UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

11-16-1979

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

Robert B. Minogue, Director
Office of Standards Development

FROM: Saul Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 74 THE STEADY-STATE FUEL ROD BEHAVIOR CODE: FRAPCON-1

References:
1. D. F. Ross/L. S. Tong letter to H. E. Ranson (DOE-RL), and R. E. Wood (DOE-ID), June 6, 1979
2. J. A. Dearien, et.al., "FRAP-S3: A Computer Code for the Steady-State Analysis of Oxide Fuel Rods," TFBP-TR-164, Revision 2, March 1978
3. D. D. Lanning, et.al., "GAPCON THERMAL-III Code Description," PNL-2434, January 1978
4. D. L. Hagrman and G. A. Reymann, "MATPRO-VERSION 10, A Handbook of Material Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior," TREE-NUREG-1180, February 1978
5. J. D. Kerrigan, D. L. Hagrman, and S. O. Peck, "FRAIL-4: A Fuel Rod Failure Subcode," CDAP-TR-012, April 1978
6. J. D. Kerrigan and D. R. Coleman, CVAP-TR-78-24, 1978

This Research Information Letter transmits the description and assessment documentation of the latest version of the steady-state fuel rod behavior code - FRAPCON-1.

1. INTRODUCTION

FRAPCON-1 is a computer code that calculates the thermal and mechanical response characteristics of a nuclear fuel rod operating under steady-state conditions. It was developed to provide both best-estimate (BE) and evaluation model (EM) calculational ability to NRC for various uses within the Office of Research and the Office of Nuclear Reactor Regulation. The need for such a code was established by NRR/RES discussions in the summer of 1977. These actions were initiated by a joint NRR/RES

74

letter (Reference 1) and included responses and feedback from the participating contractors - EG&G and BNWL. As a result of many discussions between RES and NRR technical staff, it was agreed that a new steady-state code would be developed by RES by merging the models of the RES-sponsored FRAP best-estimate code series (Reference 2) with the models of the GAPCON licensing audit code series (Reference 3). It was also agreed that RES would be responsible for overall code development and for the BE models; whereas, NRR would be responsible for the development and review of the EM models. The new code was to be optimized for ease of use, running time, and core-space usage, as well as be structured to allow for easy interchange of EM and BE models. The resulting code (FRAPCON-1) is: 1) used as a BE code to initialize the current RES best-estimate transient code; 2) used as a stand-alone, best-estimate steady-state code; or 3) used as a licensing tool with appropriate EM.models supplied by NRR.

As of the time of this writing, the EM models to be used in FRAPCON-1 are being reviewed by cognizant licensing personnel. Consequently, the contents of this letter will address only the code's capability with respect to BE models. However, since the models are interchangeable, the report will provide the user with an overall assessment of the code's abilities and enable NRR users to evaluate those models in the code which can or should be interchangeable with EM models. It will also provide a base to which comparisons can be made between the results obtained in a BE mode and those obtained when using EM options.

2. RESULTS AND EVALUATION

Code Features and Models

FRAPCON-1 is a FORTRAN IV computer code which considers the coupled effects of fuel and cladding deformation, temperature, and internal gas pressure on the overall response characteristics of a fuel rod operating under normal conditions. The cladding deformation model includes multi-axial, elasto-plastic analysis, and accounts for both primary and secondary creep. The fuel deformation includes the effects of thermal expansion, densification, and swelling on pellet dimensions.

The fuel temperature model considers the effects of pellet cracking, relocation, and gas composition in the fuel-clad gap region. Internal gas pressures are computed as a function of burnup (gas release) and average gap temperature. Material properties are supplied to the code via the MATPRO-10 subcode (Reference 4). The code is also linked to the FRAIL subcode (Reference 5) which supplies rod failure probabilities at any point in time requested by the user.

As stated earlier, the base codes used in the development of FRAPCON-1 were the FRAP-S and GAPCON codes. The new code was modified to allow for dynamic dimensioning, and was completely modularized to facilitate easy interchange of BE and EM models. Most of the BE models in the code were taken from the FRAP-S code series; whereas, most of the EM models will be based upon GAPCON models. Finally, the fuel pellet temperature calculation subroutine was changed to utilize the more efficient Method of Weighted Residuals calculational scheme from GAPCON-THERMAL-III. The above changes are summarized in Table I of Appendix A, and an in-depth description of the code and its models is presented in Enclosure 2.

Assessment of Code Capabilities

The independent assessment of the code was accomplished by a group other than the model developers (see Enclosure 3). The objectives of this work were to demonstrate the best-estimate capabilities of the code and to provide guidance to the model developers where improvements seem warranted. During the assessment, FRAPCON-1 results were compared with in-pile measurements and post-irradiation examination data for approximately 700 test rods. The results of these comparisons are summarized below for those response variables important to fuel rod behavior safety analysis. Detailed results of these and other variables are available in Enclosure 3.

(A) Fuel Centerline Temperature

Figures 1 and 2 of Appendix A illustrate the comparison of FRAPCON-1 predicted and measured centerline temperatures for unpressurized and pressurized rods, respectively. Error analysis of the plots show that the standard deviation between measurements and predictions yield corresponding values of 170°K and 294°K, respectively. The smaller deviation of the unpressurized rods is probably due to the fact that a much larger data sample (61 rods vs 32 rods) is available for these rods which would tend to mitigate the effect of any systematic data errors present. In both cases the code tended to slightly overpredict the data for low density fuel (< 95 percent TD), and slightly underpredict the data for high density fuel (>95 percent TD). However, the general overall agreement is considered to be quite good since the deviations are very close to the 20-25 percent uncertainties predicted by response surface techniques which account for such input uncertainties as operating conditions, fabrication dimensions, and material property data.

