US-APWR

4th Pre-Application Review Meeting

Fuel Design

January 31, 2007

Mitsubishi Heavy Industries, Ltd.

Meeting Attendants

Shigemitsu SUZUKI
Department Manager

Toshimichi TAKAHASHI (Fuel System Design)
Engineering Manager

Hideyuki TESHIMA (Fuel Rod Design) -Presenter-
Acting Manager of Fuel Designing Section

Nuclear Fuel & Back-end Systems Designing Department,
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Mitsubishi Heavy Industries, Ltd.

Objectives of presentation

- **The objectives of the presentation are to:**
  - ✓ Describe the Topical Report (TR) about fuel design; "Fuel Design Criteria and Methodology"
    - MHI design satisfies the design requirements specified in Standard Review Plan (SRP)
    - MHI design follows Regulatory Guide (RG) 1.70.
    - Fuel rod design code, FINE, is applicable to US-APWR fuel design.
  - ✓ Provide NRC with the information of the main topics of the TR
  - ✓ Obtain early NRC feedback on the proposed TR contents before its submittal.

Overview of Application Documents

US-APWR Design Control Document

Fuel system
- Specification
- **Criteria**
- **Methodology**
- Evaluation

Dec.2007

Topical Report of Fuel Design

Criteria
Methodology
FINE

May 2007

This Presentation Main Topic of TR

General Information of US-APWR fuel

Criteria and Methodology
- meet SRP and RG

FINE Code
- Pellet
  - Thermal Conductivity
  - Rim formation
  - Fission gas release
- Cladding
  - Corrosion & Hydrogen

Contents of this presentation

1. General Information of US-APWR Fuel
2. Design Criteria and Methodology (FA & Rod)
3. FINE* Code (Fuel Rod Design Code)
   - ✓ Overview of FINE code
   - ✓ Representative Models : High burnup effect
     - Thermal Models (including RIM effect)
     - Fission Gas Release (FGR) Model (including RIM effect)
     - Corrosion & Hydrogen Model (ZIRLO™)
   - ✓ Verification

* Fuel Rod INtegrity Evaluation

1. General Information on US-APWR Fuel

Fuel Design Features

Flexible Core Operation

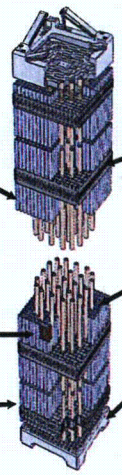
Fuel Active Length : 14ft
Fuel Rods Array : 17x17

Higher Gadolinia Content Pellet (10wt%)

Enhance Fuel Economy

Higher Density Pellet (97%T.D.*1)

Zircaloy-4 Grid (for Neutron Economy)



High Reliability

Grid Fretting Resistant Design (Shorter Span Length*2 with 11 grids & Grid Spring Design)

Corrosion Resistant Cladding Material (ZIRLO™)

Anti-debris bottom nozzle with built-in filter

Low power density (4.6kW/ft) enlarges the thermal margin

*1 T.D. :Theoretical Density *2 compared with conventional 14ft Fuel

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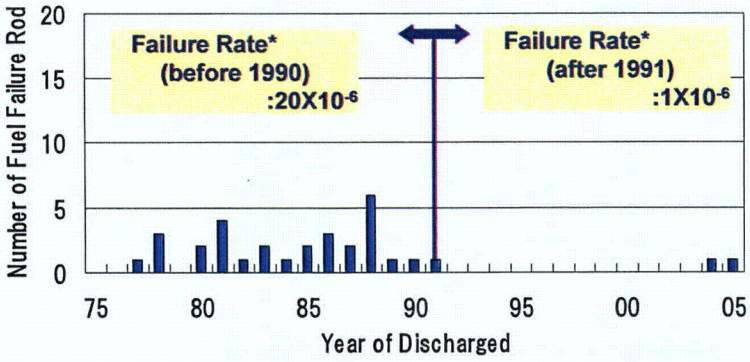
Excellent Performance

- Number of Fuel Assemblies supplied by Mitsubishi is over 17,000 as of May 2006
- Very low fuel failure rate since 1990's



*Failure Rate : Number of failed rods / Total number of fabricated rods

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Fuel Design Specification

Fuel Assemblies	US-APWR	Fuel in US
Fuel Rods Array in Fuel Assembly	17 x 17	←
Number of Fuel Rods per Fuel Assembly	264	←
Number of Control Rod Guide Thimbles	24	←
Number of in-core Instrumentation guide tube	1	←
Number of Spacer Grids	11	10*
Fuel Rods		
Outside Diameter	0.374 in.	←
Cladding Thickness	0.022 in.	←
Active Fuel Length	13.8ft	14ft *
Enrichment	Max. 5 wt%	←
Gadolinia Content	Max. 10 wt%	8wt%**
Pellet Density	97 % T.D.	95.5%T.D.*
Materials		
Cladding	ZIRLO™	←

