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TRANSIENT PERFORMANCE OF EBR-II DRIVER FUEL*

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ABSTRACT

The first phases of qualification of the EBR-II driver fuel for repeated transient overpower operation have recently been completed. The accomplishments include prediction of the transient fuel and cladding performance through ex-core testing and fuel-element modeling studies, localized in-core power testing during steady-state operation, and whole-core multiple transient testing.

The metallic driver fuel successfully survived 56 transients, spaced over a 45-day period, with power increases of ∿160% at rates of ∿1%/s with a 720-second hold at full power. The performance results obtained from both ex-core and in-core tests indicate that the fuel is capable of repeated transient operation.

INTRODUCTION

Ongoing Liquid Metal Fast Breeder Reactor (LMFBR) development programs have yielded fuel- and blanket-element designs which have demonstrated high burnup capability when subjected to steady-state irradiation conditions, but have not yet demonstrated that they will survive multiple, mild transient events. Furthermore, during normal operation of a commercial LMFBR, the fuel and blanket materials must sustain numerous power changes when load-following operation is required. The length of time at reduced power as well as the rate of approach to full power could affect the element lifetime.

Previously, issues associated with these mild transient events could only be explored through analysis and ex-core testing because a

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fast reactor facility to test fuel and blanket performance during single or multiple mild transients did not exist. However, EBR-II was recently designated as the reactor facility to fulfill this role. The existing control-rod drive capability of EBR-II allows whole-core transient ramps of up to 1.2% power per second. By early 1982, a control-rod drive modification will be installed that will allow transient ramps up to 18% power per second, which is more than sufficient to address existing issues associated with the mild transient performance of LMFBR fuels. However, before EBR-II can be utilized routinely as a facility for transient testing, the metallic EBR-II driver fuel must be qualified for transient operation without the benefit of an existing transient facility for mild transient testing.

A transient qualification program was instituted for the EBR-II driver fuel in 1979 with the objective of understanding the performance limits of the fuel when subjected to multiple overpower transients. The first phase involved the prediction of the transient fuel and cladding performance through ex-core testing and fuel-element modeling studies.

The ex-core fuel testing was aimed at quantitatively describing the fuel strain rate as a function of stress, temperature, and prior strain as well as determining the transformation kinetics of the alpha-to-gamma transformation. Tests on sections of irradiated fuel were conducted to determine the magnitude and time dependence of the fuel stress. Expected cladding reliability was determined by subjecting irradiated cladding samples to pressure-temperature transients in an ex-core testing device. The cladding-strength correlations, a fuel-flow model, and the characterization of fuel phase transformation have been combined to predict the lifetime of the fuel elements through cumulative damage function (CDF) analysis.

The second phase of the transient qualification program involved in-core localized power change testing during steady-state operation and whole-core multiple transient testing. Full prototypic testing was obtained during a 45-day period in early 1981 which was set aside for whole-core transient testing. The operating conditions of test subassemblies covered, with some margin, the entire range of temperature, burnup, and linear heat rating to which the driver fuel will be exposed during future operation of EBR-II in a transient mode.

In the following sections, the results obtained from the ex-core transient tests on irradiated driver-fuel cladding sections and driver fuel are presented along with a discussion of the analysis wherein the observed properties of the fuel and cladding were combined to predict performance of the driver fuel during the transient operation of the reactor. Next, the results obtained from in-reactor experiments, which involve both local power changes and whole-core transient tests, are discussed and compared to the performance expected from ex-core tests and analyses.

