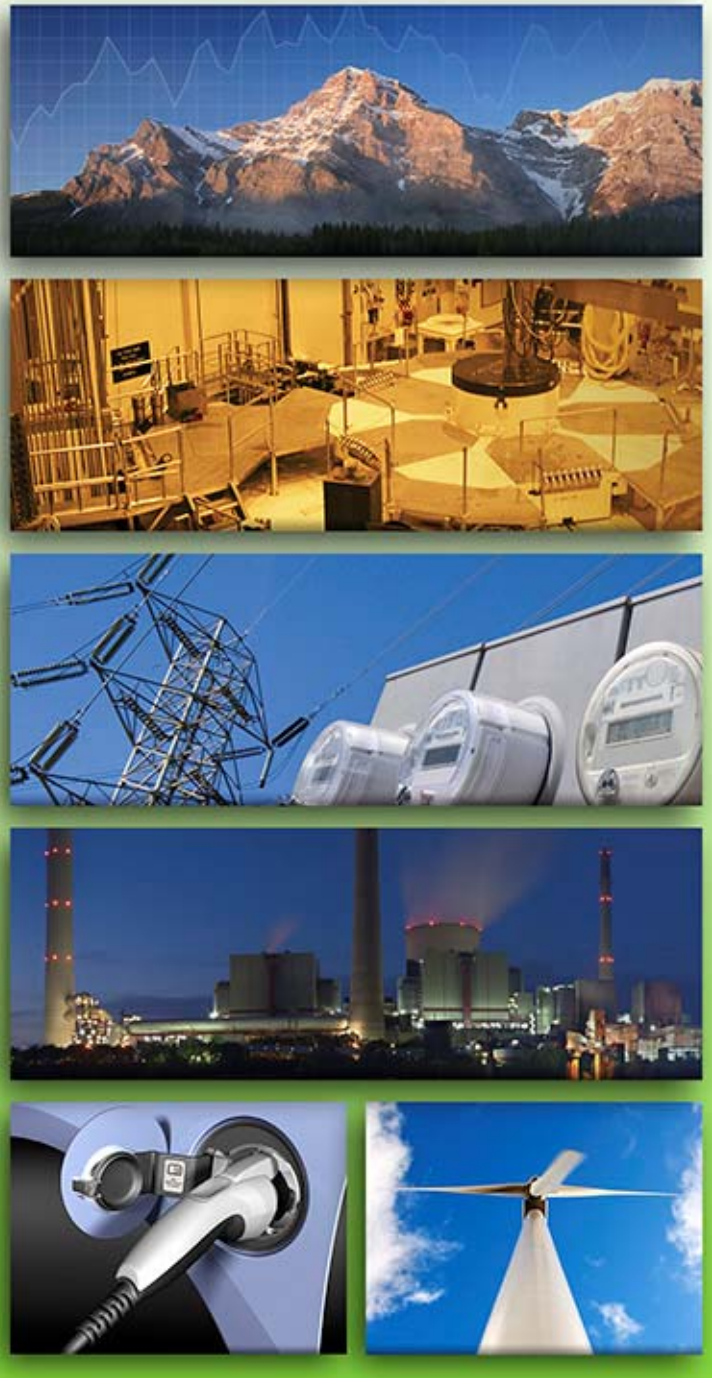


ELECTRIC POWER RESEARCH INSTITUTE

Fuel Performance Codes

Suresh Yagnik
EPRI

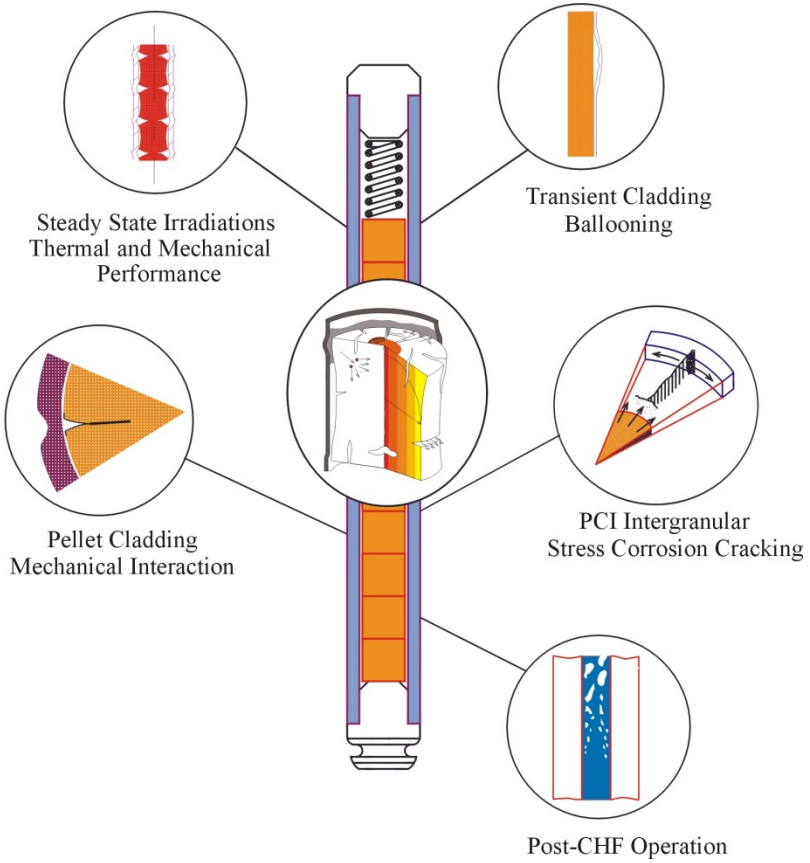
ATR National Scientific User Facility

User Week

June 9, 2010

Acknowledgements

- EPRI Falcon Team
  - Martin Pytel
- EPRI Developers
  - Anatech
  - Objexx Engineering
- Olander Lectures/UC Berkeley



© 2010 Electric Power Research Institute, Inc. All rights reserved.

Presentation Outline

- Introduction/Background
- Basics of Thermal and Mechanical Modeling
- Material Properties and Behavioral Models
- PCI/PCMI, including Cladding Damage Index
- Fission Gas Release
- Redesigning a Legacy Fuel Performance Code
- Concluding Remarks

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Introduction/Background

© 2010 Electric Power Research Institute, Inc. All rights reserved.

What is a Fuel Performance Code?

LWR fuel element is a simple object, but..

- It evolves during its service life, e.g.,
  - Thermal and mechanical changes;
  - Physical and chemical changes
- These changes occur in the fuel pellet, cladding, and
  - Within and at the gap; involving pellet-clad interactions. Also, in upper and lower plena

Given the initial geometry, operating conditions, and power history:

- Q: Will the fuel element serve its *primary function*?
  - Generating power in commercial reactors without failing
  - Meeting aims and objectives of an irradiation test
- A: Is obtained through analysis. The computational tool that is used for this purpose is a Fuel Performance Code

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Types of Fuel Performance Code

- Some codes are steady-state while others are transient:
  - Steady-state ignore transient terms;
  - Transient codes ignore long term phenomena like creep (or treat them as quasi-steady series of steps)
- Depending on how fuel behavioral and phenomenological models are treated, a FPC can be:
  - Empirical/Semi-empirical
  - Best estimate
  - First principle (with or w/o adjustable parameters)

  Or, a combination their of

Caution must be exercised in code-to-code comparisons

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Key LWR Fuel Rod Performance Considerations

- Fuel poolside (non–destructive) measurements
  - Rod growth (dimensional change)
  - Waterside corrosion (eddy current)
  - Cladding diameter change (profilometry)
  - Fission gas release (Kr-85 in plenum)
- Design limits
  - Fuel centerline temperature
  - Hydrogen pickup by cladding
  - EOL pressure
  - Clad strain < 1% (elastic + plastic)
- Analyses needed for “zero-by-ten” industry goal, e.g.,
  - Maximum Clad stress/ damage due to fuel duty

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Requirements of a Fuel Performance Code

- Computational structure and numerics, e.g.,
  - Finite element or finite difference?
  - 1D, 2D, or 3D…generation of computational grids
- Initial geometry, operating T/H conditions, and power history
  - Design of the fuel rod
  - Operating T/H conditions are time-dependent
  - Power history is ultimately obtained through core-follow neutronics codes
- Material properties functions
  - Evolution of the properties with burn-up (alternatively, with time or neutron fluence)
- Behavioral and phenomenological models

Providing correct inputs is the first important step

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Input Requirements (details)

- Fuel pellet material, dimensions, and as-fabricated characteristics e.g., enrichment, porosity, surface roughness
- Cladding material, dimensions, and as-fabricated characteristics e.g., mechanical properties, surface roughness
- Fuel rod dimension, upper and lower plena heights, end plug lengths, axial blanket height, initial fill gas composition and pressure
- Coolant pressure, temp, mass flow rate, hydraulic diameter/fuel rod pitch
- Power history :
  - Core-follow ➔ Assembly average power
  - From Assembly average power ➔ Average rod power (radial peaking)
  - From Average rod power➔ Axial position (node) power (Normalized axial power shape function)
  - From Nodal power to local radial power distribution in the pellet due to Pu redistribution

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Fuel Pin Power and Thermal Data Reconstruction

- Extraction and transformation of data
  - Lattice codes and core simulators
    - Lattice codes – PHOENIX, CASMO
    - Core simulators - MICROBURN-B/P, SP-NOVA, SIMULATE, etc.
  - Thermal hydraulic codes - VIPRE, RETRAN, etc.
- “Manual” processes used to obtain tab delineated file for importation into FalconRD
  - User-developed methods based on particular data form combinations
    - Numerous vendor and utility method combinations

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Fidelity of a Fuel Performance Code

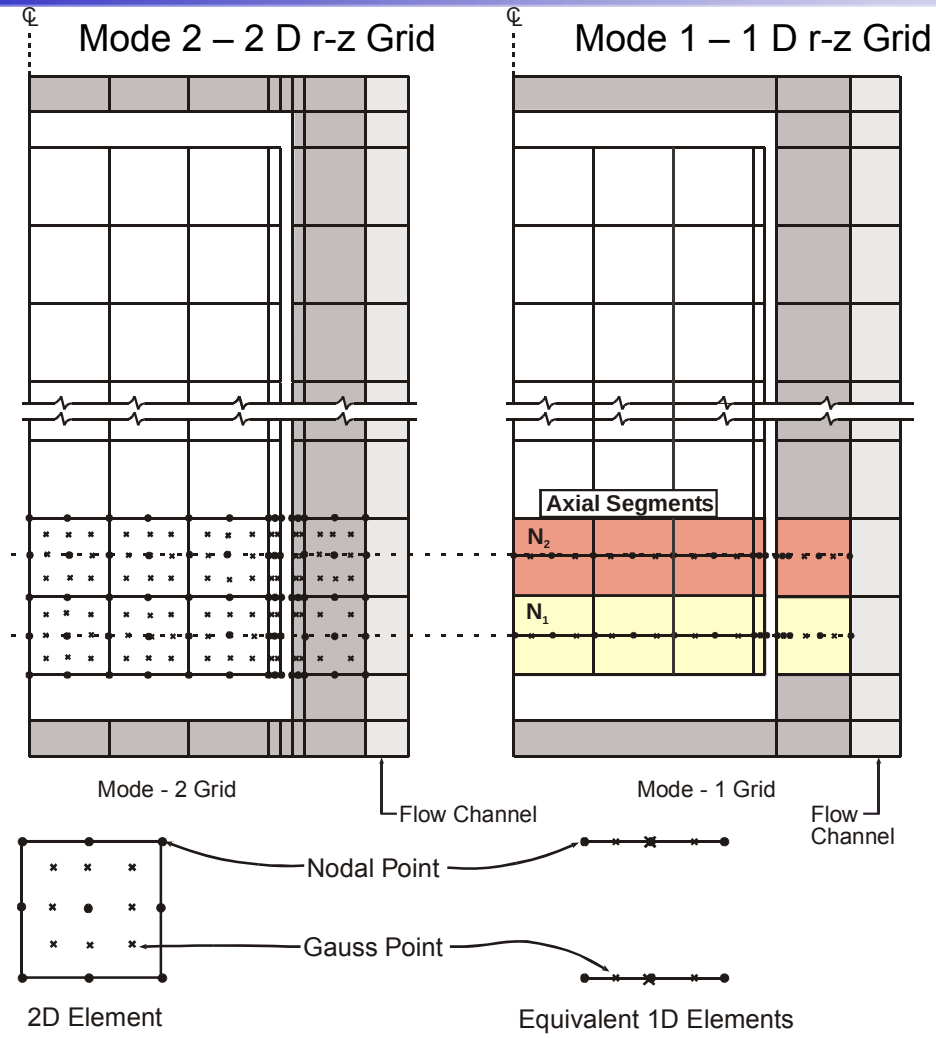
- Grid structure
  - Ability of the axial and/or azimuthal grids to capture the changes;
  - Most fuel performance codes are 1D or 2D

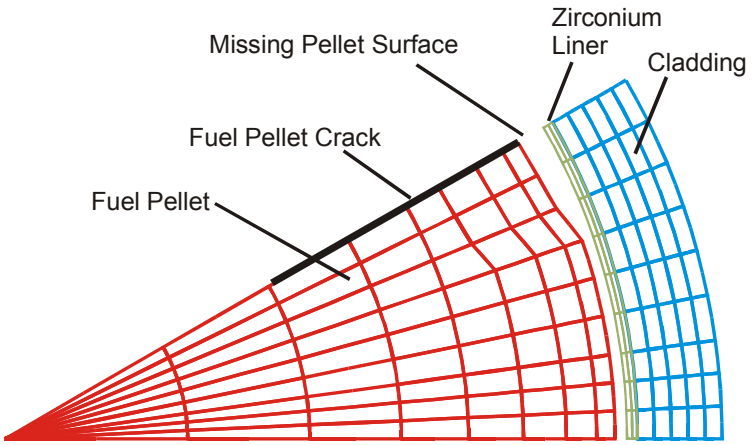
  Often have to optimize between computing power and complexity/ease of use
- Time-stepping to properly capture:
  - Steady vs transient (What exactly is “steady-state”)?
  - Full thermal and mechanical coupling
- Material properties changes and behavioral and phenomenological models with correct dependencies
  - Latest data obtained from separate effects tests and test reactor programs
  - Theoretical framework of the models including adjustable parameters

Clearly defining the analysis being sought and understanding constraints around results obtained is another important step

© 2010 Electric Power Research Institute, Inc. All rights reserved.