(B) Fission Gas Release

The data comparison for steady-state gas release predictions over a range of burnups to 46000 MWD/t is shown in Figure 3 of Appendix A. Note that for releases less than 20 percent, the code generally overpredicts the release, and that above 20 percent, the data become more evenly distributed. An overall standard deviation of 16 percent was computed from the plot. This relatively large error is due to the large scatter in experimental measurements, the operating history uncertainty, and model deficiencies. It is believed that the NRC/ANL-developed gas release code (GRASS), when linked to the next code version (FRAPCON-2), will substantially reduce the contribution of the latter.

(C) Rod Internal Pressure

The standard deviation between measured and predicted rod internal pressure, for both unpressurized and prepressurized rods, was only 1.6MPa. When compared with the results of a response surface study on FRAP-S3 (Reference 6), which compared pressure uncertainties caused by fabrication variables, operating variables, and material property input, the agreement is quite good. The Reference 6 study yielded standard deviations of 0.9, 1.59, and 2.34MPa for beginning-of-life, middle-of-life, and end-of-life conditions. Figures 4 and 5 illustrate the data comparisons (both pressurized and unpressurized rods) of FRAPCON-1 for low burnup conditions and high burnup conditions, respectively. The group of underpredicted points in Figure 4, between 7 and 12MPa, correspond to startup measurements of two rods which exhibited significant pressure transducer drift and may, therefore, not be reliable.

(D) Fuel Axial Thermal Expansion

Data comparisons for fuel axial thermal expansion were made for 20 rods (for both dished and flat pellet designs) under typical startup power ranges. The results are summarized in Figure 6 of Appendix A and show excellent agreement for strains less than 0.3 percent. Above 0.3 percent strain the code overpredicts the measured values because the fuel and cladding are in solid contact which mitigates the fuel deformation due to cladding restraining forces. The current fuel deformation models in the code do not account for this effect, but the next version of the code, FRAPCON-2, will - via both EG&G and BNWL optional fuel deformation models. The standard deviation, calculated from Figure 6, was 0.23 percent of the stack length for strains less than 0.3 percent, and 0.56 percent for strains above 0.3 percent.

(E) Permanent Fuel Axial Deformation

The type of fuel deformation assessed here is that caused by permanent dimensional changes such as fuel densification, swelling, and compression. The code currently accounts for only the first two mechanisms. Assessment was based on data from about 200 rods at burnups less than ~2900MWd/t. Therefore, the deformations reflect only that caused by densification. The results are given in Figure 7 which yielded a standard deviation of 0.45 percent of stack length.

(F) Cladding Deformation

Cladding hoop strain (i.e., change in cladding diameter) was assessed from 130 rods and reflects the performance of the cladding creep-down models in FRAPCON-1 since most of the rods experienced low burnup. Figure 8 of Appendix A illustrates the results. Note that although the agreement is quite good, (the standard deviation was 0.5 percent of clad diameter) the creep model tended to generally overpredict the amount of negative strain. It is expected that revision of the creep model in the code, from the data obtained by the NRC-sponsored creep studies in the Petten reactor, will improve the predictions. The new model should be available within 1 year.

Data comparisons for cladding axial strain suffered from the same deficiences noted above for fuel axial strain predictions due to the lack of a fuel/clad axial interaction model. This deficiency should be alleviated in the next code version - FRAPCON-2.

3. CONCLUSIONS AND USER RECOMMENDATIONS

Standard deviations for the fuel behavior responses discussed above plus other less important responses are summarized in Table II of Appendix A. Although some specific responses were slightly better predicted by FRAP-S3, the overall performance of FRAPCON-1 generally exhibits better calculational accuracy than its predecessors.

In general, FRAPCON-1 predicts fuel behavior most accurately when: 1) the fuel rods are unpressurized, 2) fuel densities exceed 94 percent T.D., 3) initial gap sizes are less than 2 percent, and 4) when plenum volumes are more than half the total void volume. Recommended options for the user include using the Ross and Stoute annular gap conductance model coupled with the Coleman cracked fuel thermal conductivity model, recommended nominal and default values for all correlation multiplication factors defined in the users manual (Enclosure 2), and nodalization and power profiles described in Section III.3 of Enclosure 3.

The following caveats should be considered by the user when interpreting code results:

(A) Fuel temperatures may be overestimated at high burnup if the initial gap is large (>2 percent), and if the fuel density is low (<94 percent TD).

(B) Although the cladding hoop stress may be overestimated under hard gap closure conditions, positive cladding strains may be underestimated under soft gap closure conditions.

(C) At power levels up to 20kw/m (~6.1 kw/ft) internal pressure predictions are very good; however, for power levels above 35kw/m (~10.7 kw/ft), the pressure may be overpredicted for low burnup and underpredicted for high burnup conditions.

As noted above, model improvements are continually being made to enhance data-prediction comparisons, and these improvements will be incorporated into future versions or modifications of the code.