DESCRIPTION OF ELEMENTS

Two types of fuel elements are used in the core of EBR-II. Mark-IA fuel is used in control and safety rods, and Mark-II fuel is used in the driver assemblies. Both the Mark-IA and Mark-II fuel elements contain a uranium-5 wt % fissium* fuel pin that is sodium bonded to stainless steel cladding. Table I compares the design features of the Mark-IA and Mark-II elements. The minimum useful burnup before breach during steady-state reactor operation for the Mark-IA fuel is 3 at.%, while that for Mark-II fuel is 10.5 at.%. The higher burnup capability for Mark-II fuel is a result of design features that allow fission gas generated within the fuel pin to migrate to the larger gas plenum of the Mark-II element. In the Mark-II element, the fuel smeared density is low enough (75%) that by the time the fuel pin swells into contact with the cladding, the porosity generated by fission gas bubbles interconnects, and the gas is released to the plenum.[1] This phenomenon does not occur in the Mark-IA fuel, which has a fuel smeared density of 85%. At such a high fuel smeared density the pores do not interconnect prior to fuel-cladding contact. As a result, since the fission gas is retained in the fuel pin, the fuel pin swelling causes large cladding stresses, and

TABLE I

Design Features of the Mark-IA and Mark-II Driver-Fuel Elements

	Mark-IA	Mark-II
Enrichment, at.% ^{235}U	52.5	67.0
Fuel pin length, mm	343	343
Fuel pin diameter, mm	3.65	3.30
Fuel volume, 10^{-6} m^3	3.6	2.9
Fuel smeared density, %	85	75
Fuel/clad radial gap, mm	0.152	0.254
Cladding wall thickness, mm	0.229	0.305
Cladding O.D., mm	4.42	4.42
Cladding material	Type 304L (SA)	Type 316 (SA)
Element length, mm	460	612
Plenum volume,[a] 10^{-6} m^3	0.67	2.41

[a]Preirradiation volume at 20°C.

*Fissium (Fs) is an equilibrium concentration of fission product elements left by the pyrometallurgical reprocessing cycle designed for EBR-II and consists of 2.4 wt % molybdenum, 1.9 wt % ruthenium, 0.3 wt % rhodium, 0.2 wt % palladium, 0.1 wt % zirconium, and 0.01 wt % niobium of the total mass.

the cladding breaches adjacent to the fuel column at about 3 at.% burnup. Burnup-limiting breaches occur in Mark-II elements at the location of the dimpled fuel-pin restrainer. The restrainer consists of three small indentations (120° apart) in the cladding at a distance of 13 mm above the top of the fuel pin. The purpose of the indentations is to preclude the possibility of excessive fuel-pin liftoff.

EX-CORE EXPERIMENTS

CLADDING PERFORMANCE

Sections of cladding from irradiated Mark-IA and Mark-II elements were tested in an apparatus that allowed simulation of the transient operation of the fuel elements in the core of EBR-II.[2] The fuel was removed from the cladding sections by acid dissolution, and the cladding was tested to breach by either ramping the internal gas pressure at constant temperature, ramping the cladding temperature at constant pressure, holding pressure and temperature constant and allowing the cladding to creep to failure, or cycling temperature and/or pressure until the cladding section failed.

The objective of these transient cladding tests was to generate a data base whereby cladding breach could be predicted over a range of transient operating conditions for the reactor. The results of these tests were correlated with the Larson-Miller Parameter (LMP) as a function of effective failure stress. The LMP is defined as $T(\ln t_r + C)$, where T is the test temperature, t_r is the time to rupture, and C is an empirically determined constant. The LMP, as originally conceived, applied only to creep tests at constant temperature and pressure. The mathematical technique whereby a LMP is derived from transient temperature and pressure conditions is given in Reference 3.

Several noteworthy features of the irradiated-cladding behavior are evident from the results. At higher LMP values, the logarithm of the failure stress decreased linearly with the LMP for all irradiation and test conditions. At low LMP values, however, the failure stress was sensitive to irradiation temperature. Cladding irradiated at lower temperatures exhibited higher failure stress; concentrations of irradiation-induced defects (loops and voids) and their consequent strengthening effects tend to reach lower saturation values at elevated temperatures. Additionally, it is observed that the results from a cladding section that contained the dimple restrainer exhibited lower failure stresses. This reduction in strength is indicative of the fact that the indentations behave as stress intensity sites. Most importantly, the cyclic temperature and pressure tests correlate well with the single ramp and creep tests.

