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Proceedings of the First Topical Meeting on Asian Network for Accelerator-driven Systems and Nuclear Transmutation Technology

(Ed.) Toshinobu SASA

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J-PARC Center
Sector of Nuclear Science Research

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Tokai-mura, Naka-gun, Ibaraki-ken

(Received December 18, 2015)

The first topical meeting on Asian Network for Accelerator-driven System (ADS) and Nuclear Transmutation Technology (NTT) was held on 26-27 October 2015 at the J-PARC Center, Japan Atomic Energy Agency, Japan. The topical meeting was an optional one in-between the regular meeting, which is held in every two years. Instead of the regular meetings, which cover all research fields for ADS and NTT, such as accelerator, spallation target, subcritical reactor, fuel, and material, the topical meeting is focused on a specific topic to make technical discussions more deeply. In this meeting, the technology for lead-bismuth eutectic alloy was selected, as it was one of the hot issues in the world, and the topic was deeply discussed by specialists in Asian countries. This report summarizes all presentation materials discussed in the meeting.

Keywords: Accelerator-driven System, Nuclear Transmutation, Liquid Metal, Lead-bismuth, Transmutation Experimental Facility, J-PARC, Minor Actinide, Asian Network

加速器駆動システム及び核変換技術に関するアジアネットワーク トピカル会合 第一回 報文集

日本原子力研究開発機構 原子力科学研究部門
J-PARC センター 核変換ディビジョン

（編）佐々 敏信

(2015 年 12 月 18 日受理)

加速器駆動システム（ADS: Accelerator-driven System）及び核変換技術（NTT: Nuclear Transmutation Technology）に関するアジアネットワークトピカル会合第一回会議が、2015 年 10 月 26〜27 日に、日本原子力研究開発機構 J-PARC センターに於いて開催された。当会合は、隔年開催の通常会合の合間に開催するものであり、加速器、核破砕ターゲット、未臨界炉、燃料、材料といった ADS 及び NTT に関わる技術全般を取り扱う通常会合に対し、特定の技術課題を深く議論することを目的としている。今回の会合では、世界的に課題となっている鉛ビスマス溶融合金の取扱い技術を課題に選定し、アジア圏の専門家による議論を行った。本報告は、会合で議論された全てのプレゼンテーションを取りまとめたものである。

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Contents

目次

1. Introduction

The first topical meeting on Asian Network for Accelerator-driven System (ADS) and Nuclear Transmutation Technology (NTT) was held on 26-27 October 2015 at the J-PARC Center, Japan Atomic Energy Agency, Japan. The topical meeting is an optional one in-between the regular meetings, which are held in every two years. Instead of the regular meetings, which cover all research fields for ADS and NTT, such as accelerator, spallation target, subcritical reactor, fuel, and material, the topical meeting is focused on a specific topic to make technical discussions more deeply.

In this meeting, the technology for lead-bismuth eutectic alloy (LBE) was selected as it was one of the hot issues in the world and had deep discussions with specialists in Asian countries. A research activity for LBE application in Germany was also presented as an invited talk to develop an understanding for key technologies. Through the discussion, the importance of cooperation in Asian region is recognized to solve the issues for application of LBE. This report summarizes all presentation materials discussed in the meeting.

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2. LBE Applications in Europe

2.1 Materials Compatibility in Heavy Liquid Metals for ADS Applications

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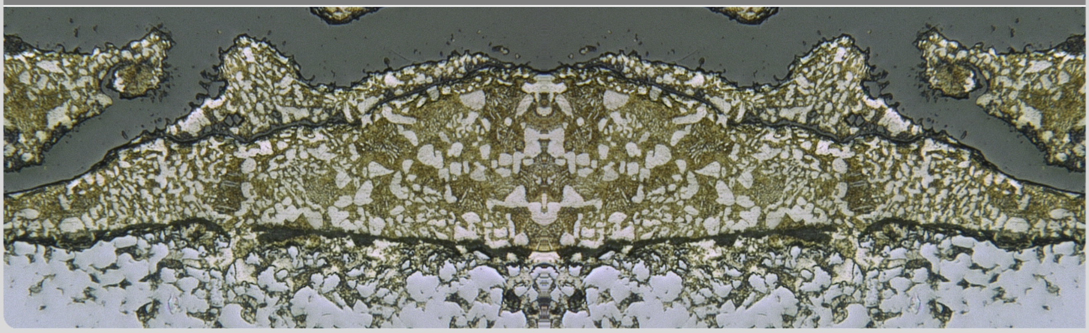
Materials Compatibility in Heavy Liquid Metals for ADS Applications

Jürgen Konys

INSTITUTE FOR APPLIED MATERIALS – APPLIED MATERIALS PHYSICS (IAM-AWP)



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Outline

- Introduction
- HLM chemistry
- European support for MYRRAH
- Corrosion of 9% Cr steels in LBE
- Corrosion of austenitic steels in LBE
- Conclusions

Lead-cooled Nuclear Reactors/Systems

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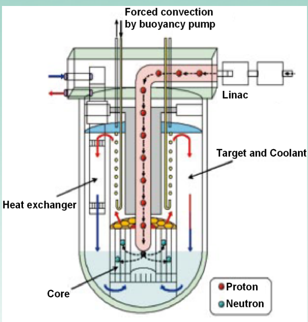
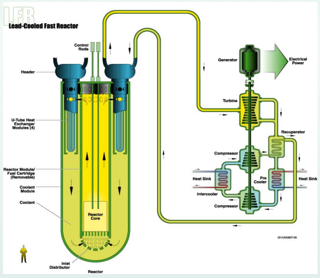


Accelerator Driven (Subcritical) System

- Transmutation of long-lived radioactive isotopes in nuclear waste
- Power generation
- Liquid lead (Pb) or lead-bismuth eutectic (LBE) as spallation target and primary coolant
- Maximum temperature, typically
  - 450 – 500°C for regular operation
  - Periodically 550°C (according to plant design)

Lead-Cooled Fast Reactor

- One of the concepts for the 4th generation of nuclear power plants (Gen IV)
- In the long-term, Pb as primary coolant at maximum ca. 800°C
- Short- to mid-term: Pb- or LBE-cooled at 450 – 550°C



3 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Application of Heavy Liquid Metals (HLMs)

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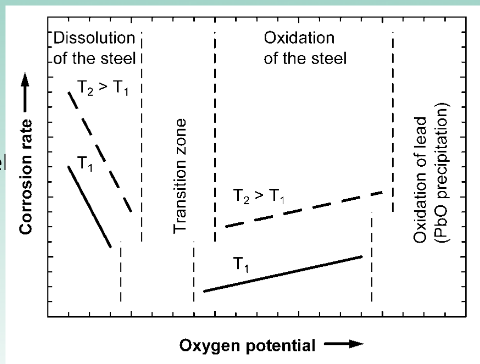
- **Favourable properties of liquid metals**
  - High thermal conductivity and boiling point → Efficient heat transfer medium/ coolant for thermal energy conversion
  - Reasonably low dynamic viscosity
  - Some show minimum interaction with neutrons (e.g., sodium and lead) → Essential for fast neutron reactors
  - Liquid heavy metals release neutrons under proton irradiation (e.g., mercury, lead and bismuth) → Allows for sub-critical nuclear fuel in a proton-accelerator driven system
  - Liquid breeder and coolant for fusion application → As eutectic Pb-16Li alloy in fusion

- **Compatibility between liquid metals and steels?**
  - Major steel elements are soluble in liquid metals
  - Formation of intermetallic phases
  - Degradation of mechanical properties
  - Prominent issue for lead alloys, especially lead-bismuth eutectic (LBE)
  - Chemistry is different for Pb/LBE **and** Pb-16Li

4 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Impact of oxygen on steel corrosion in HLMs

- "Absence" of oxygen (Pb-16Li)
  - Chemical oxygen potential too low for remarkable interactions with steel elements
  - Steel elements dissolve in the liquid metal
  - Absorption of liquid metal constituents by the steel
  - (Formation of intermetallic phases)
- Low-oxygen conditions (Pb, LBE)
  - Solid oxides of steel elements are stable
  - But, amount of oxides formed too small for a continuous surface layer
  - Concentration gradients that promote solution of steel elements may develop in the liquid metal
- High-oxygen conditions (Pb, LBE)
  - Solid oxides of steel elements form a continuous surface layer
  - Solution of steel elements still possible, but only after diffusion through solid oxide



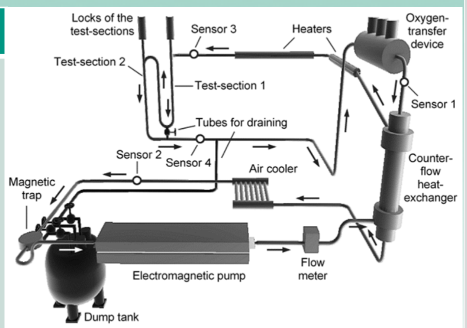
→ Transition from solution-based to oxidation-based corrosion with increasing oxygen concentration

→ **Continuous oxide layer is the goal of deliberate oxygen addition (Pb, LBE)**

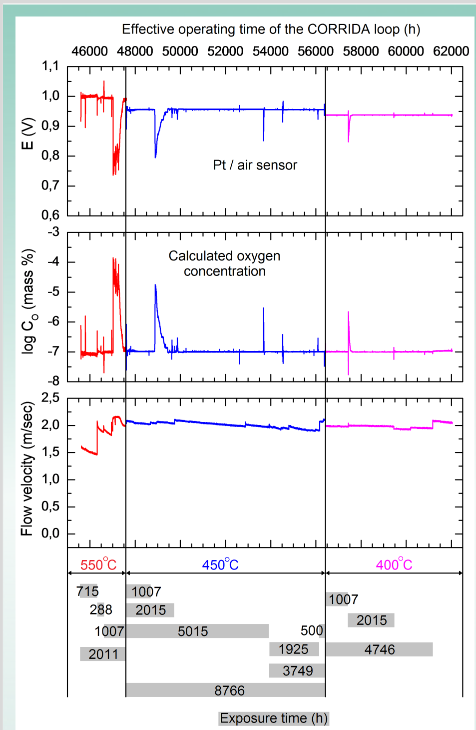
→ Locally low-oxygen conditions even when oxygen concentration in the bulk of the liquid metal is high

Corrosion testing in LBE for ADS applications

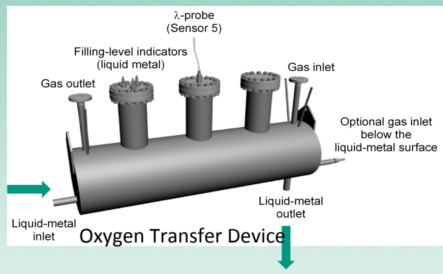
CORRIDA	
Testing characteristics	Exposure to flowing LBE, typically 2 m/s. 1000 kg circulating LBE (5.3 kg/s) Several steel samples simultaneously exposed in vertical test sections. Oxygen control via gas with variable oxygen partial pressure. Large internal steel surface in contact with the liquid metal. Temperature difference along the loop of ~100–150°C.
Sample geometry	Typically, cylindrical specimen with 7.5 cm² exposed to liquid metal.
Determination of oxygen content	Four potentiometric oxygen sensors distributed along the loop.



Constructed and operated at KIT's Institute for Applied Materials – Corrosion Department → current operational time: ca. 90,000 hours



Monitoring of test parameters



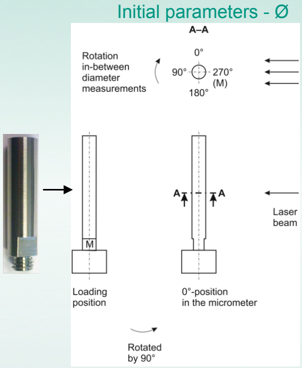
- **T = 550(+5)°C,**
  - T_{min} ≈ 385°C, c_O = 10^{-7} mass%, excursion to 10^{-4}–10^{-5} mass% O,
  - v = 2(+/–0.2) m/s, initially 1.5–1.6 m/s,
  - t = 288; 715; 1007; 2011 h
- **T = 450(+5)°C,**
  - T_{min} ≈ 350°C, c_O = 10^{-7} mass%, excursion to 10^{-5} mass% O
  - v = 2(+/–0.2) m/s,
  - t = 500; 1007; 1925; 2015; 3749; 5015; 8766 h
- **T = 400(+5)°C,**
  - T_{min} ≈ 350°C, c_O = 10^{-7} mass%,
  - v = 2(+/–0.2) m/s,
  - t = 1007; 2015; 4746 h; still continuing up to 10,000h

7 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Quantification of corrosion loss (very important!!)

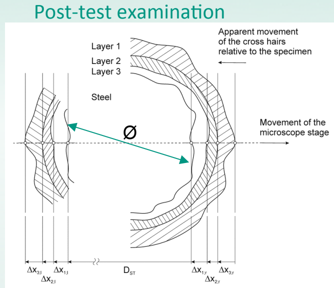
- **Goal of quantification**
  - Material loss, average of general corrosion and maximum of local corrosion
  - Thickness of adherent (oxide) scale
  - Overall change in dimensions, including the scale
  - Amount of metals transferred to the liquid metal
- **Metallographic method (cylindrical specimens)**

Initial parameters - Ø



- Measurement of initial diameter in a laser scanner with 0.1 µm res.
- Diameter of unaffected material (12 measm. with rotation angle 15°) and thickness of corrosion zones determined in a microscope (LOM) with 1 µm resolution
- Occurrence of different corrosion modes on opposing sides of the re-measured diameter is considered in the evaluation (% of surface circumference)

Post-test examination



Transverse circular cross-section

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Support for MYRRHA: EU-funded Projects

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- **MATTER**

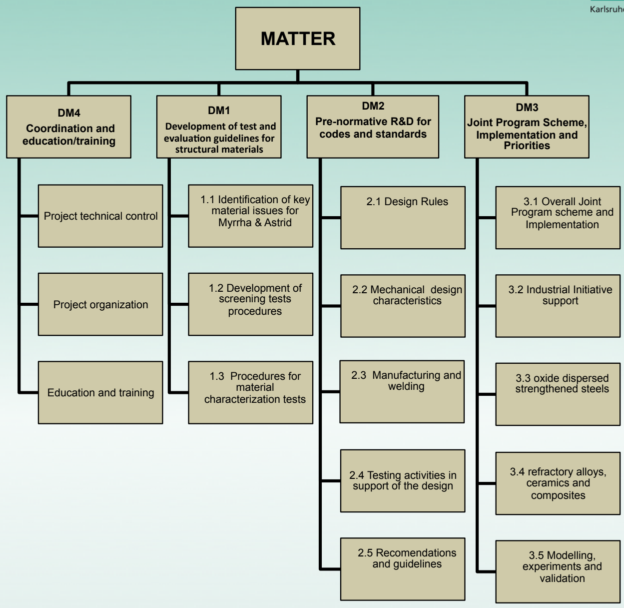
  MATerials TEsting and Rules

- **MatISSE**

  Materials Innovations for a Safe and Sustainable nuclear in Europe

- **ESNII+**

  Preparatory phase for ESNII: European Sustainable Nuclear Industrial Initiative



Support for MYRRHA: Process medium and materials

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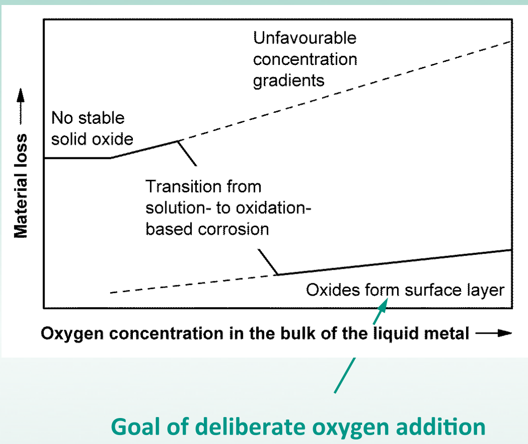
- **Process medium**
  - Lead-bismuth eutectic (LBE)
  - Addition of oxygen so as to favour oxidation over solution of material elements
  - Oxygen activity or concentration required is material- and temperature-dependent
- **Materials**
  - Austenitic steels: 316L for the main structural components, 15-15Ti in the core
  - 9Cr ferritic/martensitic steels: T91 for parts of the core support and spallation target assembly



MYRRHA design data used

Design operating parameters

Material	Temperature (°C)	Surface area (m^2)	Oxygen conc. (mass%)	Average flow velocity (m/s)
316L	400	120	~10^{-7}	To be specified
	350	419 (360)		
	310	125		
	270	1697 (1596)		
15-15Ti	410	194	~10^{-7}	To be specified
	270	1150		
T91	450	4	~10^{-7}	To be specified
	350	(59)		
	270	1 (102)		

Early operating stages

	Duration (days)	Temperature (°C)
Start-up	180	270°C
1st Power cycle	90	Components at design operating temperature; temperature transients
Downtime	90	270°C
2nd Power cycle	90	As above

11 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Objectives and approaches

- **Estimation of corrosion product formation in respect of**
  - Solution of steel elements by the LBE → **May re-precipitate and contribute to floating solid oxides or plugging**
  - Oxygen consumption, i.e., depletion if oxygen is not replaced → **Input for dimensioning appropriate oxygen-transfer devices**
  - Uptake/precipitation of solid oxides → **Contributes to deposition of solid matter; input for dimensioning filters or other to remove floating oxides**
- **Work performed**
  - Analysis of availability of required corrosion data: mechanisms, rate laws, activation energies, incubation times, surface area affected by local processes
  - Simplified spread sheet calculations for design operating conditions of **MYRRHA**, separately for the corrosion modes to be considered
  - Specific calculations for reactor start-up and first power cycles

→ **Available data is incomplete, requiring a number of assumptions and simplifications!**

12 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

9% Cr-steels tested in the CORRIDA loop

Concentration (in mass%) of alloying elements other than Fe

	Cr	Mo	W	V	Nb	Ta	Y	Mn	Ni	Si	C
T91-A	9.44	0.850	<0.003	0.196	0.072	n.a.	n.a.	0.588	0.100	0.272	0.075
T91-B	8.99	0.89	0.01	0.21	0.06	n.a.	n.a.	0.38	0.11	0.22	0.1025
E911*	8.50–9.50	0.90–1.10	0.90–1.10	0.18–0.25	0.060–0.100	–	–	0.30–0.60	0.10–0.40	0.10–0.50	0.09–0.13
EUROFER	8.82	<0.0010	1.09	0.20	n.a.	0.13	n.a.	0.47	0.020	0.040	0.11
EF-ODS-A	9.40	0.0040	1.10	0.185	n.a.	0.08	0.297†	0.418	0.0670	0.115	0.072
EF-ODS-B	8.92	0.0037	1.11	0.185	n.a.	0.078	0.192†	0.408	0.0544	0.111	0.067

* Nominal composition
† In the form of yttria (Y_2O_3)

Elements besides Cr that are likely to improve oxidation performance

Nominally 9 mass% Cr

Microstructure

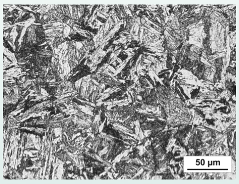
Fully martensitic: E911, T91-A

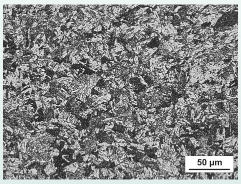
T91-B

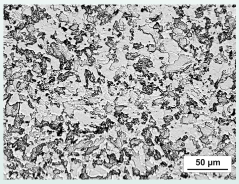
Grain size

EUROFER

Mainly ferritic: ODS-A, ODS-B



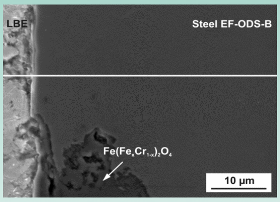




13 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Typical phenomena observed in flowing LBE on 9Cr steels at 450–550°C, 2 m/s and 10^{-6} mass% dissolved oxygen

- **Protective scaling → ideal case!!**
  - Thin Cr- (Si-) rich oxide scale (thickness ~1 µm or less)
  - Promoted by high Cr content, fine-grained structure, dispersed Y_2O_3 …
  - Favourable situation with respect to minimum material loss, but generally not of long duration (locally)

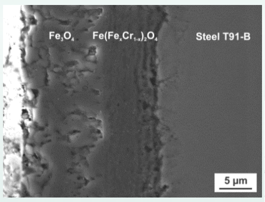


550°C

Scale failure at high local c_O (?)

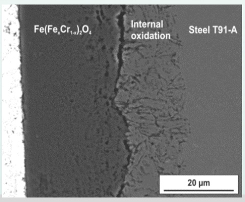
Scale failure at low local c_O (?)

- **Accelerated oxidation → most common**



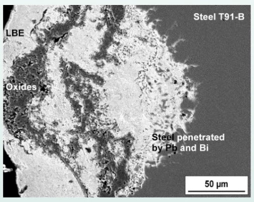
450°C

- Typical and, finally, the general corrosion process for 9Cr steel



550°C

- **Solution-based corrosion → seldom, but can happen**
  - Steel elements first dissolve but may re-precipitate in the form of oxides
  - Intermittent solution participates in accelerated oxidation processes or solution outweighs oxidation



550°C

14 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Exposure to flowing LBE at 450 or 550°C, 2 m/s and 10^{-7} mass% dissolved oxygen (nominal conditions)

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Materials T91-A and T91-B (same supplier)

- T = 550(+5)°C
  T_{min} ≈ 385°C
  c_O = 10^{-7} mass%, excursion to 10^{-4}–10^{-5} mass%
  v = 2(+/–0.2) m/s, initially 1.5–1.6 m/s
  t = 288; 715; 1007; 2011 h

- T = 450(+5)°C
  T_{min} ≈ 350°C
  c_O = 10^{-7} mass%, excursion to 10^{-5} mass%
  v = 2(+/–0.2) m/s
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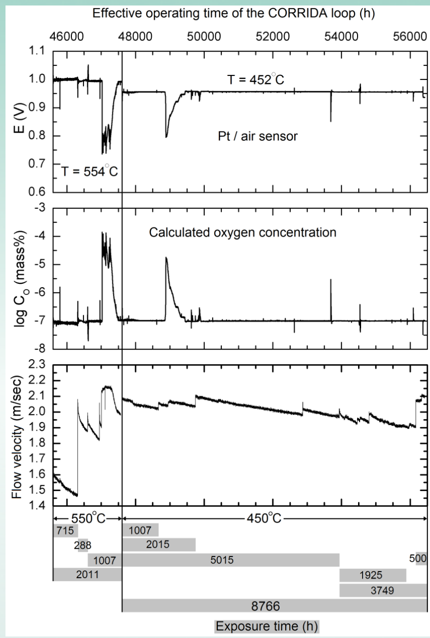

Flowing LBE at 550°C, 2 m/s and 10^{-7} mass% dissolved oxygen (nominal conditions)

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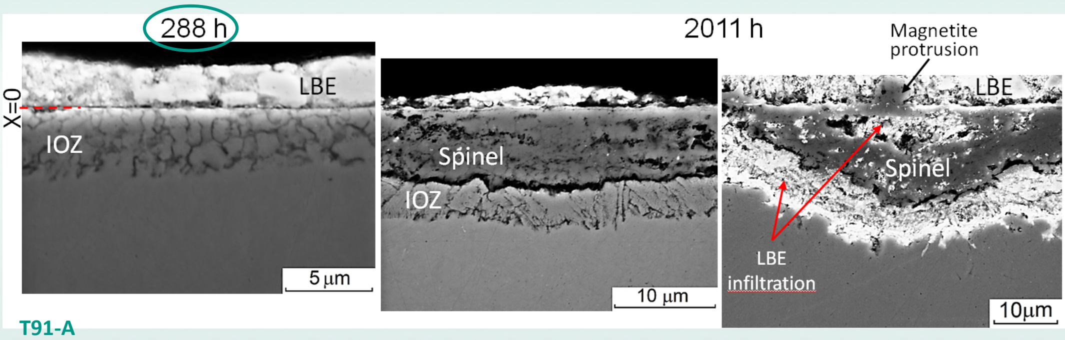
- **Accelerated oxidation**
  - Starts with internal oxidation
  - Fe-Cr spinel formation follows internal oxidation
  - Consumes outer part of the internal oxidation zone (IOZ) that may still grow at the IOZ/steel interface
  - General aspect of accelerated oxidation at 550°C, not only at low oxygen concentration of the LBE

- Outer magnetite layer is missing
- Some magnetite protrusions after excursion to higher c_O
- Corresponds to previous observations at 550°C/10^{-6} mass% O
- Fe dissolves at the spinel surface rather than forming magnetite



T91-A

Flowing LBE at 550°C, 2 m/s and 10^{-7} mass% dissolved oxygen (nominal conditions)

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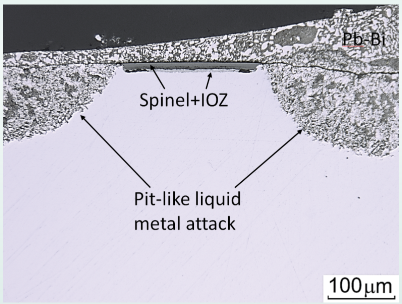
- **Solution-based corrosion**
  - Typically, affected site has pit-shape appearance
  - Non-selective dissolution of steel elements rather than selective leaching (Cr)
  - Either spinel layer or thin Cr-rich scale is present
  - Appears after failure of the thicker oxide scale formed after accelerated oxidation
  - Also, alternatively to accelerated oxidation after failure of the thin protective oxide



T91-A after exposure for 1007 h with temporary increase in c_O after ~450 h

17 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Flowing LBE at 450°C, 2 m/s and 10^{-7} mass% dissolved oxygen (nominal conditions)

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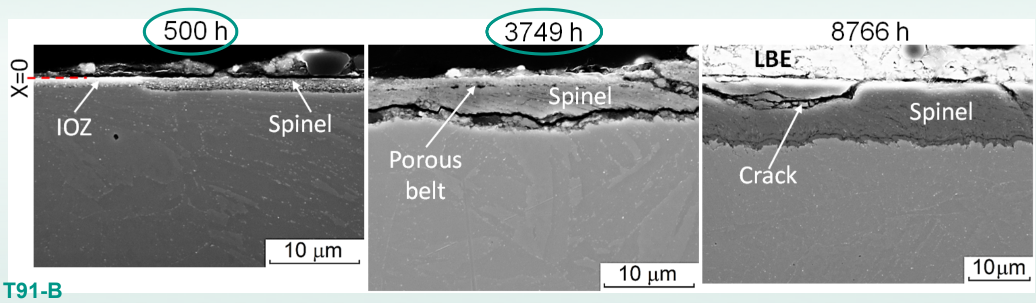
- **Accelerated oxidation**
  - Internal oxidation less pronounced, compared to 550°C
  - In general, only spinel layer observed
  - Pores in the outer part due to Fe diffusion towards the spinel surface
  - No magnetite at constantly 10^{-7} mass% O
  - Threshold oxygen concentration for magnetite formation between 10^{-7} and 10^{-6} mass% O at 450°C



T91-B

18 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Flowing LBE at 450°C, 2 m/s and 10^{-7} mass% dissolved oxygen (nominal conditions)

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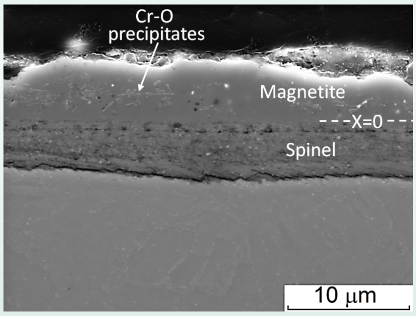
- **Magnetite formation**
  - Magnetite, in general, not present
  - Forms during temporary increase in oxygen concentration from 10^{-7} to ~10^{-5} mass%
  - Is not observed anymore some time after return to 10^{-7} mass% O
  - Metals in deposited magnetite may stem from simultaneously exposed specimens or tubing of the experimental facility



T91-B after exposure for 2015 h with intermittent increase in c_O after ~1200 h

19 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Flowing LBE at 450°C, 2 m/s and 10^{-7} mass% dissolved oxygen (nominal conditions)

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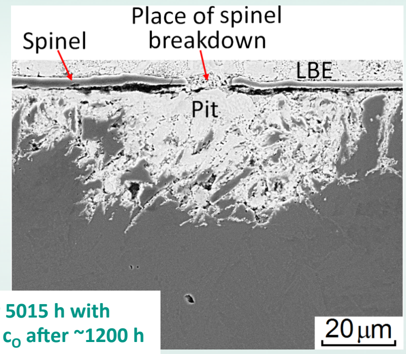
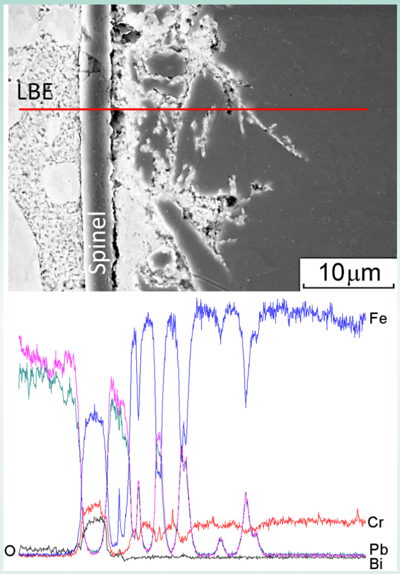
- **Solution-based attack**
  - Where spinel scale failed
  - Non-selective dissolution of steel elements





T91-A after exposure for 5015 h with intermittent increase in c_O after ~1200 h

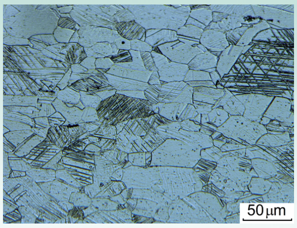
20 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Austenitic steels tested in the CORRIDA loop

Austenitic steels	Cr	Ni	Mo	Mn	Si	Cu	V	W	Al	Ti	C	N	P	S	B
316L	16.73	9.97	2.05	1.81	0.67	0.23	0.07	0.02	0.018	-	0.019	0.029	0.032	0.0035	-
1.4970	15.95	15.4	1.2	1.49	0.52	0.026	0.036	< 0.005	0.023	0.44	0.1	0.009	< 0.01	0.0036	< 0.01
1.4571	17.50	12	2.0	2.0	1.0	-	-	-	-	0.70	0.08	-	0.045	0.015	-

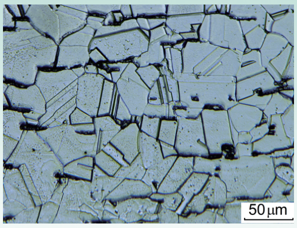
(Fe – Bal.)

1.4970 (15-15Ti)



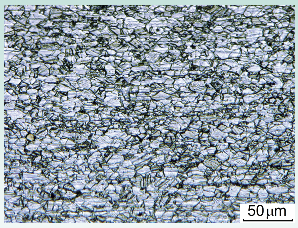
- HV_{30} = 253;
- Grain size ranged from 20 to 65 µm;
- Intersecting deformation twins.

316L



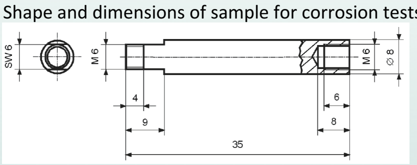
- HV_{30} = 132;
- Grain size averaged 50 µm (G 5.5);
- Annealing twins.

1.4571

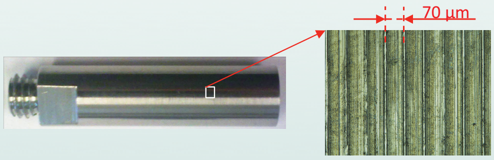


- HV_{30} = 245;
- Grain size averaged 15 µm (G 9.5).