FEM Module – Grid Generation





Mode 3 - r-θ Grid

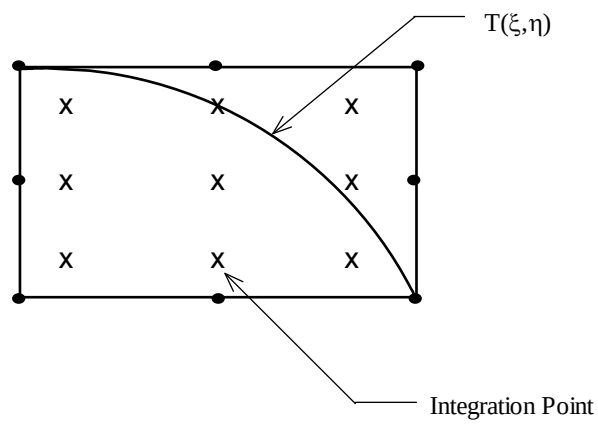
© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

FEM for Temperature and Displacement Fields

- Allows for a single compatible 2-D grid between both thermal and mechanical modules
  - Simplifies the numerical algorithms
- Uses quadratic interpolation (shape) functions in the fuel and cladding
  - Minimizes the required spatial nodalization
  - Captures parabolic temperature distribution in fuel pellet
  - Consistent with cladding large strain deformation analysis

8-Node Quadrilateral Element

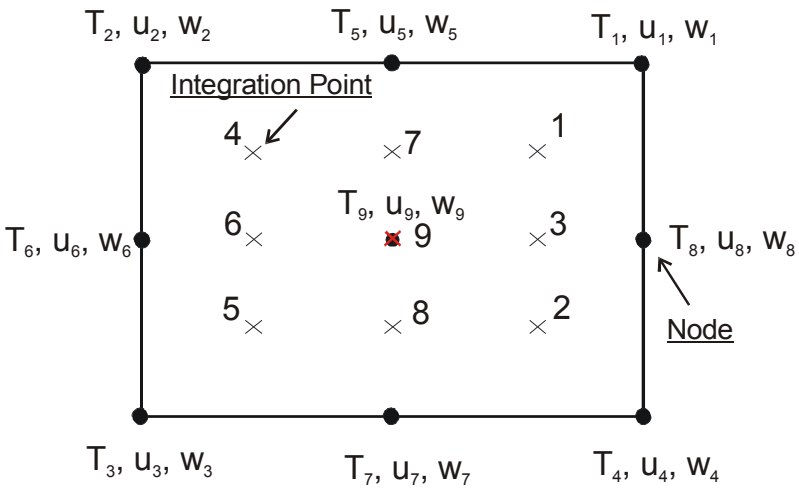


© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

FEM Nomenclature

Nodal and Integration (Gauss) Point Variables



Node Field Variables

T – Temperature
u – Displacement in 1-direction
w – Displacement in 2-direction

Integration Point Variables

Stress in i,j,k directions
Strain in i,j,k directions
Heat flux
Fission gas production, grain and grain boundary concentration, and release

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Calibration, Verification, and Validation

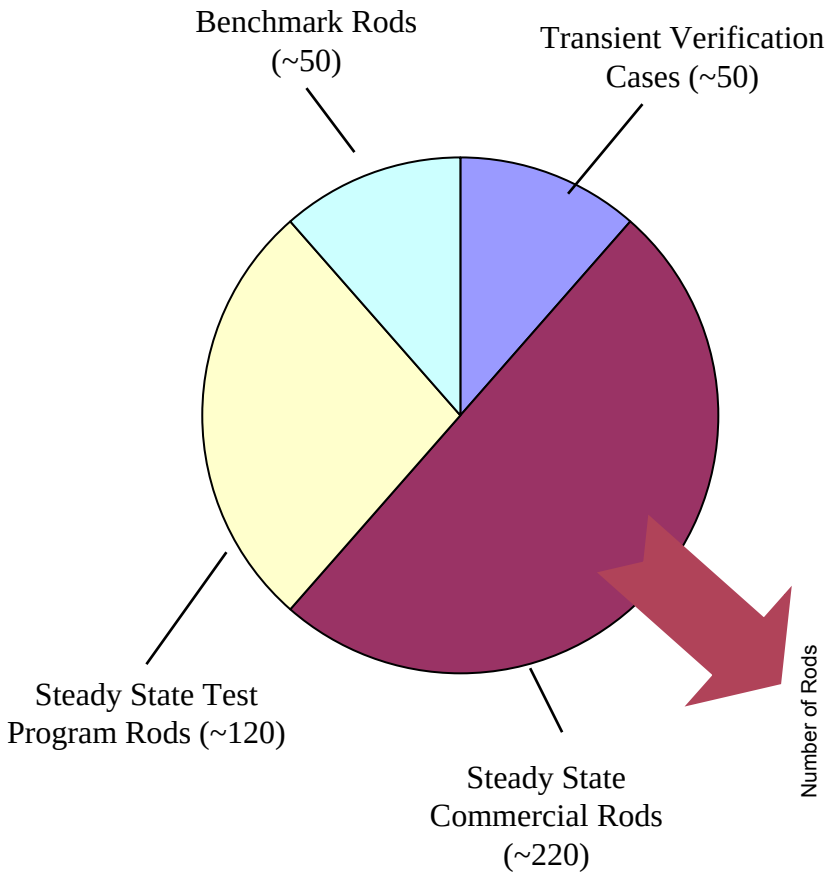
- "Calibration" is assigning values to the adjustable parameters in models
  - Separate effect tests (e.g., cladding corrosion or growth)
- "Verification" is to confirm that the code predications from dedicated test-rod data irradiated under controlled conditions
- "Validation" is an exercise to compare code prediction with the gross performance observed in LWRs
  - Includes complex interactions (e.g., growth-creep, corrosion-crud)
  - Selected cases used to fine-tune the code, then freeze the code

Avoid tendency to "always adjusting" the code

Be aware of "garbage in; garbage out"

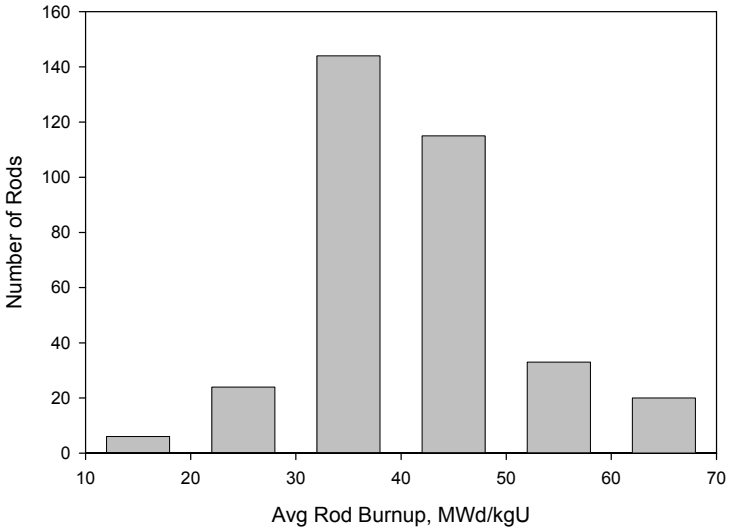
© 2010 Electric Power Research Institute, Inc. All rights reserved.

Fuel Rod Types and Burn-up Distribution



Variety of fuel rods available to develop and test the capabilities of FALCON

Burn-up Distribution of Commercial Rods



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Basics of Thermal and Mechanical Modeling

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Thermal-Mechanical Iteration Scheme

First Iteration – Start of Time step

1) Temperatures are solved using specified power and thermal boundary conditions
   – Gap conductance calculated using fuel rod deformations from previous step
2) Fuel rod deformations are solved using the new temperature distribution from (1) and mechanical boundary conditions
   – Rod internal pressure from previous step

Second Iteration

3) Thermal solution repeated using updated fuel rod deformations from (2)

4) Mechanical solution repeated using updated temperature distribution from (3)

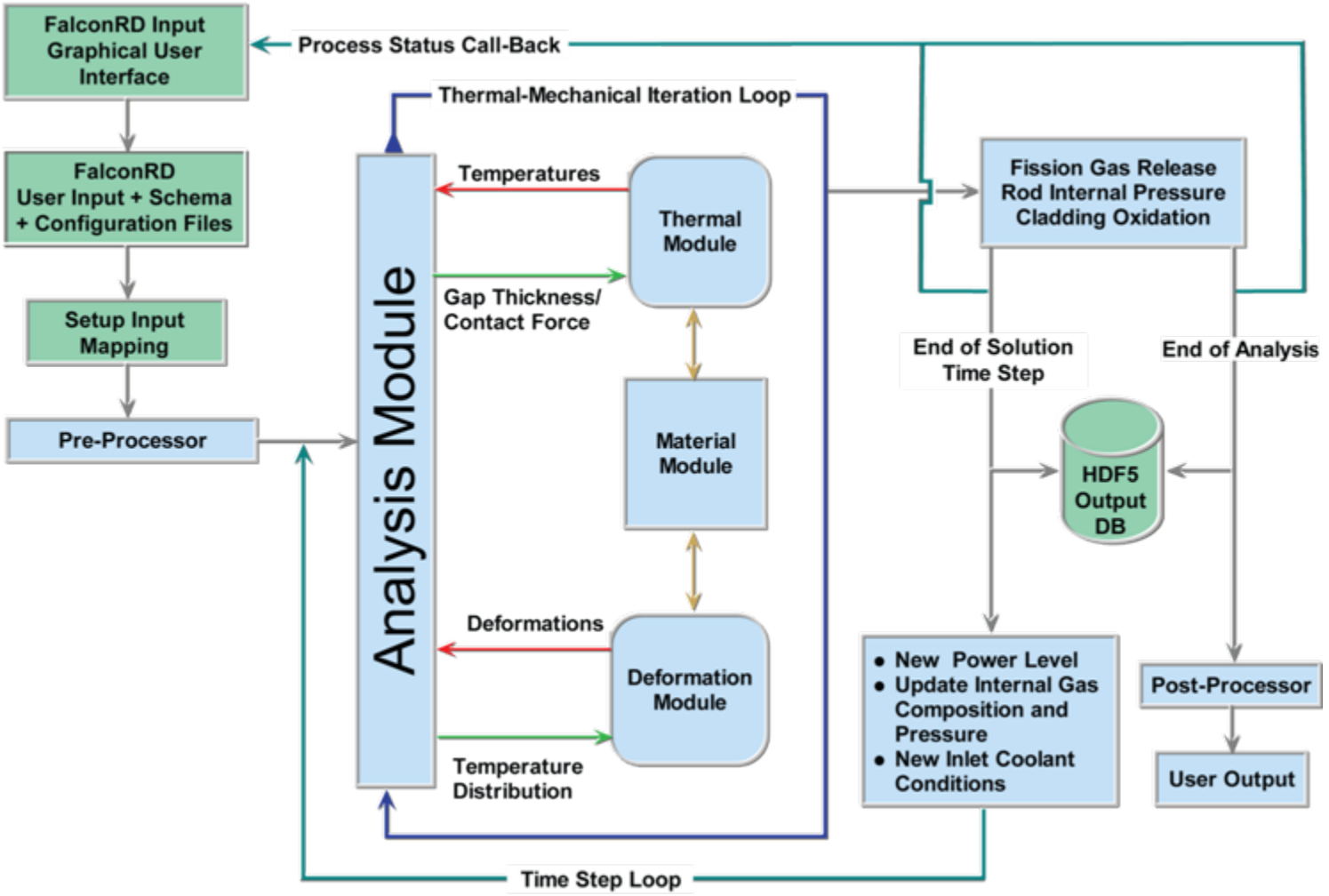
Repeated for five (5) iterations in FalconRD

End of Time step

Use final temperature distributions and fuel rod deformations to calculate fission gas release, rod internal pressure, and cladding oxidation

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Thermal-Mechanical Coupling



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Temperature is the Most Important Driver

- Most material properties are temperature dependent
- Temp also a key parameter in: fission gas release➔ gap conductance

$$\rho C_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x_i}\left(k_{ij}\frac{\partial T}{\partial x_j}\right) - Q = 0$$

ρ	– material density
C_p	– heat capacity
k_{ij}	– thermal conductivity tensor
Q	– volumetric heat generation
t	– time
x_i	– Spatial coordinates
T	– Temperature

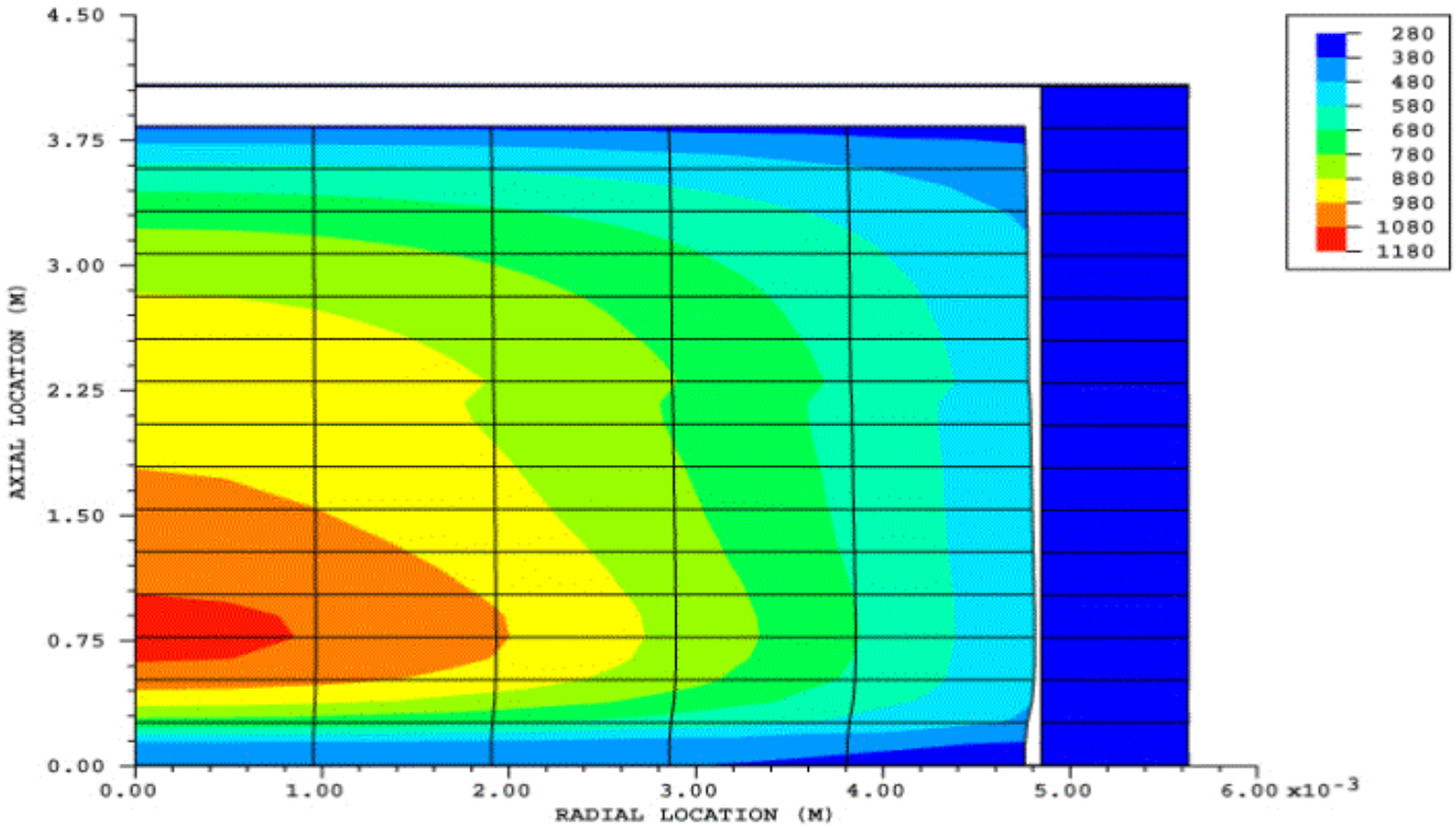
© 2010 Electric Power Research Institute, Inc. All rights reserved.

