Analysis of the LOCA Integral Tests Using FALCON

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Introduction

- Objectives
  - Use fuel rod analysis methods to minimize test artifacts that may influence the behavior of irradiated fuel during the LOCA integral tests
  - Use analysis capability to interpret the experiments and to help identify the detailed effects of burnup on fuel rod behavior under LOCA-like conditions
  - Use analysis capability to estimate the in-reactor behavior under different LOCA conditions (BE LOCA vs Appendix K)

Scope of FALCON Calculations

- Design of test specimen and definition of test conditions
  - Upper Plenum Height
  - Heated Length
  - Initial gas volume/pressure
- Evaluate potential burnup effects
  - Cladding irradiation damage
    - » None expected
  - Hydrogen effect
    - » phase transformation and thermal creep
  - Pellet-clad bonding
    - » Restricted axial gas flow
    - » Resistance to ballooning deformations
    - » Impact on thermal shock quench stresses

Clad Ballooning and Rupture Analysis

- Current analysis work using FALCON has focused on the initial phase of the experiment
  - Cladding heat up and ballooning
- Analysis approach using FALCON
  - Qualification of the cladding balloon calculations and rupture model by comparison to the out-of-cell tests
  - Modeling of the test specimen base irradiation to establish the initial conditions for the LOCA integral test
  - Modeling of the test specimen performance during the LOCA integral test

FALCON Transient Fuel Analysis Code

- Fuel rod analysis system for the transient and steady-state analysis of light water reactor fuel rods
- Uses 2-D finite element continuum representation of the fuel column, cladding, and gap regions
- Models the coupled thermo-mechanical behavior of a single fuel rod under normal conditions, operational transients, and accident conditions
- Complete and robust stress-strain constitutive model for mechanical response of the pellet, cladding, and pellet-clad gap
  – Pellet swelling, densification, and cracking
  – UO_2 creep and plasticity
  – Elastic, plastic, creep and irradiated induced deformations in the cladding
  – Pellet-cladding mechanical interaction

High Temperature Deformation (Ballooning)

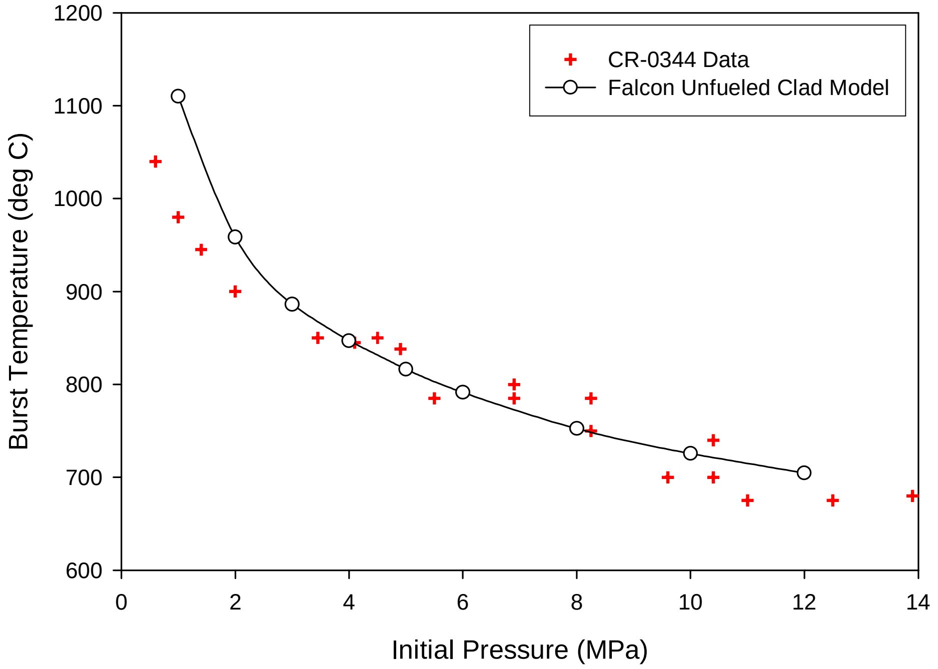
- FALCON does not distinguish between ballooning and other types of deformation
- Uses large displacement/large strain finite-deformation theory of continuum mechanics
- Clad ballooning evolves continuously as part of the deformation process
- Cladding material properties from MATPRO
  - Plan to use more recent thermal creep model based on EDGAR data

High Temperature Rupture Model

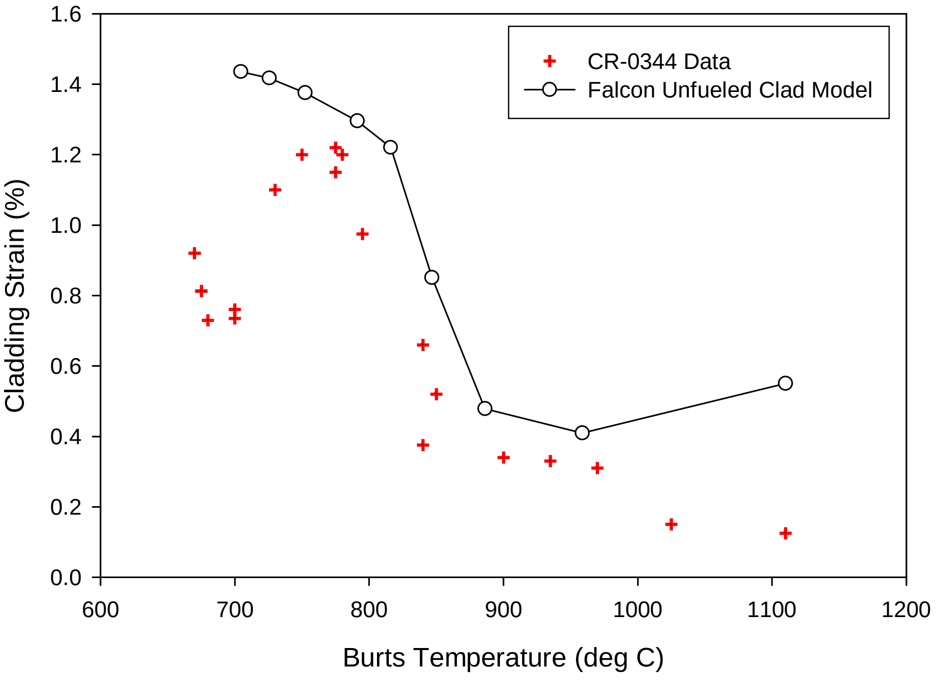
- Based on a time-temperature-stress failure criterion
- Utilizes the cumulative damage concept
  - Material accumulates damage continuously under sustained stress
  - Higher stress the shorter the time to failure
  - Qualified using high temperature burst strain/burst temperature tests
- Accumulated damage concept has been applied successfully to model stress corrosion cracking failure of Zircaloy cladding and to predict rupture during transient heating

