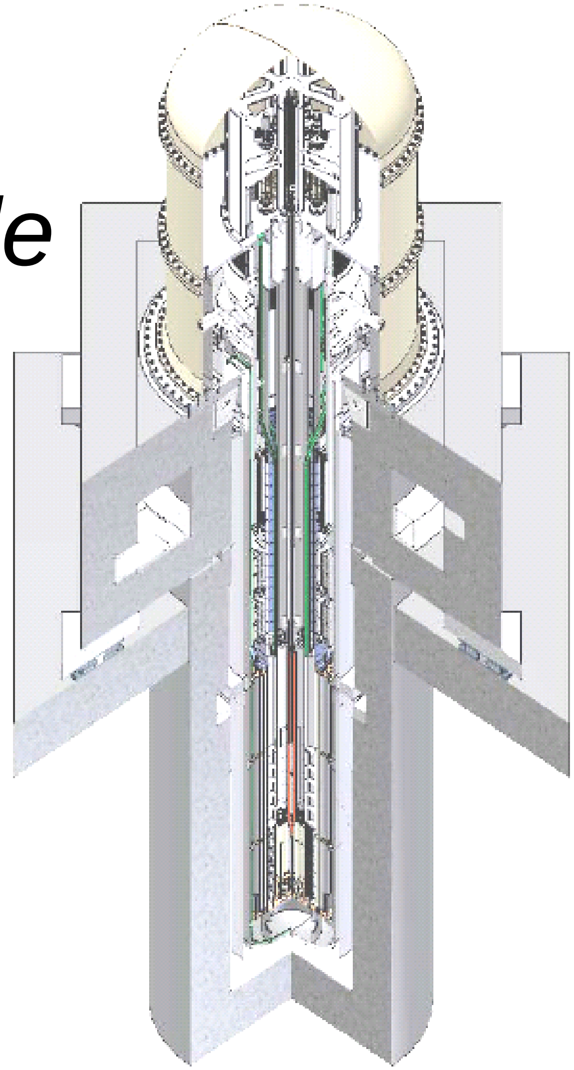
PSN-2007-0843

4S Reactor

Super-Safe, Small and Simple



First Meeting with NRC

Pre-Application Review

October 23, 2007

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4S Reactor – Goals

- Provide safe, clean, reliable, grid-appropriate power
- Minimize security and proliferation risks
- Minimize infrastructure, operation & maintenance requirements

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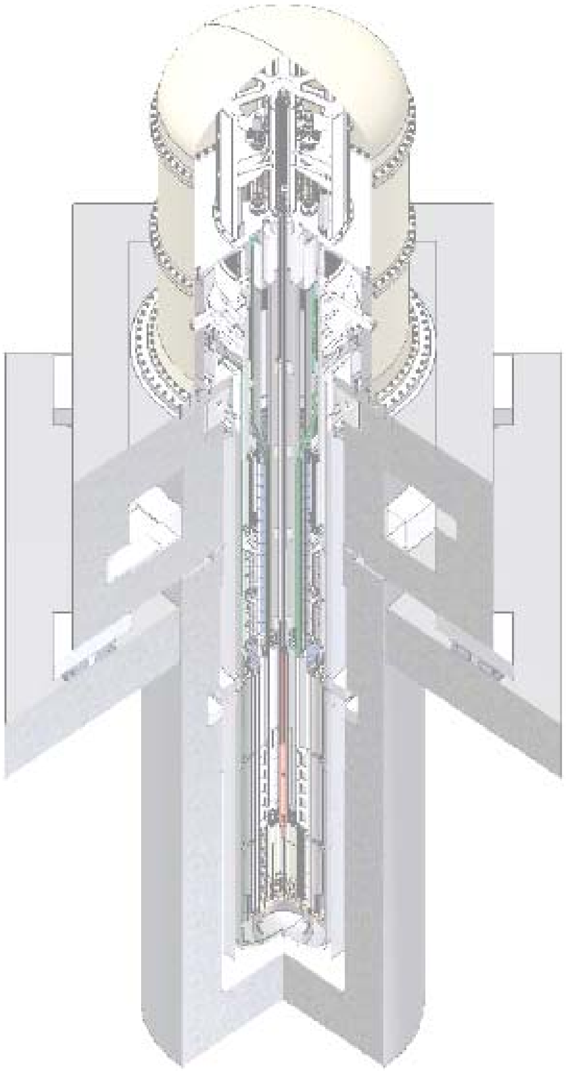
Meeting Objectives

- Provide overall introduction of 4S
- Gain U.S. NRC guidance on overall process to be followed for licensing of 4S in the U.S.
- Establish a continuing dialogue with NRC on 4S

Presentation Agenda

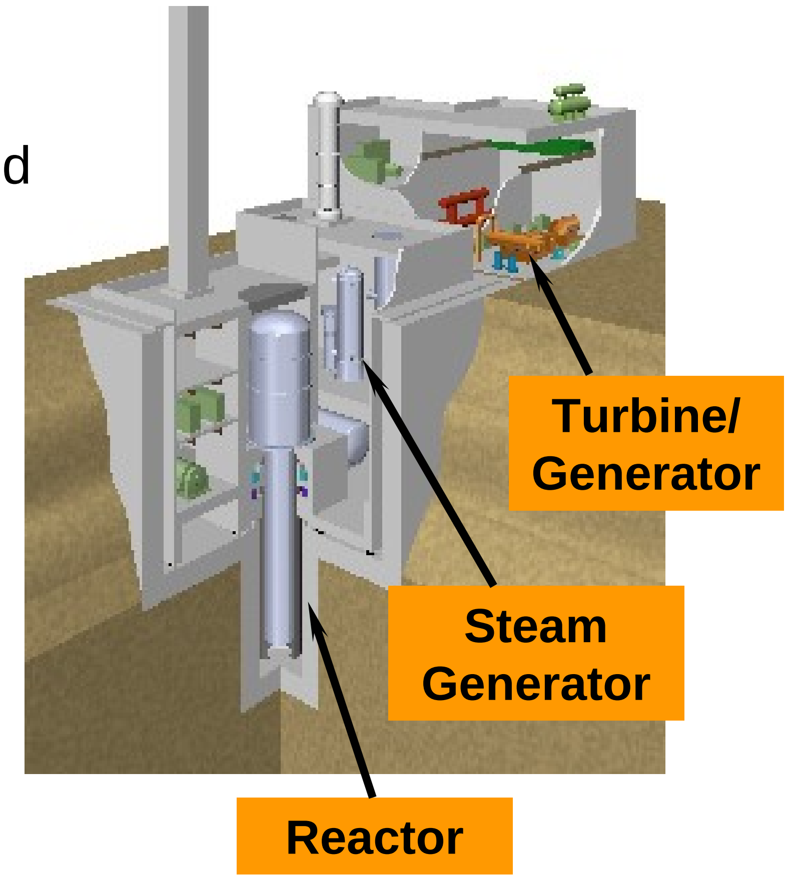
- High Level Overview
- Plant Design Parameters
- Regulatory Conformance
- Main Design Features
- Metallic Fuel Experience and Design Verification Testing
- Safety Analysis
- Conclusions

High Level Overview



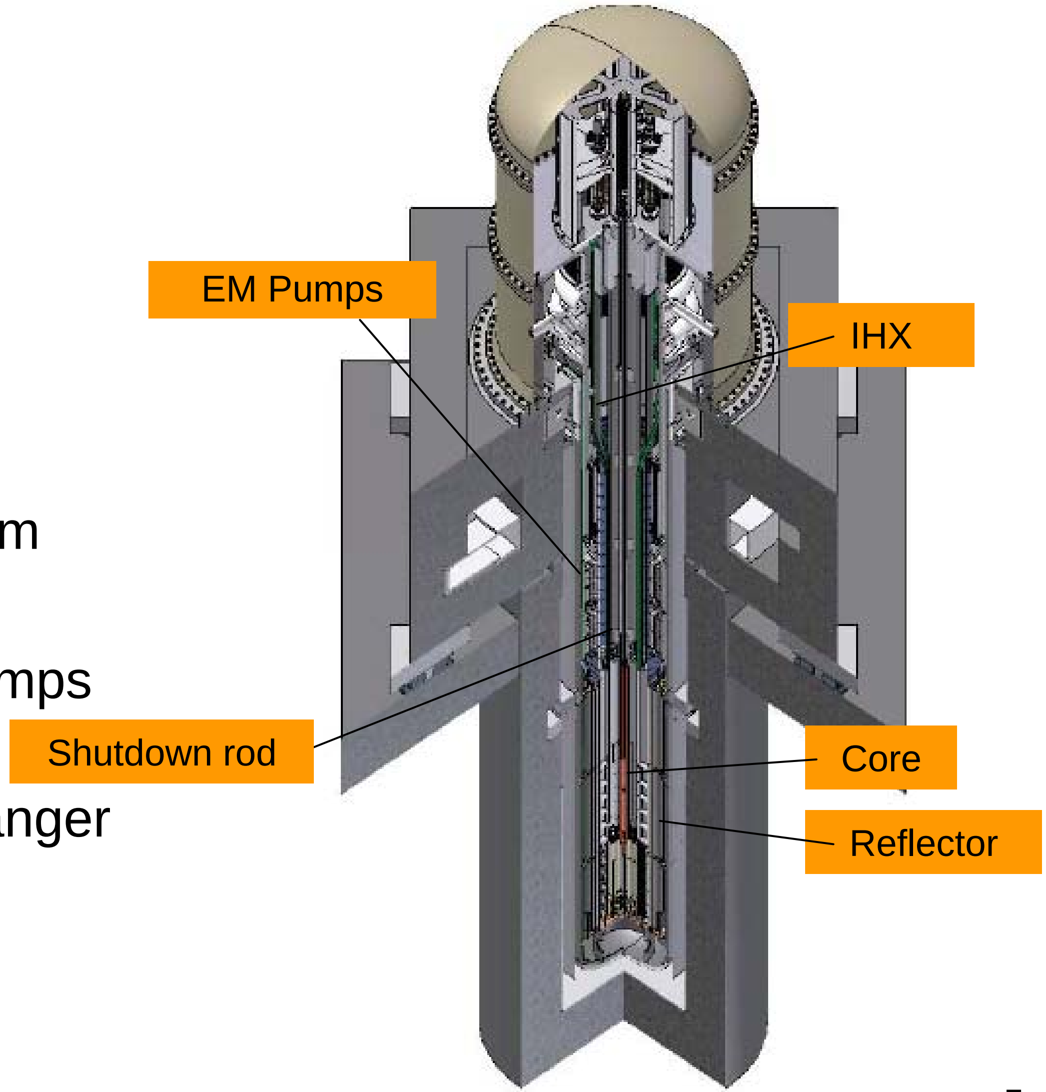
Overview

- **Sodium cooled fast reactor**
- **30 MWt (10MWe)**
- **Application**
  - Remote areas of small power demand (e.g., Galena Alaska)
  - Considered a candidate for GNEP grid-appropriate small and medium reactor design
- **Main features**
  - Passive safety
  - No onsite refueling for 30 years
  - Low maintenance requirement
  - High inherent security



