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MEMORANDUM FOR: E. G. Case, Acting Director
Office of Nuclear Reactor Regulation

R. B. Minogue, Director
Office of Standards Development

FROM: Saul Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER - #29 FUEL ROD ANALYSIS COMPUTER CODE: FRAP-T3

Introduction and Summary

This memorandum transmits the results of completed research to prepare and test the third modification of the computer code FRAP-T (Fuel Rod Analysis Program - Transient). FRAP-T is a FORTRAN IV computer code being developed to predict the transient response of a LWR fuel rod during postulated accidents such as Loss-of-Coolant Accidents (LOCA), Power Cooling Mismatch Accidents (PCM), Reactivity Initiated Accidents (RIA), or Inlet Flow Blockage Accidents (IFB). FRAP-T is also being developed to perform the calculations needed for planning and analyzing Power Burst Facility (PBF) and Loss of Fluid Test (LOFT) experiments. Although the code calculations are made on a best estimate (BE) basis, substitution of alternate models and correlations could be easily made to make evaluation model (EM) calculations. FRAP-T3 is the third annual update of the code and as such provides a relatively mature analytical capability. Improvements upon FRAP-T2 are primarily in the area of cladding behavior. Aspects of various versions of the code are shown in Table I.

The importance of improving our fuel behavior codes is recognized in a series of user requests: REG:RSR-88, "Fuel Pin Analysis Development," dated March 14, 1973; REG:RSR-118, "Regulatory Need for Additional Safety Research on Reactivity Initiated Accidents," dated November 21, 1973; Section 6.8 of the "Regulatory Assessment of the AEC Water Reactor Safety Research Program," dated August 12, 1974; "Review of Fuel Behavior Project Description," dated May 6, 1975; "NRC/NRR Technical Safety Activities Report," dated September 11, 1975.

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These user requests are for analytical models, tested against data, which will predict fuel failure and failure propagation thresholds in power reactors. A calculational tool is also needed to interpret PBF, LOFT and Halden experiments, to provide audit capability for vendor codes such as STRIKIN-II, FACTRAN, LOCTA-IV and THETA, and to support specific SD and NRR activities. This memorandum and its enclosures describe the FRAP-T3 code, its testing and our evaluation of its applicability and capability.

Results - Code Features

In FRAP-T3 the coupled effects of mechanical, thermal, internal gas and material property response on the behavior of the fuel rod are considered. Given appropriate coolant condition and power histories, FRAP-T3 can calculate rod behavior for a wide variety of off-normal situations and postulated accident conditions (e.g., BWR or PWR power transients, flow coastdown, load loss or coolant depressurization). Further details of code features (e.g., models, input requirements, output parameters) are given in Appendix B.

Results - Code Qualification

An essential part of producing an operational computer code, which can be used with a known degree of confidence, is the independent testing process (described on pages 257-267 of Appendix C). The results of such testing of FRAP-T3 are as follows. Figure 1 compares measured and predicted centerline fuel temperatures for unpressurized rods. The good agreement, generally within 10%, suggests that heat transfer is well represented by the MacDonald-Broughton ("cracked pellet") gap conductance option which was used for these calculations. Figure 2 indicates a similar comparison for rods prepressurized with helium, showing less satisfactory agreement. However, a second FRAP-T3 gap conductance model is available, following Ross-Stoute, and this option provides good thermal predictions for prepressurized rods.[1] Figure 3 shows predictions of plenum gas pressure. Most of the high pressure results fall within 10% of the measured values. Accurate prediction of this pressure is important to the ballooning behavior of fuel rods in a hypothetical LOCA. Figure 4 compares single rod PBF (annulus geometry) test data with calculations using two of the Critical Heat Flux (CHF) options which are available to FRAP-T3. Lack of a better fit may be accounted for by peculiarities of the PBF test train configuration (e.g, standoff screws and flow area). Figure 5 shows fuel temperature response following scram. An adequate

[1] TFBP-TR-186, "Gap Conductance Test Series, Test GC1-3, Test Results Report and Summary of Piggyback Tests," March 1977.

calculation of the dissipation of stored energy and decay heat immediately after scram is especially important for analyzing accident situations. Finally, Figure 6 compares results of a standard problem run with FRAP-T and with the German code SSYST. An agreement between these two independent codes implies some validity of the code predictions.