Shape and dimensions of sample for corrosion tests



General view of initial sample after finishing turning

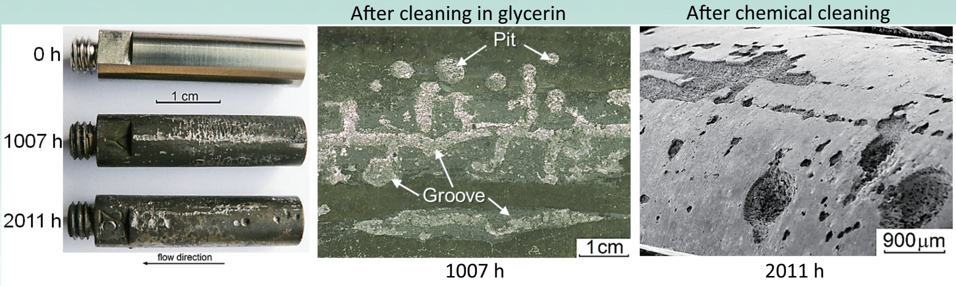


Qualification of corrosion modes on surface of austenitic steels after exposure to flowing LBE with 10^{-7} mass% O at 450 and 550°C

Surface examinations - general corrosion appearance

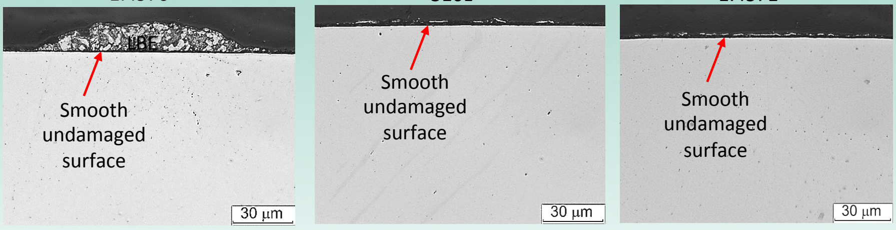
1.4970, 550°C

After cleaning in glycerin After chemical cleaning



- ❑ Oxidation – formation of golden-colored oxide film (shorter test) and green-colored oxide film (longer test)
- ❑ Light areas with exfoliated oxide film;
- ❑ Severe local solution-based corrosion attack in the form of hemispherical pits and longitudinal and transversal grooves;
- ❑ The surface area covered by the oxide film decreases with exposure time in LBE, while the number of sites affected by local corrosion attack respectively increases.

Cross-section appearance of austenitic steels after test in flowing oxygen-containing LBE (~ 2 m/s, ~ 10^{-7} mass % O) at 400°C for 4746 h.



- Smooth undamaged surface is observed on the cross-section of samples;
- Selective leaching attack is not detected under the given duration of test - 4746h;
- Samples revealed golden-colored oxide film - protective scaling;
- Corrosion tests are still continuing with expected max. duration about 10000h.

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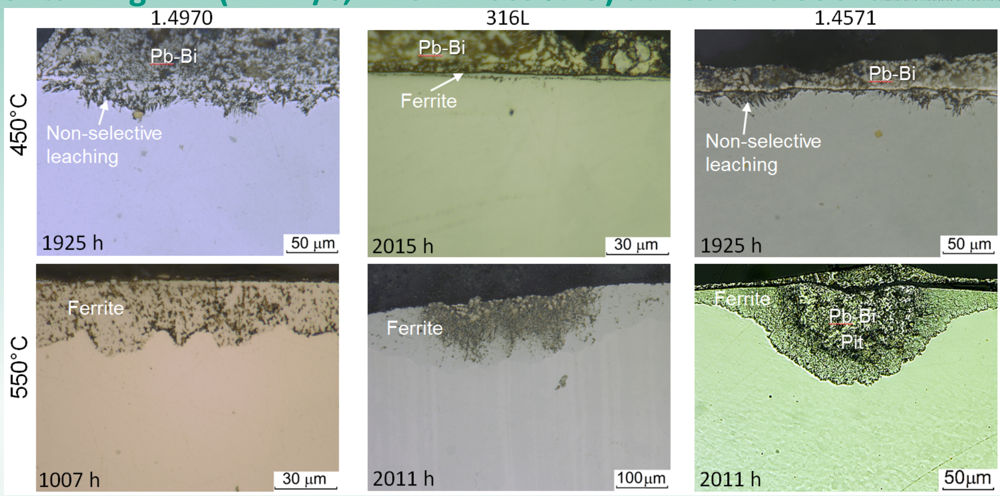
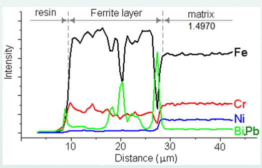
Cross-sections of austenitic steels in flowing oxygen-containing LBE (~ 2 m/s, ~ 10^{-7} mass % O) at 450 and 550°C



1.4970
550°C
2011 h



Steel	Ferrite layer composition (mass %)				
	Ni	Cr	Fe	Pb	Bi
1.4970	1.85	6.76	84.47	-	3.12
316L	1.10	8.13	86.48	-	1.95
1.4571	1.61	6.15	69.15	6.45	13.75

24 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

Local pit-type corrosion attack

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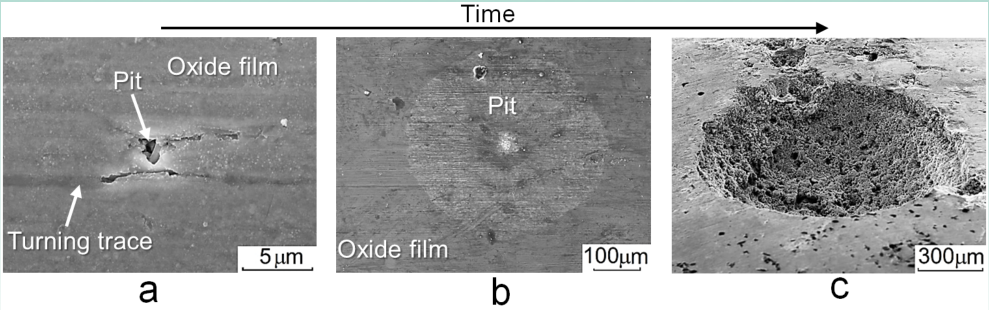
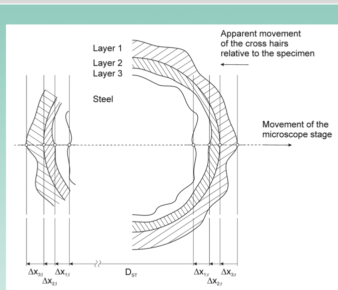
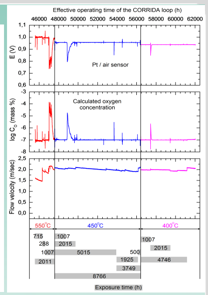
Expected sequence of evolution of corrosion pits wit time



Object analyzed	mass % O	Cr	Fe	Ni	Pb	Bi
Oxide film (a)	10.68	16.36	54.06	14.57	1.86	1.30
Oxide film (b)	7.21	16.08	63.17	10.23	2.21	-
Pit (b)	13.95	8.90	29.62	0.97	5.87	40.49

Percentage (%) of circumference affected by solution-based selective leaching attack that resulted in either formation of layer-type (L) or pit-type (P) damage





Surface appearance (%)	550°C 288h	715h	1007h	2011h	450°C 500h	1007h	1925h	2015h	3749h	5015h	8766h
1.4970											
Layer-type (L)	6	43	62	75	42		33		52	23	92
Pit-type (P)	5	-	35	16	9	*	46	*	44	11	8
(L + P)**	11	43	97	91	51		79		96	34	100
1.4571											
Layer-type (L)	4	46	68	42			17		100	4	98
Pit-type (P)	-	-	7	13		*	1	*	0	3	2
(L + P)**	4	46	75	55			18		100	7	100
316L											
Layer-type (L)	4	58	88	82					100	8	92
Pit-type (P)	4	-	8	9		*		*	0	7	8
(L + P)**	8	58	96	91					100	15	100

* - smooth surface covered by thin (~ 0.5 µm) protective Cr-based oxide film

** - L + P = selective leaching attack + protective scaling = 100%

- ❑ The percentage of surface affected by selective leaching attack increases with time.

Overview of quantification of corrosion attack at 450 and 550°C in LBE with 10^{-7} mass% O

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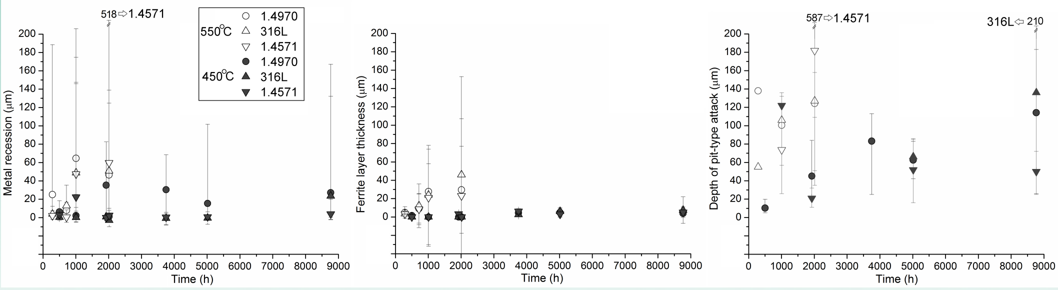
Average corrosion loss of steels, expectedly, increase with rise in test temperature from 450 to 550°C



450°C:

- ❑ Metal recession (change in diameter) does not exceed 4, 27, and 26 µm after 8,766 h for 1.4571, 1.4970 and 316L steels, respectively;
- ❑ Thickness of layer-type attack (ferrite) averaged 5, 7 and 4 µm after 8,766 h for 1.4571, 1.4970 and 316L steels, respectively;
- ❑ Depth of pit-type attack average 50, 114 and 136 µm correspondingly. The percentage of circumference affected by selective leaching increases with time and after 8,766 h reached 100 %.

550°C:

- ❑ Metal recession averaged ~ 60, 46 and 51 µm after 2011 h for 1.4571, 1.4970 and 316L steels, respectively;
- ❑ Layer-type attack averaged 23, 30 and 46 µm;
- ❑ Depth of pit-type attack averaged 182, 124 and 127 µm.

Maximum depth of solution based attack, seems to most adequately reflect corrosion losses of austenitic steels and therefore could be used as parameter for evaluation of corrosion rates using linear kinetics!

Corrosion behaviour of austenitic steels at 400, 450 and 550°C in flowing LBE (~ 2 m/s) with 10^{-7} mass% dissolved oxygen.

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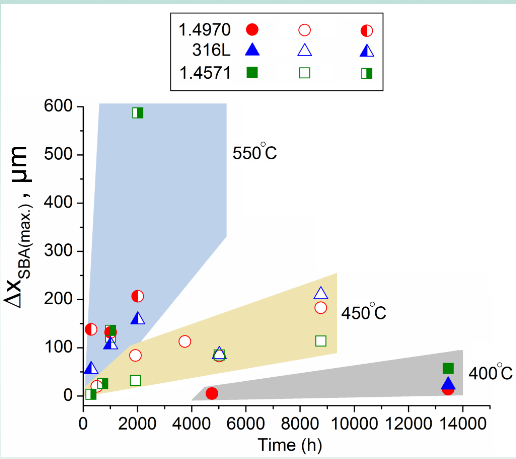
Maximum depth of solution-based corrosion attack observed (ΔXSBA(max))



Observed corrosion phenomena at:

450 and 550°C:

- ✓ Oxidation – thin Cr-based oxide film;
- ✓ Solution-based corrosion attack – ferrite layer;

In-situ formed oxide film is not a sufficient protective barrier against solution-based corrosion attack at 450 and 550°C.

400°C:

- ✓ Oxidation – thin Cr-based oxide film;
- ✓ Rare local pit-type solution-based corrosion attack;
- ✓ In-situ formed oxide film protects steels against solution-based attack at 400°C.

Maximum corrosion loss:

- ✓ 400°C: 15-60 µm after ~13000 h;
- ✓ 450°C: 120-220 µm after ~9000 h;
- ✓ 550°C: 150-600 µm after ~2000 h.

Incubation time required for initiation of solution-based attack decreases with increasing temperature from about 4500 h at 400°C to ~500 – 4000 h at 450°C and to ≤ 200 h at 550°C.

Corrosion rates of 1.4970, 316L and 1.4571 at 10^{-7} mass% oxygen at 400, 450 and 550°C

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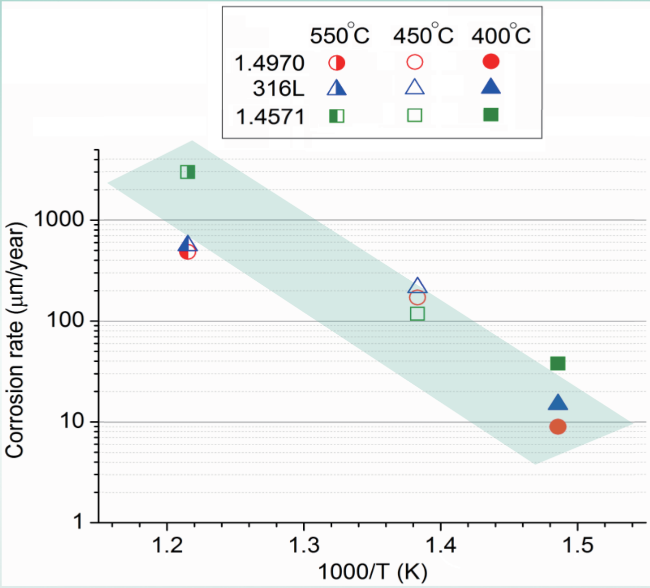

Comparison of results at 10^{-7} and 10^{-6} mass% O (CORRIDA experiments)

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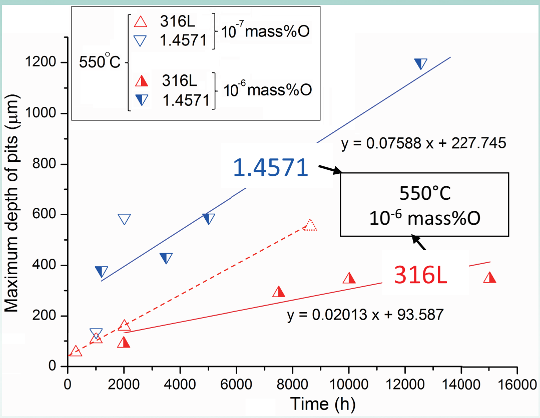

Maximum depth of pit-type corrosion attack on austenitic steels tested in flowing LBE (~ 2 m/s) depending on temperature and oxygen concentration in the melt.

- 10^{-6} mass% O – preferential oxidation (spinel formation);
- 10^{-7} mass% O – preferential solution-based selective leaching of steel constituents (Ni, Cr);
- At both concentrations the **local solution-based attack - critical factor** affecting corrosion resistance of austenitic steels in LBE;
- Incubation time for initiation of dissolution attack decreases with decreasing oxygen concentration in LBE from 10^{-7} to 10^{-6} mass%O;
- Under the similar test conditions, the finer the grain size (1.4571: 15 µm blue markers) the deeper the corrosion attack (316L: 50 µm red markers).

Possible effect of Ti(C,N) precipitation and Cr-rich lamellae on the preferential initiation and propagation of solution-based attack

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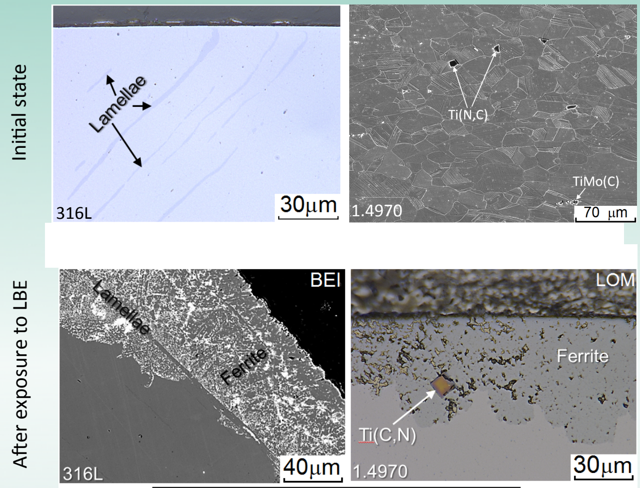

Object analyzed	mass%			
	Cr	Fe	Ni	Bi
Lamellae	18.45	70.73	3.36	-
Ferrite	6.52	68.68	1.55	17.15

- Ti(C,N) precipitation in composition of 1.4970 and 1.4571
- Cr-rich lamellae (Fe-20%Cr-4%Ni) in composition of 316L (Fe-16%Cr-10%Ni)

- Ti(C,N) precipitation and Cr-rich lamellae are corrosion resistant to LBE with 10^{-7}mass%O

Conclusions (FM-steels)

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- **400°C/ 10^{-7} mass% oxygen**
  - Primarily corrosion process is accelerated oxidation (AO)
  - Flawed and partially detached oxide scale
  - Solution-based corrosion (SB) observed locally after 4766 h
- **450 and 550°C/ 10^{-7} mass% oxygen**
  - Protective scaling locally still evident, especially after shorter exposure time
  - Dominant is AO (spinel formation)
  - Possible incipient stages of SB after 500, clearly observed after 5000 h at 450°C
  - At 550°C, incubation time of SB between ~300 and 700 h
  - ~50 µm maximum SB after 5000 h at 450°C, exceptionally severe attack observed on T91-B (950 µm) after 8766 h
  - Maximum 190 µm after 1000 h at 550°C

Conclusions (Austenitic steels)

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- Interaction of austenitic steels with flowing was accompanied by **oxidation** (400, 450 and 550°C) and **solution-based liquid-metal attack** (450 and 550°C), resulted in **selective leaching of Ni and Cr** with subsequent development of ferrite zone penetrated by LBE:
  - **400°C: oxidation –** thin Cr-based oxide film (**protective scaling)**
  - **450°C: oxidation –** thin (≤ 0.5 µm) Cr-based oxide film

    solution-based selective leaching with maximum depth of local attack 114µm (1.4571), 183µm (1.4970) and 210µm (316L) for 8766h
  - **550°C: oxidation –** thin (≤ 0.5 µm) Cr-based oxide film

    solution-based selective leaching with maximum depth of local attack 587µm (1.4571), 207µm (1.4970) and 158µm (316L) for 2011 h
- **Cr-based oxide films, formed *in-situ* on the surface of austenitic steels, are not sufficient protective barriers with respect to selective leaching, at least at 450 and 550°C in LBE with 10^{-7} mass% O!**
- In LBE with **10^{-7} mass% O, selective leaching** is the main corrosion mechanism of austenitic steels causing substantial corrosion loss, while in LBE with **10^{-6} mass% O, oxidation is dominating!!**

33 Asian ADS Topical Meeting for LBE Applications, J-PARC Center, Tokai, Ibaraki, Japan, October 26-27, 2015 Jürgen Konys

3. Activities in China

3.1 Development of LBE Technology and Related Facilities in China

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Design and R&D Activities of China LEAd-based Research Reactor CLEAR-I

Yican Wu, FDS Team

Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology

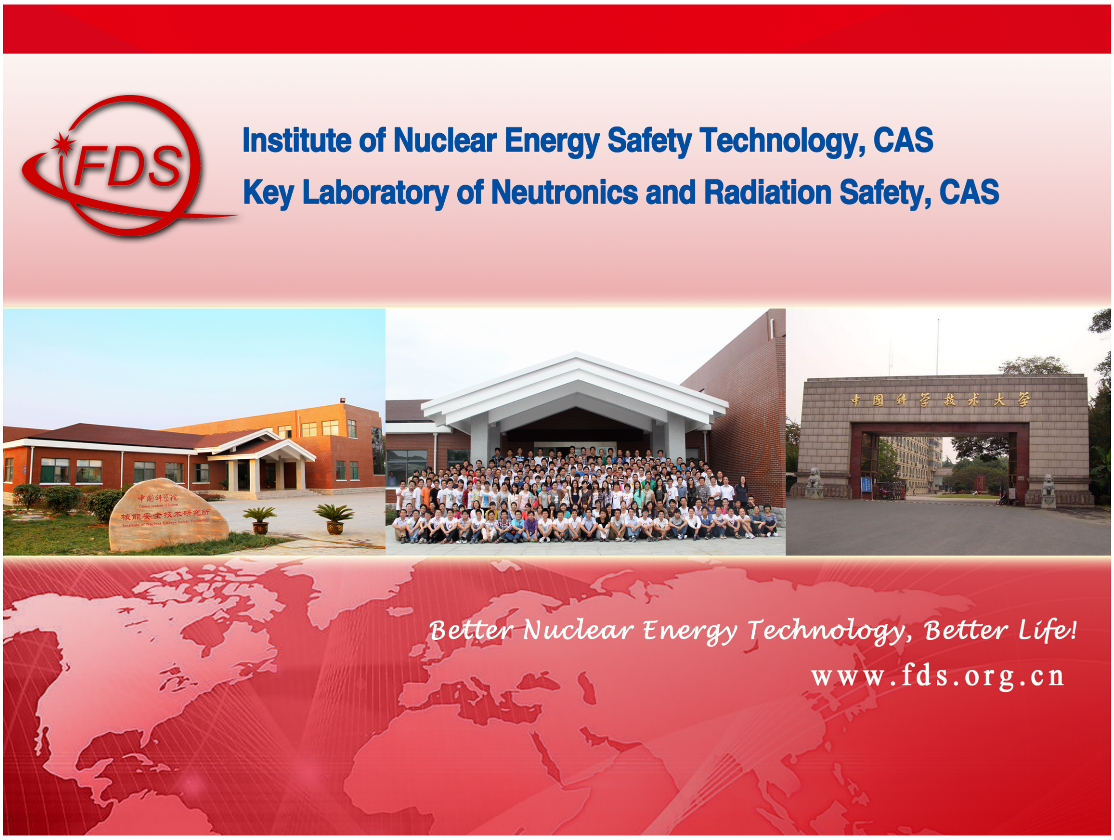
Chinese Academy of Sciences, Hefei, Anhui, 230031, China

The strategic Priority Research Program “Advanced Nuclear Fission Energy-ADS Transmutation System” had been launched by Chinese Academy of Sciences since 2011. China LEAd-based Reactor (CLEAR) was selected as the reference reactor for the ADS program, which is being performed by Institute of Nuclear Energy Safety Technology (INEST/FDS Team), Chinese Academy of Sciences. The objective of subcritical and critical dual-mode operation capability for validation of ADS transmutation system and lead cooled fast reactor (LFR) technology, and also can be used as a fundamental sciences and neutron irradiation research facility.

CLEAR-I design is based on the principles of safety reliability, experiment flexibility and technology feasibility, in which the mature fuel and materials are adopted. The conceptual design has already finished, and the engineering design is underway. The design basis and beyond design basis accidents analysis indicated that the reactor has good safety advantages with negative coefficient of reactivity feedback, large thermal inertia and the passive decay heat removal capability.

To support the design and construction of CLEAR, large lead-bismuth experiment loops, key technologies and components R&D activities are being performed. KYLIN series Lead-Bismuth experimental loops have been developed and built to carry out structure material corrosion experiments, thermal-hydraulics test and safety experiments. The key components including the control rod drive mechanism, refueling system, fuel assembly, and simulator have been fabricated and tested. In order to validate and test the lead-based reactor key components and integrated operation technology, the lead alloy cooled non-clear reactor CLEAR-S, the lead-based zero power nuclear reactor CLEAR-0 and the lead-based virtual reactor CLEAR-V are being constructed.

Keywords: lead-based research reactor, ADS, CLEAR, R&D



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Development of LBE technology and related facilities in China

Presented by Sheng Gao

Contributed by FDS Team

Institute of Nuclear Energy Safety Technology (INEST)
Chinese Academy of Sciences

Contents

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China's Plan on Nuclear Energy
(Plan up to 2020)

- **Nuclear power plant in China（By August, 2015）**
  - *25 reactors (~ 23GWe) in operation*
  - *26 reactors (~28GWe) under construction*
- **National plan of developing nuclear energy before 2020**
  - ***58 GWe in operation***
  - ***30 GWe under construction***
- **National plan for nuclear and radiation safety before 2020**
  - *More R&D are required to enhance nuclear safety, especially in the basic research of nuclear safety*
  - ***~79.8 billion RMB investment plan (~13.3 billion US dollars)***

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China's Nuclear Power Requirements and Issues
(Prediction up to 2050)

Scenario	Ratio A	Ratio B	Nucl. Power	Capacity (Approximate Scale)
Low Level	10%	6%	120GW	Double in France
Mid. Level	20%	12%	240GW	Sum in US, France and RF
High Level	30%	18%	360GW	Sum all over the world

- A: fraction of nucl. power in total electricity capacity
- B: fraction of nucl. power in total primary energy capacity

Nuclear fuel supply ?
Radioactive waste disposal ?
Safety problem ?

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Nuclear Waste Disposal Strategy

- **Report of ADS (Accelerator Driven-subcritical System) and Fast Reactor in Advanced Nuclear Fuel Cycles from** OECD/NEA
  - **ADSs are better at burning waste than fast reactors**
  - **ADSs employing a fast neutron spectrum and solid, fertile-free fuel with the primary mission of transmuting transuranics or minor actinides**
  - **ADS could support more PWR waste transmutation**
- **The strategy of sustainable fission energy in China were suggested by Chinese Experts of Academician**
  - The Fast Reactor is better used for Nuclear fuel breeding and the ADS is better used for transmutation

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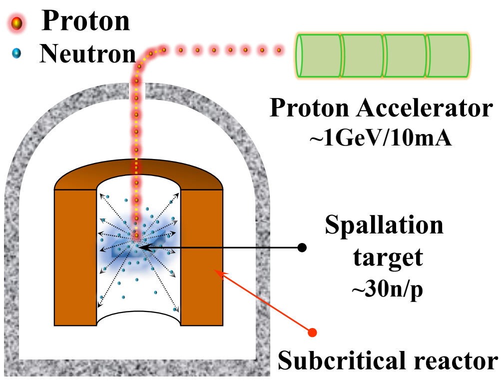
Accelerator Driven-subcritical System (ADS)



Main function:
- **Waste transmutation:**
  n + MA/FP ➔ less-harmful nucleus
- **Fuel breeding:**
  n + U^{238}/Th^{232} ➔ Fissile
- **Energy production:**
  n + U/Pu/MA ➔ Energy

Reactor technical Challenge:
- **High energy neutron:** Fast Spectrum
- **High Power Density:** Liquid metal coolant

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Fast Reactor Coolants Comparison

Coolant	Advantage	Disadvantage
Sodium	• Low cost industrial fluid • Transparent to neutrons • Low melting point, Low viscosity • **High thermal conductivity** • **Compatible with steel**	• Opaque • **Low boiling Point** • **Reactive with water and air**
Lead-based coolant	• Good heat transfer • Transparent to neutrons • **No reactive with water and air** • **High boiling point**	• Opaque • Toxic • Solid up in low temperature • **Very high density** • **Corrosion in high temperature**
Helium	• Transparent, Chemically inert • No temperature constraints • No Phase changes	• Low density • **Low thermal conductivity** • **High pressure**

Lead-based coolant has unique characteristics for fast reactor and hybrid systems.

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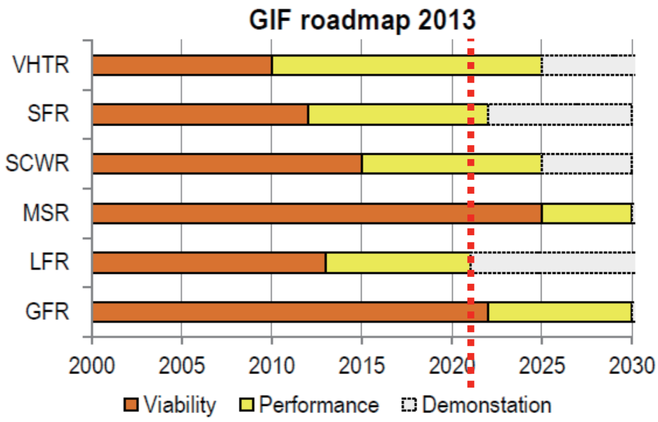
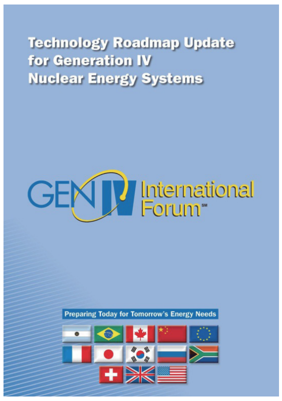
Latest Roadmap of Generation IV Reactors

—— GIF organization evaluated in 2014





LFR is expected to be the first Generation-IV nuclear system to achieve industry demonstration and commercial application.

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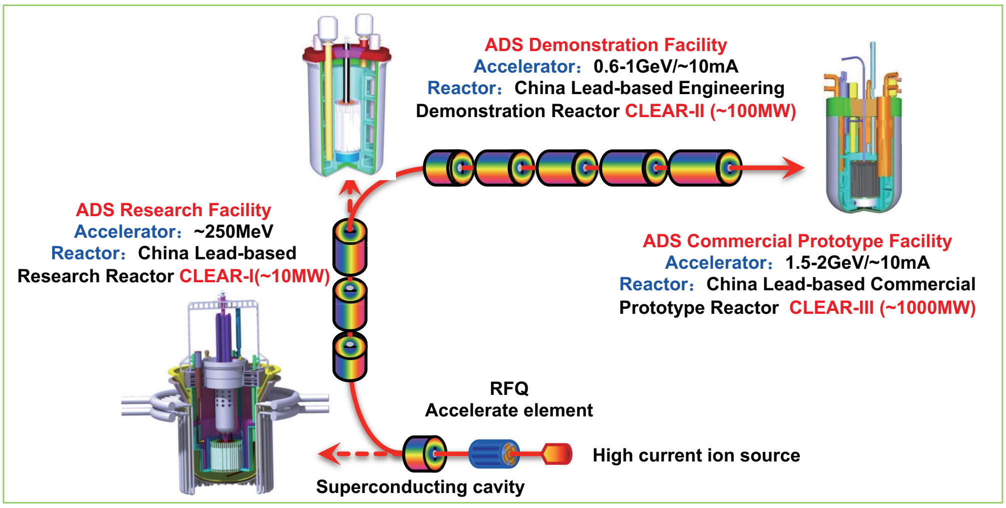
China Lead-based Reactor Development Plan

- Chinese Academy of Sciences (CAS) has launched the ADS Project, and plan to construct demonstration ADS transmutation system ~ 2030s through three stages.
- China LEAd-based Reactor (CLEAR) is selected as the reference reactor for ADS project and for Lead cooled Fast Reactor (LFR) technology development.



