GE Hitachi
Nuclear Energy
www.ge.com/nuclear

BWR Fuel & ABWR Experience

Birol Aktas
Principal Engineer
Reactor Thermal Hydraulics

1-week WNU Course, Turkey
September, 2008

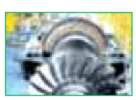
Proven..design

..construction

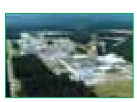
..operation

imagination at work

Outline

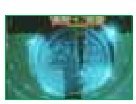


An overview GE and its Energy Infrastructure, Nuclear and Nuclear Fuel businesses



Growing the Nuclear business in Wilmington and the GE Hitachi Nuclear Energy Alliance

Nuclear refresher: The pioneering work from the late-19th century to mid-20th century

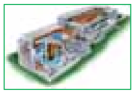


Fuel challenges: Design criteria and safety limits, and reliability

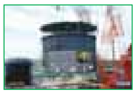
GNF solutions: Modern BWR fuel and debris filter LTPs, defense-in-depth technologies, excellence in manufacturing

HITACHI

Outline (continued)



ABWR proven design: Evolution of the BWRs from Dresden I to modern ABWR, and beyond to ESBWR.



ABWR proven construction/operation: Modularization and evolution of construction technologies, a review of either currently operating or under construction ABWRs

HITACHI

3
GEH
September 2008

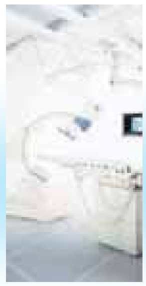
GE...

General Electric Company

Energy Infrastructure

Energy
Oil & GAS
Water & Process Technologies

Technology Infrastructure

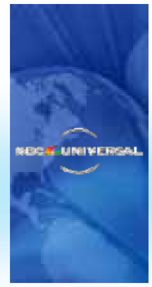


Aviation
Enterprise Solutions
Healthcare
Transportation

GE Capital

Aviation Financial Svcs
Commercial Finance
Energy Financial Svcs
GE Money
Treasury

NBC Universal



Cable
Film
International
Network
Sports & Olympics

GE...>300,000 Employees in 100+ Countries

...$170B Revenue & ~$300B Market Cap

...$90B USA...$83B International

HITACHI

GE in energy

Gas

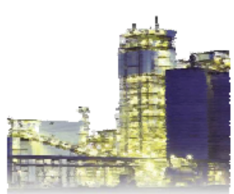
Wind

Nuclear

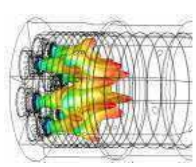
Solar

T&D

Biomass



Cleaner Coal

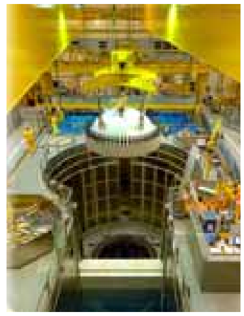


Environmental Services

Asset Optimization

HITACHI

Our Nuclear business…



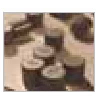
Nuclear Power Plants
- Generation III: ABWR
- Generation III+: ESBWR
- Generation IV: S-Prism

Nuclear Services
- Reactors, turbines & balance of plant
- Life extension
- Power uprates
- Performance services
- Outages and inspections

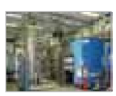
Fuel Cycle
- Boiling water reactor & mixed oxide fuel
- GE Hitachi Canada Candu fuel & handling Equipment
- Fuel Engineering Services
- Enrichment
- Nuclear Isotopes

HITACHI

Our Fuels business…



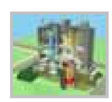
Uranium Services
- Inventory management
- Trades
- Container licensing and leasing
- Uranium storage contracts/leasing
- Downblending



Enrichment Services
- Enrichment services
- Uranium

Fuel Products & Engineering Services
- BWR fuel
- LWR fuel
- Fuels optimization
- Core reload analysis
- Engineering
- Initial cores

Candu Products & Services
- PHWR fuel
- Candu fuel handling equipment
- Parts & services
- Tritium processing



Fuel Recycling
- PRISM reactor
- Advanced Recycling Center
- Interim dry cask fuel storage

Expanding our fuel cycle offerings … aligning core competencies with adjacent, highly innovative new growth programs

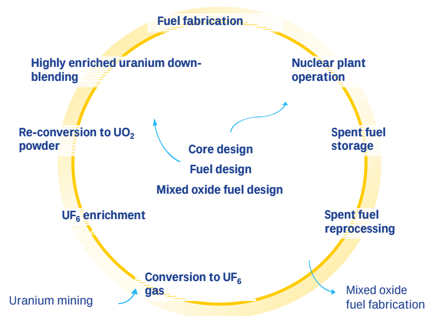
HITACHI

Nuclear fuel cycle vision

Vision

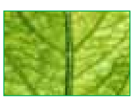
Build an integrated Nuclear Fuel Cycle… to provide a full portfolio of fuels offerings, building on external relationships to build scale and compete in a global marketplace.

Nuclear fuel cycle



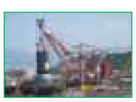
HITACHI

Nuclear…a dynamic environment



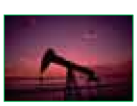
Global demand for alternative, reliable energy sources… global carbon policies… Fossils considered toxic also in geo-politics. Nuclear continues to gain public and government acceptance.

Increased regulatory environment… more focus on data, proven methods and tougher licensing requirements.



Proven advanced technology… designed in the 1990s, the only advanced reactor in operation.

Sustained operating performance… industry highly dependent on safe, reliable power generation to continue. Life extension and power uprates increasingly valuable.



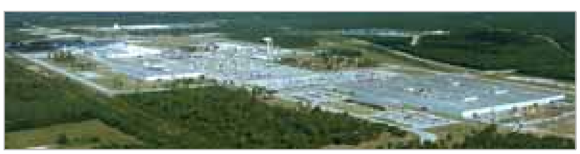
Clean winner… in comparison to Oil. 1 UO_2 pellet generates 4.8 barrel of oil equivalent (BOE) energy. A typical BWR fuel bundle is worth 165,000 BOE at ~4 times less COE.

HITACHI

Positioning for growth…

imagination at work

Wilmington site history



- 1,650 acres (300 developed)
- Over 2 million square feet footprint
- 3,100 employees (+900 in last five years)

Ground breaking 1967

GE Aircraft Engines 1980

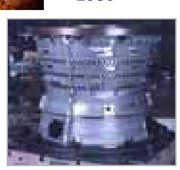
Fuel collocation 1994

Dry powder conversion 1997

GNF JV formation 2000

GENE headquarters relocation 2003

GEH JV formation 2007

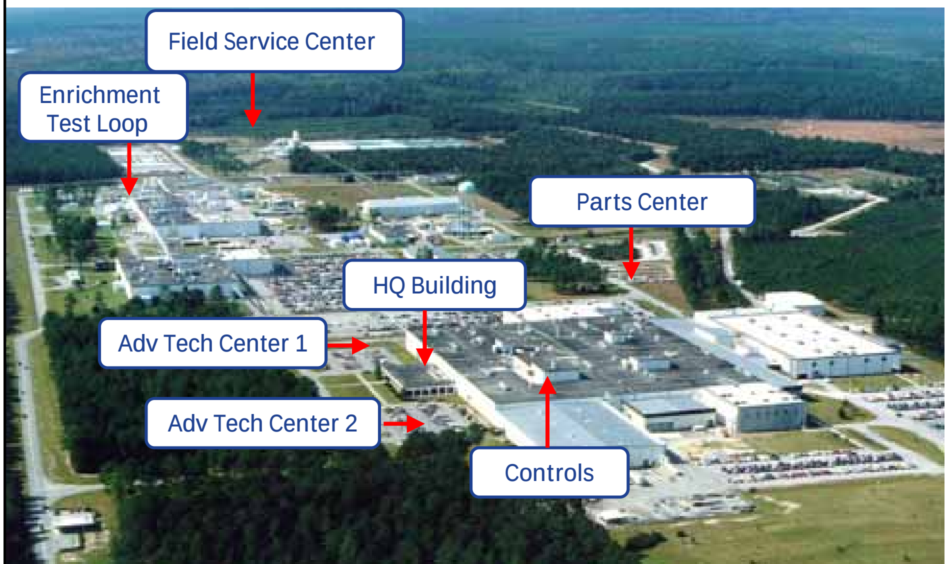


GNF Global Nuclear Fuel

HITACHI

HITACHI

Wilmington site expansion



HITACHI

GE & Hitachi alliance – July 2007

Growth

- New customer solutions
- The best people

Service excellence

- Advanced process & tools
- Flawless execution

- PWR technology
- Other

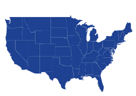
New technology

- Uranium enrichment
- Plant optimization

- New Customer Technology Center
  - Training
  - R&D
  - Innovation Labs
  - M&D Center