Comparison of FALCON Results with High Temperature Burst Data

Axially-Constrained Tube Burst Tests



Burst Temperature



Burst Strain

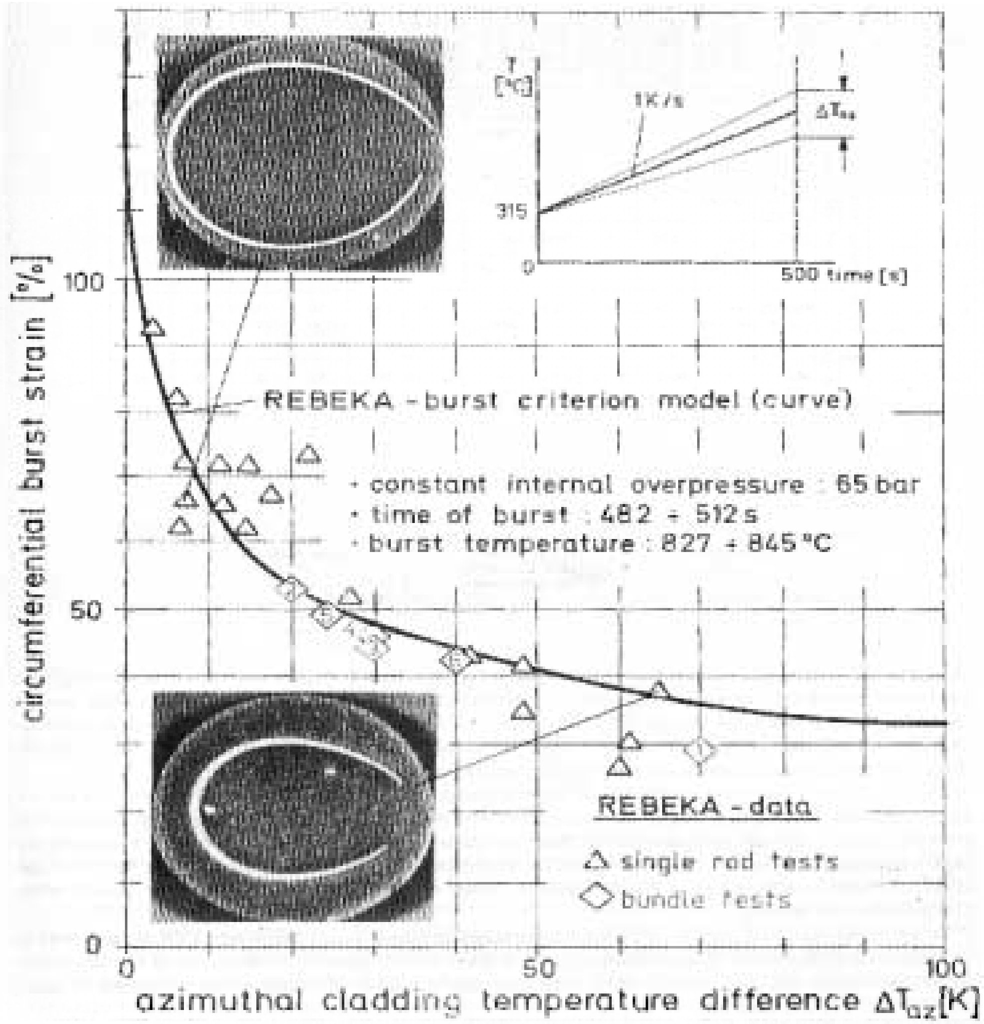
Modifications to FALCON

- Three primary modifications to analyze the behavior of the test segments
  - Upper plenum and initial internal pressure/volume considerations
    - » To account for changes in the gas inventory from the end of the base irradiation to the start of the LOCA criteria test
    - » To account for the differences in the final gas pressure of the base irradiation to that of the start of the LOCA criteria test
  - Treatment of pellet-cladding bonding
    - » Resistance to radial and axial deformations
    - » Restricted axial gas transport
  - Treatment of the thermal boundary conditions
    - » Cladding surface temperatures defined as a function of axial position and time
    - » Effect of azimuthal temperature gradient on burst strain

Pellet Bonding/Cracking Model

- Two effects considered in FALCON for pellet bonding/cracking model
  - Pellet crack stiffness for crack opening
    - » Reduced material stiffness (E_c) in each crack direction to represent the presence of a crack
    - » Increasing the stiffness to simulate sliding friction between pellet pieces decreases the amount of cladding deformation during ballooning
  - Effect of crack opening on internal gas pressure
    - » Increase in crack void volume with ballooning included in calculation of the internal gas pressure