* Westinghouse fuel, ** AREVA fuel

2. Design Criteria and Methodology (FA & Rod)

Design Criteria and Methodology

➢ Design Requirements & Guidance

✓ **10 CFR Part 50**

- General Design Criteria 10: Reactor design
- General Design Criteria 27: Combined reactivity control systems capability
- General Design Criteria 35: Emergency core cooling

✓ **Regulatory Guide 1.70 Section 4.2**

✓ **Standard Review Plan Section 4.2 (NUREG-0800)**

US-APWR design meets all these requirements and guidance

Design Criteria and Methodology

➢ The Plant Conditions for Fuel Design

✓ Based on the ANSI 18.2 classification

- Condition I : Normal operation and operational transients
- Condition II : Faults of moderate frequency
- Condition III : Infrequent faults
- Condition IV: Limiting faults

Categories of Criteria & Methodologies

- **Criteria and Methodologies are categorized complying with SRP 4.2 (covering RG 1.70)**
  - ✓ Fuel System Damage
  - ✓ Fuel Rod Failure
  - ✓ Coolability
- **All the criteria and methodologies applying to US-APWR fuel are the same as or similar to those utilized in US**

Fuel System Damage (1/2)

Items	Criteria	Approach
Cladding Stress	ASME sec. III	Analysis (FINE)
Cladding Strain	≤1%	Analysis (FINE)
Stress and loading limit other than cladding	Stress limit : ASME sec. III, Loading limit for joints	Analysis (FEM) & Experiment
Fatigue	Langer-O'Donnell Design limit	Analysis (FINE)
Fretting at Contact Point	< limiting Fretting Wear	Analysis & Experiment
Oxidation, Hydriding	No Corrosion acceleration, Keeping Ductility	Analysis (FINE) & Experiment

Explained in detail

Fuel System Damage (2/2)

Items	Criteria	Approach
Dimensional changes	Dimensional changes due to growth of fuel rods, fuel assemblies and grid spacers < acceptable limit	Analysis (Dimensional design)
Rod Internal Gas pressure	No Lift-Off (no pellet-cladding gap increase)	Analysis (FINE)
Worst Case Hydraulic Load	No Assembly Lift-Off	Analysis & Experiment
Control Rod Reactivity	No Solubility	Design (Material choice)

Fuel System Damage (1/2)

Items	Criteria	Approach
Cladding Stress	ASME sec. III	Analysis (FINE)
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Explained in detail

Design Criteria and Methodology

- **Fuel System Damage**

  Cladding Stress

  (1) **Design Basis / Criteria**

  Fuel system should not be damaged due to excessive stress under Condition I & II events

  ASME Sec. III criteria are applied

  (2) **Design Methodology**

  Stress is evaluated by FINE code

  stress due to + Inner-outer differential pressure
  + Hydraulic and seismic vibration
  + Fuel bowing
  + Grid contact
  + Ovality
  + Thermal stress

  *PCMI: pellet-cladding Mechanical Interaction

  Effect of PCMI* is assessed in the cladding strain

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Fuel System Damage (1/2)

Items	Criteria	Approach
Cladding Stress	ASME sec. III	Analysis (FINE)
Cladding Strain	≤1%	Analysis (FINE)
Stress and loading limit other than cladding	Stress limit : ASME sec. III, Loading limit for joints	Analysis (FEM) & Experiment
Fatigue	Langer-O'Donnell Design limit	Analysis (FINE)
Fretting at Contact Point	< limiting Fretting Wear	Analysis & Experiment
Oxidation, Hydriding	No Corrosion acceleration, Keeping Ductility	Analysis (FINE) & Experiment

Explained in detail

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Fuel System Damage (1/2)

Items	Criteria	Approach
Cladding Stress	ASME sec. III	Analysis (FINE)
Cladding Strain	≤1%	Analysis (FINE)
Stress and loading limit other than cladding	Stress limit : ASME sec. III, Loading limit for joints	Analysis (FEM) & Experiment
Fatigue	Langer-O'Donnell Design limit	Analysis (FINE)
Fretting at Contact Point	< limiting Fretting Wear	Analysis & Experiment
Oxidation, Hydriding	No Corrosion acceleration, Keeping Ductility	Analysis (FINE) & Experiment

Explained in detail

Design Criteria and Methodology

- ***Fuel System Damage***

Stress and loading limit : Loads applied by core restraint system

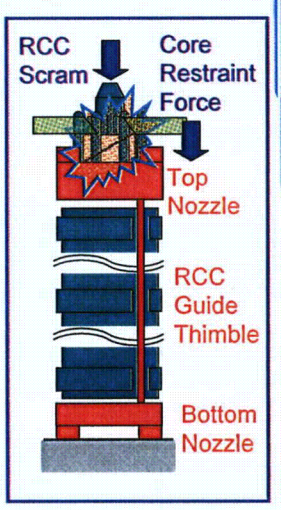
(1) **Design Basis / Criteria**

Fuel assembly should not be damaged by loads derived from core restraint system under Condition I & II events.

stress (Nozzles/RCC guide thimbles) < acceptance limit (ASME Sec.III).

