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HEDL-TME 75-47, VOL 1 OF 3
UC 79b, p

VOLUME 1

BASE TECHNOLOGY FSAR SUPPORT DOCUMENT -- PREFAILURE

TRANSIENT BEHAVIOR AND FAILURE THRESHOLD

STATUS REPORT: JANUARY 1975

26

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Prepared for the U.S. Energy Research and Development
Administration under Contract No. E(45-1)-2170

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VOLUME 1
BASE TECHNOLOGY FSAR SUPPORT DOCUMENT -- PREFAILURE
TRANSIENT BEHAVIOR AND FAILURE THRESHOLD
STATUS REPORT: JANUARY 1975

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ABSTRACT

A comprehensive compilation of the current (January, 1975) state-of-the-art understanding of fuel pin response to reactivity insertion events up to and including failure threshold is presented. All mixed oxide fuel, transient overpower tests conducted to date are described and the data collected therein are presented. Current understanding of fuel pin cladding failure mechanisms is discussed, and interpretations of fuel pin cladding failure thresholds are presented as revealed by individual tests and by the several tests collectively. Plans for future tests are discussed.

As indicated, this compilation reflects the current state-of-the-art, and complete data were not available for some of the more recent tests. All tests are subject to reinterpretation as more powerful or comprehensive analytical techniques become available. It is anticipated that this document will be supplemented and/or updated as warranted.

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I. INTRODUCTION

The analysis of hypothetical core disruptive transient overpower accidents is intimately related to fuel pin cladding behavior and failure characteristics, since the cladding forms the first barrier against release of fuel and fission products. Moreover, the time, nature and location of cladding failure influences to a significant degree the course and consequences of the accident. The purpose of this document is to present the status of the base technology related to understanding and analyzing FFTF fuel pin cladding failure during hypothetical transient overpower accident conditions.

A. Fuel Pin Design

The FFTF fuel pin is shown in Figure 1; it is 93.5 inches long. The fuel pin is clad with 0.015 inch thick, 20 percent cold worked, type 316 stainless steel; the outside diameter of this cladding is 0.230 inch. The cladding, together with the end caps, provides structural support and a hermetic seal for the internal components of the fuel pin.

The fuel column consists of a 36 inch stack of 0.195 inch diameter fuel pellets. Two natural UO_2 insulator pellets, each 0.4 inch long, and an Inconel reflector 5.7 inches long, are located both above and below the fuel column.

A fission gas plenum with an effective length of 37 inches is provided in the top of the fuel pin to limit internal gas pressure caused by fission product gas generation. Within the plenum is a spacer tube, a lag gas capsule and spring system to keep the fuel, insulator pellets and reflectors compressed during handling prior to installation in the reactor.

The nominal fuel pellet stack consists of 150 pellets, each 0.24 inch long and 0.195 inch in diameter, composed of pressed and sintered

FFTF DRIVER FUEL PIN

FIGURE 1. FFTF Fuel Pin.

mixed uranium oxide and plutonium oxide. A shallow dish (0.0035 inch deep) is formed in each end of the pellets to minimize axial thermal expansion of the pellet stack.

Each fuel pin is helically wrapped with a 0.056 inch diameter, 17 percent cold worked, type 316 stainless steel wire on a 12 inch pitch; this is to provide lateral spacing along the length of the pin.

Two hundred and seventeen such pins are contained within each driver fuel assembly.

B. Hypothesized Transients

Three levels of safety are considered in the design of the FFTF and the analysis of FTR performance. The first level of safety depends primarily upon quality design, construction, and functional testing to assure that the system performs reliably throughout its design lifetime. The second level of safety provides protection against the occurrence of some abnormal or accident conditions. Specific actions initiated within the second level of safety include those which will return the system to normal and those which terminate operation.

The third level of safety provides even further protection against the release of radioactive materials by assuring that sufficient barriers to such release are provided. Analysis of the capability of the barriers to contain radioactive materials assumes a completely hypothetical initiating event, but accounts for the naturally mitigative nature of the system and the phenomena attendant to the accident progression.

The hypothetical initiating events, used as analytical tools to evaluate the third level of safety, can be placed in true perspective by considering two safety assurance diagrams. These diagrams are intended to graphically display the following two main items - firstly, the protective system actions which are applied in the event of accidents; secondly, in the hypothetical case when these protective actions are not taken, the lines of defense which will act to return the system to normal or to effectively mitigate the consequences to acceptable levels of severity.

Figure 2 displays the safety assurance diagram for a reactivity insertion, which leads into the safety assurance diagram for a severe excursion, shown in Figure 3.

The first accident progression diagram (Figure 2), shows the possible paths and consequences following a reactivity insertion. The first two lines of defense are considered to be exceptionally strong. In confirmation of the first line of defense, a critical review⁽¹⁾ of initiating events for reactivity insertion has affirmed the design envelope of ramp rates up to 3\$/sec and steps up to 60¢, and that these reactivity insertions can not be produced by any one single identifiable event.

Faulted conditions which lead to termination of operation by the Plant Protective System (PPS), the second line of defense, are presented in Table 1. The redundancy of initiating PPS functions is additionally elaborated on in Table 2. Moreover, PPS performance will be assured through surveillance and periodic testing of the fully independent shut-down systems.

Therefore, the starting point for the transients considered here is beyond the first two levels of safety. Further, a severe excursion, as detailed in Figure 3, can occur only when faulted design and faulted protective actions occur coincidentally; there is no credible path to a severe excursion.

C. Accident Analysis Approach

In the FFTF hypothetical transient overpower accident analyses, a severe initiating event has been chosen and the subsequent progression of events has been evaluated in the most realistic, consistent manner practical. Consistent and realistic analyses of the hypothetical transient overpower accident require a mechanistic knowledge of the behavior of the fuel system under the conditions of interest. To provide the requisite understanding of fuel pin behavior, a two-fold approach has been adopted.

DIAGRAM NO.	TITLE	REVISION
CP1	ACCIDENT PROGRESSION DIAGRAM REACTIVITY INSERTION	DATE 6-13-75
LEAD-IN DIAGRAMS	FOLLOW-ON DIAGRAMS	
AP8, AP9, AP10, B1, C1, C2, C3, E1	BP1, CP2, CP5

FIGURE 2. Safety Assurance Diagram: Reactivity Insertion.

FIGURE 3. Safety Assurance Diagram: Severe Excursion.

TABLE 1

REACTOR AND HEAT TRANSPORT SYSTEM FAULT CONDITIONS CAUSING REACTOR SHUTDOWN

Limiting Fault Conditions

A. ANTICIPATED (an abnormal condition which individually may be expected to occur one or more times during the plant lifetime).

1. Ramps of less than 3¢/second insertion rate and maximum magnitude of 1.2% $\Delta k/k$ (rod withdrawal at maximum programmed speed)
2. Positive steps less than 25¢ (any closed loop fault and certain core restraint mechanism induced excursions).
3. Startup ramp less than 3¢/second insertion rate and maximum magnitude of 1.2% $\Delta k/k$ (rod withdrawal at maximum programmed speed).
4. Loss of power to a single primary or secondary pump, or to one out of four DHX fans in one DHX unit.
5. Loss of offsite electrical power.

Limiting Consequences

A. Fuel pin operational transient design limit. (Corresponds to the limit established for operational incidents per C16-1T definitions. C16-1T is an RRD standard in which criteria and requirements are specified for RRD sponsored reactor plant protective systems.)

TABLE 1 (CONTINUED)

B. UNLIKELY (an abnormal condition which individually is not expected to occur during the plant lifetime; however, when integrated over all plant components and systems, events in this category may be expected to occur a number of times). 1. Reactivity ramps of less than 10¢/second insertion rate and maximum magnitude less than 1.2% $\Delta k/k$ (rod withdrawal at maximum programmed speed). 2. Startup reactivity ramps less than 10¢/second insertion rate and maximum magnitude less than 1.2% $\Delta k/k$ (rod withdrawal at maximum programmed speed). 3. Mechanical failure of a single primary or secondary pump and partial flow blockages in a single HTS loop. C. EXTREMELY UNLIKELY (an abnormal condition of such extremely low probability that no events in this category are expected to occur during the plant lifetime, but which nevertheless represents extreme or limiting cases of failures which are identified as possible). 1. Reactivity ramps greater than 10¢/second insertion rate and maximum magnitude less than 1.2% $\Delta k/k$. Certain events (e.g., 3\$/second) in this set are hypothetical but, in the context of C16-1T, are used as the design basis for the PPS for protection against extremely unlikely faults.	B. Fuel pin integrity limit (corresponds to the limit established for minor incidents for the fuel pins according to C16-1T definitions.) C. Major incident per C16-1T definition. The PPS shall be designed to detect the occurrence of the event, scram the reactor, and also trip the HTS prime movers such that the resulting transient does not exceed the limits at which gross core geometry distortion can be expected.

TABLE 1 (CONTINUED)

2. Positive steps greater than 25¢, but less than 60¢ (maximum insertion which can be caused by core restraint mechanism or core support structure).
3. Complete failure of a penetration of the main HTS piping or auxiliary lines such as thermowells, pressure sensor taps, and drain lines.

TABLE 2

INITIATING FAULTS AND FUNCTIONS WHICH REACT TO MITIGATE ACCIDENT CONSEQUENCES

<u>Fault</u>	<u>First Function</u>	<u>Second Function</u>	<u>Third Function</u>	<u>Fourth Function</u>
1. Reactivity Ramps & Steps				
a. Startup, initial power < ~1KW, rate < 10¢/sec.†	High Startup Flux	Primary Wide Range Nuclear, Low Setting**	Secondary Flux, Increasing Delayed Flux; Primary Power Range Nuclear, High Flux*	Secondary Flux/Total Flow*,**
b. Startup, initial power < ~100KW, rate < 10¢/sec.†	Primary Wide Range Nuclear, Low Setting	Secondary Flux-Increasing Delayed Flux	Primary Power Range Nuclear, High Flux***	Secondary Flux/Total Flow*,**
c. Startup, initial power < ~20MW, rate < 10¢/sec.†	Primary Wide Range Nuclear, Low Setting	Secondary Flux-Increasing Delayed Flux	Primary Wide Range Nuclear, High Flux**	Secondary Flux/Total Flow*,**
d. Ascent to power, initial power > 40MW, rate < 10¢/sec. flow > 80%.	Primary Wide Range Nuclear, High Flux	Secondary Flux-Increasing Delayed Flux	Primary Flux ² /Loop Pressure**	Secondary Flux/Total Flow**
e. Full Power Operation, rate < 10¢/sec.	Primary Wide Range Nuclear, High Flux	Secondary Flux-Increasing Delayed Flux	Primary Flux ² /Loop Pressure**	Secondary Flux/Total Flow**
f. Full Power Operation, rate < 3\$/sec.	Primary Wide Range Nuclear, High Flux	Secondary Flux-Increasing Delayed Flux	Primary Flux ² /Loop Pressure**	Secondary Flux/Total Flow**

TABLE 2 (Cont'd)

<u>Fault</u>	<u>First Function</u>	<u>Second Function</u>	<u>Third Function</u>	<u>Fourth Function</u>
g. Full Power Operation, Step < 25¢.	Primary Wide Range Nuclear, High Flux	Secondary Flux-Increasing Delayed Flux	Primary Flux ² /Loop Pressure**	Secondary Flux/total Flow**
h. Full Power Operation, Step < 50¢.	Primary Wide Range Nuclear, High Flux	Secondary Flux-Increasing Delayed Flux	Primary Flux ² /Loop Pressure**	Secondary Flux/Total Flow**
i. Ascent to and full power, initial power > 40MW, flow > 80%, Rod drop/run in at maximum programmable speed and at latch speed	Primary Flux-Decreasing Delayed Flux	Secondary Flux-Decreasing Delayed Flux		
2. Loss of Offsite Electrical Power	Loss Of Offsite Power	Primary Flux ² /Loop Pressure	Secondary Flux/Total Flow	Low Primary Loop Flow*
3. Loss of Electrical Power to Two Heat Transport Loops	Loss of Offsite Power	Primary Flux ² /Loop Pressure	Low Primary Loop Flow	Secondary Flux/Total Flow
4. Coastdown of 1 Primary Pump	Low Primary Flow	Primary Flux ² /Loop Pressure		
a. No Control Action			a. High Primary Loop Flow	a. Secondary Flux/Total Flow

TABLE 2 (Cont'd)

<u>Fault</u>	<u>First Function</u>	<u>Second Function</u>	<u>Third Function</u>	<u>Fourth Function</u>
b. Flux-Flow Control Only			b. High Primary Loop Flow	b. IHX Primary Outlet Temp.
c. Flow Subloop Control Only			c. Secondary Flux/Total Flow	c. Reactor Outlet Plenum Temp.
5. Mechanical Failure of 1 Primary Pump	Primary Flux ² /Loop Pressure	Low Primary Flow	Secondary Flux/Total Flow	High Primary Loop Flow
6. Coastdown of 1 Secondary Pump	Low Secondary Flow	IHX Primary Outlet Temperature	Reactor Outlet Plenum Temp.	
No control action, flow subloops only, flux-flow control subloop only, or all subloops but no temp. interconnection.				
7. Mechanical Failure of 1 Secondary Pump	Low Secondary Loop Flow	IHX Primary Outlet Temperature	Reactor Outlet Plenum Temp.	IHX Primary Outlet Temp. (in the unaffected loops)
8. Loss of Heat Removal Capability of DHX Units (2-4 modules)	IHX Primary Outlet Temperature	Reactor Outlet Plenum Temp.	IHX Primary Outlet temperature (in unaffected loops)	

TABLE 2 (Cont'd)

	<u>Fault</u>	<u>First Function</u>	<u>Second Function</u>	<u>Third Function</u>	<u>Fourth Function</u>
9.	Pipe Leaks ⁺⁺	Reactor Vessel Coolant Level	Operator Action	Low Primary Flow	Flux ² /Loop Pressure Permis- sive High Primary Flow
10.	Simultaneous failure of both CLS Primary Pumps	CLS Primary Flow	Test Outlet Temperature		
11.	Loss of one CLS Primary Pump with Check Valve Failure	Flux/ CLS Primary Flow	Test Outlet Temperature		
12.	Loss of CLS Secondary Flow	CLS IHX Outlet Temperature	Test Outlet Temperature		
13.	Loss of CLS DHX Airflow	CLS IHX Outlet Temperature	Test Outlet Temperature		
14.	Loss of Power Signal to CLS Controls	Flux/ CLS Primary Flow	CLS Test Outlet Temperature		
15.	Leak in CLS Primary System	Flux/ CLS Primary Flow	Test Outlet Temperature		

TABLE 2 (Cont'd)

- * Function provides limited coverage, i.e., a trip will be initiated by the function as a result of the excursion, but may not be held within limits for the worst case excursions considered.
- ** Subsystems shown provide backup in case of failure of the associated instrument electronics and RSS comparators and protective logic; but not in case of a failure of the flux sensor, cables to the preamplifier, and the preamplifier.
- + For startup faults initiated with less than 50% primary loop flow, the Low Primary Loop Flow protective function is unbypassed when power exceeds +5%. This action also initiates a PPS trip for this fault.
- ++ Pipe leaks are not Design Basis Events for PPS. To assure maintenance of decay heat removal capability, however, the PPS must implement a reactor and HTS pump trip in response to significant leaks. Location of the leak and its size would determine first and backup protective functions.

First, an extensive experimental program has been instituted using prototypic fuel pin materials. The testing program encompasses both in-reactor and ex-reactor tests which are being performed both at HEDL and ANL. The test results to date are summarized in Appendices C and D.

Second, parallel to the testing program, an analytical development program is being executed. The purpose of this program is to assist in the correlation of experimental data and to prepare mechanistic analytical models.

II. SUMMARY AND CONCLUSIONS

A. Scope of Testing

At this time approximately 40 transient overpower tests have been conducted on oxide fuel systems in conjunction with various testing programs; of these, 22 have been conducted in direct support of the FFTF. The bulk of the testing program has been conducted by three laboratories: Argonne National Laboratory (ANL), General Electric Company (GE) and Hanford Engineering Development Laboratory (HEDL).

An explanation of some particular aspects of the TREAT* facility tests is essential to placing the proper perspective on the transient experiments reported herein. In the earliest tests, no attempt was made to "shape" the TREAT power transients. The natural TREAT transient was applied directly to the zero-power pin, although the pin may have been preheated to a specified temperature. Computerized controls were then added which allowed pre-programmed control of rod movement. Since this refinement, a period of constant power is applied for a few seconds to establish

* A brief description of the Transient Reactor Test (TREAT) Facility is presented in Appendix E. TREAT is operated by ANL at the Idaho National Engineering Laboratory (INEL).

steady state temperature distribution in the pin, then a spike transient shaped to simulate the desired reactivity insertion rate is applied. The GE tests, the initial HEDL EBR-II TREAT test series, and the first ANL tests (E1, E2, E3, E4 and H2) used natural transients; all subsequent tests have been of the shaped type.

