HEDL-SA-1743 FP

CONF-790816--6

RESPONSE OF FFTF CORE TO PROTECTED REACTIVITY ADDITION TRANSIENTS

MASTER

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August, 1979

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ANS/ENS International Meeting on
Fast Reactor Safety Technology

August 19-23, 1979 Seattle, Washington

HANFORD ENGINEERING DEVELOPMENT LABORATORY
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Energy Contract No. EY-76-C-14-2170

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ABSTRACT

The response of the FFTF core to protected reactivity insertion events was evaluated. Reactivity addition transients ranging from .05¢/s to 3$/s have been considered. The evaluation method is based on a calculational model which predicts cladding strain from modified fuel-cladding differential thermal expansion. The results show that for all ramp rates considered, the Plant Protection System (PPS) controls consequences to required limits. Comparisons made between predicted fuel damage and results of TREAT transient tests support the conservatism of the results.

INTRODUCTION

This paper presents a design evaluation of FFTF reactor fuel pin response to a broad range of reactivity addition events with the objective of demonstrating the effectiveness of the FFTF Plant Protection System (PPS). Previously such events were evaluated assuming gas pressure loading of the cladding; these evaluations presented in this paper used a modified fuel-cladding differential expansion model. The results of application of the model to Transient Reactor Test (TREAT) tests are presented to demonstrate the conservatism of the model.

FUEL PIN DESIGN REQUIREMENTS AND ACCEPTANCE CRITERIA FOR TRANSIENTS

Even though fuel pins are specifically excluded from ASME code applicability, structural design requirements (Table 1) for FFTF fuel pins are generally consistent with Section III of the ASME Boiler and Pressure Vessel Code. For routine steady state, including normal startup, shutdown, and operation of FFTF, cladding structural integrity (i.e., retention of fuel and fission products) must be maintained over the design range of operating conditions. Similarly, cladding integrity must be maintained with no significant loss of fuel pin lifetime during operational transients including scrams. The fuel pins must also withstand one emergency event or unlikely fault (e.g., pump mechanical failure or loss of all electrical power) and maintain cladding integrity. The final structural design requirement is concerned with faulted conditions or extremely unlikely faults. Such conditions are not expected, but are identified as hypothetically limiting faults for design purposes. The allowable limit for such conditions (for FFTF, a 3$/sec reactivity insertion and a Design Basis Earthquake) is beyond the cladding integrity limit, but requires a "coolable geometry" such that damage will not propagate or endanger permanent FFTF components.

Acceptance criteria for transient events are based on an overall cladding integrity limit corresponding to 0.7% permanent cladding deformation calculated according to the FCF-213 design procedure.[1] Based on the 0.7% limit, a calculated value of 0.2% strain was selected to cover steady-state operation. An additional calculated 0.1% strain (i.e., a total of 0.3%) was allocated to cover anticipated events and operational transients. The remaining 0.4% strain increment was then available to cover a single unlikely event even at the end of fuel pin design life.

ANALYTICAL MODEL

All reactivity insertion events were analyzed using the MELT-III[2] computer code which is a fast reactor, multichannel, thermal-hydraulics, neutronics accident analysis program designed to simulate reactor transient behavior. In addition to the analytical modesl used in the MELT-III computer program, the FCF-213 design procedure model for reactivity addition is interfaced with MELT-III code to allow for direct calculation of cladding strain.[3]

TABLE I

FUEL PIN DESIGN REQUIREMENT AND TRANSIENT ACCEPTANCE CRITERIA

Category	Type Event	Requirement	Examples	Acceptance Criteria
Normal Operation	Steady State	Maintain Cladding Integrity to Design Lifetime	Steady State Operation	0.2% Cladding Strain
	Operational Transients		Startup and Shutdown	
Upset	Operational Incident	Maintain Cladding Integrity to Design Lifetime	Scram; Loss of Power to One Pump; Reactivity Insertion ~3¢/sec	0.1% Cladding Strain
Emergency	Minor Incident	Maintain Cladding Ingegrity	Loss of All Electrical Power; Reactivity Insertion ~10¢/sec; continuous flow reduction	0.4% Cladding Strain
Faulted	Major Incident	Maintain Coolable Geometry	Design Earthquake	
			Reactivity Insertion <3$/sec	