The cladding performance information allows prediction of fuel-element breach if the time dependence of the fuel-element temperature and the applied stresses are known. The analytical technique for accomplishing such predictions involves application of the CDF correlation, defined as

$$\int \frac{dt}{t_r(\sigma,T,\phi t)} = 1, \tag{1}$$

where

t_r = time to rupture,
σ = applied stress on the cladding,
T = irradiation temperature,
and ϕt = accumulated neutron fluence.

To apply Equation (1) for use in the prediction of driver-fuel performance, it is necessary to know the magnitude of the stress that is applied to the cladding by the fuel as a function of temperature and time. The next section describes the experiments that were conducted on both irradiated and unirradiated fuel to gain an understanding of the fuel-cladding mechanical interaction (FCMI).

FUEL PERFORMANCE

Fuel Swelling and Creep

Cladding stress caused by pressure loading of the fuel, commonly called FCMI, is a result of the volume increase of the fuel matrix after fuel-cladding contact has been established. These stresses can be relaxed by plastic deformation of both fuel and cladding. The partitioning of these two relaxation mechanisms depends on the relative creep rates of fuel and cladding.

Experience with steady-state operation has shown that fuel creep rates are sufficiently high so that cladding rupture does not occur adjacent to the fuel after fuel-cladding contact. In the transient mode of operation, however, temperature changes in the fuel elements are much more rapid, and thus the time available for stress relaxation by fuel creep is much shorter. In order to prevent significant cladding stresses due to FCMI, appreciable fuel creep has to occur in seconds. Because no short-time creep data were available for EBR-II metallic fuel, a testing program to obtain such data using irradiated fuel was started. A brief description of this program and a discussion of the data obtained thus far follows.

Swelling of the EBR-II metallic fuel is primarily a result of the formation of fission gas bubbles. The swelling rate is determined by the rate of of fission gas generation, which results in pressure increase in the bubbles, and by the creep rate of the fuel, which determines the relaxation of the stress caused by this pressure.

During normal steady-state reactor operation, the swelling rate, $\dot{V}$, is proportional to the instantaneous overpressure in the bubble, ΔP, the surface tension of the bubble, γ, and the fuel creep rate, $\dot{\varepsilon}$, or

$$\dot{V} = (A\Delta P - \frac{2\gamma}{r}) \quad \dot{\varepsilon} , \tag{2}$$

where A is a proportionality constant, and r is the bubble radius.

At high temperatures, where the creep rate is high compared to the fission gas generation rate, the swelling rate is controlled by the fission gas generation rate except in the case of small bubbles, where the surface tension has a major effect. At low temperatures, however, the lower creep rate controls the swelling, and if the burnup rate is relatively high, considerable bubble pressures may exist.

During transient overheating the same rate relationship holds, but the heating rate replaces the gas generation rate as the generator of bubble overpressure. Because the transient heating rates affect bubble pressures much more than the burnup rates, the relaxation takes place in entirely different creep ranges.

Test equipment was installed in a hot-cell facility to measure the creep rates. Test specimens -- 38-mm-long sections of Mark-II fuel pins irradiated to 0.8 and 1.8 at.% burnup -- were rapidly induction heated under hydrostatic pressure to required temperatures in a small autoclave. Specimen volumes were measured with an immersion-density balance, and length changes were measured with a manipulator-operated micrometer.

Some of the results obtained on the 0.8 at.% burnup samples are shown in Figures 1 and 2. The data in Figure 1 show that substantial creep rates exist in the short time range and that FCMI stresses will relax to some extent. Figure 2 shows that external pressure indeed controls the swelling as the gas bubble model predicts. These data, coupled with microstructural information that was determined on the test fuel, provide a description of the transient creep and swelling as a function of temperature, stress, and burnup.