Because the TREAT facility is a thermal reactor, pronounced radial power depression and end peaking effects are obtained that are quite nonprototypic of an LMFBR. The effects are very pronounced in highly enriched pins such as the EBR-II irradiated pins, and less severe in pins of low enrichment such as the GETR irradiated pins used in the GE tests, and in the pins used in ANL tests E1, E2 and E3.

To minimize these effects, thermal neutron absorbers (filters) are applied to the exterior of the test section, with more absorber used near the ends of the fuel column. The thermal component of the flux is thus preferentially absorbed and the radial power depressions are minimized with the hardened spectrum that reaches the fuel column.

Due to the concurrent development of filters and the computerized control system, those experiments that were filtered received shaped transients. The only exceptions were ANL tests H2 and E4, which were filtered, but not shaped.

The objective of the earlier GE tests (Series II through IV) was to evaluate, in a general manner, the performance of oxide fuel systems in transient overpower accident simulations in the TREAT facility. In order to achieve this objective a variety of transient tests were performed.

The GE Series II tests involved short unirradiated UO_2 fuel columns with type 347 stainless steel cladding and little axial inertial restraint. The pins were subjected to rather severe overpower transients in the TREAT facility with the result that one fuel specimen failed.

The GE Series III tests all employed fuel irradiated in the General Electric Test Reactor (GETR). The pin design was identical to

that in Series II. Of the three pins subjected to transients in the TREAT facility, two failed. These results enabled comparison of failure thresholds for irradiated and fresh (Series II) pins.

The Series IV tests at GE investigated a wider range of design parameters and their influence on transient behavior. Parameters included fuel type and smear density; additionally the fresh fuel columns were 14.2 inches in length and were axially restrained. There were two failures (C4A and C4B) in the pelleted specimens. The influence of density could be studied by comparison with low density unfailed pins (C4C and C4D). In addition, the effect of axial restraint could be studied by comparison with the Series II results.

The GE Series V tests were performed to investigate the effects of molten fuel movement and retained fission product gases on the failure threshold. Two fuel pins were tested: both had been pre-irradiated in the GETR, both had 24 inch long fuel columns (as compared to 14.5 inch fuel columns with other GE test Series), and both had 14 inch long blankets. The blanket in one pin employed solid UO_2 pellets, and in the other, annular pellets. The two pins were tested with nearly identical transients; the one with a solid pellet blanket failed, and the one with a annular pellet blanket did not fail.

The ANL E and H Series tests were conducted to study the time of failure and the post-failure behavior of oxide fuel systems in flowing sodium. Parameters investigated included prior irradiation history, ramp rate and degree of axial restraint. The H Series of tests employed ramp rates of 50¢/sec to 1\$/sec, and the E Series of tests employed ramp rates of 3\$/sec to 5\$/sec.

The effect of increased axial restraint can be investigated by comparing the results of tests E1 and E2. The effect of ramp rate on failure and post-failure behavior can be seen by comparing the E Series results with the H Series results (E4 and H2 for fresh pins, H4 and E6 for high power pins, and H5 and E8 for intermediate power pins). The effects

of prior irradiation history can be seen for a given ramp rate by comparing tests within a series (H2, H4 and H5 for 50¢/sec to 1\$/sec ramps, and E4, E6, E7 and E8 for 3\$/sec to 5\$/sec ramps).

The initial HEDL test series (EBR-II/TREAT Series), now terminated, was performed to confirm FFTF fuel pin design, and to verify the design fuel pin damage criteria. Seven transient tests were performed on pins which had been irradiated in EBR-II. Four fuel pin failures were observed. One of these fuel pin failures was particularly notable in that it occurred prior to the melting of the fuel.

The current HEDL transient testing programs have two objectives: first, to demonstrate, through proof testing, that the fuel pins will meet the FFTF design requirements (HOP Series), and second, to define the threshold of incipient failure and to provide data for modeling of failure mechanisms (HUT Series). The HOP Series tests have parameters of ramp rate (3\$/sec and 3¢/sec), prior irradiation history (9 to 12.5 kW/ft), and cladding temperature, (corresponding to nominal and rated coolant temperatures). In the HOP Series of tests, the mitigative effect of the PPS system was simulated. The HEDL HUT Series is structured like the ANL E and H Series, having parameters of ramp rate (50¢/sec and 3\$/sec) and prior irradiation history (6 to 12 kW/ft). The simulated reactivity insertions are continued in the HUT Series tests until fuel pin cladding failure is assured. The test results will complement the ANL results.

B. Results and Conclusions

The results of transient tests conducted to date indicate that the behavior of oxide fuel systems in overpower transients is a complex function of the transient, the fuel design parameters, and the prior irradiation history. Specifically, with respect to prefailure and failure behavior, the test results indicate the following:

- Prefailure fuel motion is possible, especially in some fresh and high power fuel pins, but is unlikely to occur in systems which, like the FFTF, have a high degree of axial restraint (see section III. B).

- For the likely range of overpower conditions, the predominant failure mechanisms will be differential thermal expansion, transient-overpower-induced release of fission product gases, and melting of the cladding. The dominant mechanism will be determined by pin type and details of transient (see Section III.C).

- Fresh fuel has the highest failure threshold. For irradiated fuel there is a discernable dependence of failure threshold on fuel pin operating history (see sections III.C and E).

- Increasing axial restraint lowers the failure threshold.

- Increasing fuel smeared density lowers the failure threshold.

- There is a discernable dependence of failure threshold on transient rates for high powered fuel pins. The rate dependence is not so evident for lower power fuel pins (see section III.E).

- There is a strong propensity for any fuel which is molten to be expelled through the cladding breach at the time of cladding failure (see Appendices C and D).

- The magnitude of molten fuel redistribution prior to and following fuel pin failure is sensitive to the quantity of retained fission product gases (see Appendices C and D).

Based on the results of transient testing to date, and application of correlations derived from the data, the following can be concluded with respect to the behavior of FFTF fuel pins in an overpower transient:

- For pins in the burnup range of 20 to 60 MWd/kg and for reactivity insertion rates between 50¢/sec and 3\$/sec the location of failure is predicted to be near where the product of fuel retained energy and cladding temperature is a maximum; e.g. above the core midplane.

- The time and location of fuel pin failure can be predicted most reliably by using the damage parameter correlation (see section III.D).

- Net axial redistribution of fuel prior to failure is expected to be very small or nonexistent in the FTR fuel pin during an overpower transient.

- Substantial expulsion of molten fuel is expected following failure of the FTR fuel pin during an overpower transient.

- Unirradiated fuel pins will survive significantly longer than irradiated fuel pins.

III. FUEL PIN BEHAVIOR UNDER TRANSIENT OVERPOWER CONDITIONS

The failure of fast reactor fuel pins during transient overpower (TOP) accident conditions is a subject of great importance in that the nature of the failure events may dictate the subsequent outcome of the accident. In this section the state of the technology in the area of fuel pin failure will be explored, the test results to date summarized, and application of these data discussed.

A. Summary of Experimental Data Base

A number of test series are currently underway or planned which study prefailure and failure behavior of the fuel pin.

The objectives are:

- Definition of the mechanisms that can induce fuel damage and/or cladding failure under accident conditions.

- An understanding of the variables that govern the damage mechanisms and their interrelationship.

- Determination of the modes of failure likely to be produced during accident conditions.

- Establishment of reliable failure criteria for accident conditions.

- Provision of a data base and experimental verification of mathematical models.

- Verification of PPS adequacy.

General Electric Series II Tests⁽²⁾

The objective of the General Electric (GE) Series II experimental program was to evaluate the performance of fresh mixed oxide reactor fuel under conditions simulating accidental power excursions. Three tests were performed in the TREAT facility using 0.250 inch O D , type 347 SS cladding, 20 wt% PuO₂ mixed oxide fuel specimens. The tests were performed in instrumented, NaK-filled static capsules. A summary of results is given in Table 3.

Interpretation of test results led to the following conclusions:

- Axially-unrestrained fresh fuel can accommodate the 10 percent volume increase on melting of the mixed oxide fuel, during a severe over-power transient, without cladding deformation.
- Thermal stress does not cause cladding deformation.
- Fuel-to-cladding gap conductivities are higher in a transient than at steady state.
- Incipient failure of the fresh fuel pin can be defined by the onset of cladding melting.
- Fuel melting is required for fresh fuel cladding to be damaged during a transient.

General Electric Series III Tests⁽³⁾

The objective of the General Electric Series III tests was to experimentally evaluate the performance of irradiated mixed oxide fuel pins in an accidental overpower transient. The fuel pins used in this test series were identical to the Series II fuel pins in design but were irradiated in the GETR to burnups of 8, 70 and 73 MWd/kg. Comparison of Series II and Series III test results should indicate qualitative changes in failure threshold due to irradiation. The tests were performed in instrumented, NaK-filled static capsules.

Three tests were performed in the TREAT facility. The steady state operating history in the GETR is given in Table 4.

The test objective for each of the three Series III tests is presented in Table 5; test results are summarized in Table 6.

TABLE 3

SUMMARY RESULTS OF GE SERIES II TOP TESTS

Specimen	Reactor Power		Calculated Temperatures			Post-Irradiation Condition
	Peak (MW)	Integrated (MW-sec)	Fuel		Cladding (°F)	
			Peak (°F)	Volume Average (°F)		
C2A	176	155	4900±500	4090	1530	No cladding deformation. Fuel pin bowed. Pellet cracking and grain growth. No central void.
C2B	295	204	5000±500	4900	1800	No cladding deformation. Fuel pin bowed. Pellets cracked. Central void. Extensive fuel relocation and densification.
C2C	258	260	7700±1000	6100	2500	Cladding melted but remaining cladding not deformed radially. Fuel pin bowed during calibration transients. Extensive fuel movement and melting.

TABLE 4
STEADY STATE IRRADIATION HISTORY OF SERIES III CAPSULES BASED ON THERMOCOUPLE DATA

GETR Cycle Number	Peak Pin Power (kW/ft) Capsule					Average Pin Power (kW/ft) Capsule					Burnup (MWd/MTM)* Capsule				
	C3A	C3B	C3C	C3D	C3E	C3A	C3B	C3C	C3D	C3E	C3A	C3B	C3C	C3D	C3E
42	29.3	25.1	--	--	--	20.4	18.1	--	--	--	9200	8100	--	--	--
44	--	--	27.9	28.8	30.8	--	--	19.7	19.7	20.5	--	--	7100	7100	7300
45	--	--	27.7	28.6	24.0	--	--	21.9	22.4	17.6	--	--	8100	8400	6500
46	--	--	26.7	24.3	25.8	--	--	19.2	19.2	18.2	--	--	7200	7200	6800
47	--	--	27.3	29.2	23.9	--	--	20.4	19.9	17.8	--	--	6700	6600	5900
48	--	--	27.5	26.0	26.0	--	--	20.1	20.9	20.1	--	--	7600	7900	7600
49	--	--	27.9	31.7	23.1	--	--	19.6	22.1	16.9	--	--	9000	10200	7800
50	--	--	26.9	27.5	22.3	--	--	19.9	21.9	18.1	--	--	8600	9500	7800
51	--	--	25.1	24.9	22.2	--	--	18.6	19.3	17.7	--	--	6100	6300	5700
52	--	--	23.1	22.2	22.2	--	--	18.6	17.8	18.7	--	--	6400	6200	6500
53	--	--	25.3	25.0	23.9	--	--	17.0	17.6	20.2	--	--	6500	6800	7800

*Peak Value

TABLE 5
SUMMARY OF TEST OBJECTIVES IN
SERIES III TRANSIENT IRRADIATIONS

<u>Specimen</u>	<u>Goal Burnup* (MWd/MTM)</u>	<u>Test Objective</u>
C3B	8,000	Compare transient fuel-cladding performance to previous zero burnup specimen (C2B)
C3E	65,000	Investigate fuel-cladding performance of high burnup specimen under calculated credible FTR accident conditions.
C3C	65,000	Investigate fuel-cladding performance of high burnup specimen subjected to gross center melting of the fuel during a transient.

*Based on 200 MeV/fission and metric ton of metal (Pu + U)

TABLE 6

COMPILATION OF RESULTS FROM TEST TRANSIENTS

<u>Specimen</u>	<u>Reactor Power</u>		<u>Sample Energy Release (Btu)</u>	<u>Calculated Temperatures</u>		<u>Post- Irradiation Condition</u>
	<u>Peak (MW)</u>	<u>Integrated (MW-sec)</u>		<u>Maximum Fuel Temperature °F</u>	<u>Maximum Average Cladding °F</u>	
C3B	149	193	68	5280	1830 (800°F preheat)	Cladding deforma- tion and cracking, axial separation of the fuel column.
C3E	124	160.5	44	4900	1245 (600°F Preheat)	No radial deforma- tion or cracking of cladding. Some axial movement of the fuel.
C3C	273	239	67	5950	1295 (300°F preheat)	Cladding deforma- tion and cracking. Axial expulsion of molten fuel through bottom of fuel pin.

Interpretation and analysis of the Series II results led to the following major conclusions:

- The release of fission gases, from fuel which is melted during a transient, can be one of the primary mechanisms for cladding failure.
- The release of fission gases, from fuel which is melted during a transient, provides a substantial driving force for redistribution and dispersal of fuel.
- Compared to fresh fuel, irradiated fuel exhibits a reduced failure threshold.

General Electric Series IV Tests (4)

The General Electric Series IV tests used fresh fuel pins of different fuel densities. The tests were performed in an instrumented static sodium-filled capsule. The purpose of the tests was to observe fuel behavior from inception of abnormal operation to fuel failure and to study the effects of fuel pin design parameters on pin performance. The Series IV fuel pin design parameters are presented in Table 7. Available results of the tests are presented in Table 8.

Based on comparison of the data resulting from Series IV transient irradiations and comparison with earlier test results (Series II) the following conclusions were reached:

- Fuel pin failure is strongly influenced by the amount of fuel which becomes molten during transient irradiation.
- Axial restraint of the fuel column and/or increased column length significantly reduces failure thresholds for a given fuel pellet density.
- In pelleted specimens, decreasing the smeared density increases the failure threshold during transient operation.
- Following cladding failure, molten mixed-oxide fuel can exhibit a high degree of mobility.

TABLE 7

TASK C SERIES IV FUEL SPECIMEN DESIGNATION AND BASIC DESIGN PARAMETERS

	Specimen	Fuel Composition	Fuel Form	Smeared Density (%TD)	Fuel Column Length (inch)	Comments
Zero-Burnup Fuel Specimens	C4A	$(\text{Pu}_{0.2}\text{U}_{0.8})\text{O}_{1.98}$	solid pellet	90.4	14.2	Transient irradiation has been completed
	C4B	↓	↓	91.2	14.2	
	C4C	↓	↓	80.4	14.2	
	C4D	↓	↓	80.1	14.2	
	C4I	$(\text{Pu}_{0.2}\text{U}_{0.8})\text{O}_{1.97}$	Vipac powder	83.5	13.5	
	C4J	↓	↓	83.5	13.5	
Instrumented Fuel Specimens	C4A-II	$(\text{Pu}_{0.2}\text{U}_{0.8})\text{O}_{1.98}$	solid-annular pellet	90.1	3.0	Auxiliary fuel specimens, each of which contained in-fuel thermocouple (W5 Re/W26Re). Transient irradiation has been completed.
	C4C-II	↓	↓	nominal	3.0	
				80.4 nominal		

TABLE 8

CALCULATED MAXIMUM FUEL AND CLADDING TEMPERATURES,
AND COMPARISON OF CALCULATED AND ACTUAL FUEL MELT RADII

	Transient	Calculated Peak Fuel Temp (°F)	Calculated Peak Cladding Temp (°F)	Calculated Fuel Melt Radius ¹ (mils)	Measured Fuel Melt Radius ² (mils)	Measured Fuel Volume Melt ³ (%)	Comments
High Density Pellet Fuel	C4A-0*	≈2150	--	--	--	--	specimen failed, moderate fuel move- ment
	C4A-1**	≈5500	1400	≈86	82-87	56-63	
	C4B-0	≈2020	--	--	--	--	specimen failed, extensive fuel movement
	C4B-1	≈5800	1580	96-97	96-98	76-79	
Low Density Pellet Fuel	C4C-0	≈2900	--	--	--	--	unfailed, signifi- cant porosity movement in the molten region
	C4C-1	≈4900	1100	--	--	--	
	C4C-2***	≈5600	1260	90-91	90-92	67-70	

* 0 = calibration transient

** 1 = first test transient

*** 2 = second test transient

TABLE 8 (CONTINUED)

		Calculated Peak Fuel Temp (°F)	Calculated Peak Cladding Temp (°F)	Calculated Fuel Melt Radius ¹ (mils)	Measured Fuel Melt Radius ² (mils)	Measured Fuel Volume Melt ³ (%)	Comments
<u>Transient</u>							
Vipac Powder Fuel	C4D-0	≈3000	--	--	--	--	
	C4D-1	5200 (melt temp)	1180 (melt temp)	77-78	77-78	≈50	
	C4I-0	≈2500	--	--	--	--	
	C4I-1			(accidental undershoot, not correlated)			
	C4I-2	5200 (melt temp)	1120	61-62	≤ 60	≤ 30	localized melting and poro- sity move- ment accompanied by grain growth across 60 mils radius
	C4J-0	≈2600	--	--	--	--	
	C4J-1	≈5480	1280	83-85	78-86	49-60	specimen failed, very extensive fuel movement

TABLE 8 (CONTINUED)

Notes:

- ¹ Defined as the maximum fuel radius that reaches the thermal arrest associated with the melt temperature (assumed 5200°F). This region may include fuel which has not completely passed through its heat of fusion, even though that fuel has reached 5200°F.
- ² Defined as the extent of significant restructuring (usually dendritic substructure indicative of resolidification) and porosity movement as measured during destructive examination. The indicated ranges of melt radius are a result of multiple measurements at different axial and/or angular locations along the length of the fuel column.
- ³ The fuel volume melt is based on ratio of the cross-sectional area of the molten region of the fuel to the cross-sectional area of the interior cladding (calculated from the cladding as-fabricated inner diameter).

