LWR Fuel Performance
(with emphasis on BWR fuel)

Doug Crawford
Manager, Fuel Performance & Design
Global Nuclear Fuel
June 3, 2009

Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Topics

- Functions and Requirements for Nuclear Fuel
- Industry Challenges To and Need For Fuel Reliability
- Fuel Failure Modes and Performance Phenomena

General Functions & Requirements for Nuclear Fuel*

- Position fissile material in the reactor core in a stable and predictable manner to allow a controlled fission reaction
- Allow effective transfer of nuclear reaction heat from the fuel to the coolant (or heat transfer medium)
- Provide containment of radionuclides (fuel and fission products) for operational convenience and as a first barrier for safety
- Provide/allow a convenient means of loading fresh fuel into the core and removing and managing spent fuel
- Perform the above for (most) Design Basis Events, including normal operation

* Presenter's statement of requirements, based on experience and observation

Some Specific Functions & Requirements for Nuclear Fuel

- **Performance**
  - Exposure or burnup (fuel cycle economics)
  - Temperature and power (liner heat generation rate)
  - Compatibility with coolant and hardware
  - Reliability (operational economics)
- **Licensing (safety functions following from 10CFR21.3 and 10CFR100, AppA)**
  - Enable shutdown the reactor by allowing for the passage of the control structures between/among the fuel assemblies,
  - Enable shutdown of the reactor by establishing and maintain the arrangement of fissile material, and thus the reactivity of the fuel assembly,
  - Enable safe shutdown by maintaining coolable geometry,
  - Mitigate the consequences of accidents that could potentially result in offsite exposures comparable to the limits defined in the regulations.

Comments on LWR Technical Maturity

- LWRs - very mature in current fuel cycle:
  - 300-some units operated world-wide over span of 40+ years
  - Profitability of operations now established
- Competitive supply of reactors, fuel supplies, and services have increased market efficiencies
- Fuel cycle economics established and efficient
  - Plant operators interested in getting as much energy and value out of fuel as possible, but balance against reliability-related fuel risk
- Fuel is not a large fraction of operating cost, but fuel reliability can impact other costs and revenue generation
  - Uncertainty as well as magnitude of cost/revenue impact is a concern
  - So, fuel reliability is a key concern for reactor operators

BWR Fuel Assemblies

- Fuel Pellets stacked in rod made of a Zirconium alloy ("Zircaloy")
- Fuel Rod welded shut
- Numerous fuel rods assembled in square lattice
- Active Fuel length ~ 120 – 150 in (~ 305 – 380 cm)
- Channel Box over fuel assembly - forces water flow up through fuel
- Able to change fuel configuration as long as it stays within channel box

BWR/6 Fuel Assemblies and Control Rod Module

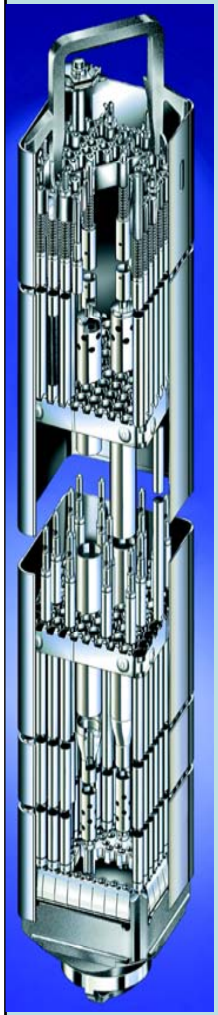
1 Top Fuel Guide
2 Channel Fastener
3 Upper Tie Plate
4 Expansion Spring
5 Locking Tab
6 Channel
7 Control Rod
8 Fuel Rod
9 Spacer
10 Core Plate Assembly
11 Lower Tie Plate
12 Fuel Support Piece
13 Fuel Pellets
14 End Plug
15 Channel Spacer
16 Plenum Spring

GE Nuclear Energy

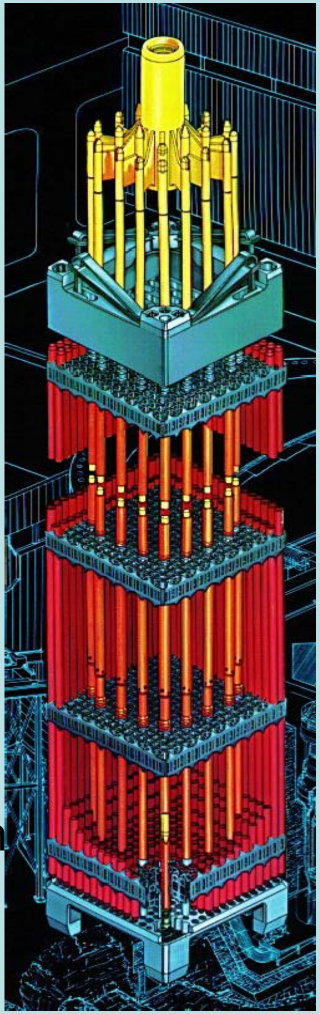
Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Fuel Characteristics



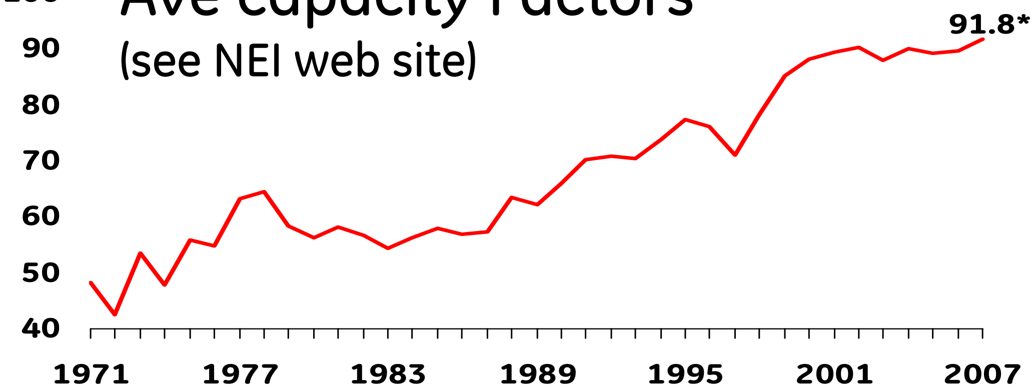
	BWR	PWR
Lattice	10x10	14x14 – 18x18
Lattice size	~5.3”	~9”
Height	120”-150”	144”-168”
Fuel	UO_2/MOx	UO_2/MOx
Fuel rods	~92	176-300
Part length rods	~14	0
Non-fueled rods	~2	20-25
Control	Ext. control rod	Int. control cluster
Cladding	Zr2 for PCI, nodular corrosion	Zr4/Zirlo/M5 for uniform corrosion & hydrogen
Channels	Yes	No
Fuel mass	~180 kgU	~600 kgU



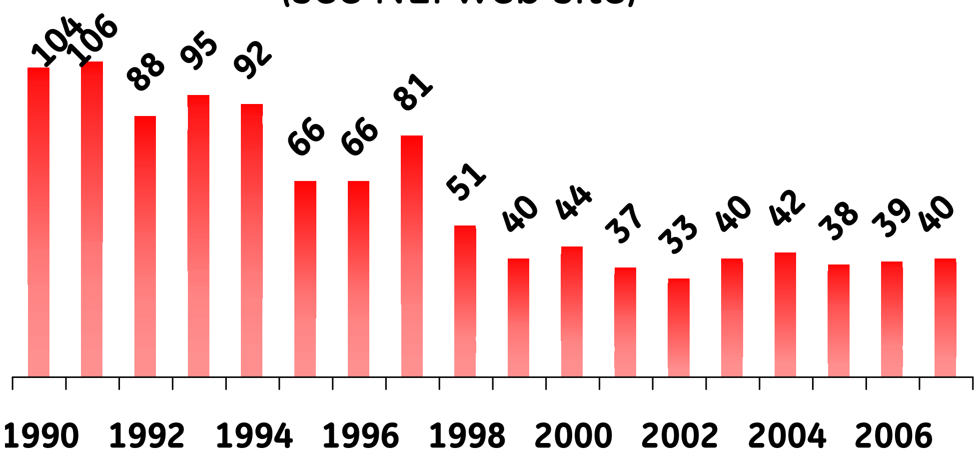
1 PWR bundle ≈ 3 ½ BWR bundles

Industry Trends

Ave capacity Factors
(see NEI web site)



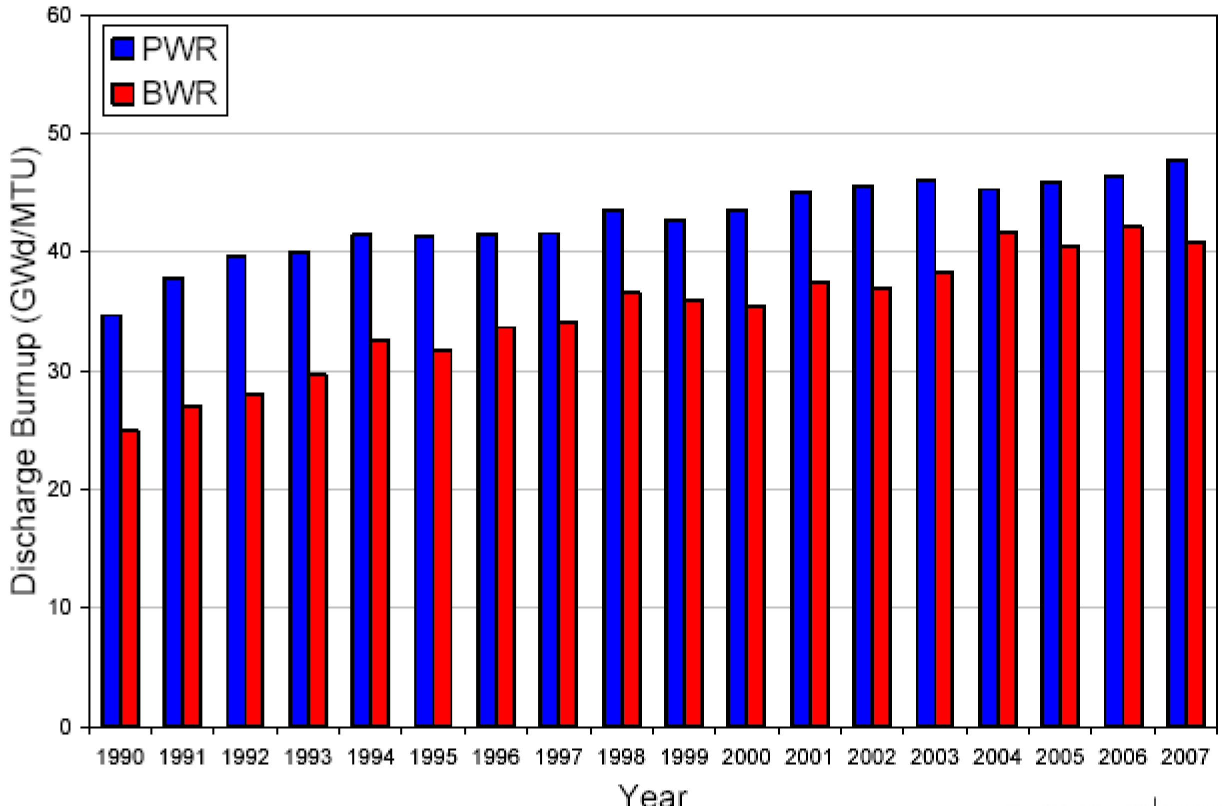
Ave outage durations
(see NEI web site)



Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Increasing Assembly Exposures



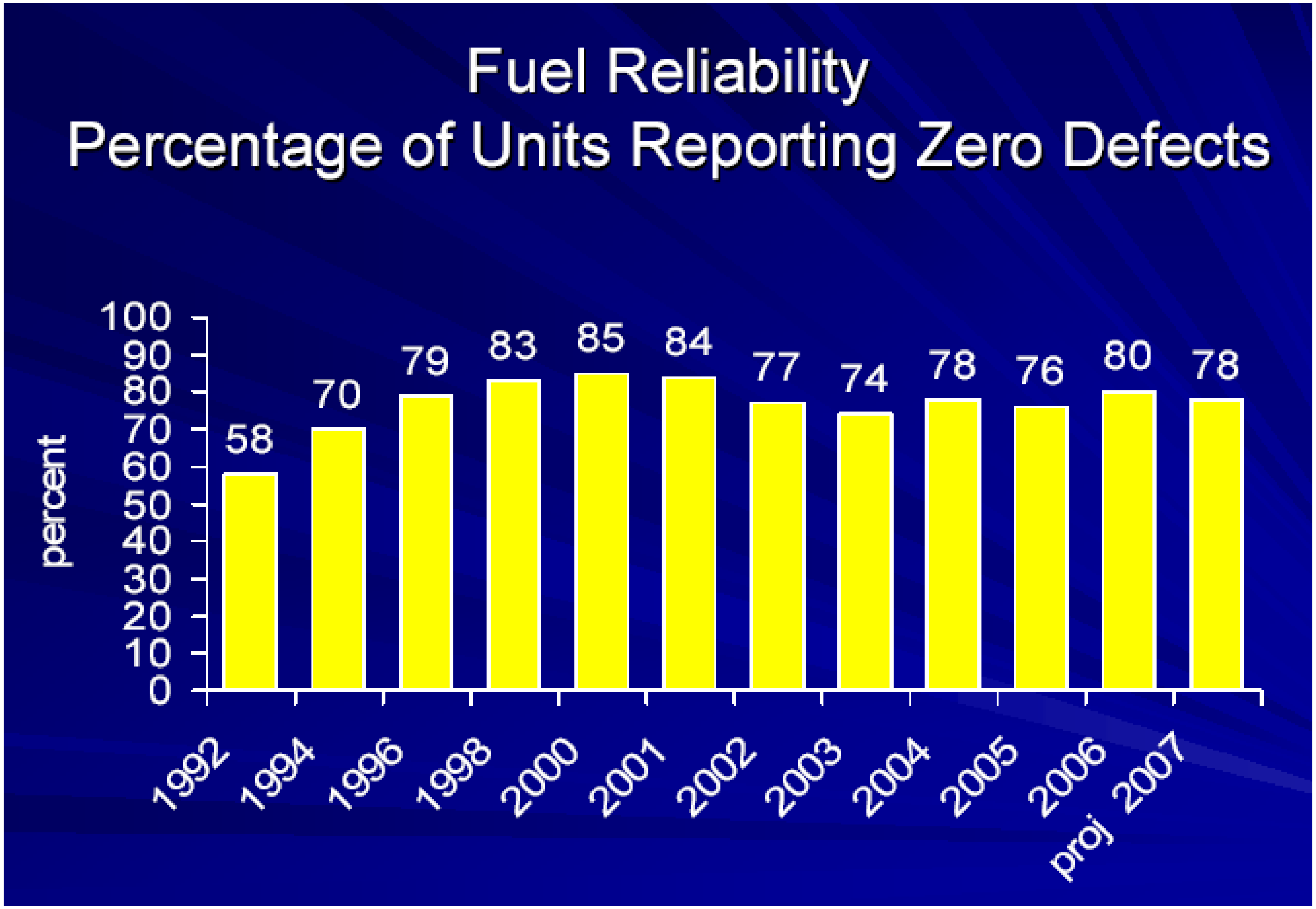
Better operations, power uprates – pushing up assembly exposure.

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Reference: EPRI Fuel Reliability Executive Committee Meeting Dallas, USA, January 23, 2008, J. Deshon, A. Kucuk - EPRI Fuel Reliability Program

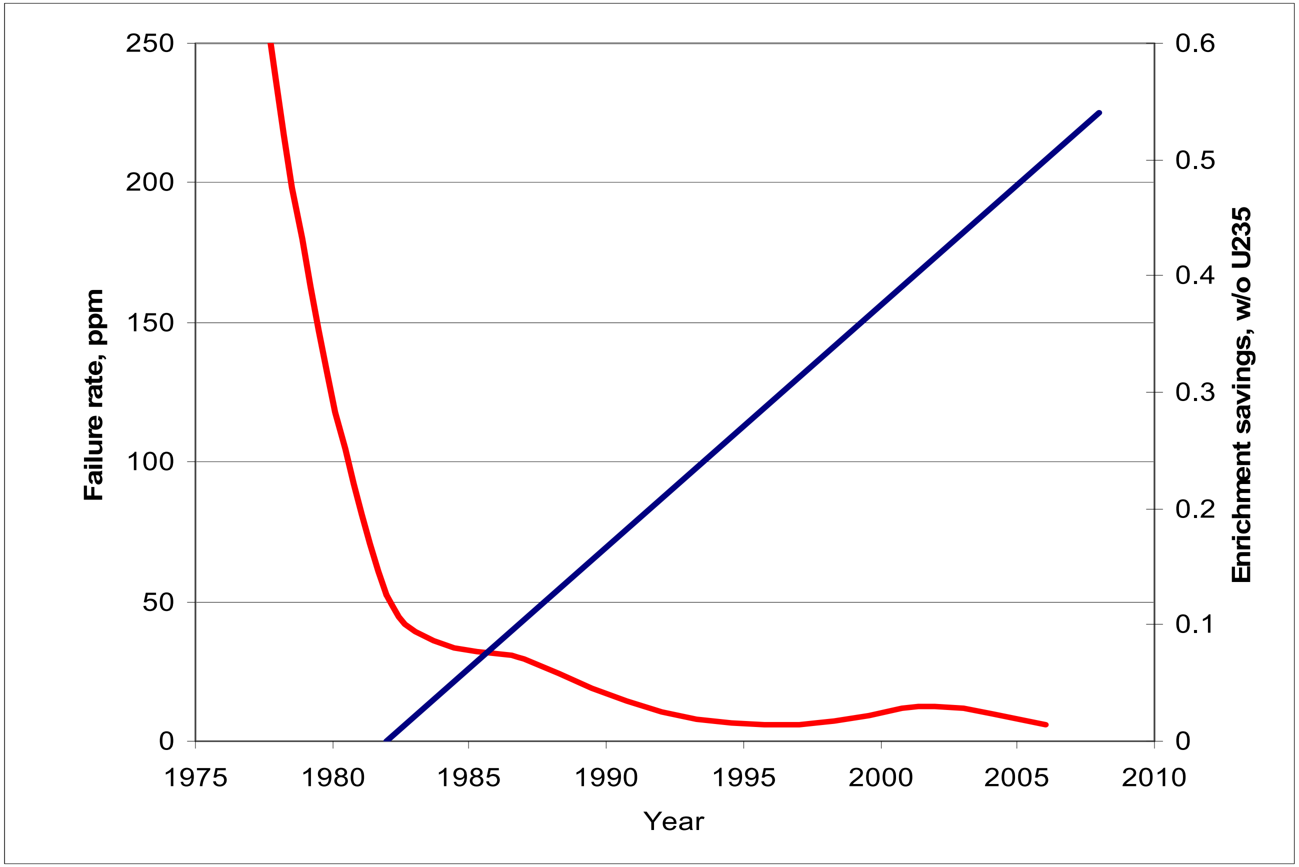
No Appreciable Change in Fuel Reliability



Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: EPRI Fuel Reliability Executive Committee Meeting Washington DC, USA, August 2007, Kurt Edsinger, EPRI Fuel Reliability Program

Tolerance of Performance Issues has Decreased



Large reduction in failure PPM and large increase in design value.

