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FUEL-CLADDING MECHANICAL INTERACTION IN IRRADIATED GCFR MIXED-OXIDE FUEL RODS

by

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INTRODUCTION

The Gas-Cooled Fast Breeder Reactor (GCFR) concept employs high-pressure (approximately 8.6 MPa) helium as the primary coolant. Metal-clad oxide fuel is used based upon available technology, but certain unique features are incorporated. Among the unique characteristics of the GCFR fuel is the use of fuel rods which have roughened outside surfaces to enhance heat transfer and a system for pressure equalizing and venting the fuel rods.

The irradiation test program for the GCFR fuel focuses on the evaluation of the unique parameters and features. One of the first of the test programs to complete irradiation was the F-1 experiment. The F-1 experiment, irradiated in EBR-II,[1] consisted of 13 rods having prototypical geometry; one of the rods attained a burnup of 14 at.% The primary distinguishing characteristics of the F-1 rods are that they were operated at relatively high cladding temperatures (to 760°C) and relatively low internal rod pressures (maximum of 4.14 MPa). The F-1 cladding temperatures were designed to be characteristic of GCFR cladding temperatures (design hot spot temperature limit of 700°C for normal events), and the rod internal pressures were maintained low to partially simulate the effect of the pressure equalization system.

The combination of high cladding temperatures and low internal pressures in the F-1 rods provides insight into the performance characteristics of the GCFR fuel design. Information relevant to fast breeder reactor oxide fuels in general is also provided. The fuel rod-cladding mechanical behavior for the unique conditions in the F-1 rods, particularly with regard to fuel-cladding mechanical interaction (FCMI), is the subject of this paper. The analyses were carried out by means of the LIFE-3 computer program.[2] Consequently, the calculated results when compared with the experimental data provide an additional verification of the LIFE-3 mechanical models employed in the high cladding temperature range.

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EXPERIMENTAL

Detailed information regarding the F-1 experiment has been reported previously.[1] The following summary describes major parameters which may be of importance to the irradiated cladding mechanical behavior.

Test Subassembly

The F-1 experiment consisted of seven capsules inside a hexagonal containment can. Each capsule had a 0.508-mm diameter wire helically wrapped along the length of the capsule. A total of 13 fuel rods were involved in the experiment (identified as G1 to G13). The fuel rods had 20% cold-worked 316 stainless steel cladding and were loaded with mixed-oxide fuel of composition (15% Pu, 85% U)O_{2-x}. The oxide-to-metal (O/M) ratio ranged from 1.95 to 1.99. Most of the fuel was in annular pellet form with smear densities in the range of 82.47% to 86.66% of theoretical density. The cladding was fabricated with a 7.62-mm outside diameter and a 0.381-mm wall thickness. The fuel-to-cladding diametral gap was 0.0864 mm for all rods. The fuel column was 342.9 mm long, corresponding to the length of the EBR-II core. The rods included a large plenum-to-fuel volume ratio (1.3 to 1.4) to accommodate fission gas release at low plenum pressures. Table I summarizes the major fabrication characteristics of the fuel rods.

TABLE I. F-1 IRRADIATION CAPSULE LOADINGS AND CONDITIONS

Fuel Rod No.	Fuel Description			Irradiation Conditions			
	Pellet Type	O/M	Smear Density, % Theoretical	Max. Clad Temp, °C	Peak Linear Power, kW/m	Burnup, at. %	Fluence, $n/cm^2 x 10^{22}$
G1	Annular (A)	1.992	82.64	740	45.3	5.36	3.88
G2	A	1.971	84.12	730	45.9	5.59	3.62
G3	A	1.987	85.52	669	42.7	2.47	2.06
G4	A	1.983	82.47	692	45.6	14.01	9.69
G5	A	1.990	83.51	716	46.3	5.12	3.39
G6	A	1.972	82.65	662	45.3	4.96	3.26
G7	A	1.984	82.54	648	45.9	4.83	3.42
G8	A	1.985	86.06	696	49.2	12.61	8.32
G9	A	1.968	84.30	706	47.6	9.67	5.96
G10	A	1.968	84.20	722	49.5	10.03	6.42
G11	A	1.947	84.56	731	52.2	10.50	6.87
G12	Solid (S)	1.976	84.30	714	47.2	9.56	5.88
G13	S	1.973	84.36	759	52.2	10.53	6.96

Irradiation Conditions

The irradiation conditions for the F-1 experiment are briefly summarized in Table I. The fuel rods operated at peak linear powers ranging from 42.7 to 52.2 kW/m; maximum clad temperatures varied from 650 to 760°C. The maximum burnup for the lead rod (G4) reached 14 at.%. The subassembly

(X-094) was irradiated in Row 7 of EBR-II. One rod (G3) was removed for destructive examination when the burnup attained 2.5 at.% and was replaced by a fresh rod (G8). At about 5.2 at.%, five more rods were removed and were replaced with unirradiated fuel rods which were similar in design. The rod linear powers and cladding temperature histories were determined from the EBR-II operating history; a typical result is shown in Fig. 1 for rod G1.

