Seminar: Activities for Lead-cooled Fast Reactors (LFR) in Generation IV International Forum (GIF)
Tamachi Campus, Tokyo Institute of Technology, Tokyo. November 9, 2012

National Status on LFR Development : Japan

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Feasibility Study on LFR by JNC/JAPC
(1999-2006)

Phase I : Extraction of typical FR system concepts

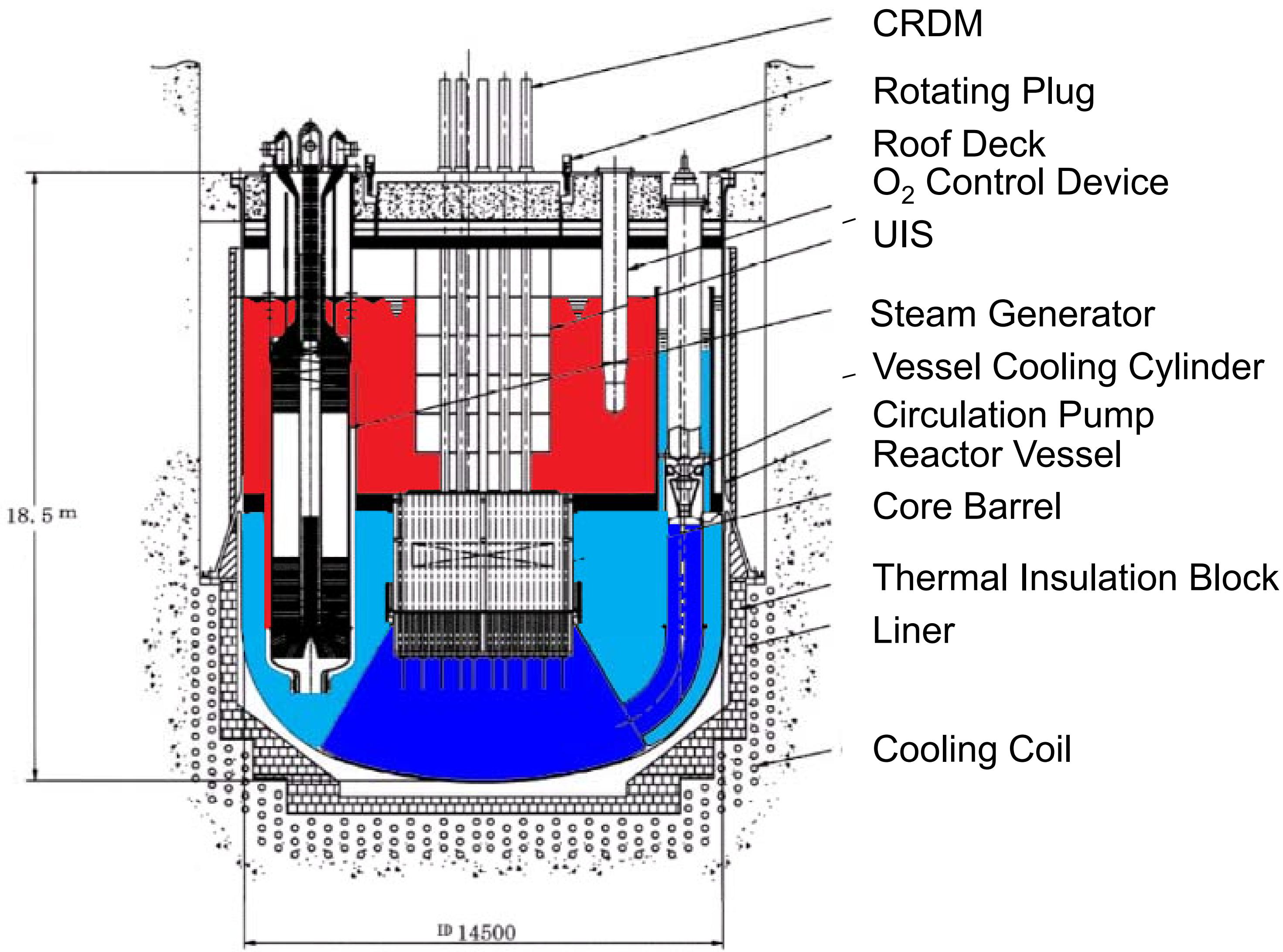
- *Coolant* Pb, Pb-Bi
- *Size* Large, Medium, Small
- *Type* Tank, Loop
- *Cooling* Natural Circulation, Forced Circulation

Phase II: Investigation of the concepts to bring out attractive properties

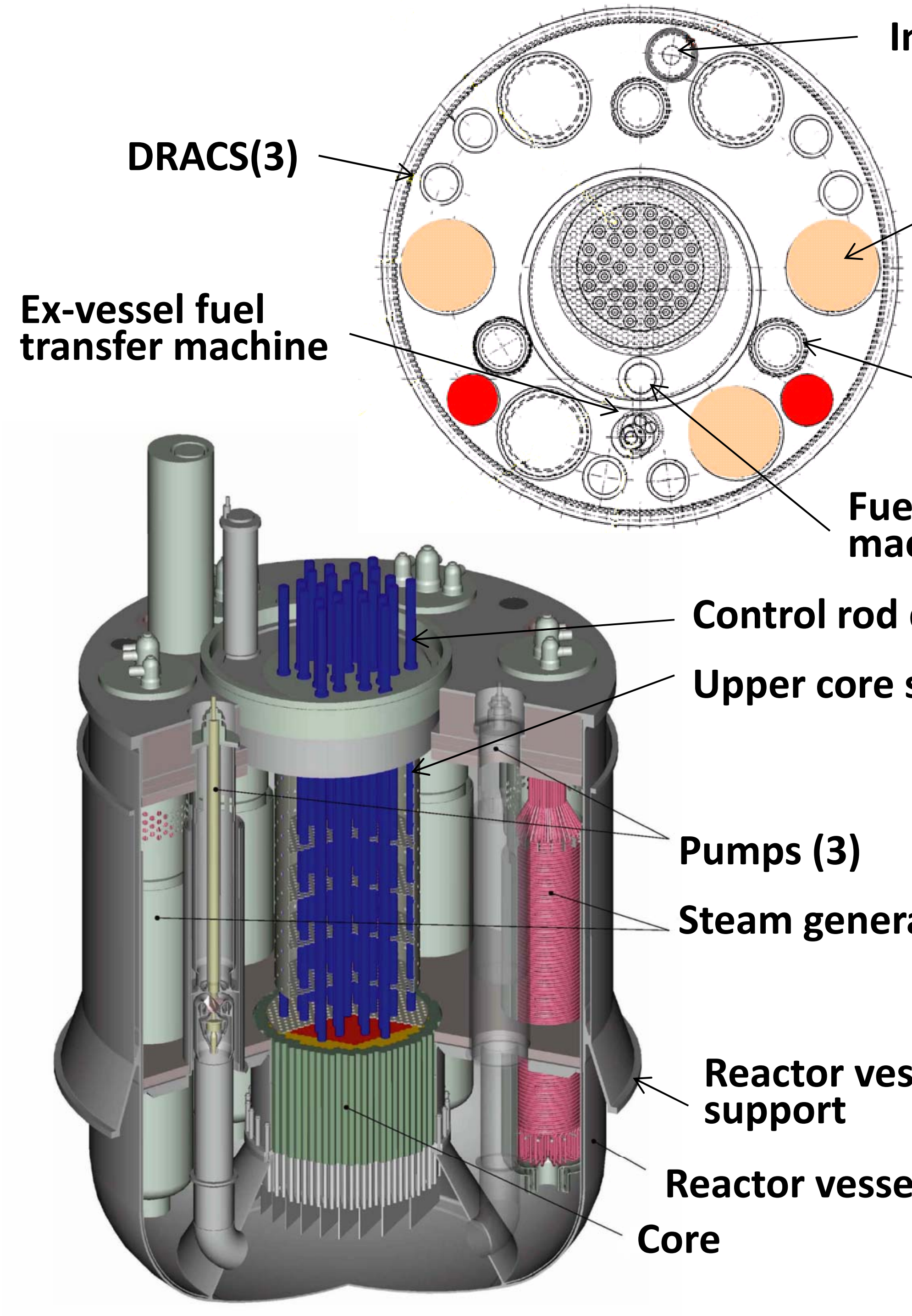
- *Coolant* Pb-Bi
- *Size* Medium
- Type Tank
- Cooling Forced Circulation

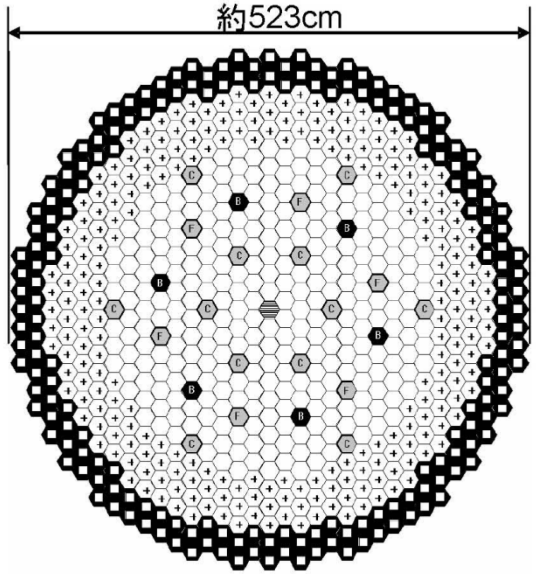
JNC: Japan Nuclear Cycle Development Institute
JAPC: The Japan Atomic Power Company

LFR Concept Selected by JNC/JAPC



Fuel cladding temperature: Reduced from 650˚C **to 570**˚C





⬡	Inner core assembly	288
⊕	Outer core assembly	246
▤	Central steel assembly	1
C	Control rod (coarse)	12
F	Control rod (fine)	6
B	Control rod (backup)	6
⬢	LBE shield	186

Plant Specification of LFR

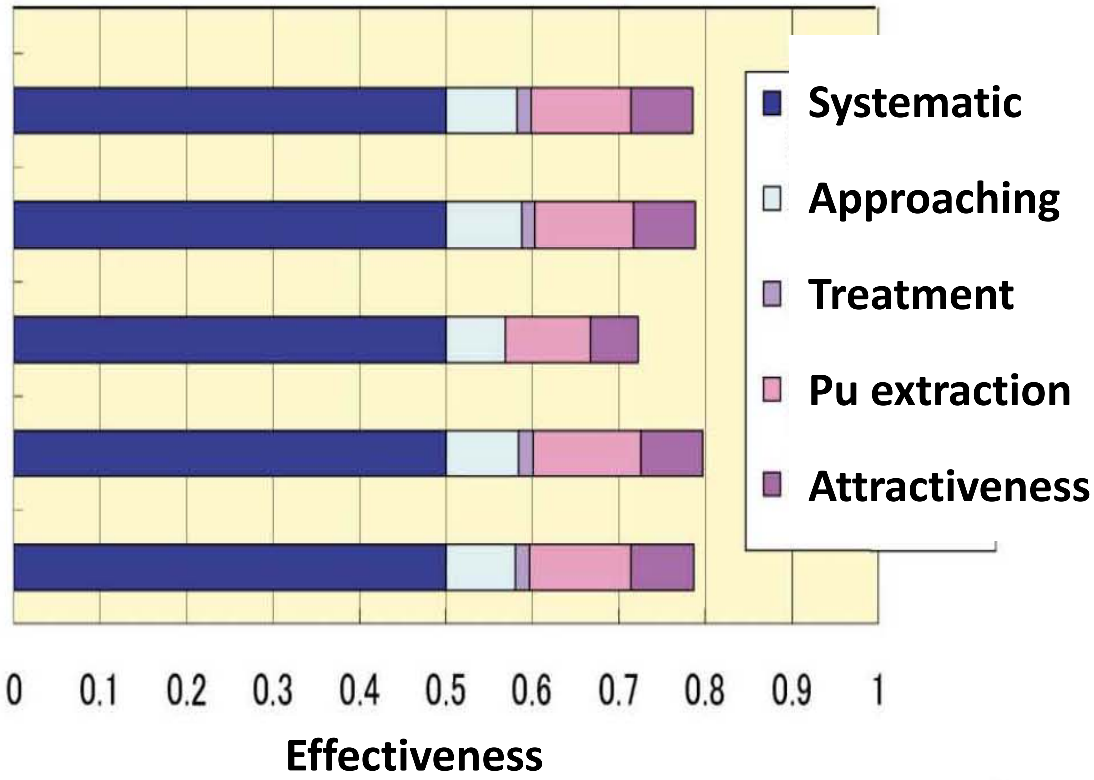
Reactor Type	Forced Convection
Electric Power	750MWe
Thermal Power	1,980MWt
Primary Coolant Temperature	445˚C/285˚C
Primary Coolant Flow Rate	3.06 x 10^5Ton/h
Steam Temperature/Pressure	400˚C/6MPa
Feed Water Temperature/Flow Rate	210˚C/3,126 Ton/h
Cycle Efficiency	～38%
Burn Up (Average)	150000 MWd/t
Breeding Ratio	1.19 (Nitride Fuel)
Decay Heat Removal System	DRACS x 3 (Natural circulation)