Evaluation

In the context of LWR system transients, FRAP is well suited to be used as a component code to describe fine details of fuel rod behavior. Furthermore, sensitivity studies with FRAP will facilitate definition of the simplest acceptable fuel description in systems codes. Substantial effort has gone into FRAP-T3 to make it a mechanistic and sophisticated code. The independent testing process has shown that several new models and subcodes, some of which are unique to FRAP-T, are important to making realistic calculations. These include the material properties package[2], the failure subcode[3], three dimensional cladding ballooning, a complete heat transfer correlation package, a transient plenum temperature model and an axial gas flow model. The material properties package and the failure subcode have been well received by the Fuel Code Review Group. Quantitative characterization of the uncertainty associated with parameters predicted by FRAP-T3 (e.g., plenum pressure, fuel centerline temperature, cladding ballooning or burnout power) has been made, and representative samples are shown in the figures.

Developments are continuously underway to remove some of the present limitations of applicability of FRAP-T3 and these developments will be incorporated in future versions of FRAP as new research data and modeling permits.

FRAP-T3 has been transmitted to the Argonne Code Center and is programmed and running on the CDC 7600 computers at INEL (Idaho), Berkeley (California) and Brookhaven (New York). We would be happy to assist your staff in running any of the FRAP standard problems listed in Table II in order to directly demonstrate the code's capability.

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[2]TREE-NUREG-1005, "A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior," December 1976.

[3]TFBP-TR-189, "FRAIL 3: A Fuel Rod Failure Subcode," April 1977.

28-610

Appendices

Appendix A contains the six figures and two tables referred to in the text. Appendix B provides a succinct description of code features and some comments concerning use of the code. Appendix C, report TFBP-TR-194, "FRAP-T3- A Computer Code for the Transient Analysis of Oxide Fuel Rods," provides detailed descriptions of the code and its testing.

Saul Levine

Saul Levine, Director
Office of Nuclear Regulatory Research

Enclosures: As stated

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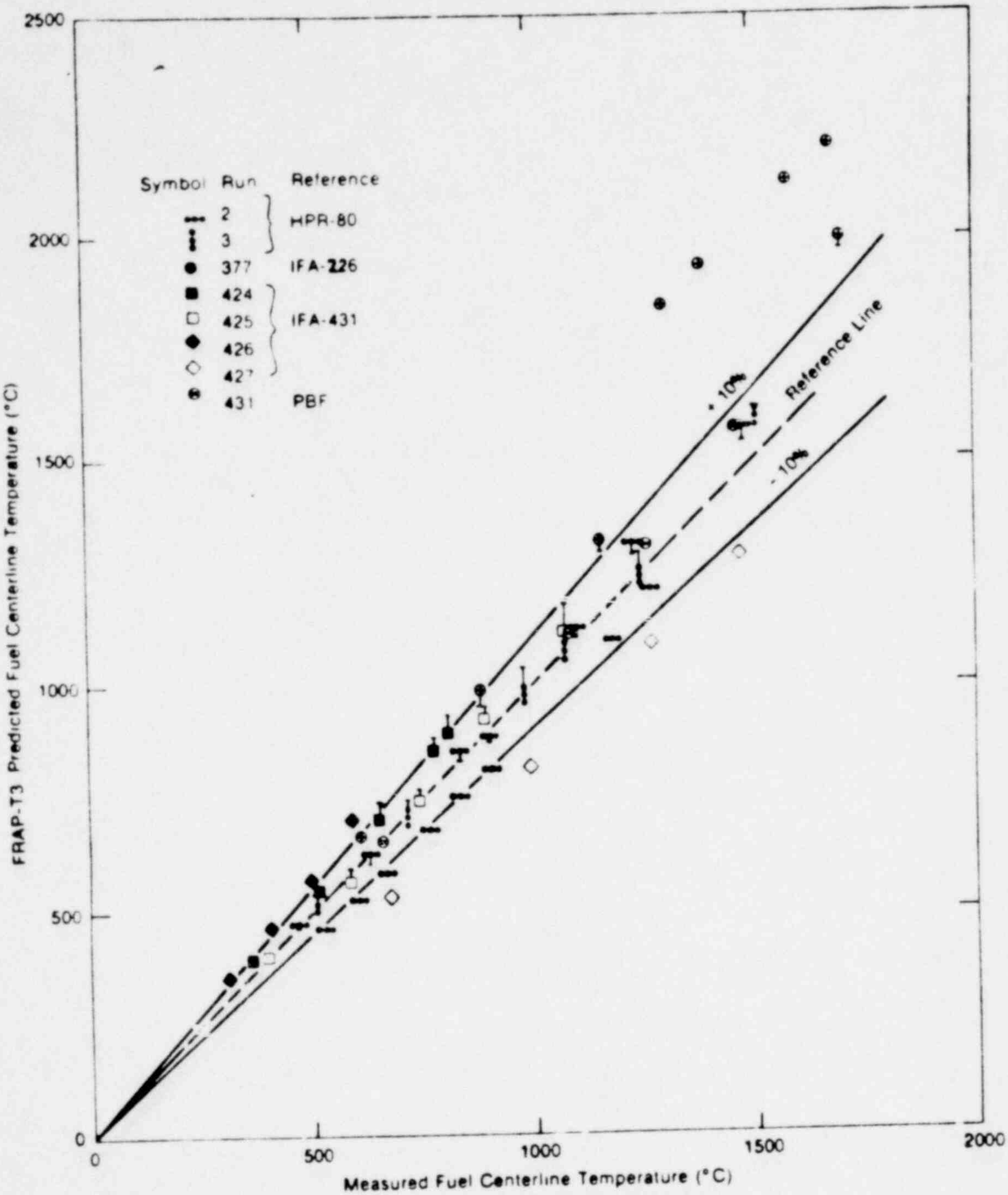
APPENDIX A

