2. CANDU Fuel Design and Performance Codes

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Outline

- Applications
- Specific codes
  - key features and validations

Needs

- Predict mechanical performance of fuel under NOC
- Design and/or qualify new products and/or operating conditions, e.g. ACR
- Predict operating values of key design parameters
  - under on-power conditions, e.g. internal gas pressure
  - account for important effects, e.g. irradiation embrittlement
- Confirm design margins
- Provide initial conditions for accident analysis codes
  - e.g. ELESTRES providing input to ELOCA

Benefits

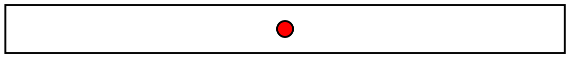
- Part of suite of tools for fuel qualification
  - tests: in-reactor + out-reactor
  - modeling: codes, spreadsheets
  - operating experience and engineering judgment
- Analyses add to proof tests
  - add on-power effects to out-reactor tests
  - extrapolate to untested combinations
  - relatively inexpensive and fast
- Provide margins and insights
- Flag potential issues early in the design stage

Categories

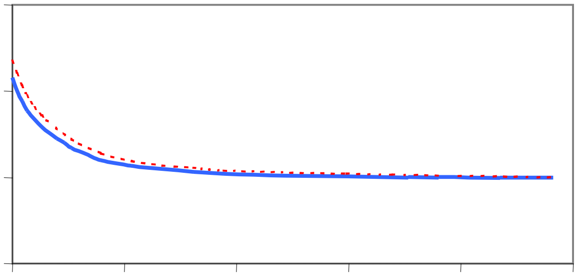
- **Thermal integrity**
  - ensure operating temperatures stay within acceptable limits
  - 3 assessments
- **Structural integrity**
  - ensure operating stresses and strains stay within acceptable limits
  - 14 assessments
- **Compatibility**
  - ensure fuel and its neighbors fit
  - 2 assessments

Thermal Integrity

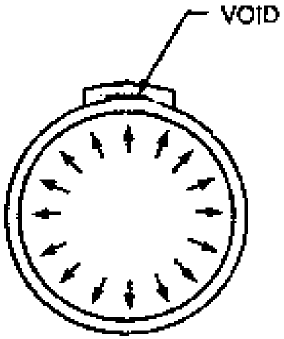
- Pellet temperature at element's axial center
  - sufficient margin to melting
  - ELESTRES code



- Pellet temperature at axial end of the fuel element
  - sufficient margin to melting
  - FEAT code



- Braze voids in bearing pads
  - prevent rapid rise in local temperature
  - FEAT code

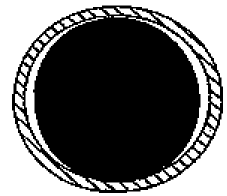


Structural Integrity

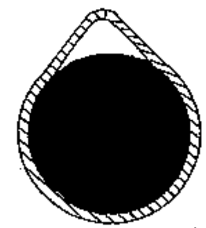
- **Fuel clad (5 assessments)**
- **Fuel element (4 assessments)**
  - endcap and vicinity
- **Fuel bundle (5 assessments)**
  - endplate
  - endplate-to-endcap weld
  - overall deformation and strength of the bundle

Structural Integrity of Fuel Clad

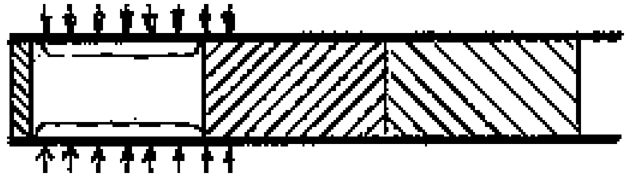
- Collapsibility (LONGER)



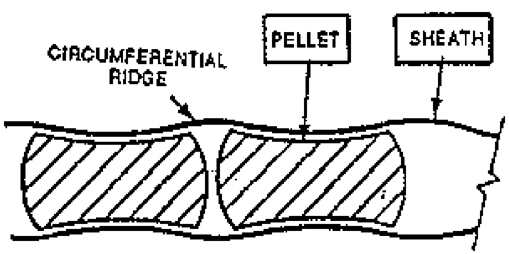
- Longitudinal ridging (LONGER)



- Collapsibility into axial gap
  - –(LONGER)

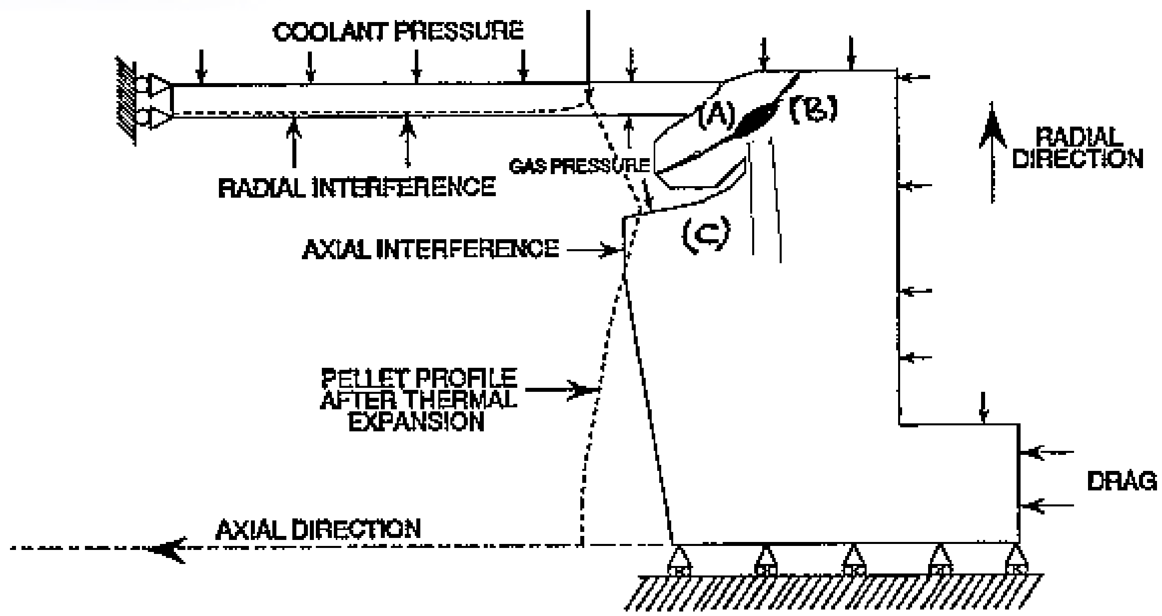


- Stress corrosion cracking at ridge (INTEGRITY, HISTOBUN)



- Load following (ELESTRES + FEAST) => SCC + fatigue

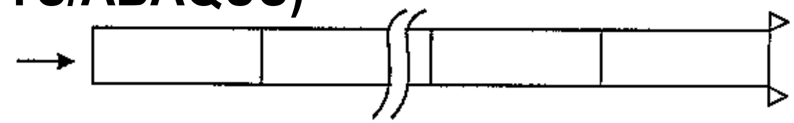
Structural Integrity of Fuel Element



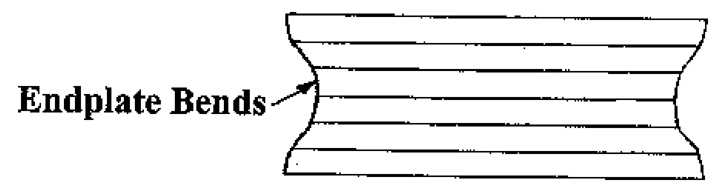
- SCC: Internal gas pressure (A) (ELESTRES)
- SCC: Pellet expansion (A) (ELESTRES+FEAST)
- Bonding within weld line (B) (FEAST)
- Endcap strength (C) (FEAST)

Structural Integrity of Fuel Bundle

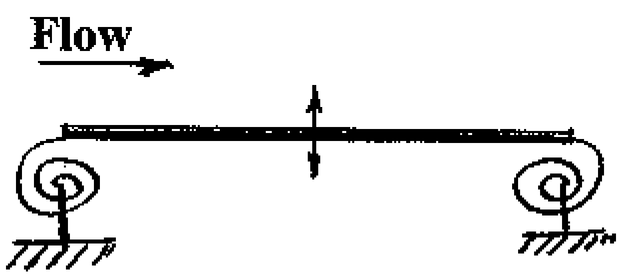
- Refueling strength (BEAM, ANSYS/ABAQUS)

