LWR Materials for Commercial Nuclear Power Applications

Brian N. Burgos
Materials Measurement Services
Research Technology Unit
Westinghouse Electric Company

ATR National Scientific User Facility
June 9, 2010

Westinghouse

LWR Materials Perspective from a Nuclear Vendor….

We have a different perspective re: materials issues facing the nuclear industry

- 50% commercial nuclear industry laboratory evaluations
  - provide immediate support 24/7
  - costs utilities $1M - $1.5M/day until issue is resolved!
- 20% internally funded R&D
  - long term revolutionary technology development
- 20% industry sponsored R&D
  - short to mid-term evolutionary technology development
- 10% DOD materials laboratory evaluations

Westinghouse

Commercial Nuclear Power Background

- US was pioneer of nuclear power development
- Westinghouse designed the first fully commercial pressurised water reactor (PWR)
  - Shippingport Atomic Power Station, 1957 - 1982
- End of 1960s, orders placed for several dozen reactors of more than 1000 MWe capacity - major construction programs initiated
- Most built by regulated utilities (often state-based) - put final capital costs into their rate base and amortised it against power sales
  - Utility consumers bore risk & paid capital cost
- 1979: Three Mile Island
- Energy Policy Act of 1992: industry deregulation initiated
- 1998: changes accelerated including mergers and acquisitions affecting ownership and management of nuclear power plants

Shippingport Atomic Power Station

"World's first full-scale atomic electric power plant devoted exclusively to peacetime uses"

- On Ohio River ~ 25 miles from Pittsburgh
- ~ 60 MWe
- Designed for:
  - powering aircraft carriers
  - serving as prototype for commercial power generation

Westinghouse

Commercial Nuclear Industry – the Dark Years…

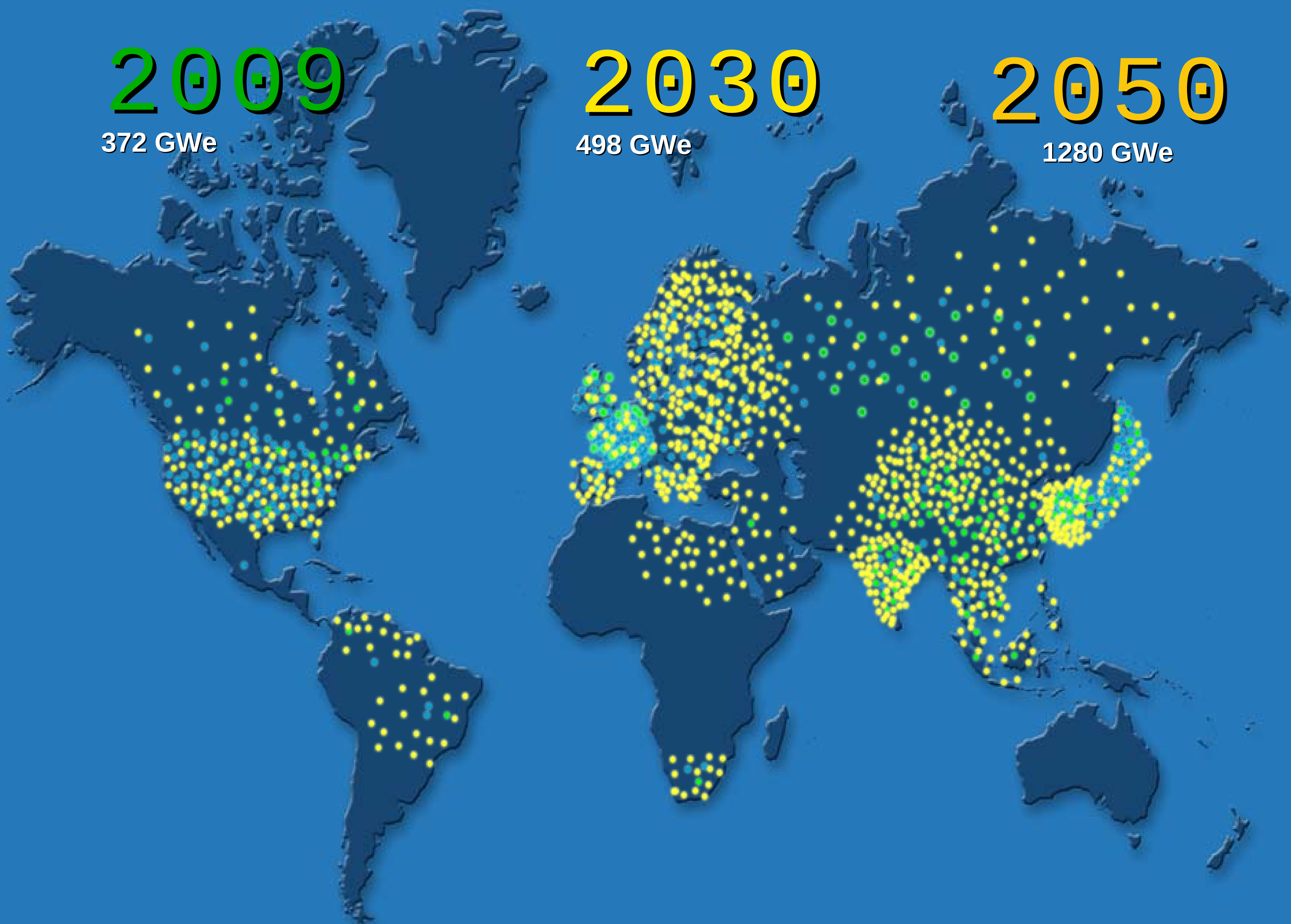
- Late 1970s to ~2002, nuclear power industry stagnant
- Many reactor orders cancelled
- Few new reactors ordered worldwide – none ordered in US
- Share of nuclear in world electricity remained fairly constant at 16-17%
- Advanced R&D, materials research stagnant or non-existent
- Numerous university nuclear engineering programs shut down
- Research and test reactor facilities world wide shut down
- Nuclear manufacturing capabilities shut down – essentially no US capability remains for large components

THE COLLAPSE OF NUCLEAR REACTOR ORDERS AFTER 1973 OIL CRISIS

The number of new nuclear plants ordered reached a high of 35 in 1972, and then collapsed to zero after the "oil crisis" of 1973. Three Mile Island accident occurred in 1979.

Source: Atomic Industrial Forum

Westinghouse



Does not represent actual plant locations.

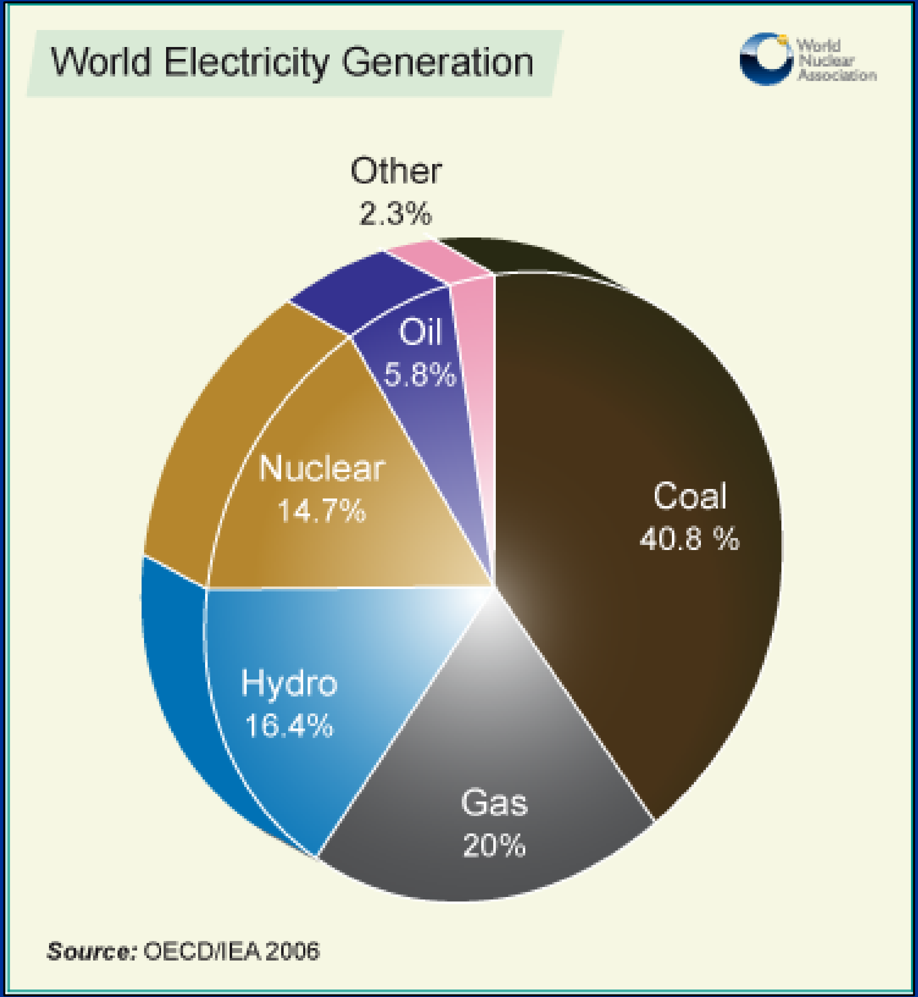
GWe = Giga Watts Electric

Politics of the Industry….

- 1993: Clinton's announced in his first State of the Union address that nuclear power research was "no longer needed" and that federal funding would be eliminated
- 1998: Department of Energy's Office of Nuclear Energy had <u>no</u> funding for research activities
- Unknowns:
  - Obama administration support for nuclear power?
  - impact of recent global financial crisis?
  - oil prices?
  - ~~global warming~~ climate change, green house gas emissions, carbon tax?
  - ability of alternative fuels to produce large amounts of base load power?
  - energy independence?

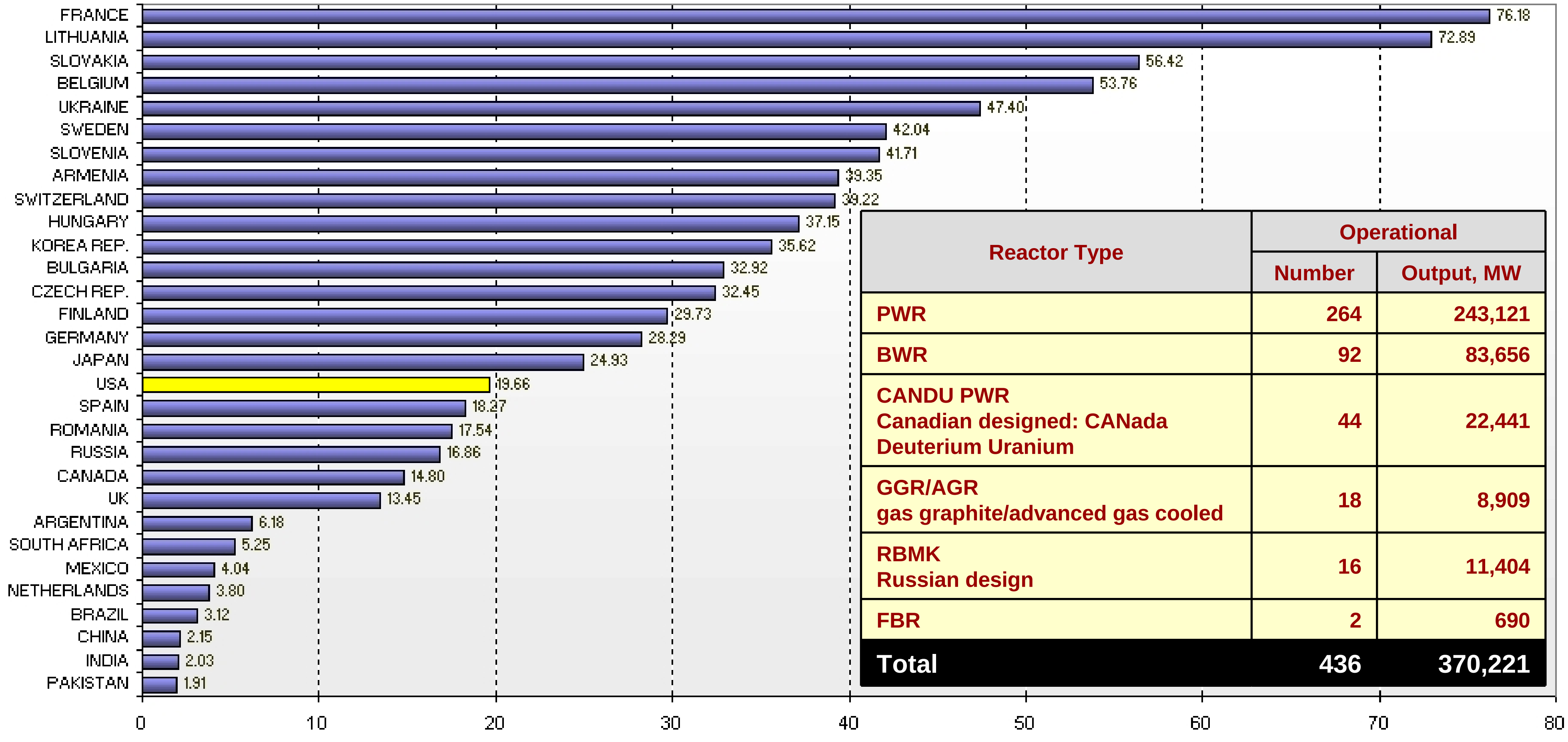
Current World and US Nuclear Power Plant Generating Capacity