A new era

- New global reach & capacity
  - N. America
  - Asia
  - Europe



- BWR technology
- United States

The BWR experts

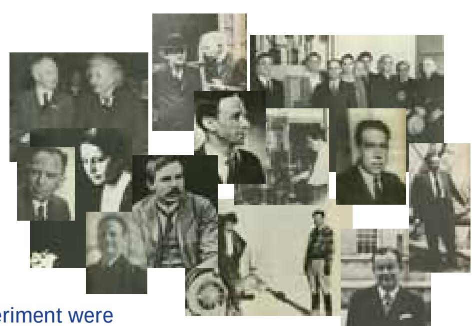
GE | Hitachi

- BWR technology
- Japan

HITACHI

Nuclear Refresher…

Pioneering work from the late-19th century to mid-20th century



Radioactivity… discovered by Becquerel and Curie

Atomic nucleus… discovered by Rutherford

Neutron… discovered by Chadwick

Neutron bombardment… Hahn-Strassman performed an experiment making the Uranium nucleus unstable and produced new isotopes.

Nuclear fission… Meitner-Frisch understood the new isotopes in the Hahn-Strassman experiment were not produced by radioactive decay. It was nuclear fission.

Foundations of nuclear physics… by Bohr

Manhattan project… Three Hungarians convinced Einstein to warn FDR about the potential dangers of an enemy bomb capable of changing the wars

Chicago Pile One… the first nuclear to go critical designed by Fermi et al

HITACHI

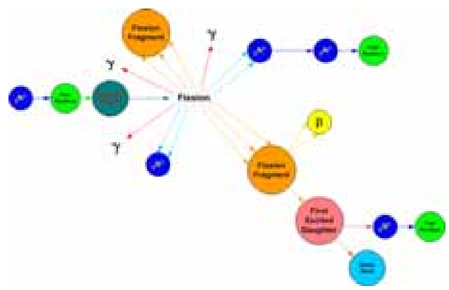
Nuclear fission…

Fissile isotopes… capture a slow neutron and split, e.g. ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu

Fertile isotopes… become fissile upon capturing a neutron, e.g. $^{232}Th \rightarrow {}^{233}U$, $^{238}U \rightarrow {}^{239}Pu$

Fast neutrons… when captured by a heavy nucleus can induce fission, e.g. ^{232}Th, ^{238}U, ^{240}Pu

The fission energy… in the form of kinetic energy of fragments, radiation from reaction, radiation from decaying fragments



HITACHI

Discovered by Fermi slowing down of neutrons made nuclear reactors a reality

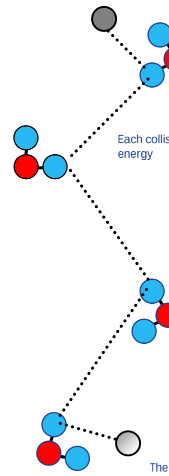
Higher capture cross sections… by heavy nuclei have for slower neutrons

Slowdown of neutrons… can be achieved by collisions with light nuclei

Average number of collisions… that typically takes to slow neutrons down to thermal energies in BWRs is 19

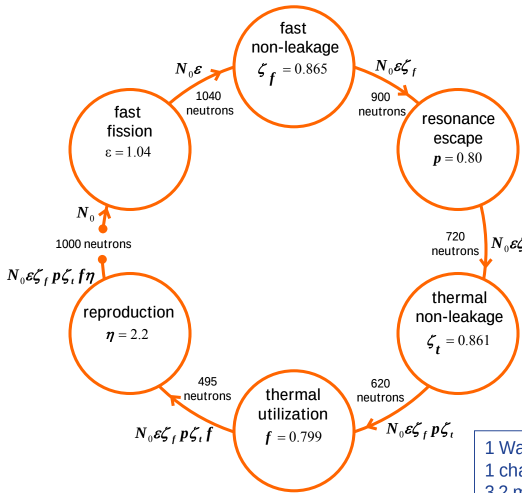
Light water… not only slows down but also shows relatively significant tendency to capture.

Moderator efficiency… is a compromise between scattering and absorption, e.g. Deuterium, Carbon, Beryllium nuclei have less affinity to capture neutrons



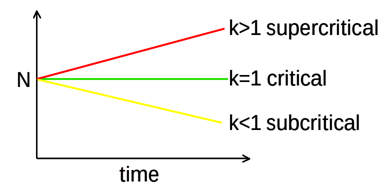
HITACHI

The economics of neutrons, neutronics, is the first step to designing reactors



Multiplication factor:

$$k = N_1/N_0 = \eta f \varepsilon p \cdot \zeta_f \zeta_t$$

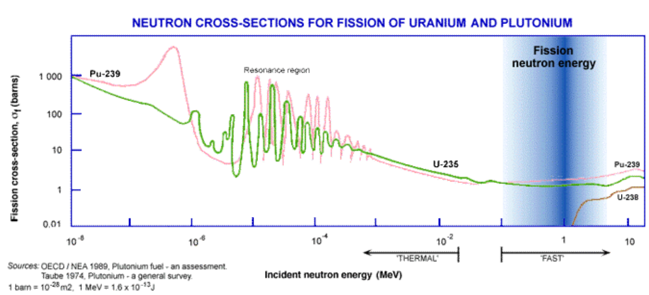


1 Watt = 32 billion reactions/sec
1 chain reacting neutron -> ~10000 reactions/sec
3.2 million chain reacting neutrons will produce 1 Watt

Reaction cross-section…

Target area… correlates the probability of an interaction between an incoming neutron and a target nucleus. Measured in units of barn (1 barn = 10^{-24} cm^2)

Temperature dependent… random thermal motion of target nucleus increases the capture probability of an incoming neutron, and hence, the Doppler broadening of resonance peaks.



Early nuclear reactors were designed and operated during WWII

Chicago Pile Number One... consisted of layers of graphite blocks and Uranium slugs, the first reactor gone critical (Fermi et al, 1942)

Hanford Production Reactors... played a major role in the Manhattan project.

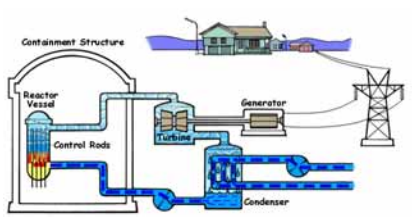
Naval reactor... S2W was a pressurized water reactor to power USS Nautilus (Rickover et al, 1955)

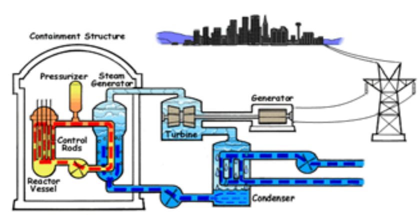
The first reactor... to put electricity on the grid was a boiling water type.

Arco, Idaho became the first community fully powered by nuclear energy on July 17, 1955 by a 15 MWt boiling water type reactor paired to a 2MW generator.

