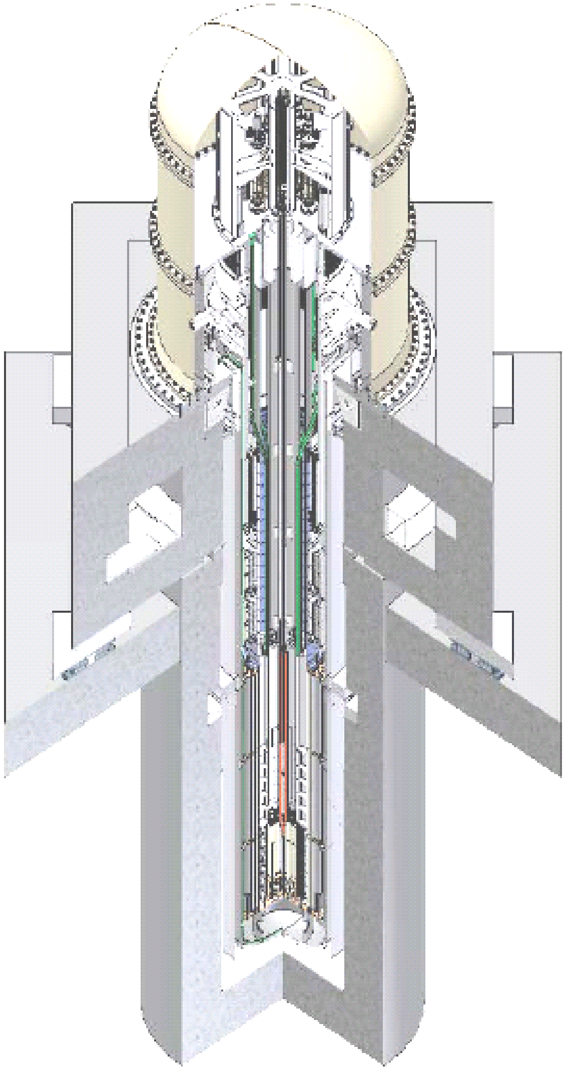
4S Reactor

Super-Safe, Small and Simple



Second Meeting with NRC
Pre-Application Review

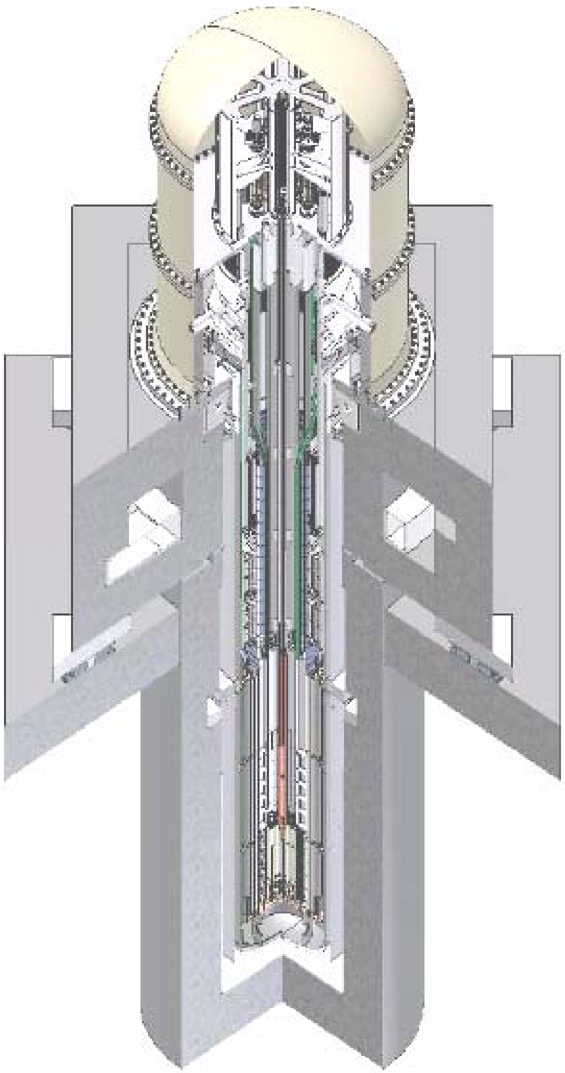
February 21, 2008

CRIEPI
TOSHIBA
Leading Innovation
Westinghouse

Meeting Agenda

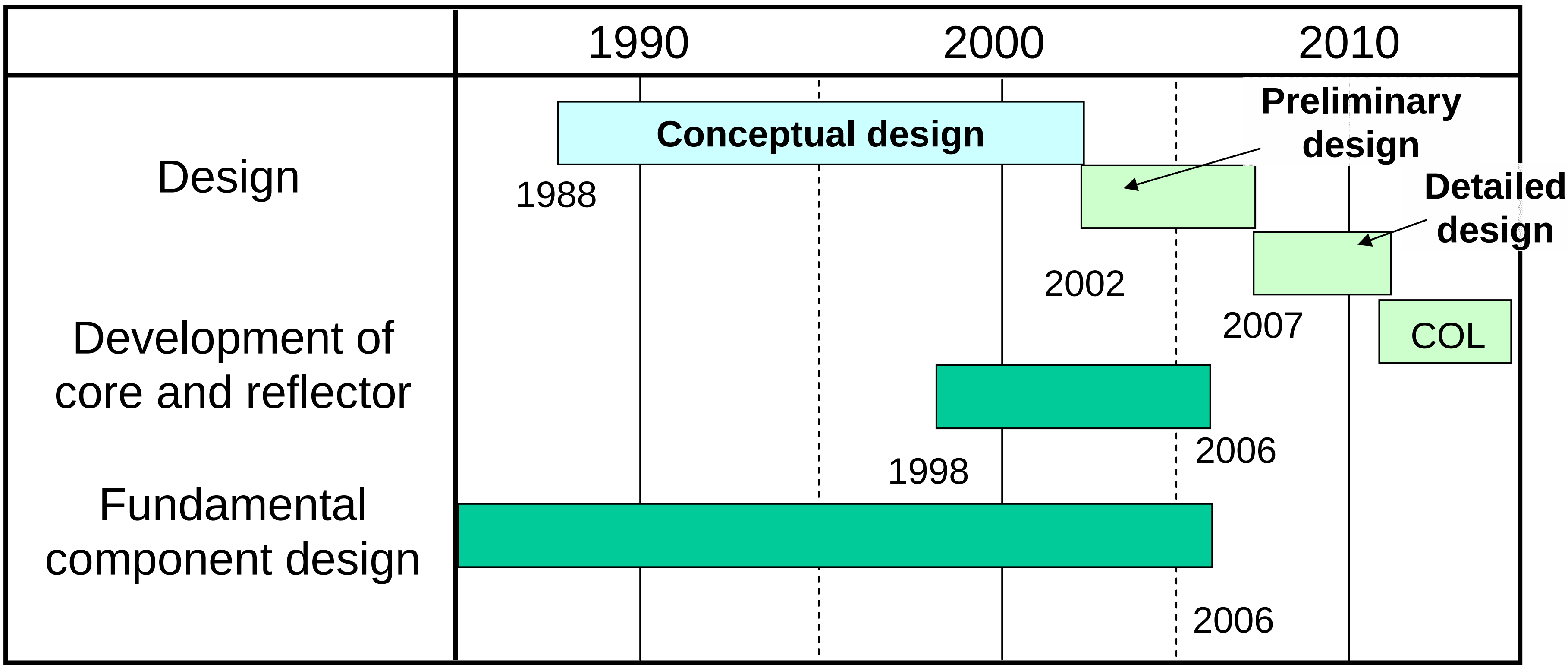
- **Program Overview** – Dr. Richard F. Wright, Westinghouse
- **System Design** – Dr. Richard F. Wright, Westinghouse
- **Long Life Metallic Fuel** – Dr. Abdellatif Yacout, ANL
- **Conclusions** – Dr. Richard F. Wright, Westinghouse

Program Overview



Current Status of 4S Design

- Preliminary design for reactor and HTS is complete.
- Preliminary safety design is complete.
- Over 50 international technical papers exist in open literature.



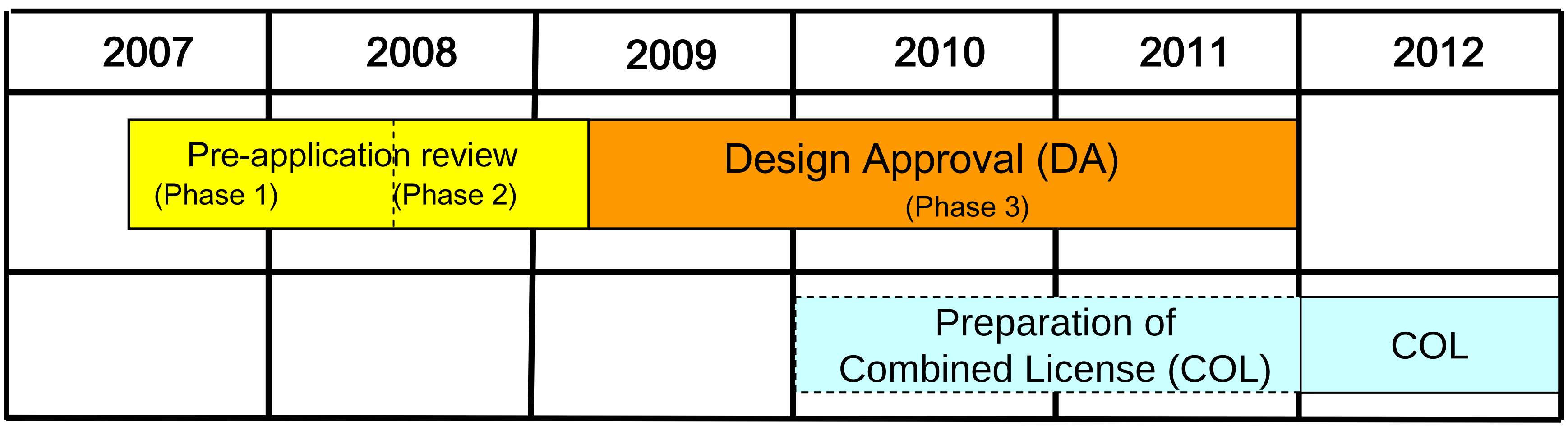
CRIEPI

TOSHIBA
Leading Innovation

Westinghouse

Proposed Licensing Approach

- **Submit Design Approval application in 2009**
  - **Phase 1:** Complete a series of meetings with NRC to identify issues to be addressed before Design Approval application
  - **Phase 2:** Submit technical reports and obtain NRC feedback to address the issues identified in Phase 1
  - **Phase 3:** Submit Design Approval application and obtain FSER
- **Application referencing Design Approval application – Toshiba expects U.S. customer will submit a COL .**



Phase 1 – Proposed Licensing Approach

	2007	2008	
	4Q	1Q	2Q
1st Meeting High level overview	▼		
2nd Meeting – Today System design Long-life metallic fuel		▼	
3rd Meeting* Safety design and regulatory conformance			▼
4th Meeting* PIRT review			▼

* Subject to NRC concurrence

CRIEPI TOSHIBA Leading Innovation Westinghouse

Phase 2 – Proposed Licensing Approach

- **Schedule of technical reports for NRC review**

– Long-life metallic fuel		
• Analysis methodology		
• Fuel performance	April	2008
– Safety analysis		
• Analysis methodology		
• Safety analysis results	October	2008
– PIRT & test program	November	2008
– Seismic isolation	December	2008
– Responses to NRC questions	December	2008

Summary of the First Meeting

October 23, 2008

- **High level overview**
  - Schedule and organization
  - Plant overview
- **Plant design parameters**
- **Regulatory conformance**
- **Main design features**
  - Key features of 4S and safety features including:
    - Passive safety
    - No on-site refueling for 30 years
    - Low maintenance requirements
    - High inherent security

Summary of the First Meeting (cont)

October 23, 2008

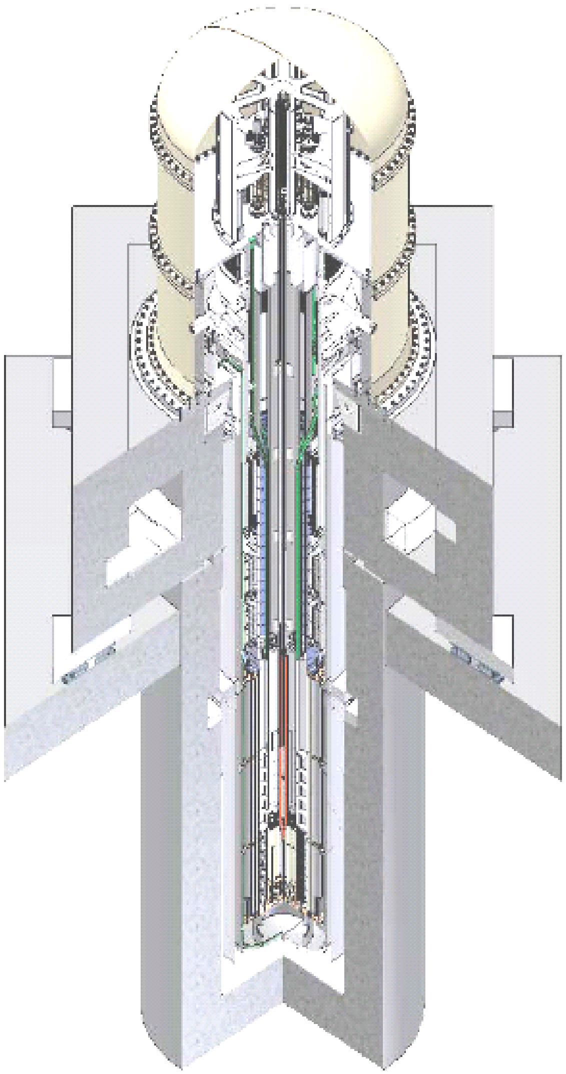
- **Metallic fuel experience and design verification tests**
  - Large experience base for metallic fuel
  - Tests include critical experiments, sodium tests of EM pump, double-walled steam generator, etc.
- **Safety analysis**

Near term action:

Hold a series of 4S topical and design familiarization meetings with the staff in coming months

4S Reactor

Super-Safe, Small and Simple



Second Meeting with NRC
Pre-Application Review

System Design

February 21, 2008

CRIEPI

TOSHIBA
Leading Innovation

Westinghouse

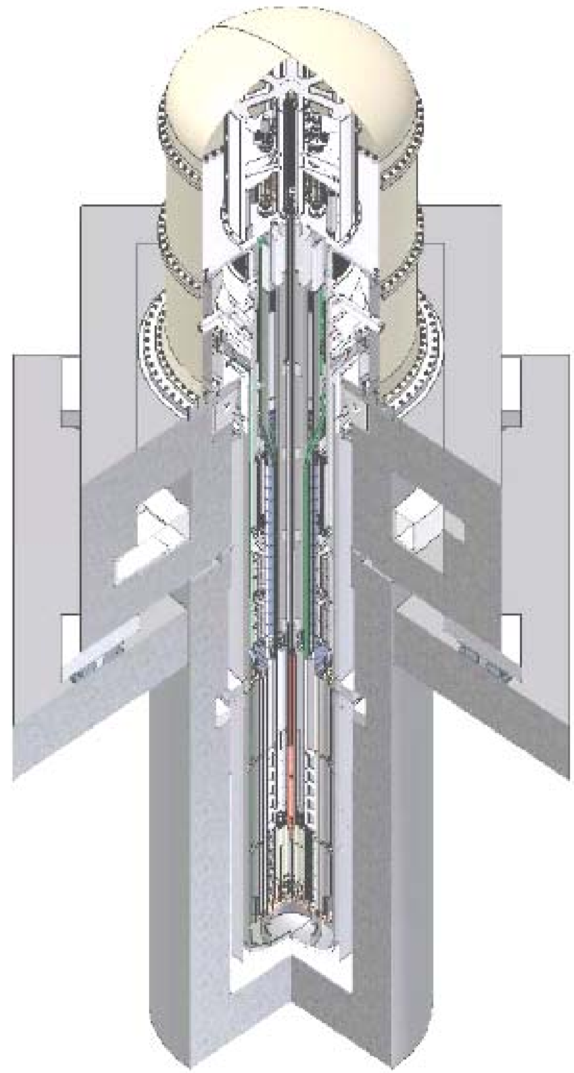
Presentation Overview

- Presentation Purpose
- Plant Description
- Core and Fuel
- Heat Transport System
- Containment System
- Instrumentation and Controls
- Summary

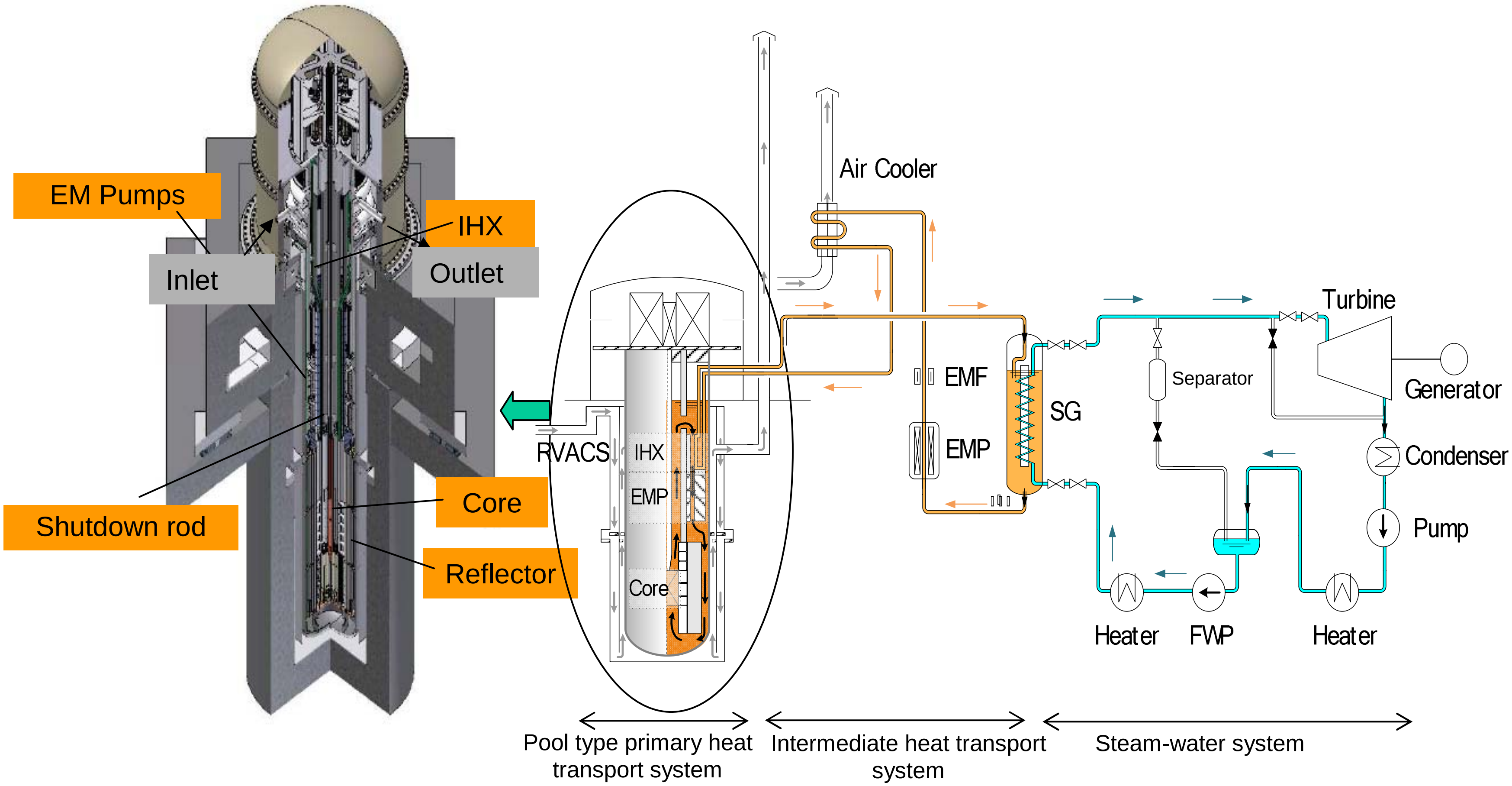
Presentation Purpose

- Familiarize the NRC with the 4S system design
- Obtain NRC feedback in areas related to 4S system design

Plant Description



4S System Configuration



CRIEPI TOSHIBA Leading Innovation Westinghouse

Plant Design Parameters

- **Plant Parameters**

– Electric output	10 MWe
– Core thermal output	30 MWt
– Number of loops	1
– Primary sodium inlet/outlet temperature	355 / 510°C (671 / 950°F)
– Primary sodium flow rate	547 t/h
– Intermediate sodium inlet/outlet temperature	310 / 485°C (590 / 905°F)
– Intermediate sodium flow rate	482 t/h
– Turbine throttle conditions	Flow rate: 44.2 t/h Pressure: 10 MPa (1450 psi) Temperature: 450°C (842°F)

CRIEPI TOSHIBA Leading Innovation Westinghouse

Plant Design Parameters (cont.)