- 436 commercial nuclear power reactors operating in 30 countries
  - total capacity = 370,000 MWe
- ~15% of the world's electricity and ~20% of US electricity as continuous base-load power
- 250 research reactors operating in 56 countries
- 220 nuclear powered ships and submarines
- 53 commercial nuclear power plants in 15 countries under construction
  - total capacity = 47,000 MWe



Westinghouse

Nuclear Share in Electricity Generation by Country, 2008



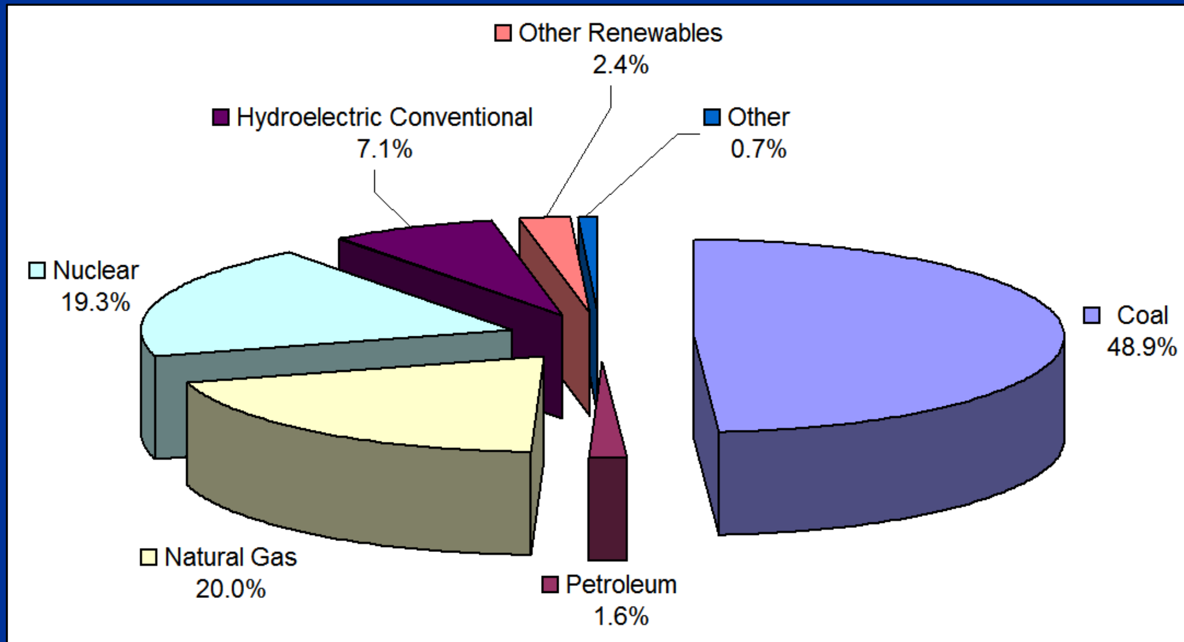
Note: The nuclear share in Taiwan, China was 19.6%

Reactor Type	Operational	
	Number	Output, MW
PWR	264	243,121
BWR	92	83,656
CANDU PWR Canadian designed: CANada Deuterium Uranium	44	22,441
GGR/AGR gas graphite/advanced gas cooled	18	8,909
RBMK Russian design	16	11,404
FBR	2	690
Total	**436**	**370,221**

Westinghouse

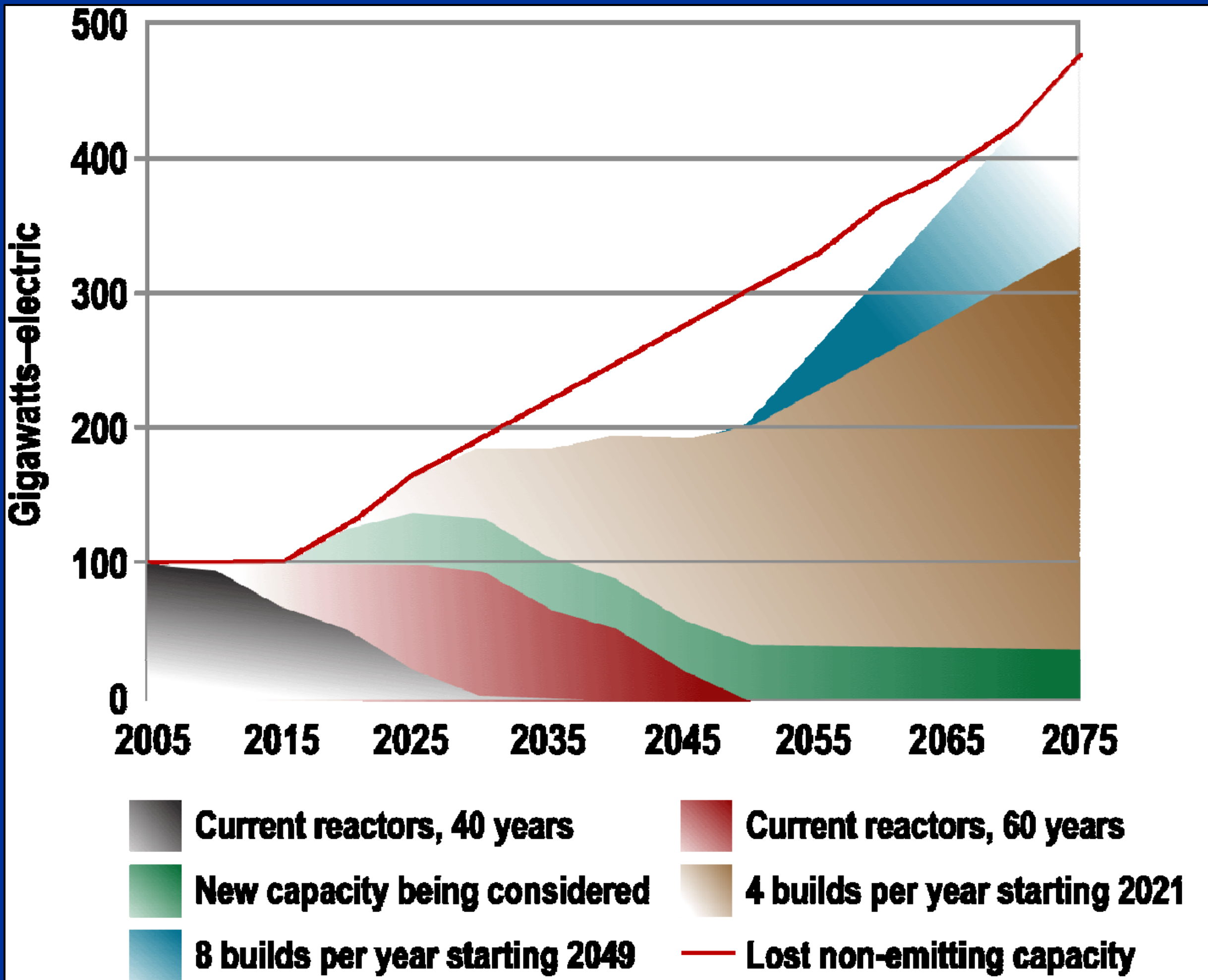
Power Generation Market – Westinghouse's Business

- HUGE electric power market
- Sales of electricity in the US alone ~ $200B per year



2006 US sources of electricity
Source: Energy Information Administration

Sustaining the Nuclear Power Generating Base in the USA



Keep current reactors operating – way past original design life

Basis to build new reactors – on existing technology

Development of new reactors – non LWRs ?

New materials ?

Westinghouse

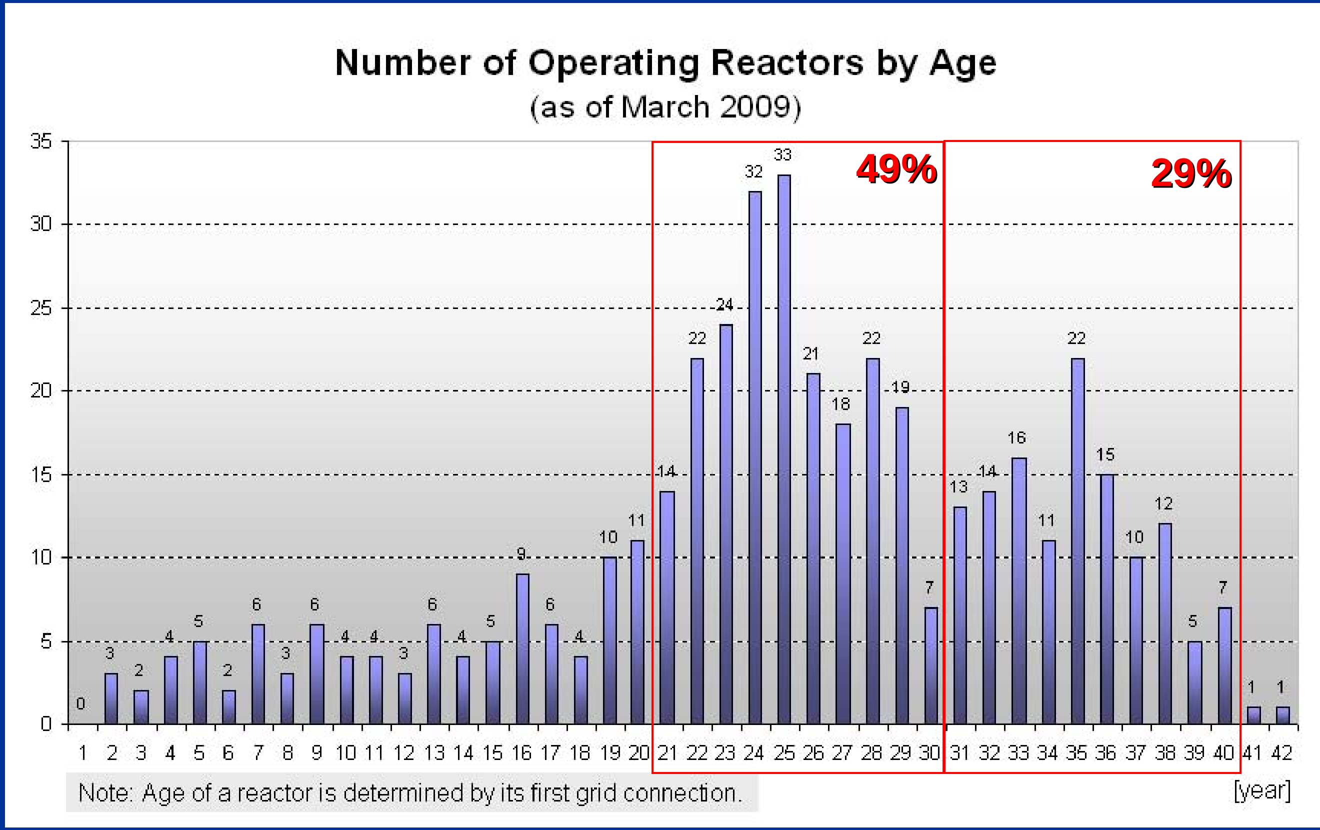
Current Trends in Commercial Nuclear Power

1. Aging of worldwide existing fleet
2. Building of today's new power plants (Generation III+)
3. Designing of tomorrow's Generation IV reactors and advanced reactors
4. Aging of nuclear talent workforce

Westinghouse

Status of Commercial Nuclear Power
Aging of Existing Fleet

- Current US fleet of 104 reactors is aging
  - 809 billion kWh in 2008
  - operated by 30 different power companies
  - extraordinary high capacity factor of ~92%
- Originally licensed for a 40 year operating lifetime
- Nearly all plants have applied/will apply for an additional 20 year life extension ⇨operating lifetime of 60 years
- Talk now of 80 or 100 year lifetimes!

