INDEPENDENT ASSESSMENT OF FRAPCON-1 AND FRAP-T5

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1605 236

INDEPENDENT ASSESSMENT OF FRAPCON-1 AND FRAP-T5

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The fuel behavior programs, FRAPCON-1 and FRAP-T5, have been independently assessed. The objectives of the assessment effort were to demonstrate where best estimate model capabilities exist and to provide guidance for model development where improvements seem warranted. FRAPCON-1 is the steady state fuel behavior program derived from the FRAP-S3 program developed by EG&G Idaho and the GAPCON-Thermal-3 code developed by Battelle Pacific Northwest Laboratories in Richland, Washington. FRAP-T5 is the fifth version of the transient fuel rod behavior program developed at EG&G Idaho. The primary application of FRAPCON-1 is to supply initial conditions to FRAP-T5 to account for steady state irradiation prior to a transient event.

Two general types of analyses were conducted during the assessment of FRAPCON-1 and FRAP-T5. First, the analysis of fuel behavior for commercial rods was used to evaluate general code performance characteristics. Second, the analysis of results between code calculations and the measured behavior of test rods was used to evaluate model accuracy.

Overall, FRAPCON-1 exhibited better calculational accuracy than the previously assessed FRAP-S3 code. The centerline temperatures are predicted well for the unpressurized rods and generally overpredicted for pressurized rods. Better centerline temperature agreement is also noted when (a) as-built pellet-cladding gap size is less than 2% of the pellet diameter, and (b) rod operating power levels are greater than 45 kW/m. Rod internal pressures are well characterized at startup, but unpressurized rods are underpredicted and pressurized rods are overpredicted at higher burnups. Also, the extent of permanent fuel deformation is accurately predicted, but the amount of permanent cladding deformation is overestimated.

Since FRAPCON-1 and FRAP-T5 are sister codes, model consistency is necessary. Results of the commercial rod studies show that the steady state models are consistent between FRAPCON-1 and FRAP-T5 at beginning-of-life, and the permanent effects of prior irradiation are correctly communicated from FRAPCON-1 to FRAP-T5 at higher burnups.

Results of the FRAP-T5 calculation/data comparisons indicate improvement in overall code predictability. When calculating the onset of critical heat flux, adequate code predictability is observed for pressurized water reactor system conditions, but a modeling deficiency is noted for boiling water reactor low mass flux conditions. During a reactor shutdown event, the initial temperature and the rate of temperature decrease are overestimated, but equilibrium temperature following shutdown is accurately predicted. During reactivity initiated accidents (RIA), performance of the FRAP-T5 thermal model is reasonable, but the cladding failure criteria for RIA-type scenarios are questionable and warrant further development. For loss-of-coolant accidents, the FRAP-T5 thermal model reproduces data trends well, but the deformation models seem overly sensitive to system operating conditions.

Independent Assessment of FRAPCON-1 and FRAP-T5

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1605 239

Subjects Analyzed During Independent FRAPCON-1 Assessment

- Commercial rod studies
- Code-data comparisons
  - Thermal models
  - Pressure models
  - Deformation models

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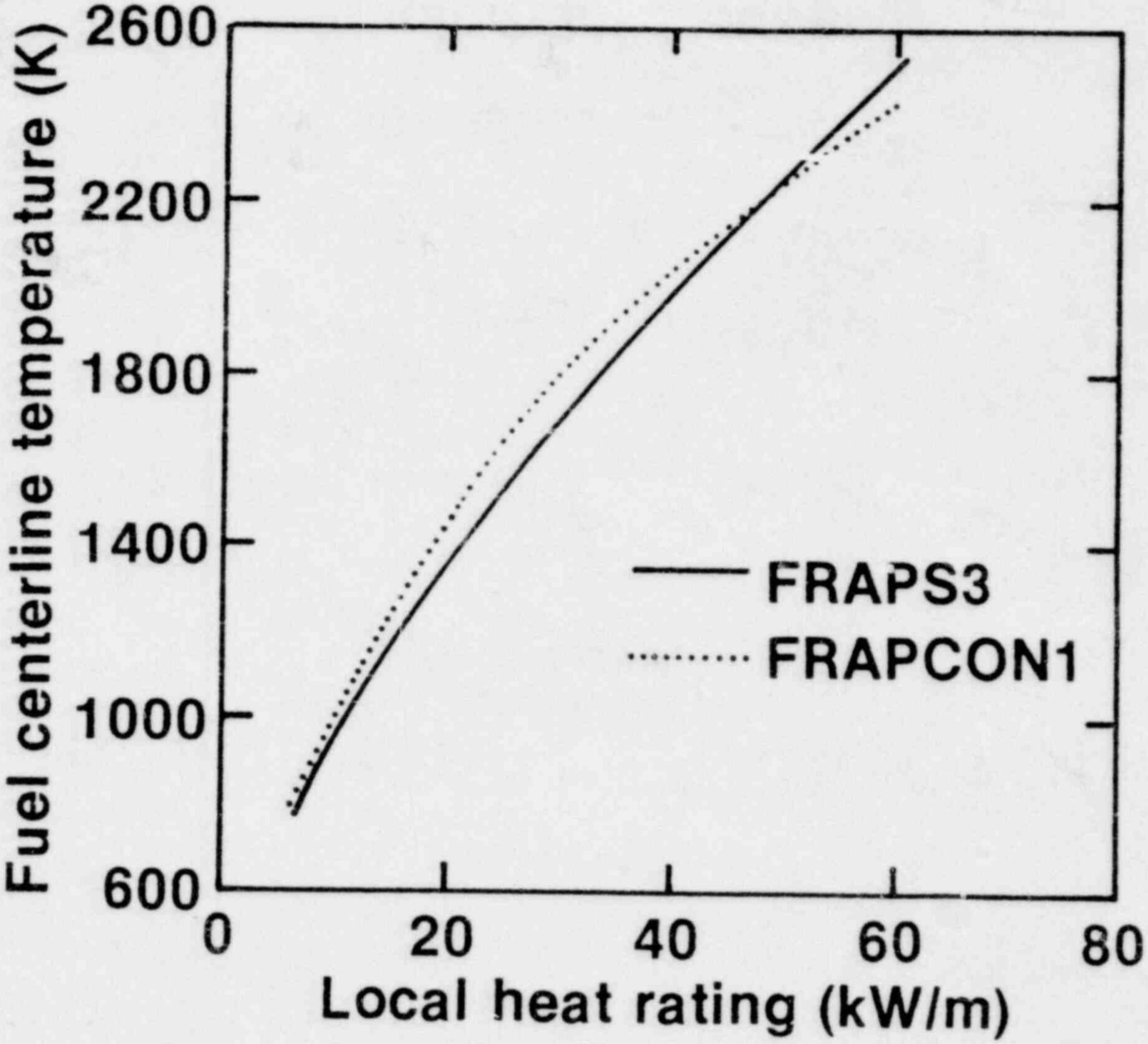
Beginning of Life Fuel Centerline Temperature (7 x 7 Rod)



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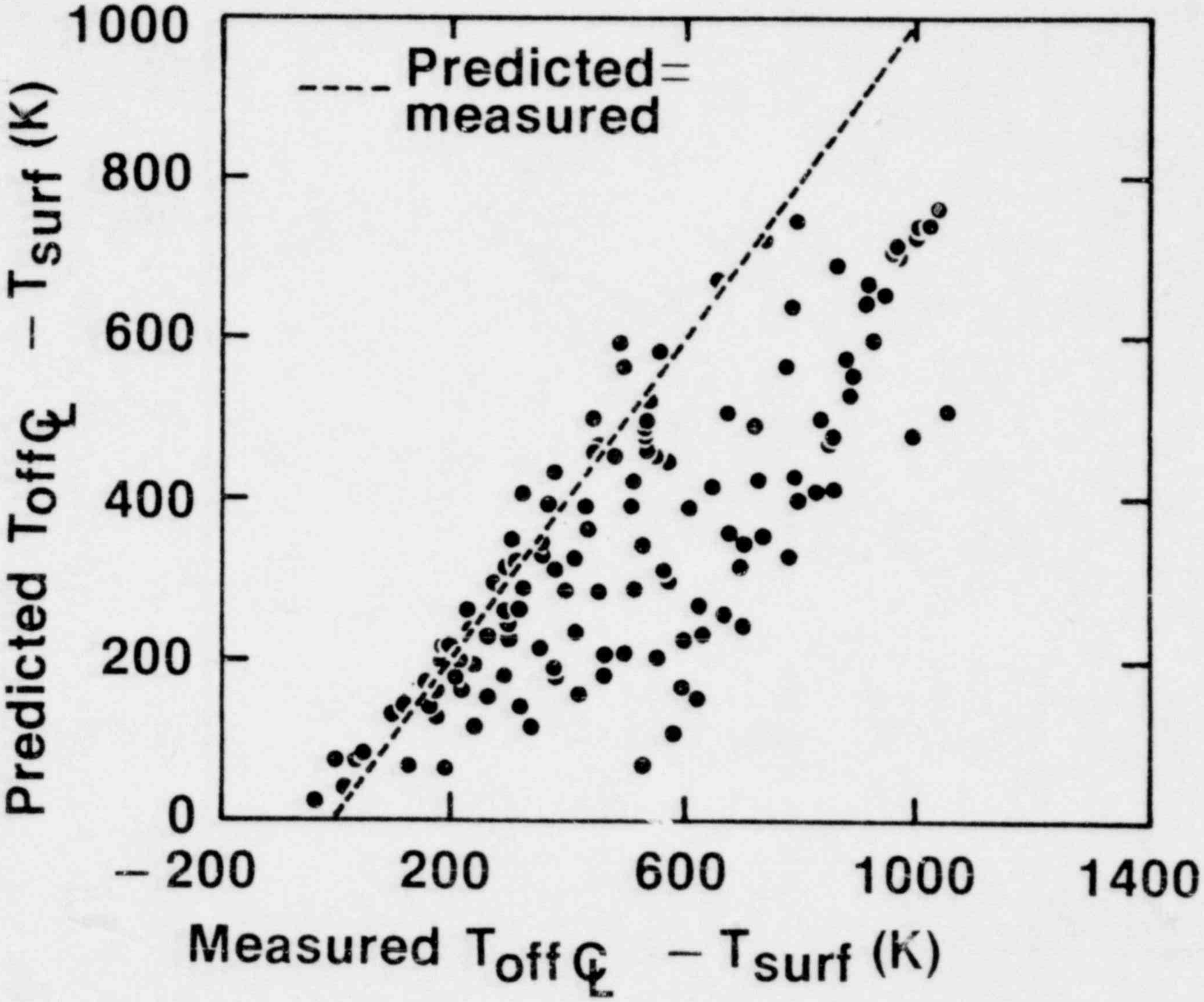
Comparison of Measured and Predicted Temperature Drop in Outer Portion of Fuel Pellet



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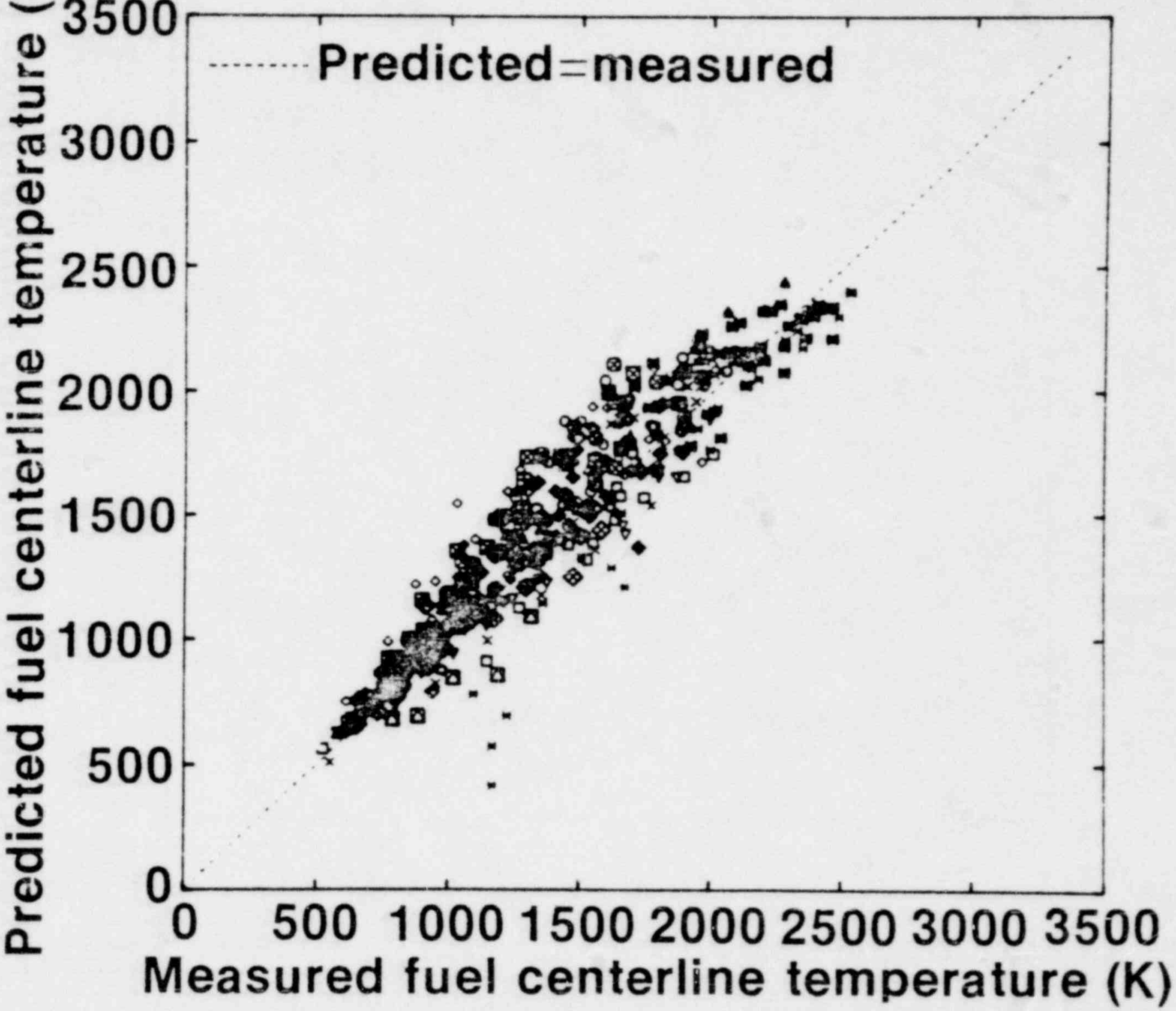
Unpressurized Rods Centerline Temperature Comparison