- **Reactor Core**

– Core height	2.5 m (8.2 ft)
– Equivalent core diameter	0.95 m (3.1 ft)
– Fuel / cladding material	U-10%Zr / HT-9 steel
– 235U enrichment (inner / outer)	17 / 19 %
– Average burnup	34,000 MWd/t

- **Reactor Vessel**

– Design pressure	0.3 MPa (44 psi)
– Design temperature	550°C (1022 °F)
– Inner diameter / thickness	3.5 m / 25 mm (12 ft / 1.0 inch)
– Total height	24 m (79 ft)
– Material	Type 304 stainless steel

Plant Design Parameters (cont.)

- **Heat Transport Systems**

– Primary EM pump	Single stator type Linear annular induction pump
– (IHX)Intermediate heat exchanger	Shell-and-tube type Straight tube
– Steam generator	Double wall tube helical coil type Modified 9Cr-1Mo Steel

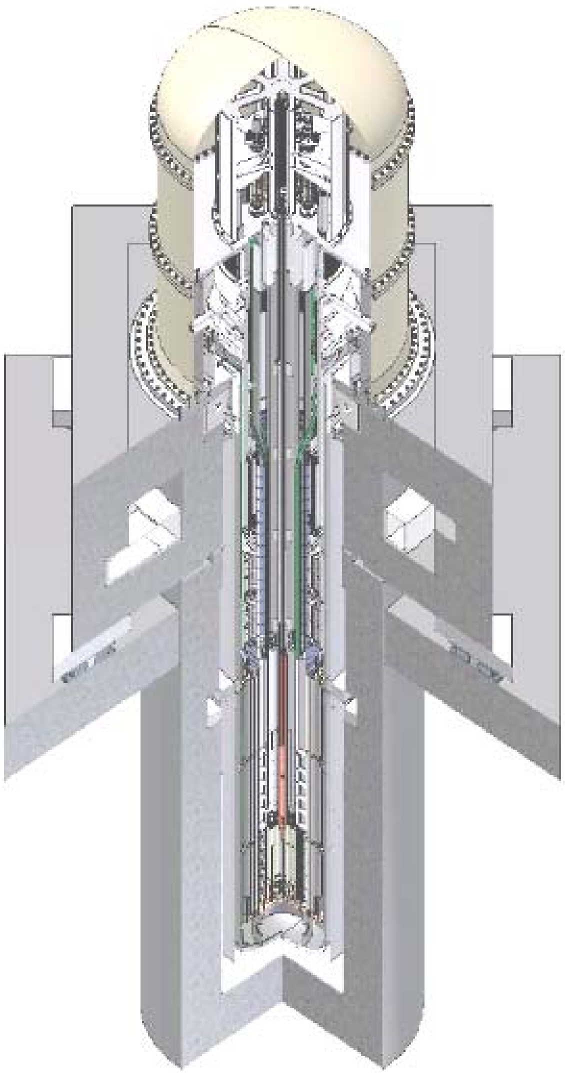
- **Containment**
  - Guard vessel and top dome

- **Reactor Building**

– Dimensions	29 m long	(95 ft)
	24 m wide	(79 ft)
	22 m high	(72 ft)

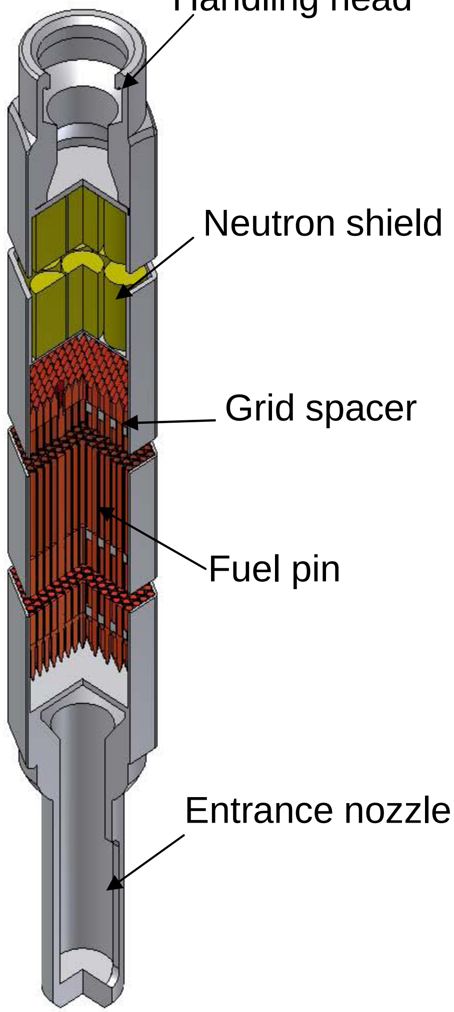
CRIEPI TOSHIBA Leading Innovation Westinghouse

Core and Fuel



Fuel Design

• **Fuel material**	U-10% Zr (metal)
• **Fuel pin diameter**	14 mm
• **Smear density (BOC)**	78%
• **No. of pins/assembly**	169
• **Spacer type**	Grid
• **Cladding material**	HT-9
• **Duct material**	HT-9

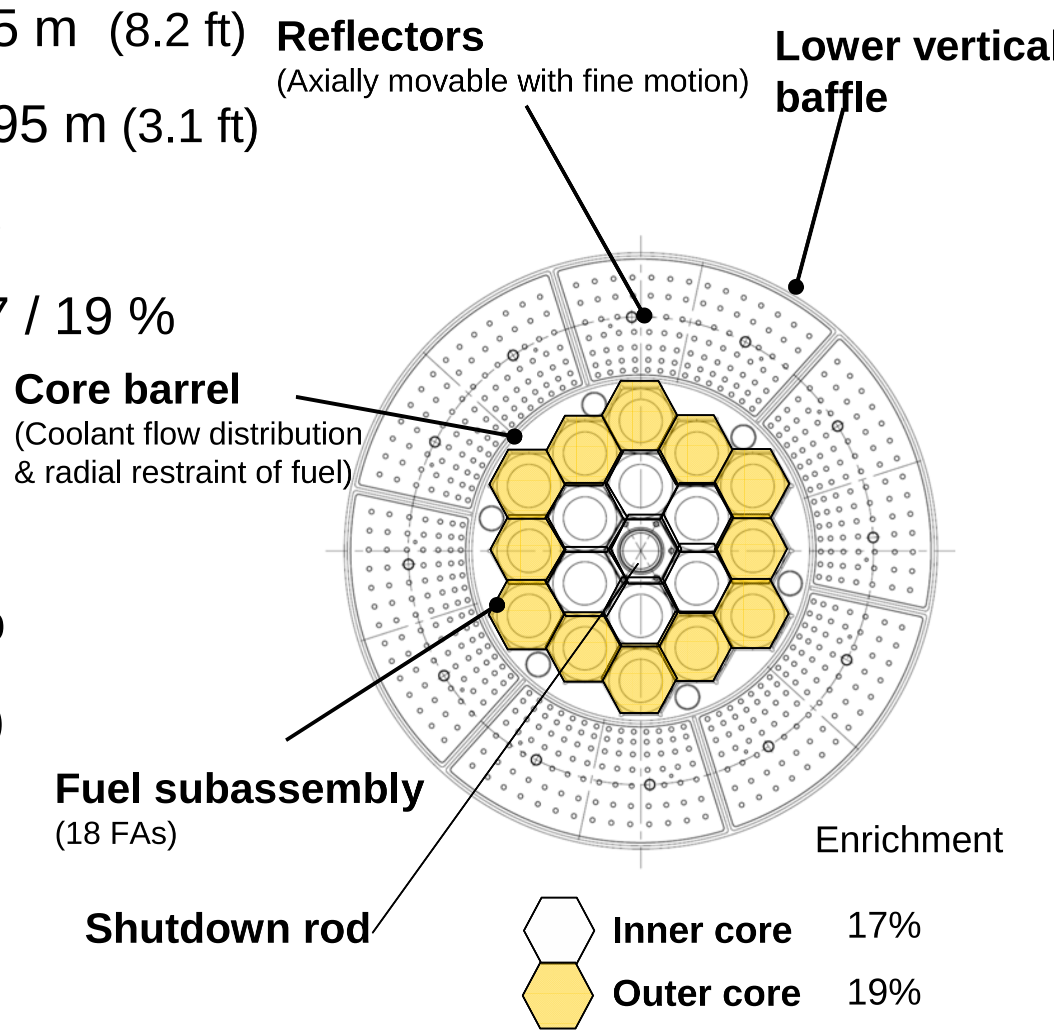


CRIEPI TOSHIBA Leading Innovation Westinghouse

Core Design -Neutronics-

- Core
  - -Core height 2.5 m (8.2 ft)
  - -Equivalent core diameter 0.95 m (3.1 ft)
  - -Fuel subassembly number 18
  - -Enrichment (inner/outer) 17 / 19 %
- Reflector
  - -Movable annular reflector
  - -Material Mod9Cr1Mo
  - -Size Thickness 38 cm (1.2 ft)

    Height 2.7 m (8.8 ft)



CRIEPI TOSHIBA Leading Innovation Westinghouse

Core Design -Thermal Hydraulics

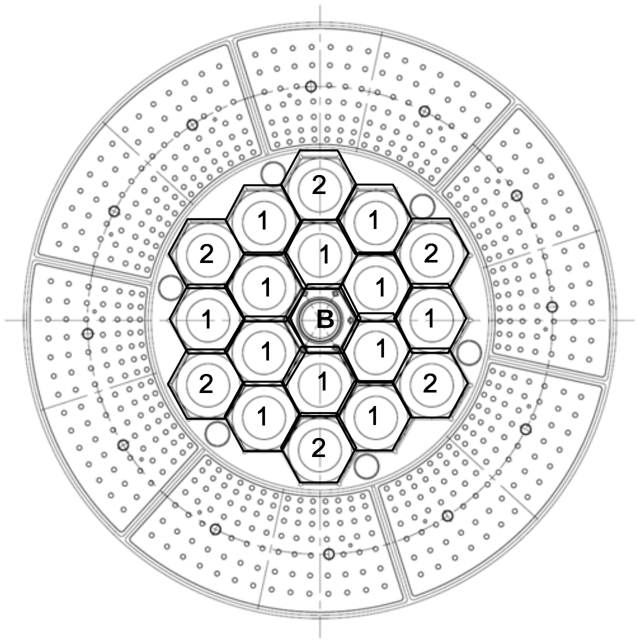
- Outlet/inlet temp. 510 / 355 deg.C
- Pressure drop 0.1 Mpa
- Core flow rate 152 kg/s
- Flow distribution

  Two orifice zones

  Flow rate 1 8.4 kg/s

  2 7.4 kg/s
- Cladding hot spot temp.

  609 deg.C (1129 F)

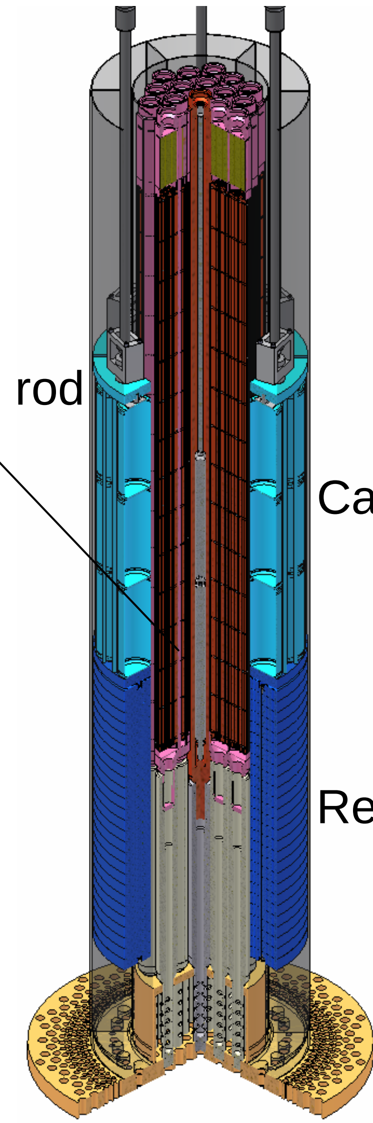


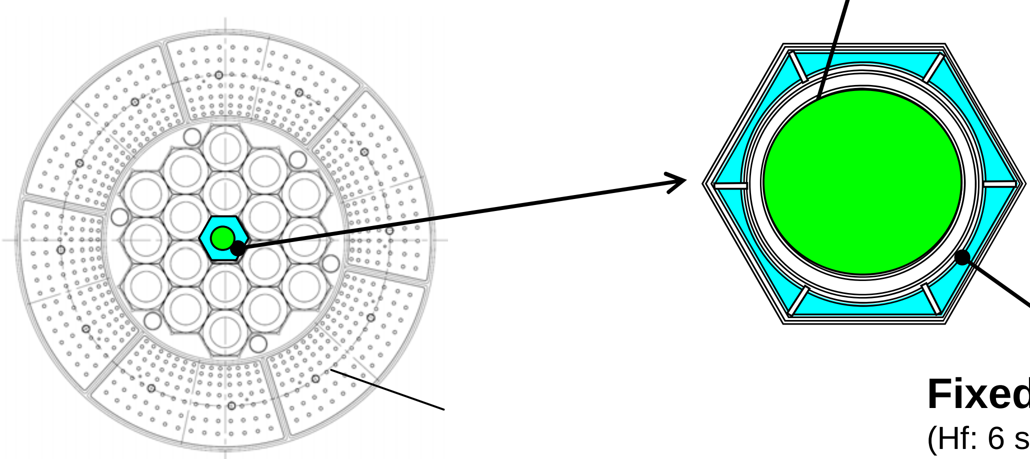
Orifice zone
B: Shutdown rod
1: Inner core
2: Outer core

Reactivity Control

- **Material**

Reflector	Modified 9Cr-1Mo
Cavity	Modified 9Cr-1Mo
Shutdown Rod	B_4C
Fixed Absorber	Hf





Reflectors
(Axially movable with fine motion,drop down for scram)

CRIEPI TOSHIBA Leading Innovation Westinghouse

Reactivity Control

Available Systems	Reflector	Shutdown Rod	Fixed Absorber
Start up & normal shutdown	✓	✓	-
Burn-up compensation	✓	-	✓
Scram (Gravity)	Δ*	Δ	-