Contents

I. Introduction

II. Research Progress

1. Reactor Design
2. Key Technology R&D
3. Safety Assessment

III. Development Prospects

IV. Summary

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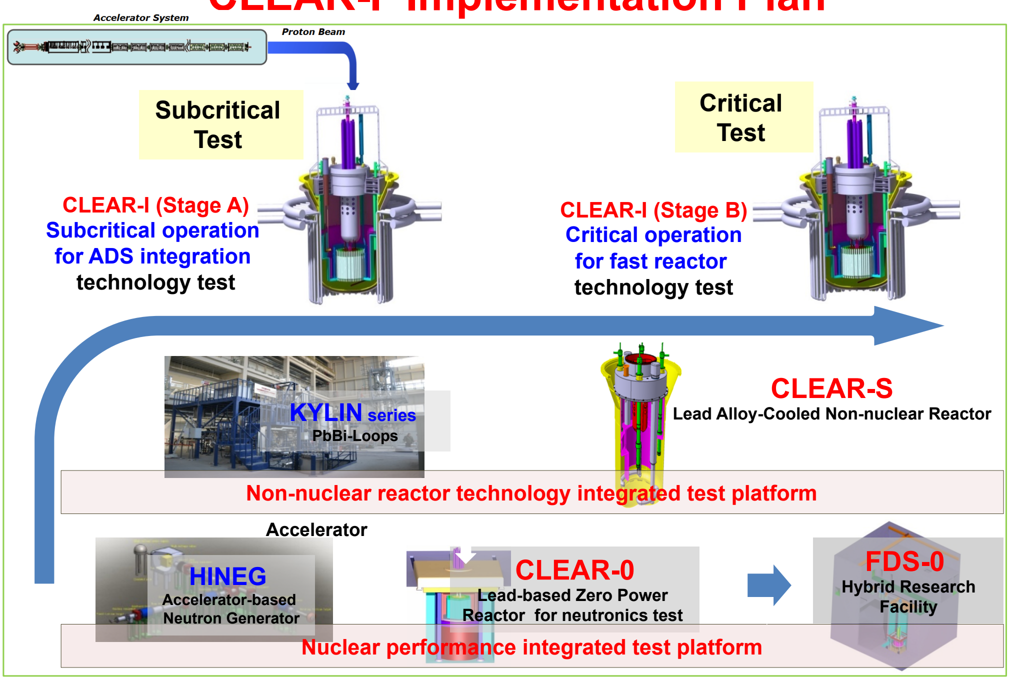
CLEAR-I Implementation Plan



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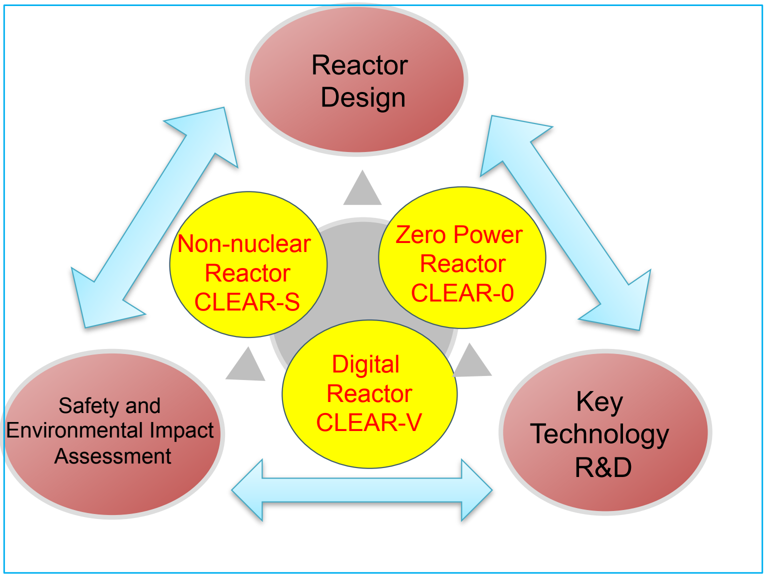
Development Strategies for CLEAR Reactor



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Current Status of CLEAR-I Project

- **Reactor Design**
  - **2011：Conceptual Design**
  - **2012：Detailed Conceptual Design**
  - **2015：Preliminary Engineering Design**
- **Technical R&D**
  - **2011：PbBi Loop and Components Conceptual Design**
  - **2013：PbBi Loop Construction and Components Fabrication**
  - **2014：Thermal-hydraulic and material test and design of integrated test platform**
  - **2015：Lead alloy cooled non-nuclear reactor CLEAR-S Design and Construction**
- **Safety Analysis**
  - **2011：Safety characteristics evaluation and software development**
  - **2012-2015：Software V&V, Accident and Environmental Impact Analysis**

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CLEAR-I Design Objective and Principle

Design Objectives

- ADS and Lead cooled Fast Reactor technology validation platform
  - Neutronics; Thermal hydraulics; Safety characteristics
  - Key components R&D and measurement control technology
- Fundamental science and neutron irradiation research platform
  - Fuel and material irradiation
  - Isotope production and nuclear technology training

Design Principles

- Feasible technology
  - Mature material and fuel; Low power; Pool type vessel
- Reliable safety
  - Natural circulation; Passive decay heat removal system
- Capability of flexible experiment
  - Dual mode operation; Remote handling refueling system
- Technical continuity
  - MOX fuel, Minor actinides transmutation fuel…

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CLEAR-I Main Design Parameters

Parameter		Values
Core	Thermal power (MW)	10
	Activity height (m) Activity diameter (m) Fuel (enrichment)	0.8 1.05 UO_2(19.75%) at first
Cooling System	Primary coolant Inlet/Outlet temperature (℃) Primary coolant mass flow rate (kg/s) Coolant drive type Heat exchanger Second coolant Heat sink	LBE ~300/385 529.5 Forced Circulation 4 Water Air cooler
Material	Cladding Structure	15-15Ti/316Ti 316L

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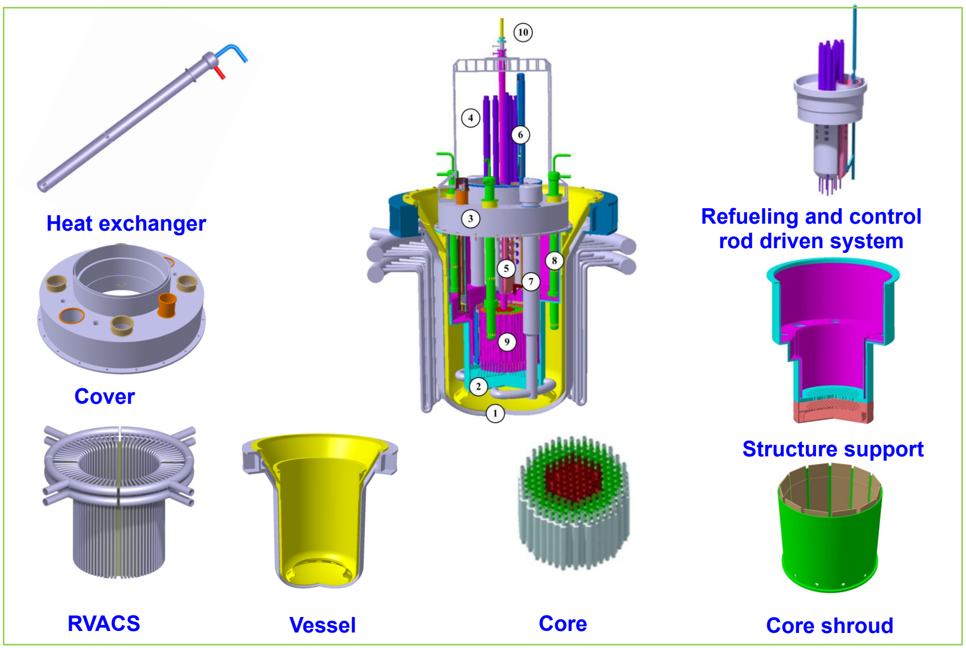
Overview of CLEAR-I Structure



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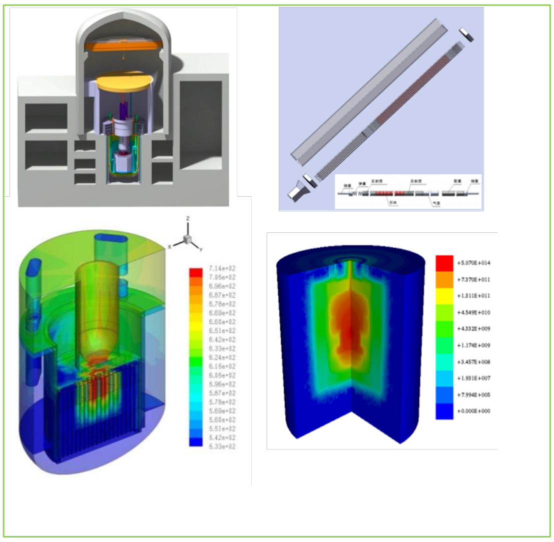
CLEAR-I System Design Status

- The detailed conceptual design has been done (more than 20 Systems)
- Preliminary engineering design is underway

1. Nuclear Design
2. Thermo-hydraulic Design
3. Coolant System
4. Reactor Structure
5. Reactivity Control System
6. Refueling System
7. LBE Process System
8. Fuel Assembly
9. Safety System
10. I&C System
11. Application System
12. Radiation Protection System
13. Auxiliary System
14. …



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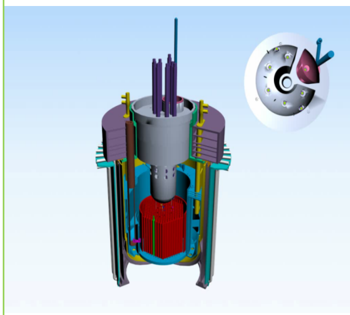
Design Features: Multi-functions

- **Dual-mode operation**
  - Critical for LFR technology test
  - Subcritical for ADS technology test
- **Innovation refueling system for ADS**
  - Dual-rotating plug
  - Split type central measure post
- **Flexibility experiment**
  - Different criticality (deep subcritical to critical)
  - Different fuel type(UO_2/MOX/MA…)
  - Irradiation platform for fundamental sciences



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Design Features: Inherent Safety

- **Lead-based coolant safety advantages**
  - Chemical inertial, low operation pressure, high boiling temperature, etc.
- **Large thermal inertia**
  - Large coolant inventory to power ratio (~700t / 10MW)
- **Passive safety**
  - Primary coolant: natural circulation
  - Passive decay heat removal: RVACS
- **Low erosion-corrosion effect**
  - Low velocity (<1m/s in core)
  - Low operation temperature (300°C-400°C)
- **Others**
  - Negative reactivity feedback
  - Subcritical operation

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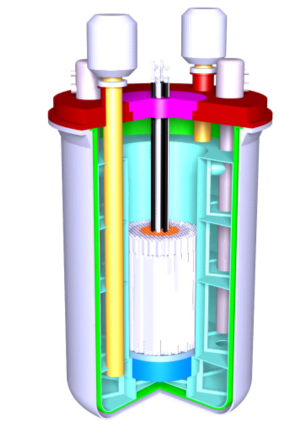
CLEAR-II: Lead-based Experimental Reactor

- A test platform for ADS integral test and materials experiment, fuel test.
- High neutrom flux test reactor for ADS DEMO and fusion reactor materials

Design objective	Engineering validation
Accelerator power	0.6-1GeV/~10mA)
Keff	~0.98
Thermal power	~100MW
Spallation target	Windowless or window Pb-Bi Target
Fuel	MOX
Coolant	Liquid Pb-Bi/Pb



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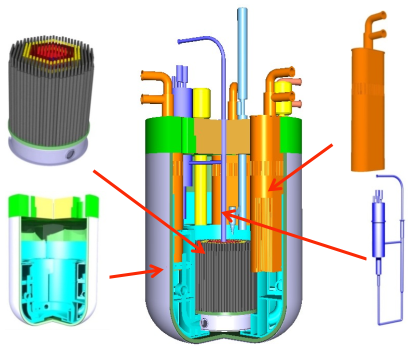
CLEAR-III: Lead-based Demonstration Reactor

- To demostrate the nuclear waste transmutation technology using ADS

Design objective	Waste transmutation
Accelerator power	15MW (1.5GeV/~10mA)
K_{eff}	~0.98
Thermal power	~1000 MW
Spallation target	Windowless Pb-Bi Target
Fuel	TRU+Zr
MA Transmutation	400kg/y
Coolant	Liquid Pb-Bi



Contents

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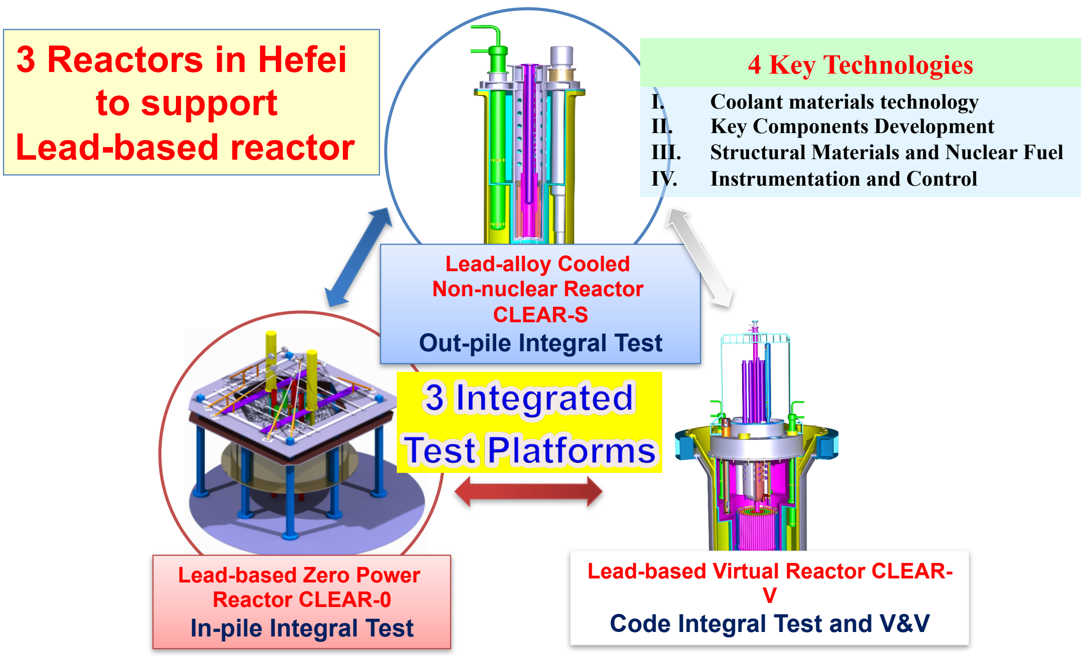
Key Technology for Lead-based Reactor



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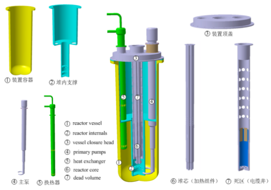
Lead Alloy Cooled Non-nuclear Reactor (CLEAR-S)

Materials and LBE technology test loop KYLIN-I (2010, in operation)

Reactor key technology validation loop KYLIN-II (2010-2013, in operation)

Key component integral test platform (2014-2016, under construction)



Thermal convection loop KYLIN-I
Forced convection loop PREKY
Static/Rotating device KYLIN-RT/ST

Multi-function LBE loop KYLIN-II
–Corrosion loop
–Thermal-hydraulic loop
–Safety loop

Lead Alloy Cooled Non-nuclear Reactor CLEAR-S

- Loop design, construction and control
- Loop Circulation and measurement
- LBE technology (Oxygen control)
- Material corrosion R&D

- Material and components validation
- Natural /Forced/ Mixed circulation
- Fuel assembly testing
- Safety accident research (SGTR. etc.)

- Reactor Integral Circulation testing
- Reactor Integral safety testing
- Reactor components validation
- Reactor operation and measurement

Series PbBi loops were built to develop the LBE technology and support the design and construction of CLEAR.

Key Technology R&D

- LBE facilities and experiments
  - ✓ Materials and LBE technology facilities and test
  - ✓ Reactor key technology validation loops and test
  - ✓ Lead-based cooled non-nuclear reactor
- Key technology R&D for reactor

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Materials and LBE technology test facilities

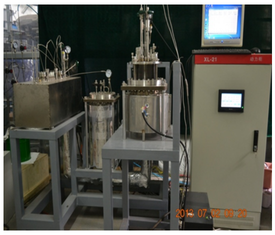
❑ Objectives

- Key technologies of large-scale loops
- Corrosion mechanisms and components of flow measurement and control
- Oxygen control and purification technologies

❑ Development Course

- 2010：the first thermal convention corrosion loop
- 2011：Pre-research loop for measurement and control of liquid metal, development of mechanical pump and electromagnetic pump
- 2012：Oxygen control system and oxygen sensors, small-scale corrosion device with OCS


Thermal convention corrosion loop


Corrosion device with OCS


Pre-research loop for measurement and control of liquid metal

Key Technology R&D

- LBE facilities and experiments
  - ✓ Materials and LBE technology facilities and test
  - ✓ Reactor key technology validation loops and test
  - ✓ Lead-based cooled non-nuclear reactor
- Key technology R&D for reactor

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Reactor key technology validation loop KYLIN-II

❖ Main functions

- **Materials corrosion and LBE chemical control**
  - Corrosion of structural materials
  - OCS, purification, etc.
- **Thermal-hydraulic Behavior of HLM**
  - Natural/Forced/Mixed circulation
  - Fuel Bundle test
  - CFD and System Code validation
- Reactor Typical/Severe Accident Test

KYLIN-II loop

❖ Typical parameters

- **Temperature: 550°C, 1100°C(Max.)**
- **Mass flow rate: 50m^3/h**
- **Total power: ~2MW**
- **Inventory of PbBi: ~20t**

KYLIN-II Materials test loop

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KYLIN-II Materials test loop

❖ Main functions:

- Corrosion of structural materials
- LBE conditioning technology (Oxygen, etc.)
- Key components development testing
- Instrumentation technology

❖ Main parameters:

- Operating temperature : 350 ~550℃
- Flow velocity: 0~3m/s
- Oxygen concentration: 10^{-9}~10^{-6}wt%
- PbBi inventory: ~3t

KYLIN-II Materials test loop

31

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KYLIN-II Ultra-high Temperature Materials Corrosion Loop

❖ Main functions:

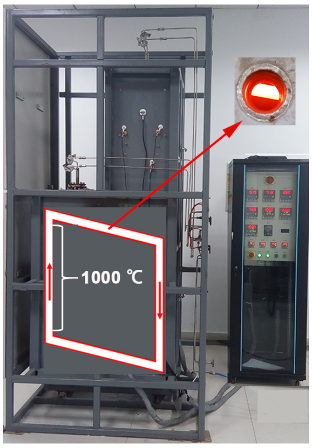
- Corrosion test under extreme accidents
- Development of Structural material potential used at ultra-high temperature

❖ Main parameters:

- Maximum operating temperature : > 1000 ℃
- Flow velocity: 0.1 m/s
- Structural material: high purity quartz tube

❖ Key issues:

- Selection and development of structural material
- High density heating technology
- Sealing technology and in-situ sampling



KYLIN-II –UM- loop

KYLIN-II (UM) thermal-convection loop has been operated at 1000 ℃ and can be used to investigate the potential of the LBE operated at evaluated temperature.

32

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Facilities for Mechanical Tests in LBE

❑ Objectives

→ Explore mechanisms of LME, SCC sensitivity
→ Fatigue, Creep, Tensile properties test in LBE with oxygen control

SSRT facility

Stress corrosion facility

❑ Design Parameters

→ Temperature up to 600℃
→ Static LBE
→ Gas phase oxygen control

2012-2014

Creep facility

Fatigue facility

Most of the Facilities have been built till to 2014. Fracture toughness facility will also been designed and constructed next year

KYLIN-II Thermal-hydraulic test loops

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KYLIN-II TH FC: Forced Circulation Loop

Design objectives

- Characteristics of heat transfer in 7 pin assembly bundle
- Flow resistance on full scale fuel assembly simulator of CLEAR-I
- Heat transfer capability of heat exchange and heat transfer coefficients
- Pressure drop measurement of key components
- Chemical control performance under forced circulation

Main parameters

- Temperature : 500℃
- Material : 316L
- Main pipe : Φ 76x5mm
- Flowing rate (mechanical pump) : 50m^3/h
- Thermal power : 80 kW
- Secondary loop : Pressured water
- Max. Pressure : 10MPa

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KYLIN-II TH NC: Natural Circulation Loop

Design objectives

- Natural circulation characteristic
- Gas-lift enhanced natural circulation
- LBE heat transfer characteristic
- Validation of CFD and RELAP code

Major parameters

- Temperature : 200~500℃
- Circulaition height : 6m
- Max flowing rate : 0. 5 m^3/h (NC) ; :1. 5 m^3/h (Gas-lift)
- Heat pin power : 0~24kW
- Length of HS: 1800mm
- Max temperature difference: 150℃
- Maximum wall heat flux: 43.4 W/cm^2

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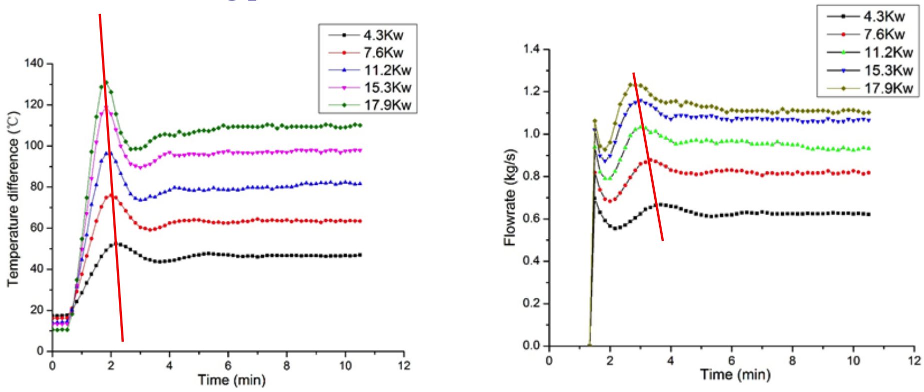
Natural Circulation Tests

The temperature differences and the LBE mass flow rate with different heating powers



- The natural circulation can be easily established and stabilized in a few minutes.
- The higher input power, the higher temperature peak and the less time for steady NC needed to stabilize.

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KYLIN-II TH MC: Mixed Circulation Loop

Design objectives

- Thermal-hydraulics characterization of natural and forced circulation under steady and transient condition
- Heat transfer, pressure drop, cladding temperature on fuel pin assembly
- Overall heat transfer coefficients and efficiency of heat exchanger
- Code development and validation
- Gas injection enhanced circulation research
- Gas phase oxygen control, filtering and getter

Main parameters

- Temperature : 500℃
- Design pressure : 1.2MPa
- Velocity : 2m/s (FC) , 0.15m/s(NC), 0.5m/s(GEC)
- Thermal power /heat exchange : 300kW
- Second side : Pressured water
- Pressure : 10MPa

KYLIN-II Safety test loop

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KYLIN-II Safety Test loop

❖ Experimental Functions:

- Vapor explosion of PbBi contacting with water
- Steam bubble transportation monitoring
- Heat-exchanger manufacture technique validation

❖ Main parameters:

- Temperature : 200~550℃
- Pressure of water: ~25MPa
- PbBi inventory: ~3t

❖ Key issues:

- Innovation heat-exchanger development and testing
- Shock pressure measurement and evaluation
- LBE two-phase inspection and monitoring

The construction has been finished and the experimental verification for accident evaluation test will be performed in this year.

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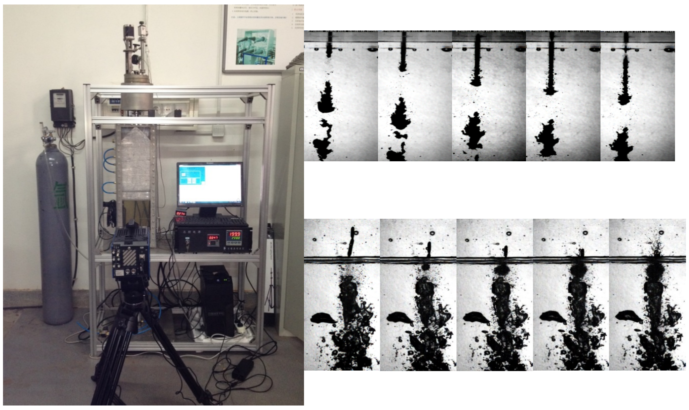
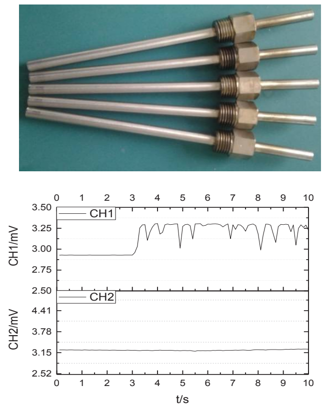
Mechanism investigation of LBE with water for SGTR



Steam explosion facility and LBE-water interaction photos



Void fraction probe

LBE/water interaction experiment to simulate SGTR accident for reactor, No steam explosion was observed. Further work focus on the code-code benchmark.

Key Technology R&D

- **LBE facilities and experiments**
  - ✓ **Materials and LBE technology facilities and test**
  - ✓ **Reactor key technology validation loops and test**
  - ✓ **Lead-based cooled non-nuclear reactor**
- **Key technology R&D for reactor**

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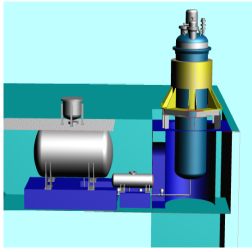
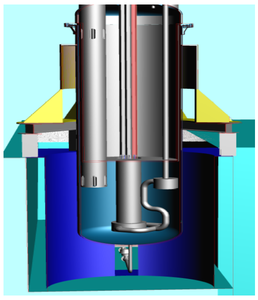
Lead-based Cooled Non-nuclear Reactor CLEAR-S

Functions

- **Reactor prototype components validation**
  - **Pump, HX, DHR…;**
  - **Refueling machine, Control rod driven system.**
- **Pool thermal-hydraulic integral test**
  - **Integral circulation test in pool type facility;**
  - **Code V&V (RELAP, CFD, etc.).**
- **Large scale SGTR (interaction of HLM with water)**





Parameters

- **Dimensions: 1:1 height, 1:2.5 diameter to CLEAR-I**
- **Temperature: 250°C~550°C**
- **Thermal power: 2.5MW (7 full scale fuel bundles)**
- **Mass flow rate: 100m³/h**
- **Inventory : 200 tons**

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Design Parameters for CLEAR-S

	Item	Value
LBE	Temperature	300/550 ℃
	Volume	204 ton
Fuel Assembly	Power	2.5 MW
	Number	7 (full scale FPs)
Main Vessel	Diameter	2000 mm
	Height,	6500 mm
Heat Exchanger	Structure	Double wall
	Power	2.5MW
Main Pump	Mass flow	100m³/h
	Head	0.4 MPa
DHR		0.175 MW
Secondary Loop	Coolant	Pressured water
	Pressure	10 MPa

Key Technology R&D

- LBE facilities and experiments
  - ✓ Materials and LBE technology facilities and test
  - ✓ Reactor key technology validation loops and test
  - ✓ Lead-based cooled non-nuclear reactor
- Key technology R&D for reactor

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Key Technologies I: Coolant Materials Technology

◆ Preparation of lead alloy

- ✓ 12.5 tons of high purity ingots
- ✓ Homogeneous
- ✓ Purity：99.9999%

PbBi ingots（12 tons）

Industrial scale of high purity LBE has been prepared.

◆ Oxygen measurement and control

- ✓ Pt/air and Bi/Bi_2O_3 developed by INEST
- ✓ Gas phase control and solid phase control technology

Oxygen control system has been operated for more than 5000hrs.

Oxygen measurement and control

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Oxygen measurement and control

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Key Technologies II: Key Components Development

◆ Pumping technology

- ✓ EMP ($5m^3/h$, 0.75MPa) has been operated for more than 5000hrs
- ✓ Mechanical pump ($50m^3/h$, 2MPa) with anti-corrosion coating has been developed
- ✓ Gas lift technology

Mechanical pump

EMP

◆ Heat exchanger technology

- ✓ Double wall HX
- ✓ Heat-exchanger for LBE with different coolant materials (air, oil, etc.)

Double wall heat-exchanger

LBE-LBE HX

Different types of pump and heat-exchanger have been developed.

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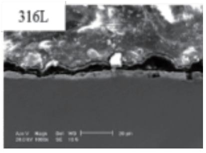
Key Technologies III: Structural Materials and Nuclear Fuel

◆ R&D of nuclear-class structural materials

- ✓ Development technology of nuclear-class structural material
- ✓ Platform of non-nuclear performance tests and data accumulation of out-of pile performance
- ✓ Development of neutron irradiated experiment and in-pile service performance

R&D and verification test system of material has already implemented.



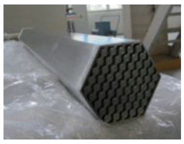
Results of flow corrosion experiments under oxygen control

Slow stain rate test

◆ R&D of nuclear fuel

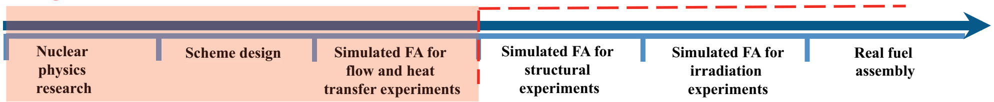
- ✓ Scheme design and preliminary engineering design of fuel assembly
- ✓ Preparation of full-scale simulated FAs and thermodynamic experiments

Experiments of full-scale simulated FAs **has already been done, and experimental data has been given.**



Full-scale simulated FA for flow experiments (61 pins/ wire wrapped)

Full-scale simulated FA for heat transfer experiments (61 pins/ 290kW)



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Key Technology IV: Instrumentation and Control

➢ **1:2.5 Scaling Verification platform for Fuel Handling System**
- Double rotating plugs design Verification
- Assembly interfaces and fixed way verification, etc..

➢ **1:1 Scope Verification platform for Control Rod Drive Mechanisms**
- Validation on the Impact of LBE (High Density / Lead Vapor)
- Verifying the design of Control Rod Drive Mechanisms, etc..

➢ **CLEAR Full Scope Simulator**
- Reactor safety analysis and serious accident simulation
- Reactor operator training, etc..

➢ **LBE target prototype**
- Provide test data of pressure drop of LBE target, and plot property curve
- Validate CFD simulation of LBE target, etc..

Fuel handling system

Simulation control room

Control rod drive mechanisms

LBE target prototype

The fabrication of verification platform have been accomplished, and the experimental testing are under way.

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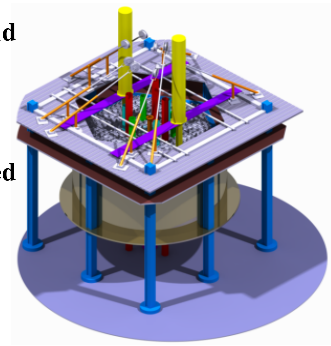
Experimental Platform for Nuclear Technology

—— Lead-based Zero Power Reactor (CLEAR-0)

- **Pre-research Facility of PbBi Cooled ADS**
- **Detailed conceptual design for CLEAR-0 has been finished**
  - **Verification of the nuclear analysis method, code and database for PbBi Cooled ADS;**
  - **Verification of the nuclear design and control technology;**
  - **Provide experimental data of Zero Power Reactor based on CLEAR-I to support the licensing;**

Nuclear Design, Structure, Core and Standard Assemblies, Shielding, Reactivity Control System, Measuring System, I&C System, Plant and Auxiliary System (7 systems, 10 key equipments)



Zero Power Reactor (CLEAR-0)

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Highly Intensified Neutron Generator(HINEG)

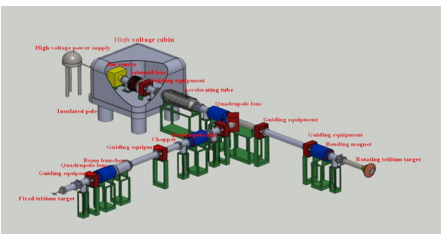
- **Neutron with different energy**

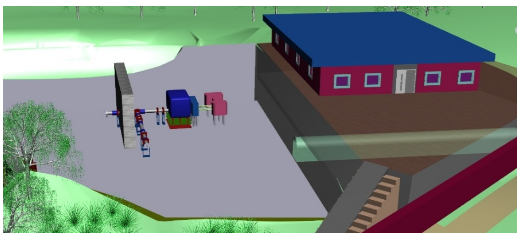
  D+D ⟶ ^{3}He+n(2.5MeV)

  D+T ⟶ ^{4}He+n(14.1MeV)

- **Steady/pulse dual-modling**
  - **Steady intensity:10^{13}n/s** (Phase I)
  - **Pulsed width:1.5ns**

- **Test objectives**
  - **Reactor design verification**
  - **Materials radiation experiments**
  - **Radiation protection and environmental impact**
  - **Application of nuclear technology**
  - …





Engineering design has been finished, construction is underway.