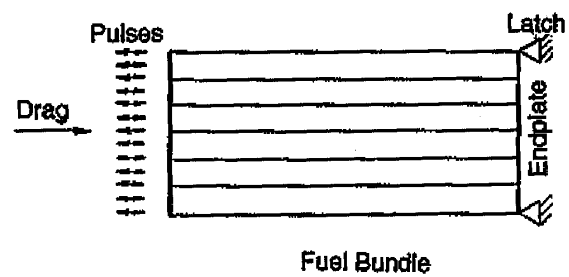


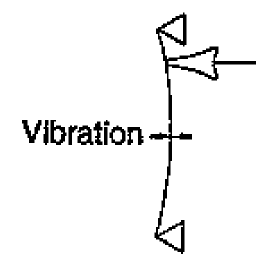
- Power ramp strength (BEAM, ABAQUS)



- Fatigue: lateral, axial (BEAM, H3DMAP/ABAQUS)







- Buckling: BOW

Compatibility

- Crevice corrosion: FEAT
  - restricted cooling, elevated temp
  - concentration of LiOH, accelerates corrosion
  - local temperature less than critical

- Bow, sag, droop: BOW
  - circumferential delta-temp, delta-length
  - gravity, hydraulic drag
  - thermal, elastic, creep effects
  - prevent overheating and jamming
  - maintain sufficient clearances with neighbors

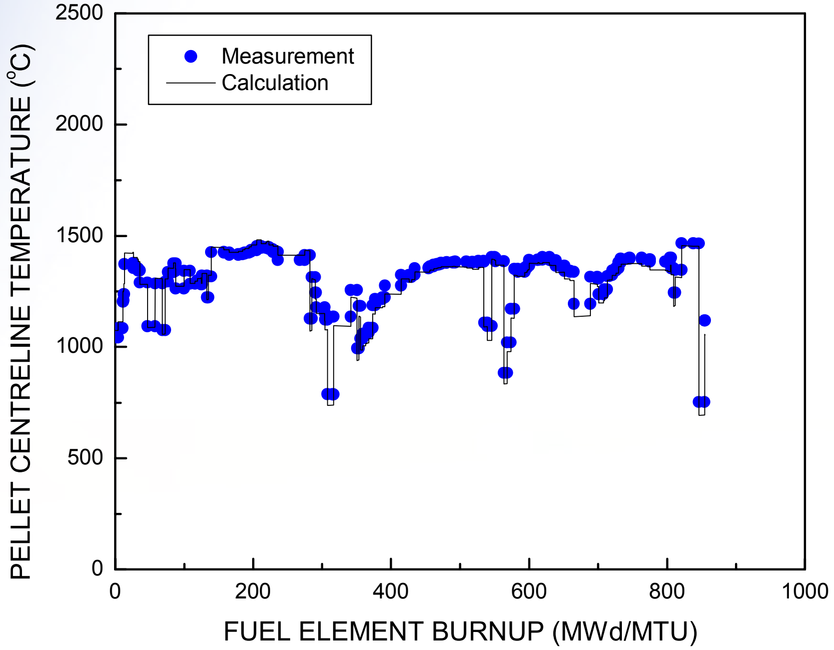
Specific Fuel Codes

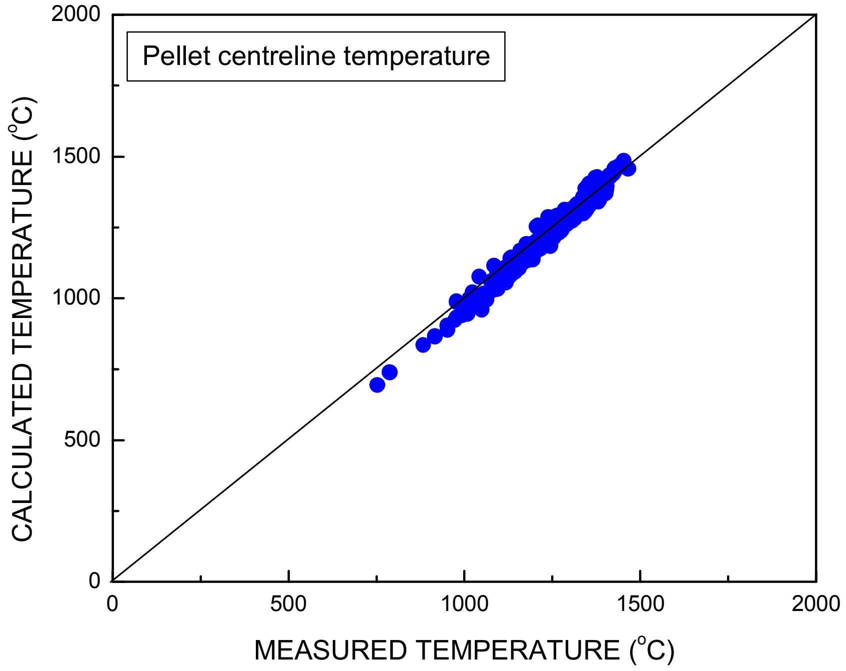
- Specific in-house fuel performance codes
  - key features, illustrative validations
- Used for fuel design assessments for last 20 years
- Many validations and documentations over the years
  - experimental data
  - independent analytical results
- Rigorous configuration management
- Formally qualifying all fuel codes
  - ISO 9001-2000
  - CSA N286.7 Standard

ELESTRES

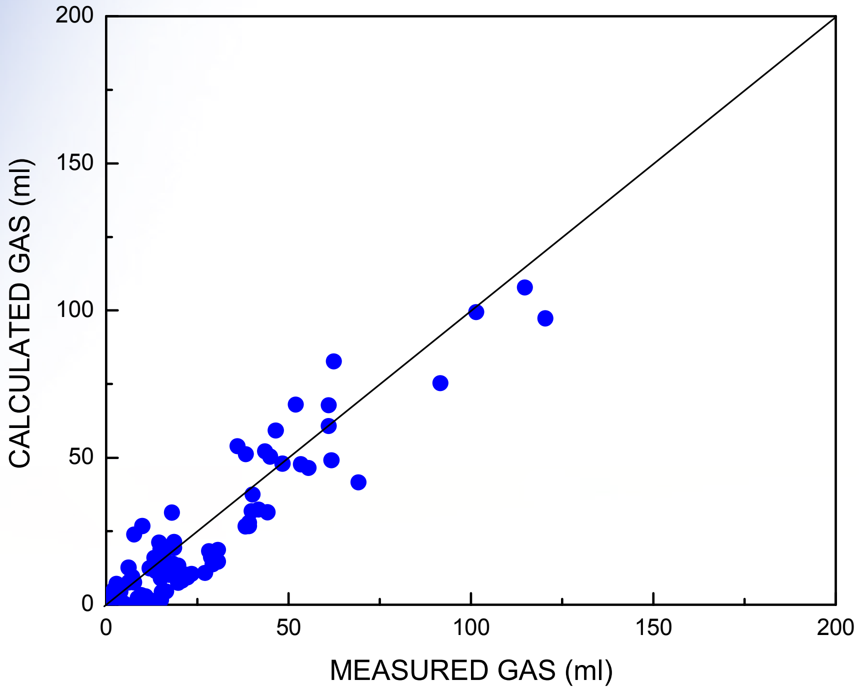
- Used to calculate temperature, fission gas release, internal pressure, and clad strain including circumferential ridge
- Temperature
  - heat generation, heat conduction, flux depression, thermal conductivity, gap/contact, finite difference, 100 radial annuli
- Fission gas release
  - microstructural models, generation, diffusion, grain boundary sweep, bubble growth and interlinkage, release via tunnels
- Strain
  - densification, fission product swelling, thermal expansion, elasticity, plasticity, creep, cracking, radial and axial gaps, finite element, 2-dimensional
- Validation against ~ 130 irradiations