HITACHI

Light water reactors have two types: boiling water and pressurized





Boiling Water Reactors
- Direct cycle
- 70 bar
- The reactor fuel generates steam
- Few plant components
- Small/wet containment
- Simpler reactivity control
- Simpler load following capability
- Higher tolerance to transients

Pressurized Water Reactors
- Dual cycle
- 155 bar
- The heat exchanger generates steam
- Many plant components
- Large/dry containment
- Complex reactivity control
- Complex load following capability
- Lower tolerance to transients

HITACHI

Design advantages of ABWRs

Boiling Thermodynamics

- Low coolant saturation temperature
- High heat transfer coefficients
- Neutral water chemistry

Inherent advantages due to large negative void coefficient of reactivity

- Ease of control using changes in core flow for load following
- Inherent self-flattening of radial power distribution
- Spatial xenon stability
- Ability to override xenon to follow load

HITACHI

Fuel Challenges…

Central to successful design and operation of nuclear reactors

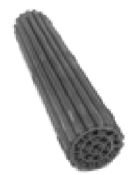
Uranium-235… the only fissile isotope found in nature

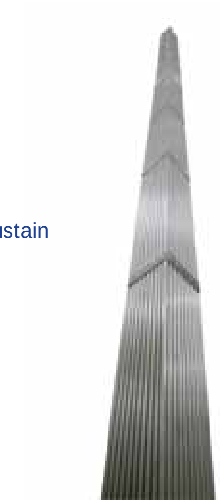
Water moderated… UO_2 in ceramic form inside Zircaloy tubes, immersed in water

Light water… can't sustain chain reacting neutron populations due to absorption of neutrons by Hydrogen

Heavy water… moderate neutrons without significant absorption and sustain critical neutron populations with Natural Uranium

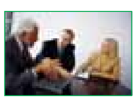
Slightly enriched… Uranium to 2% to 5% and moderated by light water can achieve criticality.





HITACHI

Careful fuel cycle planning

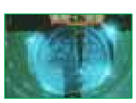


Fuel cycle management… energy requirements, compliance with design criteria for preventing fuel failures, cost

Cycle length… is a utility choice, designed to produce a desired amount of energy

18 months/cycle
30 days/month
x 0.98 capacity factor
530
- 20 days/outage
510

510 day
x 3.9 GW
1989 GWd



Reload analysis… number of bundles, bundle types, enrichment strategies, loading pattern, proven compliance with design criteria

Regulating authority… gives a license to the reactor core before reload

HITACHI

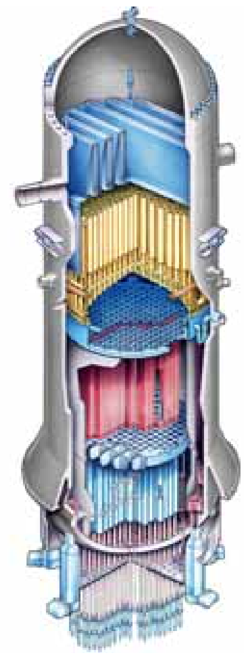
Small parts, large components...

Fuel pellets
(Ø=1cm x1cm)

Fuel rods
(Ø=1cm x 400cm)

Channel box
(13.5cm x 13.5cm x 400cm)

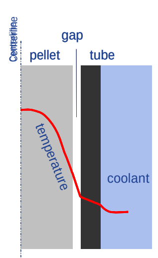
Reactor pressure vessel
(D = 7.1m, H=21.1m)

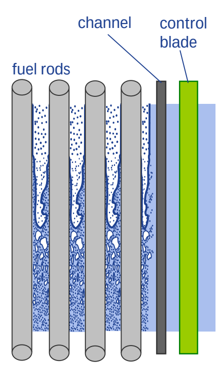


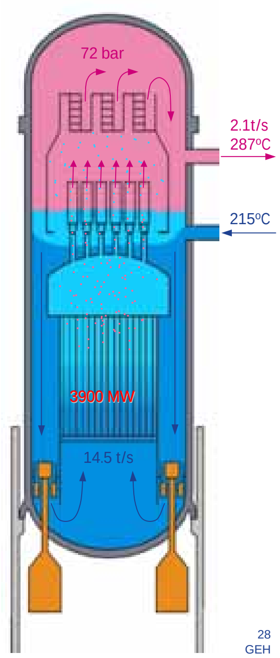
HITACHI

Reactor thermal hydraulics

Avg volumetric heat = ~51 MW/m^3
Avg assembly power = ~4.5 MW
Avg assembly flow = ~16 kg/s







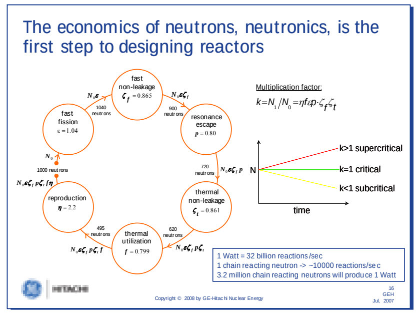
HITACHI

Extra fuel to last until the end of cycle

Sustained chain reacting neutron population... must be maintained throughout the cycle.

Thermal utilization and moderation... will change with burn-up.

Excess reactivity... makes k > 1



HITACHI

Excess reactivity is compensated...

Moving control blades... change power gradually

Burnable absorbers... balance reactivity and help mitigate local peaking

Recirculation flow rate... can change power rapidly

Reactivity... gives the change in multiplication factor

$$\rho = 1 - 1/k$$

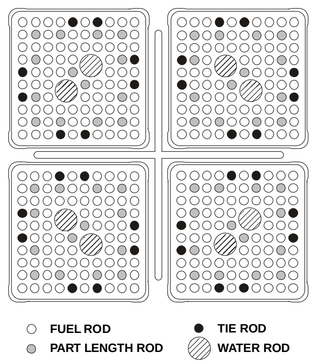
HITACHI

Margins built-in to design relative to safety limits prevent fuel rod failures

Safety limits... (and hence the magnitude of margins) impact the cycle energy efficiency and the cost per KWh

Fuel design criteria

- reactivity limits
- thermal-mechanical limits
- operational limits



Margins to reactivity limits is the objective of a fuel cycle analysis

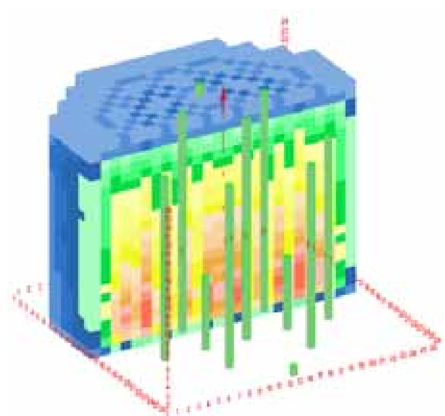
Core loading... minimizes leakage, maximizes utilization

Hot excess... defined as the excess reactivity due to pulling all blades out in hot critical core, curbs the excess reactivity

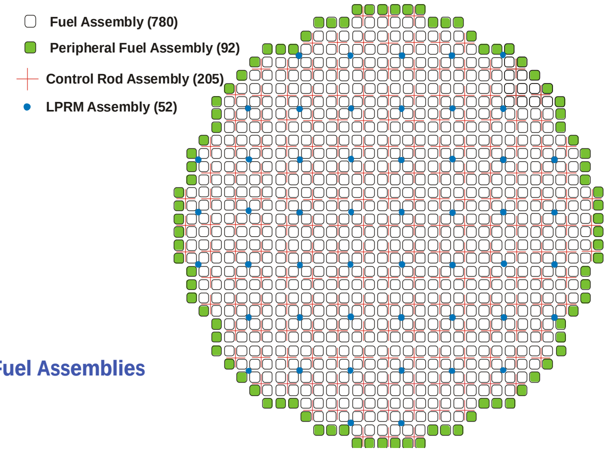
$$\rho_{\text{hot-excess}} = k - 1$$

Cold shutdown margin... introduces a minimum available negative reactivity realized by inserting all blades in a cold critical core.