✓ – Needed

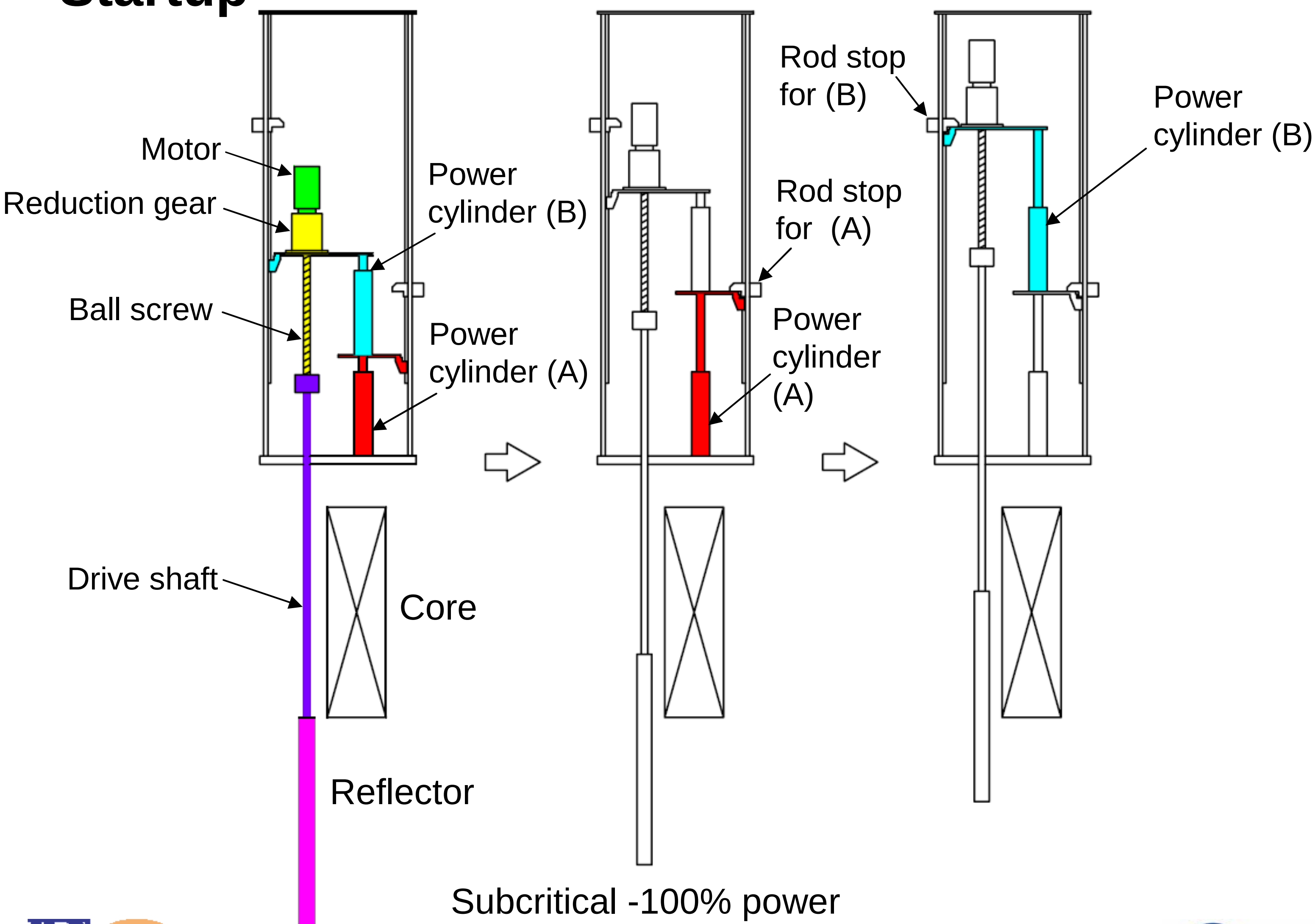
Δ – Redundant and diverse

* - Provides one reflector stuck margin

CRIEPI TOSHIBA Leading Innovation Westinghouse

Reactivity Control –Startup-

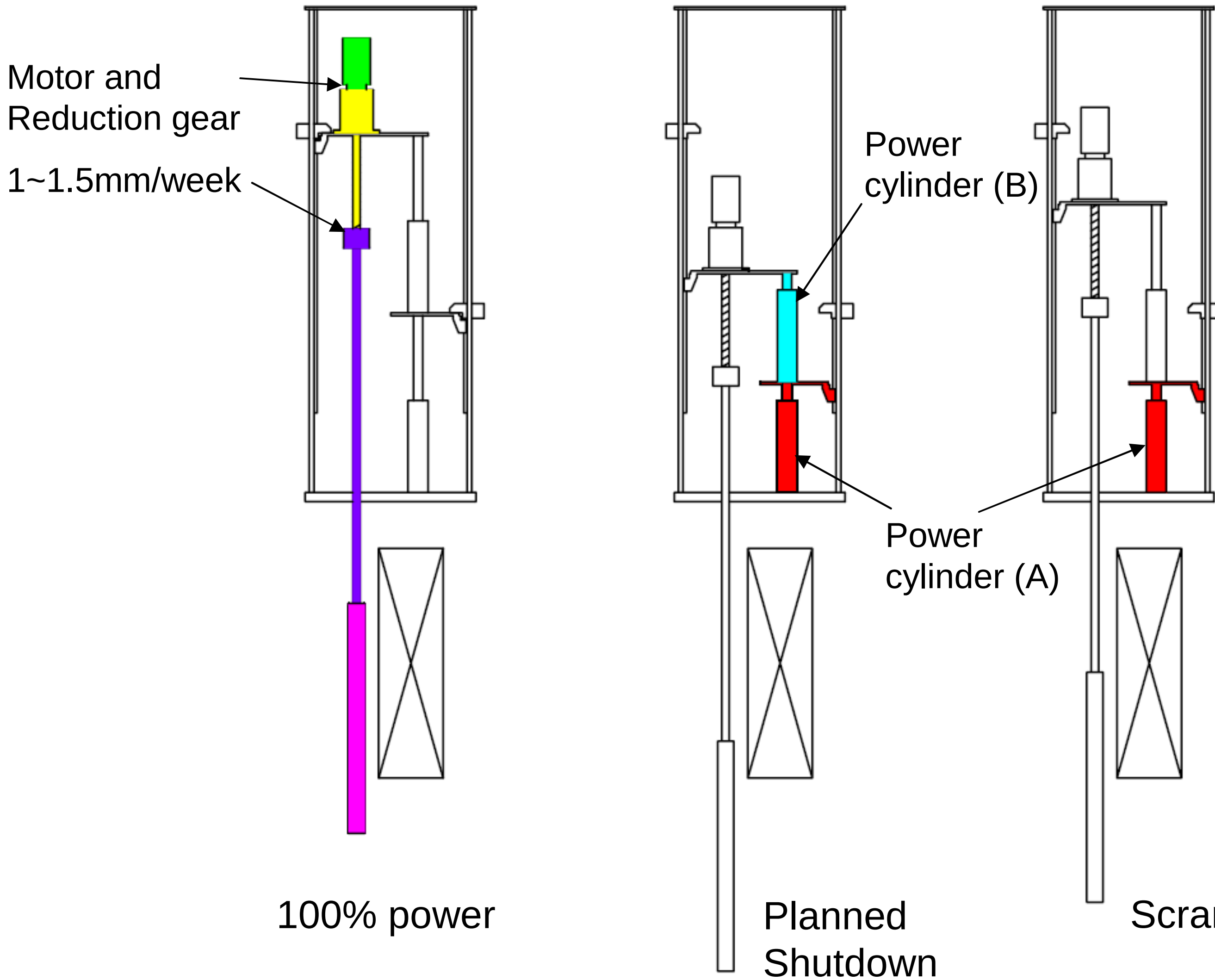
- **Startup**



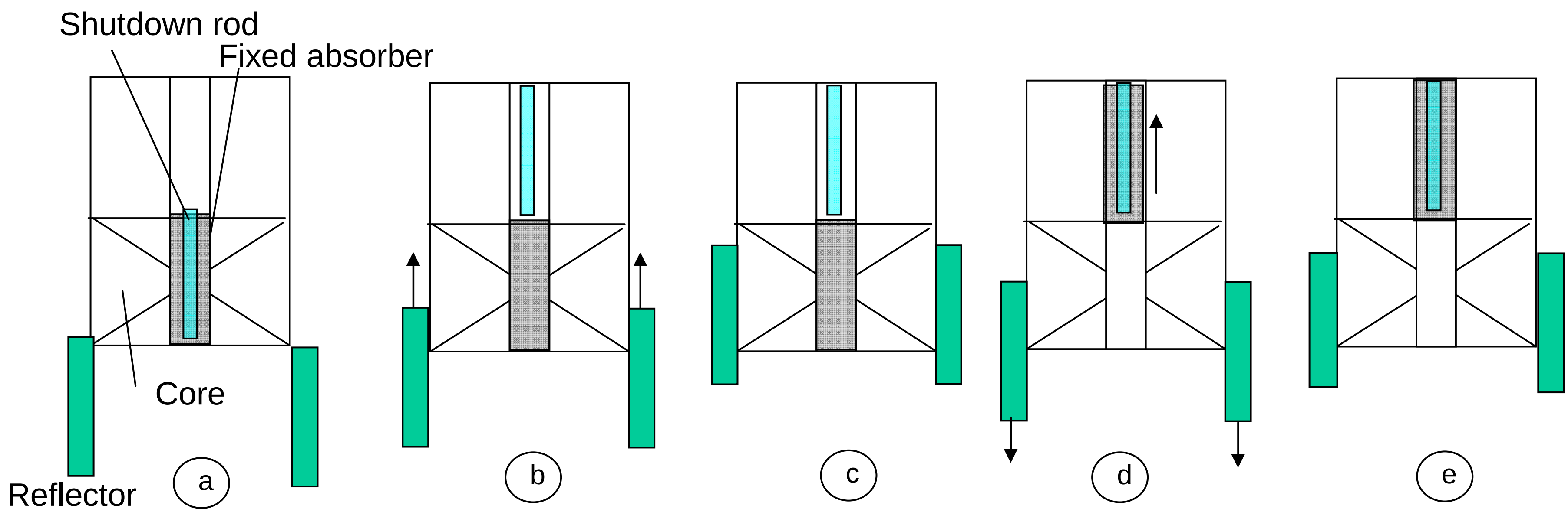
Subcritical -100% power

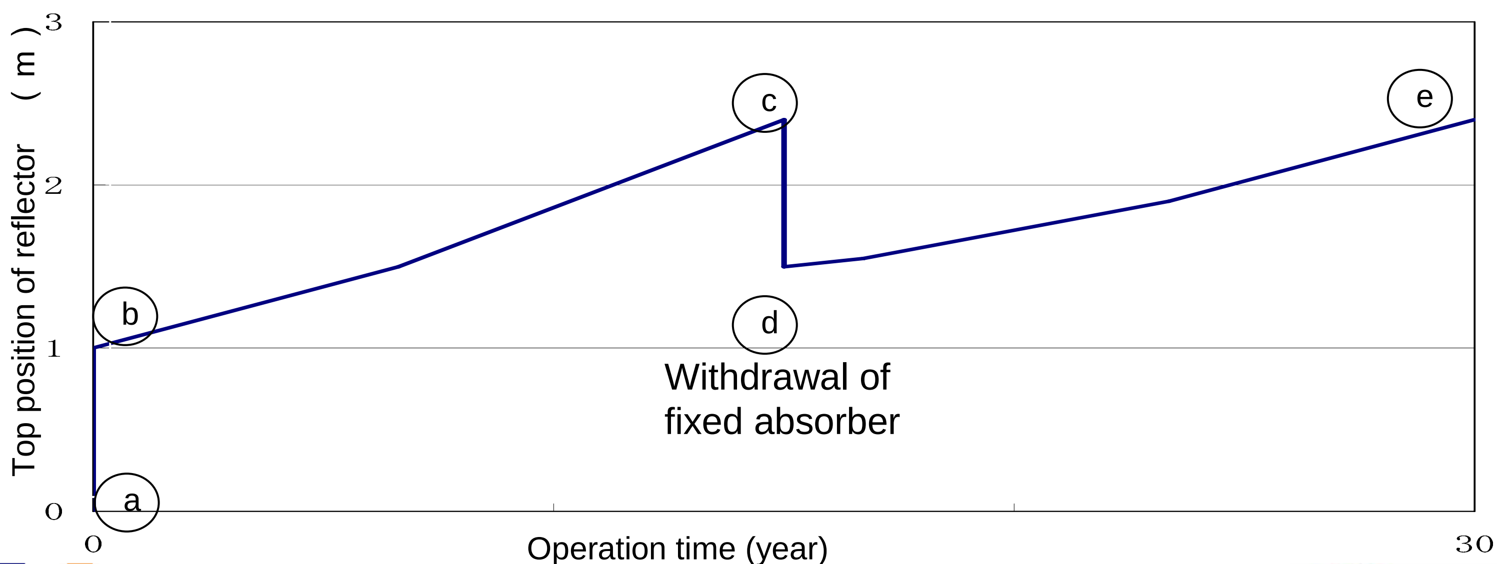
Reactivity Control – Shutdown, Scram-

- **100% power, Shutdown, Scram**

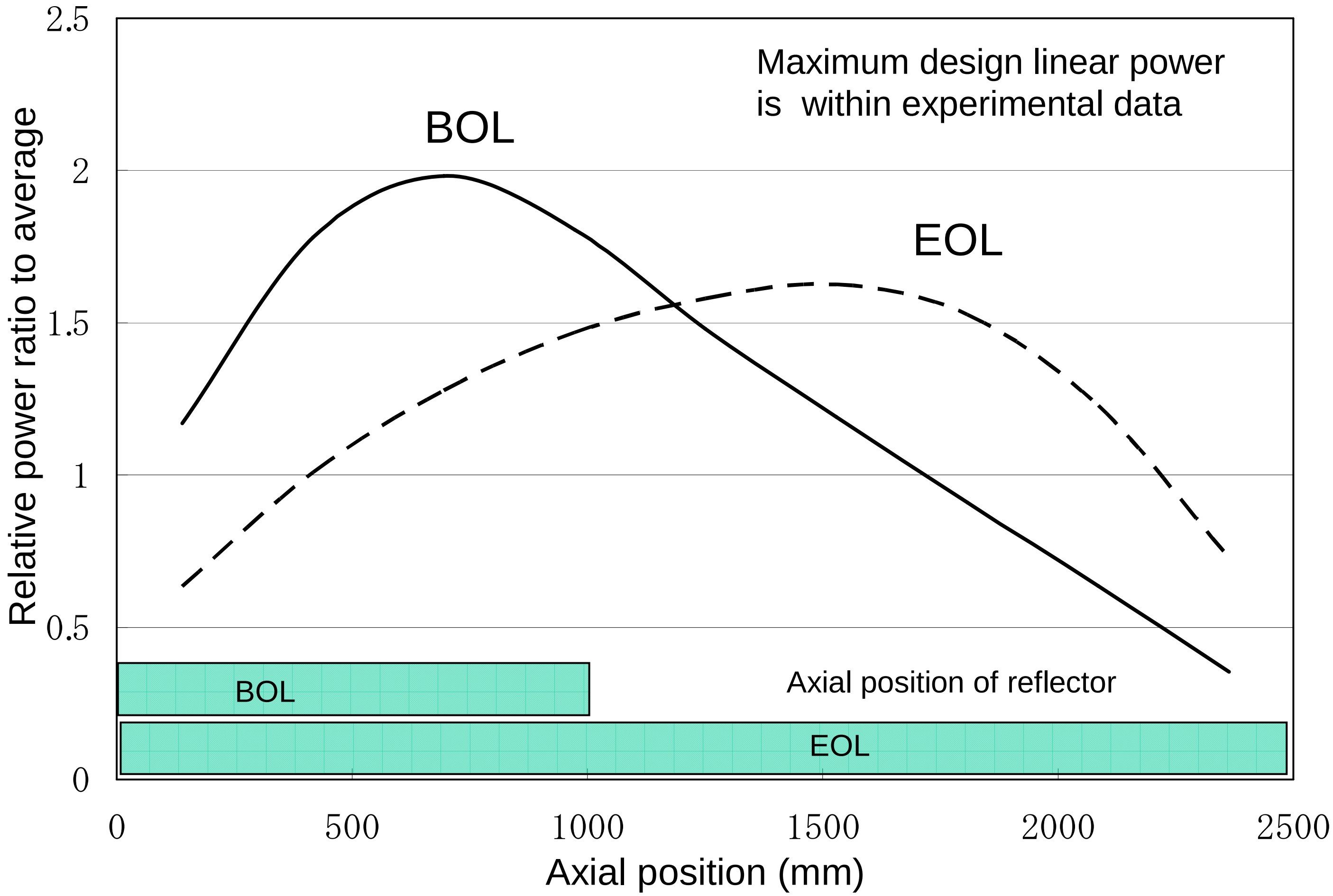


Burn-up Compensation



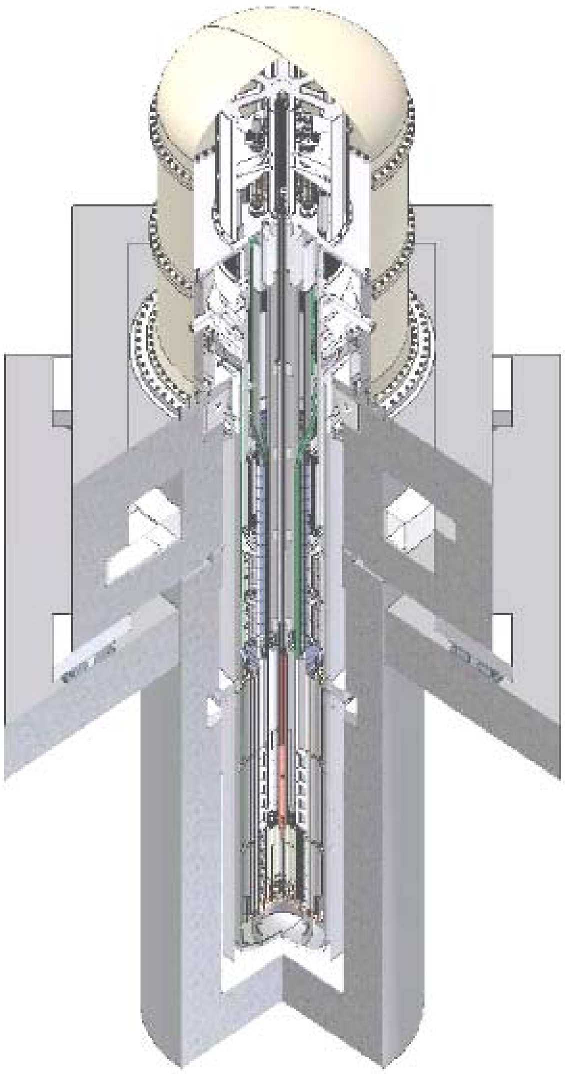


Axial Power Distribution

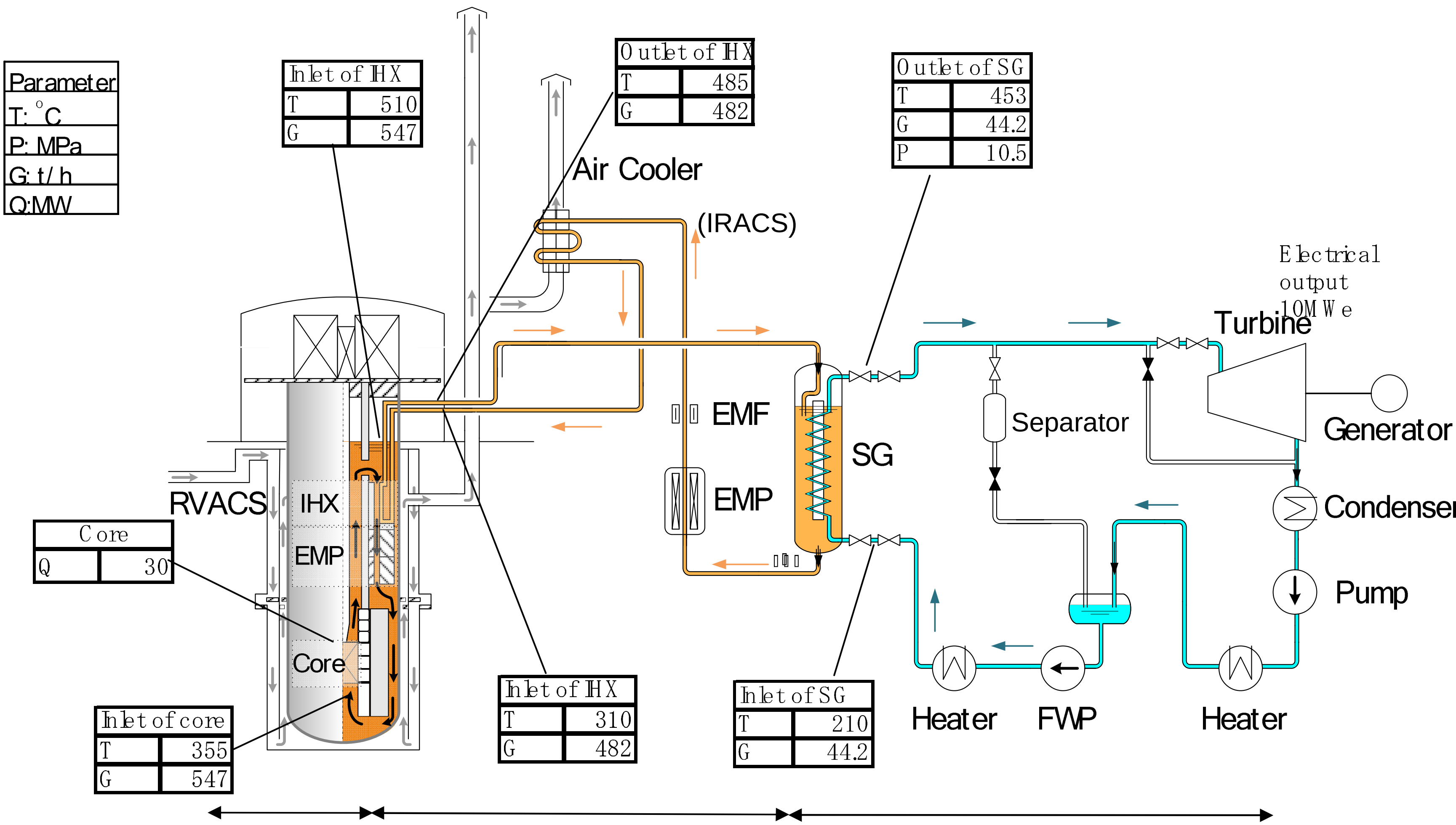


Relative Power distribution of a fuel pin in inner core region

Heat Transport Systems



Heat Transport Systems



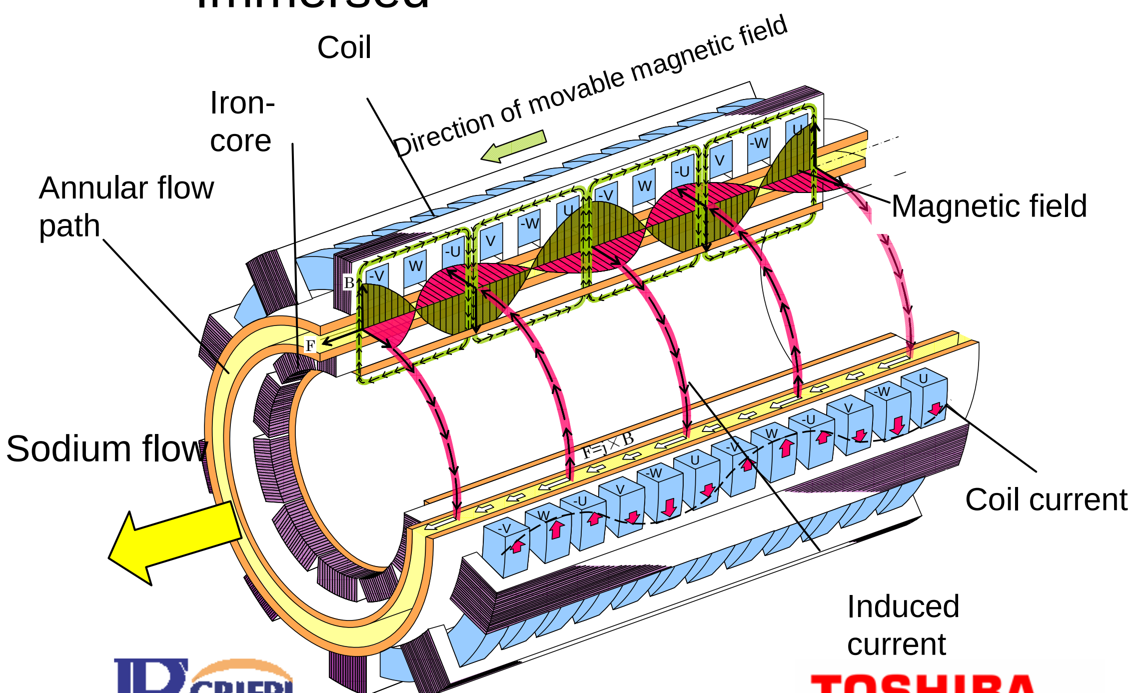
Primary heat transport system

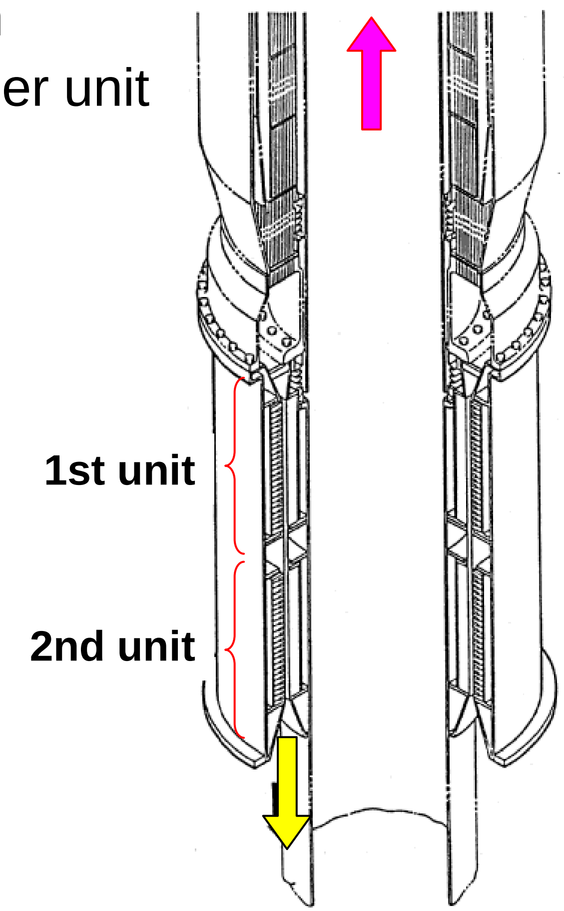
Intermediate heat transport system

Steam-water system

Primary EM Pumps

- Performance
  - Flow rate 10.6 m^3/min
  - Rated discharge pressure 0.05 MPa per unit
- Type
  - Annular linear induction EM pumps
  - Single stator
  - Immersed