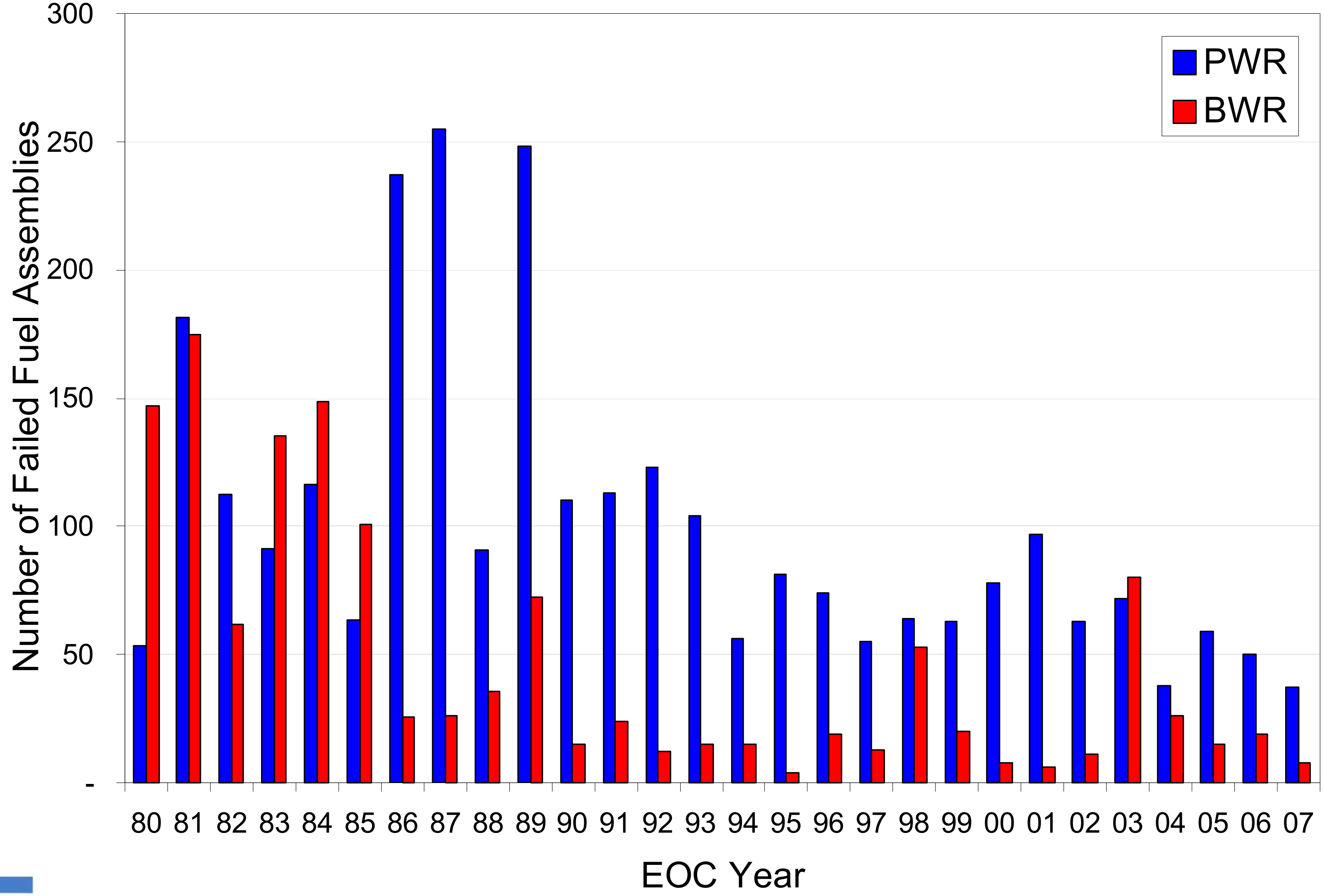
Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Reference: World Nuclear Fuel Cycle 2008, "Making it Work – Reliability and Optimization", Russell Stachowski, Global Nuclear Fuel.

A comparison of PWRs and BWRs

Historically, PWRs more tolerant of fuel failures due to secondary system, but less so now

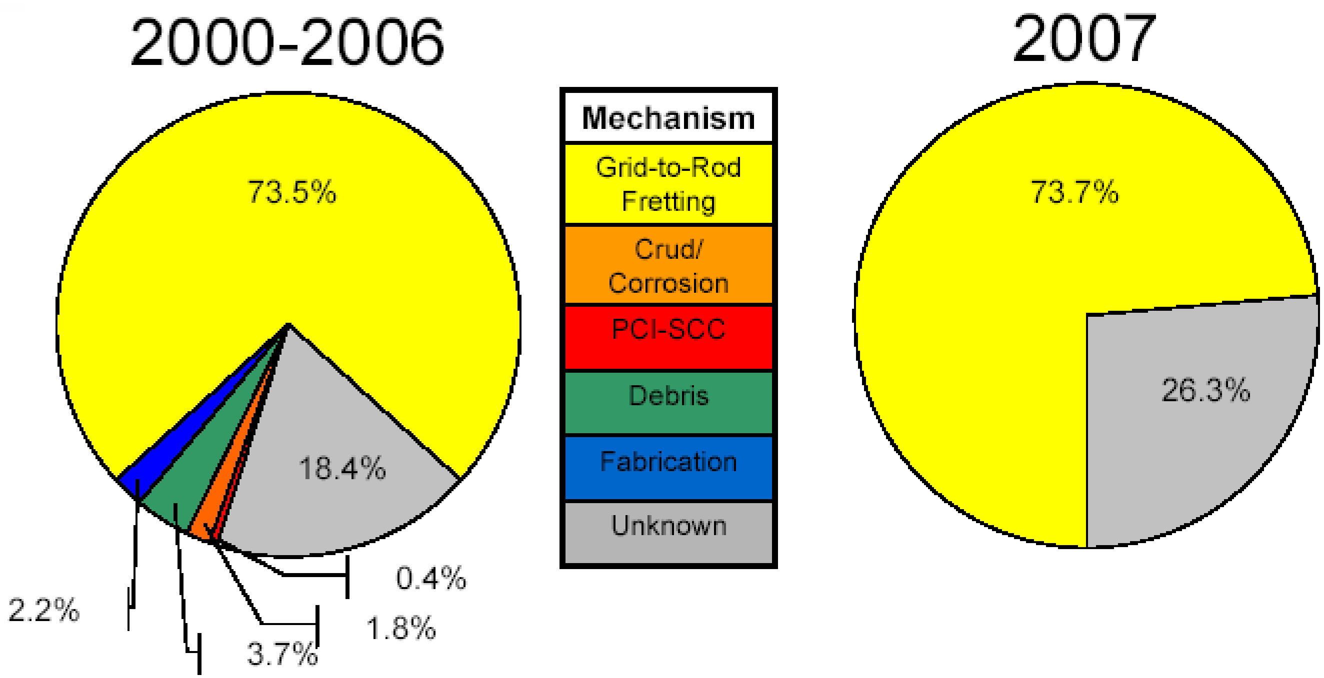


Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Reference: EPRI Fuel Reliability Executive Committee Meeting Dallas, USA, January 23, 2008, J. Deshon, A. Kucuk - EPRI Fuel Reliability Program

PWR Failure Mechanisms
(per the EPRI FRED Database)

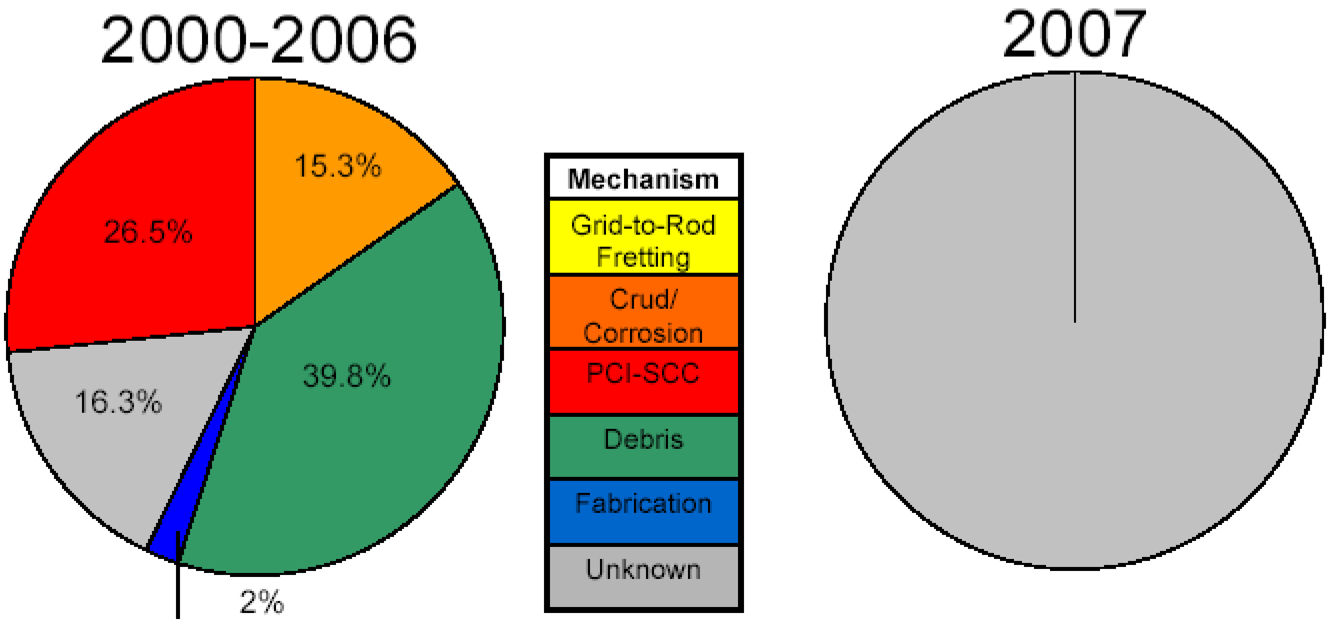


- PWR failures distributed amongst numerous plants
- Grid fretting is largest contributor

Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: EPRI Fuel Reliability Executive Committee Meeting Dallas, USA, January 23, 2008, J. Deshon, A. Kucuk - EPRI Fuel Reliability Program

BWR Failure Mechanisms
(per the EPRI FRED Database)

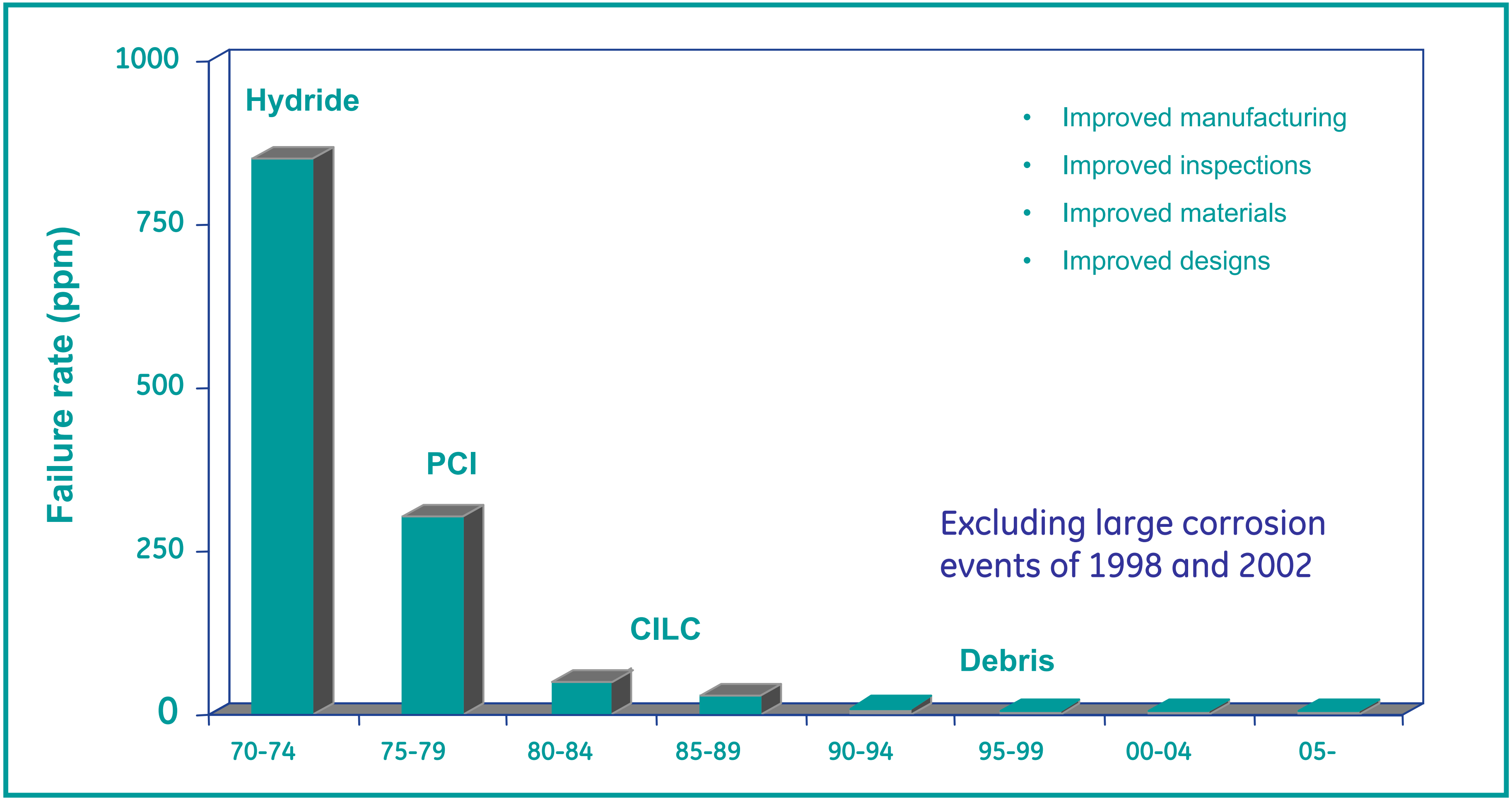


- BWR failures dominated by a few plants
- Corrosion events, PCI and debris are largest contributors

Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: EPRI Fuel Reliability Executive Committee Meeting Dallas, USA, January 23, 2008, J. Deshon, A. Kucuk - EPRI Fuel Reliability Program