Plant Description

- **Reactor**
  - Core
    Metallic fuel core (U-10%Zr)
  - Reactivity control
    Movable reflectors
  - Shutdown system
    Shutdown rod and reflectors
  - Primary heat transport system
    - Pumps: Annular type
      Electro-magnetic (EM) pumps
    - IHX: Annular type
      intermediate heat exchanger



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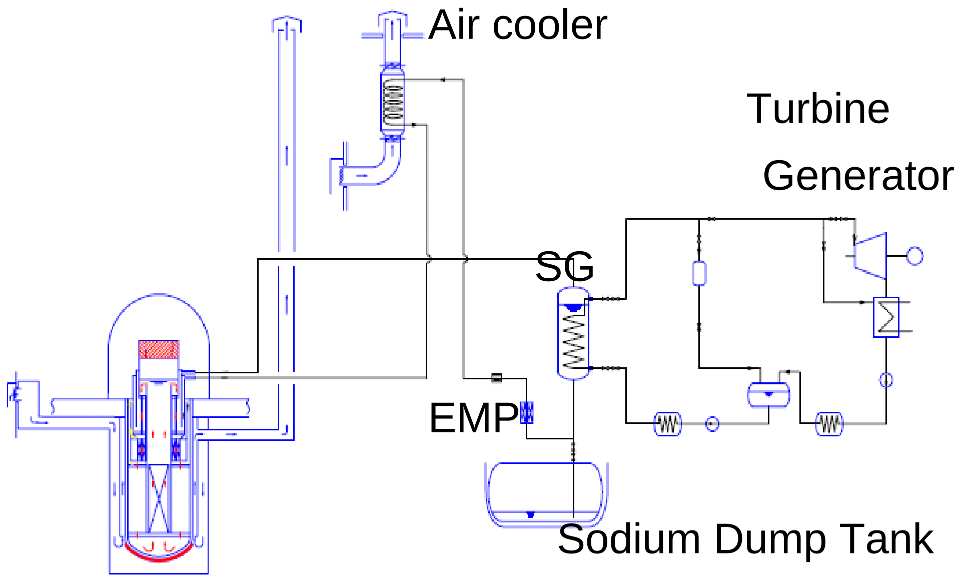
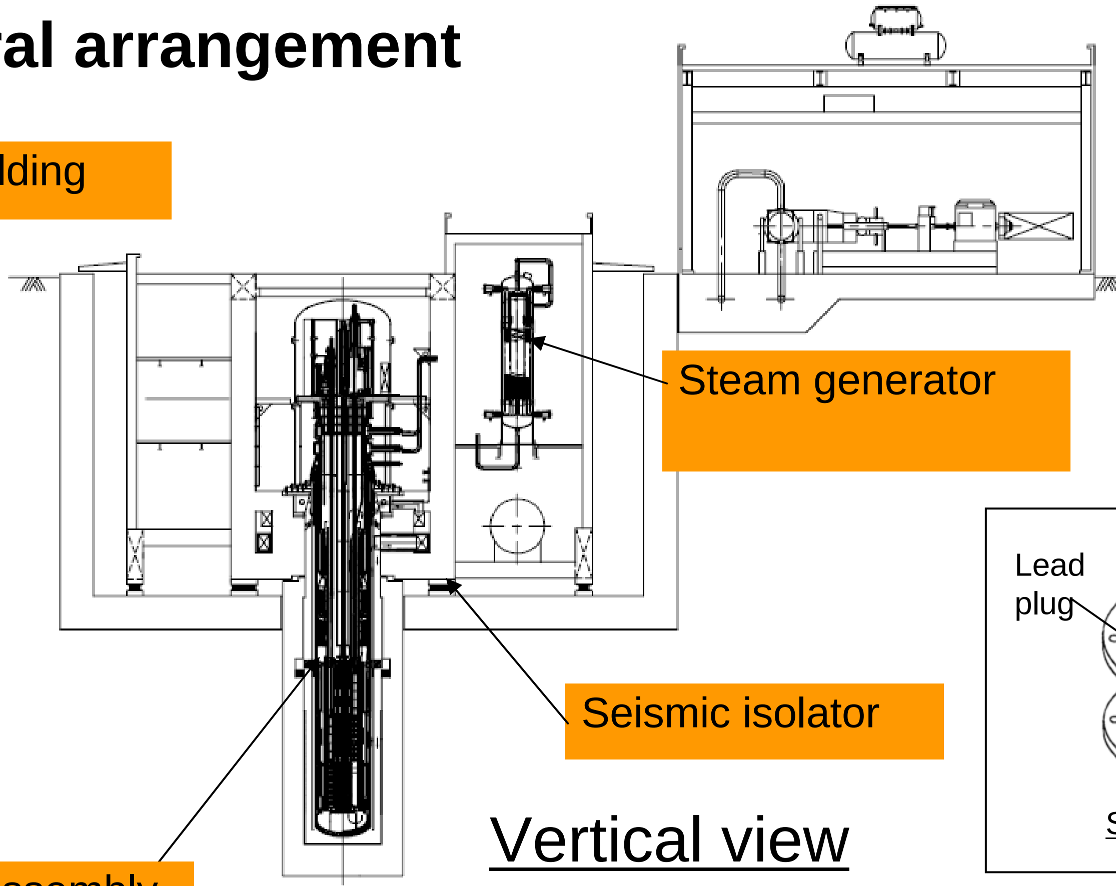
Plant Description

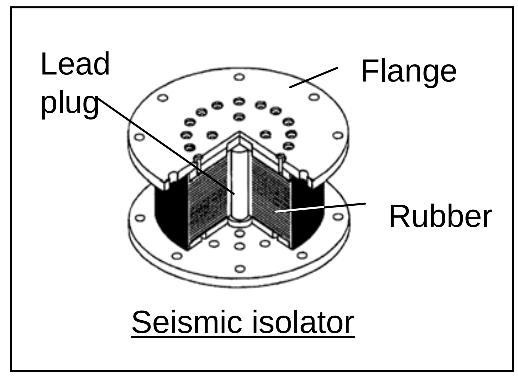
- **Heat transport systems**
  - Primary heat transport system: Inside the reactor
  - Intermediate heat transport system
    - Steam generator
    - EM pump
    - Air cooler
    - Dump tank
  - Water & steam system
    - Turbine Generator



Plant Description

- **General arrangement**





– Seismic isolation is adopted for the reactor building.

– Reactor building is below grade.

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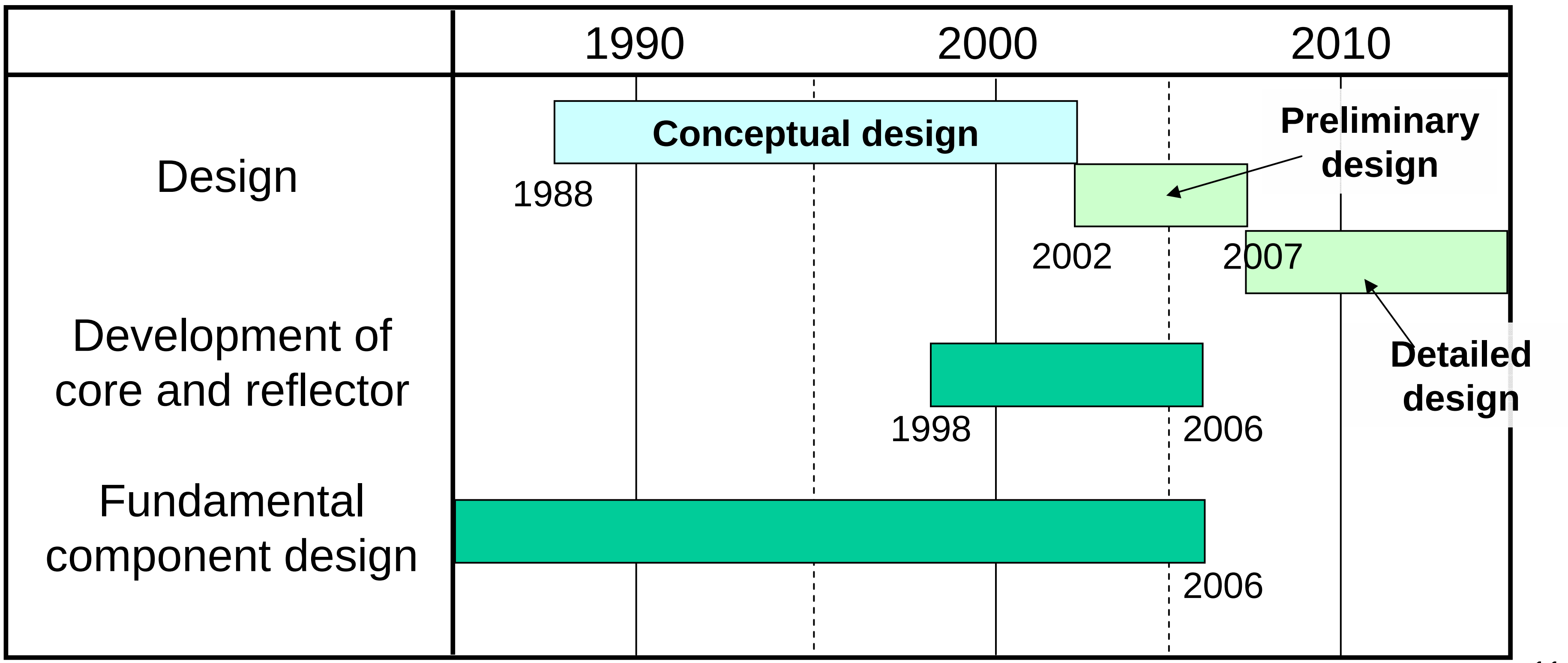
Status of 4S Design

- **Existing tests to support 4S Licensing**
  - Decades of experience with sodium-bonded metal fuel
  - Integral tests
    - Critical experiment
    - Heat transfer test of RVACS (Reactor Vessel Auxiliary Cooling System)
  - System and component tests
    - Fuel hydraulic test
    - Test of reflector drive mechanism
    - Sodium test of steam generator
    - Sodium test of EM pump
    - Test of seismic isolator

Status of 4S Design

- **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.



Project Organization

Manager of 4S Project: Yoshiaki Sakashita (TOSHIBA)

TOSHIBA

- Nuclear Systems & Services Division
  - Quality Assurance Dept.
- Plant Project Engineering Dept.
  - Advanced System D&E Dept.
  - Turbine D&E Dept.
  - Control & Electrical Systems D&E Dept.
  - Nuclear Energy Equipment Manufacturing Dept.

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4S Licensing Lead
B. F. Maurer

CRIEPI

- Nuclear Technology Research Laboratory
  Sr. Researcher: Nobuyuki Ueda
  - Civil Engineering Res. Lab.
  - Material Science Res. Lab.