General Electric Series V Tests (5)

The General Electric Series V tests were performed in order to study the effects of molten fuel movement and fission product gases on transient failure thresholds. Pins employed in these tests were 0.250 inch OD type 316 SS clad UO_2 fuel pins. The pins were tested in the TREAT facility, in an NaK-filled instrumented static capsule, after prior irradiation in the GETR. Two specimens were tested: specimen C5A contained a 24 inches long active fuel column and a 14.25 inches long UO_2 blanket above the active fuel. Specimen C5B employed fuel which was identical except that the upper blanket contained annular pellets with a 0.070 inch I D.

The summary of the GETR steady state irradiation results is tabulated in Table 9. The transient test results are shown in Table 10.

Interpretation and analysis of the Series V test results have led to the following conclusions:

- Increasing fuel and blanket length, without provision for internal pressure relief, lowered the failure threshold.
- The annular blanket was apparently instrumental in preventing failure of C5B through accommodation of ~4% of the total fuel volume.
- Fission gases, released as a result of melting of fuel, contributed substantially to the driving force for dispersion of fuel,
- Provision of an accommodation volume for molten fuel and internal pressure relief can increase the fuel pin failure threshold.
- The results tend to substantiate earlier observations as to the mobility of melted fuel during a transient in both directions away from the fuel midplane (i.e., core centerline), when internally pressured by retained fission gases from prior irradiation.

ANL H Series Tests (6)

The H series transient overpower experiments in the TREAT facility were originally conceived as failure threshold experiments. As accident

TABLE 9

SUMMARY OF GETR IRRADIATION RESULTS, PHYSICS CALCULATIONS

GETR Cycle No.	<u>Average Power</u> (kW/ft)		<u>Peak Power</u> (kW/ft)		<u>Average Burnup</u> (MWd/MTM)		<u>Peak Burnup</u> (MWd/MTM)	
	<u>C5A</u>	<u>C5B</u>	<u>C5A</u>	<u>C5B</u>	<u>C5A</u>	<u>C5B</u>	<u>C5A</u>	<u>C5B</u>
87	10.3	9.8	12.5	12.0	4900	4700	5900	5700
88	9.4	9.9	11.6	12.3	4400	4700	5500	5800
89	10.0	9.1	12.3	11.3	4500	4100	5600	5100
90	9.1	8.8	11.3	10.9	4100	3900	5000	4900
					17900	17400	22000	21500

TABLE 10
SUMMARY OF TRANSIENT TEST RESULTS

Specimen	C5A	C5B
TREAT Transient	TT 1239	TT 1233
Peak Sample Power (kW/ft)	160	155
Total Specimen Power (cal/g)	338	339
Peak Fuel Temp (°F)*	≈5500	≈5500
Peak Cladding Temp (°F)	> 2500+	≈1400
Cladding Breached	Yes	No
Cladding Deformation (%)	1.2 - 1.8++	1 - 1.6
Molten Fuel (%)	≈35	≈35
Fuel Movement	Extensive	Extensive
Central Void	Yes	Yes

* Estimated; effect of fuel movement
and/or failure not considered.

+ Melting occurred after initial breach due to gas blanketing.

++ For 8 inch section below failure zone.

analyses developed and need for experimental verification of the analyses for the FFTF became better defined, the H series was reoriented to provide data on failure and post-failure behavior of mixed oxide fuel systems in 50¢/sec to 1\$/sec overpower transients.

The H series tests were performed in Mark II flowing sodium test loops in the TREAT facility. Various configurations of test pins were used including single-pin and seven-pin clusters.

A summary description of test fuel pins used in the H series tests is presented in Table 11. A summary of test results is shown in Table 12.

TABLE 11
TEST VARIABLES DESCRIPTION: H SERIES

<u>Test Designation</u>	<u>Number & Type of Pin</u>		<u>Average Coolant Velocity ft/sec</u>
	<u>Center</u>	<u>Edge</u>	
H2	1 fresh PNL-17		20.8
H3	1 irradi. PNL-17	6 fresh PNL-17 type	13
H4	1 irradi. NUMEC F	6 fresh PNL-17 type	13.2
H5	1 irradi. PNL-17	6 fresh PNL-17 type	12

TABLE 12
TEST RESULTS: H SERIES
CALCULATED CONDITIONS AT ELEVATION OF MAXIMUM FUEL ENTHALPY

<u>Test Designation</u>	<u>Radial Av Fuel Enthalpy cal/g</u>	<u>Cladding Midwall Temp. °F</u>	<u>% Fuel at or Above Solidus</u>	<u>Fuel Pin Failure?</u>
H2	285	1590	76	Yes
H3	145	1200	0	No
H4	190	1325	40	Yes
H5	180	1350	25	Yes

Analysis and evaluation of the data from the above tests lead to the following conclusions:

- Fresh fuel pins can sustain very high fuel enthalpy and melt fraction without failure. For the H series tests, fresh fuel pin failure followed coolant boiling.
- In the H series tests no significant difference was discovered in the failure threshold of the two irradiated fuel types tested (high power and intermediate power).
- Failure occurred in all cases as the melt front approached the radius at which the fission gas content of the fuel becomes appreciable.
- Failures occurred in the top half of the fuel pin.

ANL E Series Tests ⁽⁶⁾

The E series tests were originally conceived as beyond failure tests for very severe excursions. After the first four tests, the need for experimental verification of accident analyses became better defined and the E series was reoriented to investigate the failure and post-failure behavior of mixed oxide fuel systems in 3\$/sec to 5\$/sec transients.

All of the E series tests have been performed in Mark II flowing sodium test loops with various fuel pin configurations including 1, 3 and 7 pin clusters.

A description of the test section and pin type is given in Table 13.
A summary of results is shown in Table 14.

TABLE 13
TEST INFORMATION: E SERIES

<u>Test Designation</u>	<u>Number & Type of Test Pin</u>		<u>Average Coolant Velocity ft/sec</u>
	<u>Central</u>	<u>Edge</u>	
E1	1 fresh UO ₂ annular	6 hollow	12.5
E2	1 fresh UO ₂ annular	6 hollow	14.5
E3	3 MTR irradiated UO ₂		14.5
E4	1 fresh P N L - 1 7		18.0
E6	1 Irradiated NUMEC F	6 fresh	11.7
E7	7 Irradiated	NUMEC F	15.0

TABLE 14
TEST RESULTS: E SERIES
CALCULATED CONDITIONS AT ELEVATION
OF MAXIMUM FUEL ENTHALPY AT TIME OF FAILURE

<u>Test Designation</u>	<u>Radial Av Fuel Enthalpy cal/g</u>	<u>Cladding Midwall Temp. °F</u>	<u>% Fuel at or Above Solidus</u>	<u>Fuel Pin Failure?</u>
E1	380	1600	80	No
E2	430	1800	92	Yes
E3	225	1230	0	Yes
E4	340	1930	100	Yes
E6	280	1510	80	Yes
E7	215	1150	65	Yes

It has been concluded from the above data that:

- Failures appear to involve release of relatively large quantities of gas.
- Failures occur when the solidus boundary approaches the gas bearing region of the fuel.
- Failures occur in the top half of the fuel pin.

HEDL EBR-II/TREAT Series

The initial test series by HEDL was performed on EBR-II irradiated fuel pins. The objectives of the test program were to confirm the FFTF fuel pin design and to verify its performance with respect to design damage criteria. The fuel pins were tested in instrumented NaK-filled static capsules in the TREAT facility. Details of the fuel pins are given in Table 15. A summary of transient test results is shown in Table 16.

TABLE 15

NOMINAL PARAMETERS FOR PNL 1 & 2 TEST FUEL PINS

Cladding	0.250 inch O D type 304 SS
Fuel	25 wt% PuO ₂ ; 75 wt% UO ₂
U enrichment	93%
Smeared density	88%
Fuel column length	13.5 inches
Linear Power	8 to 10 kW/ft
Burnup	10 to 50 MWd/kg

TABLE 16

A SUMMARY OF TRANSIENT TEST RESULTS FOR HEDL EBR-II/TREAT SERIES

<u>Test</u>	<u>Test Condition</u>	<u>Pin Response</u>
PNL 1-2	No melting (4800°F)	0.55% strain, fission gas release
PNL 1-1	80% melting	Gross failure
PNL 1-8	No melting	Hot spot failure
PNL 2-1	40% melting	Failure prior to fuel melting
PNL 2-10	No melting	Slight strain, bubble formation
PNL 1-7	No melting	0.4% strain, bubble formation
PNL 2-11	4900°F	Gross failure

Analysis and interpretation of the above results led to the following conclusions:

- Fission gas can be released from low power fuel pins prior to fuel melting.
- Precipitation and growth of fission gas bubbles within the fuel grains can cause an appreciable increase in fuel volume.
- Failure of fuel pins is possible (at least in natural TREAT transients) prior to melting of significant quantities of fuel.

HEDL Engineering Proof Test Series

The objective of the HEDL Overpower (HOP) Test Series is to demonstrate by proof tests that the prototypic fuel pins meet all design

criteria and requirements. The tests to date have been conducted with EBR-II irradiated fuel pins in NaK bonded static capsules in the TREAT facility. All tests to date have been conducted with shaped and filtered transients simulating the thermal history associated with a 3\$/sec ramp rate. In all tests, except HOP 3-3C, functioning of the PPS on a secondary trip was simulated. Such tests are called "terminated" transient tests.

The results of the tests conducted to date, and the characteristics of the pins tested, are tabulated in Table 17.

Analysis and interpretation of the test results lead to the conclusion that the FFTF fuel pins will meet the design requirements for the terminated 3\$/sec reactivity accident.

HEDL Unterminated Transient Test Series

The objectives of the HEDL Unterminated Transient (HUT) Test Series are:

- To verify the failure thresholds for mixed oxide fuel pins in overpower transients as a function of ramp rate, operating history, fluence and burnup.
- To provide information on mechanisms for fuel pin failure during overpower transients.

These tests are being conducted with mixed oxide fuel pins which have been preirradiated in EBR-II. The transient irradiations are conducted in instrumented NaK bonded capsules in the TREAT facility. A summary listing of the testing program is given in Table 18.

TABLE 17
ENGINEERING PROOF TEST SERIES RESULTS

<u>Test</u>	<u>Pin</u>	<u>Steady State</u>			<u>Transient</u>	<u>Results</u>
		<u>Power kW/ft</u>	<u>Burnup Mwd/kg</u>	<u>Fluence x 10⁻²²</u>		
HOP 3-3A	PNL 17-34	8-10	30	2.4	3\$/sec	Power coupling low tested as HOP 3-3C
HOP CAL	PNL 17A-50	- Unirradiated -			Calibration	Power coupling for 60% enriched test pin, filtered capsule determined
HOP 3-3B	PNL 17-21	8-10	31	2.4	3\$/sec	No cladding strain
HOP 3-1A	ANL A EW-13	11	7	0.8	3\$/sec	No cladding strain
HOP CAL/Ni	- Empty capsule for gamma heating determination -				Calibration	12% of heat due to gamma heating
HOP 3-2A	P 23A-27	12	21	2	3\$/sec	Test power 25% high ~0.4%*
HOP 3-2B	P 23A-30	11	42	4	3\$/sec	Test Power 25% high ~0.3%*

* Incremental strain

TABLE 18
TRANSIENT OVERPOWER TEST SERIES

<u>Test</u>	<u>Transient</u>	<u>Test Pin</u>
HOP 3-3C*	3\$/sec	PNL-17, 30 MWd/kg, 8-10 kW/ft
HUT CAL-1*	Calibration	Unirradiated PNL-9
HUT CAL-2*	Code Calibration	Mixed Gap & Pellet Geometry
HUT 5-3A*	50¢/sec	PNL-10, 50 MWd/kg, 9 kW/ft
HUT 5-5A*	50¢/sec	PNL-9, 47 MWd/kg, 6 kW/ft
HUT 5-1A*	50¢/sec	PNL-11, 47 MWd/kg, 12 kW/ft
HUT 3-3A	3\$/sec	PNL-10, 50 MWd/kg, 9kW/ft
HUT 3-5A	3\$/sec	PNL-9, 47 MWd/kg, 6 kW/ft
HUT 3-1A	3\$/sec	PNL-11, 47 MWd/kg, 12 kW/ft
HUT CAL-L1	Calibration	3-Unirradiated, 36 inch long
HUT 3-L2	3\$/sec	3-Unirradiated, 36 inch long
HUT 5-5B	50¢/sec	PNL-9, 47 MWd/kg, 6 kW/ft
HUT 5-1B	50¢/sec	PNL-11, 47 MWd/kg, 12 kW/ft
HUT 5-3B	50¢/sec	WSA-3 ~140 MWd/kg, 9 kW/ft
HUT 5-3C	50¢/sec	WSA-3 ~140 MWd/kg, 9 kW/ft
HUT 3-3B	3\$/sec	WSA-3 ~140 MWd/kg, 9 kW/ft
HUT 3-3C	3\$/sec	WSA-3 ~140 MWd/kg, 9 kW/ft
HUT CAL-L3	Calibration	Unirradiated 34 inch long
HUT 5-L4	50¢/sec	GETR ~70 MWd/kg, 13 kW/ft
HUT 3-L5	3\$/sec	GETR ~70 MWd/kg, 13 kW/ft
HUT X-L6	T.B.D.	GETR ~70 MWd/kg, 13 kW/ft

* These tests have been performed as of January 1975.

Although the HUT series tests are underway and the data to date are neither completely reduced nor fully evaluated, preliminary conclusions are possible.

- Use of the transient data in failure correlations indicate that the data are consistent with information coming from other testing programs.

- The failure thresholds exhibit a discernable microstructural dependence with high power pins being most resistant to failure.

B. Prefailure Fuel Motion

Motion of molten fuel within the cladding, prior to fuel pin failure, is a distinct possibility for a number of pin types. Pre-failure fuel motion in the axial direction, if it occurs, can cause significant reactivity decreases resulting in early accident termination, perhaps even before pin failure. This discussion is primarily concerned with axial fuel motion because of the important impact of such motion on the course of the accident.

Fresh fuel, and high power irradiated fuel in particular, favors motion of molten fuel prior to failure of the cladding. In fresh fuel, large areal melt fractions are likely before cladding failure occurs. In high power irradiated fuel pins, that is, fuel pins that have operated in excess of 10.5 kW/ft maximum linear heat rating in steady state, the presence of a large extensive center void may naturally promote relocation of molten fuel. Other factors that tend to promote axial fuel motion include thermal expansion, volume increase upon the melting of fuel, pressures generated by released fission gases, and pressures generated by fuel vapor. The absence of mechanical or inertial axial restraints in design will promote fuel motion axially.

Extensive fuel motion was observed in General Electric tests C2B and C3B. Both fuel pins had 6 inch long fuel columns with 1.5 inches of insulator pellets, restrained axially by compressed steel wool. This system offers a moderate amount of axial restraint. The C2B fuel pin was not irradiated, whereas the C3B fuel pin was irradiated in the General Electric Test Reactor to a burnup of 8,000 MWd/MTM. The C2B transient test achieved an areal melting of approximately 90% at the time of failure. Fuel motion in this test was predominately downward and appeared to have been influenced by gravity (see Figure 4). There was no direct measurement of fuel motion in this test; fuel motion was inferred from the post-test examination. By contrast, in test C3B, 50 areal percent of the irradiated fuel melted. As a result of this melting, axial fuel relocation occurred in both upward and downward directions. The manner of this axial fuel relocation suggests the expansion of fission gas bubbles within the

FIGURE 4. Transverse and Longitudinal Cross Sections of Specimen C2B.

molten volume as the principal driving force for fuel relocation (Figure 5). It cannot be conclusively determined how much of the fuel motion occurred prior to failure in this test; however, due to the benign failure and the lack of fuel ejection, it appears that fuel motion could have occurred no later than at the time of failure.