Volumetric Heat Generation

- Fission heat generation in pellet
  - Considers radial and axial variations
- Gamma heating in cladding and coolant
  - Proportional to the fission power
- Heat of zirconium oxidation
  - Result of high temperature oxidation process
- Radioactive decay heat from fission products
  - 1979 ANS-5.1

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Typical temperature range in fuel (300 – 1200ºC)



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

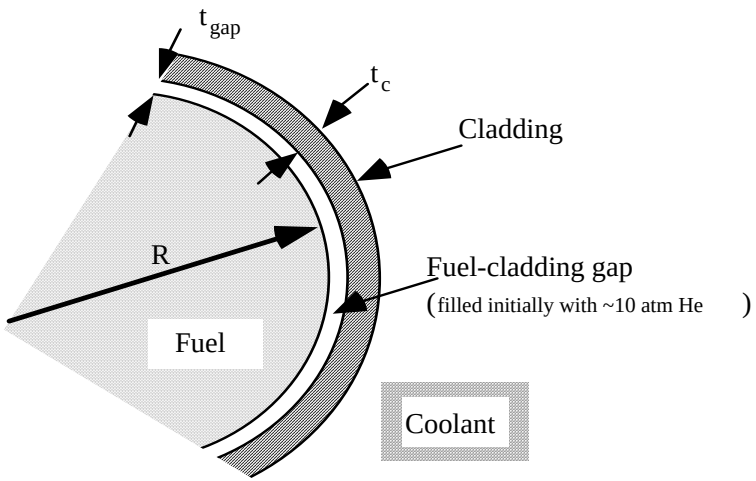
Steady State Temperature Distribution in the Fuel: Compare Code Results with Analytical Solutions in Simplified cases

- Simple form of fuel conductivity

$$k = (A + BT)^{-1}$$

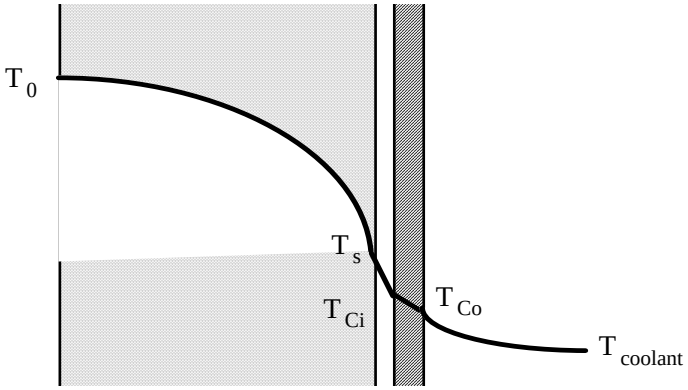
$$\frac{T - T_S}{T_0 - T_S} = \frac{\exp\left[\frac{Bq'}{4\pi}(1 - \frac{r^2}{R^2})\right] - 1}{\exp\left[\frac{Bq'}{4\pi}\right] - 1}$$

$$\rightarrow 1 - (r/R)^2 \text{ as } B \rightarrow 0$$



- Temp drop through the gap

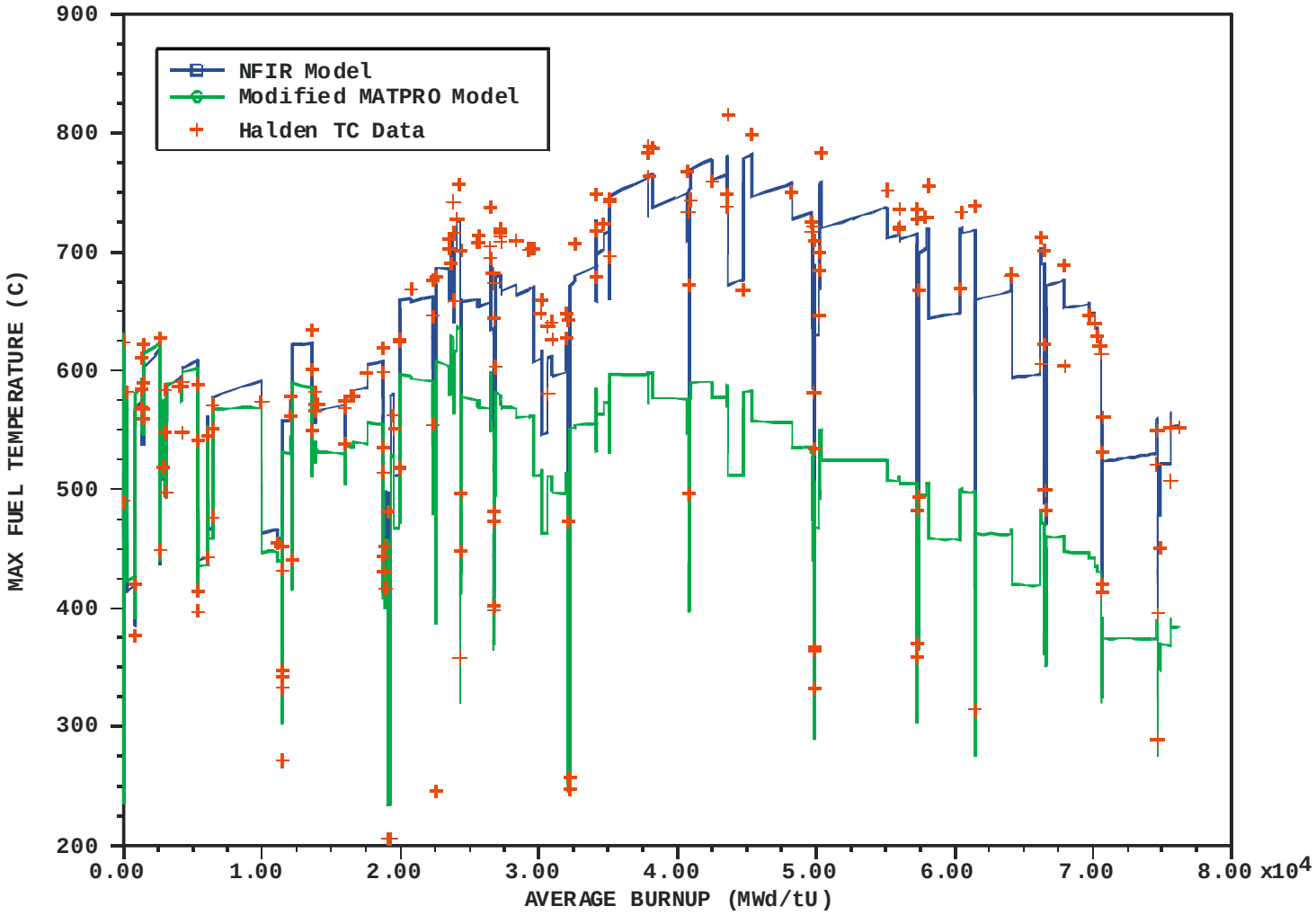
$$T_{CI} - T_{CO} = \frac{\delta_C}{k_C} \frac{q'}{2\pi R}$$



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Impact of Fuel Thermal Conductivity

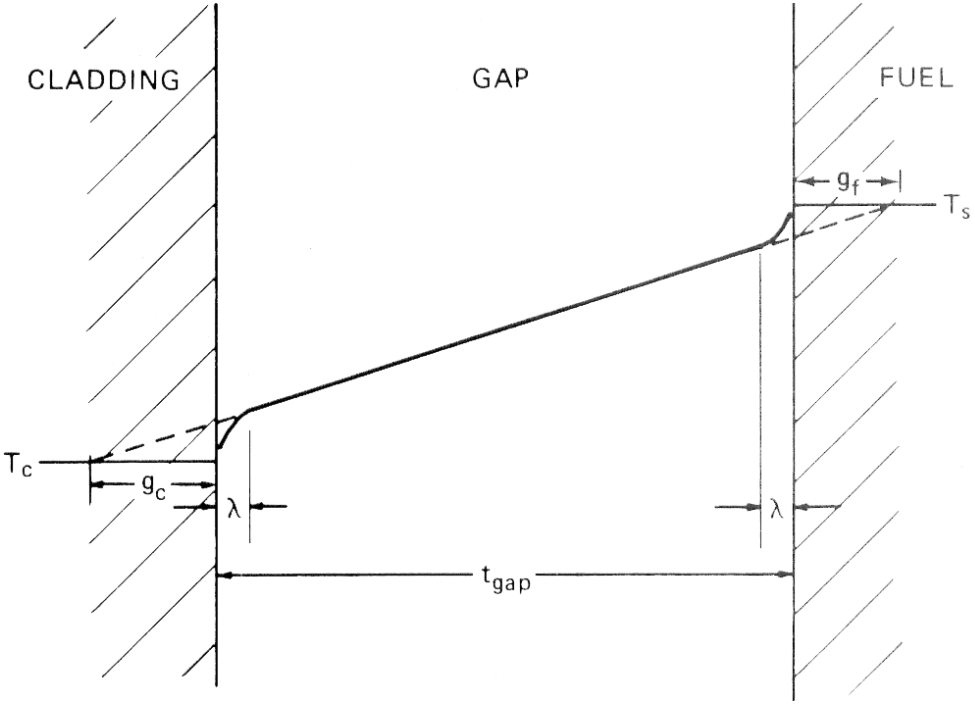


© 2010 Electric Power Research Institute, Inc. All rights reserved.

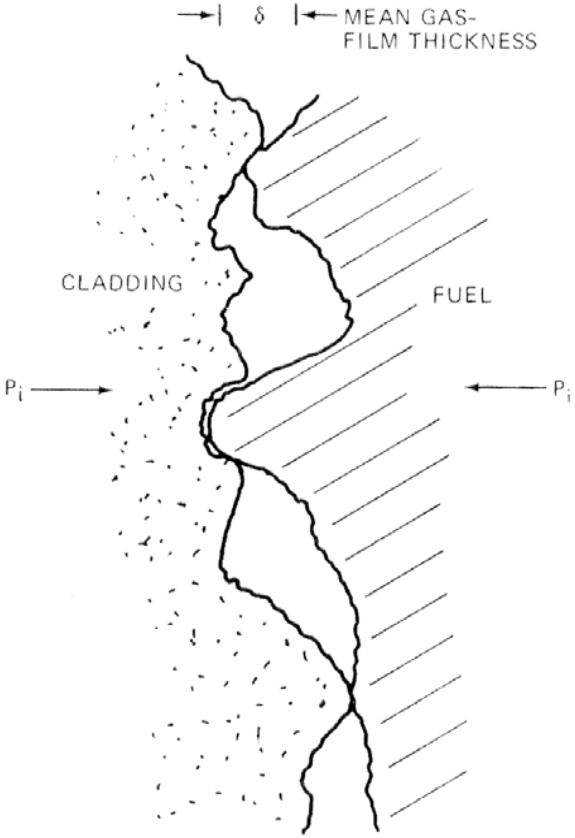
ELECTRIC POWER RESEARCH INSTITUTE

Pellet-Cladding Gap

Open Gap Condition



Closed Gap Condition



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Fuel Rod Deformations

- Fuel and cladding thermal expansion
- Pellet solid swelling, densification, and relocation
- Pellet cracking, creep, plasticity, and hot-pressing
- Cladding irradiation and thermal creep
- Cladding elongation by irradiation growth
- Cladding elastic and plastic deformations (PCMI, ballooning, etc.)

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Stress-Strain Relations

- Incremental Stress-Strain Equation

$$\Delta \underset{\sim}{\sigma} = \underset{\approx}{H}\, \Delta \underset{\sim}{\varepsilon} - \underset{\sim}{R}$$

$\Delta \underset{\sim}{\sigma}$ – *Stress increment*

$\underset{\approx}{H}$ – *Material constitutive matrix*

$\Delta \underset{\sim}{\varepsilon}$ – *Strain increment*

$\underset{\sim}{R}$ – *Internal stress vector*

$$\underset{\sim}{\sigma}^{i} = \underset{\sim}{\sigma}^{i-1} + \Delta \underset{\sim}{\sigma}$$

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Stress-Strain Relations: Axi-symmetric Simplification

- General elastic theory is applied in fuel and cladding with certain simplifying assumptions:
  - Axisymmetric system in r-z analyses
  - Fuel and clad axial movements are allowed at different rates but planes perpendicular to z-direction remain so during deformation
  - Time dependent phenomena (e.g., creep and swelling) are treated as series of quasi steady-state
  - Clad ID is subject to
    - internal pressure (initial + FGR) in open gap
    - Hydrostatic PCMI in closed gap
  - Clad OD is subject to coolant pressure

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Stress-strain constitutive equations (2)

- Reversible: Elastic and thermal
- Irreversible: Plastic and creep

- <u>Constitutive relations</u> (elastic + plastic + creep + thermal):

$$\varepsilon_{\theta,tot} = \tfrac{1}{E}\left[\sigma_\theta - \nu(\sigma_z + \sigma_r)\right] + \varepsilon_{\theta,pl} + \varepsilon_{\theta,cr} + \alpha\Delta T$$

$$\varepsilon_{z,tot} = \tfrac{1}{E}\left[\sigma_z - \nu(\sigma_\theta + \sigma_r)\right] + \varepsilon_{z,pl} + \varepsilon_{z,cr} + \alpha\Delta T$$

$$\varepsilon_{r,tot} = \tfrac{1}{E}\left[\sigma_r - \nu(\sigma_\theta + \sigma_z)\right] + \varepsilon_{r,pl} + \varepsilon_{r,cr} + \alpha\Delta T$$

© 2010 Electric Power Research Institute, Inc. All rights reserved.