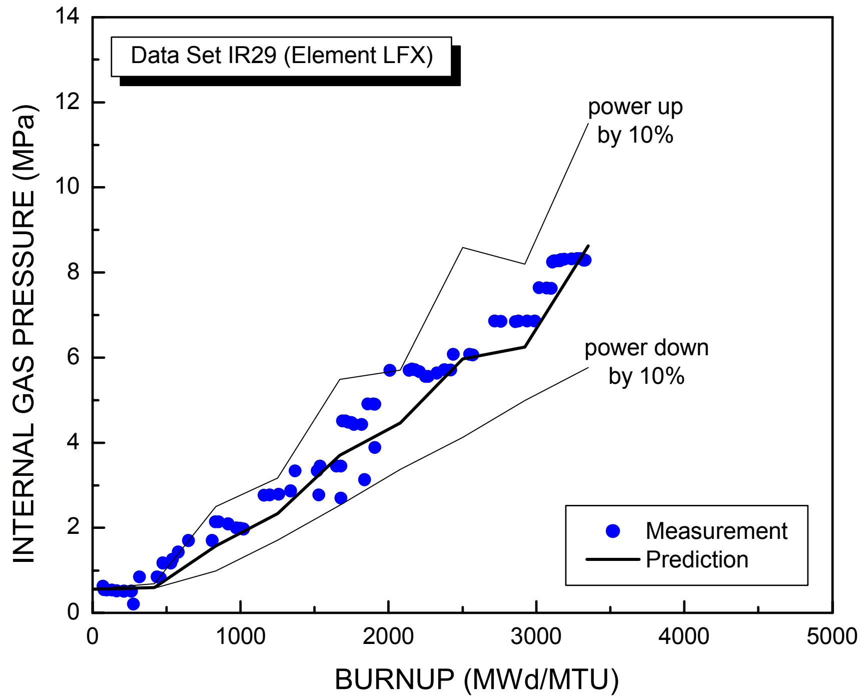
ELESTRES: Pellet Temperature
EXP-FIO-142