EM pumps in series

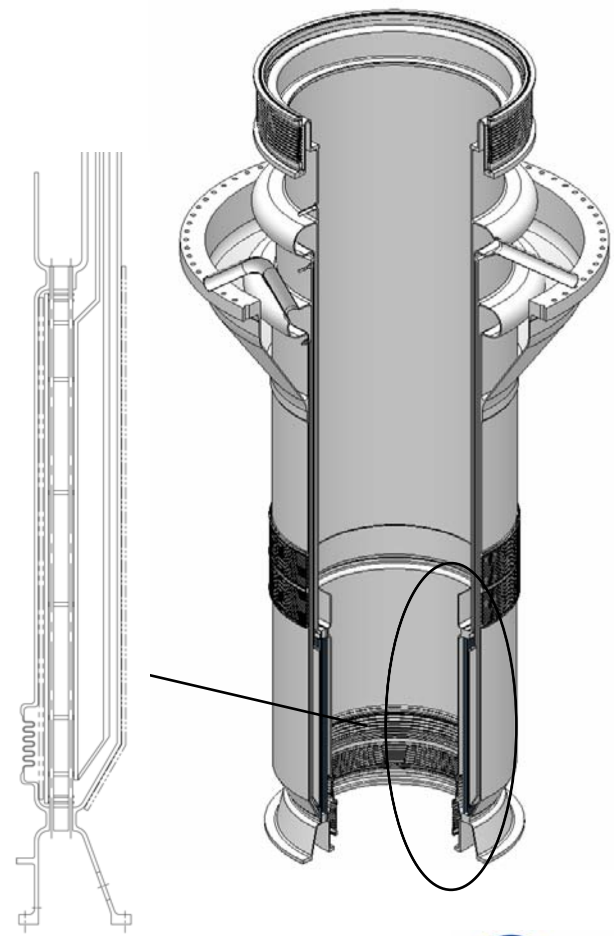
CRIEPI

TOSHIBA Leading Innovation

Westinghouse

Intermediate Heat Exchanger

- Performance
  - Heat exchange capacity
- Type
  - Located inside the RV
  - Shell and tube IHX
  - Primary coolant in tube inner s
  - Intermediate coolant in shell s
  - Annular arrangement
  - Tube number 1074
  - Tube diameter 21.7 mm
  - Four tube radial rows



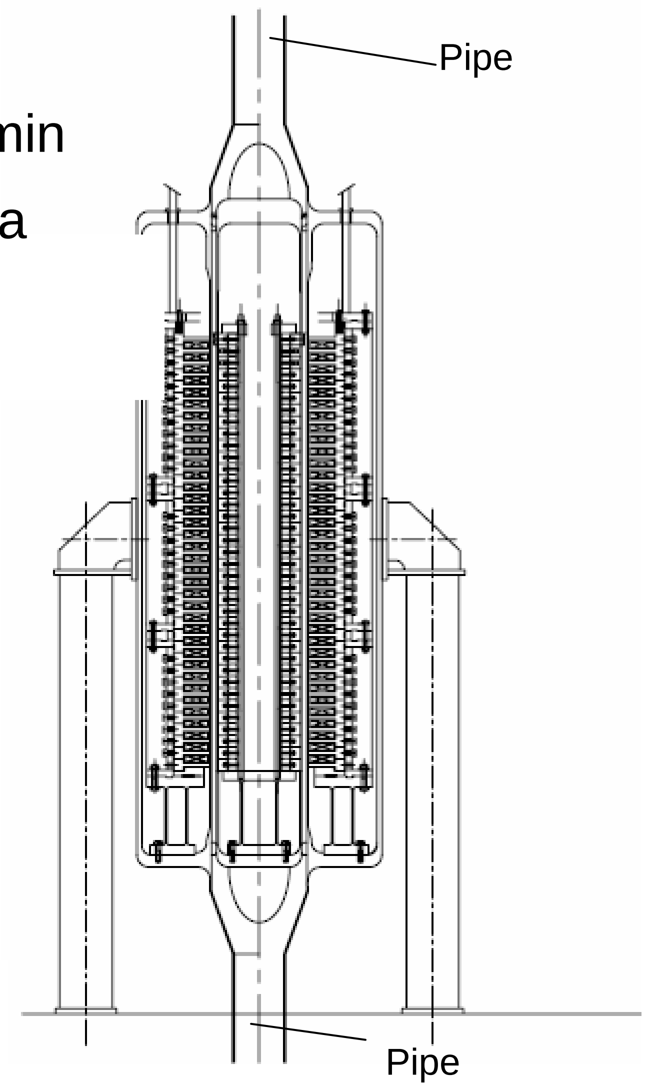
CRIEPI

TOSHIBA
Leading Innovation

Westinghouse

Intermediate EM Pump

- Performance
  - Flow rate 9.3 m3/min
  - Rated discharge pressure 0.25 MPa
- Type
  - Annular linear induction EM pump
  - Single stator
  - Not immersed



CRIEPI TOSHIBA Leading Innovation Westinghouse

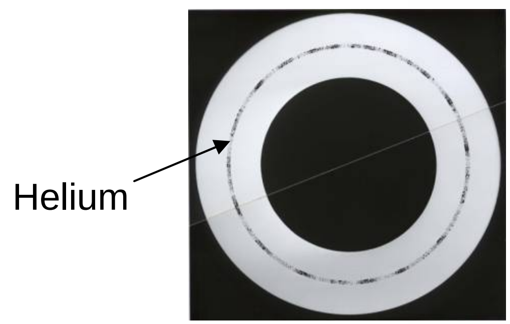
Steam Generator

- Performance
  - Heat exchange capacity 30 MWt
  - With inner tube leak detection capability
    - Moisture detection in helium between inner and outer tubes at inner tube breach
    - Outer tube leak detection at the intermediate heat transport loop
  - Helium detection in the sodium at outer tube breach

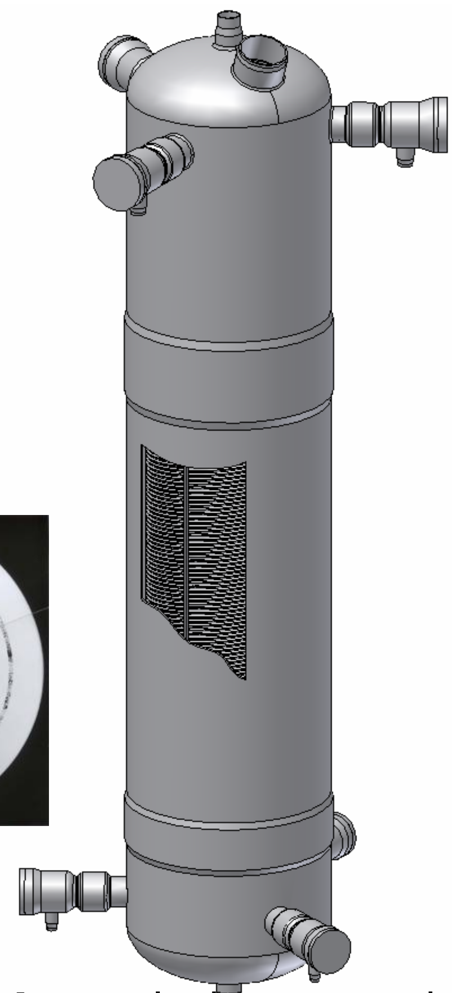
$$P_{steam} > P_{He} > P_{Na}$$

(10.2 MPa) (0.55 MPa)

- Type
  - Once through type
  - Double walled helical coil tube

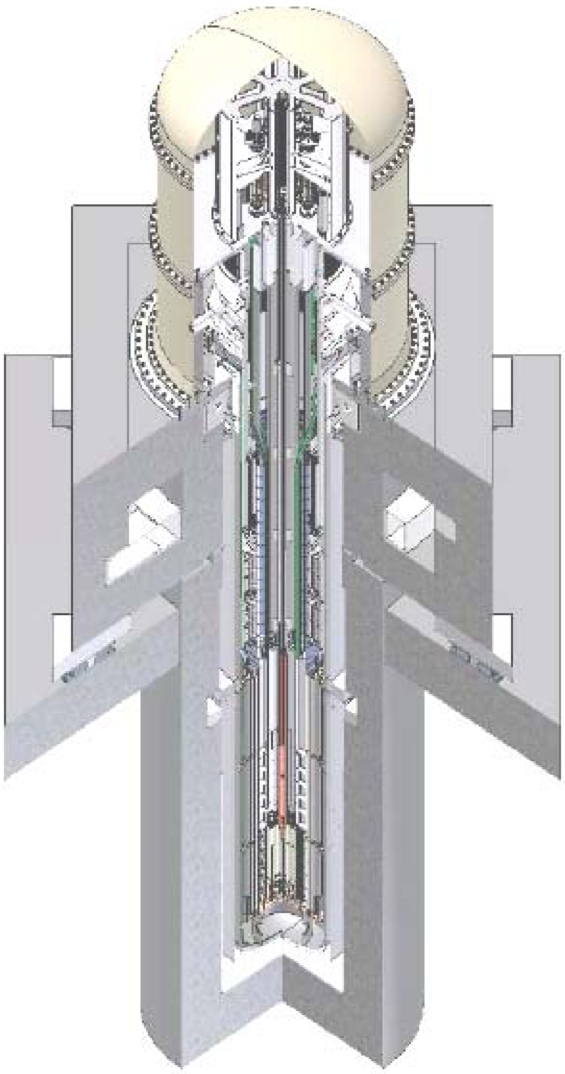


Double wall tube



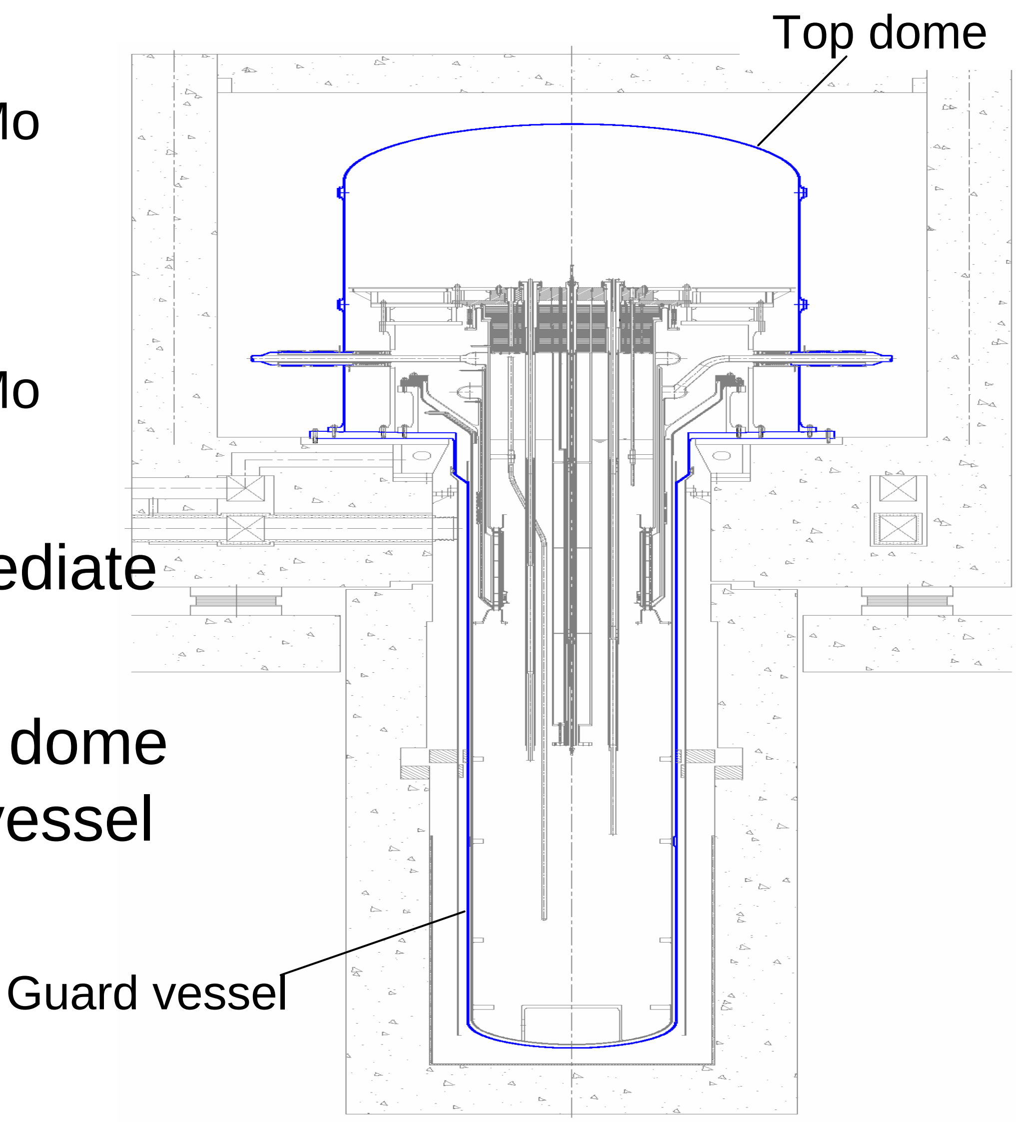
* This R&D has been performed as a part of joint R&D projects under sponsorship of the nine Japanese electric power companies, Electric Power Development Co., Ltd. and the Japan Atomic Power Company (JAPC).

Containment System



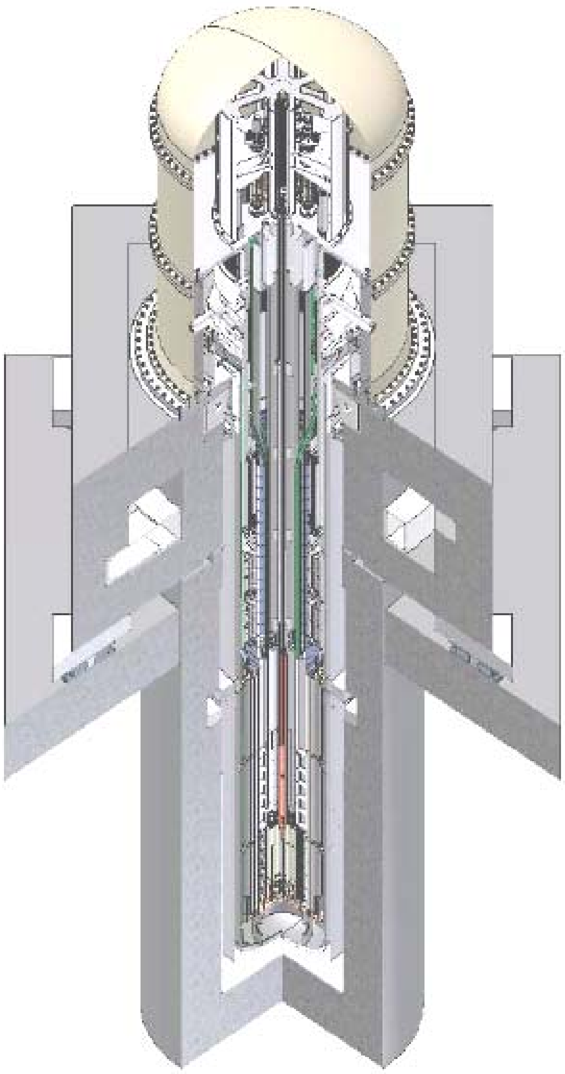
Containment

- Guard vessel
  - Material 2 1/4Cr-1Mo
  - Diameter 3.65 m
- Top dome
  - Material 2 1/4Cr-1Mo
  - Diameter 8 m
- No isolation valve in intermediate heat transport system pipe
- Nitrogen atmosphere in top dome and space between guard vessel and reactor vessel



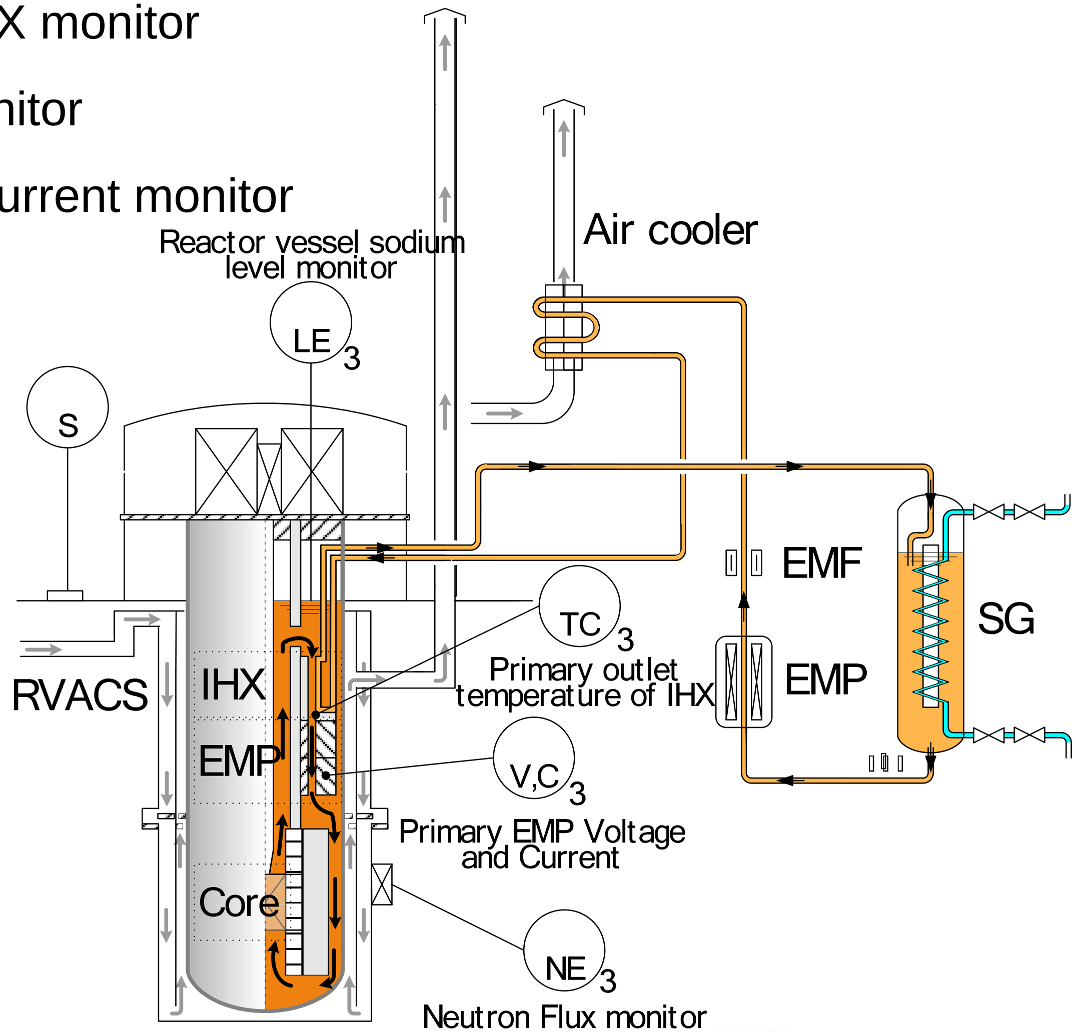
CRIEPI TOSHIBA Leading Innovation Westinghouse