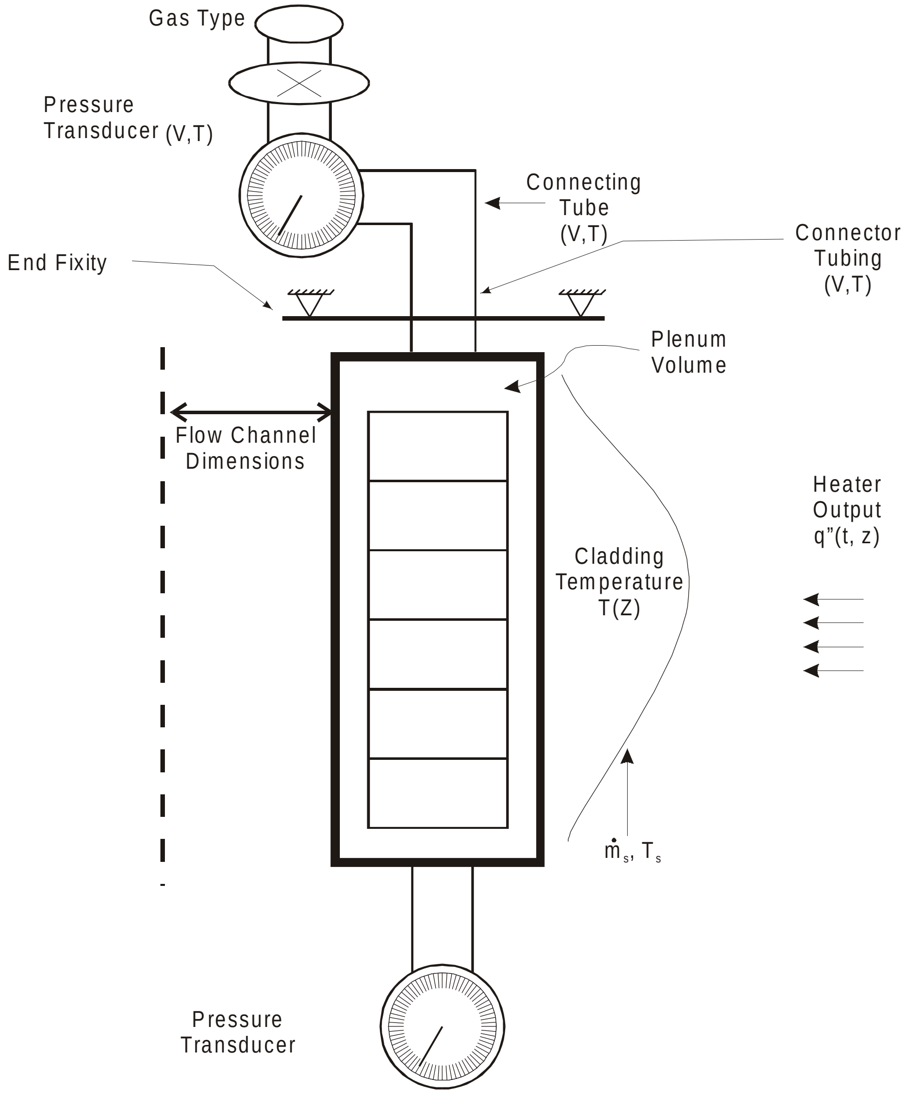
Azimuthal Temperature Effect on Burst Strain



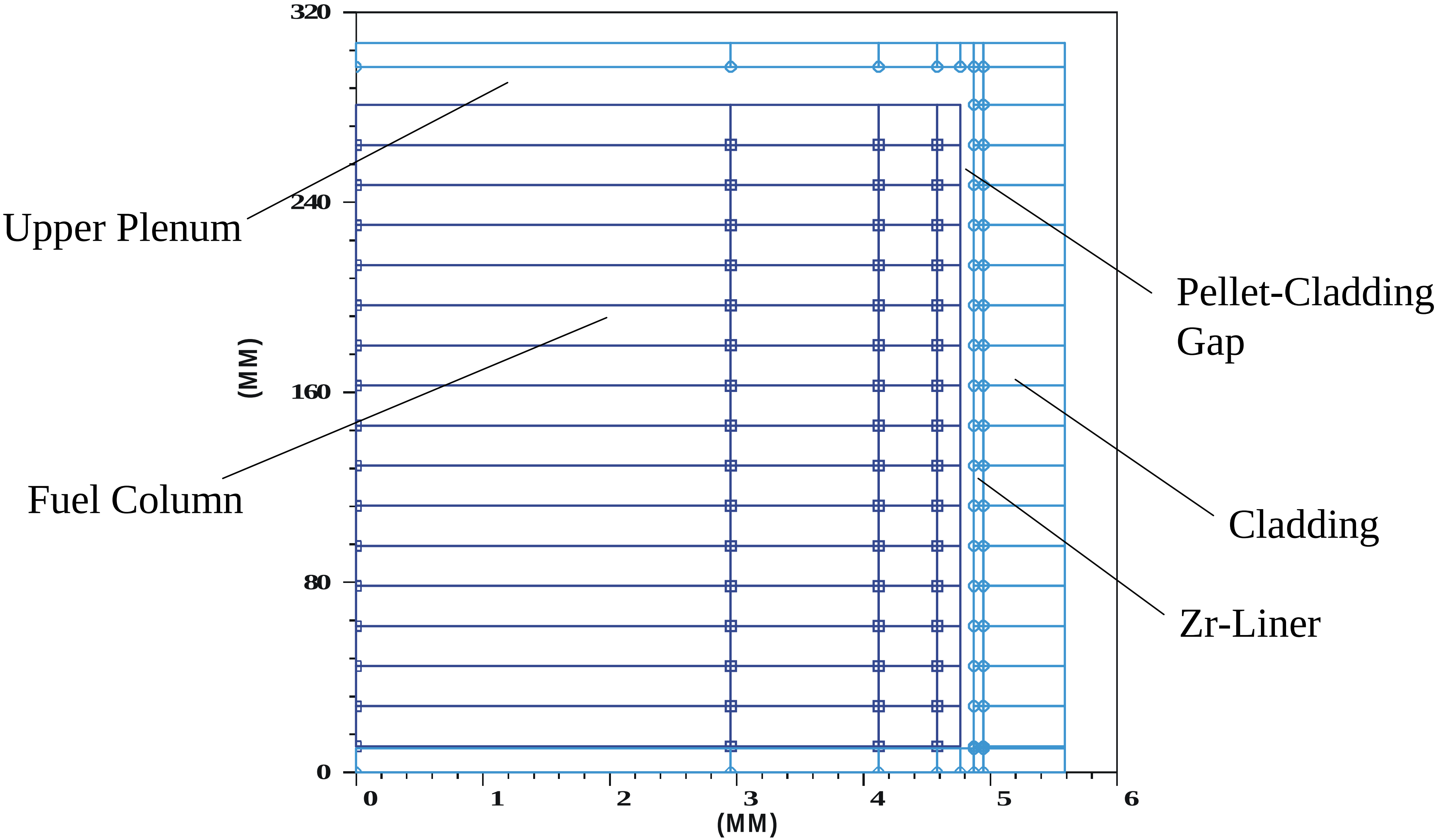
Analysis of ANL Experiments

- FALCON Calculations
  - Several early out-of-cell tests used in the development of the apparatus
  - Out-of-Cell Tests #3 and #4
  - In-cell Tests 1A and 1B
- Comparison to Data
  - Internal pressure at burst
  - Burst temperature
  - Cladding deformations