Postirradiation Examination

The postirradiation examinations are still in progress. Nondestructive examinations have been completed; gamma spectrometry and neutron radiography indicated that the fuel rods were intact and there were no abnormalities. Profilometry showed that none of the rods had undergone significant cladding diametral changes as a result of irradiation. Immersion density measurements revealed that there were no irradiation-induced changes in the density of the cladding within experimental errors.

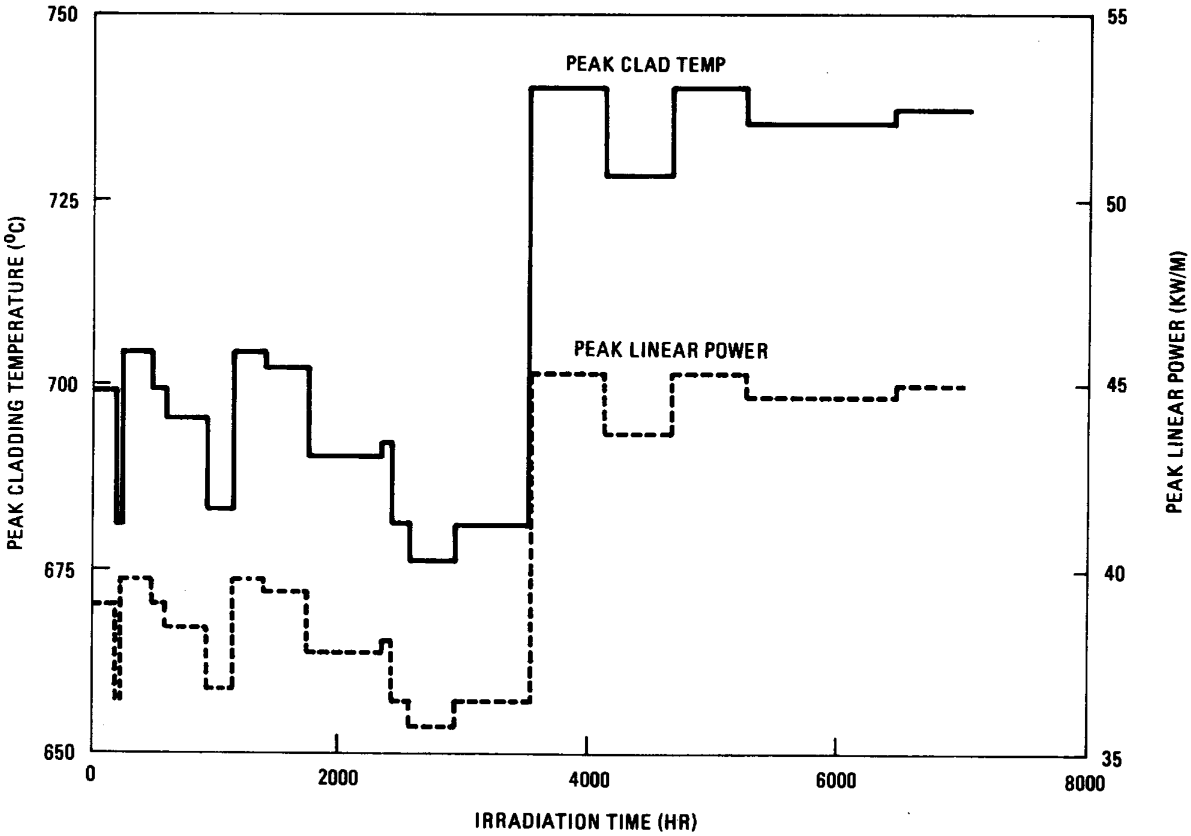

Fig. 1. F-1 rod G1 peak cladding temperature and linear power

CLADDING MECHANICAL STRAIN ANALYSIS

LIFE Model

The analysis of the F-1 cladding mechanical strain was performed using the LIFE-3 code.[2] For a given power history and coolant condition, LIFE-3 calculates cladding mechanical deformation resulting from thermo-elasticity, thermal and irradiation-induced creep, and irradiation-induced swelling. In the analysis the cladding in the fuel region was divided into four axial sections, with an additional plenum section connected to the top of the fuel region to represent all the voids available within the fuel rod for the fission gases.

