Cladding Stress at Failure

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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

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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)

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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 Zircaloy-4 Tubes Tested in Steam with Internal Heaters, ORNL/NUREG/TM-245 and NUREG/CR-0345 (October 1978).

R. H. Chapman, Multirod Burst Test Program Quarterly Progress Report for April - June 1976, ORNL/NUREG/TM-74 (January 1977).

R. H. Chapman, Multirod Burst Test Program Progress Report for July - December 1977, ORNL/NUREG/TM-200 and NUREG/CR-0103 (June 1978).

R. H. Chapman, Multirod Burst Test Program Progress Report for January - March 1978, ORNL/NUREG/TM-217 and NUREG/CR-0225 (August 1978).

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R. H. Chapman, Multirod Burst Test Program Quarterly Progress Report for October - December 1976, ORNL/NUREG/TM-95 (April 1977).

R. H. Chapman, Multirod Burst Test Program Quarterly Progress Report for January - March 1977, ORNL/NUREG/TM-108 (May 1977).

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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).

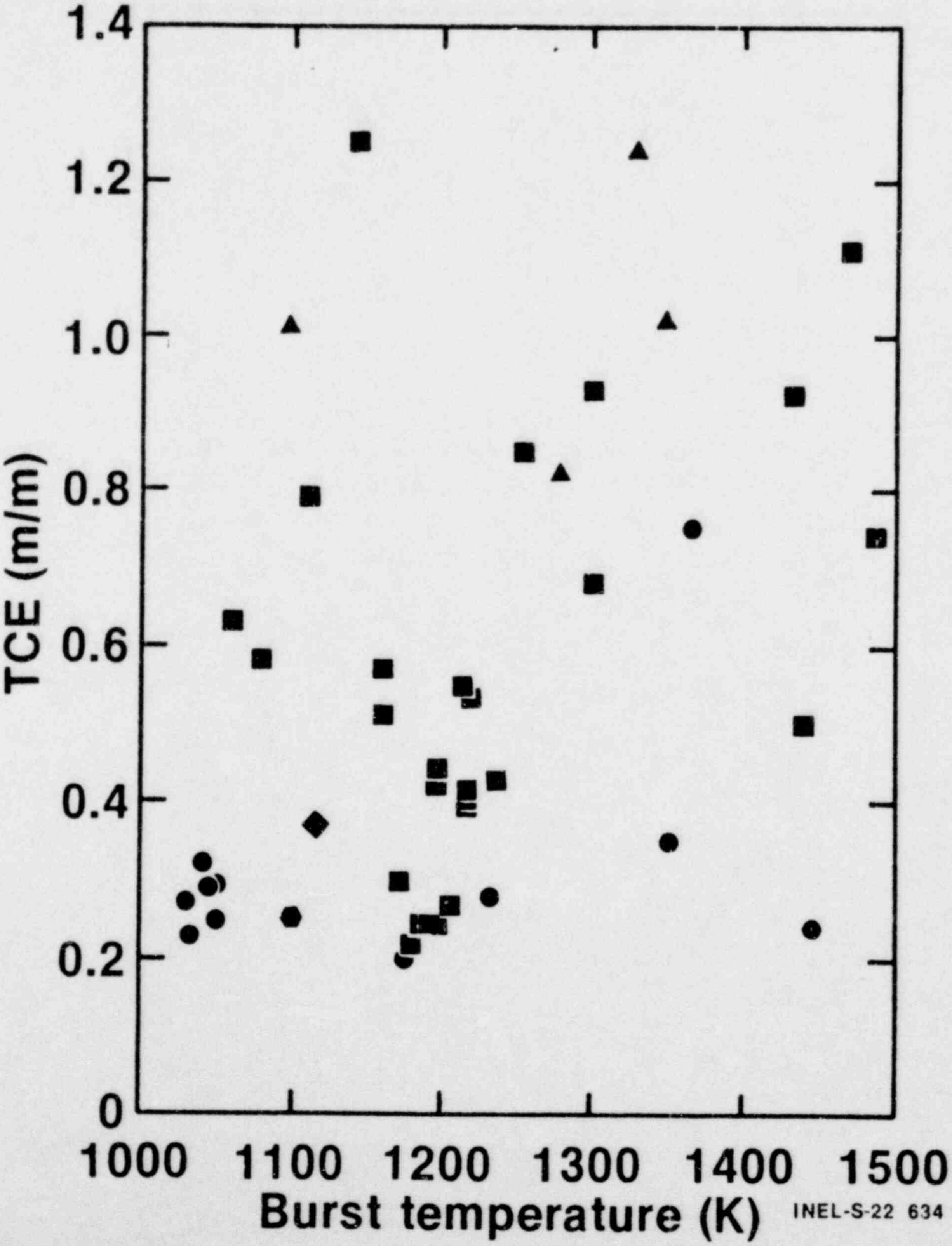
▲ H. M. Chung and T. F. Kassner, Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam Under Transient-Heating Conditions: Summary Report, ANL-77-31 and NUREG/CR-0344 (July 1978).