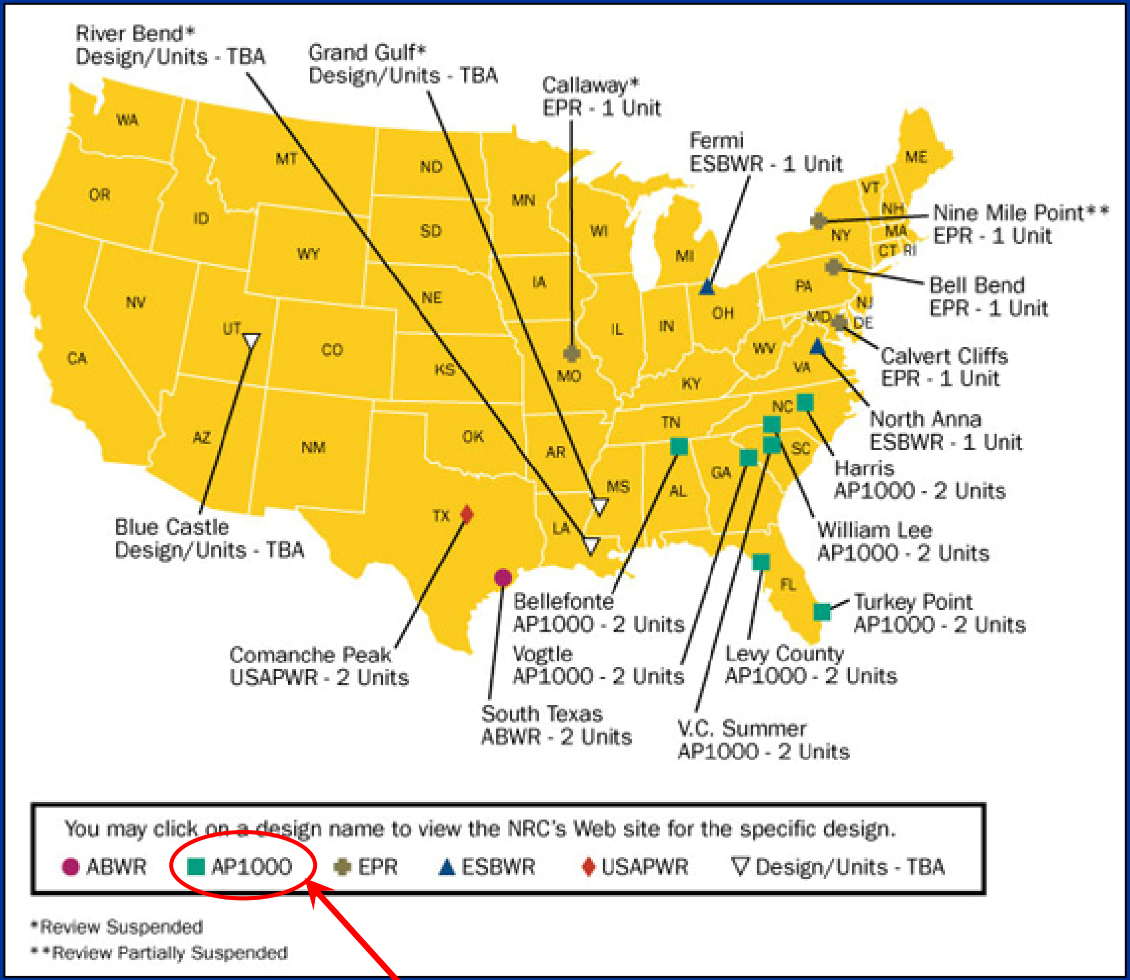


'Aging gracefully' but…..what are the materials issues associated with an additional 20 years of service? 40 years?, 60 years!?

Westinghouse

Status of Commercial Nuclear Power
Building of Today's New Power Plants (Generation III+)

- Near halt in construction for last 30 years - no new construction starts since 1977
- In US alone - 17 license applications to build 26 new nuclear reactors made since mid-2007
- License for all new plants = 60 years
- Expected that 4 to 8 new units may come on-line by 2018
- Westinghouse building new reactors now in China

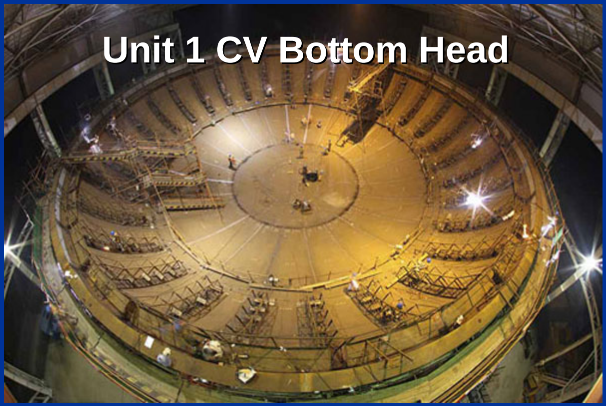


These reactors use the same materials as the existing fleet but the plant design is different and new manufacturing vendors/technologies are being used – what is the impact on material performance?

Westinghouse's new reactor design is called the AP1000.
14 potential new AP1000s planned!

Westinghouse

Status of Commercial Nuclear Power – China Builds
Building of New Power Plants (Generation III+)



AP1000 Sanmen China

Sheffield Forgemasters (UK) stainless steel reactor coolant pump casings

- for China AP1000 new builds
- ~18 ton
- complex mechanical and metallurgical requirements
- critical to reactor operation: pump pressurized coolant at ~ 65,000-95,000 gal/min

Westinghouse

Video of CA-20 Module Installation

Weight ~ 1,020 tons
69 ft W x 44 ft L x 69 ft H

Westinghouse

Status of Commercial Nuclear Power
Advanced Reactors and Generation IV Reactor Designs

- Number of small light-water reactor (LWR) and non-LWR designs
- Application: use for generating electricity in isolated areas or producing high-temperature process heat for industrial purposes
- U.S. NRC expects to receive applications for staff review and approval of some of these designs as early as Fiscal Year 2011

These reactors are 'on the drawing boards' now – will most likely use new materials!

Design	Applicant
International Reactor Innovative and Secure (IRIS)	Westinghouse Electric Company
NuScale	NuScale Power, Inc.
Pebble Bed Modular Reactor (PBMR)	PBMR (Pty.), Ltd.
Super-Safe, Small and Simple (4S)	Toshiba Corporation
Hyperion	Hyperion Power Generation, Inc.
Power Reactor Innovative Small Module (PRISM)	GE Hitachi Nuclear Energy
mPower	Babcock and Wilcox Company

Westinghouse

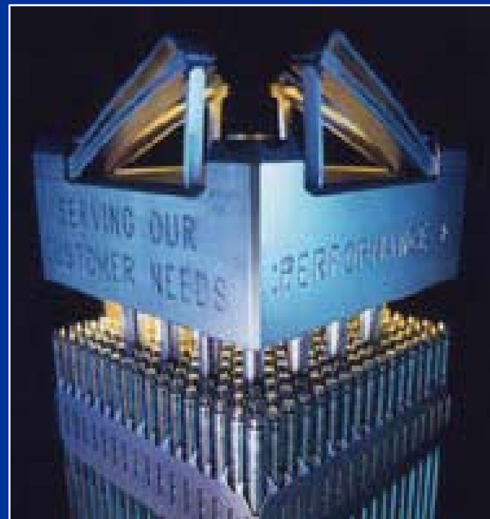
How does this impact Westinghouse?

- Significant growth (3X increase in # of employees in last 4 years) – GROWING PAINS!
  - currently, ~ 15,000 employees worldwide
  - Westinghouse's work alone for four new plants in China has created 5,000 US jobs in 20 states
    - engineering, materials and design
    - manufacturing
- Building new corporate headquarters
- Opened several new office locations worldwide
- Several recent strategic buy-outs
- Workforce:
  - significant recruiting & hiring
  - expert knowledge retention initiatives
  - training centers opening
  - strategic alliances with universities

Westinghouse

Westinghouse's Three Core Businesses

Nuclear Services
Maintenance, repair and replacement of equipment; provider of engineering services and methods for the design, operation and safety of nuclear power plants worldwide



Nuclear Fuel
Single-source fuel provider for PWR, BWR, VVER, AGR, and Magnox reactors worldwide

Nuclear Power Plants
Specializing in the technology of new nuclear power plants and component manufacturing

Nearly 50% of the nuclear power plants in operation worldwide, and nearly 60% in the US, are based on Westinghouse technology

Westinghouse

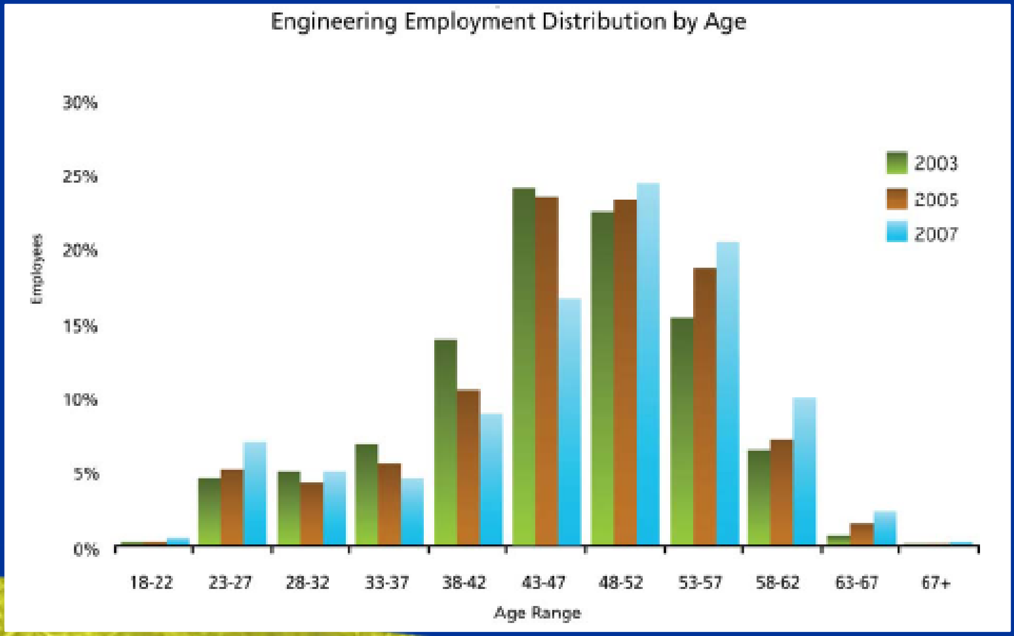
Nuclear Talent – Next 5 Years

Nuclear utility industry:
- 35% of work force eligible to retire
- 11% lost through non-retirement attrition
- up to 46% of work force may be lost

Nuclear vendors (i.e., Westinghouse):
- 41% of work force eligible to retire or may change employers

Engineers in nuclear industry:
- 35% of work force eligible to retire
- 12% lost through non-retirement attrition
- 16% promoted outside of the work force
- up to 62% of work force may be lost