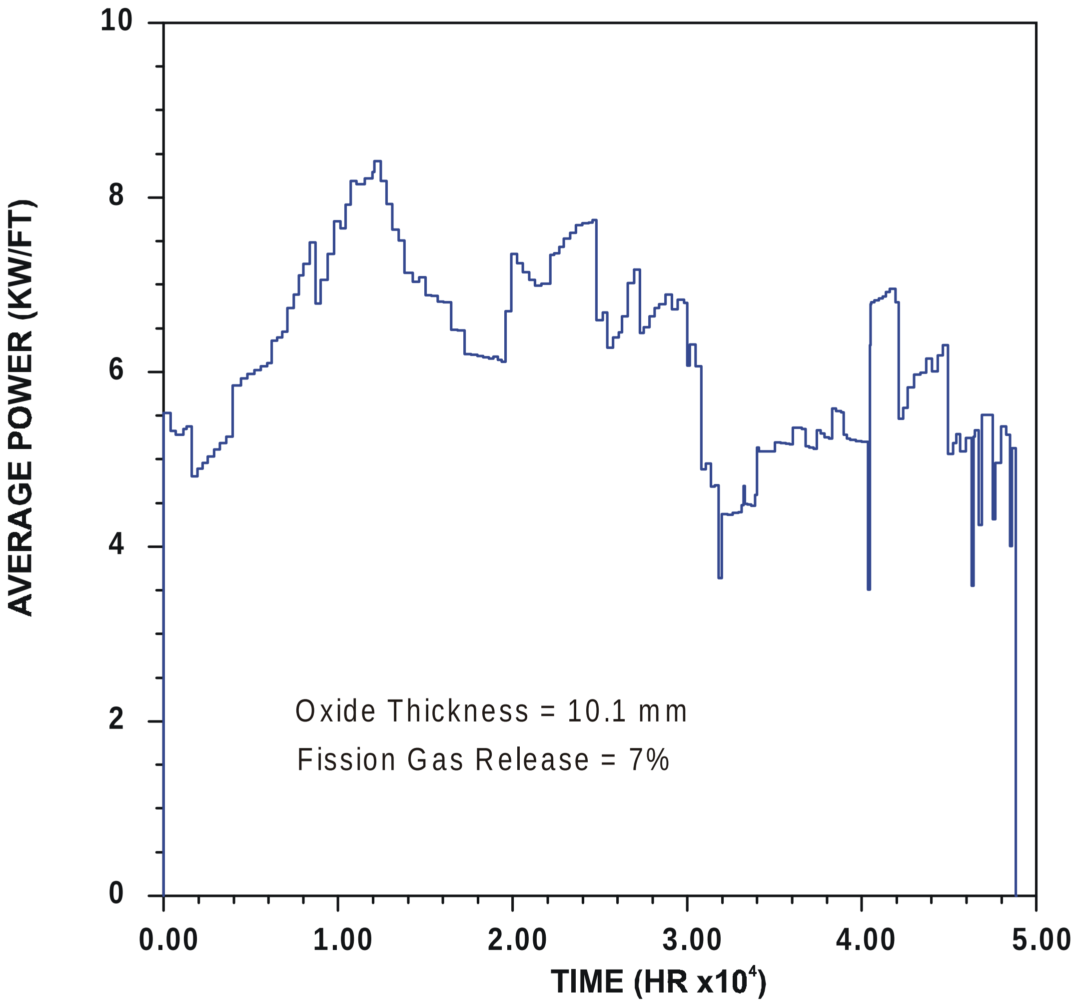
LOCA Integral Test Setup



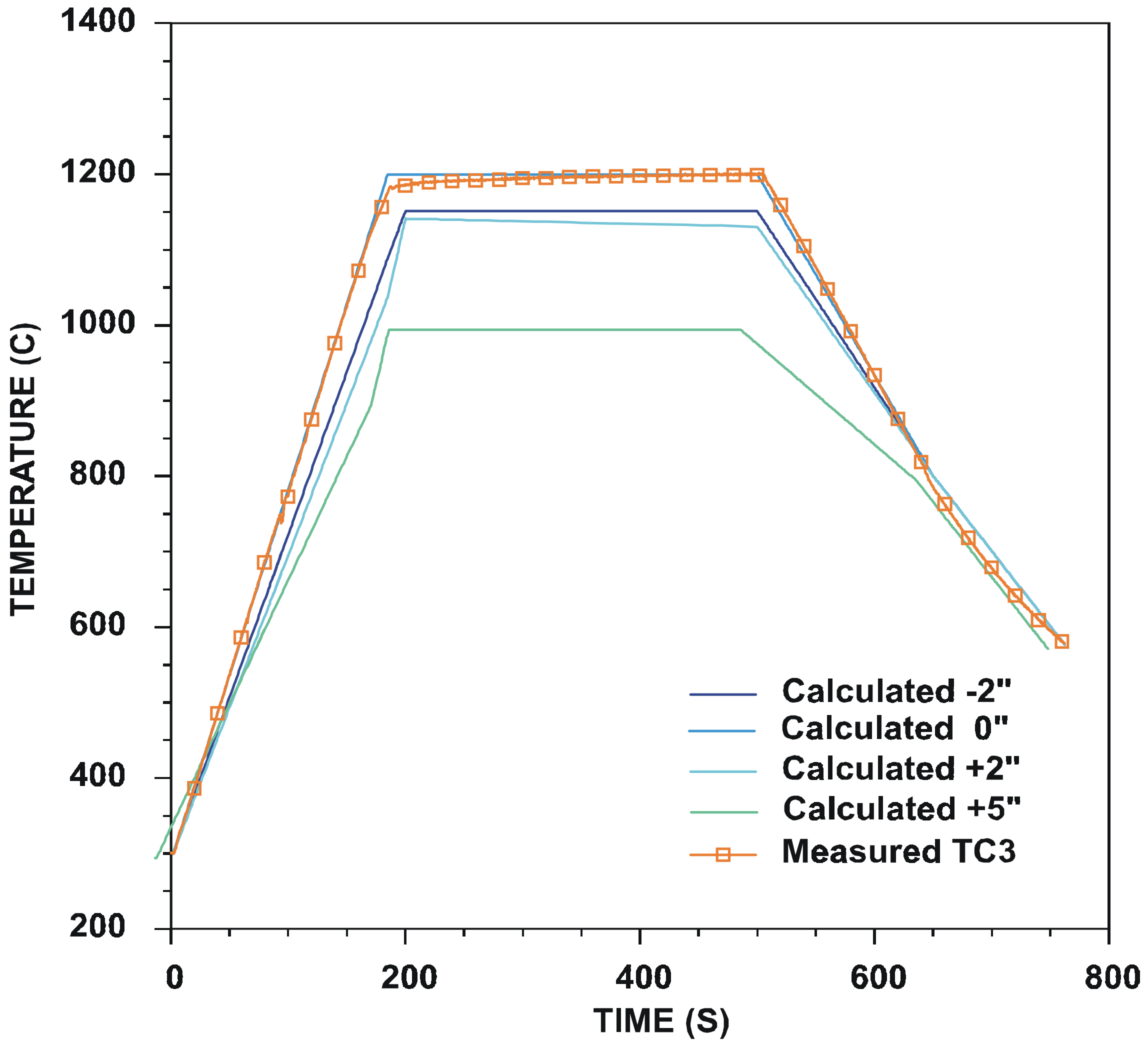
FALCON Model