(2) **Design Methodology**

Static analysis by FEM is used to obtain deformation and stress of RCC guide thimbles and nozzles.



Fuel System Damage (1/2)

Items	Criteria	Approach
Cladding Stress	ASME sec. III	Analysis (FINE)
Cladding Strain	≤1%	Analysis (FINE)
Stress and loading limit other than cladding	Stress limit : ASME sec. III, Loading limit for joints	Analysis (FEM) & Experiment
Fatigue	Langer-O'Donnell Design limit	Analysis (FINE)
Fretting at Contact Point	< limiting Fretting Wear	Analysis & Experiment
Oxidation, Hydriding	No Corrosion acceleration, Keeping Ductility	Analysis (FINE) & Experiment

Explained in detail

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Fuel System Damage (1/2)

Items	Criteria	Approach
Cladding Stress	ASME sec. III	Analysis (FINE)
Cladding Strain	≤1%	Analysis (FINE)
Stress and loading limit other than cladding	Stress limit : ASME sec. III, Loading limit for joints	Analysis (FEM) & Experiment
Fatigue	Langer-O'Donnell Design limit	Analysis (FINE)
Fretting at Contact Point	< limiting Fretting Wear	Analysis & Experiment
Oxidation, Hydriding	No Corrosion acceleration, Keeping Ductility	Analysis (FINE) & Experiment

Explained in detail

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Design Criteria and Methodology

- **Fuel System Damage**

Fretting Wear

(1) **Design Basis / Criteria**

The fuel cladding wear should be limited to the acceptable reduction of cladding wall thickness

(2) **Design Methodology to evaluate the cladding wear**

Design specifications (grid, span…),
rod natural frequency and vibration mode analyzed by FEM,
and semi-empirical model for hydraulic vibration
are taken into account to quantify the wear.

Fuel System Damage (1/2)

Items	Criteria	Approach
Cladding Stress	ASME sec. III	Analysis (FINE)
Cladding Strain	≤1%	Analysis (FINE)
Stress and loading limit other than cladding	Stress limit : ASME sec. III, Loading limit for joints	Analysis (FEM) & Experiment
Fatigue	Langer-O'Donnell Design limit	Analysis (FINE)
Fretting at Contact Point	< limiting Fretting Wear	Analysis & Experiment
Oxidation, Hydriding	No Corrosion acceleration, Keeping Ductility	Analysis (FINE) & Experiment

Explained in detail

Fuel System Damage (2/2)

Items	Criteria	Approach
Dimensional changes	Dimensional changes due to growth of fuel rods, fuel assemblies and grid spacers < acceptable limit	Analysis (Dimensional design)
Rod Internal Gas pressure	No Lift-Off (no pellet-cladding gap increase)	Analysis (FINE)
Worst Case Hydraulic Load	No Assembly Lift-Off	Analysis & Experiment
Control Rod Reactivity	No Solubility	Design (Material choice)

Fuel Rod Failure

Items	Criteria	Approach
Hydriding	No primary hydriding	Fabrication Control
Collapse	No collapse	Design (High Density Pellet etc.)
Fretting	< Limiting wear	See Fuel Damage
Overheating of Cladding	T/H (SRP 4.4)	
Overheating of Fuel Pellets	No Melting	Analysis (FINE)
Excessive Fuel Enthalpy	Safety (SRP15)	
Pellet/Cladding Interaction	Cladding Strain < 1% & No Pellet Melting	Analysis (FINE)
Bursting	Safety (SRP15)	
Mechanical Fracturing (LOCA + Seismic)	< 90% Yield Stress	Analysis (FEM)

Explained in the presentation of Thermal & Hydraulic design

Coolability

Items	Criteria	Approach
Cladding Embrittlement (& General Cladding Melting)	Safety (SRP15)	
Violent Expulsion of Fuel		
Fuel Rod Ballooning		
Structural Deformation Fuel Coolability (Fuel Assembly Structural Damage From External Forces)	< Limiting Grid deformation < acceptable stress (RCC/Nozzles) No Thimble buckling	Analysis (FEM)