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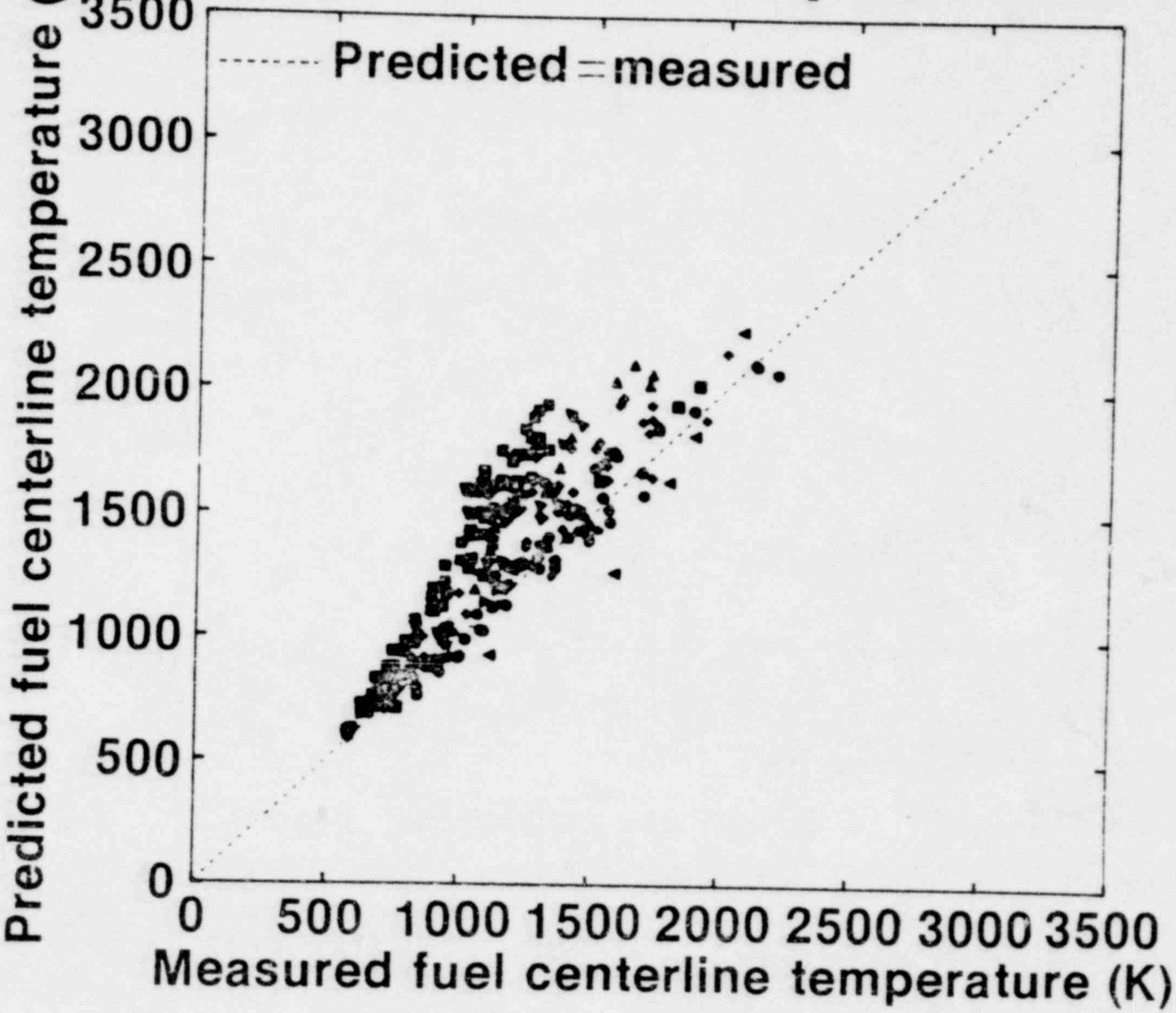
Pressurized Rods Centerline Temperature Comparison



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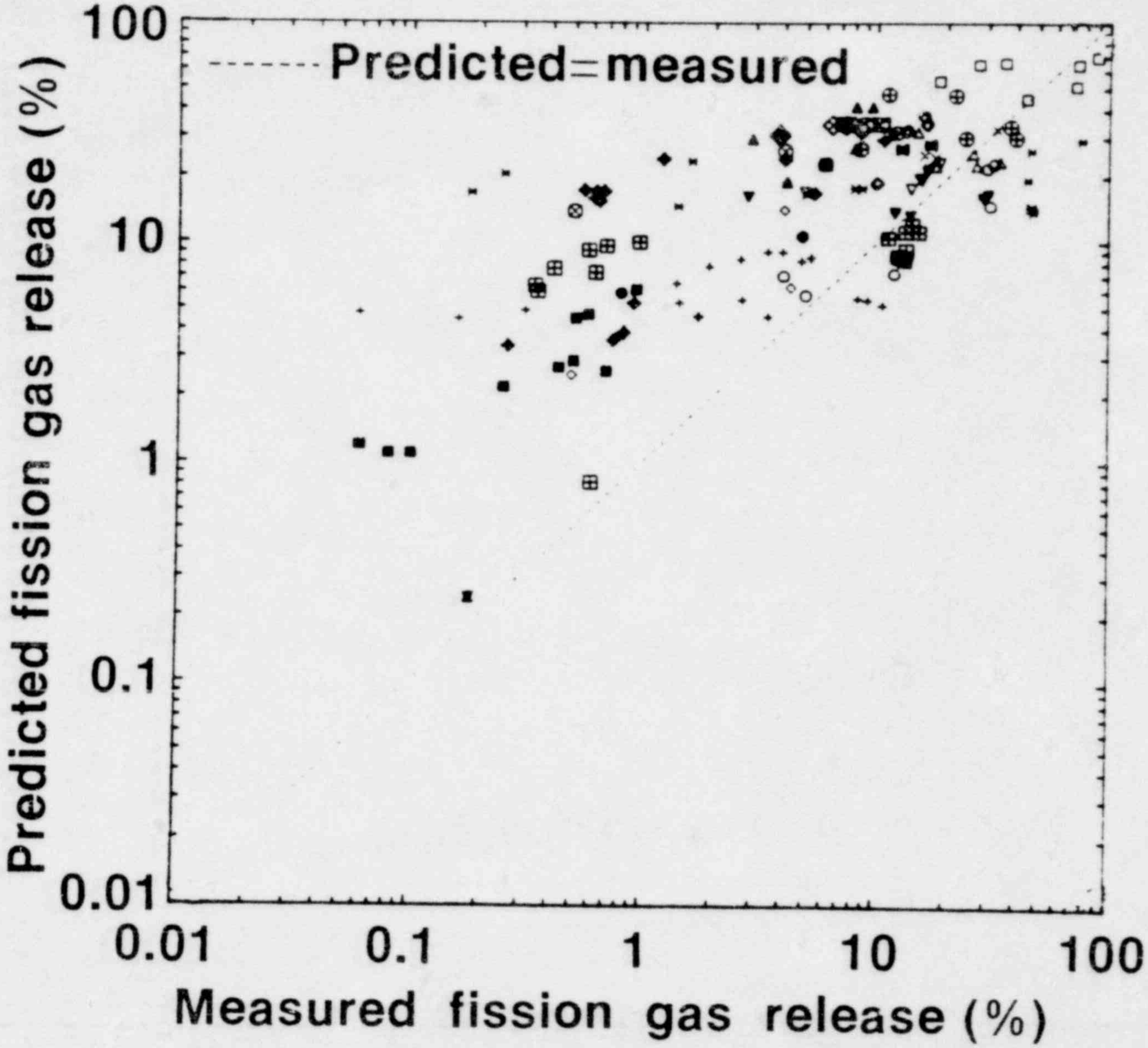
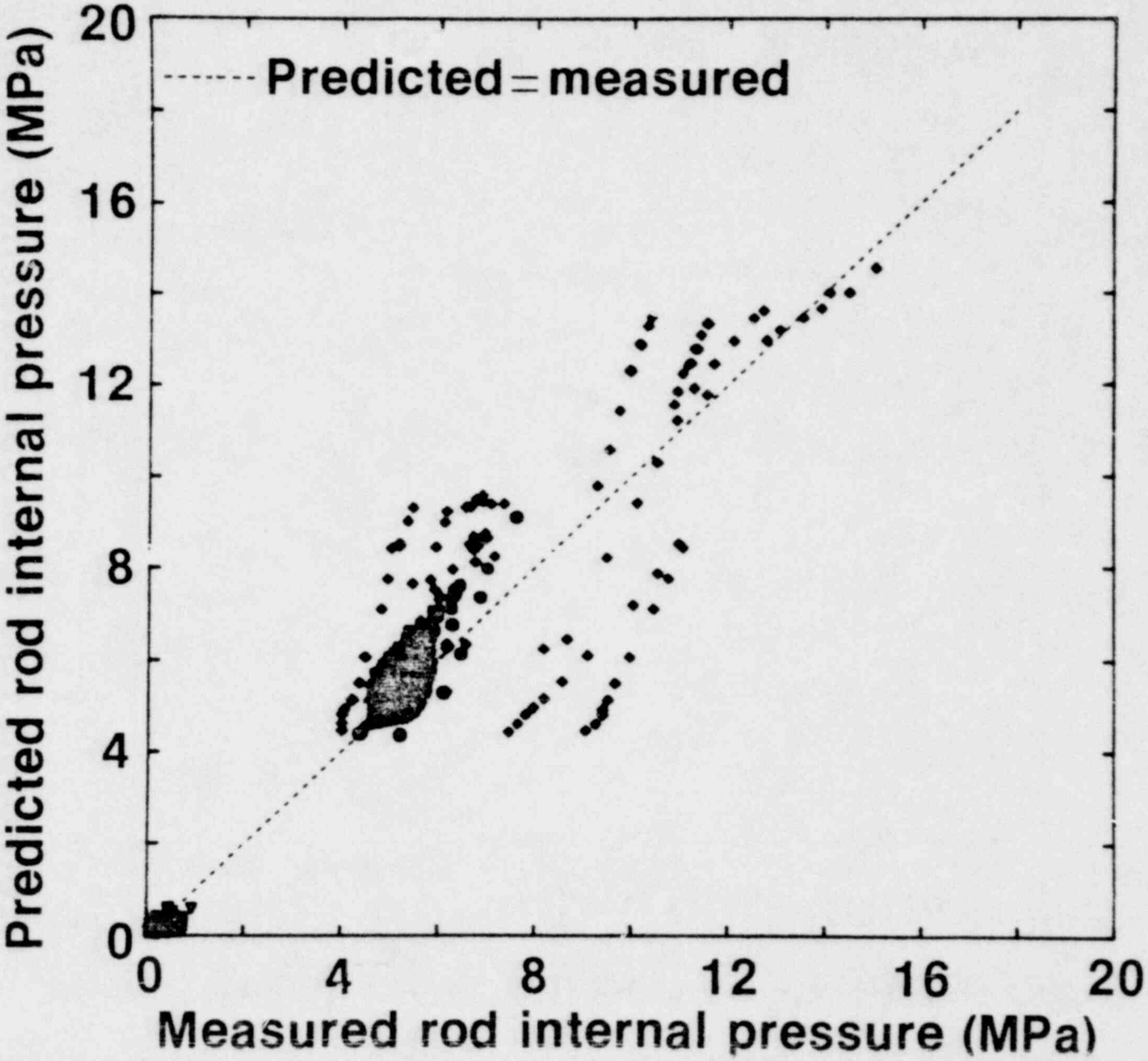
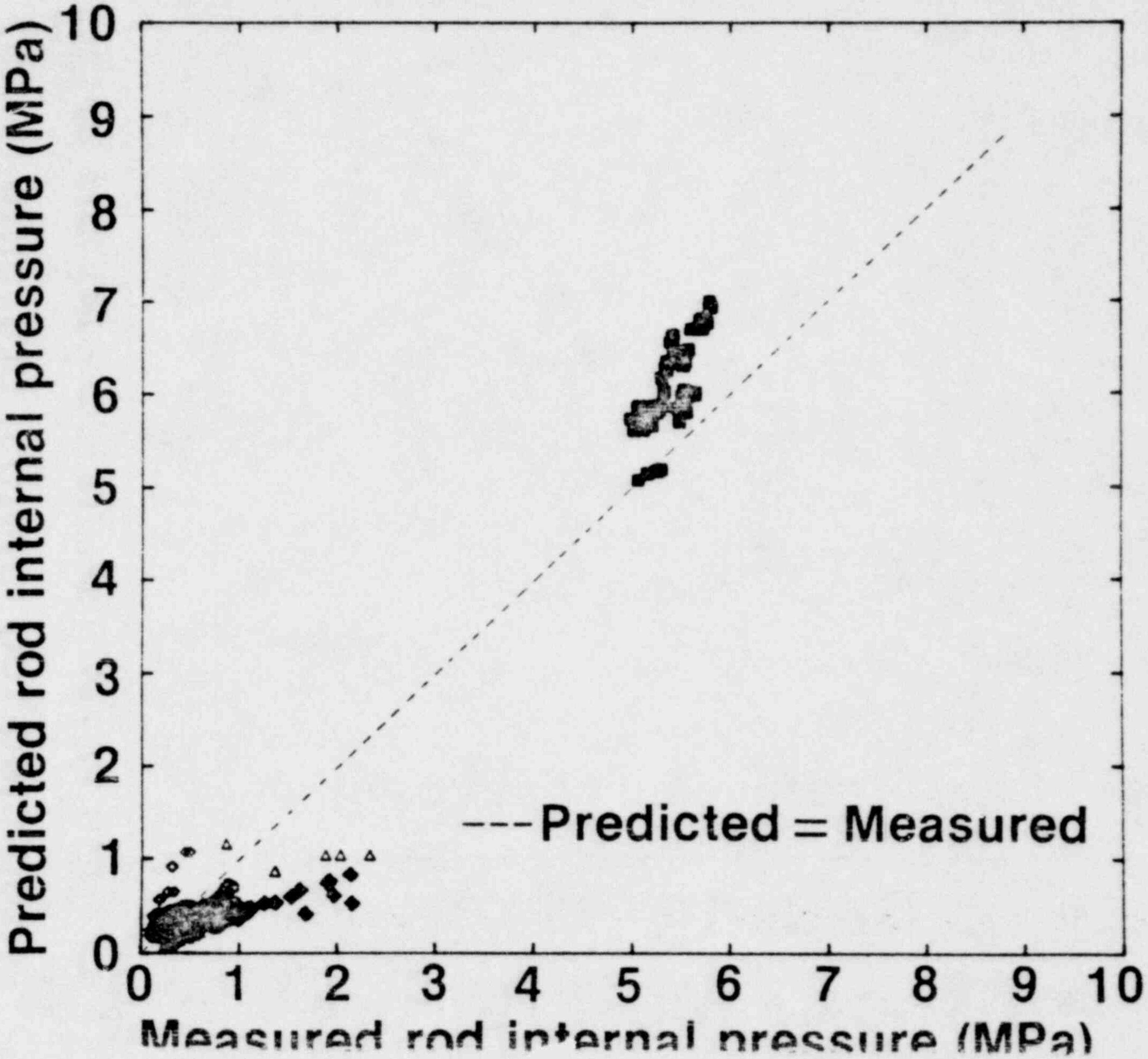
Fission Gas Release



