ratio of the irradiated material value to the unirradiated material value at the same temperature, provides a measure of the net effect of irradiation on ductility. The strain ratio results in Figures 10 and 11 indicate that the reduction in ductility occurred

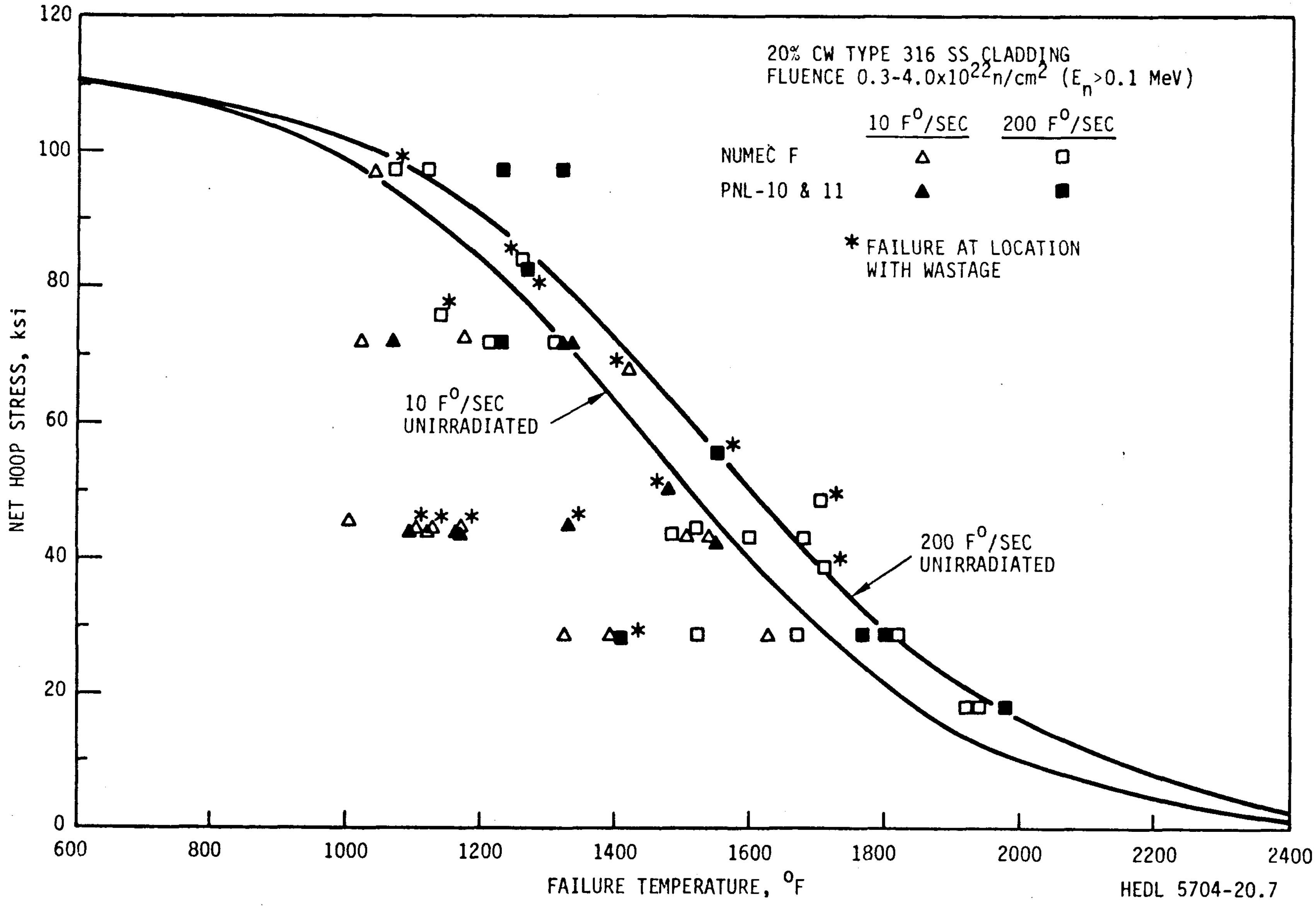

FIGURE 5. Failure Stress During Thermal Transients for Irradiated Fuel Pin Cladding.