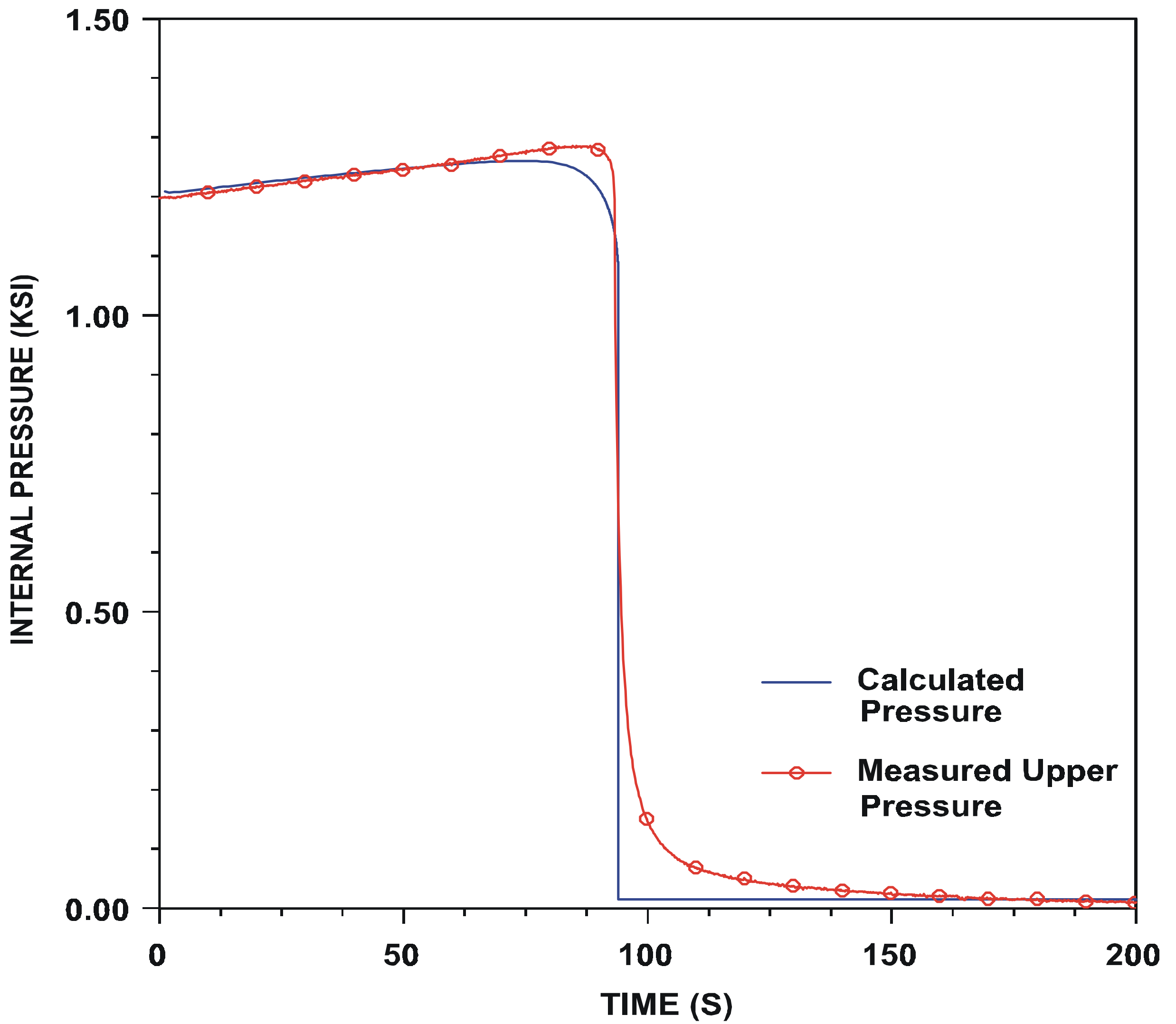
Base Irradiation Power History



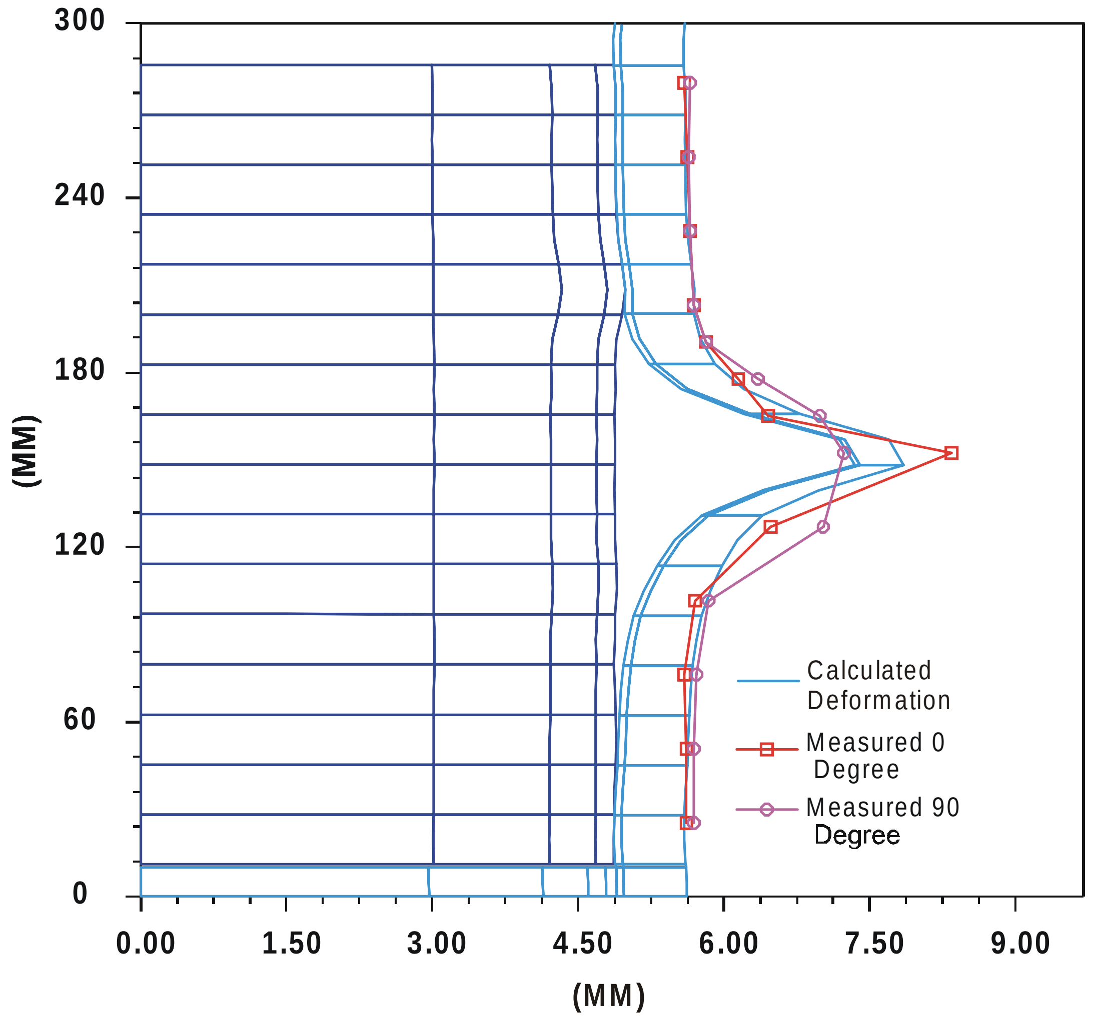
Temperature as a Function