$$CSDM = 1 - k_{\text{all-blades-in}}$$



ABWR Core Configuration



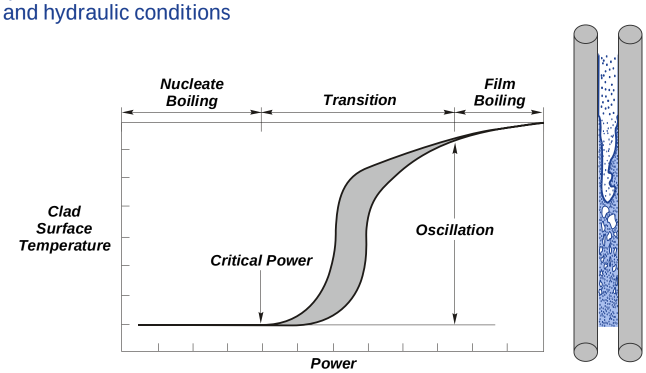
872 Fuel Assemblies

Criteria for transients and accidents are translated to quantitative limits

1. ASME Code compliance for reactor pressure
2. No clad overheating during normal operation and anticipated transients
   – Remain above minimum critical power ratio (MCPR)
   – No damage due to excessive cladding strain from pellet expansion (strain < 1%, no centerline melting)
3. Compliance with 10CFR50.46 limits for accidents
   – Fuel clad temperature < 1200°C
   – Local oxidation < 17%
   – Core wide oxidation < 1%

A power limit is imposed to avoid boiling transition heat transfer

The critical power is not a constant, a function of thermal and hydraulic conditions

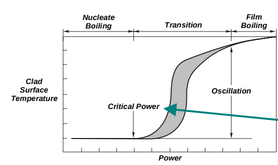


Critical Bundle Power…

The critical power… of a fuel assembly is a function of

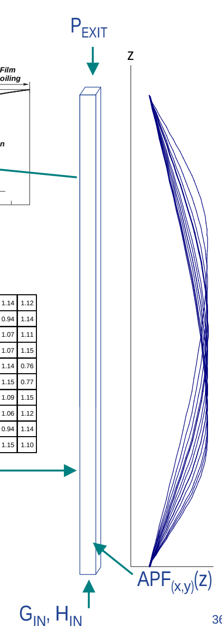
- Mass flux and enthalpy at inlet
- Pressure at exit
- Axial & radial power distribution

Models… are based on experimental data from full-scale electrically heated prototypes



1.01	1.14	1.27	1.16	0.78	0.78	1.15	1.14	1.14	1.12
1.14	0.93	1.10	1.10	1.15	1.13	1.08	1.08	0.94	1.14
1.10	1.05	0.94	1.15	0.94	1.02	1.14	1.10	1.07	1.11
1.14	0.90	1.15	1.03	0.34			0.93	1.07	1.15
0.78	1.17	1.09	0.34	0.34			1.01	1.14	0.76
0.78	1.15	1.02			0.34	0.34	0.92	1.15	0.77
1.15	1.08	0.94			0.34	1.01	0.93	1.09	1.15
1.10	1.07	1.09	0.95	0.93	0.94	0.94	0.93	1.06	1.12
1.14	0.94	1.11	1.07	1.13	1.15	1.08	1.07	0.94	1.14
1.11	1.14	1.10	1.16	0.81	0.77	1.14	1.08	1.15	1.10

r(x,y)

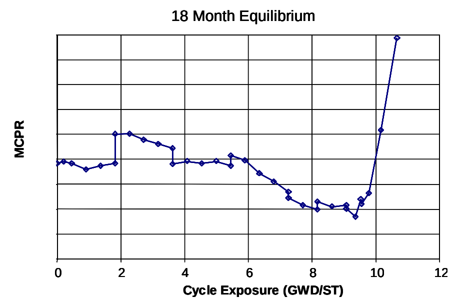


CPR margin…

CPR for all bundles is established at every cycle exposure point

$$CPR = \frac{\text{Critical Power}}{\text{Bundle Power}}$$

The lowest Minimum CPR during a cycle sets the margin to safety limit

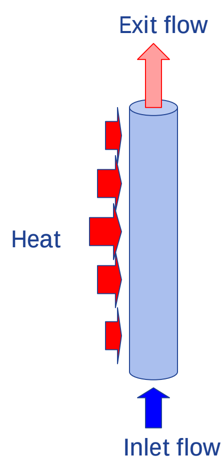


Reactor is analyzed not only at normal conditions but also for transients

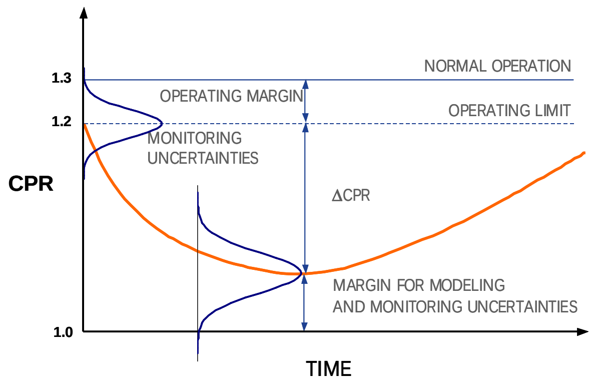
At **steady state**, the inlet and exit flows are identical

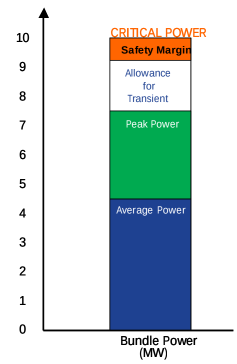
The **flow at inlet** or **heat generation** may undergo a transition

Transient conditions may increase or decrease the fuel temperature



The margin to boiling transition is monitored for anticipated transients





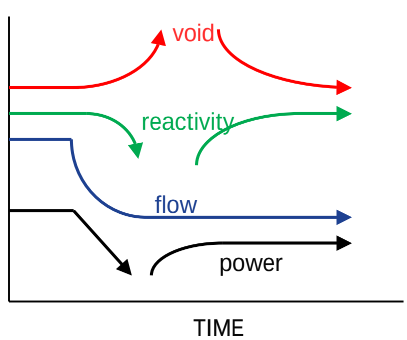
A BWR quickly reacts to a flow transient and reaches a steady power

Flow reduction causes more steam to be produced

Increased void reduces moderation of neutrons

Power goes down

Large void reactivity coefficient overrides the Xenon build up and make ABWR the best plant option for load following.



Analysis accounts for non–uniform core power distribution

Peak bundle power:

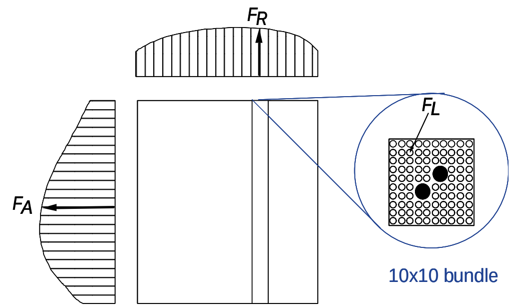
$$Q_{peak} = Q_{avg} F_R$$

Peak planar power:

$$MAPLHGR = \frac{Q_{avg}}{H} F_R F_A$$

Peak linear power:

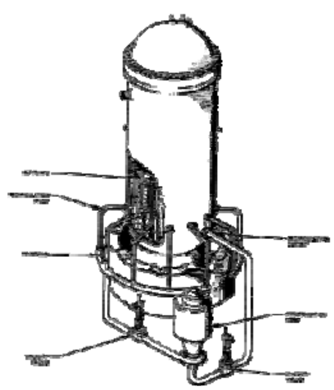
$$MLHGR = \frac{Q_{avg}}{H} F_R F_A F_L$$