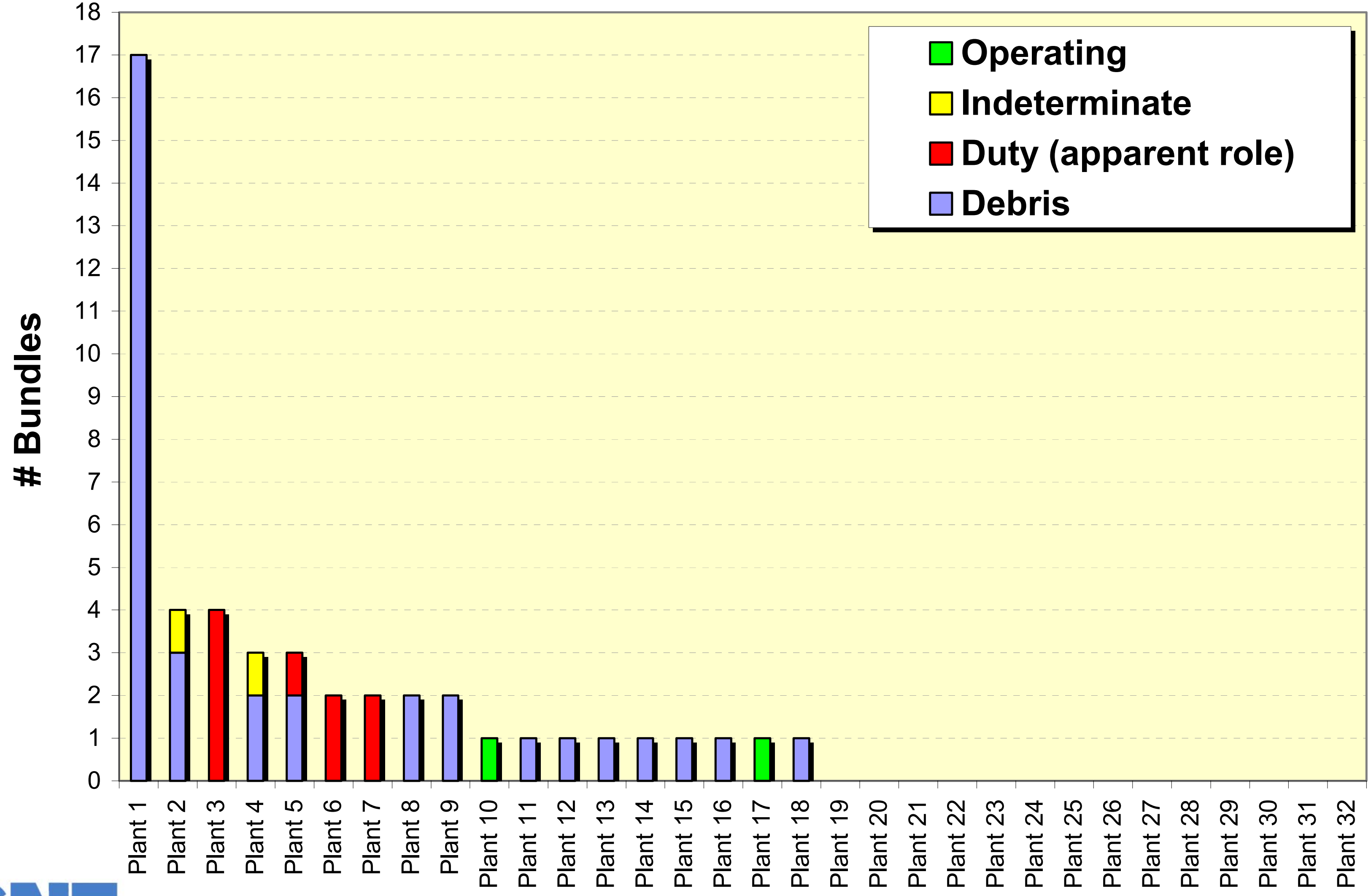
GNF Fuel Reliability 1975 - 2005



Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

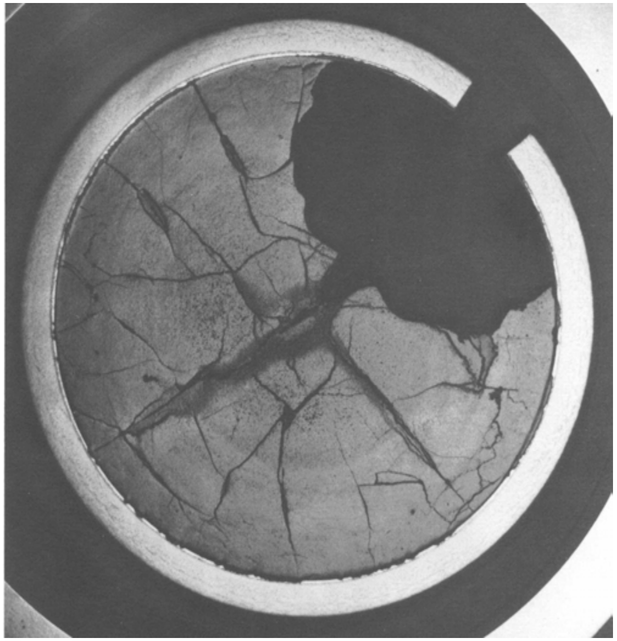
GE 14 Leakers by Plant – 2000 to 2009



Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

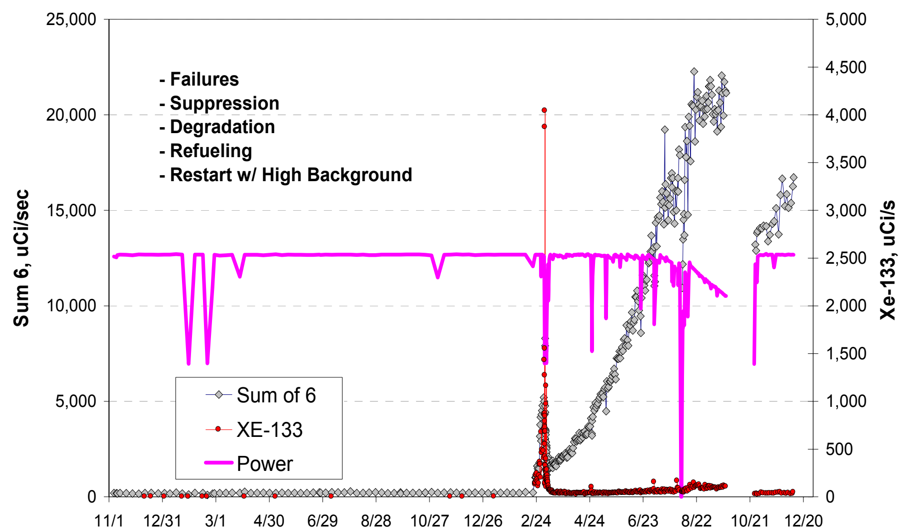
Fuel Failures in BWRs

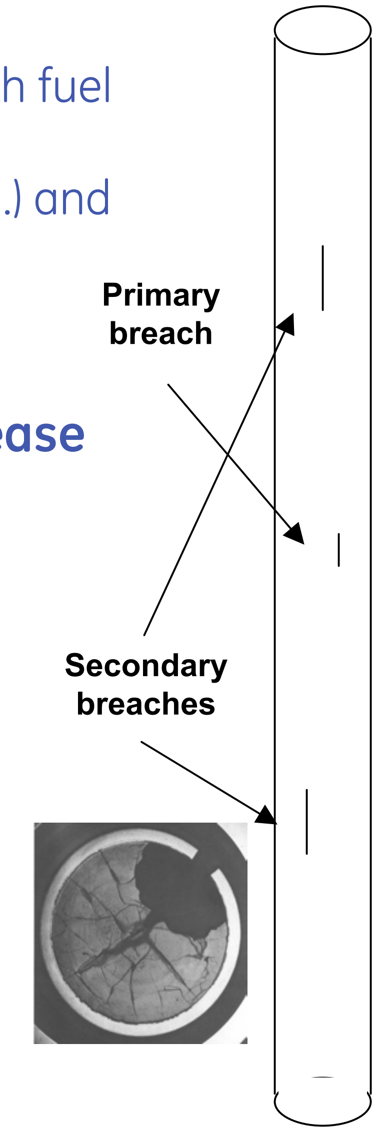
- Less of an issue for PWRs
  - BWR water more oxidizing, less secondary degradation in PWRs
  - PWRs have fewer exposure issues because primary-secondary loop design keeps radionuclides out of the steam system
- Radiological Consequences
  - can be large due to oxidizing reactor coolant
  - fuel pellet oxidation/erosion if secondary clad damage occurs
  - contamination of plant systems, higher background activity



Impact of BWR Fuel Failures (Breaches or Leakers)

- **Secondary degradation**
  - Coolant enters fuel rod through primary breach to react with fuel and cladding and migrate to other axial locations
  - Reaction products include U_3O_8, & UO_3 (with higher spec vol.) and embrittling ZrO_2, and ZrH_4
  - Exacerbate primary breach and induce other, secondary breaches
- **Primary and secondary breaches open further and release radionuclides to primary coolant**
  - leads to radiation exposures from primary system for maintenance personnel





Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Options for Addressing Leaking Fuel Rod(s)

- Mid-cycle outage to remove and replace bundle with leaker or mitigate secondary degradation and continue operations
  - Loss of generation revenue and/or purchase of replacement power at unfavorable rates
  - Disruption to planned outage schedules and operating resources
- Or leaking bundle(s) can be found for subsequent, localized reduction in power to reduce degradation rate
  - Power suppression testing used to find leaking rod(s); requires short period of reduced power
  - Insert control blade(s) in region of breached fuel rod(s)
  - Continue to follow/monitor fission product through cycle
  - Means some, smaller loss of generation revenue
- Plants must balance need to limit radiation exposure (ALARA) to personnel against generation revenue loss

Key Phenomena Responsible for LWR Fuel Reliability and Performance

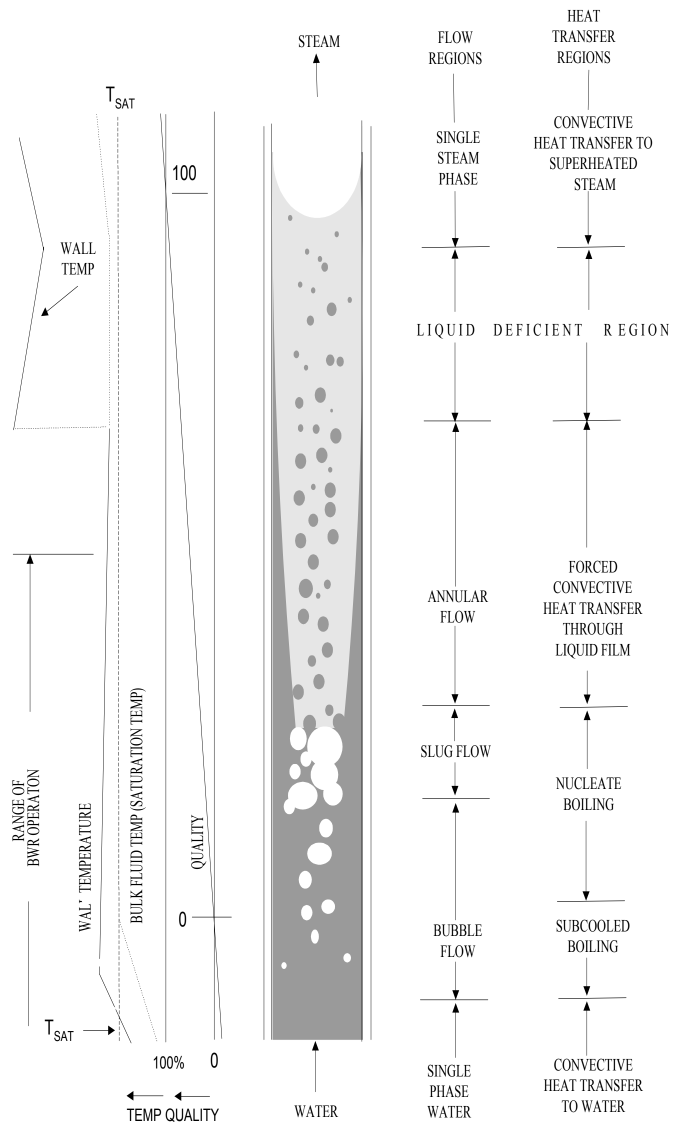
- Flow-induced vibration of captured debris – fretting wear of cladding
- Flow-induced vibration of fuel rods against grids (PWRs) – fretting wear of cladding
- Corrosion – thin the cladding and reduce the load-bearing wall thickness; hydrogen uptake into cladding forms hydrides that embrittle and deform with higher specific volume
- Fission gas release – increases the fuel rod's internal pressure and stresses the cladding; can lead to cladding creep-out, increasing pellet-cladding gap and cladding temperature
- Fuel pellet thermal expansion and cracking during power increases (blade pulls in CR sequence exchanges) – puts stress on cladding and releases aggressive fission products to inside cladding surface
- Crud deposition – spallation of crud and oxide creates local regions that are cooler (less insulation) and which can accumulate higher hydrogen, which embrittles
- Irradiation growth – dimensional changes and deformation to structural components and cladding

Flow regimes and heat transfer

BWR

Efficient heat transfer through boiling heat transfer

Wetted surface keeps fuel temperature close to saturation temperature



PWR

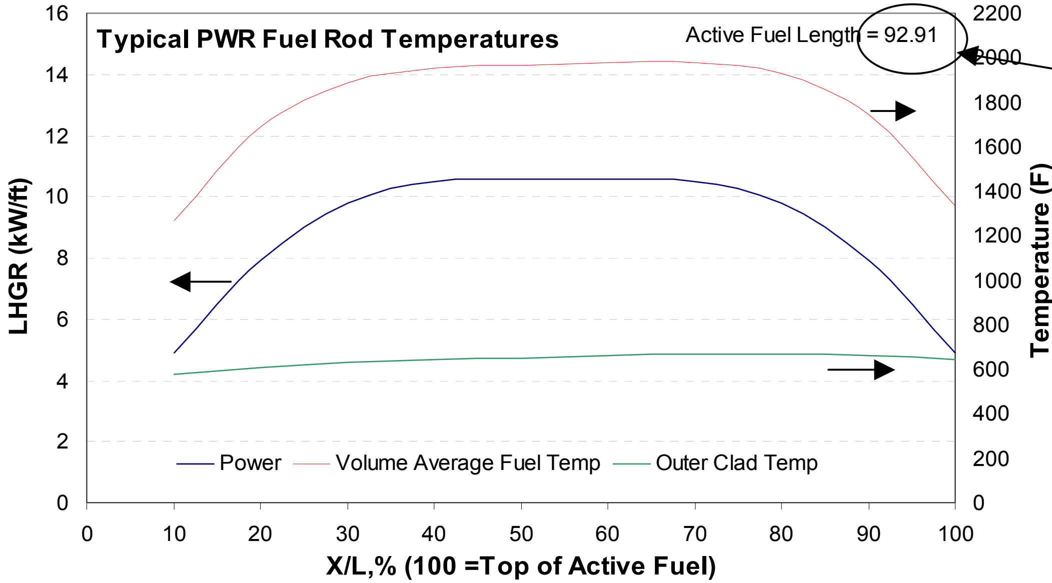
High flow velocities enhance convective heat transfer

Subcooled liquid means axially varying temperature profile for cladding/fuel

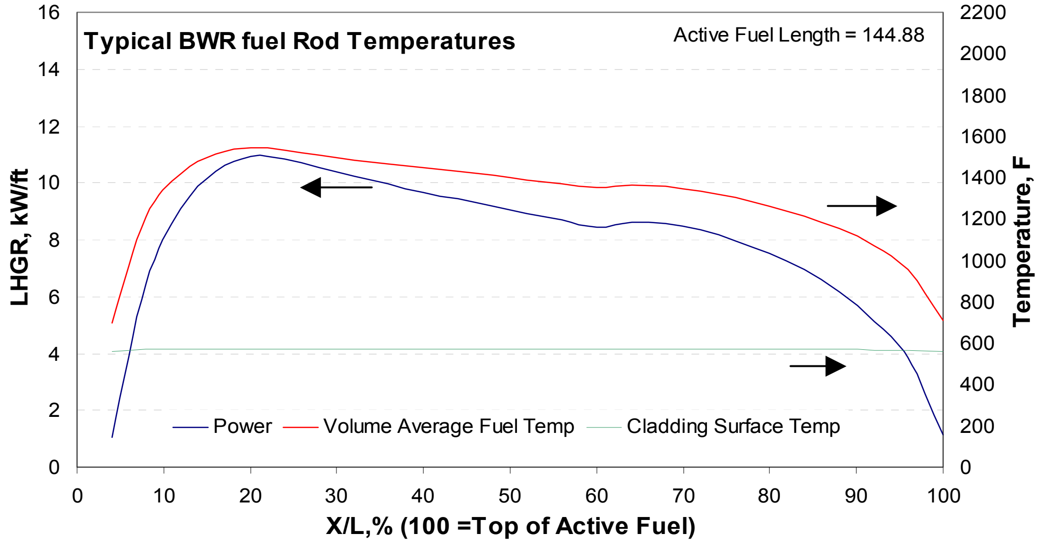
Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

BWR and PWR Fuel Rod Temperatures



(Note that PWR rod lengths are typically 144 – 168 inches; this length ok for illustration)

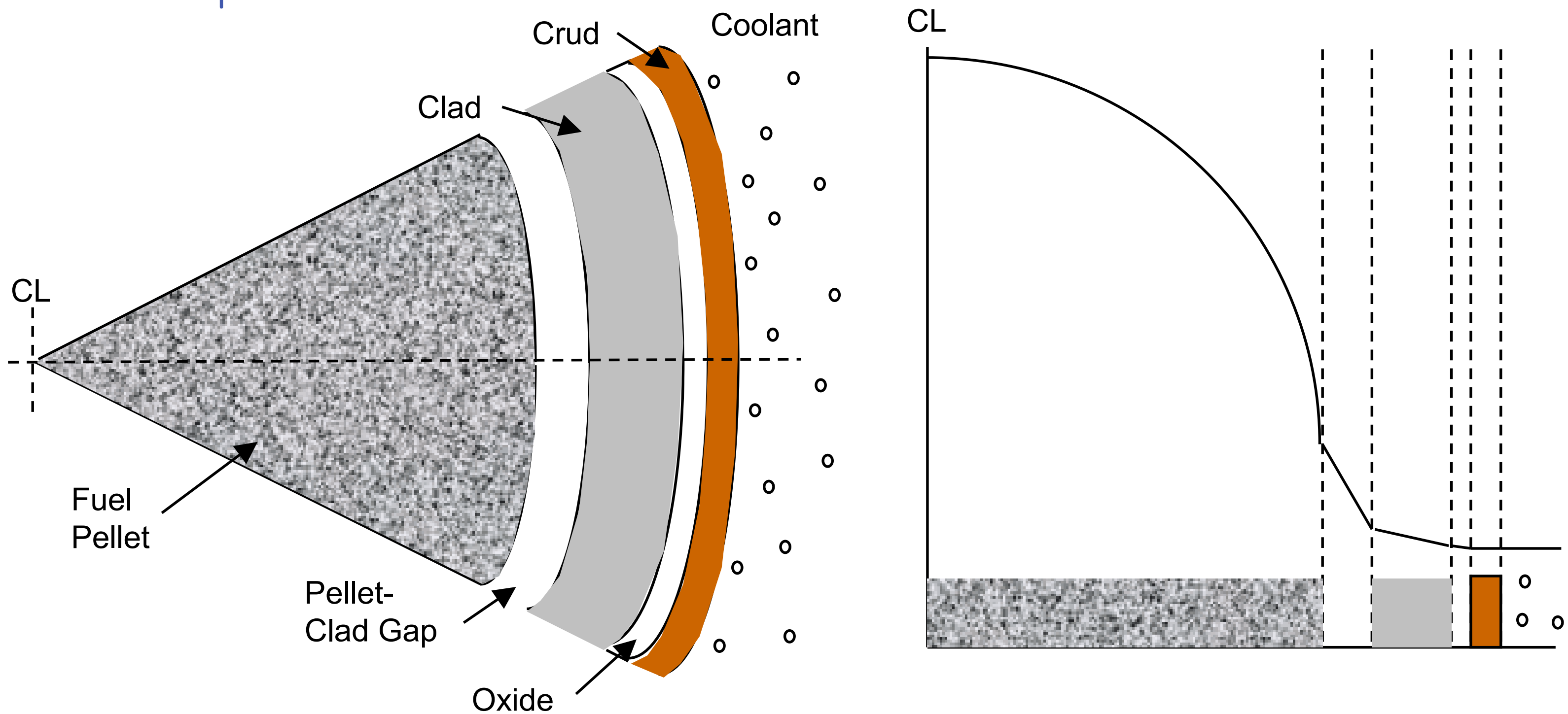


Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Fuel Rod Thermal-Mechanical Performance Phenomena

- Fuel rod thermal-mechanical performance evaluated using licensed methodologies
- Provides assessment of fuel and cladding temperature, properties, and response

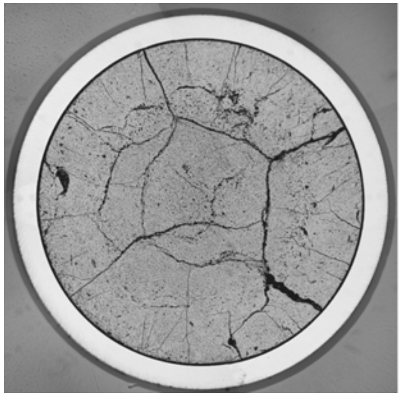


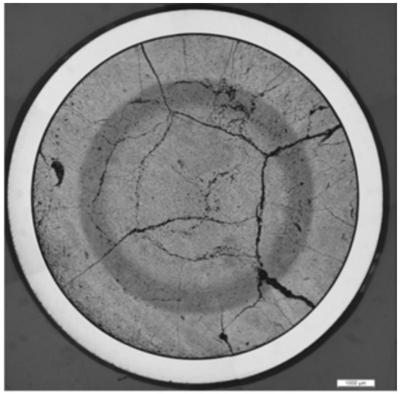
Basic Fuel Rod Cross-Section and Temperature Distribution

Fuel Pellet Phenomena

- **Fuel thermal expansion**
  - Volumetric (isotropic) expansion
  - Function of fuel temperature
  - **Closes** pellet-cladding gap, pellet radial and transverse cracks
- **Fuel cracking and relocation**
  - Radial translation of fuel pellet fragments
  - Caused by release of strain energy on cracking with supplemental progression
  - Function of temperature, geometry, exposure
  - **Closes** pellet-cladding gap, **opens** radial cracks

Metallographic cross section of fuel rod at ~20 GWd/MTU



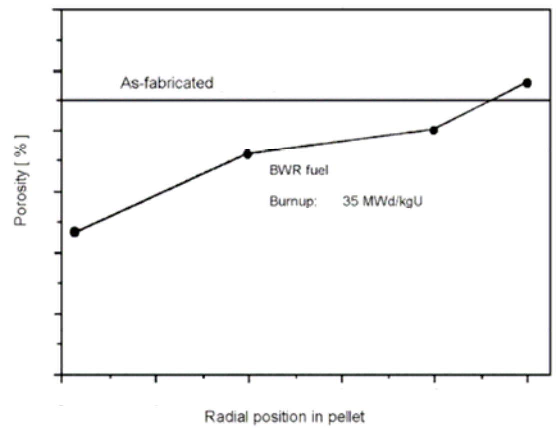


Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Fuel Pellet Phenomena (cont.)