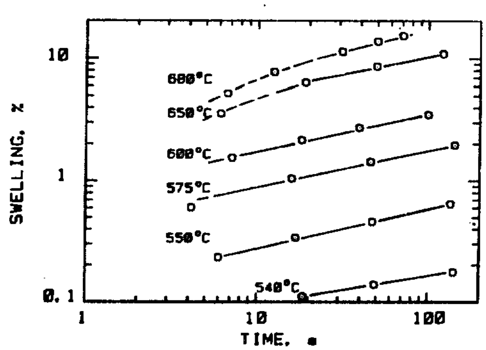

Fig. 1. Effect of temperature on transient swelling of fuel irradiated to 0.8 at.% burnup (0.7 MPa external pressure).

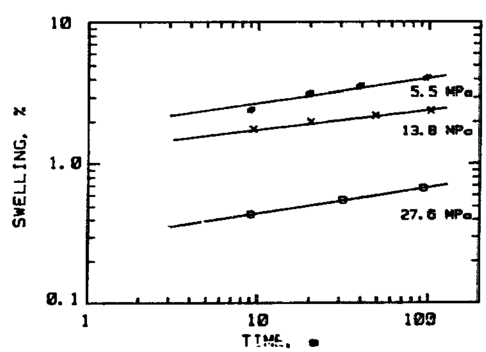

Fig. 2. Effect of external pressure on the transient swelling of fuel at 600°C irradiated to 0.8 at.% burnup. (No swelling was observed within 900 seconds at 34.5 MPa external pressure.)

Fuel Phase Transformation and Thermal Expansion

The fraction of the EBR-II metallic driver fuel transformed from one phase to another and the rate of transformation must be characterized because the volume increase of the high-temperature gamma phase is significant. This volume change could contribute FCMI stress that could lead to premature breach of driver-fuel elements during transient, as well as steady-state, operation. Likewise, the difference between the thermal expansion of the fuel and of the cladding and the increase in the temperature gradients during overpower conditions will also contribute FCMI stress. The following summarizes experimental results of thermal-expansion and transformation kinetics determined by dilatometry, both isothermally and nonisothermally.

Sections of unirradiated driver fuel have been tested in a precise differential dilatometer system under an inert atmosphere to determine thermal expansion and the magnitude and rate of transformation as a function of temperature. The thermal expansion agreed very well with earlier measurements.[4,5] Measurements of length and volume increase indicated an approximate 1% volume increase from the alpha to the gamma phase. The alpha-to-gamma transformation proceeded rapidly, and always completely, within the heat-up rate of 1°C/s. The gamma-to-alpha transformation was found to be more sluggish. Both experimental and analytical results indicate that the phase-transformation kinetics of the metallic driver fuel are such that significant FCMI could be generated during the transient operation of EBR-II if it were not balanced by creep relaxation.

FCMI

Transient fuel swelling, phase transformation, and differential thermal expansion could all contribute to FCMI. The thermal expansion of the fuel is only slightly greater than that of stainless steel cladding in the range of the transient operating conditions. However, the temperature increase of the fuel is significantly greater than that of the cladding due to the transient overpower. For the hottest element in EBR-II undergoing a 30% overpower condition, the differential strain is approximately 0.35%. The sum of this differential strain, the 0.36% phase-transformation strain, and a significant transient fuel-swelling strain, could generate significant FCMI stress. The resulting FCMI was calculated with a finite element model using the properties described. The maximum amount of FCMI was found to occur in a high-smear-density fuel element at burnups in excess of 1.5 at.%. The results of these calculations are shown in Figure 3. The FCMI for regular driver-fuel elements was substantially less. The stress-time histories, as shown in Figure 3, were used in the CDF formulation, Equation (1), to predict the expected damage in a series of in-core tests described in the following section. The results of the CDF analysis indicated that the metallic fuel elements should survive the transient tests with little additional damage accumulation.

IN-CORE TESTS

LOCAL POWER CHANGE TESTS

To obtain preliminary information on the transient performance of EBR-II driver fuel without exposing the complete core to transient operation, two types of tests generating local power changes were conducted. The following in-reactor tests were conducted to characterize the transient performance and verify out-of-reactor test results.