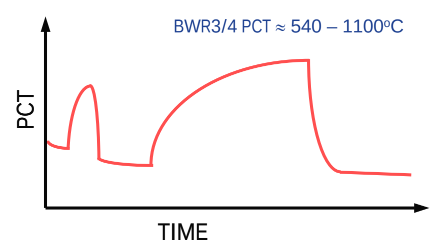


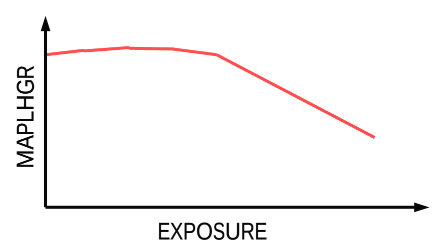
Q: bundle power
H: bundle height

MAPLHGR limits core power to assure sufficient cooling during DBA LOCA

Refill & reflood stage restores liquid and quenches core





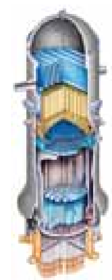


No concern over PCT in ABWR cores

Internal pumps... in ABWR eliminates the large pipes attached to the RPV below core elevation

No core uncovery... in ABWRs after design basis accidents – PCT is not a concern

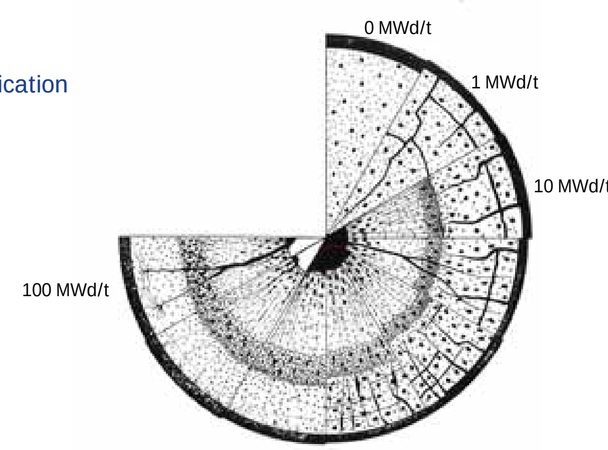
BWR3/4



ABWR

Oxide fuel evolves structurally during irradiation

- Thermal expansion
- Irradiation-induced densification
- Irradiation swelling
- Cracking and relocation
- Creep
- Hot pressing
- Melting
- Rim formation

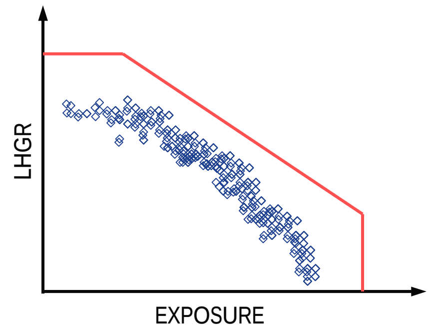


Source: Fundamental Aspects of Nuclear Reactor Fuel Elements, D. Olander

LHGR limits core power due to thermal and mechanical constraints on fuel rod

An envelop of **LHGR vs. Exposure** is used to monitor the heat output

The **no centerline melt** and **strain < 1%** limits are checked for limiting AOOs.



HITACHI

Fuel reliability issues can shut down a nuclear reactor or restrict its operation

Grid-to-rod fretting...is the primary cause of fuel failure in PWRs

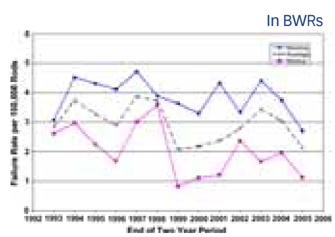
Debris fretting... is the primary cause of fuel failure in BWRs.

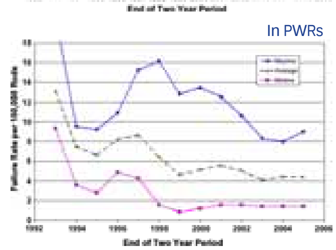
Few isolated cases in BWRs...with relatively large number of failures affecting specific designs

Generic mechanisms in PWRs... led to failures in a number of PWRs.

Significant impact... plant shutdowns, increased surveillances, restrictions on operation, and enhanced regulatory oversight.

No acceptable failure rate... 1 per 100,000 is regarded as "best-in-class"





Source: Rusch et al, "Nuclear fuel performance: Trends, remedies and challenges," J. of Nuclear Materials (in press)

HITACHI

GNF Solutions…

Defense-in-depth…

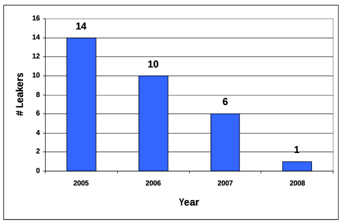
Defense-in-Depth cornerstones

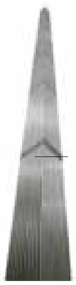
Debris mitigation	PCI/Duty relief
Corrosion mitigation	Manufacturing excellence

Key program attributes

- Debris ingress prevention
- Maximum cladding corrosion resistance
- Real-time plant water chemistry monitoring (including high-risk fuel species)
- Accurate, benchmarked, state-of-the-art methods
- High quality, PCI-resistant pellets
- Robust manufacturing processes

GNF industry leading performance





HITACHI

48
GEH
September 2008

US Nuclear Industry has set a goal to achieve zero fuel failure by 2010

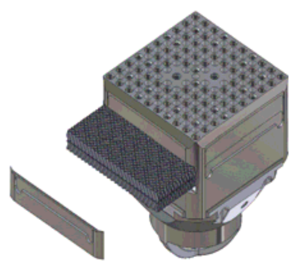
Back to basics
- Defense-in-Depth
- Industry Focused
- Rigorous NPI process
- Accountability
- “Boring” Fuel

Technology
- Differentiated Innovation
- Increased R&D Investment
- Next Generation Fuel
- Next Generation Methods
- Technology Integrator

HITACHI

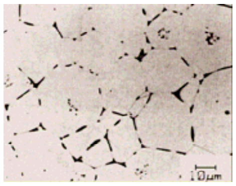
The Defender^{TM} – Next Generation Debris Filtration Technology

Features
• Non-line-of-sight filtration
• Provides filtration technology for GNF’s 10x10 product lines
• Contains thermal hydraulically matched characteristics to the Generation I and II filters
• Superior filtration without increased pressure drop achieved through multi-port, non-line-of-sight filtration combined with two-stage flow redirection and separation



HITACHI

Defense-in-depth



Added protection against pellet cladding interaction (PCI)

• Data gathered through GNF's new gamma scan system are being developed to confirm today's nuclear methods.
• GNF's next-generation methods reflect state-of-the-art technology and world-class accuracy.
• Added operating margin is provided during power maneuvers through soft-duty operating guidelines integrated into the plant process computer.
• The integration of fuel duty into rod maneuver decisions is accomplished through fuel rod stress modeling that is then incorporated in the process computer.
• GNF's additive fuel will provide added protection against PCI, particularly when coupled with GNF's P8 barrier cladding; this is fully demonstrated by ramp tests and operating experience

Manufacturing Excellence. . .

• High quality pellets are delivered through GNF's pellet grinder and optical inspection system.
• Pellet and rod quality are maintained during and after rod load through soft rod loading and handling.
• Improved debris, hydrogenous, and pellet chip control.