Core Design

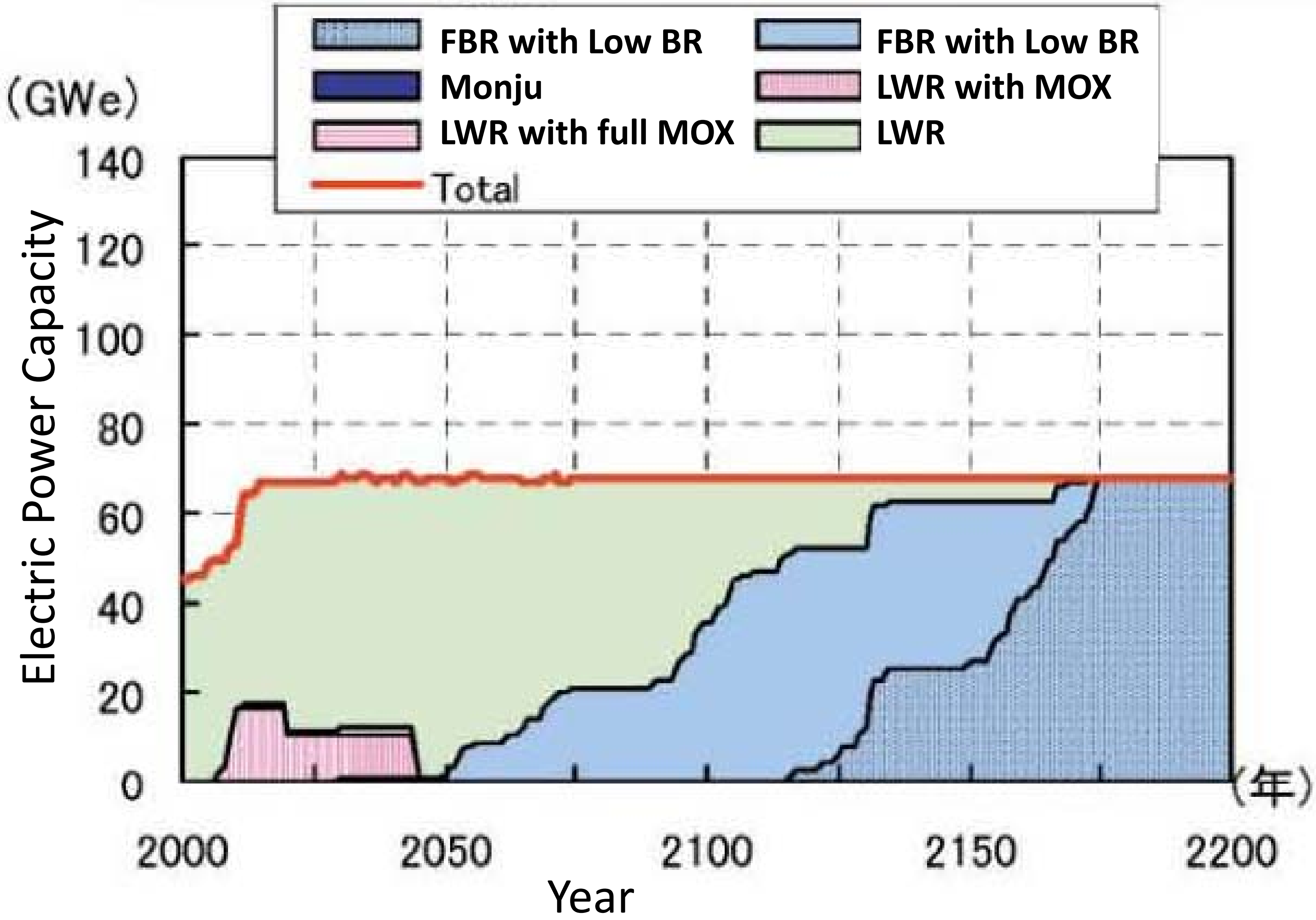
Type	Two region homogeneous core
Refueling Interval	18 months
Number of Batches	6
Core Height	70 cm
Axial Blanket (Upper/Lower)	0/18 cm
Equivalent Core Diameter	443 cm
Number of Fuel Assemblies (Inner/Outer)	252/192
Radial Blanket	—
Number of Control Rods (Main/Backup)	24/7
Number of Radial Shielding materials	Pb-Bi 84, Zr-H 90

Proliferation Resistance

SFR/MOX/Wet Process/
Simple Pelet
SFR/MOX/Oxide Electrolysis/
Vibrated Pelet
SFR/Metal/Metal electrolysis/
Shashuts
LFR/Nitride Fuel/Wet Process/
Simple Pelet
GFR/Nitride Fuel/Wet process/
Coated Particle



R. Nakai, et al., “Multidimensional Evaluation on FR Cycle Systems,” JNC Technical Review, No.24, (2004.11) pp.205-219.



R. Nakai, et al., “Multidimensional Evaluation on FR Cycle Systems,” JNC Technical Review, No.24, (2004.11) pp.205-219.

Political Decision for Development of FBR Cycle System in Japan

- 1999 - 2006, **JNC/JAPC** : Feasibility Study on **Commercial FR Cycle System**

  Phase I (1999-2000): Extraction of **typical FR system concepts**

  Phase II (2001-2006): Investigation of the concepts to bring out **attractive properties**

- 2006, **MEXT**: **Research and development policy** of FR Cycle System
- 2006, **AEC**:

  Basic policy on R&D FBR cycle technologies over the next decade ----- **Selection of SFR and GFR**

AEC: Japan Atomic Energy Commission

MEXT: Ministry of Education, Culture, Sports, Sci. and Tech.-Japan

JNC: Japan Nuclear Cycle Development Institute

JAPC: The Japan Atomic Power Company

JAEA: Japan Atomic Energy Agency

Main Reasons of Exclusion of LFR from Future Commercial Fast Reactor in Japan

According to Technical Summary of FR systems (2006)

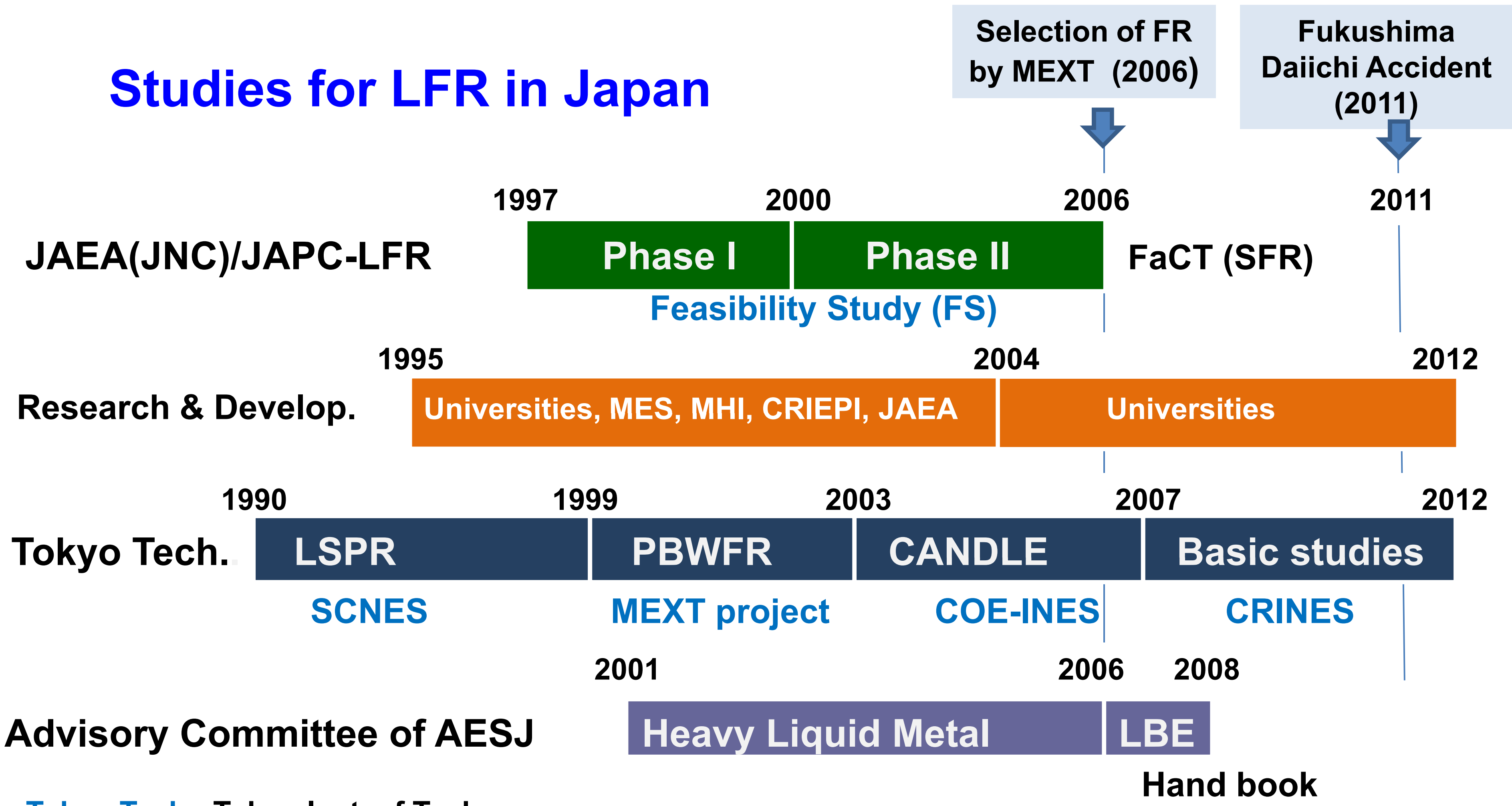
Feasibility Study on Commercialized Fast Reactor Cycle Systems by JNC/JAPC

1. LFR has the potential to achieve core performance equivalent to SFR by applying nitride fuel, and meet all the design requirements.
2. Essential issues are
   - **Corrosion of steel** (fuel cladding)
   - Nitride fuel

Problems:

- No alternative technologies for these issues
- International cooperation is ***unlikely for a breakthrough in the fundamental issues***
- No country has taken leadership at the GIF project

Studies for LFR in Japan



Tokyo Tech.: Tokyo Inst. of Tech.
AESJ: Atomic Ener. Soc. of Japan
JNC: Japan Nucl. Cycle Dev. Inst.
JAEA: Japan Atomic Ener. Agency
JAPC: The Japan Atomic Pow. Company
MEXT: Min. of Edu.,Cul.,Sports, Sci. Tech.
MES: Mitsui Eng. & Shipbuild.
MHI: Mitsubishi Heavy Indus.
CRIEPI: Central Res.Inst. of Elec.Pow. Indus.

SCNES: Self-Consistent Nucl. Ener. Sys.
COE-INES: 21st Cen. Center of Excel. Program “Inno. Nucl. Ener. Sys. for Sustainable Dev. of the World
CRINES: Center for Res. into Inno. Nucl. Sys.
FS: Feasibility Study on Commer. FR Cycle Sys.
FaCT: FR Cycle Sys. Tech. Dev. Project

Inherent and Passive Safety Features of LFR

- **Larger scattering cross section**

  → High neutron confinement performance, Better neutron economy, Large fuel *P*/*D*
- High performance of Pb-208 due to low capture cross section (See GLABAL 2011 Paper No.398761, Pb-208 is the final stable nucleus in Th decay chain)
- Pb-206 is low activation coolant (See ICONE-8385)
- **Heavy nuclide mass** → Low moderating power → Hard spectrum → Negative coolant void coefficient, Better MA burning capability
- **Low burn-up reactivity swing** → Long life core
- Higher boiling temperatures → No coolant boiling in transient conditions

Inherent and Passive Safety Features of LFR

- Chemical inertness with water and air

  → No chemical reaction, No hydrogen generation and fire
- Lowest stored potential energy compared with water and sodium

  → No release of chemical / mechanical energy, No vaporization and pressurization
- Heavy coolant → Lift-up and dispersion of fuel pellets → Avoid of re-critical accident

Additional Advantages of LFR

- Large scattering cross section of lead → Good neutron confinement → Smaller core size
- Large shielding effects for neutrons and γ-rays → Reduction of thickness of reflectors and shields
- Large fuel *P*/*D* → High level of natural circulation capability
- No production of γ-ray emitters → Much lower dose-rate around primary loops

  γ-ray emitter (Na-24 : half-life of 15 h) in SFR
- Heavy coolant → Lift force of gas/steam bubbles → Capability of coolant circulation without pumps

Drawbacks of LFR

- Production of alpha-ray emitter, Po-210 from neutron irradiation of Bi & Pb → Need of Po-210 measure
- High solubility of Ni, Fe, etc. → Need of material corrosion measure
- Very heavy coolant → Restriction of reactor size / Need of seismic measure/ Erosion measure (<2m/s)
- Melting temperature of Pb (327˚C) → High operation temperature
- Bi resource is not abundant → Selection of lead (Pb) rather than LBE (Pb-Bi)

Concept of LSPR studied in 1990s

(LBE-cooled long-life Safe Simple Small Portable Proliferation resistant Reactor)

◆**Long life core**

◆ **Small** reactors are constructed in factories of the nuclear energy park,

◆**Transported** to the site, and deployed.

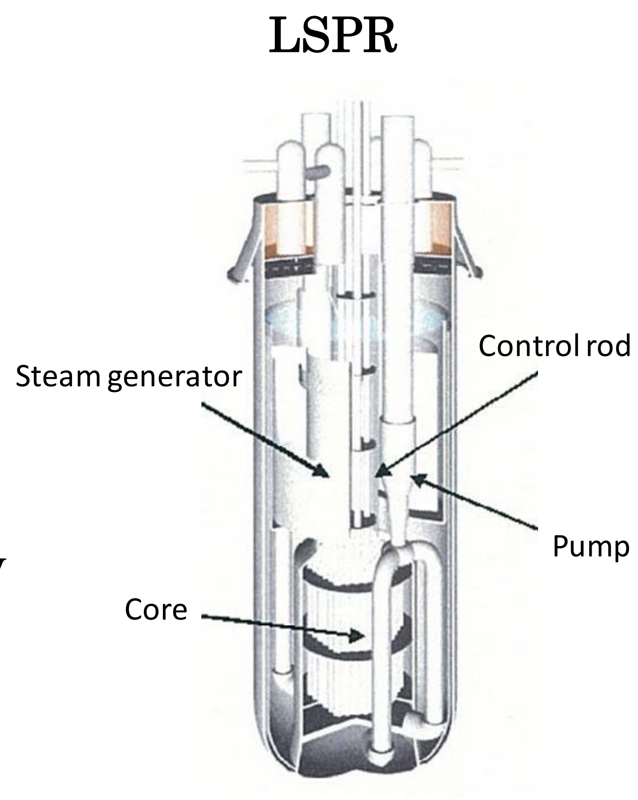
◆**Sealed** reactor vessel without being opened at the site.