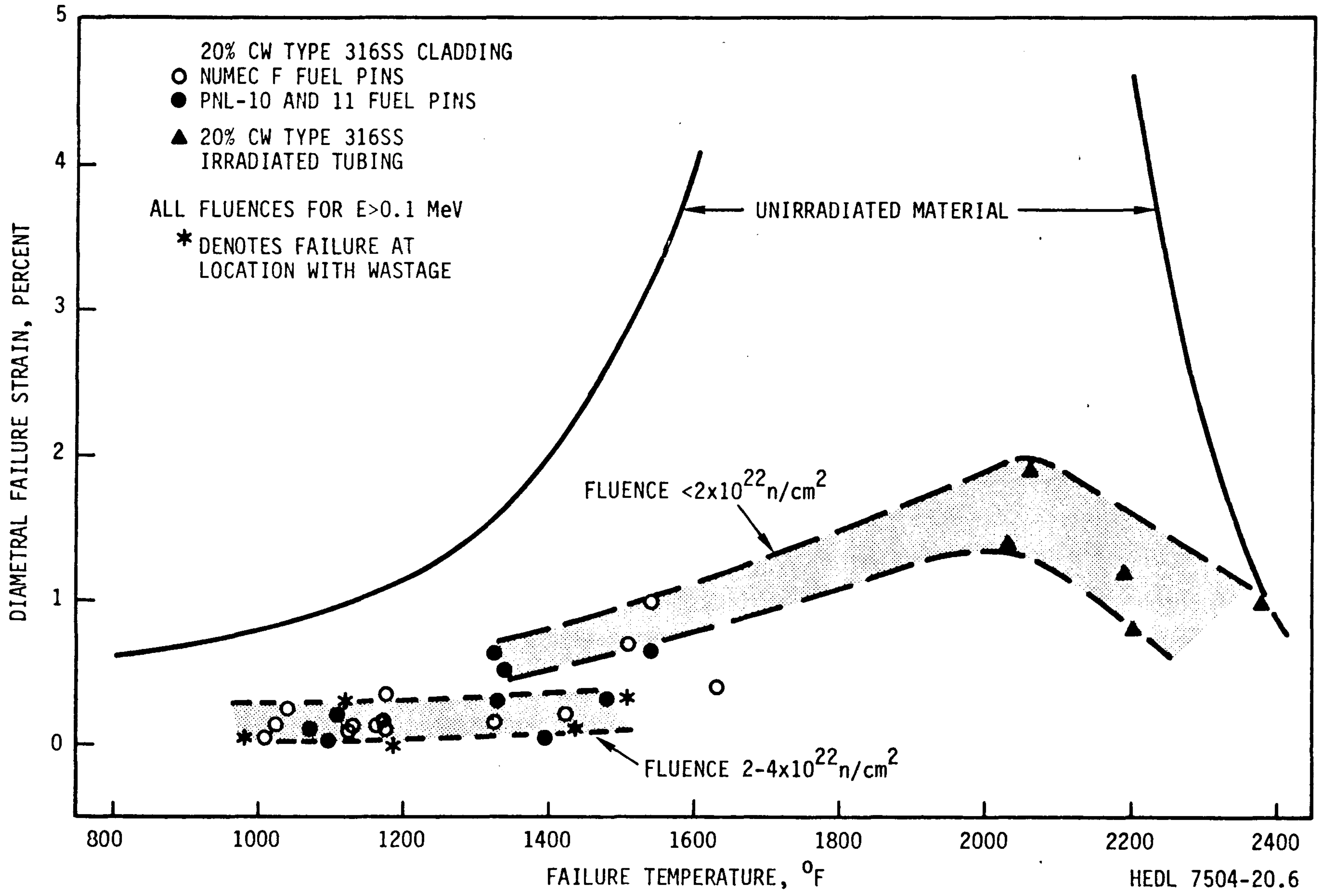

FIGURE 6. Effect of Neutron Irradiation on Cladding Diametral Failure Strain During 10 F°/sec Thermal Transient.

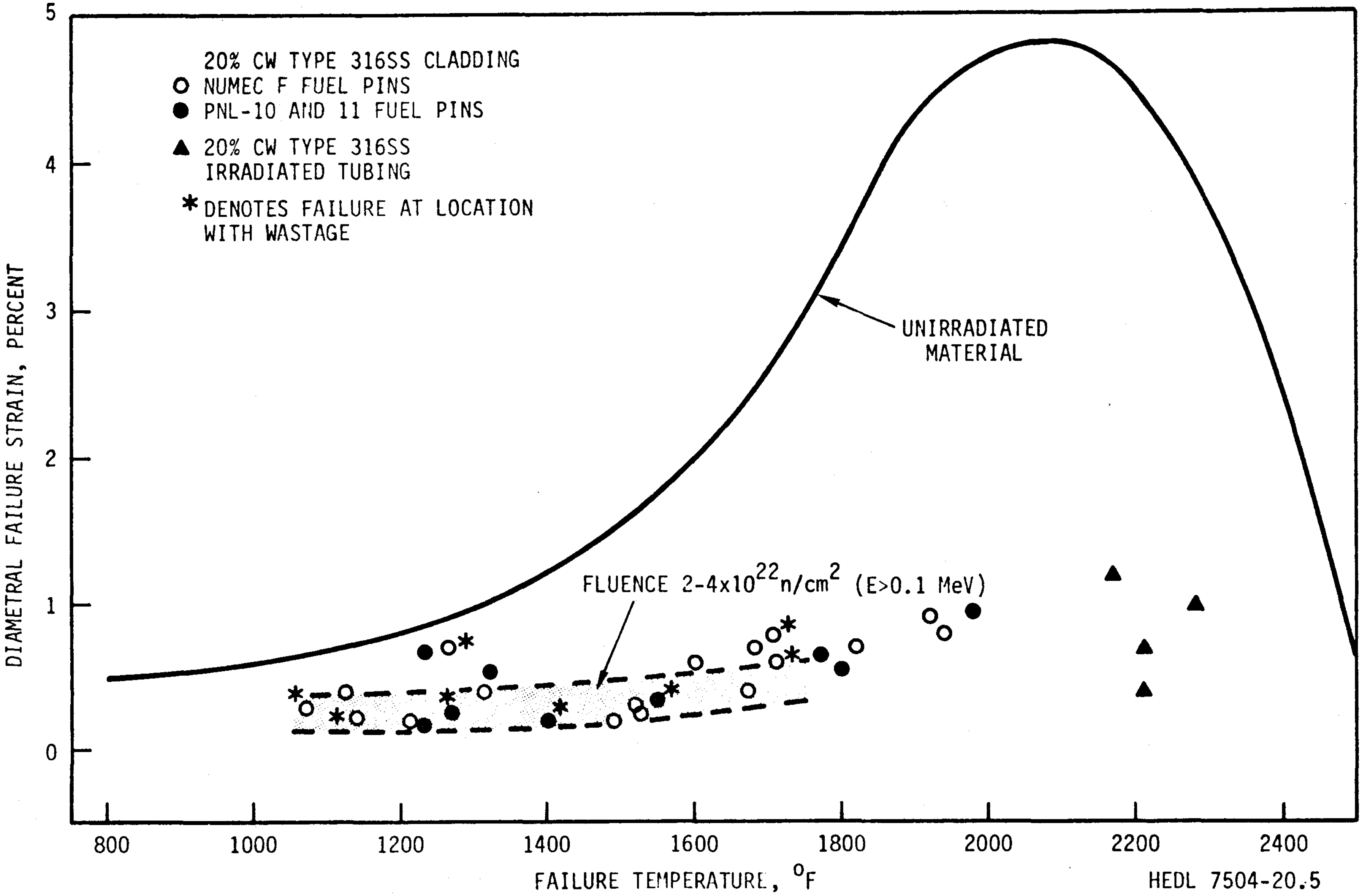

FIGURE 7. Effect of Neutron Irradiation on Cladding Diametral Failure Strain During 200 F°/sec Thermal Transient.