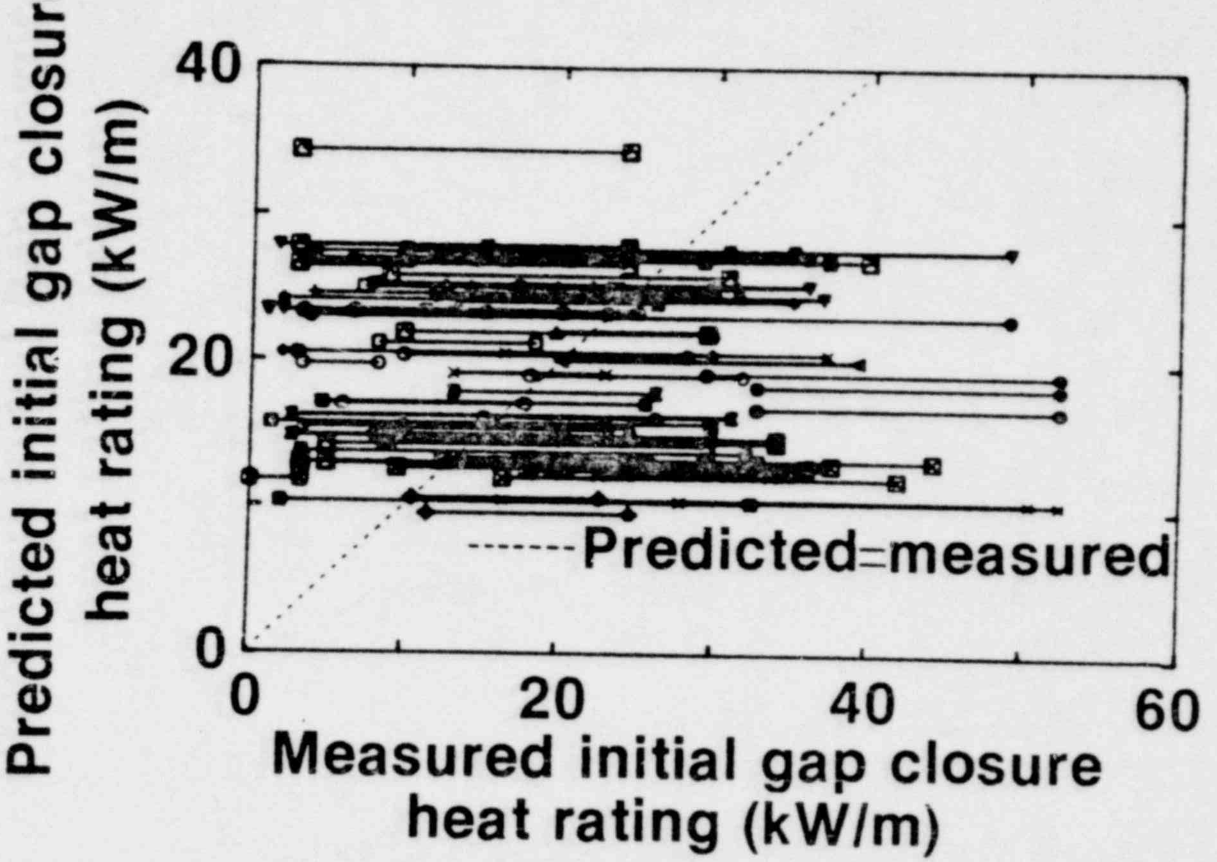
Rod Internal Pressure (Low Burnup)



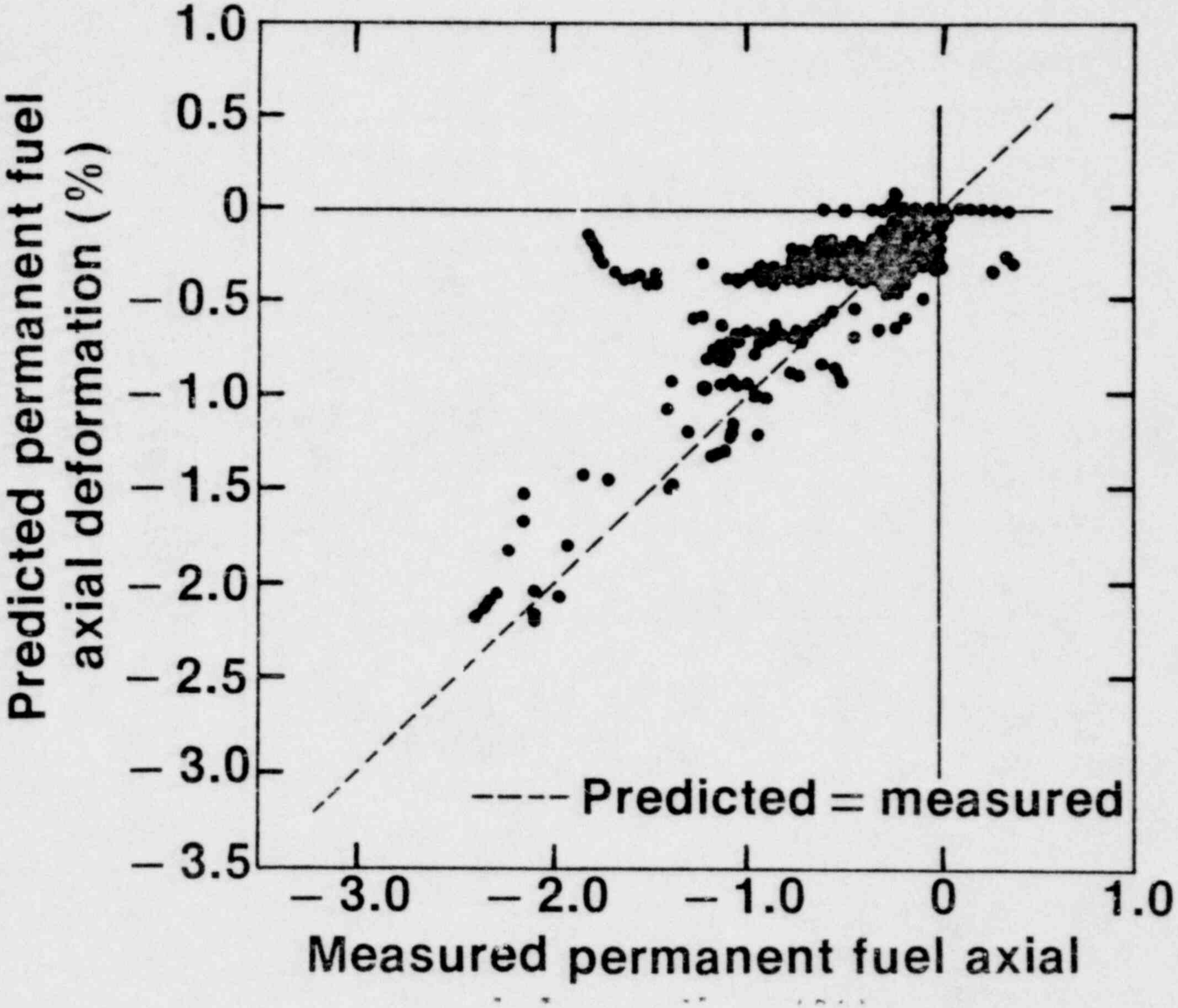
FRAPCON-1 Predicted Against Measured Rod Internal Pressure at High Burnup Conditions



Gap Closure Comparison



Permanent Fuel Axial Deformation Comparison



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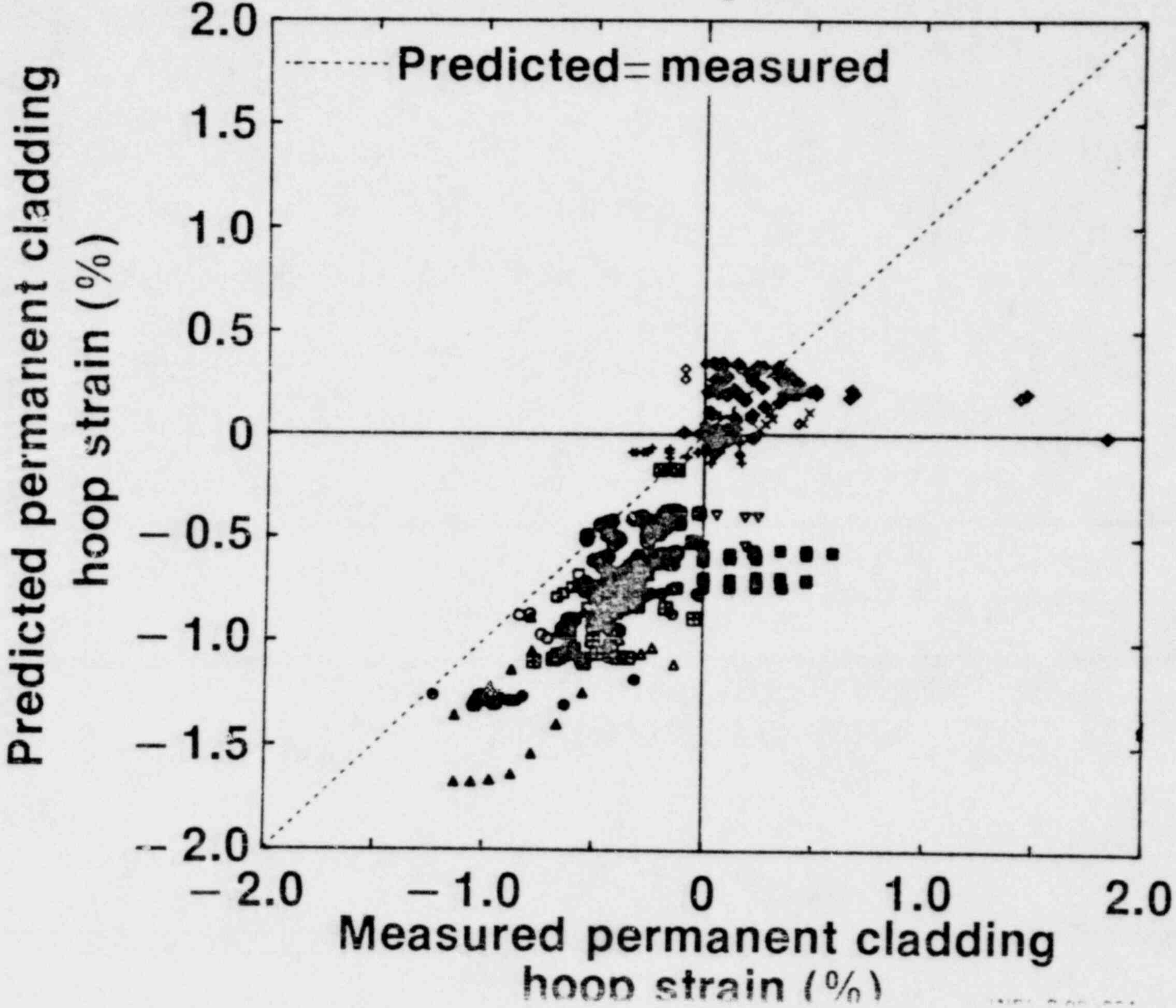
Permanent Cladding Hoop Strain Comparison



FRAPCON-1 Standard Model Error

Output Parameter	Sample Size (Rods/Points)	Standard Deviation
Fuel centerline temperature	32/274 (P) 61/472 (U)	294 K 170 K
Released fission gas	145/145	15.9%
Rod internal pressure	20/330 (U) 28/285 (P)	1.38 MPa 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%

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FRAPCON-1 Standard Model Error

Output Parameter	Sample Size (Rods/Points)	Standard Deviation
Permanent cladding hoop strain	154/358	0.47%
Permanent cladding axial strain	96/119	0.15%
Cladding surface corrosion layer	40/69	5.8 μm
Cladding hydrogen concentration	33/46	37.2 ppm
Gap conductance	17/112 (U) 20/115 (P)	10821 W/m^{2}K 21200 W/m^{2}K
Fuel off-centerline temperature	20/111	208 K

Subjects Analyzed During Independent FRAP-T5 Assessment

- Commercial rod studies
- Code-data comparisons
  - CHF onset
  - Reactor shutdown
  - Reactivity initiated accident
  - Blowdown during LOCA
  - Refill during LOCA

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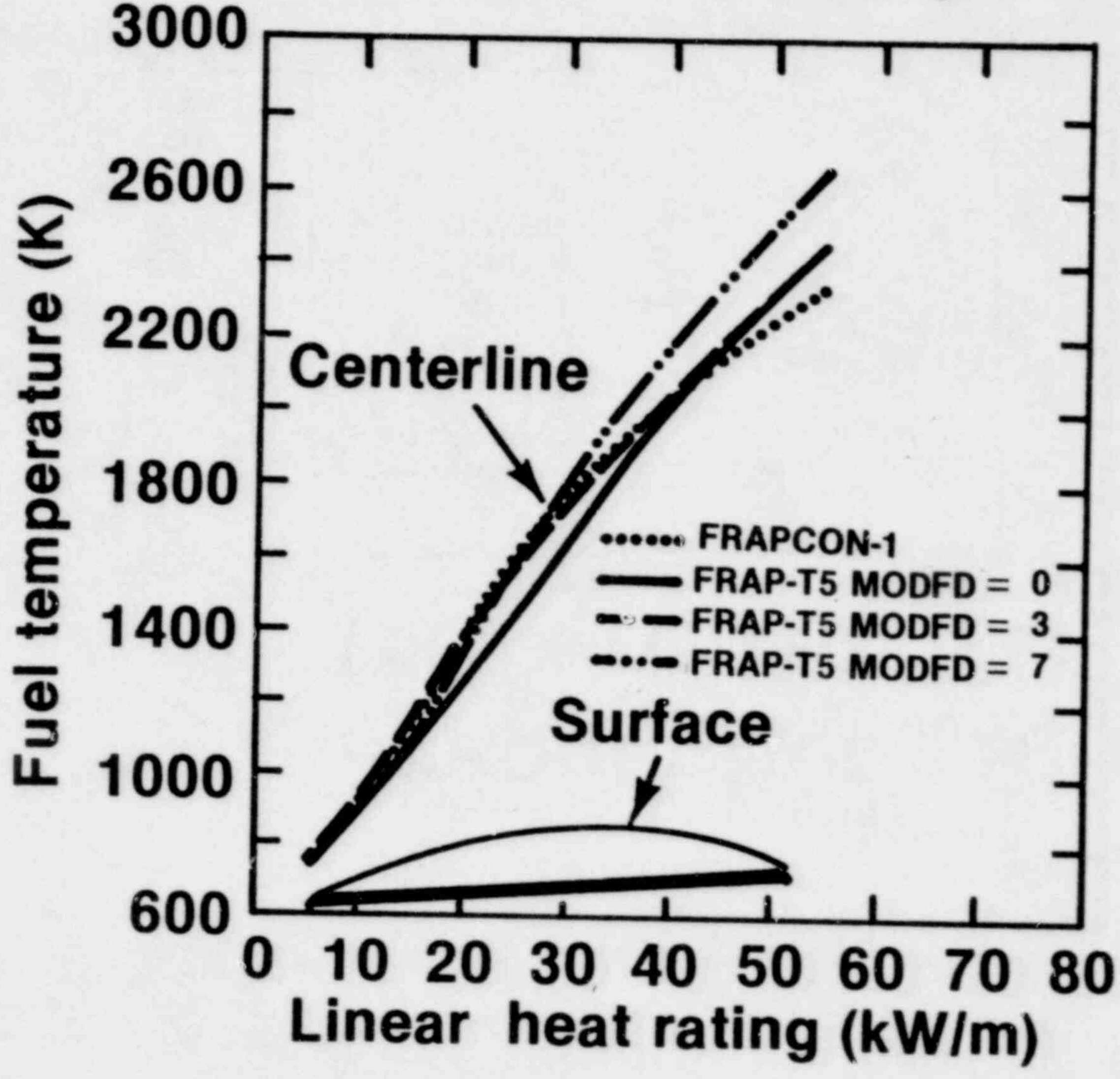
BOL Fuel Temperature
(15 x 15 Rod)