Explained in detail

Design Criteria and Methodology

➢ Fuel Coolability

Fuel Assembly Structural Damage From External Forces

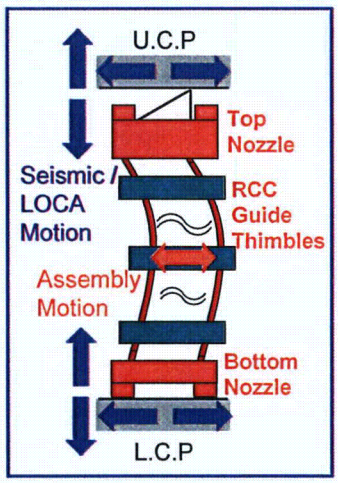
(1) Design Basis / Criteria

: Under the superposition of seismic and LOCA, insertion of RCC and core-cooling should not be prevented

- Limiting the grid spacer deformation
- Stress (RCC / Nozzles)
  < acceptance limit (ASME Sec. III)
- No buckling of RCC guide thimbles

(2) Design Methodology

FEM analysis is used to obtain deformation of assembly and stress of RCC guide thimbles and nozzles



3.FINE Code (Fuel Rod Design Code)

FINE code

- **MHI developed FINE code in 1980's. Most of the main models of PAD code were replaced with MHI's own models in FINE code.** Further modifications had been made up to 2001 in order to apply the code to the higher burnup usage (55GWd/t (FA)) in Japan.
- **MHI had developed its original models** based on the post irradiation examinations and other tests.

Presentation Contents of FINE

- **Overview of FINE code**
- **Representative Models**
  - ✓ Thermal Models
  - ✓ Fission Gas Release (FGR) Models
  - ✓ Corrosion & Hydrogen models (ZIRLO™)
  - ✓ Other models
    - Other pellet models,
    - Other cladding models,
    - pressure calculation,…
- **Verification**

In this presentation

MHI developed models for High burnup

MHI applied widely used models to the database

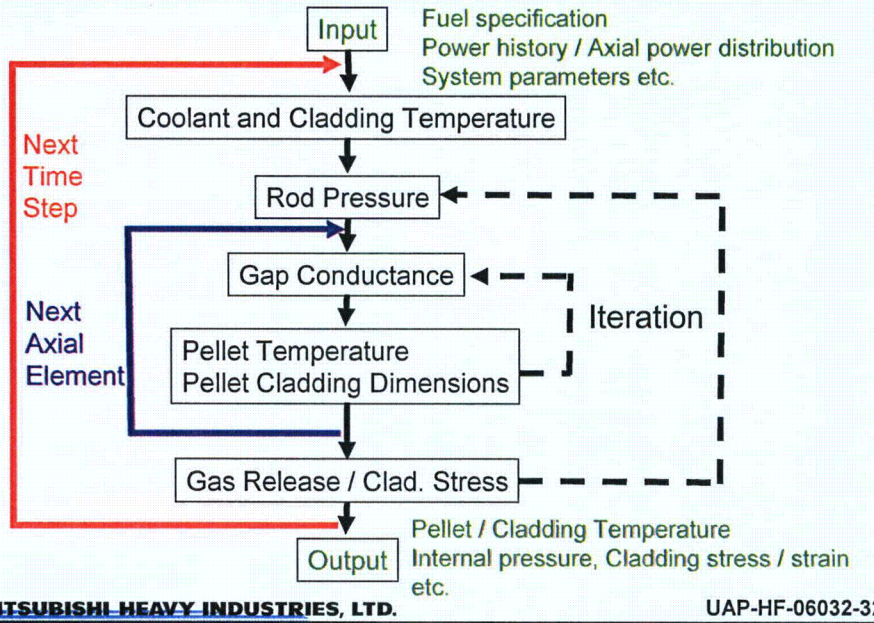
Overview of FINE code

- **FINE has been licensed in Japan**
  - ✓ UO_2, Gadolinia (~10wt%) doped fuel, MOX
    Zircaloy-4, ZIRLO™ , MDA* cladding tube
  - ✓ 55GWd/t (Assembly Average Burnup) fuel utilization in Japan. MOX is licensed up to 45GWd/t.