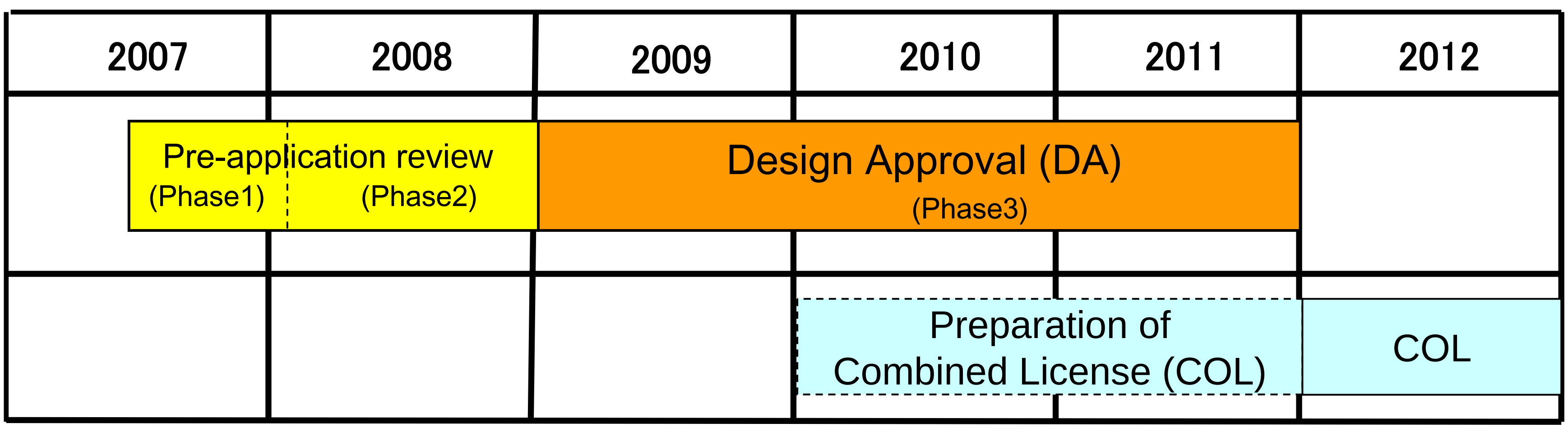
Argonne National Laboratory

Nuclear Engineering Division

(Technical support)

Proposed Licensing Approach

- **Submit Design Approval application in 2009**
  - **Phase 1:** Complete a series meetings with NRC to identify issues to be addressed before Design Approval application
  - **Phase 2:** Submit technical reports and obtain NRC feedbacks 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

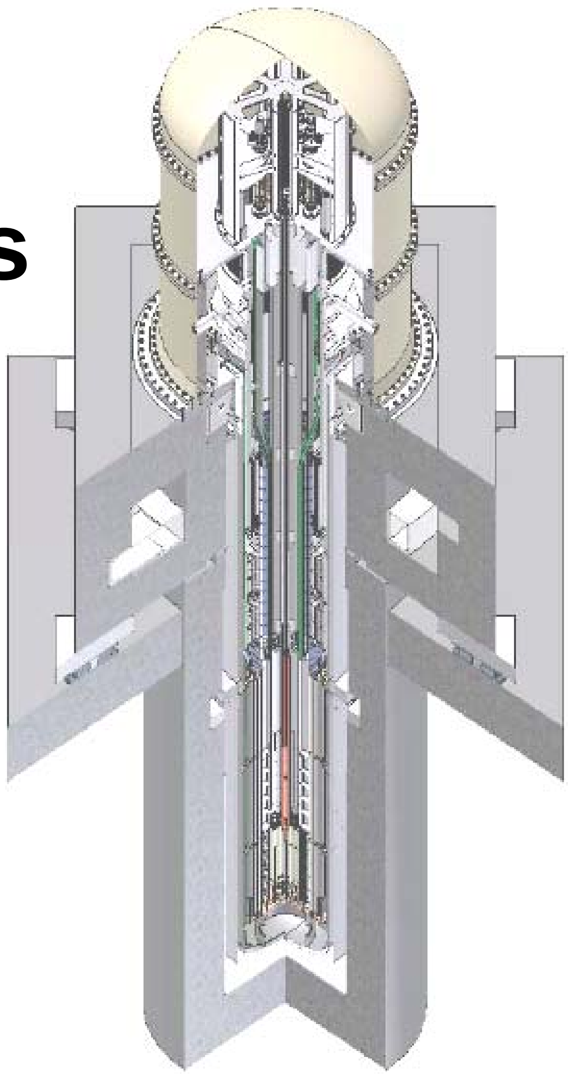
	2007			2008	
	Oct.	Nov.	Dec.	Jan.	Feb.
1st Meeting - Today High level overview	▼				
2nd Meeting* Long-life metallic fuel System design familiarization Safety design familiarization		▼			
3rd Meeting* Seismic isolation Regulatory conformance				▼	
4th Meeting* PIRT review					▼

* Subject to NRC concurrence

Phase 2 - Proposed Licensing Approach

- **Phase 2 -Schedule of technical reports for NRC review**
  - Seismic isolation — Feb. 2008
  - Long life metallic fuel
    Analysis methodology — Mar. 2008
    Fuel performance — Apr. 2008
  - Safety analysis
    Analysis methodology — Jun. 2008
    Safety analysis result — Jul. 2008
  - PRA level 1 — Aug. 2008
  - PIRT & test program — Sep. 2008

Plant Design Parameters



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 deg.C (671 / 950 deg.F)
Primary Sodium Flow Rate	547 t/h
Intermediate Sodium Inlet / Outlet Temperature	310 / 485 deg.C (590 / 905 deg.F)
Intermediate Sodium Flow Rate	482 t/h
Turbine Throttle Conditions	Flow Rate 44.2 t/h Pressure 10 MPa (1450 psi) Temperature 450 deg.C

Plant Design Parameters

▪ Reactor Core

Core Height	2.5 m	(8.2 ft)
Equivalent Core Diameter	0.95 m	(3.1 ft)
Fuel / Clad Material	U-10%Zr / HT-9 steel	
235U Enrichment (inner / outer)	17 / 19 %	
Average Burn-up	34,000 MWd/t	

▪ Reactor Vessel

Design Pressure	0.3 MPa	(44 psi)
Design Temperature	550 deg.C	(1022 deg.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

Heat Transport Systems

Primary EM Pump	Single stator type Linear annular induction pump
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)

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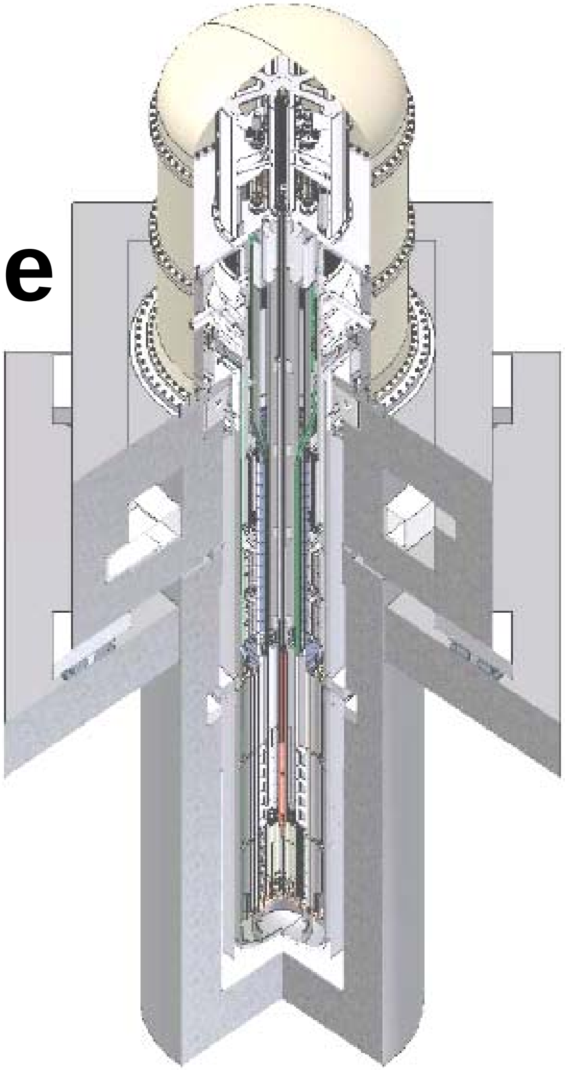
Regulatory Conformance



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Code and Regulatory Conformance

- **Current Status**
  - Principal Design Criteria (PDC) for 4S completed
  - Regulatory Guides applicability/exceptions completed
  - Applicable Codes and Standards identified and applied

Code and Regulatory Conformance

- **Principal Design Criteria**
  - Regulatory basis - 10CFR52.47, Staff evaluation in CRBRP and PRISM LMR PSER
  - Approach
    - Evaluate 10CFR50, Appendix A applicability and completeness for 4S reactor
    - Use what is applicable, modify or replace what is not
  - Results: ~50% 10CFR50, Appendix A applicable, remainder removed or changed for 4S application

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Code and Regulatory Conformance

▪ Regulatory Guides (RG)

– Regulatory basis – 10CFR52, SECY-94-084[1], Standard Review Plan (SRP) (NUREG-0800)

– Approach

RGs categorized as:

- Inapplicable (strictly LWR)
- Applicable (reactor type independent)
- Partially applicable (intent considered)

– Results: exceptions to RGs identified and justified for the following RG Divisions:

1 (power reactors), 4 (environmental and siting), 5 (materials and plant protection) and 8 (occupational health)

1-Policy and Technical Issues Associated with the Regulatory Treatment of Non-safety Systems in Passive Plant Designs, 1994

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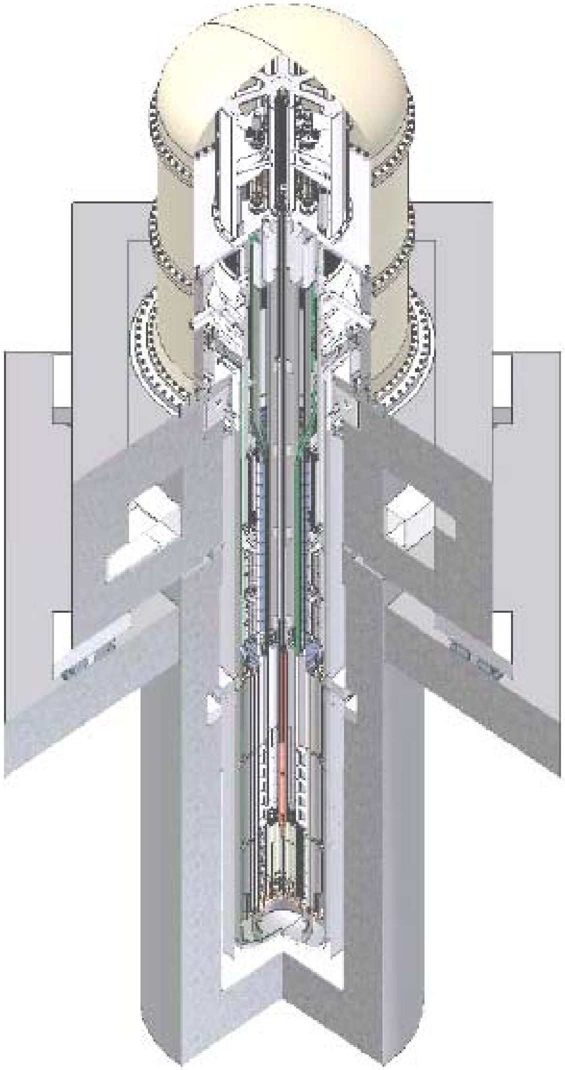
Code and Regulatory Conformance