Nuclear Energy Institute



Westinghouse

LWR Materials-Specific Trends and Concerns

Commercial Nuclear Power Reactor Materials

Ferritic low alloy steels	• Reactor, pressurizer, and steam generator pressure vessels • Steam generator tube sheet • Large bore piping
Ni base alloys	• Reactor vessel head penetrations • Steam generator tubing • Piping (D-M) welds • Corrosion resistant cladding (by weld deposits) • Fuel assembly and spring applications
Stainless steels	• Reactor internals (barrel, formers, bolts) • Support plates • Control rods • Piping • Corrosion resistant cladding (by weld deposits)
Zr alloys	• Fuel cladding • Fuel grids • In-core instrumentation tubing

Assembly is by pinning, welding and bolting

Westinghouse

Materials Issues For Existing Plants

Ferritic low alloy steels	• Irradiation embrittlement • Resistance of head penetrations to stress corrosion cracking (SCC) • Fatigue of piping
Ni base alloys	• SCC of head penetration welds • SCC of dissimilar metal welds in reactor vessel and pressurizer nozzles • SCC in steam generator tubing • Protection of steam generator tube sheets
Stainless steels	• Internals hardening and embrittlement • SCC of baffle bolts • SCC of welded internals • Mitigation of piping welds • Thermal and irradiation embrittlement of cast austentic stainless steel
Zr alloys	• Fuel rod leakage • Integrity of welds • New materials with reduced oxidation/hydriding • CRUD formation mitigation

- Industry currently manages all of these issues – US fleet operating at ~92% of capacity factor

Westinghouse

Reactor Operating Conditions Imposed on Materials

- Coolant: water with B, Li and H additions, pH~7.0
- Coolant flow ~300,000 gals/min (~17 ft/sec, ~12 mph)
- Coolant operates at P = 2200 psi
- Coolant T_{in} ~550ºF, T_{out} ~620ºF
- Fast neutron flux ~ 10^{14} cm^2/sec (E >1 MeV)
- Operating exposure: Fuel ~5 year, Plant ~60 years

Reactor Materials Issues in New Plants

Low Alloy steels	Availability in Large Sizes, Fabrication & Welding, Irradiation Embrittlement – New PTS Rules, Fatigue of Piping
Ni Base Alloys	Long Term SCC of Head Penetration & Dissimilar Metal Welds Long Term SCC in SG Tubing,
Stainless Steels	Long Time Internals Hardening and Embrittlement, SCC of Bolting, Potential for Swelling at Longer Times
Zr Alloys	Fuel Rod Integrity, Integrity of Welds, Drive to Higher Burn Up, Pellet Clad Interactions

The Nuclear Power Generation Industry and Pant Designs Will Call for Currently Validated Materials Performance to Continue to Meet Better than 90% Capacity Factor Operations

Concern for New Nuclear Plants: Component Supply

Reactor Pressure Vessel Bottom Petal

- Dimensions
  - OD: 25.0’
  - ID: 17.4’
  - H: 5.4’
- Weight: 80 tons

Reactor Pressure Vessel Core Region Shell

- Dimensions
  - OD: 24.5’
  - ID: 23.4’
  - H: 13.0’
- Weight: 127 tons

Reactor Pressure Vessel Integrated Type Closure Head

- Dimensions
  - OD: 13.2’
  - H: 5.6’
- Weight: 38 tons

Requirements

- Manufacturing infrastructure
- Testing and validation of new vendors and manufacturing processes
- Timely supply

Westinghouse

Concern for New Nuclear Plants: Validation/Testing of New Components

High performance pressure boundary components require:

- uniform chemistry and structure
- validated mechanical properties – strength and toughness
  - properties must be exhibited in all sections

High performance production parts require:

- materials qualification testing to support component acceptance

Processing of Integrally Forged Piping Segments

Requires Westinghouse to develop new suppliers as well as develop new components!

Westinghouse

Concern for New Plants : Component Fabrication Capability

Welded stainless steel reactor core shroud
(CE design)

- **Large complex welded structures need processes to minimize residual stresses etc.**

Westinghouse

Examples of Recent RTU Materials Evaluation Studies

- Residual stress measurement/evaluation
    - pre- and post-stress mitigation technology application
    - as a function of manufacturing processing
- Stress relaxation in nuclear components during service
- Repair and mitigation via metallic cold spray technology
- Failure analysis of nuclear components
- Microstructural analysis of welded structures
- Materials data management
- Structural weld overlay for pressurizer nozzles
- Testing and evaluation of highly irradiated ex-service nuclear components

Effects of Irradiation/Aging on Metals Performance

Potential age-related degradation mechanisms:

- Stress corrosion cracking (SCC)
- Irradiation assisted stress corrosion cracking (IASCC)
- Wear
- Fatigue
- Thermal aging embrittlement
- Irradiation embrittlement
- Void swelling
- Thermal and irradiation-induced stress relaxation or irradiation creep
- Erosion/corrosion

Focus: What factors influence these material degradation mechanisms and how to quantify, forecast and manage their impact on plant component performance.

Quantitative measurements of the degradation in materials properties after known power plant irradiations are the key to predicting and managing future plant component performance.

Difficulties in Studying Highly Irradiated Materials

1. <u>Rarity of test material</u>
   - developing a true understanding of material behavior requires a significant amount of laboratory test data ⇨ requires a significant amount of test material
   - obtaining acceptable material, in terms of both quantity and irradiation exposure levels, is difficult
     - **test reactors** irradiations
     - **most preferred approach:** evaluate material machined from retired PWR components but opportunities to obtain such materials are rare
       - extraction of irradiated materials is expensive
       - requires considerable coordination between sponsors, data customers, material extraction vendors and testing entities

Current issue: test reactors versus power reactors? – what are the real differences in driving materials behavior?

Difficulties in Studying Highly Irradiated Materials

2. **Number of parameters which must be evaluated**
   - material chemistry, microstructure, thermo-mechanical processing history
   - irradiation level, irradiation temperature, irradiation environment, various stress levels
   - material property of interest? – tensile, creep, crack initiation, crack growth rate, fracture toughness, swelling

which parameters do you choose to test as independent variables?
…..and which do you try to hold constant?

3. **Testing of highly irradiated material is logistically complex**
   - all materials must be handled, machined and tested remotely in hot cell facilities
   - remotely controlled test equipment must be calibrated and qualified
   - highly skilled laboratory personnel required

Westinghouse

Unique Aspects of Evaluating Highly Irradiated Materials

Typical Evaluations for Improved Understanding of Irradiated Materials Performance

Mechanical Testing

- Remote machining of highly precise test specimens
- Testing of specimens in a variety of environments:
  - air
  - PWR or BWR simulated water
  - inert gas
- Testing of specimens at a range of temperatures (generally room temperature to ~650°F)
- Mechanical Testing:
  - tensile/slow strain rate tensile
  - Charpy V-notch
  - crack initiation (O-rings)
  - fracture toughness
  - crack growth rate

Materials Examinations

- Hardness
- H and He gas content analysis
- Failure analysis
- Density analysis

Microstructural Evaluations

- Cutting/mounting/polishing/etching of highly irradiated specimens
- Metallography
- Scanning electron microscopy
- Transmission electron microscopy

Analytical/Modeling Evaluations

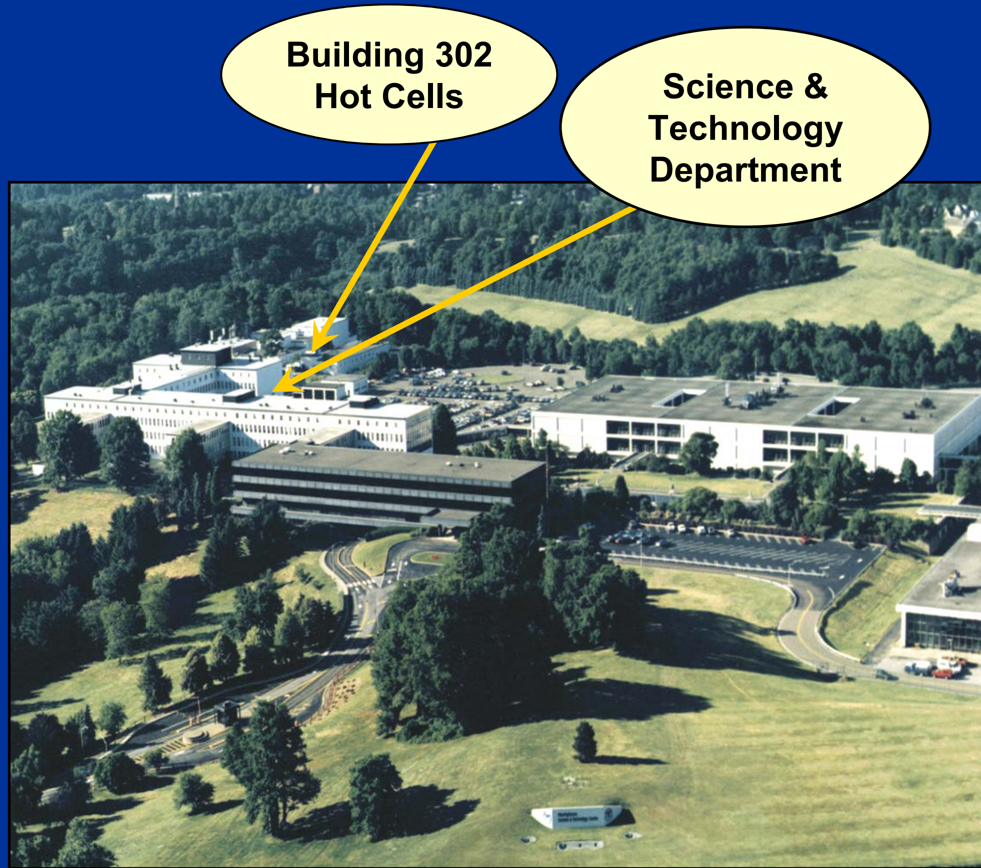
- Finite element analysis:
  - stresses
  - temperatures
  - fluences
- Mechanistic models describing material behavior
- Predictive equation development fitting experimental data sets

Westinghouse's Unique Experience Base

- Westinghouse's Hot Cell Facility and Remote Metallographic Facility (RMF) has been testing, evaluating and characterizing irradiated reactor internals materials for 35 years!

Where do we evaluate the materials?