28-612



Predicted versus measured fuel centerline temperature for unpressurized rods.

FIGURE 1

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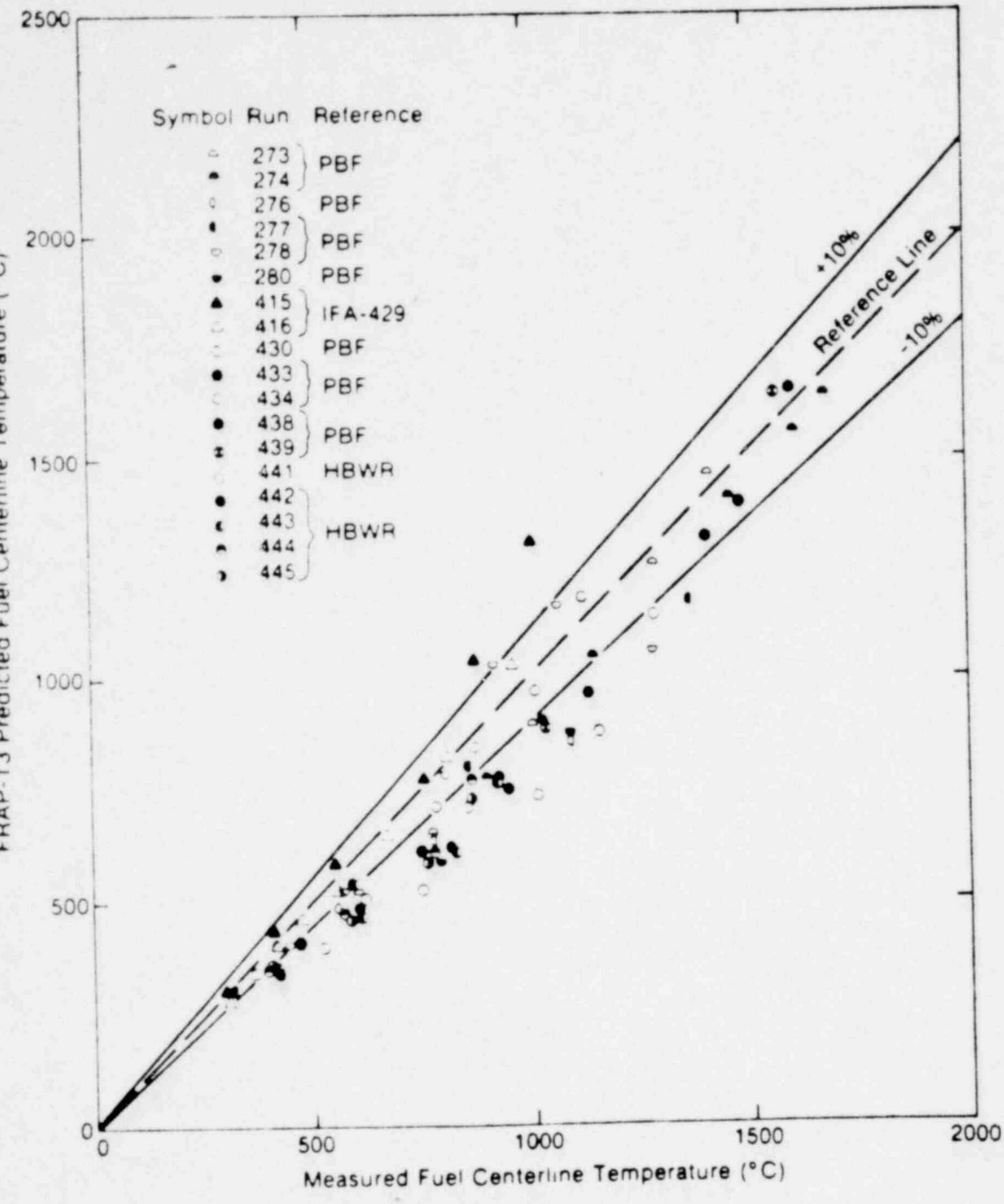
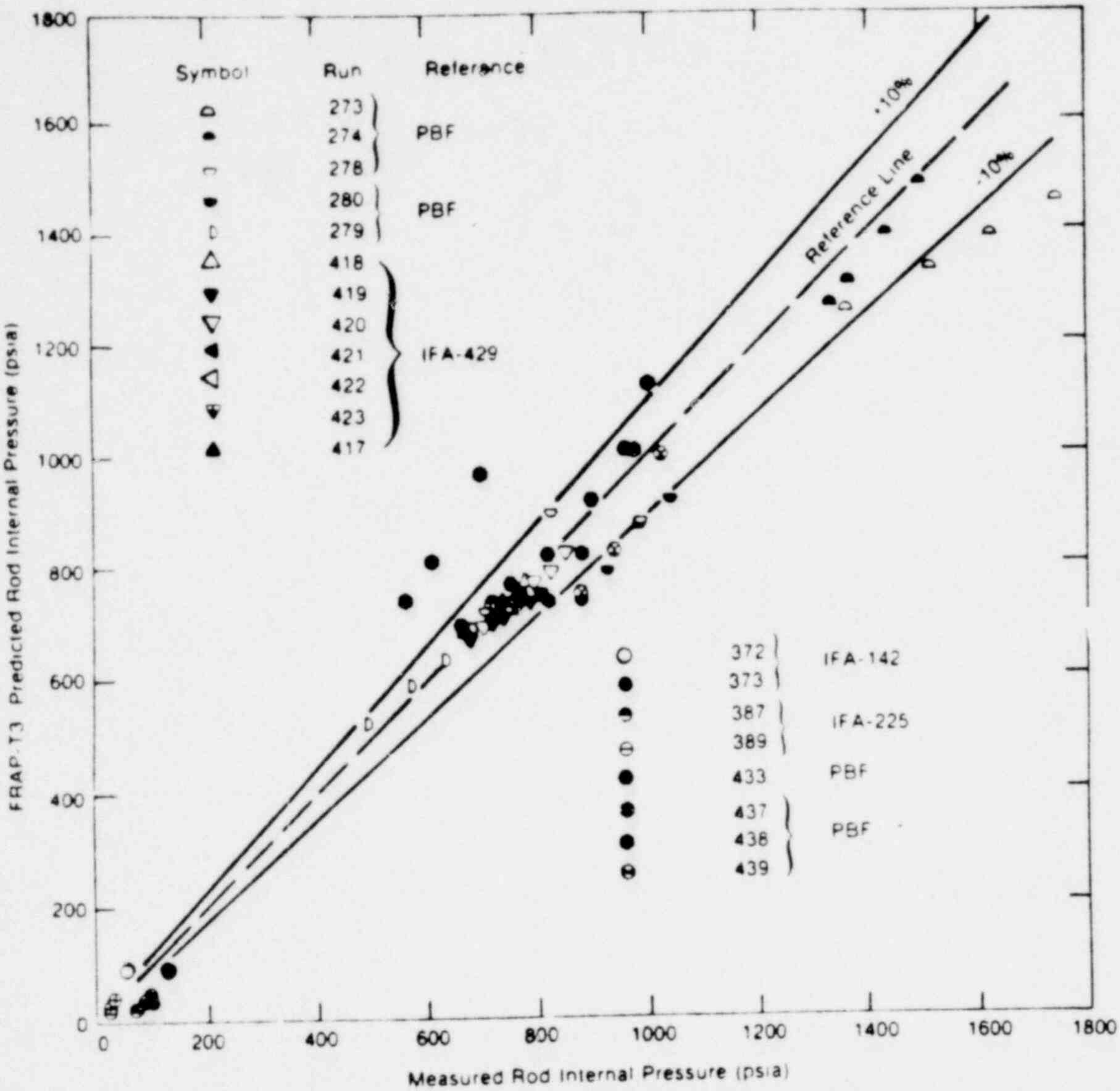