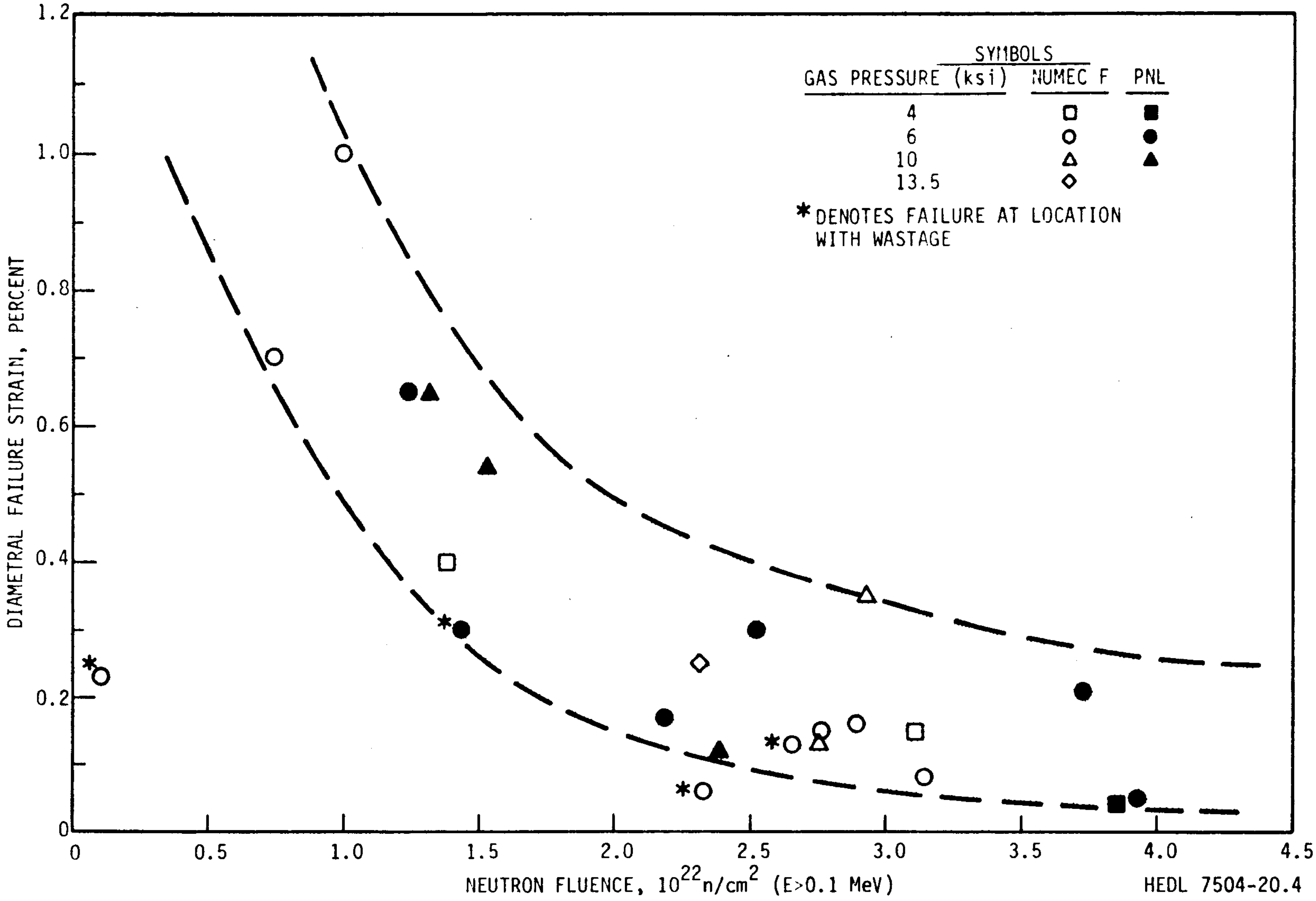

FIGURE 8. Effect of Neutron Fluence on Cladding Diametral Failure Strain for 10 F°/sec Thermal Transient.

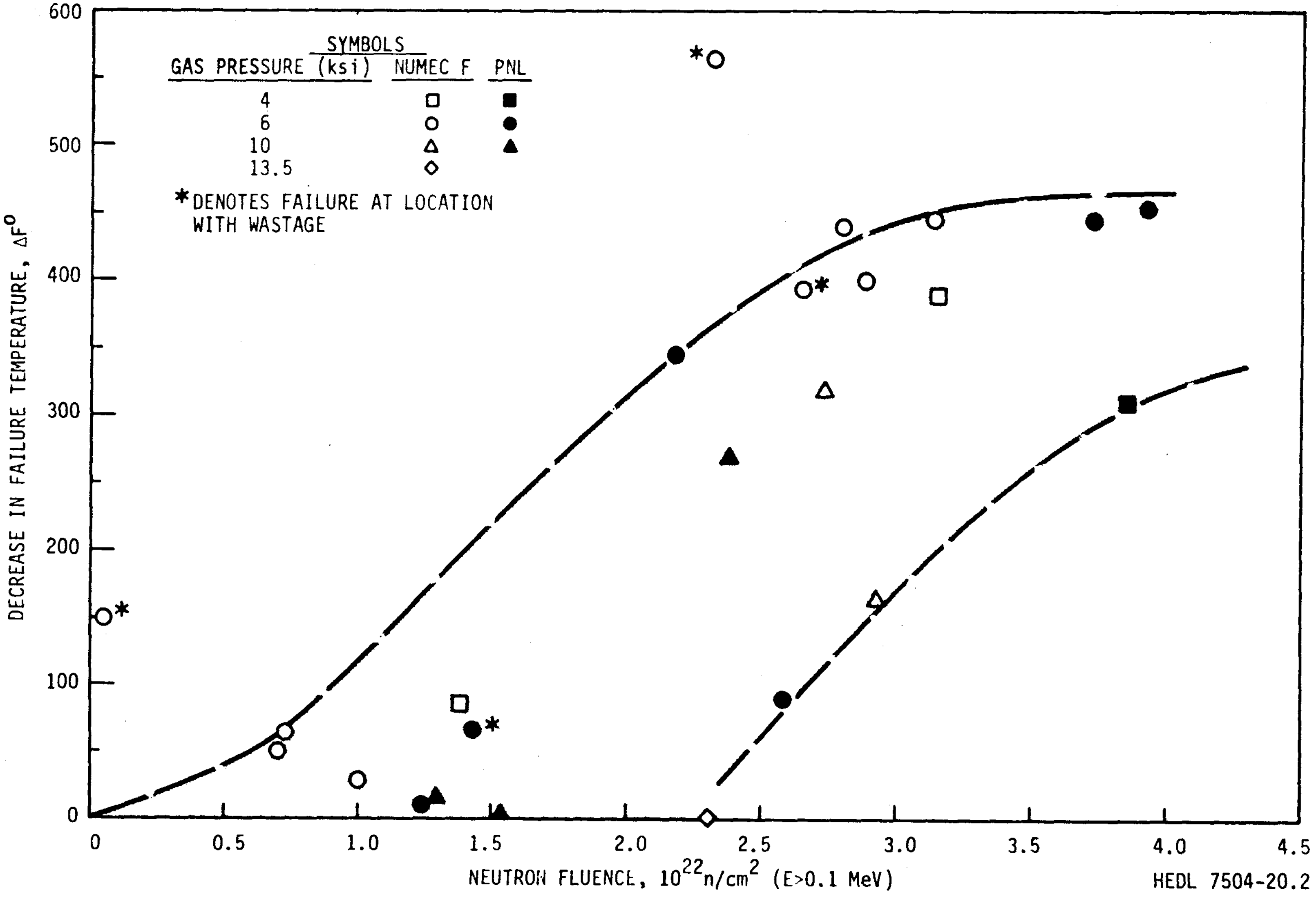

FIGURE 9. Effect of Neutron Fluence on the Decrease in Cladding Failure Temperature for 10 F°/sec Thermal Transient.