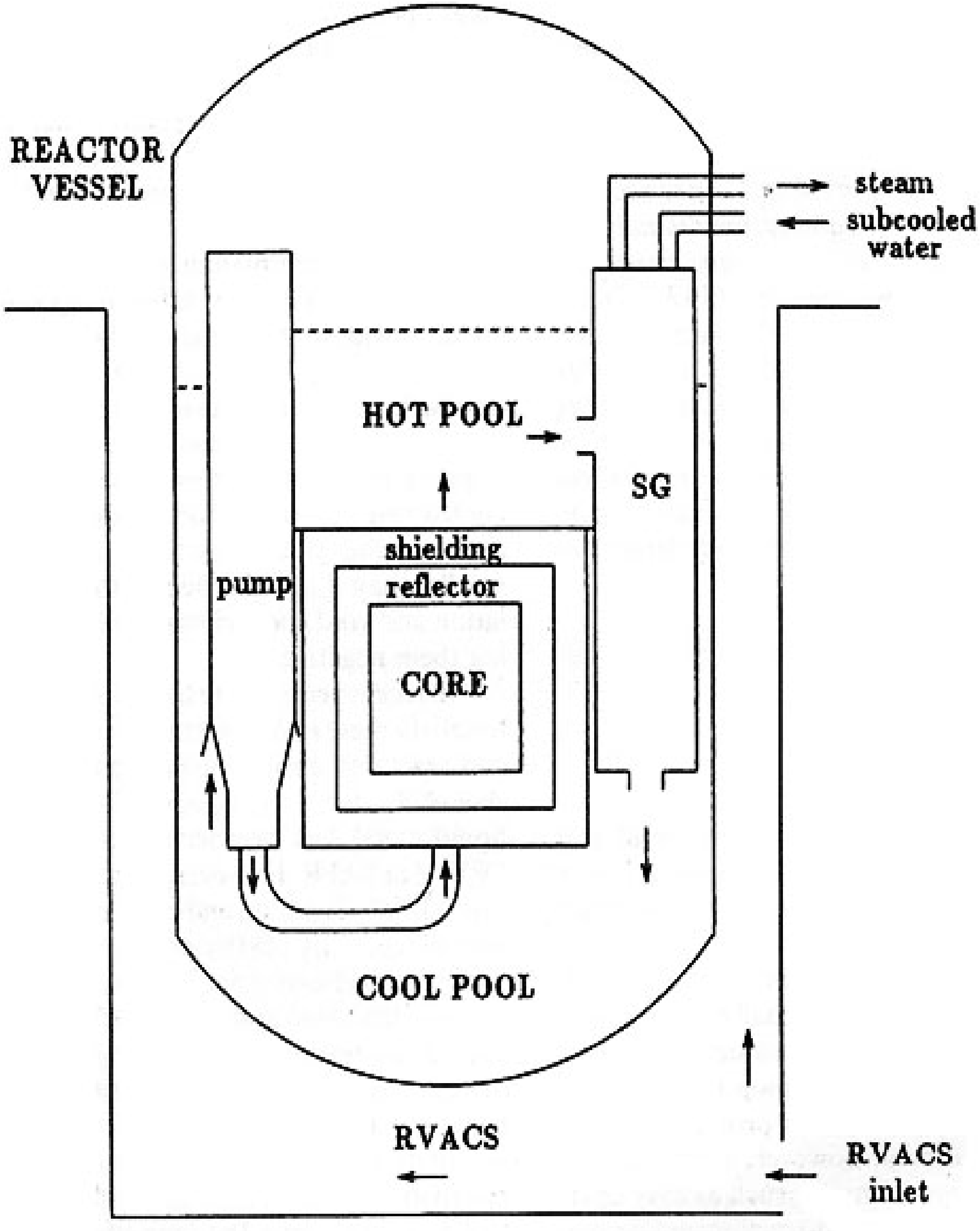
◆Excellent **proliferation resistance** in refueling

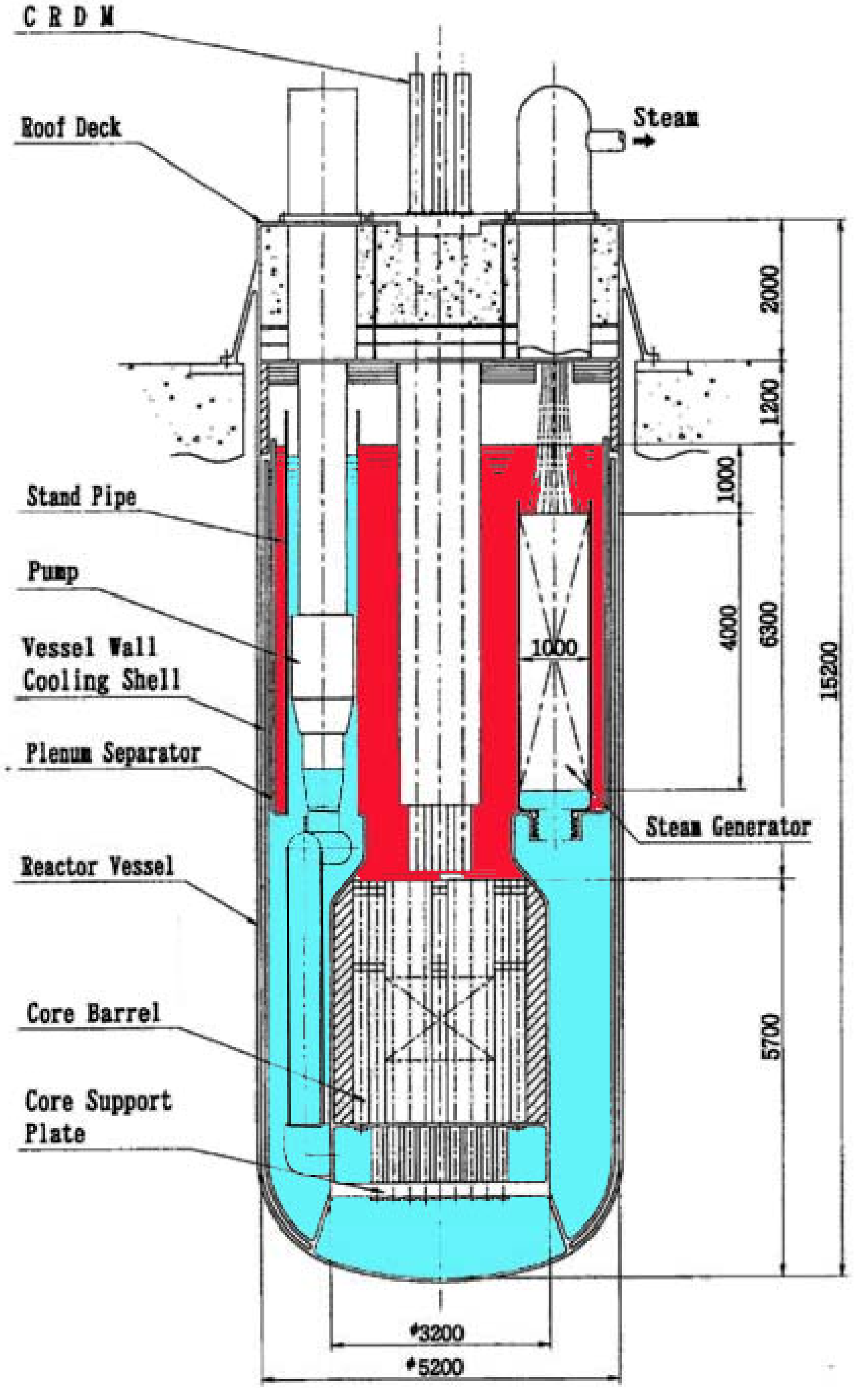
-At the end of the reactor life, it is **replaced** by a new one. The old one is **shipped** to the the nuclear energy park.

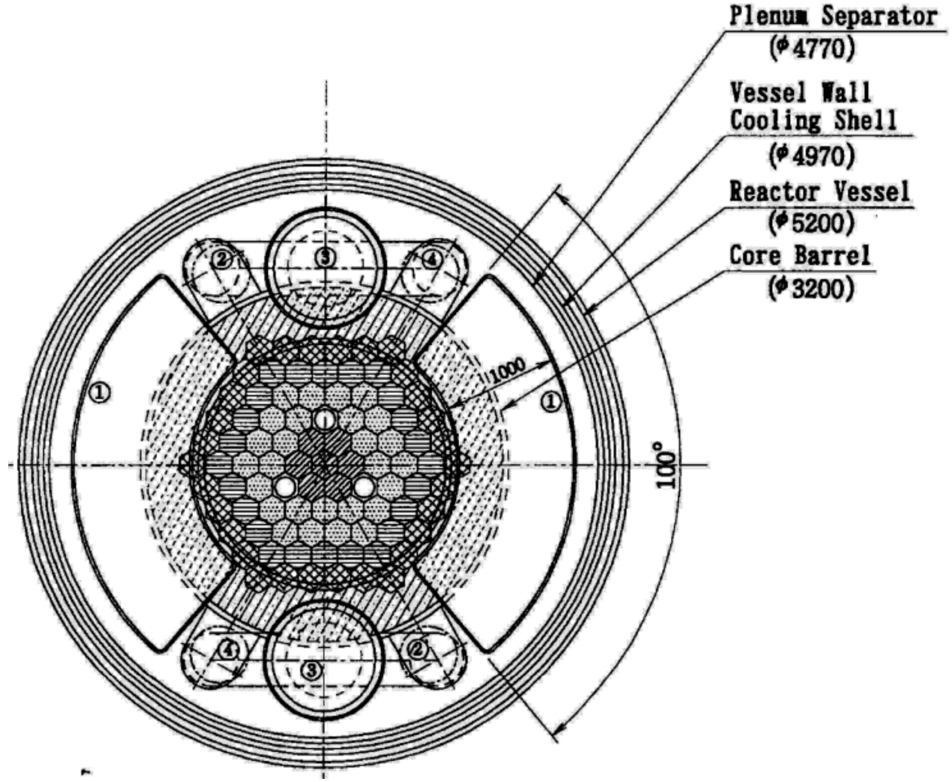
◆Environment

-No radioactive waste left at the site. (Site is **free from waste problems**.)

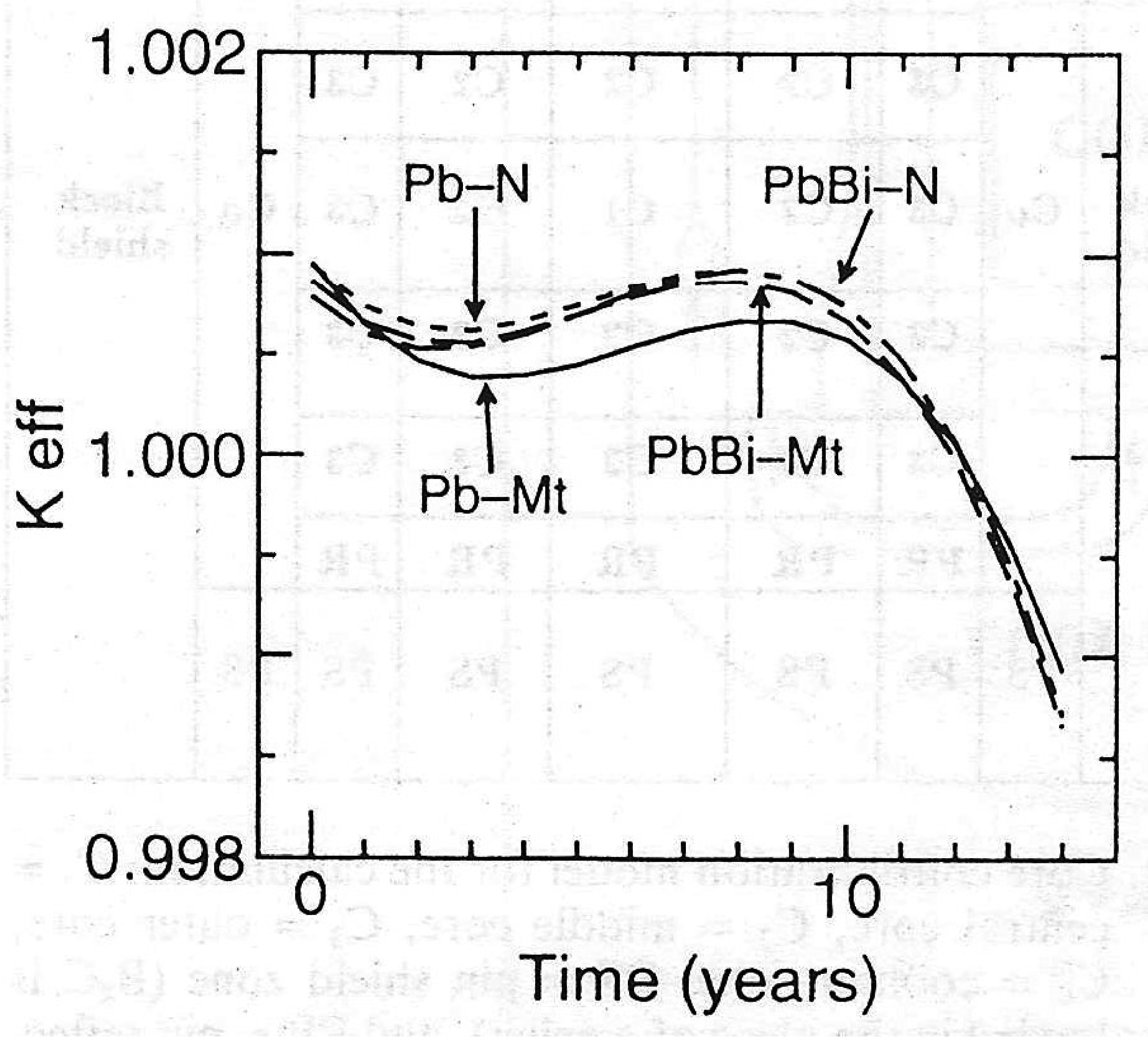



REACTOR VESSEL
steam
subcooled water
HOT POOL
SG
shielding
reflector
pump
CORE
COOL POOL
RVACS
RVACS inlet