- George Westinghouse Research & Technology Park – 'old Science & Technology Center, STC'
- Science and Technology Department (STD), Pittsburgh, PA
- STD specializes in:
  - material evaluations and testing including hot cell capabilities
  - next generation reactor designs
  - chemical processing
  - decision analysis



George Westinghouse Research & Technology Park in Churchill

Westinghouse

Westinghouse Hot Cell Facts…

- One of only 3 commercially available hot cell facilities available in the U.S.
- Building 302:
  - 36” reinforced concrete base to support massive weight of the hot cells
  - ~50% of second floor devoted to fans/filtration systems
  - entire building maintained at negative pressure with the high level cells under the lowest pressure
  - building is ‘self-sufficient’ – independent natural gas back-up generator/power systems

Building 302 located at the George Westinghouse Research & Technology Park in Churchill

Westinghouse

Hot Cell Testing

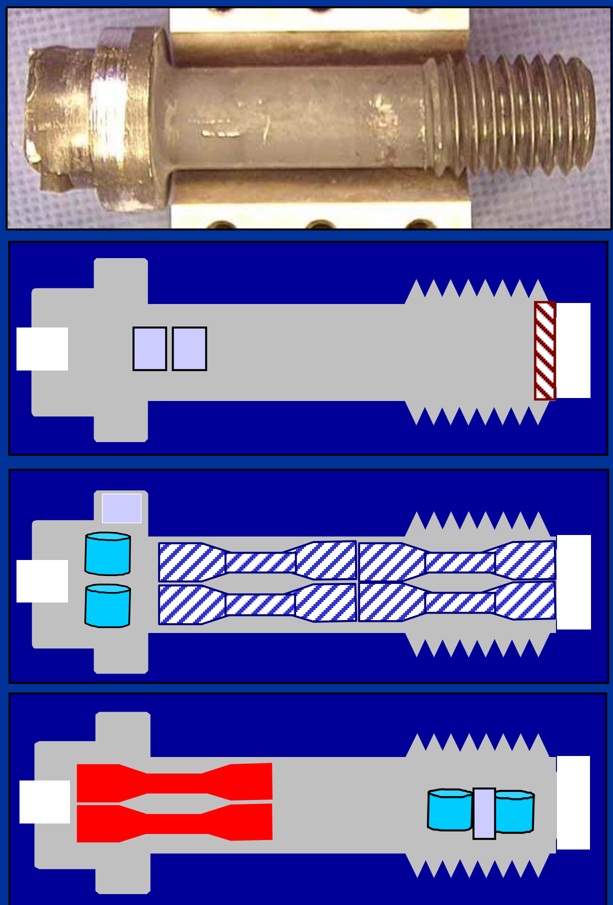
- For the examination & testing of irradiated materials
- Key capabilities include:
  - 30,000 curie licensed hot cell
    - 9 stations with remote manipulators
    - video camera monitoring
    - in-cell computerized controlled machining
    - coarse capability to handle large component
    - fine capability for precision test specimen machining
  - mechanical testing laboratory
  - autoclave laboratory
  - materials microstructural and chemical characterization laboratories
- Irradiated materials storage facilities – underground storage pits
  - one-of-a-kind reactor materials remnants dating back ~ 30 years

Hot cell stations with remote manipulators

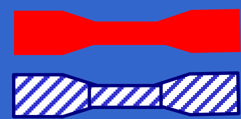
Westinghouse

Example of Optimized Material Utilization

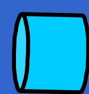
machining/testing multiple specimens from baffle bolts

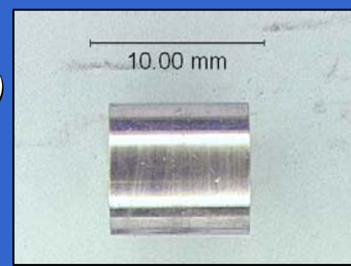


tensile specimen or slow strain rate tensile (SSRT) specimen



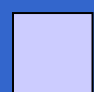
O-ring (crack initiation) specimen

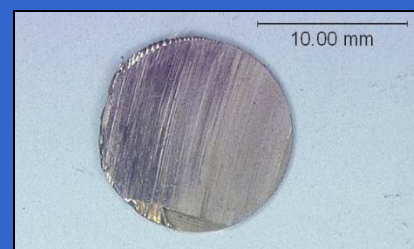




chemistry specimen

metallographic specimen

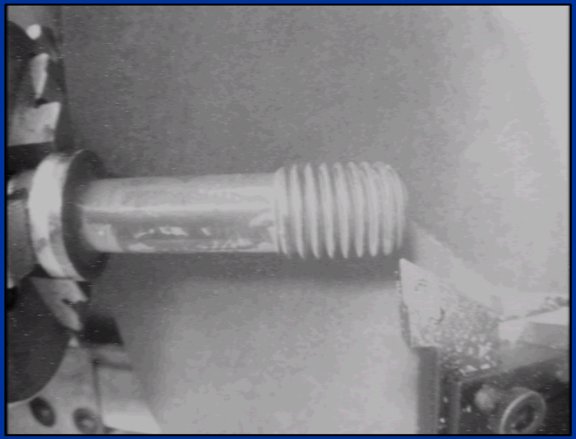


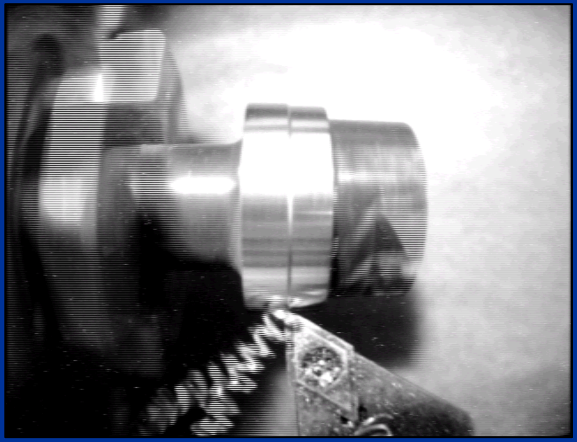


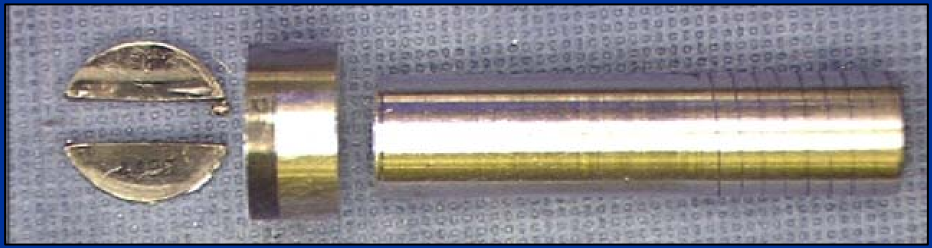
Westinghouse

Remote Specimen Machining in Hot Cell
(all done with manipulator arms!)

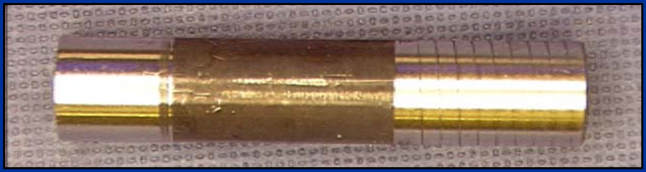
Removal of threads and head material with hot cell lathe



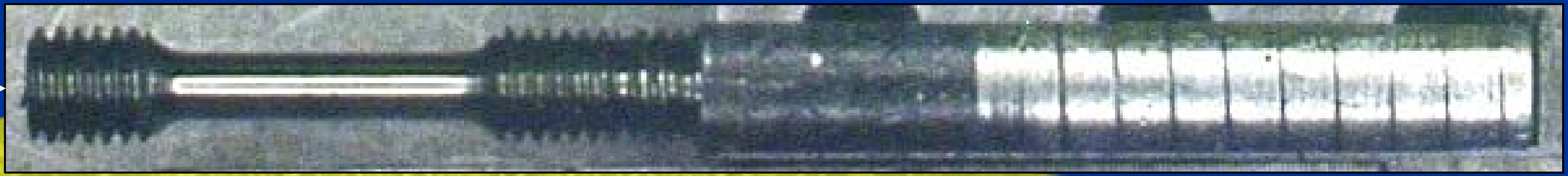




Tensile specimen which has been machined but not yet separated from the bolt segment



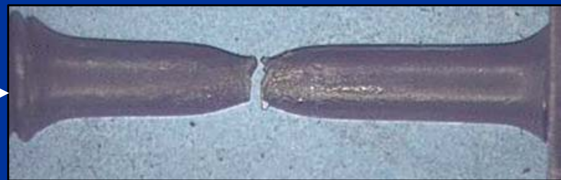
Entire bolt turned to a uniform diameter for tensile specimen machining

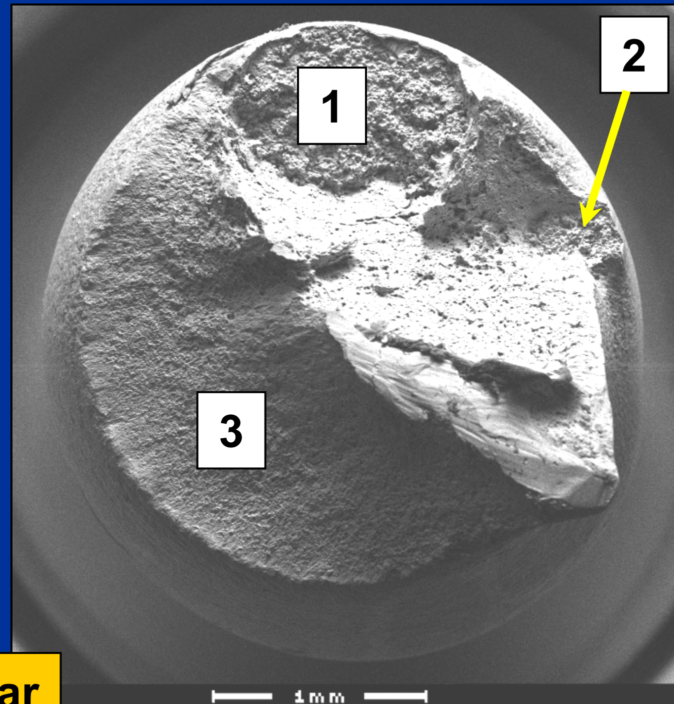


Westinghouse

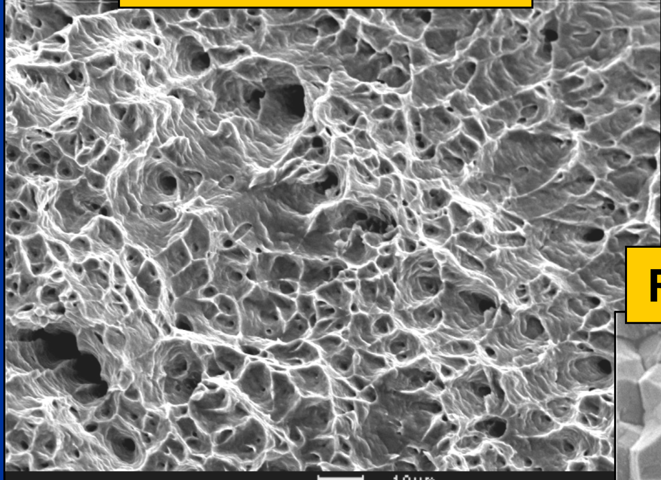
Scanning Electron Microscopy Analysis of Specimen Fracture Faces