● 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).

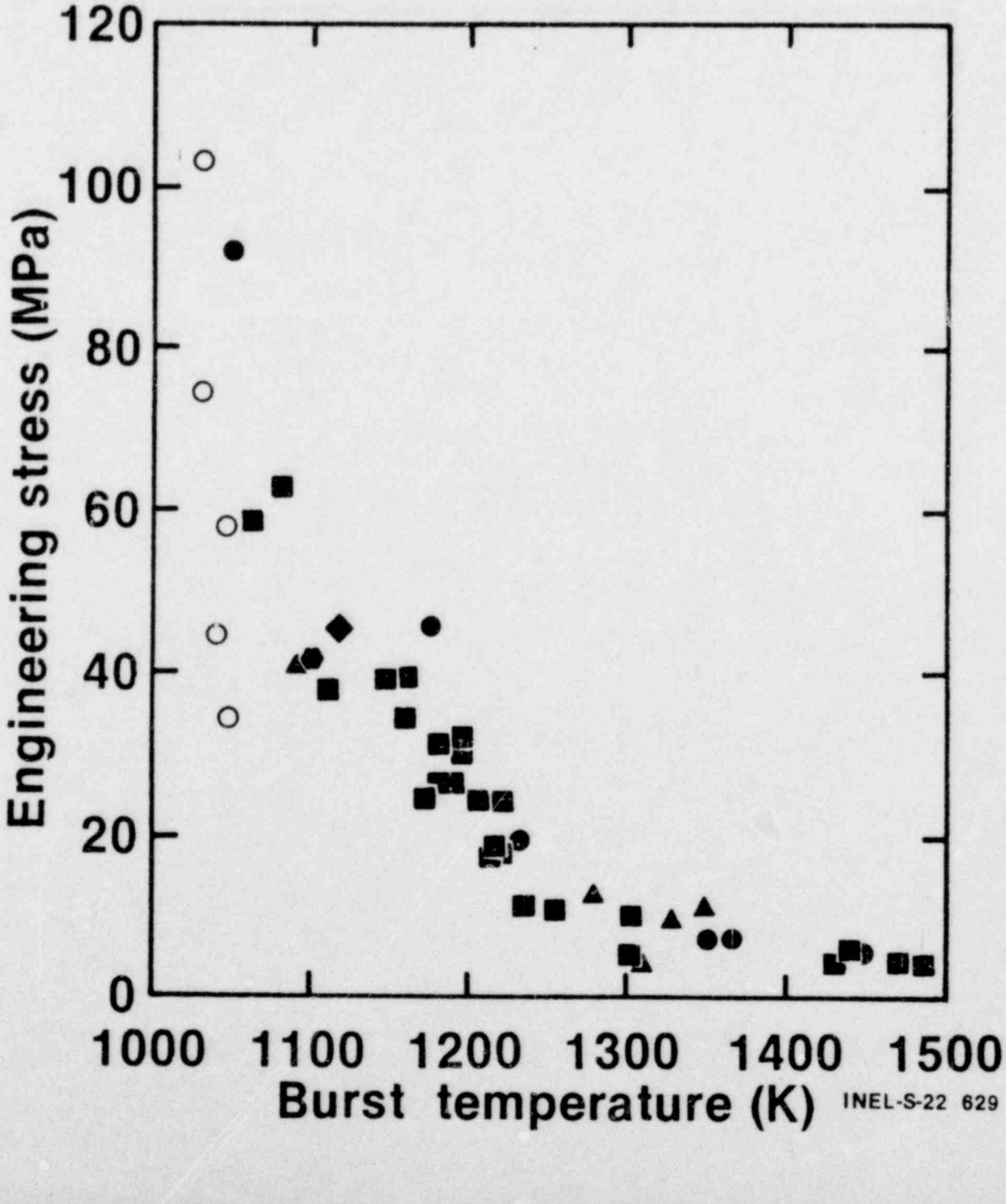
▬ E. H. Karb, "Results of the FR-2 Nuclear Tests on the Behavior of Zircaloy Clad Fuel Rod", Paper presented at the 6th NRC Water Reactor Safety Research Information Meeting, Gaithersburg, Maryland, November 1978.