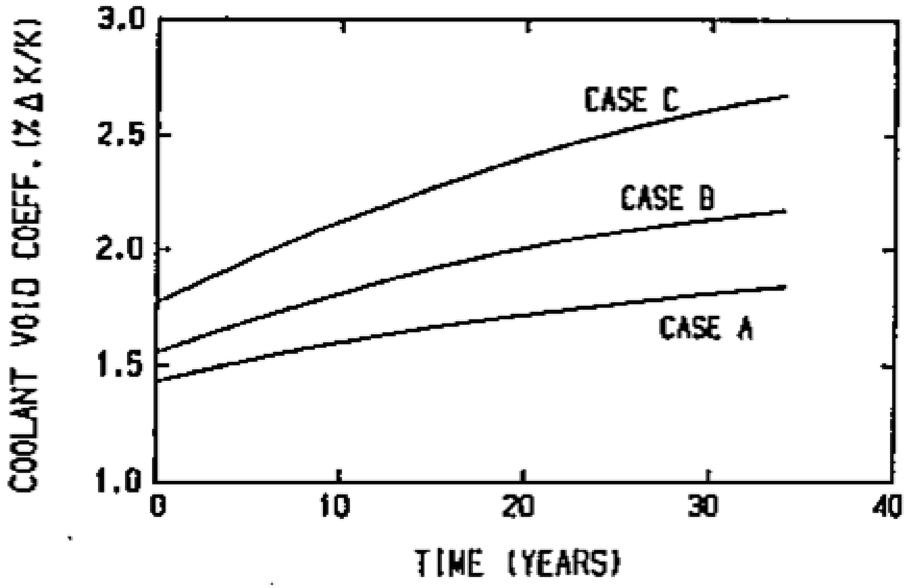

C R D M
Roof Deck
Steam
Stand Pipe
Pump
Vessel Wall
Cooling Shell
Plenum Separator
Reactor Vessel
Core Barrel
Core Support
Plate
Steam Generator
2000
1200
1000
4000
6300
15200
5700
1000
ϕ3200
ϕ5200


Plenum Separator
(ϕ4770)
Vessel Wall
Cooling Shell
(ϕ4970)
Reactor Vessel
(ϕ5200)
Core Barrel
(ϕ3200)
1000
100°

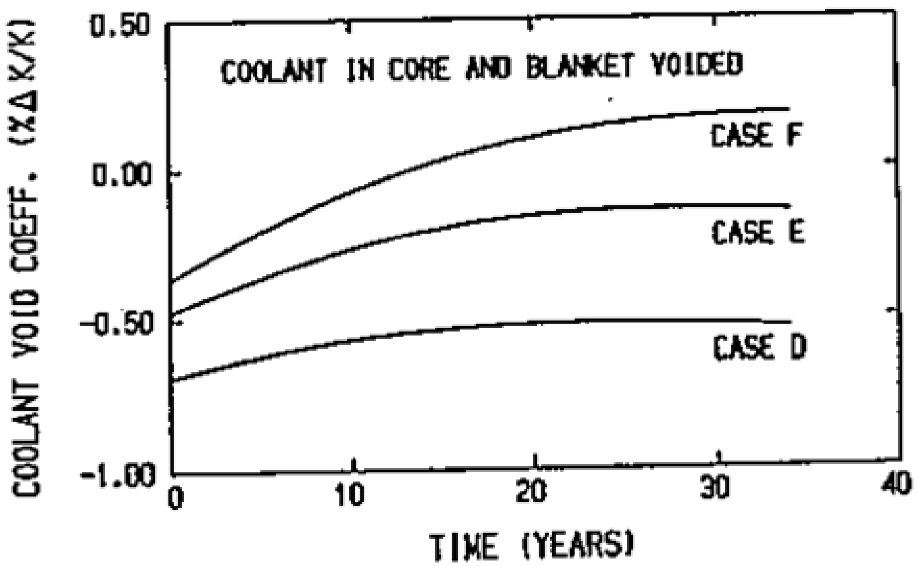
Long Life Core (Reactivity Swing)



Comparison of coolant void coefficient between SFR and LFR

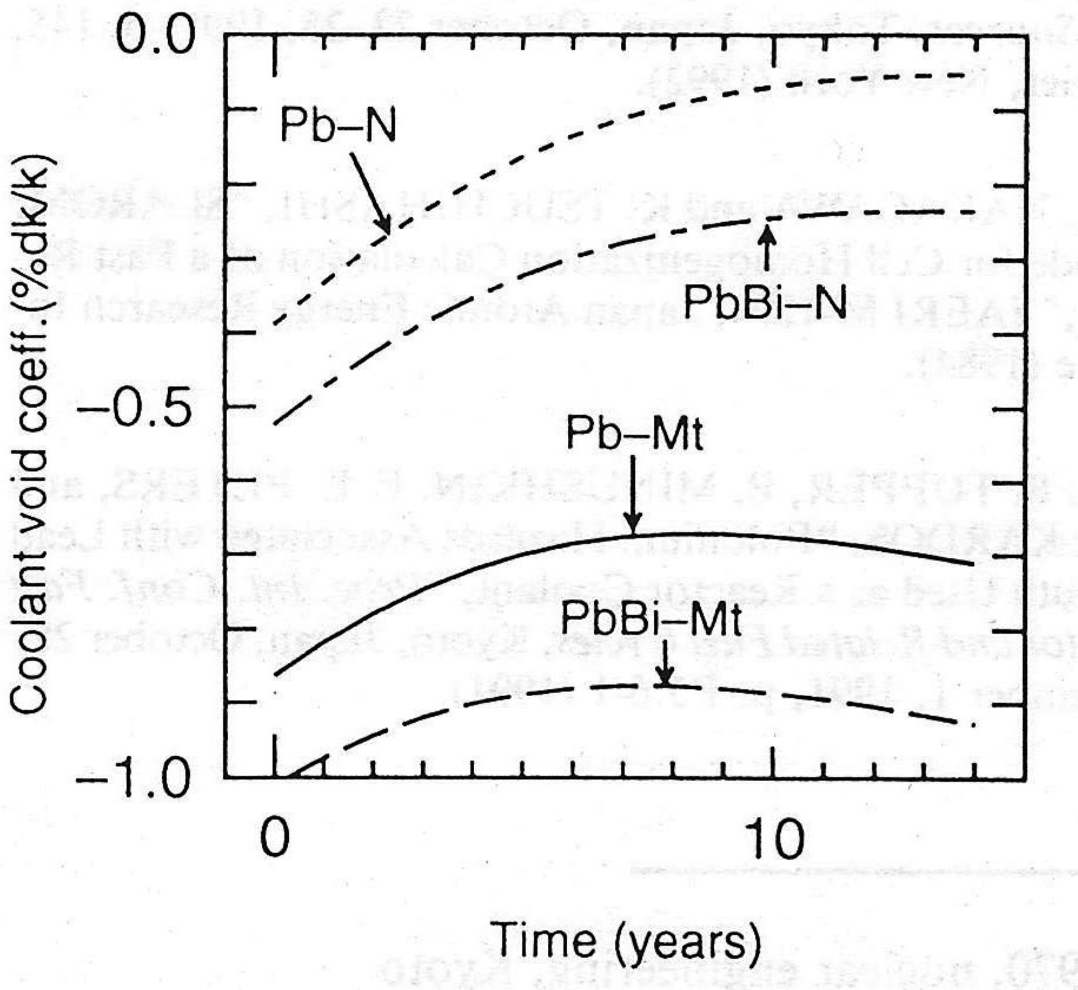


SFR



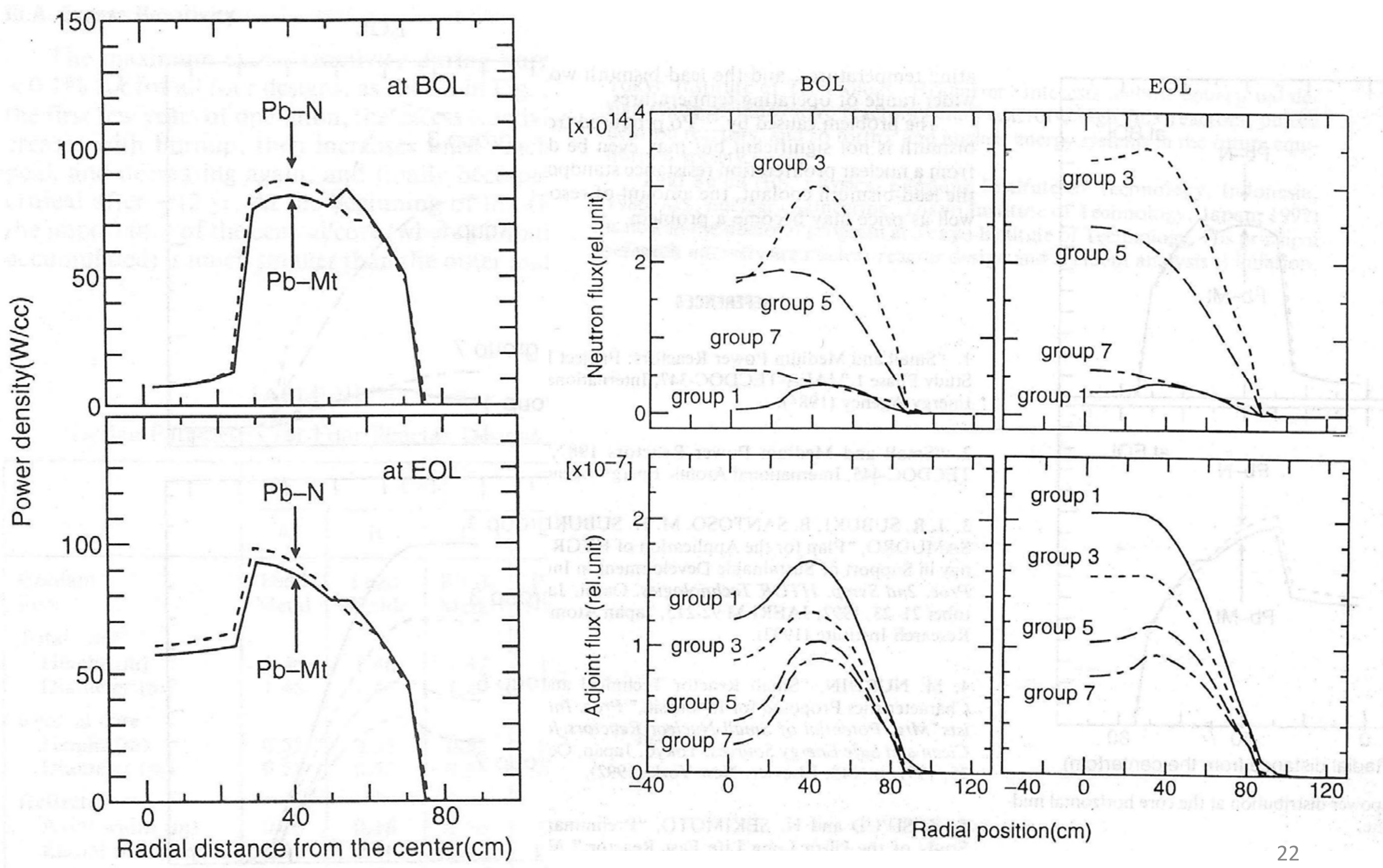
LFR (LBE)

Comparison of coolant void coefficient between metallic fuel and nitride fuel



- *Metallic fuel*: lower than Nitride fuel
- *LBE coolant*: lower than Lead coolant

Distribution of Newtron Flux

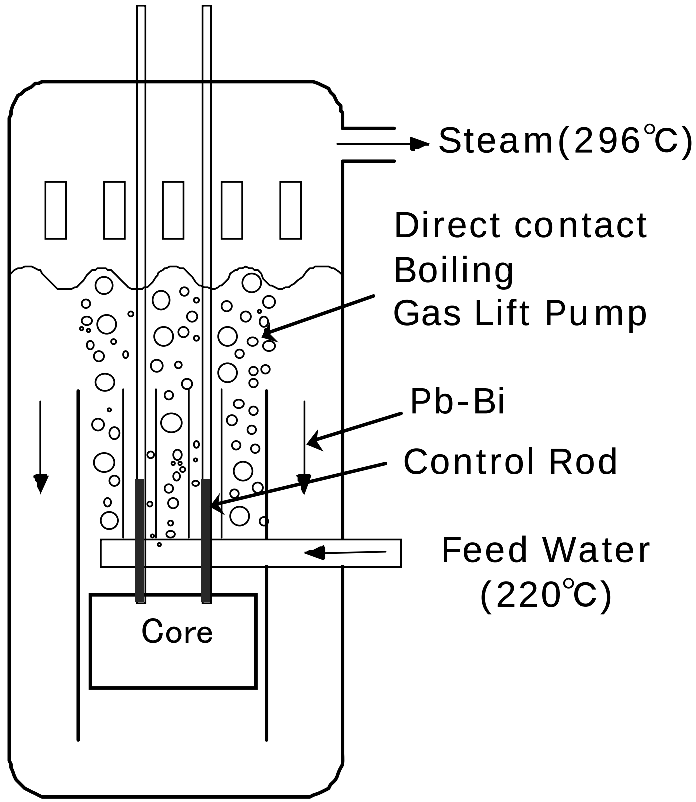


Simplified and Economical LFR

PBWFR (Pb-Bi-cooled direct contact boiling Water Fast Reactor) -Tokyo Tech.