autoclave SSRT testing in PWR water environment

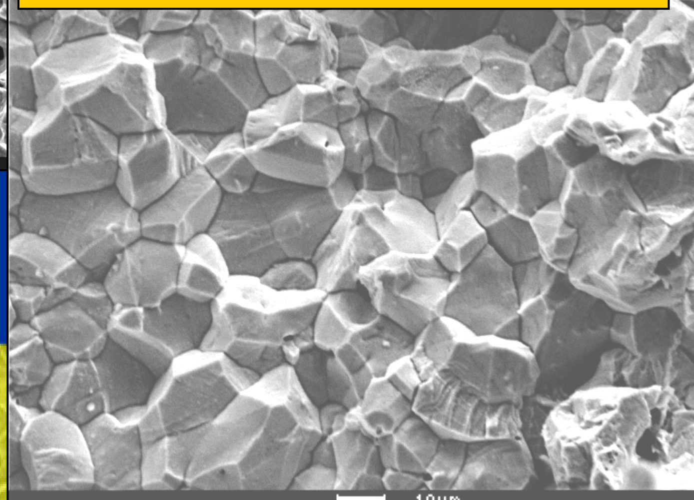




Region 3: Ductile



Regions 1 & 2: Intergranular

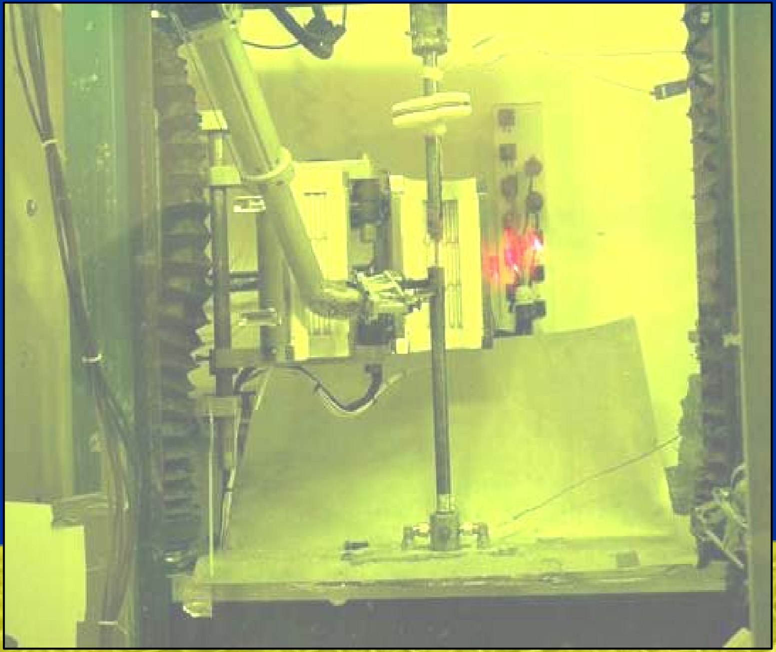


Regions 1 & 2
intergranular fracture

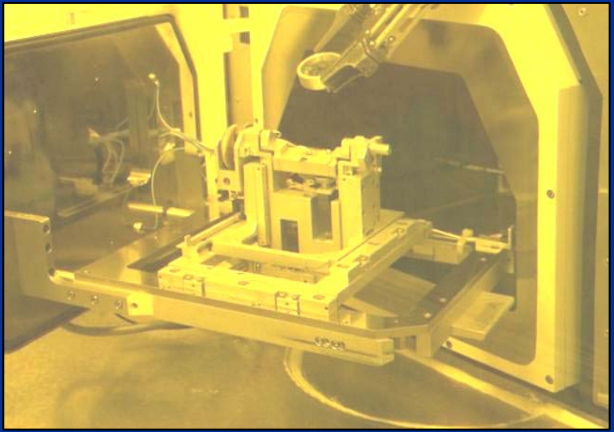
Region 3
ductile fracture

In-Cell sectioning of retired reactor head segment

Hot SEM with remote loading system



Hot Cell High T Tensile Testing



Remote loading of SEM sample

Westinghouse

Charpy Impact Testing at the Westinghouse Hot Cell

This is a movie clip

Examples of Direct Industry Materials Support

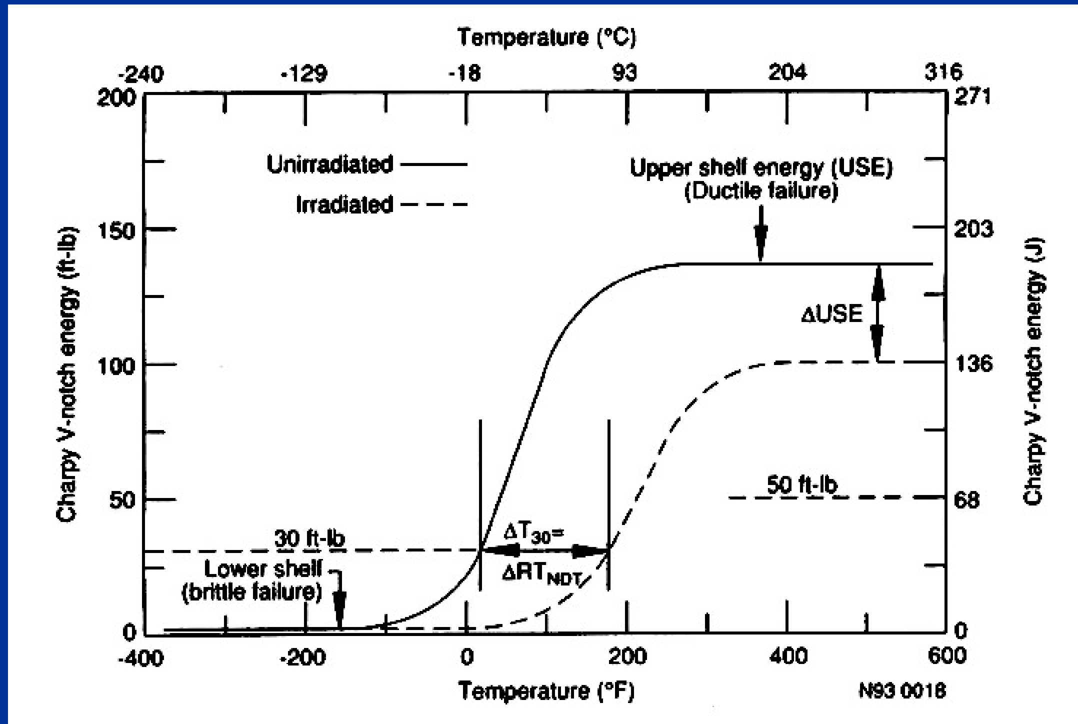
Reactor Pressure Vessels Industry Needs

Plant operations need vessel materials' fracture resistance to support

- Pressurized Thermal Shock (PTS) - License requirement
- Operational Limitations – heat up/cool down "curves"

Ferritic steels become embrittled in neutron and thermal environments. These changes are manifested in:

- Reduction in the toughness during ductile fracture
- Tendency to brittle fracture at onsets at increasing temperatures



Charpy Fracture Toughness Curves Reflect RPV Steel Embrittlement

Westinghouse

Reactor Pressure Vessels Technical Approach

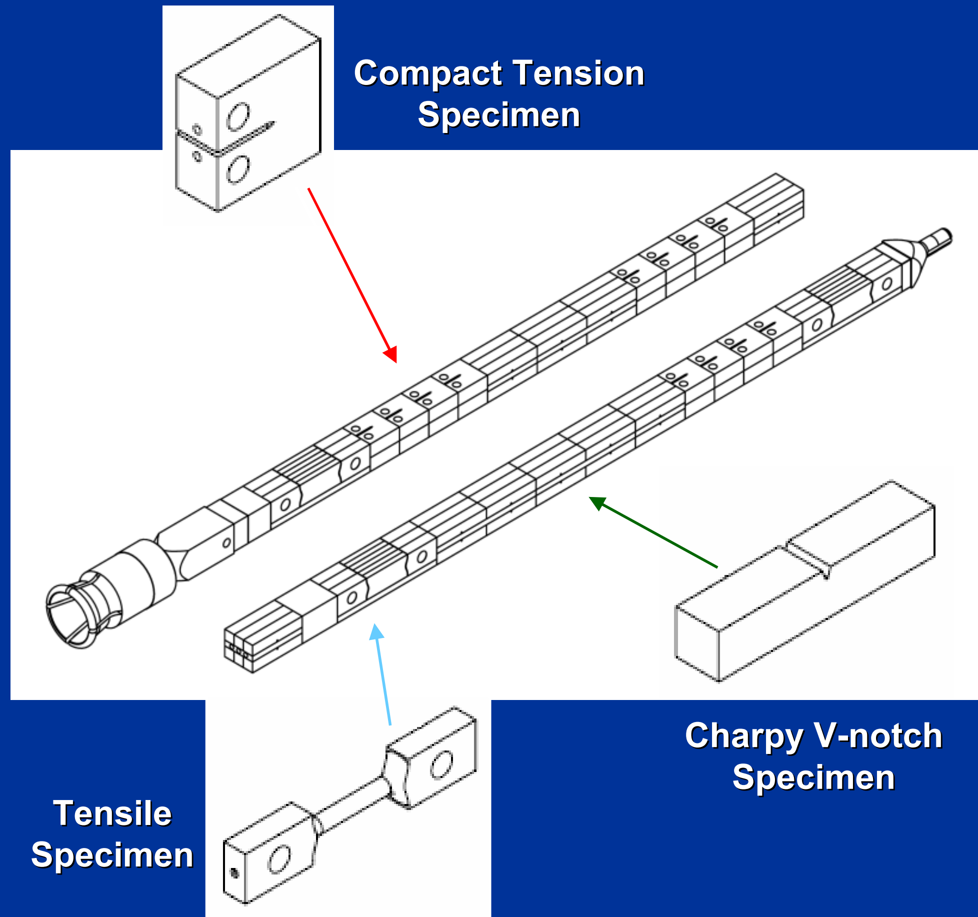
Surveillance Capsules have been employed for many years to monitor RPV steel embrittlement

- Quantitative evaluation of irradiation induced embrittlement via Transition Temperature Shift (TTS) and/or reduction in Upper Shelf Energy (ΔUSE)

- Data for individual vessels : Welds , Plates and Forgings

- Embrittlement data provide the basis for PTS rule compliance and operator curves for the plant

Modern capsules will incorporate fracture toughness specimens as well as Charpy specimens



Reactor Pressure Vessels Technology Progress

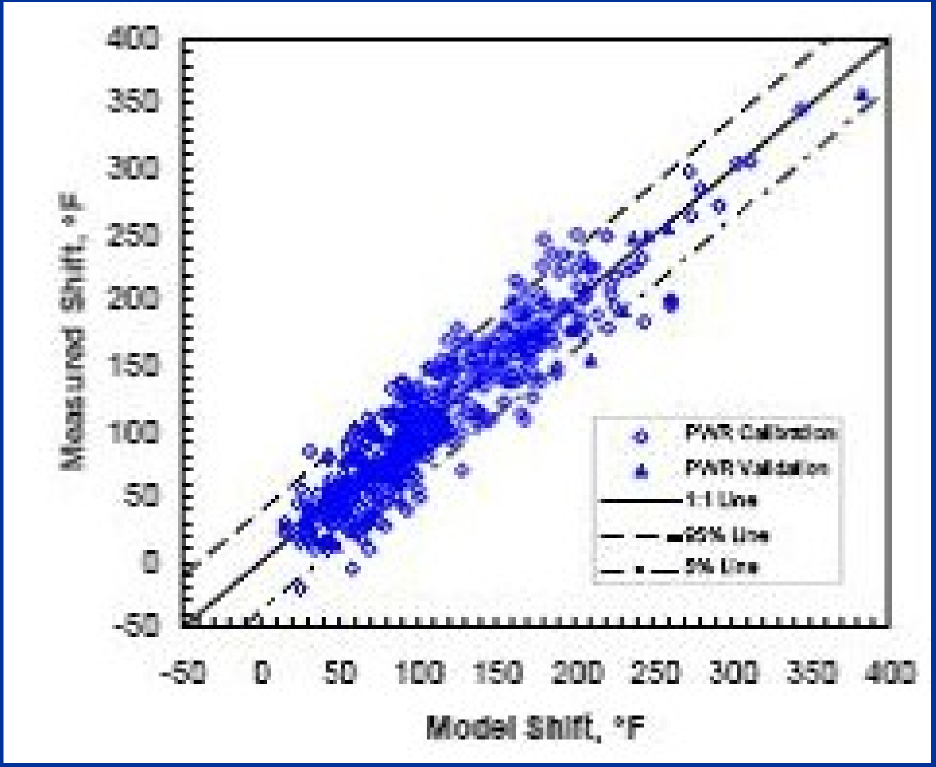
Several hundred surveillance capsules have been tested

- An extensive database of shift vs alloy chemistry, irradiation dose and irradiation temperature exists
- Predictive models are available based on previous capsule results

Provide support to ongoing plant operations

Provide the basis for relicensing

Microstructural and local chemistry analysis has provided the scientific basis for the correlation models



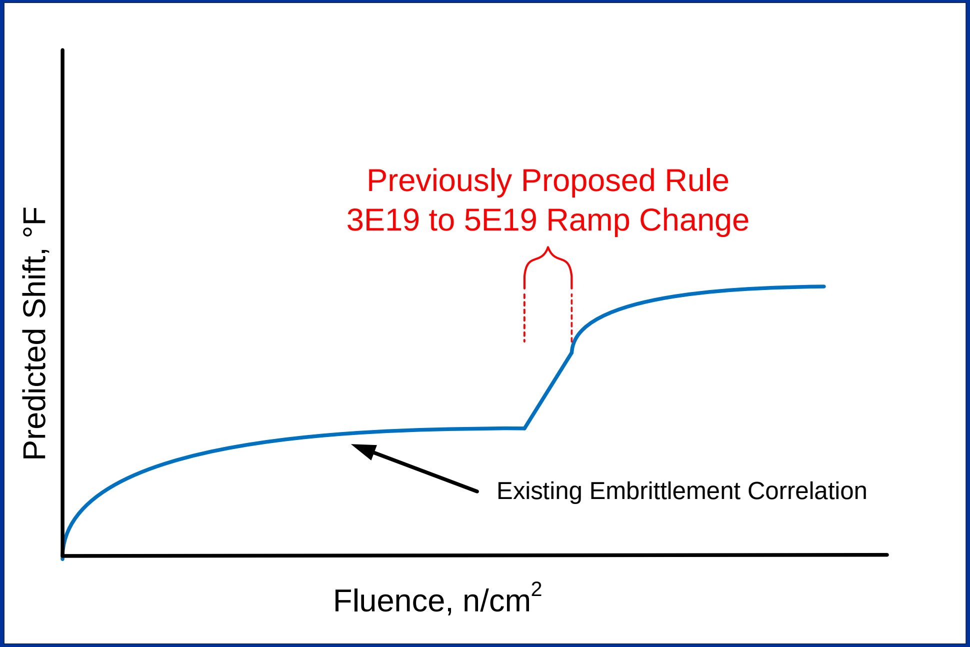
Correlation of Model Predictions and Measured TTS for Commercial Plant Irradiated RPV Steels