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Digital Virtual Reactor (CLEAR-V)

for Integrated Design and Simulation of Advanced Reactors

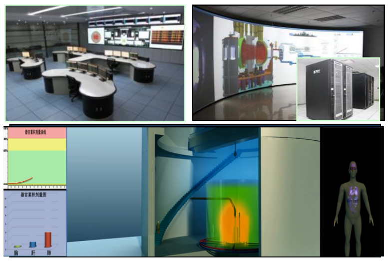
- **Multi-physics Integrated Simulation**

  Monitor the performance of any part of the reactor at any point in full cycle.

  - Neutronics (VisualBUS, SuperMC), Neutronics-Thermohydraulics (NTC), Irradiation Damage (MSC), Probabilistic Safety /Reliability (RiskA), System Parameter Optimization /Economical Assessment (SYSCODE), etc.

- **Cloud Computing based High-performance Simulation**
  - Nuclear Safety Cloud: database / codes services ..
  - Hybrid architecture based parallel computing CPU + CPU

- **Virtual Reality based Lifelike Simulation**
  - Virtual tour, assembly & design validation
  - Maintenance optimization & training



Digital Reactor ➔ Virtual Plant

Contents

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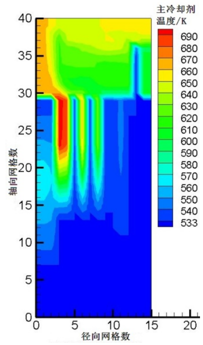
Preliminary Safety Analysis

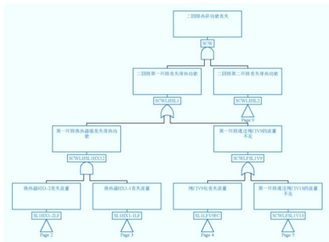


❖ Accident Analysis

- **Accident classify and initial events definition**
- **Analysis code preparation**
  - ✓ RELAP, MELCOR, NTC (self-developed), CFD (commercial)
- **Typical accident analysis**
  - ✓ (U/P)LOHS, LOFA, Reactivity Insertion, SBO, etc.

❖ Probability Safety Analysis

- **The 1 class internal event PSA has been done**
- Quantify risk assessment and safety object study
- Risk comparison between design options



Preliminarily analysis results shows that under the typical accident reactor core will not be damaged and the decay heat can be removed effectively

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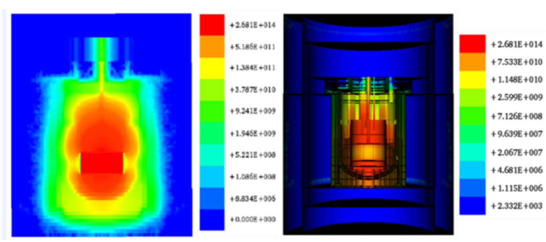
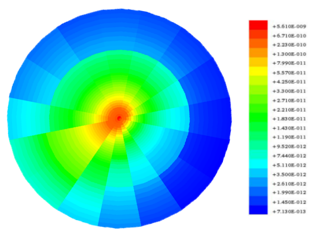
Environmental Impact Assessment

❖ Studies of Environmental Impact Assessment Report

- ✓ Radioactive inventory in reactor
- ✓ Radioactive waste disposal system and reactor decommissioning
- ✓ Environmental impact during normal operation / under accident
- ✓ Character and safety of Lead-Bismuth
- ✓ Environmental impact of construction
- ✓ Monitoring both effluent and environment



Radioactive distribution in reactor



Dose distribution under **an accident**

Dose of public was far below the value in Chinese national standards (GB).

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Code V&V

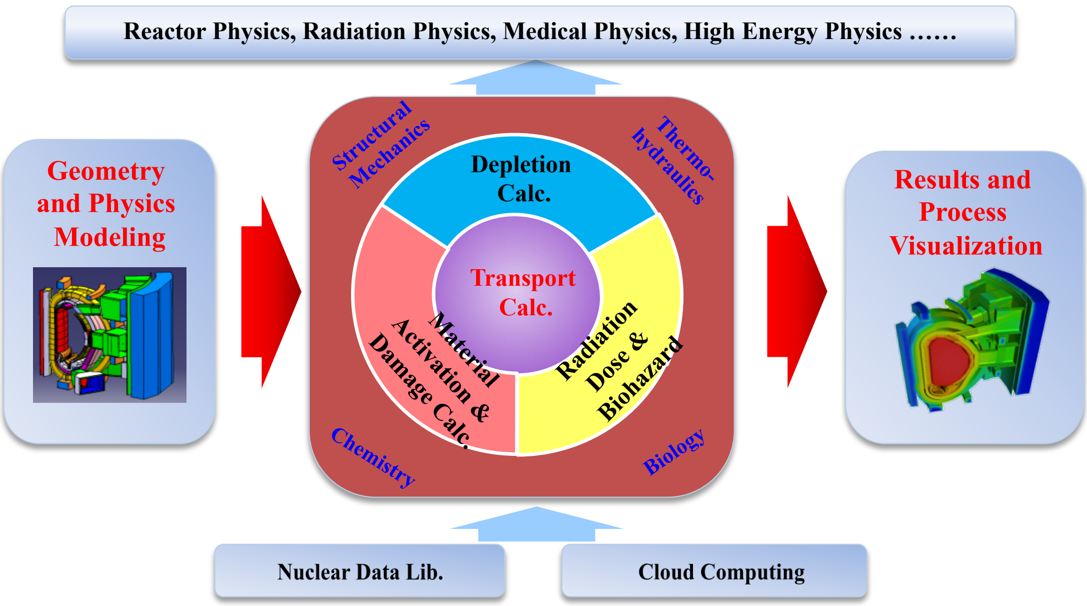
CLEAR-I design and analysis code V&V methodology and system has been established.

- **Code – code benchmark**
- **Verification Experiment**
  - **More than 10 facilities**
  - **Self-developed & Cooperation (domestic / abroad institute)**
- **Cooperation & communication**
  - **Nuclear and Radiation Safety Center**
  - **State Nuclear Power Software Development Center**

Codes	Organization	Facilities
Nuclear Design / Nuclear Database	NPIC	HFETR
	North West Nuclear Technology Institute	Xi'an Pulsed Reactor
	CIAE	CEFR
	Belgium SCK-CEN?	VENUS-F（Guinevere）
	Russia?	BOR-60/BFS-1/2
	Swiss PSI?	SINQ
Thermal-hydraulics	INEST CAS	KYLIN-II
		KYLIN-S
Accident Analysis	INEST CAS	KYLIN-II KYLIN-S
	Italy ENEA?	NACIE
	Korea SNU?	HELIOS
Shielding Design	CIAE	CPNG6

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

SuperMC: Super Monte Carlo Simulation Program for Nuclear and Radiation Process



Contents

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

Lead-Based Reactor Characteristics

❖ Lead-Based Coolant Technologies

Lead Bismuth	Low operation temperature →Early application for ADS
Lead	High power conversion coefficient →Long-term electricity application for GIF LFR
Lead Lithium	Tritium breeding →Long-long term application for fusion

- Similar properties, key technologies shared with others
- Can be applied for both critical and sub-critical systems

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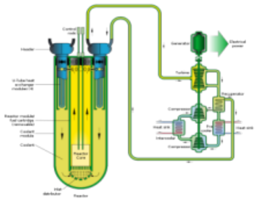
Application Prospects of Lead-based Reactors

Energy: Generation IV/Fusion/Hybrid Reactors

- ✓ LFR-One of Generation IV reactors
- ✓ Promote the development of fusion/ hybrid reactors



Isotopes Production

- ✓ Tritium for fusion test reactor start -up
- ✓ Other radioactive isotopes

Hydrogen/Sea Water Desalination

- ✓ Hydrogen is a clean energy and has great market potential
- ✓ The world's fresh water gap is 200 billion/year, per capita in China is only a quarter of world average

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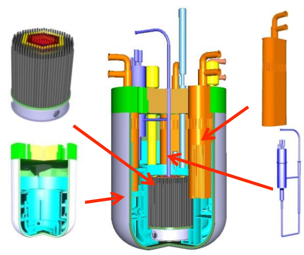
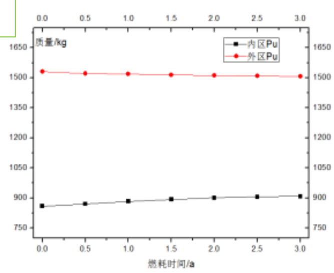
CLEAR-SFB: Lead-based Reactor for Spent Fuel Burning

—Spent Fuel Generate Power 'Trash into Treasure'

- Based on relatively simple reprocessing requirements, no need to separate of Pu and MA;
- Supplement depleted uranium after first loading, without fissile fuel added;
- MA net decrease, none extra nuclear waste production;
- Long period and deep burnup operation, high economic and resource utilization for single cycle.



Parameters	Values
Thermal Power (MW)	1000
TSR_{MA} (kg/y)	29.6
Average Burnup (GWd/t HM)	150
Refueling Cycle (yr.)	3



Fissile nuclide mass change with burnup

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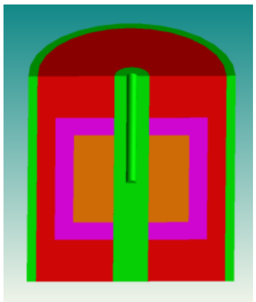
Key Laboratory of Neutronics and Radiation Safety,CAS

CLEAR-Th: Lead-based Reactor for Thorium Burning —Efficient Utilization of Th

- **Supplement depleted uranium after first loading, without fissile fuel added;**
- **Integration of conversion and burning of Th-U, no separation of U-233;**
- **MA net decrease, none extra nuclear waste production;**
- **Long period and deep burn-up operation, high economic and resource utilization for single cycle.**

Parameters	Values
Thermal Power (MW)	1000
Fuel composition	Spent fuel TRU+Th
Average burnup (GWd/t HM)	150
Refueling Cycle (yr.)	3



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Key Laboratory of Neutronics and Radiation Safety,CAS

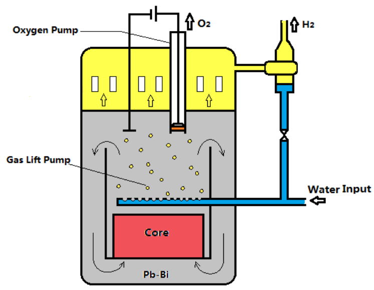
CLEAR- H: Lead-based Reactor for Hydrogen Production —Low Temperature Hydrogen Production

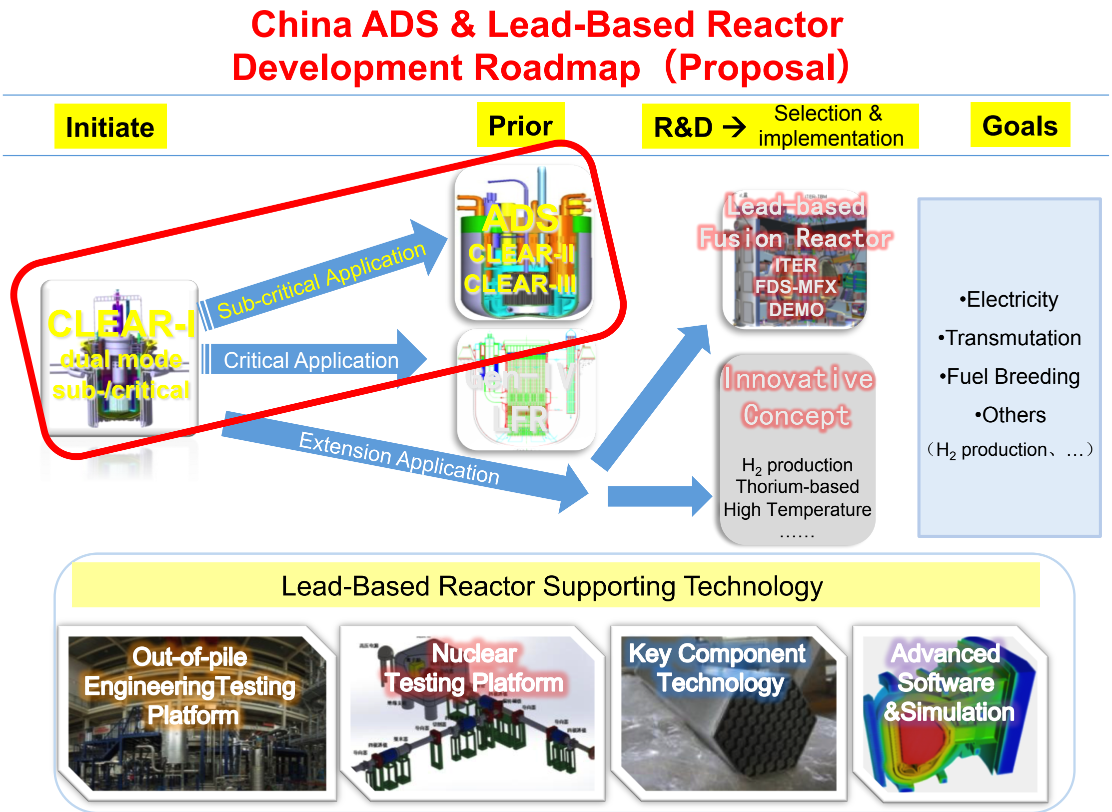
- **New hydrogen production technology based on lead-based alloys with low temperature and high efficiency, Pb/LBE as coolant and hydrogen-containing substances, materialize by oxygen control technology;**
- **Integration of reactor and hydrogen production by direct contact heat transfer, simplified equipment and save cost.**

Parameters	Values
Reactor Type	Integration pool-type fast reactor
Thermal Power	200MW
Fuel	UN
Refueling Cycle	No reloading
Coolant	Pb/LBE
Hydrogen-containing substances	Water
Hydrogen Production	~2880kg/h
Efficiency	>55%

$Pb+H_2O \Leftrightarrow Pb+H_2+[O]$

$PbBi+H_2O \Leftrightarrow PbBi+H_2+[O]$





Contents

I. Introduction

II. Research Progress

III. Development Prospects

IV. Summary

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

Summary

- China LEAd-based Rector (CLEAR) has been selected by CAS as the ADS reference reactor and Generation IV advanced reactor development emphasis;
- CLEAR series lead-based reactor conceptual design has been carried; the preliminary engineering design Lead-bismuth cooled research reactor CLEAR-I is underway;
- KYLIN series Lead-bismuth experimental facilities and key components for CLEAR has already constructed and the experiment research is under way.
- CLEAR-S Lead-alloy cooled non-nuclear reactor and the test component are under construction and fabrication.
- Construction of Zero-power experimental Facility CLEAR-0 and High Intensify D-T fusion Neutron Generator (HINEG) is underway.
- Widely international cooperation on lead-based reactor design and technology R&D is welcome.

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Key Laboratory of Neutronics and Radiation Safety,CAS

Thanks for Your Attention

Website: www.fds.org.cn
E-mail: contact@fds.org.cn

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences (INEST, CAS)

- **Jointly sponsored by:**
  - Hefei Institutes of Physical Science, CAS (CASHIPS)
  - University of Science and Technology of China (USTC)
- **Key programs:**
  - Advanced Fission Reactor Design and R&D (ADS - CLEAR)
  - Fusion/Hybrid Reactor Design and R&D (ITER/FDS)
  - Nuclear Safety Innovation Project for Scientific and Technological Development
- **10 Divisions, 400~500 Staff + 200~300 Students**

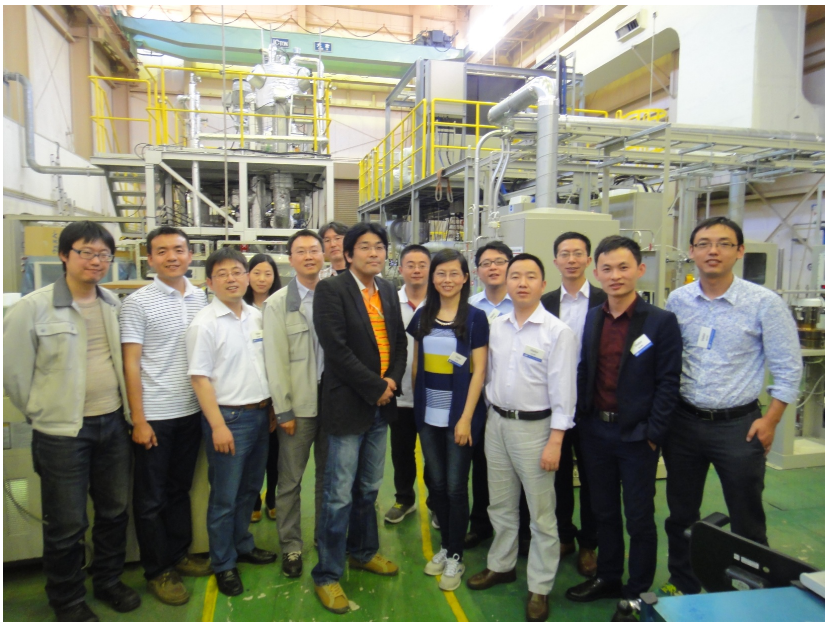
~400 members

Major Research Areas:

1. **Nuclear reactor safety**
   (reactor design, nuclear detect & experiments, safety analysis methodology, …)
2. **Radiation safety and environmental impact**
   (radiation protection & shielding, chemistry safety of nuclear energy, …)
3. **Nuclear emergency and public safety**
   (nuclear safety culture, nuclear accident emergency, nuclear power economics, …)

The major professional/fundamental research basis for nuclear energy safety technology in China to promote the efficient and safe application of nuclear energy.

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS



4. Activities in Korea

4.1 Current Status of the Development of Electromagnetic Pumps in Korea

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Current Status of the Development of Electromagnetic Pumps in Korea

Hee Reyoung Kim
Ulsan National Institute of Science and Technology

Pilot electromagnetic (EM) pumps with the flowrate of 60 L/min ~ 900 L/min and the developing pressure of 1 bar ~ 4 bar have been developed for the circulation of liquid sodium in the sodium fast reactor (SFR) in Korea since1990. The EM pump, which has no mechanical part contacting with the liquid metal fluid of the high chemical reactivity and strong corrosiveness, is required to circulate the liquid sodium coolant in the sodium fast reactor without particular maintenance for a long period. The EM pump using a Lorentz' force generated by the vector product of current and magnetic field perpendicular to it have been designed for the sodium, wood's metal, lead and lead lithium by magnetohydrodynamic (MHD) and equivalent electric circuit method. The MHD analysis was carried out for the EM pump with coupled properties of electromagnetics and fluid mechanics, where Maxwell's equations and fluid equations should be solved together. The EM pump was fabricated taking into environmental condition such as operation temperature and chemically reactive sodium based on the analysis result. The experimental characterization on the flowrate and developing pressure showed a good agreement with theoretical prediction. The characteristic of the MHD pressure drop by the magnetic field was experimentally analyzed where the drop was proportional to the velocity and the square of the external magnetic field. The stability criteria for the annular linear induction EM pump, the flow under the high magnetic field was thought to be kept stable even in a higher fluid velocity for low perturbation with a long wave length. The EM pump technology for design and fabrication is expected to be directly applied to the transportation of liquid metals used as a coolant in the LFR, TWR, MYRRHA, ITER and SFR due to the same principle of generation of electromagnetic force on the electrically conducting liquid.

The First Topical Meeting on Asian Network for Accelerator-driven Systems (ADS) and Nuclear Transmutation Technology (NTT)
J-PARC Center, Japan, October 26-27, 2015

Current Status of the Development of Electromagnetic Pumps in Korea

Hee Reyoung Kim & Jaesik Kwak

2015. 10. 26 (Mon)

J-PARC Center

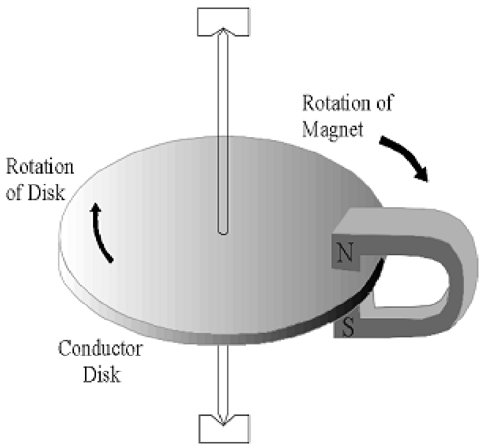
Ulsan National Institute of Science and Technology

Contents

Contents

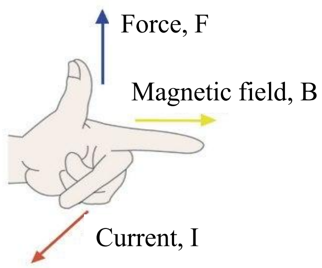
Fundamental Principle of EM Pump

◆ **Generation of rotating magnetic field**



Arago's disk

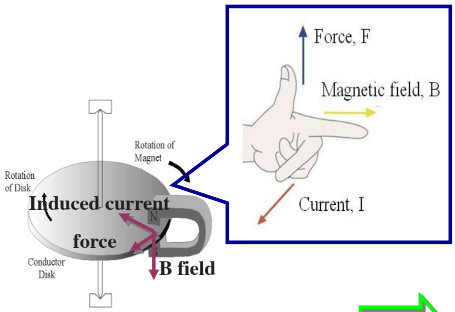
◆ **Generation of electromagnetic force**



Fleming's left hand rule

- Current perpendicular to the magnetic field
- Generation of force perpendicular to both current and magnetic field

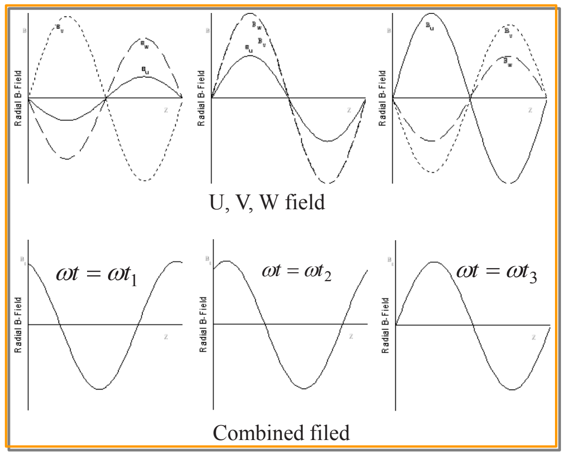
◆ Rotating magnetic field



Arago's disk

- The disk rotates in the direction of a rotating magnet
- Moving magnetic field instead of rotating magnetic field
  => linear induction pump or motor

◆ Moving magnetic field



<Moving magnetic field by three phase alternative current>

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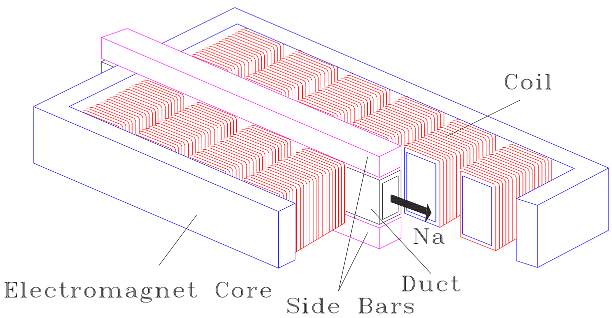
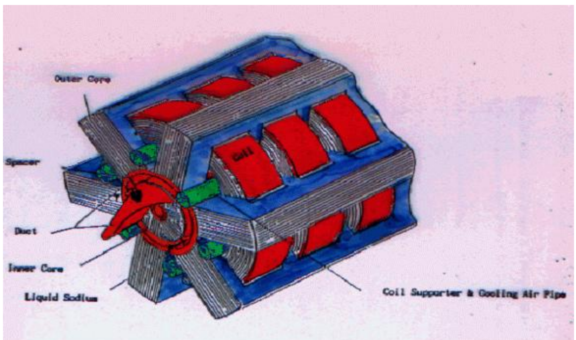
Electromagnetic Pumps



Flat Linear Induction Pump (FLIP)
(사각단면형 선형유도전자펌프)



Annular Linear Induction Pump (ALIP)
(환단면형 선형유도전자펌프)

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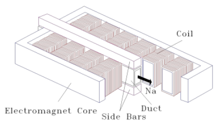
II. Development of EM Pumps in Korea

- Development Status of EM Pumps
- EM Pumps! Past, Present and Future

Development Status of EM Pumps

◆ **1990**

- Design and manufacturing of a flat linear induction EM pump
  - Fluid : Wood's metal and liquid sodium
  - Experimental verification of the difference of pumping flow rate due to electrical conductivity and density.



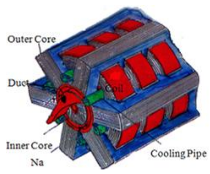
- Conceptual and detailed design of externally-supported-duct type and submersible-in-pool type annular linear induction EM pumps

◆ **1991**

- Manufacturing of the 6 outer core slot-externally-supported-duct type annular linear induction EM pump with a flow rate of 60 L/min and an operation temperature of 400℃.

◆ **1992~1993**

- Design and manufacturing of an externally-supported-duct type annular linear induction EM pump with a flow rate of 60 L/min (12 outer core slots).



◆ **1994**

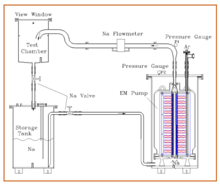
- Design and manufacturing of an externally-supported-duct type annular linear induction EM pump with a flow rate of 60 L/min (12 outer core slots and 8 core blocks).
- Design of an externally-supported-duct type annular linear induction EM pump with a flow rate of 800 L/min.

◆ **1995~1996**

- Design and manufacturing of a sodium submersible-in-pool type annular linear induction EM pump with a flow rate of 60 L/min and an operation temperature of 600℃.

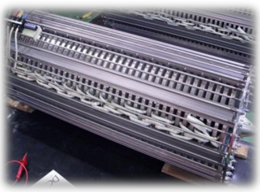
◆ **1997~1999**

- Design and manufacturing of a sodium submersible-in-pool type annular linear induction EM pump with a flow rate of 200 L/min and an operation temperature of 600℃.
- Characteristic experiment on flow rate on the change of frequency.



◆ **2000~2011**

- Design and manufacturing of an EM pump with a flow rate of 900 L/min for the test of sodium thermohydraulic effect for a sodium fast reactor.
- Design and manufacturing of an EM Pump with a flow rate ~100 L/min for sodium cleanup and instrumentation system.



- Design, manufacturing and characteristic experiment of an EM Pump for circulation of lead-bismuth for a fusion reactor.

◆ **2012~**

- Design and manufacturing of the sodium transportation EM Pump with a flowrate of 100 L/min for material corrosion test.

EM pumps! Past, Present and Future

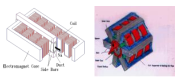
• Verification of the principle

• experimental characterization

• Application
- corrosion, component test,
- MHD pressure drop

• Large EM pumps for SFR and ITER

Pilot type pump



• Flat and annular type with ~60 LPM
• Temperature: 400℃$_{max}$
• Fluid : Wood metal and Sodium

Magneto-thermo hydraulic measurement

• Annular pipe-supported, pool-immersed and center-return type with ~200 LPM
• Temperature: 600℃$_{max}$
• Fluid : Sodium

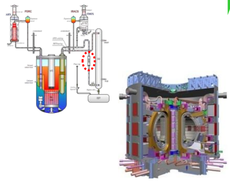
Material corrosion estimation

• Annular pipe-supported type with ~60 LPM and 4 bar
• Temperature: 500℃$_{max}$
• Fluid : Lead-bismuth

STELLA verification and MHD for nuclear fusion reactor

• Annular pipe-supported type with ~2,265 LPM and 4 bar
• Temperature: 550℃$_{max}$
• Fluid : Sodium and Lead-lithium

Prototype pump for Liquid Metal Reactor and fusion reactor



• Annular pipe-supported, pool-immersed pump with >50,000 LPM
• Temperature: 600℃$_{max}$
• Fluid : Sodium and lithium

1992 1997 2002 2007 2012

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11

III. Experimental Characterization and Application of the EM Pumps

- Background and Objective
- The MHD Dynamic Analysis
- The Design and Manufacturing of the EM pump
- Experimental Verification
- Applications

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12

Background and Objective

- **In the sodium fast reactor, the electrically conducting sodium liquid metal is used as a coolant.**
  - Therefore, EM pump appropriate for the liquid metal coolant circulation is required.
  - EM pump, which has no mechanical part contacting with the liquid metal fluid of the high chemical reactivity and strong corrosiveness, is required to circulate the liquid metal coolant without particular maintenance for a long period.

- **Magnetohydrodynamic analysis is carried out for EM pump with coupled properties of electromagnetics and fluid mechanics.**
  - Maxwell's equations including Ampere's law, Faraday's law, Ohm's law and Gauss' law, and fluid equations including continuity equation and momentum equation should be solved together.