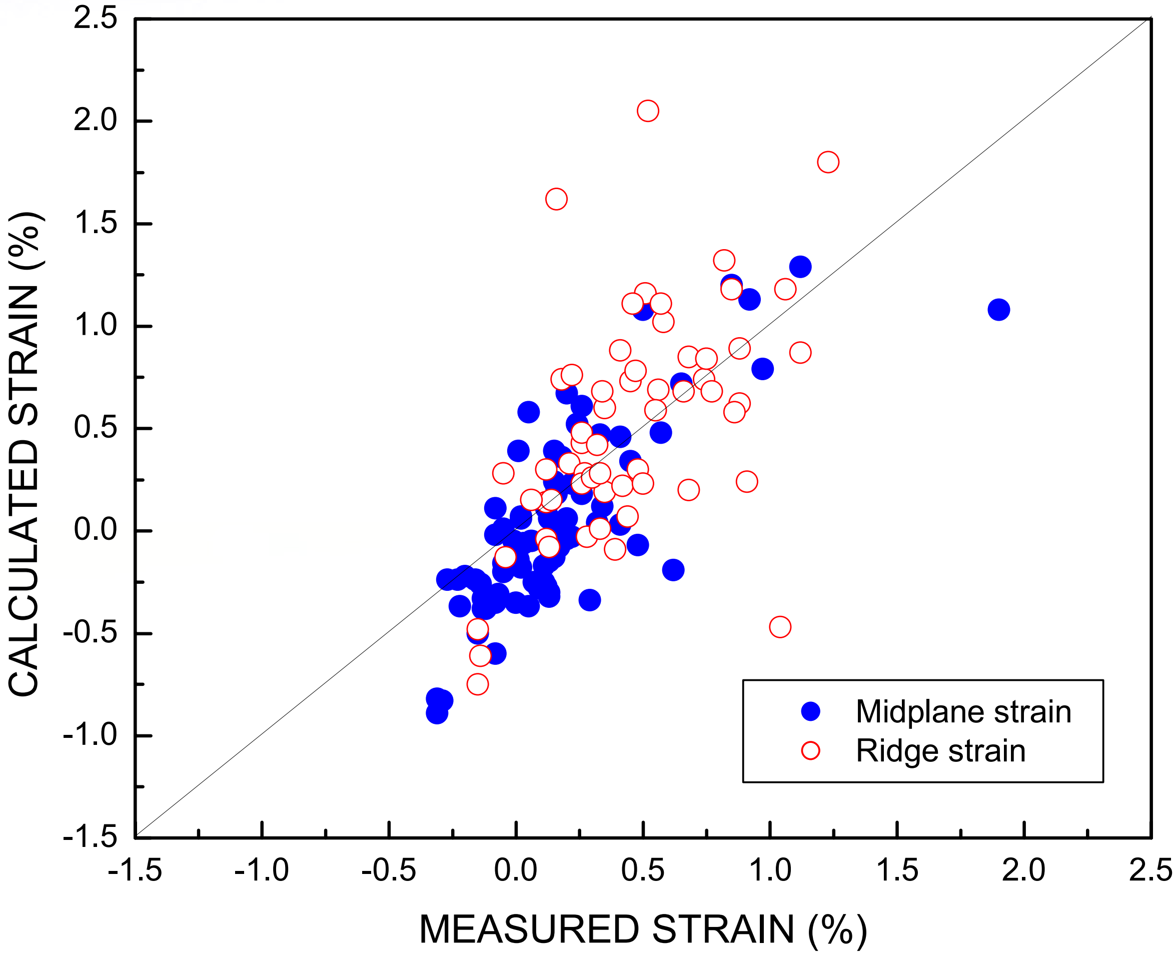


ELESTRES: Fission Gas





ELESTRES: Clad Strain

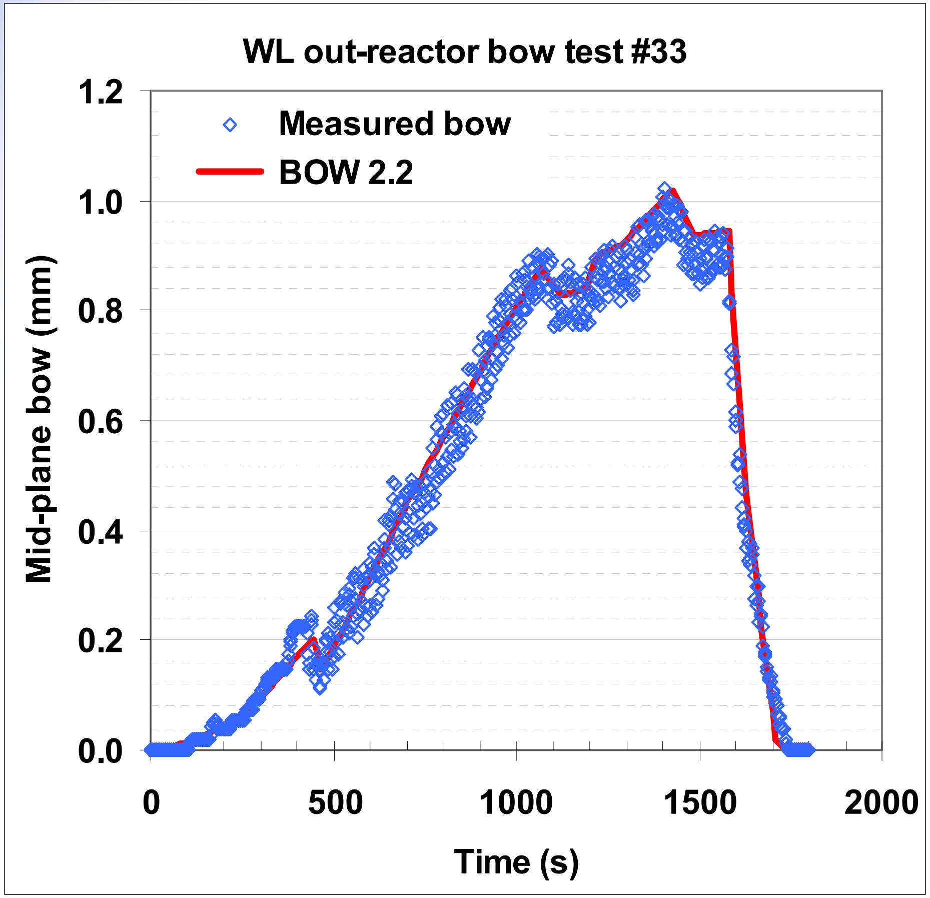


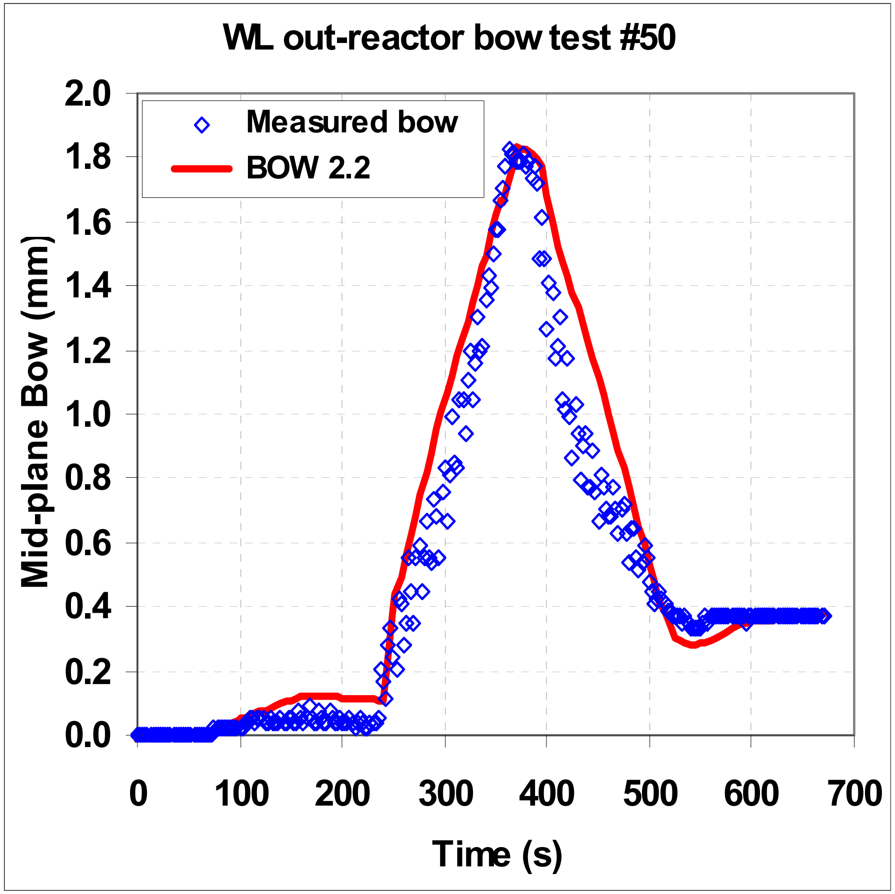
BOW

- Used to calculate deflections of fuel elements: bow, sag and droop
- Circumferential and axial temperature gradients in clad and pellets
  - neutron flux gradients, dry patches, non-uniform heat transfer coefficient, and coolant temperature
- Hydraulic drag, gravity, length differentials, creep
- Endplates, pellets (including cracking), appendages, neighboring fuel elements and pressure tubes
- As-fabricated bow, variations in material properties, etc.
- Finite element method
- Validation against 5 experimental measurements plus 46 independent analytical solutions (generally within 1%)