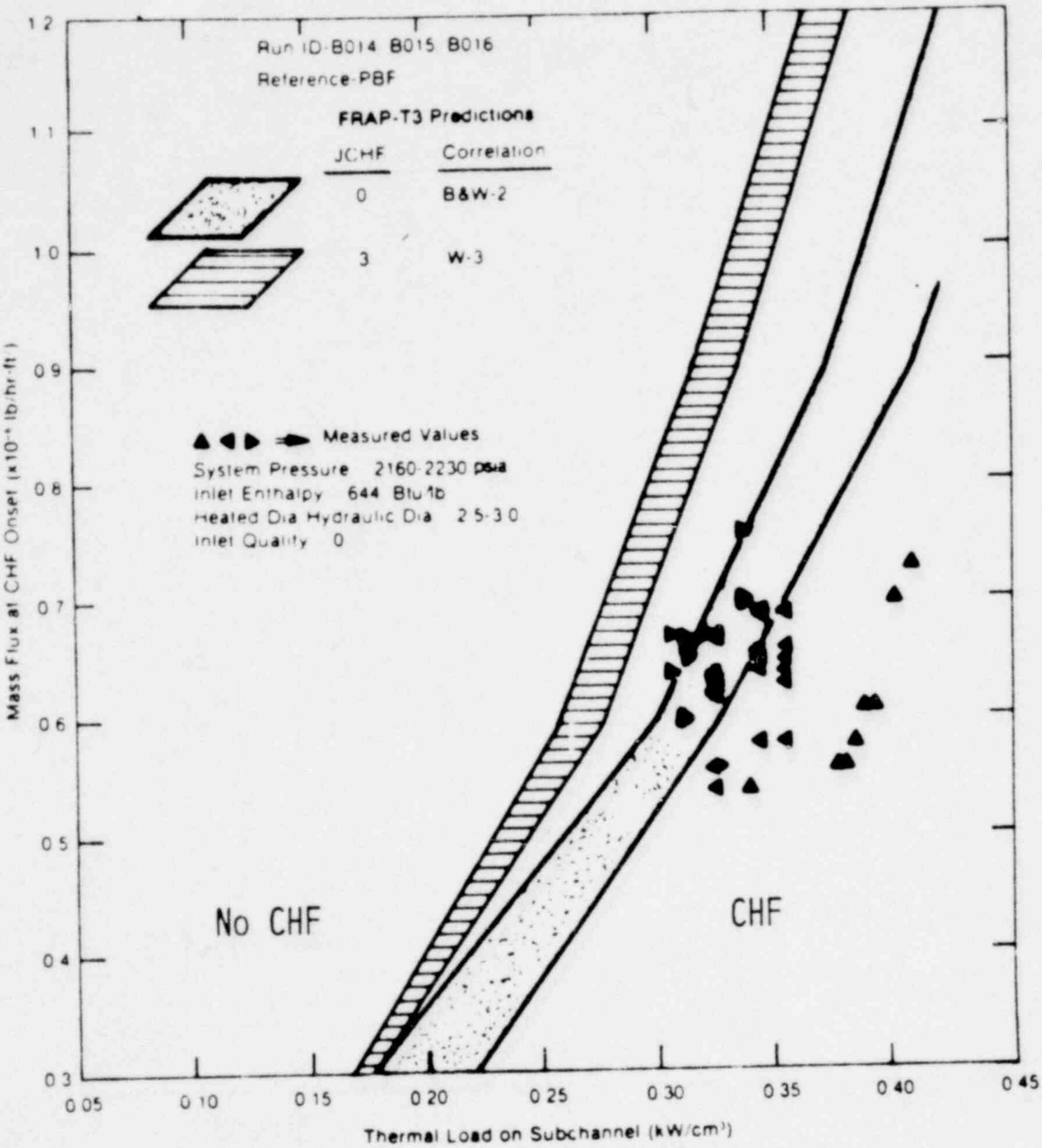
Predicted versus measured fuel centerline temperature for pressurized rods.

FIGURE 2



Predicted versus measured rod internal pressure during heatup.

FIGURE 3



PBF Inlet mass flux at CHF onset vs rod thermal output for low flow area tests.