- **An effective design analysis method is developed for designing an EM pump from the results of the complicated magnetohydrodynamic analysis and applied to the actual design.**

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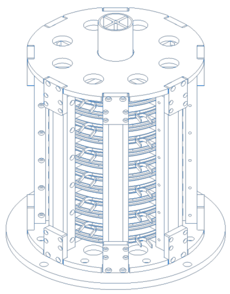
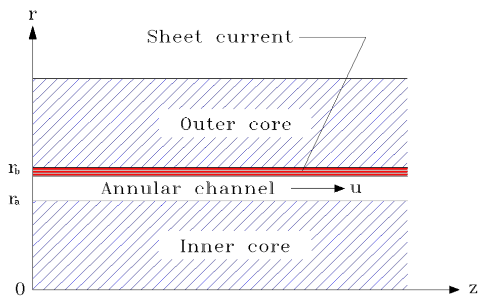
Magnetohydrodynamic Analysis

◆Analysis for EM pump





- Governing equations

$$\nabla \bullet \mathbf{v} = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \bullet \nabla)\mathbf{v} = -\nabla p + \frac{1}{R_e}\nabla^2 \mathbf{v} + \frac{H_a^{\ 2}}{R_e}\mathbf{J} \times \mathbf{B}$$

$$\nabla \times \mathbf{B} = R_m \mathbf{J} \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \bullet \mathbf{B} = 0 \qquad \mathbf{J} = \mathbf{E} + \mathbf{v} \times \mathbf{B}$$

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◆ Solutions

$$u = \gamma\left(1 - \frac{1}{I_0(\alpha r_a)K_0(\alpha r_b) - K_0(\alpha r_a)I_0(\alpha r_b)}\right)\left((K_0(\alpha r_b) - K_0(\alpha r_a))I_0(\alpha r) + (I_0(\alpha r_a) - I_0(\alpha r_b))K_0(\alpha r)\right)$$

$$B_r = \frac{j\sqrt{2}k^2R_0^2}{\delta\{K_0(\delta r_a)I_0(\delta r_b) - I_0(\delta r_a)K_0(\delta r_b)\}}(K_0(\delta r_a)I_1(\delta r) + I_0(\delta r_a)K_1(\delta r))$$

$$B_z = \frac{j\sqrt{2}kR_0}{K_0(\delta r_a)I_0(\delta r_b) - I_0(\delta r_a)K_0(\delta r_b)}(K_0(\delta r_a)I_0(\delta r) - I_0(\delta r_a)K_0(\delta r))$$

$$J = -(1-u)B_r$$

$$f_z = (1-u)\frac{B_r B_r^c}{2}\frac{H_a^2}{R_e}$$

where,

$$R_e = \frac{\rho R_0 v_0}{\mu} \quad H_a = \sqrt{\frac{\sigma B_0{}^2 R_0{}^2}{\mu}} \quad R_m = \mu_0 \sigma R_0 v_0 \quad \beta = \frac{1}{1+(\frac{R_m s}{kR_0})^2} \quad \gamma = 1 - \frac{R_e}{\beta^2 H_a^2}\frac{\eta(1-s)^2}{4} \quad \delta = \sqrt{|(kR_0)^2 + jkR_0R_m|}$$

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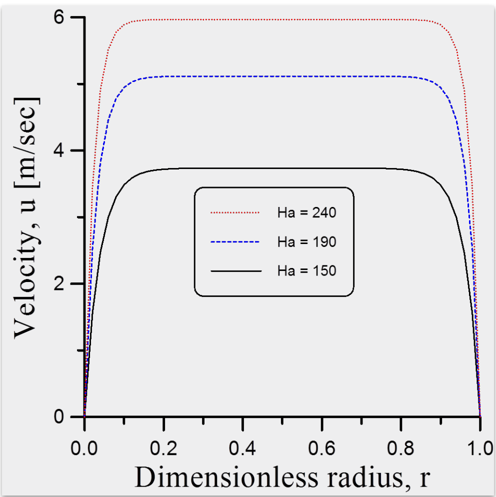
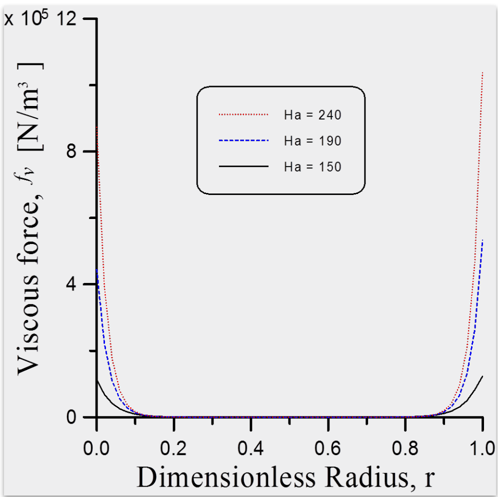
15

◆ Analysis results



Flow velocity



Viscous force

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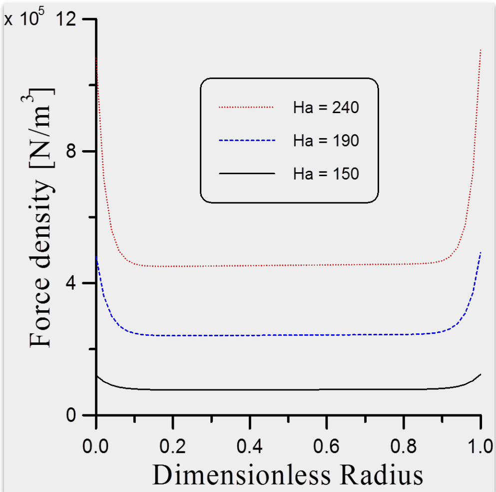
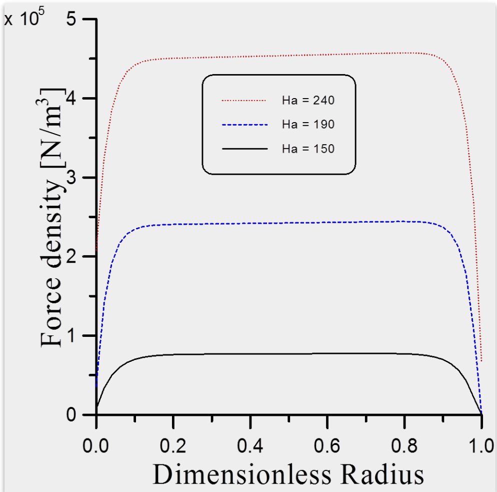
16



Electromagnetic force



Pumping force

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17

Flat velocity distribution

viscous force ≪ electromagnetic force

=>Pumping force ≒ Electromagnetic force **!**

- The developed pressure from the MHD analysis is $\dfrac{36\sigma s f \tau^2 (\mu_0 k_w N I)^2}{p g_e^{\,2} \{\pi^2 + (2\mu_0 \sigma s f \tau^2)^2\}}$, which is equal to that from the electrical analysis.
- The liquid fluid can be treated as a solid.
- Therefore, the electrical approach is available without complicated and tedious mathematical procedure.

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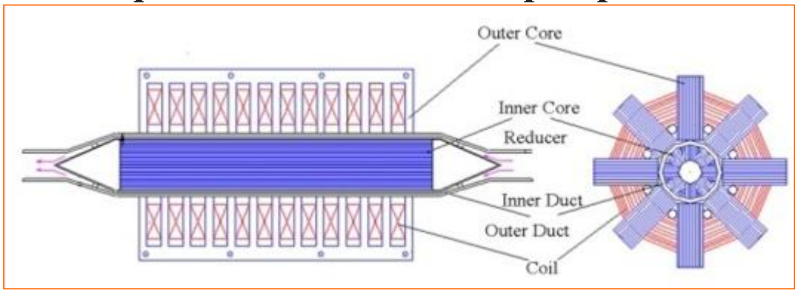
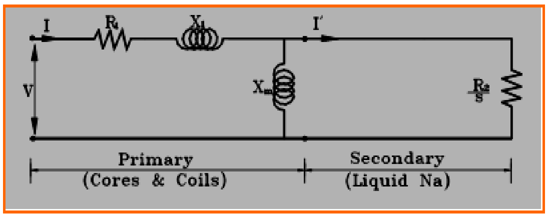
18

Design and Manufacturing of the EM Pump

◆ **The electric equivalent circuit for EM pump**





$$R_1 = \frac{\pi \rho_c q k_p{}^2 m^2 D_0 N^2}{k_f k_d p \tau^2} \qquad R_2 = \frac{6\pi D \rho_r{}'(k_w N)^2}{\tau p}$$

$$X_1 \cong \frac{2\pi \mu_0 \omega D_0 \lambda_c N^2}{pq} \qquad X_m = \frac{6\mu_0 \omega \tau \pi D_0 (k_w N)^2}{\pi^2 p g_e}$$

- The Developed pressure :

$$\Delta P = \frac{36\sigma s f \tau^2 (\mu_0 k_w N I)^2}{p g_e{}^2 \{\pi^2 + (2\mu_0 \sigma s f \tau^2)^2\}}$$

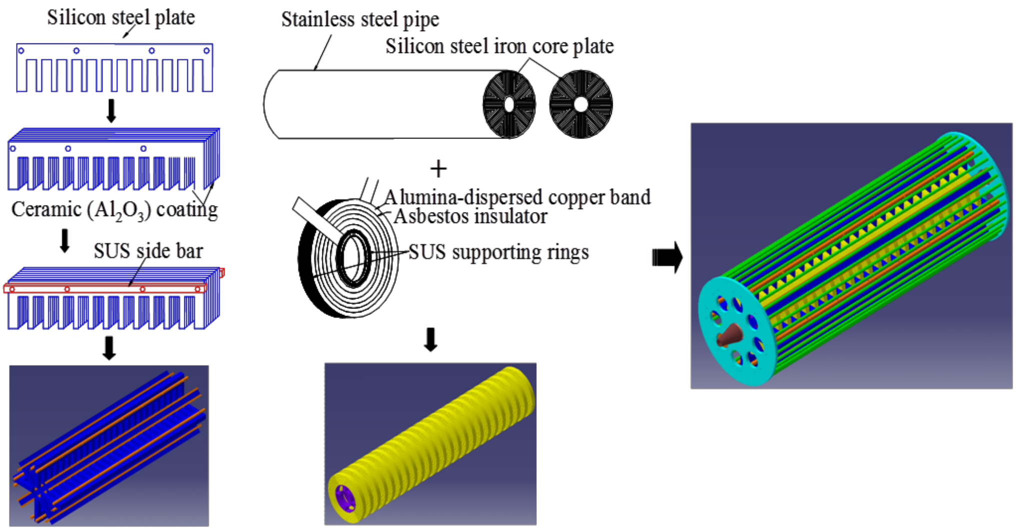
- Friction loss :

$$\Delta P_L = \frac{\rho \eta L v^2}{2g}$$

  - Pole pitch (Core length), Diameter of inner core, Slot width, Inter-core gap, Number of pole pairs, Coil turns…

Optimized design according to the change of variables

◆ Manufacturing of the EM Pump



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21

◆ Design Analysis of EM pump

Variables		Increase	Decrease
Geome-trical	Pole pitch (Core length)	○Increased magnetizing reactance due to the high Laithwaite Goodness Factor ○Increased weight of the device and impedance	○Decreased flow speed due to the low synchronized speed
	Diameter of inner core	○Increased developing pressure ○Stabilized flow	○Decreased leakage reactance ○Decreased weight of the device
	Slot width	○Increased magnetizing current due to the Increased effective inter-core gap	○The more magnetic flux from the outer stator
	Inter-core gap	○Increased magnetizing current	○Increased frictional loss
Electro-magnetic	Input frequency	○Decreased electrical conductivity due to skin effect ○Increased end effect	○Decreased speed of the moving magnetic field ○Decreased magnetizing and leakage reactance
	Number of pole pairs	○Decreased end effect ○Decreased magnetizing reactance	○Decreased length of the device on the fixed pole pitch
	Electrical conductivity of liquid metal	○Large electromagnetic force	○Decreased Joules' loss ○Reduced End-effect wave
	Coil turns	○High magnetic field on the same input current	○Increased leakage reactance ○Increased heat generation on the constant input voltage

=> Optimized design on the variable change

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◆ The completed EM pumps

Externally supported pipe type

Pool-immersed type

Center Return

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23

Experimental Verification

◆ Preliminary test

<I=140A, V=80V, VI=20kVA>

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24

<I=100A, V=100V, VI=17kVA>

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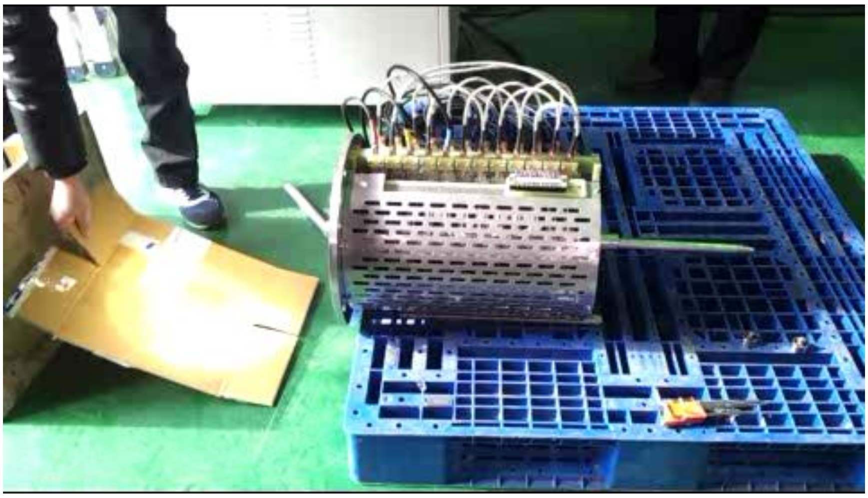
25



<I=20A>

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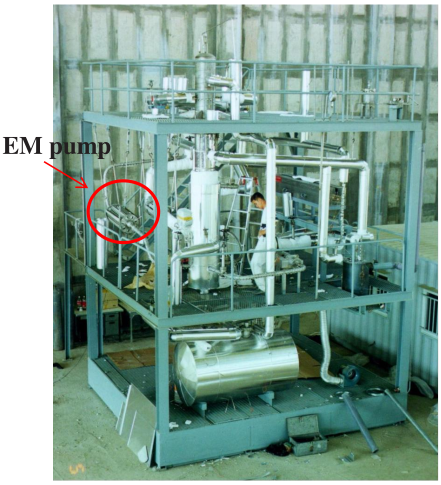
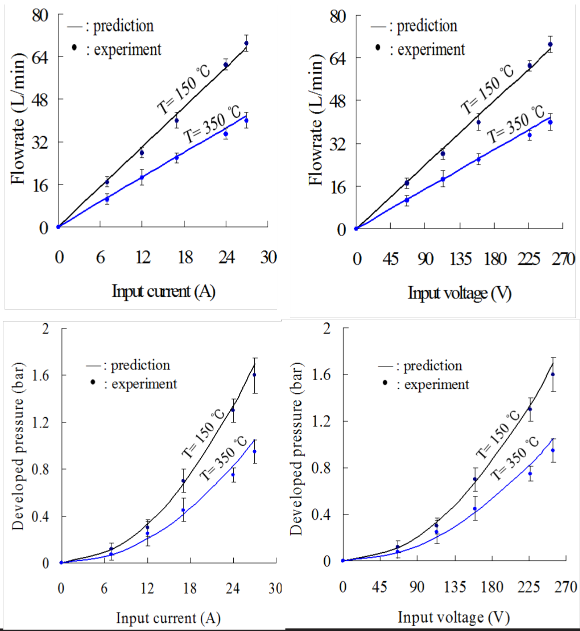
26

◆ Experiments



-Flowrate : 54 L/min

-Developed pressure : 1.3 bar



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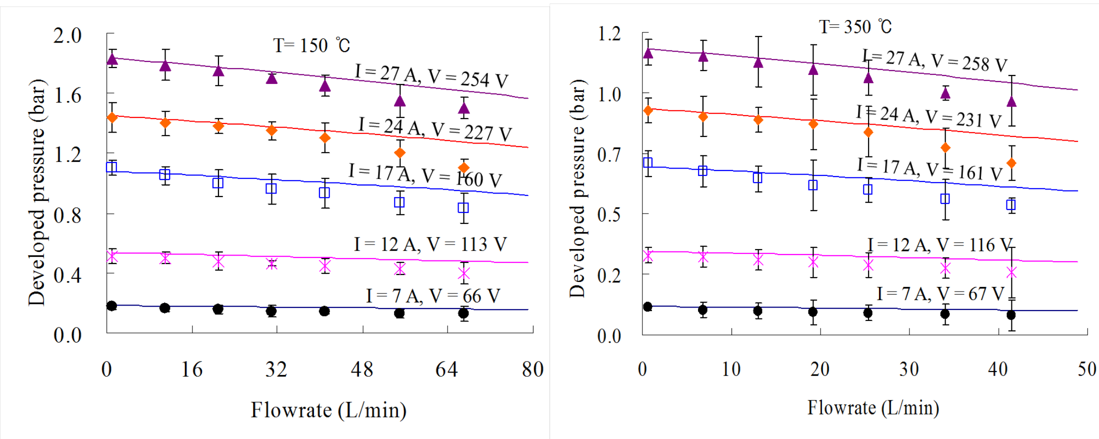

"Good agreement with the theoretical calculation"

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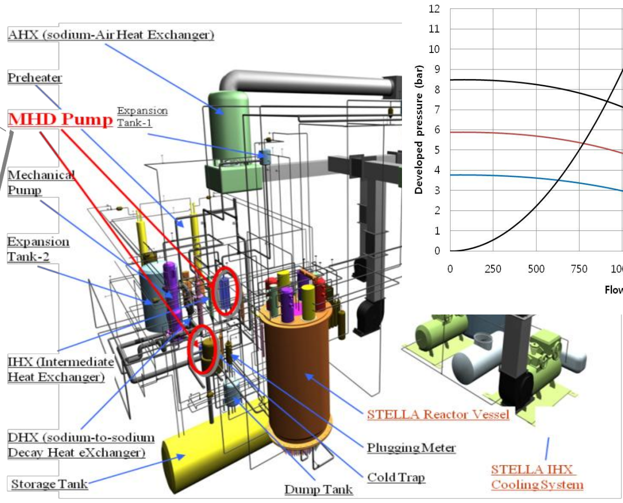
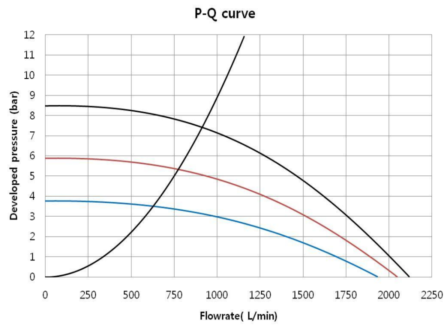
Applications

◆ The EM pump for the sodium thermo hydraulic components test for the future SFR

Flowrate
-900 L/min
Developed pressure
-4 bar
Temperature
-550 ºC
Pump Length
-0.95 m
Pump Diameter
-39 cm
Input current
-180 A
Input voltage
-548 V





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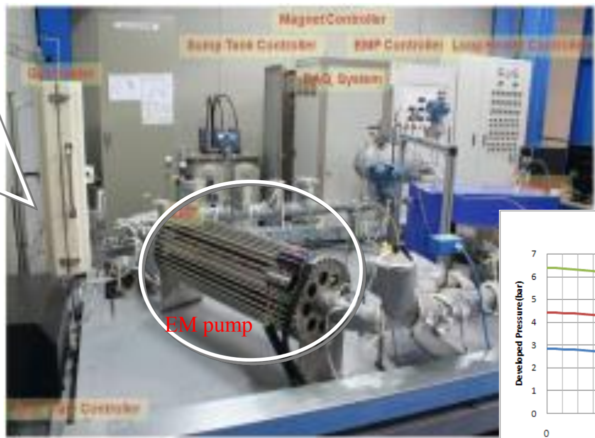
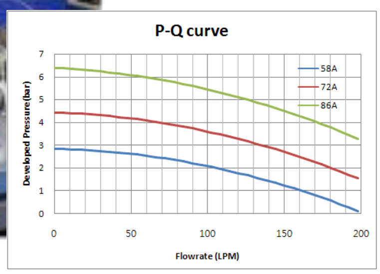
29

◆ The EM pump for the MHD experiment of the liquid PbLi flow in the ITER

Flowrate
-60 L/min
Developed pressure
-1 bar
Temperature
-500 ºC
Pump Length
-1 m
Pump Diameter
-33 cm
Input current
-62 A
Input voltage
-311 V





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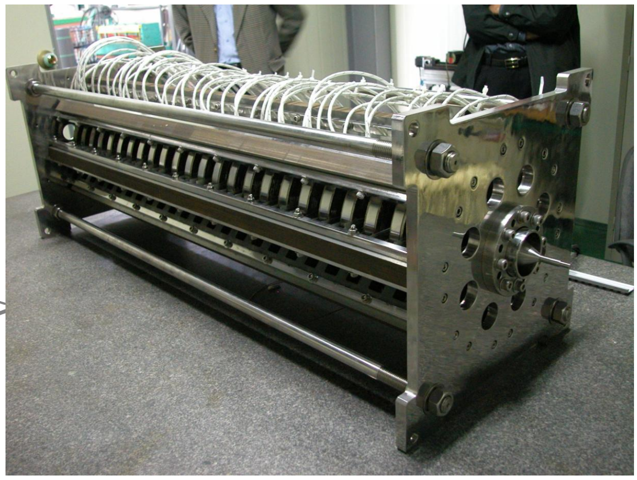
30

◆ The EM pump for the experiment of the liquid PbBi flow

Flowrate
-60 L/min
Developed pressure
-4 bar
Temperature
-500 °C
Pump Length
-1 m
Pump Diameter
-28 cm
Input current
-52 A
Input voltage
-353 V



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31

◆ The EM pump for the corrosion test of the material in the sodium environment

Flowrate
-9 L/min
Developed pressure
-4 bar
Temperature
-550 °C
Pump Length
-40 cm
Pump Diameter
-31 cm
Input current
-23 A
Input voltage
-250 V

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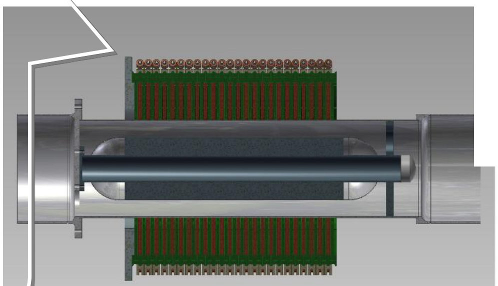
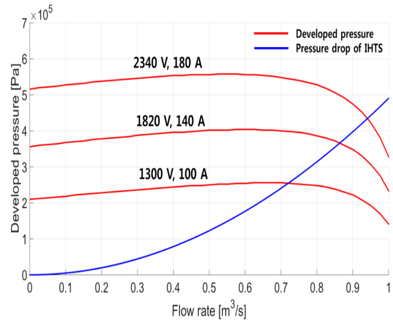
32

◆ The performance estimation of EM pump for IHTS of PGSFR with 150 MWe

Flowrate
 -51,400 L/min
Developed pressure
 -3.7 bar
Temperature
-322 °C
Pump Length
-<3 m
Pump Diameter
-<2.2 m
Input current
-140 A
Input voltage
-1820 V


EM pump for PGSFR (designed by ANL)



Estimation by UNIST

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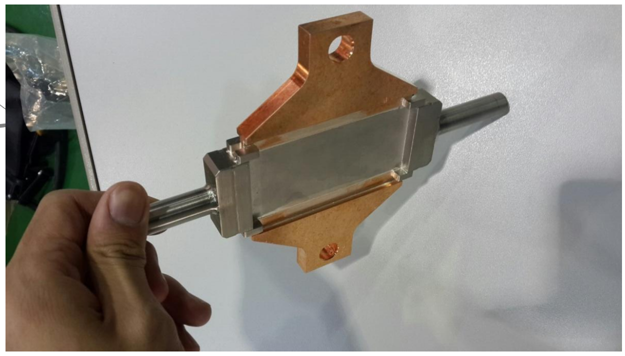
33

◆ The DC pump for test of the reaction between sodium and CO_2

Flowrate
 -3 L/min
Developed pressure
 -0.05 bar
Input current
-200 A
Input voltage
- ~ mV



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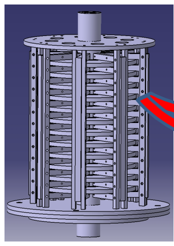
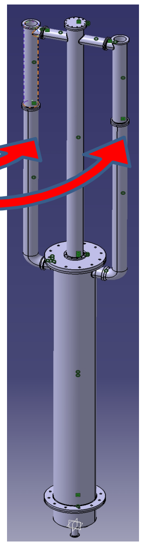
34

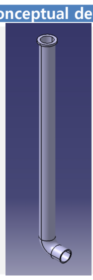
Lead-bismuth EM Pump for URANUS SMR

◆ Conceptual design of lead-bismuth EM pump for experimental test (installed in downcomer pipe)

Flow rate
 -150 L/min
Developed pressure
 -9,911 Pa
Input current
-60 A
Input voltage
- ~ 52V





Conceptual design	Shape	pipe	
	Size	ID (mm)	n/a
		OD (mm)	n/a
		A (m²)	n/a
		t (mm)	n/a
		L (mm)	2210
	Connection	Heat exchanger	(from)
		Downcomer (barrel)	(to)
	Requirements	- Connected between outlet of heat exchanger and inlet of downcomer (barrel). - ID and OD must be same with heat exchanger.	

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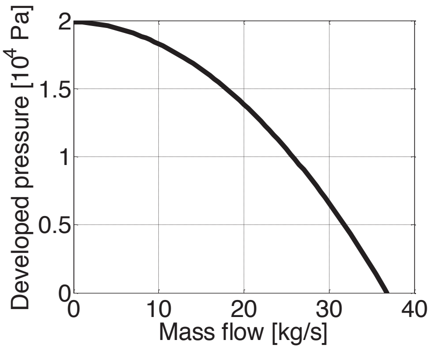
	Design variables	Unit	Values
Hydrodynamic	Flowrate	[L/min]	150
	Mass flowrate	[kg/s]	25.88
	Developed pressure	[Pa]	9911
	Temperature	[K]	573
	Velocity	[m/sec]	0.885
	Slip	[%]	94.1
	Reynolds number		178892
	Pressure loss	[Pa]	9553
Geometrical	Core length	[mm]	500.0
	Outer core diameter	[mm]	243.0
	inner core diameter	[mm]	30.0
	Inter core gap	[mm]	21.0
	Flow gap	[mm]	18.0
	Inner duct thickness	[mm]	1.0
	Outer duct thickness	[mm]	1.0
	Slot width	[mm]	20.00
	Slot depth	[mm]	60.50
	Core depth	[mm]	85.50
	Core thickness	[mm]	25.0
	Stacked coil thick	[mm]	44.0
	Coil support ring	[mm]	10.00
	Space in slot depth	[mm]	6.50
	Tooth width	[mm]	20.00
	Slot pitch	[mm]	40.00
	Conductor width	[mm]	16.00
	Conductor thickness	[mm]	2.00
	Insulator thickness	[mm]	2.00
Electrical	Input current	[A]	60.0
	Input voltage	[V]	52
	Impedance	[Ohm]	0.9
	Input VA	[kVA]	5.4
	Input power	[kW]	2.0
	Power factor	[%]	36.8
	Goodness factor		0.7
	Pole pitch	[cm]	12.50
	Number of slot	[#]	12
	Turns/slot	[#]	22
	Number of pole pairs	[#]	2
	Slot/phase/pole	[#]	1



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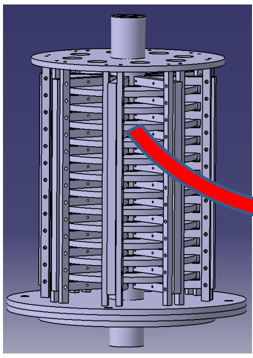
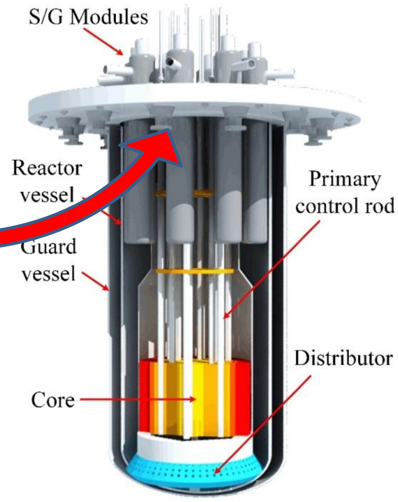
◆ Conceptual design of lead-bismuth EM pump for URANUS SMR (installed in lower section of S/G Modules) with the output of 100MWth

Flow rate
-3,298 L/min
Developed pressure
-29,688 Pa
Input current
-178 A
Input voltage
- ~ 807 V





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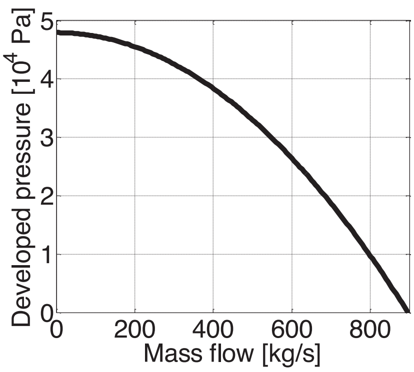
37

	Design variables	Unit	Values
Hydrodynamic	Flowrate	[L/min]	3298
	Mass flowrate	[kg/s]	568.25
	Developed pressure	[Pa]	29688
	Temperature	[K]	573
	Velocity	[m/sec]	1.968
	Slip	[%]	86.9
	Reynolds number		1722789
	Pressure loss	[Pa]	41994
Geometrical	Core length	[mm]	1000.0
	Outer core diameter	[mm]	519.0
	inner core diameter	[mm]	34.0
	Inter core gap	[mm]	81.0
	Flow gap	[mm]	78.0
	Inner duct thickness	[mm]	1.0
	Outer duct thickness	[mm]	1.0
	Slot width	[mm]	20.41
	Slot depth	[mm]	136.50
	Core depth	[mm]	161.50
	Core thickness	[mm]	25.0
	Stacked coil thick	[mm]	120.0
	Coil support ring	[mm]	10.00
	Space in slot depth	[mm]	6.50
	Tooth width	[mm]	20.41
	Slot pitch	[mm]	40.82
	Conductor width	[mm]	16.41
	Conductor thickness	[mm]	6.00
	Insulator thickness	[mm]	2.00
Electrical	Input current	[A]	178.0
	Input voltage	[V]	807
	Impedance	[Ohm]	4.5
	Input VA	[kVA]	248.9
	Input power	[kW]	73.3
	Power factor	[%]	29.5
	Goodness factor		1.0
	Pole pitch	[cm]	12.50
	Number of slot	[#]	24
	Turns/slot	[#]	30
	Number of pole pairs	[#]	4
	Slot/phase/pole	[#]	1



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38

IV. Summary

Summary

◆ **The EM pump was analyzed and designed using an equivalent electric circuit method.**

◆ **The characteristic of the pilot EM pumps was experimentally verified.**

- Its experimental result will contribute to the design of the liquid metal coolant system in the fast reactor or nuclear fusion reactor.

◆ **The technology of EM pump design and fabrication was established for the transportation of the liquid metal in the SFR.**

- It is expected to be directly applied wherever the liquid metal is used as a coolant in the LFR, SFR, TWR, MYRRHA and ITER.


Thank you for your attention!
ご清聴ありがとうございました.

4.2 Preliminary Core Design Analysis of a Subcritical Dedicated Burner Loading Thorium-based Oxide Fuel

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Preliminary core design analysis of a subcritical dedicated burner loading thorium-based oxide fuel

Jueun Lee*[1)], Yong-Hoon Shin[1)], Seung Woo Hong[2)], Myung Jae Song[3)] and Il Soon Hwang[1)]

1) School of Energy Systems Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea

2) Department of Physics, SungKyunKwan University, 25-2, Seobu-ro, Jangan-gu, Suwon-si, Gyeong Gi-do, Republic of Korea

3) Korea Radioactive Waste Society, 150, Deokjin-dong, Yuseong-gu, Daejeon, Republic of Korea

***Corresponding author:** *happylje14@snu.ac.kr*

Spent nuclear fuel is a pressing issue in most nuclear power generation countries including Korea, because onsite storage facilities are filling up with no further solutions available. As a way of reducing the burden of spent nuclear fuel, partitioning and transmutation (P&T) based on pyroprocess-SFR system can eliminate 99.9% of TRU. Still, 0.1% of TRU, 10kg per year [1, 2], is remaining despite of such P&T process when Korean nuclear power fleet produces 1,000 tons of SNF per year. Subcritical system using Thorium-based oxide fuel can incinerate the rest, leaving behind only low and intermediate level wastes. Hence, the aim of this study is to design a subcritical dedicated burner to incinerate the residue.

A subcritical system which uses thorium-based oxide fuel for the purpose of managing spent nuclear fuel by burning TRU and long live fission product has been designated as TORIA (Thorium Optimized Radionuclide Incineration Arena). For coolant and target material, lead-bismuth is selected. By adopting thorium based oxide fuel, the support ratio [3] can be increased over that of uranium based oxide fuel because there is less additional TRU generation during operation. Fabrication of thorium-based oxide fuel is already shown to be feasible on industrial scale [4]. Safety margin of TORIA, which is a subcritical system, is higher than that of critical system. In addition, TORIA has high temperature feedback property [5] and low void coefficient.

The design of TORIA is based on the earlier critical reactor design designated as PASCAR (Proliferation-resistant, Accident-tolerant, Self-supported, Capsular, and Assured Reactor) [6]. Basic design requirements are to maintain geometrical profiles and core power density of PASCAR by proportional reduction of the core size. TORIA is designed for 30MWth and average effective multiplication factor during effective full power days is 0.955. Required proton beam current at the energy of 600MeV and 500MeV is 1.43mA and 2mA, respectively. Fuel composition was determined using the flowsheet of PyroGreen [1]. Mass ratio between Th and TRU is decided to be Th:TRU=0.632:0.368.