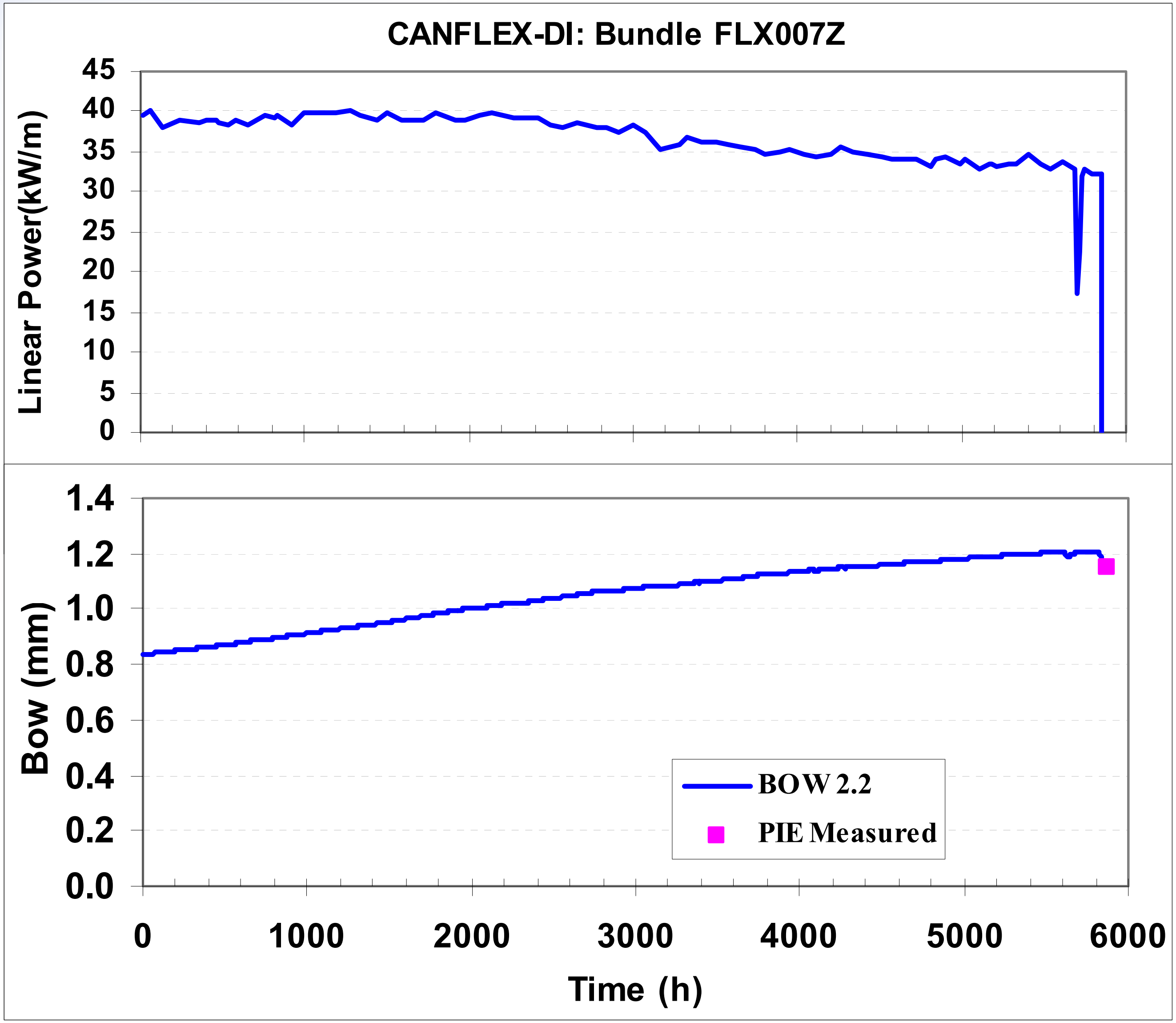
BOW vs. WL Tests

Eccentric heaters





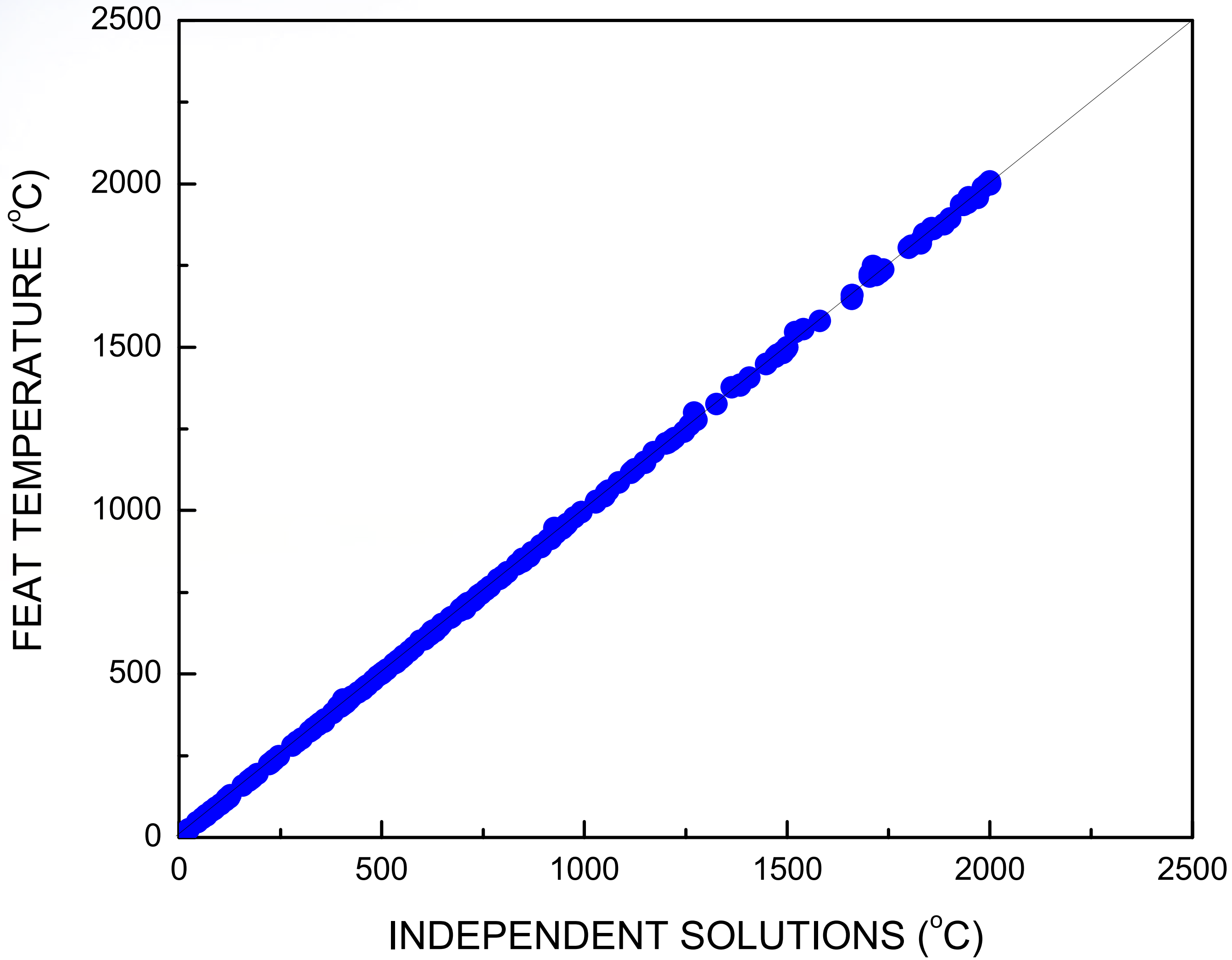
BOW vs. CANFLEX PIE



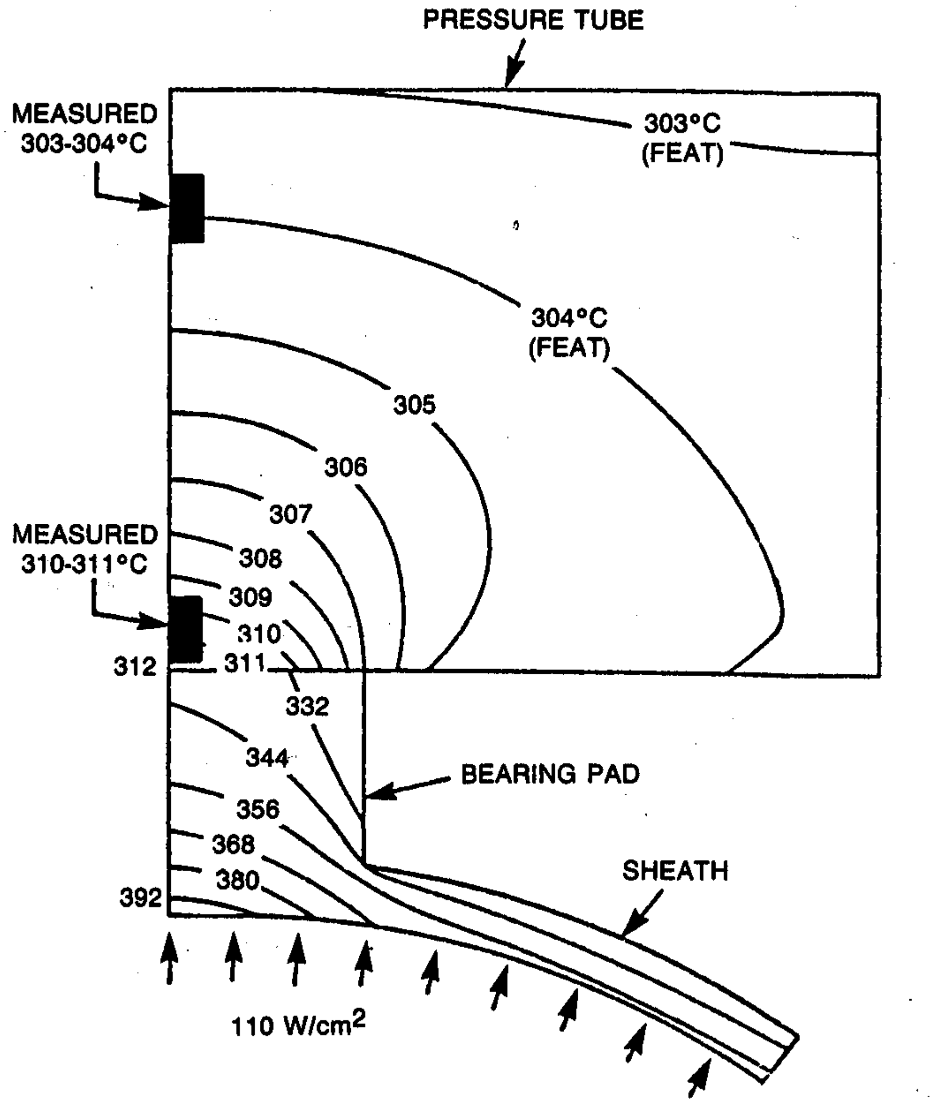
FEAT

- Used to calculate local peak temperatures
  - end-temperature peaking, crevice corrosion between bearing pad and pressure tube, braze void between clad and bearing pad
- 2-D heat conduction, non-linear heat transfer
- Steady-state or transients (e.g. LOCA)
- Flux depression (diameter, enrichment, burnup)
- Variations in material properties (thermal conductivity, specific heat and density)
- Time-dependent boundary conditions
- Multiple bodies (gaps between pellet and clad)
- Finite elements: arbitrary shapes
- Validation against 4 test measurements and 27 independent analytical solutions