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

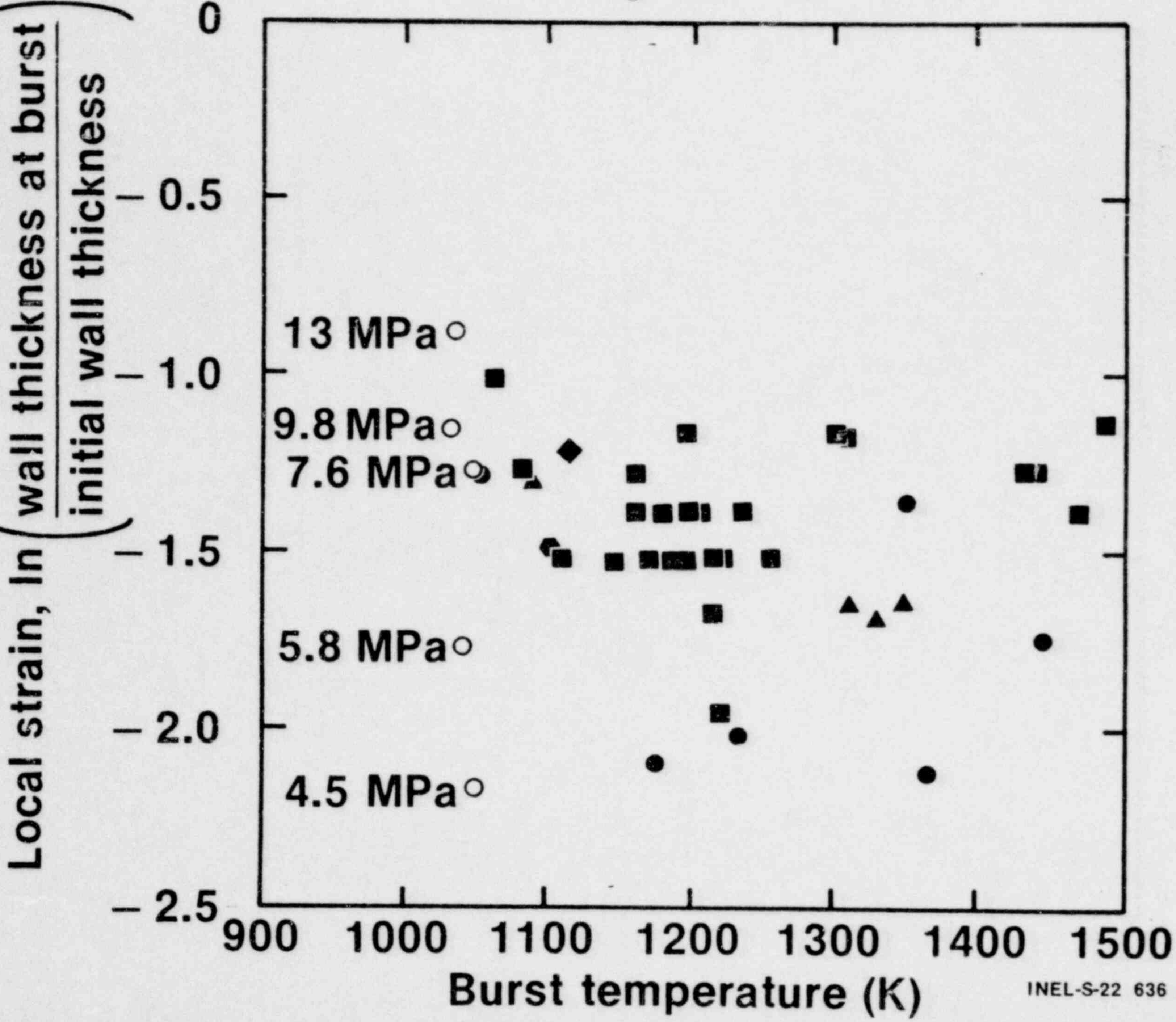
Total Circumferential Elongation Versus Temperature