The effect of axial restraint is dramatically illustrated by a comparison of General Electric tests C5A and C5B. C5A and C5B fuel pins contained 24 inch long fuel columns, with a 14.25 inch UO_2 blanket. In the case of C5A, this blanket contained solid pellets; in test C5B, the blanket pellets were annular. These fuel pins were irradiated at peak powers approaching 12.3 kW/ft in the General Electric Test Reactor to a peak burnup of approximately 22,000 MWd/MTM. Following irradiation they were subjected to transients in the TREAT facility. The transients were nearly identical and produced approximately 35% areal melting. In test C5A there was extensive failure near the top of the fuel column, whereas in test C5B failure did not occur. In C5B the molten fuel was displaced upward into the annular blanket region. General Electric Company staff concluded the following regarding these tests: "There appears to be some potential to extend this limit (failure threshold) when provisions (e.g., annular blanket) for molten fuel accommodation and internal pressure relief are incorporated into the fuel design. The annular blanket configuration was apparently instrumental in preventing the failure in C5B through accommodation of 4% of the total fuel volume, or 11% of the molten fuel volume. Fission gases, released as the fuel approached its melting temperature during the transient, apparently contributed substantially to the driving forces for fuel relocation and dispersion. The expansion of the released fission gas bubbles resulted in movement of molten fuel up the annular blanket in specimen C5B, and extensive dispersal of fuel into the coolant annulus of specimen C5A."

Prefailure fuel motion has also been observed in three tests performed by Argonne National Laboratory. In two of these tests, E1 and E2, direct evidence of prefailure fuel motion is available from the fast neutron hodoscope data. In the E4 test, a hodoscope record was not

(a) Photomicrograph

(b) Alpha Autoradiograph

FIGURE 5. Axially Near-Uniform Post-Test Fuel Distribution in Test C3B.

available but the post-test condition of the fuel pin was consistent with prefailure motion as once-molten fuel was found in the plenum spacer tube and in the spring region.

The fuel pin used in the E1 test had a 13.5 inch long fuel column with essentially no axial restraint. As a result of the transient irradiation in the TREAT facility, 95 areal melt percent of the UO_2 fuel was approached. Failure did not occur, but the hodoscope data indicated gross axial fuel movement. Post-test radiography confirmed gross fuel motion. Fuel was distributed throughout the entire length of the fuel pin. An artist's rendering of the post-test radiograph and the actual radiograph are shown in Figure 6.

The fuel pin used in the H2 transient test was an unirradiated PNL-17 axially restrained fuel element (PNL 17-42). Approximately 75 areal percent of the fuel was calculated to have been molten as the hottest axial location as a result of the transient. Fuel motion near the top of the fuel column was observed at a time when the fuel at that location was approaching the solidus temperature. Initial fuel motion was confined to the region near the top of the column, but later motion was observed in lower regions of the fuel column.

No direct evidence from the hodoscope is available for the E4 test. The E4 test was identical to the H2 test except for ramp rate, and because the E4 transient was more energetic, 100% areal melting was approached. Post-test examination revealed evidence that suggests that prefailure upward fuel flow may have contributed to the initial failure. Specifically, cladding interior damage was detected at or above the location of the insulator pellet, and frozen fuel was found in the plenum spacer tube.

Although both H2 and E4 tests were filtered, axial flux shaping was not included in the filter. In general, the top and bottom fuel pellets in a test without axial flux shaping operate at a considerably higher power than the balance of the fuel column because they are exposed to the neutron flux through a larger solid angle. The filtering applied to tests H2 and E4

FIGURE 6. Artist's Rendering of Post-Experiment Radiographs of E1 Sample, Showing Extensive Movement of Molten Fuel Inside the Unfailed Cladding (113-2996).

pins undoubtedly reduced but may not have totally suppressed end peaking. It is possible that very localized end peaking may have contributed to the motion observed in tests H2 and E4.

The balance of the ANL tests H4 and E6 (high power irradiated fuel), and H5 and E7 (intermediate power irradiated fuel) have not produced data suggesting prefailure axial fuel motion. The hodoscope data for these tests have not been completely processed; however, there are no preliminary indications of prefailure fuel movement. Because the well developed central void, characteristic of the high power pins tested in H4 and E6, predisposed these particular tests to axial prefailure fuel motion, it is significant that the data indicated that no motion occurred.

The ANL tests share several common features with the GE Series II and Series III tests with regard to prefailure fuel motion:

- With the exception of C3B, all of the tests in which prefailure fuel motion occurred were performed with unirradiated fuel.

- All of the tests in which prefailure fuel motion occurred involved extensive melting > 50 areal percent. In all but one case the extent of melting exceeded 75 areal percent.

- In all cases the axial restraint was less than would be expected in the FFTF.

- The neutron flux axial profile was unshaped in all of these tests. As previously pointed out, this phenomenon gives rise to elevated powers at the top and bottom of the fuel column with attendant early melting at these locations.

To summarize, conditions favorable to axial fuel motion are felt to include:

- High fuel melt fractions.
- Lack of axial restraint.
- Space in which motion can occur.
- Retained fission gas or fuel vapor to serve as a driving force.

These conditions are met to the greatest extent in fresh and high power irradiated pins. Fresh pins are known to have a high resistance to failure which allows formation of high melt fractions prior to failure; also, the lack of bonding between fresh pellets and most likely "slip" conditions between fuel and cladding minimizes axial restraint. High power irradiated fuel pins possess a well developed central void into which melted fuel can move, and also have a relatively high resistance to failure, promoting high melt fractions prior to failure. Additionally, fission gases are available to provide a fuel motion driving force.

Experimental evidence is available to show that axial fuel motion does occur. In all tests to date in which fuel axial motion has been observed, one or more of the following factors has been present:

- The fuel pin had not been irradiated previously.
- Axial restraint was absent or less than expected in the FFTF.
- Axial power was not shaped.

Although presumed to be predisposed toward axial fuel motion, such motion has not been observed to date in tests of high power irradiated pins in which power end peaking was suppressed.

It is therefore tentatively concluded that axial prefailure fuel motion would not significantly affect the course of an accident transient. However, much data remains yet to be evaluated. In particular, examination of several of the HEDL HUT series of tests has just begun and no hodoscope results are yet available on any of these tests.

C. Failure Mechanisms

A number of mechanisms for producing cladding failure during a transient overpower accident have been postulated. Some mechanisms have been experimentally observed. The fundamental processes responsible for producing cladding failure are known to be a complex function of irradiation

history and transient conditions. In this section, postulated failure mechanisms will be presented and supporting experimental data will be described.

1. Postulated Failure Mechanisms

The following failure mechanisms have been postulated as possibly effective in certain types of overpower transients:

- Coolant boiling on the cladding outer surface.
- Cladding melting due to contact with molten fuel on the inner surface.
- Failure due to fuel vapor pressure.
- Differential thermal expansion between cladding and fuel.
- Fission gas release due to fuel melting.
- Fission gas release prior to fuel melting.
- Transient induced fuel swelling.

The relative importance of each of the above failure mechanisms is controlled by fuel design, irradiation history and details of the overpower transient. In some cases a single mechanism may dominate the failure process, but in general, failure is produced by a combination of mechanisms.

The first two failure mechanisms enumerated above are controlled largely by conditions in the coolant; the balance of the failure mechanisms are controlled by fuel conditions and cladding properties.

Failure Due To Coolant Boiling On The Cladding Surface

In order that this mechanism be responsible for failure, the fuel pin must survive until relatively late in the transient so that severe coolant conditions have time to develop. This implies that little or no fission gas be present and the potential for differential thermal expansion be minimized. Such conditions exist in a fresh fuel pin where there is no fission gas, the fuel-to-cladding gap is at a lifetime maximum and the cladding ductility is at its greatest. In such pins the coolant could

reach saturation at the outlet prior to failure due to differential expansion. It is possible that failure in this mode could also occur in higher power fuel pins relatively early in life when the cladding retains high ductility, the presence of a center void partially compensates for fuel-to-cladding gap closure, and the generated fission gas has largely been released.

While failures of this type have been experimentally observed, it should be pointed out that coolant preheat temperatures and system pressure play a large role in determining onset of boiling and that experimental conditions do not match reactor conditions in every case.

Failures in the ANL Tests H2 and E4 were evidently produced by this mechanism.⁽⁶⁾ In both cases coolant boiling was clearly indicated by loop instrumentation to have persisted for about 40 to 50 microseconds prior to failure. Disruption of heat transfer by surface boiling then leads to melting of the stainless steel cladding. Outlet flowmeter records are shown in Figure 7 for these tests. It was postulated that boiling in these cases was very localized and might have been associated with very local coolant conditions near spacer wires. Some credence is lent to this hypothesis by the fact that the bulk coolant outlet temperatures at failure for H2 and E4 were different, being ~1470° and 1730°F, respectively. At the time E4 failed, due to localized boiling and dryout, 100% of the fuel was at or above the solidus temperature.

Cladding Melting Due To Contact With Molten Fuel On The Inner Surface

It has been postulated that penetration of molten fuel through fuel cracks and subsequent contact with the cladding inner surface could cause fuel pin failure during Transient Overpower Series (TOPS) accidents severe enough to melt significant quantities of fuel. Operation of this mechanism is apparently dependent upon the coolant temperatures at the axial elevation of contact.

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FIGURE 7. Flowmeter Records for ANL Tests H2 and E4. (6)

Molten fuel penetration of cracks in fuel pellets, and subsequent contact with the cladding inner surface without apparent damage to the cladding, has been observed during the post-test examination of a number of transient tested fuel pins. Included were, the General Electric C4A⁽⁴⁾ and C4X⁽⁷⁾ and the ANL tests E1⁽⁸⁾ and D1⁽⁹⁾. Photomicrographs of once molten fuel quenched on the inner cladding surface for test D1 and C4X are shown in Figure 8. In all of these tests the bulk coolant temperature was quite low throughout the transient and it is likely that heat transfer from the cladding exterior precluded melting from the inner surface.

The ANL test E2⁽⁸⁾ is a potential exception to the behavior observed in other tests. The failure mechanism in test E2 is not clearly identified; the post-test remains are consistent with failure by melt through, although at the time of failure the bulk coolant temperature was quite low (~850°F). The observed cladding melting was under a spacer wire and therefore may be related to very localized conditions.

In general, it is felt that failure due to cladding melting will not occur in the absence of elevated bulk coolant temperatures and, in that case, failure may occur as a result of molten fuel on the inner cladding surface inducing local coolant boiling on the cladding exterior.

Fuel Pin Failure Due To Fuel Vapor Pressure

Fuel pin failure due to vaporization of fuel can occur only under very special circumstances. First, the fuel pin must be fresh or have very little fission gas in the matrix or fission gas pressurization will precipitate failure before fuel vaporization can occur. The fuel-cladding gap must be large in order to preclude failure by differential expansion. Further, in order to generate temperatures sufficient to vaporize fuel without precipitating failure by some other mechanism, the transient heating rate must be very rapid.

It is unlikely that mixed oxide fuel pins of the Fast Test Reactor (FTR) type could ever be failed exclusively by vapor pressure;

FIGURE 8. Areas Of Molten Fuel Contact With Cladding Inner Surface For ANL Test D1⁽⁹⁾ and GE Test C4X⁽⁷⁾.

rather fuel vapor pressure could be a potential contributor to failure acting in concert with other mechanisms. This has been the case experimentally. In the General Electric test C2C⁽²⁾ the transient and the test vehicle were designed to enhance fuel pin failure by fuel vapor formation. However, the post-test examination did not indicate failure by this mechanism. Further, in ANL test E2 the post-test remains are not consistent with failure due to fuel vaporization even though temperature on the fuel centerline exceeded 6500°F⁽⁸⁾.

Differential Thermal Expansion Between Cladding And Fuel

The different thermophysical properties of the fuel and cladding and the different heating rates of these components during transient overpower accidents give rise to differential thermal expansion. Differential thermal expansion is always active in transient situations and, depending on the details of fuel design and the nature of the transient, may be a very powerful failure mechanism.

The degree to which the fuel pin cladding is stressed by differential thermal expansion is very sensitive to the fuel-to-cladding gap dimension since this parameter controls the time at which fuel-to-cladding contact occurs. Beyond the time of contact, the nature of the loading depends on the fuel density, porosity distribution, differential heating rates and degree of axial restraint.

Since differential thermal expansion is always present in transient situations; it is always a potential failure mechanism. Indeed, it probably influences, to varying degrees, most fuel pin failures. However, in most cases, it probably acts in concert with other failure mechanisms. The best opportunity to observe the effect of pure differential expansion should be in a fresh fuel pin since fission gas is absent. However, in most tests using prototypic fresh fuel, failure due to differential expansion has not been observed because of the large fuel-to-cladding gap in fresh pins; most fresh pins have failed due to coolant boiling on the cladding surface. The only tests performed to date, which indicate that

differential thermal expansion was the primary failure mechanism, are the General Electric tests C4A and C4B ⁽⁴⁾. General Electric concluded that "It is evident from the calculated temperatures of the inner capsule that boiling of the sodium coolant was not a cause of initial cladding failure," and "The cause of initial cladding failure in the Series IV specimens cannot be attributed to contact of molten fuel with the cladding, although such contact can be a potential contributor to the failure mechanism."⁽⁴⁾ Further, the fuel temperatures do not seem to be high enough to have produced fuel vapor driven failure at the indicated cladding temperatures. Therefore, it is concluded that in these tests differential thermal expansion was the primary failure mechanism. It should be noted, however, that the smeared fuel density in these tests was high (~91% TD) and that the fuel-to-cladding diametral gap was small (~4 mils). Both of these effects tend to enhance differential expansion. The cladding diametral deformations produced in tests C4A and C4B are listed in Table 19.

TABLE 19
SUMMARY OF TRANSIENT-INDUCED DIMENSIONAL
CHANGES, C4A AND C4B FUEL SPECIMENS

Fuel Specimen	Cladding Diametral Deformation			
	Average		Peak	
	mils	%	mils	%
C4A	1.15	0.46	8.9	3.2 to 3.6
C4B	--	--	~1.0	~0.4

It can be concluded that differential thermal expansion is potentially a contributor to any failure, but that in most cases it is not possible to clearly identify differential expansion as the principal failure mechanism.

Fission Gas Release Due to Fuel Melting

One of the fundamental differences between the behavior of fresh fuel and irradiated fuel is the presence of gaseous fission products. The potential for fission gas contribution to fuel pin failure was recognized early and investigation of the role of fission gas was one of the objectives of the General Electric Series III test program. ⁽³⁾

Fission gas is produced within the fuel grain during irradiation; as irradiation continues the gas becomes redistributed under the influence of thermal gradients. In the colder unrestructured fuel most of the fission gas remains within the fuel matrix; as temperatures increase the fission gas release also increases so that in the equiaxed grain growth region grain boundary porosity begins to appear, and in the columnar grain growth region release of generated gas is essentially complete. In a transient overpower accident the fission gas which was retained in the fuel matrix is released by the melting of the fuel matrix. This gas is then available to act as a free gas and to pressurize the molten volume. Such pressure may be transmitted to the cladding (although the details of this transmission are currently uncertain) and act to produce cladding strain.

In order for this mechanism to become active, melting must progress into the gas bearing fuel which is dependent on the radial distribution of fission gas, which is in turn dependent upon irradiation history. In FTR type fuel pins which have operated in the steady state at linear powers greater than 9 kW/ft considerable melting may be required before gas bearing fuel becomes molten.

In the General Electric Series III tests it was concluded that "The release of fission product gases from fuel which is melted during a transient can be one of the primary mechanisms for cladding failure under these conditions." Figure 9 shows the characteristic structure of once molten fuel and the size and distribution of fission gas bubbles at the solidus boundary from test C3B. ⁽³⁾

FIGURE 9. Fuel in Area of Concentrated Porosity (Fission Gas Bubbles)
Immediately Adjacent to Molten Boundary: Test C3B (3).