- **Fuel irradiation swelling**
  - Volumetric (isotropic) expansion
  - Caused by fission products (solid+gaseous) deposition in the fuel lattice structure
    - Displaced larger volume than the parent atoms
  - Function of fuel exposure
  - Newer data indicate higher swelling rate at high burnup due to the "rim" structure formation and less accommodation of pores
  - **Closes** pellet-cladding gap, pellet radial and transverse cracks
- **Fuel irradiation-induced densification**
  - Volumetric (isotropic) contraction
  - Caused by diffusion of vacancies (pores) to grain boundary sinks
  - Function of fuel temperature, microstructure, and exposure
  - Complete by ~5 GWd/MTU
  - **Opens** pellet-cladding gap, pellet radial and transverse cracks



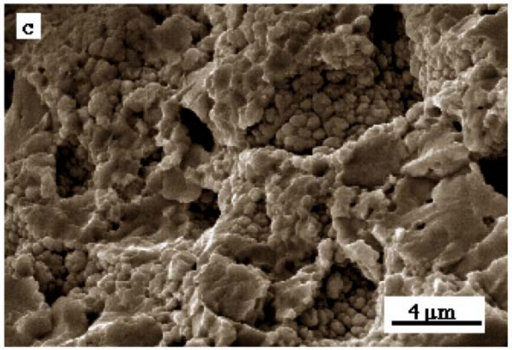
Fuel Pellet Phenomena (cont.)

- **Fuel creep**
  - Directional deformation in response to applied loads (induced stresses)
  - Conversion of elastic strain to permanent strain through material diffusional flow
  - Function of pellet temperature, stress, fission rate, density, grain size
  - **Redistributes** pellet strain distribution, **closing** pellet cracks and **reducing** pellet and cladding stress
- **Fuel hot pressing**
  - Material flow into pellet porosity resulting in volumetric contraction
  - Driven by hydrostatic stress state and fuel creep properties
  - Function of pellet temperature, stress, fission rate, density, grain size
  - **Opens** pellet cracks, reduces pellet and cladding stress
- **Fuel melting**
  - Volumetric (isotropic) expansion caused by lower density of molten fuel
  - Melting temperature decreases with exposure
  - **Closes** pellet-cladding gap, pellet radial and transverse cracks
  - Concern over effect on cladding and fuel slumping

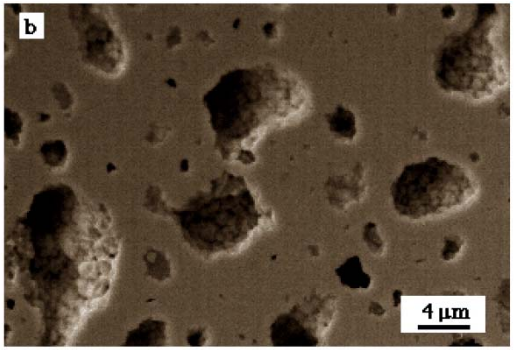
Fuel Pellet Phenomena (cont.)

- **Fuel rim formation**
  - Pellet periphery microstructural evolution occurring at high exposures
  - Caused by high fission rate at pellet periphery resulting in lower density region of sub-grain particles and fission gas bubbles
  - Function of exposure
  - Primary effect is regionally reduced thermal conductivity and higher fuel temperatures with minor volumetric expansion

SEM of scratched surface (~90 GWd/MTU)



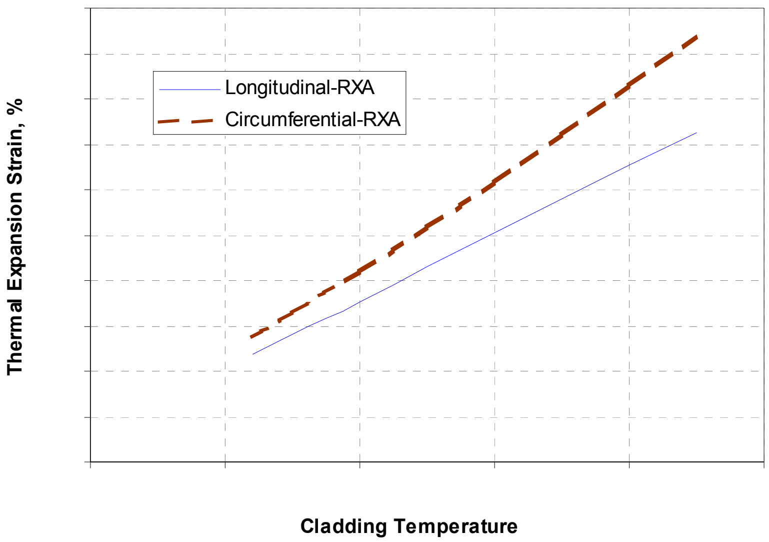
SEM of polished surface (~90 GWd/MTU)



Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Fuel Cladding Phenomena

- **Cladding thermal expansion**
  - Anisotropic expansion
  - Function of cladding temperature
  - **Opens** pellet-cladding gap



- **Cladding crud deposition**
  - Buildup of reactor water corrosion products on outer surface of cladding
  - Caused by mass transfer of soluble and insoluble reactor water impurities to fuel rod heat transfer surface
  - Function of operating time
  - **Provides heat transfer resistance**, increasing fuel and cladding temperatures; Spallation of crud creates cold spots in cladding

Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

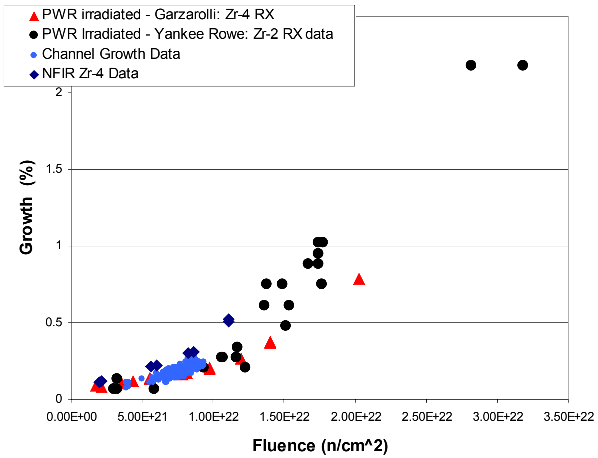
Fuel Cladding Phenomena (cont.)

- **Cladding oxidation**
  - Formation of corrosion layer at outer cladding surface
  - Caused by oxidizing environment with both thermal and athermal components
  - Function of cladding temperature, cladding material, operating time
  - Impedes heat transfer, increasing fuel and cladding temperatures.
  - Results in cladding thinning, and correspondingly increased cladding stresses, with absorption of embrittling hydrogen

- **Cladding Hydrogen Uptake**
  - Function of cladding temperature, cladding material, operating time, fluence,….
  - Reduces cladding ductility
  - Increase the failure potential by DHC/HAC

Fuel Cladding Phenomena (cont.)

- **Cladding creep**
  - Directional deformation in response to applied loads (induced stresses)
  - Conversion of elastic strain to permanent strain through material diffusional flow
  - Function of cladding temperature, stress, fast fluence
  - **Closes or opens** pellet-cladding gap, which affects heat transfer (possible cladding creep feedback)
- **Cladding irradiation growth**
  - Elongation of the cladding tube and control rod guide tubes (PWRs)
  - Caused by irradiation-induced defect generation within the zirconium crystal lattice
  - Function of cladding microstructure, temperature, fast fluence
  - In PWRs can lead to deformation of constrained control guide tubes, impeding motion of control rods
  - **Reduces** gap-closure effect induced by pellet-clad axial interaction

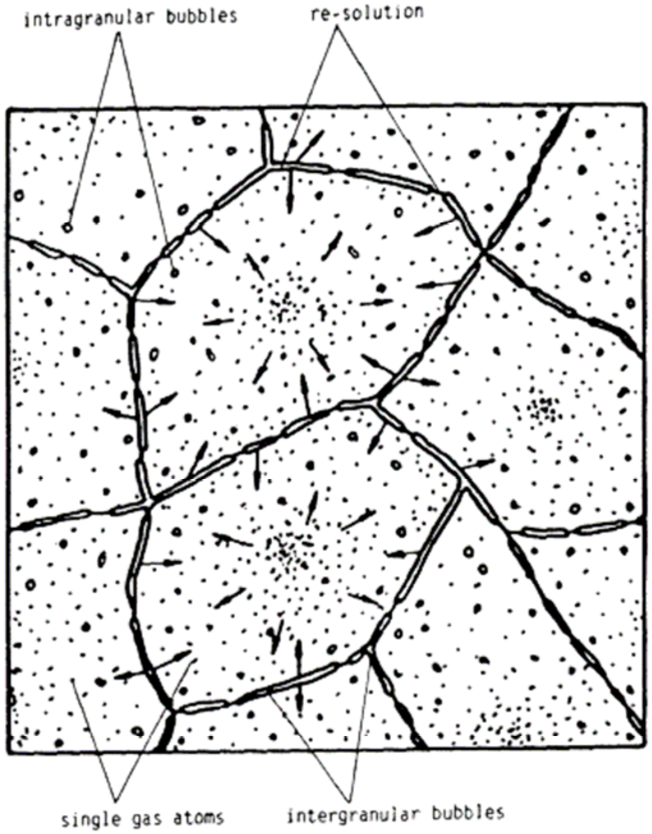


Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Integral Fuel Rod Phenomena

- **Fission Gas Release**
  - Release of gaseous fission products from fuel pellets to fuel rod void space
  - Caused by diffusion of fission gas atoms to grain boundaries and collection at grain boundaries until sufficient inventory for gas bubble interlinkage and release from free pellet surfaces
  - Function of fuel temperature, exposure
  - Results in dilution of high thermal conductivity helium fill gas with low conductivity fission gases thereby reducing pellet-cladding thermal conductance and **increasing fuel temperatures. Increases fuel rod internal pressure.**



Schematics of fission gas in fuel

Figure by A. Massih

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

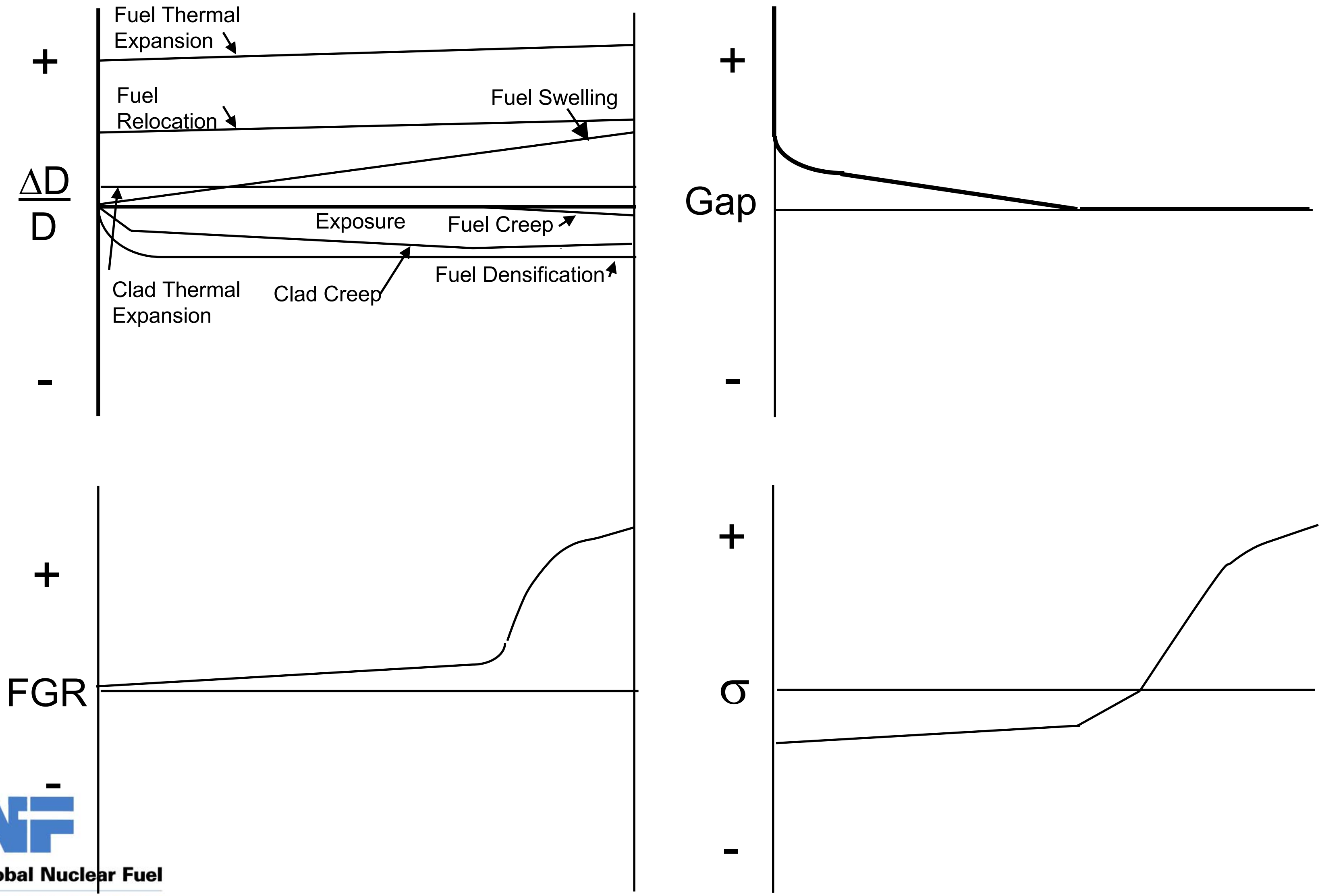
Integral Fuel Rod Phenomena (cont.)

- **Fission Gas Release and Fuel Burnup**
  - Burnup independent components
    - Gas atoms generated near pellet outer surface and pellet crack surfaces released by direct recoil and knock-out and thermal diffusion
  - Burnup dependent components
    - Gas atoms generated in fuel interior released by
      - Concentration gradient diffusion to grain boundaries
      - Bubble formation on grain boundaries
      - Bubble interlinkage and release
- **Pellet-Cladding Thermal Conductance**
  - Gas Conduction - f(gap, gas constituents, temperature, surface roughness); decreases with burnup due to f.g release
  - Contact Conduction - f(contact pressure, material strength, conductivity, roughness)
  - Radiation - f(surface temperature, emissivity)

Integral Fuel Rod Phenomena (cont.)