Results

The LIFE-calculated cladding diametral changes are compared with the experimental profilometry data in Fig. 2 for axial section 3 (i.e., x/L = 0.625 from the bottom of the core). It is seen that they are in good agreement. Additionally, when the LIFE-calculated axial distribution of the cladding diametral changes is compared with the profilometry curves, they have the same shape, as shown in Fig. 3. These results indicate that the cladding mechanical models used in the LIFE-3 code are applicable to and valid at the higher temperature range of the GCFR fuel rod design.

FUEL-CLADDING MECHANICAL INTERACTION (FCMI)

LIFE Analysis

The contribution of FCMI to the F-1 cladding strains is of particular interest. The low pressure stresses result in conditions under which FCMI strains, if any occurred, should be more distinguishable. Five fuel rods from the F-1 experiment were chosen for the FCMI study: G1, which represents a low burnup and a step power increase rod; G4, the highest burnup rod; G7, the lowest cladding temperature rod; G8, the medium burnup and highest fuel smear density rod; and G13, the highest cladding temperature rod.

Cladding mechanical strain generally arises from the combined effect of the FCMI and the plenum gas pressure (Pg). Unfortunately, the calculation of the mechanical strain due to FCMI and Pg is coupled in the LIFE code. To separate these two components, two LIFE analyses were performed for each rod, namely with and without incorporation of fuel

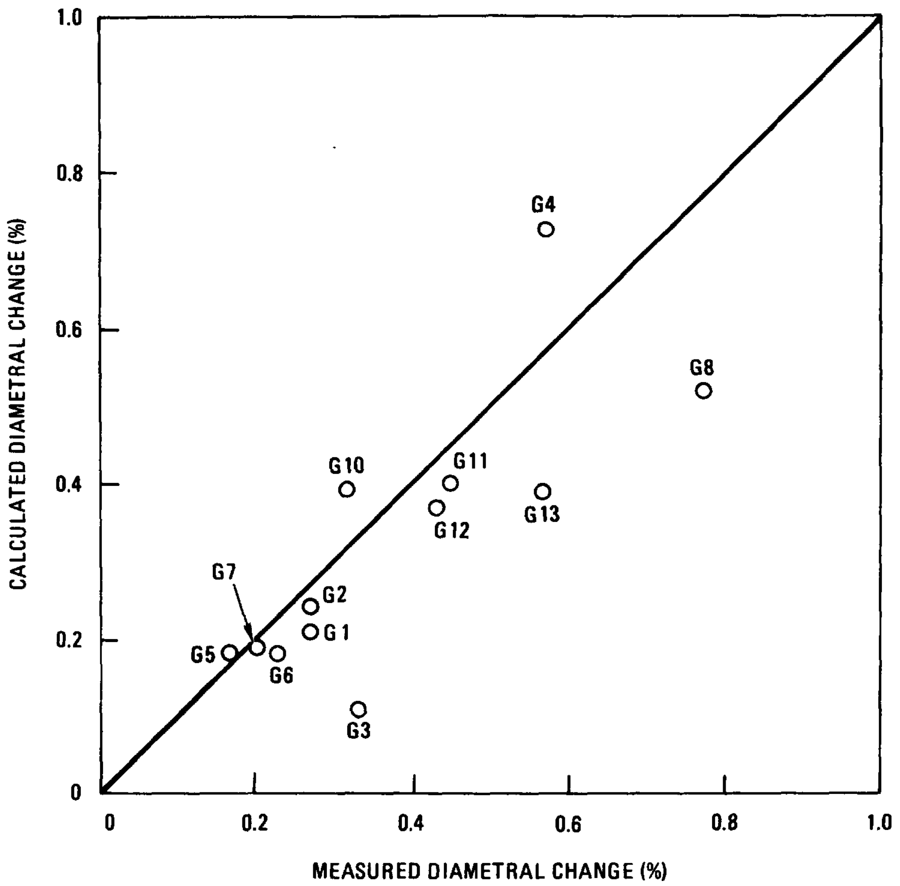

Fig. 2. Comparison of LIFE-calculated and measured cladding diametral change at axial station 3 for the F-1 experiment