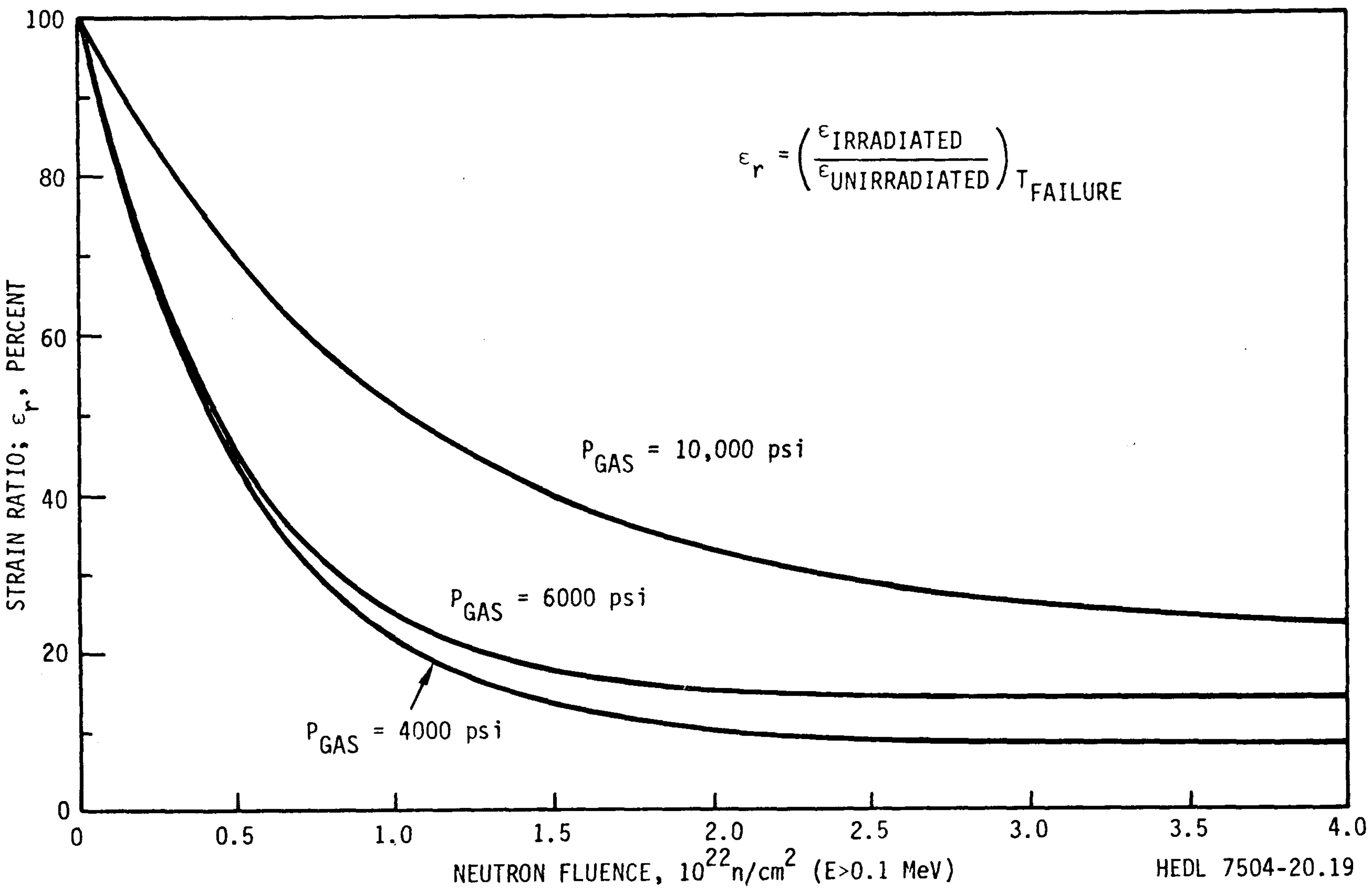

FIGURE 10. Effect of Neutron Fluence on Strain Ratio for a Heating Rate of 10 F°/sec.