- **Applicable Codes and Standards**
  - Applicable Codes and Standards identified and applied (reactor vessel & internals, steam generator, reactor protection system, etc.)
    - ASME
    - ANSI/ANS
    - IEEE
  - New code needs have been identified and codes are being developed.
    - Seismic isolation
- **QA Program – 10CFR50 Appendix B, ASME-NQA-1**

Main Design Features



Main Design Features

- Safety Features
- Key Features of 4S
  - Passive safety
  - No onsite refueling for 30 years
  - Low maintenance requirement
  - High inherent security

Safety Features

- Low pressure system with pool design and guard vessel – no LOCA
- Negative coolant temperature coefficient promotes safe, stable operation.
- Large margin to coolant boiling or cladding failure
- Reliable, redundant and diverse scram systems
- Smaller excess reactivity with metallic fuel core design – limited potential for reactivity insertion accident
- Passive, reliable, and diverse shutdown heat removal systems

Safety Features

- Fuel-sodium chemical compatibility – allows run beyond cladding breach
- Double-walled steam generator tubes with leak detection protect against sodium-water reaction
- Past experience is applied to design features to mitigate effects of secondary sodium leaks.
- Capability to survive beyond design basis events without core damage

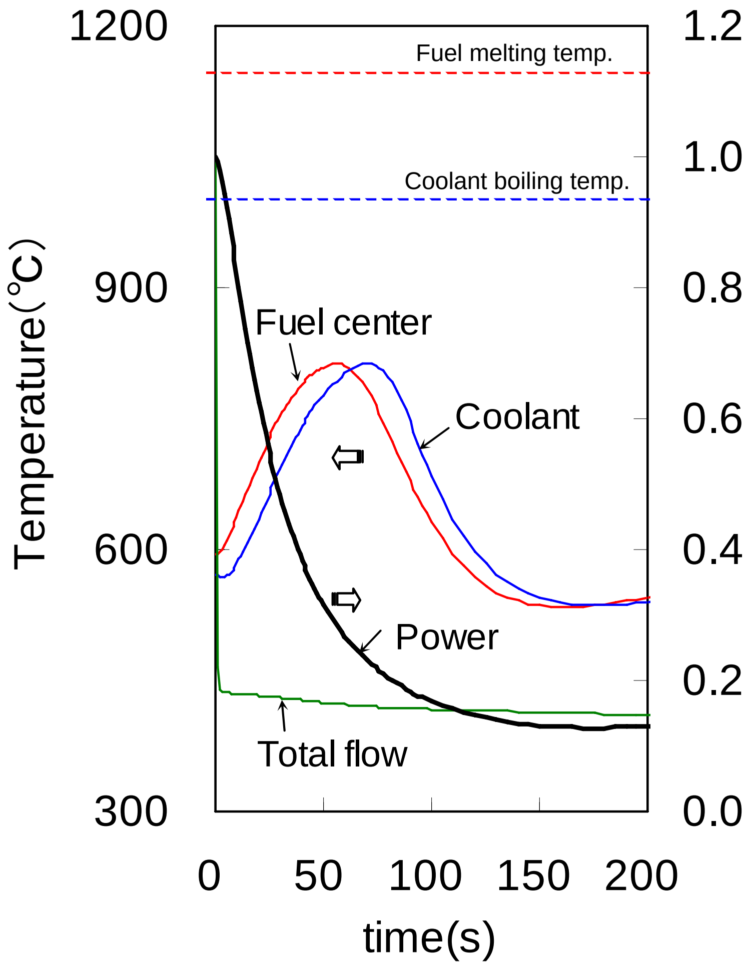
Passive Safety

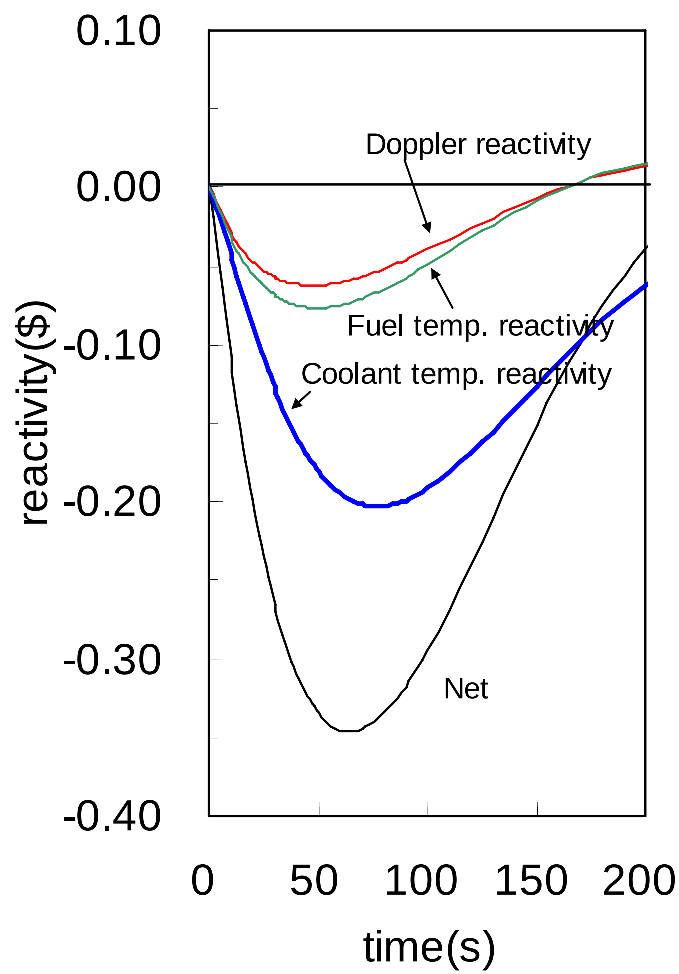
Target	Design	Achieves
Passive reactor shutdown capability	Long cylindrical core with small diameter	Negative coolant reactivity
Passive decay heat removal	RVACS*1 IRACS*2	Natural circulation & Natural air draft

*1 Reactor Vessel Auxiliary Cooling System
*2 Intermediate Reactor Auxiliary Cooling System

Passive Shutdown for Unprotected Events

- Safety Analysis of Unprotected sudden loss of flow
  Large margin to coolant boiling and fuel melting





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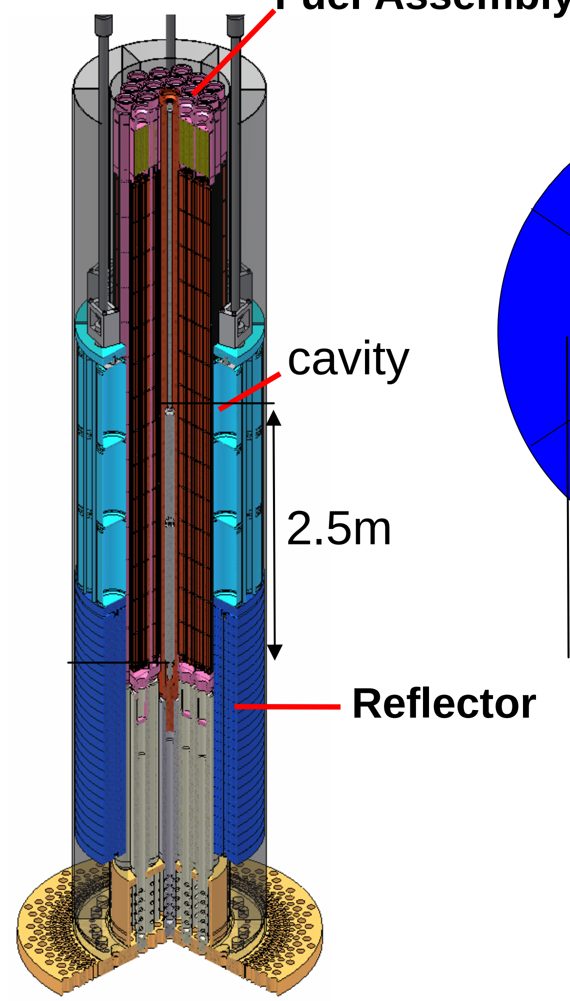
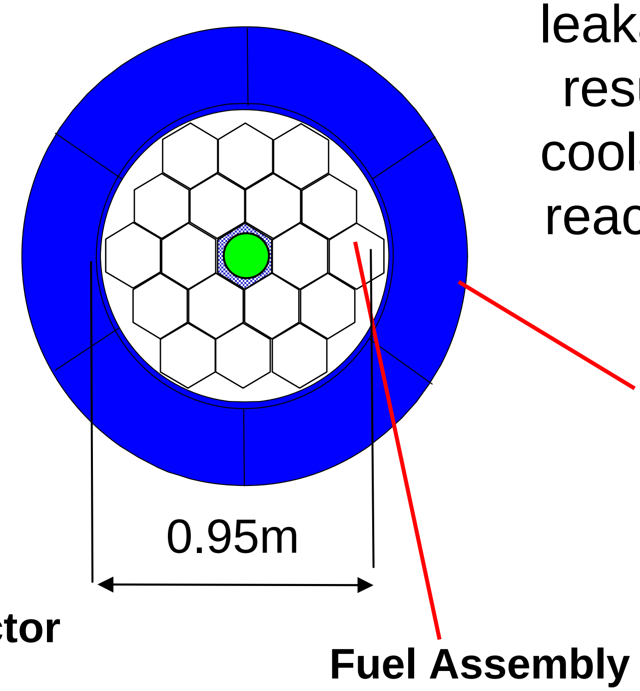
Long Cylindrical Core with Small Diameter





Enhancement of neutron leakage mechanism results in negative coolant temperature reactivity coefficient