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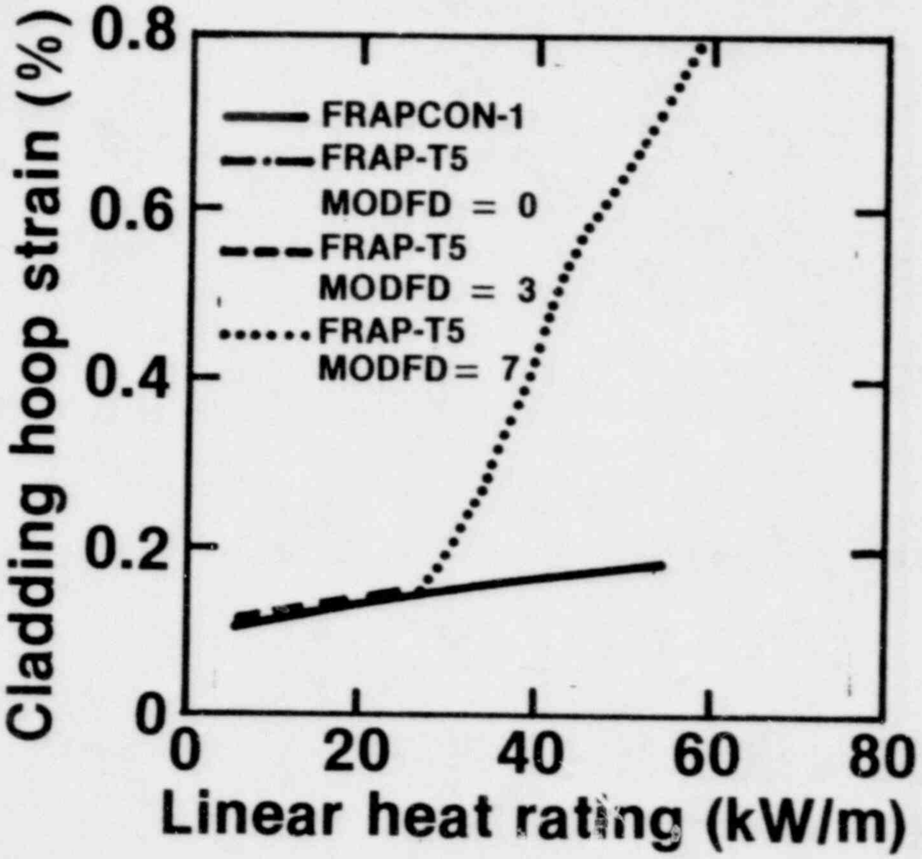
BOL Cladding Hoop Strain
(15 x 15 Rod)



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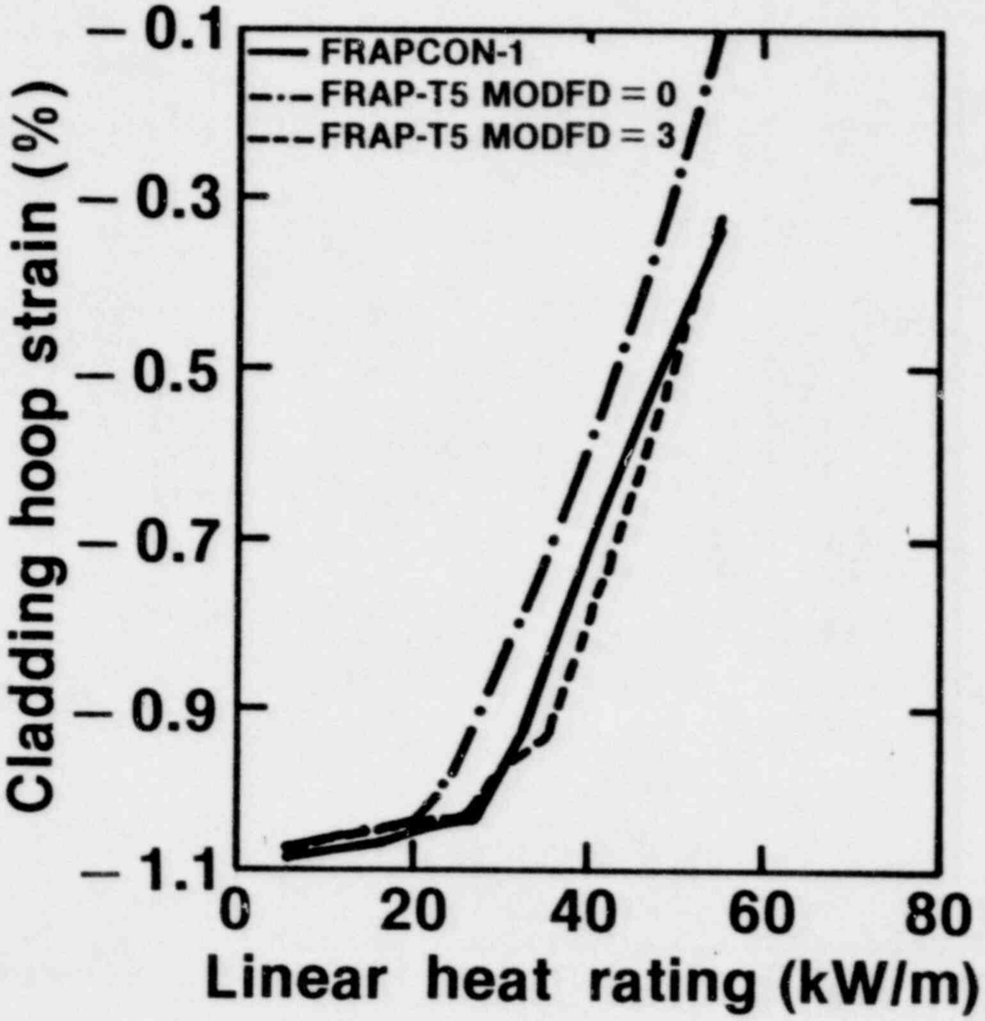
EOL Cladding Hoop Strain
(15 x 15 Rod)



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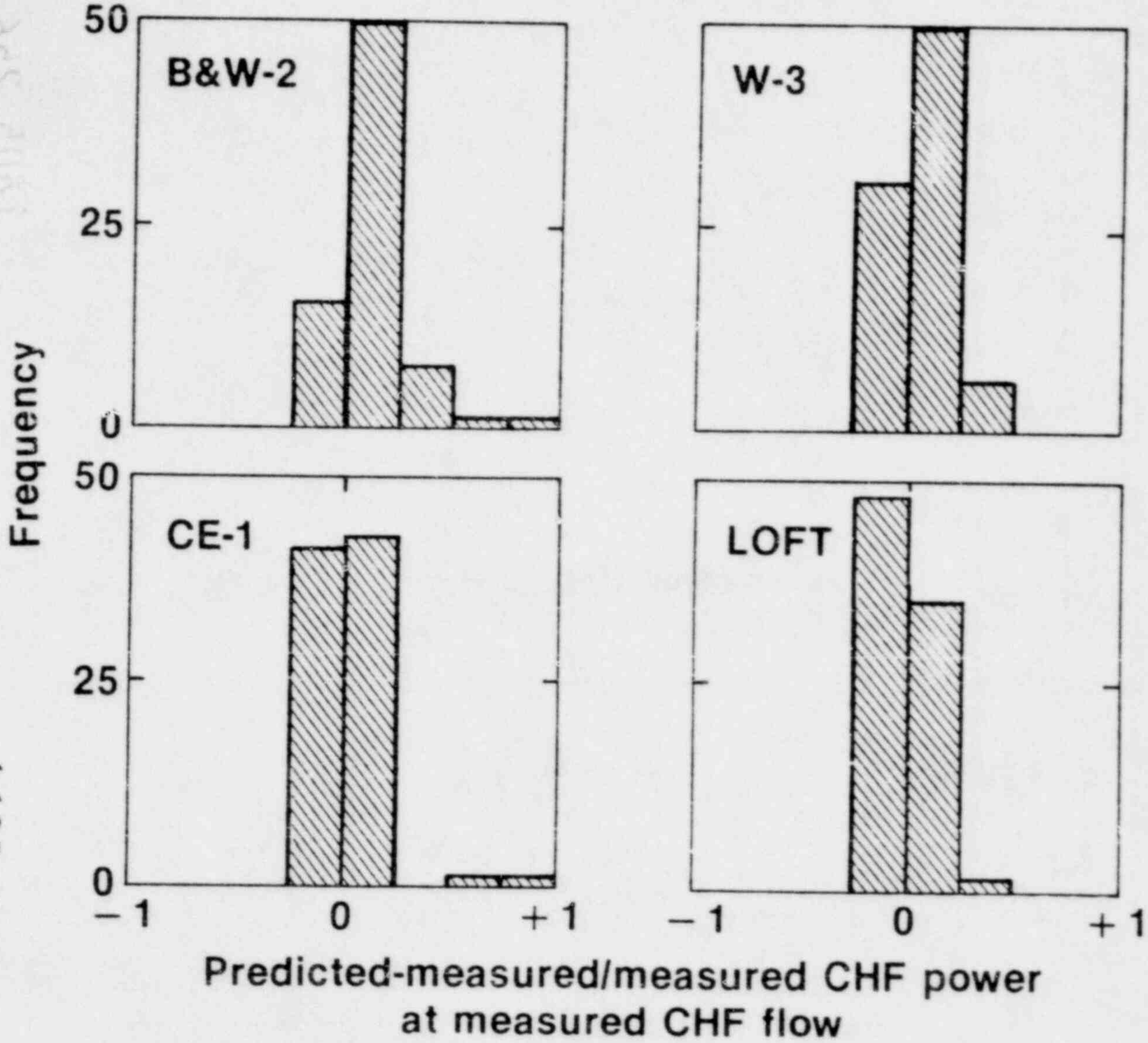
CHF Power Error Under Known Flow Conditions



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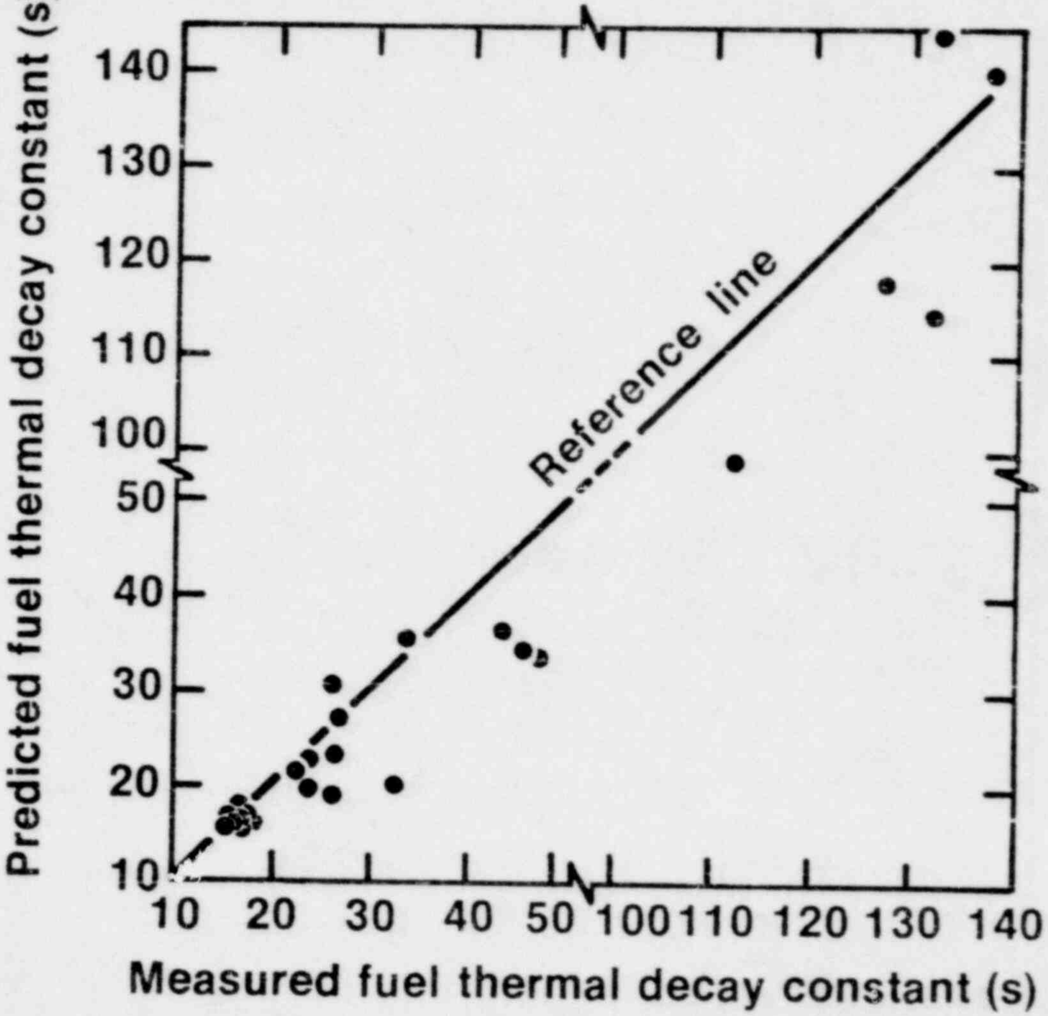
Fuel Thermal Decay Constant Comparison