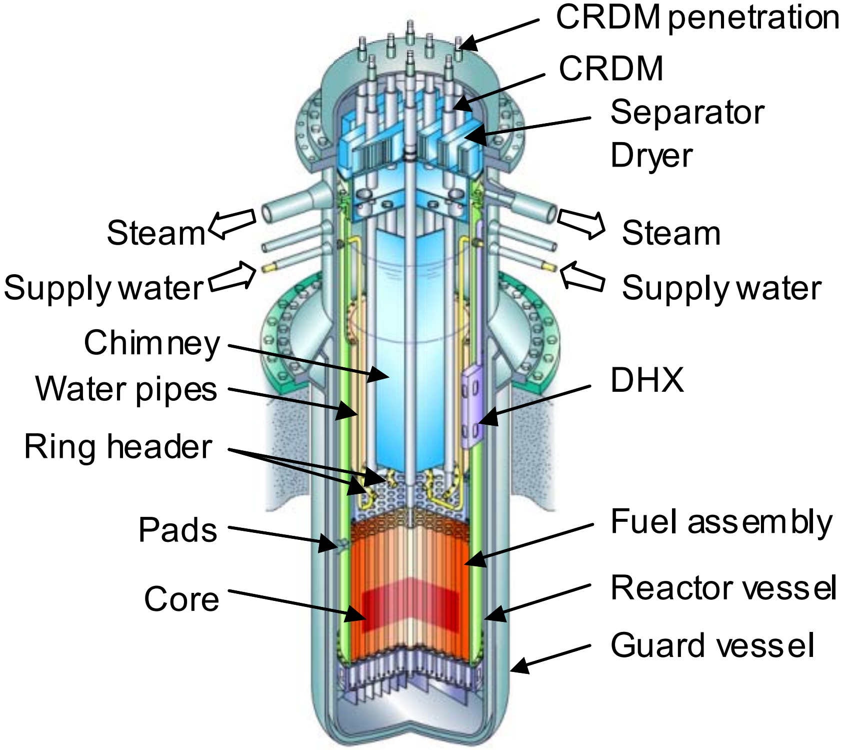
To avoid corrosion and erosion, the components that contact lead alloy should be eliminated as much as possible.

●Concern of corrosion --- Steam generator tubes (hot LBE)
●Concern of erosion --- Impellers of primary pumps (10m/s)

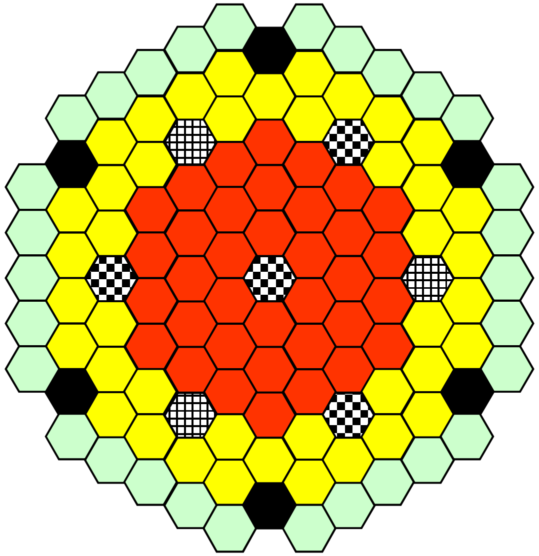


PBWFR (cont'd)

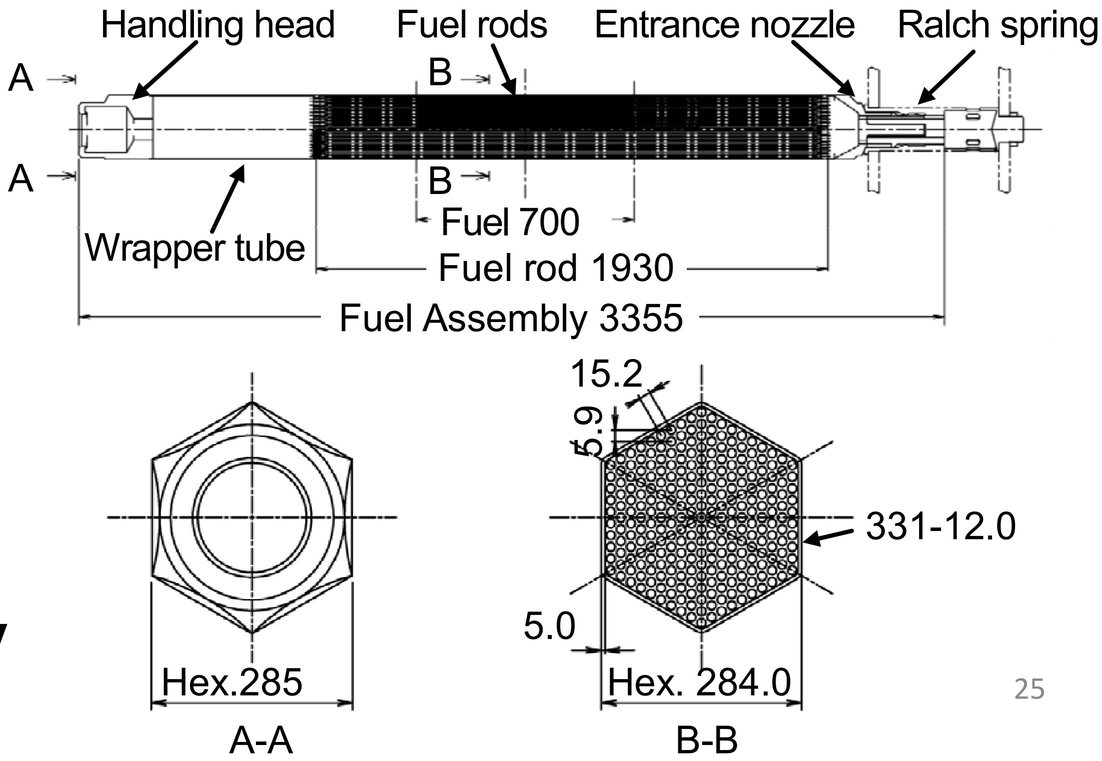
■Elimination of SGs and primary pumps by direct injection of a feed water into hot LBE above core
■ Injected feed water boils in a chimney
■ Steam bubbles drive coolant circulation



PBWFR: Core design



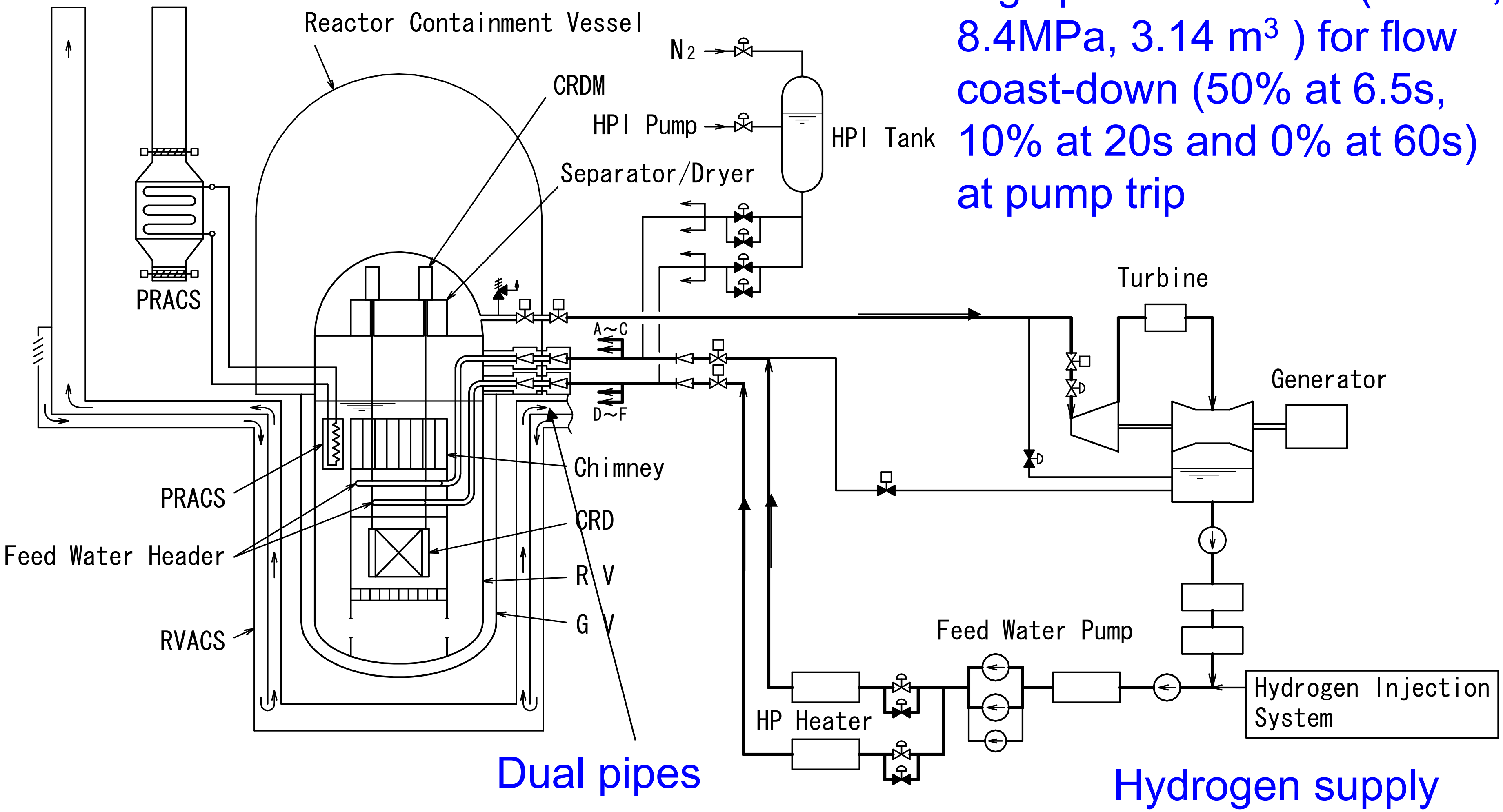
Inner Core Fuel Assembly		36
Outer Core Fuel Assembly		42
Pb-Bi Shielding Assembly		30
Coarse Control Rod		4
Fine Control Rod		3
Backup Control Rod		6
	Total	121



Fuel assembly

PBWFR: Plant systems and fuel handling

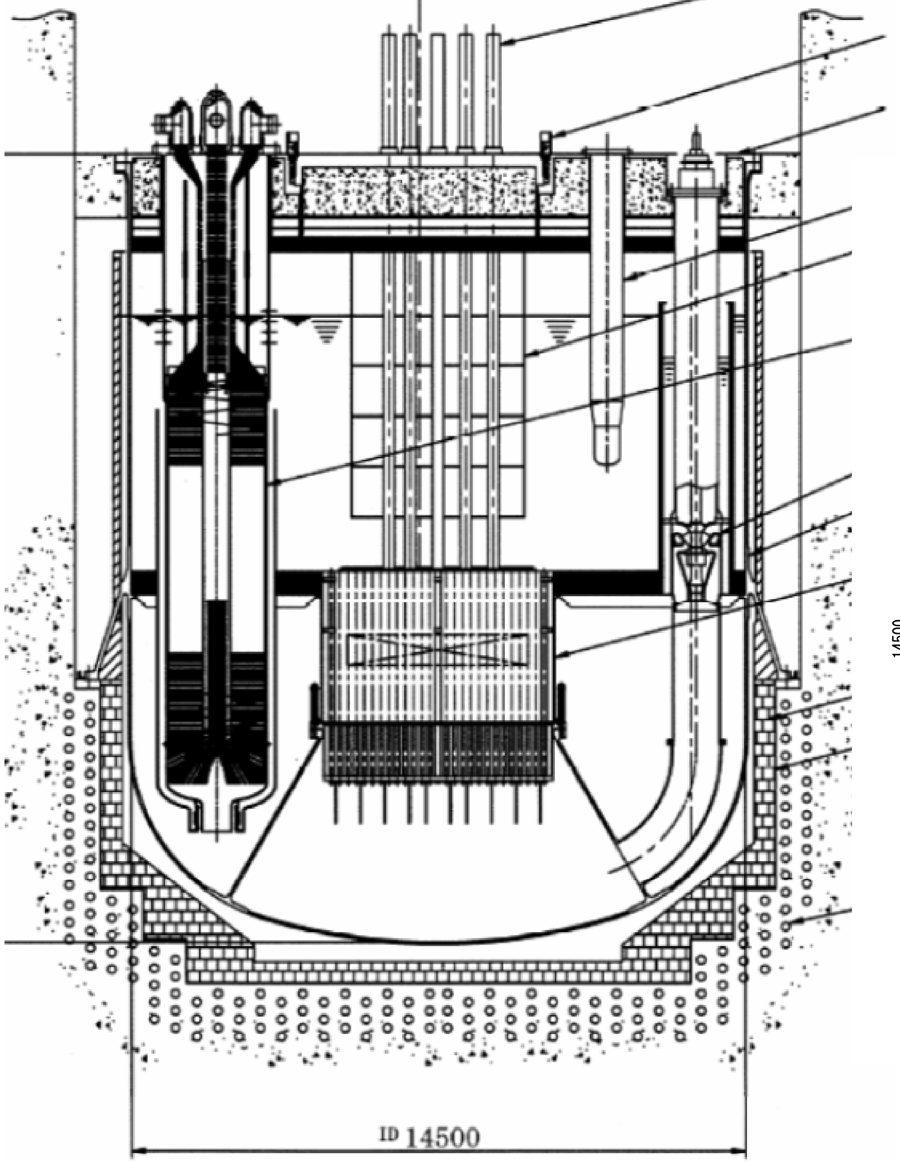
High pressure water (200˚C, 8.4MPa, 3.14 m^3) for flow coast-down (50% at 6.5s, 10% at 20s and 0% at 60s) at pump trip



Main parameters of LSPR and PBWFR (Tokyo Tech.)