- **Fuel-cladding radial interaction**
  - Initially, no significant radial contact between pellet and cladding; cladding stress state determined simply from fuel rod internal-external pressure difference
  - With increased pellet and cladding expansion, pellet-cladding radial contact occurs, but cracked pellet structure is highly compliant and cladding stress is low
  - With further increased pellet and cladding expansion, pellet strains are redirected to close pellet cracks and the pellet becomes stiffer, resulting in greater cladding stress
  - Elevated cladding stress due to pellet-cladding contact is a **primary failure mechanism**
- **Fuel-Cladding axial interaction**
  - Stochastic stacking of fuel pellets within cladding tube results in axial friction buildup along length of fuel rod
  - Function of fuel rod geometry, fuel and cladding axial expansion
  - Fuel column axial expansion stretches cladding axially, resulting in Poisson contraction- induced displacement of cladding inward toward the fuel pellet and **closure of the pellet-cladding gap**

Fuel Performance Steady State Operation



Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

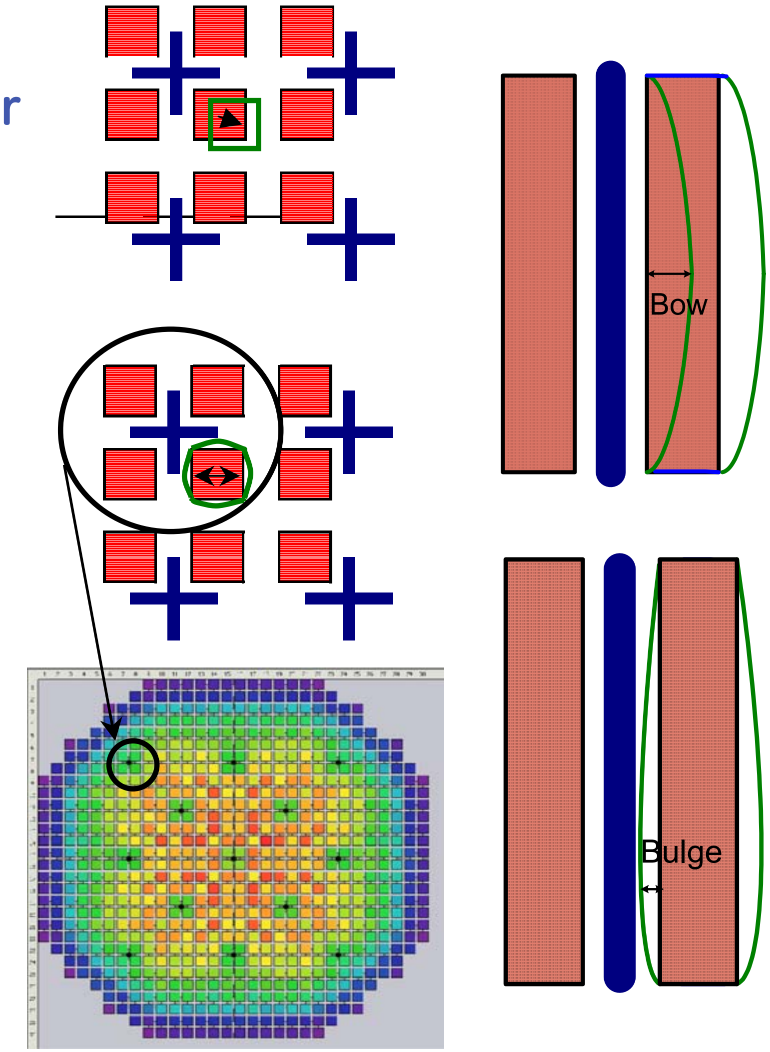
Channel Deformation

Fuel channels in boiling water reactor (BWR) deform as bow & bulge

- Fast fluence gradient-induced bow
- Control blade – channel shadow corrosion-induced bow
- Bulge
  - fluence & pressure differential creep component
  - pressure elastic component

Deformed channels lead to control blade interference

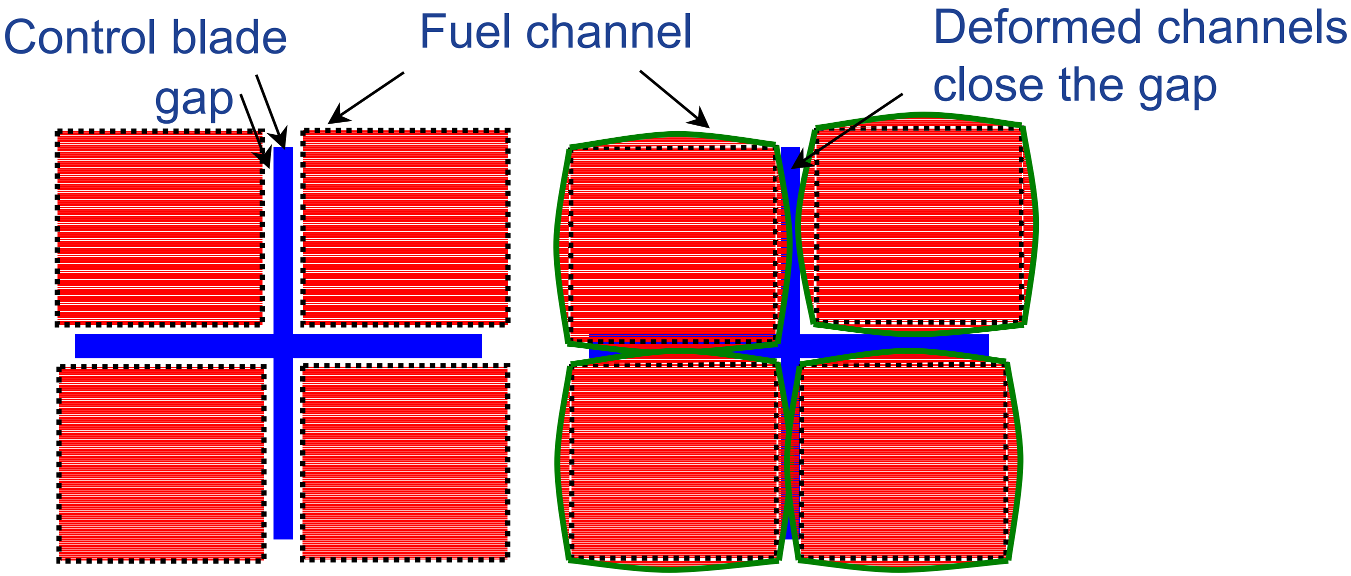
Analogous to control rod guide tube deformation in PWRs



Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Interference Considerations

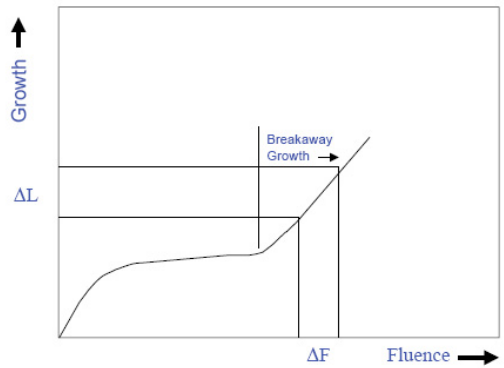


- Safety & licensing… scram time, reactor & blade structural analyses
- Operational impacts
  - Periodic monitoring & surveillance plans
  - No-settle & inoperable cells
- Outage impact for re-channeling

Channel Distortion Mechanisms

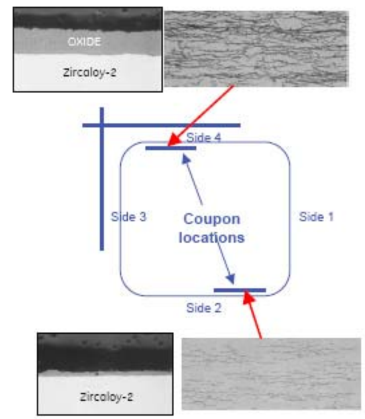
Fuel Surveillance

Fluence Gradient Bow

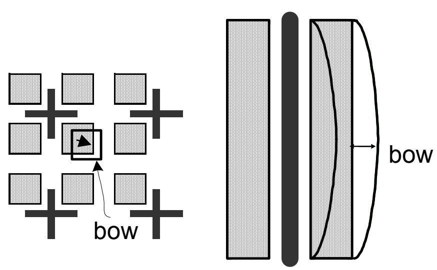


$$\Delta L \propto \Delta F$$

Shadow Bow

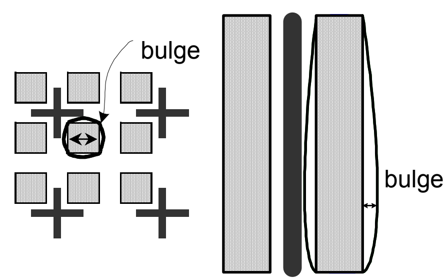


$$\Delta L \propto \Delta H$$



Top view Front view

$$Bow \propto \Delta L$$



Top view Front view

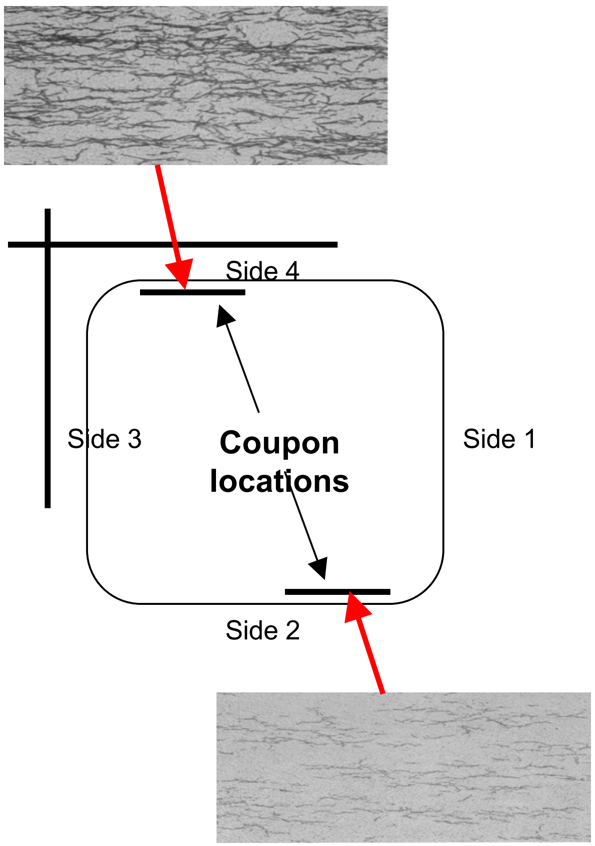
$$Bulge \propto \Delta P$$

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Shadow Corrosion-Induced Channel Bow

Fuel Surveillance



- Initiated by shadow corrosion of channel faces adjacent to the control blade
- Differential corrosion results in differential hydrogen absorption and channel bow

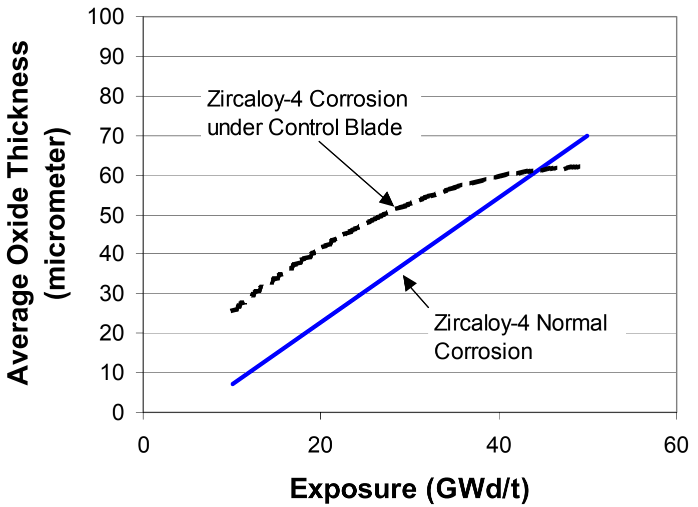
GNF
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: Mahmood, Lin, and Dubecky, Proceedings of the 2007 International LWR Fuel Performance Meeting San Francisco, Paper 1061, California, September 30 – October 3, 2007.

The Advantage of Zircaloy-4

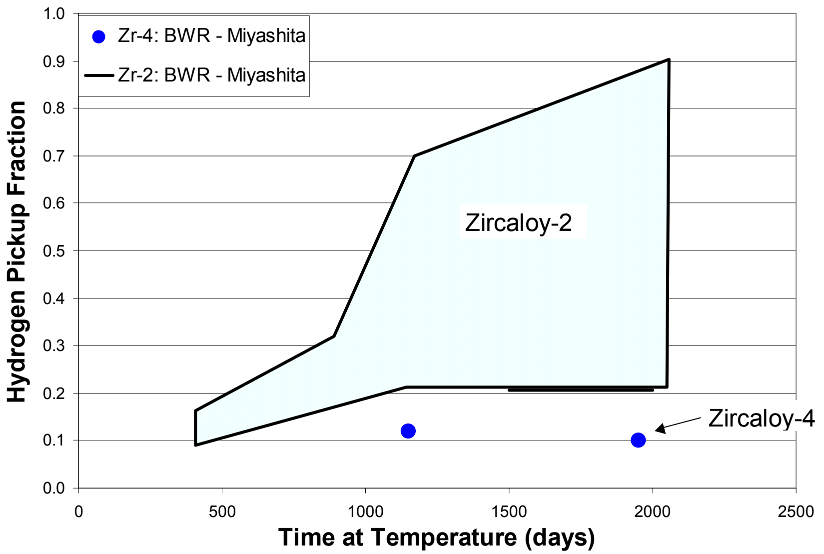
$$Bow \propto \Delta H = H_p \Delta t_T$$

Δt_T = Blade Side – Non Blade Side



Δt_T appears to diminish with exposure

K. Fukuya et al., Proceedings International Topical Meeting on Light Water Reactor Fuel Performance, West Palm Beach, FL, April 17-21, 1994, ANS (2004).



Zr-4 H_p is ~10%

Zr-2 H_p ↑ with irradiation time

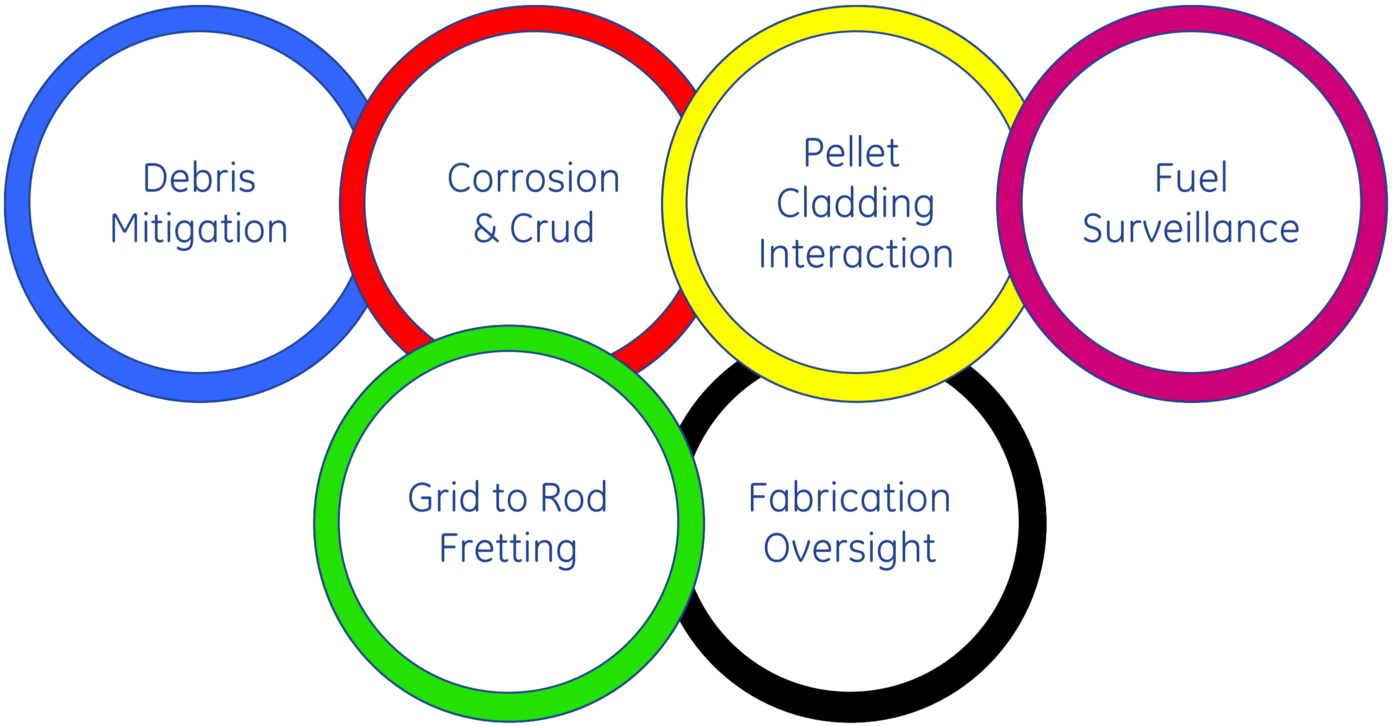
T. Miyashita et al., Proceedings of the 2007 International LWR Fuel Performance Meeting, San Francisco, CA, Sept. 30-Oct. 3, 2007, ANS (2007).

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Addressing Institute of Nuclear Power Operations "Zero Leakers by 2010" Initiative

Institute for Nuclear Power Operations. "Guidelines for Achieving Excellence in Nuclear Fuel Performance," INPO Report No. INPO 07-004, Rev. 1, March 2009.



What Kind of Debris?

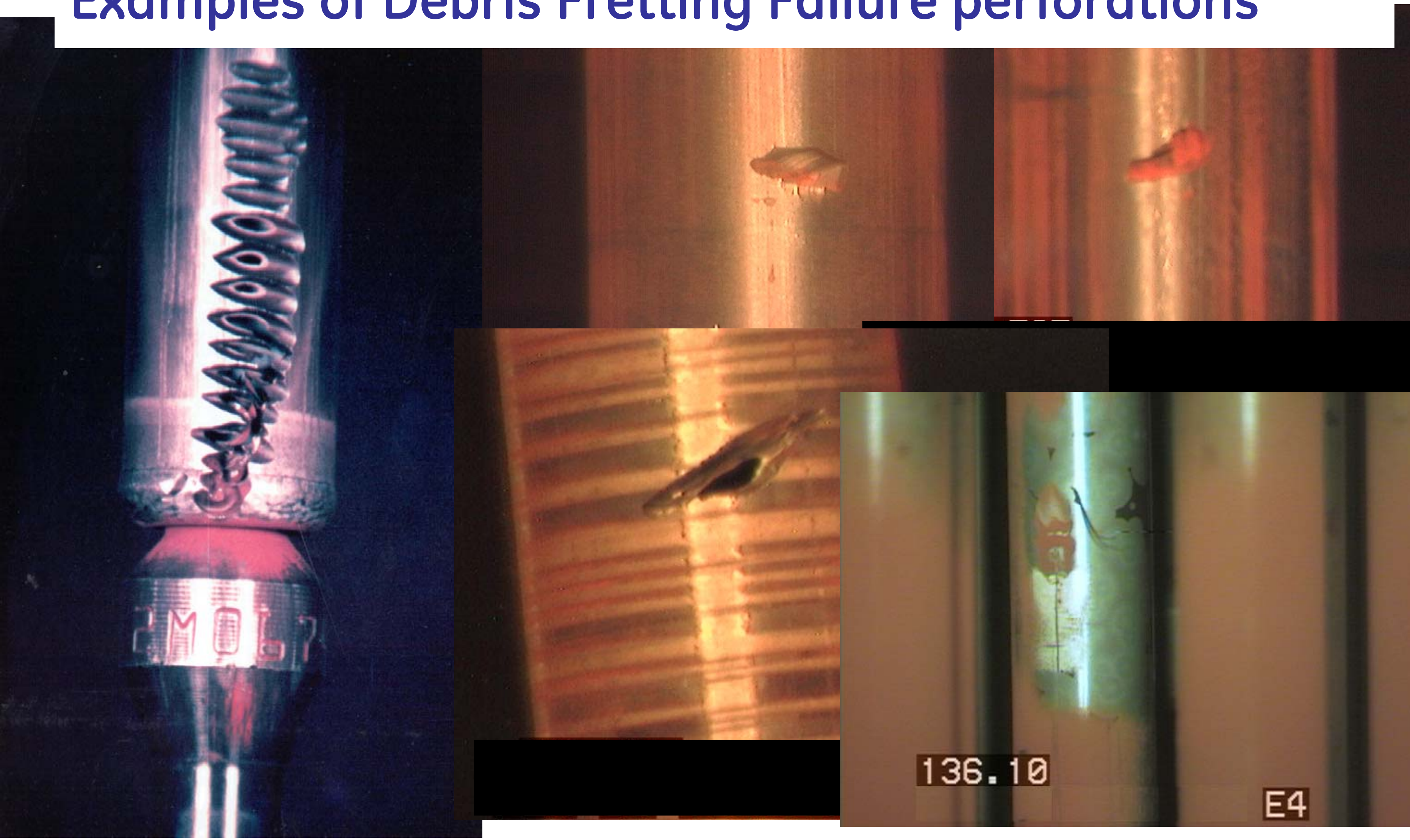
Debris Mitigation

Large and small items found in a feedwater heater - in a plant/cycle where one debris fretting fuel failure occurred