The reactivity addition model is a volume accountability procedure. The fission gas in the fuel region (sealed in the fuel at the onset of a TOP event) is accommodated by the volume available inside the cladding after subtraction of fuel volume, non-sintered fuel porosity and solid fission-product swelling. The increasing pressure of the included gas is assumed to be transmitted uniformly and undiminished to the cladding inside surface. A dynamic balance is established between cladding strength and gas pressure loading as the cladding deforms, partially accommodating the gas pressure. The gas pressure increase is caused primarily by reduction of volume due to fuel thermal and fusion expansion; hence, the model is basically differential thermal expansion between fuel and cladding.

The acceptance criteria are a part of the FCF-213 design procedure (which also includes specific material properties and other performance models) and are to be compared only with strain calculated according to the design procedure. Comparison of either criteria or calculated strain with observed strain for prototypic fuel pin cladding is inappropriate. Application of these criteria is shown to be conservative in terms of predicting cladding failure by the results of TREAT tests.

INPUT PARAMETERS AND MAJOR ASSUMPTIONS

In analyzing protected reactivity insertions, two important parameters which merit consideration are the total time required to insert the control rods and the associated reactivity worth of the rods. In the FTR, there are two independent shutdown systems: the Primary Reactor Shutdown System (PRSS) with three safety rods and the Secondary Reactor shutdown System (SRSS) with six control rods. Either system is capable of terminating design basis events to within allowable limits. The reactivity worth of the primary control rods was determined assuming the maximum worth rod to be stuck in the full out position. This results in a primary system worth (for two rods) of 3.2% k/k. The position of the secondary rods and thus, the secondary reactivity insertion tables, vary with reactor state (low power, full power or low power physics testing), but in all cases conservative values were used. A scram reactivity insertion is shown versus time in Figure 1.