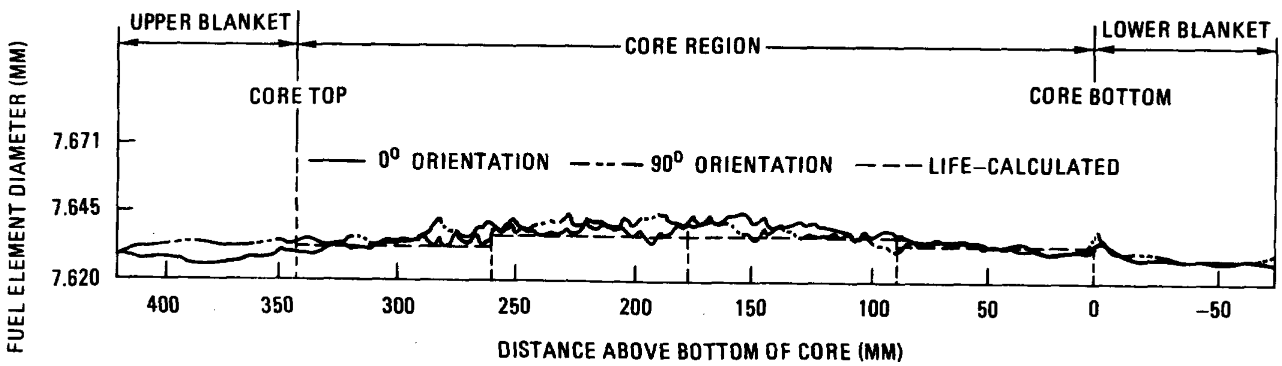

Fig. 3. Comparison of LIFE-calculated and measured axial distribution of diametral changes for F-1 rod G1

swelling. The fuel swelling was suppressed to eliminate FCMI but yet maintain the actual plenum gas pressure history. A typical pressure history is shown in Fig. 4 for rod G1. The difference in the cladding strains for the swelling and non-swelling fuels is attributed to FCMI.

Results

The results of the analyses are summarized in Table II, indicating that the FCMI contributed significantly to the cladding mechanical strain in the F-1 fuel rods. To further illustrate this, a typical plot of circumferential creep strain at axial section 3 for swelling and non-swelling fuels is shown in Fig. 5 for rod G1. As can be seen from this plot, the strains resulting from internal pressure alone (i.e., the curve for the non-swelling fuel) are practically negligible compared with the total calculated strain with fuel swelling included. The rapid change in the strain shown in Fig. 5 corresponds to a step power increase which causes differential thermal expansion between the fuel and cladding.

TABLE II. CLADDING CIRCUMFERENTIAL CREEP STRAIN DUE TO Pg + FCMI AND FCMI ALONE

Fuel Rod No.	Max. Clad Temp, °C	Peak Burnup, at.%	Fuel Smear Density, at.%	FCMI Circum. Creep Strain, 10^{-4}	FCMI + Pg Circum. Creep Strain, 10^{-4}
G1	740	5.86	82.64	18.0	21
G4	692	14.01	82.47	23.0	73
G7	648	4.83	82.54	15.5	18
G8	696	12.61	86.06	26.5	52
G13	759	10.53	84.36	21.0	39

Factors Influencing FCMI

The factors considered to be important in controlling FCMI (fuel smear density, burnup, and cladding temperature) are listed in Table II. The following conclusions are suggested by these results:

- FCMI is greatly influenced by the fuel smear density; higher fuel smear densities result in greater FCMI, as suggested by rod G8.
- If cladding metal swelling is insignificant as in the case of the F-1 experiment, higher burnup results in greater FCMI cladding strain as evidenced by rods G4 and G13.
- Comparison of rods G4 and G13 suggests that the effect of cladding temperature on FCMI is insignificant.