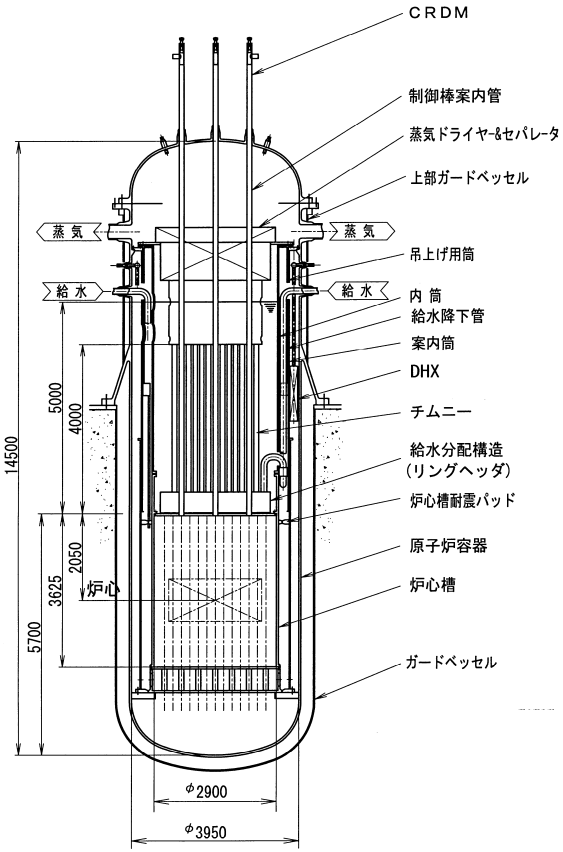
	LSPR-50	PBWFR-150
Power, Thermal/Electric, MW	**150/53**	**450/150**
Thermal efficiency, %	35	33
Core diameter/height, m	1.652/1.08	2.78/0.75
Fuel	**U-Pu-10%Zr mettalic or U-Pu nitride**	**U-Pu Nitride**
Fuel pin diameter, mm	10	12
P/D, Inner core/Outer core	1.12/1.18	1.3/1.3
Linear power density, W/cm	51.9 (Average)	363 (max.)
Pump type/unit number	Mechanical / 2	**Gas lift /1**
Temperature, inlet /outlet, ˚C	360/510	310/460
Coolant flow rate, t/h	12,300	73,970
Steam generator, Type/Unit number	Serpentine tube/2	Direct contact/1
Temperature, Feed water/Steam, ˚C	210/280	220/296
Steam pressure, MPa	6.47	7.0
Reactor vessel, diameter/height, m	5.2/15.2	4.69/19.8
Refueling interval, y	**12**	**10**

JAEA
Φ14.5m, 18.5mH



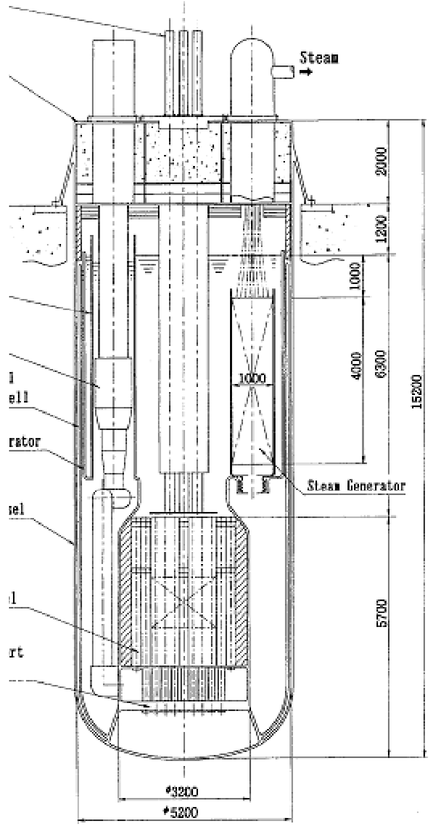
710MWe

PBWFR
Φ3.95m,14.5mH

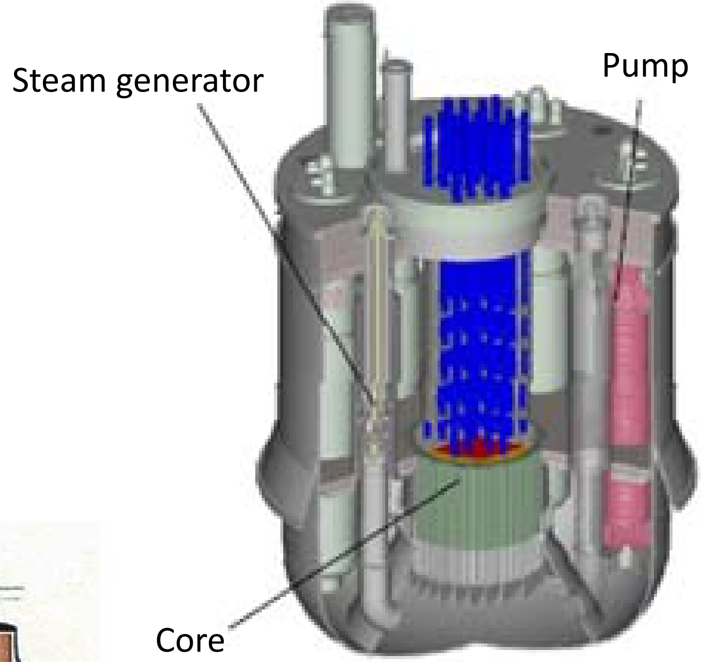


150MWe

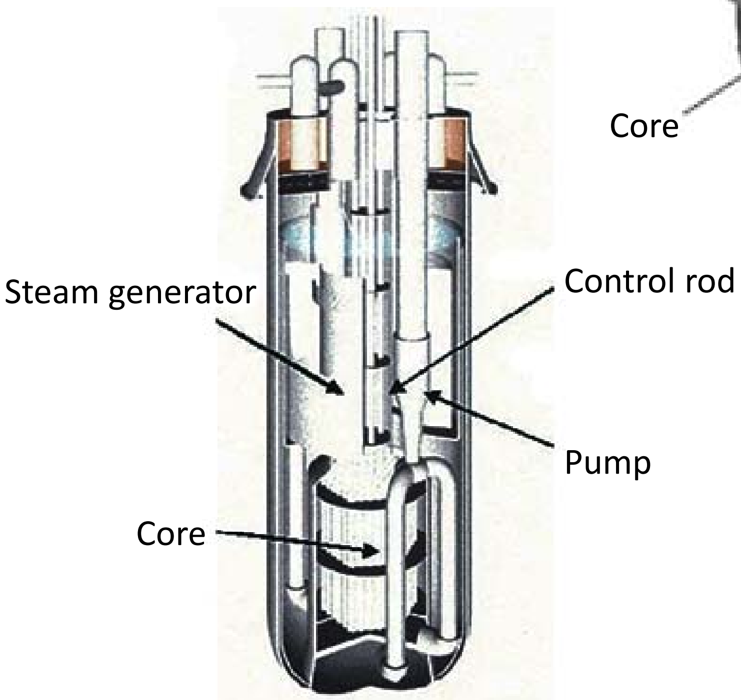
LSPR
Φ5.2m, 15.2mH



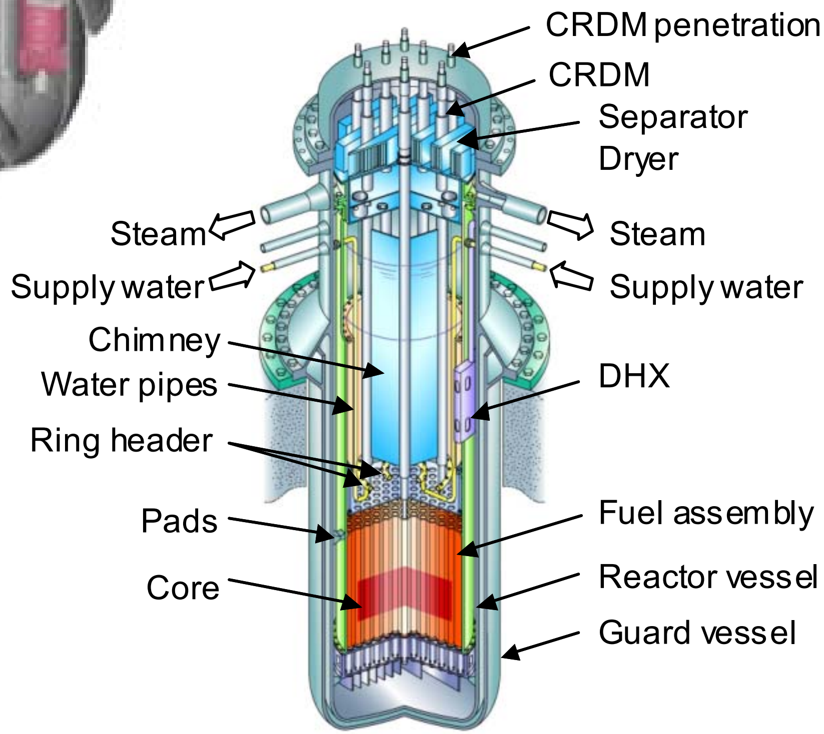
50MWe



JAEA(JNC)/JAPC-LFR
(750MWe)



Tokyo Tech.-LSPR (50MWe)

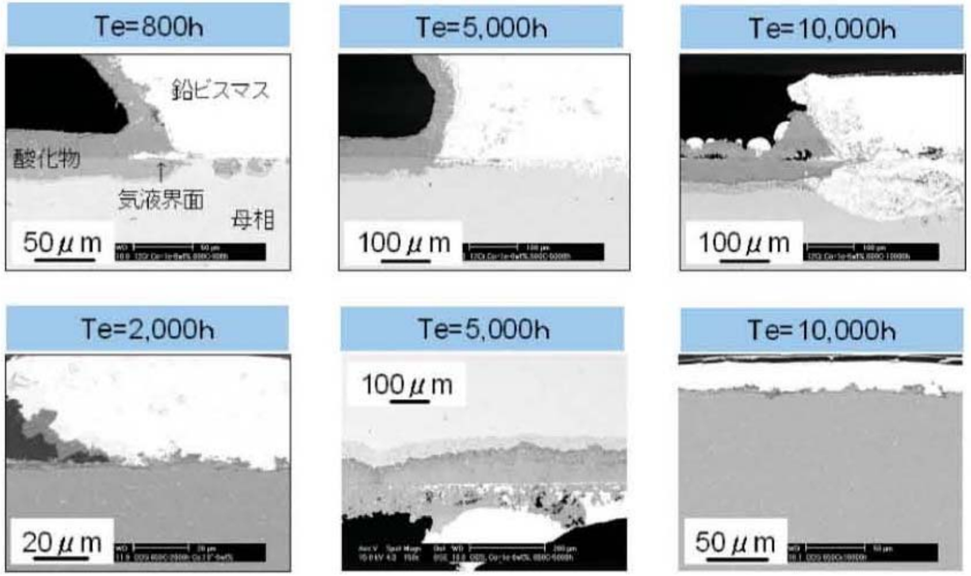


Tokyo Tech.-PBWFR (150MWe)

Evaluation of Corrosion Resistance Based on Existing Steels by JNC/FZK

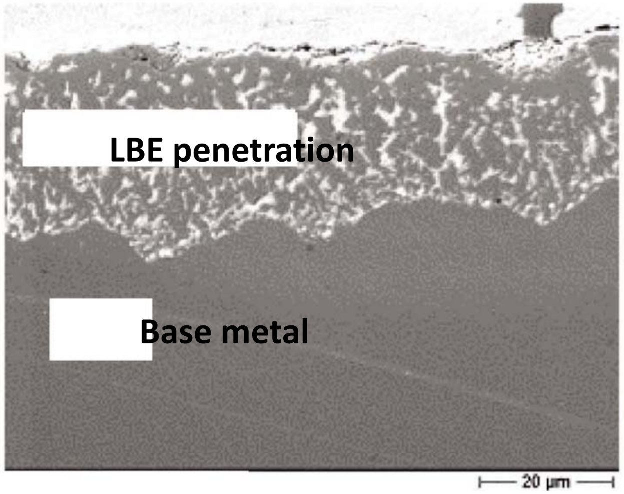
12Cr steel
600 ˚C

ODS steel
650 ˚C

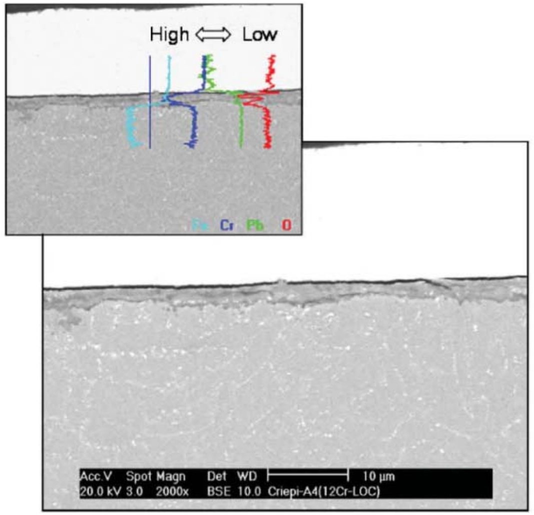


Upside down

Stagnant corrosion test at O-concentration of 10^{-6}wt%



316FR 550 ˚C, 2000h, $C_O 10^{-8}$wt%



12Cr steel 650˚C, 2000h, $C_O 5\times10^{-7}$wt%

No improvement of material for corrosion resistance

Choice of Cladding Temperature (570˚C) Based on Correlation of Oxidation Rate Obtained for Existing Steels by JNC/FZK

Correlation of oxidation rate

$$\phi = A_0 \exp\left[\frac{-Q}{RT}\right] t^{1/2}$$

ϕ : Oxide thickness (μμm)