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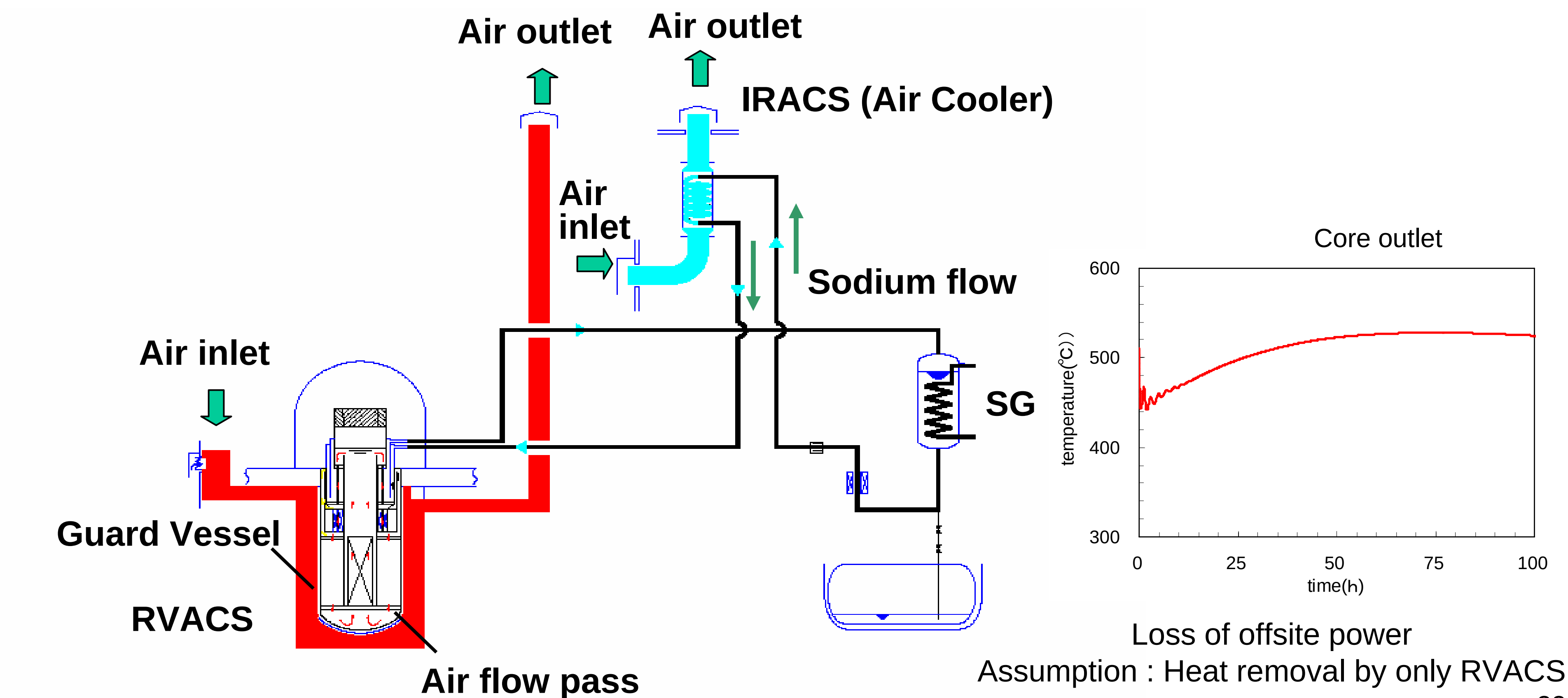
Passive Decay Heat Removal

- **Heat removal by natural circulation & natural air draft**
  - RVACS: Natural air draft outside the guard vessel
    - Sufficient cooling capacity by only RVACS
  - IRACS: Natural circulation of sodium and air draft of air cooler



Loss of offsite power
Assumption : Heat removal by only RVACS

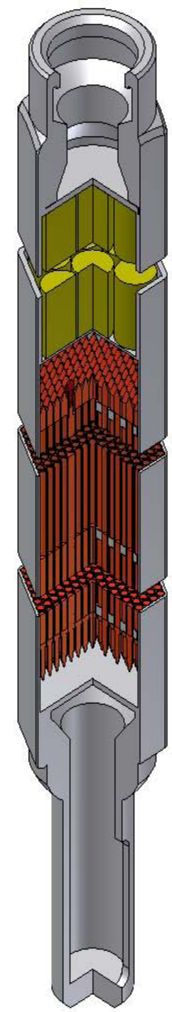
No Onsite Refueling for 30 years

Target	Design	Achieves
Long life core	High volume fraction metallic fuel core	Small burn-up reactivity swing due to larger amount of fuel
	Long cylindrical core with small diameter	
	Reflector controlled core	Neutron leakage control

Metallic Fuel

- Fuel volume fraction of 50% (40% typical LMR)
- Sodium-bonded metallic fuel (sodium between fuel slug and cladding) – high thermal conductivity
- Fuel integrity for 30 years
  - Burn-up within experience range (EBR-II)
  - Fuel pins maintain integrity against creep damage for 30 years

Fuel pin diameter	14mm
Fuel pin P/D ratio	1.08
Fuel material	U-10%Zr
Smear density (BOC)	78%
No. of pins/assembly	169
Material of clad/assembly	HT-9



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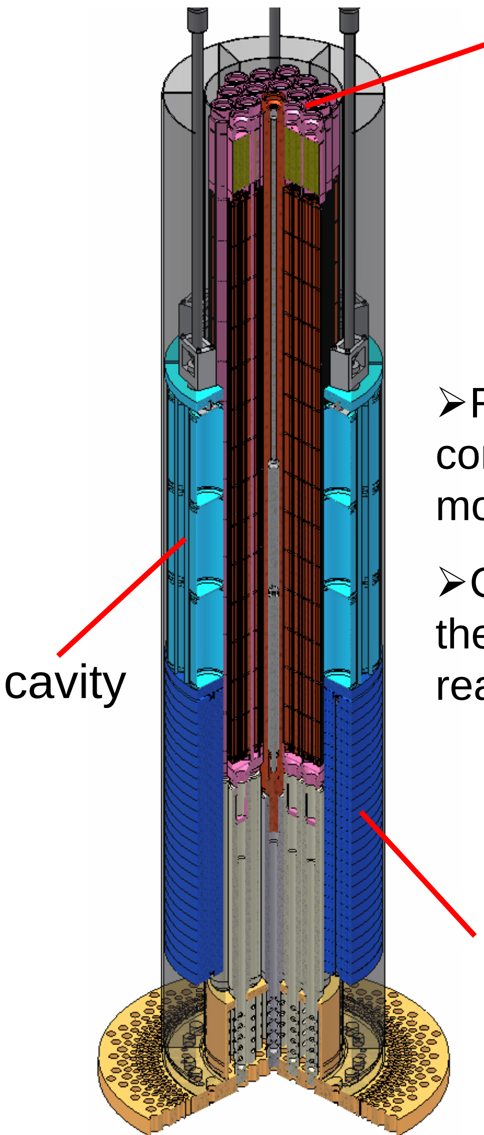
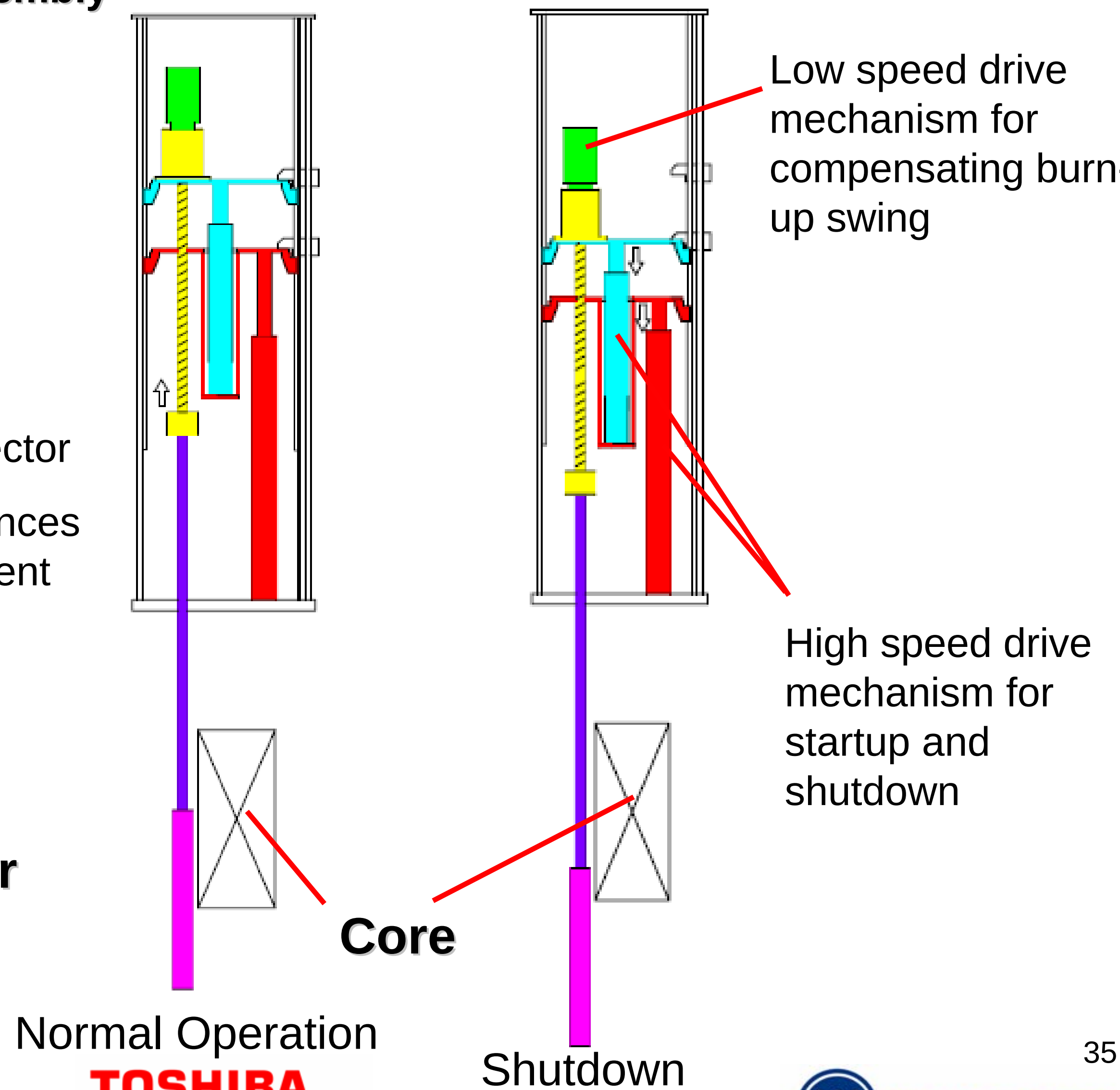
Reflector Controlled Core



- ➢Reactivity controlled by movable reflector
- ➢Cavity enhances the replacement reactivity



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Low Maintenance Requirement

Target	Design	Achieves
Maintenance-free reactor internals	Reflector	No replacement of control device
	EM pump	Elimination of moving parts
	Material selection	Compatibility between coolant and structure

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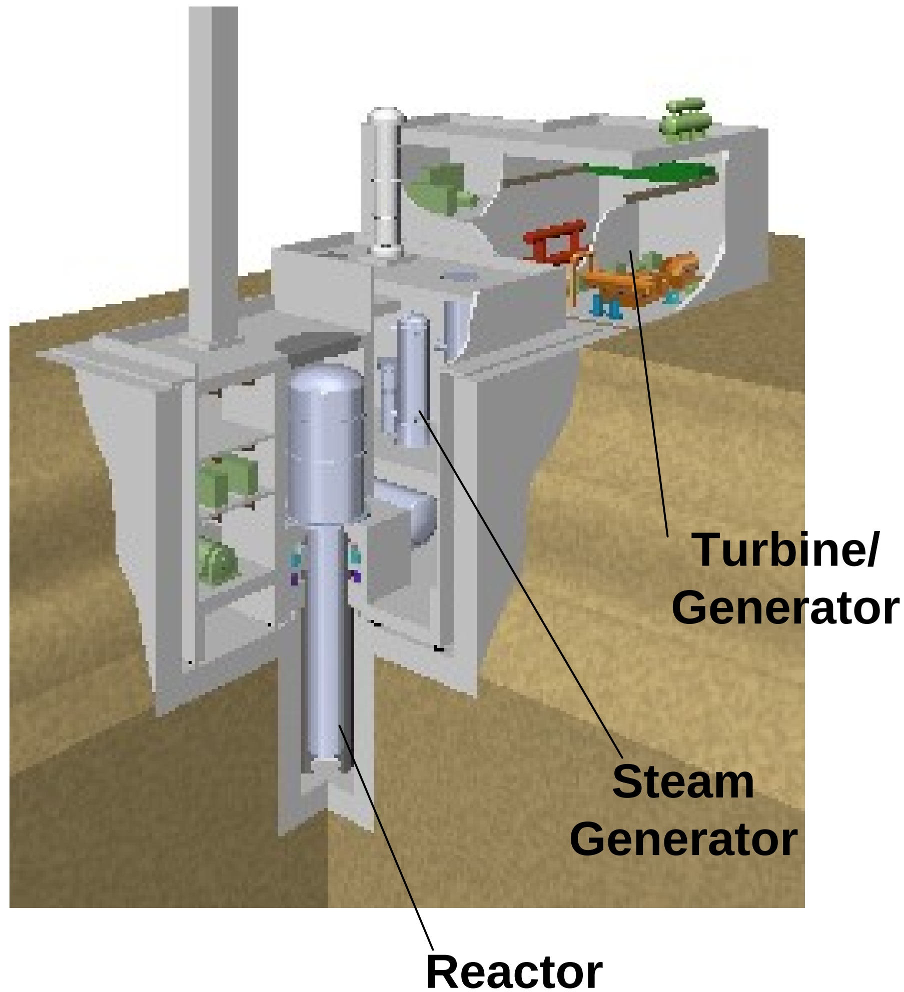
High Inherent Security