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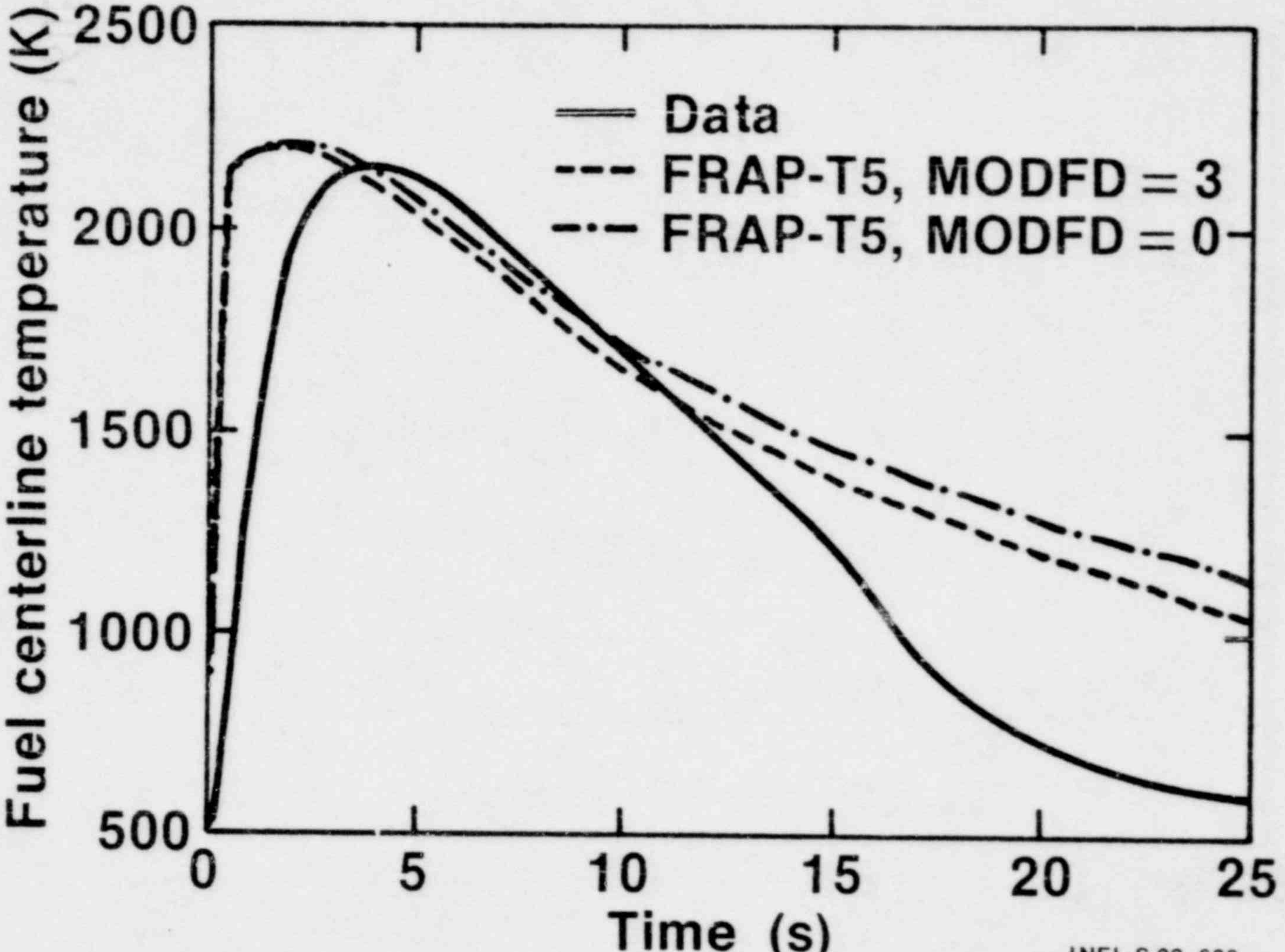
Fuel Centerline Temperature History (RIA 1-1, ROD 801-3)



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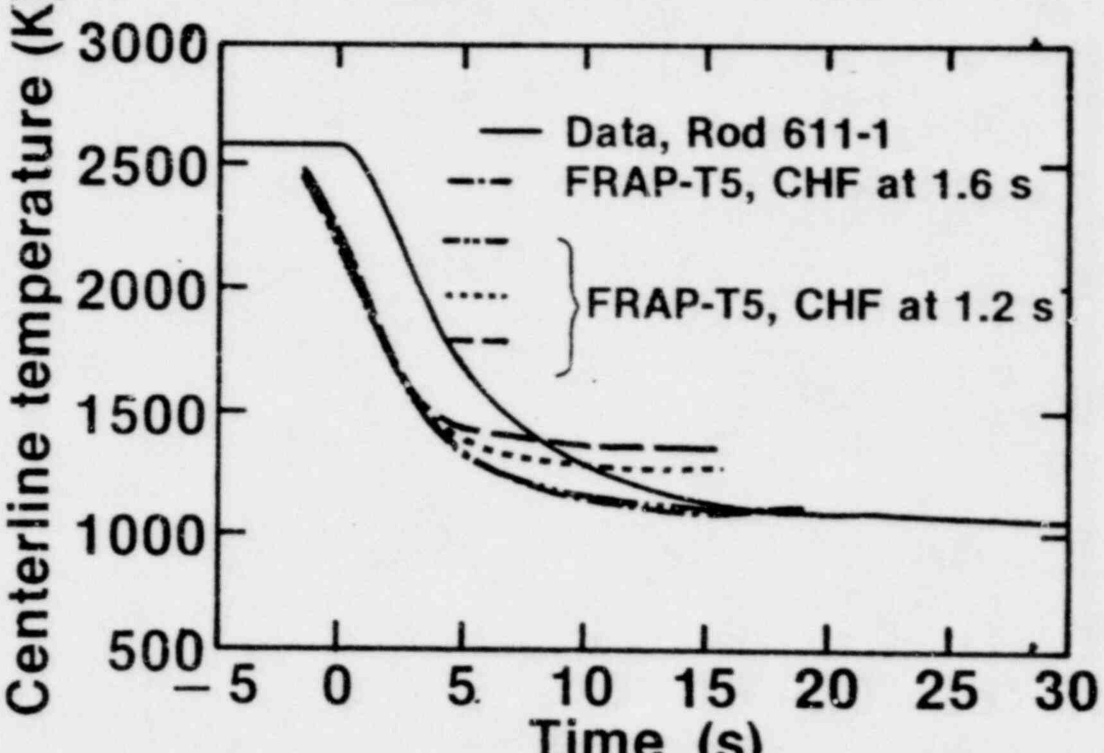
Centerline Temperature History (LOC-11C)



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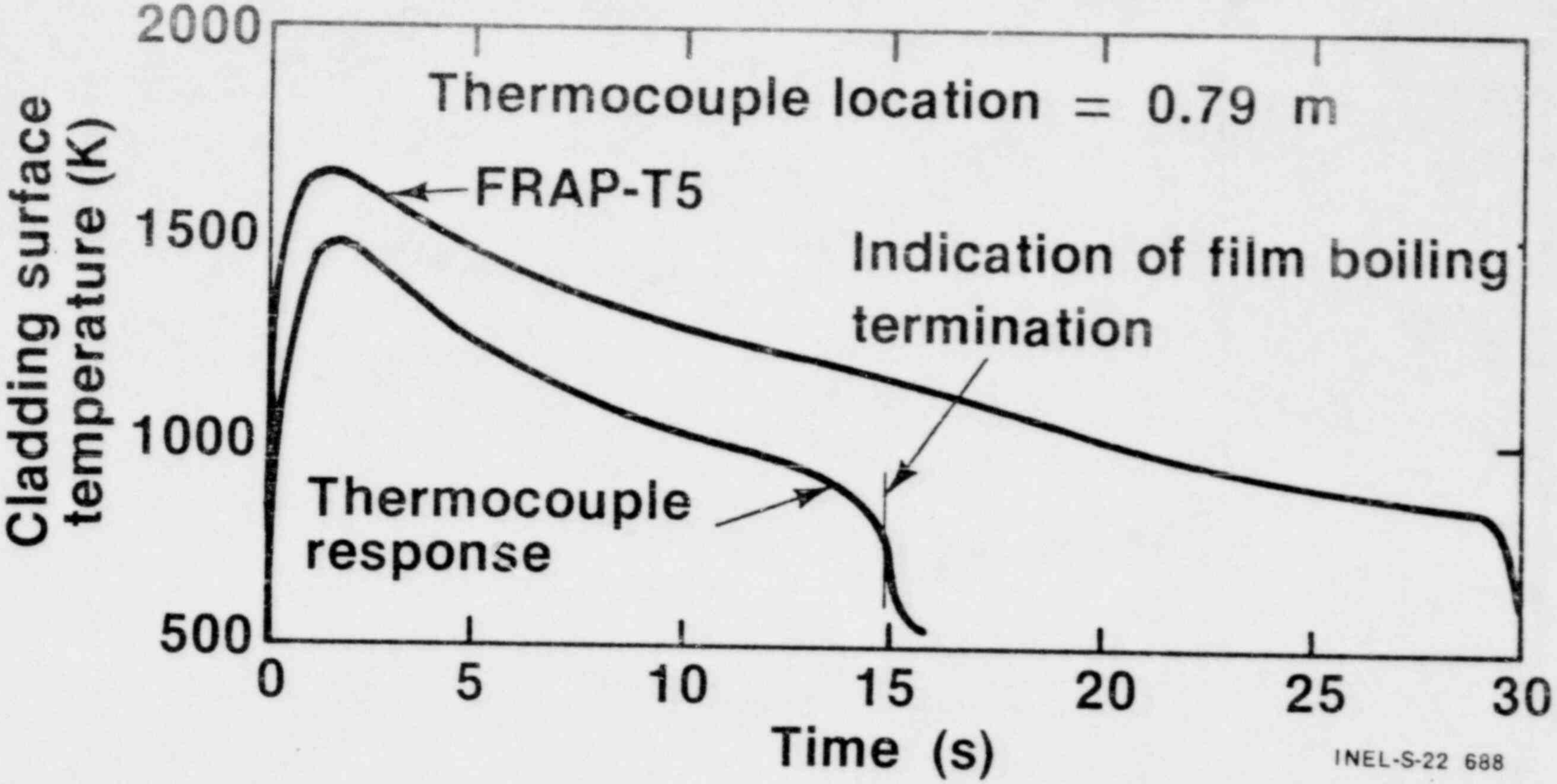
Cladding Surface Temperature History for RIA 1-1, Rod 801-3



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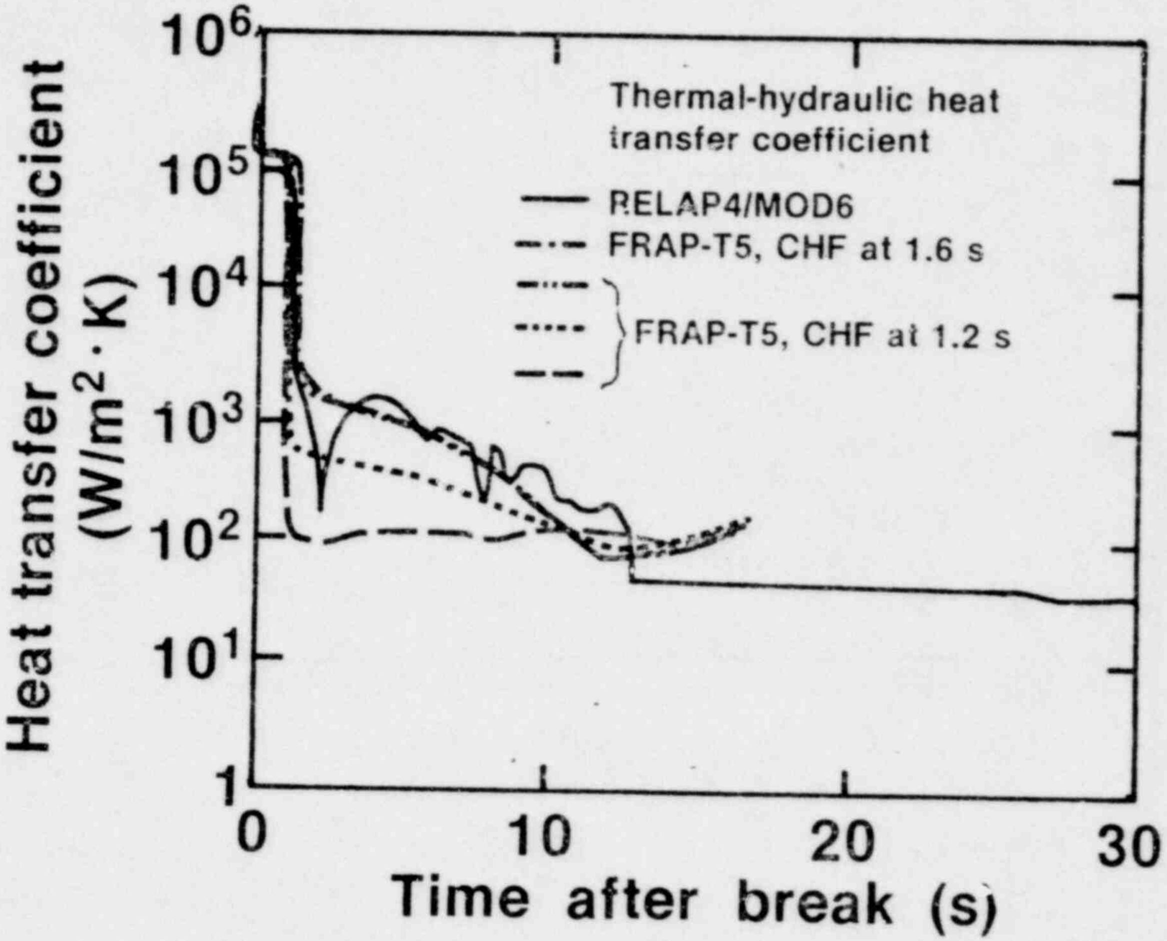
Cladding Surface Heat Transfer History (LOC-11C)