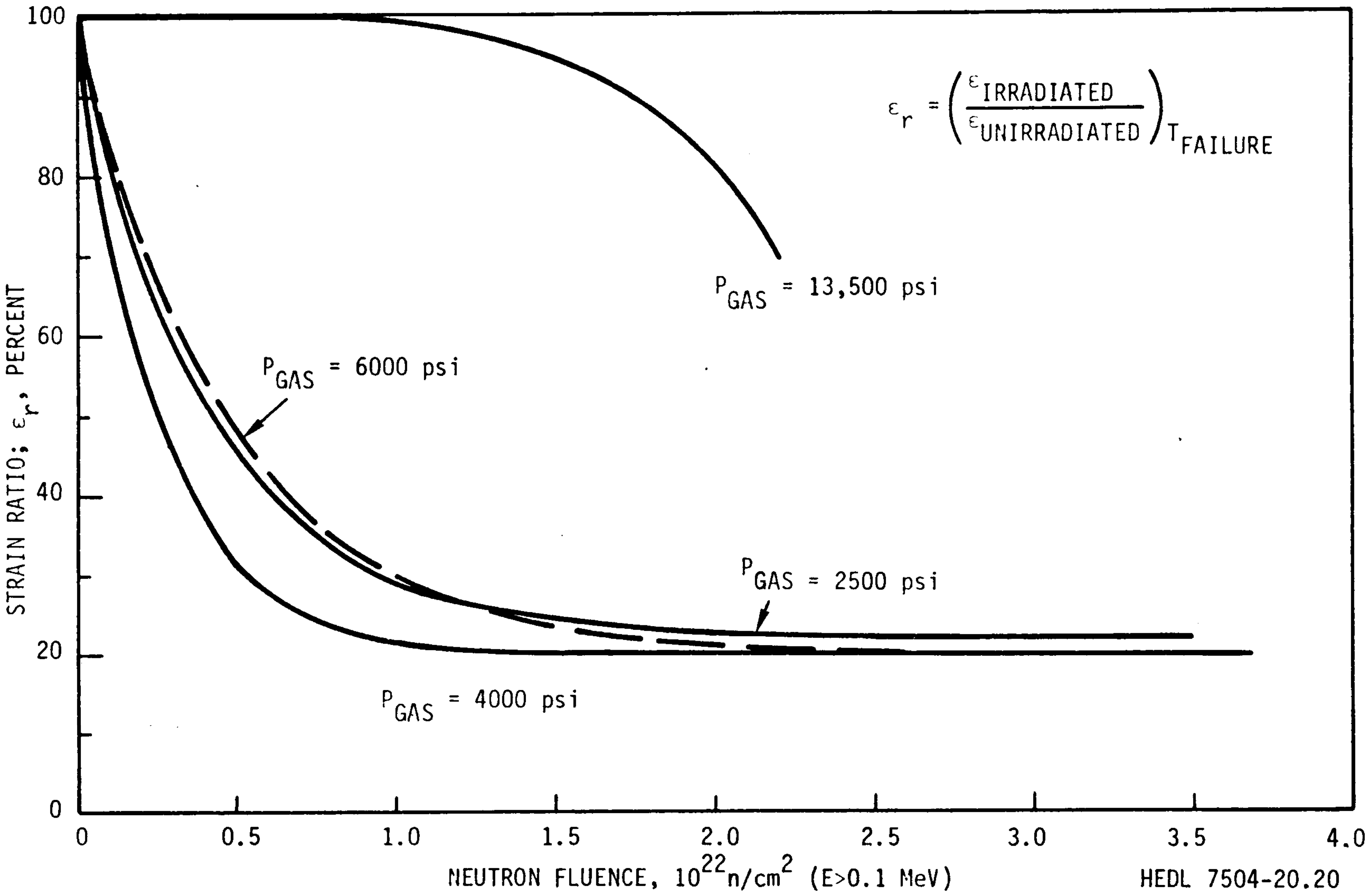

FIGURE 11. Effect of Neutron Fluence on Strain Ratio for a Heating Rate of 200 F°/sec.

at low fluences and has saturated at 2 x 10^{22}n/cm^2. Similarly, the failure stress ratio of the irradiated material failure stress to the unirradiated material value at the same temperature in Figures 12 and 13 provides a proper measure of how the failure strength has been changed by irradiation.

Intergranular Embrittlement

In Figure 14 the decrease in failure temperature is shown as a function of the failure strain, which demonstrates that the cladding with lower failure strain exhibited the larger decrease in failure temperature, and, consequently, failure strength. This behavior is opposite to that of increasing strength with decreasing ductility commonly exhibited by metals, and is a definite sign that a cracking (noncontinuum) process interferes with the ability of the cladding hoop ligament to bear tensile loads. The decrease in load-bearing capability occurred only under conditions of partial or total intergranular fracture. Intergranular fracture does not inherently require extensive local strain. Hence, if low-ductility intergranular fracture is a potential, then at any highly stressed local region, a grain boundary opening or microcrack can occur before the remaining material across the section can bear stress. Consequently, the failure strength in tension is reduced. The ductility of intergranular fracture is reduced by helium embrittlement(8) and a hard or strong crystal.(9) Therefore, a higher irradiation fluence should decrease the ductility and reduce the failure strength under conditions of low-ductility intergranular fracture.

Figure 5 shows that several of the 200F°/sec tests at a hoop stress of 97.2 ksi had failure temperatures greater than that for the unirradiated material. These test conditions forced a high strain rate at sufficiently low temperatures that transgranular failure occurred, which allowed the radiation

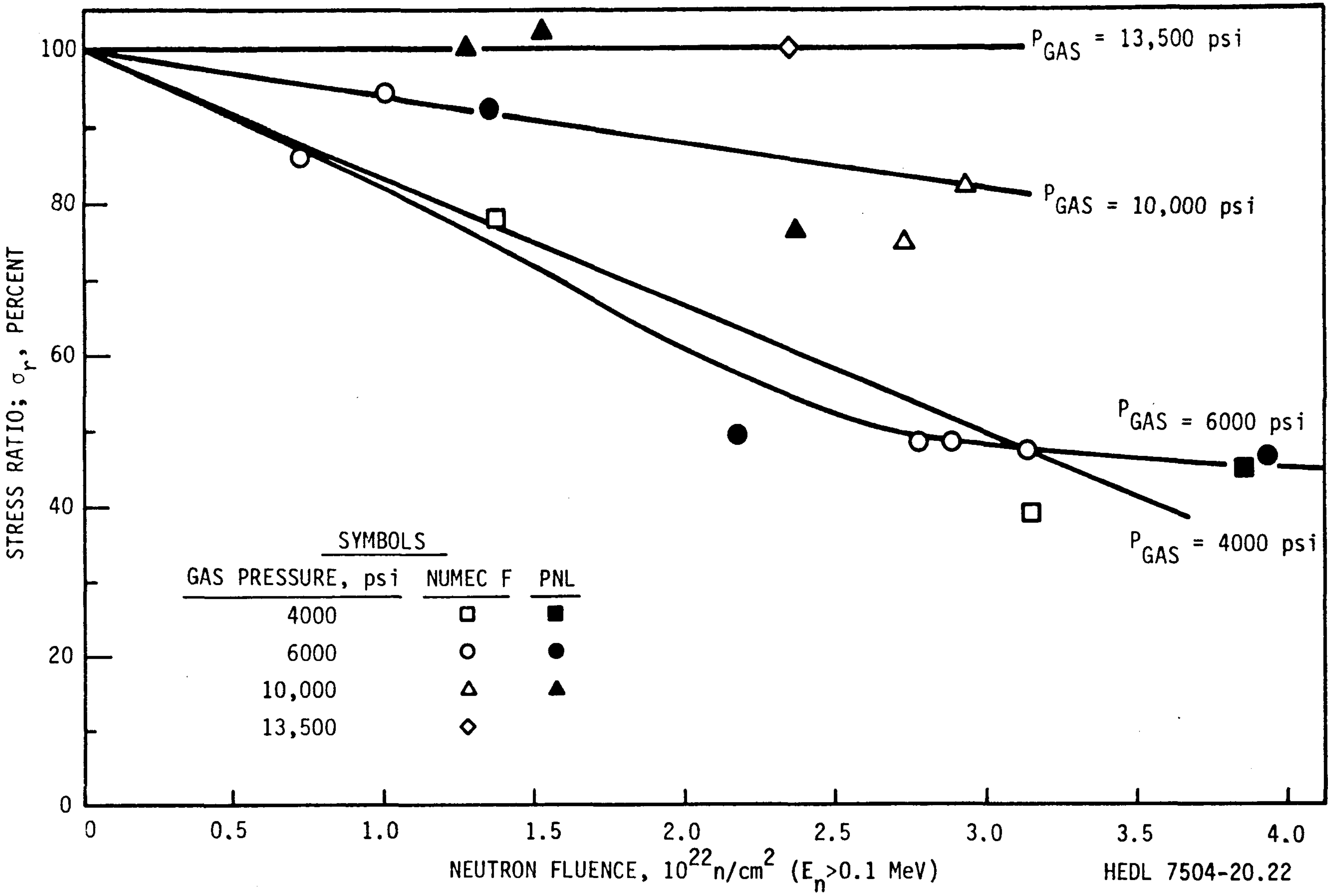

FIGURE 12. Effect of Neutron Fluence on Stress Ratio at 10 F°/sec.