Engineering Stress Versus Temperature



Local Strain Versus Temperature



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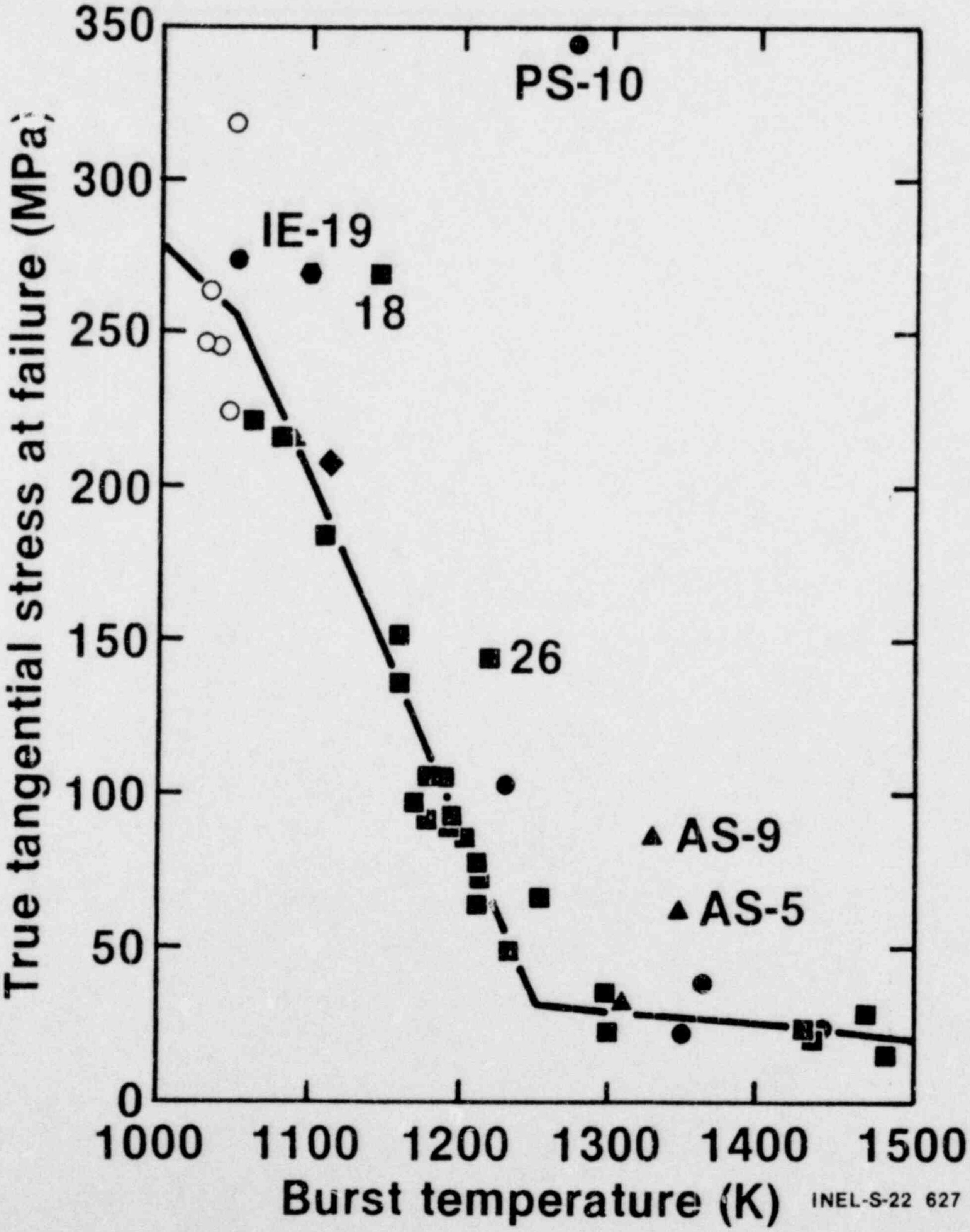
True Stress at Failure vs Temperature