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Enclosures:
1. Appendix A (Includes two tables and eight figures)
2. "FRAPCON-1: A Computer Code for the Steady-State Analysis of Oxide Fuel Rods," CDAP-TR-78-032-R1, November 1978
3. "Independent Assessment of the Steady-State Fuel Rod Analysis Code FRAPCON-1," CAAP-TR-050, May 1979

APPENDIX A

TABLE I

DIFFERENCES BETWEEN FRAPCON AND FRAP-S3

	FRAP-S3	FRAPCON
Heat Conduction	Stacked 1-D radial using $\int kdT$, effective fuel thermal conductivity	Stacked 1-D radial using Method of Weighted Residuals, effective fuel thermal conductivity
Fuel, cladding and gas properties	MATPRO-9	MATPRO-10A
FRAP-T Links	FRAP-S3/T2,T3,T4	FRAPCON/T5
Programming features	Modular coding	Modular coding, Dynamically dimensioned with respect to nodelization and power-time steps, modified code iteration structure to optimize efficiency

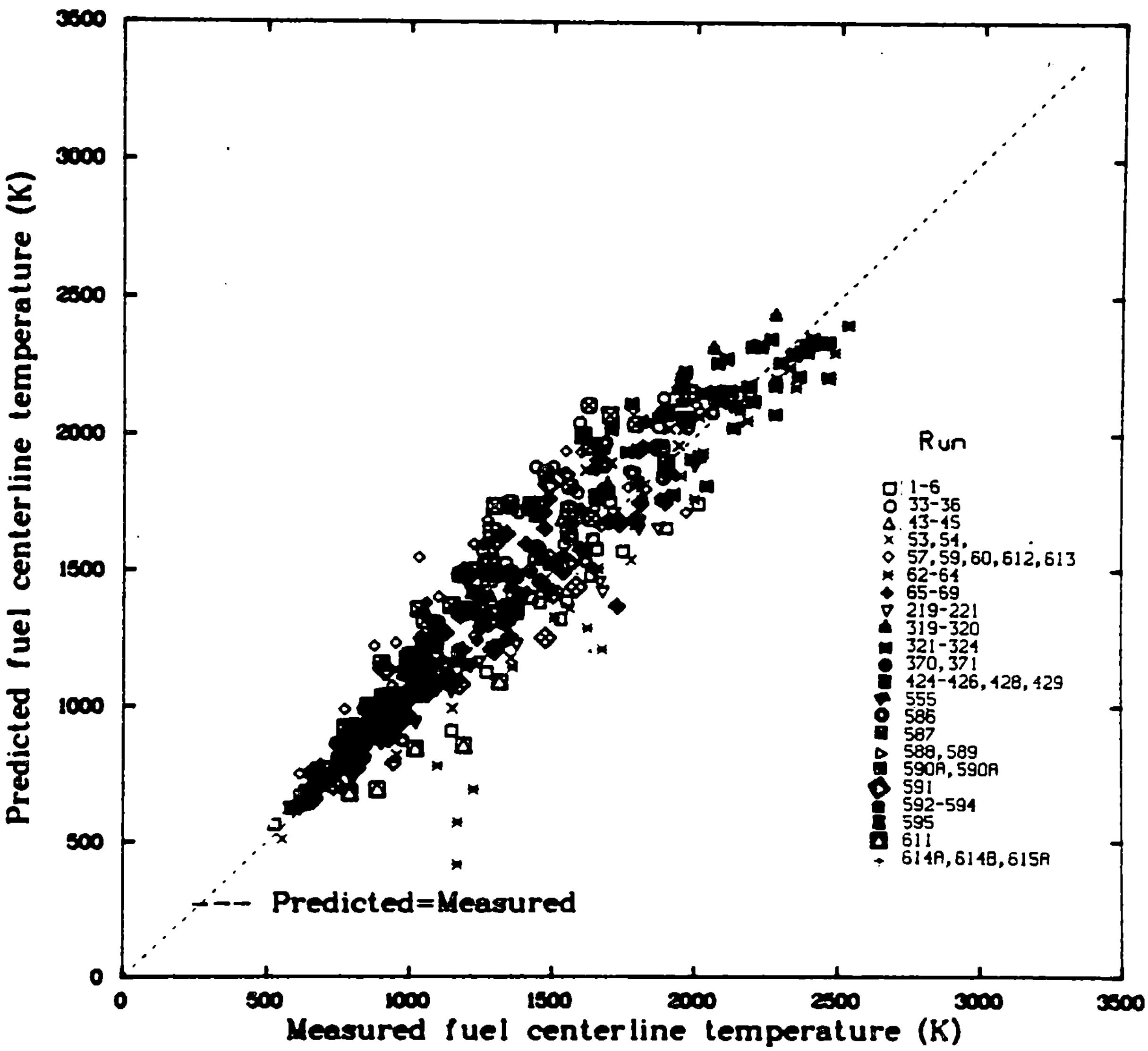

Fig 1 FRAPCON-1 predicted against measured centerline temperatures for unpressurized rods.