It is also instructive to examine the ANL tests H4, H5, E6 and E7.⁽⁶⁾ Failure in H4 and H5 occurred at a time when the melting front had advanced into the gas bearing fuel. In the case of E7, assuming first failure in the hottest peripheral pin, the asymmetric melt volume led to melting of gas bearing fuel on the hot side. The calculated thermal histories at the various microstructure region boundaries for tests H4, H5, and E6 are shown in Figure 10.⁽⁶⁾

The radial distribution of retained fission gases in each of the microstructural regions as determined by laser sampling⁽¹⁰⁾ is shown in Figure 11. By comparing the radial fission gas distribution with the calculated radial position of the solidus isotherm at the time of failure for tests H4 and H5 (Figure 11) it may be seen that failure occurred when the solidus boundary approached the gas bearing fuel. In the case of E6 the solidus boundary penetrated a considerable distance into the gas bearing fuel (Figure 10). A combination of strain rate and heating rate effects in the cladding, and time dependence of gas release and cavity pressurization in the fuel, explains the attainment of more severe conditions in the more rapid transient. Further, the release of gas may have been enhanced by release prior to melting in the "gassy" fuel adjacent to the molten zone. This effect is discussed in more detail in the following section.

Fission Gas Expansion Prior To Fuel Melting

While the release of fission gas on fuel melting has been known to occur for some time, the release of fission gas prior to melting is a relatively recent discovery.

It was experimentally observed in several early HEDL transient tests⁽¹¹⁾ that the volume of fission gas in the unfailed never-molten test pin was greater than the volume of fission gas in pins that had undergone only steady state irradiation. A comparison of pretest (as measured from sibling pins) fission gas release with post-transient test fission gas release for the appropriate unfailed, never-molten HEDL tests is presented

FIGURE 10. Thermal Histories For ANL Tests H4, H5, and E6. (6)

COLUMNAR	EQUIAXED	UNRESTR	PNL-17 REGIONS
VOID	COLUMNAR	EQ-AX UNRES	NUMEC F REGIONS

FIGURE 11. Distribution Of Fission Gases In Sibling Pins For Tests H4, H5, and E6.(10)

in Table 20. Figure 12 presents a comparison of fuel morphology for transient tested and steady state irradiated fuel pins. It can be seen that extensive changes have occurred in the fuel structures even in the absence of melting: the grains themselves exhibit an accumulation of fission gas bubbles and the grain boundaries have built up considerable porosity.

Figure 13 presents a more detailed view of morphological changes, in particular the energy dependence of grain boundary separation during a transient. The upper photomicrograph was made during the destructive examination of the nontransient tested fuel pin PNL 17-6. The sample was taken from near the axial midplane and the section shown is from mid-radius. The steady state energy density was 460 J/g, and there is relatively little porosity evident either on the grain boundaries or within the grain.

TABLE 20
COMPARISON OF PRE-TEST AND POST-TEST FISSION GAS RELEASE

Test Designation	Fission Gas Release (Steady State)	Fission Gas Release After Transient
PNL 1-2	8%	24%
PNL 1-7	8%	18%
PNL 2-10	50%	78%

Remaining photomicrographs are from a similar fuel pin subjected to the test HOP 3-3C, a transient simulation of a 3\$/sec FTR overpower incident. The center photomicrograph was taken from mid-radius of a region of the fuel pin in which the peak retained energy density was 680 J/g or about 220 J/g greater than steady state. The grain boundaries contain a large amount of porosity, small intragranular pores have formed and the edge of the grains are denuded. The lower photomicrograph represents a region that incurred a maximum retained energy density of 920 J/g.

PNL 1-14

5 μ
(6000X)

PNL 1-2

50 μ
(750X)

1 μ
(37,000X)

IRRADIATED TO $\sim 10,000$ MWd/MTM

50 μ
(750X)

1 μ
(37,000X)

IRRADIATED TO $\sim 10,000$ MWd/MTM
PLUS TRANSIENT TESTED

FIGURE 12. Bubble Formation During A Transient Test Is Shown In The Right-Hand Pictures. The Left-Hand Pictures Were Taken After Steady State Irradiation Only.

FIGURE 13. Transient-Induced Grain Boundary Separation.

These fuel grains are completely separated, the porosity within the grains is now quite large and there are extensive areas of denuded grains. It was concluded from these experimental observations that the potential for redistribution of fission gas exists any time the temperatures associated with steady state operation are exceeded.

A series of experiments at HEDL provide observations and data on the response of fast flux (EBR-II) irradiated fuel materials when subjected to rapid heating in the laboratory.⁽¹²⁾ Fuel samples within a resistively heated tungsten tube are subjected to thermal transients in a system providing for temperature and pressure measurements, in addition to continuous gamma radiography of the sample.

Results for heating fuel at rates of 200C°/sec are presented in Figure 14. Unirradiated UO₂ slumps rapidly when melted. Low power irradiated fuel with uniform fission gas distribution was observed to break apart below the melting point, resulting in dispersal from the effect of released fission gas. Extensive gas bubble formation occurs below the solidus, and bubble expansion results in a foam-like structure at the melting temperature. High power irradiated fuel behaves differently, consistent with the relative gas distribution and content. Less fuel motion is observed; the major effect of fission gas is to slow downward displacement upon melting. Selected metallography of the post-test fuel is shown in Figure 15.

Measurements of the temperature dependence of gas release indicate that gas release begins at fuel temperatures near 2000°C, and a significant fraction of the fission gas has been released when fuel reaches the melting temperature.

The exact mechanisms for release of fission gases prior to melting are not known precisely. However, work performed at ANL by Gruber⁽¹³⁾ indicates that migration of fission gas from fuel grains to the grain boundaries can proceed quite rapidly under certain conditions of thermal

FIGURE 14. Temperature Dependence of Gas Release Obtained from Analyses of Data from Rapid Heating of High Power Density Fuel. (12)

FISSION GAS RELEASE DURING HEATING MICROSTRUCTURES FROM PHASE II CAPSULE

FIGURE 15. High Magnification Micrographs from Areas Selected to Show the Effect of Increase Maximum Temperature Obtained During Rapid Heating. (12)

upset. This hypothesis is supported by the work of Stahl and Patrician (14) in the measurement and comparison of fission gas radial distributions in transient tested and nontransient tested fuel pins. By comparing pre-and-post-test radial fission gas distribution, Stahl found that large fractions of gas retained in the fuel at the inception of the transient were released during an overpower transient which produced no melting. The details of the radial fission gas distributions are presented in Figure 16.

The manner in which the released fission gas loads the cladding is the subject of ongoing research programs.

Transient-Induced Fuel Swelling

It has been experimentally observed that fission gas bubbles can be formed within the fuel grain by heating the fuel beyond its steady state operating temperature (see Figure 12). This phenomenon has been observed in virtually every transient test to date.

Gruber proposed a model in which fission gas molecules coalesce under elevated temperature conditions. (13) These bubbles can then migrate to the grain boundary at a velocity inversely proportional to their size. Stahl concludes "On the basis of the above proposals, it would seem reasonable to assume that, during steady state operation intragranular bubbles can grow to a maximum of $\sim 650 \text{ \AA}$ in quasi-equilibrium with the resolution rate. These bubbles are most likely to be pinned to dislocations. During the transient, the fission gas in small bubbles (if they are present) or in solution can migrate and grow by diffusion and coalescence to form bubbles (up to $\sim 650 \text{ \AA}$) that can be pinned by dislocations".

Such growth of intragranular bubbles created during the transient can cause fuel swelling which could act to load the cladding. The swelling of fuel due to intragranular bubble precipitation and growth does not appear to be radially uniform but reaches a maximum typically beyond mid-radius. The maximum observed $\Delta V/V$ in a HEDL test due to intragranular bubble growth was $\sim 3.6\%$.

FIGURE 16. Comparison Of Laser-Sampling Data For Transient Tested Fuel Pin PNL 17-24 And Sibling PNL 17-10. (10)

2. Interaction of Failure Mechanisms During Overpower Transients

It is difficult to directly determine the effect of individual failure mechanisms in the reactor. The effect must be determined by data reduction and post-test examination. However, by a combination of analysis and examination it is possible to construct likely interaction sequences. The sequence will vary depending upon the fuel type and transient conditions. Four types of fuel will be considered here, and the effect of transient rate on the behavior of each type will be discussed: 1) fresh fuel, 2) low power irradiated fuel, 3) intermediate power irradiated fuel, and 4) high power irradiated fuel. Conditions bearing on failure mechanisms will be described.

Fresh Fuel

Fission gases are absent; the fuel-to-cladding gap is at its maximum, the cladding has its maximum ductility and the fuel pellets are in their as-fabricated condition. The absence of fission product gases obviates the last three mechanisms discussed in the preceding section. Consequently, one would expect failure through coolant boiling on the cladding outer surface, by differential thermal expansion, or by fuel vapor formation. Boiling on the cladding surface and differential thermal expansion between the fuel and the cladding show some sensitivity to transient rate; however, the rate dependence is probably not a first order effect. On the other hand, in order for a fuel pin to fail by generation of fuel vapor pressures, the rate must be exceedingly rapid. That is, vapor must be formed before the fuel pin can fail either due to coolant boiling or differential thermal expansion. Transient rates of requisite magnitude are not considered credible and this mechanism will not be discussed further here. The onset of coolant boiling on the cladding surface is controlled predominantly by the pressure in the system and the bulk inlet temperature. In certain slower transients in which considerable thermal energy is transferred through the cladding to the coolant it is quite likely that coolant boiling on the surface will be the direct cause of cladding failure. Even in this case, however, differential thermal

expansion plays a role. It is probable that in such slow transients the fuel cladding gap will close and that the fuel will be loading the cladding at the time of the onset of boiling. For rapid transients differential expansion may be the predominant failure mechanism. The fuel will retain a considerably larger fraction of the total deposited energy and the gap will be closed earlier while the coolant temperatures are relatively low. In this case differential expansion will become the dominating force relatively early in the transient. In such a case, one would expect differential thermal expansion may produce failure. Certainly, as transients become more rapid, thermal expansion will play a larger role in the deformation and failure of the cladding.

Low Power Irradiated Fuel

Low power fuel is defined as fuel that has been irradiated in the steady state at maximum linear heat rates of less than 9 kW/ft. Fuel of the FFTF design forms no central void or columnar grains at linear heat ratings below 9 kW/ft. This fuel is characterized by high retention, within the fuel matrix, of fission gases that have been generated. For fuel pins with maximum linear heat ratings in the range of 4 to 6 kW/ft the fuel-to-cladding gap probably does not close. For fuel pins with maximum linear heat ratings between 8 and 10 kW/ft fuel-to-cladding gap at power persists until near the end-of-life. This implies that, before differential thermal expansion can become effective in straining the cladding, the gap must be closed. This will necessarily delay the onset of cladding loading due to differential thermal expansion. The more rapid the transient the faster the gap will be closed in this case and the earlier cladding loading due to differential thermal expansion will occur. Because of the large inventory of fission gas within the fuel matrix and on the fuel grain boundaries, all three fission gas release mechanisms are likely to become operable at some time during the uninterminated transient with low power fuel. It is unlikely that low power fuel can survive very much melting before pressurization of the central cavity or localized gas release becomes high enough to cause cladding failure. However, prior

to melting, appreciable amounts of fission gas can be released from the fuel grain to the grain boundaries. Grain boundary cracking, crack propagation and link-up, can therefore lead to release of the gas. In general, the gas acts to expand the grain boundaries, thereby causing an increase in the volume of fuel. In addition, precipitation and coalescence of fission gas bubbles in regions bearing fission gas can lead to as much as 4% local change in fuel volume. All these fission gas effects tend to increase the loading on the cladding which may already have been loaded by differential expansion. It is probable that all these mechanisms act in concert to cause cladding failure; that is, differential thermal expansion can stress cladding until it is plastically deforming or nearly so. By this time, fission gas release has probably proceeded to the point that the fuel pin cladding will be carried through the plastic region into failure. The exact interaction of these failure mechanisms depends very much on specific irradiation history of the fuel pin and the details of the overpower transient. For transients proceeding at a slower rate, all of the failure mechanisms are affected. Differential thermal expansion is somewhat delayed because heating of the fuel tends to proceed with greater heat loss to the cladding. Fission gas effects still proceed as before, but with a sufficiently slow transient there is enough time for accommodation of the released gases to regions of relatively less gas concentration, or, in a sufficiently slow transient, by equilibration of the gases with the plenum. In such cases, loading of the cladding may be delayed until some substantial melting can occur.

Intermediate Power Irradiated Fuel

Intermediate power fuel is defined as fuel that has been irradiated at steady state at maximum linear heat rates from 9 to 10.5 kW/ft. At 9 kW/ft columnar grain growth will begin in fuel pins of the FTR design. This leads to formation of an incipient center void. The columnar grain growth region bears no fission gas at all within the fuel matrix. The gas which is generated in this region migrates rapidly to the center void. Laser sampling performed at Argonne National Laboratory indicates that most of the fission gas is retained in outer (more dense) equiaxed structures. The unstructured fuel retains most of the fission gas which is generated

within the fuel matrix. The immediate consequence of restructuring is that considerable melting may proceed before fission gas is released by this mechanism. In fact, all the columnar grain region, and perhaps some of the equiaxed grain region, may be molten before significant quantities of fission gas are released by melting from the fuel matrix to pressurize the molten volume. Furthermore, for pins with linear heat ratings in this range, the fuel-to-cladding gap closes quite rapidly. Pins operating at maximum heat rates above approximately 10.5 kW/ft have their gap closed under hot conditions. Below 10.5 kW/ft, gap closure proceeds somewhat more slowly. The effect of more rapid fuel-to-cladding gap closure is that loading due to differential thermal expansion will become operative relatively early in the transient. This, coupled with the fact that fission gas cannot be released until relatively late in the transient, means that the early loading of the cladding probably proceeds from differential thermal expansion alone. Cladding stress due to fission gas release may become of comparable magnitude later in the transient. During a rapid transient with intermediate power irradiated fuel, differential thermal expansion is likely to account for most deformation of cladding, with fission gas release contributing sufficient loading to precipitate the failure. In slower transients fission gas release may play a larger role. In any event, the failure threshold for fuel microstructures of this type is likely to be considerably higher than for lower power microstructures.

High Power Irradiated Fuel

Fuel that has been irradiated under steady state conditions at a maximum linear heat rating greater than 10.5 kW/ft is defined as high power irradiated fuel. Such fuel pins are characterized by formation of a large center void, large columnar grain growth region, and small equiaxed and unrestructured regions. In such microstructures all fission gases are retained in the outermost radial region of the fuel. The fuel-to-cladding gap closes quite early in life. The absence of fission gases in the central regions of the fuel pin causes the fuel pin to behave quite similarly to fresh fuel. The pronounced difference is that, in high

power irradiated fuel, the fuel-to-cladding gap is initially closed and consequently loading, due to differential thermal expansion, can proceed from the inception of the transient. This loading is somewhat mitigated by the large central void and compliant volume of the fuel pin. It may be seen, by comparing tests C5A and C5B from General Electric with the Argonne tests E1 and E2, that axial motion of molten fuel relieves the radial loading from cladding. The presence of a large center void provides the means by which fuel may readily move axially. Considerable melting of fuel may occur before any fission gas is released to the cavity or before gas is released from the grain boundaries and precipitates within the grains. Typically, melt fractions approaching 80 to 90% can be accommodated in high power fuel pins. The absence of fission gas effect, coupled with relief from cladding loading due to differential thermal expansion through axial motion of the fuel, causes fuel pins of this description to have the highest failure threshold of all irradiated fuel pins. As with fresh fuel, high power irradiated fuel is likely to be less sensitive to transient rate. In very rapid transients one would expect differential thermal expansion to play a large role and possibly to precipitate failure of the fuel pin before large quantities of fuel can be melted. However, such transient rates are exceedingly high and considered incredible in the FTR.

3. Summary

The interaction of the principal mechanisms for cladding strain is controlling, whether cladding ductility or cladding stress is the preferred cladding failure criterion. Under conditions of loading by fission gas, cladding strain does not significantly reduce the applied stress. Minor differences in the cladding ductility will not prevent failure when the applied stress exceeds the load-bearing capability. For such loading mechanisms, stress is probably the better failure criterion. For secondary type loading, such as thermal expansion, stress is probably relieved by cladding strain, and cladding ductility would be the better failure criterion.

Transient-induced fission gas release will tend to be a primary type loading mechanism, although the extent to which it approaches true gas loading is unknown. In a low power fuel, this type loading would be expected and minor cladding ductility differences may not influence the failure position or time. Rather, failure should occur where load-bearing capability of the cladding is exceeded.

The fuel swelling, due to intragranular precipitation and growth of fission gas bubbles, will probably tend to be analogous to a primary loading mechanism, although stress may eventually diminish as the cladding strains. Due to the kinetics of bubble precipitation and growth, loading on the cladding is strongly influenced by thermal rate.

The above discussion is qualitatively based on post-test examination data and calculations. While this represents the current thinking on the subject of interaction of failure mechanisms, complete confirmation must await further examination, further testing and further analyses.