of Time for Test 2 (Phase B)



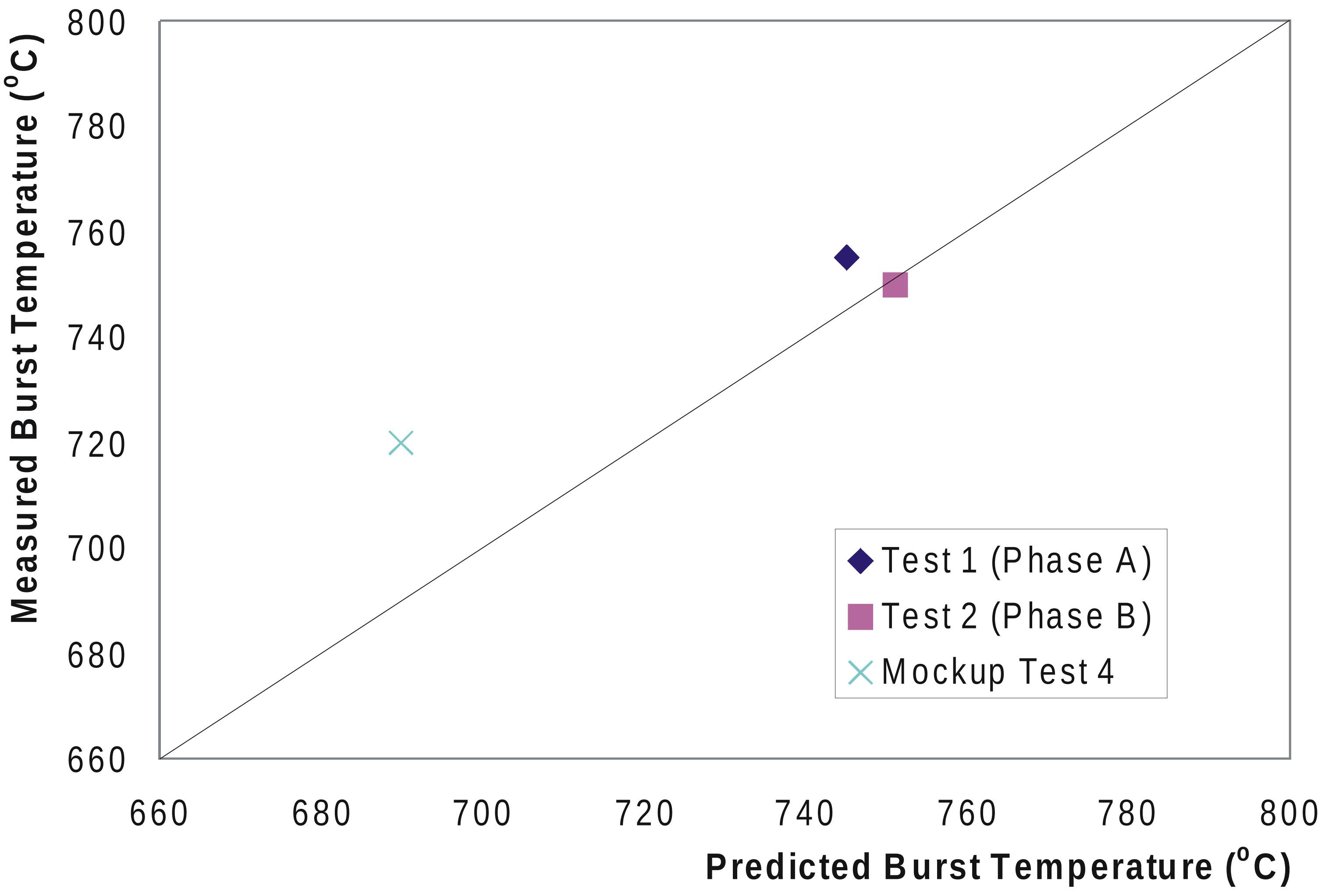
Inner Pressure as a Function of Time for Test 2 (Phase B)