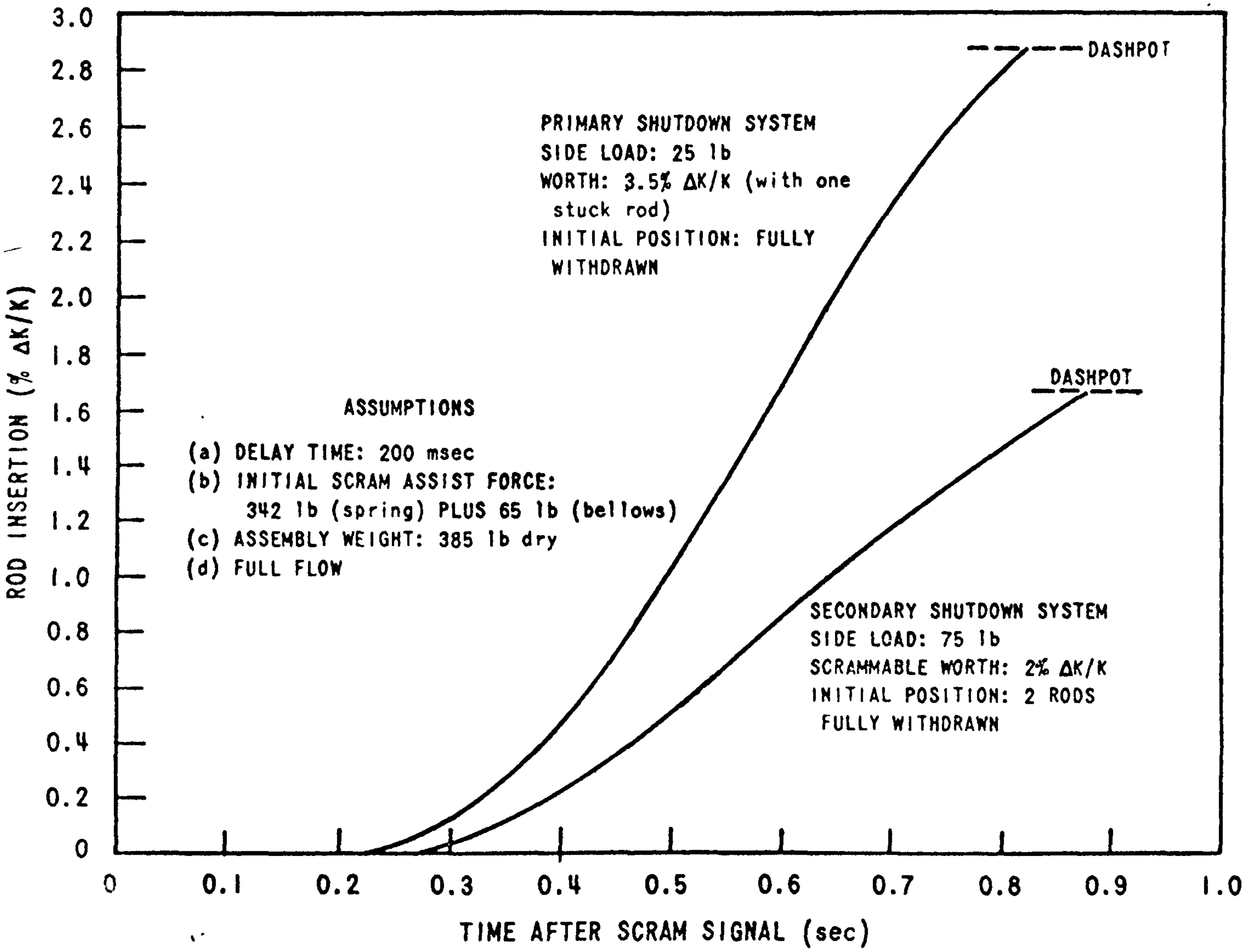

FIGURE 1 - Rod Insertion Versus Time Characteristics for Reactor Shutdown System.

For both primary and secondary scrams, a time delay of .2 seconds between the scram trip and initial rod insertion was employed to account for magnetic field decay of the rod latching mechanism and plant protective system electronic-circuitry delay. The measured delay time is aprpoximately 85 ms.

The subassembly that was modeled corresponded to the central core assembly in the FFTF beginning-of-life (BOL) core, and is the peak power channel. Only 80% of the total Doppler feedback and 100% of the full sodium void and fuel worths were assumed. The major input parameters are listed in Table II.

The reactor power was assumed to be at 408 MW allowing for a 2% controller dead bnad. The nominal reactor inlet temperature was 633 °K ± 8°K, and the nominal coolant flow was 120.18 ± 4.33 gm/s for each pin in the peak channel. The low bound of inlet temperature (625°K) and higher coolant flow (124.51 gm/s) are used in the strain analysis to ensure conservative results. The subsequent low cladding temperature limited the cladding expansion and reduced the void volume available. The resultant increased gas pressure caused maximum cladding strain. The fuel-cladding as fabricated gap was 0.1 mm., corresponding to the statistical minimum as-fabricated gap size consistent with maximum allowable fuel density. Because of fissile fuel maldistribution, uncertainties due to power level measurements and nuclear power distribution, the heat flux of the peak subassembly was increased by 10.8%, which represents the statistical sum of the above three subfactors. All the subfactors mentioned above either decreased the void volume inside the cladding or increased the heat flux. Consequently, maximum calculated cladding strain was assured. The conventional method of using hot channel factors was also applied and relevant input parameters were changed in the calculation of maximum cladding temperature.