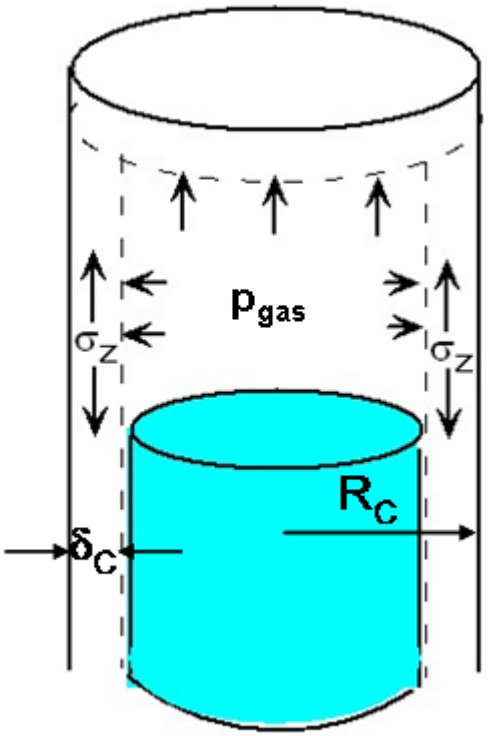
Compare with Analytic Solution: Open Gap

- fission-gas and system pressure

Open gap:

• thin - wall tubes, $\sigma_\theta = (p_{gas} - p) R_C / \delta_C$;

$$\sigma_z = \tfrac{1}{2}\sigma_\theta$$



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Open gap ID pressure (Fill gas + FGR)

$$p_{gas} = \frac{R\sum n_i}{\sum V_i / T_i}$$

i = void region in fuel element

- plenum
- gap
- cracks

R = gas constant

n_i = moles gas in region i

V_i = volume of region i

T_i = temperature of gas in region i

© 2010 Electric Power Research Institute, Inc. All rights reserved.

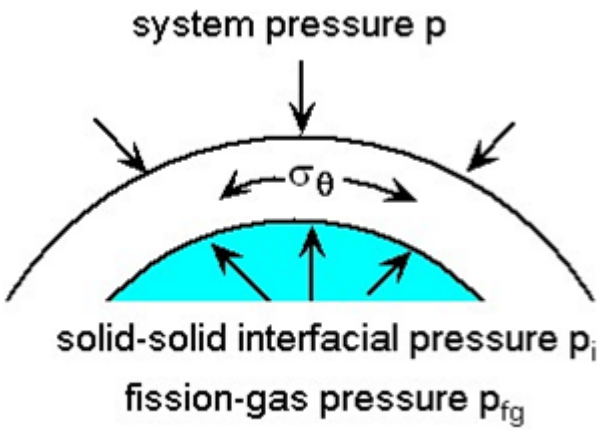
Compare with Analytic Solution: Closed Gap

- <u>forces acting on the cladding arise from</u>:

  - fuel swelling (closed gap, or hard PCMI)

$$\sigma_\theta = (p_i - p)\, R_C / \delta_C$$

$$\sigma_z = \sigma_\theta$$



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Material Properties and Behavioral Models

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Key thermal and mechanical properties and behavior models

Material	**Thermal Properties**	**Mechanical Properties**	**Behavioral Models**
Fuel	Specific Heat Capacity Thermal Conductivity Emissivity Melting Temperature	Thermal Expansion Young's and Shear Modulus Compressive Yield Stress Fracture Strength Thermal/Irradiation Creep Densification Swelling Relocation	Fuel Swelling Steady State Fission Gas Release Transient Fission Gas Release Radial Power Distribution High Burnup Structure
Cladding	Specific Heat Capacity Zircaloy Thermal Conductivity ZrO_2 Thermal Conductivity Zirconium Dioxide Emissivity Melting Temperature	Thermal Expansion Young's Modulus for Isotropic Cladding Shear Modulus for Isotropic Cladding Yield Stress Plastic Strain Hardening Annealing of Cold Work/Irradiation Damage Meyer Hardness Thermal/Irradiation Creep Irradiation Growth	Low Temperature Oxidation (Water) High Temperature Oxidation (Steam) Phase Transformation Stress Corrosion Cracking High Temperature Rupture
Gap	Gas Thermal Conductivity Gas Viscosity Temperature Jump Distance	Friction Coefficient	Open and Solid Gap Conductivity

© 2010 Electric Power Research Institute, Inc. All rights reserved.

UO_2 Material/Behavior Models

Model	Source	Primary Dependency
Thermal Properties		
Specific Heat and Enthalpy	MATPRO	T, O/M ratio
UO_2 Thermal Conductivity	MATPRO/ESCORE NFIR/Turnbull User Defined	T, burnup, porosity, Gd enrichment
Emissivity	MATPRO	T
Melting Temperature	MATPRO Literature	Burnup
Mechanical Properties		
Thermal Expansion	MATPRO	T, PuO_2 fraction, molten fraction
Solid Swelling	MATPRO	T, burnup
Densification	MATPRO or ESCORE	T, burnup, Initial density, resintering temperature
Relocation	ESCORE or User Input	Burnup, power level
Pellet Cracking	Smeared Crack	T, E, ε_o, ε_f, σ_y
Elastic Modulus and Poisson's Ratio	MATPRO	T, ρ, O/M ratio, burnup, PuO_2 fraction
Thermal/Irradiation Creep	MATPRO	T, t, grain size, ρ, fission rate, O/M ratio, stress

© 2010 Electric Power Research Institute, Inc. All rights reserved.

UO_2 Material/Behavior Models (cont'd)

Behavioral Models		
Model	**Source**	**Primary Dependency**
Steady State Fission Gas Release	ANS5.4 Forsberg-Massih ESCORE User Defined	T, burnup, grain size, resolution parameter
Transient Fission Gas Release	EPRI-CE	T
Radial Power Distribution	TUBRNP RADAR-G User Defined	T, ϕ, fission rate, Pu species fractions, burnup, U enrichment, and Gd enrichment
High Burnup Rim Structure	TUI/Lassmann	Local Burnup

User Defined - User defined subroutine available and/or Input data options can be used to over-ride internal model

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Zircaloy Material/Behavior Models

Model	Source	Primary Dependency
Thermal Properties		
Specific Heat	MATPRO	T
Thermal Conductivity	MATPRO, NFIR	T, Φ, Gd
ZrO_2 Thermal Conductivity	MATPRO and PFCC	T
Emissivity	MATPRO	T, oxide layer thickness
Mechanical Properties		
Thermal Expansion	MATPRO	T
Elastic Modulus and Poisson's Ratio	MATPRO	T, O_2, Φ, cold work
Zr Plastic Deformation	MATPRO modified	ϵ_p, $\dot{\epsilon}$, T, cold work, Φ, O_2
Annealing	MATPRO	T, ~ΔT, Δt, Φ, cold work, ϕ
Zr Mechanical Limits	MATPRO/NFIR	T, cold work, Φ, O_2, $\dot{\epsilon}$
Failure	PCI/SCC, Transient Rupture, SED	T, t, σ, ε_{burst}
Thermal and Irradiation Creep	MATPRO ESCORE Limbäck-Andersson User Defined	T, σ, ϕ, Φ, $\dot{\epsilon}$
Irradiation Growth	MATPRO ESCORE Franklin User Defined	Φ, cladding type or cold work
Meyer Hardness	MATPRO	T

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Zircaloy Material/Behavior Models (cont'd)

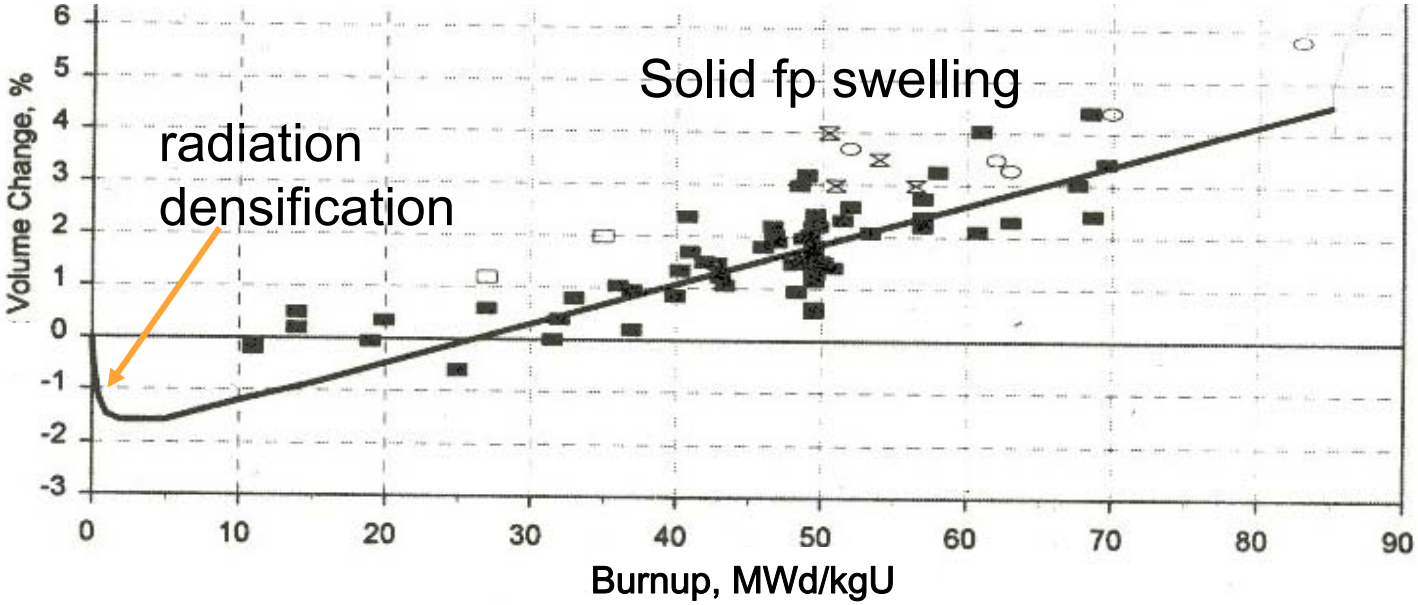
Behavioral Models		
Model	**Source**	**Primary Dependency**
Low Temperature Oxidation (BWR and PWR corrosion during normal operation)	MATPRO PFCC-EPRI/SLI User Defined	T, Sn content, SPP distribution, Li content
High Temperature Oxidation (LOCA temperature regime)	Cathcart Baker-Just Leistekov Urbanic User Defined	T

User Defined - User defined subroutine available and/or input data options can be used to over-ride internal model

© 2010 Electric Power Research Institute, Inc. All rights reserved.

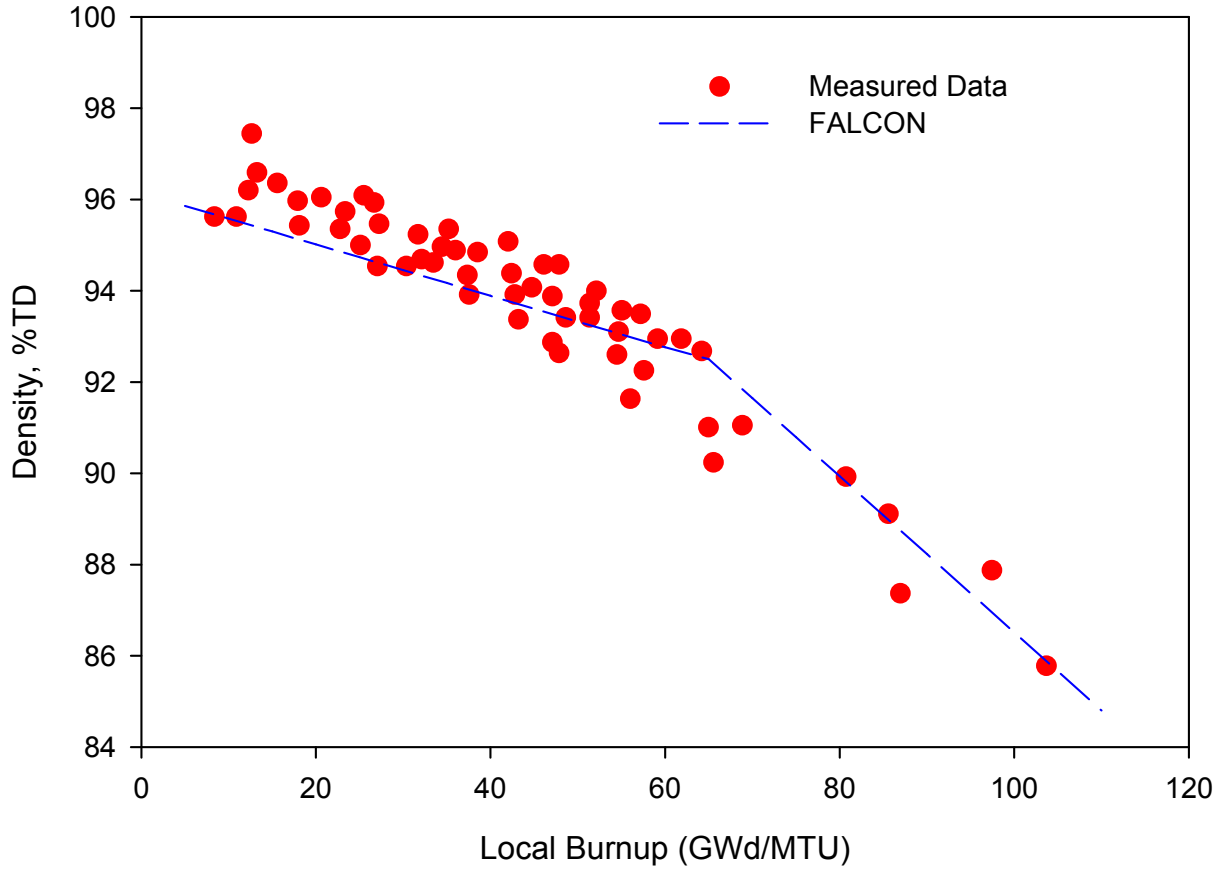
Pellet Densification

- Densification is the removal of as-manufactured porosity during irradiation in the reactor
  - Function of pellet manufacturing process, temperature and burnup
  - Results in decrease in pellet dimensions



© 2010 Electric Power Research Institute, Inc. All rights reserved.