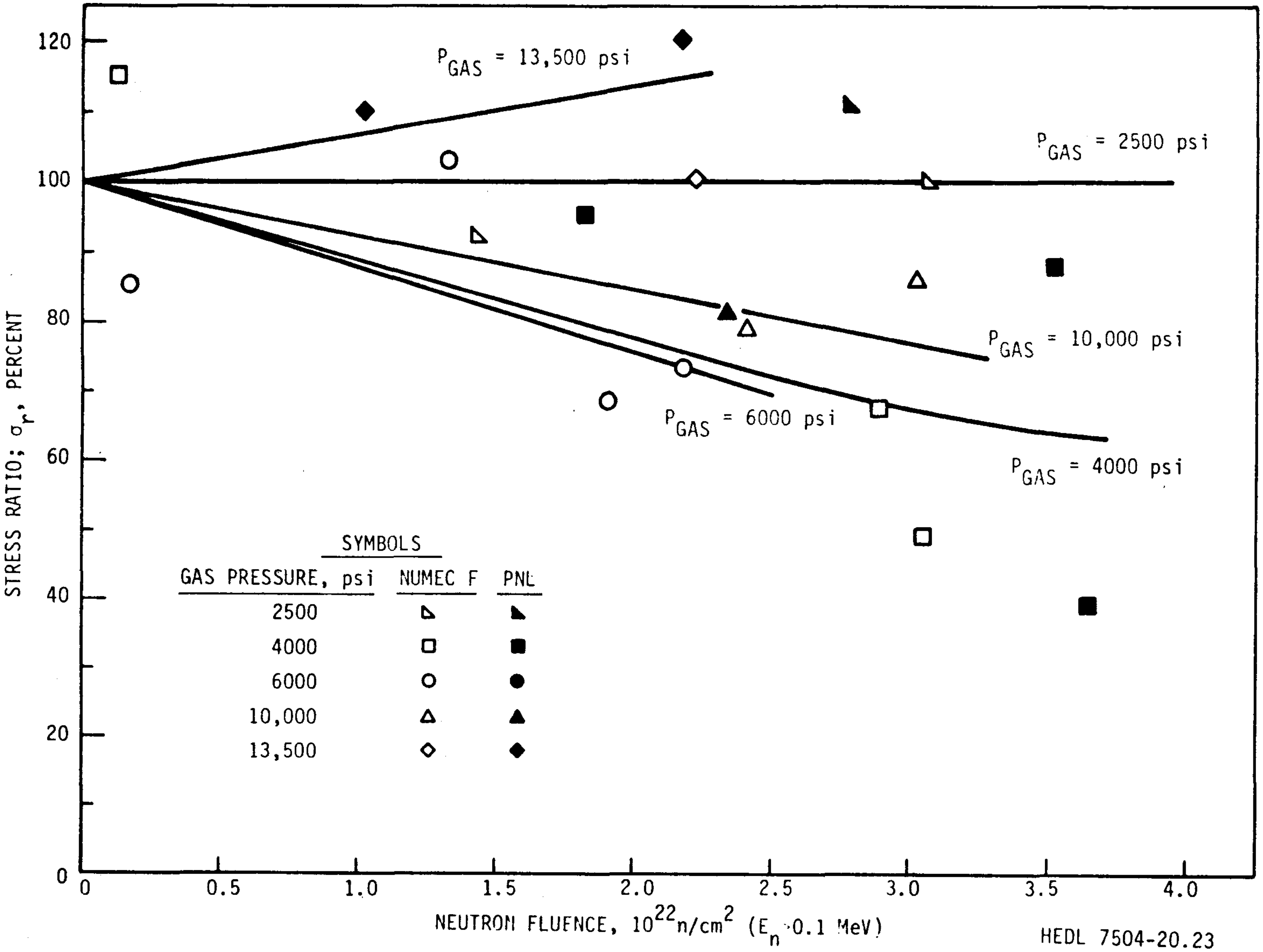

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FIGURE 13. Effect of Neutron Fluence on Stress Ratio at 200 F°/sec.

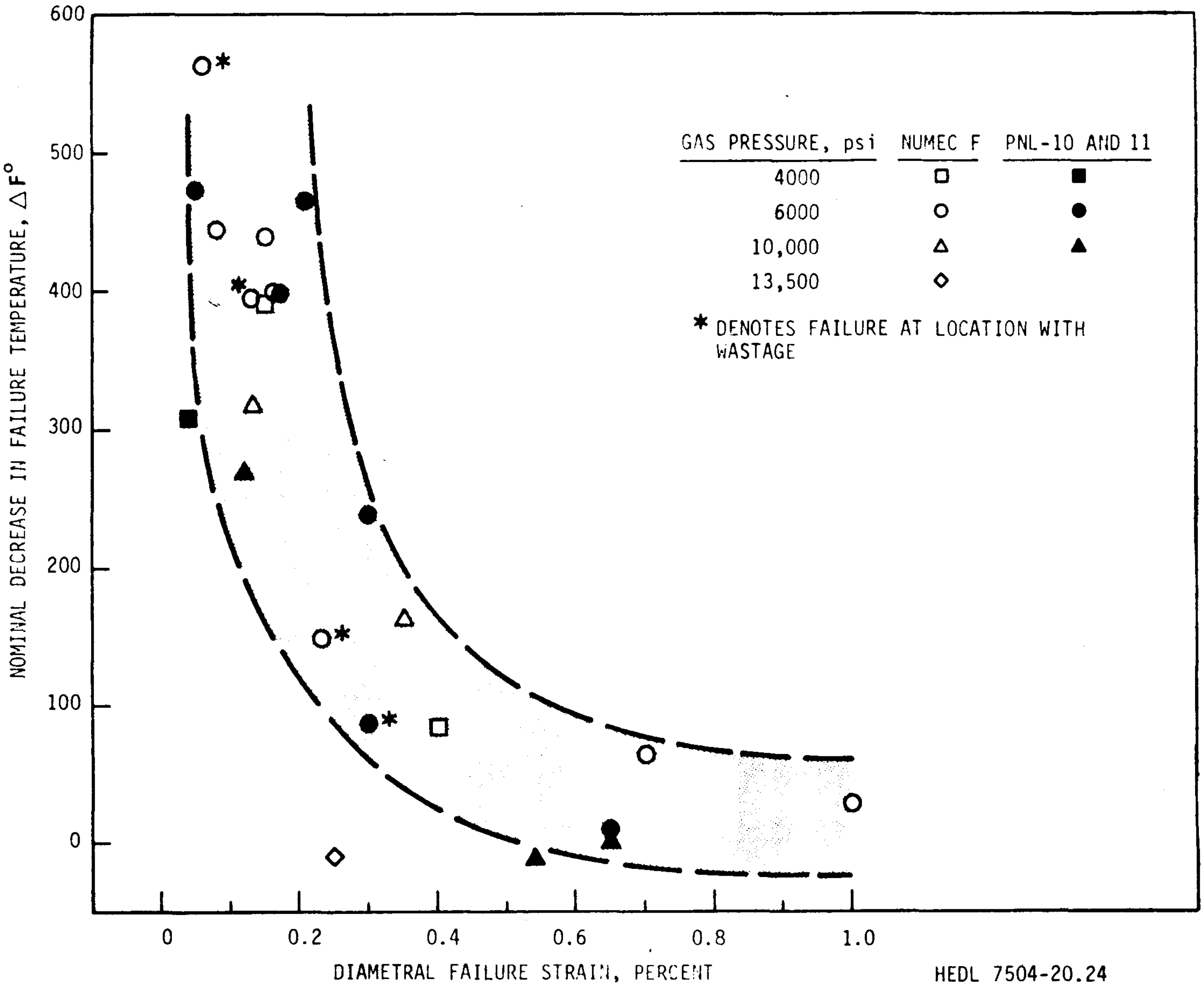

FIGURE 14. Relationship Between Decrease in Failure Temperature and Diametral Failure Strain During a 10 F°/sec Thermal Transient.