A deterministic code system for fast neutronics analyses, consisting of TRANSX [7], DANTSYS [8], and REBUS-3 (DIF3D) [9], was used and the external source was not considered for this preliminary analysis. Calculation result of deterministic method is shown to be reliable on a subcritical system compared with Monte-Carlo method [10, 11].

The preliminary core design satisfied the basic design goal. It is expected to be useful in the step of detailed core design by understanding characteristics of core loaded with thorium-based oxide fuel. Detailed core design should consider external neutron source, and optimization about fuel composition, geometrical arrangements, etc. is necessary.

References

[1] OECD/NEA, “Spent Nuclear Fuel Reprocessing Flowsheet”, Paris, France, 2012.

[2] Jung, H.S., et al., “Environmental assessment of advanced partitioning, transmutation, and disposal based on long-term risk-informed regulation: PyroGreen”. Progress in Nuclear Energy 58 (2012):, 27-38.

[3] Lim, J.-Y., Kim, M.-H., “A new LFR design concept for effective TRU transmutation, Progress in Nuclear Energy” 49 (2007).

[4] OECD/NEA, “Introduction of thorium in the nuclear fuel cycle”, Nuclear Science, 2015

[5] G. A. Richards, D.E. Serfontein, The influence of thorium on the temperature reactivity coefficient in a 400 MWth pebble bed high temperature plutonium incinerator reactor, 2012.

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[7] MacFarlane, R.E., “TRANSX: 2 a Code for Interfacing MATXS Cross-Section Libraries to Nuclear Transport Codes”, LA-12312-MS. Los Alamos National Laboratory, New Mexico, USA, 1992.

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[9] Toppel, B.J., “A User’s Guide for the REBUS-3 Fuel Cycle Analysis Capability”, ANL-83-2. Argonne National Laboratory, Illinois, USA, 1983.

[10] OECD/NEA, “Comparison Calculations for an Accelerator-driven Minor Actinide

Burner", NEA/NSC/DOC(2001)13, 2002.

[11] OECD/NEA, "Benchmark on Computer Simulation of MASURCA Critical and Subcritical Experiments," NEA/NSC/DOC(2005)23, 2005.

The First Topical Meeting on Asian Network for Accelerator-driven Systems and Nuclear Transmutation Technology
26th October. 2015

Preliminary Core Design Analysis of a Subcritical Dedicated Buner Loadin g Thorium-based Oxide Fuel

Jueun Lee*[1)], Yong-Hoon Shin[1)], Seung Woo Hong[2)],
Myung Jae Song[3)] and Il Soon Hwang[1)]

1) School of Energy Systems Engineering, Seoul National University
2) Department of Physics, SungKyunKwan University
3) Korea Radioactive Waste Society

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1

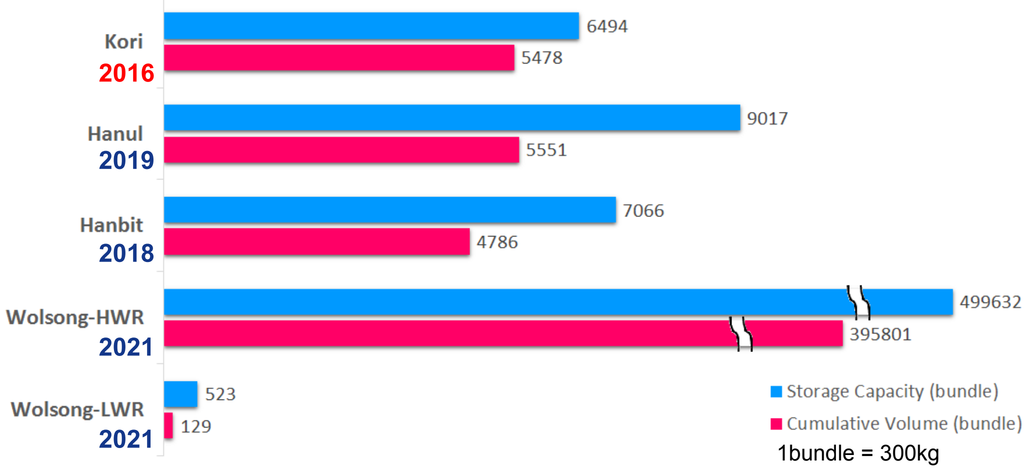
Outline

1. Why is SNF a pressing issue?
2. Pyroprocess-SFR system
3. Pyroprocess-SFR-TORIA system
4. Concept of TORIA
5. Characteristics of TORIA
6. Design criteria of TORIA
7. Calculation method
8. Calculation result
9. Conclusion

Why is SNF a Pressing Issue?

SNF management of Korea

The Spent Fuel Storage Status (2th quarter of 2015)



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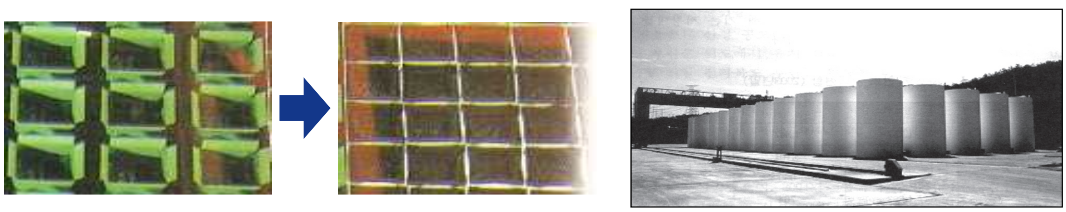
† 한국수력원자력, www.khnp.co.kr

Why is SNF a Pressing Issue?

SNF management of Korea

- Expansion of storage capacity (since 1990)
  - Replace the low-capacity racks by the high-capacity racks
  - Move SNF in the AR pool of the older unit to that of the younger unit within the same site
  - Build dry storage & MACSTOR/KN-400 for CANDU SNF

- There is no specific decision about SNF.



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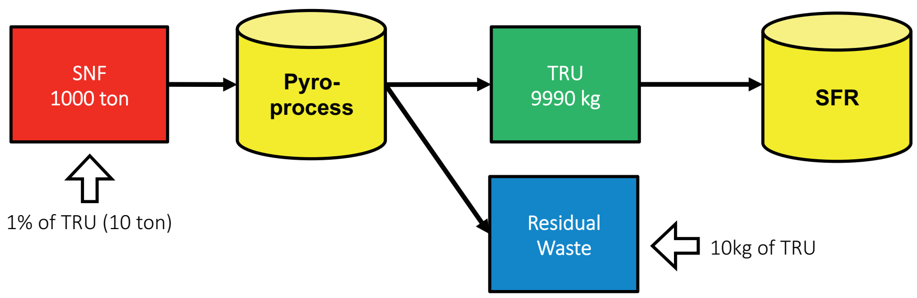
Pyroprocess-SFR System

- Anticipated amount of SNF is about 1000 ton per year at 2025 in Korea
  - It contains 1% of TRU, which is about 10 ton.
- Pyroprocess separates TRU from SNF
  - Separated TRU goes to SFR
  - Residual waste contains about 10kg of TRU



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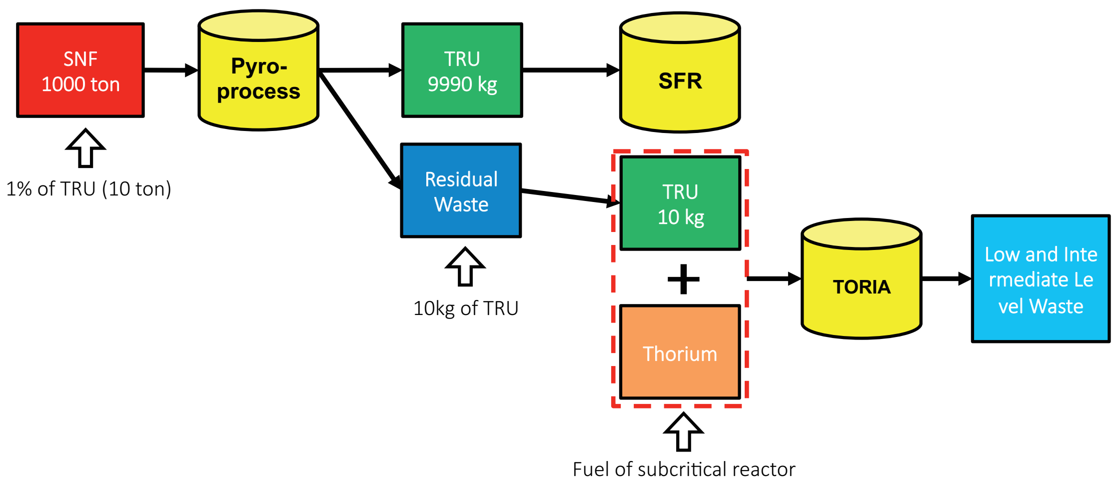
Pyroprocess-SFR-TORIA System

Residual waste containing TRU is mixed with thorium and used for fuel of TORIA. This system leaves behind only low and intermediate level waste.



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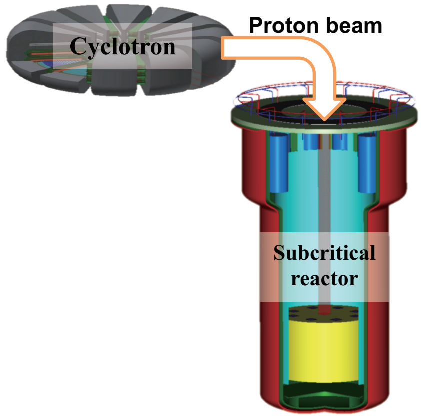
Concepts of TORIA

- **TORIA**: Thorium Optimized Radionuclide Incineration Arena
- **Purpose**
  - TORIA is designed for the purpose of managing spent nuclear fuel by burning TRU and long-lived fission product.
- **Characteristics**
  1. Accelerator-driven subcritical system
  2. Dedicated burner
  3. Thorium based oxide fuel
  4. LBE as coolant and target material

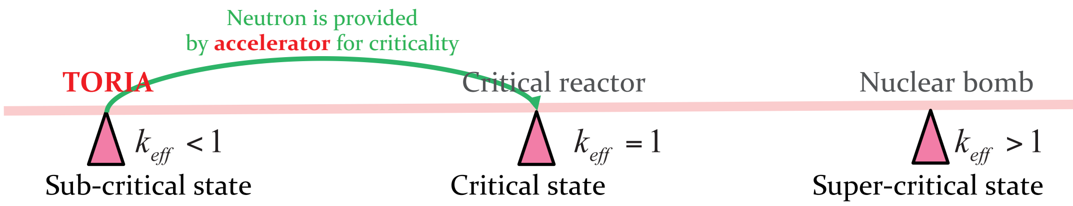


Conceptual diagram of TORIA

Characteristics of TORIA

1. Accelerator driven subcritical system

- Safety margin of TORIA, which is an accelerator-driven subcritical system (ADS), is higher than that of critical system.
  - Low delayed neutron fraction is acceptable in the safety aspect.
- Inherent safety characteristics †
  - "Fundamental property of a design concept that results from the basic choices in the materials used or in other aspects of the design which assures that a particular potential hazard can not become a safety concern in any way."

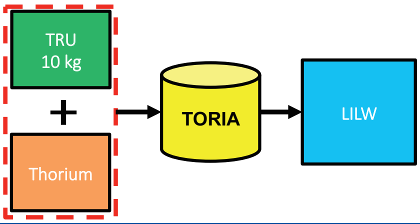


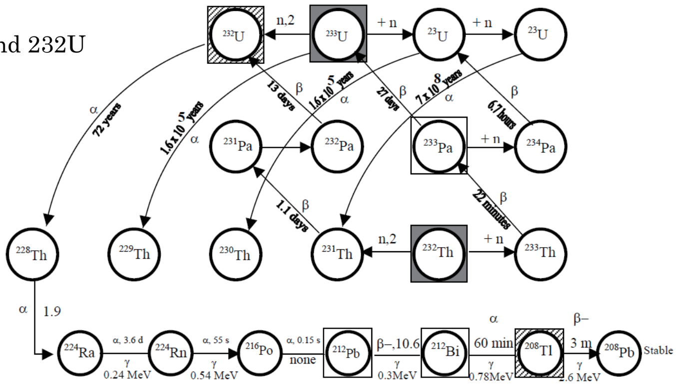
† "Safety related terms for advanced nuclear plants," IAEA-TECDOC-626, September (1991)

Characteristics of TORIA

2. Dedicated burner

- **Subcritical system using thorium-based oxide fuel can incinerate the high level waste, leaving behind only low and intermediate level wastes.**
- Much less quantity of plutonium long-lived minor actinides are formed in 232Th–233U fuel cycle as compared to the 238U–239Pu fuel cycle.
  - As a result, radiotocxicity associated in spent fuel is reduced at 232Th-233U fuel cycle
  - 232Th–233U fuel cycle
    : 231Pa, 229Th, 230U, and 232U
  - 238U–239Pu fuel cycle
    : Np, Am, Cm, and Pu





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† IAEA, Thorium fuel cycle-Potential benefits and challenges, 2005

Fig. 25. Main isotopes in 232Th–233U fuel cycle. †

Characteristics of TORIA

2. Dedicated burner

- PWR to transmutor support ratio†

$$SR = \frac{\text{Decreased transuranic isotope mass during 1 year at a transmutation reactor}}{\text{Increased transuranic isotope mass during 1 GWe production at LWR (PWR)}}$$

  - By adopting thorium based oxide fuel, the support ratio can be increased over that of uranium based oxide fuel because there is less additional TRU generation during operation.

Reactor	Fuel type	Criticality	Coolant	Power (MWth(MWe))	SR	Reference
PEACER-300	U-TRU-Zr	Critical	LBE	850 (300)	2.085	†
KALIMER-600	U-TRU-Zr	Critical	Na	1500 (600)	2.180	††
Generic ADS /w TRU	TRU	Subcritical	-	-	3.422	†††
Generic ADS /w MA	MA	Subcritical	-	-	3.750	†††
Energy Amplifier Demo Facility	Th/PuO2	Subcritical	LBE	80	3.492	††††
Energy Amplifier Demo Facility	U/PuO2	Subcritical	LBE	80	0.571	††††

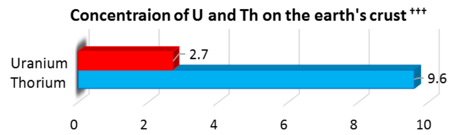
† Lim, J.-Y., Kim, M.-H., "A new LFR design concept for effective TRU transmutation, Progress in Nuclear Energy" 49, 2007
†† Ser Gi Hong, Sang Ji Kim, Yeong Il Kim and Dohee Hahn, 600 MWe Sodium Cooled Fast Reactor Core Designs for Efficient TRU Transmutation, Transactions of the Korean Nuclear Society Spring Meeting (2006)
††† M. Cappiello, The potential role of accelerator driven systems in the US, ICRS-10/RPS 2004, Madeira (PT), 2004
†††† M. Dahlfors, Sensitivity to Nuclear Data and Neutron Source Type in Calculations of Transmutation Capabilities of the Eneregy Amplifier Demonstration Facility

10

Characteristics of TORIA

3. Thorium based oxide fuel

- Thorium is 3 to 4 times more abundant than uranium and is widely distributed in nature as an easily exploitable resource in many countries. ††
- Proliferation resistance
  - Thorium fuel cycle generates 233U
  - High 233U inventory implies high dosed unless shielded
- Production of long-lived minor actinides and plutonium are suppressed
  - Safety improvement of disposal site
- Higher chemical and radiation stability of ThO2 ††
  - Higher thermal conductivity and lower coefficient of thermal expansion compared to UO2
- Fabrication of thorium-based oxide fuel is already shown to be feasible on industrial scale†



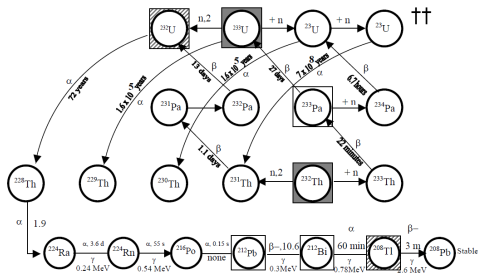


Fig. 25. Main isotopes in 232Th–233U fuel cycle.

† OECD/NEA, "Introduction of thorium in the nuclear fuel cycle", Nuclear Science, 2015
†† IAEA, Thorium fuel cycle-Potential benefits and challenges, 2005
††† Jungmin Kang and Frank N. von Hippel, U-232 and the proliferation-resistance of U-233 in spent fuel, 2001

Characteristics of TORIA

4. LBE as coolant and target material

LBE is a eutectic alloy of lead and bismuth (Pb : Bi = 44.5 : 55.5)

1. Lead does not react with water or air
   - Secondary heat exchanger circuit is not needed unlike SFR.
   - Steam generators are installed inside the rector vessel.
2. Very high boiling point (Lead: 1750°C, LBE: 1670°C)
   - Reduced core voiding reactivity risk
   - Lower probability of loss of coolant during an accident
3. High density
   - **Target material of accelerator beam, high n/p**
   - No need for core catcher (molten clad float and breached fuel could float)
   - Neutron reflector
4. Low moderating capability and low absorption cross-section
   - No need of compact fuel rods (large p/d)
   - Fast neutron spectrum
5. Natural circulation
   - LBE density strongly depends on temperature
   - Passive removal of heat from the reactor without dangerous over-heating of the core

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Characteristics of TORIA

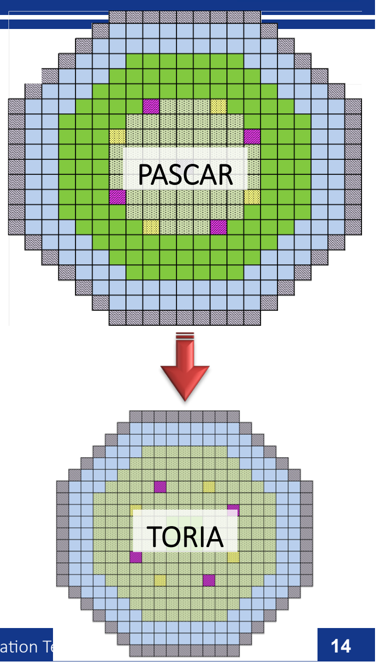
4. LBE as coolant target material

6. Negative void coefficient
7. Safer in the case of a fuel cladding rupture.
   - Lead and LBE has chemical bonding with radiotoxic fission products such as I and Cs
8. Control of corrosion/erosion
   - Compatibility between the coolant and structural steels
9. Coolant activation
   - ${}_{209}\mathrm{Bi} + n \longrightarrow {}_{210}\mathrm{Bi} \xrightarrow[5d]{\beta^-} {}_{210}\mathrm{Po} \xrightarrow[138d]{\alpha} {}_{206}\mathrm{Pb}$
   - Po-210 is of importance due to its high radiotoxicity, chemical toxicity, and heat generation
10. Seismic safety
    - Seismic risk due to large mass of coolant
11. Overcooling transient (secondary side) may cause coolant freezing (melting point : 125°C)
12. LBE is expensive
    - Bismuth is rare material

Design Criteria of TORIA

Preliminary core design

- The design of TORIA is based on the design of PASCAR
  - PASCAR: Proliferation-resistant, Accident-tolerant, Self-supported, Capsular, and Assured Reactor †
- Proportional reduction of the core size
  - To maintain geometrical profiles and core power density
- Things considered to decide core design
  - The amount of TRU needed to be burned.
  - Accelerator performance
  - Construction expenses



† Choi, S., et al. "PASCAR: Long burning small modular reactor based on natural circulation" Nuclear Engineering and Design 241.5 (2011): 1486-1499.

Design Criteria of TORIA

Preliminary core design

- Power of TORIA: 30MWth
  - It is decided to burn 10kg of TRU per year.
    - ✓ It is calculated from proportional relation between power of commercial reactor and mass of uranium depleted.

- Average effective multiplication factor(k_{eff}) is set to be 0.955

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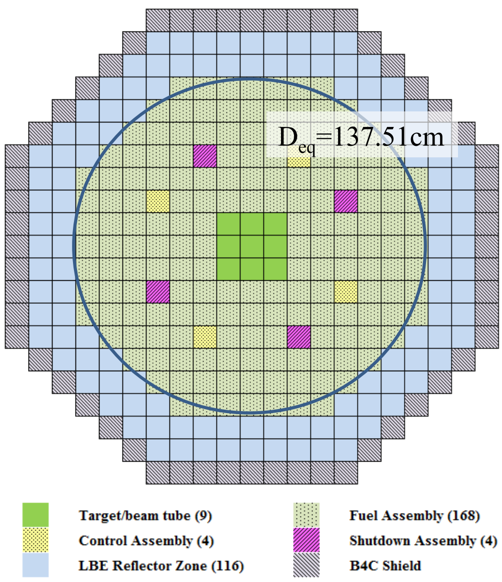
Design Criteria of TORIA

Preliminary core design

Main parameters of preliminary core

Thermal power	$30MW_{th}$
Power plant efficiency	35%
Refueling interval	1000 days
Primary coolant	Lead-bismuth eutectic
Fuel type	(Th-TRU)O2
Cladding, structure material	HT9
Pellet nominal density (%TD)	100.0
Active core height/equivalent diameter (H/D_{eq})	<1
Number of pins per one assembly	64 including 4 skeletal bar
Average effective multiplication factor	0.955
Average core power density	28.856W/cc
Average linear power density	4.252kW/m
Average discharge burnup	14.127MWd/kgHM



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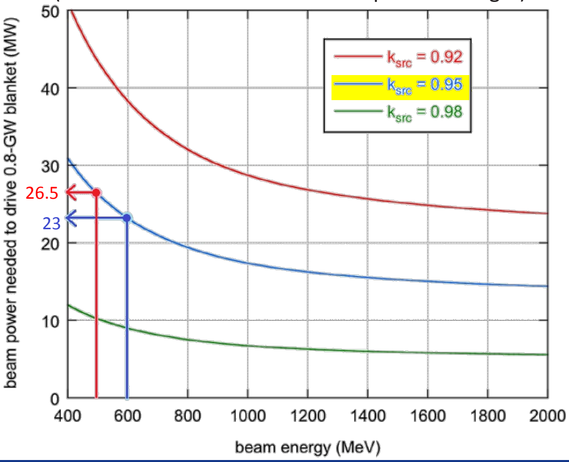
Design Criteria of TORIA

Accelerator

The protons are injected onto a spallation target to produce source neutrons for driving the subcritical core, and proton is generated by accelerator

Beam power needed to drive a 0.8-GW ADS subcritical core
(assumes a 50-cm-diameter LBE spallation target) †



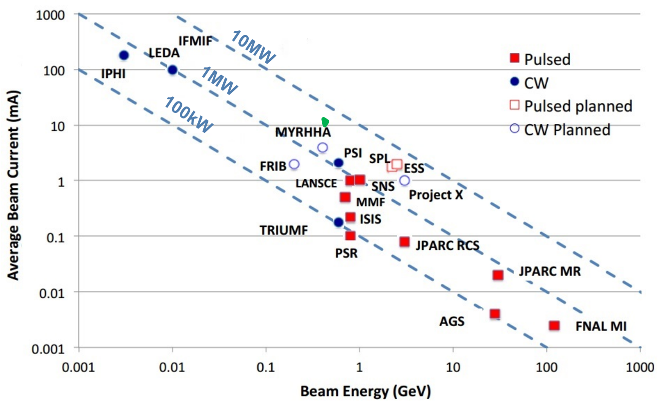
Rx Power \ Beam Energy	500 MeV	600 MeV
800 MWth	26.5 MW	23 MW
MYRRHA 100 MWth		3MW (600MeV, 5mA)
TORIA 30 MWth	1 MW (500 MeV, 2 mA)	0.86 MW (600 MeV, 1.43 mA)

†H. Aït Abderrahim, et. al., "Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production" ADS white paper 2010

Design Criteria of TORIA

Accelerator

- Required proton beam current at the energy of 600MeV and 500MeV is 1.43mA and 2mA, respectively.



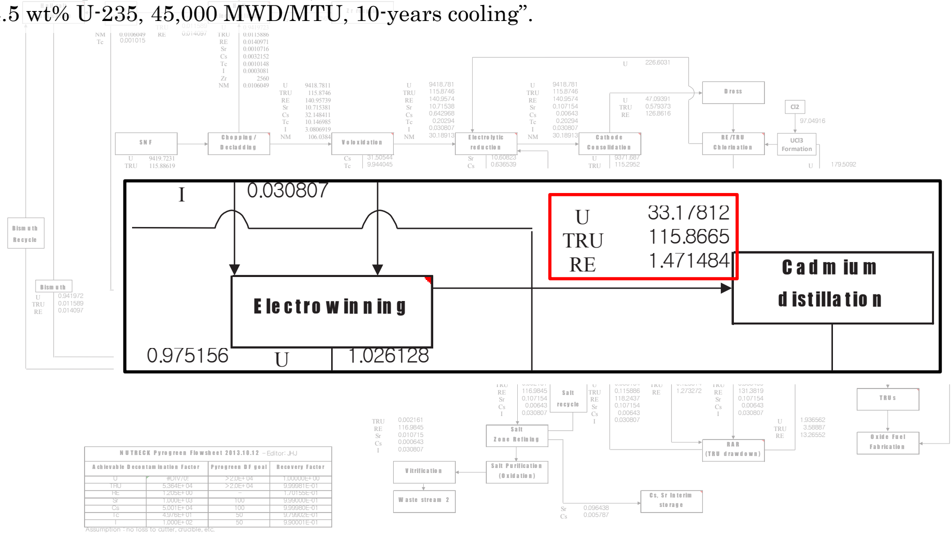
"On the whole, the development status of accelerators is well advanced, and beam powers of up to 10 MW for cyclotrons and 100 MW for linacs now appear to be feasible. However, further development is required with respect to the beam losses and especially the beam trips to avoid fast temperature and mechanical stress transients in the reactor." †

†"Acclerator Driven Stems (ADS) and fast reactors in advanced nuclear fuel cycles," 2002,

Design of TORIA

Fuel composition

Fuel composition was decided by "Flow sheet and mass balance of 10 MTHM of oxide fuel with 4.5 wt% U-235, 45,000 MWD/MTU, 10-years cooling".



†OECD/NEA, "Spent Nuclear Fuel Reprocessing Flowsheet", Paris, France, 2012

Design of TORIA

Fuel composition

- U: TRU: RE= 33.178: 115.87: 1.4715

TRU Composition (Mass fraction)♪					
Uranium♪		TRU♪			
Isotope	Mass fraction	Isotope	Mass fraction	Isotope	Mass fraction
U234	1.99E-04	NP237	4.59E-02	AM241	5.05E-02
U235	8.34E-03	PU238	1.36E-02	AM242M	6.51E-05
U236	4.14E-03	PU239	5.18E-01	AM243	8.81E-03
U238	9.87E-01	PU240	2.38E-01	CM243	2.83E-05
♪	♪	PU241	7.75E-02	CM244	1.68E-03
♪	♪	PU242	4.64E-02	CM245	8.78E-05
♪	♪			CM246	1.05E-05
Sum♪	1.00	Sum♪		1.00	

- Mass ratio between Th and TRU is decided to be **Th:TRU=0.633:0.367.**

Calculation method

OECD/NEA benchmark

- There were international benchmarks about accelerator driven system calculations.
    1. Theoretical benchmark
        - Comparison calculations for an accelerator-driven minor actinide burner (1999~2001)
    2. Experimental benchmark
        - Benchmark on computer simulation of MASURCA critical and subcritical experiments: MUSE-4 benchmark (2001~2005)
- The discrepancies are given from the data libraries used in both benchmarks.
- In the case of calculation methods, there is no clear evidence which method is adequate for ADS.

  (Method: deterministic method/ Monte-Carlo method)

Combinations of codes and libraries of the different solutions †

	JEF-2.2	ERALIB1 JEF-2.2	ENDF/B-6	ENDF/B-5	JENDL-3.2
Deterministic					
MC2-ERANOS	ANLjefe		ANLb6m	ANLb5m	
ERANOS2.0		CEA			
ECCO-ERANOS	ENEA				
ECCO-ERANOS	ANLjefm				
ERANOS-1.2-33g	PSIejf4 (New ^{239}Pu total)	PSIeral			
TORT Sn	KFKI (172 & 4 groups)				
LOOP2			RRCK		
Monte Carlo					
MCNP4b			UPM		
MCNP4c	PSIjef2 (^{239}Pu partial X-sections)		CNRS		
MCNP4c	PSIjef3 (^{239}Pu total X-sections J)		PSIb6		
MCNP4c	PSIjef4 (^{239}Pu partial X-sections F)		PSIb6ures (Unresolved resonances)		
MCNP4c3	CIEMAT (^{239}Pu fr. CEA)				
MCNP4c3	SCKjef (^{239}Pu fr. CEA)		SCKendf		
MCNP4c3	NRG (+ ENDFB6.2+ JENDL3.2)		FZJ (+ ENDFB5)		
MCNP4c3	RIT				
MCNP4c2	UMM (+ ENDFB6.2)				
MCNP4c2	VTT (4 cases)		VTT (2 cases)		VTTjjdl (+ 1 case)
VIM			ANLVIM		
MVP					JAERI + ^{197}Au (ENDFB6)

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†OECD/NEA, "Benchmark on computer simulation of MASURCA critical and subcritical experiments_MUSE-4 benchmark", NEA/NSC/DOC(2005)23

Calculation method

TRANSX2.15-DANTSYS3.0-REBUS-3 code system

- Deterministic code system for fast neutronics analyses, consisting of TRANSX2.15, DANTSYS3.0, and REBUS-3 was used in the preliminary core design.
- KAFAX-F22 library is based on JEF-2.2 library.
    - ✓ MATXS format library is generated from JEF-2.2 using NJOY
    - ✓ Neutron: 80 group, 1.3888x10-4eV ~ 200MeV
    - ✓ Photon: 24 group, 10keV~30MeV

Energy group of KAFAX-F22 and ISOTXS

80 Groups						24 Groups	
Group No.	Upper Energy Boundary (MeV)	Group No.	Upper Energy Boundary (MeV)	Group No.	Upper Energy Boundary (MeV)	Group No.	Upper Energy Boundary (MeV)
1	2.00E+01	28	1.43E-01	55	2.61E-03	1	2.00E+01
2	1.69E+01	29	1.11E-01	56	2.31E-03	2	6.07E+00
3	1.49E+01	30	8.65E-02	57	2.03E-03	3	3.68E+00
4	1.35E+01	31	6.74E-02	58	1.80E-03	4	2.23E+00
5	1.19E+01	32	5.25E-02	59	1.58E-03	5	1.35E+00
6	1.00E+01	33	4.09E-02	60	1.40E-03	6	8.21E-01
7	7.79E+00	34	3.18E-02	61	1.23E-03	7	4.98E-01
8	6.07E+00	35	2.81E-02	62	1.09E-03	8	3.02E-01
9	4.72E+00	36	2.61E-02	63	9.61E-04	9	1.83E-01
10	3.68E+00	37	2.48E-02	64	7.49E-04	10	1.11E-01
11	2.87E+00	38	2.19E-02	65	5.83E-04	11	6.74E-02
12	2.23E+00	39	1.93E-02	66	4.54E-04	12	4.09E-02
13	1.74E+00	40	1.70E-02	67	3.54E-04	13	2.48E-02
14	1.35E+00	41	1.50E-02	68	2.75E-04	14	1.50E-02
15	1.19E+00	42	1.33E-02	69	1.67E-04	15	9.12E-03
16	1.05E+00	43	1.17E-02	70	1.01E-04	16	5.53E-03
17	9.30E-01	44	1.03E-02	71	6.14E-05	17	3.35E-03
18	8.21E-01	45	9.12E-03	72	3.73E-05	18	2.03E-03
19	7.24E-01	46	8.05E-03	73	2.26E-05	19	1.23E-03
20	6.39E-01	47	7.10E-03	74	1.37E-05	20	4.54E-04
21	5.64E-01	48	6.27E-03	75	8.32E-06	21	6.14E-05
22	4.98E-01	49	5.53E-03	76	5.04E-06	22	3.73E-05
23	4.36E-01	50	4.88E-03	77	3.06E-06	23	1.37E-05
24	3.88E-01	51	4.31E-03	78	1.13E-06	24	4.14E-07
25	3.02E-01	52	3.80E-03	79	4.14E-07		1.39E-10
26	2.35E-01	53	3.35E-03	80	1.52E-07		
27	1.83E-01	54	2.96E-03		1.39E-10		

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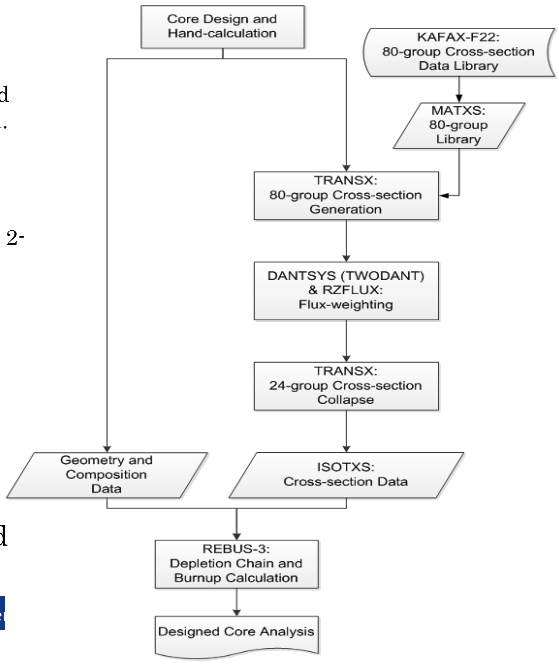
Calculation method

TRANSX2.15-DANTSYS3.0-REBUS-3 code system

- TRANSX2.15 and DANTSYS3.0
  - Generating effective cross section.
  - ✓ TRANSX2.15 uses MATXS format library and input file containing composition information. And it gives CX file in the form of ISOTXS
  - ✓ DANTSYS3.0 uses ISOTXS file generated by TRANSX2.15.
  - ✓ DANTSYS3.0 uses TWODANT module using 2-D transport calculation.
  - ✓ Binary format of ISOTXS is translated to ASCII format to be used in REBUS-3.
- REBUS-3
  - ✓ Depletion chain and burnup calculation
  - ✓ Nuclear design and evaluation
- The external source was not considered for this preliminary analysis.