Instrumentation and Controls



Reactor Protection System Sensors

- Neutron flux monitor
- Primary outlet temperature of IHX monitor
- Reactor vessel sodium level monitor
- Primary EM pump voltage and current monitor
- Seismic acceleration monitor

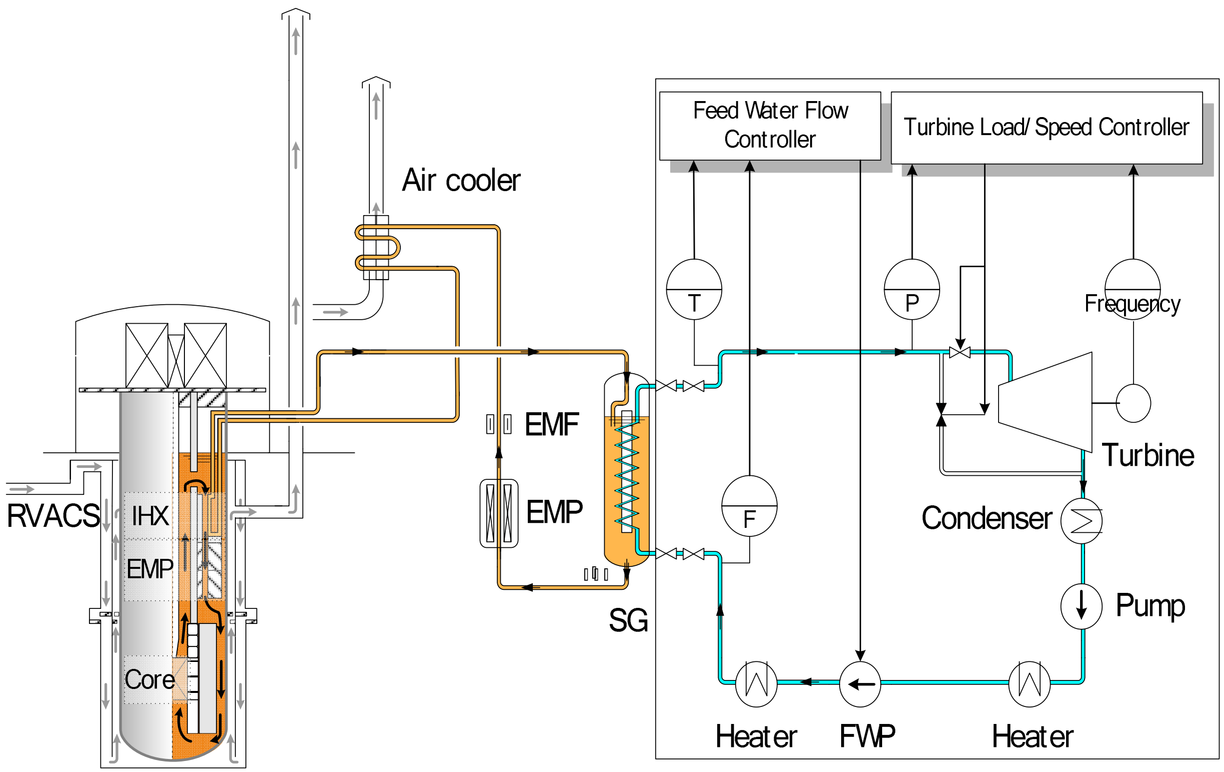


The passive safety feature result in significant simplification of reactor protection systems

All sensors are located in the primary system.

Plant Control

- Plant Control at 100% operation
  - Reactor thermal power 100 %
  - Primary flow rate 100 %
  - Intermediate flow rate 100 %
- Load following
  - Turbine bypass



Summary

- The core design keeps the reactor operating without refueling for 30 years.
- The fuel is designed to maintain integrity during 30 years life and is well within thermal and burnup design limits.
- The reflector drive mechanism maintains reactor operation and prevents excess reactivity insertion.
- The heat transport systems design eliminates moving parts.
- The intermediate heat transport system includes double-walled SG tubes to reduce the risk of sodium-water reaction.
- The containment is designed with passive heat removal capability.
- The reactor protection system is a simple design.

The 4S is a simple, safe, reliable design.

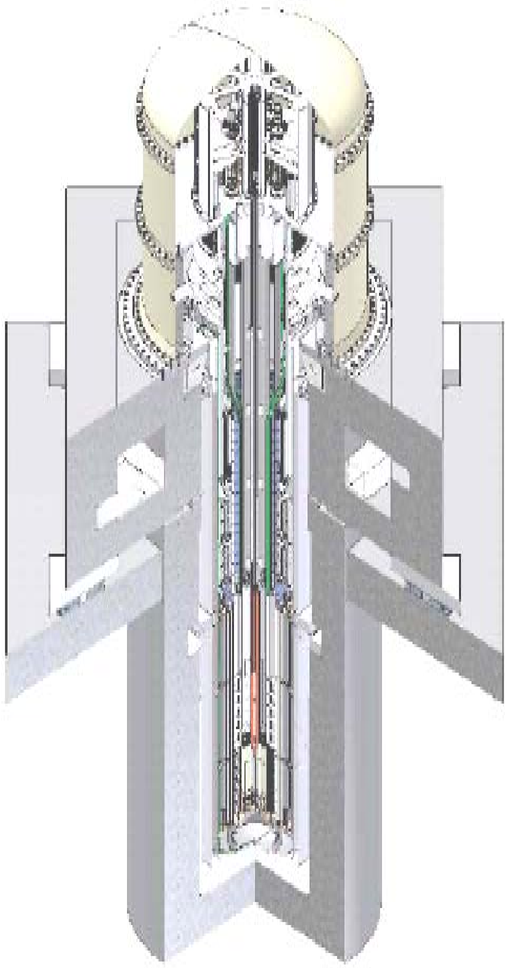
CRIEPI TOSHIBA Leading Innovation Westinghouse

4S Reactor

***S**uper-**S**afe, **S**mall and **S**imple*

Second Meeting with NRC Pre-Application Review

Long Life Metallic Fuel



Presented by
Abdellatif M. Yacout
Argonne National Laboratory

February 21, 2008

CRIEPI · TOSHIBA Leading Innovation · Argonne National Laboratory · Westinghouse

Presentation Overview

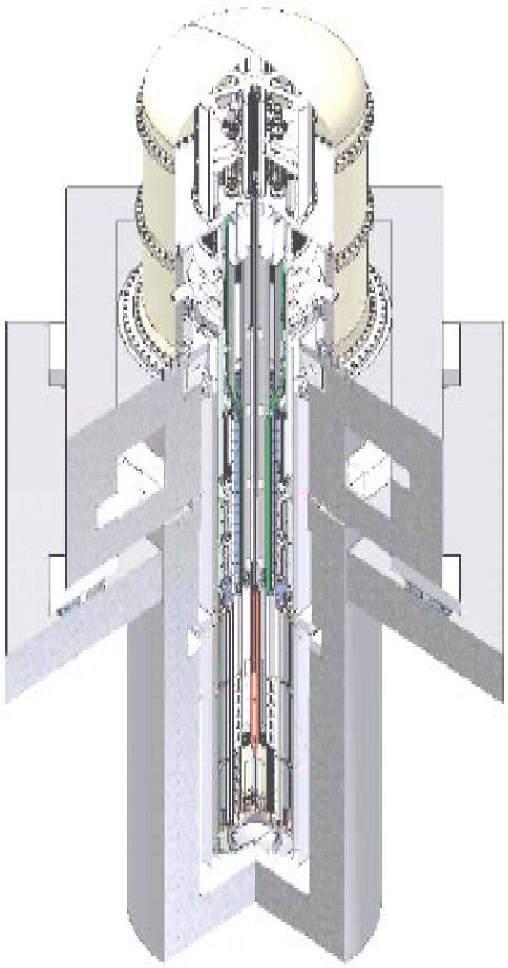
- Presentation Purpose
- Metallic Fuel Experience
- 4S Fuel Design
- Steady-State Performance
- Transient Behavior
- 4S Fuel Design Features
- 4S Fuel Design Evaluation
- Summary

Presentation Purpose

- Familiarize the NRC with the 4S fuel design and the performance of metallic fuel
- Obtain NRC feedback in areas related to fuel design and performance

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Metallic Fuel Experience

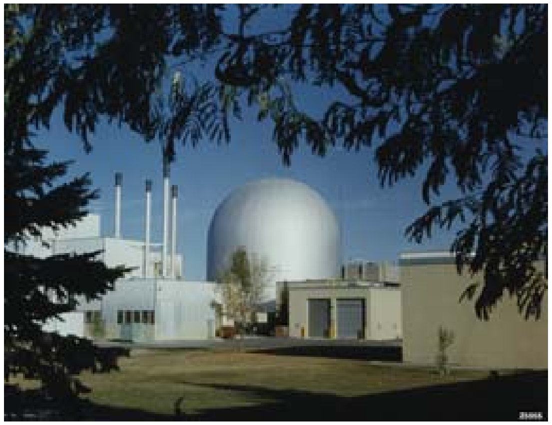


Metallic Fuel History

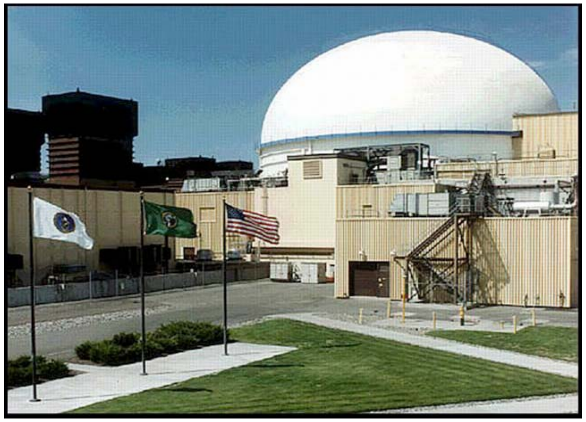
- Over 30 years of irradiation experience
- EBR-I, Fermi-1, EBR-II, FFTF
- U-Fs*, U-Mo, U-Pu-Fs*, U-Zr, U-Pu-Zr, others
- EBR-II
  - > 40,000 U-Fs* pins, **> 16,000 U-Zr pins** & > 600 U-Pu-Zr pins irradiated, clad in 316 stainless steel, D9 & **HT9**
- FFTF
  - **> 1000 U-Zr pins**, mostly in HT9
  - Vast experience with HT9 cladding

*Fs – Simulated Fission Products

EBR-II



FFTF



CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Metallic Fuel Experimental Database

(Steady-State)

- EBR-II experiments to look at parameters and phenomena of interest to fuel performance
  - Prototype fuel behavior
  - RBCB* and failure mode
  - Fuel swelling and restructuring
  - Lead IFR** fuel test
  - Fabrication
  - Design parameters
  - High cladding temperature
  - Large fuel diameter
  - Blanket safety
  - Fuel qualification
  - Fuel impurities

*RBCB – Run beyond cladding breach
**IFR – Integral fast reactor

- FFTF experiments to look at
  - Fuel column length effects
  - Lead metal fuel tests
  - Metal fuel prototype
  - Metal fuel qualification

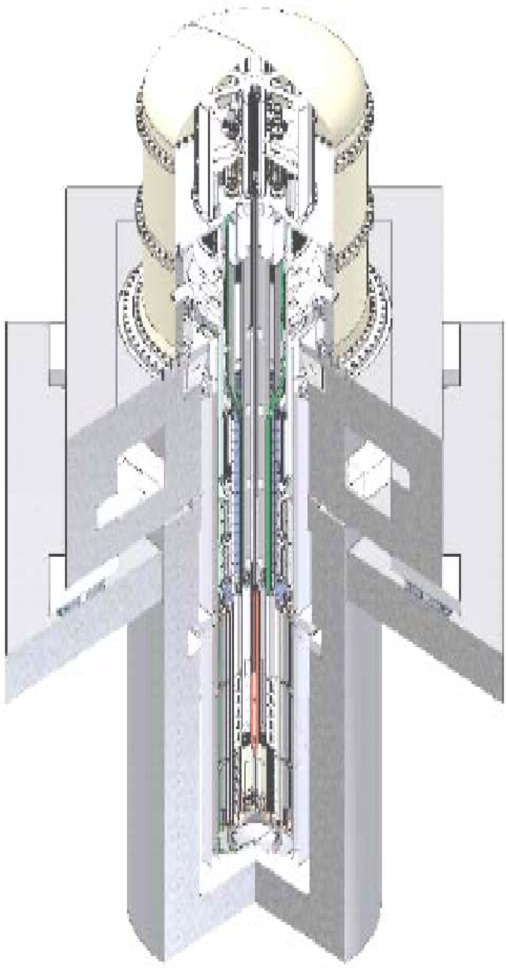
Metallic Fuel Experimental Database

(Transient)

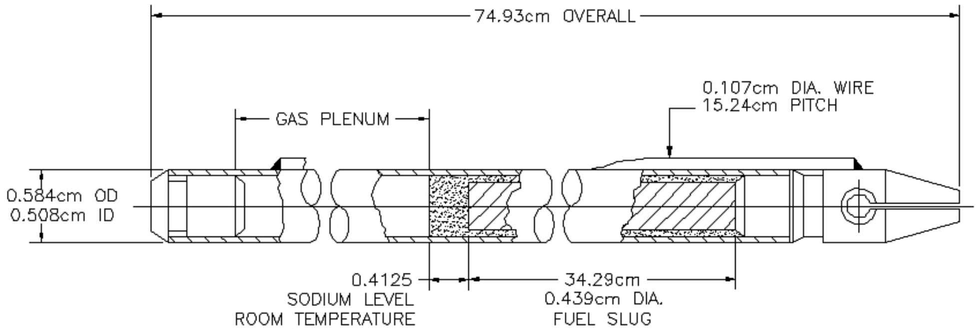
- **In-Pile**
  - Run beyond cladding breach (RBCB) experiments:
    - 6 RBCB tests U-Fs
    - U-Pu-Zr/U-Zr
  - 6 TREAT tests:
    - U-Fs in 316SS
    - U-Zr/U-Pu-Zr in D9/HT9
- **Out-Pile**
  - Whole pin furnace tests (WPF)
  - Fuel behavior test apparatus (FBTA)
  - Diffusion compatibility tests

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

4S Fuel Design

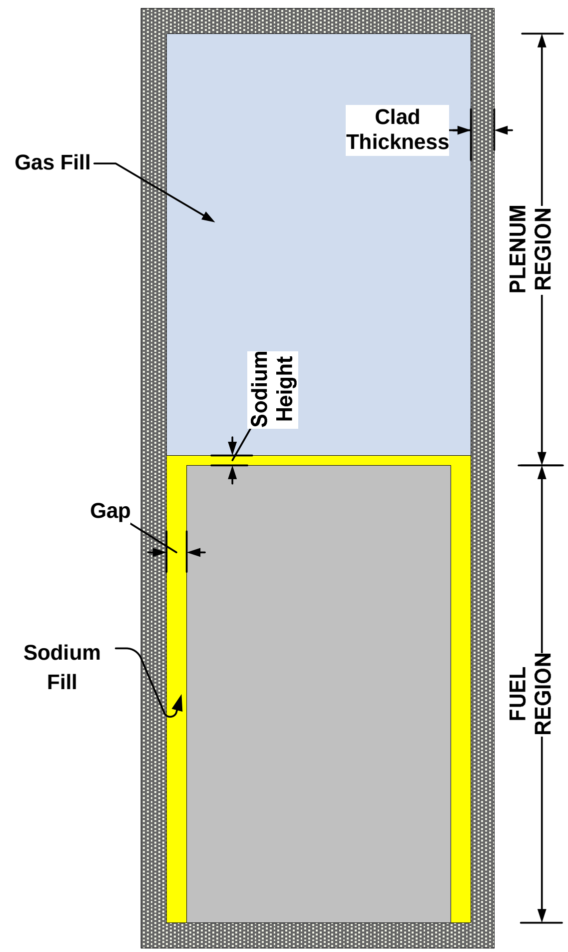


Typical Metallic Fuel Design



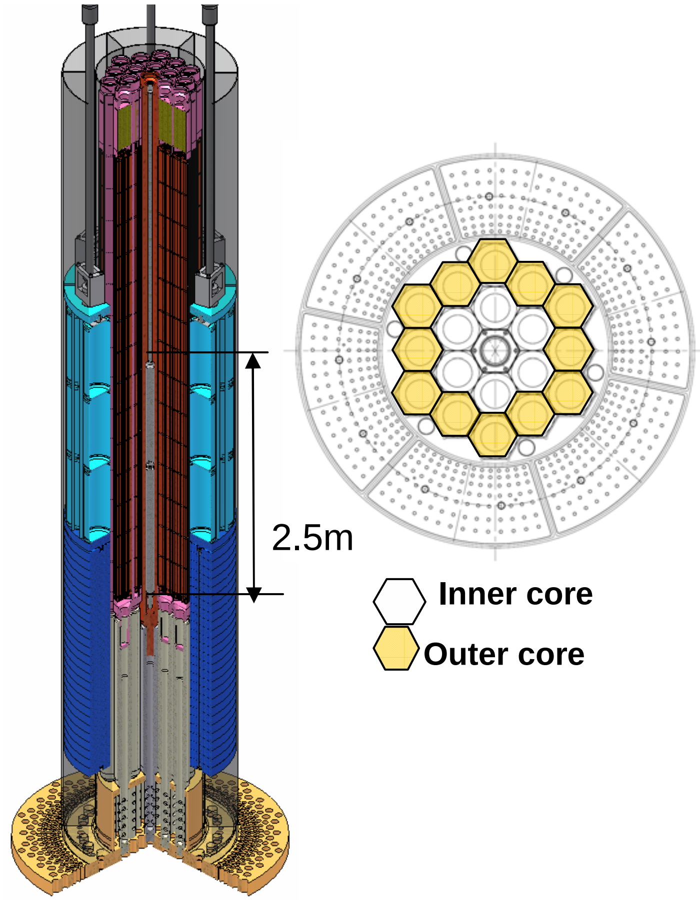
Typical EBR-II Metallic Fuel Pin

(Pahl, et al., 1990)