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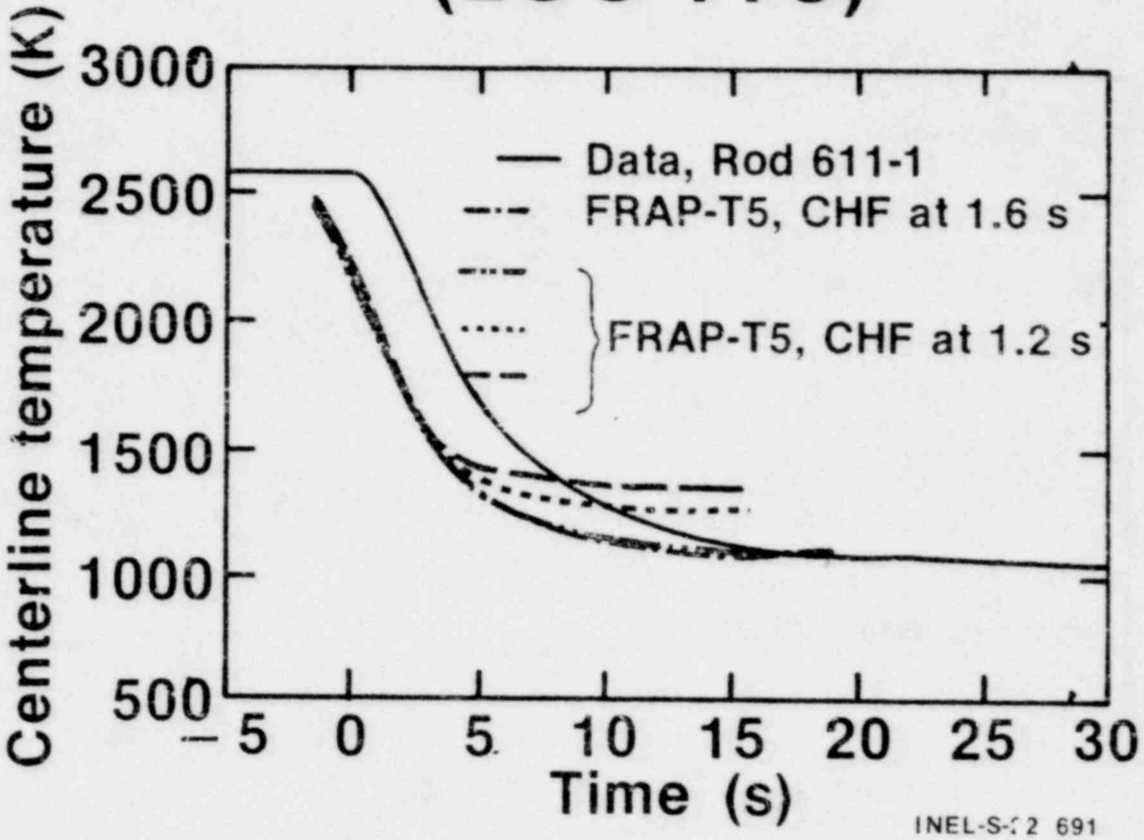
Centerline Temperature History (LOC-11C)



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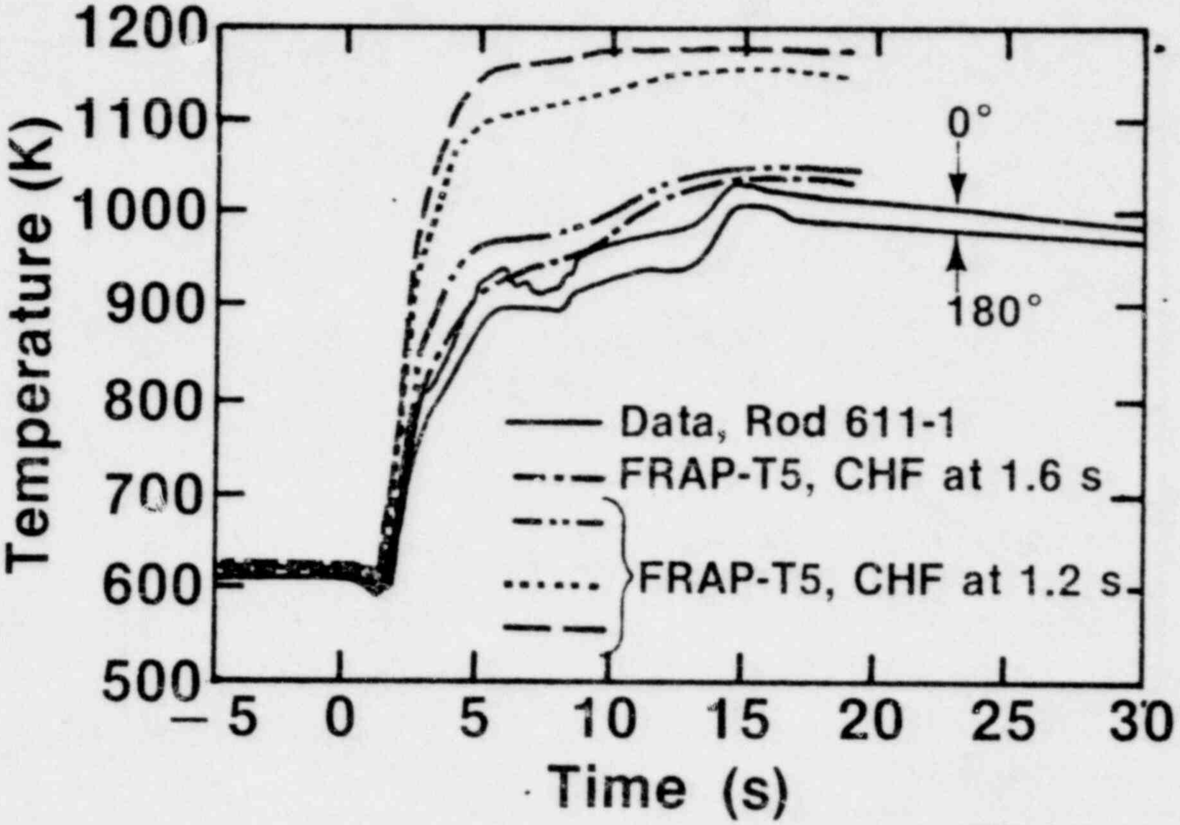
Cladding Surface Temperature History (LOC-11C)



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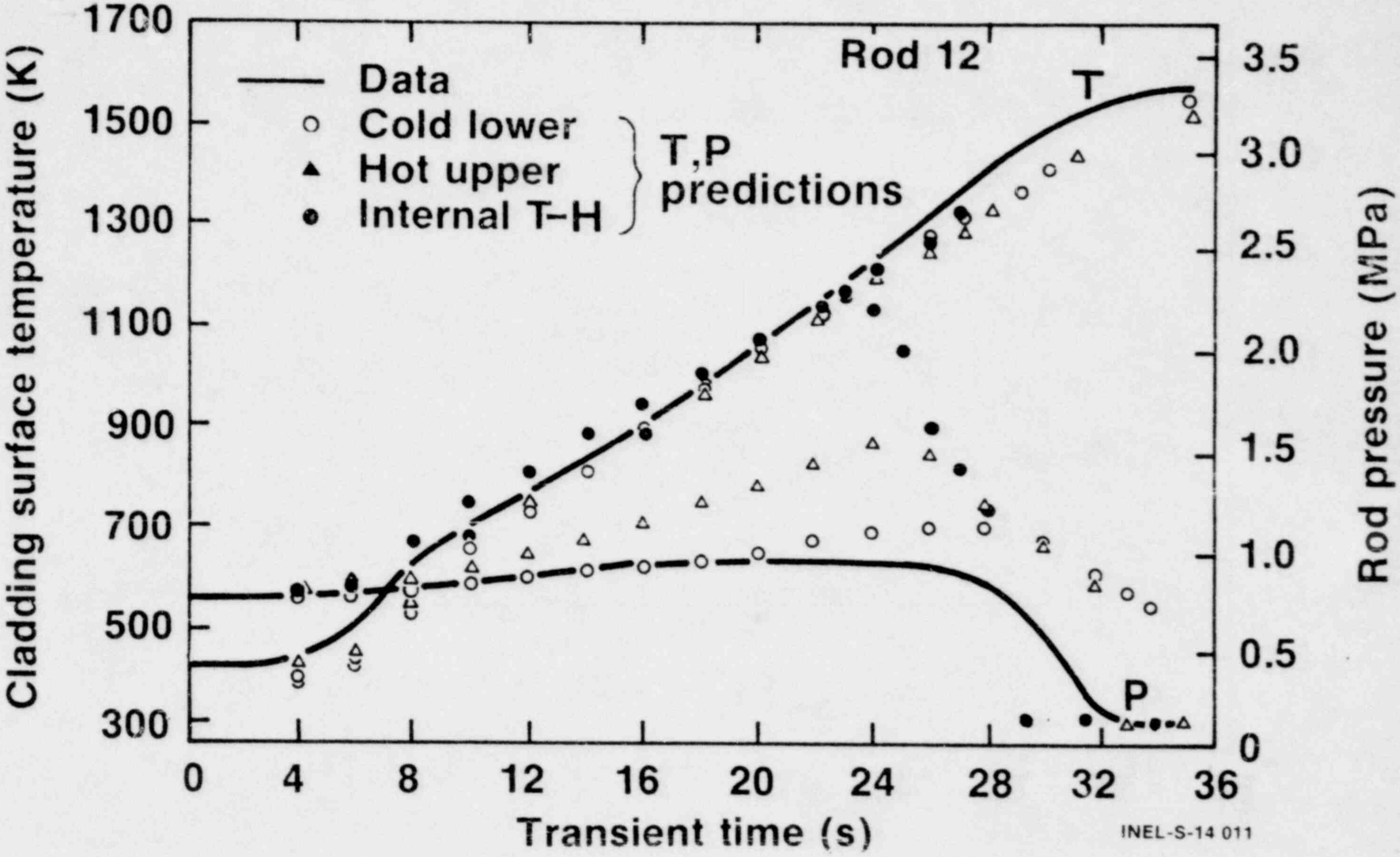
Internal Pressure and Cladding Surface Temperature Response

(TREAT Test FRF-2)



Standard Model Errors

FRAP-T5

Output parameter	Sample (rods/pts)	Standard error $\left[\sum_{i=1}^{n} \frac{(P_i - M_i)^2}{(n-1)}\right]^{0.5}$
CHF power at known flow	30/87	0.04 kW/cm^3 channel
CHF flow at known power	30/87	390 kg/s-m^2
Initial fuel center temperature at shutdown	21/32	250 K
Fuel thermal decay constant during shutdown	21/32	9.7 s
Equilibrium fuel center temperature during shutdown	21/32	57 K

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Summary
FRAPCON-1

- Centerline temperatures are predicted well for unpressurized rods, and generally overpredicted for pressurized rods
- Rod internal pressures are well characterized at startup, but unpressurized rods are underpredicted and pressurized rods are overpredicted at higher burnups
- The extent of permanent fuel deformation is accurately predicted; the extent of permanent cladding deformation is overestimated.

Summary

FRAP-T5

- The steady state models are consistent between FRAPCON-1 and FRAP-T5 at beginning-of-life, and the permanent effects of prior irradiation are correctly passed from FRAPCON-1 to FRAP-T5 at high burnups.

- Adequate onset of CHF modeling is used for PWR system conditions, but deficient for BWR low mass flux conditions.

- During a reactor shutdown event, the rate of centerline temperature decrease is overestimated, but equilibrium temperatures are accurately predicted.

- The thermal performance of FRAP-T5 during RIA and LOCA events is reasonable.

CLADDING STRESS AT FAILURE

Presented at
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Gaithersburg, Maryland

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CLADDING STRESS AT FAILURE

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One of the principal objectives of fuel behavior research is the prediction of the configuration of fuel after severe transients. A recent revision of the cladding failure criteria contained in the MATPRO materials properties package has clarified several aspects of the experiment data and promises to place analytical code predictions on a much sounder basis than has previously been possible.

The new cladding failure criterion is true tangential stress. Arguments are presented which demonstrate that cladding failure should be predicted by comparing the tangential component of true stress to the failure stress. Heating rate and strain rate do not affect this criterion but irradiation and cold work increase it somewhat. The failure stress as a function of temperature is given by the following expressions.

For temperatures less than or equal to 750 K,

$$\sigma_{\theta F} = 1.36\ K_A \tag{1}$$

For temperatures between 750 and 1050 K,

$$\sigma_{\theta F} = 46.9\ K_A \exp \quad - \frac{2.0*10^6}{T^2} \tag{2}$$

For temperatures greater than or equal to 1050 K,

$$\sigma_{\theta F} = 7.7\ K_A \tag{3}$$

where

$\sigma_{\theta F}$ = tangential component of true stress at burst (Pa)

K_A = strength coefficient for annealed cladding as determined with the MATPRO CKMN subcode (Pa)

T = temperature (K).

For cold-worked or irradiated cladding the failure stress is increased by four tenths of the increase of the strength coefficient due to irradiation and cold work.

The new failure criterion has been coupled to a modified version of the BALLOON code to show that cladding shape at burst is dependent on all the variables which affect the cladding deformation history. Burst temperatue, burst pressure, axial temperature gradients, and circumferential temperature gradients play a major role in determining the final cladding shape.

Cladding Stress at Failure

Presented by
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1605 272

Cladding Stress at Failure

- Previous cladding failure criteria
- Model development
- Cladding shape at failure
- Conclusions

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Previous Cladding Failure Criteria (FRAIL)

- Failure criteria based on correlations for
    - Engineering failure strain (total circumferential elongation)
    - Engineering failure stress

- Failure probabilities calculated with each correlation and largest probability assumed

- Inconsistent probabilities, large uncertainties and important new data suggested need for revision

Present Cladding Failure Criterion

- Failure predicted when true stress exceeds failure stress at any location
- $\sigma_{\theta \text{failure}} = A K + 0.4 \Delta K$

K = Strength coefficient of annealed zircaloy

ΔK = Change in K due to cold work and irradiation

A = 7.7 for temperatures above 1050 kelvin, 1.36 for temperatures below 750 kelvin

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Model Development (I)

Data set collected using tests which reported

- Initial cladding dimensions
- Total Circumferential Elongation (TCE)
- Temperature and pressure at failure
- Wall thickness at failed region
- Estimated radii of curvature (axial and azimuthal)

1605 276

INEL-S-22 626

Model Development (II)

Data were used to test four proposed failure criteria

- Engineering strain (TCE)
- Engineering stress
- Local strain
- True stress

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R. H. Chapman, Multirod Burst Test Program Quarterly Report for April - June 1977, ORNL/NUREG/TM-135 (December 1977).

R. H. Chapman, J. L. Crowley, A. W. Longest and E. G. Sewell, Effect of Creep Time and Heating Rate on Deformation of Zirçaloy-4 Tubes Tested in Steam with Internal Heaters, ORNL/NUREG/TM-245 and NUREG/CR-0345 (October 1978).

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■ D. O. Hobson and P. L. Rittenhouse, Deformation and Rupture Behavior of Light-Water Reactor Fuel Cladding, ORNL-4727 (October 1971).

▲ H. M. Chung and T. F. Kassner, Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam Under Transient-Heating Conditions: Summary Report, ANL-77-31 and NUREG/CR-0344 (July 1978).