hardening to increase the failure strength. Therefore, below about 1200°F at 200F°/sec and below about 1000°F at 10F°/sec transgranular failure will occur and irradiated failure strengths equal to or greater than that for the unirradiated material are anticipated.

Summary of Irradiation Effects

The irradiated cladding failure stress and ductility data are summarized in Figure 15. At 200F°/sec above 1200°F the ductility and failure strength of the cladding are reduced; however, above 1600°F the ductility increases and the available results do not show decreased failure strength. The fracture mode is still intergranular, but the ductility is not low enough to interfere with load-bearing capability. At 10F°/sec there are insufficient higher temperature failure data to define the behavior. However, for the above reason, it is anticipated that above about 1400°F the ductility will increase to about 1%.

For both heating rates, at lower failure temperatures and higher stresses, the irradiated material failure stress curve is shown to rise discontinuously to the unirradiated material curve as the fracture changes from intergranular to transgranular. At temperatures above 1400 and 1600°F the failure stress curves are expected to gradually approach the unirradiated curves, as the reduced crystal shear strength allows blunting of stress concentrations.

Comparison with TREAT Tests

During an integral fuel pin transient test the fuel loading on the cladding is not known. Nevertheless, a knowledge of the cladding properties will enable a more rational inference or extraction of the fuel loading function from TREAT tests. The ductility exhibited in an integral fuel pin transient test should be similar to that exhibited by an FCTT specimen which

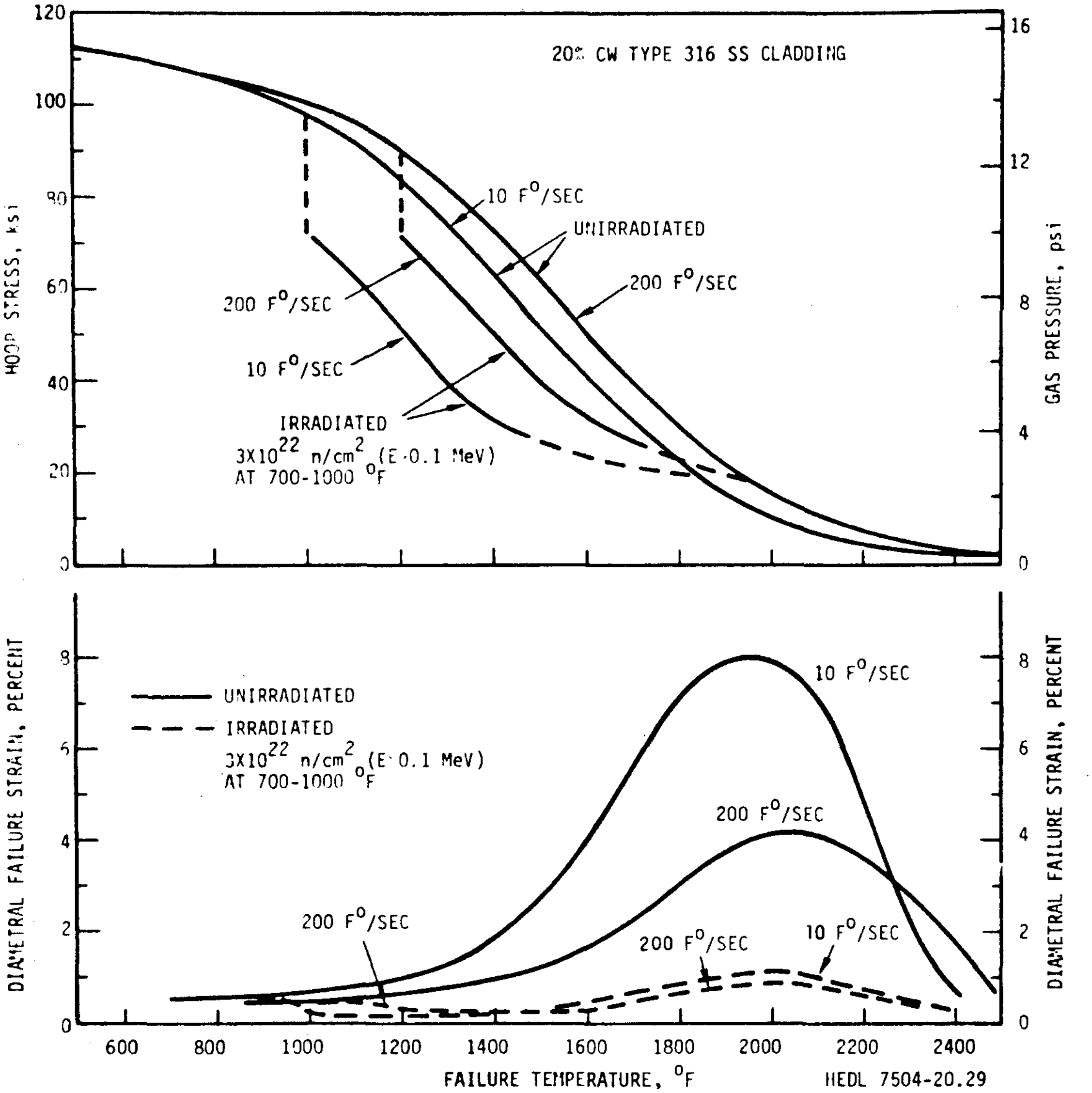

FIGURE 15. Effect of Irradiation on the Failure Strength and Ductility.

experienced similar irradiation and transient conditions. Furthermore, the failure strength exhibited in the FCTT results may be employed to gain insight into the cladding loadings imposed by the various fuel behavior phenomena. For example, knowing the steady-state irradiation conditions and the transient heating rate and failure temperature for an integral fuel pin transient test will enable estimation from FCTT results of the stresses which must have been applied to produce cladding failure.

An example comparison of FCTT data with the HOP 3-3C and H5 TREAT tests is given in Table I. The failure stress and failure strain values for FCTT results were taken from Figures 8 and 10 through 13. The FCTT failure strain values agree well with that from the TREAT pins.