HITACHI

GNF2 Advantage^{TM} delivers

Features

High Energy Fuel Rod Design
• Increased Plenum Volume
• High Mass Pellet

Reactivity – Enhancing Part Length Rods
• Optimized Two-Phase Pressure Drop
• Multiple Lengths
• Positioned for Improved Reactivity

Advanced Spacer Design
• Reduced Thickness Inconel Grid
• Flow Wings

Advanced Debris Filter – The Defender™
• Equivalent Pressure Drop
• Debris Shield also Available

Simplified Channel
• Thick Ends and Corners
• Fewer Welds
• Formed Features

Benefits

Reduced Fuel Cycle Costs
• Reduced Batch Size at Constant EUP
• Improved Nuclear Efficiency
• Bundle U Mass
• Improved Axial H/U ratio
• Optimized Cold Shutdown Margin

Increased Energy
• Increased Exposure Capability
• Supports 24-Month Cycles @ 120% Power

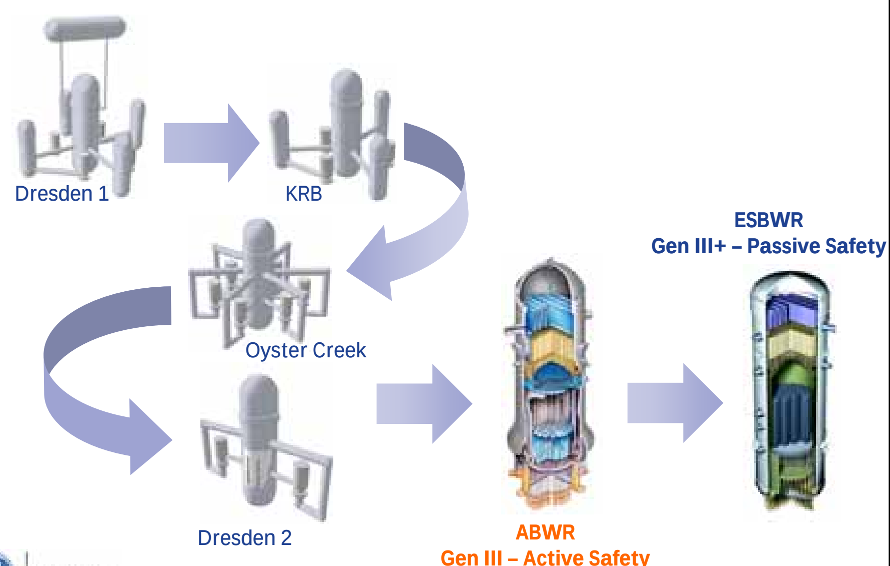
Operating Flexibility
• Accommodates High Assembly Power
• Increased Critical Power Margin
• Increased Loading Pattern Flexibility
• Low Pressure Drop

Reliability and Quality Enhancements
• Enhanced Debris Mitigation (Defender™
•Debris Filter Lower Tie Plate (DFLTP))
• Enhanced Corrosion-Resistant Cladding
• Improved Manufacturing Process

HITACHI

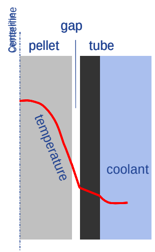
ABWR proven design…

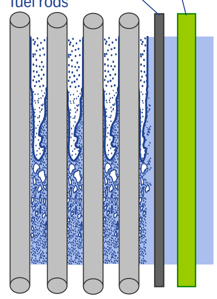
BWR evolution – 50 years in the making

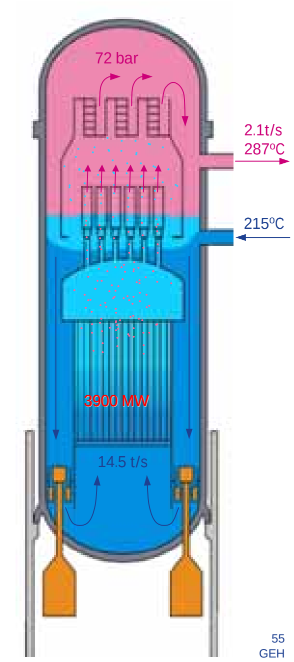


Reactor thermal hydraulics

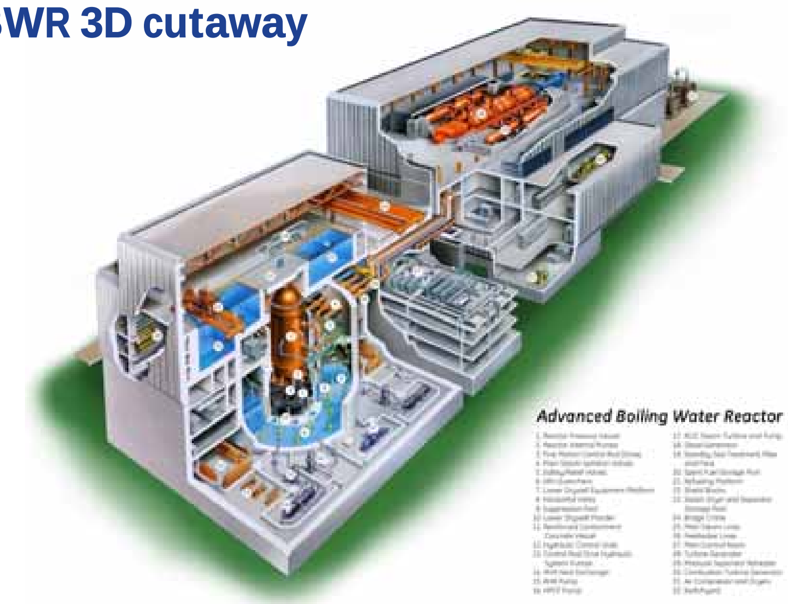
Avg volumetric heat = ~51 MW/m^3
Avg assembly power = ~4.5 MW
Avg assembly flow = ~16 kg/s







ABWR 3D cutaway



ABWR – Generation III… proven design

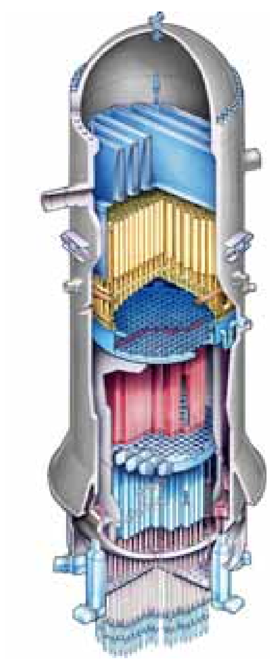
The only advanced GEN III reactor in operation now…

Primary Design Goals
- Design simplification
- Improved safety and reliability
- Reduced construction, fuel and operating costs
- Improved maneuverability
- Reduced occupational exposure and radwaste

Product Achievements
- ✓ Reactor Internal Pumps
- ✓ New CRD Design – Fine Motion
- ✓ Advanced digital controls
- ✓ Multiplexed fiber-optic cabling network
- ✓ Pressure suppression containment w/ horizontal vents
- ✓ No core uncovery in Design Basis Accidents (CDF = 1.7×10^{-7})
- ✓ Cylindrical reinforced concrete containment
- ✓ Structural integration of the containment and reactor building
- ✓ Severe accident capability

HITACHI

ABWR… proven design



Licensed/Certified in 3 Countries
- First Design Certified by USNRC (1997)
- Generation III

Four operating in Japan (First COD 1996)

Several more under construction/planned

Certified Design @ 3,926 MWt or ~1350 Mwe

Significant margins in the nuclear island
(potential for uprates to 1500MWs)

Modern 10x10 fuel product lines with
PCI & corrosion resistant fuel

Extended fuel cycle lengths up to 2 years

Large design margins provide flexibility
(thermal margins >15%)

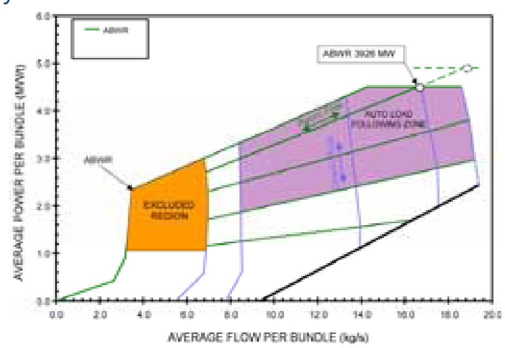
HITACHI

Copyright © 2008 by GE-Hitachi Nuclear Energy

Reactor internal pumps (RIP) and fine motion control rods drives (FMCRDs)