UO_2 Swelling



Data from S. Bremier, C.T. Walker, and R. Manzel, OECD/AEN/NEA Seminar on Fission Gas Behavior in Water Reactor Fuels, September 2000.

© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Gap Behavior Models

Model	Source	Model Dependency
Thermal Properties		
Gas Thermal Conductivity	MATPRO	T, P, gas species fractions
Temperature Jump Dist.	Kennard	T, P, gas species fractions
Gap Conductance	Ross-Stoute/Mikic-Todreas User Defined	T, surface roughness, gap thickness, emissivity, P, Meyer Hardness
Mechanical Properties		
Friction Coefficient	User Input	N/A

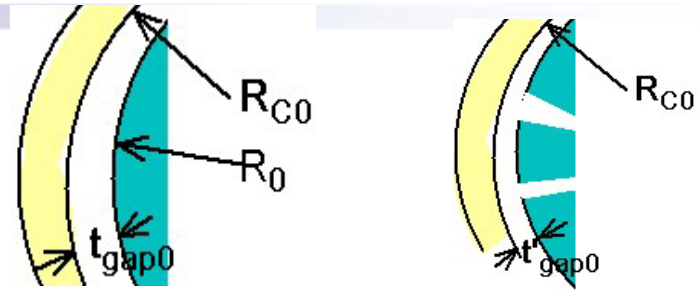
© 2010 Electric Power Research Institute, Inc. All rights reserved.

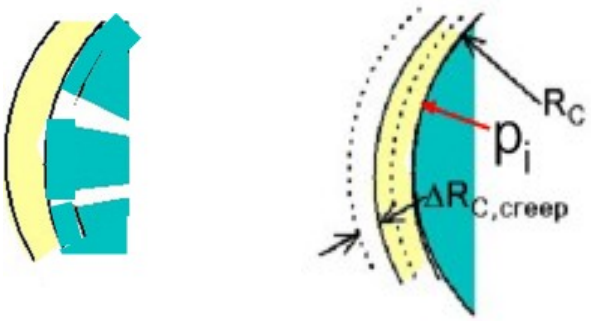
PCI/PCMI, including CDI (Cladding Damage Index)

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Gap Closure and PCMI

- Open gap - hot but intact pellet
- Initial cracking & relocation
  - a fraction ~ 0.5 of initial hot gap is converted to void volume inside cracks
- Soft PCMI – fuel first contacts cladding – no interfacial pressure
- Hard PCMI – void volume eliminated from fuel – high interfacial pressure

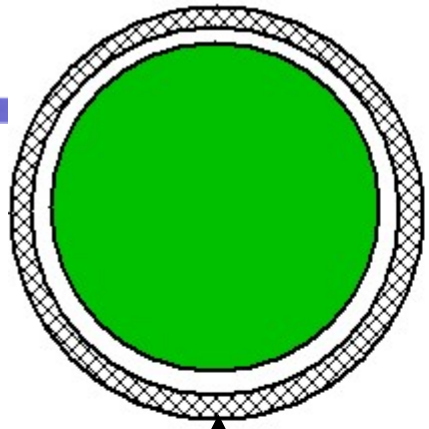




© 2010 Electric Power Research Institute, Inc. All rights reserved.

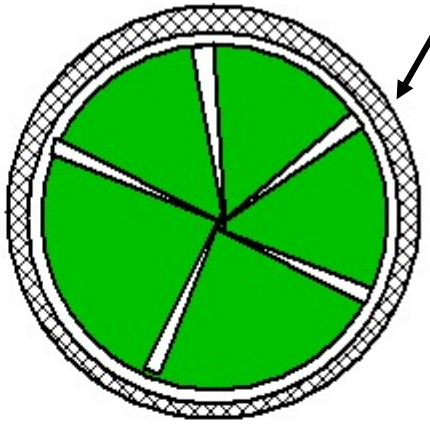
ELECTRIC POWER RESEARCH INSTITUTE

- **cracks predominantly radial – do not interfere with heat conduction**



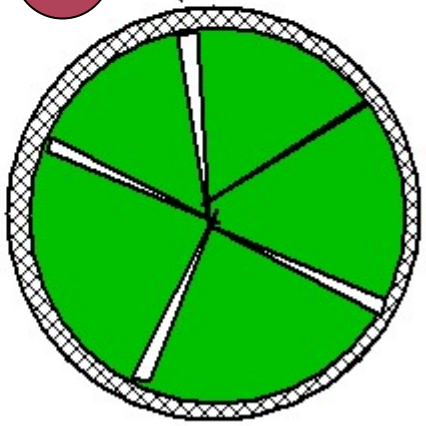
initial - hot
no cracking

1



initial - at power
partial gap closure

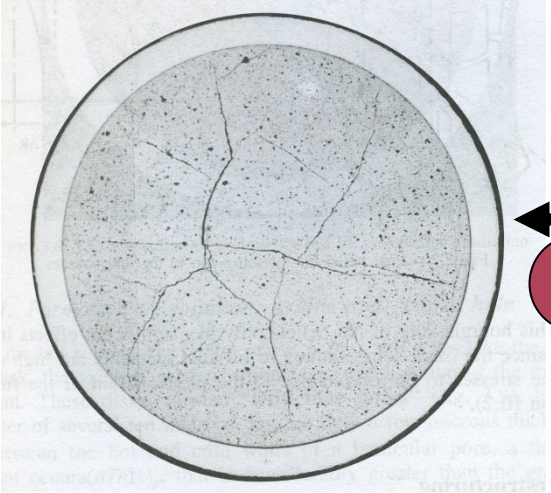
2



"Soft" PCMI starts

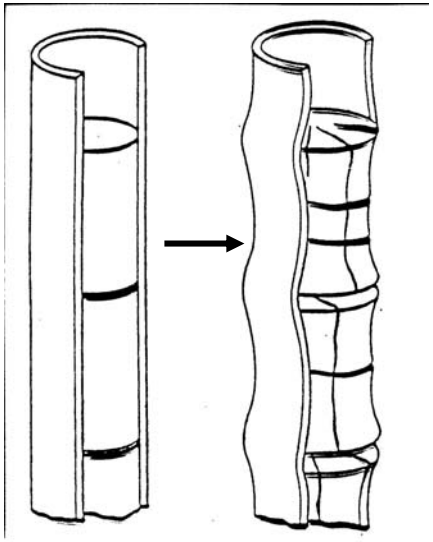
3

"hard" PCMI



fission-product swelling causes gap to disappear and cracks to heal

Hour-glassing of cracked pellet



PCMI = pellet-cladding mechanical interaction

rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Cladding Failure Models

- Three separate failure regimes are considered
  - Pellet-Cladding Interaction (PCI) failure by Intergranular Stress Corrosion Cracking (ISCC)
  - High temperature rupture (ballooning and burst)
  - Mechanical fracture due to PCMI

- Two different approaches are used to calculate the cladding failure potential
  - Cumulative damage concept is used for PCI and high temperature rupture
  - Critical limit state based on the cladding strain energy density is used for mechanical fracture

© 2010 Electric Power Research Institute, Inc. All rights reserved.

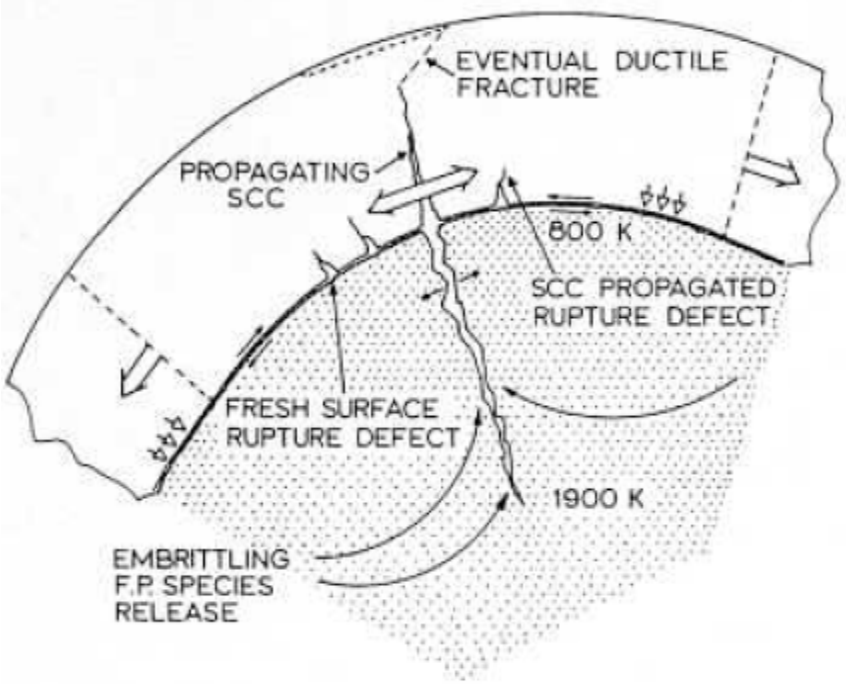
PCI/SCC — Mechanism

During service:

- Complex fuel cracking and relocation
- High local clad stresses, even at low LHGR
- Embrittling fission product may initiate ISCC

The crack may become through wall:

- Statistical nature of the mechanism
- Deterministic modeling is useful

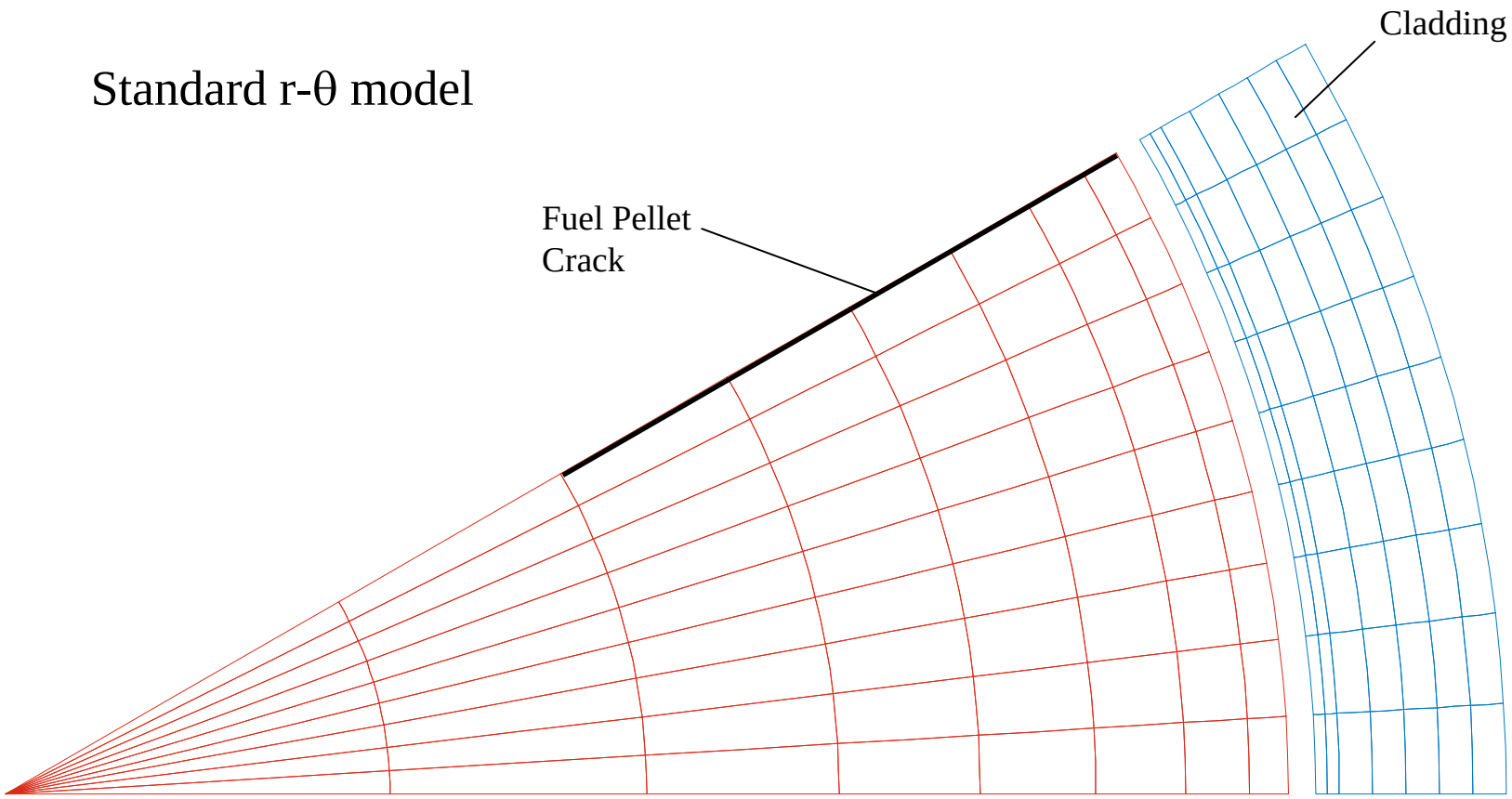


© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

FALCON PCI Modeling

Standard r-θ model



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

PCI — Failure Model In FALCON

- Cumulative Damage Index (CDI)
  - Assumes the material undergoes cumulative damage due to a sustained stress
    - Higher the stress, the shorter the time to failure
  - For an applied stress of σ_o lasting for a time Δt

$$\Delta D = \frac{\Delta t}{t_f(\sigma_0)} \qquad D = \sum_{i=1}^{n} \Delta D_i$$

where $t_f(\sigma_0)$ is the time to failure had the stress, σ_0, been applied for the total time

Δ D and D are incremental and total cumulative damage, D is given by

© 2010 Electric Power Research Institute, Inc. All rights reserved.

SCC Cumulative Damage Index (CDI)

- Assumes the material undergoes cumulative damage due to a sustained stress
  - Higher the stress, the shorter the time to failure

- For an applied stress of σ_o lasting for a time Δt

$$\Delta D = \frac{\Delta t}{t_f(\sigma_0)}$$

where $t_f(\sigma_0)$ is the time to failure had the stress, σ_0, been applied for the total time

- Total cumulative damage, D, is then given by

$$D = \sum_{i=1}^{n} \Delta D_i$$

© 2010 Electric Power Research Institute, Inc. All rights reserved.