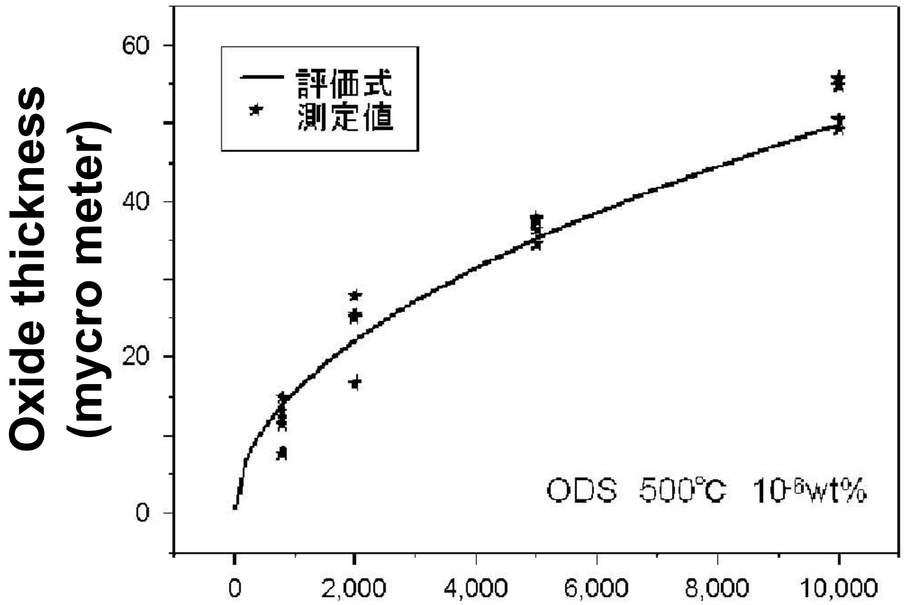
t : Time (h)

Q : Superficial activation energy

R : Gas constant

T : Temperature

A_0 : 8.91×10^4



ODS steel 500˚C, $C_O 10^{-6}$wt%

(Limited conditions)

Techniques for Corrosion Resistance

Oxygen control in lead/LBE

- Self-healing of oxide protection layer on material surface

Improvement of Materials

- Existing steels containing high Cr
- Addition of Si or Al to steels
- Surface coating by Al alloy

Already reported in Russia, and studied in Japan, EU and U.S.A in 2006

In spite of the statement "International cooperation is ***unlikely for a breakthrough in the fundamental issues"***

in JNC/ JAPC Report in 2006

Corrosion Resistance of Existing Steels in Flowing Condition

Tokyo Institute of Technology, 1999-2006

Material	Contents	Temp. (˚C)	Oxygen content (wt%)	Time (h)	Result
SUS316	18Cr14Ni2Mo	550	3.7×10^{-8}	1000	Penetration
SCM420	1Cr0.2Mo	550	3.7×10^{-8}	1000	Worst
F82H	8Cr2Mo2W	550	3.7×10^{-8}	1000	Worse
NF616	9Cr0.5Mo2W	550	3.7×10^{-8}	1000	Worse
ODS	12Cr2W	550	3.7×10^{-8}	1000	Worse
HCM12A	12Cr2W	550	3.7×10^{-8}	1000	Worse
STBA26	9Cr1Mo	550	3.7×10^{-8}	1000	Better
HCM12	12Cr1Mo	550	3.7×10^{-8}	1000	Best

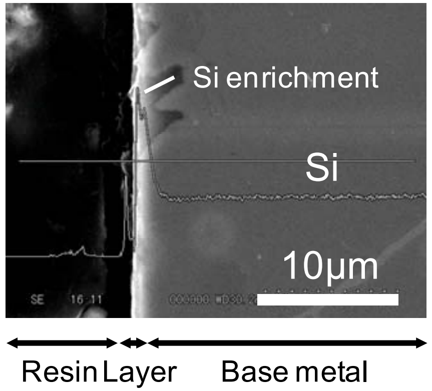
Corrosion Resistance of Existing Steels *Containing Si or Al* in Flowing Condition

Tokyo Institute of Technology, ***1999-2006***

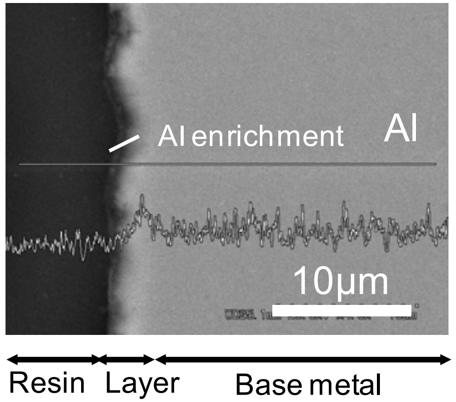
Material	Contents	Temp. (˚C)	Oxygen content (wt%)	Time (h)	Result
SUS405	12Cr1Si	550	3.7×10^{-8}	1000	Good
SUS430	16Cr0.6Si	550	3.7×10^{-8}	1000	Good
SUH3	10Cr0.7Mo2Si	550	$1.7\text{-}3.7 \times 10^{-8}$ 1×10^{-6}	500-2000	Good
Recloy10	18Cr1Al	550	1.7×10^{-8} 1×10^{-6}	500-2000	Good
NTK04L	18Cr3Al	550	1.7×10^{-8} 1×10^{-6}	500-2000	Good

550˚C

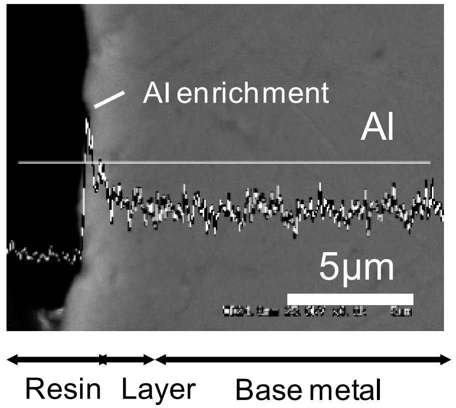
After 2000-h exposure



SUH3



Recloy10



NTK04L

Corrosion Resistance of ODS Steel *with Addition of Al* in Stagnant Condition

JAEA,FZK, etc. 2009

Material	Addition	Flow/Stagnant	Temp. (˚C)	Oxygen content (wt%)	Time (h)	Result
13.7–17.3Cr-ODS steel	3.5 wt% Al, wt%	Stagnant	550, 650	10^{-8}, 10^{-6}	5000	Good

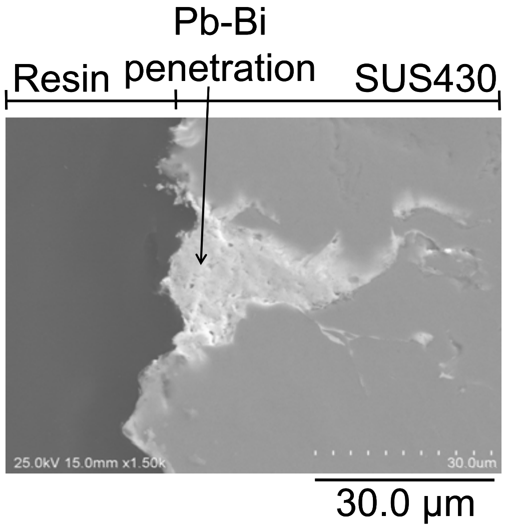
- Addition of Al: Effective for corrosion resistance
- Addition of minor amount of Zr: Favorable influence
  To prevent ODS particles from combining with Al and coarsening
- Solely Increasing Cr concentration: Not effective

Corrosion Resistance of Existing Steels *Containing Si or Al* in Stagnant Condition

Tokyo Institute of Technology, 2010

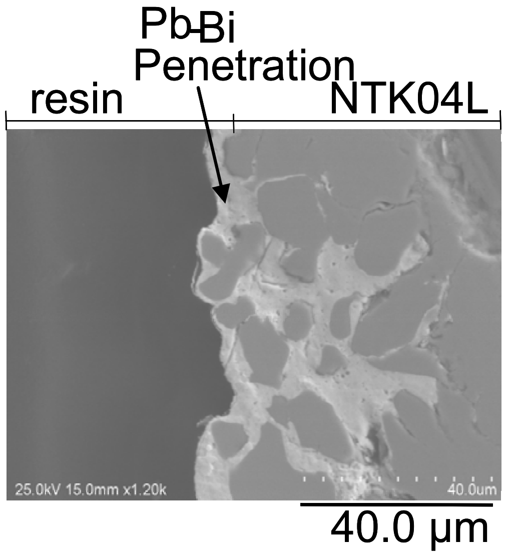
Material	Contents	Temp. (˚C)	Oxygen content (wt%)	Time (h)	Result
SUS430	16Cr0.6Si	700	$5x10^{-6}$	1000	Penetration
STBA26	9Cr1Mo	700	$6.8x10^{-7}$	1000	Penetration
Recloy10	18Cr1Al	700	$5x10^{-6}$	1000	Penetration
NTK04L	18Cr3Al	700	$5x10^{-6}$	1000	Penetration

700˚C



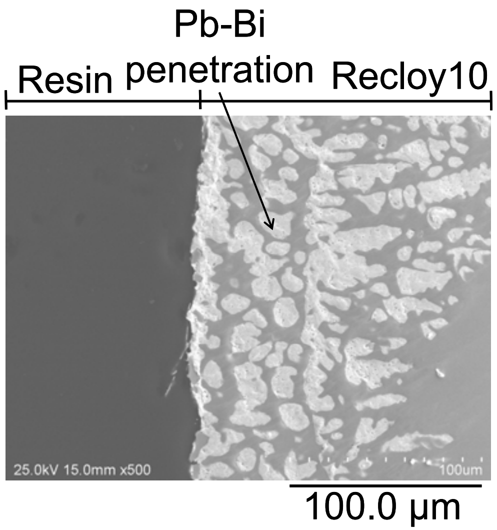
SUS430

(18Cr-0.75Si)



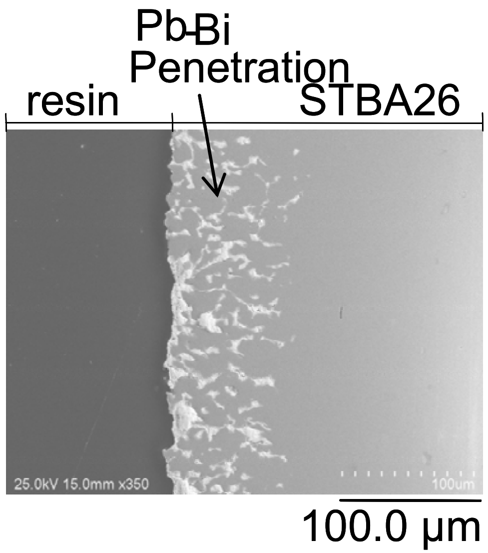
NTK04L

(17.8Cr-0.4Si-3.34Al)



Recloy10

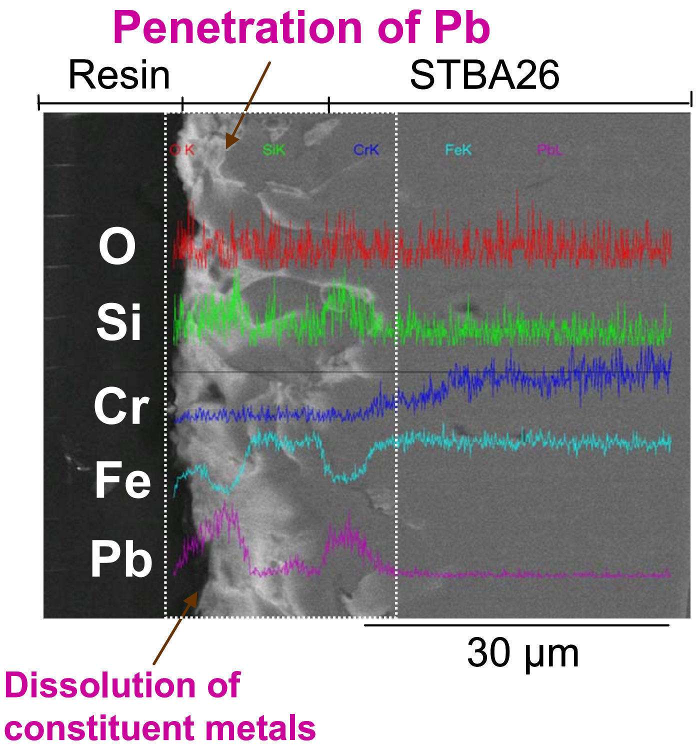
(17.7Cr-1Si-0.9Al)



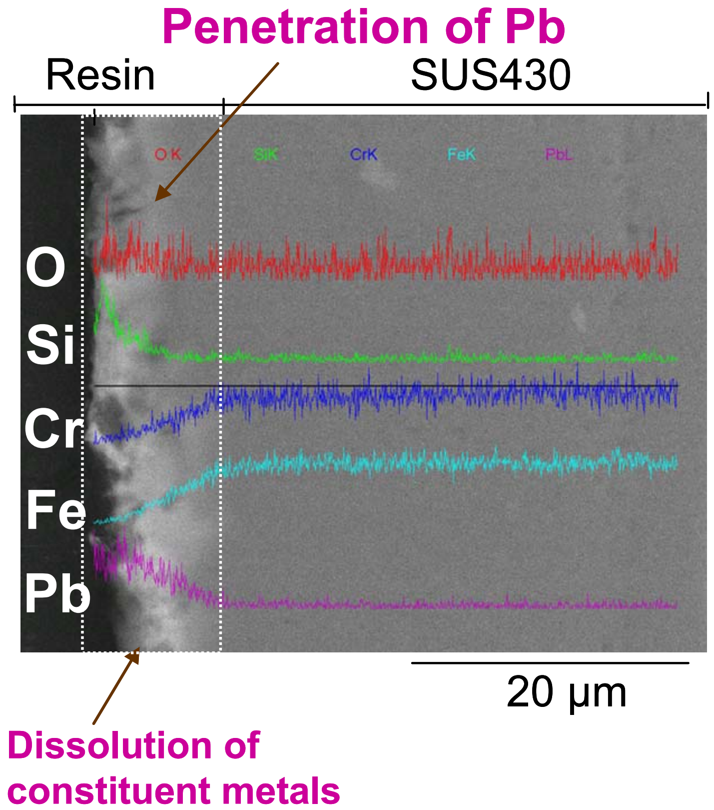
STBA26

(9Cr-0.2Si)