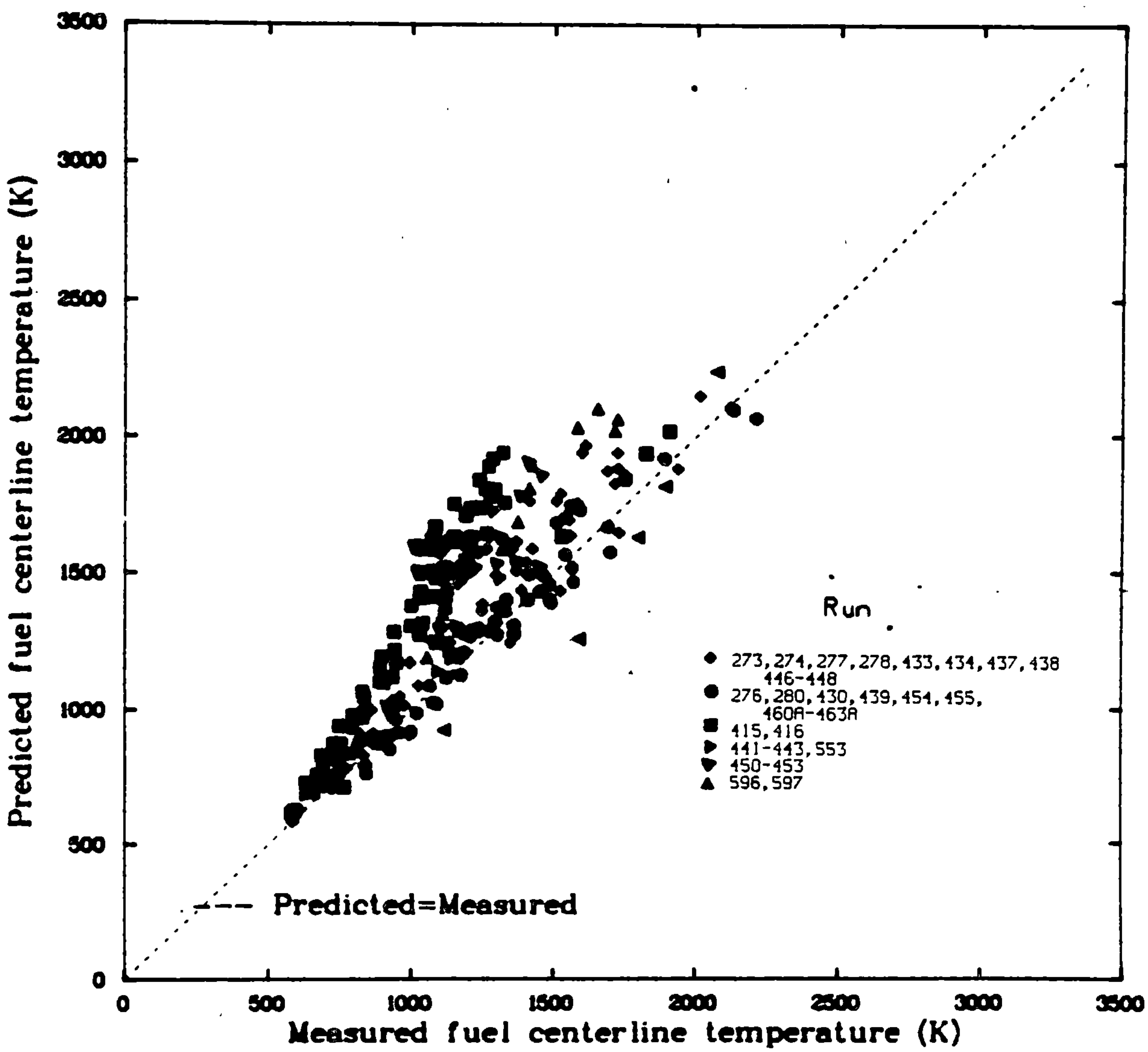

Fig. 2 FRAPCON-1 predicted against measured centerline temperatures for pressurized rods