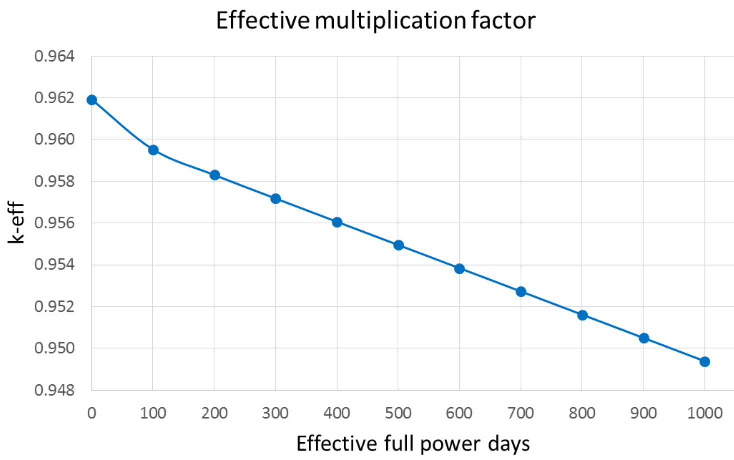


Calculation result

Effective multiplication factor

Average effective multiplication factor is 0.955 and total defect of effective multiplication factor is about 1300pcm.

Time(days)	k_{eff}
0	0.962
100	0.960
200	0.958
300	0.957
400	0.956
500	0.955
600	0.954
700	0.953
800	0.952
900	0.951
1000	0.949



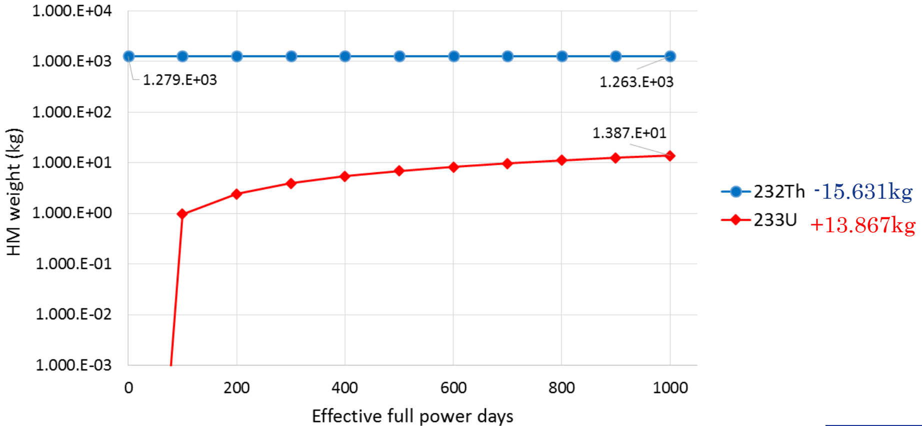
Calculation result

Mass balance-uranium and thorium

- Fertile/fissile fuel cycles: 232Th breeds 233U

$$^{232}Th \xrightarrow{(n,\gamma)} {}^{233}Th \xrightarrow[T_{1/2}=22min]{\beta^-} {}^{233}Pa \xrightarrow[T_{1/2}=27d]{\beta^-} {}^{233}U$$

- Production of 233U compensates defect of k_{eff}.



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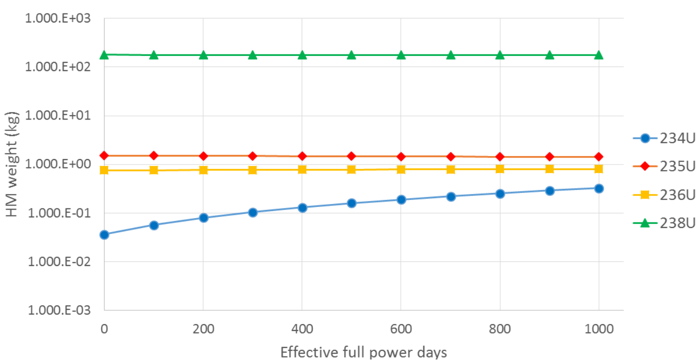
Calculation result

Mass balance-uranium and thorium

(kg)	BOC	EOC	EOC -BOC
232Th	1278.660	1263.030	-15.631
233U	0.000	13.867	13.867
234U	0.036	0.325	0.289
235U	1.510	1.418	-0.092
236U	0.750	0.803	0.053
238U	179.012	176.953	-2.059



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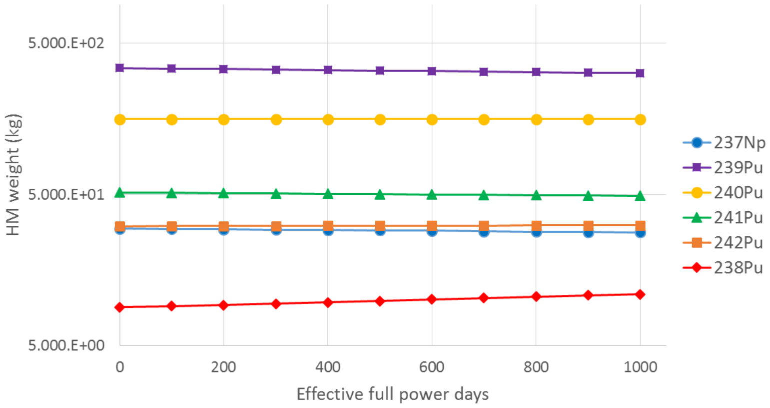
Calculation result

Mass balance-transuranic elements

- The quantity of produced neptunium and plutonium is small.
  - Neptunium and plutonium are produced by transmutation of 238U which is loaded at BOC rather than 232Th.

(kg)	BOC	EOC	EOC -BOC
237Np	29.691	28.044	-1.647
238Pu	8.991	10.929	1.938
239Pu	**342.915**	**317.960**	-24.954
240Pu	157.634	157.534	-0.099
241Pu	51.442	48.875	-2.567
242Pu	30.807	31.291	0.484

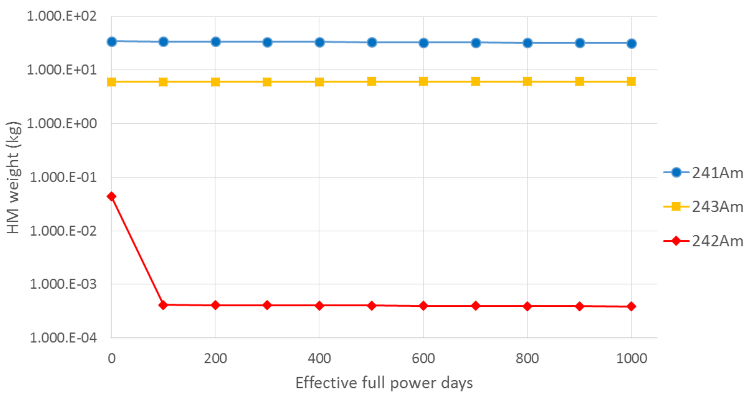


Calculation result

Mass balance

- Major isotopes in terms of loaded mass among actinides (239Pu, 241Am) are burned effectively.

(kg)	BOC	EOC	EOC -BOC
241Am	**34.376**	**31.783**	-2.592
242Am	0.044	0.000	-0.044
243Am	6.018	6.104	0.086

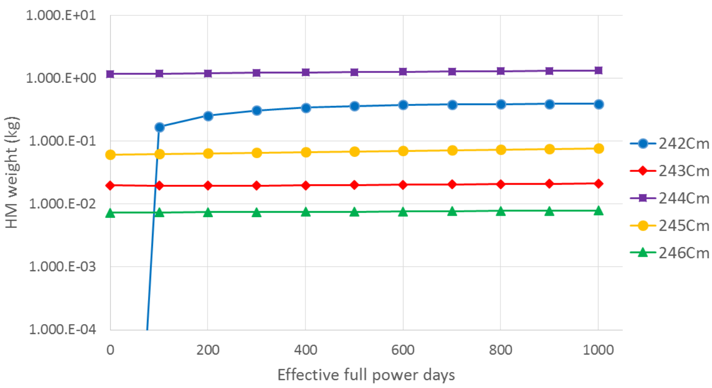


Calculation result

Mass balance-transuranic elements

- Generation of curium is suppressed compared to other types of reactors.

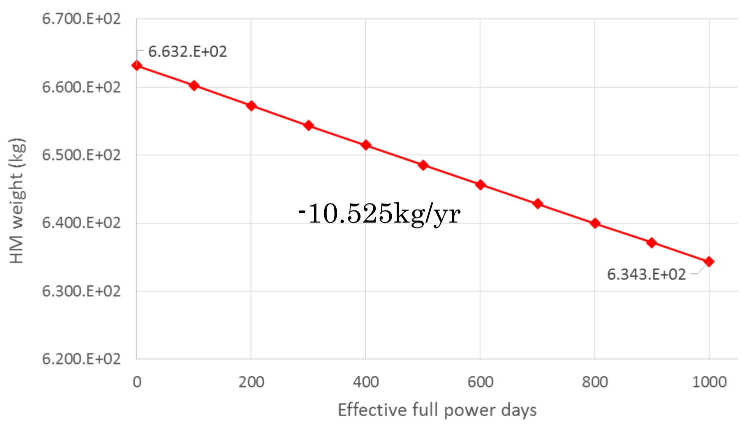
(kg)	BOC	EOC	EOC -BOC
242Cm	0.000	0.390	0.390
243Cm	0.020	0.021	0.001
244Cm	1.171	1.325	0.154
245Cm	0.061	0.077	0.015
246Cm	0.007	0.008	0.001



Calculation result

Mass balance-transuranic elements

- Total TRU destruction is about 28.834kg during 1000 days (1 cycle).
  → 10.525 kg TRU destruction per year



Conclusion

- 99.9% of spent nuclear fuel can be reused by pyroprocess-SFR system, and rest of long –lived TRU elements are burned by TORIA, subcritical dedicated burner. As a result, spent nuclear fuel can be declassified from HLW to LILW by Pyroprocess-SFR-TORIA system.
- Amount of transuranic elements generation in thorium fuel cycle is small compared to uranium fuel cycle.
- TORIA puts its priority on transmutation of high radiotoxic transuranic elements. Transmutation of long-lived fission products such as Tc-99 and I-129 will be studied further.
- TORIA considers cyclotron as proton supplier, which is considered to be feasible, economically efficient, and reliable.
- It is expected to be useful in the step of detailed core design by understanding the characteristics of core loaded with thorium-based oxide fuel. It should consider external neutron source and optimization including fuel composition, geometrical arrangements, etc. is necessary.

The First topical Meeting on Asian Network for Accelerator-driven Systems and Nuclear Transmutation Technology 31

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Thank you

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5. Activities for J-PARC Transmutation Experimental Facility

5.1 TEF-T Target Station Design and Maintenance

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TEF-T Target Station Design and Maintenance

Hironari OBAYASHI, Hidemitsu YOSHIMOTO, Kazushi YAMAGUCHI,
Tao WAN, Hiroki IWAMOTO, Shigeru SAITO, and Toshinobu SASA
Target Technology Development Section, Nuclear Transmutation Division,
J-PARC Center, JAEA

Japan Atomic Energy Agency (JAEA) has been researching and developing an accelerator-driven system (ADS) as a dedicated system for the transmutation of long-lived radioactive nuclides. The ADS proposed by JAEA uses lead bismuth eutectic (LBE) as a target material and a coolant. Construction of the Transmutation Experimental Facility (TEF) is planned under the framework of the J-PARC project as a preceding step before the construction of demonstrative ADS. In TEF, ADS target experimental facility (TEF-T) is aimed for the acquisition of irradiation data of ADS's candidate materials by using 400MeV-250kW proton beam.

Almost concept of LBE spallation target system was based on a mercury target system in J-PARC. A target vessel with irradiation samples is installed to the fixed irradiation position by a trolley. The evaluated maximum dpa value of irradiation samples was 8 dpa/y. However, requirement from PIE experiment is over 15 dpa. Hence repetitive irradiation will be performed in TEF-T. Comparing with the mercury target, LBE target requires preheating system for operation. As a result of application test, the packaged-heater system worked well. Because the target vessel and surrounding environment becomes the strong radioactivation state after bombardment of proton beam, the remote maintainability is required to exchange each component. The design of basic layout of LBE target system was performed by considering the drain route and maintainability. Further design harmonized with remote operation by MSM and PM will be performed.

1st TM Asia ADS & NTT
27-29, Oct., 2015

TEF-T Target Station design and Maintenance

○H.Obayashi, H.Yoshimoto, K.Yamaguchi, T.Wan,
H. Iwamoto, S.Saito, T.Sasa

J-PARC Center, JAEA

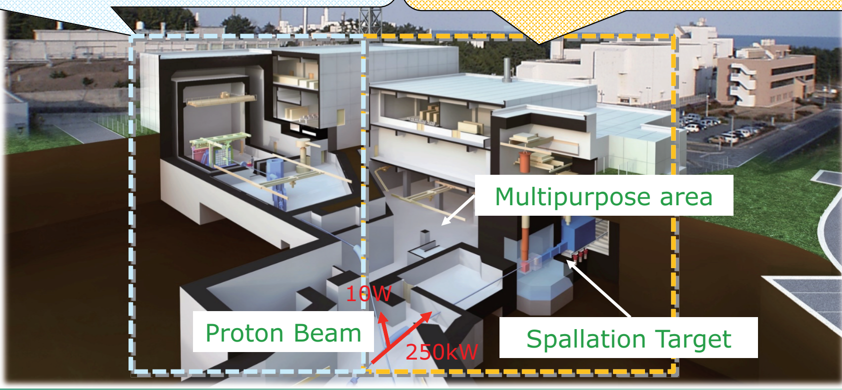
1

Outline of TEF-T (1/2)

- Construction of the Transmutation Experimental Facility (TEF) is planned under the framework of the J-PARC project as a preceding step before the construction of demonstrative ADS.

TEF-P: Transmutation Physics Experimental Facility
Purpose: Reactor physics

TEF-T: ADS Target Test Facility
Purpose: Material irradiation



2

Outline of TEF-T (2/2)

Purpose of TEF-T

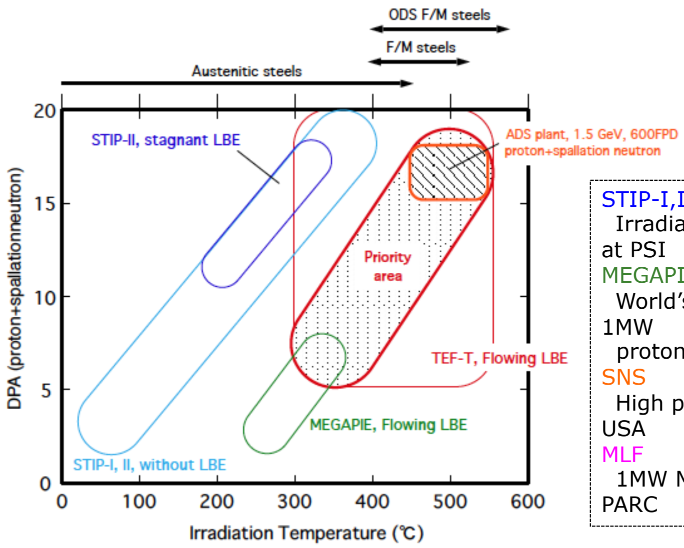
- To get ADS material irradiation data
- Demonstration of components

Specifications of TEF-T Spallation Target

Item	Specification
Coolant / Target medium	Lead-Bismuth Eutectic alloy (LBE)
Working temperature	400-500˚C Max. in LBE 550˚C Max. in irradiation sample
Control of oxygen concentration	Available
Power of proton beam	400 MeV-250 kW

3

Material data taken by TEF-T Target



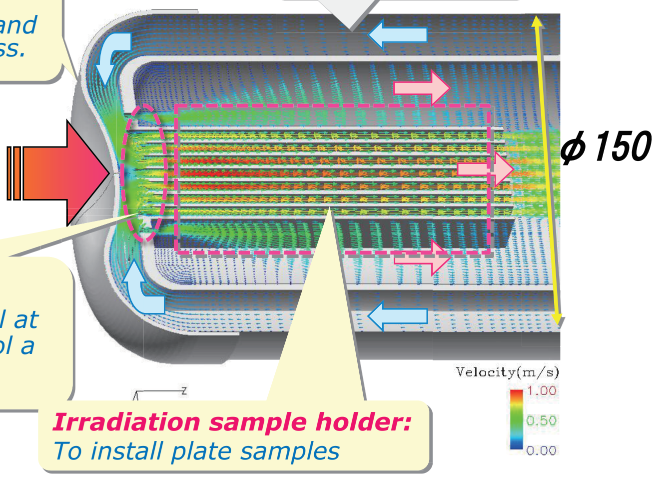
STIP-I,II
Irradiation in Stagnant Pb-Bi performed at PSI
MEGAPIE
World's first Pb-Bi spallation target with 1MW
proton beam performed at PSI
SNS
High power spallation neutron source in USA
MLF
1MW Mercury spallation target of J-PARC

- Irradiation data at higher temperature range than existing experiments is required to realize ADS

Conceptual design of target vessel

Conceptual design of target vessel

- Flow configuration: Coaxially arranged annular flow channel



Beam window: *To assist returned flow and reduce the thermal stress.*

Perforated plate: *To improve heat removal at beam window and control a flow in sample region.*

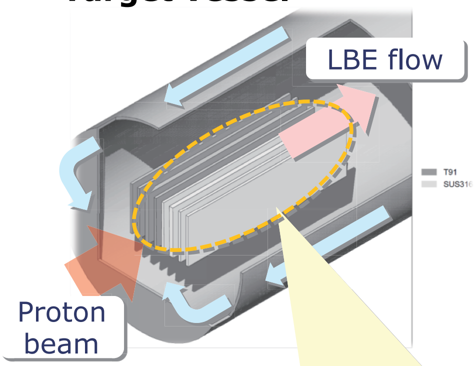
Irradiation sample holder: *To install plate samples*

R&D for present design ⇒ Dr. Wan

JAEA Nuclear Transmutation Division, J-PARC Center, Japan Atomic Energy Agency J-PARC

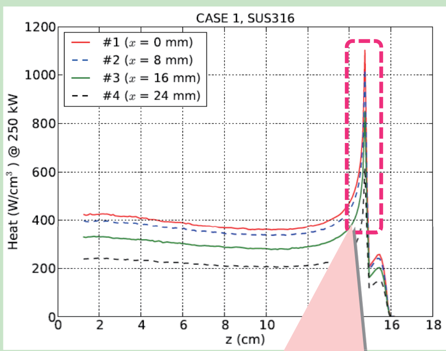
Heat deposition

Target vessel



Irradiation samples
Number: 8 samples (present design)
Material: T91, 316SS, other candidate

Calculated Heat deposition by PHITS code



Bragg peak
Appeared at depth of 15 cm

- Extremely high heat deposition

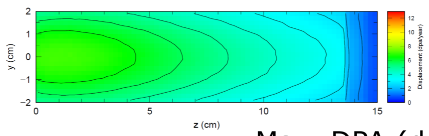
Length of irradiation samples
⇒ reduced < 14 cm

Evaluated irradiation damage of samples

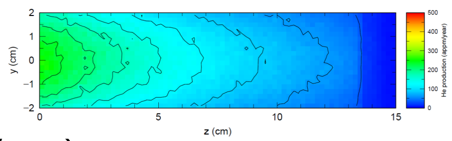
Estimation of DPA and Helium production of irradiation samples

Example) Peak beam current density : 20 mA/cm² = planning ADS plant in JAEA

DPA



He Production



		Max. DPA (dpa/year)		Max. He Production (dpa/year)	
		T91	SUS316	T91	SUS316
Inner	Sample #1	7.6	7.7	249	254
↕	Sample #2	6.8	6.8	217	222
↕	Sample #3	5.8	5.9	181	175
Outer	Sample #4	4.7	4.7	137	129
	BW	6.0	—	274	—

- Max. DPA of Irradiation sample is 7-8 dpa/year (≈4,500hr).

⇒required irradiation sample for PIE experiment: 15≤

Repetitive irradiation will be performed in TEF-T.

JAEA Nuclear Transmutation Division, J-PARC Center, Japan Atomic Energy Agency J-PARC

Design of Target system

High radiation environment

- **Almost concept was based on MLF(mercury target system) in J-PARC.**

○Target vessel is installed to the irradiation position by trolley.

⇒ Present trolley design will be introduced by Mr. Yoshimoto.

○ Remote exchanging of each component is performed by MSM & PM.

Difficulties to use of LBE

- **Preheating device & insulator**
- **Control of oxygen concentration**

⇒ Introduced by Dr. Sugawara & Mr. Yamaguchi

- **Flow monitoring system**

⇒ Introduced by Obayashi (tomorrow)

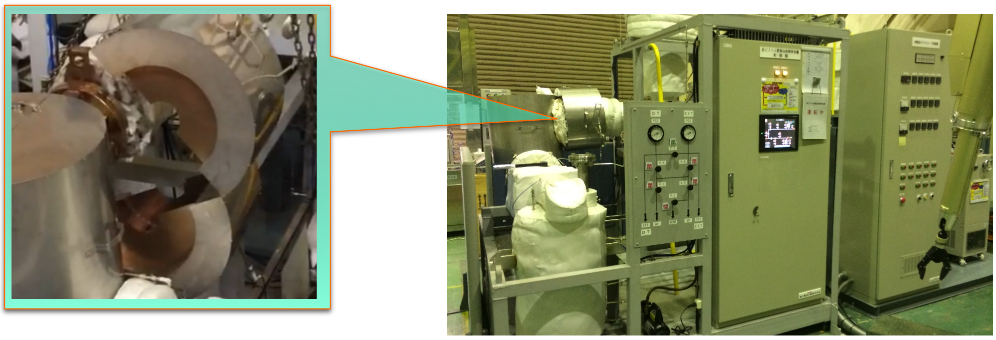
- **Other component for LBE handling**

⇒ Introduced by Dr. Sasa & Obayashi

Hironari OBAYASHI TEF-T Target Station Design and Maintenance

Remote preheating device & insulator

- To exchange/remove each component, removing of preheating device & insulator is necessary.



- Comparing with Hg target, Pb-Bi target requires preheating system for operation.
- Application of the technology from fast reactor "Monju"
- Works well at basic handling test
- Further improvement to optimize remote handling is underway.

9

JAEA Nuclear Transmutation Division, J-PARC Center, Japan Atomic Energy Agency J-PARC

Design of Target system

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⇒ Introduced by Dr. Sasa & Obayashi

10

Hironari OBAYASHI TEF-T Target Station Design and Maintenance

Target trolley (1/3)

Designed based on the experience in MLF

- Similar structure was adopted.
- Some modification is necessary.

(by using LBE: temp. condition, exchanging method, etc.)

Basic design concept

- Application of elemental technology for LBE handling

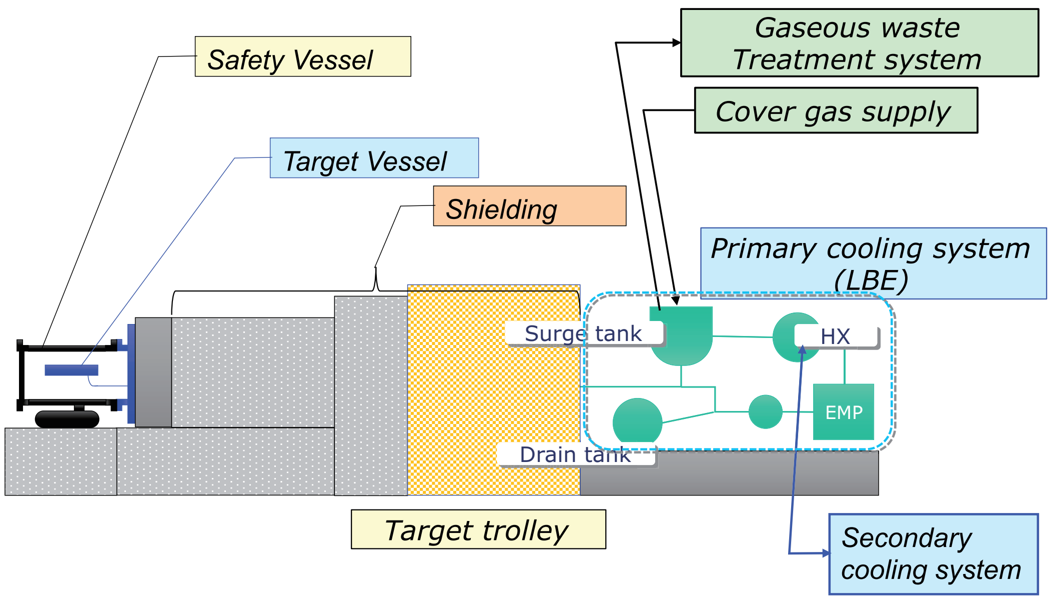
⇒ Packaged system, HX, EMP, monitoring system…

- Reduction of overall height of primary cooling system

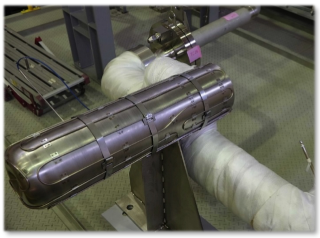
⇒ Slope angle of 1/25 is considered for drain of LBE

- Considering accessibility for remote handling device

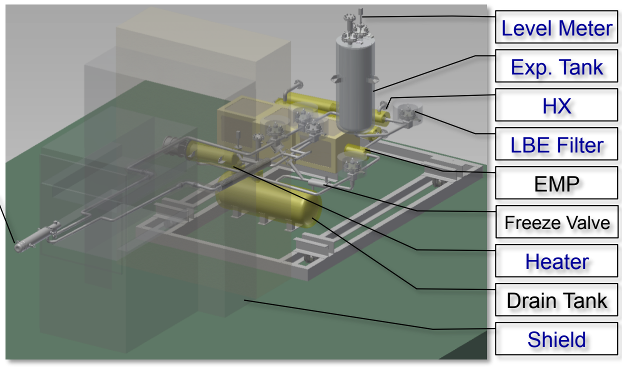
Target trolley (2/3)



Target trolley (3/3) Conceptual view



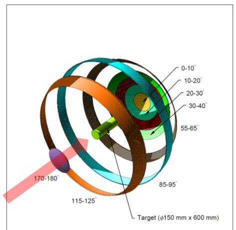
Target Mockup



- Base layout was finished considering the drain route and maintainability through shield window.
- Further design harmonized with remote operation by MSM and PM will be performed.

Radiation shielding of target station

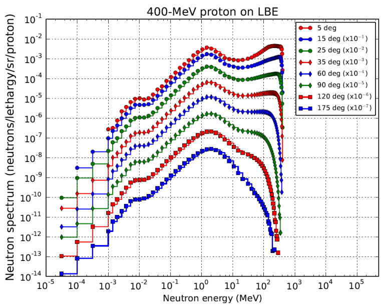
Thickness of shielding material



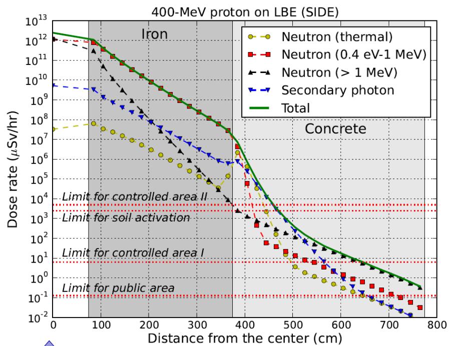
Target: LBE
Dimension: 15 cm$^{\Phi}$ x 60 cm

400 MeV proton beam

Neutron source



Neutron Spectrum from target



Attenuation of radiation

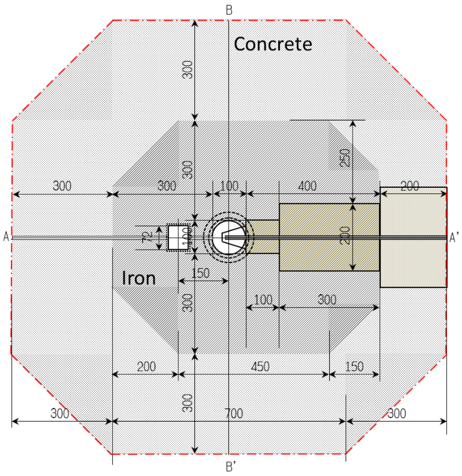
Determine Shield Thickness

e.g., Iron 3 m, Concrete 3 m on the side of LBE target

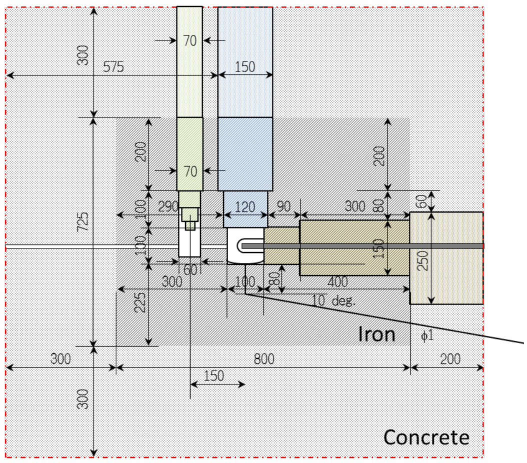
Radiation shielding of target station

Thickness of shielding material

Rough Structure of Shielding



Plain View



Elevation View

15

Summary

- **Design of TEF-T Target system has been performed.**
  - Basic design of target trolley & rough structure of shielding were performed.
  - Design upgrade will be performed by latest R&D result.
- **Remaining issues**
  - Detail design by considering remote handling procedure
  - Safety evaluation with fixed experimental parameters.