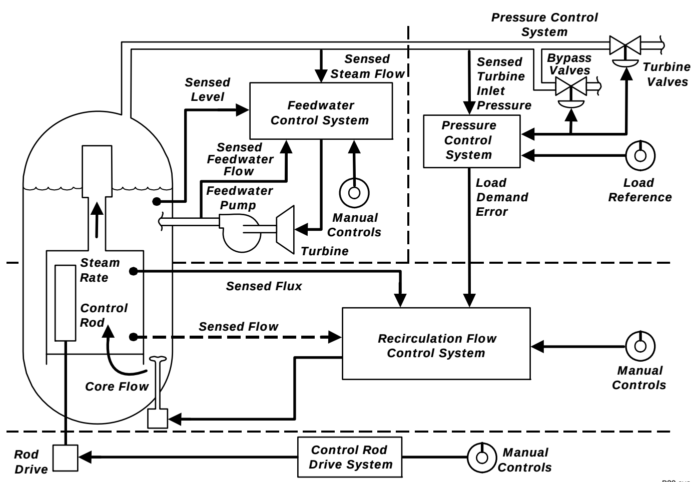
10 internal pumps... give an ability to change power rapidly with pump speed (up to 1%/sec of rated power)

Fine motion control rods... provide additional ability to change power more slowly (1-3%/min of rated power)



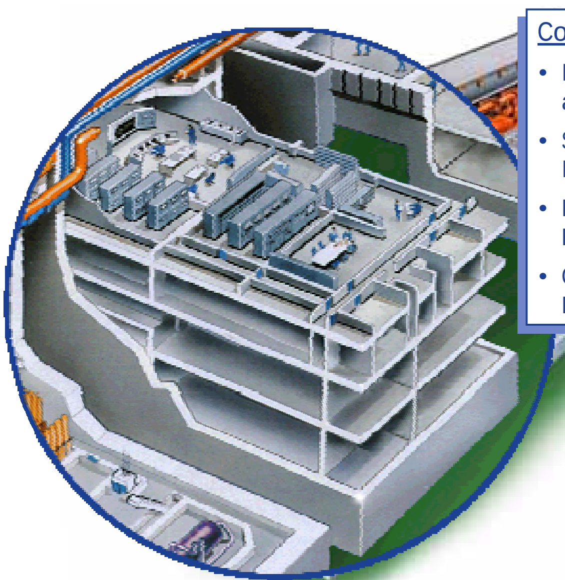
HITACHI

(A)BWR Control systems



HITACHI

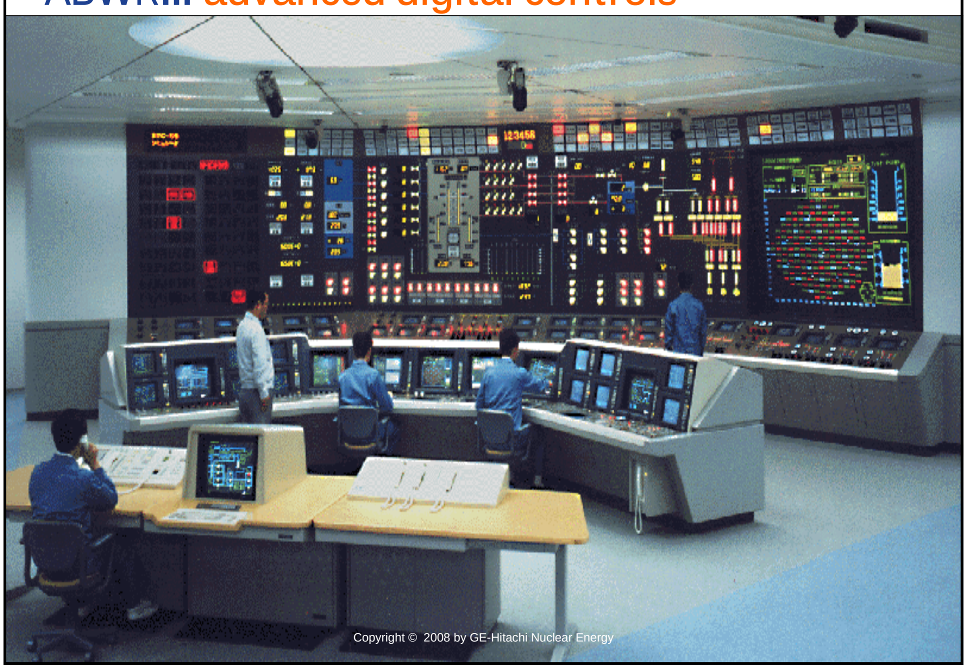
ABWR... advanced digital controls



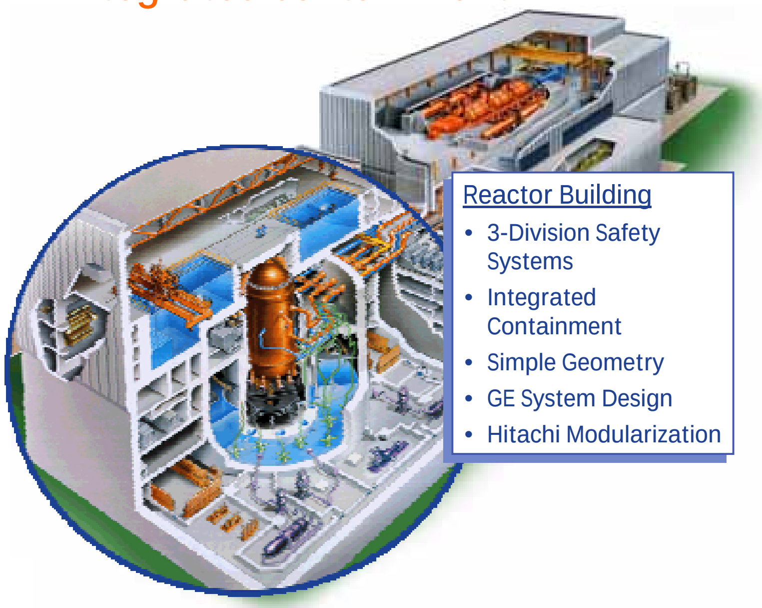
Control Building

- Integrated Digital Control and Protection Platform
- Simplified Man Machine Interface
- Main Control Room Below Grade
- Control System Design Deployed

ABWR... advanced digital controls



ABWR... integrated containment



Reactor Building
- 3-Division Safety Systems
- Integrated Containment
- Simple Geometry
- GE System Design
- Hitachi Modularization

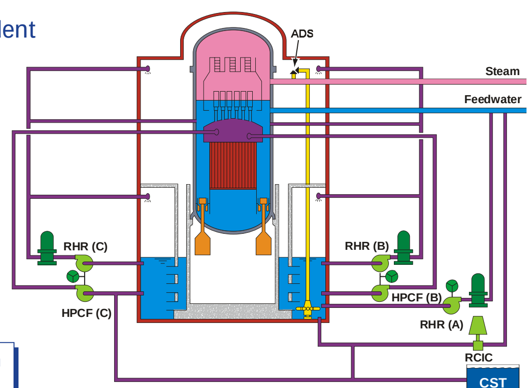
ABWR... 3-division safety systems

Completely redundant and independent mechanical and electrical divisions

Each division has high and low pressure make up capabilities

Three emergency diesel generators, Lungmen has a 4th – swing diesel

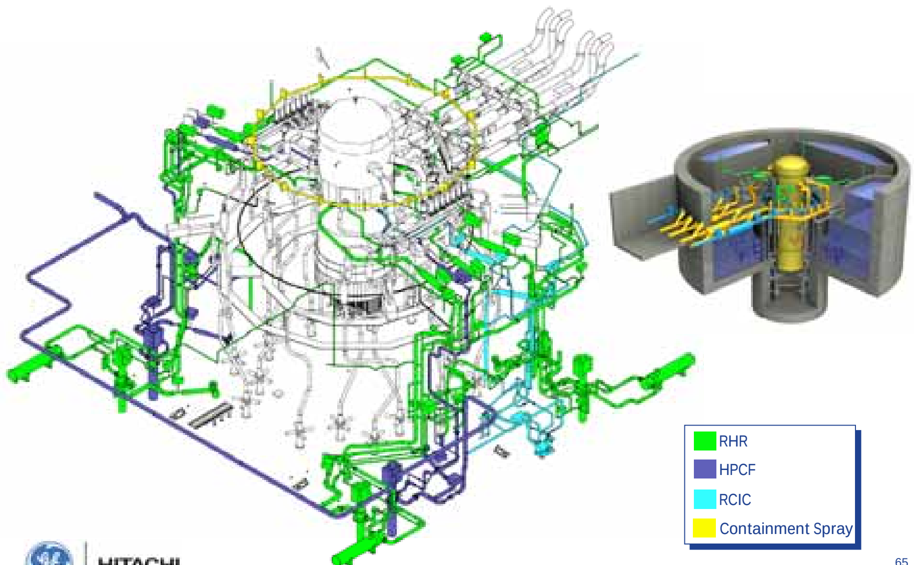
Standard plant design utilizes a large on-site gas turbine generator