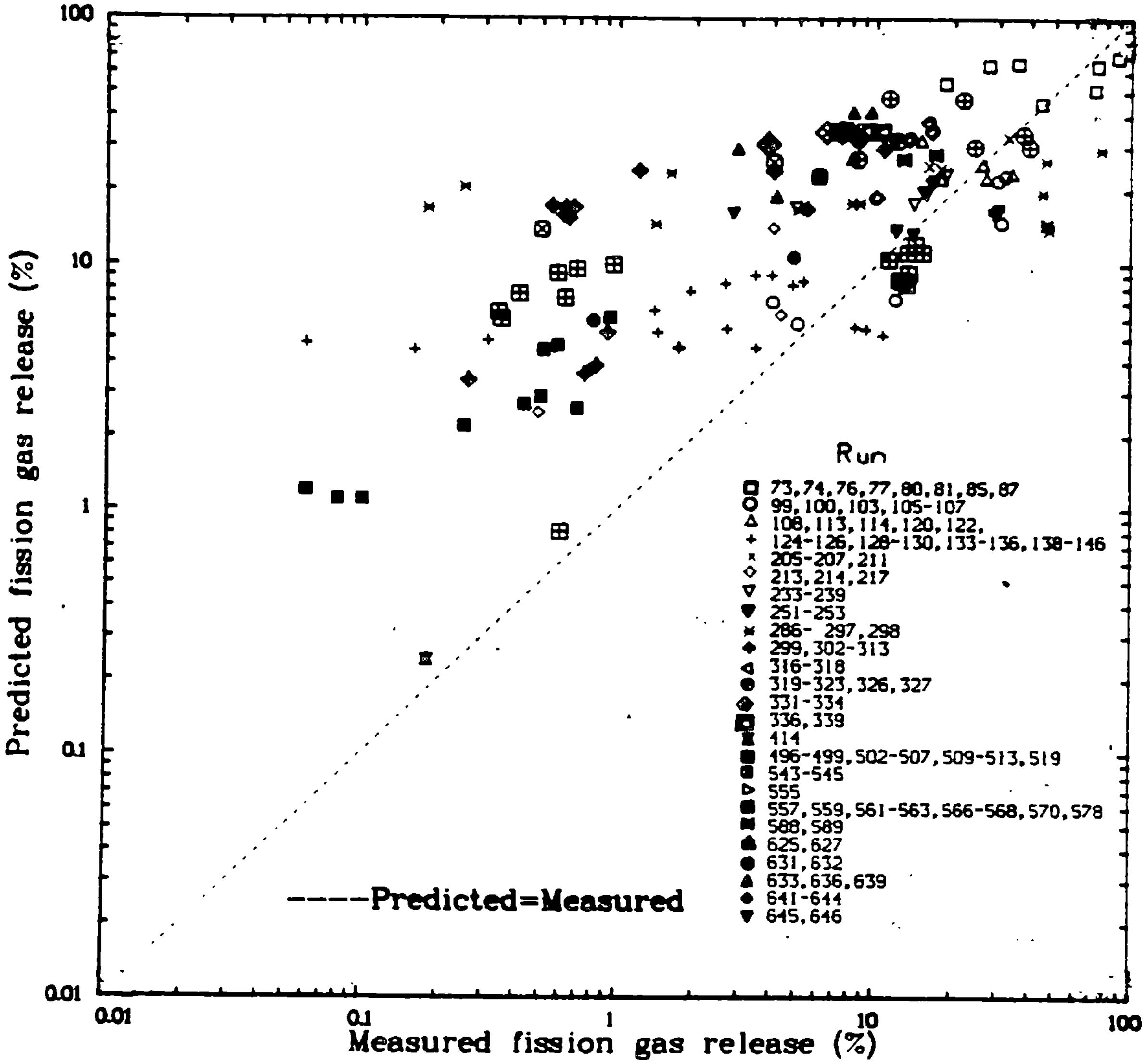

Fig. 3 FRAPCON-1 predicted against measured fission gas release fraction.