FEAT vs. Analytical Solutions



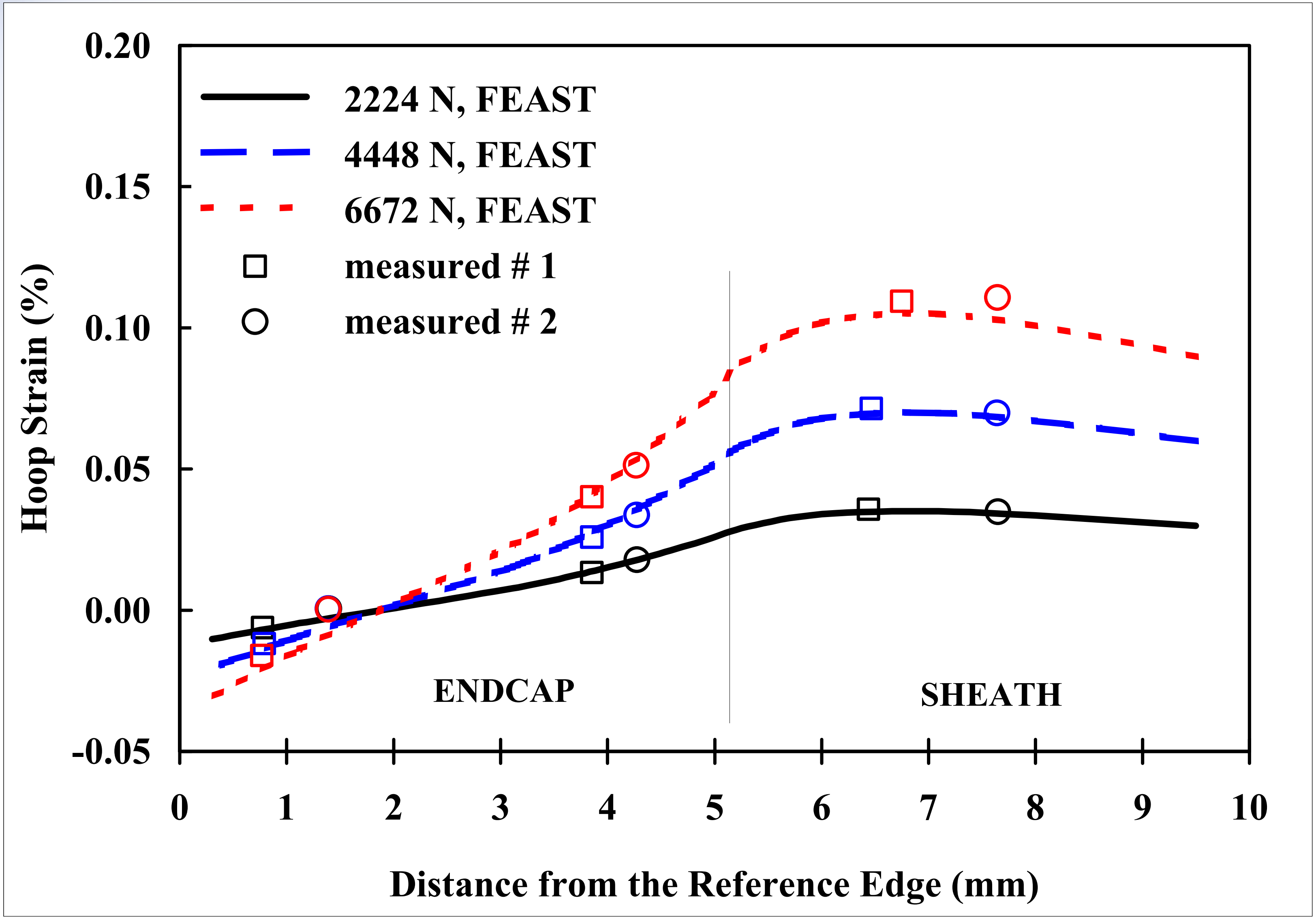
FEAT vs. Measurements



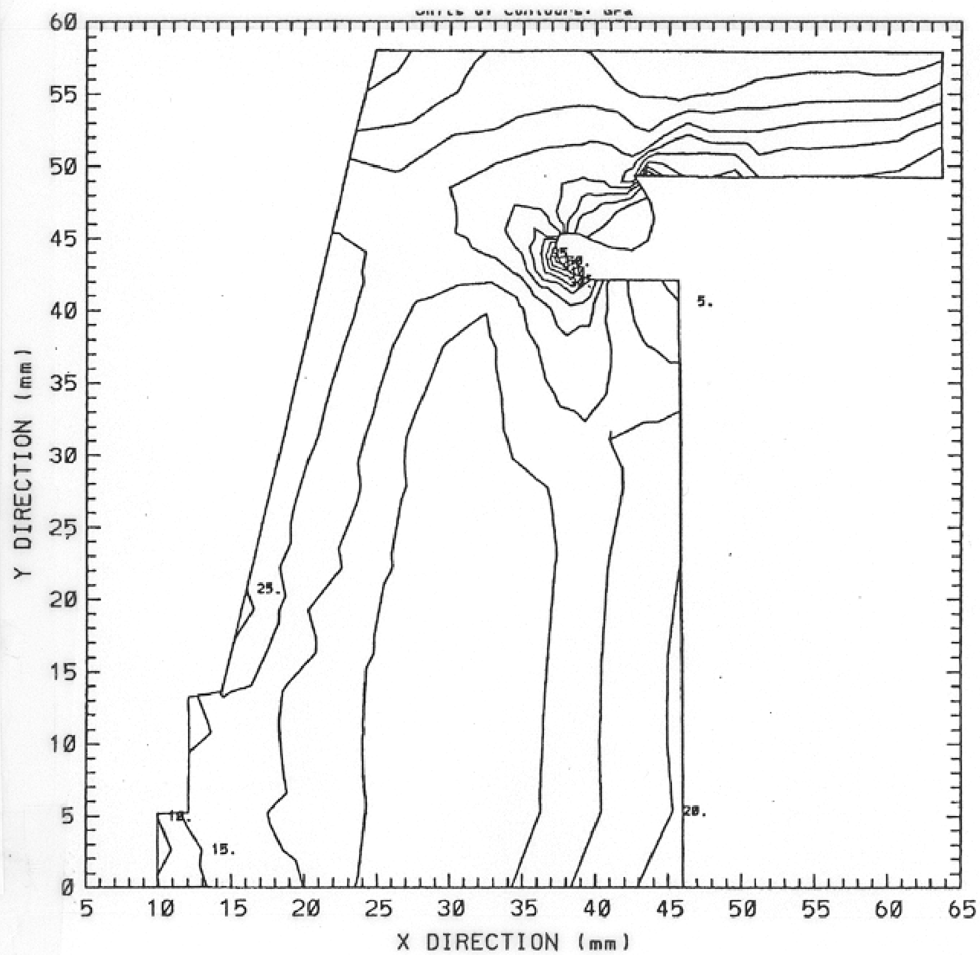
FEAST

- Used to calculate detailed local stresses, strains
  - near endcap, at ridge
- Work density calculation for input into stress corrosion cracking
- Thermal, elastic, plastic, creep, stress relaxation
- Finite element method, 2-dimensional, non-linear stress analysis
- Validated against
  - 2 experimental measurements
  - 18 independent analytical solutions (max diff. of ±1% for half the cases, peak deviation among all cases ±5%)
- Also captures well the observed cracking near endcap junctions