D. Cladding Properties And Conditions

During an overpower transient the temperature of the fuel pin cladding is rapidly elevated above its steady state service temperature. Simultaneously, the expanding fuel internally loads the cladding. 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 allowing 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 temperature conditions. Therefore, a specific testing program is underway at HEDL, utilizing a recently developed Fuel Cladding Transient Tester (FCTT) ⁽¹⁵⁾ to generate the requisite mechanical property information on irradiated and unirradiated fast reactor fuel cladding under temperature ramp conditions.

The simulated transient testing 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 heated at ramp rates of $10^{\circ}\text{F}/\text{sec}$ and $200^{\circ}\text{F}/\text{sec}$ above the steady state irradiation temperature until straining and/or failure occurred. 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. 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.

The deformation behavior and failure strength and ductility of unirradiated 20% CW Type 316 stainless steel cladding are shown in Figure 17. The failure temperatures increased with decreasing internal pressure. The specimens heated at $200^{\circ}\text{F}/\text{sec}$ are "stronger" than the $10^{\circ}\text{F}/\text{sec}$ specimens because less thermal recovery or annealing of the cold worked microstructure occurred. In the lower half of Figure 17, the diametral strain for various pressures is plotted as a function of attained temperature; also, the diametral failure strain is shown as a function of temperature. 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 $10^{\circ}\text{F}/\text{sec}$ was greater than at $200^{\circ}\text{F}/\text{sec}$ because more time was available for recovery and/or annealing of the cladding cold worked condition.

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 Figure 18. Under the FCTT test conditions, a decrease in the failure temperature for an irradiated specimen, relative to the unirradiated specimen, implies

FIGURE 17. Deformation Behavior and Failure Strength and Ductility of Unirradiated 20 Percent Cold Worked Type 316 Stainless Steel Cladding.

FIGURE 18. Effect of Irradiation on the Failure Strength and Ductility of 20% Cold Worked Type 316 SS Cladding.

that the load-bearing capability is reduced in the region from 1000 to 1600°F. The lower portion of Figure 18 shows that the ductility is also the lowest in this temperature region. For the 10F°/sec heating rate, the lowest ductility and greatest decrease in failure temperature occur at 1200 to 1600°F.

The temperature range from 1000 to 1600°F is the region in which the irradiated cladding is most susceptible to low-ductility intergranular fracture due to helium embrittlement. Under tensile stresses, with conditions of low-ductility intergranular fracture, a grain boundary opening or micro-crack can initiate and propagate from a highly stressed local region, without the remaining material across the section being significantly stressed. Consequently, the hoop (tensile stress) load-bearing capability of the material is high. Figure 19 demonstrates that cladding with lower failure strains exhibited the larger decreases in failure temperature.

The ductility of intergranular fracture is reduced by helium embrittlement⁽¹⁶⁾ and a hard or inherently "strong" crystal.⁽¹⁷⁾ Irradiation to a higher fluence will generate more helium and will produce more irradiation-induced hardening. Therefore, during a test or loading situation in which low-ductility intergranular fracture can occur, one would anticipate that material irradiated to a higher fluence would exhibit a greater decrease in failure temperature; such a situation is indeed the case as indicated in Figure 20. At temperatures above the 1000 to 1600°F range in Figure 18, the inherent strength of the cladding is reduced sufficiently that intergranular fracture does not proceed without appreciable prior deformation, so that the failure temperature and load-bearing capability are not decreased. At lower temperatures and higher strain rates the fracture mode changes from intergranular to transgranular fracture. At 10F°/sec this fracture transition occurs at approximately 1000°F, while at 200F°/sec it is at 1200°F. In face-centered cubic metals transgranular fracture occurs by a shear process which requires large amounts of strain for the crystals to fracture; even for highly irradiated material the

HEDL 7501-86.4

FIGURE 19. Relationship Between Decrease In Failure Temperature And Diametral Failure Strain.

HEDL 7503-149.1

FIGURE 20. Effect of Irradiation Fluence on the Decrease in Failure Temperature During Temperature Transients.

ductility is greater than 0.5%.⁽¹⁸⁾ Therefore, below the intergranular fracture range, the ductility increases as shown in Figure 19.

In the low-ductility intergranular fracture region the lowest ductility occurred at the 10F°/sec heating rate. As demonstrated in Figures 18 through 20, this lower ductility brings about a greater decrease in failure temperature and loss of load-bearing capability.

It has been discussed how steady state irradiation conditions and transients could affect the loading of the cladding and the cladding mechanical properties during the transient. Also, it has been postulated that the transient loading characteristics should determine the selection of a cladding failure criteria. Finally some general (although not rigorous or quantitative) concepts have been formulated relating how certain fuel loading functions and cladding mechanical responses may individually influence failure. This information is useful in guiding data correlation, however, detailed fuel pin failure modeling from the loading functions and cladding mechanical properties requires additional quantitative information.

E. Empirical Failure Correlations

In the absence of detailed data on the loading history of the cladding during transient overpower accidents, empirical expressions have been developed to describe the failure threshold for mixed-oxide fuel pins. A number of such correlations have been developed; in this section the following correlations will be discussed:

- Fuel melting criteria.
- Cladding strain correlation.
- Fuel enthalpy correlation.
- Damage parameter correlation.

1. Fuel Melting Criteria

One of the earliest criteria for describing the threshold for incipient failure was the fuel melting criteria. In the General Electric

Series III experiments a relationship between columnar grains radius, radial position of the solidus boundary and time of failure was noted. The relationship is given in Table 21.

TABLE 21
COMPARISON OF AREAL MELT PERCENT AT FAILURE
WITH COLUMNAR GRAIN AREA PERCENT

<u>Test Designation</u>	<u>% Molten at Failure (Calculated $\geq$ Solidus)</u>	<u>Columnar Grain Area %</u>	<u>Failure</u>
C3B	51	50	Yes
C3E	30	70	No
C3C	67	70	Yes

It was concluded from the above results that fuel pin failure was a possibility if the columnar grain region of the fuel had been melted. On this basis, it was postulated that melting of fuel through the gas-free columnar grains into the gas-bearing equiaxed grains was necessary to produce fuel pin failure.

The foregoing conclusions were in part substantiated by ANL test results using similar pins (containing significant volumes of columnar grains). The ANL tests, however, were conducted at different thermal rates and exhibited a rather strong rate dependence, a feature not noted in the General Electric Series III tests. In addition, a better definition of the radial distribution of fission gases was possible for the ANL tests because of a capability for laser sampling of sibling fuel pins. With a more precise definition of the radial fission gas distribution it was possible to determine the volume of fission gas within any isotherm as a function of time.

At lower thermal rates both the PNL-17 and NUMEC F fuel pins appeared to fail as the solidus isotherm approached the radius at the beginning of a significant buildup of gas content.

At higher thermal rates (up to an equivalent of 3\$/sec), data are available only for NUMEC F type fuel pins. It would appear that at elevated thermal rates the solidus isotherm penetrates further into the gas-bearing region of the fuel. While it is not known why this is so, at least two plausible explanations exist:

- There is a time dependence for gas release and pressurization such that at higher thermal rates more melting will take place for a given pressure level in the molten volume.
- The cladding strain rates are significantly different. It is natural to expect greater strength for a given temperature at high thermal (strain) rates.

Perhaps the greatest weakness of the melt criteria for fuel pin failure is the lack of implicit thermal rate dependence. Undoubtedly a physical basis exists, upon which transient melting in fuel pins containing restructured fuel, can be related to failure thresholds; however, at this time lack of knowledge regarding thermal rate effects and the details of the radial distribution of fission gases make the failure criteria largely qualitative.

In summary the advantages of the fuel melting criteria are:

- Provision of a strong physical basis in the radial distribution of fission gases.
- Provision of reproducible experimental results at any particular thermal rate.

The disadvantages are:

- Failure prior to melting is not explained.
- Cladding condition, state or properties are not considered.
- No quantitative dependence on thermal rate effects currently exists.

2. Cladding Strain Criteria

Loss of cladding integrity is the definition of fuel pin failure. Therefore, it is reasonable to expect that some measure of cladding performance could be used as a reliable indicator of incipient failure. Normally cladding strain is chosen as the indicator of cladding performance, since strain is a measurable quantity. However, since the details of fuel loading are not completely understood at this time, the strain predictions exhibit varying degrees of accuracy. While it is not possible at this time to predict the absolute magnitude of the strain in any particular test, it is possible to accurately predict relative strains among several tests. An example of this application will be given in this section.

In the planning for HEDL test HOP 3-3C, prediction of the point of incipient cladding failure was based on calculated cladding strains for ANL tests H3, H5 and E6. All of these tests (HOP 3-3C, and H3, H5 and E6) were previously summarized, and full details on each one are given in appendices C (H3, H5 and E6) and D (HOP 3-3C). Pertinent aspects of each one are repeated in the following discussion.

The pre-irradiated pins tested in H3, H5 and E6 were PNL 17-24, PNL 17-25 and NUMEC F-056, respectively. The pre-irradiated pin tested in HOP 3-3C was PNL 17-34. Tests H3 and H5 used simulations of thermal aspects of a 1\$/sec ramp and a 50¢/sec ramp, respectively. Test H3 was deliberately terminated short of a failure, and no measurable permanent strain was detected. Fuel pin failure occurred in test H5, and a peak cladding permanent strain of 0.25% was measured. Test E6 (in which the failure occurred) and test HOP 3-3C (the test being planned) involved simulations of the thermal aspects of a 3\$/sec ramp.

The respective power transients for the four tests are shown in Figure 21. The corresponding calculated effective non-elastic strains at the outer cladding surface are shown in Figure 22. The

FIGURE 21. Comparison Of Pin Powers For TREAT Transients H3, H5 And E6 With The Proposed Transient HOP 3-3C.

FIGURE 22. Comparison Of Effective Non-elastic Cladding Strain For TREAT Transients H3, H5 And E6 With Proposed Transient HOP 3-3C.

calculated strains were clearly much higher than actually occurred; the basis of the method, however, was to use the calculated strains as a relative manner. The failure criterion would be based on the calculated strain at time of failure in evaluated tests. The cladding properties used and the method of calculation thus were of secondary importance.

In the case being considered, a criterion of 1.67% effective non-elastic strain at the outer cladding surface was chosen, based on the H5 test. A higher strain was calculated for the E6 test than for the H5 test; the H5 test result was chosen as the failure criterion because it was more conservative.

The design test transient for HOP 3-3C, shown in Figure 21, was terminated so that the calculated strain would match the strain failure criterion of 1.67% near the end of the transient. During the test, pin failure was observed at 0.8 sec. into the spike transient, failure occurring at 96% of total energy release. The predicted time of pin failure was in excellent agreement with the observed time. Thus it was demonstrated that calculated cladding strain, relative to that for a known test procedure, can be used to predict time of failure.

3. Enthalpy Criteria

Enthalpy or retained energy failure criteria have been suggested at intervals for some time. In 1969 Hikido and Field suggested instantaneous energy density as an appropriate failure criteria. Since the concept has physical significance, and enthalpy can be related to real processes, it was decided that an enthalpy correlation should be attempted.

In order to correlate the in-reactor data derived from the transient testing of various fuel microstructures it was necessary to choose suitable parameters. Since all three strain mechanisms (differential expansion, gas release, and gas precipitation) are activated by, and are in some way proportional to, departure from the thermal equilibrium at

steady state; a correlation parameter which expressed the degree of thermal upset of the system was chosen. That parameter was retained energy density; that is, the net energy density accumulated in the fuel due to the transient. As a means of incorporating cladding properties, calculated cladding temperature at the time and location of failure was chosen.

The correlation in Figure 23 has been developed from transient tests on three distinct microstructures, which are illustrated in Figure 24. The relationship of the EBR-II fuel pin microstructures to that of an FFTF fuel pin is depicted in Figure 24. The low power PNL-1 and -2 irradiated fuel contained a small equiaxed grain growth region with a surrounding region of unrestructured fuel. The PNL-17 fuel contained a well-developed equiaxed grain growth region with some unrestructured fuel. The PNL-17 subassembly operated in EBR-II at the two power levels of 8.5 and 11 kW/ft. As a result the fuel microstructures resemble those expected for 8.5 kW/ft operation and the gas release more closely resembles that expected from 11 kW/ft operation. These intermediate microstructures are very similar to the microstructures that occur at the top of the center void in unirradiated pins that have a continuous range of microstructures. The high power fuel pins used in this correlation were from experimental assembly X097 and had a microstructure consisting of a large central void and an extensive columnar grain growth region, surrounded by equiaxed grain growth regions and unrestructured fuel. Cladding temperatures in steady state ranged from 700°F to 1000°F.

The data recorded during TREAT tests performed by HEDL and ANL on the above test pins were used to calculate the energy density and cladding temperatures at the time and location of failure. The lines in Figure 23 represent the most probable failure thresholds for the three different microstructures. The indicated failure threshold for the high power microstructures is based on data obtained by transient testing X097 fuel pins at ANL and by General Electric Series III transient irradiations. The threshold for intermediate power microstructures was derived from tests conducted on PNL-17 fuel pins by HEDL and ANL. The low power failure threshold is based upon PNL-1 and -2 fuel pins tested by HEDL.

HEDL 7409-69.4

FIGURE 23. Empirical Transient Overpower Fuel Failure Correlation.

FIGURE 24. Comparison of FTR Pin and EBR-II Irradiated Pins.

These results are in agreement with the following general features of the cladding mechanical property results previously discussed: the critical temperature region, 1000°F to 1600°F; the effect of transient rate and strain rate; and the effect of irradiation temperature.

Tests HOP 3-3C and H5 were conducted on sibling PNL-17 fuel pins with intermediate power-level fuel microstructure, but the transient rates were 3\$/sec and 50¢/sec, respectively. Although there was a large difference in transient rate, similarity in cladding temperatures at failure indicates that the loading must have been of the primary type. In that event, the real differences in cladding ductility in this temperature range, as determined by ex-reactor tests, would be insufficient to significantly affect the failure time and the apparent insensitivity to ramp rate would be explained. The fact that the faster transient actually failed at a slightly lower transient temperature is consistent with the fact that, relative to cladding temperature, the fuel melt front will advance further into the gas-bearing region of the fuel during the fast transient.

Since the ductility and load-bearing capability of the cladding is reduced most in the 1000°F to 1600°F region, fuel pin failures may preferentially occur here. Based on the ductility data in Figure 18, if a fuel pin undergoing constant strain rate loading does not fail in this region, it should not fail until about 2000°F.

4. Damage Parameter Correlation

The damage parameter correlation was developed because it became apparent that the enthalpy correlation did not satisfactorily correlate the data. To explain the problem with the enthalpy correlation, some background information on its usage is helpful. In practice, the trace of a particular transient in fuel enthalpy and cladding temperature would be superimposed on Figure 23, with failure conditions being determined by the intersection of the transient trace and the failure threshold line for the appropriate microstructure. It was theorized that rate effects (differences between fast and slow transients) would be reflected by fanning out of the

transient traces. A fast transient trace would be steeper, and would intersect the failure threshold line for the relevant microstructure at relatively high enthalpy and low cladding temperature, as compared to a slow transient trace.

Results of the ANL H4 test, in particular, did not seem to bear this out. Comparisons of calculated traces at similar axial locations for several ANL tests clearly showed that rate differences did not significantly affect the path of a trace. In fact, it can be seen in Figure 23 that the data points appear to fall more or less on a straight line with a positive slope. Apparently, rate effects are manifested in a different fashion than theorized.

A comparison of data from ANL H4 (50¢/sec) and E6 (3\$/sec) tests strongly suggested a trade-off between time and severity of conditions. Calculated transient traces at comparable axial locations for the H4 and E6 central pins followed essentially the same path. The major difference between the two tests was that E6 proceeded further along the path in less time than did H4.

Accordingly, a different approach to empirical correlation was sought, one which would incorporate time-into-transient as a primary parameter. A cumulative damage approach was chosen. It was reasoned that it was neither fuel alone nor cladding alone, but interaction between the two that was important. That interaction might be represented by the ratio between a parameter reflecting the transient driving force and one reflecting a relevant cladding structural property, the ratio being multiplied by a function of time into transient. Properly defined, such a correlation would assume the same value at the time of failure under all types of circumstances.

Considerable success has been experienced with the following formulation:

$$D.P. = \left(\frac{\Delta H_e}{Y} \right)_{\text{time averaged}} \left((a + C) \left(V_f \right) \left(t_t \right)^b \right) \quad \text{Equation (1)}$$

where,

D.P. = damage parameter

$$\left(\frac{\Delta H_e}{Y} \right)_{\text{time averaged}} = \frac{\sum_{i=1}^{i=n} \frac{\Delta H_{e_i}}{Y_i} \Delta t_i}{\sum_{i=1}^{i=n} \Delta t_i}$$

$$\Delta H_{e_i} = \sum_{j=1}^{j=i-1} (H_{j+1} - H_j) \exp \left(-d (t_i - t_j) \right)$$

ΔH_{e_i} = effective mean enthalpy upset of the non-columnar grains region over ith time step.