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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 $\sigma_\theta = \sigma_{\theta\,failure}$ 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

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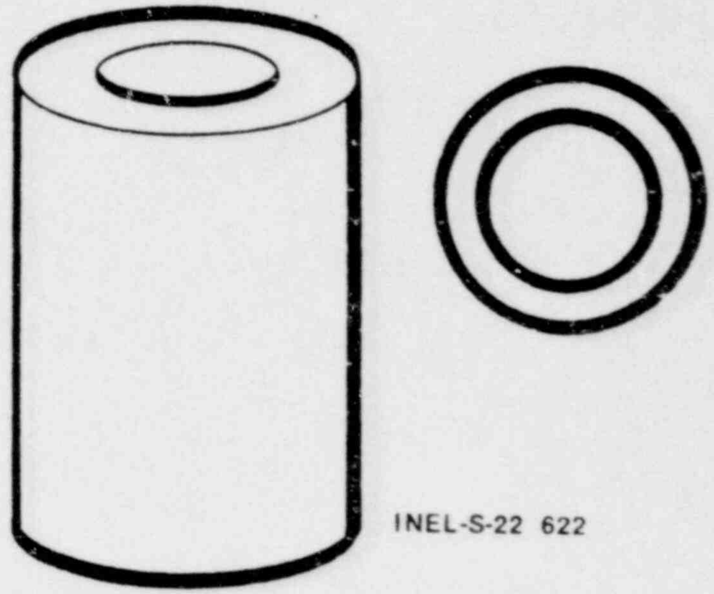
Cladding Shape at Failure

- For axial and azimuthal symmetry

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

$$\text{or} \quad \varepsilon_\theta = \text{Ln} \sqrt{\frac{W_o \sigma_\theta}{PR_o}}$$



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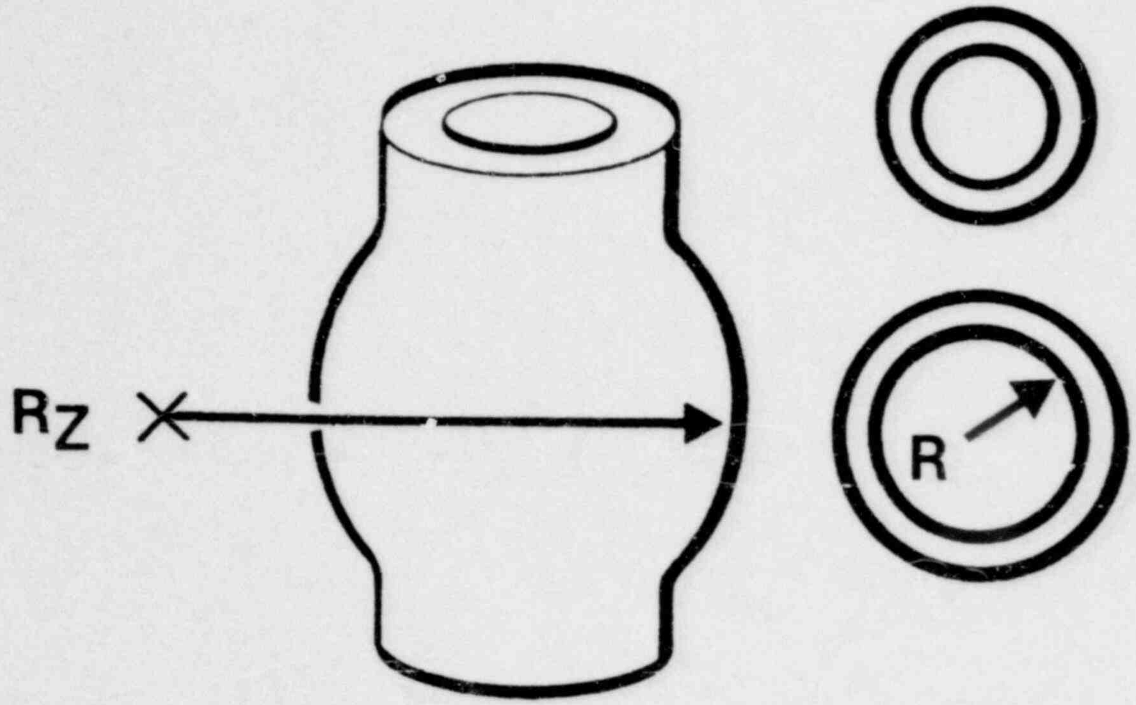
Cladding Shape at Failure