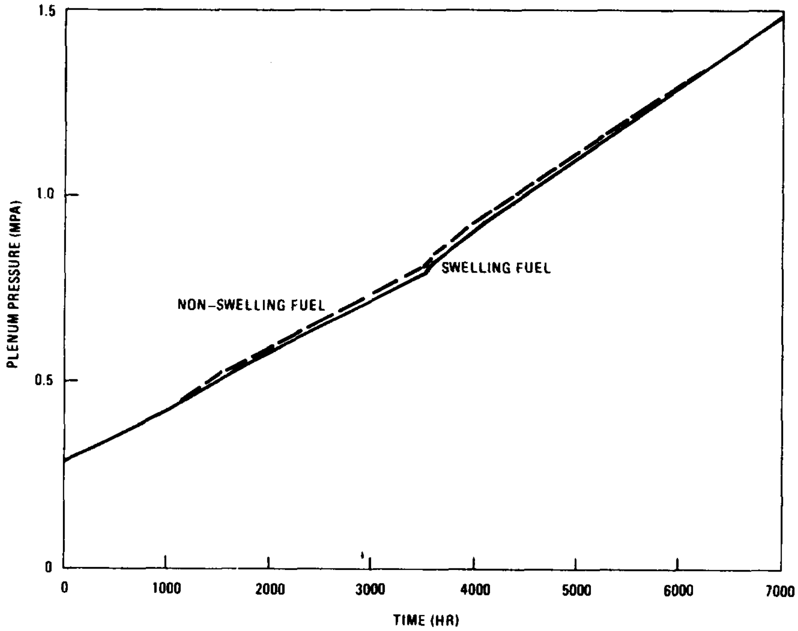

Fig. 4. F-1 rod G1 plenum pressure history

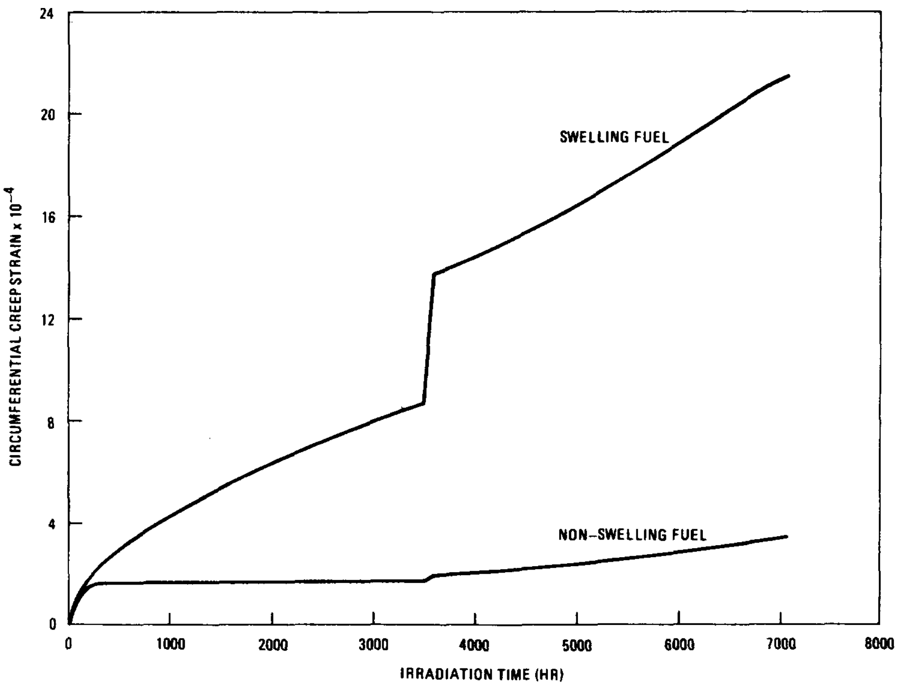

Fig. 5. F-1 rod G1 clad circumferential creep strain for axial section 3

In addition, the power history plays an important role in FCMI. A step power increase of the time when the fuel-to-cladding gap has reached the minimum can increase FCMI, as evidenced by the results given in Fig. 5.

SUMMARY

The profilometry data from the F-1 experiment have been used to validate the LIFE computer program modeling of the cladding temperature and differential pressure conditions representative of GCFR fuel rods. Furthermore, the LIFE-calculated results indicate that the cladding strains experienced by the F-1 rods were primarily the result of FCMI instead of being pressure stress induced.

The maximum mechanical strains (metal swelling strains were negligible) were well within acceptable limits for the high-temperature, low-pressure, and high-burnup conditions represented in the F-1 experiment. The strains, while quite acceptable, are considered to be conservative. Although the F-1 rod differential pressures were made representative, the hydrostatic pressure conditions were not representative. In the GCFR pressure equalized and vented rod design, the 8.6-MPa coolant pressure exists within as well as outside of the fuel rods. An effect of the pressure within the fuel rod is to suppress fission gas bubble swelling.[3] This is an important mechanism which tends to mitigate fuel-to-gap closure, especially early in life before clad swelling occurs. Since this effect was not represented in the F-1 rods, the rods experienced more FCMI than would be expected in the GCFR rod design. Consequently, in the absence of significant clad swelling, the clad integrity threats appear minimal in the GCFR pressure equalized and vented fuel rod design for even higher burnup or clad temperature conditions than experienced in the F-1 experiment.

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