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Realistic Fuel Rod Methodology for BWRs

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Non-proprietary Version

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Realistic Fuel Rod Methodology for BWRs
Outline

- > Objectives
- > RODEX4 Best Estimate Fuel Rod Code
- > RODEX4 Validation
- > Methodology Summary
- > Methodology - Normal operation scenario
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- > Application Examples

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Realistic Fuel Rod Methodology for BWRs
Objectives

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Realistic Fuel Rod Methodology for BWRs Methodology Need

> Determine realistic BWR thermal-mechanical design margins
- Quantify uncertainties
- Allow licensing of higher rod powers in appropriate scenarios
- Improve design guidance

> Basis for future upgrades
- Gain experience with high burnup models

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Realistic Fuel Rod Methodology for BWRs Objective

> License a realistic methodology to analyze fuel rod performance in a BWR core that:
- Address uncertainties in:
  - reactor parameters,
  - reactor operation,
  - fuel parameters,
  - fuel rod models
- Evaluate projected scenarios:
  - normal operation
  - anticipated transients
- Quantify design margins:
  - expressed in probabilistic terms

> Code and methods development guided by NRC recommended CSAU/PERT process

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Realistic Fuel Rod Methodology for BWRs Methodology Components

> A best-estimate fuel rod code – RODEX4

> A method of evaluating fuel batches

- Analysis of projected operational scenarios
- Determination of statistical variances of input variables
- Analysis of the uncertainty propagation through the code of the known input statistical variances

> Evaluation of results relative to criteria expressed in probabilistic terms

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Realistic Fuel Rod Methodology for BWRs Criteria Basis

> Fuel rod thermal-mechanical criteria based on SRP 4.2, Fuel System Design , NUREG-0800

> Described in "Generic Mechanical Design Criteria for BWR Fuel Designs", ANF-89-98(P)(A) Rev. 1 & Sup. 1

> Supplemented in "Realistic Thermal-Mechanical Methodology for BWRs", BAW-10247(P)

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Realistic Fuel Rod Methodology for BWRs
Fuel Rod Criteria

> Fuel Performance Criteria

- For normal operation
  - Rod internal pressure
  - Clad collapse margin (revised from ANF-89-98)
  - Fatigue usage
  - Clad strain
  - Clad corrosion (revised from ANF-89-98)
- During AOOs
  - Clad strain
  - Pellet centerline temperature

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RODEX4
Fuel Rod Performance Code

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RODEX4 Applicability

> Best-estimate code to predict the thermal-mechanical behavior of a single fuel rod in steady-state and transient conditions

> Will be used for:

- Normal operation fuel design analyses
- Anticipated operational occurrence analyses
  - [
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RODEX4 Improvements relative to RODEX2/RODEX3