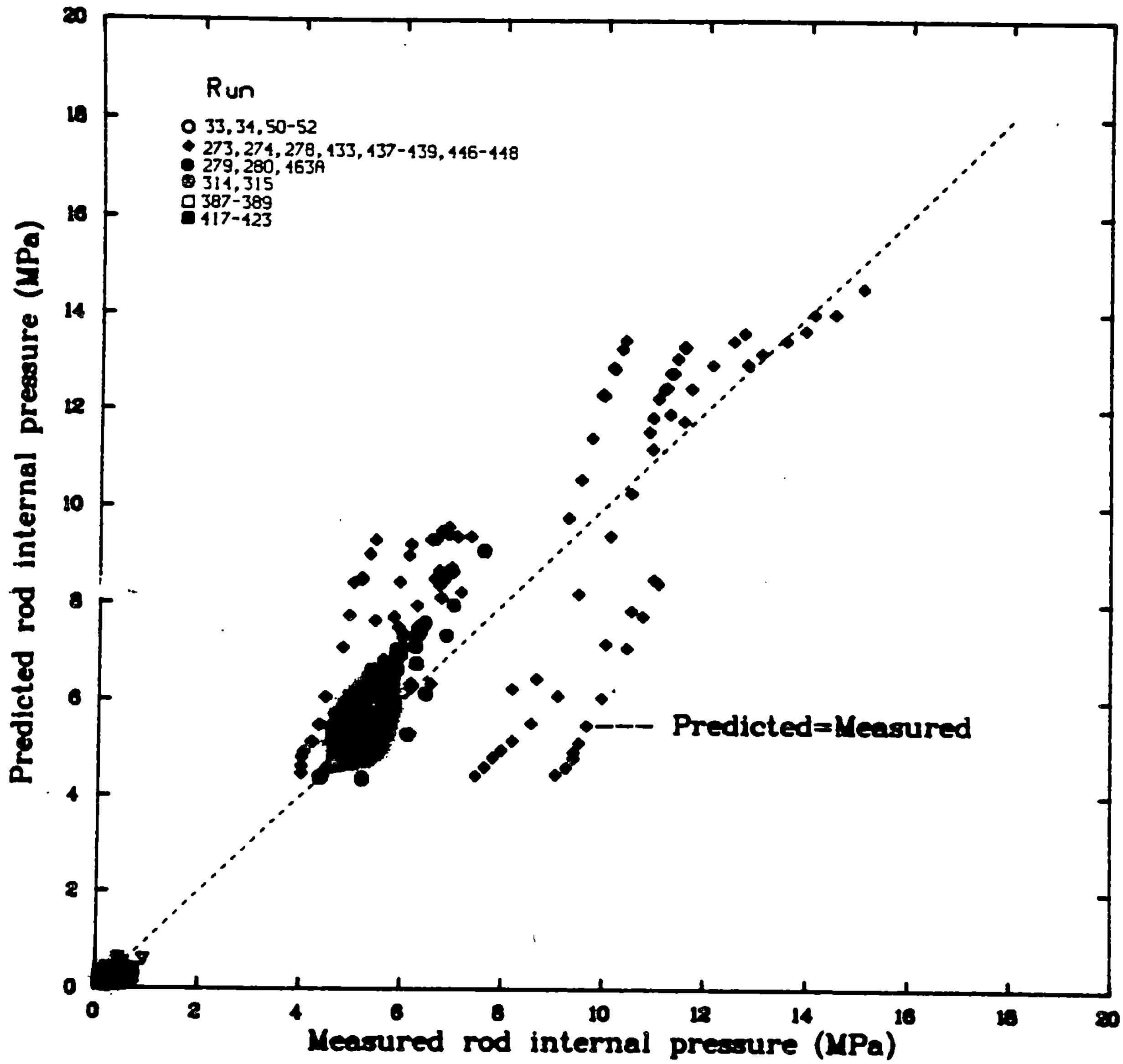

Fig. 4 FRAPCON-1 predicted against measured rod internal pressure

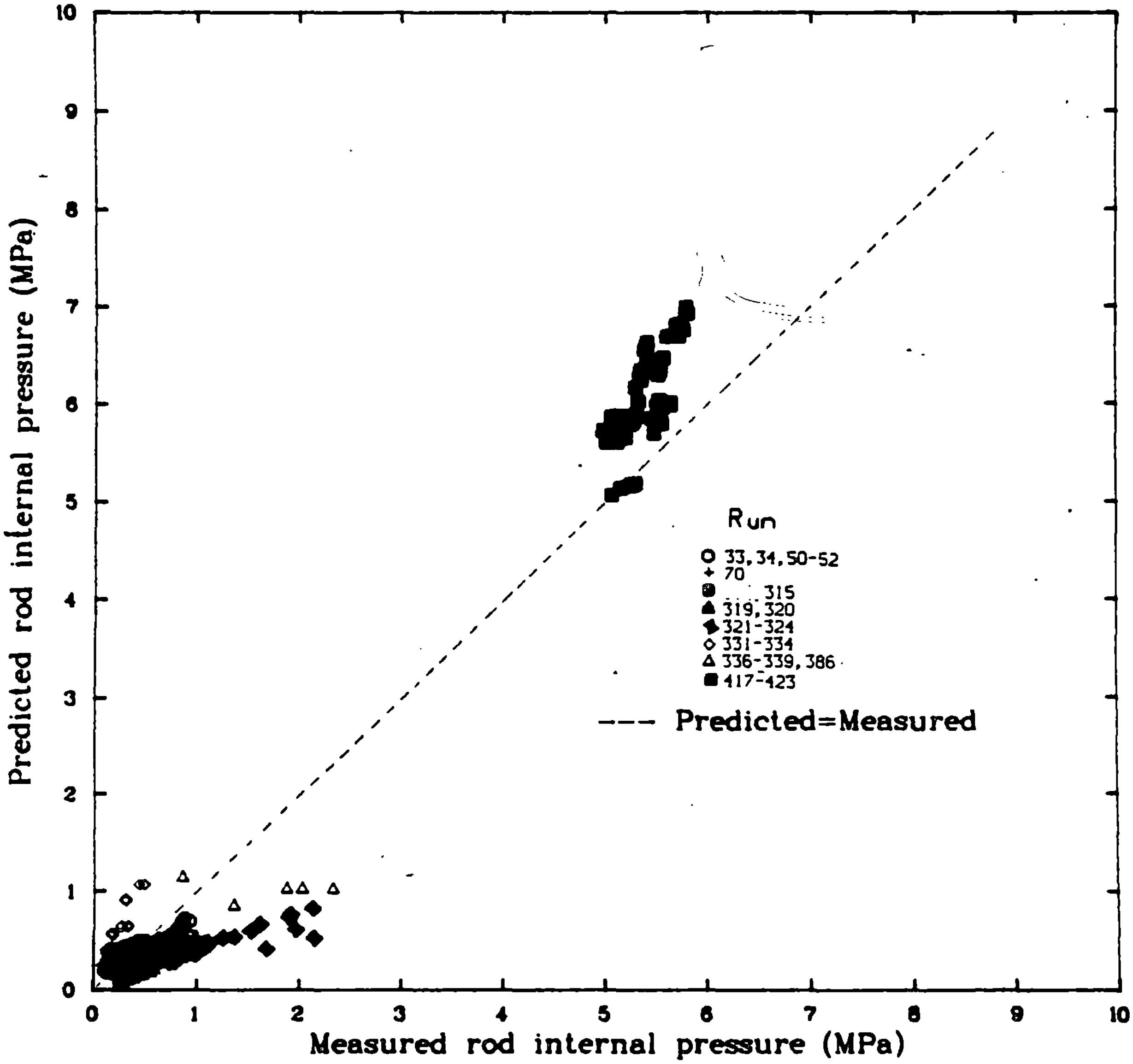

Fig. 5 FRAPCON-1 predicted against measured rod internal pressure at high burnup conditions.