700˚C

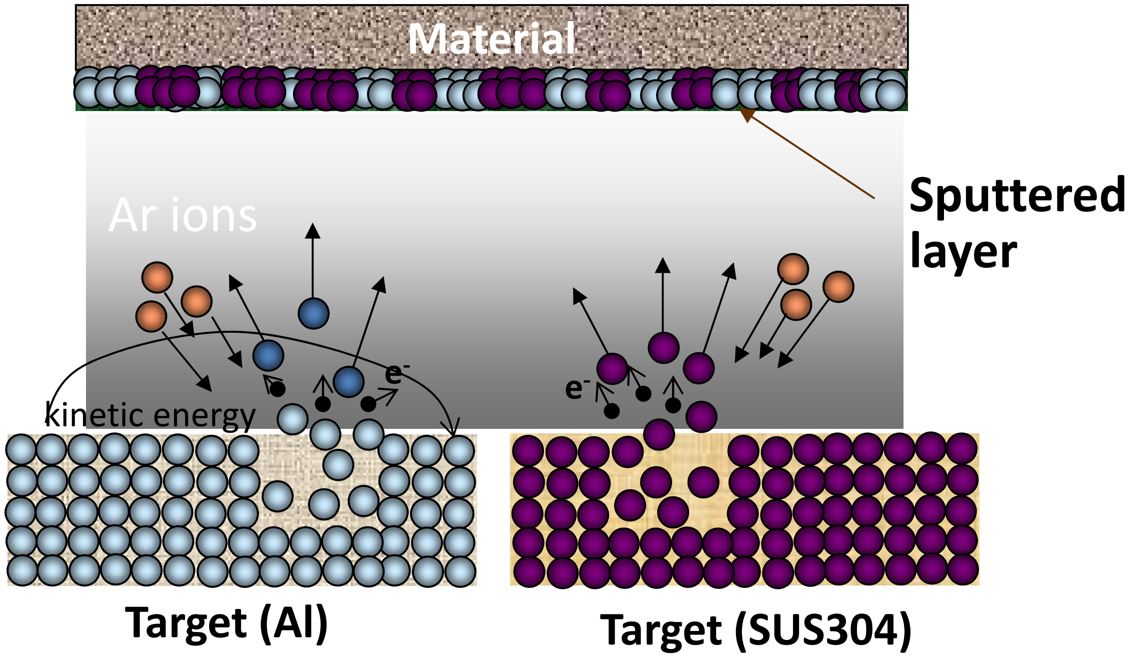


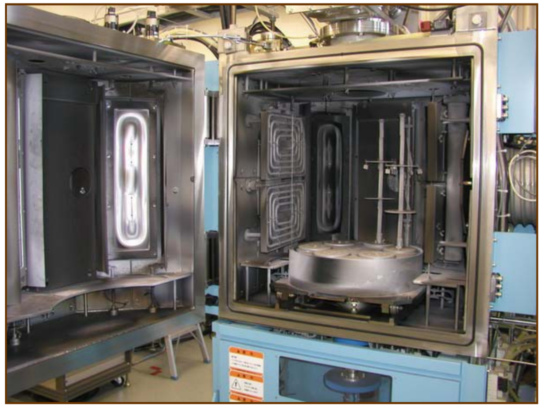
STBA26
(9Cr-0.2Si)



SUS430
(18Cr-0.75Si)

Fe-Al Alloy Coating using Unbalanced Magnetron Sputtering Technique

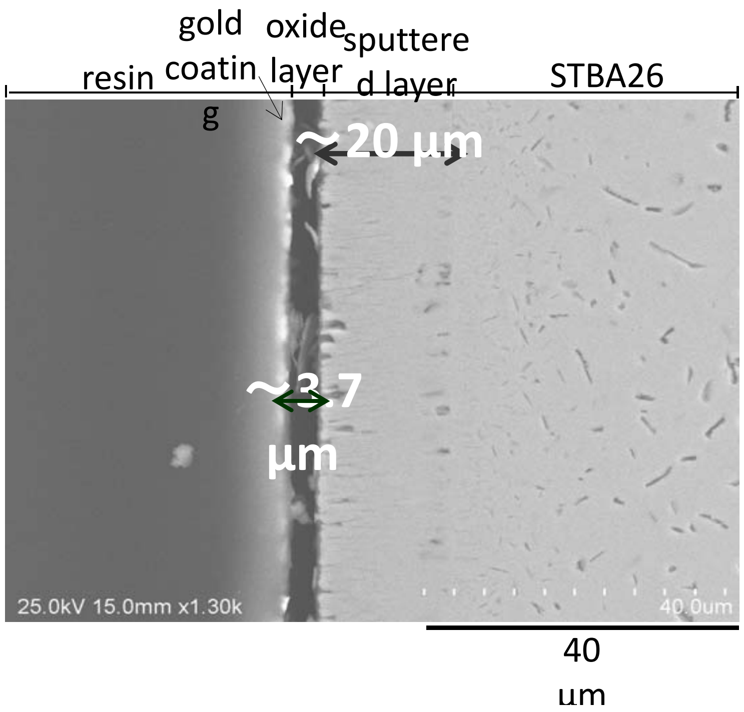


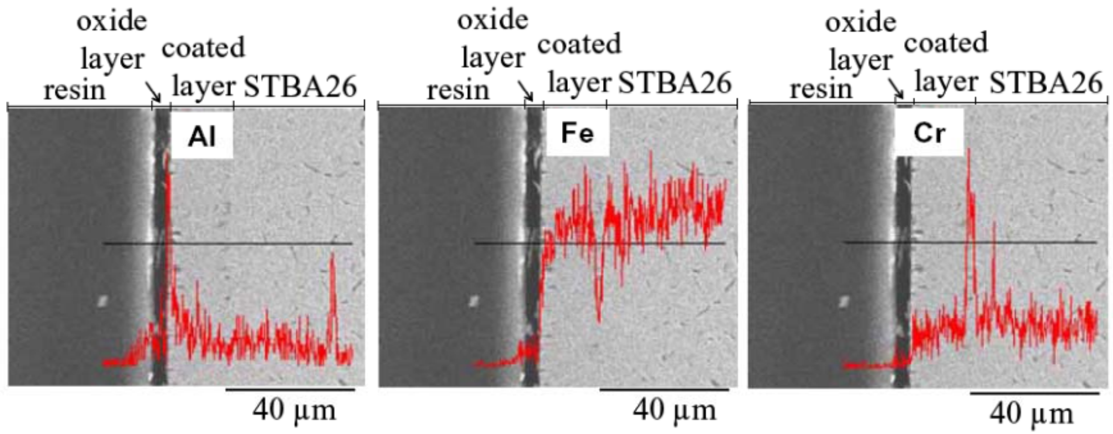


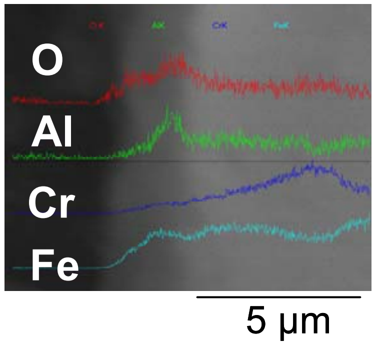
Corrosion Resistance of Existing Steels *with Fe-Al Alloy Coating* in Stagnant Condition

Tokyo Institute of Technology, 2010

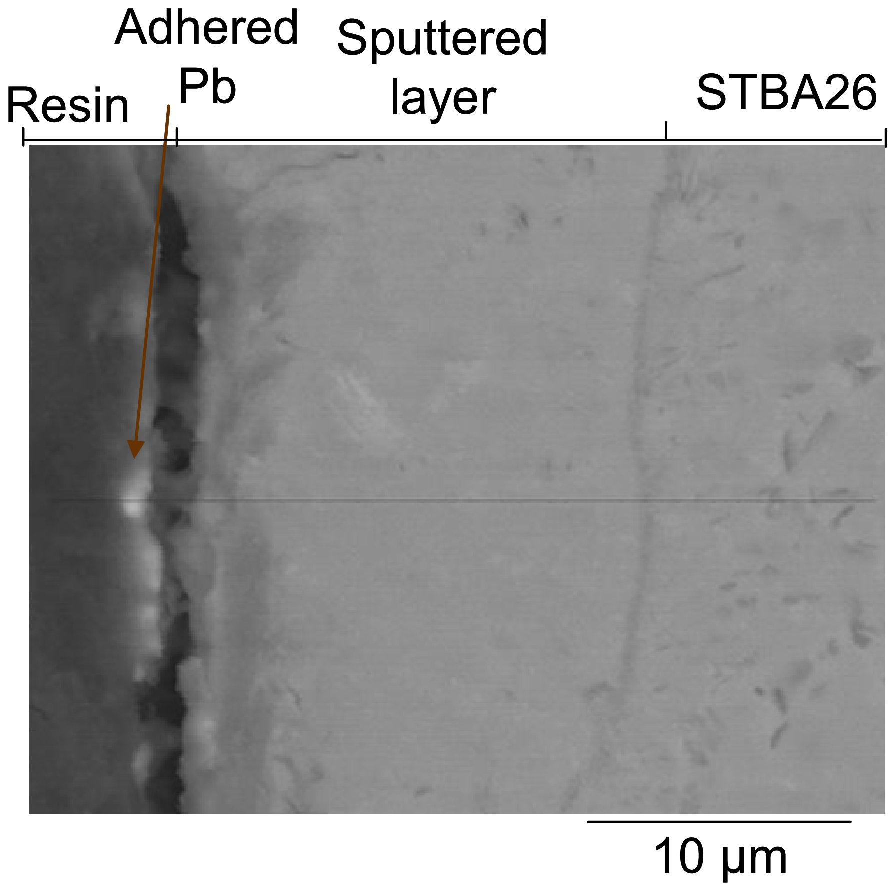
Material	Contents	Temp. (˚C)	Oxygen content (wt%)	Time (h)	Result
STBA26	9Cr1Mo	700	6.8×10^{-7}	1000	Good

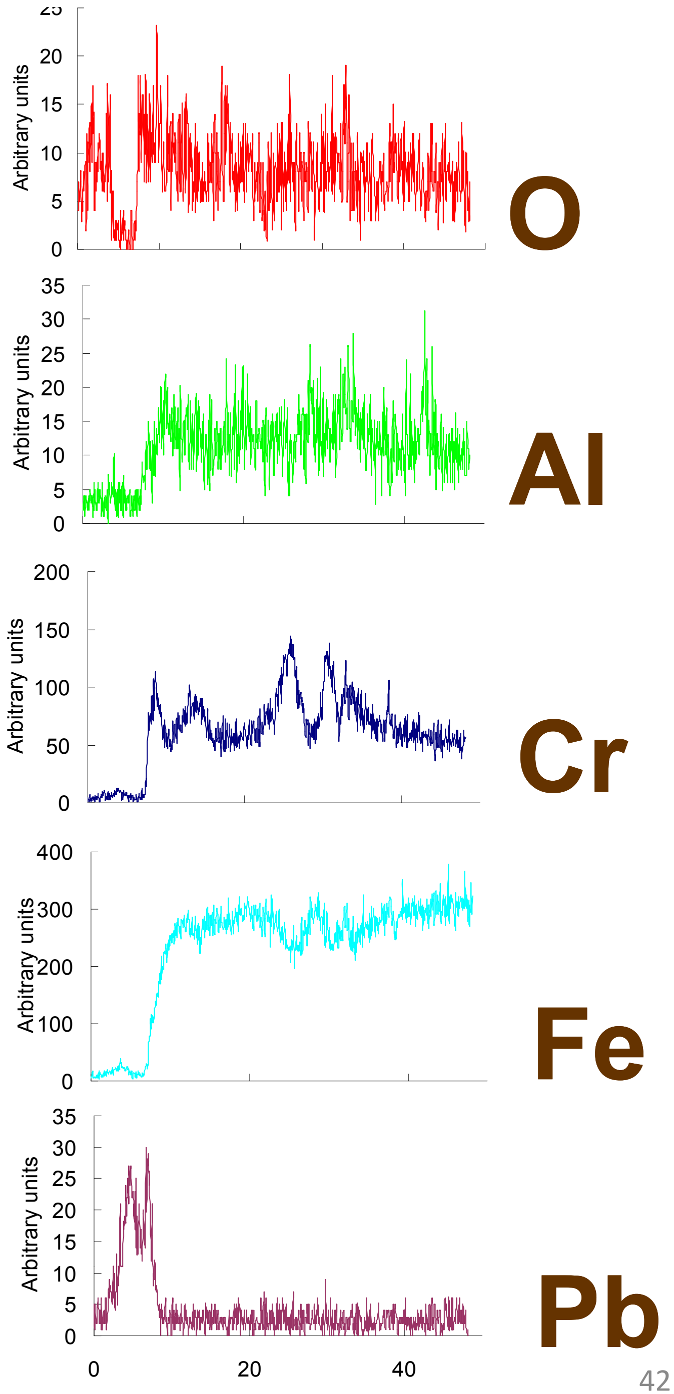





O
Al
Cr
Fe
5 µm

700˚C


Adhered Pb
Sputtered layer
Resin
STBA26
10 µm


Arbitrary units
O
Al
Cr
Fe
Pb
0
20
40

Corrosion Resistance of ODS Steels *with Addition of Al and Al-alloying surface Treatment* in Stagnant Condition

JAEA,FZK, etc. 2009

Material	Addition	Flow/Stagnant	Temp. (˚C)	Oxygen content (wt%)	Time (h)	Result
9Cr-ODS steel	3.3-3.8wt% Al	Stagnant	650, 700	10^{-8}, 10^{-6}	10000	Good

- Addition of Al: Effective for corrosion resistance
- Addition of minor amount of Zr or Hf
- Al-alloying surface treatment by the GESA facility

Thank you
for your kind attention!