RESULTS AND DISCUSSION

The analyses reported here were made for the 680°F inlet coolant temperature condition. Termination of the transients by both the primary

TABLE II

INPUT PARAMETERS FOR REACTIVITY INSERTION EVENTS

Parameter	Value *
Steady State:	
Reactor Power (2% dead band inc.)	408 MW
Coolant Flow Rate (peak channel)	124.51 gm/sec (103.6% of normal)
Coolant Inlet Temperature	680°F ± 15°F
Burnup	80 MWD/kg
Gas Gap (distance between fuel and clad)	.0039 in.
Fuel Density	91.01% of theoretical density
Average Pin Heating Rate (peak channel)	10.51 Kw/ft
Maximum Pin Heat Rate (peak channel)	12.78 Kw/ft
Maximum Hot Pin Heating Rate (maximum pin with hot channel heat flux factors)	14.14 Kw/ft
Transient:	
Power Level Scram Trip	464 MW 500 MW (.05¢/sec insertion only)
Time Delay (between reactivity insertion and scram trip)	0.2 sec
Doppler Coefficient	-.004 Tdk/dt
Sodium Expansion Feedback Coefficient	-1.0×10^{-6}/°F (EOL)
All other Feedback Terms	0

* To be converted to SI units.

and secondary shutdown systems has been considered. A summary of the results is provided in Table III.

It is significant to note that a fast transient with a ramp rate of a few dollars per second, a step insertion event and a slow transient with ramp rate of a fraction of a cent per second all induce additional calculated cladding strain. The latter is due to the large energy release caused by the long duration of the slow transient. The resulting differential thermal expansion of the fuel-cladding subsequently causes the inelastic cladding strain. The 3$/s reactivity insertion terminated by the secondary shutdown system at end-of-life was predicted to result in additional 0.24% cladding strain assuming pre-transient strain of .3% However, if no pre-transient strain were assumed, the resultant cladding strain due to the above transient is .65%, which is below the .70% limit. The hot channel cladding temperature history and the permanent cladding strain history areshown in Figure 2 for the 3$/s transient. For the case of loss of hydraulic balance, for which no realistic mechanism has been identified as an initiator, 76 irradiated assemblies were hypothesized to rise and later fall back into place; the evaluation showed that no cladding failures would be expected. The control rod withdrawal at minimum speed terminated by the secondary shutdown system is an unlikely event since the primary trip function was assumed to have failed. The calculated cladding strain for that event is 0.14% which is below the 0.7% strain limit. In all events analyzed, fuel melting is not predicted except for the hypothetical 3$/s transients. In this case, a real fuel melting of 6% and 25% was calculated for the transients terminated by the primary and secondary shutdown system respectively.

COMPARISON OF DESIGN PROCEDURE PREDICTIONS AND EXPERIMENTAL DATA

Two types of TREAT transient overpower (TOP) tests have been performed: cladding integrity limit tests, in which a reactivity ramp rate is continued to fuel pin cladding failure; and "terminated" tests, in which fuel pins are subjected to simulations of events terminated by the secondary

TABLE III

ADDITIONAL CALCULATED CLADDING STRAIN AND CLADDING TEMPERATURE IN HOT PIN FOR REACTIVITY INSERTION EVENTS*

INCIDENT	STRAIN (%)	TEMPERATURE (°F) **	
		Inside Cladding	Fuel Centerline
1. Continuous Control Assembly Withdrawal at Low Power (5 watts)			
a. 0.05¢/sec or less	0	≤ 538	≤ 689
b. 4.1¢/sec	0	519	616
c. 29¢/sec	0	575	826
2. Continuous Control Assembly Withdrawal at Full Power			
a. 0.05¢/sec or less	≤ 0.14	≤1420	≤4842
b. 3.4¢/sec	0	1317	4829
c. 24¢/sec	0	1280	4580
3. Loss of Hydraulic Balance to Fuel Assemblies (1.25$ in .09 sec)	0.18	935	1702
4. Single Fuel Assembly Meltdown (2.88$/sec, 72¢ Total)	0.13	1362	4937
5. Closed Loop Section Meltdown (1$/sec, 24¢ Total)	0	1291	4669
6. Cold Sodium Insertion (4.2¢/sec)	0	1307	4819
7. Single Control Assembly Meltdown (3$/sec used)	0.65	1470	25% Areal Melting
8. Radial Displacement of Fuel Assemblies (35¢ step insertion)	0	< 1362	< 4937
9. Sodium Voiding (7¢ step insertion)	0	1309	4602

* These events were terminated by the secondary shutdown system.