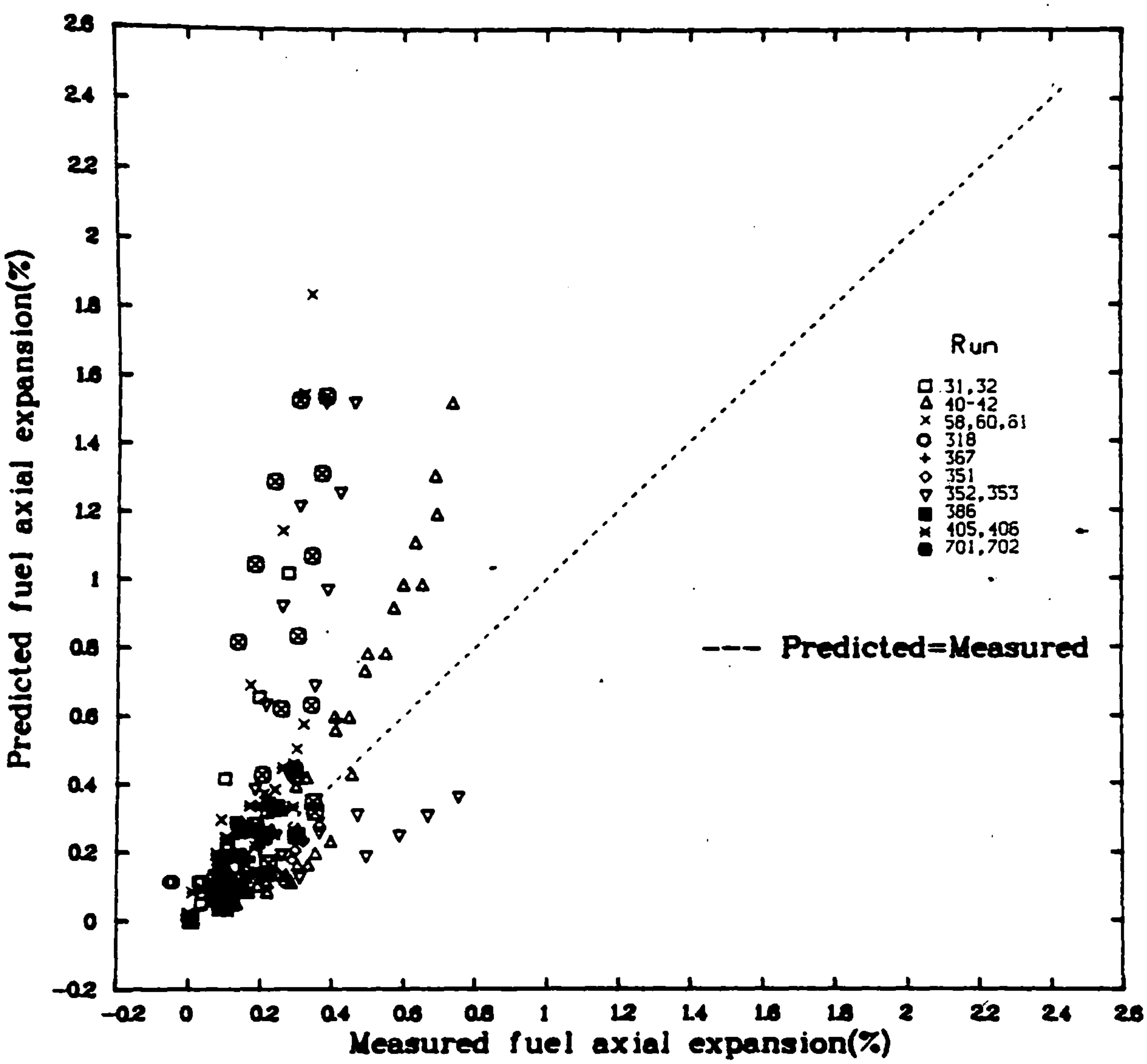

Fig. 6 FRAPCON-1 predicted against measured fuel axial expansion during heatup.

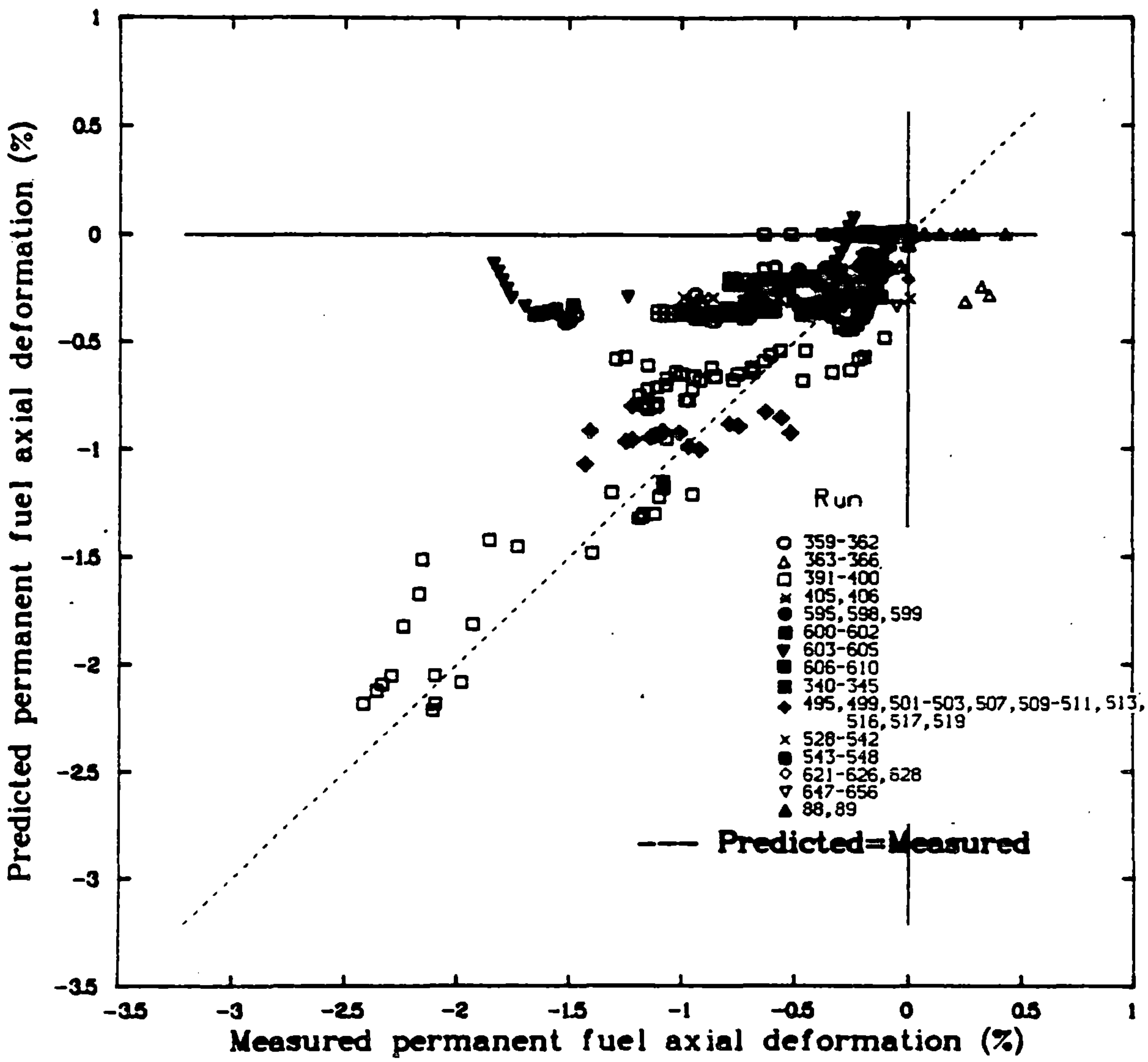

Fig. 7 FRAPCON-1 predicted against measured permanent fuel axial deformation.