In condensate filter demineralizer

GNF Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Examples of Debris Fretting Failure perforations

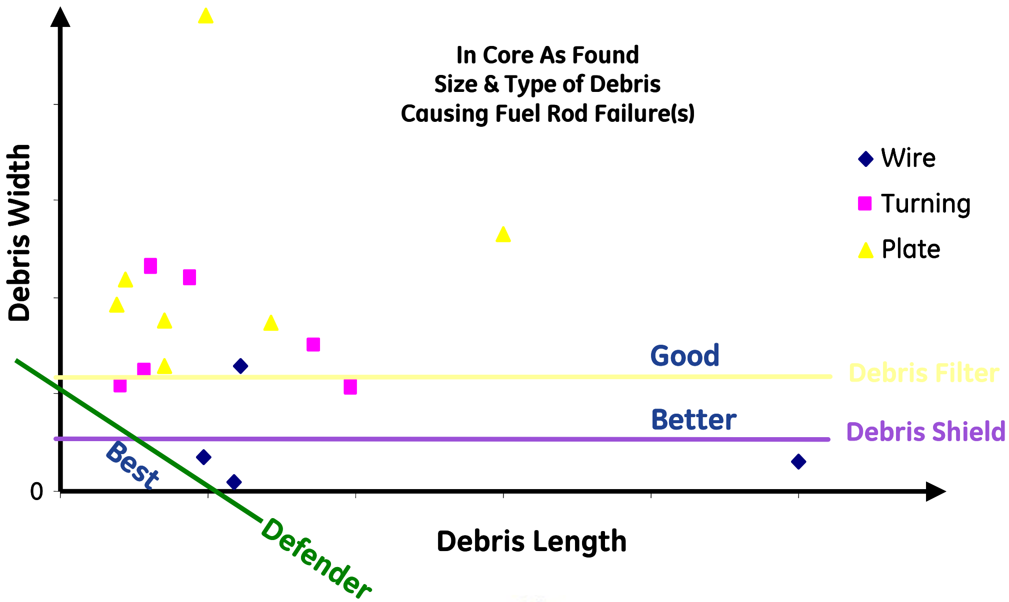


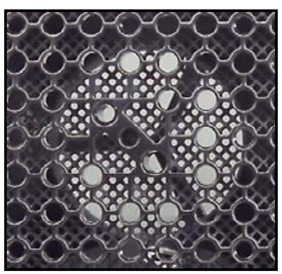
Global Nuclear Fuel

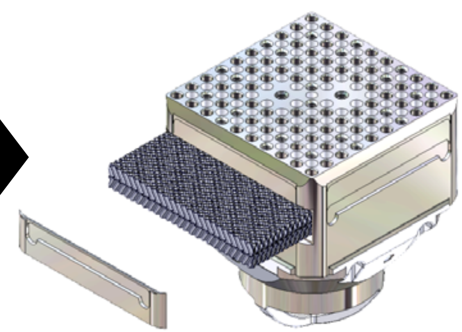
A Joint Venture of GE, Toshiba, & Hitachi

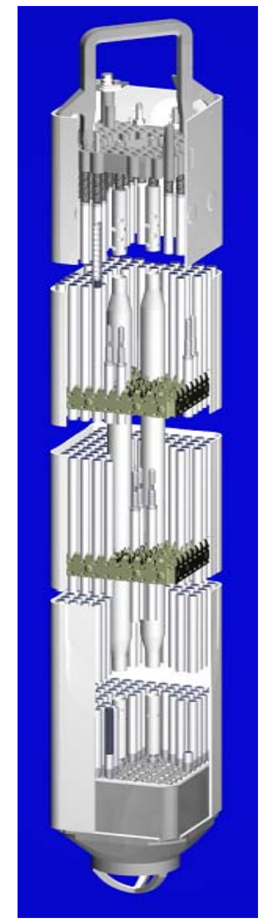
Debris Filter Technology

Debris
Mitigation



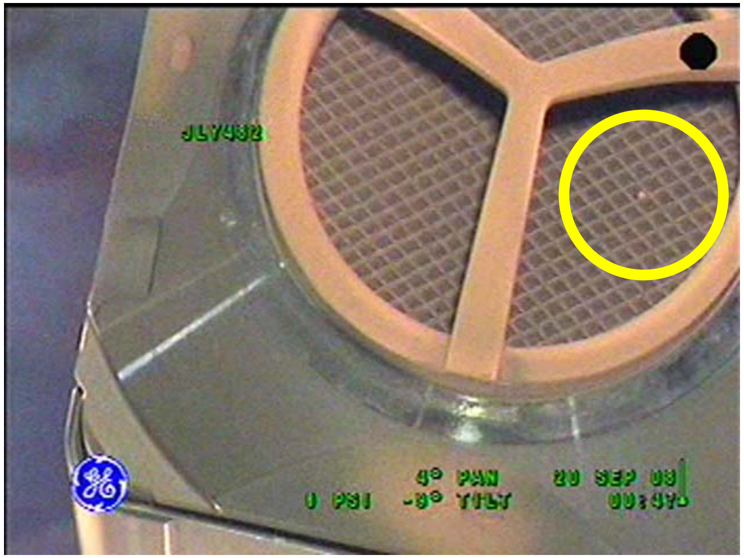


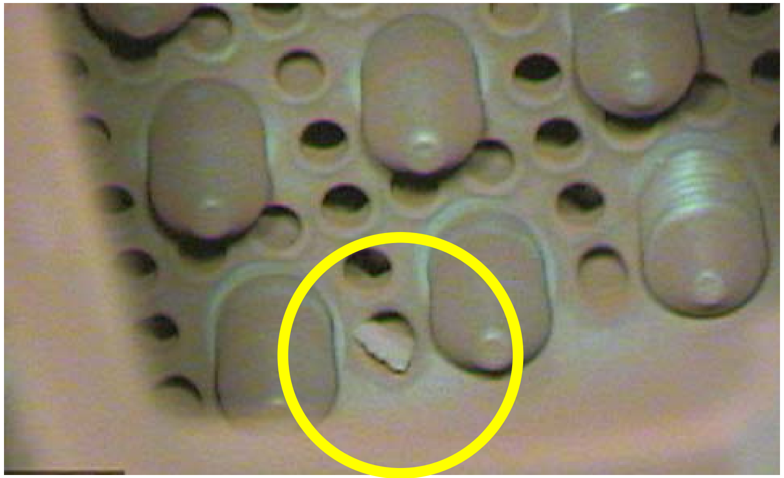


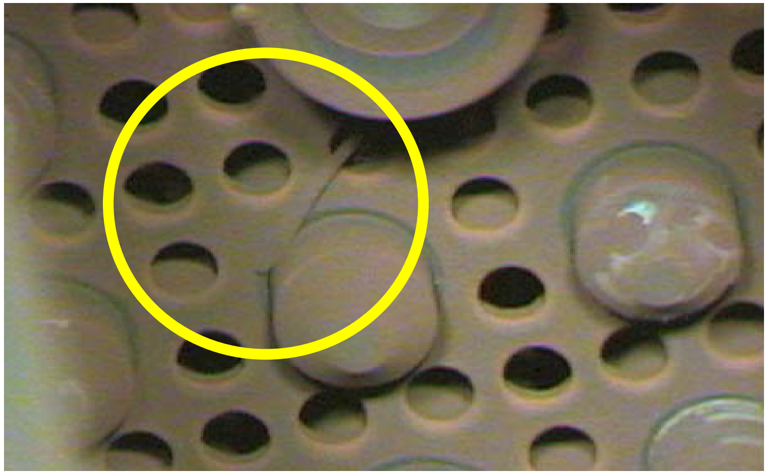


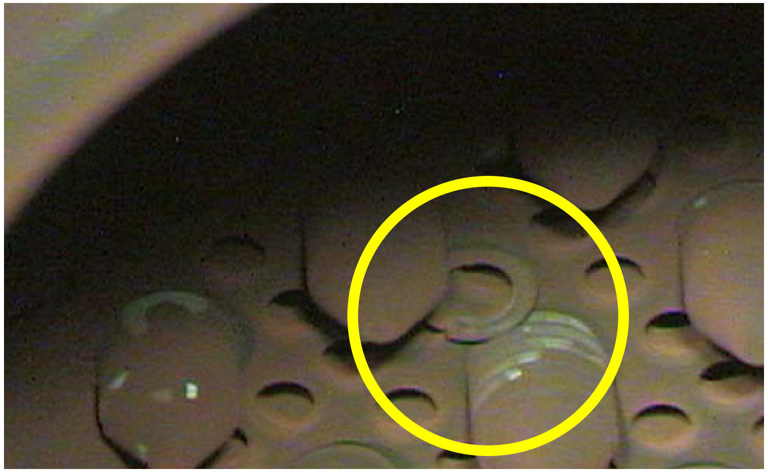
Keep it out of the assembly with a filter on the lower nozzle (lower tie plate)

Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi







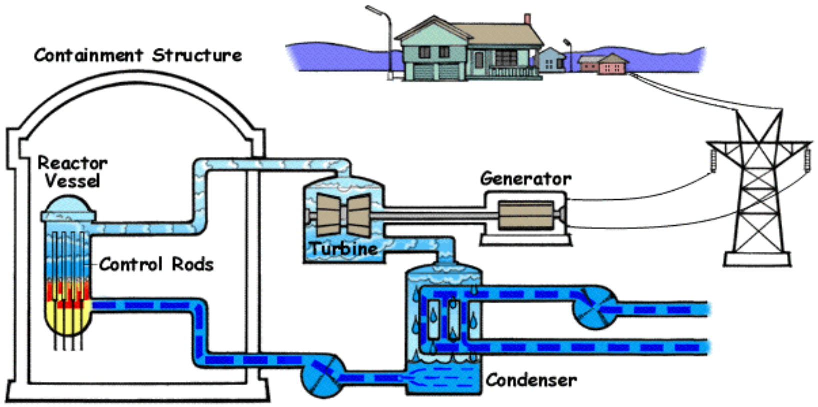


Global Nuclear Fuel

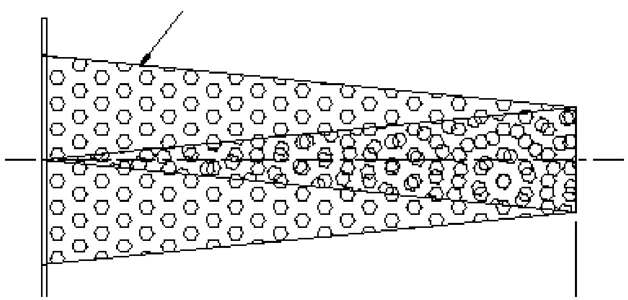
A Joint Venture of GE, Toshiba, & Hitachi

Keep Debris Out of the Reactor Vessel

Debris Mitigation



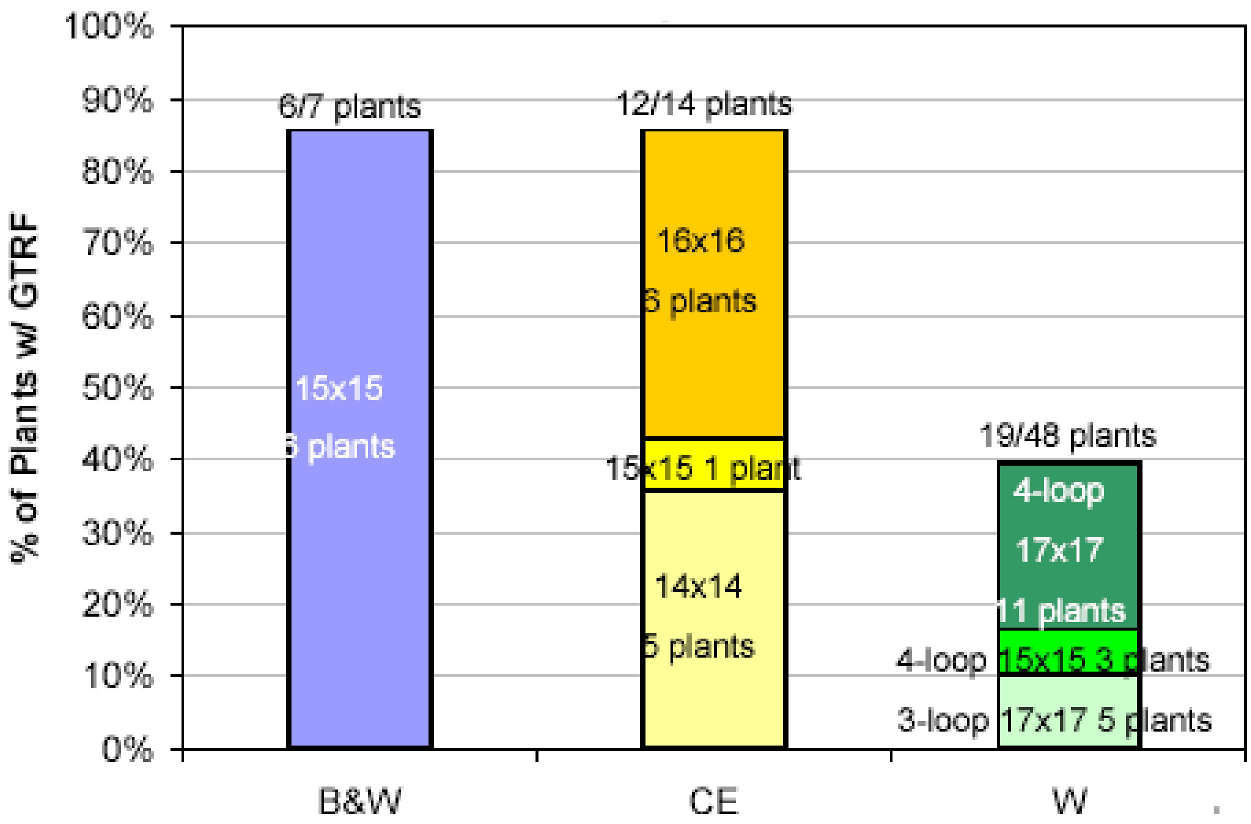
Inline strainers



House keeping is critical

Total GTRF by plant type 2000-2007

Grid to Rod Fretting



Reference: EPRI Fuel Reliability Executive Committee Meeting Dallas, USA, January 23, 2008, J. Deshon, A. Kucuk - EPRI Fuel Reliability Program

GNF Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

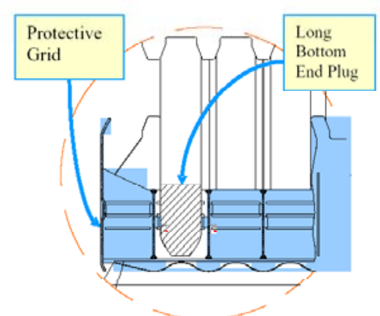
Mechanisms for PWR GTRF (1 of 3)

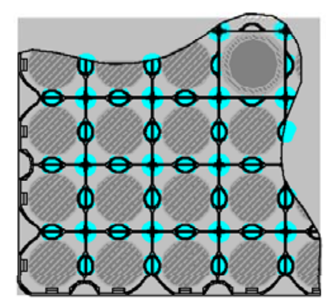
Grid to Rod Fretting

- In all cases, rods rub against spacer grids
  - Fretting wear over time breached cladding
- Baffle Jetting: failures in core periphery
  - Baffle cooling ➔ flow jets emerging from between baffle plates
  - Causes flow-induced instability of rod vibration ➔ high-amplitude oscillations
  - Addressed by changing baffle cooling configuration
- Core-inlet Crossflow: failures in core center, lower 2 spans
  - Higher coolant flow at periphery of inlet ➔ crossflows toward center to balance out
  - W placed grid in bottom of assembly to dissipate flow jets and stabilize bottom of fuel rods

Reference: R. Buechel, Z. Karoutas and R. Lu, “Grid To Rod Fretting Performance of Westinghouse Fuel,” Proceedings of the 2008 Water Reactor Fuel Performance Meeting, Seoul, Korea, Paper 8080, October 19– October 22, 2008.

David Chapin, William Rabenstein, Miguel Aulló, Alberto Cerracín, and Göran Boman “EFG Fuel Designs And Experience in EDF Reactors,” Proceedings of the 2006 International LWR Fuel Performance Meeting Salamanca, Spain, Oct 23- Oct 25, 2006.