The results obtained from application of FCTT results to an integral fuel pin test should be considered as an approximation since the FCTT does not precisely duplicate integral fuel pin transient conditions. Heating rates in the FCTT cannot be controlled separately from strain rates; thus, while the former is probably of secondary importance, the precise interplay of the two is not duplicated by the FCTT. Because the cladding wall temperature increases uniformly in the FCTT, effects of cladding wall temperature gradients are not included. Nevertheless, valid inferences on the course of loading in an integral fuel pin test can be made using FCTT results.

Fuel Effect on Cladding Properties

Figure 16 compares the failure strength of the fuel cladding specimens with results from unfueled, unstressed cladding tubing subjected to similar irradiation conditions. The unfueled, unstressed specimens were irradiated in EBR-II at 860 to 1050°F to fluences of $3.6 \times 10^{22} n/cm^2$; thus, the neutron and thermal exposures are very similar to that of the NUMEC F, PNL-10 and PNL-11 fuel pins.

TABLE I

COMPARISON OF TREAT TESTS WITH FCTT RESULTS

TREAT Test	Fuel Pin	Approximate Failure Conditions	FCTT Cladding Results	
			Failure Strain(1)	Failure Stress(4)
HOP 3-3C	PNL-17-34	1400°F	0.2-0.5%(2)	55,000 psi Hoop Stress
3\$/sec	30,000 MWd/MTM 700-1100°F $2.4 \times 10^{22} n/cm^2$	0.35% Strain(1)	0.29%(3)	
H5	PNL-17-25	1480°F	0.2-0.5%(2)	48,000 psi Hoop Stress
50¢/sec	30,000 MWd/MTM 700-1100°F $2.4 \times 10^{22} n/cm^2$	0.35% Strain(1)	0.29%(3)	

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(1) All strain values are the incremental transient strain, and do not include the strain which occurred during the steady-state EBR-II irradiation.

(2) Range of values.

(3) Value calculated from average of strain ratios for 200F°/sec tests at 6000 and 10,000 psi gas pressure from Figure 11.

(4) Values calculated from average of stress ratios for 200F°/sec tests at 6000 and 10,000 psi gas pressure from Figure 13.

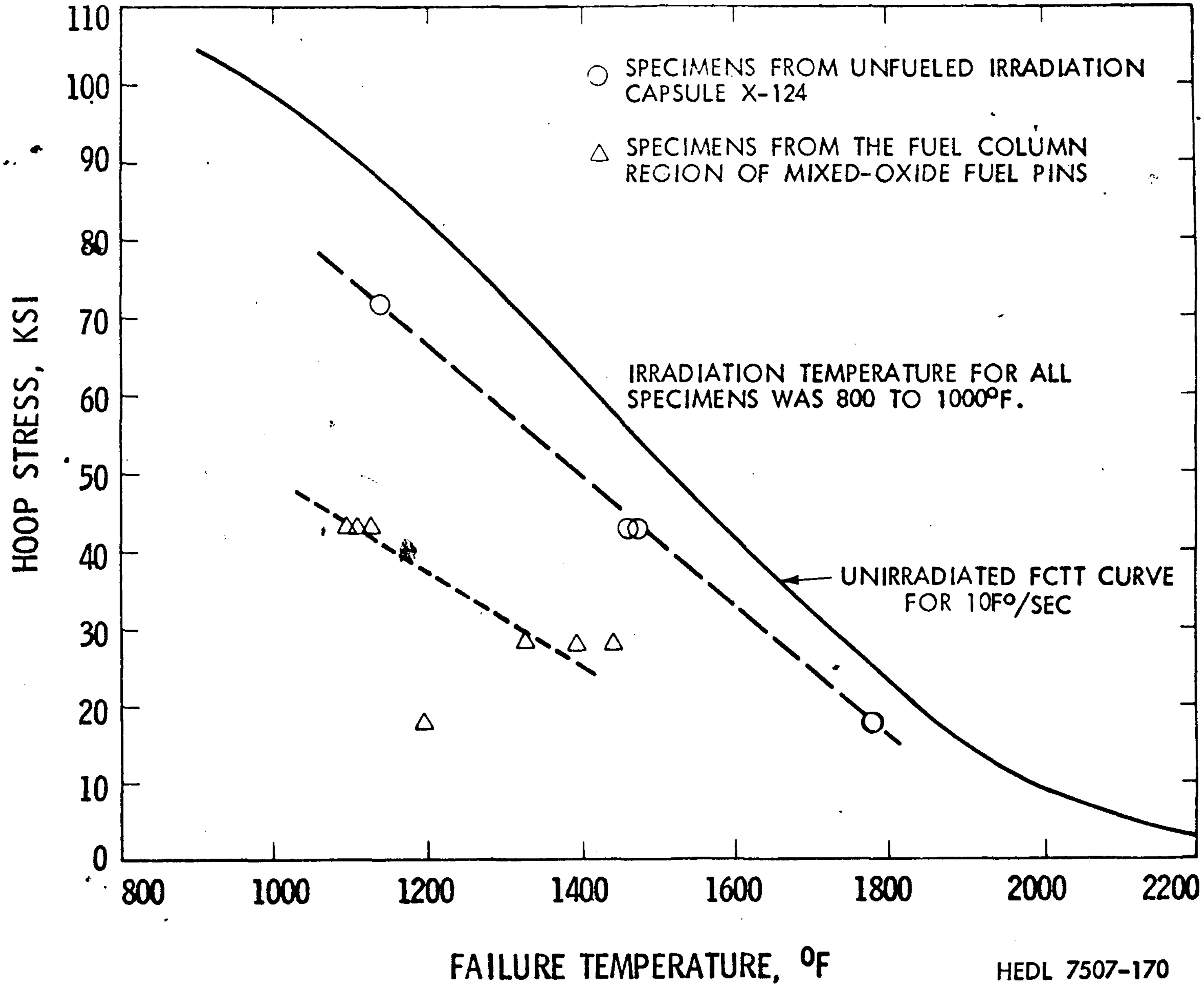

Figure 16. Comparison of Fueled and Unfueled Specimen Transient Behavior for a Neutron Fluence of 3-4 x 10^{22} n/cm^2 (E > 0.1 MeV)

The "weaker strength" behavior of the fuel column cladding could not be accounted for on the assumption that the nominal amounts of wastage degrade the failure strength as a result of wall thinning.(4) However, even small amounts of inner surface intergranular attack provide stress raisers or crack starters which promote the low-ductility intergranular fracture and loss of failure strength. Also the stresses from thermal gradients or fuel-cladding mechanical interaction during the EBR-II irradiation may have initiated microcracks or otherwise consumed cladding life to a greater extent than that experienced by the unfueled cladding.

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