Two EBR-II control rods were moved in and out of the core in opposite directions simultaneously at 2 mm/s over a 356-mm range without affecting full-power reactor operation. Dosimetry measurements verified that when a control rod was moved into the core, its integrated power increased 25%. Localized power changes from near 0 to 80% above nominal with rates up to 0.9%/s were obtained in a control rod by translation of fuel into the core. In one test, two control rods, at 0.5 at.% and 2.5 at.% burnup, were simultaneously cycled in and out of the core 120 times during a 24-hour period of full-power, steady-state reactor operation. The rod with 2.5 at.% burnup was then removed for postirradiation examination; the low-burnup rod was irradiated to 2.5 at.% during subsequent steady-state operation before it was removed for examination.

Element profilometry on the elements from the rod cycled at 2.5 at.% burnup indicated cladding diameter increases nearly four times greater than has been observed on elements with similar burnup that were not cycled (see Figure 4). Elements from the rod that were cycled at low burnup and then irradiated to a high burnup during steady-state operation showed cladding diameter increases about twice that observed on elements that were irradiated to similar burnups during steady-state operation only. These results indicate signficant FCMI for the high-smear-density Mark-IA fuel design.

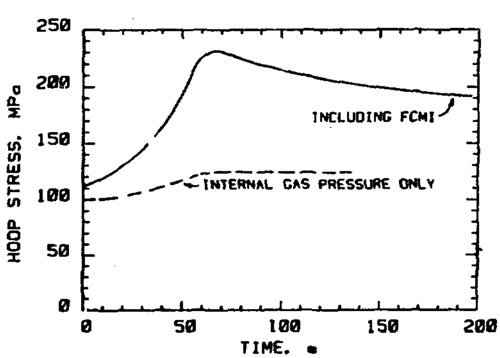

Fig. 3. Cladding hoop stress in a Mark-IA element with fuel-cladding contact during a low-ramp-rate transient.

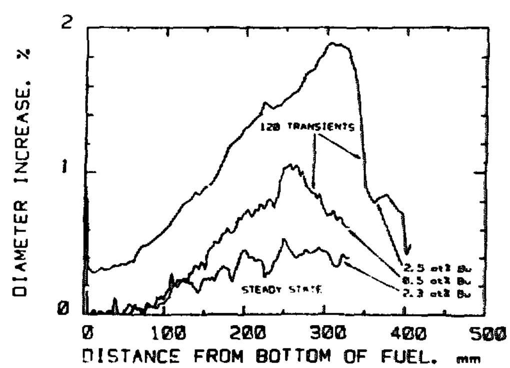

Fig. 4. Diameter increase of Mark-IA elements subjected to steady-state and transient operation.

In another test, a control rod was irradiated alternately for one hour in the core and 23 hours out of the core for 141 cycles during normal steady-state full-power reactor operation. The rod was removed at about 2.5 at.% burnup. Examination of elements from this rod showed no additional diameter increase due to cycling.

Driver fuel can also be subjected to limited overpower conditions due to the radial flux gradient in EBR-II. Two full-worth driver-fuel test subassemblies were intentionally interchanged between their respective row-2 and row-5 core positions 12 times while they underwent steady-state irradiation to about 7.5 at.% burnup. Each interchange exposed the fuel elements within these subassemblies to power changes of 15 to 25% over their full length. Irradiation of these subassemblies with no indication of fuel-cladding breach and only minimal diameter increase demonstrated the capability of EBR-II driver fuel to withstand mild transients.

WHOLE-CORE TRANSIENT TESTS

Recently, whole-core transient tests were conducted with the EBR-II driver fuel to determine its transient performance capability.