Reactor Pressure Vessels Technology Progress

Issues exist relatvie to high fluence exposure

- Embrittlement correlation based on existing data and not high fluence data (> 5E19 n/cm^2)
- Can test reactor data adequately model PWR embrittlement?
- Test reactor data would penalize plant shift values. This impacts both license extension and new plant builds

Current industry initiatives being developed to obtain high fluence data from existing fleet without disrupting withdrawal requirements and to correlate test reactor data



Initial efforts to define high fluence region penalized operating fleet significantly

AP1000 Reactor Pressure Vessels

Surveillance program licensed to ASTM E185-82

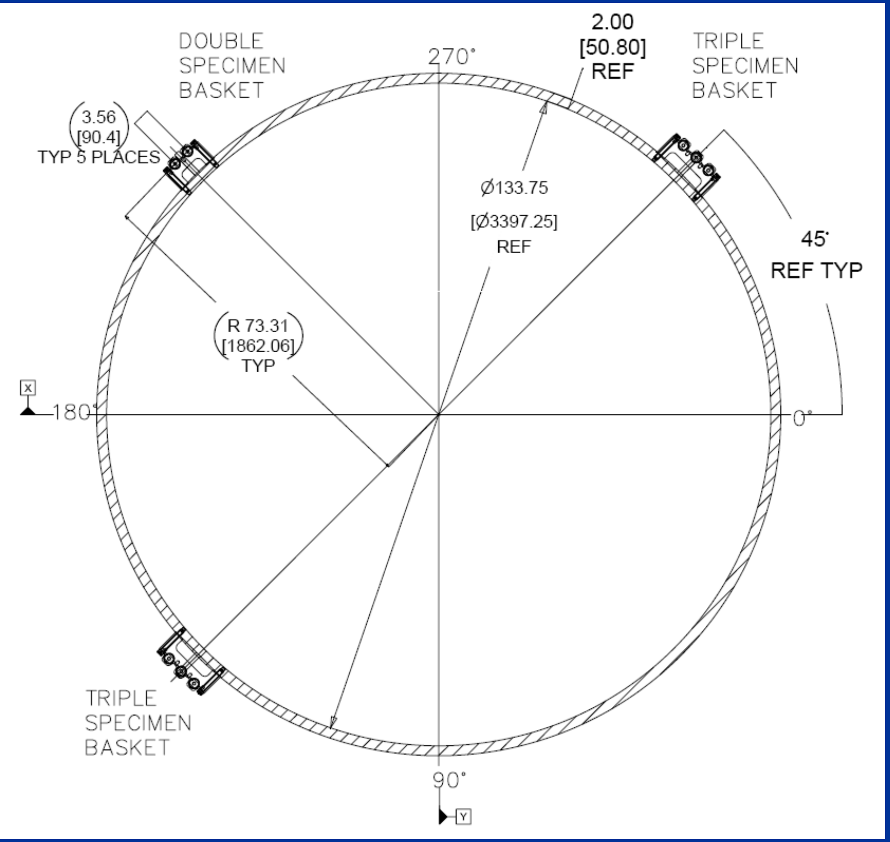
- Meets the intent of guidelines provided in ASTM E185-02
- Niobium wires replacing past dosimeters materials
- Additional 1/2T-CT compact tension specimens provided

Vessel materials include forging (508 Class 3) and circumferential weld

- Vessel materials low in wt% Cu and moderate wt% Ni

Surveillance capsule programs will be plant specific

Eight (8) surveillance capsules per plant.

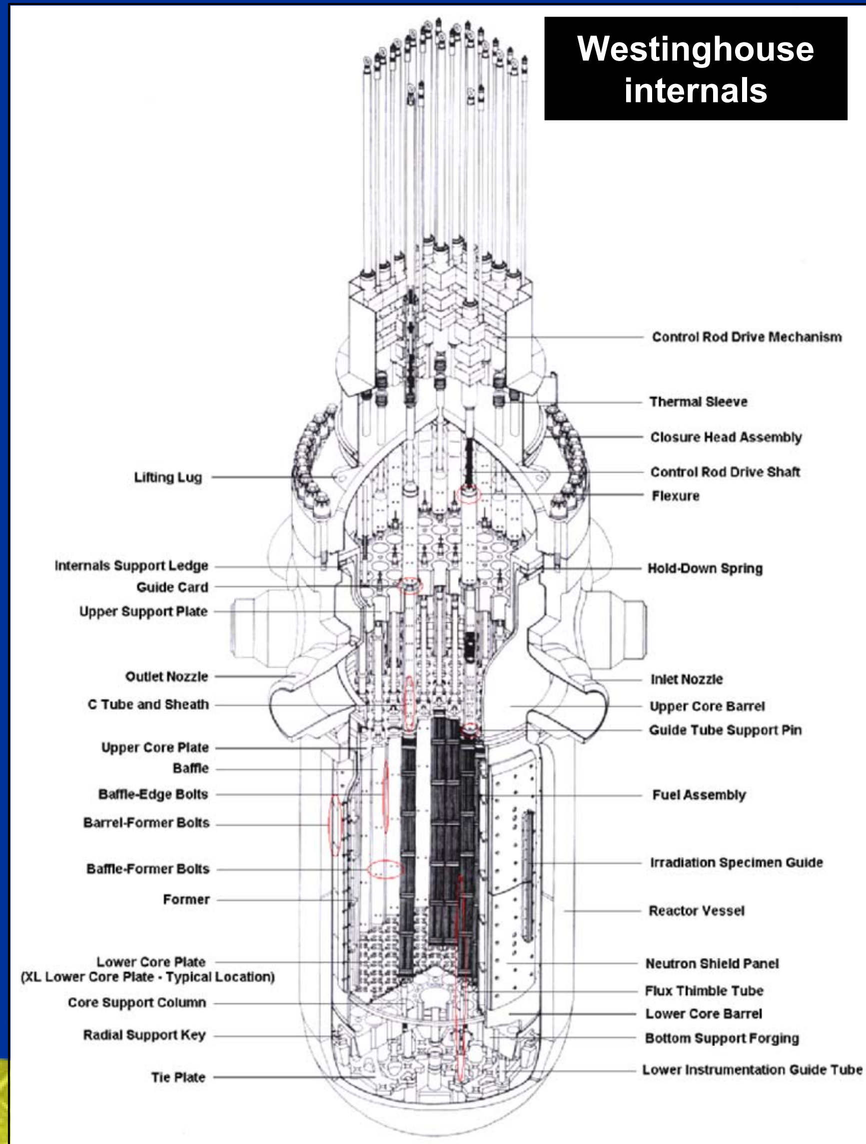


Surveillance Capsule Location about AP1000 Reactor Core

Westinghouse

Reactor Internals

- Major structures within a reactor vessel having one or more functions such as:
  - supporting the core
  - maintaining fuel alignment
  - directing primary coolant flow
  - providing radiation shields for the reactor vessel
  - guiding in-core instrumentation
- ~100 components are classified as internals
- Material degradation under reactor operating conditions may potentially impair the components' ability to meet functional requirements



Westinghouse

Reactor Internals Materials

- Austenitic stainless steels:
- a stainless steel with a minimum of 16% Cr and 7% Ni
- resistant to corrosion in water/moist air environments

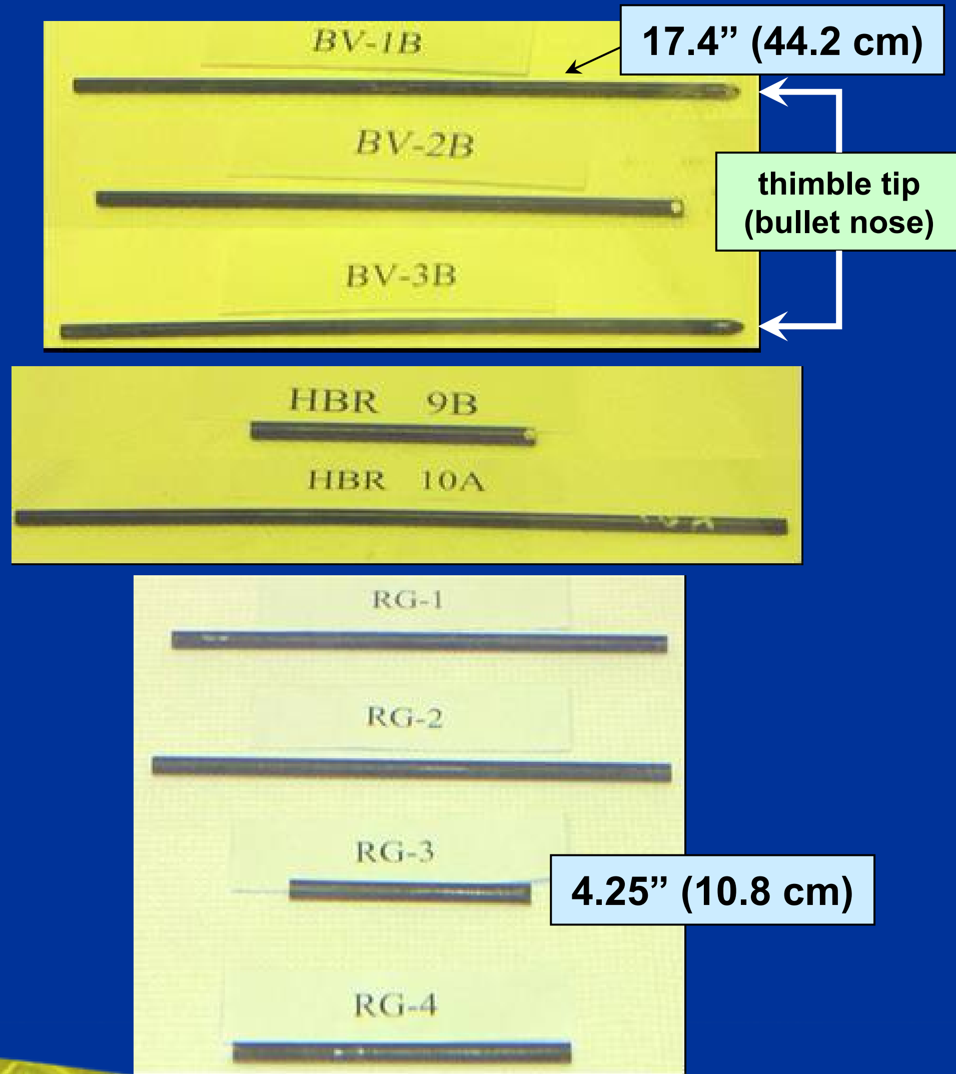
An example of some of the ~100 components classified as internals:

Assembly	Sub-Assembly	Component	Material
Lower Internals Assembly	Baffle and Former Assembly	Baffle bolting lock bars	304 SS
		Baffle-edge bolts	316 SS, 347 SS
		Baffle plates	304 SS
		Barrel-former bolts	316 SS, 347 SS, 304 SS
		Former plates	304 SS
	Bottom Mounted Instrumentation (BMI) Column Assemblies	BMI column bodies	304 SS
		BMI column bolts	316 SS
	Core Barrel	Upper core barrel	304 SS
		Lower core barrel	304 SS
	Flux Thimbles (Tubes)	Flux thimble tube plugs	304 SS
		Flux thimbles (tubes)	316 SS
	Head Cooling Spray Nozzles	Head cooling spray nozzles	304 SS
	Neutron Panels/Thermal Shield	Neutron panel bolts	316 SS
		Thermal shield or neutron panels	304 SS