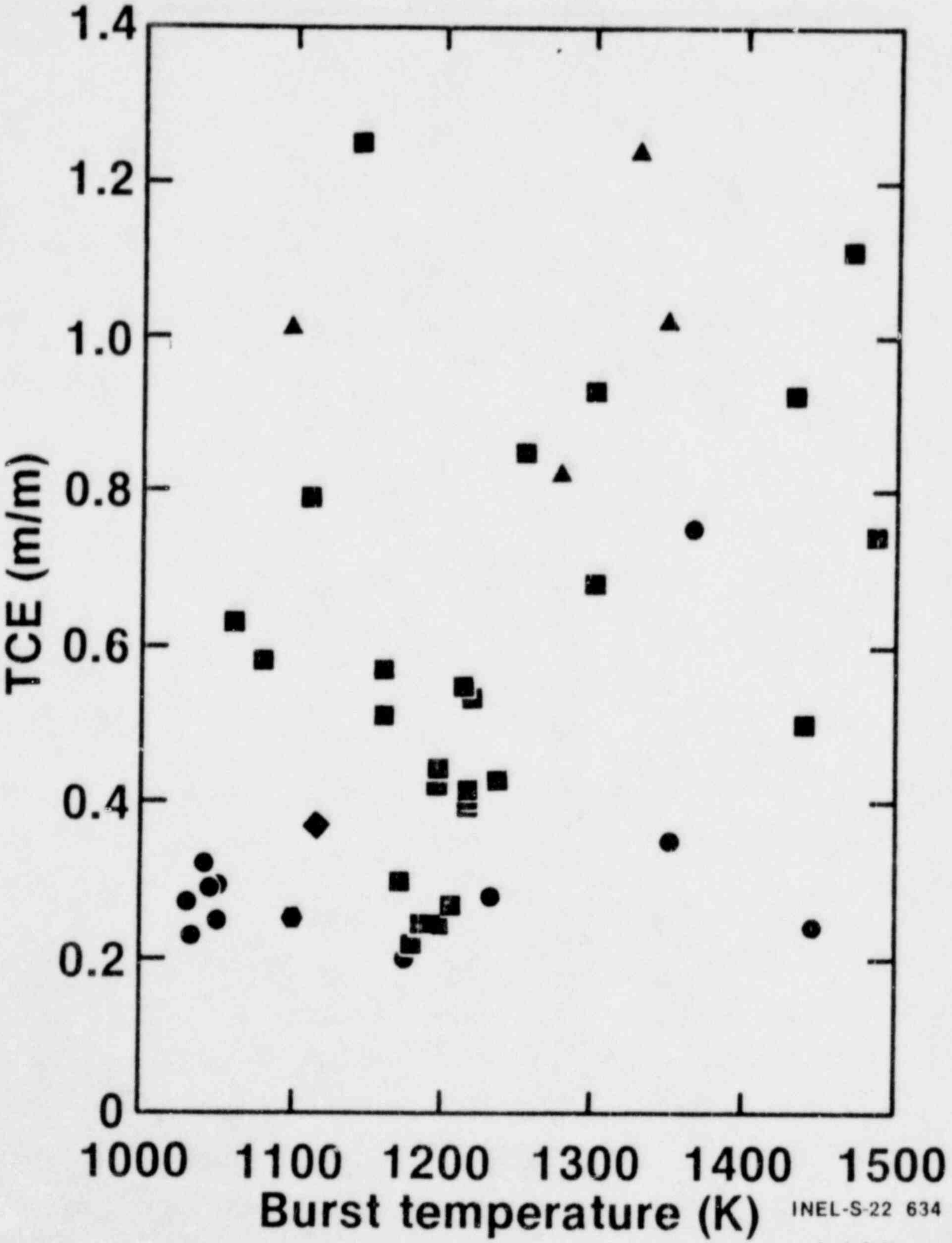
● T. F. Cook, S. A. Ploger and R. R. Hobbins, Postirradiation Examination Results for the Irradiation Effects Test IE-5, TREE-NUREG-1201 (March 1978).

▬ E. H. Karb, "Results of the FR-2 Nuclear Tests on the Behavior of Zircaloy Clad Fuel Rod", Paper presented at the 6th NRC Water Reactor Safety Research Information Meeting, Gaithersburg, Maryland, November 1978.

◆ K. Wiehr and H. Schmidt, Out-of-Pile Versuche zume Aufblahvorgang von Zirkaloy-Hullen. Ergebnisse aus Vorversuchen mit verkurzten Brennstabsimulatoren, KfK 2345 (October 1977).

1605 279

Total Circumferential Elongation Versus Temperature



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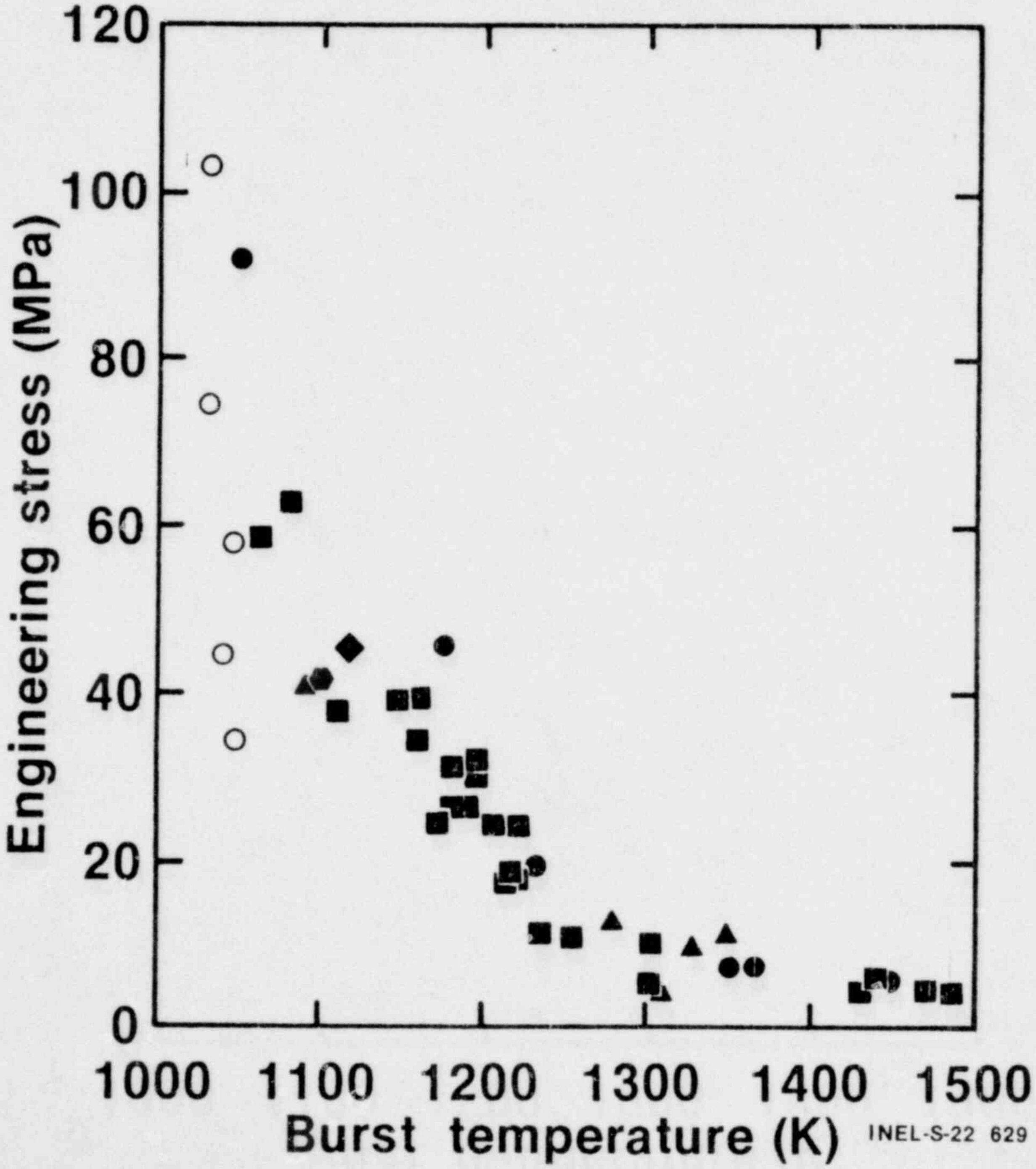
Engineering Stress Versus Temperature



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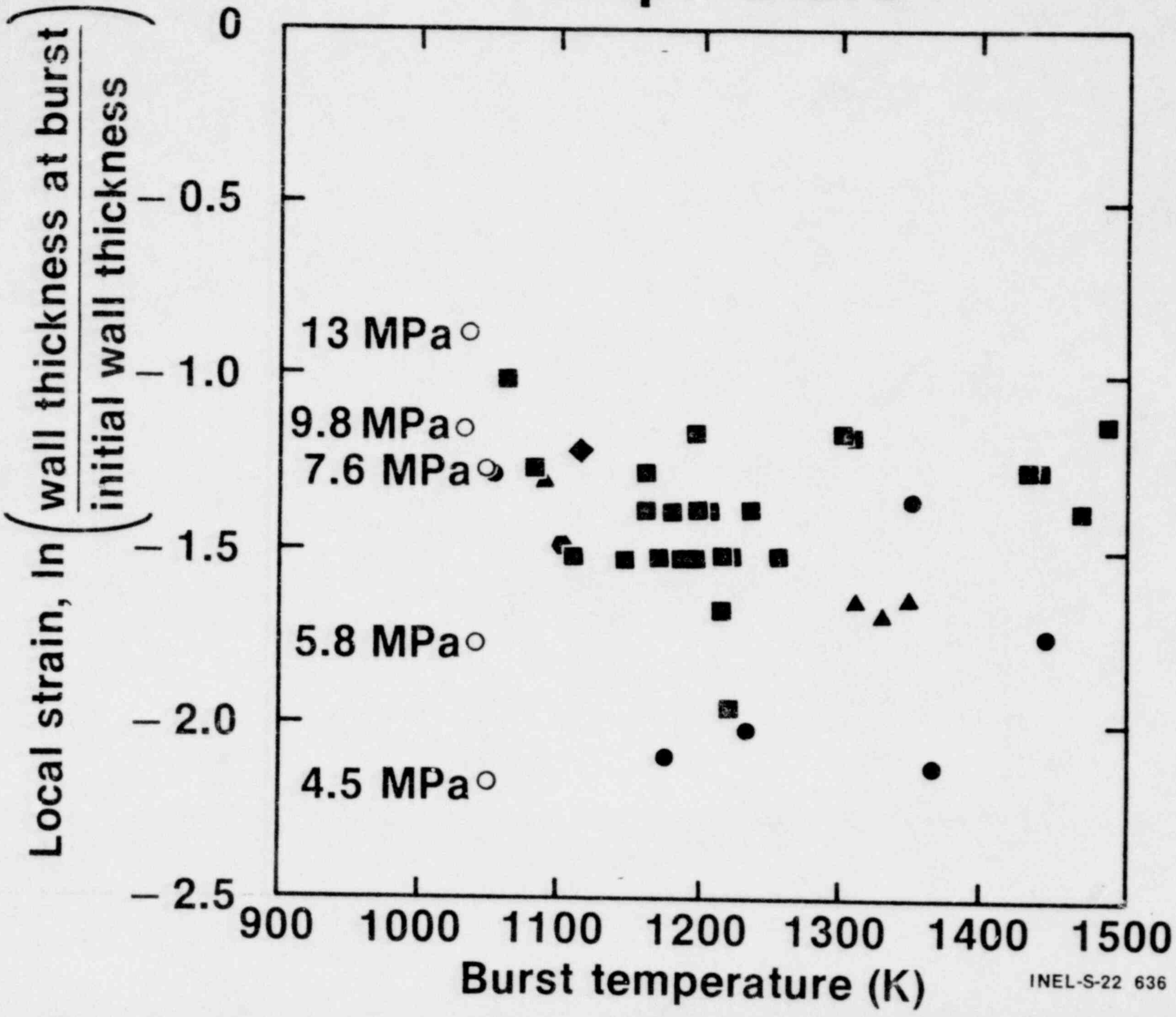
Local Strain Versus Temperature



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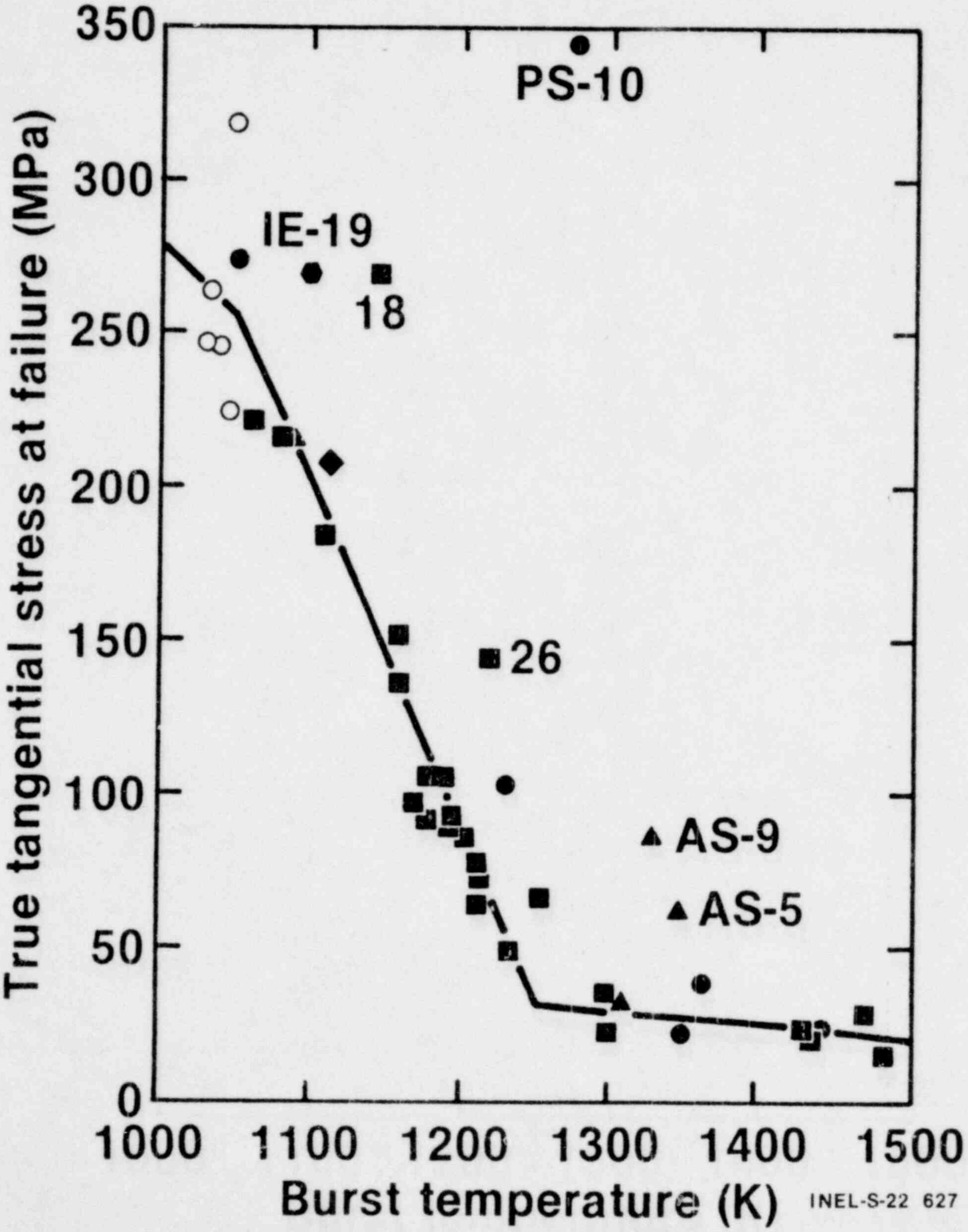
True Stress at Failure vs Temperature