Target	Design
Below-grade siting to protect the reactor from external hazard	Small reactor
Sealed reactor No onsite fuel storage	No refueling needed for 30 years

Suitable for Below-grade Siting

- Below-grade siting to protect from external hazard such as missile or airplane impact



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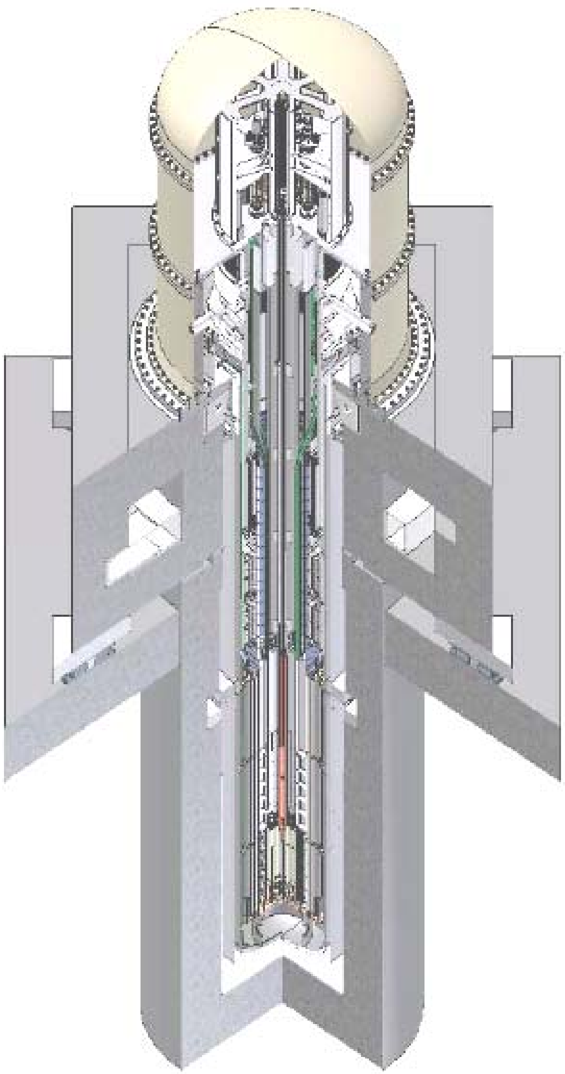
Main Design Features - Summary

- Passively achieve fundamental safety functions
- Allow simplified operation and maintenance
- Enhance security and proliferation resistance

Metallic Fuel Experience
and
Design Verification Testing



Metallic Fuel Experience

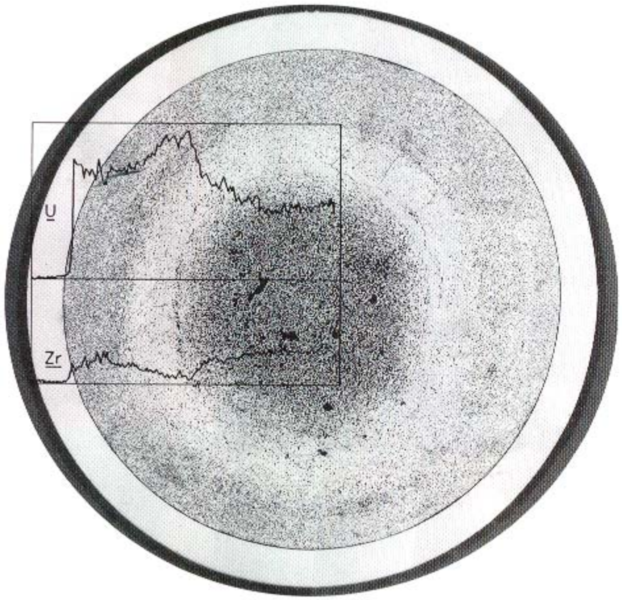
- Over 30 years in-reactor experience with metallic fuel irradiation
  - >16,000 U-Zr pins irradiated at EBR-II without failure at operating conditions
  - >40,000 U-Fissium pins irradiated at EBR-II
  - >600 U-Pu-Zr pins irradiated at EBR-II
  - Longer length fuel tested in FFTF
  - Large experimental database of PIE data

Metallic Fuel Experience

- Significant experience in transient fuel performance
  - Transient Reactor Test (TREAT) transient tests
  - Fuel Behavior Test Apparatus (FBTA) out of pile tests
  - Whole Pin Furnace (WPF) tests
  - Run beyond cladding breach (RBCB)
- Fuel-cladding interaction diffusion couples testing – lab scale

Metallic Fuel Experience

- 4S Fuel Performance Evaluation
  - LIFE-METAL (ANL) validated fuel performance code has been used to evaluate 4S fuel.
  - Results show that 4S fuel retains its integrity over the 30 year lifetime at expected operating conditions.



Cross section of Irradiated U-10Zr Fuel

Tests to Support 4S Design

Design Feature	Verification Item	Required Testing	Status
Long cylindrical core with small diameter	Nuclear design method of reflector control core with metallic fuel	Critical experiment	**Done**
Reflector controlled core			
High volume fraction metallic fuel core	Confirmation of pressure drop in fuel subassembly	Fuel hydraulic test	**Done**
Reflector	Reflector drive mechanism with fine movement	Test of reflector drive mechanism	**Done**
RVACS	Heat transfer characteristic between vessel and air	Heat transfer test of RVACS	**Done**
EM pump	Structural integrity Stable characteristics	Sodium test of EM pump	**Done and Planned**
Steam generator (Double wall tubes)	Structural integrity Heat transfer characteristic Leak detection	Sodium test of steam generator Leak detection test	**Done and Planned**
Seismic isolation	Applicability to nuclear plant	Test of seismic isolator	**Done**

Critical Experiment

- **Objective**

  Validation of nuclear design methodology of reflector controlled core by using mockup of 4S core at FCA (Fast Critical Assembly)
  - Criticality
  - Sodium void reactivity
  - Reflector reactivity.

FCA

This photo is offered by JAEA

- **Result** [1,2]

  Nuclear design methodology meets major neutronics characteristics within the sufficient accuracies.

  Criticality is predicted within 0.4%Δk.

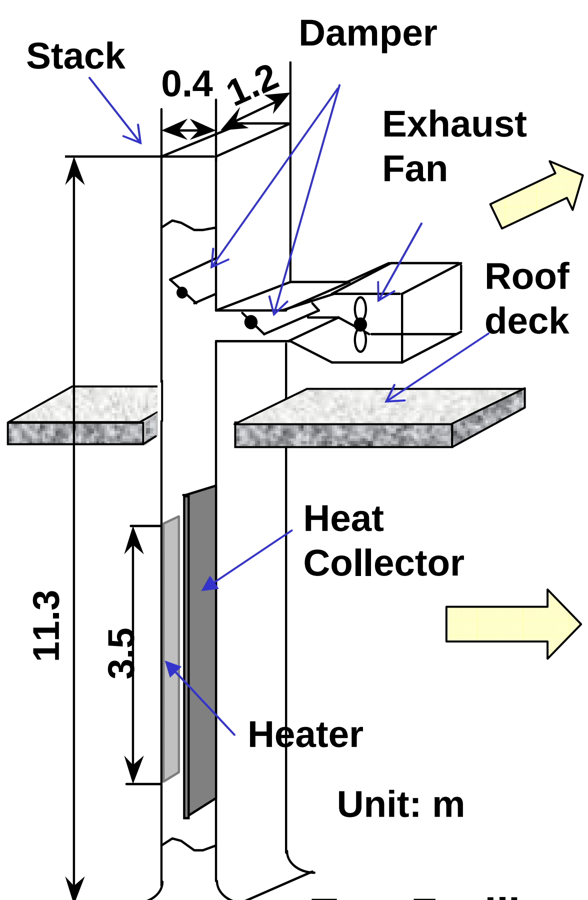
R&Ds has been performed by CRIEPI in collaboration with JAEA as a part of " Innovative Nuclear Energy System Technology (INEST) Development Projects" under sponsorship of MEXT (JAPAN).

1) Development of Neutronics Analysis Technique for Non-Refueling Core (Part 1: Critical Experiment)
S.Okajima, M.Fukushima and T.Takeda, 2005 ANS Winter Meeting
2) Development of Neutronics Analysis Technique for Non-Refueling Core Part 2: Method
T. Takeda, T.Kitada and S.Okajima, 2005 ANS Winter Meeting

Heat Transfer Test of RVACS

Objective

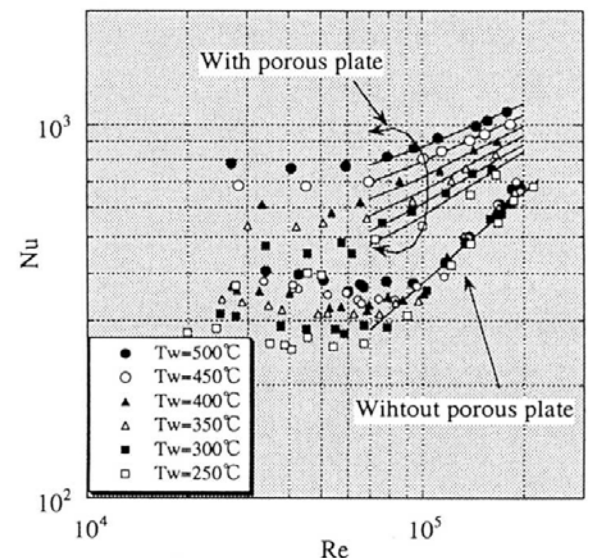
Identification of heat transfer coefficient between vessel and air



Test Facility

Result

Development of empirical equation



Obtained heat transfer correlation of the air side

Y. Nishi, I. Kinoshita, "Applicability of reactor vessel auxiliary cooling systems for FBRs (Effect of air duct pressure loss on heat removal characteristics)",Proc. of International Sessions -The 73rd JSME Spring Annual Meeting-,2-4/April, 1996, Nihon Univ., JAPAN