> New mechanistic pellet and cladding mechanics

> New mechanistic fission gas release and gaseous swelling models

> Burnup dependent fuel thermal conductivity

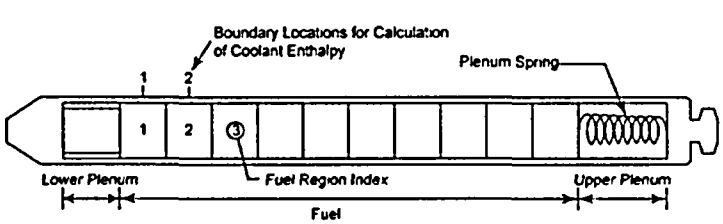
> Clad ridging and ovality

> Pellet rim effect

> Updated material properties

> Transient thermal solution

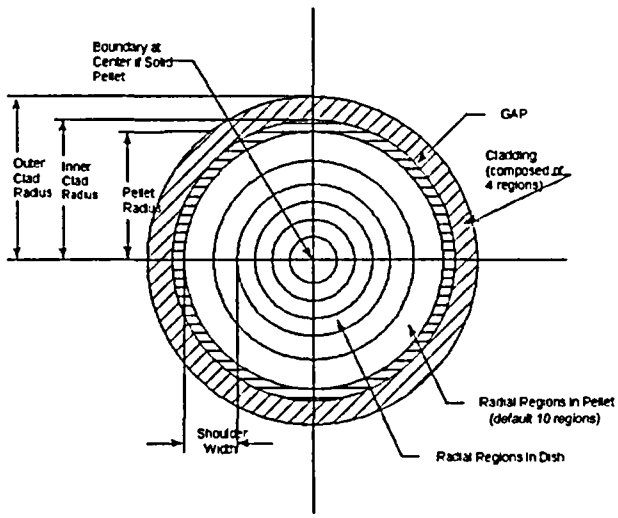
RODEX4
Rod in Coolant Channel



coolant flow direction

- typically 25 axial regions in a BWR
- zones for natural, enriched UO_2 and UO_2-Gd_2O_3

RODEX4
Radial Zoning



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RODEX4
Summary – Thermal / Irradiation Models

> Gap conductance with pellet eccentricity and contact conductance
> Steady state thermal diffusion equation
  - during normal irradiation
> Fuel densification
> Fuel solid swelling (1% per 10 GWd/MTU)
> Accommodation of solid swelling by as-fabricated porosity
> Integrated fission gas release and gaseous swelling model
> Rim porosity affecting thermal conductivity
> Transient thermal diffusion equation
  - during fast transients
  - conductivities dependent on geometry and temperature evolution through the transient, considering specific heats

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RODEX4
Summary - Mechanics

> Pellet mechanics: axi-symmetric, cracked pellet
> Cladding mechanics: axi-symmetric, anisotropic viscoplastic properties
> Pellet-cladding mechanical interaction: 2D-(r, z) model
> Pellet hourglassing: empirical
> Cladding ridging: pellet end and mid-pellet radial calculations
> Cladding ovality
> Axial locking of the pellets in the cladding

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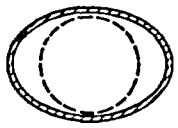
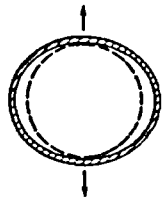
RODEX4
Cladding Ovality

Pellet-clad ovality contact
locks column
potentially allowing axial gaps



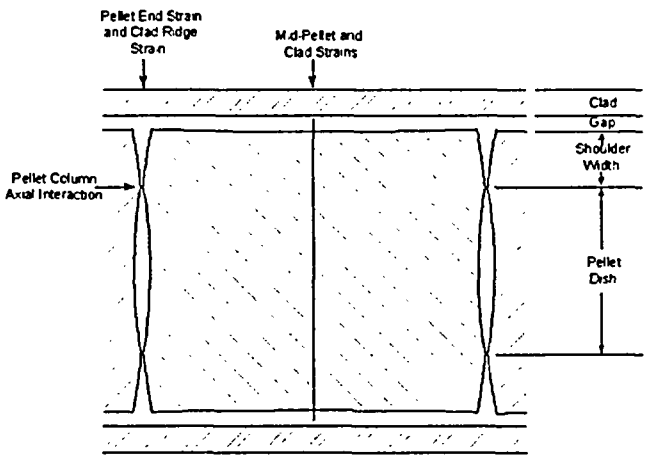


Pellet Cladding
Mechanical Interaction
at minor axis

Bending

Inner Diameter
Tensile Stress
at major Axis

RODEX4
Pellet-clad interactions



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RODEX4
Summary - Fuel Rod

> Rod free volume, and inner pressure (perfect gas law)
> Cladding axial elongation due to creep and growth
> Cladding outer corrosion: MATPRO for BWRs
> Fuel, cladding and gas properties - MATPRO 1993
> Water properties - IAPWS-IF97 (Siemens standard)

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RODEX4
Validation

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RODEX4 Validation Database Scope

> A variety of BWR and PWR fuel rod, pellet, and cladding types
- Extends the validation beyond the characteristics of FANP fuel

> A variety of fuel tests and irradiations
- Extends the validation range to the projected operating envelope