CDI Application

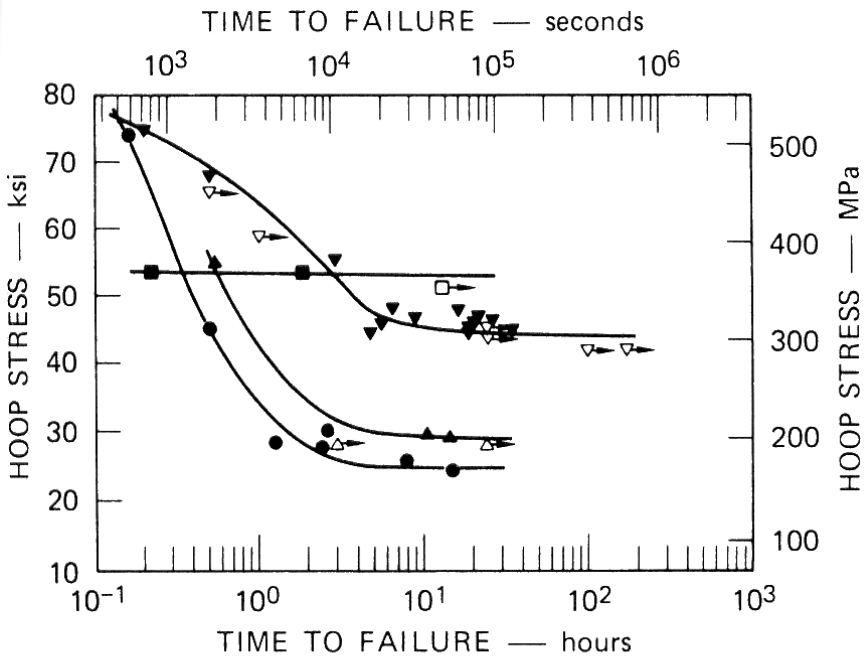
- The CDI has been validated against ramp test experimental data
  - Adapts the theory to application
  - Accounts for differences between fuel rod environment and out-of-pile SCC test data
- Validation parameter, β, is applied as follows

$$D = \sum_{i=1}^{n} \frac{\Delta t_i}{\beta t_{f\,i}}$$

- Provides a framework for rod failure determination via the SCC mechanism

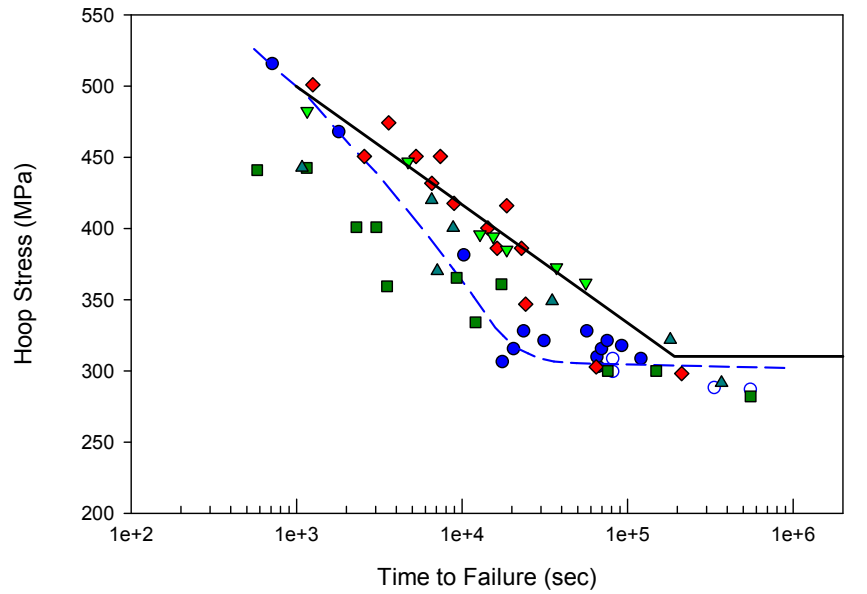
© 2010 Electric Power Research Institute, Inc. All rights reserved.

SCC Time-to-Failure Data



- ▼ Unirradiated, stress relieved Zr4 at 630K
- ▲ Irradiated, stress relieved Zr4 at 630K
- ■ Unirradiated, annealed Zr2 at 620K
- ● Irradiated, annealed Zr2 at 620K

Open symbols indicate no failure

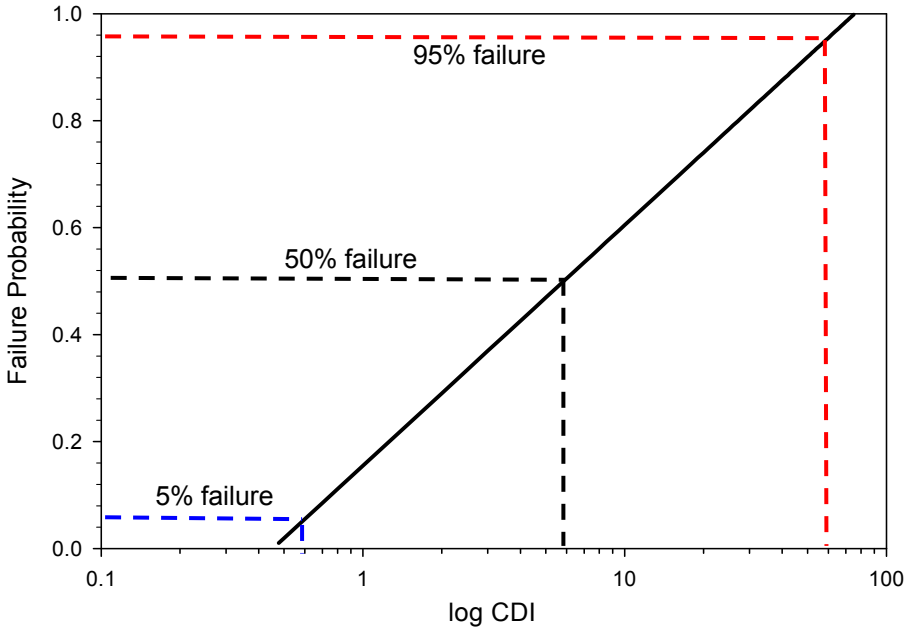


© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

CDI Validation and Failure Threshold

- PWR failure threshold – β defined



Failure Probability %	CDI
99	71.84
95	58.5
50	**5.85**
5	0.585
1	0.477

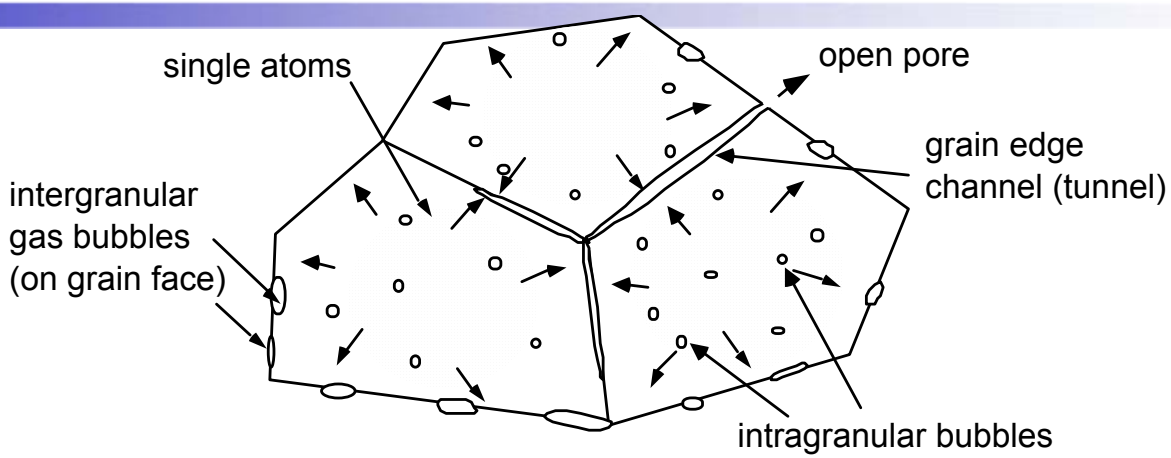
© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Fission Gas Release

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Fission Gas Production/Basics



1. Production in grain at a rate $\beta = Y_{fg}\dot{F}$ atoms fg/cm^3-s

2a. fg diffuses towards grain boundary; diff. coef. = D

2b. Some fg trapped in <u>intra</u>granular bubbles

3a. fg atoms arrive at grain boundary (gb)

3b. fg trapped in <u>inter</u>granular bubbles – N atoms fg /cm^2 gb

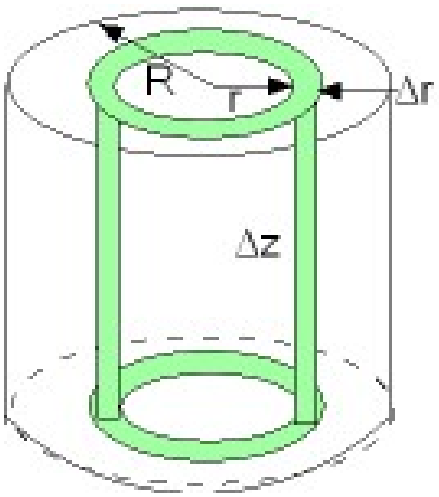
4. Bubble *interlinkage* on gb leads to release to rod interior

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Fission Gas Release/Basics

- the fuel stack is divided into J x K isothermal cylindrical annuli (sections) of length Δz and radial thickness Δr

- $\Delta v_{j,k}$ = volume of section j,k = $2\pi r \Delta r \Delta z$



$n_{j,k}$ = moles fg produced in time t in section j,k = $N_{Avog}^{-1} Y_{fg} \dot{F}\, \omega(z_j)\, \Delta v_{j,k} \times t$

$\dot{F}$ = axial - average fission rate at j

- obtain from LHR : $\overline{q}'_{FA} = E_{fiss} \pi R^2 \dot{F}$

$\omega(z_j)$ = axial power-shape function; E_{fiss} =3.2x10^{-11} J/fiss

- $m_{j,k}$ = cumulative moles of fg released from sect. j,k

$$f_{rod} = \sum_{j=1}^{J} \sum_{k=1}^{K} m_{j,k} \div \sum_{j=1}^{J} \sum_{k=1}^{K} n_{j,k}$$

© 2010 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Intragranular diffusion

$$\frac{\partial C}{\partial t} = \frac{D}{\eta^2}\frac{\partial}{\partial \eta}\left(\eta^2 \frac{\partial C}{\partial r}\right) + \beta \qquad 0 \le \eta \le a$$

C = fg concentration in matrix of fuel, atoms/cm^3

D = fission-gas diffusivity in fuel, cm^2/s

a = radius of equivalent spherical grain ~ 5 μm

BC at $\eta = 0$: $\partial C/\partial \eta = 0$

BC at $\eta = a$: $C(a,t) = 0$ (if *re-solution* neglected)

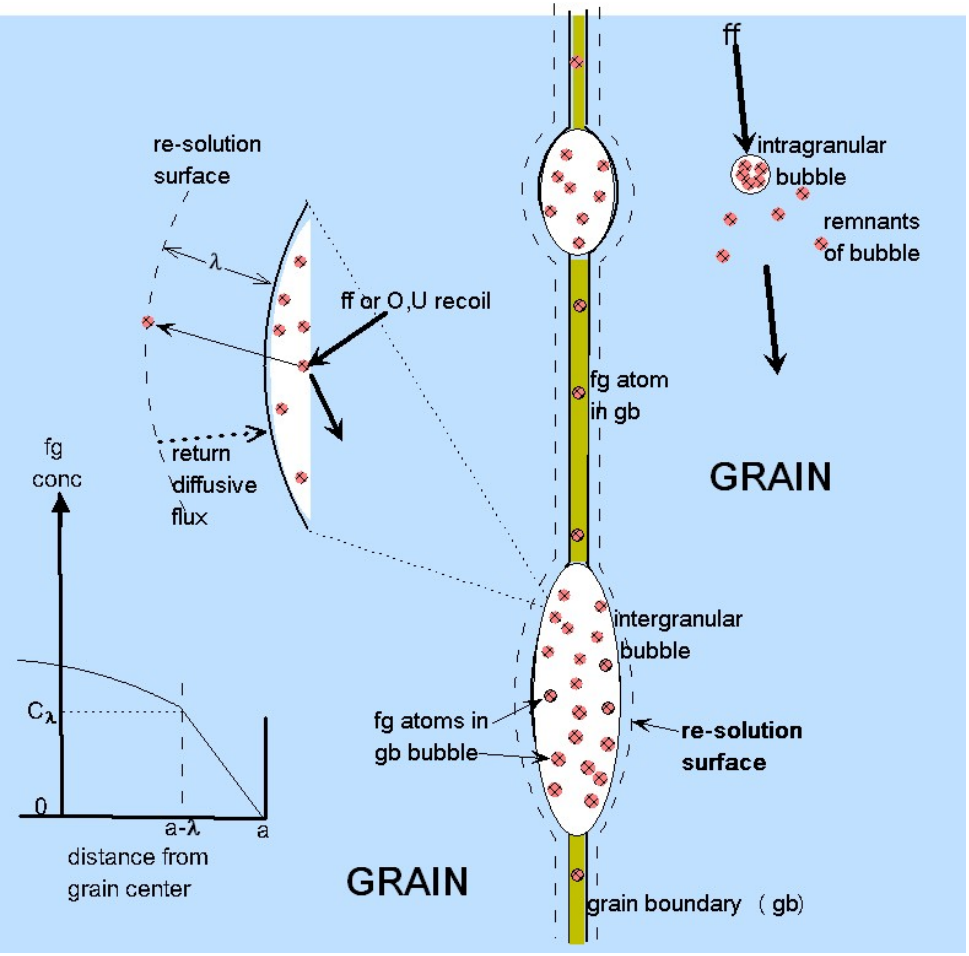
$$\textbf{flux to gb from one grain} = \mathbf{J^*} = -\mathbf{D}\left(\frac{\partial \mathbf{C}}{\partial \eta}\right)_{\eta=\mathbf{a}} = \frac{\mathbf{2}}{\sqrt{\pi}}\beta\sqrt{\mathbf{Dt}}$$

(each gb is fed by two grains)

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Re-solution from intergranular bubbles

- ff or O,U recoil collision with fg in bubble
- If ~300 eV transferred to fg atom it is re-solved
- re-solution depth λ~10 nm
- *re-solution parameter*: probability/s of an atom being re-solved b ~ 10^{-5}



© 2010 Electric Power Research Institute, Inc. All rights reserved.