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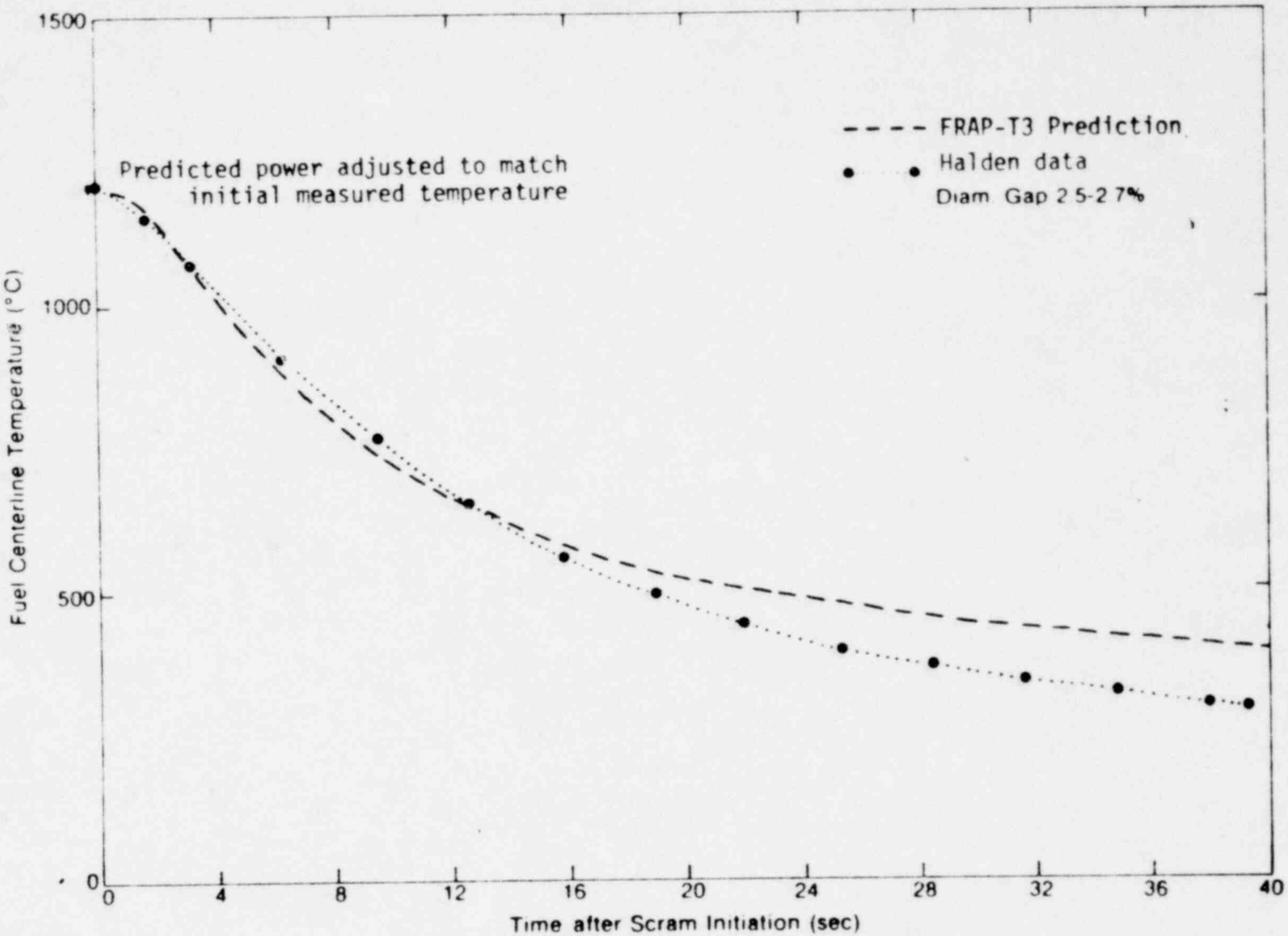
FIGURE 4



FRAP-T3 fuel temperature response after scram at 5600 MWd/t.