Fuel Irradiation Conditions

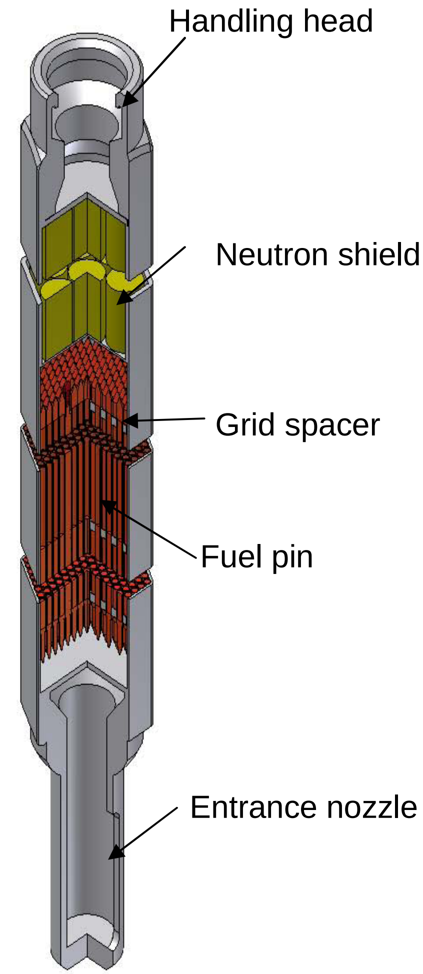
Core design



Core height	2.5 m
Equivalent core diameter	0.95 m
Fuel / cladding material	U-10%Zr / HT9 steel
235U enrichment (inner/ outer)	17 / 19%
Number of subassemblies	18
Peak fast neutron flux	$2X10^{23}$ n/cm^2
Average/peak burnup	34,000/55,000 MWd/t
Nominal peak cladding temperature	567°C
Primary sodium inlet/outlet temperature	355/510°C

Fuel & Subassembly Design for 30 Years Life

- **Fuel Pin Designed for 30 Years Life**
  - Adequate cladding thickness and gas-plenum volume with proven HT-9 cladding material and low linear power
  - Sodium-bonded metallic fuel within an experience range of burnup and neutron fluence
  - Design based on EBR-II and FFTF data including blanket fuel data for 30-year irradiation
  - Analyzed with LIFE-METAL Code (ANL)
- **Fuel Subassembly Design**
  - Each fuel subassembly constitutes a distinct flow channel
  - Fuel subassemblies provide axial shielding to limit neutron activation of the support structure and vessel



CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Fuel Design Parameter Comparison

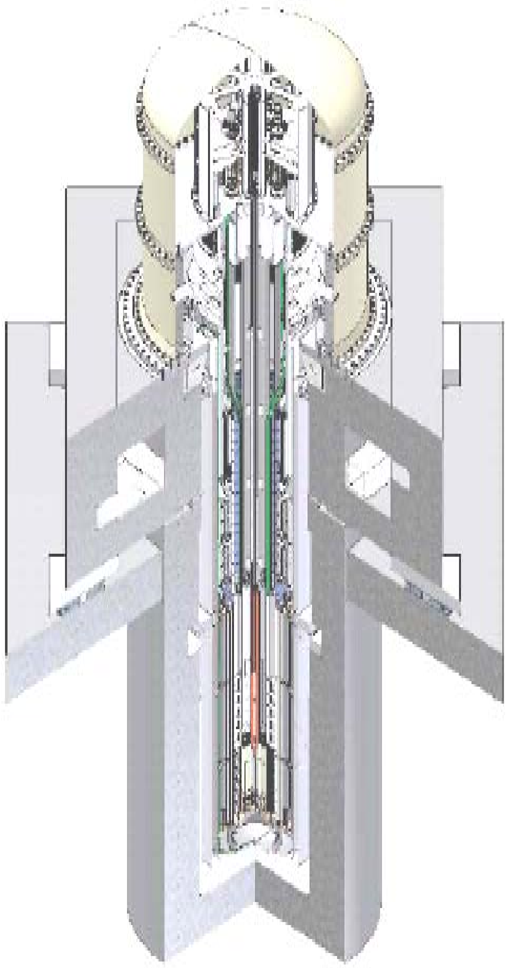
Key Parameter	EBR-II/FFTF	4S
Peak Burnup, 10^4MWd/t	5.0 – 20	< 5.5
Maximum linear power, kW/m	33 – 50	8
Cladding hotspot temperature, °C	650	609
Peak center line temperature, °C	<700	<630
Peak radial fuel temperature difference, °C	100 - 250	< 30
Cladding fast fluence, n/cm^2	up to 4 x 10^{23}	2 x 10^{23}
Cladding outer diameter, mm	4.4 - 6.9	14
Cladding thickness, mm	0.38 – 0.56	1.1
Fuel slug diameter, mm	3.33 – 4.98	10.4
Fuel length, m	0.3 (0.9 in FFTF)	2.5
Plenum/fuel volume ratio	0.84 to 1.45	1.3
Fuel residence time, years	1 - 3	30
Smeared density, %	75	78

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Fuel Material – Fuel Alloy: U-10Zr

- High thermal conductivity
- Compatible with sodium coolant
- Sufficiently high melting temperature for safety considerations
- Large experimental database
- Used as **driver fuel** in EBR-II where over 16,000 pins were irradiated
- **Qualified** as driver fuel in FFTF
- Previous comments from **NRC review of PRISM (NUREG-1368)** fuel qualification plan related to U-Pu-Zr fuel and U-Pu-MA-Zr fuel

Steady-State Metallic Fuel Performance

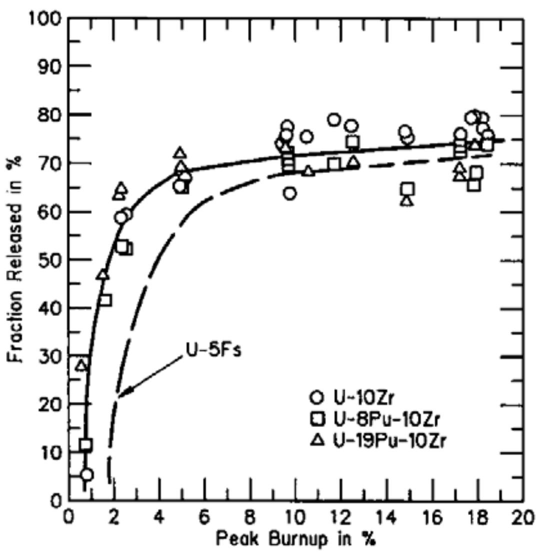


Steady-State Performance Topics

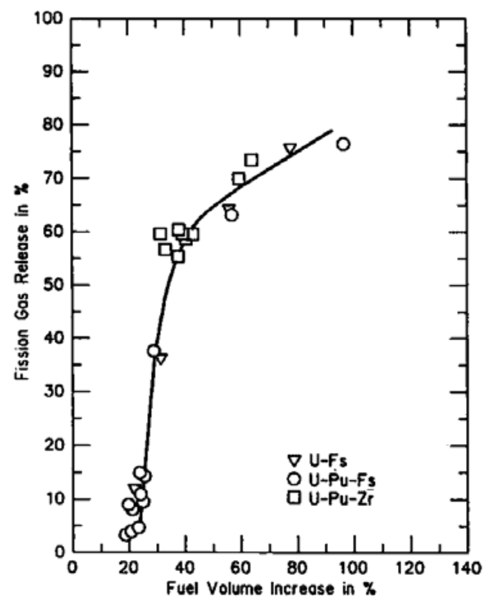
- Fission gas release (FGR)
- Fuel swelling
- Constituent redistribution and zone formation
- Fuel-cladding chemical interaction (FCCI) & rare earth migration
- Fuel-cladding mechanical interaction (FCMI)
- HT-9 cladding performance
- HT-9 cladding failure

Fission Gas Release (FGR)

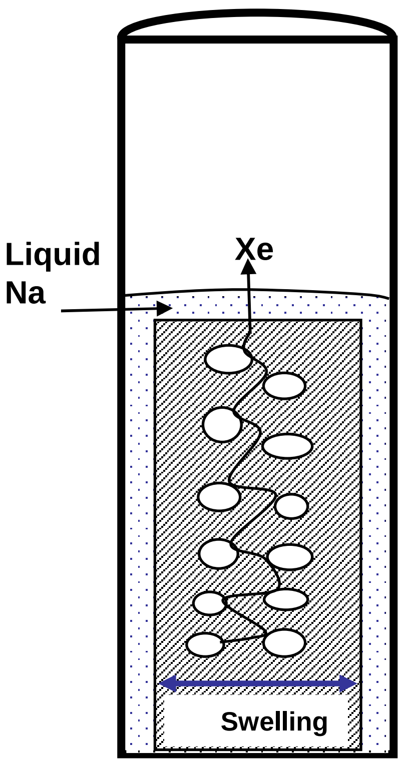
- Insoluble fission gases, Xe and Kr, accumulate in fuel until inter-linkage of porosity at sufficient burnup leads to release of large fraction of gas.
- The fission gases accumulate in plenum region and constitute the primary clad loading mechanism.



FGR vs. Burnup (Hofman & Walter, 1994): U-5Fs slightly lower because of beneficial effect of Si inclusion

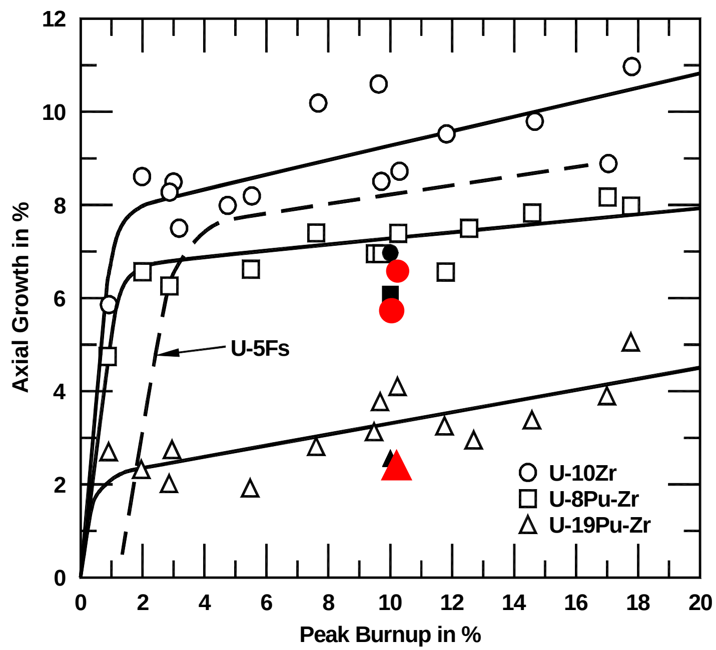


FGR vs. Fuel Swelling (Hofman & Walter, 1994): Independent of metal-fuel type



Fuel Swelling

- This is driven by nucleation and growth of immobile fission-gas bubbles.
- Low fuel smeared density (~75%) combined with high swelling rate allows rapid swelling to ~33 vol% at ~2 at.% burnup where inter-linkage of porosity results in large gas release fraction which decreases the driving force for continued swelling.
- 4S swelling behavior is expected to be similar to U-10Zr fuel irradiated in EBR-II and FFTF.

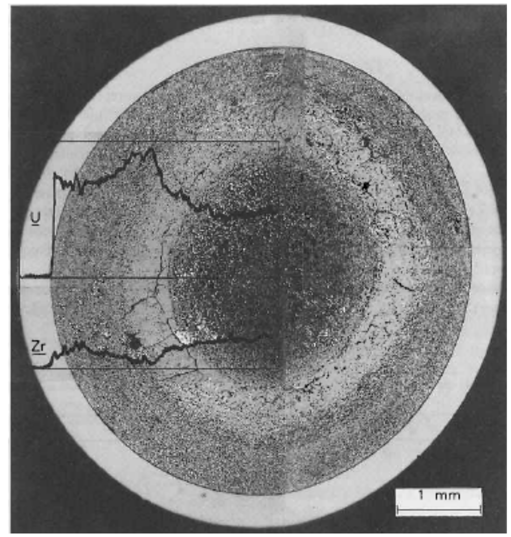


EBR-II fuel length increase in various metallic fuels as a function of burnup where closed symbols correspond to FFTF data (ANL-AFCI-211)

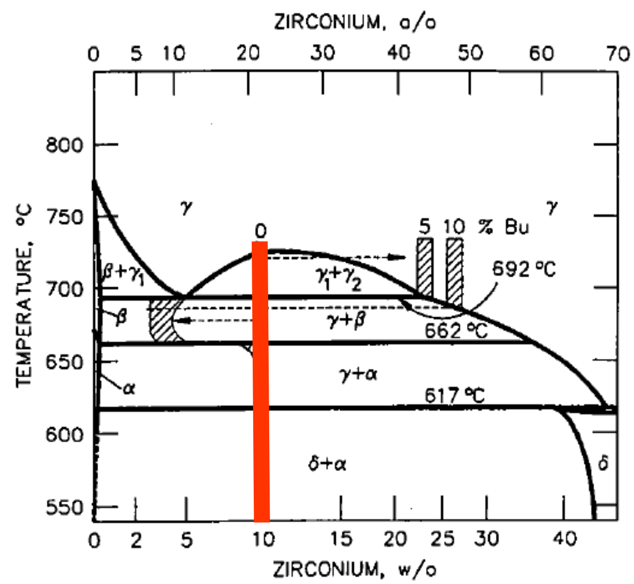
CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Constituent Redistribution & Zone Formation

- Fuel melting temperature decreases in Zr-depleted region (this zone occurs off the fuel center).
- Local fission rate changes.
- Changes occur in swelling characteristics.
- Reliable predictive model has been developed.
- No significant redistribution is predicted for 4S design based on model estimates.



Metallographic cross section with superimposed radial microprobe scans at top of U-10Zr pin DP-81, experiment X447 (Hofman, et al., 1995)

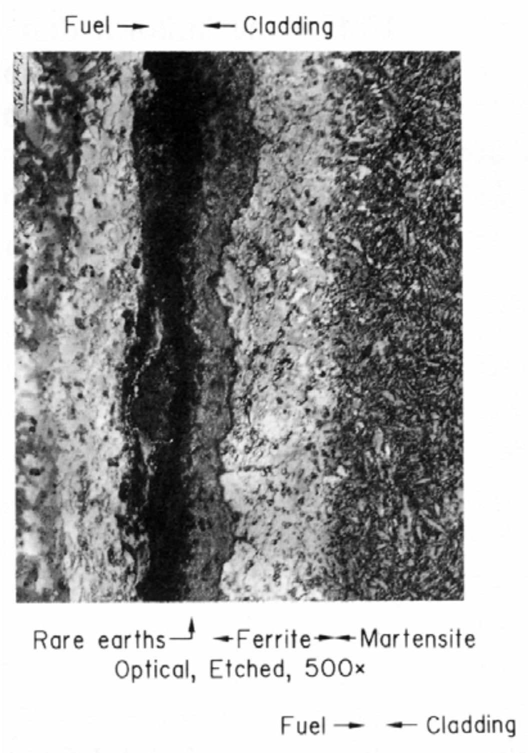


U-Zr Phase Diagram

CRIEPI · TOSHIBA Leading Innovation · Argonne National Laboratory · Westinghouse

Fuel Cladding Chemical Interaction (FCCI) & Fission Product Migration

- At steady-state, FCCI is characterized by solid-state interdiffusion.
- Interdiffusion forms U/Fe alloys with lower eutectic temperature.
- Decarburized zone at fuel-clad interface is expected in HT-9 cladding.
- RE fission products (La, Ce, Pr, Nd) form a brittle layer of cladding.
- Penetration depth data are available from in and out-of-pile measurements.
- 4S fuel design provides enough margin to accommodate FCCI (low fuel temperature, low linear power, low burnup, and thick cladding).



FCCI of U-10Zr/HT-9 due to inter-diffusion of fuel/cladding constituents after 6 at% burnup at 620^{o}C
(Hofman & Walter 1994)

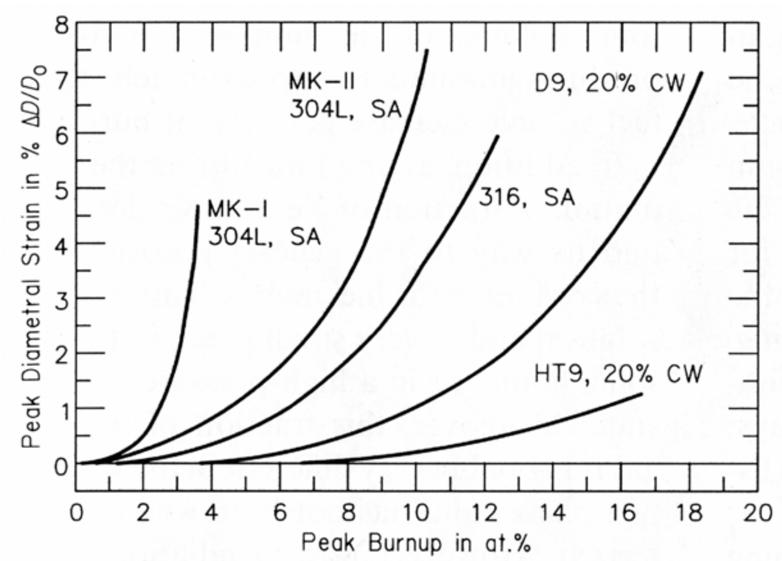
CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Fuel Cladding Mechanical Interaction (FCMI)

- This is due to accumulation of solid fission products at high burnups.
- Low fuel smeared density (~75%) allows for a large amount of fuel swelling (~30%) and gas release which reduces FCMI.
- Porous fuel at low burnups (<5 at.%) does not exert significant force on cladding.
- This is not a concern for the low burnup 4S metallic fuel design.

HT-9 Cladding Performance

- Ferritic-Martensitic alloy with adequate swelling resistance, toughness, strength, and ductility
- Low void swelling up to 200 displacement per atom (dpa), ~4×10^{23} n/cm^2 > 0.1 Mev
  - 4S: ~2×10^{23} n/cm^2 > 0.1 Mev, 100 dpa
- 100s of HT9 clad pins irradiated in EBR-II and 1000s of pins irradiated in FFTF
- Stress rupture limitations due to thermal creep at high temperatures > 650 ^oC
  - 4S peak clad hot channel temperature is ~610 ^oC

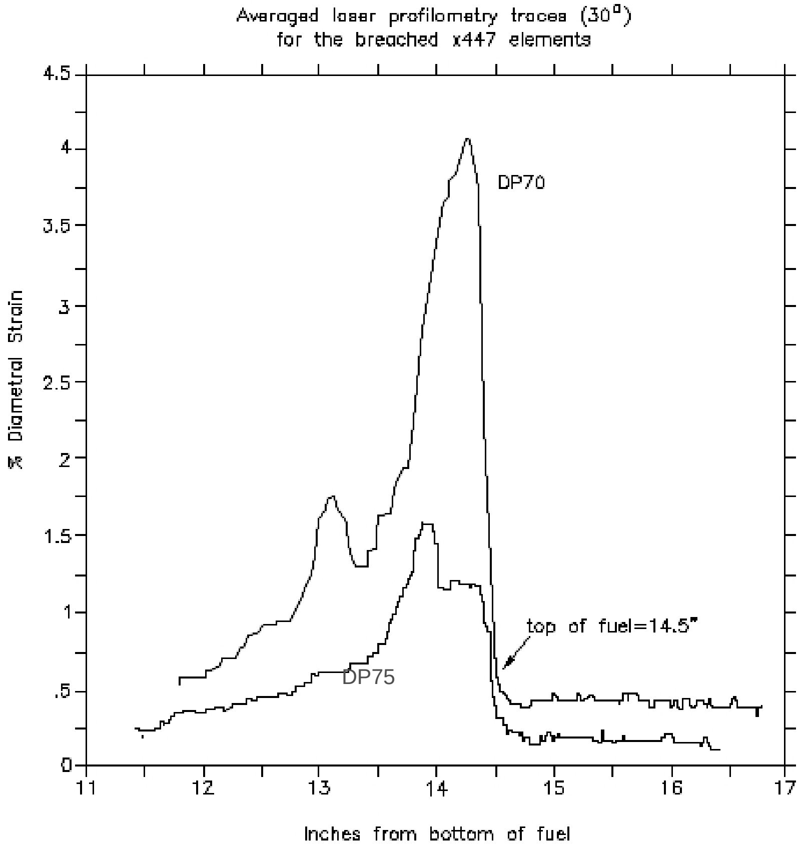


Void swelling behavior of HT9 cladding compared to other steels (Pahl, et al., 1992).