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1605 283

Cladding Shape at Failure

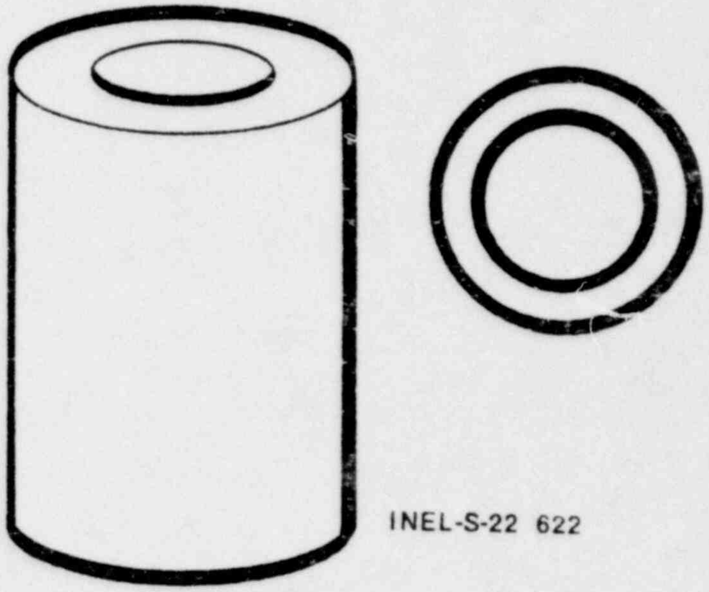
- New failure criterion intended to improve predictions of cladding shape at failure
  - Calculate cladding shape versus time with a mechanical code
  - Failure occurs when $\sigma_\theta = \sigma_{\theta\ \text{failure}}$ anywhere
- This approach explains the large scatter in TCE. TCE is sensitive to:
  - Temperature versus time
  - Temperature versus position
  - Pressure versus time
- Closed form solutions for symmetric deformation provide insight

Cladding Shape at Failure

- For axial and azimuthal symmetry

$$\sigma_\theta = \frac{PR}{W} = \frac{PR_o \exp(\varepsilon_\theta)}{W_o \exp(-\varepsilon_\theta)}$$

or $$\varepsilon_\theta = \mathrm{Ln}\sqrt{\frac{W_o\,\sigma_\theta}{PR_o}}$$



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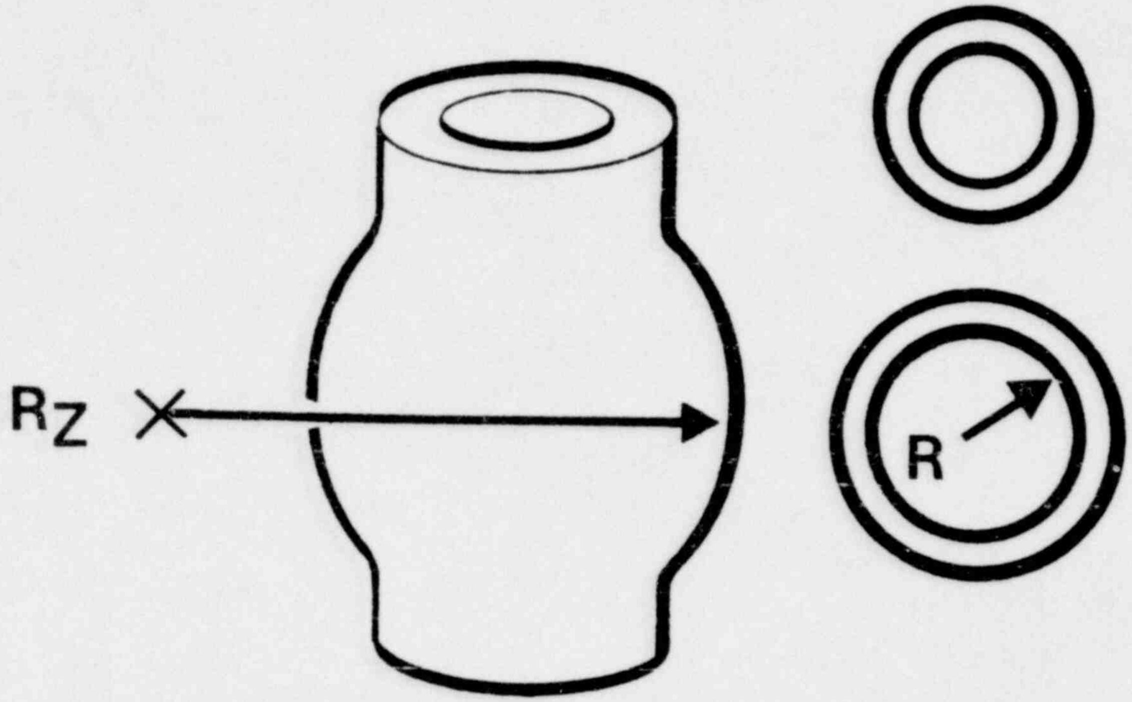
Cladding Shape at Failure

- For azmuthal symmetry



$$\varepsilon_\theta = \text{Ln}\left[\sqrt{\frac{W_o\,\sigma_\theta}{PR_o}} + \frac{\sigma_z W_o}{2PR_z} + 1/2\left(\frac{\sigma_z W_o}{2PR_z}\right)^2\right]$$

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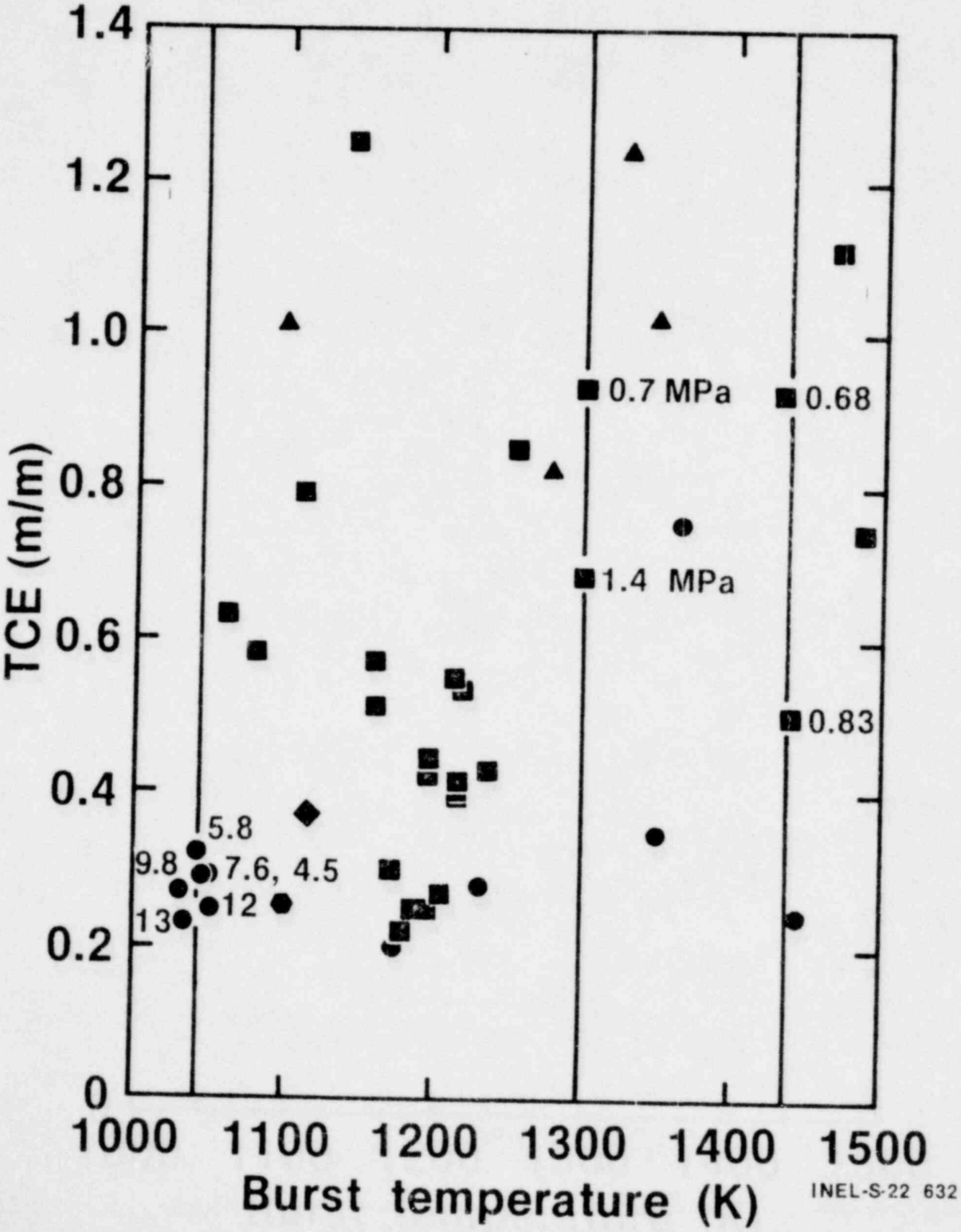
Total Circumferential Elongation Versus Temperature



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Cladding Shape at Failure

- For nonsymmetric deformation a modified version of BALLOON used
  - Perturbation theory approach (Kramer and Dietrich ANL-77-95)
  - Anisotropy added
  - MATPRO equation of state for plastic deformation
  - MATPRO cold work annealing model
  - Input pressure and temperature versus time

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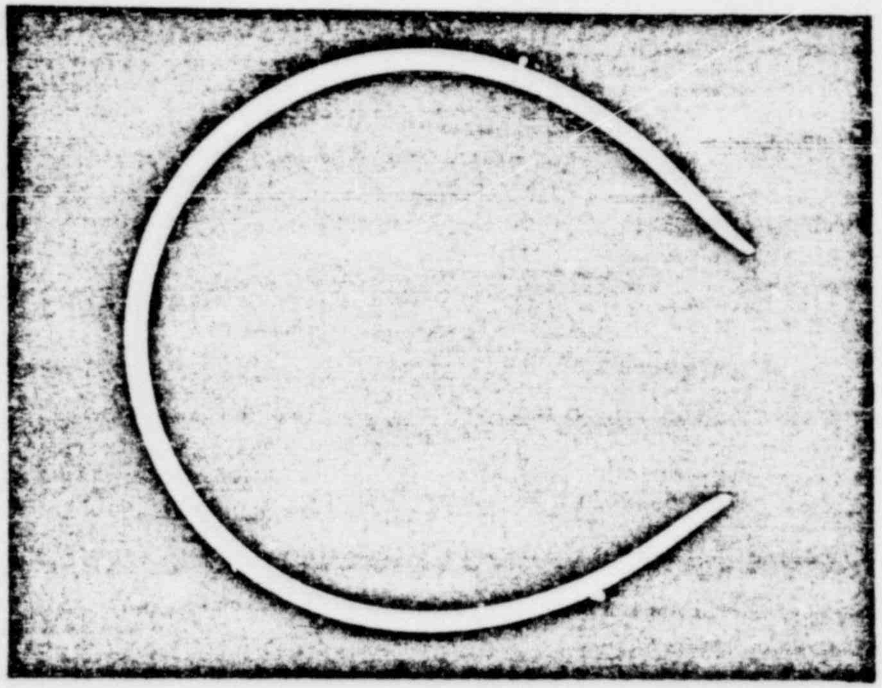
- Preliminary comparison to ORNL/NUREG/ TM-245 data consistent with true stress interpretation

Test SR-37 Cross Section

SR-37



TCE 23%
Elevation 18.0 cm
Time to burst 17.4 s

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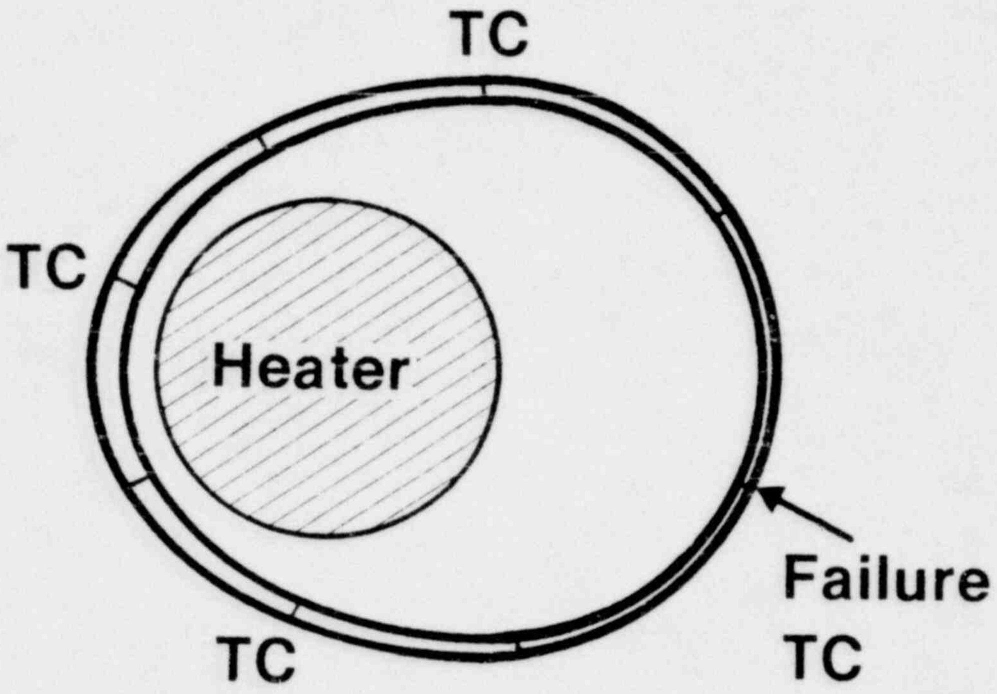
Code Predicted Cross Section



TCE 57%
Elevation 18.7 cm
Time to burst 18.4 s

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Cladding Shape at Failure

- TCE away from burst area predicted accurately
- Large predicted strains in burst area caused by
    - Temperature averaging between thermocouple locations
    - Coarse model grid (8 circumferential and 8 axial nodes)
    - Deformation sensitivity to unknown axial temperature gradients
- Predicted strain accurate at 67 cm because strain much less sensitive to small input errors when strain is small

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Conclusions

- Cladding failure during ballooning best described by true stress
- Cladding shape at (after) burst affected by all variables which affect deformation history
- Preliminary experience with coupling mechanical codes to new failure criterion has explained scatter in TCE versus temperature plots

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