> Maximum use of available test data
- Broadens range of validation
- Consistent calibration of interacting models in all irradiation tests and operation regimes adds strength to validation

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RODEX4 Validation Domain

> Fuel	: UO_2 and UO_2- gadolinia fuels
> Reactor	: PWR and BWR
> Pellet	: Solid and annular pellet, with and without dish
> Cladding	: Zry-2, Zry-4 CWSR or annealed
> Burnup	: Beyond 62 GWd/MTU rod average
> Operating modes	: Base irradiation, slow transients, and fast transients

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RODEX4 Validation
International Programs Database (1/2)

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RODEX4 Validation
International Programs Database (2/2)

<u>International Database</u>

Total: 323 rods 197 PWR rods 121 BWR rods 5 test rods

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RODEX4 Validation
Commercial Irradiation Database

(primarily FGR, creep, oxidation)

Reactor	Fuel type	Rod number	PWR rods	BWR rods	UO_2 rods	Gadolinia rods
Total		958	451	507	844	114

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RODEX4 Validation
Calibration Process

> Separate-effects tests establish model parameters
- Primarily properties determined during out-of-pile tests

> Integral tests provide final model adjustments
- Well characterized irradiations used for initial adjustments
- Full database used for final adjustment and verification

> Objective: Predicted/Measured Ratio = 1.0
- P/M = 1.0 (temperature, low arithmetic uncertainty)
- Log (P/M) = 0.0 (FGR, high multiplication uncertainty)

> Calibration of each model requires cycling through all models with the complete database

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RODEX4
Final Validation

> Accuracy has been demonstrated by comparing the code predictions to the measured rod behavior for:

- Pellet centerline temperature
- Fission gas release fraction
- Rod free volume
- Clad creep down and ramp strains
- Clad creep ovality
- Rod growth
- Clad oxidation

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RODEX4 Validation
Predicted vs. Measured Temperatures (Halden)

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RODEX4 Validation
Temperature Predictions vs. Exposure (Halden)

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RODEX4 Validation
Predicted vs. Measured FGR International Database

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RODEX4 Validation
Predicted vs. Measured FGR Commercial Database

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RODEX4 Validation
Clad Strain Prediction

Mark-BEB Rod 65-2 - Rod Diameter at Pellet End

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RODEX4 Validation
Clad Strain Increment Prediction

Mark-BEB Rod 65-2 - Rod Diameter Increase

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RODEX4
Range of Validation

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RODEX4 Calibration Summary of Results

> Predicted/Measured results show little or no bias (*RODEX4 Code is Best Estimate*)

> *Validation range covers planned application*

> Variances are addressed in model uncertainty development

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Methodology Summary

Methodology Summary
Overall Objective

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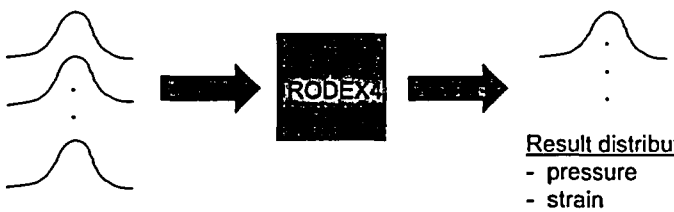
Realistic Fuel Rod Methodology for BWRs
Evaluation Process



Input:
[

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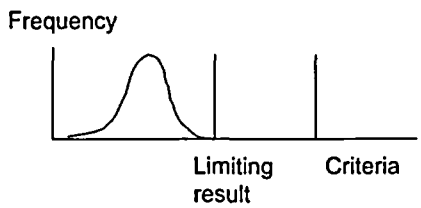
Result distributions:
- pressure
- strain
- corrosion, etc.