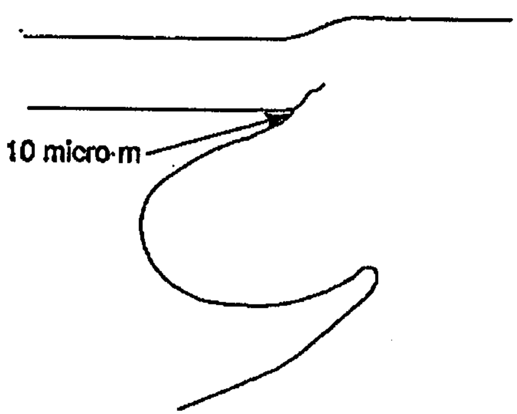
FEAST: Endcap Strains



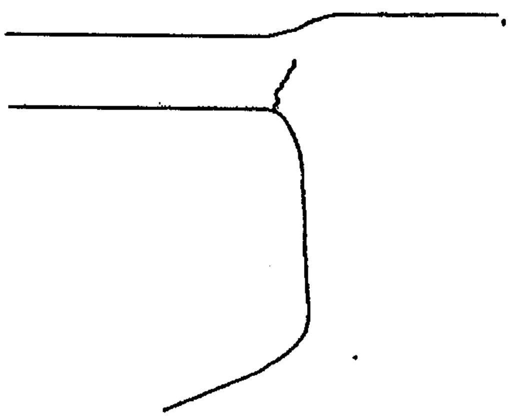
FEAST: Stress Concentrations



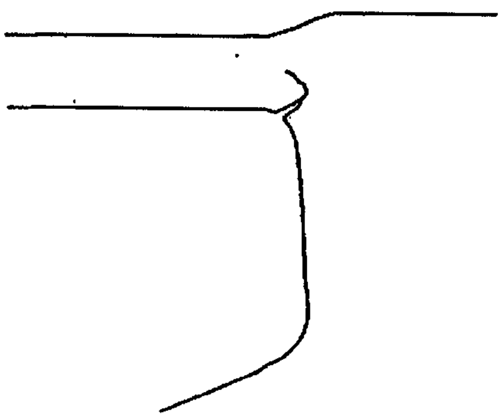
FEAST: Endcap Cracking



GEOMETRY 2



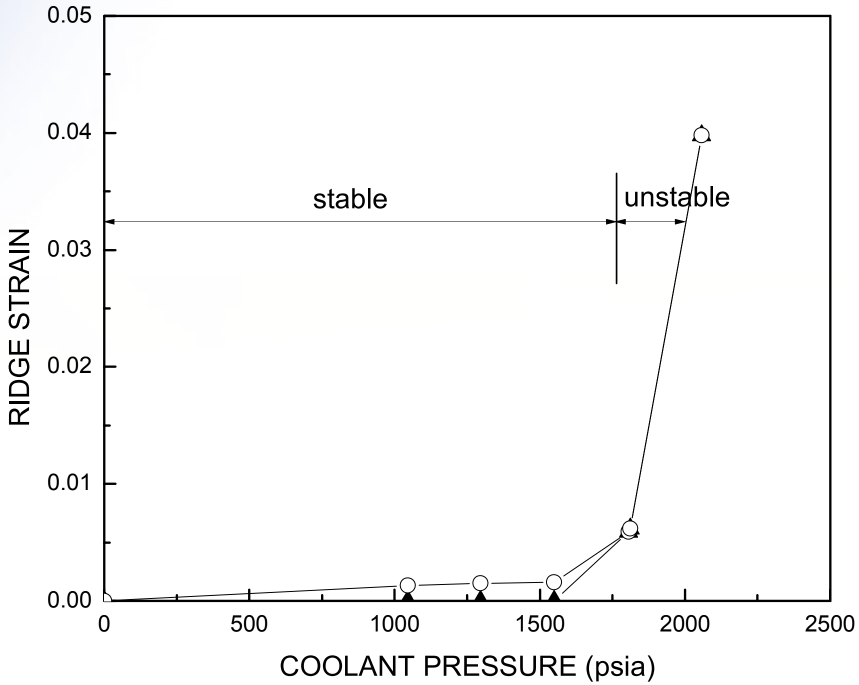
GEOMETRY 4

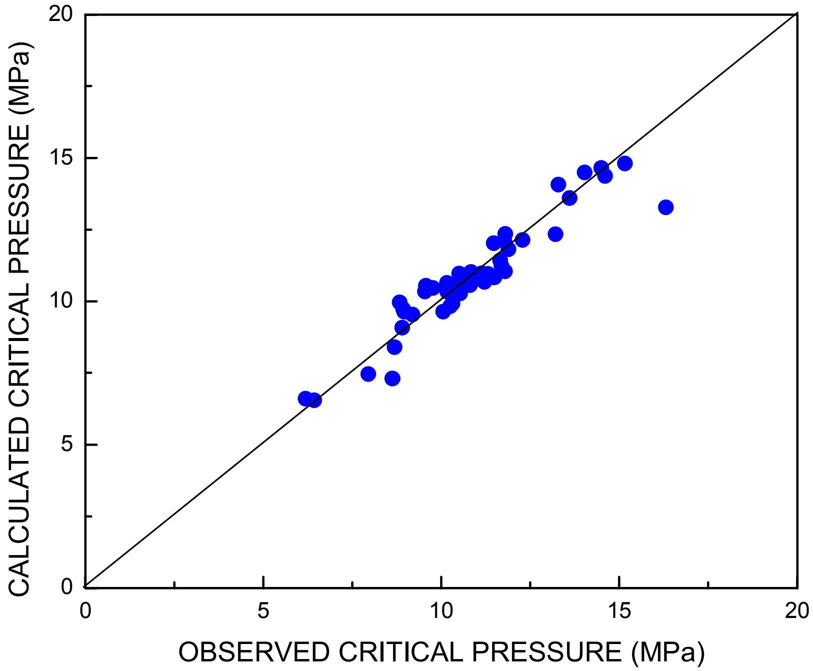


GEOMETRY 5

LONGER

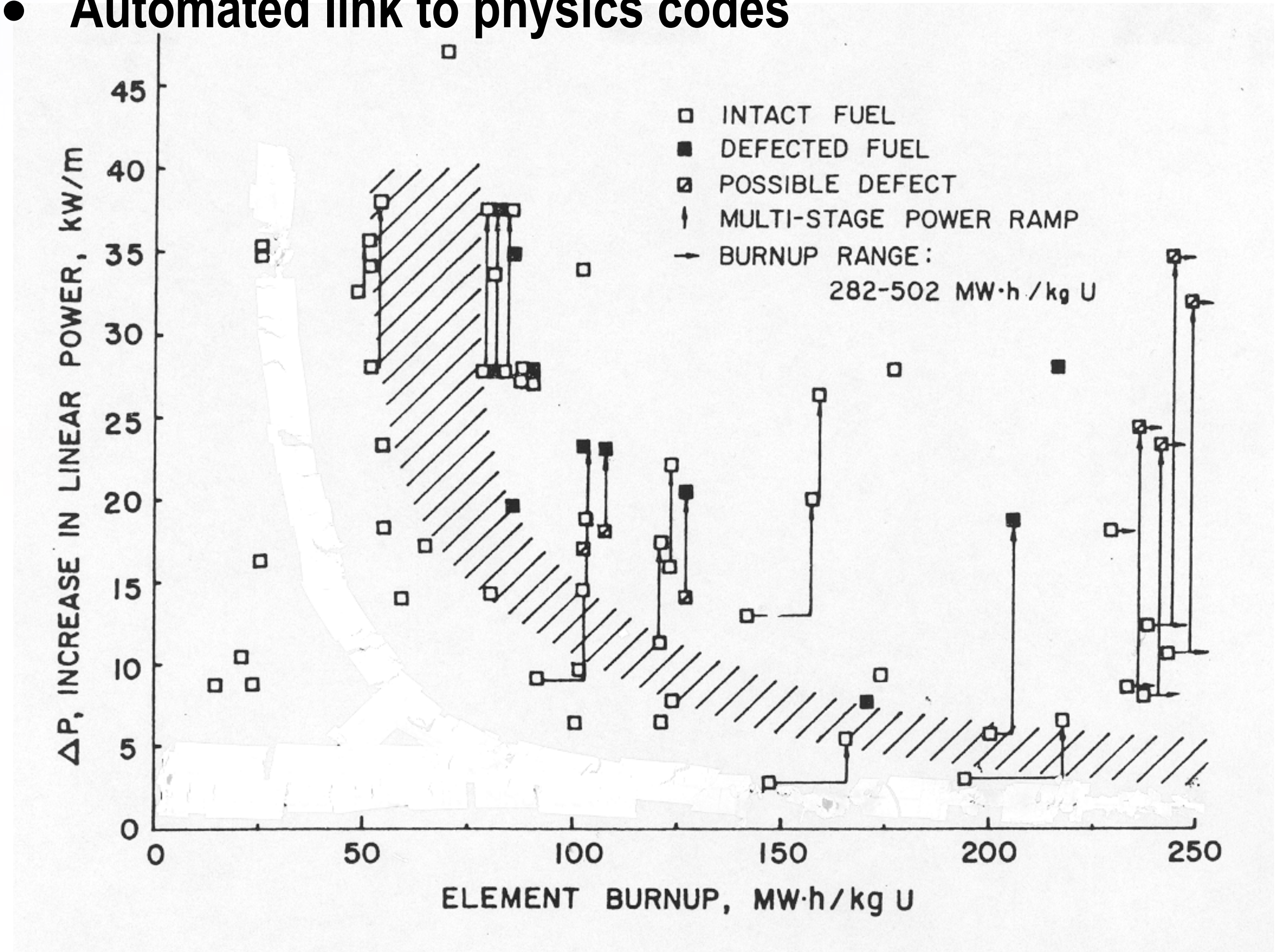
- Used to calculate clad collapse due to coolant pressure
- 48 data points