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Fuel Hydraulic Test

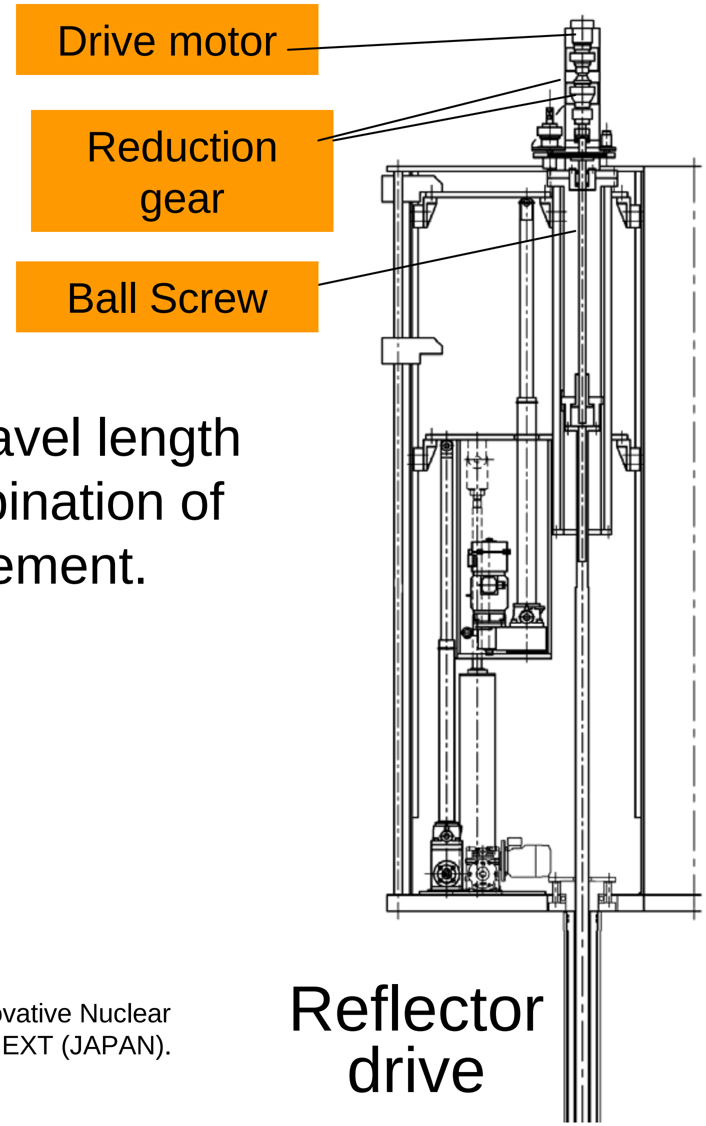
- **Objective**
  - Verification of pressure drop for high volume fraction metallic fuel core including the grid spacer
  - Pressure drop measurement by water test
- **Results** 1)
  - Developed the empirical equation of pressure drop
  - Selected grid spacer design for low pressure drop

R&Ds have been performed by CRIEPI in collaboration with JAEA as a part of " Innovative Nuclear Energy System Technology (INEST) Development Projects" under sponsorship of MEXT (JAPAN).

1) Development of Advanced Fuel Subassembly for Non-Refueling Core
T.Koga, S.Nishimura and I,Kinoshita, 2005 ANS Winter Meeting

Test of Reflector Drive Mechanism

- **Objective**
  - Verification of reflector drive mechanism by scale model
- **Results**
  - Confirmed target speed over the travel length is within ±1 micron/hr for the combination of ball screw and reduction gear movement.



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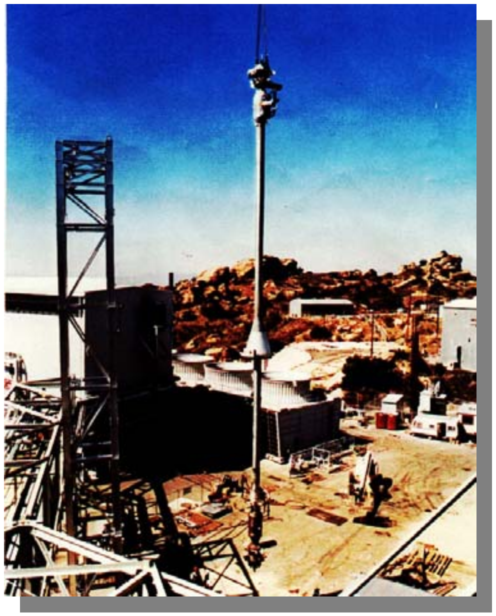
Sodium Test of Steam Generator

- **Objective**
  - Demonstration of double wall tube steam generator



Double wall tube SG at ETEC

TOSHIBA REVIEW Vol.46, No.3, pp.235 (1991)

- **Results**
  - Sodium tests of the Few Tube Test Model (13 tubes, 6 active) for over 10,000 hrs at ETEC[1]
  - Verified heat transfer characteristics of double wall tubes
  - Confirmed moisture detection capability at the inner tube failure

1 - ETEC – Energy Technology Engineering Center (DOE), Los Angeles, CA

Sodium Test of Electromagnetic Pump

- **Objective**

  Demonstration of large size EM pumps

EM Pump
(160 m^3 / min)

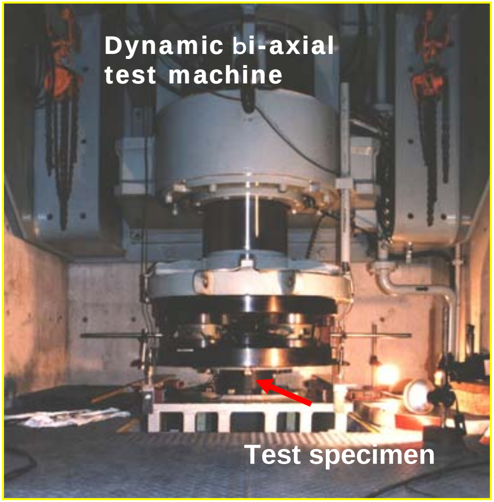
- **Results** [1)]
  - Sodium tests for over 2,550 hrs at ETEC
  - Confirmed the integrity of stator support and coil insulation up to 600℃
  - Confirmed flow stability in the required operation range

1)Ota et al., "Development of 160m3/min Large Capacity Sodium-Immersed Self-Cooled Electromagnetic Pump", J. Nucl. Sci. Tech., Vol.41, No.4, pp.511-523 (2004)

Test of Seismic Isolator

- **Objective**

  Confirmation of seismic isolator characteristics and design assumptions



- **Results** [1)]

  Confirmed seismic isolator characteristics

  - Linear critical strain
  - Static shear modulus
  - Youngs modulus

1-Technical Guide line on seismic Base isolated System for Structural Safety design of Nuclear Power Plant JEAG (Japan Electric Association Guideline) 4614-2000

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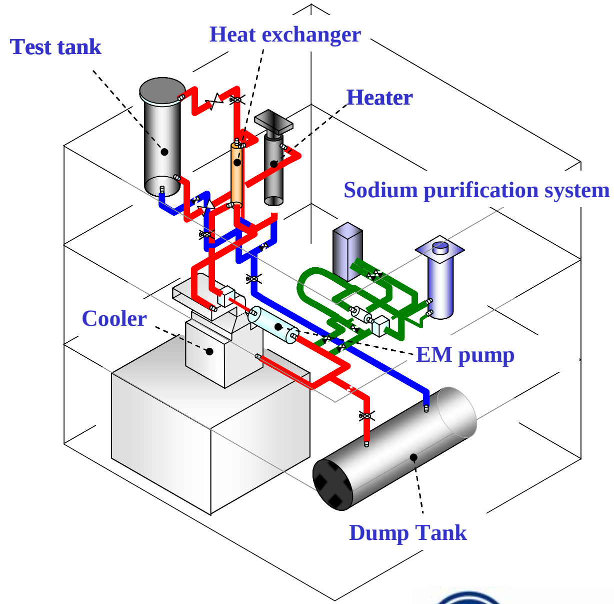
Test Facility for Future Tests

- **TOSHIBA Sodium Component Test Facility**
  - Facility will be completed December 2007
  - Functional testing will start January 2008
  - Planned tests
    - Demonstration of large-scale EM pump
    - Verification of leak detection system at the outer tube failure of steam generator



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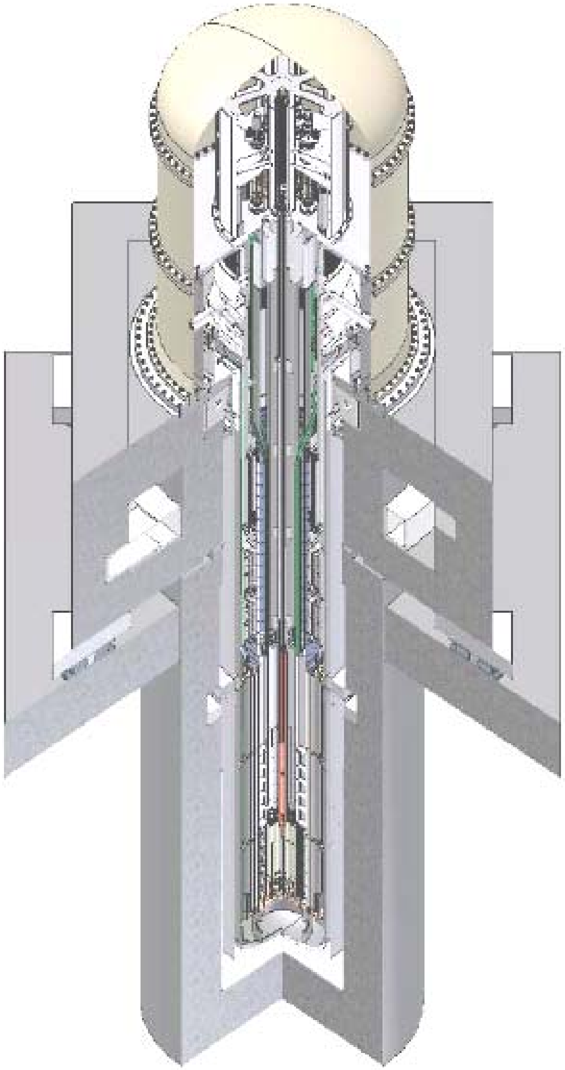
4S Testing - Summary

- 4S design is based on large LMR experimental basis in Japan and around the world.
- Metallic fuel has been extensively tested in and out of reactor over several decades.
- Performance of 4S metallic fuel design has verified based on existing data and fuel performance simulations.
- Unique features of 4S design have been extensively tested.
- New sodium test facility will be used for additional confirmation of 4S systems and component design and performance.