    * Mitsubishi Developed Alloy : 0.8Sn, 0.5Nb, 0.2Fe, 0.1Cr
- **US-APWR, FINE is applied to**
  - ✓ **UO_2, Gadolinia (~10wt%) doped fuel**
    ZIRLO™ cladding
  - ✓ **Burnup limit : 62GWd/t (Rod Average Burnup)****

    ** Equivalent to the above Japanese utilization

FINE: Calculation Flow



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Presentation Contents of FINE

- **Overview of FINE code**
- **Representative Models**
  - ✓Thermal Models
    - Thermal conductivity degradation with burnup
    - RIM* formation
  - ✓Fission Gas Release (FGR) Models
    - Recoil & Knockout, Diffusion Model
    - Fission gas release from RIM* region
  - ✓Corrosion & Hydrogen Model (ZIRLO™)
- **Verification**

* High burnup structure observed at the peripheral region of pellet

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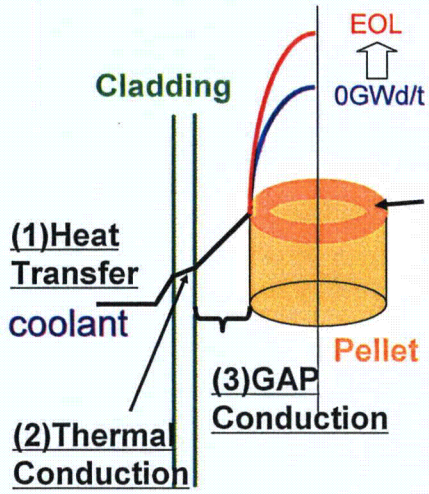
Thermal Models



(4) Pellet Thermal Conductivity Degradation with Burnup

(5)RIM formation at High Burnup
= Higher Porosity
= Lower Thermal Conductivity

The models for (4)~(5) are MHI original models

The models for (1)~(3) are widely used models

Pellet Thermal Conductivity(1/5)

Pellet thermal conductivity degradation with burnup is taken into account in FINE code

$$k_{95} = \frac{1}{A + \alpha \cdot Gd + \beta \cdot Bu + B \cdot T} + C \cdot T^3$$

Where
- k_{95} : Thermal conductivity of 95% Theoretical Density
- A, B, C : Constant
- Gd : Gd content
- α : Constant
- Bu : Burnup
- β : Degradation Factor

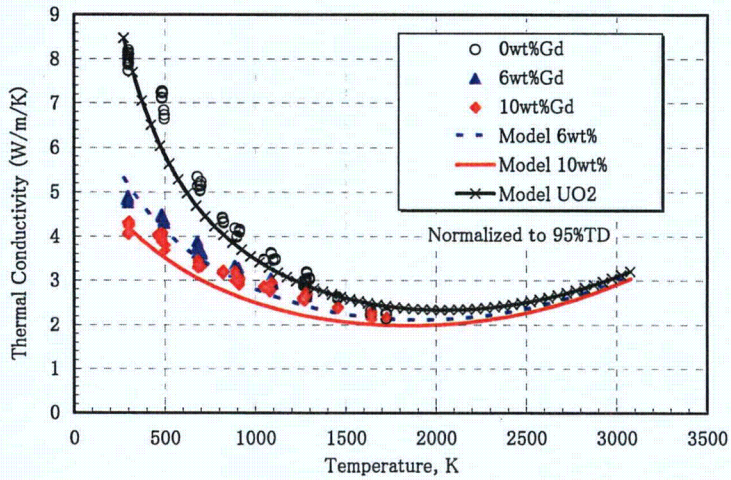
Porosity (p) correction model of BAKKER is adopted

$$\frac{k_x}{k_{100}} = (1-p)^n$$

k_x : Thermal conductivity of x%TD
x=(1-p)x100

Pellet Thermal Conductivity(2/5)

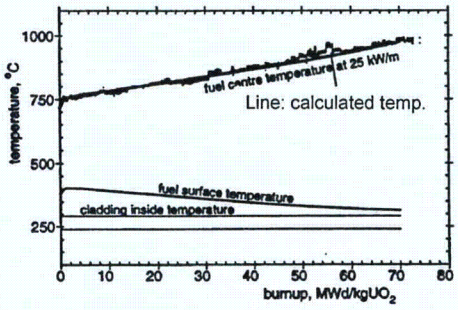
Effect of Gd content



Kosaka et al., "Thermal Properties and Irradiation Behavior of Gd Fuel", IAEA Technical Committee Meeting on Advances in Pellet Technology for Improved Performance at High Burnup, Oct. 1996, Tokyo

Pellet Thermal Conductivity(3/5)

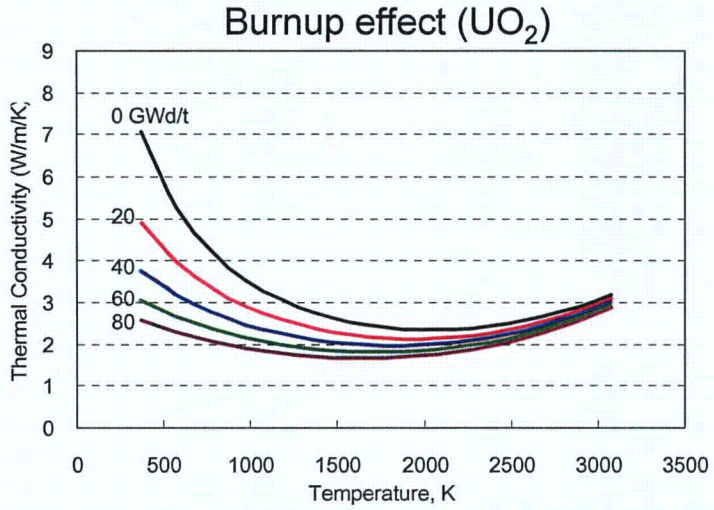
➢Thermal conductivity degradation with burnup