ADS – automatic Depressurization
CST – Condensate Storage Tank
HPCF – High Pressure Core Flooder
RHR – Residual Heat Removal

HITACHI

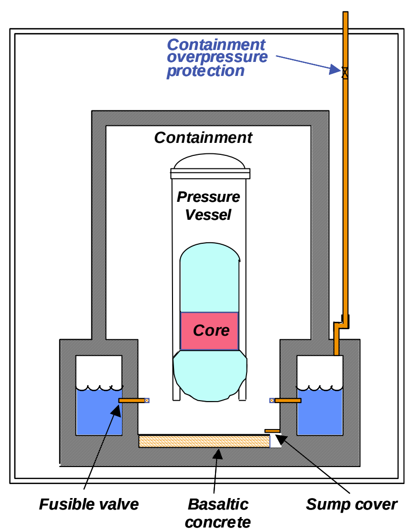
ABWR... ECCS & integrated containment



HITACHI

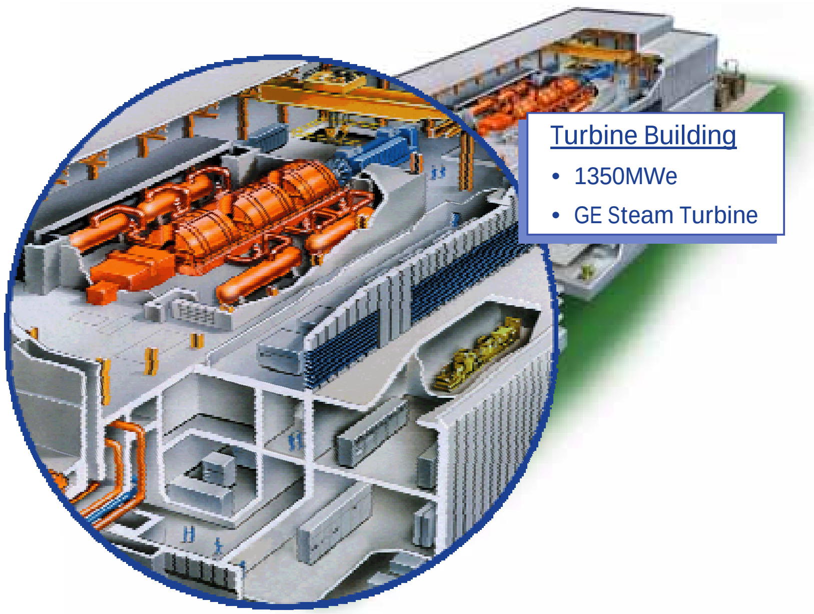
ABWR... Severe accident capability

- Inerted Containment
- Lower drywell flood capability
- Lower drywell special concrete & sump protection
- Suppression pool - fission products scrubbing & retention
- AC Independent water addition via fire pumps
- Containment overpressure protection



HITACHI

ABWR... GE steam turbines

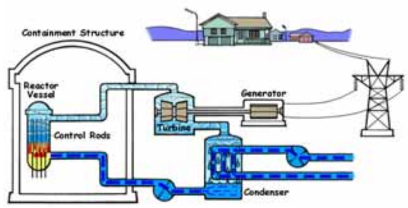


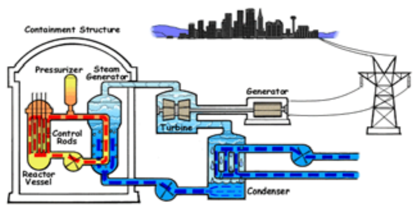
ABWR... enhanced safety, improved O&M

Feature	ABWR	BWR/6
Recirculation	Vessel-mounted Reactor Internal Pumps	Two external loop recirc system with jet pumps
Control Rod Drives	Fine-motion CRDs	Locking piston CRDs
I&C	Digital, multiplexed, FO, multiple channel	Analog, hardwired, single channel
Control Room	Operator-task based	System-based
ECCS	3-division ECCS	2-division ECCS plus HPCS
Reactor Vessel	Extensive use of forged rings	Welded Plate
Primary Containment	Advanced – RCCV, compact, inerted	Large, low pressure, not inerted
Secondary containment	Reactor building	Shield, fuel, auxiliary & DG buildings
Severe accident mitigation	Inerting, drywell flooding, containment venting	Not specifically addressed

HITACHI

Light water reactors have two types: boiling water and pressurized





Boiling Water Reactors
- Direct cycle
- 70 bar
- The reactor fuel generates steam
- Few plant components
- Small/wet containment
- Simpler reactivity control
- Simpler load following capability
- Higher tolerance to transients

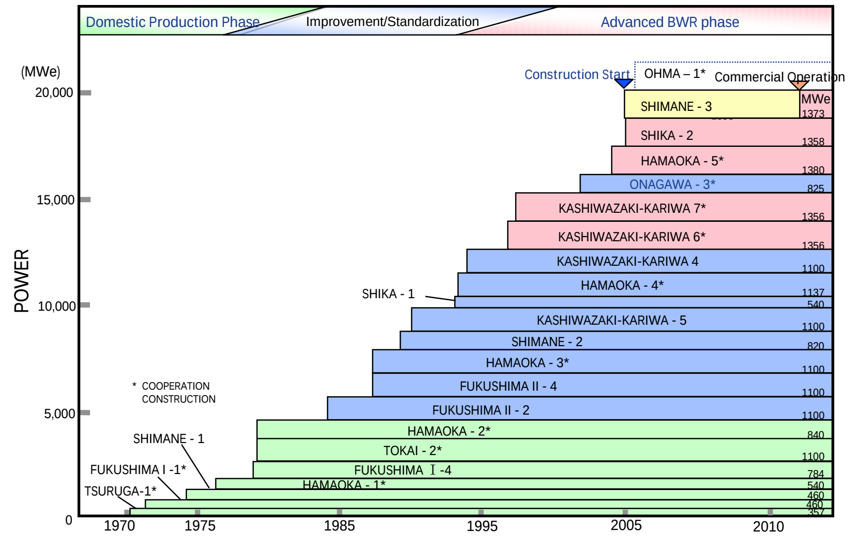
Pressurized Water Reactors
- Dual cycle
- 155 bar
- The heat exchanger generates steam
- Many plant components
- Large/dry containment
- Complex reactivity control
- Complex load following capability
- Lower tolerance to transients

HITACHI

ABWR proven construction/operation...

imagination at work

ABWR...proven construction/operation



Courtesy: Our Alliance Partner, HGNE

ABWR...proven construction/operation

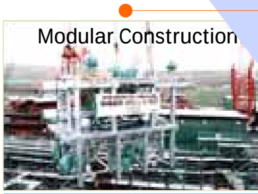
Evolution of Construction Technologies

1st Generation
Open-Top Construction
with Tower Crane

1985

2nd Generation
Large Crawler Crane for
Block/Modular Construction

1990



3rd Generation (ABWR)
Expanded Open-Top/Parallel Construction
Expanded Block/Modular Construction

2000

4th Generation (ABWR)
- Dedicated Module Factory
- Hybrid Module, Block/Module Enlargement
- Ubiquitous Technology for Logistics and Progress Control

Courtesy: Our Alliance Partner, HGNE

Summary

- ABWR – the only Gen III advanced plant proven in operation
- Designed & built with the customer in mind – increase safety, reduce O&M
- More than 20 reactor-years of commercial operation
- Proven advanced construction techniques, demonstrated construction schedule