Safety Analysis



Event Classification

- Design Basis Events
- Beyond Design Basis Events

Design Basis Events

- **Design Basis Events**
  - Increase in heat removal by the water steam system
  - Decrease of heat removal by the water steam system
  - Loss of primary or secondary coolant flow
  - Increase of primary or secondary coolant flow
  - Anticipated reactivity insertion at full power operation
  - Anticipated reactivity insertion at start up
  - <u>Loss of offsite power</u>
  - Local fault
  - Sodium leakage
  - Single tube failure of SG (one boundary)
  - Cover gas release
  - Fuel handling system failure after plant life time

Beyond Design Basis Events

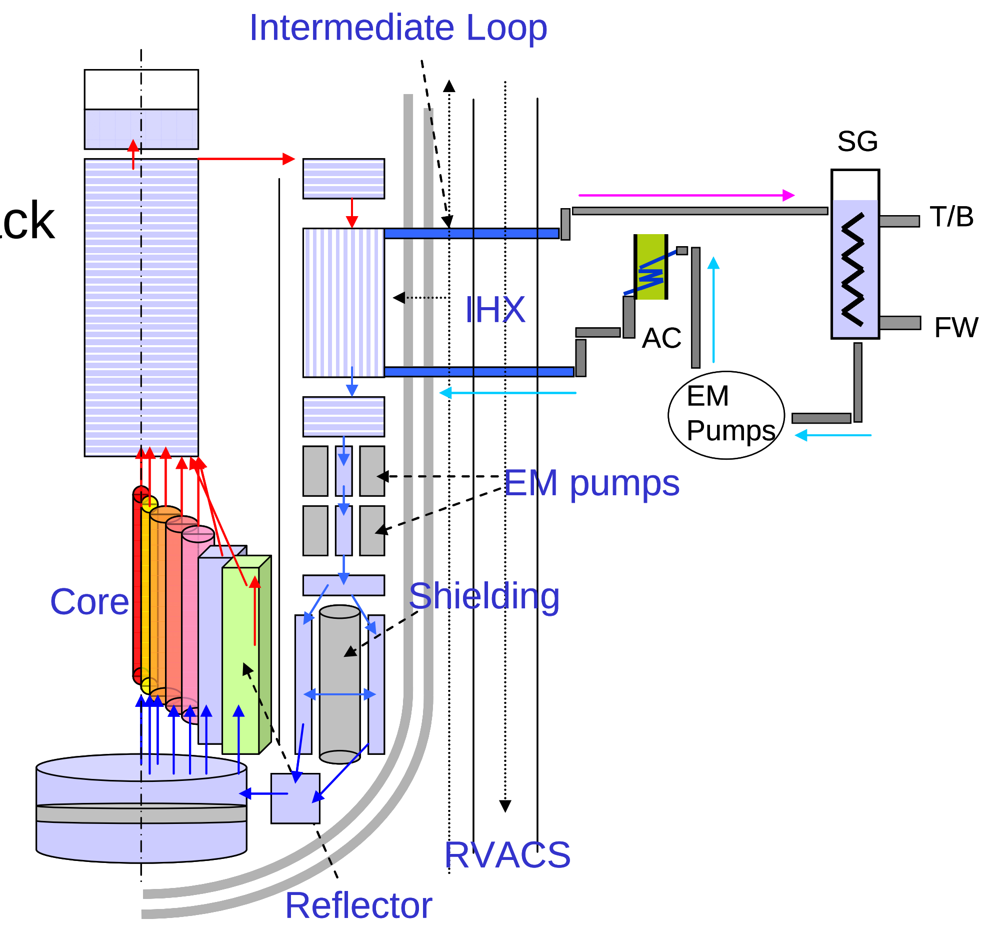
- **Beyond Design Basis Events**
  - Unprotected loss of flow
  - Unprotected transient over power
  - Unprotected loss of heat removal by water system
  - IRACS failure and loss of partial function of RVACS
  - Sodium water reaction

Comprehensive analysis has been performed to identify accident sequences.

Preliminary results show that no sequence has been identified that results in core damage.

Analysis Methodology

- **Analysis code : ARGO-3**
- **Models**
  - –Point kinetics
  - –Spatial effect of reactivity feedback
  - –Multiple channels in core
  - –One-dimensional flow network



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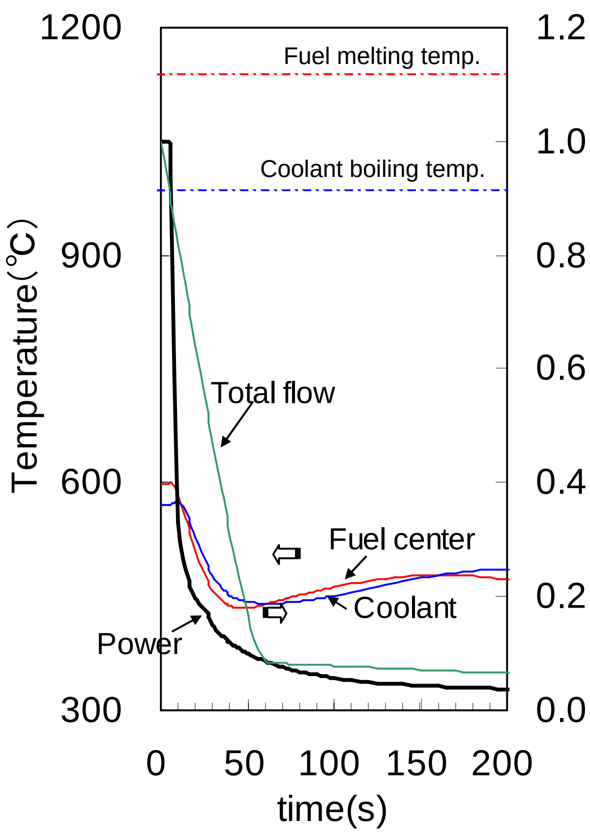
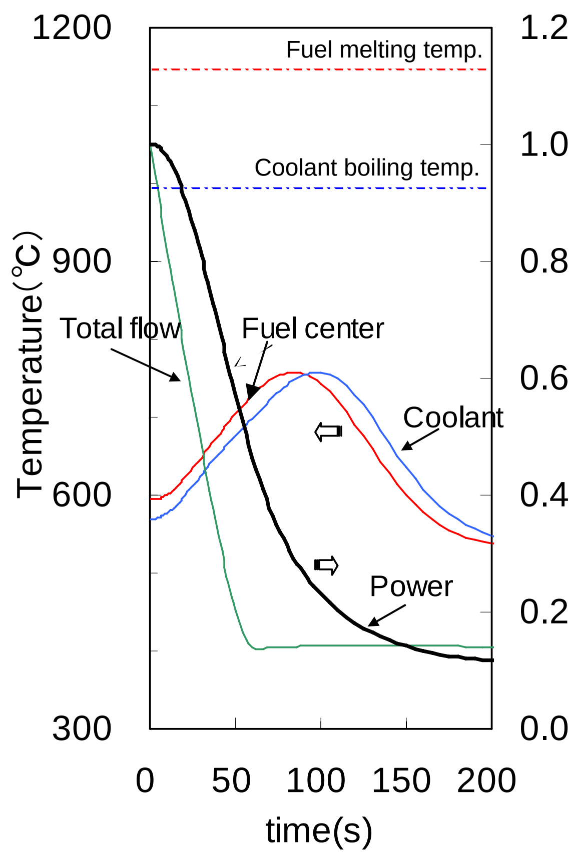
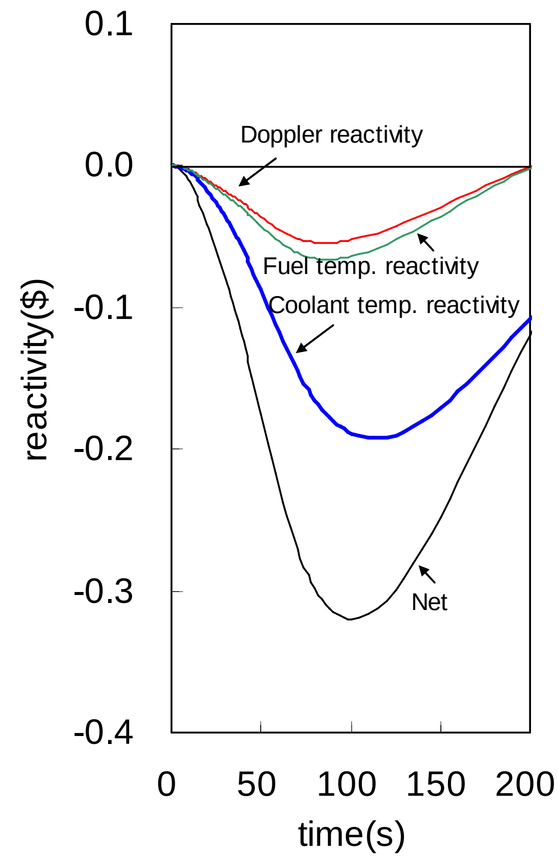
Analysis Results

DBE
Loss of offsite power



BDBE
Unprotected loss of flow





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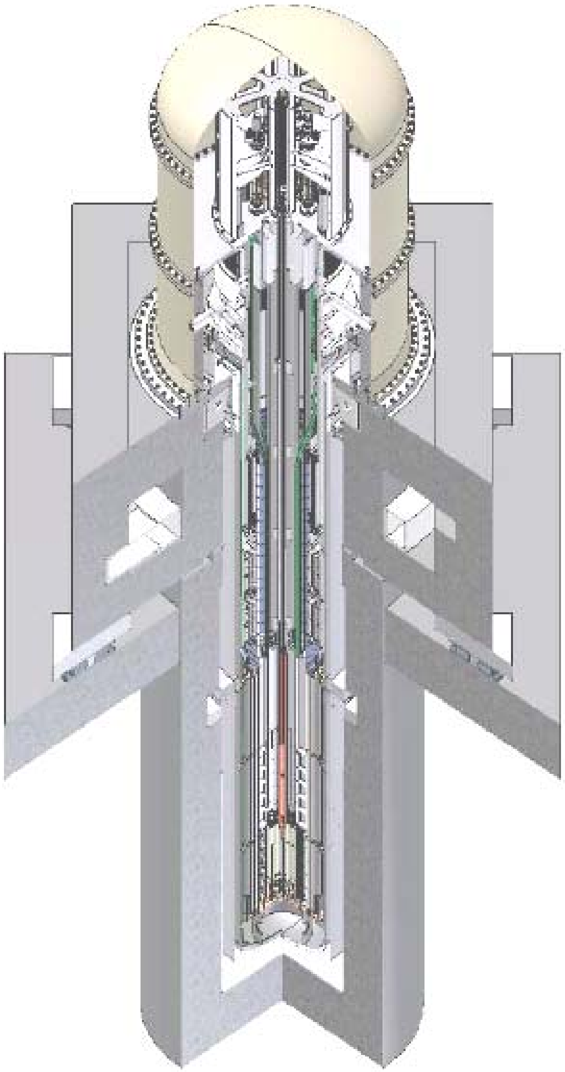
Conclusions



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Conclusion

- Preliminary design is complete.
- Extensive testing needed for design verification has been completed.
- 4S is a mature design.

Toshiba and its partners are requesting continuing dialogue with NRC leading to 4S Design Approval.

Phase 1 – Proposed Licensing Approach

	2007			2008	
	Oct.	Nov.	Dec.	Jan.	Feb.
1st Meeting - Today High level overview	▼				
2nd Meeting* Long-life metallic fuel System design familiarization Safety design familiarization		▼			
3rd Meeting* Seismic isolation Regulatory conformance				▼	
4th Meeting* PIRT review					▼

* Subject to NRC concurrence