✓Temperature at constant power increases with burnup at the same rate

W.Wiesenack, "Assessment of UO2 Conductivity Degradation Based on In-Pile Temperature Data", ANS 1997 International Topical Meeting on LWR Fuel Performance, March 1997, Portland, Oregon

Pellet Thermal Conductivity(4/5)



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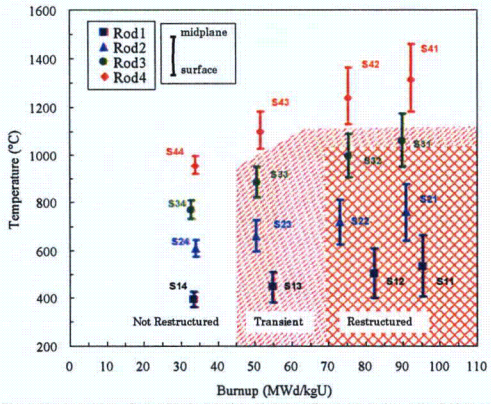
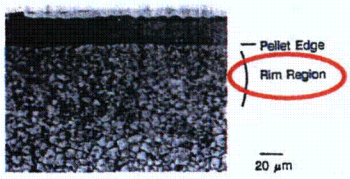
RIM Formation (1/2)

- **FINE code adopts RIM models**
  - ✓ RIM formation condition (High Burnup Rim Project)



Temp. < 1100 deg.C

Burnup> 50-60 GWd/t



[Left figure] M.Kinoshita et al, "High Burnup RIM Project (II) Irradiation and Examination to Investigate RIM-Structured Fuel", ANS 2000 International Topical Meeting on LWR Fuel Performance, April 2000, Park City, Utah
[Right figure]J.O.Barner et al., "Relationship between Microstructure and Fission Gas Release in High Burnup UO2 Fuel with Emphasis on the RIM Region", ANS/ENS International Topical Meeting on LWR Fuel Performance, April 1991, Avignon, France

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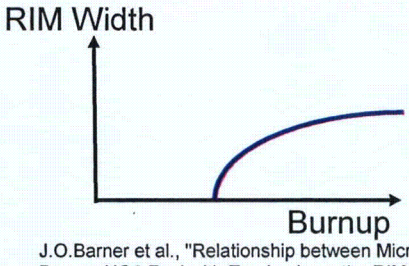
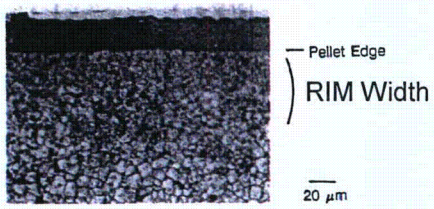
RIM Formation (2/2)

- **RIM Width based on BARNER et.al.**

$$W = \sqrt{A \cdot (BU - BU_{thresh})}$$

Higher porosity region (width) increases with burnup.
= Lower thermal conductivity





J.O.Barner et al., "Relationship between Microstructure and Fission Gas Release in High Burnup UO2 Fuel with Emphasis on the RIM Region", ANS/ENS International Topical Meeting on LWR Fuel Performance, April 1991, Avignon, France

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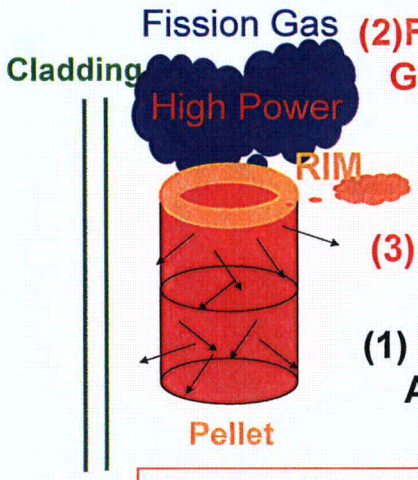
  - ✓Corrosion & Hydrogen Model (ZIRLO™)
- **Verification**

* High burnup structure observed at the peripheral region of pellet

Fission Gas Release Model



(2)FGR at High Temperature Gas Diffusion & Release through Grain Boundary = Diffusion model

(3) FGR from RIM Region

(1) Recoil & Knockout ANS5.4 model is applied.