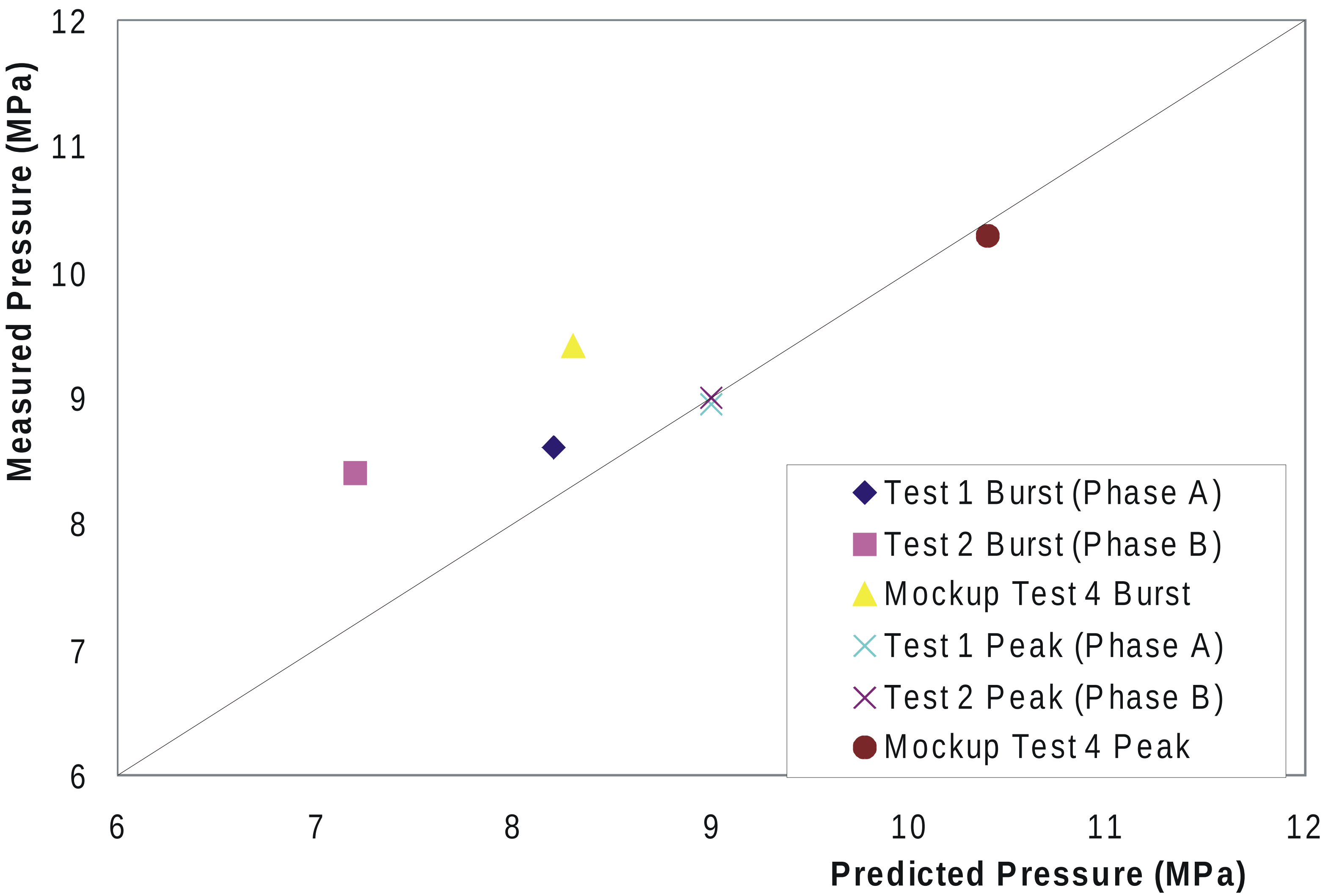
Deformation Profile Comparison for Test 2 (Phase B)



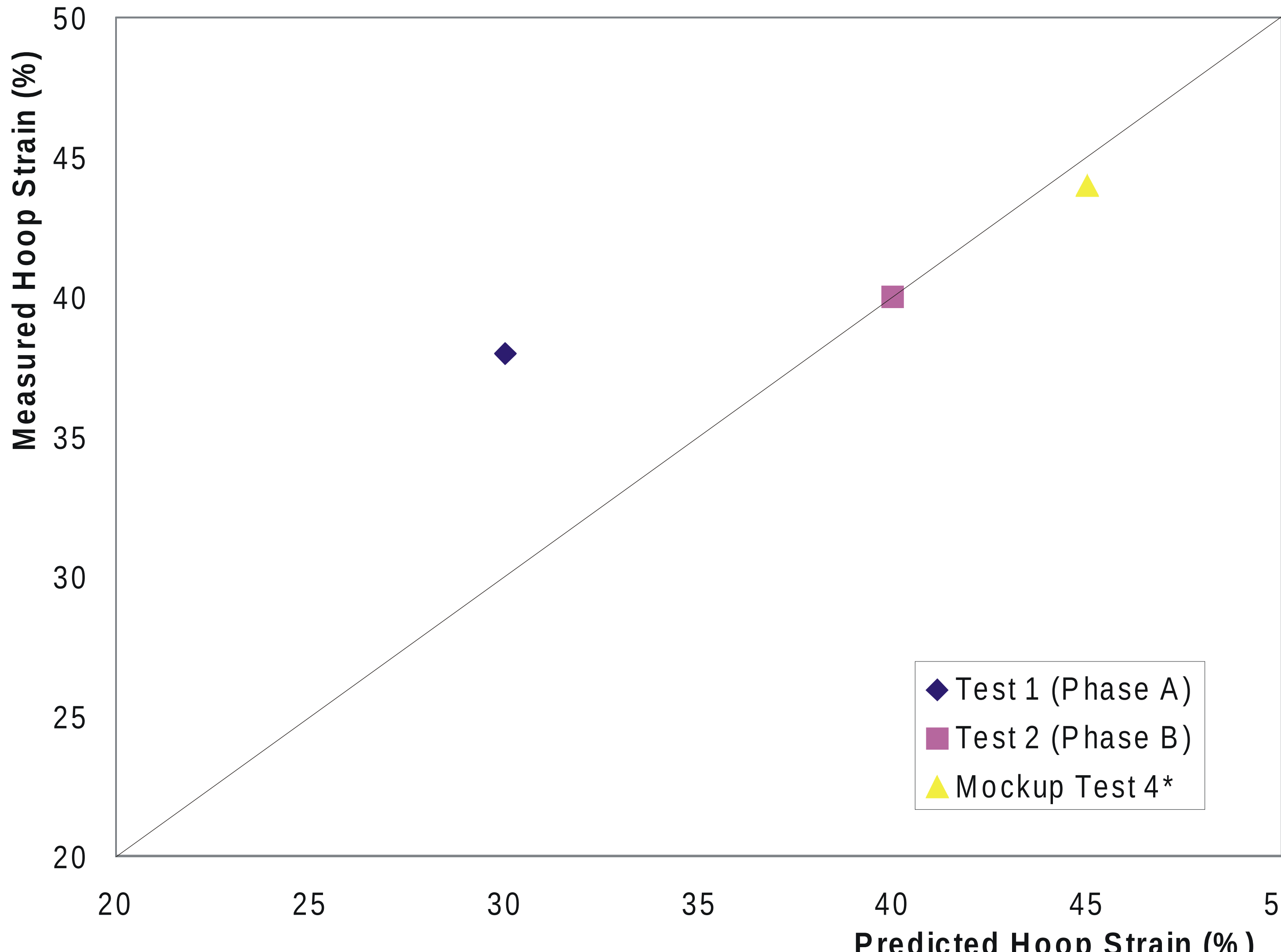
Measured vs. Predicted Burst Temperature