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

HT-9 Cladding Failure

- No failures in EBR-II or FFTF under normal operating conditions
- Only two HT9 failures in a high temperature experiment (~660°C)
  - Near top of fuel at the highest cladding temperature (stress rupture)
- Lower 4S peak hot channel cladding temperature (~610°C) reduces the likelihood of failure



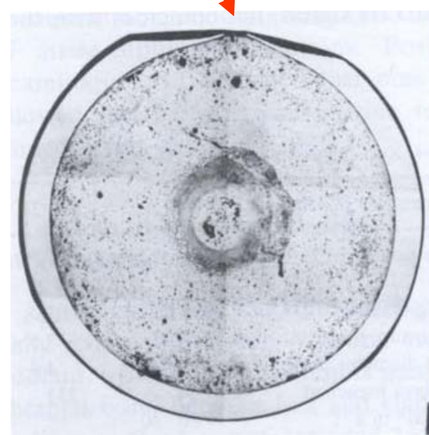
Profilometry of metal fuel/HT9 cladding creep failure tests showing failed pins, DP70 and DP75 (Pahl, et al., 1993)

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Run Beyond Cladding Breach (RBCB)

- **EBR-II RBCB experiments**
  - An area of cladding was machined down to 25-50 μm (<10% of cladding thickness is left).
  - After a short period of irradiation, cladding failure occurred at the machined spot.
- **Test Results**
  - **No chemical interactions** between fuel and coolant
  - **No fuel loss into coolant** (under normal conditions)
  - **No significant liquid or solid FP** escape
  - Only release of **fission gas and Cs** retained in the bond sodium **detected**
- 4S fuel is expected to have similar RBCB behavior.

Thinned cladding



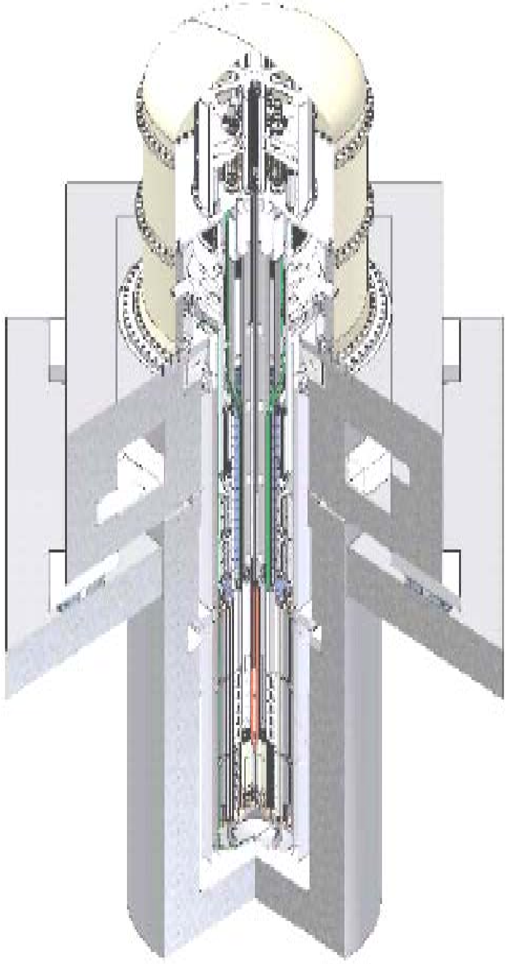
U-19Pu-10Zr
HT-9

Metallographic cross-section through cladding breach of a metallic fuel element after RBCB operation
(Batte' and Hofman, 1990)

Steady-State Performance Summary

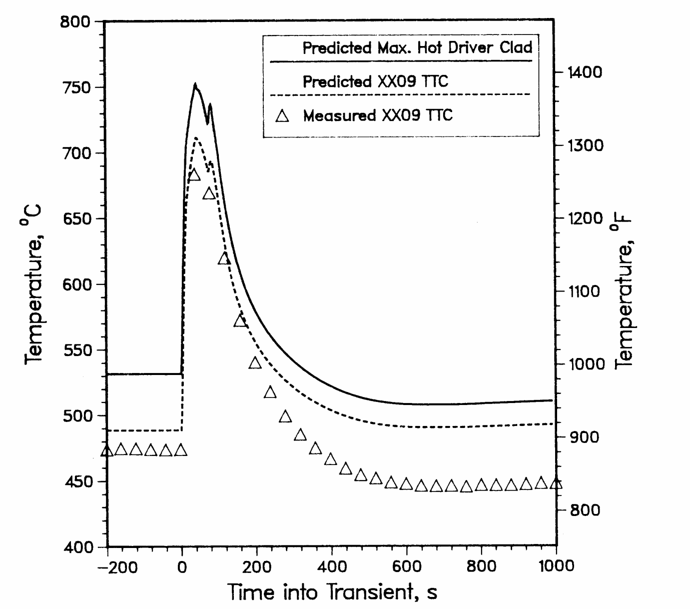
- 4S fuel swelling behavior is expected to be similar to that of U-10Zr fuel irradiated in EBR-II and FFTF.
- No significant fuel constituent redistribution is predicted for 4S design based on model estimates.
- 4S fuel design provides enough margin to accommodate FCCI (low fuel temperature, low linear power, low burnup, and thick cladding).
- FCMI is not a concern for the low burnup 4S metallic fuel design.
- HT9 cladding exhibits low swelling at 4S conditions.
- Low 4S peak hot channel cladding temperature (~610 ^{o}C) reduces the likelihood of failure.
- Benign RBCB behavior of the 4S fuel is expected based on experience with RBCB tests at EBR-II.

Transient Behavior



Metallic Fuel Characteristics

- **Excellent transient capabilities**
  - Does not impose restrictions on transient operations capabilities
  - Sample history of a typical driver fuel irradiated during the EBR-II inherent passive safety tests conducted in 1986:
    - 40 startups and shutdowns
    - 5 15% overpower transients
    - 3 60% overpower transients
    - 45 loss-of-flow (LOF) and loss-of-heat-sink tests including a LOF test from 100% without scram
  - No fuel failures

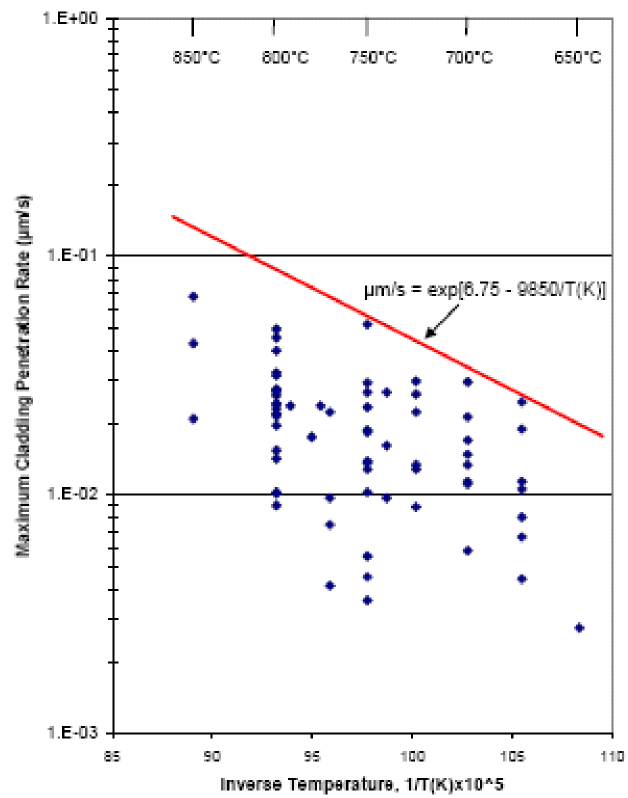


Unprotected loss-of-flow test in EBR-II demonstrated the benign behavior predicted (Mohr, et al., 1987)

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Transient Tests

- In–pile TREAT (Transient Reactor Test Facility) tests evaluated transient overpower margin to failure, pre-failure axial fuel expansion, and post-failure fuel and coolant behavior.
- Hot cell furnace testing of pin segments (fuel pin test apparatus), and full-length pins (whole pin furnace) showed significant safety margin for particular transient conditions.
  - Penetration depth data were measured and provided the basis for penetration depth correlations

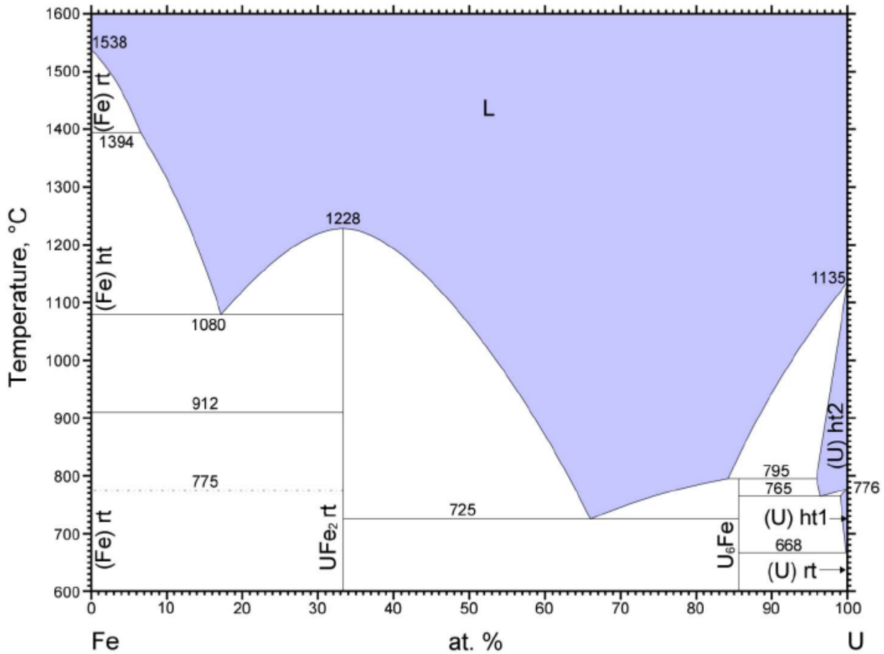


Effective cladding penetration rates from FBTA tests for speciments tested for 1.0 hour (Tsai, et al., 2007)

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

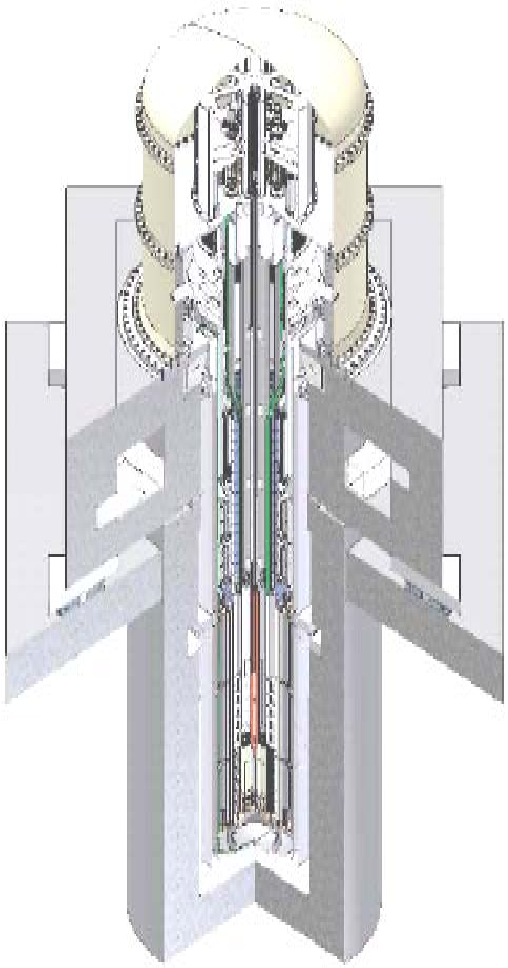
Eutectic Formation Temperature between Fuel and Cladding

- Critical parameter for metal fuel design
- Onset of eutectic formation occurs between 650 – 725°C
- Rapid eutectic penetration at a much higher temperatures
- Places limits on the coolant outlet temperature to provide adequate margin to onset of eutectic formation



The Iron-Uranium Phase Diagram (Okamoto, 1990)

4S Fuel Design Features



Fuel Design Parameter Comparison

Key Parameter	EBR-II/FFTF	4S
Peak Burnup, 10^4MWd/t	5.0 – 20	< 5.5
Max. linear power, kW/m	33 – 50	8
Cladding hotspot temperature, °C	650	609
Peak center line temperature, °C	<700	<630
Peak radial fuel temperature difference, °C	100 - 250	< 30
Cladding fast fluence, n/cm^2	up to 4 x 10^{23}	2 x 10^{23}
Cladding outer diameter, mm	4.4 - 6.9	14
Cladding thickness, mm	0.38 – 0.56	1.1
Fuel slug diameter, mm	3.33 – 4.98	10.4
Fuel length, m	0.3 (0.9 in FFTF)	2.5
Plenum/fuel volume ratio	0.84 to 1.45	1.3
Fuel residence time, years	1 - 3	30
Smeared density, %	75	78

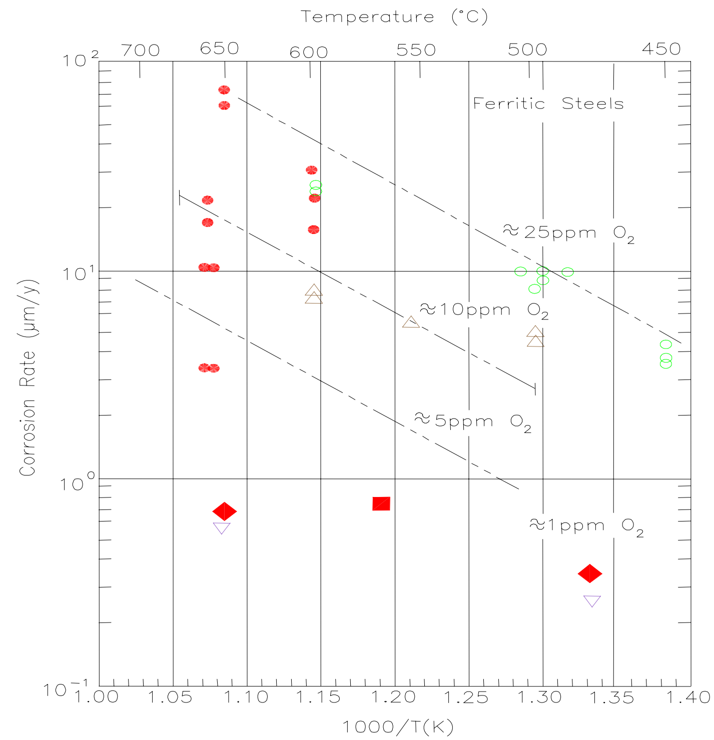
CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Long Core Life

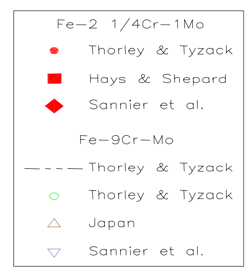
- **HT-9 Thermal Creep**
  - Low burnup → low plenum pressure → low cladding stresses.
  - Low cladding temperature
    - Even at hot spot temperature of ~ 610 °C, thermal creep rate is small.
    - Limited thinning of the cladding due to FCCI retains sufficient load bearing cladding thickness.
  - Cladding thickness is more than twice the typical cladding thickness for metallic fuel.
- Thermal creep under 4S conditions is not expected to be a life-limiting factor.

Long Core Life (cont.)

- **Sodium Corrosion**
  - Mainly due to oxygen content in the primary sodium
    - EBR-II controlled oxygen to a few ppm.
    - 4S design targets oxygen <3 ppm.
  - Experience with EBR-II blanket pins over similar residence times showed no corrosion problems.
    - Some of the blanket subassemblies remained in the sodium pool for the full EBR-II operation of about 29 years.
- No significant HT-9 corrosion is expected at the temperatures and target oxygen levels for 4S.



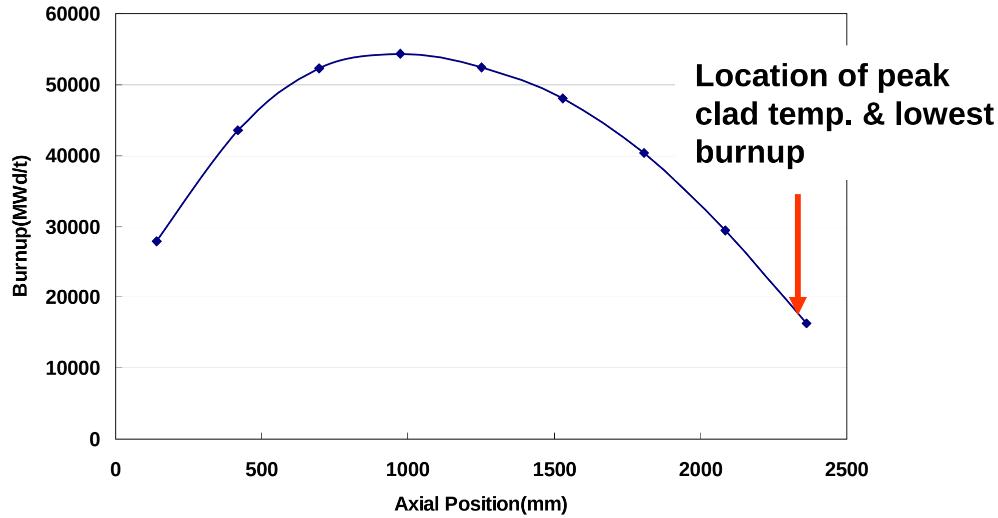
Sodium corrosion data for ferritic-martensitic alloys (Natesan, 2007)

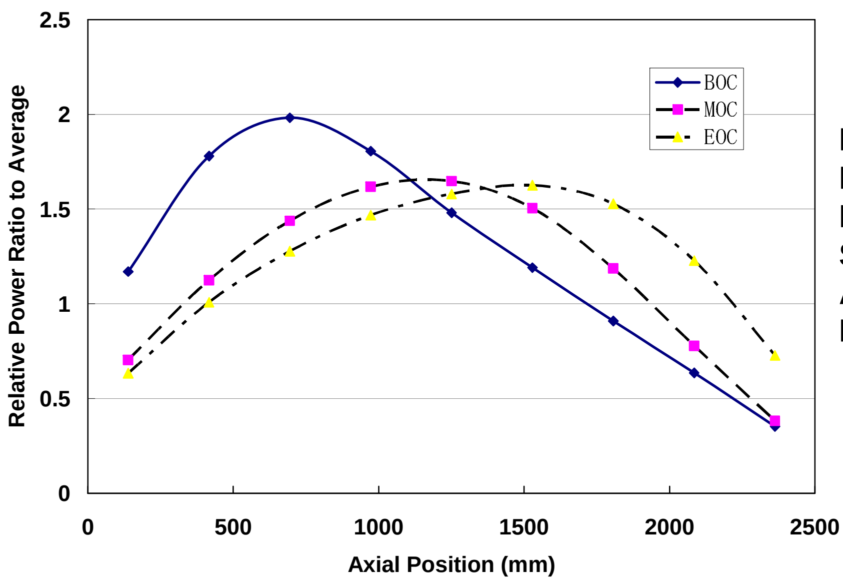


CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Long Core Life (cont.)