(2), (3) : Original Model→ Explained later

Diffusion Model (1/2)

➢ **Fission Gas Release (FGR)**

due to Diffusion mechanism based on Grain Boundary Saturation Model

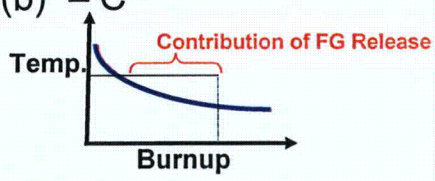
(a)Fission gas in grain diffuses to grain boundary

(b) Fission gas at grain boundary is resoluble into grain due to irradiation effect

-Fission gas concentration = (a) – (b)

-FGR depends on "(a) – (b)" – C* at the high temperature

C* : Concentration limit



FGR from RIM Region

- **Fission Gas Release from RIM Region**

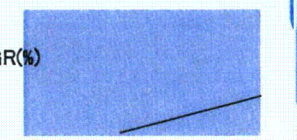
Based on the BARNER et.al. Model

$$\Delta R_{RIM} = A \cdot (BU - BU_{thresh})$$

A : Coefficient

BU : Burnup

BU_{thresh} : Threshold burnup for FGR



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Corrosion & Hydrogen

- The corrosion model has two transition points: Z1 and Z2.
- The corrosion improvement factor is applied to Zircaloy-4 model : ZIRLO™ model
- Hydrogen pickup rate of ZIRLO™ derived from irradiation data is applied to Zircaloy-4 model : ZIRLO™ model

(1)$Z<Z_1$

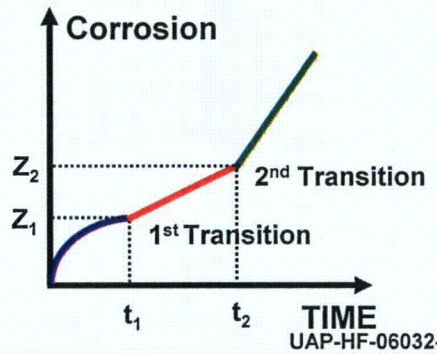
$$Z = \left[A_1 \exp\left(-\frac{Q_1}{RT} \right) \cdot t \right]^{1/3}$$

(2)$Z_1 \le Z < Z_2$

$$Z = A_2 \exp\left(-\frac{Q_2}{RT} \right)(t - t_1) + Z_1$$

(3)$Z_2 \le Z$

$$Z = A_3 \exp\left(-\frac{Q_2}{RT} \right)(t - t_2) + Z_2$$



Verification

- **Verification with Irradiation Data**
  - ✓ Verification Data Summary
  - ✓ Representative Comparison between Measured and Calculated Data
    - Fuel Centerline Temperature
    - Fission Gas Release
    - Corrosion & Hydrogen
- **Verification with Other Code**
  - ✓ to be described in detail in the Topical Report

Verification Data Summary

- **Plant**
  - Test Reactor : Saxton, Halden, R2, BR2
  - Commercial Reactor
    : Mihama, Ohi, Takahama, Genkai, Ikata,
    Zion, Surry, Farley, North Anna, Zorita, Trojan, BR3, Vandellos
- **Data**

Fuel Centerline Temperature	~86GWd/t
Fission Gas Release, Rod Internal Pressure	~65GWd/t
Pellet Dimension Change (Density)	~70GWd/t
Cladding Dimension Change (Growth, Creep)	~63GWd/t
Corrosion, Hydrogen	~62GWd/t

ZIRLO™ had been irradiated in Ohi, North Anna, BR3, Vandellos and R2.

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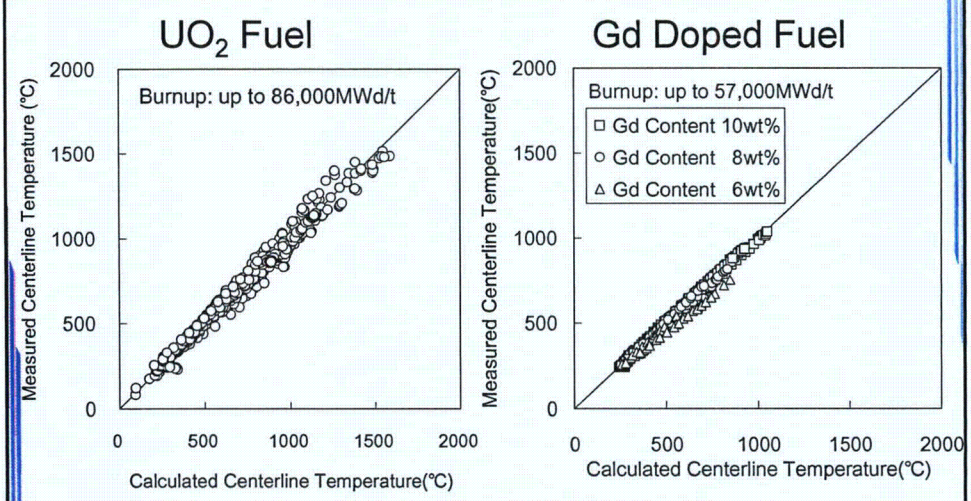
Fuel Centerline Temperature



✓All the data were measured in Halden Reactor by thermocouple or extension thermometer.