Qualification tests of the driver fuel required increased heat rating, decreased coolant flow, and increased fuel and cladding temperature to be prototypical of the projected transient operating conditions at the appropriate ramp rates and hold times. The driver fuel was therefore subjected to repeated transients simulating those expected to be demanded by transient experimenters. Only one reference type of transient was performed. During each transient, reactor power was increased from 24 to 62.5 MWt, held at 62.5 MWt for 720 seconds, and then decreased back to 24 MWt. The power increase and decrease were at the maximum control-rod drive speed. This corresponded to a reactivity insertion rate of about 1¢/s and a nominal power increase of about 1%/s. The transients were repeated three times a day every other day until 56 transients were obtained.

Several test subassemblies were intentionally irradiated under these conditions. Seven were designed specifically for the transient tests. They consisted of four 91-element test driver-fuel subassemblies with reduced flow orifices, one control-rod subassembly with Mark-II elements, one test subassembly under the breached-fuel test facility and operating at elevated temperatures, and one driver-fuel subassembly containing driver-fuel elements that had breached before the transient-test period. In addition, several subassemblies within the core were designated to operate through the transient-test period and beyond to characterize reliability and performance.

Of the four test driver-fuel subassemblies, two were in row 2, and two were in row 5. In each row one subassembly had a peak cladding temperature of 600°C, and the other a peak cladding temperature of 630°C. These temperatures correspond to the nominal and allowed peak temperatures for driver fuel under transient conditions. The driver-fuel elements in the test subassembly under the breached-fuel test facility were operated at a peak cladding temperature of 660°C which corresponds to the allowed peak cladding temperature with uncertainties included. The peak cladding temperature of the driver-fuel elements in the control rod was 600°C. The control rod was inserted into the core before each transient and withdrawn subsequent to each transient to obtain even greater power increases than could be obtained on fuel within the core alone.

During the transient-test period, the burnup on the Mark-IA fuel-element designs used in higher-worth control rods was limited to 1.5 at.%, a value based upon the analysis of data obtained from the ex-core testing programs.

The transient-test period was successful; no cladding breaches were generated, and those elements which were operated beyond breach through 56 transients exhibited no degradation. Only one of the three previously breached elements continued to release fission gas. Following the transient-test period, all of the test subassemblies and selected fueled subassemblies were examined to characterize performance. Examination of the higher-worth control rod containing high-smear-density Mark-IA driver fuel at 1.5 at.% burnup indicated no degradation of performance, minimal diameter increase, and no cracking in the B_4C pellets as had been observed in earlier local power change tests. None of the low-smear-density Mark-II driver fuel exhibited performance degradation. No additional cladding strain was generated due to transient operation. No additional fuel swelling or fuel-pin liftoff was observed. Whole-core transient test results and analyses thus far indicate that the driver fuel is fully capable of sustained steady-state and transient operation at low ramp rates.

Further qualification is in progress to verify the adequate performance and reliability of the driver fuel to ramp rates nearly ten times as great. Whole-core high-ramp-rate transient tests will be conducted in EBR-II in mid-1982. It is expected that the fuel will be fully qualified for repeated transient and steady-state operation.

CONCLUSIONS

1. A data base was established to predict the cyclic-transient performance of the Type 316 stainless steel cladding through ex-core experiments on irradiated cladding. It was found that a CDF based on the creep-rupture behavior of the cladding provided an excellent means of correlating the cyclic behavior.

2. The FCMI that occurs in EBR-II driver fuel during transient operation was determined by studies aimed at obtaining quantitative data on the individual components of the FCMI. Swelling, creep, phase-transformation, and thermal-expansion data were generated and used in a finite element model to calculate the cladding stresses during the course of the anticipated transient events.

3. The FCMI analyses were coupled with the transient performance information on irradiated cladding through the CDF formulation to predict the fuel-element lifetime during transient operation. It was found that the driver fuel was capable of sustaining multiple mild transients without cladding breach.

4. In-core tests involving both local power changes and whole-core power transients confirmed the predictions. The standard driver fuel as well as seven special experiments sustained 56 power transients at a reactivity insertion rate of 1¢/s between reactor powers of 24 and 62.5 MWt without cladding breach.

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