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Methodology Summary
Statistical Method

> Perform analyses for each scenario

> Evaluate propagation of input uncertainties through the analyses

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> The limiting result for each criterion shall be below the design limit

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Methodology Summary
Example Internal Pressure Results - Distribution

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Methodology Summary Evaluation of Results

- Normal operation
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- Slow transients
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- Fast transients
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Methodoloogy – Normal Operation Scenario, with Uncertainty Analysis

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Methodology
Normal Operation Scenario

> Criteria evaluated
- Rod internal pressure, collapse margin, clad fatigue usage, strain, corrosion

> Scenario
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Normal Operation Scenario
Typical Power History Excerpt

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Normal Operation Scenario
Power Uncertainties

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Uncertainty Evaluation
Measured/Calculated Power Distribution

Table 5.4 BWR Core Simulator Code Measured Power Distribution Uncertainty

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Uncertainty Evaluation
Axial Profile

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Uncertainty Evaluation
Manufacturing Parameters

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Uncertainty Evaluation
Clad Diameter Distribution

Figure 5.1 Clad Inside Diameter Distribution

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Uncertainty Evaluation
Plenum Length Distribution Uncertainty

Figure 5.3 Fuel Rod Plenum Length Distribution

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Uncertainty Evaluation
RODEX4 Models and Influence

> Pellet gaseous diffusion coefficient, affects:
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> Clad irradiation creep parameter, affects:
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> Clad oxidation parameter, affects:
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Uncertainty Evaluation
RODEX4 FGR Predicted/Measured Histogram

Figure 5.4 Histogram of the FGR Data Comparisons (International Database>1%)

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Uncertainty Evaluation
RODEX4 Model Uncertainty Summary

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Methodology
AOO Slow Transient Scenario

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Methodology
AOO Slow Transient Scenario (1/2)

> Criteria evaluated
- Clad strain increment
- Pellet centerline temperature

> Base Scenario as for Normal Operation

> Postulated Slow Transients
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Methodology
AOO Slow Transient Scenario (2/2)

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Methodology
AOO Fast Transient Scenario

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Methodology
AOO Fast Transient Scenario (1/3)

> **Criteria evaluated**
- **Clad strain increment**
- **Pellet centerline temperature**
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AOO Fast Transient Scenario

AOO Fast Transient Scenario
Typical Limiting Fast Transient

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Methodology
AOO Fast Transient Scenario (2/3)

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Methodology
AOO Fast Transient Scenario (3/3)

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AOO Fast Transient Scenario RODEX4 Model Uncertainties

Table 5.5 Fast Transient Model Uncertainties

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Examples

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Examples
Summary

- Normal operation
  - Examples demonstrated for BWR-6 and BWR-4 with different operating strategies, for transition cores, equilibrium cores, UO_2 rods and UO_2-Gd_2O_3 rods
  - Sensitivity studies performed for uncertainty groups, power level
- Slow transients
  - Examples demonstrated for CRWE for BWR-4, UO_2 rods and UO_2-Gd_2O_3 rods
- Fast transients
  - Examples performed for a BWR-4 for 3 FWCF transients, for UO_2 rods and UO_2-Gd_2O_3 rods

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Examples
Internal Pressure Results for Normal Operation

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Examples
Collapse Margin Results for Normal Operation

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Examples
Oxidation Results for Normal Operation

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Examples
Methodology Steps for Fast Transients (1/2)

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Examples
Methodology Steps for Fast Transients (2/2)

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Examples
Fast Transient Strain Increment vs. Burnup

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Examples
Transient Pellet Centerline Temperature versus Burnup

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Examples
Fast Transient Strain Increment

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Examples
Fast Transient Pellet Centerline Temperature

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Realistic Fuel Rod Methodology for BWRs Conclusion

> A BWR methodology was established, guided by the CSAU process, to evaluate normal operation and AOO transient scenarios.

> Realistic fuel rod evaluations were performed with RODEX4.

> RODEX4 is a best estimate code with extensive validation.

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> Results have been evaluated relative to established criteria and expressed in probabilistic terms.

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Backups

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Table 6.4 Sensitivity Study Results BWR-6 UO2 Rods

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Table 6.1 Parameters for BWR-6 Transition and Equilibrium Batches

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Statistical Method
Number of Runs (1/2)

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Statistical Method
Number of Runs (2/2)

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RODEX4
Gap Eccentricity