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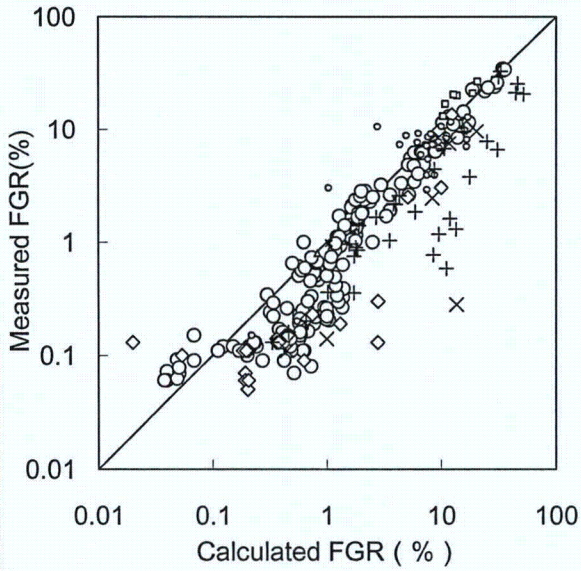
Fission Gas Release



Remark: Small symbol denotes lower density pellet results (< 94%TD)

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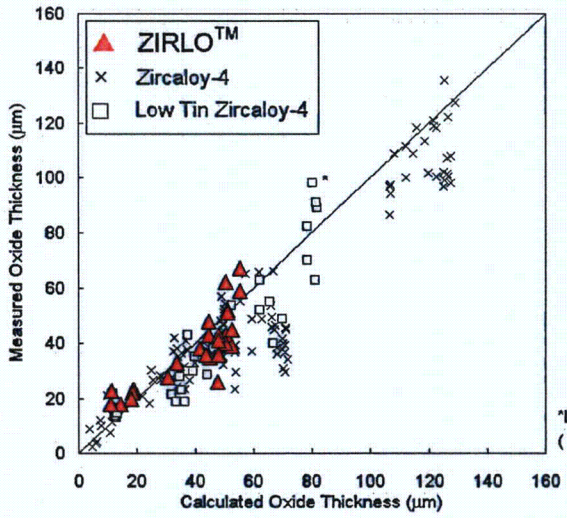
Cladding Corrosion



*Lift off of oxide observed (Vandellos)

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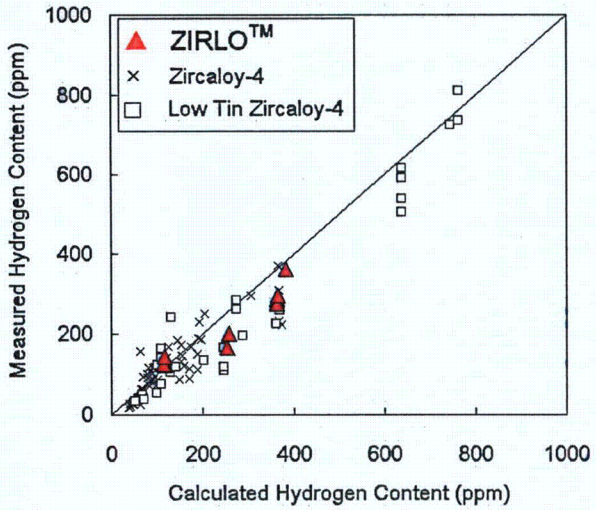
Hydrogen Content



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Summary

- The main topics of the topical report of the US-APWR fuel are summarized.
  - ✓Design criteria and methodology for US-APWR fuel cover the requirements specified in SRP
  - ✓MHI design follows RG.
  - ✓The representative FINE models and their verification are introduced.
  - ✓FINE code is applicable to US-APWR fuel design (up to 62 GWd/t (Rod average)) .
- All of these items will be described in the topical report. (Submittal Schedule : May 2007)

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Contents of Topical Report

"Fuel Design Criteria and Methodology"

1. Introduction
2. Design Criteria and Methodology
   - ✓ Fuel System Damage
   - ✓ Fuel Rod Failure
   - ✓ Coolability
3. FINE Code (Fuel Rod Design Code)
   - ✓ Overview of FINE code
   - ✓ Models *
   - ✓ Verification *

* Described in detail for all models