- 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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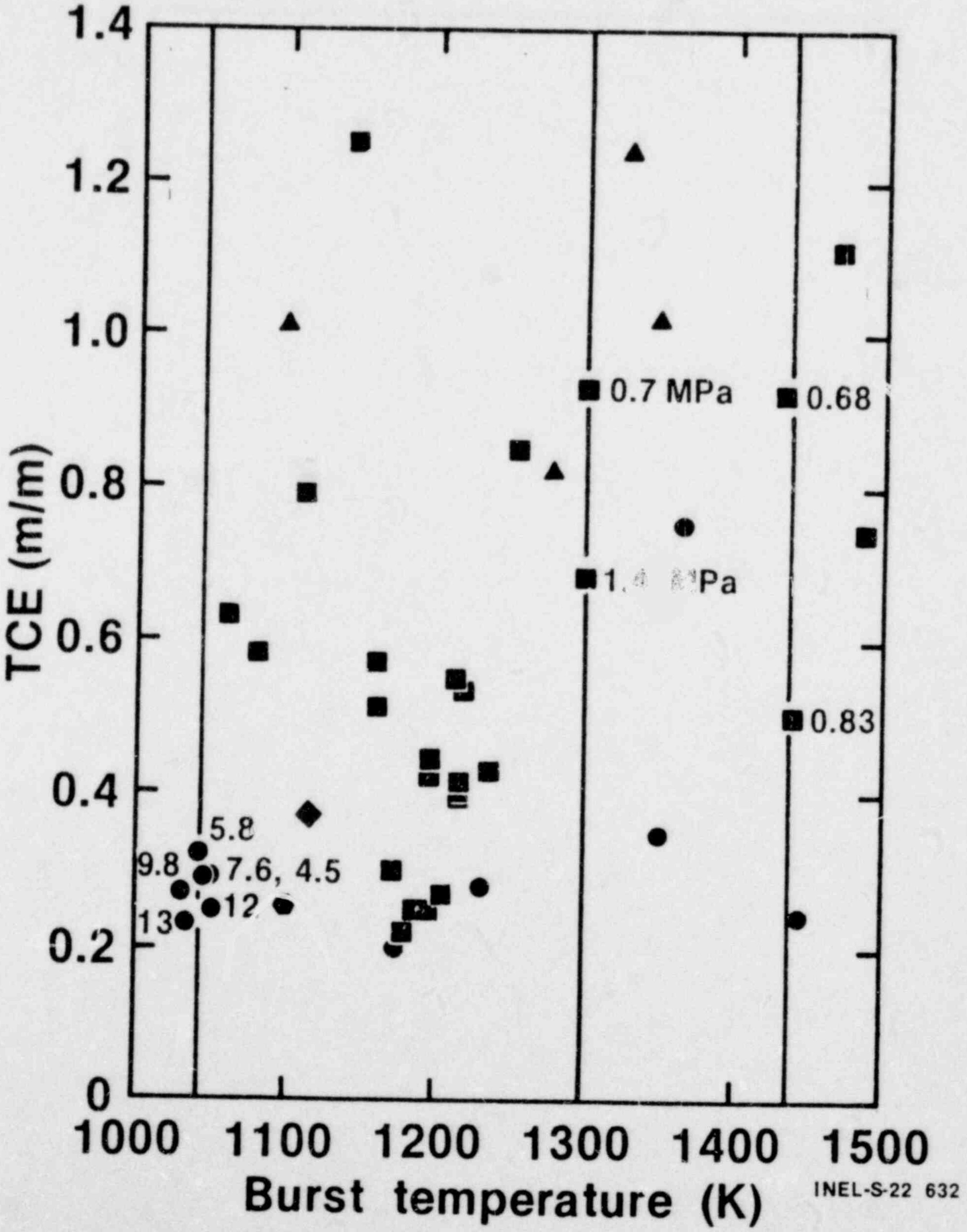
Total Circumferential Elongation Versus Temperature