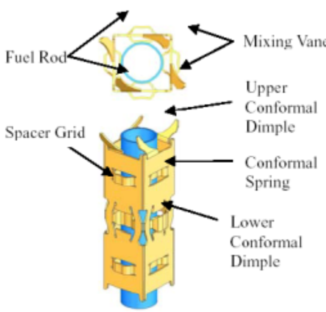




Mechanisms for PWR GTRF (2 of 3)

Grid to Rod Fretting

- **Fuel Assembly Vibration: failures in various core locations & grids**
  - Mixing vane grids induced periodic lateral forces that amplified assembly's natural vibrations
  - Lateral forces unbalanced in direction
  - Addressed by designing mixing vanes for balanced flow pattern
- **Fuel rod vibration: failures in core periphery near baffle**
  - Higher-exposure fuel; low-amplitude rubbing of fuel rods against grid supports
  - Normal, turbulence-induced vibration of fuel rod
  - Addressed by increased spring & support contact area w/ balanced vane pattern
- **Inlet and Outlet Flows in certain CE Plants: failures in core periphery near baffle**
  - Flow holes in lower core support plate and tie tubes extending between upper support plate and hold-down plate create regions of maximum turbulence and cross flow at lower and upper end of assembly
  - Addressed by grid spacer design

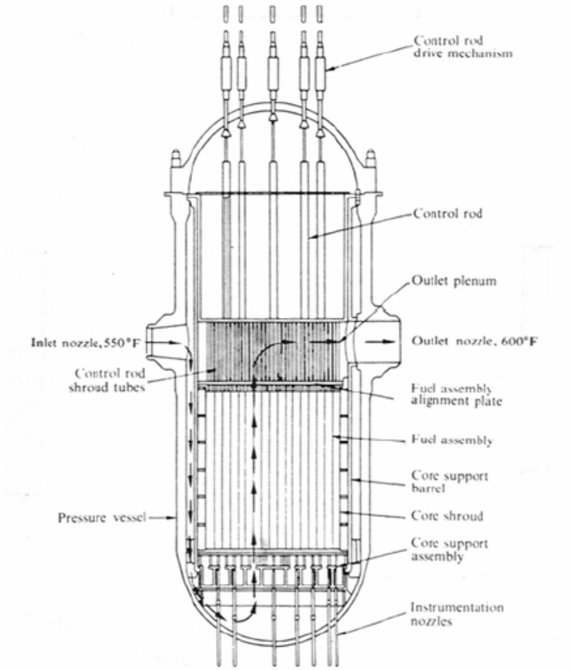


Reference: R. Buechel, Z. Karoutas and R. Lu, "Grid To Rod Fretting Performance of Westinghouse Fuel," Proceedings of the 2008 Water Reactor Fuel Performance Meeting, Seoul, Korea, Paper 8080 October 19– October 22, 2008.

Yong Hwan Kim, Kyong Lak Jeon, and Kyu Tae Kim, "Advanced Nuclear Fuel Development an Fuel Rod Fretting Wear Evaluation," Proceedings of the 2005 International LWR Fuel Performance Meeting Kyoto, Japan, October 2– October 6, 2005.

PWR Flow Leading to GTRF

Grid to Rod Fretting



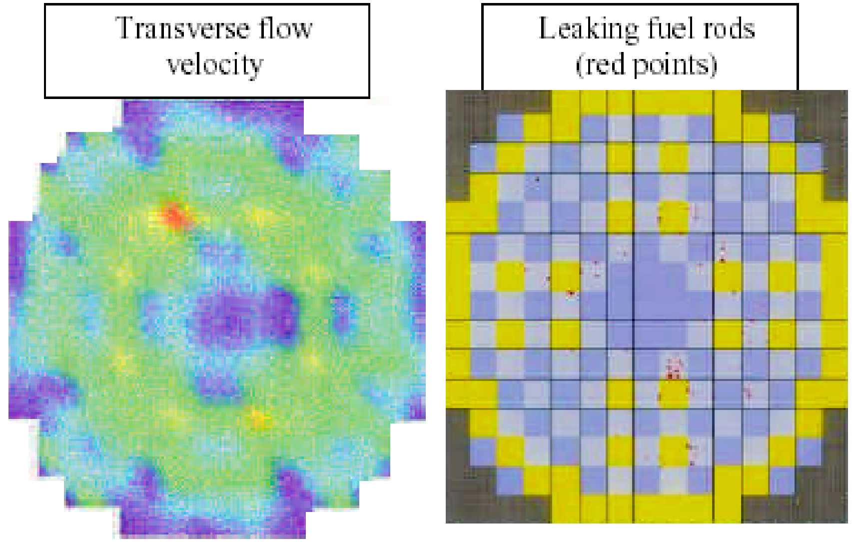
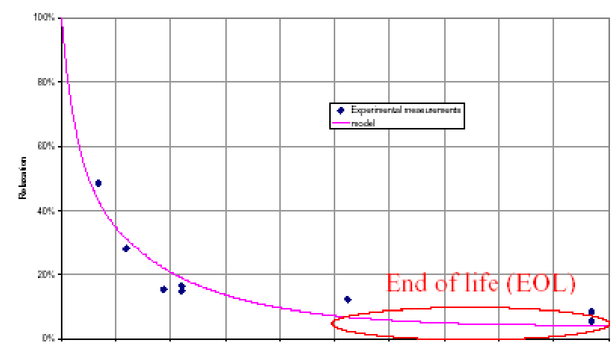


Figure 5 : comparison between cross flow computation and leaking rods due to grid to rod fretting, on EDF 1300 MWe core

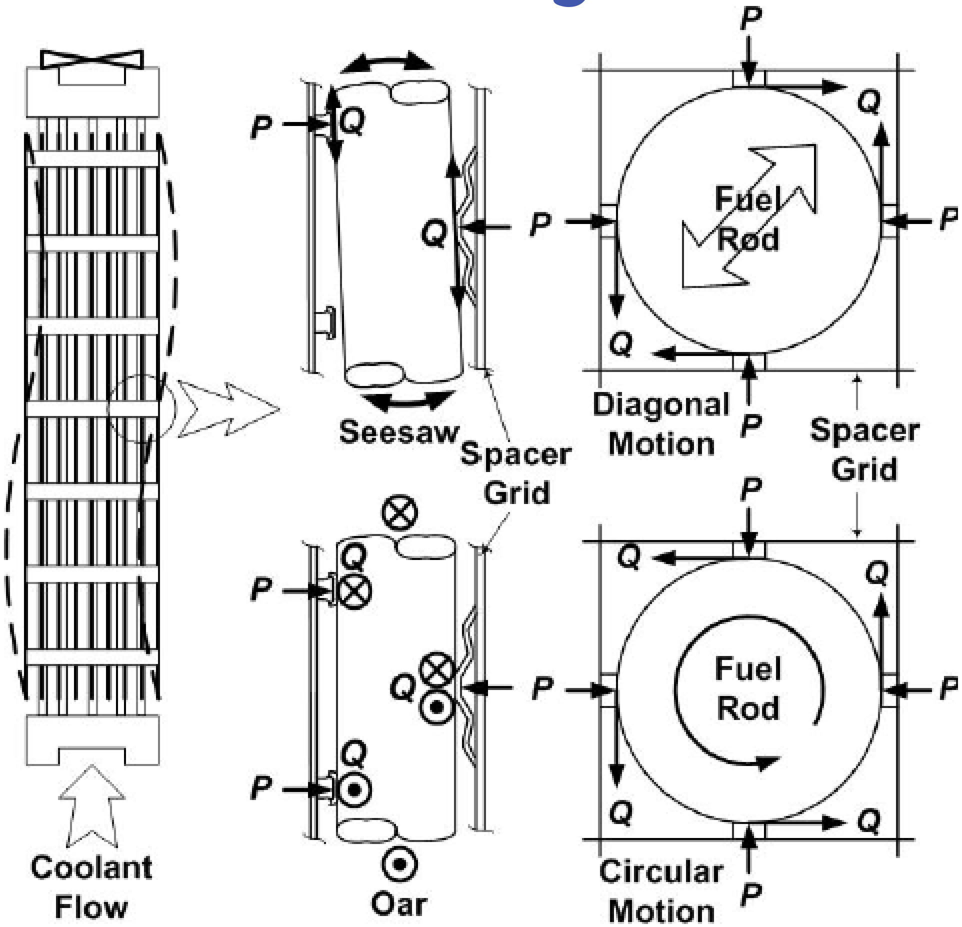


Reference: Nicolas Baillon and Nicolas Waeckel, "Grid To Rod Fretting Wear In EDF PWR From Operating Problems To New Designs Qualification Method," Proceedings of the 2005 International LWR Fuel Performance Meeting Kyoto, Japan, October 2– October 6, 2005.

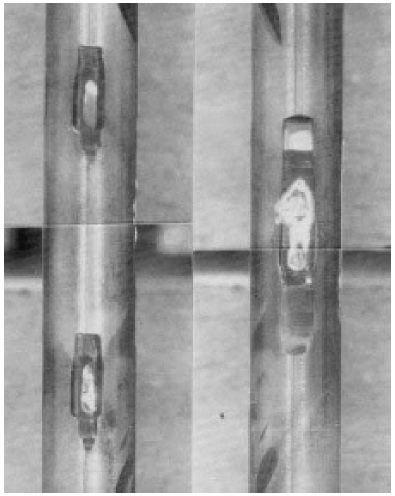
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Motions Causing GTRF in a PWR

Grid to Rod Fretting



The motions which can cause grid to rod fretting in a PWR



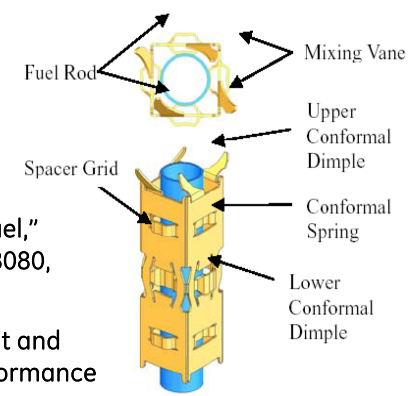
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: Hyung-Kyu Kim and Young-Ho Lee, "Experimental Study on the Influence of the Supporting Condition and Rod Motion on the Fuel Fretting Damage," Proceedings of the 2007 International LWR Fuel Performance Meeting, Paper 1023, San Francisco, California, September 30 – October 3, 2007.

Factors that Affect PWR GTRF

Grid to Rod Fretting

- Grid spring force
  - Too high means more wearing force at cladding surface contact
  - Too low allows relaxation of spring and loss of motion restraint
- Grid-to-rod gap size; increased by:
  - Irradiation growth (Zr spacer grids) and creep-induced relaxation
  - Cladding creep-down reduces cladding OD
- Peripheral locations exacerbate phenomena
  - Lower fuel rod dilation due to lower power in peripheral locations
  - Less fuel rod axial growth and elongation to distribute wear over greater surface area
- Initial grid-to-rod contact area
  - Larger contact area means force distributed over su



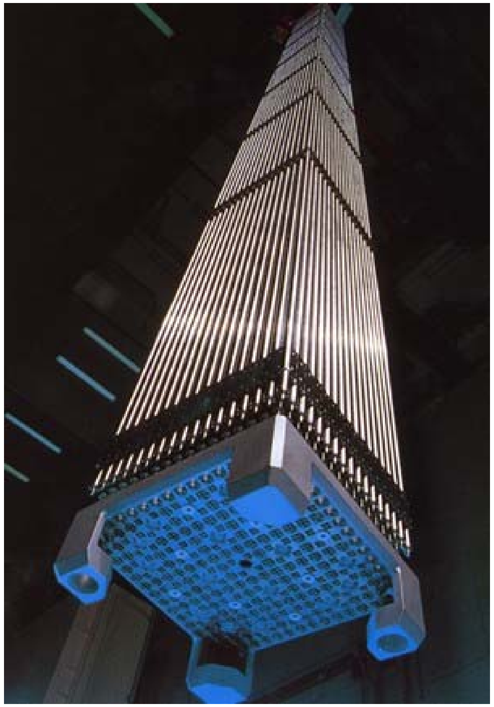
Reference: R. Buechel, Z. Karoutas and R. Lu, "Grid To Rod Fretting Performance of Westinghouse Fuel," Proceedings of the 2008 Water Reactor Fuel Performance Meeting, Seoul, Korea, Paper 8080, October 19– October 22, 2008.

Yong Hwan Kim, Kyong Lak Jeon, and Kyu Tae Kim, "Advanced Nuclear Fuel Development and Fuel Rod Fretting Wear Evaluation," Proceedings of the 2005 International LWR Fuel Performance Meeting Kyoto, Japan, October 2– October 6, 2005.

Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Grid-to-Rod Fretting (GTRF) is not a Problem for BWRs

Grid to Rod Fretting



A PWR bundle does not have a channel

A BWR has a channel

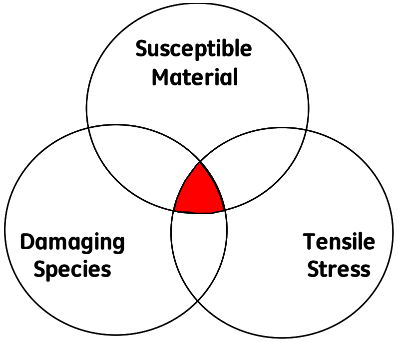
- BWRs have channels
- Different in-core flow characteristics
- Different spacer designs

Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Pellet Cladding Interaction

Pellet Cladding Interaction

- **PCI (pellet-clad interaction) is a SCC (stress corrosion cracking) mechanism**
  - Pellet expands, cracks, and stresses cladding
  - Opened crack releases aggressive fissions products that attack cladding ID
  - Failure occurs with right combination of rod power, power change, and "incubation" time prior to change
- **Not random**
  - correlated with plant power maneuvers (blade pulls)
  - correlation with core location (in, or occasionally near, blades that were pulled)– symmetry for multiple failures
  - Can be mitigated in part by careful power changes and control rod maneuvers



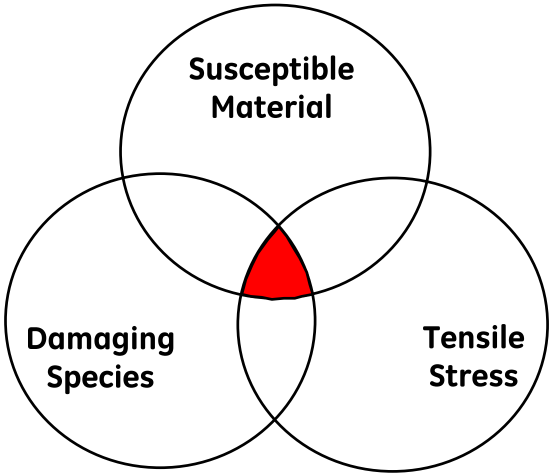
GNF Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

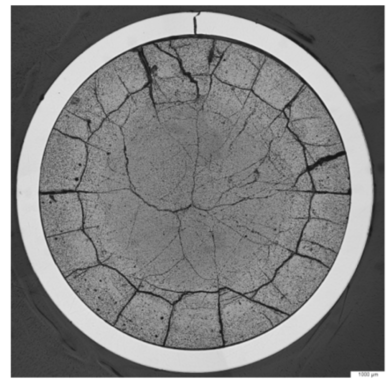
References: P. B. Hoffmann, and P. Dewes, Proceedings of the 2004 International Meeting on LWR Fuel Performance, Paper 1059, Orlando, Florida, September 19-22, 2004.

Dewes-Erlangen, et al. Proceedings of the 2005 Water Reactor Fuel Performance Meeting, Paper No. 1141, Kyoto, Japan, Oct. 2-6, 2005.

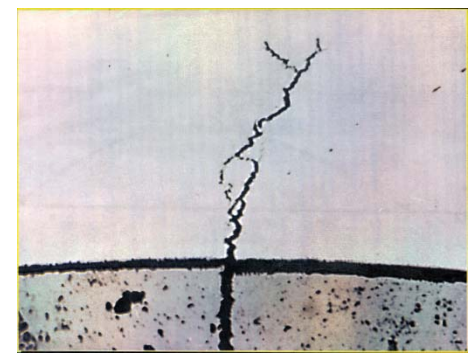
PCI Type 1 & Mitigation

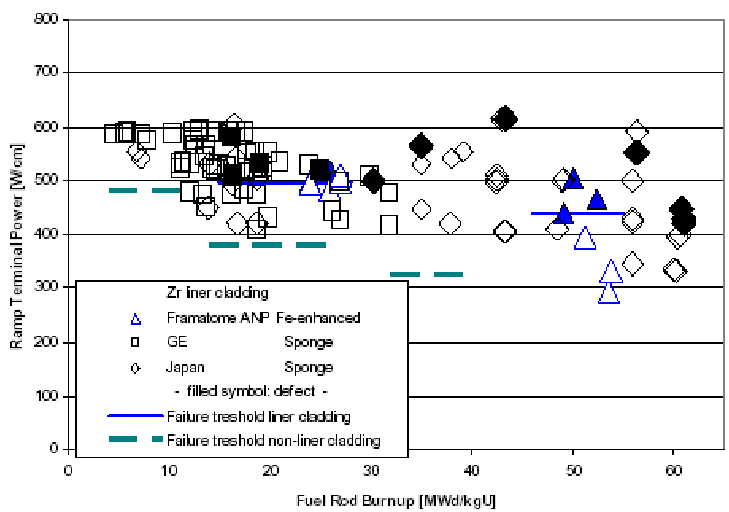
Pellet Cladding Interaction





Type 1 – classic PCI





Barrier liner is the current solution for classic PCI.

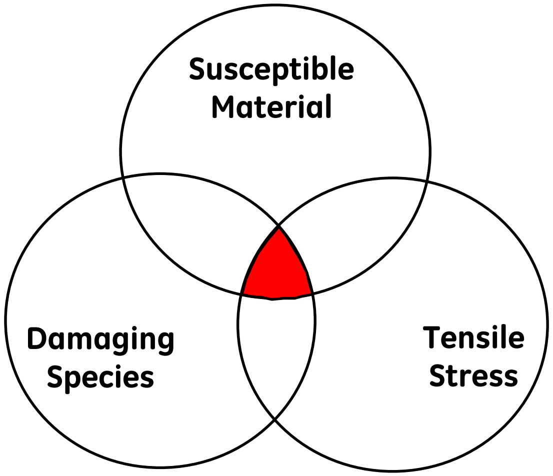
Global Nuclear Fuel

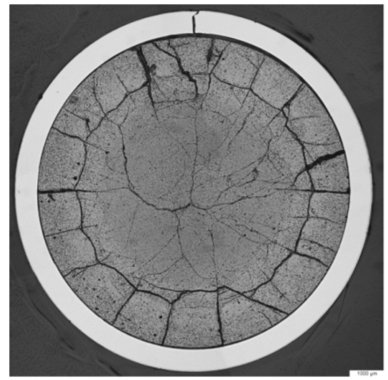
A Joint Venture of GE, Toshiba, & Hitachi

Reference: P. B. Hoffmann, and P. Dewes, Proceedings of the 2004 International Meeting on LWR Fuel Performance, Paper 1059, Orlando, Florida, September 19-22, 2004.