** To be converted to SI unit.

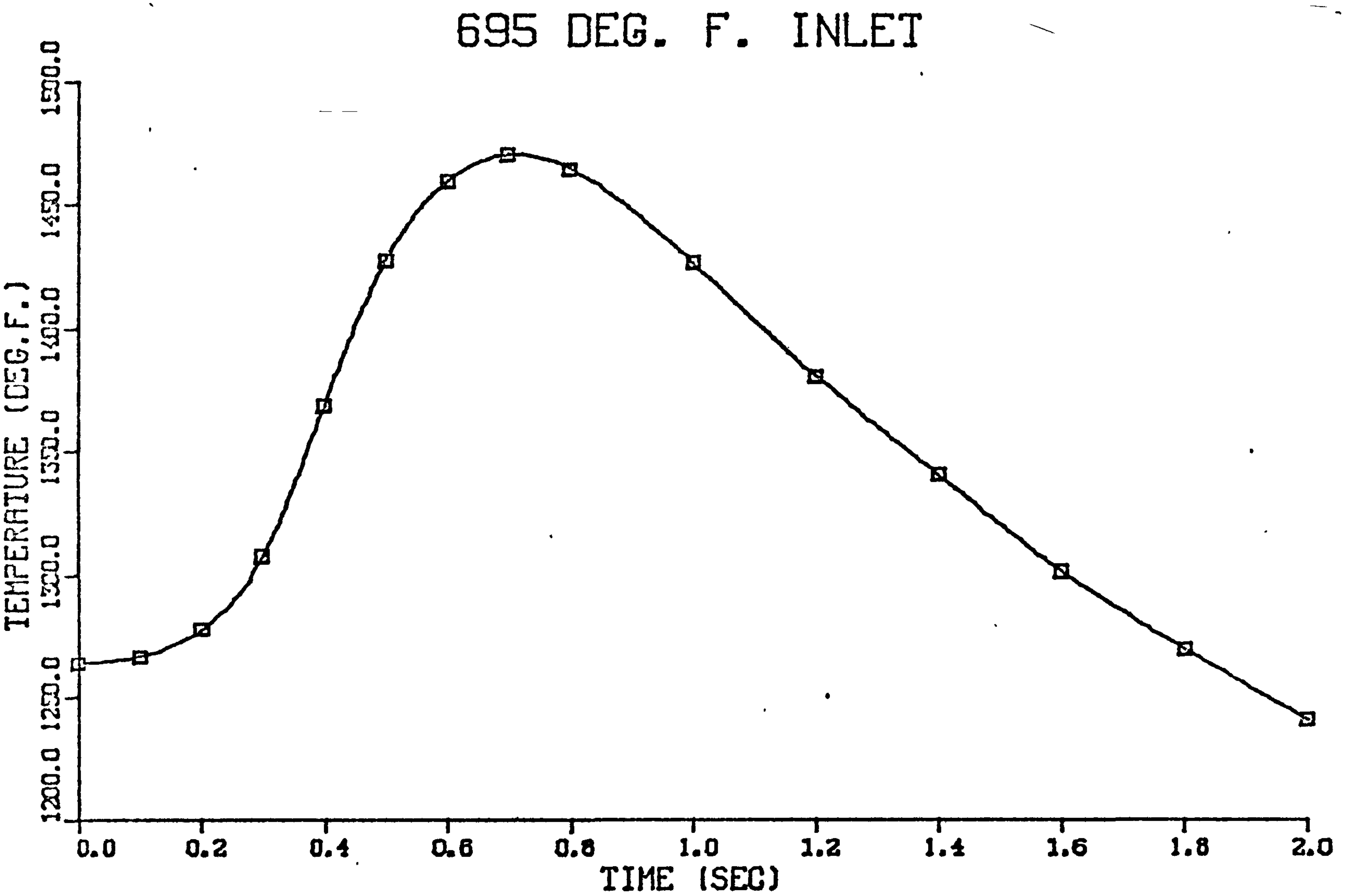

FIGURE 3A MAXIMUM CLADDING TEMPERATURE, SINGLE CONTROL ASSEMBLY MELTDOWN (3$/sec ASSUMED)

* To be converted to SI unit.