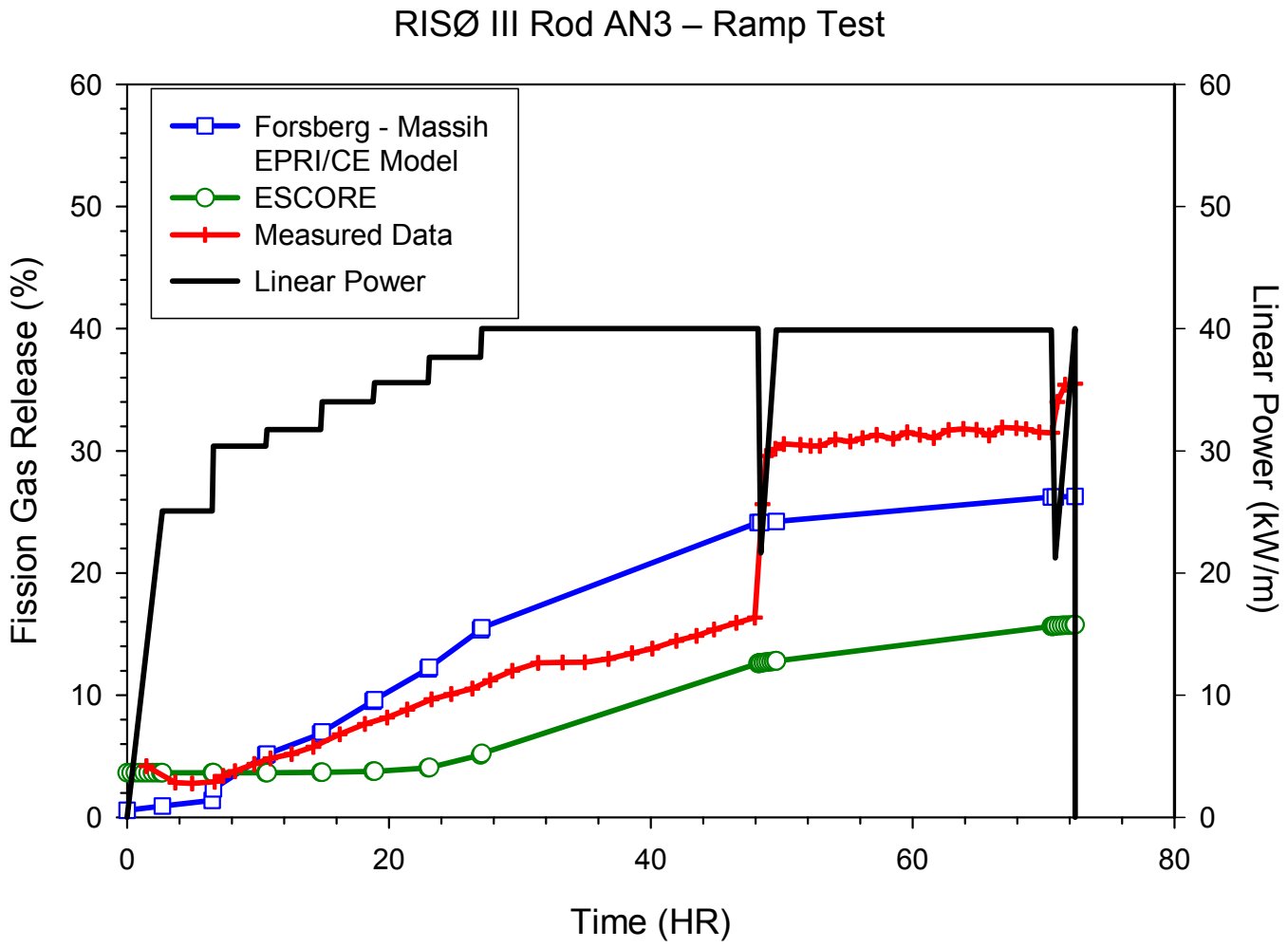
ELECTRIC POWER RESEARCH INSTITUTE

Fuel Rods Used in FGR Benchmarking

Case	Average Burnup (GWd/tU)	Number of Rods	Description – Rod Type, Irradiation History
DOE/Br-3	59.6	1	PWR, steady state
Grand Gulf	39.9	2	BWR, commercial, steady state
HB Robinson	64.3	2	PWR, commercial, steady state
HBC	48.2	1	PWR, steady state
HBEP	45.5	4	PWR & BWR, steady state
IFA 418	13.6	1	HBWR, steady state
IFA 432.3	28.9	1	HBWR, steady state
IFA 519.9	91.2	1	HBWR, steady state
IFA 533.2	51.5	1	HBWR, steady state
IFA 597	61.1	1	BWR, steady state, base irradiation only
KKL	27.3	2	BWR, commercial, steady state
Limerick	55.3	2	BWR, commercial, steady state
Over Ramp	23.8	1	PWR, steady state & ramp
RISO III	44.0	4	PWR/BWR, steady state & ramp
Super Ramp	45.2	1	PWR, steady state & ramp
Tribulation	56.5	4	PWR, steady state

© 2010 Electric Power Research Institute, Inc. All rights reserved.

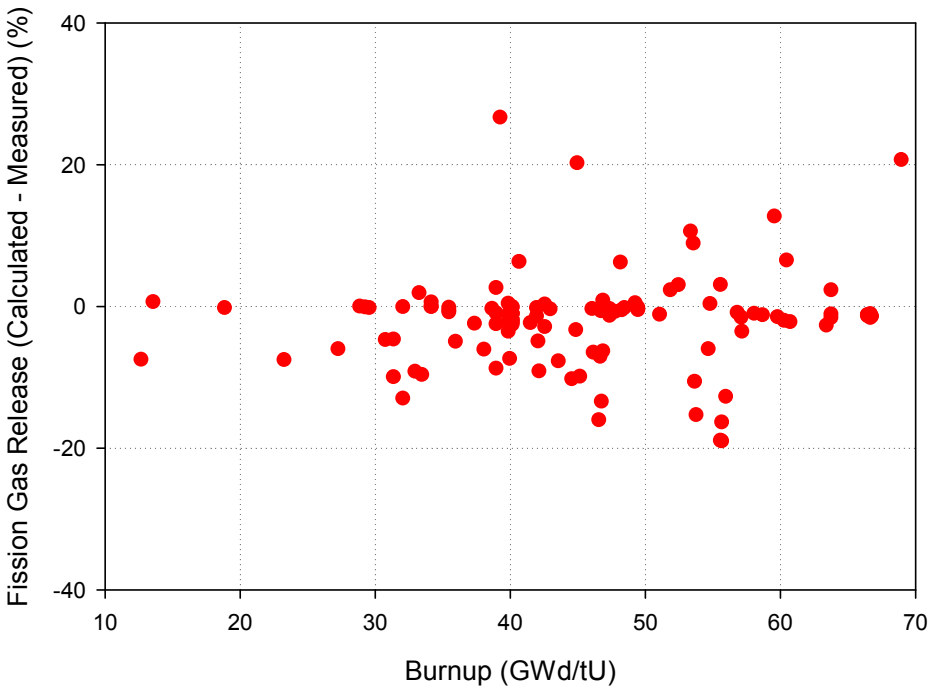
Fission Gas Release

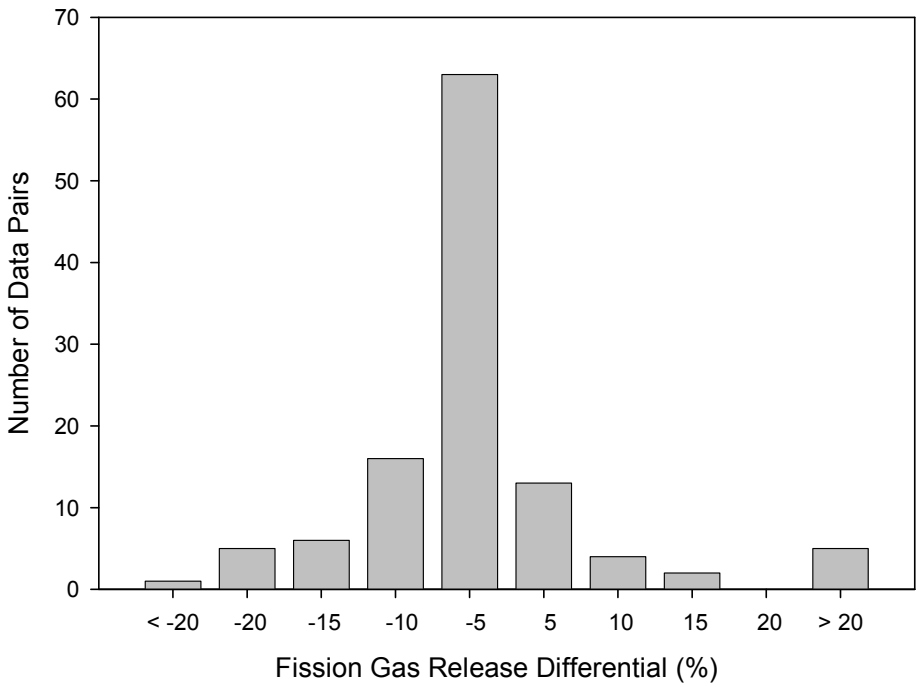


© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Assessment of Fission Gas Release Predictions – Validation Set





Mean error of estimate = - 1.3%

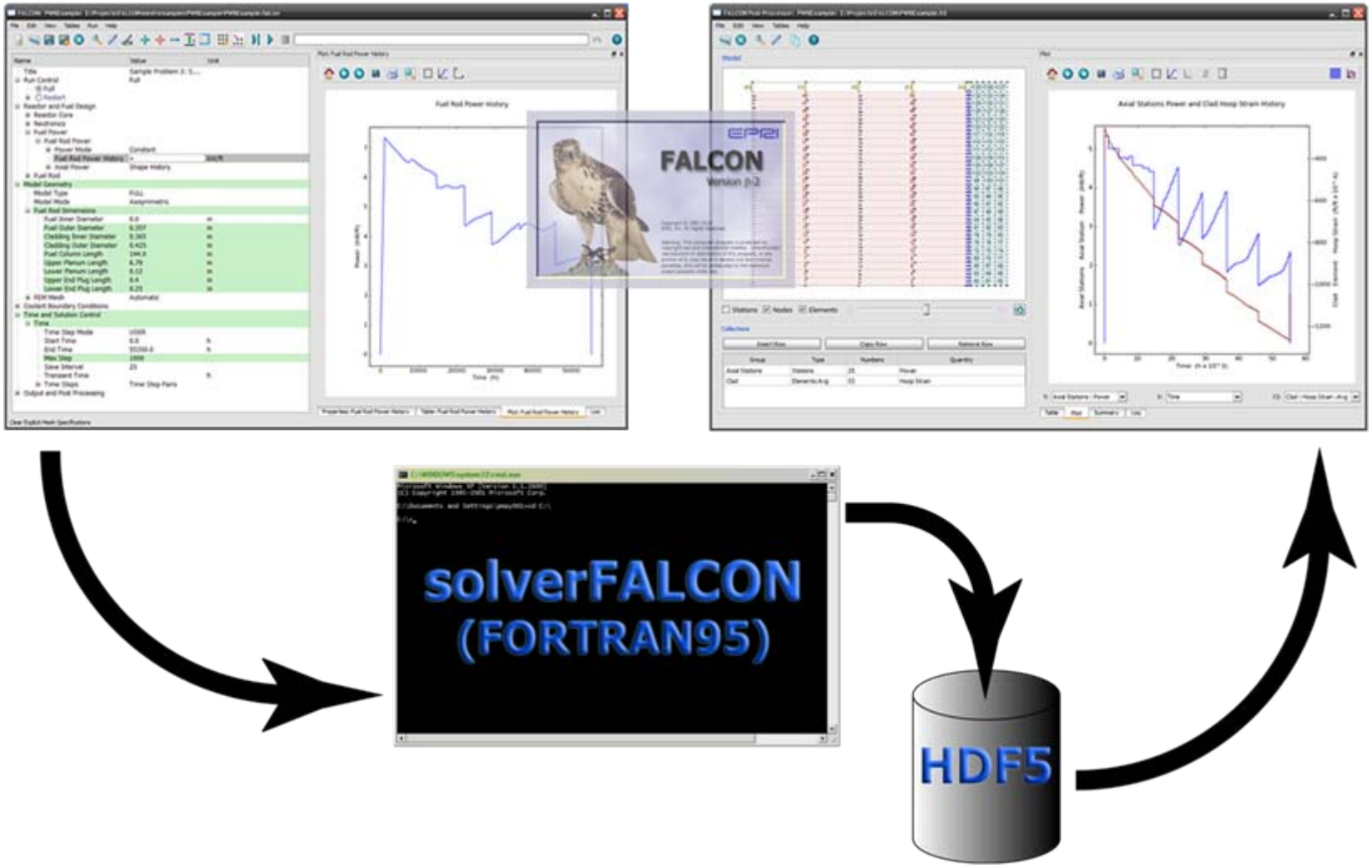
© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Redesigning a Legacy Fuel Performance Code

© 2010 Electric Power Research Institute, Inc. All rights reserved.

Redesigned FALCON Use Structure



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

FALCON Redesign Objectives

Accommodate Change!

- Usability
- Maintainability
- Reliability
- Extensibility

Use a Clear Workscope Delineation

1. Software Development
2. Fuel Physics Modeling
3. Customer Support

Don’t Change the Answers!

© 2010 Electric Power Research Institute, Inc. All rights reserved.