Westinghouse

Example Internals Project: Test Materials

- Nine cut Type 316 SS thimble tube sections
- O-ring test specimens were machined directly from these as-received tube sections
- Tube sections were cut from various positions along the full axial length thimbles obtained from the central region of the core
- Material chemistries documented by materials test certifications; all elements were within specification limits



Images not to same scale

Westinghouse

Test Materials

Plant	Material	Tube Nominal Dimensions			EFPY	Removed from Operation	Tube Section	
		ID	OD	Wall Thickness			Identification Number	Length
		mm						cm
Beaver Valley Unit 1	Type 316 15% CW	5.080	7.569	1.24	14.3	2000	BV-1B	44.2
							BV-2B	36.8
							BV-3B	43.2
H.B. Robinson Unit 2		6.858	9.804	1.47	9.9	~1987	HBR-9B	15.2
							HBR-10A	43.2
Ringhals Unit 2		5.207	7.645	1.22	20.2	2004	RG-1	24.0
							RG-2	24.1
							RG-3	10.8
							RG-4	14.4

Three different O-ring ID/OD combinations – requires 3 separate ANSYS FE stress analyses

The Ringhals material, with a maximum dpa level of 76 dpa, is believed to be the most highly irradiated ex-service austenitic stainless steel ever evaluated

BV-2B thimble section measured 1.3 R at 12” ⇨ ~ 750 R at ½”

Crack Initiation (O-Ring) Testing Procedure

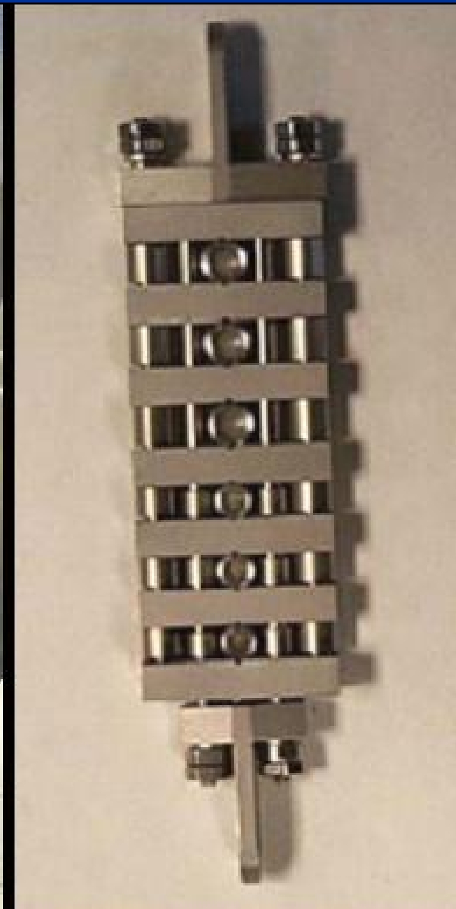
- Performed at 340°C (644°F) in a shielded autoclave with four independent pull rods
- Autoclave sits in an 8" (20 cm) thick shield and includes an 8" (20 cm) thick autoclave head – allows for test runs to occur outside of the hot cell
- Water supply system is a 'once-through' water system
  - two large water storage tanks are utilized
  - water samples taken from each tank analyzed using ion chromatograph and atomic absorption techniques
- Monitoring and recording of test conditions performed continually using data acquisition system - following data continually recorded during testing:
  - water T (T is held constant to within 2°C of the specified test T)
  - autoclave P
  - extension of each pull rod using calibrated linear variable displacement transducers (LVDTs)
  - load on each pull rod using calibrated load cells
- Simulated PWR water environment consisting of deionized water with H_3BO_3 and LiOH additions (~1000 ppm as B, ~2 ppm as Li)

• dissolved oxygen	< 5 ppb	• pH	~6.9 at room T
• dissolved hydrogen	~30 cm^3/kg	• conductivity of deionized water	<0.3 μs/cm
• chlorine	< 30 ppb	• total dissolved solids	<0.2 ppm
• fluorine	< 30 ppb	• dissolved silica	<0.1 ppm

Crack Initiation (O-Ring) Testing Procedure

- Four custom-designed O-ring test fixtures which compress the specimens during testing
- O-rings loaded into test fixtures remotely with up to six specimens loaded into a single fixture
  - if all four test fixtures are utilized, a maximum of 24 samples can be tested simultaneously in the same autoclave
- Individual specimen lengths varied so that a variety of stresses can be applied to different specimens loaded into the same test fixture

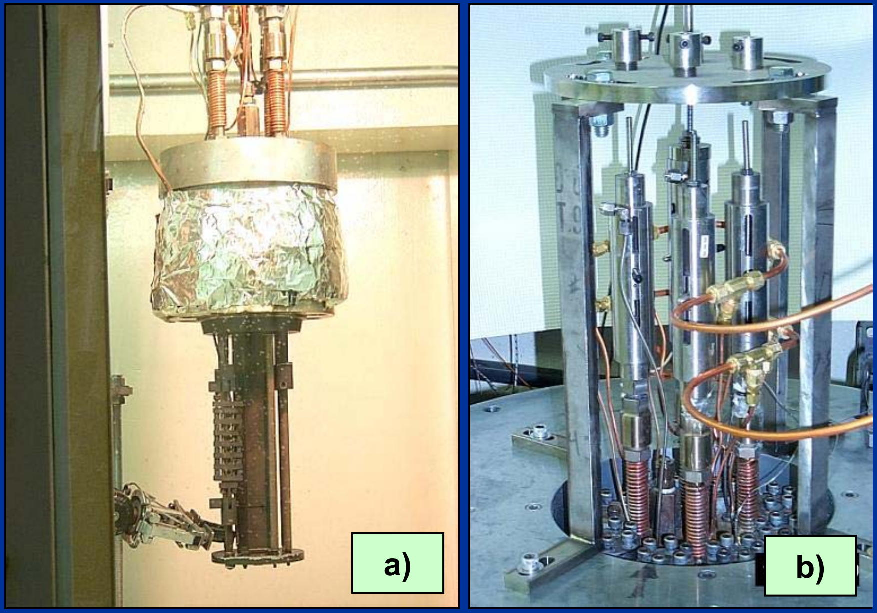
no specimens loaded



6 specimens loaded

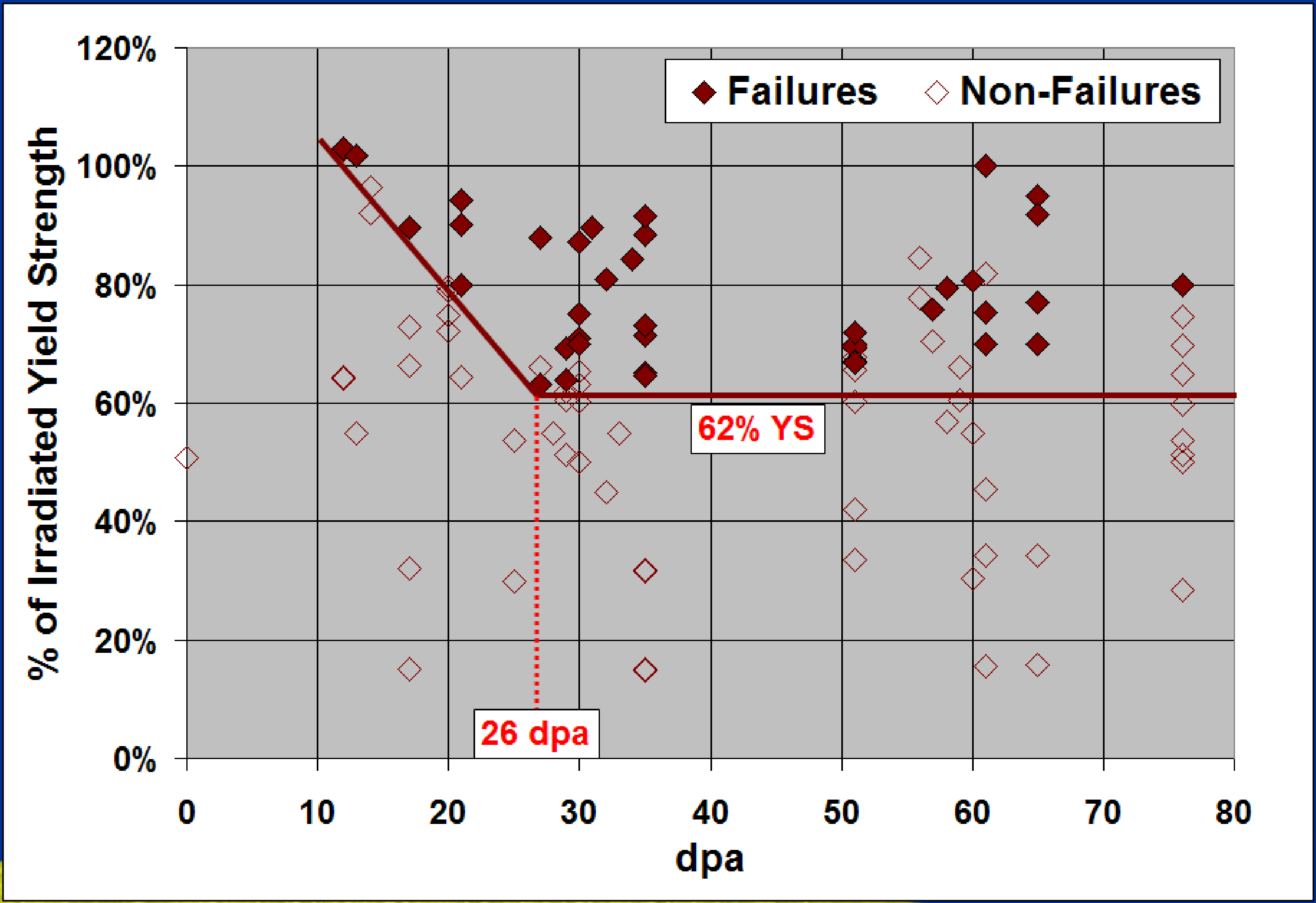
Crack Initiation (O-Ring) Testing Procedure

- One end of each test fixture is remotely attached to a pull rod
- Loads are applied individually to each pull rod
- Each load train contains a monitored load cell and a LVDT which indicates deflection if a failure occurs
  - the time to cracking (as indicated by a load drop and movement in the LVDT) is recorded
- Testing of specimens can be performed over any desirable test time
  - for this work, test times ranged from ~ 600 hours (25 days) to 4,000 hours (5.5 months)



a) shielded autoclave head showing one O-ring test fixture in place
b) autoclave test assembly showing four pull rods penetrating through autoclave head

Crack Initiation (O-Ring) Test Results for 3 Heats of Highly Irradiated Stainless Steel



By far largest irradiated material crack initiation database worldwide

Long Time Service/Dose Materials

Next Large Hot Cell Testing Program

Westinghouse has been in negotiations for ~ 5 years

- 160 MWe 1 loop Westinghouse reactor in Spain
- Initial criticality: 06·1968
- Commercial start: 02·1969
- 38 years of operation (26 EFPY)
- Shutdown April 2006
- Highest fluence regions are >50 dpa

José Cabrera (Zorita) Nuclear Power Plant
Photograph courtesy of Foro Nuclear

Goals and Objectives:

- Provide data to support on-going plant operations, re-licensing applications, aging materials management plans, etc.

Westinghouse

Summary

‘Tip of the iceberg’ exposure to LWR nuclear materials and Westinghouse’s Hot Cell Facilities

- Visit our facilities
- More in-depth discussions
- Potential for collaborative programs
  - extensive archival material in inventory
  - tapping into our hot materials evaluation expertise

Brian Burgos
Manager, Materials Measurement Services
Westinghouse Hot Cell Facility
Research & Technology Unit
(412) 256-1067
burgosbn@westinghouse.com

Westinghouse