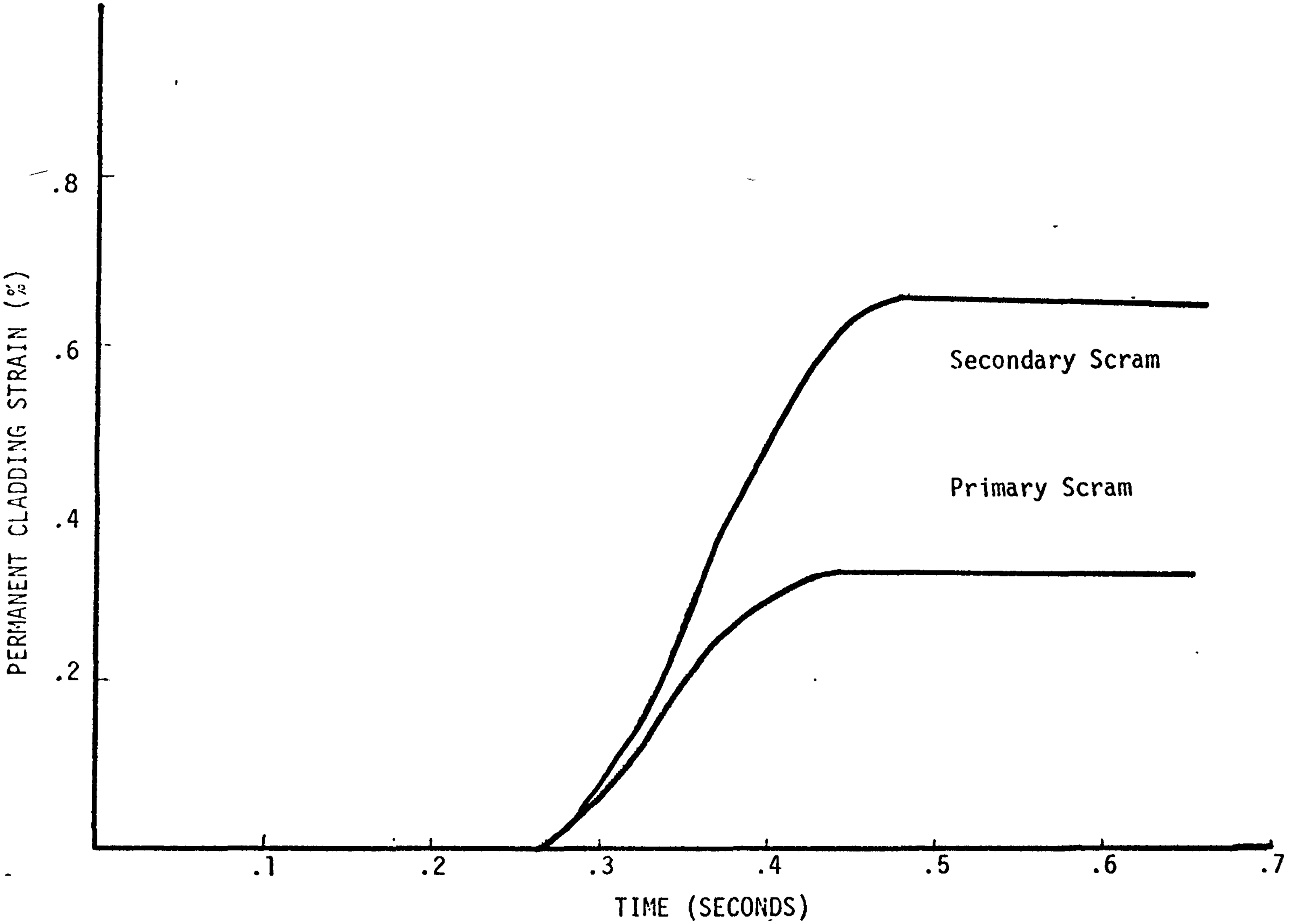

FIGURE 3B COMPARISON OF PRIMARY AND SECONDARY SCRAM FOLLOWING A 3$/SEC REACTIVITY INSERTION scram function of the PPS. The former tests provide data on failure thresholds, and provide a measure of the conservatism of design procedure TOP failure predictions. The latter tests can provide data relevant to the 0.1% incremental strain criterion for upset events.