Y_i = yield strength over the ith time step, psi

Δt_i = length of ith time step, sec.

H_j = enthalpy upset at the beginning of jth time step, J/g

H_1 = base enthalpy

= steady state or threshold enthalpy, (412 J/g) whichever is greatest, for start of transient

H_{j+1} = same as H_j for end of jth time step, J/g

t_j = time into transient at end of jth time step
 t_i = time into transient at end of ith time step
 c = concentration of retained fission gas, cc/g
 V_f = volume fraction of gassy (non-columnar grains) region
 t_t = elapsed time into transient, sec.
 $a, b \& d$ = empirical constants
 = 1.0, 0.5, and 0.5, respectively

All of the failure mechanisms enumerated in Section III.C.1, with the exception of coolant boiling and cladding melting, are driven by thermal upset of the fuel. In the damage parameter correlation ΔH_{ej} , the effective mean enthalpy upset in the non-columnar fuel, is a measure of the thermal disequilibrium which drives the failure mechanisms. The cladding yield strength, Y , is a measure of the cladding's ability to survive the thermal upset without permanent damage.

Viewed in this context, the time averaged ratio $(\frac{\Delta H_e}{Y})$ is a measure of the propensity for cladding failure at any given time. That is, the probability of failure at a particular location during any time step is directly proportional to the thermal upset at that location and inversely proportional to the cladding yield strength at that location.

The term c , the concentration of fission gas, and V_f , the volume fraction of non-columnar grain fuel, are included to account for the fact that different steady state irradiation conditions produce different fission gas distributions.

Most of the time dependence and, therefore, rate dependence, enters the correlation by way of the term $t^{0.5}$. This term accounts for the experimentally observed trade-off between time into transient (or thermal rate) and final severity of condition at failure. Although this behavior was previously discussed in connection with H4 and E6, it is worth

emphasizing that tests with higher thermal rates, and hence shorter durations, proceed to relatively more severe thermal upsets at the time of failure. The time weighting factor $t^{0.5}$ accounts for this behavior.

The correlation is applied by calculating the parameters according to Equation (1) for several axial elevations and the entire time of the transient up to failure. The damage parameter is accumulated for each axial location and the value at the time and axial location of failure is noted.

The correlation has been applied to several prototypic TREAT tests. The upper portion of Table 22 shows the results for five tests (ANL tests H4, H5 and E6, and HEDL tests HOP 3-3C and HUT 5-3A) in which well characterized failures occurred. A failure criterion value of 0.38×10^{-2} for the damage parameter was obtained by averaging the values in Table 22 for the foregoing tests. The failure criterion value, possibly also the correlation formulation, may change as test analyses are refined, and as new test results are obtained.

The lower portion of Table 22 shows the results for two tests (HUT 5-5A and HUT 5-1A) in which identifiable failures did not occur. Both tests simulated 50¢/sec reactivity addition accidents. A low power microstructure pin (PNL 9-25, ~5 kW/ft) was tested in HUT 5-5A, and a high power microstructure pin (PNL 11-28, ~12 kW/ft) in HUT 5-1A. Although no identifiable failure occurred in either test, the results from both are useful in evaluating the correlation.

The results of HUT 5-1A are not inconsistent with the correlation. Postirradiation examination thus far has shown strong indications that the pin tested is very near failure; the failure parameter was calculated to be 0.3×10^{-2} as compared to the failure criterion value of 0.33×10^{-2} .

The results of the HUT 5-5A test are less positive. Postirradiation examination results thus far indicate little damage to the pin other than $\Delta D/D$ measurement of ~0.2%. Further evaluation of the

TABLE 22
TRANSIENT EMPIRICAL FUEL FAILURE CORRELATION RESULTS

Test	Steady State Linear Heat Rate	Burnup	Transient	Failure Time Sec. into Transient	Damage Parameter Value	% Deviation from Mean
	kW/ft	MWd/MTM				
H4	10.6	39,500	50¢/sec	0.94	0.360×10^{-2}	- 6.3
H5	8.1*	29,500	50¢/sec	1.4	0.364×10^{-2}	- 5.2
HUT 5-3A	8.1	49,000	50¢/sec	2.61	0.404×10^{-2}	+ 5.2
E6	11.5	42,600	3\$/sec	0.587	0.371×10^{-2}	- 3.4
HOP 3-3C	7.8*	28,300	3\$/sec	0.8	0.421×10^{-2}	+ 9.6
<hr/>						
HUT 5-1A	12.5	47,200	50¢/sec	3.425**	0.301×10^{-2}	-21.6***
HUT 5-5A	5.5	46,500	50¢/sec	3.08**	0.365×10^{-2}	- 4.9

*Linear heat ratings at beginning of life are given for the PNL-17 pins used in these two tests.

**Positive indications of failure were not received during test, and subsequent examination has yet to confirm failure for either pin. The time listed is that of the most severe conditions during the transient.

***Neither HUT 5-5A nor HUT 5-1A results were included in determination of mean value of parameter.

correlation on the basis of this test must await verification of the thermal transient when the experimental melt fraction has been determined.

There was no doubt that a failure occurred in ANL test F7. However, the location of the failure is not known precisely, and the time of the failure is uncertain in that it can be argued that the second failure event was more characteristic of such failures than the first. Additionally, the applicability of the correlation to E7 would be questionable, since the failure most probably occurred on a peripheral pin which was subject to a marked asymmetric power distribution. Accordingly, no results are quoted for test E7.

The correlation defined by equation (1) is preferred over the correlation presented in Figure 23 because the former correlation does the following:

- It predicts rate effects such as are indicated to exist by the cladding material behavior data previously presented, and are also discernible in TREAT facility transient pin tests.
- It provides a quantitative method for transition between microstructures that were treated as discrete jumps by the correlation in Figure 23.
- It predicts results that more closely agree with data than does the correlation presented in Figure 23.

In summary, the correlation defined by equation (1) is recommended for use in predicting time and location of failure of irradiated pins for transient overpower accidents, within the limitations discussed in a later section. The correlation is limited in scope, but is believed to be the most generally applicable available means of predicting failure conditions for the transient overpower accident.

5. Application And Limitation Of Damage Parameter Correlation

To apply the correlation, transient enthalpy and cladding temperature, as defined for the correlation, are computed as a function of time into the transient for several axial locations along the fuel pin. The steady state columnar grains radius, fission gas concentration and enthalpy can be computed from steady state irradiation data or for a hypothetical case, with the aid of codes such as SIEX.⁽¹⁹⁾ The value of the damage parameter is then computed as a function of time into the transient for each axial location. The failure time and location is bracketed by the axial location which reaches the criterion value of the damage parameter earliest, and by that adjacent axial location which has the next highest parameter value. A value of 0.380×10^{-2} is currently recommended as a failure criterion for the damage parameter.

The TREAT tests analyzed consisted of two parts; an initial portion wherein the power was held nearly constant for a few seconds (known as the flattop) to simulate the steady state temperature distribution of the fuel pin, and a portion with a sharp power increase (called the spike) to simulate the particular reactivity addition accident. In some cases, the steady state temperature distribution was significantly overshoot during the flattop. A two-part transient results in such cases when the correlation is applied strictly as formulated. The initial part of the transient (during the flattop) is relatively mild, with steady state temperature conditions being approached. During the spike however, temperatures accelerate sharply upward. When time-averaging is applied across both parts of the transient, the condition severity during the spike is artificially diluted. To ensure that application is consistent with other tests, the correlation has been

applied separately to the two portions of the transient for such tests, maintaining continuity only in the calculation of the effective enthalpy. The damage parameters calculated for the two parts of the transient are added to obtain the damage parameter for the test.

The correlation is subject to the following limitations:

- The correlation is not applicable to failure prediction for fresh fuel pins. The range of exposures for test pins to which the correlation has been applied is 30,000 to 50,000 MWd/MTM. As with any empirical correlation, extrapolation beyond the range of data, for which the correlation has been tested, is risky. Probably use in the range of 20,000 to 60,000 MWd/MTM would not significantly increase uncertainty.
- Application of the correlation to very complex transients; for example, transients with widely and erratically varying power multiplication periods would not be advisable. Applicability of the parameter, after fuel and cladding temperatures have peaked out, is questionable. It is recommended that increases in the parameter be disregarded after such has occurred.
- Use of the parameter to determine whether failure will occur or not has not been validated, but is to be investigated.
- The range of steady state linear power rates of pins for which the correlation has been tested is 6 kW/ft to 12.5 kW/ft, and use outside this range is not recommended. Additionally, this data base for the correlation includes only one truly low power microstructure pin (HUT 5-5A, PNL 9-25) and the validity of that experiment as a failure data point is still open to question.* Additional low power microstructure data is needed for validation of the correlation.

* No obvious signs of failure were noted in transient data for the test. At present, an incipient failure is assumed to have been achieved at the most severe conditions.

- Application of the correlation to accidents in which pin power is not the driving force, or even where it is not the only driving force, has not been established. The correlation is most probably not applicable in accidents that do not include a significant power ramp.

- The correlation is not applicable to radial power distributions with a maximum to minimum ratio exceeding about 2. Caution is advised in applying the relation to asymmetric power distributions.

- The correlation has not been validated for other than nominal FTR fuel pin geometry, cladding (316 SS, 20% CW), and fuel composition.

The average deviation between individual test damage parameters and the failure criterion was determined to be 6%, with a maximum deviation of 10%. In terms of failure time deviation, the average deviation was found to be approximately 20 milliseconds (0.020 seconds) for all transients. These deviations do not include the effects of uncertainties in the failure time and location observations nor in the calculated steady state columnar grains radius or retained fission gas concentration. The failure location is particularly uncertain in the case of ANL tests which are carried well beyond failure on a planned basis.

The data base is too small to warrant statistical treatment of uncertainties.

ACKNOWLEDGEMENTS

This compilation summarizes the work of several years by several organizations, in particular ANL, GE and HEDL. The results of truly significant work by many individuals is reported herein. Regretfully, it is simply not possible to recognize all such individual contributions, and so none has been singled out.

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APPENDIX A

SAFETY DEVELOPMENT PROGRAM FOR EVALUATION OF THE TRANSIENT OVERPOWER HYPOTHETICAL CORE DISRUPTIVE ACCIDENT

A.1 INTRODUCTION

Understanding the course and consequence of a hypothetical transient overpower (TOP) accident is dependent upon understanding the many phenomena attendant to such accidents. To achieve some degree of realism in modeling the TOP accident and predicting its results, a mechanistic approach has been adopted in the FFTF safety studies. To verify the postulated accident sequence and to resolve uncertainties in the understanding of basic phenomena influencing the TOP accidents, a broadly based experimental program has been initiated.

The experimental program in support of FFTF Safety Development not only emphasizes testing of prototypic FFTF fuel pins, but utilizes experimental data obtained from programs not directly related to the FFTF. Results of all testing programs will be found in Appendices C and D. The discussion in this Appendix will be limited to those programs which bear upon the failure behavior of mixed oxide fuel pins.

A.2 OBJECTIVES AND SCOPE

The principal objective of the FFTF safety development program in support of the TOP hypothetical core disruptive accident (HCDA) is to provide test data as input for the analysis of the TOP HCDA. Figure A-1 presents a generalized accident sequence following an arbitrary insertion of reactivity. The ultimate outcome of the accident, disassembly or benign shutdown with coolable geometry, depends in large measure on the time of fuel pin failure, the location of fuel pin failure, the failure type and the nature of fuel motion. Therefore, the specific tasks involved in the safety development program are:

- To verify models related to the pivotal areas of the accident sequence.

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FIGURE A-1. Transient Overpower Accident Analysis Sequence.

- To resolve remaining uncertainties in the accident sequence.
- To provide data for advanced modeling of important phenomena.

To accomplish these objectives an in-reactor experimental program has been instituted at ANL and HEDL. This program builds on the data from earlier experimental programs at Argonne National Laboratory, Hanford Engineering Development Laboratory, Battelle-Northwest and General Electric. The current program is divided into three experimental and phenomenological domains: The region defined by transients terminated by the plant protective system (PPS), transients not terminated by the PPS and proceeding to incipient failure, and finally, unterminated transients proceeding well beyond failure of the fuel pin.

In each of these experimental domains, experiments are being performed to investigate fuel pin behavior as influenced by the following parameters:

- Reactivity rates from 3¢/sec to 3\$/sec.
- Maximum linear heat rates from 6 to 12 kW/ft.
- Fuel pin burnups from 0 to 50 MWd/kg (fluence from 0 to 5×10^{22} nvt).

In the currently defined in-reactor testing program all of the tests are being conducted in the Transient Reactor Test (TREAT) facility.

A.3 PROGRAM DESCRIPTION

The program described in this section is being conducted both in-reactor and out-of-reactor. The in-reactor testing program is being conducted at two sites, HEDL and ANL, for the wide range of variables described in the preceding section.

The PPS terminated transients are being performed by HEDL and are designated the HEDL Over Power (HOP) series tests. The tests to the failure threshold are also being conducted by HEDL and are designated the HEDL Unterminated Test (HUT) series. All beyond failure tests are conducted at ANL and are designated E or H series tests, depending on the transient rate being simulated.

a) HOP Series Tests

The principal objective of the HOP series tests is to demonstrate by direct proof-test that the FFTF fuel pin meets all design and performance requirements under terminated transient conditions. The fuel pins used in this test series have been previously irradiated in EBR-II. The TREAT transients are specified so that the test provides excellent thermal simulation of specific FFTF transients. The test fuel pins are highly characterized prior to TREAT irradiation, and detailed post-test examinations are performed to determine the effect of the transient.

Table A-1 presents the various categories of FFTF abnormal events and describes the limiting transient for each category. A series of transient tests are being performed to simulate each limiting transient for various fuel pin conditions and steady state operating histories. A description of the HOP test series is presented in Table A-2.

It will be noted that for each accident category, except loss of electrical power (LOEP), tests are being performed for a variety of linear heat rates and maximum burnups. The 3\$/sec tests will be performed in NaK bonded static capsules, while the 3¢/sec and LOEP tests will be performed in flowing sodium test loops. All of the loop tests involve three irradiated fuel pins. The pins will be tested within individual flow tubes so that the pins are, to the maximum extent practical, thermally and neutronically isolated. This will ensure that the three subject pins receive the same transient.

In Table A-2 the tests HOP 3-2A, HOP 1-2A and HUC 1-2A are labeled (PTO). PTO is an abbreviation for Post Transient Operation and in tests so designated two of the three test pins will be returned to EBR-II for continued operation following transient irradiation, whereas the third fuel pin will be destructively examined to determine the effects of the transient.

TABLE A-1
ABNORMAL EVENT AND LIMITING TRANSIENT FOR FFTF

<u>Category - Severity</u>	<u>Selected Transient</u>
Steady State and Operational Transients	
Conditions within design range and expected changes	None
Operational Incident	
No loss of effective component lifetime	<10¢/sec ramp
Minor Incident	
Component damage within specified lifetime loss	total power loss
Major Incident	
Damage requires replacement	3\$/sec ramp
Design Base Accident	
Hypothetical event involving the primary barrier	None

TABLE A-2
HOP SERIES TEST DESCRIPTION

<u>Test Designation</u>	<u>Transient Simulation</u>	<u>Test Pin</u>		
		<u>Test Fuel Pin(s)</u>	<u>Heat Rate kW/ft</u>	<u>Burnup MWd/kg</u>
HOP 3-1A*	3\$/sec	ANL-A	12	8
HOP 3-2A*	3\$/sec	P-23A	12	21
HOP 3-2B*	3\$/sec	P-23A	12	44
HOP 3-3B*	3\$/sec	PNL-17	8 to 10	30
HOP 3-3D	3\$/sec	WSA-3	9	140
HOP 3-3E	3\$/sec	WSA-3	9	140
HOP 3-2A(PTO)	3\$/sec	P-23B/C(3)	12	30
HOP 1-3A	3¢/sec	WSA-3(3)	9	140
HOP 1-3B	3¢/sec	WSA-3(3)	9	140
HOP 1-2A(PTO)	3¢/sec	P-23B/C(3)	12	30
HUC 1-2A(PTO)	L.O.E.P.	P-23B/C(3)	12	30

*Tests completed as of 11/1/74

Relationship Of Tests To Failure Behavior

The HOP series tests do not directly relate to failure, or pin behavior at failure. The principal objective of this test series is to demonstrate that the performance requirements for the FFTF fuel pin can be met. However, it is likely that some information indirectly related to failure thresholds will be developed as a result of the post-transient destructive examination of the fuel pins, especially those subjected to more severe transients. In particular, the transient tested fuel pins will be examined to determine any changes in cladding dimensions, release of fission gas, or changes in fuel microstructures. If any or all of the above changes occur it may be possible to develop information relating to failure mechanisms, since failures are related to such changes.

b) HUT Series Tests

The primary objectives of the HUT series tests are:

- To define the fuel pin failure threshold as a function of linear heat rating, burnup, fluence and ramp rate.
- To study conditions in the fuel pin at or near the failure threshold.