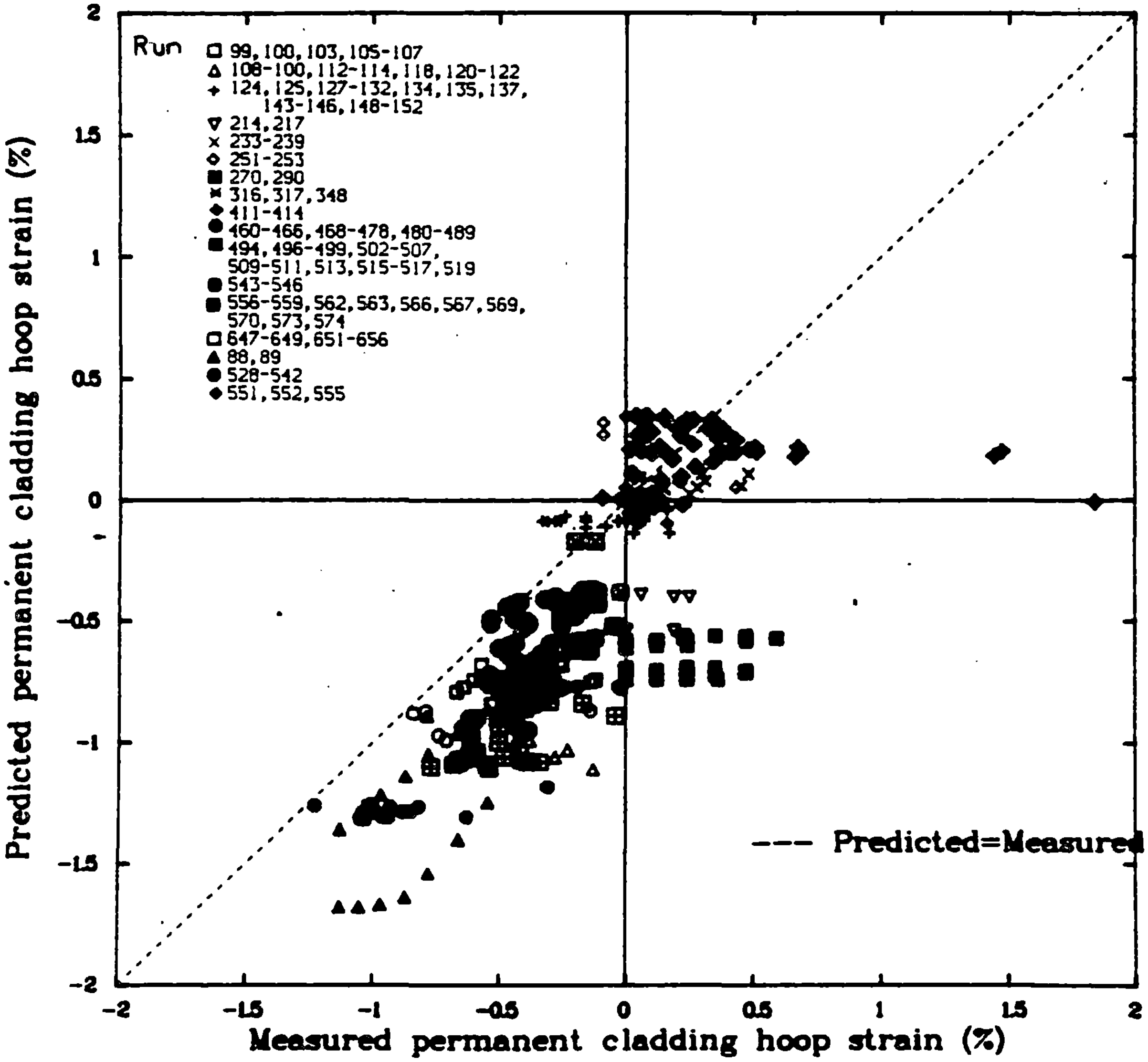

Fig. 8 FRAPCON-1 predicted against measured permanent cladding hoop strain.

TABLE II

FRAPCON-1 MODEL ASSESSMENT — SUMMARY OF STANDARD DEVIATIONS BETWEEN MEASUREMENTS AND PREDICTIONS

Output Parameter	Sample Size (# of Rods/# of Points)	Standard Deviation FRAPCON-1
Fuel Centerline Temperature	32/274 (Pressurized Rods)	294K
	61/472 (Unpressurized Rods)	170K
Released Fission Gas	145/145	15.9%
Rod Internal Pressure	20/330 (Unpressurized Rods)	1.38 MPa
	28/285 (Pressurized Rods)	1.93 MPa
Gap Closure Heat Rating	88/88	11.4 KW/M
Axial Fuel Thermal Expansion	18/160	0.37%
Permanent Fuel Axial Deformation	97/354	0.45%
Permanent Cladding Hoop Strain	154/358	0.47%
Permanent Cladding Axial Strain	96/119	0.15%
Cladding Surface Corrosion Layer	40/69	5.8 micron
Cladding Hydrogen Concentration	33/46	37.2 ppm
Gap Conductance	17/112 (Unpressurized Rods)	10821 W/m^2K
	20/115 (Pressurized Rods)	21200 W/m^2K
Fuel Off-Centerline Temperature	20/111	208K

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