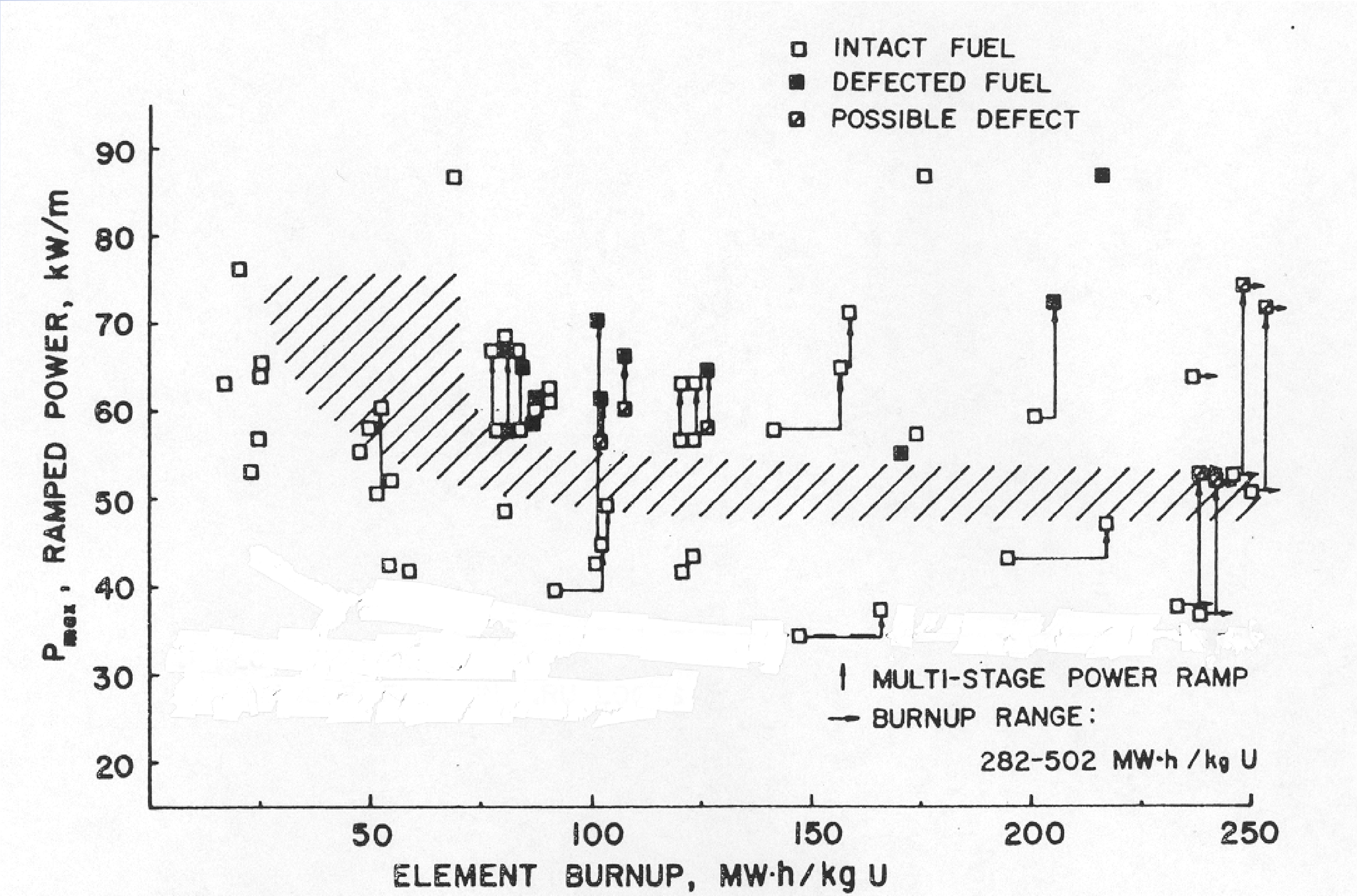


HISTOBUN

- Used to predict core-wide defect probability
- Contains several correlations for stress-corrosion cracking
- Automated link to physics codes

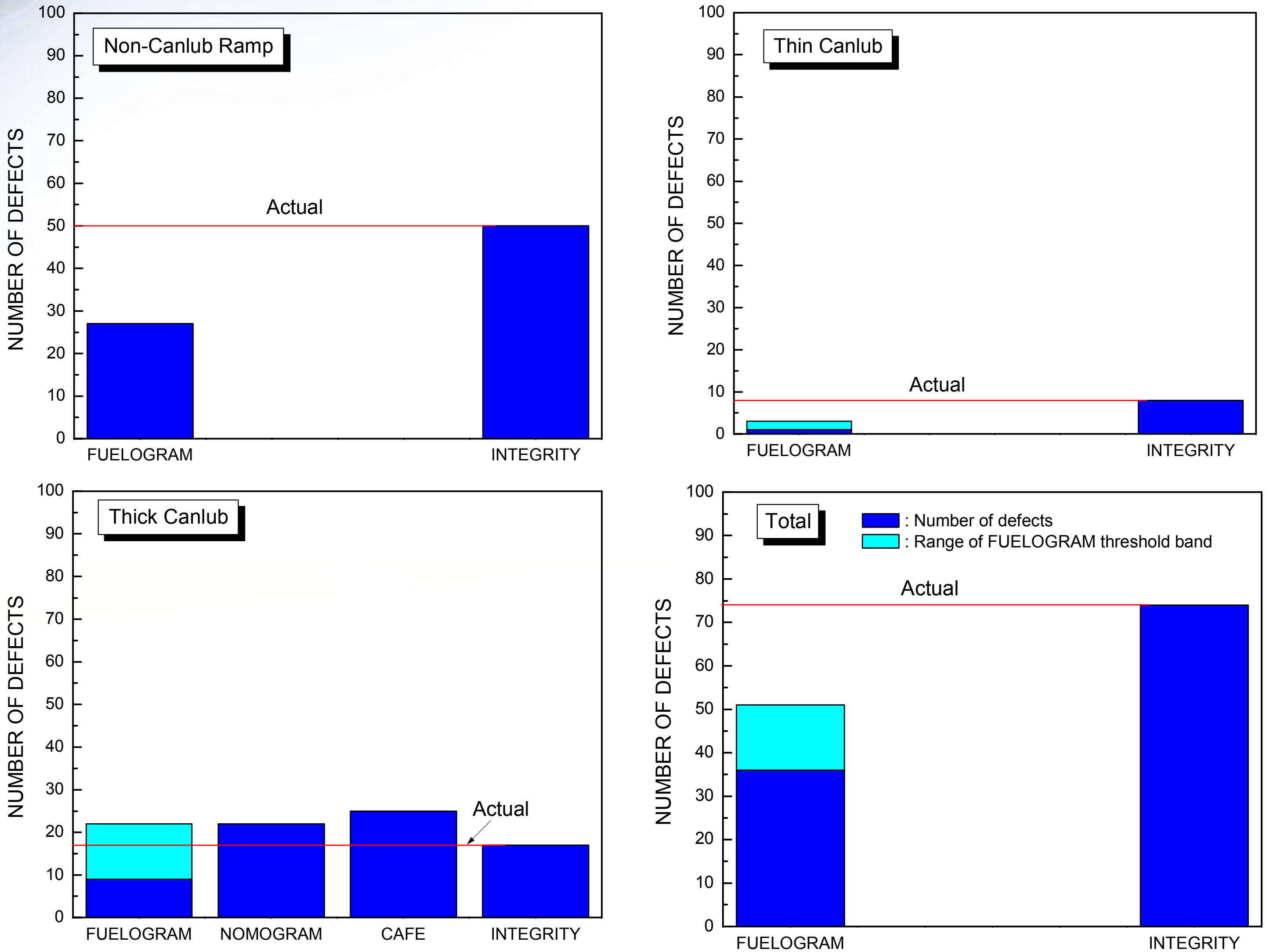


HISTOBUN (continued)



INTEGRITY

- **Mechanistic calculation of environmentally-assisted cracking**
  - single power ramps (stress corrosion cracking)
  - multiple power ramps (stress corrosion fatigue)
  - cyclic power changes (corrosion assisted fatigue)
- **More confident extrapolations to relatively data-sparse regions**
  - extended burnups
  - design changes (e.g. pellet shape, element diameter)
  - specification ranges (e.g. diametral clearance)


Non-Canlub Ramp
Actual
NUMBER OF DEFECTS
FUELOGRAM
INTEGRITY
Thin Canlub
Actual
NUMBER OF DEFECTS
FUELOGRAM
INTEGRITY
Thick Canlub
Actual
NUMBER OF DEFECTS
FUELOGRAM
NOMOGRAM
CAFE
INTEGRITY
Total
: Number of defects
: Range of FUELOGRAM threshold band
Actual
NUMBER OF DEFECTS
FUELOGRAM
INTEGRITY
0
10
20
30
40
50
60
70
80
90
100

Summary

- Computer codes are an essential part of suite of tools for fuel qualification, along with tests, operational experience and engineering judgments
- Analytical assessments of thermal integrity, structural integrity, and compatibility
- 19 types of assessments, 11 computer codes
- Mechanistic models give additional confidence in extrapolations to relatively data-sparse regions

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