FALCON Redesign Specifications

- Develop a GUI “front-end”
  - Changes additions must be user-friendly
- Develop a post-processor
  - Ability to query output anywhere in the mesh
  - Output need not be specified in the input
- Modernized core FORTRAN solver
- Support parallel runs and command line interface (non-GUI)
- Make it cross-platform (Windows, Linux, Mac OS X) and 32 and 64-bit compatible
- Support all user types and levels
  - Beginner to Advance
  - Universities to Commercial Licensee

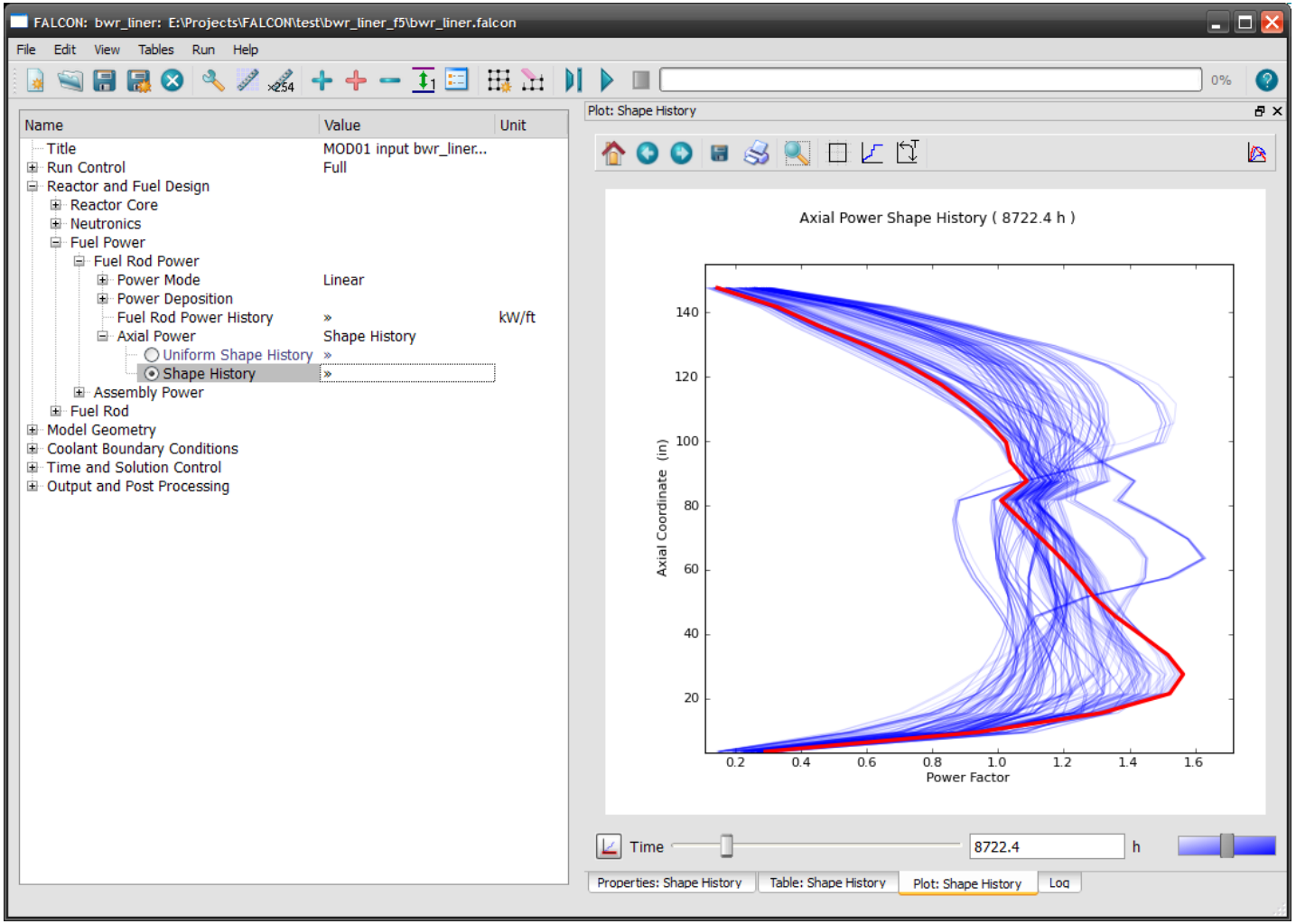
© 2010 Electric Power Research Institute, Inc. All rights reserved.

FALCON 1.0 Input Features

- Input organization and field names chosen for clarity
- Embedded descriptions of every input in the GUI
- On-the-fly input validation: **info**, **warnings**, and **errors**
- Histories/functions
  - Advanced plotting: overlay, slicing, zoom/pan, …
  - Advanced table editing: copy, paste, scale, …
  - Optionally loaded from text files
- "Schemas" to reduce/tailor inputs in a certain class of analyses
- "Levels" can hide rarely used fields
- Button to fill in full mesh from "automatic" mesh specs
- "Dry run" for deep input check & view mesh

© 2010 Electric Power Research Institute, Inc. All rights reserved.

FALCON 1.0 (Pre-Processor)



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Modern Redesign Process

- Tools: Python, Fortran 95, Qt, HDF, Mercurial, …
  - The right tool/language for each task
  - Standard packages: Don’t reinvent the wheel
- Process: Agile development, test-driven, object-oriented design
- Collaborative development support system (Trac)
  - Establish Collaborative R&D between “Software” and “Analytical” experts
  - Continually factor in feedback from users/licensees

© 2010 Electric Power Research Institute, Inc. All rights reserved.

FALCON Trac Server (wiki and issue tracking system)

FALCON - Mozilla Firefox

File Edit View History Bookmarks Tools Help

ELECTRIC POWER RESEARCH INSTITUTE

Search

logged in as stuart | Logout | Help/Guide | About Trac | Preferences

Wiki | Action | Documentation | Materials | Timeline | Roadmap | Browse Source | Repositories | View Tickets | New Ticket | Search | Admin

Start Page | Index | History | Last Change

Welcome to the FALCON Redesign Project Site

This is the home of the FALCON redesign project being carried out by Objexx Engineering, Inc. for the Electric Power Research Institute (EPRI) with the collaboration of ANATECH Inc..

Status

- The FALCON beta-1 has been released as of 2009/12
- The FALCON 1.0 feature set is under development
- The FALCON 1.0 release is planned for mid-2010

Overview

FALCON is being redesigned to improve maintainability and flexibility and to add a graphical front end that supports a range of new features including multiple run scenarios and output visualization.

A Python front end GUI and controller layer is being built to take advantage of the development efficiency of Python and to use its support for run-time configurability. Many of the FALCON attributes will be loaded at run-time from configuration files to allow easy customization. The GUI is being developed with PyQt, a Python wrapper around the excellent, cross-platform Qt framework.

The Fortran core of FALCON will be carefully restructured and modernized to improve extensibility while assuring that its computational behavior is preserved. A comprehensive testing system will be built as we proceed to provide a safety net.

Resources

The main project resources are organized into these areas that appear in the navigation bar:

Development | Action | Documentation | Materials | Repositories

Additional Resources

Feature | Design | Packaging | Installers | Developers | Fortran | Tickets | Testing

Done

© 2010 Electric Power Research Institute, Inc. All rights reserved.

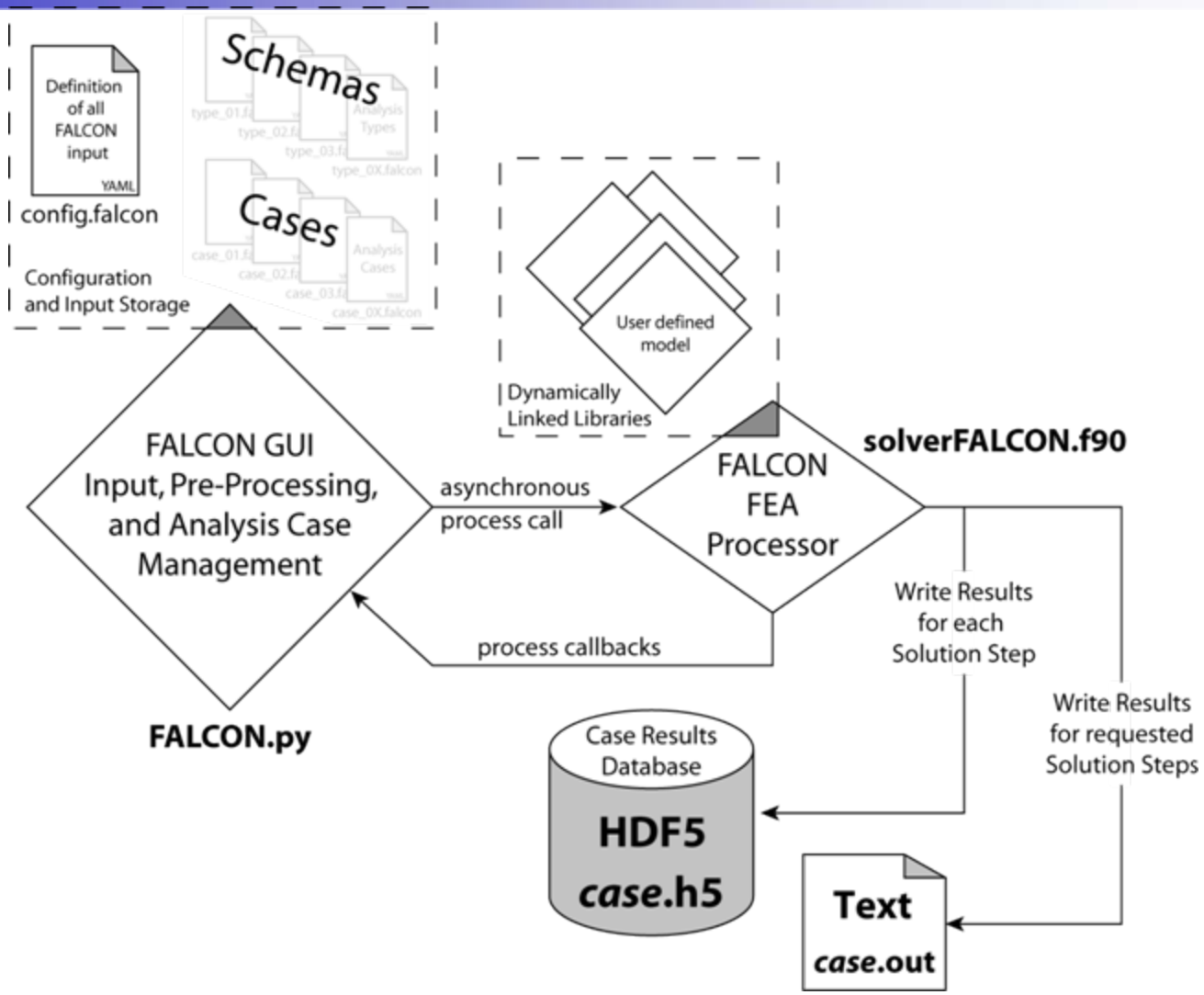
ELECTRIC POWER RESEARCH INSTITUTE

Phased and Agile Development Approach

- Modernize and restructure the FALCON code
  - FORTRAN no longer the best language for the user-side application
  - Initially keep the inner finite element solver in FORTRAN but clean FORTRAN 77 to FORTRAN 95
  - Remove hard-wired behavioral models that may be proprietary
- Keep the existing pedigree of V&V already completed
- Design for ongoing evolution of FALCON capabilities
- Provide user-extensions can be plugged in as dynamic link libraries
  - Data proprietary to user's fuel vendor

© 2010 Electric Power Research Institute, Inc. All rights reserved.

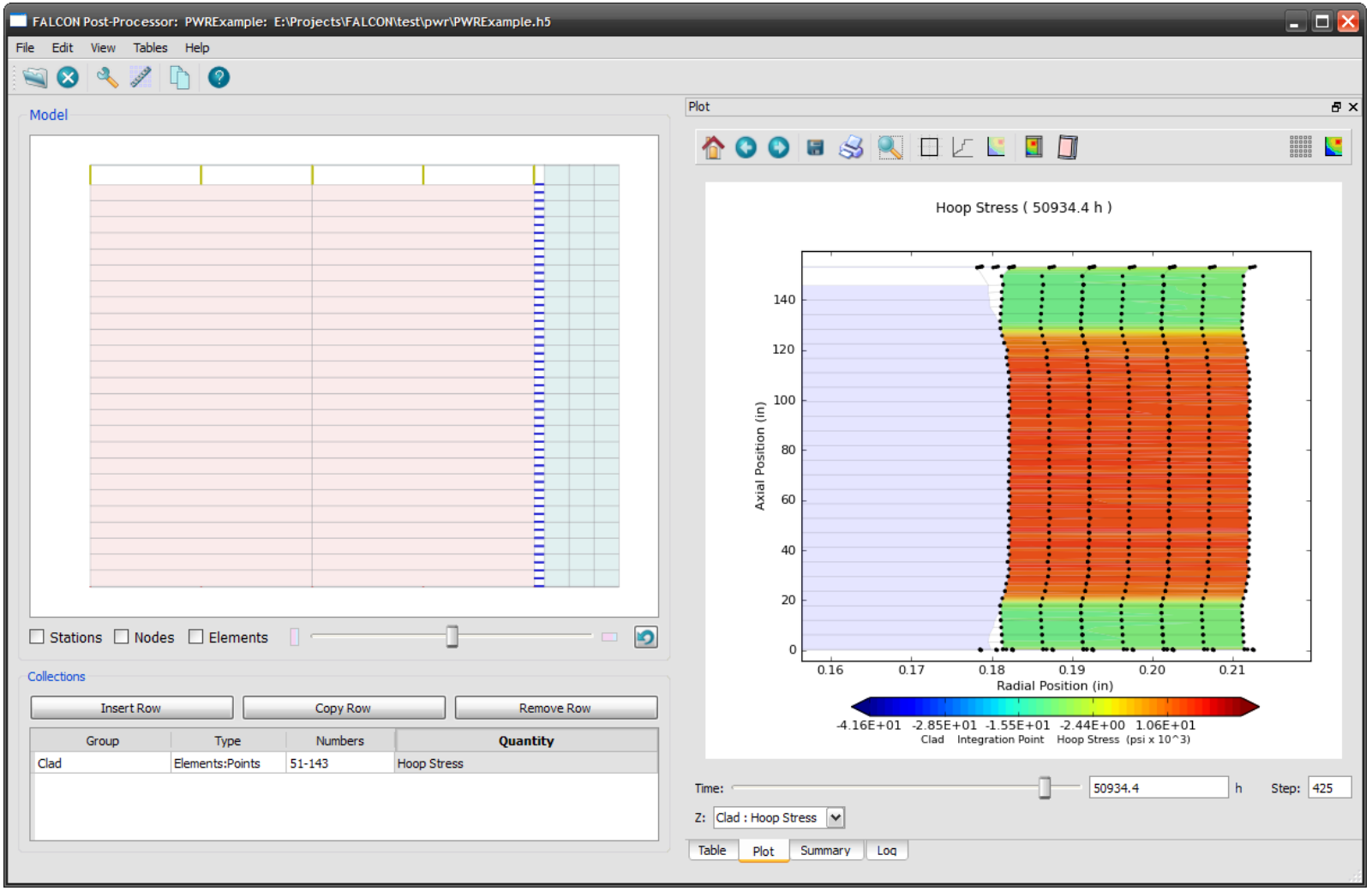
Redesigned Structure



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

FALCON 1.0 Post-Processor



© 2010 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

FALCON Usage

- Research (5)
  - EPRI, PSI (Swiss), GISC (Japan), and EDF DRD (France)
- Utility Members (8)
  - Exelon, TVA, Xcel, Progress Energy, Duke, KHNP (Korea), ETN (Brazil), and Iberdrola (Spain)
- Vendors (2)
  - KNF (Korea) and MHI (Japan)

© 2010 Electric Power Research Institute, Inc. All rights reserved.

User Group Interactions and Benefits

- Advice on installation and use of the code
- Troubleshooting (via phone and emails)
- Trouble reporting by all users and remedial actions
- Access to Interim code updates (before formal release of the next MOD):
- Code enhancement of generic interest
- Annual UG meetings and experience exchange

© 2010 Electric Power Research Institute, Inc. All rights reserved.