Measured vs. Predicted Burst Pressure



Measured vs. Predicted Hoop Strain



Summary of Results

- Comparison to ANL Experiments
  - FALCON ballooning and burst response agrees well with the behavior observed in the out-of-cell and in-cell tests
    - » Final cladding deformations
    - » Burst temperature and pressure
    - » Confirms the limited effect of burnup for BWR fuel
  - Some differences observed
    - » Most likely caused by the uncertainty in the temperature at the burst location
    - » Axi-symmetric ballooning calculated in FALCON

Future Work

- Current Activities
  - Complete the analysis to include quench for the out-of-cell tests
  - Compare ECR results to measured data
  - Continue to analyze the ANL experiments
- Future Activities
  - Evaluate the effects of variations in initial conditions (H content, burnup, etc.)
  - Extend analysis to advanced alloys
- Potential Applications
  - Analyze differences in cladding mechanical response between Appendix K and BE LOCA conditions

Appendix K vs BE LOCA PCT's

PWR PCT History

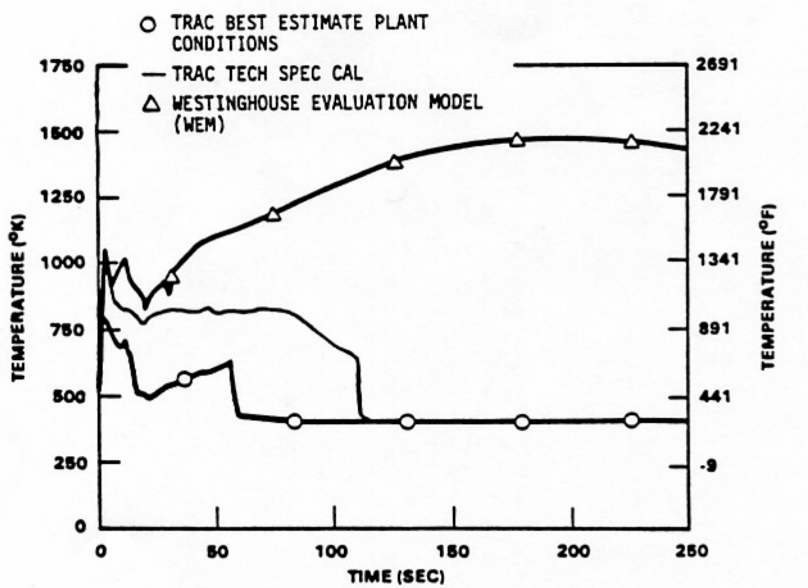
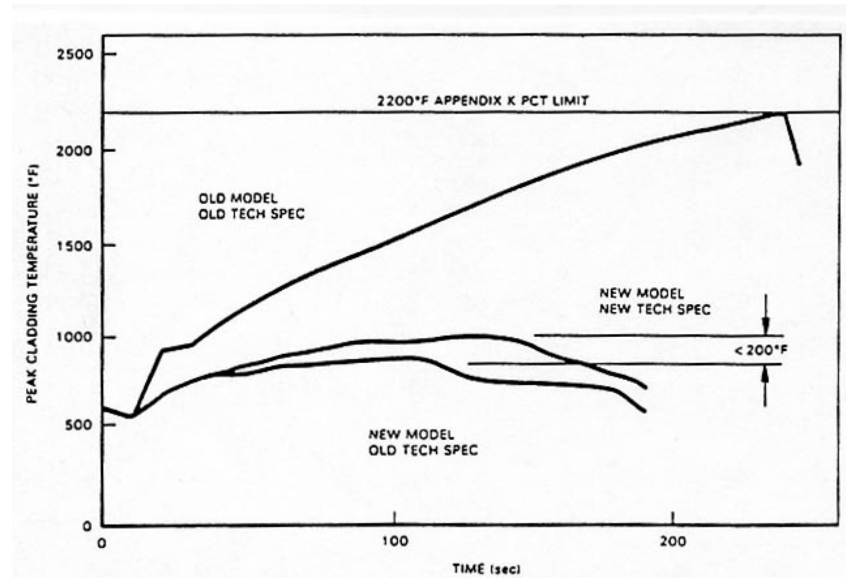


Figure 2. Comparison Between TRAC Best Estimate Calculations and Westinghouse Evaluation Model for Typical Four Loop Plant

Reference: Cadek, F.F. et. al., "Best Estimate Approach for Effective Plant Operation and Improved Economy," Proceedings: The Appendix K Relief Workshop, EPRI NP-6568, November 1989

BWR PCT History



Reference: Sozzi, G.L.., "On the Development of New BWR Models – Technology Application and Results," Proceedings: The Appendix K Relief Workshop, EPRI NP-6568, November 1989