In the TREAT tests, in general, the test assembly was taken to a predetermined temperature profile by electrical heaters. Then a two-part TREAT power transient was applied. The power was increased rapidly to a predetermined level and held constant at that power for a few seconds to achieve a simulation of steady-state fuel and cladding temperature distribution. (This period is known as a flat-top period). At the end of the flat-top, a power ramp designed to provide thermal simulation of the design reactivity insertion rate was applied.

The design procedure was applied to eighteen cladding integrity tests and to ten terminated tests.[4]

The results of the cladding integrity tests and of two of the terminated tests are summarized in Table IV-A (The two terminated tests included in Table IV-A were inadvertently overpowered, and the results of these tests are relevant only to cladding integrity.) As can be seen from Table III-A, the predicted failure time for the cladding integrity tests was invariably earlier than the observed failure times. For the two overpowered terminated tests, failure was predicted but not observed.

The test results of the six terminated tests to which the design procedure was applied are shown in Table IV-B. No measurable strain was observed in any of these tests. However, since for most tests, cladding strain was not predicted, no conclusion can be drawn from these results concerning the conservatism of the design procedure.

CONCLUSION

The above results show that the FFTF PPS can handle a very wide range of limiting postulated reactivity insertion events with ramp rate

TABLE IVA
COMPARISON OF PREDICTED AND OBSERVED FAILURE TIMES FOR CLADDING INTEGRITY LIMIT TESTS

Experiment	Fuel Pin	Predicted Failure Time Seconds into Spike	Observed Failure Time Seconds into Spike
HOP 3-3C*	PNL 17-34	0.65	0.80
HUT 5-7A	PNL 9-25	2.76	No Failure
HUT 5-7B	PNL 9-34	3.53	4.72
HUT 5-5A	PNL 10-17	2.70	3.25
HUT 5-2A	PNL 11-28	2.76	No Failure
HUT 5-2B	PNL 11-15	2.51	3.62
HUT 3-7A	PNL 9-45	0.65	No Failure
HUT 3-7B	PNL 9-54	0.74	0.94
HUT 3-2A	PNL 11-47	0.58	0.70
HUT 3-5B	PNL 10-42	0.49	No Failure
HUT 3-6A	WSA 3-35	0.40	0.54
HUT 3-6B	WSA 3-28	0.46	0.63
HUT 5-5B	PNL 10-72	3.25	No Failure
HUT 3-5A	PNL 10-20	0.56	No Failure
HUT 5-1A	P-14-309	2.91	3.78
HOP 3-1B	P-23A-27	0.42	No Failure
HOP 3-2C	P-23A-30	0.43	No Failure
H4	NUMEC-F-051	0.62	0.94
H5	PNL 17-25	1.78	1.9
E6	NUMEC-F-056	0.41	0.59

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*Lead Experiment of HUT Series.

TABLE IV B

TERMINATED TESTS

Experiment	Fuel Pin	Results
HOP 3-2B	PNL 17-21	Max. Strain Predicted: 0, Observed: 0
HOP 3-1A	ANL-A-EW13	Max. Strain Predicted: 0, Observed: 0
HOP 3-1B	P-23A-27	Max. Strain Observed: 0.4%
HOP 3-2C	P-23A-30	Max. Strain Observed: 0.3%
HOP PTO 1-2A*	P-23B-22A P-23C-17A P-23C-52C	Max. Strain Predicted: 0, Observed: 0
H3**	PNL 17-24	Max. Strain Predicted: 0.2%, Observed: 0

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* Multiple Transient Test Sequence: Four Tests Simulating 3¢/sec Reactivity Insertion Event Terminated by the Secondary PPS.

**ANL Test.

up to 3$/sec at 633°K inlet condition and can hold the consequences of all incident categories to the required limits.

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