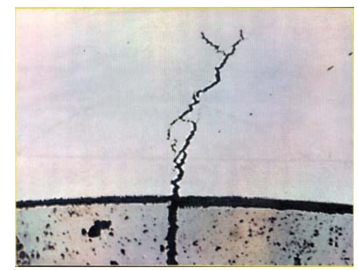
PCI Type 1 & Mitigation (cont)

Pellet
Cladding
Interaction

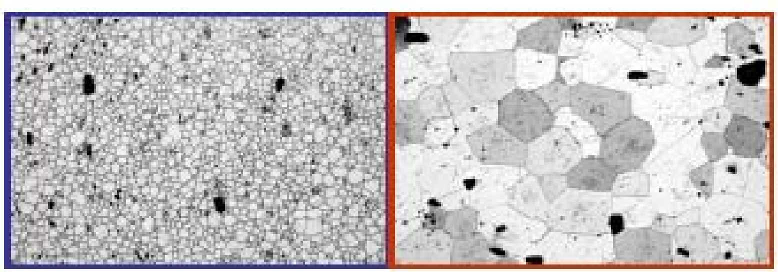




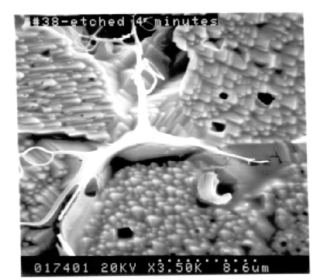
Type 1 – classic PCI

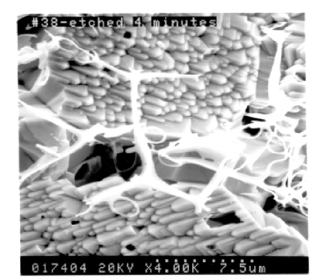


Chromia doped pellets



Alumina silica doped pellets



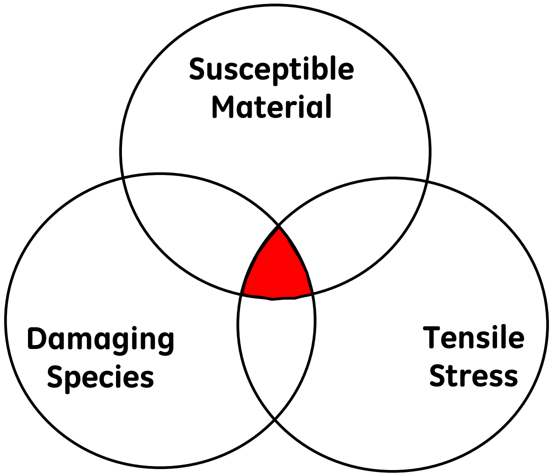


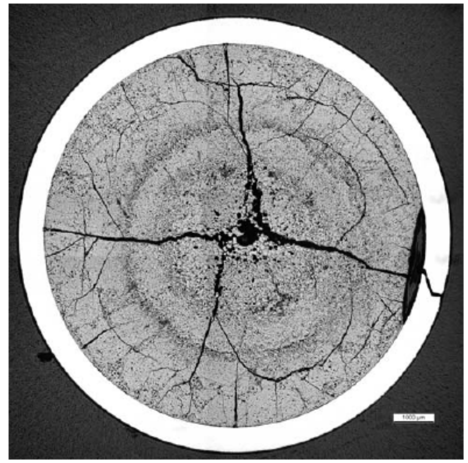
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: Dewes, et al., Proceedings of the 2007 International LWR Fuel Performance Meeting San Francisco, Paper 1071, California, September 30 – October 3, 2007.

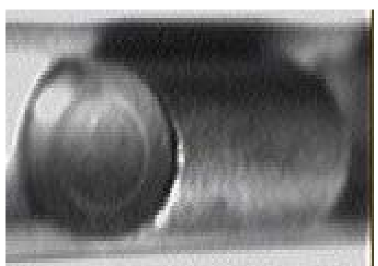
PCI Type 2 & Mitigation

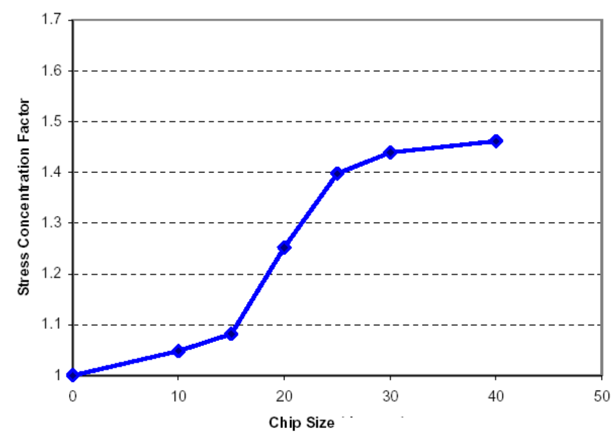
Pellet Cladding Interaction





Type 2 – missing pellet surface





Assuring the perfect pellet

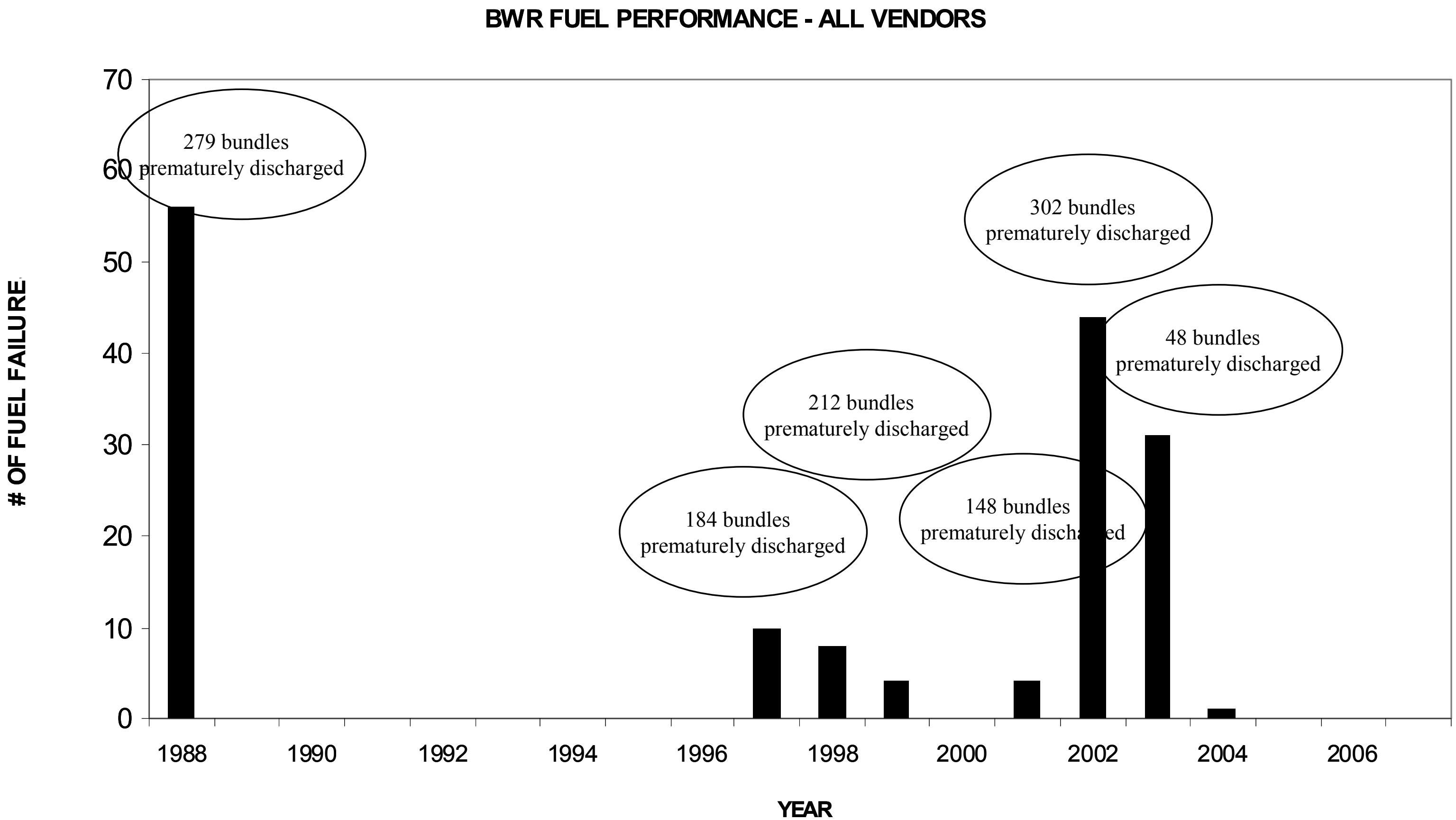
Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Reference: P. B. Hoffmann, and P. Dewes, Proceedings of the 2004 International Meeting on LWR Fuel Performance, Paper 1059, Orlando, Florida, September 19-22, 2004.

BWR Corrosion Events

Corrosion & Crud



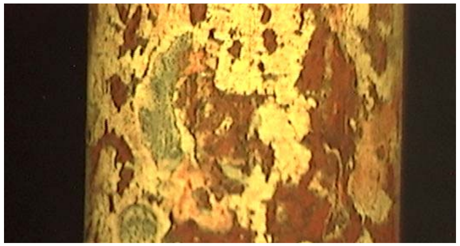
- Each corrosion event typically $50M+
- Cannot assume mechanism has been eliminated

GNF Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

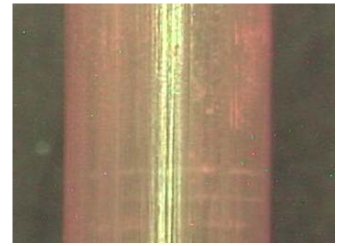
Reference: Proceedings of the 2008 International LWR Fuel Performance Meeting, Seoul, Korea, Octoberr 19–October 23, 2008, John Schardt

Accelerated corrosion failure characteristics

Affected Fuel



Same fuel in another similar plant



Corrosion & Crud

- 5 of 6 involved plants with copper condensers
  - 4 of 6 with filter demineralizer condensate treatment
- 5 of 6 involved fuel in 1st cycle of operation
  - Most vulnerable to chemical/crud upsets
- All involved fuel that operated successfully in other plants
- All involved water chemistry within industry experience base
  - Per standard monitoring practices

Is it the water chemistry….YES (it has to be atypical)

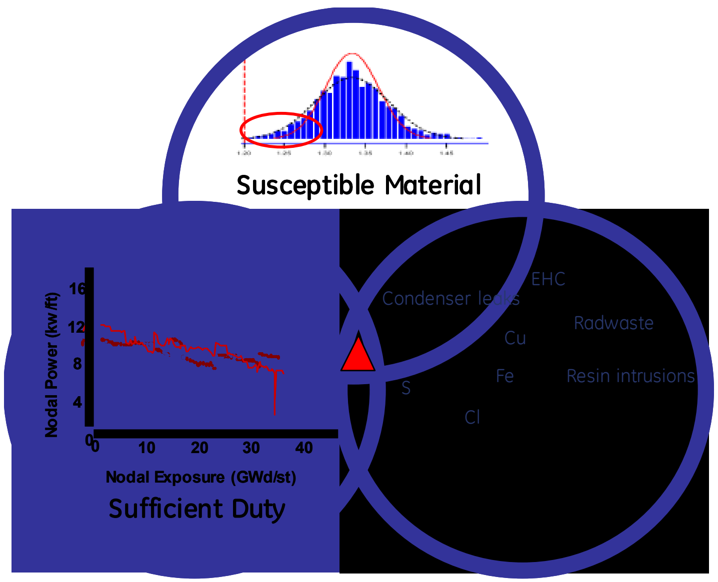
Is it the fuel….YES (it wasn't robust enough)

GNF
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: Proceedings of the 2008 International LWR Fuel Performance Meeting, Seoul, Korea, Octoberr 19–October 23, 2008, John Schardt

Road to Eliminating Accelerated Corrosion ….robust fuel cladding

Corrosion & Crud



- **Fuel vendors need to continue**
  - Increased fuel characterization
  - Cladding development
  - Complete ex-reactor test to gather data on potential root causes.
- **Real time water chemistry monitoring on today's fleet to understand impacts of transient.**
- **A sense of urgency around fuel inspections when plant chemistry transients are experienced.**
- **Real time monitoring incorporated on all new plants.**

Manufacturing Defect (weld contamination)

Fabrication Oversight

Early life - typically fresh fuel

Steady-state operation

Modest offgas release

Difficult to distinguish vs. fretting (in operation)

Changes Lead to Surprises

Fuel Surveillance

Performance	Vehicle	Fuel Impact
Capacity Factor ***Power Density*** ***Fuel Efficiency*** ***Cycle Length*** *Life Extension* *Reactor Protection*	**Large batch sizes (→ 50%)** **High exposures**	**Extensive control of 1st cycle fuel** **Appears to lead to shadow corrosion-induced bowing**

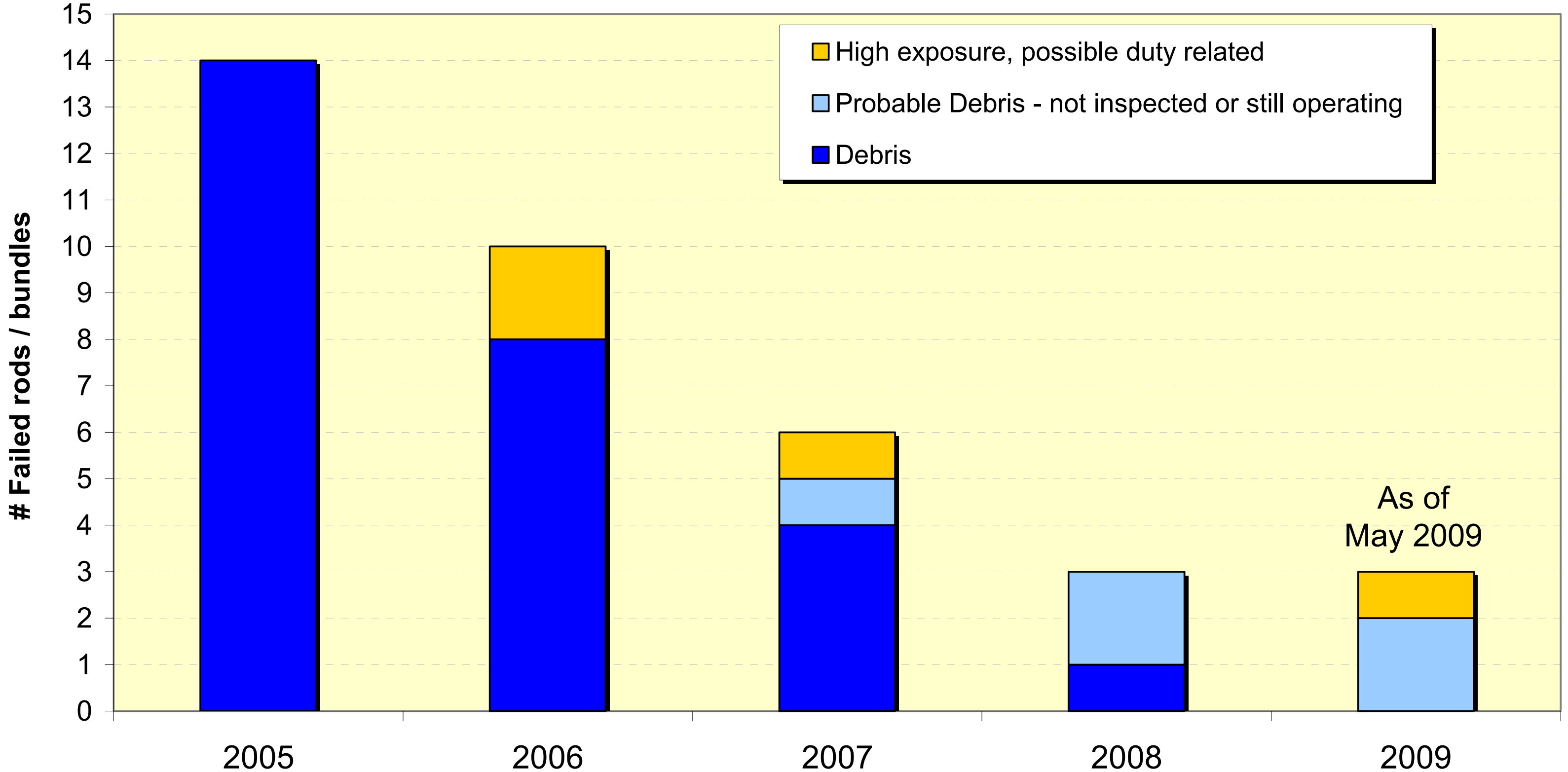
GNF Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Reference: KTG Fachtagung Karlsruhe March 30-31, 2004 Recent GNF Fuel Performance Experience , Schardt, Potts, and Stachowski

Summary

- LWR fuel technology and the LWR fuel industry are mature
  - Plant utilization and fuel utilization have increased over the past 20 years
  - Fuel reliability is increasingly important to LWR operators
- Fuel Reliability has increased tremendously over 40 yrs
- Leading causes of fuel rod failures (breaches) are grid-to-rod fretting for PWRs debris fretting
  - PWRs: grid-to-rod fretting, followed by debris fretting and fabrication defects
  - BWRs: debris fretting, followed by PCI (duty-related failures)
  - Corrosion and crid-induced failures in PWRs and BWRs now appear to be under control, although reasons for excursions not fully known
- Channel deformation in BWRs (irradiation growth and shadow corrosion) and guide tube deformation in PWRs (irradiation growth?) present challenges

Recent GNF Reliability Performance – Getting Closer



6.92	4.96	2.87	1.48	1.48

Failure Rate in ppm (# failed rods / # million rods in operation each year)

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Acknowledgements

- EPRI presentation materials
- Andy Lingenfelter
- Nayem Jahingir
- Bob Rand
- Victor Smith
- Russell Stachowski
- Rob Schneider
- John Schardt
- Paul Cantonwine
- Others

Questions

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Doug Crawford

Address: 3901 Castle Hayne Road, Wilmington NC 28401-0780

Email: Douglas.Crawford@gnf.com

- Education
  - PhD Nuclear Engineering (1991, University of Michigan)
  - MBA (2005, University of Chicago)
  - MS Nuclear Engineering (1986, University of Washington)
  - BS Metallurgical Engineering (1984, University of Idaho)
- Experience
  - Global Nuclear Fuel, 2007 – present. Manager, Fuel Performance & Design
  - Idaho National Laboratory, 2005 – 2007. Department Manager, Nuclear Fuels & Materials. Department emphasis on fuels for gas-cooled reactors, fast reactors, research reactors, and LWRs
  - Argonne National Laboratory-West, 1990 – 2005. Positions held include Associate Division Director, Department Manager, Section Manager, & Nuclear Engineer. Technical emphasis on fast reactor fuels and materials, LWR fuels, and nuclear materials processing and management

Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi