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Overview of fast reactor development of Toshiba – 4S and TRU burner

Nordic-Gen4 Seminar

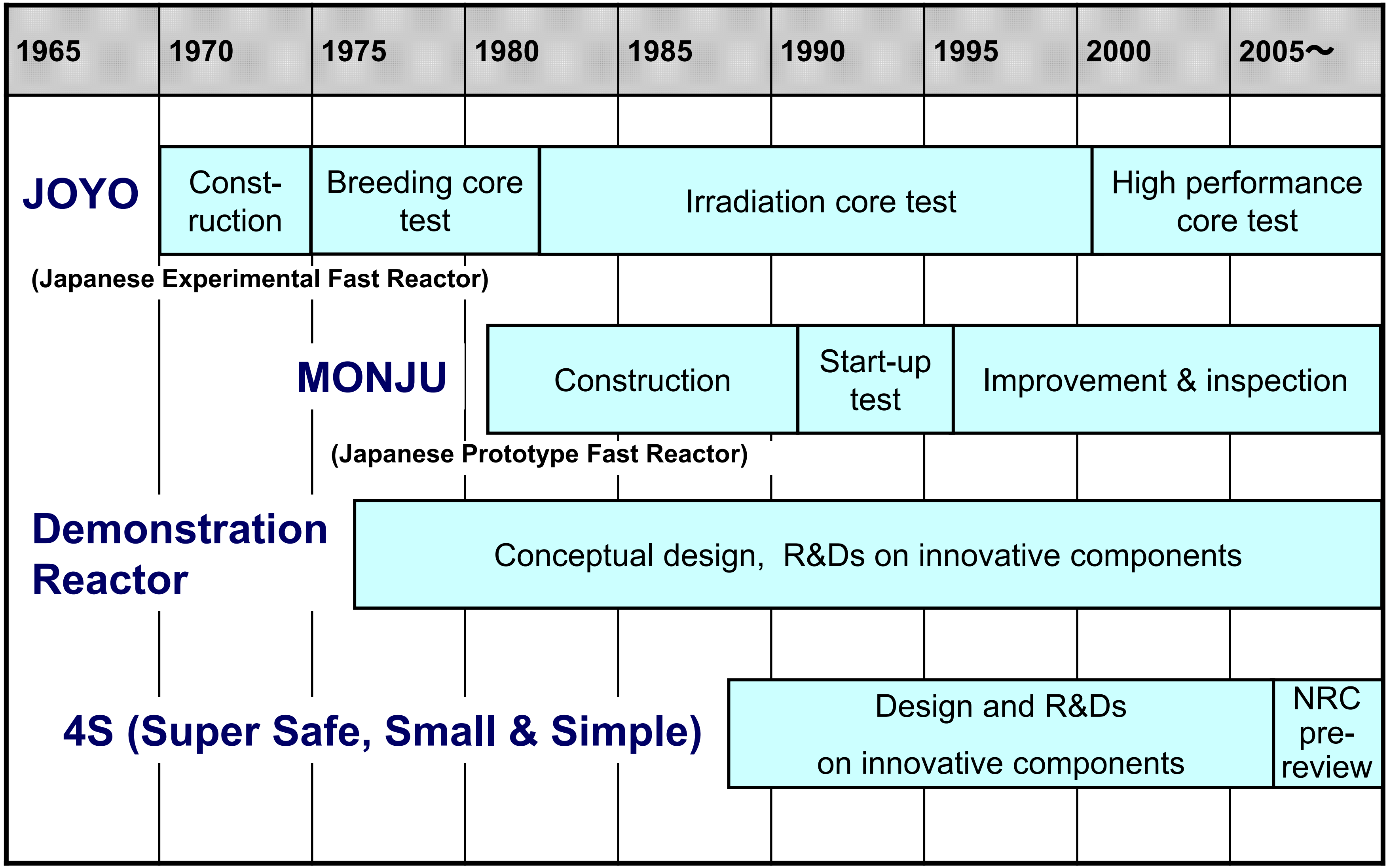
5th September 2014

Toshiba Corporation
Power Systems Company

Outline

1. The 4S Development
   - History
   - 4S plant overview and safety characteristics
   - Key technology development
2. TRU burning fast reactor development
   - Approach
   - Feasibility of Uranium-free Metallic Fuel Core
   - Feasibility of TRU Metal Recovery from LWR System
3. Concluding Remarks

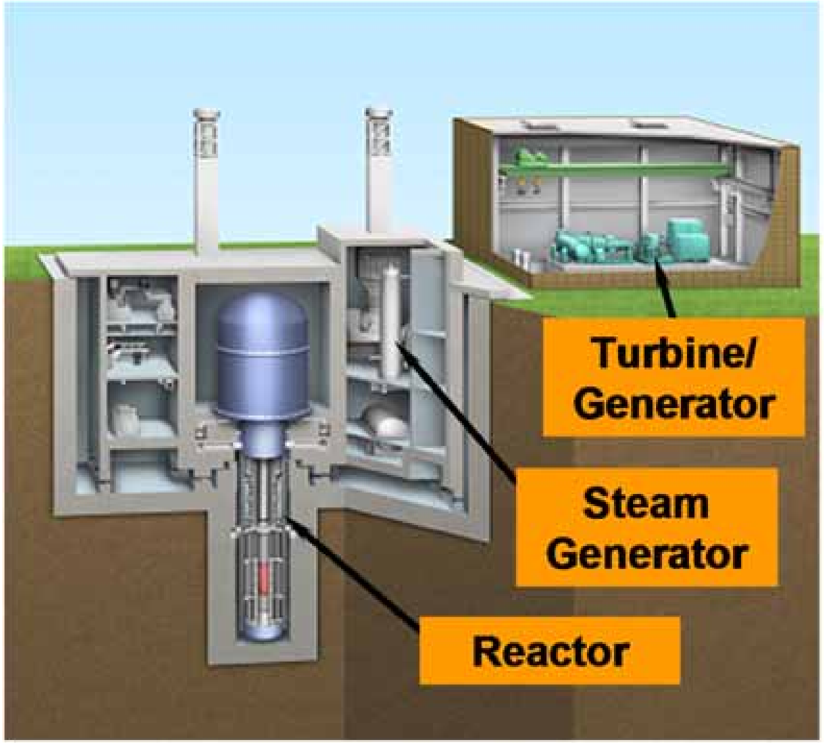
Fast Reactor Development Overview



4S Reactor

4S: Super-safe, Small and Simple

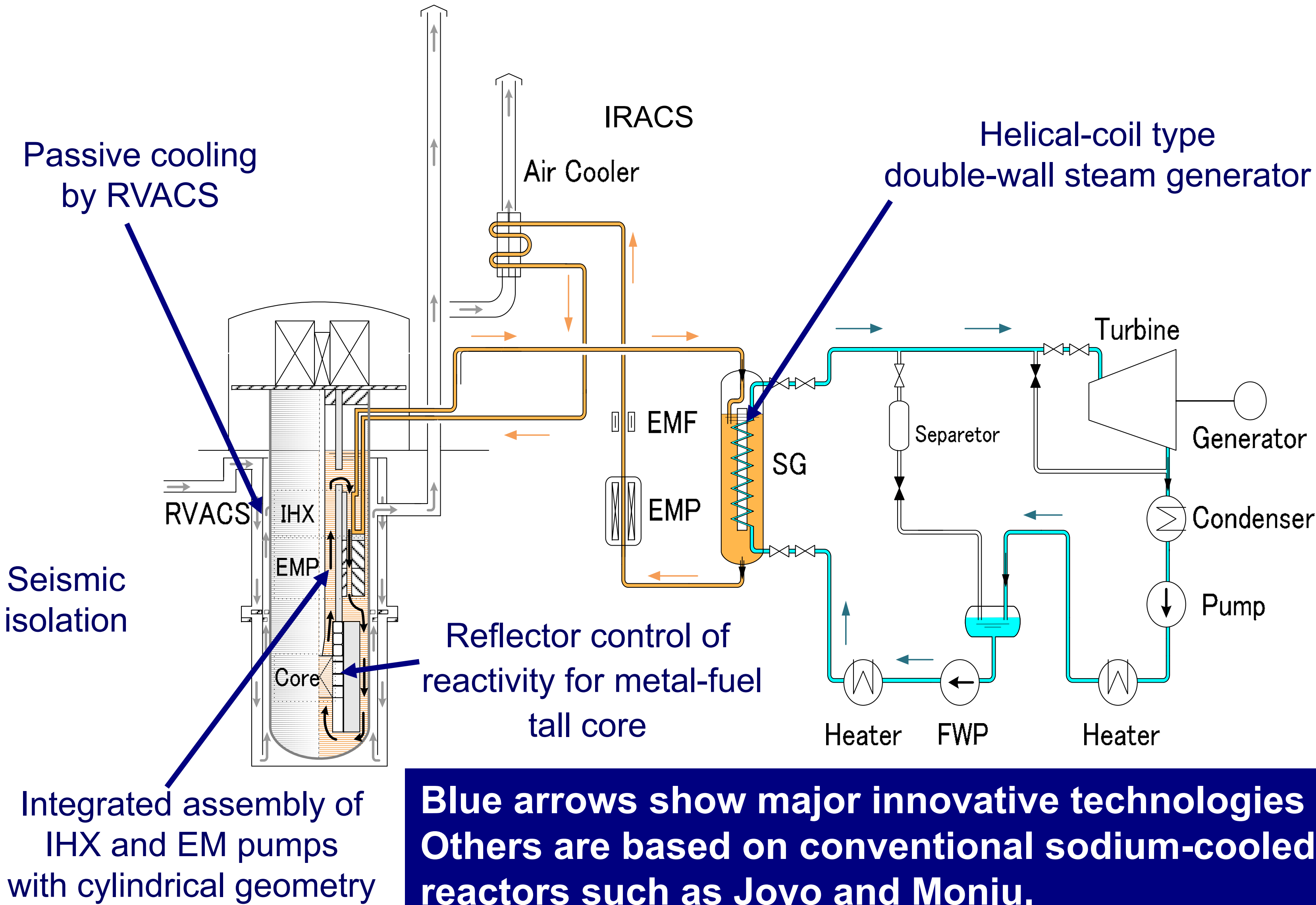
- Sodium-cooled pool type fast reactor
- Electric output
  - ✓ 10 MWe (30 MWt), 50MWe (135MWt)
- Main features
  - ✓ Passive safety
    Passive decay heat removal
  - ✓ Long refueling interval
    10 MWe: 30yrs
  - ✓ Fewer maintenance requirements
- Multi purpose application
  - ✓ Power supply in remote areas
  - ✓ Sea water desalination
  - ✓ Steam supply for oil sand extraction
  - ✓ Hydrogen production



Co-developer: CRIEPI

Developing partners: ANL, Westinghouse

4S Plant System



Blue arrows show major innovative technologies on 4S. Others are based on conventional sodium-cooled fast reactors such as Joyo and Monju.

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Safety feature against severe accident

- **Lower Probability of Severe Accidents**

Safety Issues	4S's safety design to mitigate and prevent from severe accident
Station black out (SBO)	Core damage is avoidable without any emergency power supply system by passive decay heat removal system with natural circulation. There is no limitation for duration time.
Loss of heat sink in spent fuel pool	No need for spent fuel pool due to long-term cooling (about 1 year) after the long-term operation (i.e., 30 years) and then stored in dry cask for the 10MWe-4S.
Final heat sink in emergency situations	Air is the final heat sink (RVACS and/or IRACS)
Containment system	Containment system consists of top dome and guard vessel.
Earthquakes	Reactor building is supported by seismic isolators.
Tsunami / Flood	Watertight structure to protect residual heat removal system from water blockage.
Aircraft impact	Constructed under ground to avoid direct aircraft crash.

RVACS: Reactor Vessel Auxiliary Cooling System, IRACS: Intermediate Reactor Auxiliary Cooling System

Full-scale Test of EM Pump for 4S

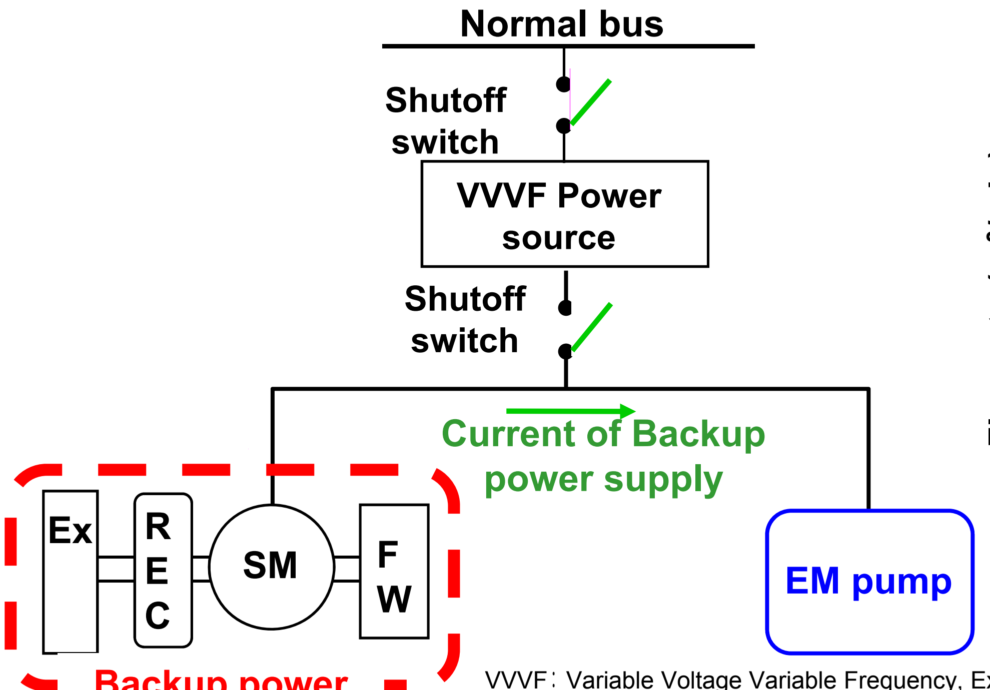
Toshiba Sodium Loop Test Facility

Full-scale EM Pump

The performance of the EM pump has been demonstrated for the rated power condition of 4S in February, 2010

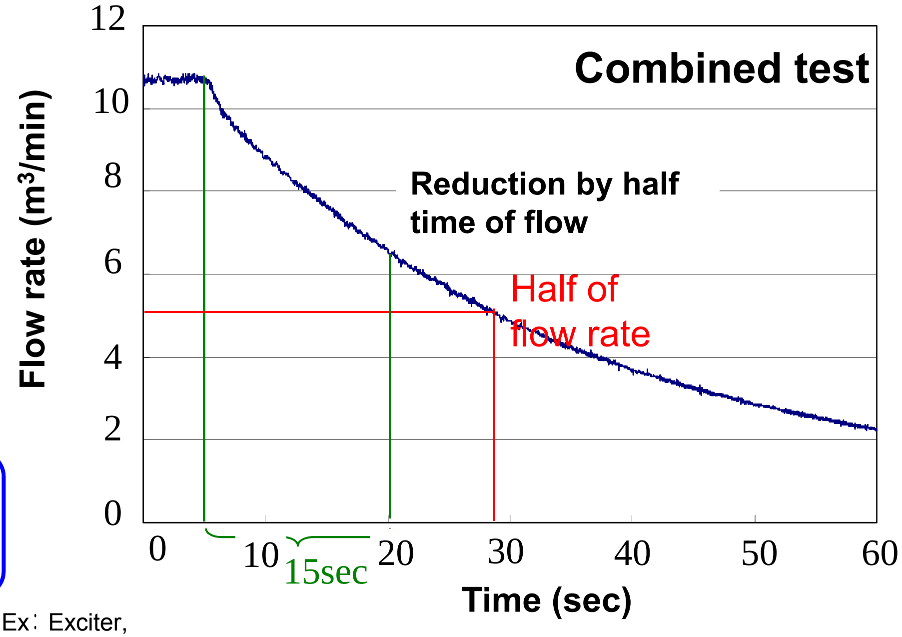
(This study is a part of “Development of high temperature electromagnetic pump with large diameter and a passive flow coast compensation power supply to be adapted into medium and small reactors of GNEP” funded by METI.)

Backup Power System for EM pump



VVVF: Variable Voltage Variable Frequency, Ex: Exciter,
REC: permanent magnet rectifier, SM: Synchronous Motor, FW: Fly wheel

Control circuits are unnecessary by using a permanent magnet exciter.



Test result

Power supply control system

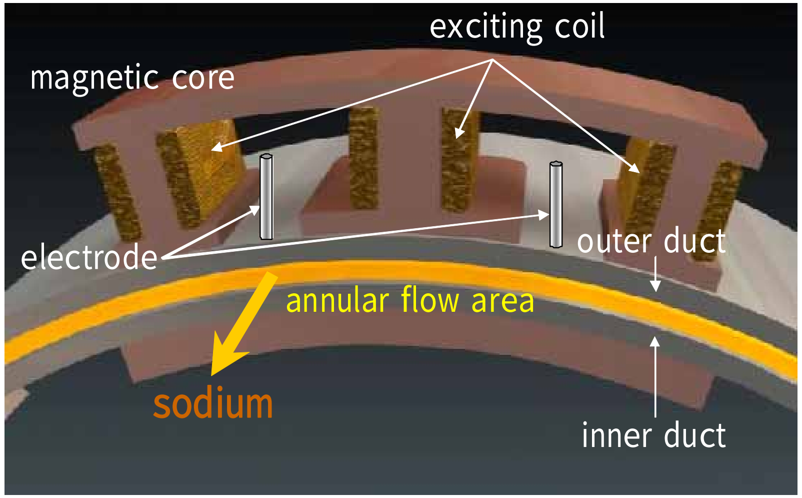
Required flow coast down characteristic can were obtained by the backup power supply system during reactor trip.

Testing Status for 4S

Design Feature	Major Verification Item	Required Testing	Status
Long cylindrical core with small diameter	Nuclear design method of reflector controlled 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 fine movement	Test of reflector drive mechanism	**Done**
RVACS	Heat transfer characteristics between vessel and air	Heat transfer test of RVACS	**Done**
EM pump/flowmeter	Structural integrity Stable characteristics	Sodium test of EM pump/flowmeter	**Done**
Steam generator (Double wall tubes)	Structural integrity Heat transfer characteristics Leak detection	Sodium test of steam generator Leak detection test	**Ongoing**
Seismic isolation	Applicability to nuclear plant	Test of seismic isolator	**Done**

Electro-Magnetic Flow-Meter (EMF)

- **Measure sodium flow rate under high temperature and radiation circumstance in reactor vessel by six segmented EMFs.**
- **Simple components: exciting coil, magnetic core, a pair of electrodes**
- **Flow-meter can be calibrated by one segment EMF.**
- **Temperature: 395 ℃**
- **Sodium flow velocity: 5 m/sec**



Configuration of one segment EMF

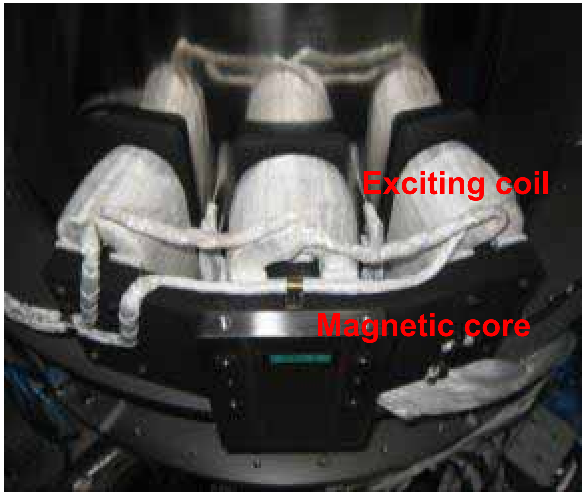


Photo of EMF test equipment

This study is the result of "Development of a new EMF in Sodium-cooled Fast Reactor" entrusted to "Toshiba" by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan.

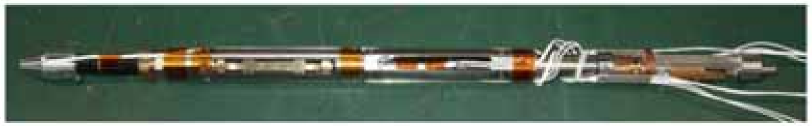
Double-Wall Steam Generator (cont.)

- **Manufacturing technologies of double-wall tube including helical-coil processing have been established in 2011.**

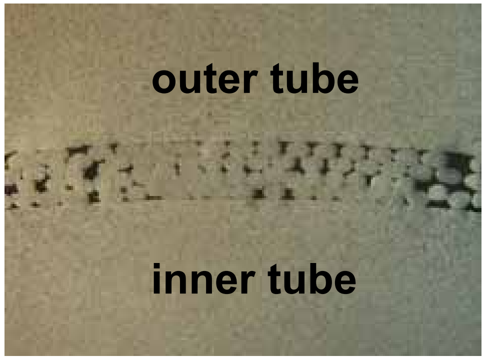
Section view

10 meter-long double-wall tube with wire mesh

Welded portion of inner tube



Laser welding machine for inner tube



Wire mesh layer was not blockaded by helical processing

Helical-coil processed tube of welded double-wall tube

(funded by METI)

Y. Kitajima et. al., "Development of a Helical-Coil Double Wall Tube Steam Generator for 4S Reactor", ICONE19, 2011.

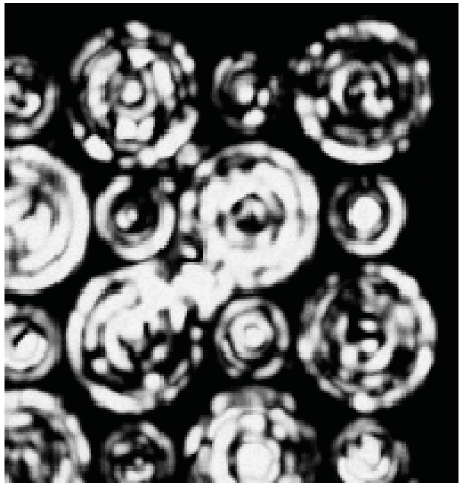
Ultrasonic Visual Inspection

- Ultrasonic visualizing technology to observe in-vessel structures under sodium during reactor shutdown.
- Matrix-arrayed transducer (36x36 piezoelectric elements)
- High-speed signal processing unit (Synthetic aperture focusing)
- Resolution:

  horizontal: 2mm, vertical: 0.5mm (at 1m distance under sodium)

Matrix-arrayed transducer

Visualizing test target



Visualizing Test results

Journal of Nuclear Science and Technology, Vol.37, No.9, p.769-779,
“Development of Under-sodium Three-dimensional Visual Inspection Technique Using Matrix-arrayed Ultrasonic Transducer”

USNRC Pre-application Review

Overview and Plan, October 23, 2007

Photo: NRC Website http://www.nrc.gov/

System Design & Metallic Fuel,
February 21, 2008

Safety Design & Regulatory Conformance,
May 21, 2008

PIRT, Testing Program, and
Conformance with NRC Safety Policy,
August 8, 2008

References

- Materials submitted to NRC **Available at http://adams.nrc.gov/wba/**

Meeting with NRC:

(1) ML072950025 : First Meeting with NRC Pre-Application Review on October 23, 2007
(2) ML080510370 : Second Meeting with NRC Pre-Application Review on February 21, 2008
(3) ML081400095 : Third Pre-Application Review Meeting with NRC on May 21, 2008
(4) ML082190834 : Fourth Pre-Application Review Meeting with NRC on August 8th, 2008

Technical reports:

(5) ML081440765: "4S Design Description" on May 2008

(6) ML082050556: "LONG-LIFE METALLIC FUEL FOR THE SUPER SAFE, SMALL AND SIMPLE (4S) REACTOR" on June 2008

(7) ML090650235: "4S Seismic Base Isolation Design Description" on February 2009

(8) ML092170507: “4S Safety Analysis" on July 2009

(9) ML101400662: “Phenomena Identification and Ranking Tables (PIRTs) for the 4S and Further Investigation Program.” on May 2010

(10) ML102940207: ”4S Response to 73 FR 60612 , Policy Statement on the Regulation and Advanced Reactors and SECY-10-00034, Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor designs.” on October 2010

(11) ML11277A236: "4S Core Nuclear Design Codes and Methods Validation.“ on September 2011

(12) ML11277A234: "Evaluation for 4S Emergency Planning Zone." on September 2011

(13) ML121290607: "Phenomena Identification and Ranking Tables for 4S Beyond-Design-Basis Accidents - Local Faults and Sodium-Water Reaction.” on April 2012

(14) ML12296A021: "Prevention of Severe Accident." on September 2012

(15) ML12296A029: “4S Safety Design Criteria.” on September 2012

(16) ML12278A087: "Validation of 4S Safety Analysis Code SAEMKON for Loss of Offsite Power Event.“ on September 2012

(17) ML13037A423: “Aircraft Impact Assessment for 4S” on August 2012

(18) ML13070A347:“Design Description of the 4S Instrumentation and Control System” on Feburuary 2013

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2. **TRU burning fast reactor development**

   - **Approach**
   - **Feasibility of Uranium-free Metallic Fuel Core**
   - **Feasibility of TRU Metal Recovery from LWR System**

3. Concluding Remarks

Introduction

- **Problem statement**
  - ✓ The worldwide concern on plutonium stock-pile from a viewpoint of nuclear security
  - ✓ The worldwide concern on minor actinide (MA) treatment from a viewpoint of high-level nuclear waste management.
- **Current typical trend to solve the problem**
  - ✓ MOX fuel utilization in LWRs
  - ✓ Actinide recycling (U, Pu, MA) in fast reactors
- **However, there is a growing need to burn excess plutonium and MAs (i.e., TRU) as fast as possible in the near term.**
- **The fastest way to burn TRU is to use uranium-free fuel since it does not produce any new TRU.**

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Our approach

- ➢ **Issues of uranium-free TRU burning systems in the past studies**
  - ✓Conventional oxide fuel : Hard to use PUREX process due to its insolubility in nitric acid solution
  - ✓Inert-matrix fuels (e.g., MgO-, Tc- or W-based oxide fuel etc.) : Need to develop new reprocessing technology
  - ✓Accelerator-driven fast reactor with metallic fuel: Needs to develop accelerator technologies (ref. the USDOE ATW program)
- ➢ **Our approach**
  - ✓A practical burning system should have the role of a commercial power plant, not just a waste burner when we consider a financial aspect of the actual phase. **[Economy]**
  - ✓Fewer R&D needs **[Minimum R&D]**
  - ✓We do not see a nuclear phase-out scenario. Key technologies to be used in the system should be common to the future sustainable nuclear system using uranium after the burning. **[Common to the future technology]**
  - ✓Simple system to reduce cost **[Economy]**

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Our approach

- **Advantage of uranium-free metallic fuel fast reactor**
  - ✓Easy to recycle by pyro-process and injection casting **[Economy], [Minimum R&D]**
  - ✓Excellent TRU-burning characteristics by hard neutron spectrum (large σ_f/σ_c) **[Economy]**
  - ✓Easy to change to an actinide recycling using uranium after the burning in the future **[Common to the future technology]**
  - ✓Excellent potential to transmute long-lived fission products in the future **[Common to the future technology]**

- **Objectives of this study**
  - ✓ Develop "TRU Burning fast reactor cycle using uranium-free metallic fuel"
  - ✓ Clarify the feasibility of the system

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Key issues considered in this study

1. **Decrease of the Doppler feedback**

   ex. metallic fuel w/ uranium : -1×10^{-3} Tdk/dT

   w/o uranium : -6×10^{-4} Tdk/dT

2. **Increase of burnup reactivity swing**

   ex. metallic fuel w/ uranium : ～1%Δk/kk'/150days

   w/o uranium : ～6%Δk/kk'/150days

3. **Fabrication of the TRU fuel with high decay heat**
4. **Recovery process for metallic TRU without uranium from LWR system**
5. **Proliferation resistance for the uranium-free fuel management**

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

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Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Parametric survey scheme

➢ Base condition

Reactor power	714 MWth (300 MWe)
Operation cycle length	150 days
Fuel type, fuel pin dia.	TRU-10wt.%Zr metal alloy, 0.65 cm$^{\Phi}$
Core dia./core height	180 cm / 93cm
TRU composition	LWR discharged (10 years' cooled)

➢ Parametric survey

✓ To enhance Doppler feedback

- 21 fuel alloy materials
- 4 neutron spectrum moderators

✓ To reduce burnup reactivity swing

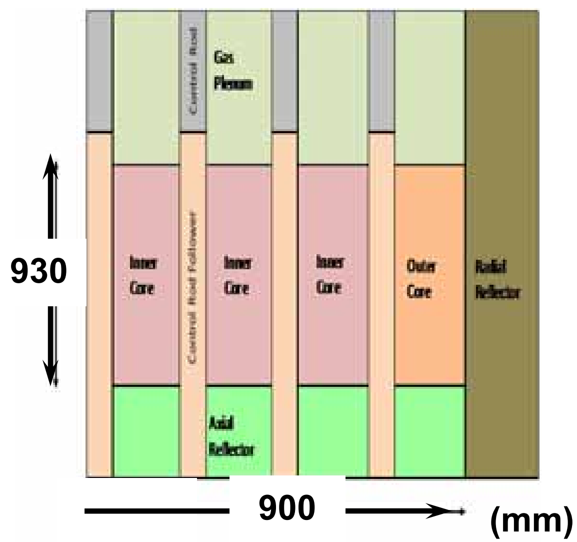
- Core height reduction (core volume kept constant)
- B_4C absorber introduction around core
- Increase of the number of refueling batches (fuel burnup)

➢ Analysis method

✓ 2-D diffusion-burnup (STANBRE code and DIF-3D code)

✓ 70-group cross sections from JENDL-4.0

✓ Homogeneous compositions of fuel alloy, structure, coolant, and spectrum moderator



RZ geometry for the base configuration

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

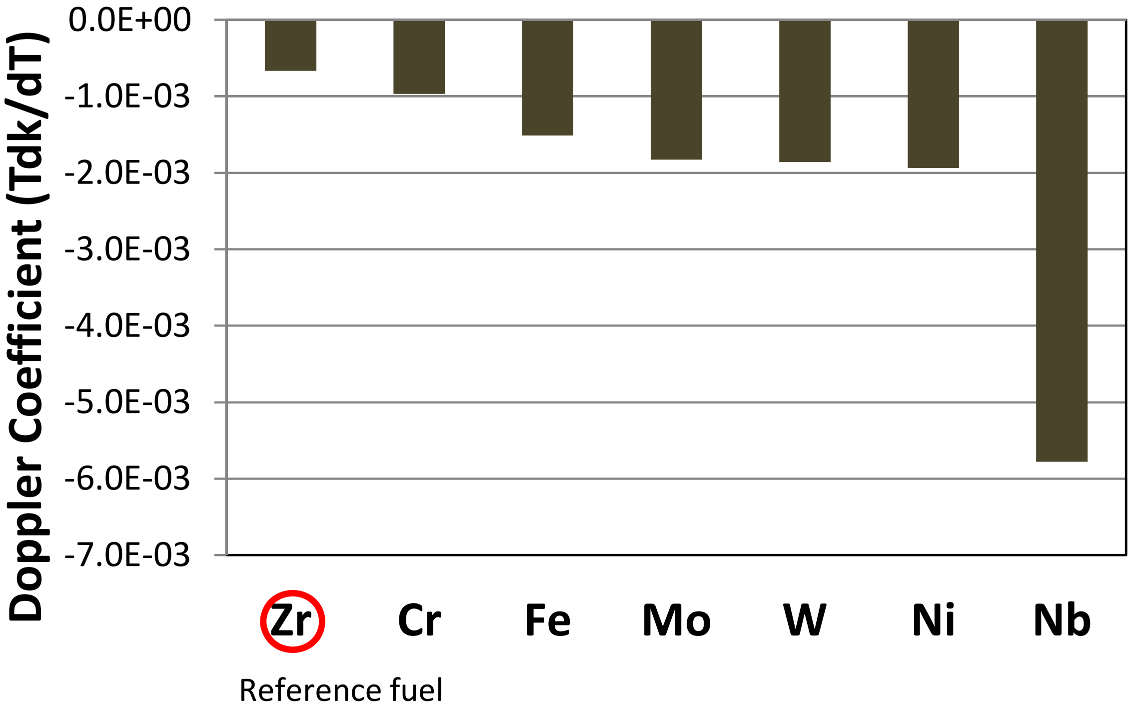
Doppler feedback - fuel alloy materials (1/2) -

- **21 materials were evaluated as TRU alloy metal material.**

  Cr, Mn, Fe, Ni, Nb, Mo, Tc, Ru, Rh, Pd, Nd, Sm, Gd, Tb, Dy, Er, Tm, Ta, W, Os, Au

- **Nb, Ni, W, Mo, Fe, and Cr improve Doppler coefficient compared to Zr that is used in a conventional metal fuel alloy (TRU-Zr alloy).**

- **However, - - - -**



Volume fraction of the material:

23 – 28 vol.%/core*

* The fraction is adjusted to maintain K_{eff}=1.0 at EOC

EOC: End of Cycle

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Doppler feedback - fuel alloy materials (2/2) -

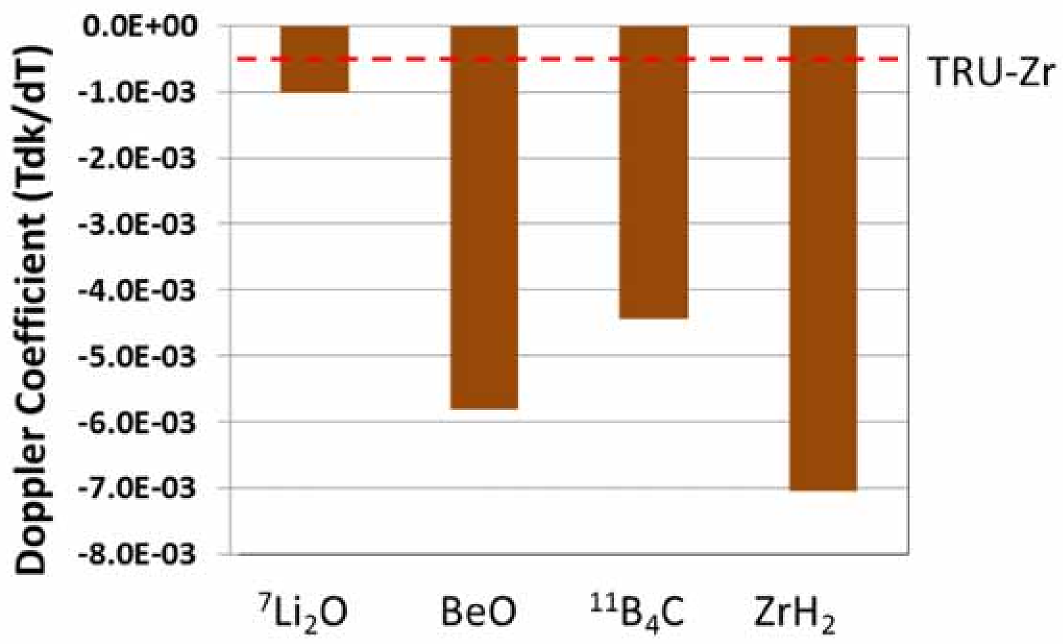
- **Ni and Fe alloys:** Too low fuel melting-point (below 500 ℃)
- **W alloy:** Too high melting point (over 3,000 ℃) to fabricate fuel by injection casting.
- **Mo and Nb alloys:** According to the phase diagrams on Pu-Mo alloy and Pu-Nb alloy*, the allowable contents would be limited to less than 5 wt.% and 3 wt.% respectively, to keep melting point of fuel alloy below 1200℃ to prevent Am vaporization during injection casting. They are too small to enhance the Doppler feedback.
- Therefore, Zr was chosen as a fuel alloy material.

* J.Nucl. Mat. 383 (2008) 112-118, Properties of plutonium and its alloys for use as fast reactor fuels, ASM Alloy Phase Diagram Center.

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Doppler feedback - neutron moderator -

- Doppler coefficient is remarkably improved by introduction of BeO, $^{11}B_4C$ (100%^{11}B), or ZrH_2 .
- ZrH_2 may cause dissociation of hydrogen during accident.
- $^{11}B_4C$ needs isotope enrichment that may cause economic penalty.
- Therefore, BeO was chosen as a neutron moderator material.



Volume fraction of the neutron moderator:

26 – 30 Vol%/core*

* The fraction is adjusted to maintain K_{eff}=1.0 at EOC

EOC: End of Cycle

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Burnup reactivity swing reduction (1/2)

- It is difficult to increase conversion ratio since fissile enrichment cannot be controlled due to absence of uranium.
- Although the reduction of neutron parasitic capture by spectrum hardening is effective to reduce burnup reactivity swing, it also decrease the Doppler feedback.
- Then, it is important for uranium-free core to increase the fissile amount (i.e., fuel HM inventory) at BOC for burnup reactivity swing reduction because it reduces the specific power (MW/kgHM) of fuel.
- Therefore, the following parametric surveys were carried out.
  - ✓ Core height reduction
  - ✓ B_4C absorber introduction around core
  - ✓ Increase of the number of refueling batches (fuel burnup)

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Burnup reactivity swing reduction (2/2)

- **Results**

survey case	reduction of burnup reactivity swing (%)
Core height reduction (93→65cm)	-12
B_4C absorber at core peripheral region	-5
Increase of the number of refueling batches : 5 to 7 (Increase of fuel burnup)	-5

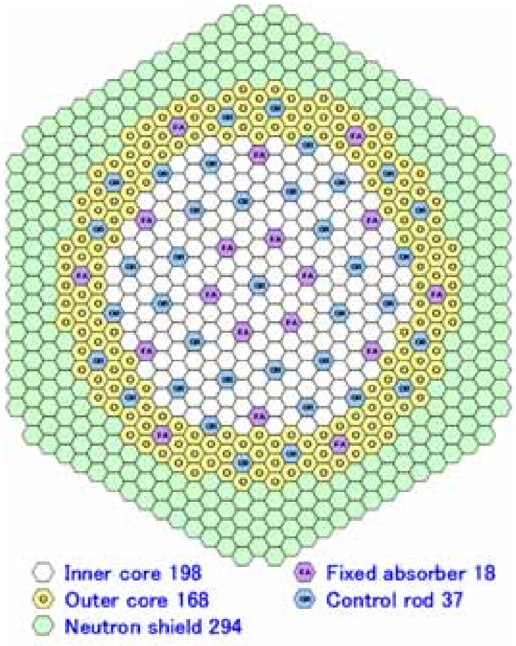
- **Reduced core height (65 cm) was chosen to reduce burnup reactivity swing .**

- **Further investigation needs to be done to achieve longer operating cycle length.**

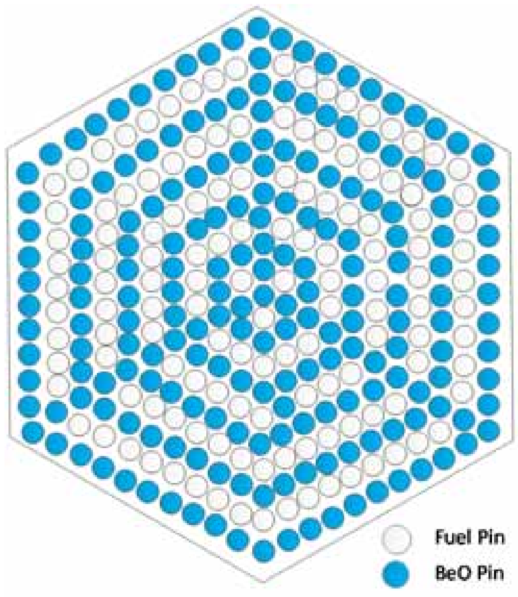
Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Developed TRU burning uranium-free core (1/2)

- **TRU-Zr alloy**: Improve Doppler feedback under the condition of < 35 wt.%Zr content to prevent Am vaporization during injection casting
- **BeO neutron moderator pins**: Improve Doppler feedback, separately located in fuel subassemblies
- **65 cm core height**: Reduce burnup reactivity swing
- **150 days operation cycle length**: Control reactivity by conventional control rod system



Core layout



Fuel S/A cross section

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Developed TRU burning uranium-free core (2/2)

Reactor power	714 MWth (300 MWe)
Operation cycle length	150 days
Fuel composition (inner core / outer core)	TRU-35wt.%Zr / TRU-19%wt.% Zr
Fuel pin dia.	0.48 cm$^{\Phi}$
TRU composition	LWR discharged (10 years' cooled)
Core dia. / core height	250 cm / 65cm
Burnup reactivity swing	5.1% dk/kk'
Power density (average)	260 W/cc
Linear heat rate (average)	220W/cm
TRU inventory	2.17 ton at BOEC
TRU burning rate	260 kg/EFPY
Doppler coefficient at EOEC	-3 x 10^{-3} Tdk/dT
Sodium void reactivity at EOEC	< 0 %dk/kk'
Decay heat of fresh fuel material	32 w/kgHM (acceptable for fabrication)
Decay heat of fresh fuel subassembly	240 w/SA (acceptable for fabrication)

The developed 300MWe core burns TRU produced by 1.2 GWe LWR.

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

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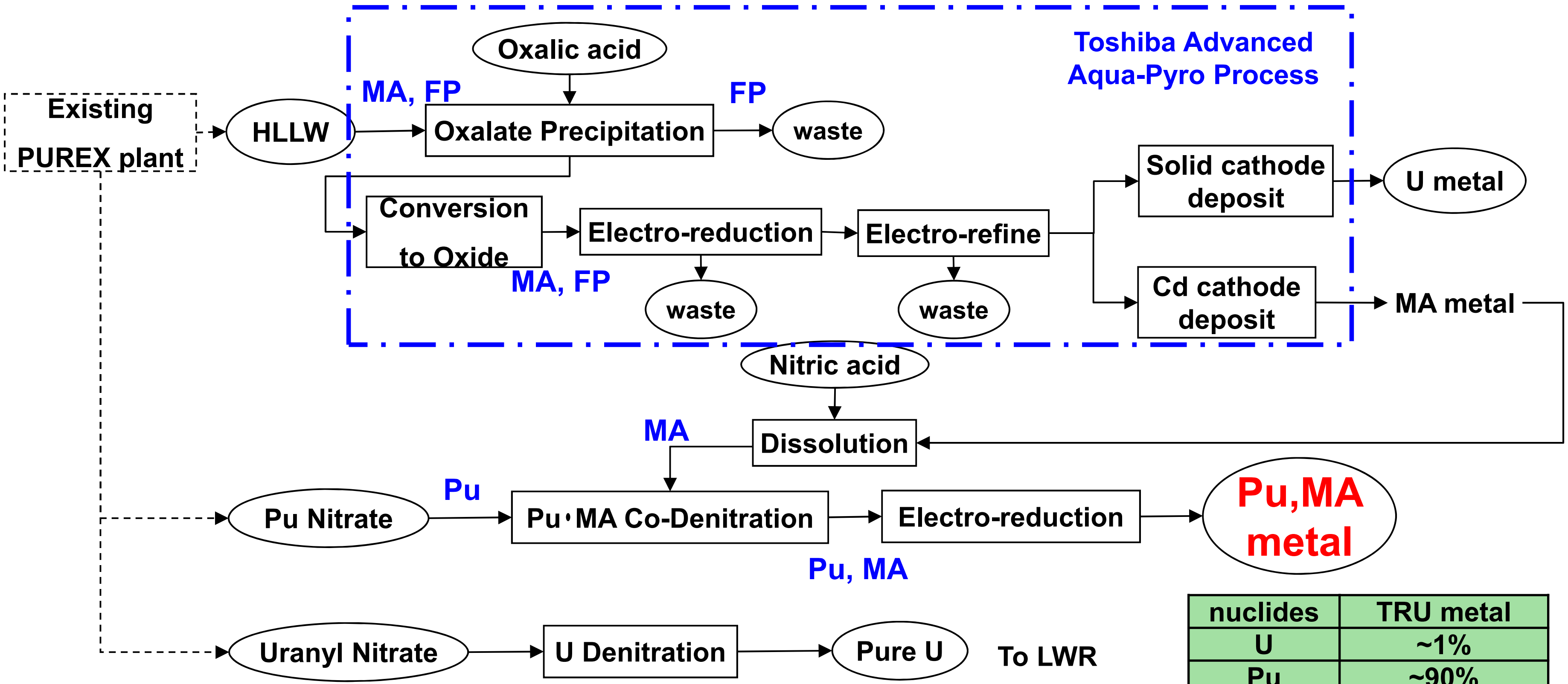
TRU metal recovery from PUREX plant

1. The Toshiba Advanced Aqua-Pyro Process recovers MA metal from HLLW of PUREX.
2. The recovered MA is mixed with Pu nitrate in PUREX process.
3. Finally, TRU metal is recovered by electro-reduction following Pu-MA co-denitration



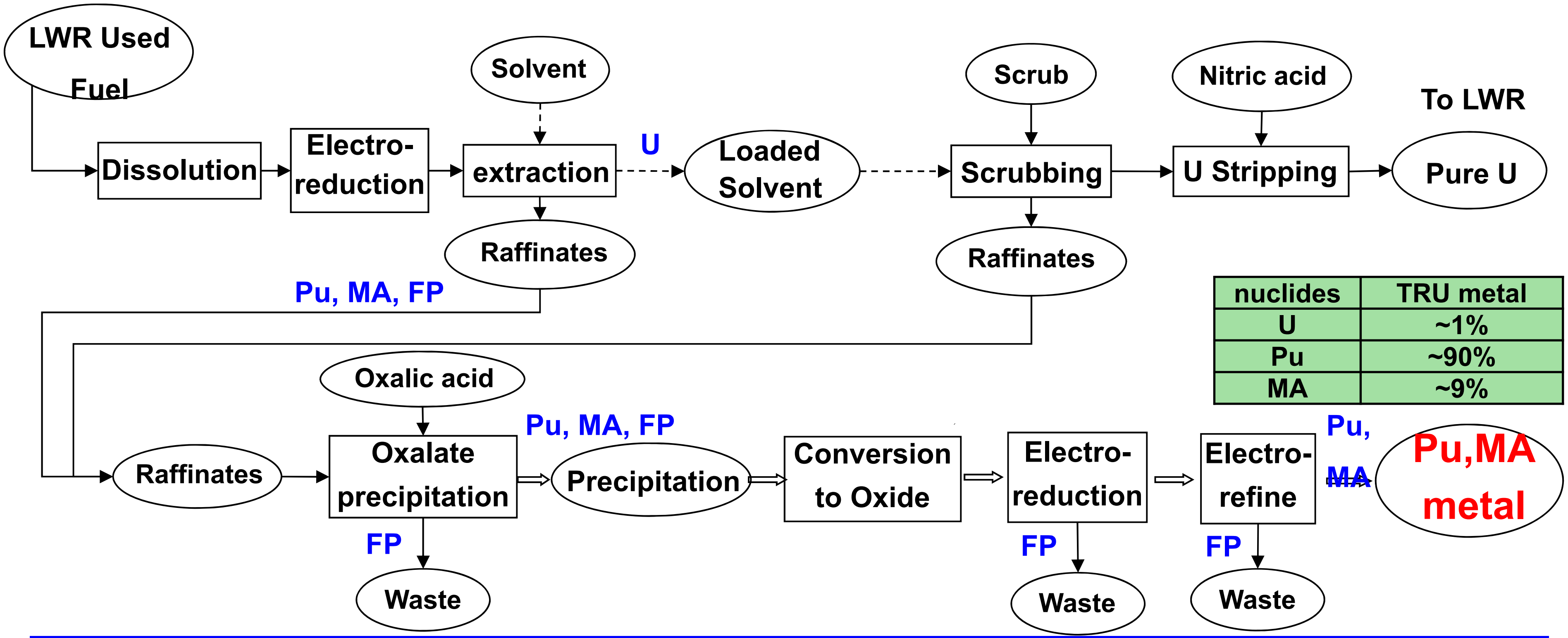
nuclides	TRU metal
U	~1%
Pu	~90%
MA	~9%

The Advanced Aqua-Pyro Process enables to recover TRU metal from PUREX plant.

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

TRU metal recovery from LWR used fuel

1. The Toshiba Hybrid Reprocessing Process **recovers only uranium** from nitric acid solution by aqueous electro-reduction followed by solvent extraction at first.
2. Then, **Pu and MA are recovered together as a metal form by pyro-process** following oxalate precipitation and oxide conversion maintaining proliferation resistance.



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The Hybrid Reprocessing Process recovers TRU metal from LWR used fuel maintaining proliferation resistance.

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Concluding Remarks - 4S development

- Toshiba has been participating national project for fast reactor development and played important role on construction
- The 4S is based on proven and reliable technology and incorporated in innovative technology to enhance safety performance
- Most of major component/equipment have been demonstrated and confirmed expected performance
- Inspection under sodium is also essential technology to maintain sodium cooled fast reactor and has been demonstrated.
- The 4S along with its enhanced nuclear safety would be a key social infrastructure for energy supply at remote area.

Concluding Remarks – TRU burning fast reactor(1/2)

- The key issues have been investigated to clarify the feasibility of a TRU burning fast reactor cycle using uranium-free metallic fuel.
  - ✓ Doppler coefficient for reactor safety
  - ✓ Burnup reactivity swing for acceptable reactor operating cycle length
  - ✓ Fabrication of TRU fuel with high decay heat
  - ✓ Recovery method for uranium-free metallic TRU from LWR fuel
  - ✓ Proliferation resistance for uranium-free TRU fuel management.
- The issues of Doppler coefficient and burnup reactivity swing can be solved by using TRU-Zr alloy fuel, BeO neutron moderator and reduced core height.
- One year operation of this 300 MWe core burns the TRU that is produced by 1.2 GWe-year operation of a conventional LWR.
- The 35%Zr alloy fuel enables to avoid Am vaporization. The decay heat of the fresh fuel is acceptable level for fuel fabrication.

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

Concluding Remarks – TRU burning fast reactor(2/2)

- **The Toshiba Advanced Aqua-Pyro and the Toshiba Hybrid Reprocessing Process are capable of recovering uranium-free metallic TRU fuel from LWR fuel while maintaining proliferation resistance.**
- **Thus, the prospect of the TRU burning fast reactor cycle using uranium-free metallic fuel has been confirmed.**
- **Toward the realization of the system, further investigation needs to be done.**
  - ✓ **Improve and optimize core and fuel design (e.g., BU reactivity swing)**
  - ✓ **Confirm characteristics of the uranium-free TRU-Zr alloy fuel including irradiation performances**
  - ✓ **Demonstrate the core performances including critical experiment**
  - ✓ **Demonstrate the fuel recovering processes including decontamination factor of fission products**
  - ✓ **Demonstrate remote fuel fabrication**

Source: ICAPP 2014 April 6-9, 2014 Charlotte, USA

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