In order to meet the second objective it is necessary to terminate the transient as soon as possible after fuel pin failure in order to minimize the thermal energy addition after failure. Since the failure threshold (first objective) in most cases is not precisely known, it is not always possible to terminate the transient at the optimum time. Early termination may not produce failure; late termination may result in significant energy deposition after interruption of cooling due to pin failure, with consequent wide-spread destruction of the fuel pin (and loss of potential post-transient examination data). For this reason it may be necessary to perform certain of the designated tests more than once.

As with the HOP tests, the test pins for the HUT experiments are preirradiated in EBR-II and encompass a wide range of burnups, fluences and linear test ratings. Table A-3 presents the HUT test description.

The NaK-bonded static capsule will be used to perform all the tests involving EBR-II irradiated fuel pins. A MK II-C flowing sodium test loop will be used to perform all tests involving 36-inch long fuel columns, either fresh or preirradiated in the GETR.

Anticipated Fuel Pin Failure Behavior

At least one of the tests in a given sequence of tests (HUT X-XA, B, C) will produce failure of the test pins. Other tests in the sequence will serve to confirm the observed failure threshold and provide post-transient examination data.

The results will define a heat rate, burnup and ramp rate dependent failure threshold for use in safety analyses. Further, the post-transient examinations will provide data relating to failure mechanisms and will provide data for modeling activities. In particular fuel morphology, fission gas distribution, porosity distributions and cladding effects will be noted. It is anticipated that the results of these tests will help to define the way in which cladding is loaded during a transient overpower event, and that a pronounced microstructural dependence of failure threshold will be exhibited.

c) E And H Series Tests

There are two important objectives in the ANL E and H series tests:

- To provide data on the behavior of fuel pin/coolant systems at times relatively long after fuel pin failure.

TABLE A-3
HUT SERIES TEST DESCRIPTION

<u>Test Designation</u>	<u>Transient Simulation</u>	<u>Test Pin Identification</u>	<u>Heat Rate (kW/ft)</u>	<u>Burnup (MWd/kg)</u>
HOP 3-3C*	3\$/sec	PNL-17	8 to 10	30
HUT 5-3A*	50¢/sec	PNL-10	9	50
HUT 5-5A*	50¢/sec	PNL-9	6	47
HUT 5-1A*	50¢/sec	PNL-11	12	47
HUT 3-3A	3\$/sec	PNL-10	9	50
HUT 3-5A	3\$/sec	PNL-9	6	47
HUT 3-1A	3\$/sec	PNL-11	12	47
HUT 3-L2**	3\$/sec	3 unirradiated 36-inch long fuel columns		
HUT 5-5B	50¢/sec	PNL-9	6	47
HUT 5-1B	50¢/sec	PNL-11	12	47
HUT 5-3B	50¢/sec	WSA-3	9	140
HUT 5-3C	50¢/sec	WSA-3	9	140
HUT 3-3B	3\$/sec	WSA-3	9	140
HUT 3-3C	3\$/sec	WSA-3	9	140
HUT 5-L4**	50¢/sec	(GETR)	13	70
HUT 3-L5**	3\$/sec	(GETR)	13	70
HUT X-L6**	TBD	(GETR)	13	70

*Complete as of 11/30/74
**MK-II Loop

- To provide data, through instrumentation, on the time and location of fuel pin failure.

Only the second objective is relevant to the discussion here.

In virtually every case the E and H series tests proceed well beyond failure, and as a consequence there is typically extensive melting and redistribution of fuel. Extensive realignments of geometry are instructive when studying post-failure effects, but tend to destroy the evidence related to the details of failure. Therefore, the ANL tests are used primarily to determine time of failure and, to the extent possible, the location of failure.

The fuel pins tested to date have been either EBR-II irradiated or fresh pins of the PNL-17 type. The heat ratings have varied from 6 to 11.5 kW/ft and the burnups from 30 to 60 MWd/kg.

All tests were performed in a MK II flowing sodium test loop. Table A-4 lists the test section geometry. Table A-5 presents the E and H series test description.

TABLE A-4
ANL E AND H SERIES TEST GEOMETRIES

<u>Test Designation</u>	<u>Transient Simulation</u>	<u>Quantity of Pins</u>	<u>Mix</u>
H2	50¢/sec	1	Fresh
H3	↓	7	1 Irradiated + 6 Fresh
H4	↓	7	1 Irradiated + 6 Fresh
H5	↓	7	1 Irradiated + 6 Fresh
E4	3\$/sec	1	Fresh
E6	↓	7	1 Irradiated + 6 Fresh
E7	↓	7	7 Irradiated
E8	↓	7	↓

TABLE A-5

ANL E AND H SERIES TEST DESCRIPTION

<u>Test Designation</u>	<u>Transient Simulation</u>	<u>Test Pin Identification</u>	<u>Heat Rate (kW/ft)</u>	<u>Burnup (MWd/kg)</u>
H2*	50¢/sec ↓	PNL-17	Fresh	Fresh
H3*		PNL-17	8 to 10	30
H4*		NUMEC F	11.5	42
H5*		PNL-17	8 to 10	30
H6		PNL-9	6	60
H7		GETR	13	30
E4*		PNL-17 type	Fresh	Fresh
E6*	3\$/sec ↓	NUMEC F	11.5	42
E7*		NUMEC F	11.5	42
E8*		PNL-10	9	40
E9		GETR	13	30

* Tests completed 11/1/74.

A.4 ANTICIPATED RESULTS AND APPLICATION TO FAILURE TECHNOLOGY

The results to date have demonstrated two things:

- Fresh fuel pins are extremely resistant to failure and have a failure threshold which is much higher than any other fuel type.
- There is a failure threshold microstructural dependence in that there is an observed relationship between equiaxed grain boundary and position of the solidus isotherm at the time of failure.

It is anticipated that these results will be borne out by continued testing and that fuel pin failure threshold can be directly related to the steady-state linear heat rate.

APPENDIX B

STEADY STATE FAST FLUX IRRADIATIONS*

B.1 DESIGN OF THE FFTF FUEL PIN

The FFTF fuel pin design and operating conditions are summarized in this section.

a) Description Of The FFTF Fuel Pin

Figure B-1 describes schematically the FFTF driver fuel pin. The 93.6 inch long fuel pin is clad with 0.230 inch diameter x 0.015 inch wall thickness, AISI type 316, 20% cold-worked stainless steel tubing. The tubing is wrapped with a 0.056 inch diameter 17% cold-worked type 316 stainless steel wire spacer having a pitch of 1 foot. The $(U,Pu)O_{1.96}$ fuel consists of dished-end pellets with an active core length of 36 inches and a fuel planar smear density of 85.5% of theoretical. The top end gas plenum provides a plenum-to-fuel volume ratio of 1.09. A total of 217 fuel pins are assembled into one 12 foot fuel assembly.

b) Operating Conditions Of The FFTF Fuel Pin

The FFTF fuel pin operating environment is summarized as:

Peak Hot Spot Cladding Temperature	1217°F
Peak Fluence	2×10^{23} n/cm Total
Operating Time	300 Full-power Days
Maximum Sodium Velocity	23 fps
Maximum Oxygen Level in the sodium	2.0 ppm

* A more detailed discussion of the steady state program will be found in the steady-state FSAR support document.⁽¹⁾

FFTF DRIVER FUEL PIN

FIGURE B-1. FFTF Fuel Pin.

Peak Linear Heat Rate	12.6 kW/ft
Max. Axial Coolant ΔT (Assembly)	380°F
Peak Burnup	80,000 MWd/MTM

These data correspond to a coolant inlet temperature of 600°F and a bulk coolant outlet temperature of 900°F (482°C). The design is such that operation at 800°F (430°C) coolant inlet temperature is not precluded. The design lifetime of the fuel assembly is 300 full-power days. However, 408 days at 75% availability are required to reach the peak design burnup of 80,000 MWd/MTM. The peak neutron flux is 7×10^{15} n/cm²-sec (total) or about 4.3×10^{15} n/cm²-sec $E > 0.1$ MeV.

B.2 STEADY STATE IRRADIATION PROGRAM

a) Organization

Concurrent with, and continuing after the design analysis, an irradiation test program was conducted in the U. S. to provide statistically significant data from prototypic fuel pin tests in EBR-II and to perform tests in TREAT to simulate design basis operational transients as well as hypothetical accident transients. By mid-1974 about 900 fuel pins, with 20% cold worked type 316 stainless steel cladding, had been irradiated or were being irradiated in EBR-II. About 600 reference design fuel pins in EBR-II have performed satisfactorily to peak fluences of up to 6.2×10^{22} n/cm² $E > 0.1$ MeV, (50% goal fluence) and peak burnups to 65,000 MWd/MTM (80% FFTF goal burnup). In addition, about 300 fuel pins with annealed type 304 or type 316 stainless steel cladding, representative of earlier FTR fuel pin designs, have reached peak fluences up to 1.2×10^{23} n/cm², $E > 0.1$ MeV, and peak burnups to 130,000 MWd/MTM (greater than 1.5 times goal burnup). About 900 other less prototypic fuel pins have also been irradiated and have reached burnup figures of up to two or more times the goal burnup. Several EBR-II test subassemblies have been denoted as "run-to-failure" tests to develop realistic failure criteria for steady-state operation.

The HEDL steady-state irradiation program in support of the FFTF fuel development program is organized into five basic categories. These are:

- 900°F bulk coolant outlet operation.
- 1100°F bulk coolant outlet operation.
- Fuel thermal performance limits.
- Irradiation-to-failure and beyond failure.
- Irradiation of vendor-produced fuels.

The initial FFTF design requirements were for operating conditions at bulk coolant outlet of 900°F. However, a major design criterion has been "not to preclude operation at 1100°F bulk outlet temperature." Thus irradiation tests have been included in the program with operating conditions, principally coolant and cladding temperatures, in the temperature ranges anticipated for the FFTF fuel pins when operating at nominal and rated bulk coolant outlet temperatures.

Another major criterion for the FFTF has been that no fuel melting shall occur under normal operating conditions. Tests to establish linear heat rating limits to fuel melting are being conducted to verify that this thermal performance limit criterion can be met in the FFTF without imposing restrictive operating conditions.

Achievement of the initial goal exposure irradiations, at the 900°F and 1100°F bulk coolant outlet operations, will confirm adequacy of the fuel design for these conditions. However, further definition of performance limits is required to establish the margins between goal and actual lifetime limits. A number of tests are being irradiated to failure for this purpose.

b) Scope

The scope of the steady-state irradiation program in support of the FFTF fuel development program includes irradiation tests conducted in the fast neutron flux Experimental Breeder Reactor-II (EBR-II) and in the thermal neutron flux General Electric Test Reactor (GETR). The irradiation tests are designed to provide statistical confidence in application of results to correlation of test parameters, prediction of fuel performance

in FFTF, and formulation of bases for selection of optimized mixed-oxide fuel pin designs. Post-irradiation examinations include mensuration, neutron radiography, gamma-ray spectroscopy, pulsed eddy current, metallography, burnup analysis, fission gas analysis, autoradiography, electron microscopy and microprobe analysis, chemical analysis of cladding and wire wrap and determination of mechanical properties of the irradiated cladding.

Fuel pin performance under steady-state conditions is determined by a complex interrelationship of fabrication parameters such as fuel density, form and chemistry, and cladding characteristics, such as mechanical properties and radiation-induced swelling. Pin performance is also influenced by operating variables such as fuel burnup, linear heat rate, cladding temperature and fluence. Capability of the reference FFTF fuel system to perform reliably and predictably throughout its design lifetime must be demonstrated with a high degree of confidence through testing of prototypic FFTF fuel pins. Knowledge of fuel performance must be sufficient to enable prediction of fuel and cladding behavior at the burnup and fluence levels anticipated in the FFTF at reactor coolant exit temperatures up to 1100°F. Continued emphasis is therefore placed on irradiation testing of statistically significant numbers of test fuel pins over a range of applicable variables, and on systematic analytical evaluation of the effects of these test parameters on pin performance. Failure thresholds and mechanisms at protracted fuel exposures must be determined for assessment of design margin-to-failure. Additional irradiation testing being performed will compare the performance of vendor-produced FFTF fuel pins to HEDL-fabricated fuel pins to assure that the data obtained to date from the HEDL-fabricated fuel pins are applicable to the FFTF core. Vendor-produced fuel pellets will be irradiated under various conditions of power, temperature and burnup to evaluate thermal performance and dimensional stability characteristics. Fuel pins containing vendor-produced fuel will be irradiated at high cladding temperatures to higher exposures to evaluate fuel-to-cladding chemical compatibility. Additional prototypic HEDL test pin assemblies will be irradiated to supplement performance data on fuel pin-to-bundle mechanical interaction, vibration and

wear, and fuel performance during exposure to FFTF goal burnup. These fuel pins will also provide a source of irradiated pins for run-to-failure and run-beyond-failure testing activities in this program. Instrumented fuel pins will be irradiated to further reduce uncertainties in the prediction of thermal performance capability of FFTF fuel pins.

Specific items of fuel pin performance to be evaluated for the 900°F and 1100°F operating conditions are:

- Fuel pin mechanical behavior in bundles, such as propensity for vibration and/or wear against one another.
- Fuel-pin-bundle-to-duct mechanical interaction. Wire wrap ability to maintain separation of fuel pins.
- Adequacy of wire wrap to end cap welds and end cap to cladding welds.
- Amount of fission gas released from fuel into fuel pin plenum. (Measure of plenum gas pressure and gas retained in fuel).
- Cladding mechanical strain.
- Irradiation swelling in cladding.
- Fuel restructuring (size of central void, columnar and equiaxed grains).
- Fuel dimensional stability (fuel densification and gap closure).
- Cladding wastage allowances,
 - Fabrication tolerances
 - Undetected defects
 - Coolant-to-cladding chemical interaction
 - Fuel-to-cladding chemical interaction
 - Cladding wear.
- Chemical interaction between fission produced cesium and fuel pin insulators.
- Verification of fuel pin and subassembly thermal/hydraulic calculations.

Irradiation tests are being conducted in 37-pin and 61-pin subassemblies to evaluate these performance items.

- Determination of the linear power at which fuel melting occurs as a function of fuel pellet-to-cladding gap size and fuel exposure.
- Measurements of pellet-to-cladding gap closure rate as a function of fabricated gap size, heat rate and fuel burnup.

The items to be evaluated in irradiation-to-cladding breach, and irradiation beyond cladding breach tests, are:

- Margin to failure (burnup beyond FFTF goal burnup).
- Fuel pin failure location (plenum of fuel region).
- Influence of failure on surrounding pins.
- Fuel-to-coolant interactions over short and long term residence following failure.
- Techniques for detection and location of failed fuel pins.
- Extent of fuel and fission gas release from failed fuel pins.

The irradiation tests of vendor-produced fuels are intended to evaluate:

- If any unanticipated fuel performance characteristics are introduced by the vendor process.
- The thermal performance characteristics of vendor-produced fuel as compared to the HEDL-produced fuel.
- Chemical interaction between cladding and vendor-produced fuel.
- Low power, low burnup fuel column dimensional stability and fuel restructuring.
- Fission gas release from the fuel to the fuel pin plenum.

Irradiation tests of the vendor-produced fuels are conducted in capsules in the GETR, and as 37-pin subassemblies in the EBR-II.

B.3 SUMMARY

Results from the steady-state testing program to date have been analyzed and now allow greater burnup capability to be reliably predicted for FFTF fuel because:

- Fuel pin performance has exceeded the lower limit prediction of design.
- Cladding wastage was demonstrated to be significantly less than assumed in design, such that it now appears that the FFTF fuel pin can reach at least 80,000 MWd/MTM peak burnup, with peak cladding temperatures up to at least 1250°F.
- Steady-state fuel pin lifetimes have been predictable, and all failures in the unencapsulated run-to-failure pin tests have been very small pinholes.
- Advances in transient testing technology now permit accurate simulations of FFTF transients to demonstrate the design adequacy of the fuel pins to accommodate Plant-Protective-System-terminated transients, as well as to define realistic failure criteria for transient operation. Initial tests at TREAT show a substantial margin-to-failure for Plant-Protective-System-terminated transients.
- Analyses of both steady-state and transient irradiation test data indicate that the FFTF fuel pin will perform satisfactorily for the FFTF heat rates and design basis transients to burnups in excess of 80,000 MWd/MTM.

REFERENCES FOR APPENDIX B

- (1) Fuels Department Staff, HEDL Steady-State Irradiation Testing Program - Status Report, HEDL-TME 75-48, October 1975.

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