- **Fuel Cladding Chemical Interaction**
  - Lowest burnup at top of fuel (< 2 at%) minimizes contact with cladding where the fuel surface temperature is highest.
  - Low fission rate and low fuel temperature gradient near the top of the fuel limit the migration of rare earths to the cladding.
- FCCI Minimized





Power Profile at Different Stages vs. Axial Location

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Larger Fuel Pin Diameter

- **Data for performance of large diameter pins in EBR-II**
  - Large fuel slug diameter driver fuel test, with 5.71 mm slug diameter (Crawford, et al., 1994)
  - U-Zr blanket qualification tests, with 7.95 mm slug diameter (Pahl, et al., 1992)
  - EBR-II blanket subassemblies (Seidel, et al., 1984)
- No specific effect of increasing the pin diameters other than the influence on radial temperature and power profiles

Long Fuel Pins

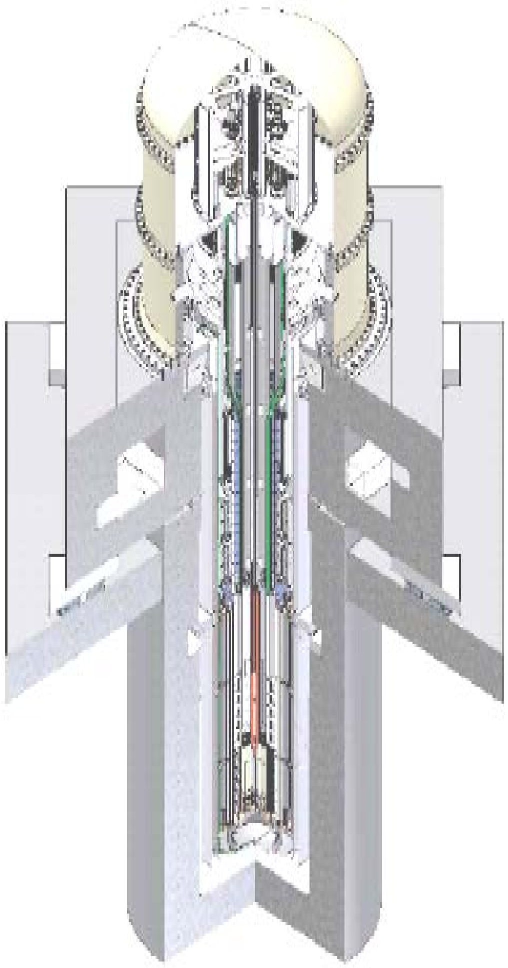
- **Irradiation data**
  - EBR-II short pins (34.3 cm)
  - FFTF long pins (91.4 cm)
  - EBR-II long blanket pins (>150 cm)
- **Observations from long pins irradiated in FFTF** (Tsai, et al., 1995)
  - Axial fuel growth as predicted
  - Fission gas release to gas plenum comparable
  - No evidence of enhanced FCMI
  - No difference in constituent migration
  - No evidence of densification

EBR-II Blanket Fuel Performance

- Some subassemblies in the core for the full life of EBR-II of about 29 years (*about the same as 4S*)
- Depleted uranium blanket rods with very low power (up to 4.3 kW/m), high smeared density, very small plenum, and cladding temperatures up to 600°C (*nearly the same as 4S*)
- Blanket pins about 150 cm long
- Blanket experiments at high smear density (85% & 90%) (*greater than 4S*)
- Examination of EBR-II blanket pins
  - No evidence of significant sodium corrosion or FCCI

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

4S Fuel Design Evaluation



Fuel Design Criteria

- **Steady-State Criteria**
  - Approach similar to CRBR and PRISM designs in addition to the MK-V fuel design of EBR-II (L. Briggs, et al., 1995)

$$\varepsilon_{THN} \leq 1.0\%$$

$$CDF_N \leq 0.05$$

$$\overline{\sigma}_H < 150 \text{ MPa}$$

No Fuel Melting

No Eutectic Liquefaction at Fuel – Clad Interface

CDF_N = Cumulative damage function during normal operation

ε_{THN} = Thermal component of plastic hoop strain during normal operation

$\overline{\sigma}_H$ = Radially averaged primary hoop stress

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

Fuel Design Criteria (cont.)

- **Cumulative Damage Function (CDF)**

$$CDF = \int_0^t \frac{dt}{t_r(\sigma, T)} \quad \leq \quad 0.05$$

- **Stress Rupture Correlation**

$$\log_{10} t_r = A + \frac{B}{T} + \frac{C}{T} \log_{10} \sigma \qquad 700 \leq T \leq 1100K$$

  - σ = hoop stress, MPa (gas pressure &/or FCMI)
  - t_r = time to rupture, hrs

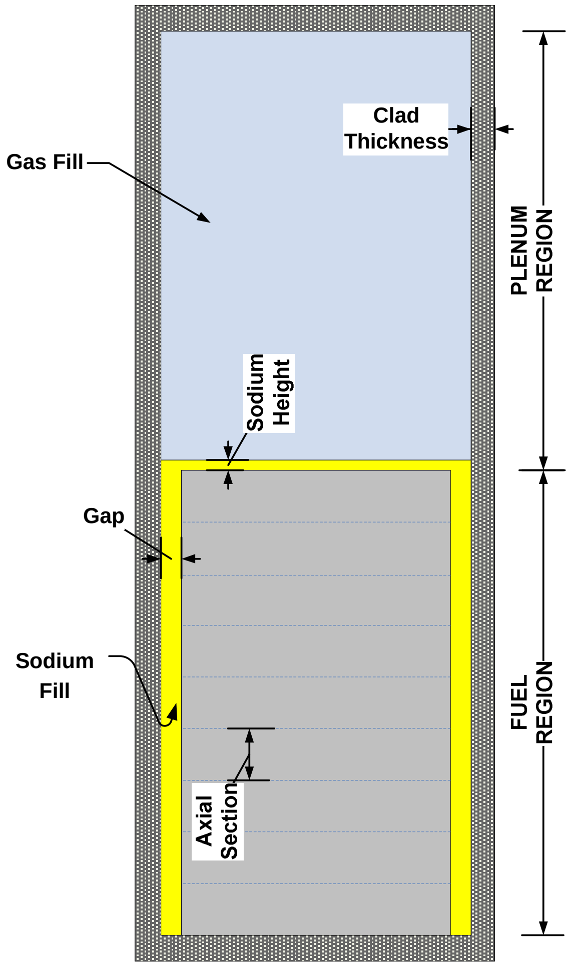
  - 0.05 value is based on HT9 out-of-reactor stress-rupture data and LIFE-METAL calculations.
  - Conservative criteria so transient performance of clad is not significantly degraded by steady state operations.

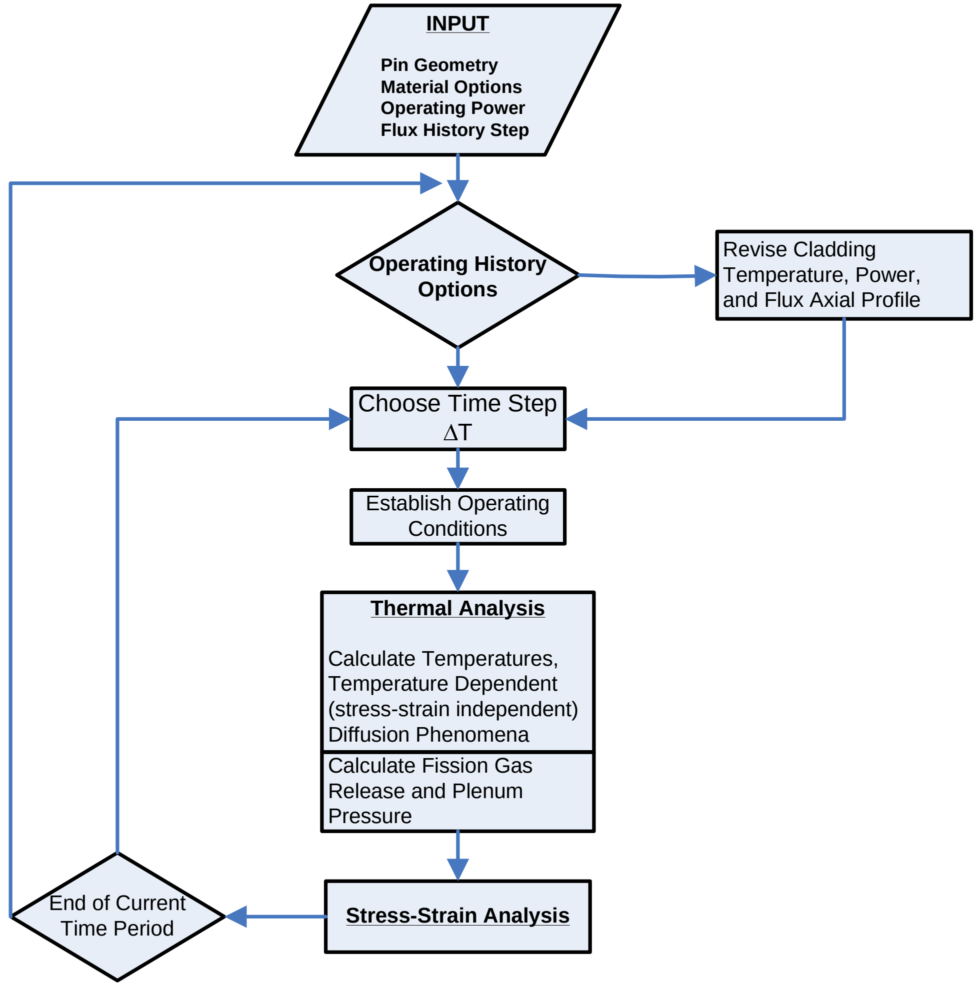
Performance Assessment Code: LIFE-METAL

- **LIFE-METAL/LIFE-4**
  (Billone, et al., 1986 / Boltax, et al., 1990)
  - One-dimensional, plane strain analysis of thermal and mechanical behavior of cylindrical fuel elements
  - Code calibrated to thermal/structural benchmark problems with closed analytic solutions
  - Analytic property correlations used where available
  - Capability to analyze up to point of cladding breach for:
    - Complete power history
    - Steady-state conditions
  - Calibrated to EBR-II, FFTF, and TREAT fuel element PIE data
    - LIFE-METAL calibration included Data from 111 irradiated fuel pins, different cladding type, different fuel composition
    - Calibration data include fission gas release, fuel axial strain, fuel diametral strain, cladding diametral strain, cladding penetration depth
  - Used to calculate:
    - CDF, cladding strains from swelling, creep, and thermal expansion
    - Stress histories from fuel-cladding interaction and FG pressure
    - Cladding damage and element lifetime

Performance Assessment Code: LIFE-METAL (cont.)

- **Code Structure – Single-pin evaluation**



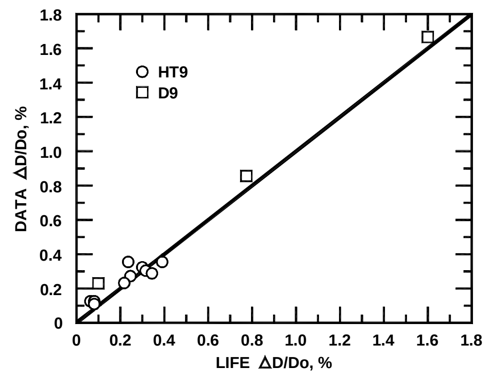


CRIEPI | TOSHIBA Leading Innovation | Argonne National Laboratory | Westinghouse

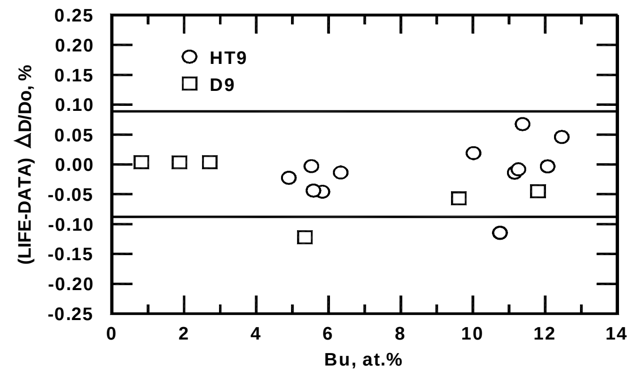
Calibration of LIFE-METAL Model

- **Validation Summary (Billone, et al. 2007, ANL-AFCI-211)**

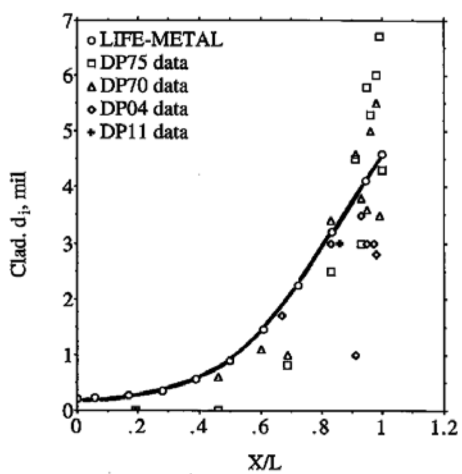
Diametral Strain



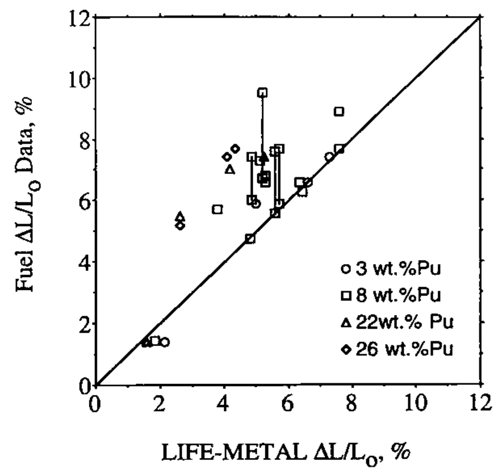
Diametral Strain



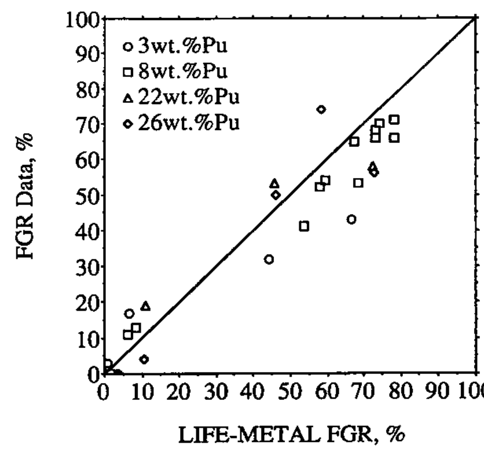
Depth of Penetration



Axial Growth



FG Release



LIFE-METAL Design Evaluation

- **Evaluation Results**
  - Analysis Conditions
    - Peak fuel pin burnup 5.5 at%
    - Peak fast fluence $2x10^{23}n/cm^2$
    - Peak hot channel cladding temperature ~ 610°C
  - Results at EOL
    - Enough margin to design limits

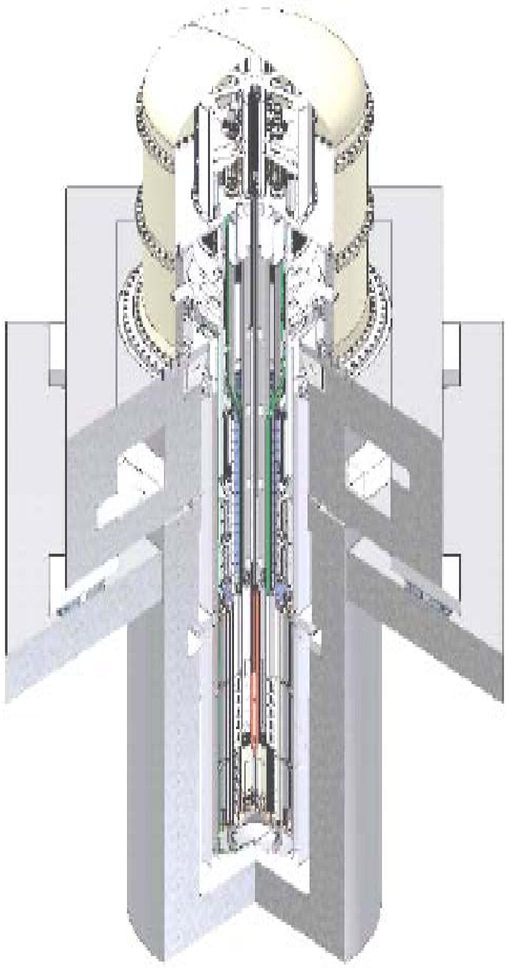
	Calculated	Criterion
CDF	**10-5**	**0.05**
Thermal creep strain	**0.14%**	**1%**
Plenum pressure hoop stress	**< 50 MPa**	**150 MPa**

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

LIFE-METAL Design Evaluation (cont.)

- **Sensitivity Study**
  - Calculations assume contact between the fuel and cladding at the highest temperature region at the top of the fuel early in life
  - Results using cladding temperatures up to 630°C show no violation of the design criteria
    - CDF **< 0.05**
    - Thermal creep strain **< 1%**
    - Hoop stresses **< 150 MPa**

Summary



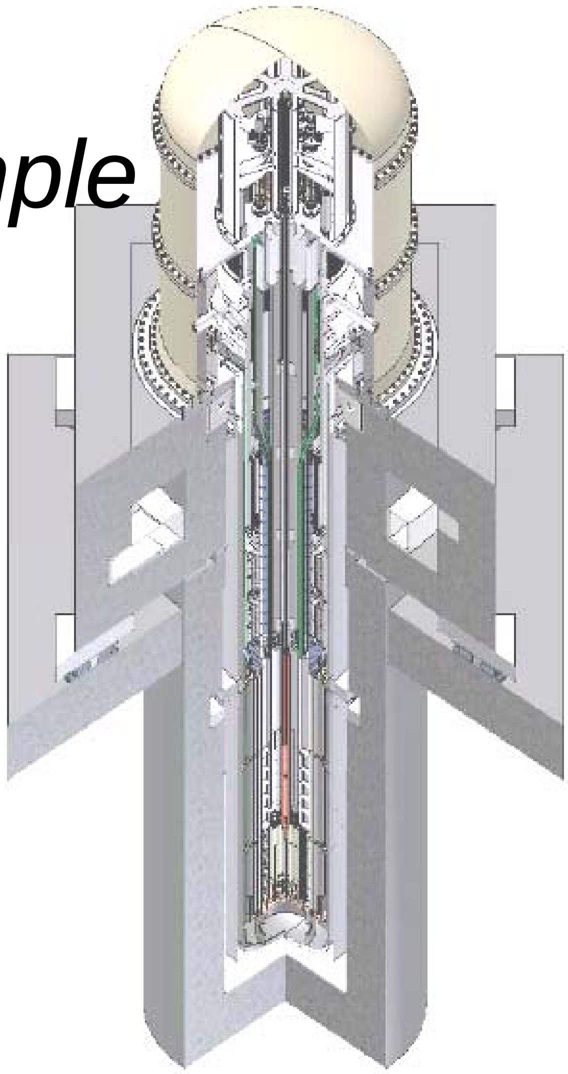
Summary

- Over 30 years in-reactor experience with metallic fuel irradiation.
- Extensive database of metallic fuel behavior is available.
- Based on the operating conditions and design parameters of the 4S and experience with metallic fuel irradiation, the 4S fuel is expected to perform adequately with no significant degradation.
- Design evaluation using the metallic fuel performance code, LIFE-METAL, shows that the 4S design meets a set of conservative pre-specified fuel integrity design criteria.
- Based on both experimental database and fuel performance code assessments, the 4S fuel is expected to perform adequately during normal conditions.

CRIEPI TOSHIBA Leading Innovation Argonne NATIONAL LABORATORY Westinghouse

4S Reactor

Super-Safe, Small and Simple



Second Meeting with the NRC

Pre-Application Review

Conclusions

February 21, 2008

Conclusions

- **4S is a mature technology that is ready for commercialization.**
  - Preliminary systems design complete and detailed design in progress
  - Significant body of test data to support key components
  - Proven and tested fuel experience to support the 30-year core lifetime
- **4S U.S. licensing process has begun.**
  - Pre-application review meetings & topical reports
  - Target for FDA - 2010

Phase 1 – Proposed Licensing Approach

	2007	2008	
	4Q	1Q	2Q
1st Meeting High level overview	▼		
2nd Meeting – Today System design Long-life metallic fuel		▼	
3rd Meeting* Safety design and regulatory conformance			▼
4th Meeting* PIRT review			▼

* Subject to NRC concurrence

CRIEPI
TOSHIBA Leading Innovation
Westinghouse