FIGURE 5

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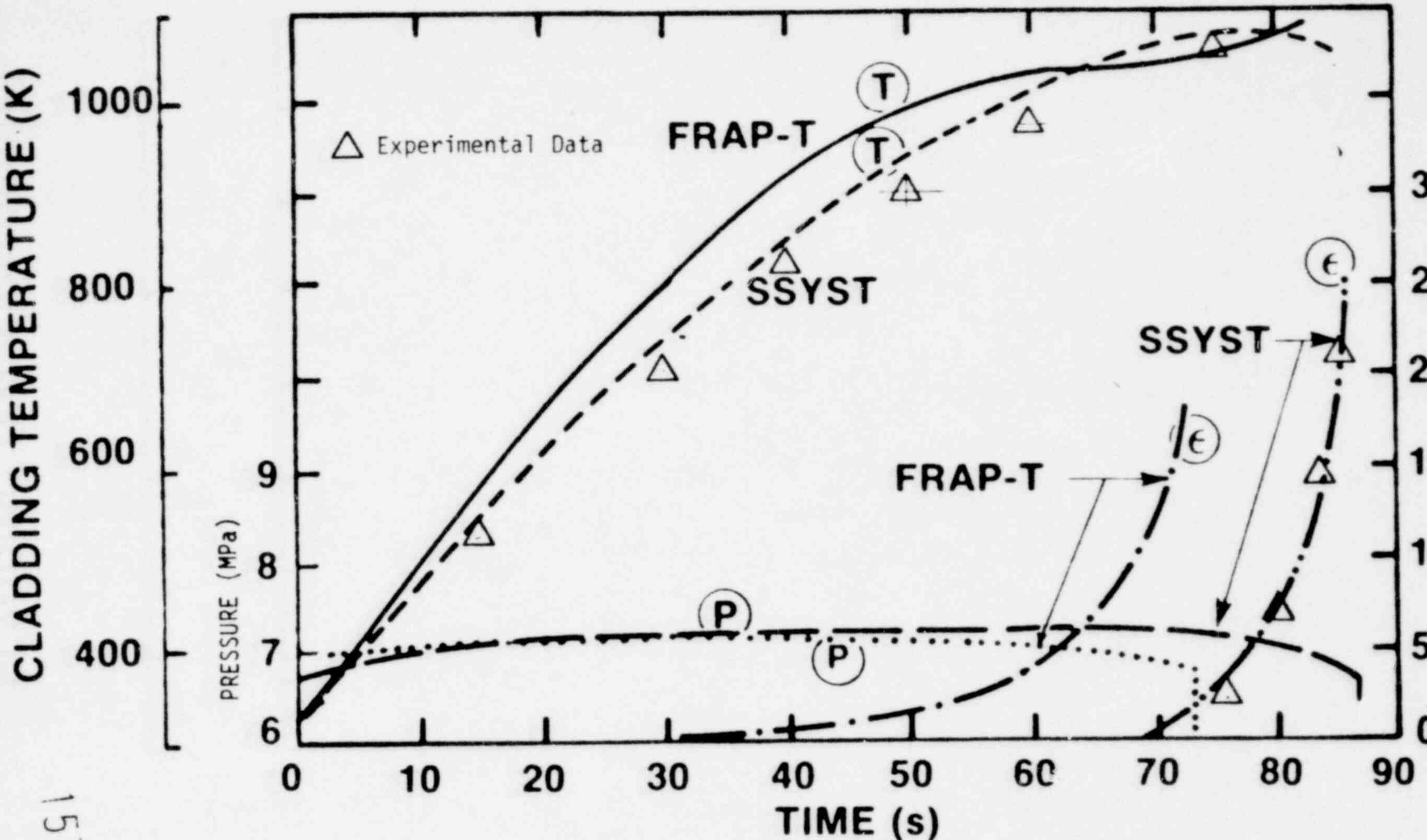
28-616



FRAP-T3 and SSYST Predictions for Standard Problem PNS-4238 LOCA Heatup Test

FIGURE 6

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TABLE I

CAPABILITIES OF VARIOUS VERSIONS OF FRAP-T

Phenomenon Modeled	FRAP-T1	FRAP-T2	FRAP-T3
Heat conduction	Stacked 1-D radial	Stacked 1-D radial	Stacked 1-D radial, 2-D r-θ
Gap conductance	Modified Ross and Stoute	Modified Ross and Stoute, Cracked pellet	Modified Ross and Stoute, Cracked pellet
Plenum gas temperature	Coolant temperature + 10°F	Six-node transient energy balance, boundary conditions from surface temperature subcode	Six-node transient energy balance, simplified boundary conditions
Metal-water reaction	Baker-Just	Baker-Just	Cathcart
Internal pressure	Compressible, laminar gas flow, constant Hagen number	Compressible, laminar gas flow, constant Hagen number	Ideal gas law, compressible, laminar gas flow, variable Hagen number open porosity considered
Cladding deformation	Uncoupled stress-strain equations, no fuel-cladding interaction, no ballooning model, no creep	Triaxial coupled plastic stress-strain equations, fuel-cladding interaction, intermediate balloon model, no creep	Triaxial coupled plastic stress-strain equations, fuel-cladding interaction, advanced balloon model, strain-rate effects, cold-work and fast neutron flux effects, computation optimization, no creep.
Decay heat	No model	No model	ANS model 5.1 (1971)

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28-618

TABLE I (continued)