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

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

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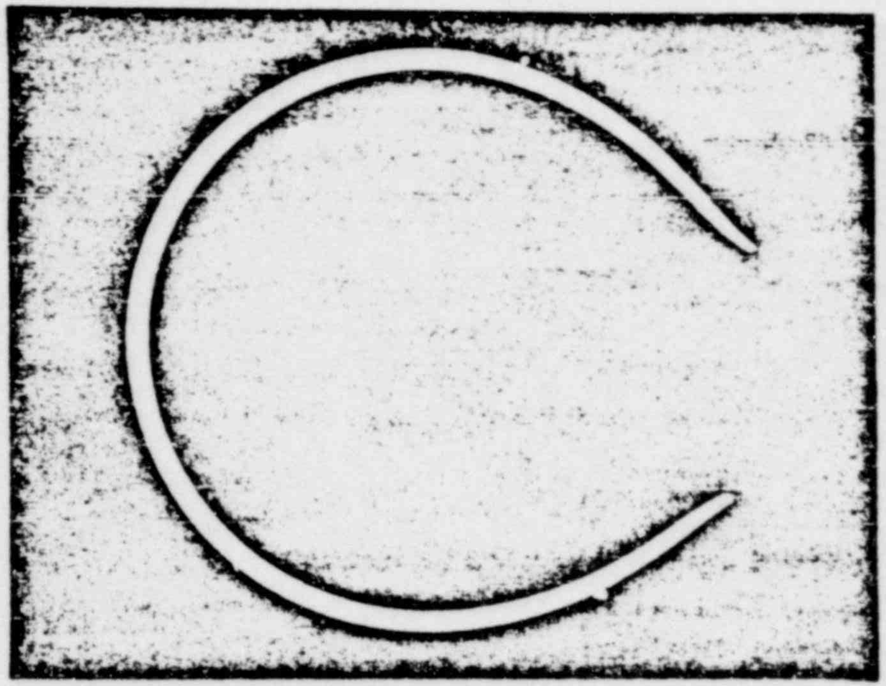
Test SR-37 Cross Section

SR-37



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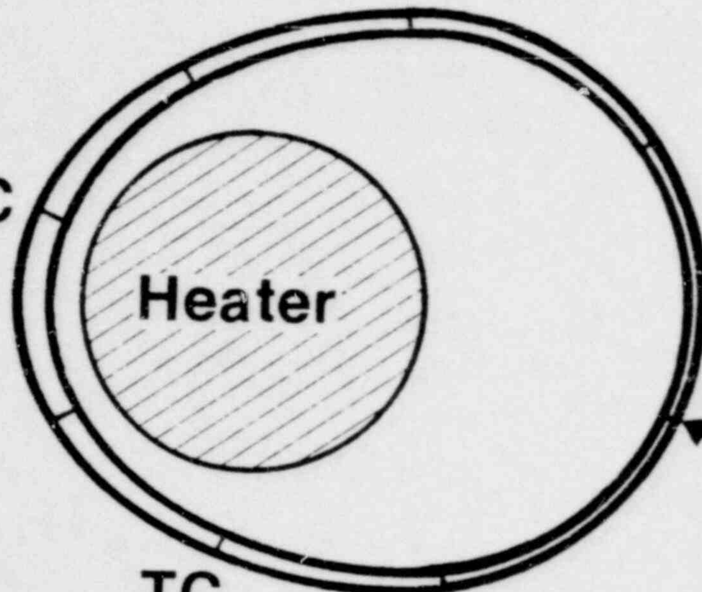
TCE 23%
Elevation 18.0 cm
Time to burst 17.4 s

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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