Phenomenon	FRAP-T1	FRAP-T2	FRAP-T3
Cladding failure	Failure if instability strain exceeded	Failure if total circumferential strain exceeded	Failure probability computed, overstress, overstrain, eutectic melting, and oxidation failure types modeled
Fuel deformation	GAPCØN-I Model	GAPCØN-I Model, free thermal expansion model	GAPCON-I Model, free thermal expansion model
High flow film boiling heat transfer correlations	Groeneveld	Groeneveld Dougall-Rohsenow Tong-Young Condie-Bengston	Groeneveld Dougall-Rohsenow Tong-Young Condie-Bengston
Low flow film boiling heat transfer correlations	Berenson	Groeneveld	Modified Bromley ($\alpha<0.6$) free convection ($\alpha\geq0.6$)
Critical heat flux correlations	B&W-2 Barnett Modified Barnett	B&W-2 W-3 Barnett Modified Barnett General Electric	B&W-2 W-3 Barnett Modified Barnett General Electric
Slip ratio correlation	Homogeneous	Modified Bankoff-Jones	Marchaterre-Hoglund
Water properties	RELAP3 tables	Wagner steam tables	Wagner steam tables
Fuel, cladding and gas properties	MATPRO-2	MATPRO-6	MATPRO-8

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TABLE II

FRAP-T STANDARD PROBLEMS

TYPE	DESCRIPTION	DATE
LOCA	PWR Cold Leg Break Using Supplied Heat Transfer Coefficients or RELAP Coolant Conditions	--
LOCA	TREAT Test 2, BWR Rods	1971
Slow Power Ramp	Halden Reactor Project, Norway	1967
Power-Cooling-Mismatch	PBF Test PCM 8-1	1976
Reactivity Initiated Accident (RIA)	BWR Hot Standby Conditions, 250 Cal/G	--
RIA	SPERT Test GEX-692	1969
ATWS	BWR Main Steam Isolation Closure Valve Accident (90% Relief)	--

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APPENDIX B

DESCRIPTION OF CODE FEATURES

The phenomena modeled by the code include: (1) heat conduction; (2) elastic-plastic cladding deformation; (3) fuel-cladding mechanical interaction; (4) transient fuel rod gas pressure; (5) heat transfer between fuel and cladding; (6) cladding-water chemical reaction; and (7) heat transfer from cladding to coolant. Consideration of the mechanical deformation of the fuel and cladding is of particular significance, since a realistic prediction of rod geometry during an accident (e.g., LOCA) is desired. The probability of pellet cladding interaction related failures is calculated, even though the models needed for a true description of local effects are missing. Effects of prior irradiation must be input from another source (e.g., FRAP-S).

FRAP-T3 is linked to a modular material properties package, MATPRO-8, which contains correlations for all fuel, cladding, and gap gas properties needed by the code. Each correlation is contained in a separate function subprogram or subroutine. No material properties need be specified by the code user. FRAP-T3 is also linked to the Wagner water properties package, which was developed for the RELAP-4 code. This package defines subcooled, saturated, and superheated water properties.

FRAP-T3 requires input data (in either metric or engineering units) which specify cold state fuel rod geometry, transient power, transient condition of coolant surrounding fuel rod, and amount (or pressure) and type of gas in the fuel rod. Input data are also required to specify mesh size (radial and axial incremental dimensions used in computation), time step and accuracy. This permits the code user to have some control over the computer CPU time needed to execute a problem. Transient coolant conditions can be specified in several ways. These options have been chosen to provide maximum flexibility. For example, card input of coolant conditions or heat transfer coefficients, or magnetic tape input of coolant conditions calculated by RELAP-4 can be used.

Code printout, which occurs at input specified time intervals, includes fuel rod radial temperature distribution at an arbitrary number of axial positions, fuel diameter, gas gap thickness, gap conductance, cladding diameter, axial length change, internal pressure, power, surface heat flux, and cladding hoop strain. The code can be instructed to generate plots of the above output parameters as a function of time. It is also possible to generate 16mm motion pictures of the output.

Based on our review of FRAP-T3, we believe the following observations would be helpful to code users; (1) At hot plenum pressures above 500 psi the MacDonald-Broughton gap conductance model (so called cracked pellet model) predicts excessive values and the Ross-Stoute model option is recommended. (2) Two model options are available for computing fuel radial displacement (free thermal expansion model or GAPCON-THERMAL-I model). Since FRAP-T3 was verified (and to some extent developed) using free thermal expansion, that model option is recommended. (3) The stress-strain model in MATPRO is not applicable above 1500 F (temperature at which a metallurgical phase transformation begins in Zircaloy). This generally causes an overprediction of cladding circumferential strain at burst. Measured strains of 0.1 to 0.7 in/in are predicted to be 0.6 to 0.9 in/in.