16

Nuclear Transmutation Division, J-PARC Center, Japan Atomic Energy Agency

End

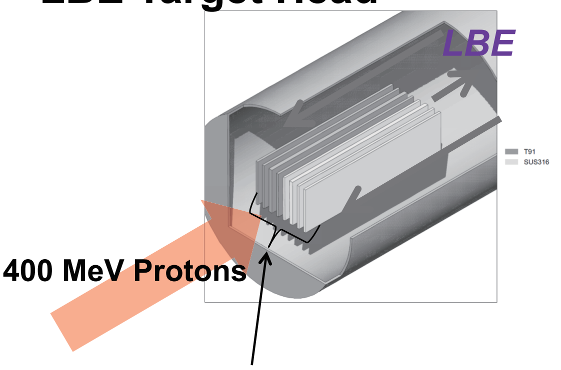
Thank you for your kind attention.

17

Hironari OBAYASHI TEF-T Target Mock-up Loop

Irradiation Performances

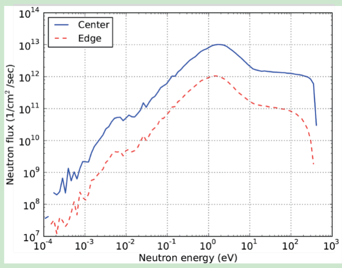
LBE Target Head



Irradiation Samples (2 mm^t)

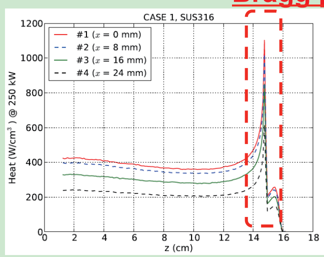
- **T91**
- **SUS316**

Neutron Flux



Heat

Bragg peak



Length of irradiation samples < 14 cm

July 10, 2014 T-TAC, TEF-T Overview and Multipurpose Use 18

5.2 LBE Primary Loop and Target Trolley Design

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LBE primary loop and target trolley design

The First Topical Meeting on Asian Network for ADS & NTT
2015/10/26

Hidemitsu Yoshimoto
Target Technology Development Section,
Nuclear Transmutation Division, J-PARC Center, JAEA

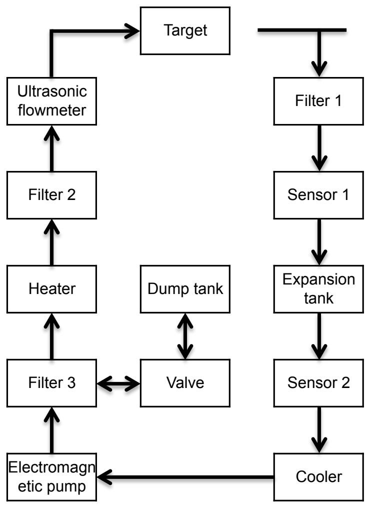
Contents

1. Design concept
2. Arrangement conditions
3. Appearance and equipment layout
4. Maintenance
5. Summary

1. Design concept

- Since the heat is generated by the proton beam into the target, deposited heat are removed by LBE.
- Cooler is placed in the LBE loop for heat removal.
- Heater is also locates to adjust the LBE target inlet temperature.
- To inhibit corrosion of the inner surface of pipes, oxygen sensor is placed to control oxygen concentration in LBE.
- Electromagnetic pump is used to circulate LBE.
- Ultrasonic flow meter is used to observe LBE flow rate.
- These devices are mounted on a target trolley with shields.
- Spallation target can be exchanged by remote handling.
- Location of sensor and the filter are designed to be exchanged with remote handling.

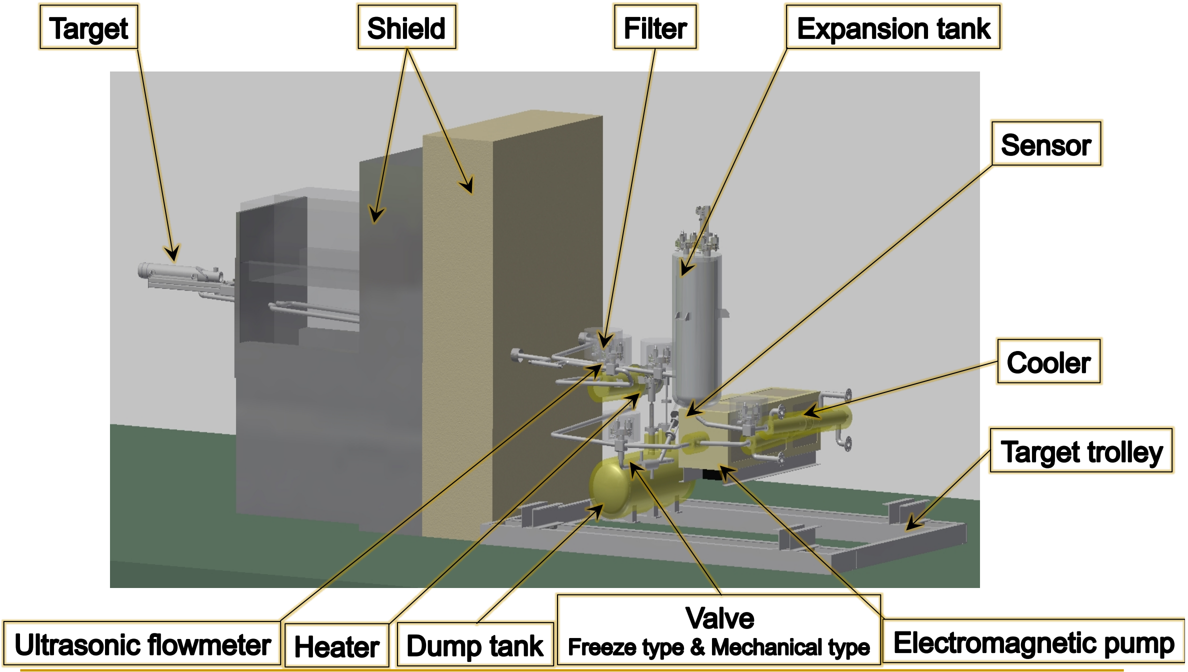
LBE primary loop configuration



2. Arrangement conditions

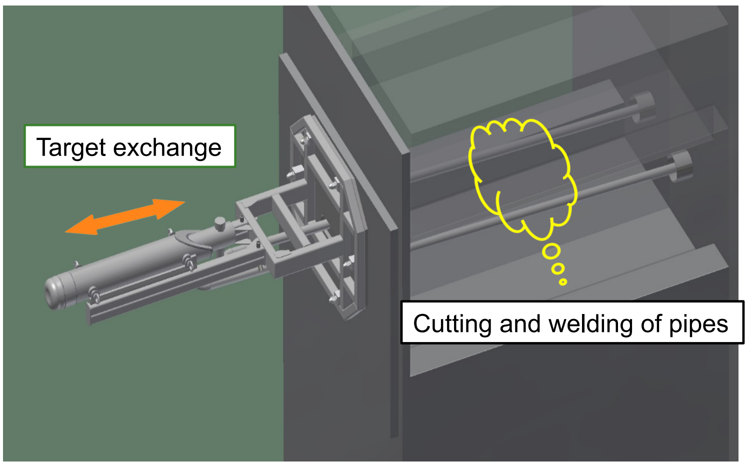
- In order to collect all LBE into drain tank at system shutdown, loop is arranged with the gradient of 1/25 towards the drain tank.
- Installation height of the loop is designed as low as possible.
- Loop is also arranged to pull out the drive unit (coil) of the electromagnetic pump from the target trolley.
- Freeze valve is selected for the drain valve of the primary loop.
- In the viewpoint of remote handling replacement, the sensors and the filters are located besides the shield wall which install the manipulators.
- Target exchange by the remote handling is essential.

3. Appearance and equipment layout



4.Maintenance ①

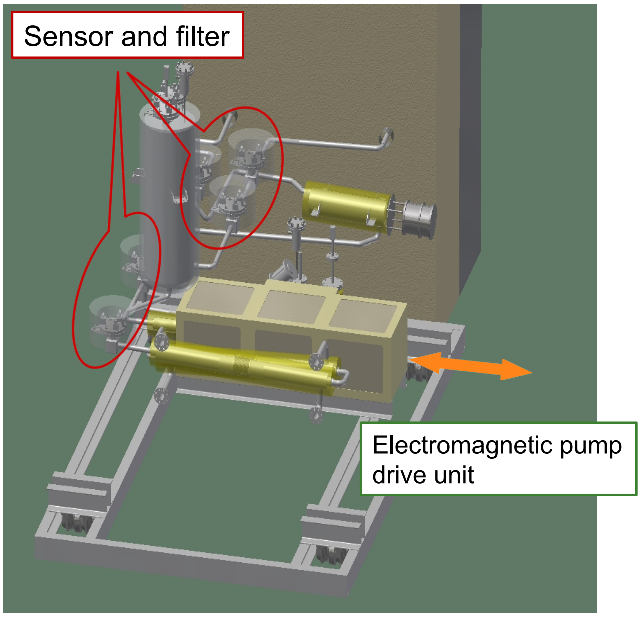
・Target exchange



Cutting pipes in remote handling
↓
Replaced with a new target
↓
Welded pipes in remote handling

4. Maintenance ②

・Sensor and filter exchange



It pulled out an electromagnetic pump drive unit.

Sensor and filter replacement in remote handling.

It is placed on the wall side in view of the operation in the Master-slave manipulator.

5. Summary

- By basic arrangement it has been completed, to advance the construction of the selection and handling procedures of remote handling equipment.
- For remote operation the exchange of the target, a tool selection or development, go to establish and verify the procedure.
- We are just leaving the detailed design of the target trolley.

5.3 Target Analysis and Monitor System

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Target analysis and monitor system

Tao WAN, Hironari OBAYASHI, Toshinobu SASA

Target Technology Development Section, Nuclear Transmutation Division,

J-PARC Center, Japan Atomic Energy Agency

JAEA has proposed an accelerator-driven system (ADS) for transmutation of high-level radioactive waste. Principally to accumulate material irradiation data for ADS, an ADS Target Test Facility (TEF-T), will be constructed within the framework of J-PARC. In the TEF-T, liquid lead-bismuth eutectic (LBE) will be adopted as the coolant and spallation material, which to be bombarded by pulsed proton beams (250 kW, 400 MeV, 25 Hz, 0.5 ms in pulse duration).

To guarantee the feasibility of target vessel, structural analyses should be implemented to assess the structural integrity, and the CFD analyses should be performed to optimize the LBE flow as well. On the other hand, severe erosion/corrosion damage on target vessel due to contact with fast flowing LBE could be foreseeable. So it is expected to install a monitor system to evaluate damage, and further to estimate the lifetime and ensure the stable operation of the target.

In the present work, firstly, the stress imposed on the target vessel, including the static stress caused by design pressure and thermal stress, as well as the dynamic stress due to the pressure waves, were calculated. The structural integrity of target vessel was found can be guaranteed when beam current density is below 30 $\mu A/cm^2$. Secondly, un-parallel plate-type flow guides were added to effectively reduce the stagnant regions of LBE, which attributes to the axisymmetric configuration of target vessel. Furthermore, a Laser Doppler Vibrometer (LDV) system has been proposed as the in-situ target monitor system. A technique, Wavelet Differential Analysis (WDA), has been developed to quantitatively evaluate damage on the target vessel.

In the future, experiments will be carried out to verify the effects of flow-guides on LBE flow behavior and to validate the effectiveness of developed in-situ structural integrity diagnostic technique.

Target Analysis and monitor system

Target Technology Development Section,
Nuclear Transmutation Division,
J-PARC Center

Tao WAN, Hironari OBAYASHI, Toshinobu SASA

2015.10.26
Asian ADS Topical Meeting for LBE Applications

2

Contents

- Background & Purpose
- Target analysis
- Structural integrity diagnostic technique development
- Summary & Future work

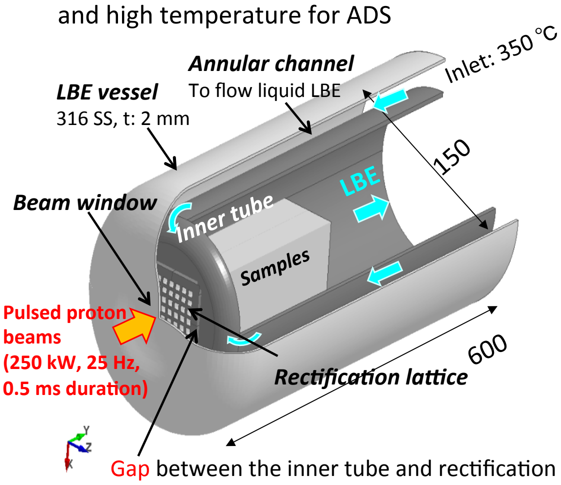
3

Background & Purpose

TEF-T LBE spallation target

LBE: Lead-Bismuth Eutectic

- Flow behavior of LBE
- R&D of materials under irradiation, LBE flow and high temperature for ADS



Gap between the inner tube and rectification lattice to flow LBE to cool the samples.

Target analysis

Guarantee the feasibility of target vessel

- ***Structural analysis***
  - *Assess the structural integrity of target vessel*
- ***CFD analysis***
  - *Optimization of LBE flow*
  - *Minimize the possibility of damage occurrence*

Target monitor system

Severe erosion/corrosion damage is expected

⇩

- ***Structural integrity diagnostic technique***
  - Damage evaluation
  - Lifetime estimation
  - Stable operation

4

Contents

- Background & Purpose
- **Target analysis**
- Structural integrity diagnostic technique development
- Summary & Future work

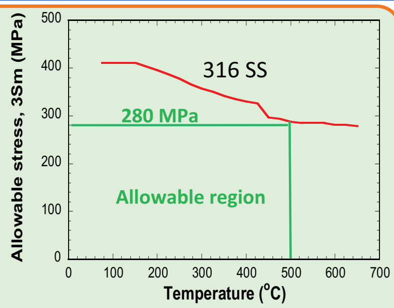
5

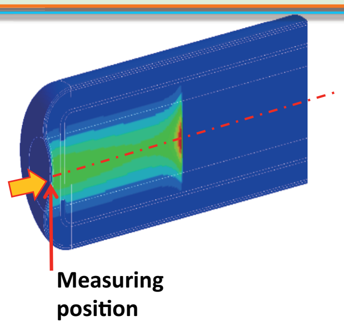
Structural analysis for original target design

Guarantee the structural integrity of LBE vessel

(imposed stress < allowable stress)

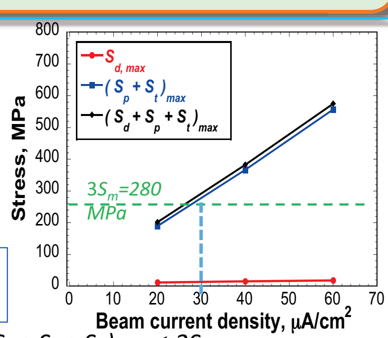
- Static stress:
  - due to design pressure, S_p
  - due to thermal stress, S_t
- Dynamic stress due to pressure waves: S_d





Gaussian beam
Power: 250 kW
Energy: 400 MeV
Pulse duration: 0.5 ms
LBE flow rate: 1 L/s
Inlet temp.: 350 ℃
Design pressure: 0.3 MPa

Not consider fatigue, irradiation ...

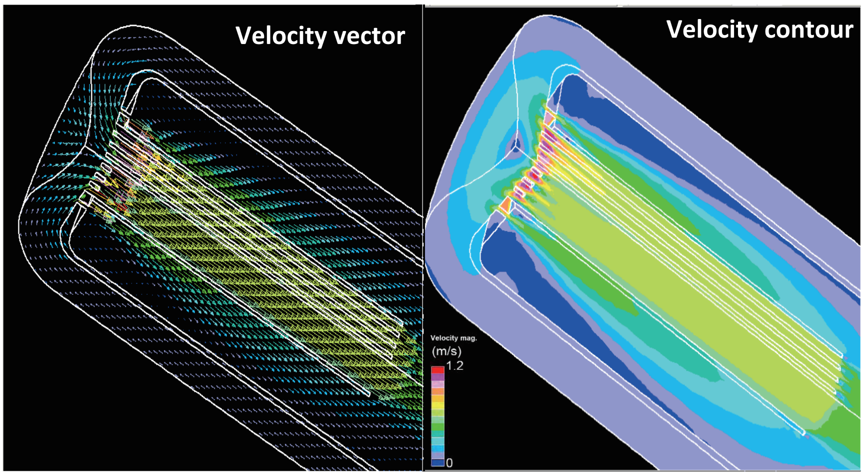


- When the beam current density is below 30 μA/cm², $(S_d + S_p + S_t)_{max} < 3S_m$.
- **The structural integrity of the target vessel could be guaranteed when beam current density is below 30 μA/cm² from the viewpoint of generated stress. However, ...**

6

CFD analysis for original target design

LBE flow rate: 1 L/s

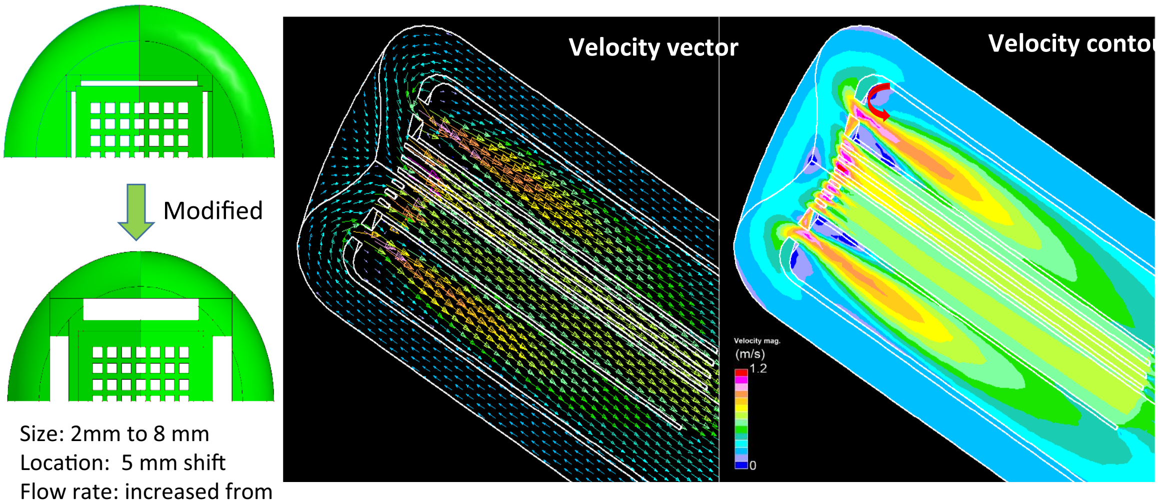


Concerned issues

- **Stagnant region can be observed at the center of beam window because of asymmetrical LBE flow.**
- **There are large stagnant regions in the inner tube as well.**
- **To ensure sufficient margin in the target design, it is recommended to reduce the stagnant regions as much as possible or move them away from the center.**

7

Effects of gap size and location



Size: 2mm to 8 mm
Location: 5 mm shift
Flow rate: increased from 1 L/s to 1.9 L/s

- **To reduce the stagnant region in the inner tube, the size and location of gap between inner tube and rectification lattice were modified.**
- **Stagnant regions in the inner tube was significantly reduced.**
- **Circular flow could be observed around the stagnant region in the inner tube.**

8

Effects of unparallel plate-type flow guides

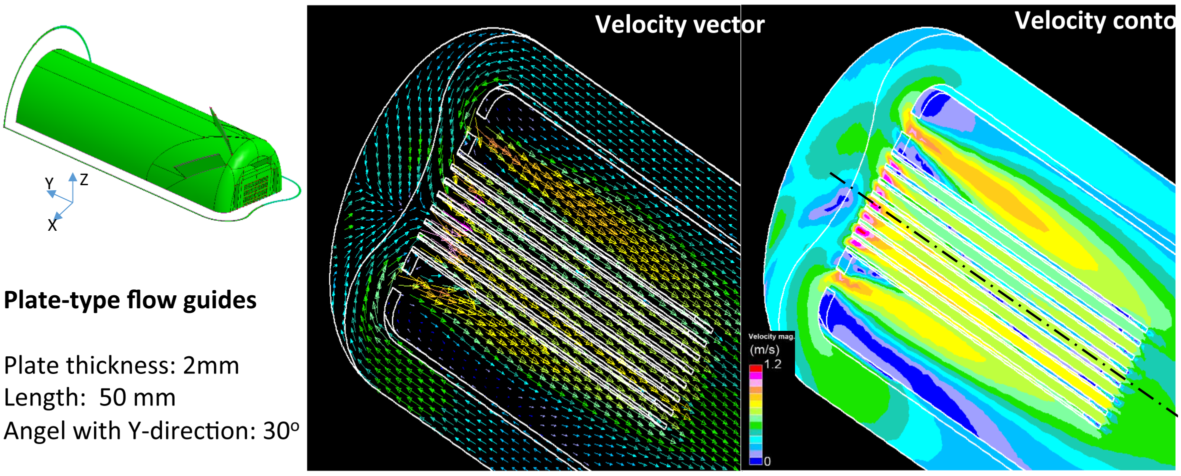


Plate-type flow guides

Plate thickness: 2mm
Length: 50 mm
Angel with Y-direction: 30°

- **By adding the flow guides, the stagnant region at the center of beam window was moved away from the center position.**
- **Stagnant region: approximately 6 mm off-center.**
- **Size of stagnant region was reduced.**

9

Contents

10

Target monitor system

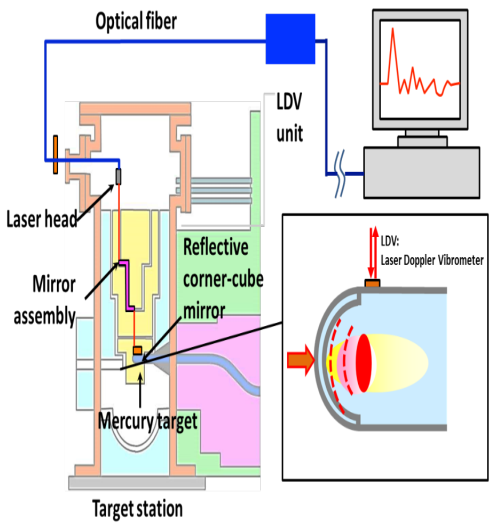
The laser Doppler vibrometer (LDV) system is proposed to be installed as one of the in-situ target monitor systems, to evaluate the structural integrity for the TEF-T LBE target.

LDV system

- *Monitor on the structural vibration caused by the pressure waves, might be affected by the imposed damage; cavitation erosion, etc.*
- *Cavitation signals with high frequency components*

Merits:

- *Can be applied in high irradiation environment*
- *Remote & noncontact*
- *Assemble flexibly*

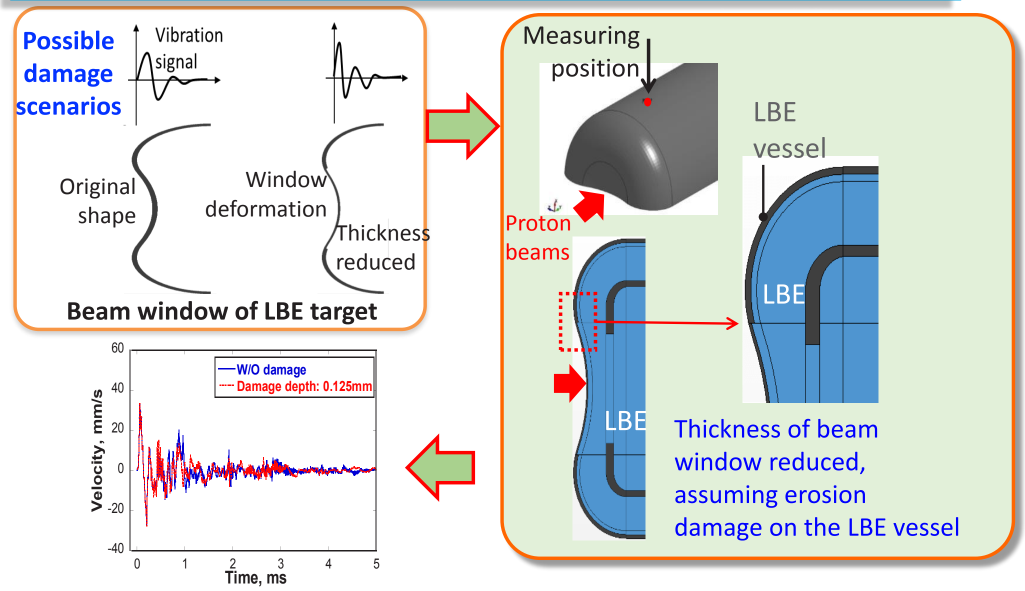


LDV system installed @ JSNS Hg target

11

Structural vibration detection

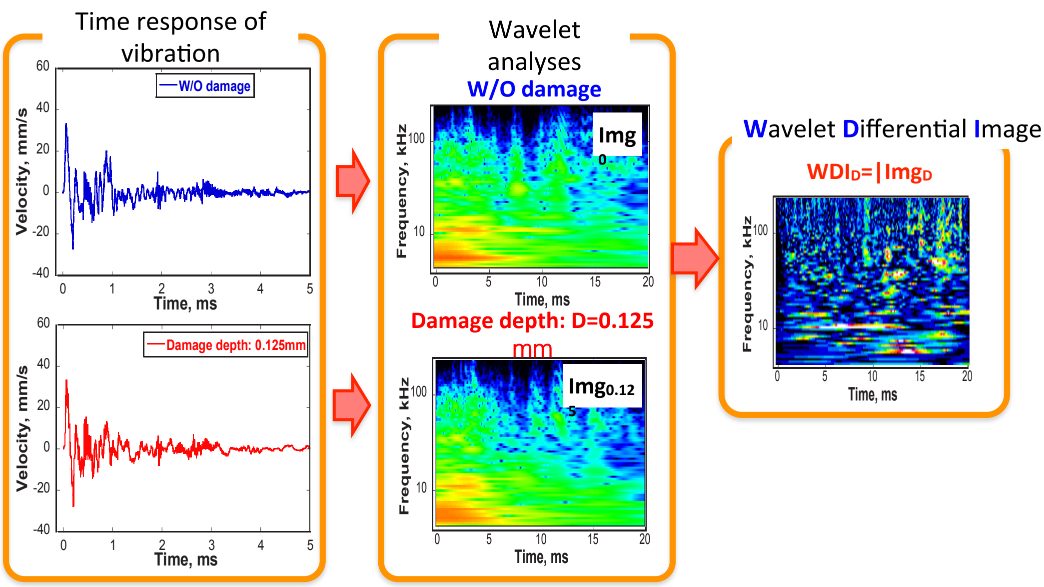
■ To study the dependency of target vessel vibration on erosion damage, the numerical simulations were carried out;



• Need to clearly and quantitatively evaluate the differences of the vibration signals.

12

Wavelet Differential Analysis (WDA)



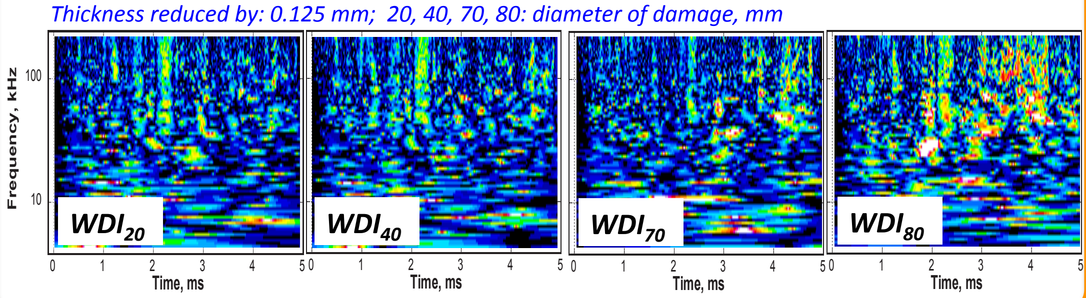
• The technique, Wavelet Differential Analysis, was developed to clearly indicate the differences between vibration signals.

Dependency of target vibration on damage size & depth

13

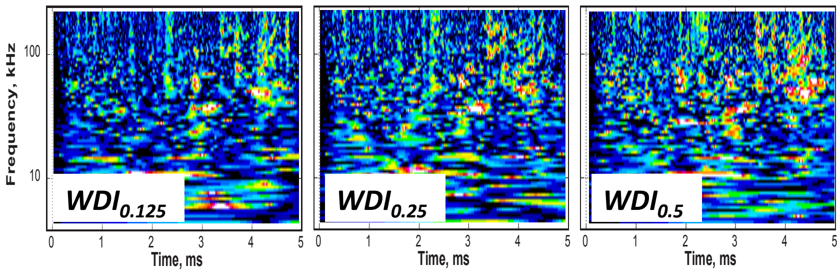
Dependency on damage size

Thickness reduced by: 0.125 mm; 20, 40, 70, 80: diameter of damage, mm



Dependency on damage depth

Diameter of damage: 70 mm; 0.125, 0.25, 0.5: Thickness reduced, mm



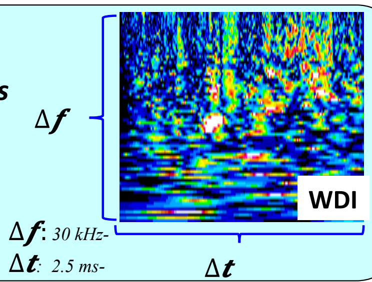
Average intensity of WDI

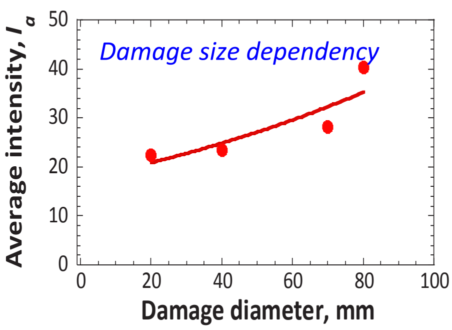
14

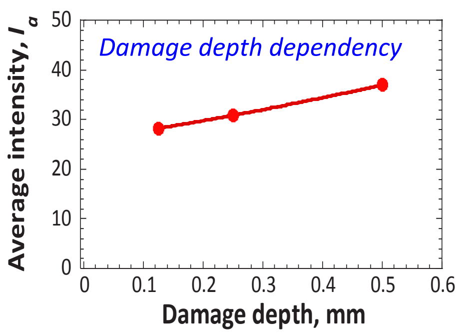
Average intensity: I_a

to quantitatively investigate the differences of wavelet differential image

$$I_a = \int^{\Delta f}\int^{\Delta t} A(t,f)\,dt\,df$$







- **With increasing the damage size and depth, the I_a *of WDI* increases steadily.**

15

Summary & Future work

□ Target analysis

- The structural integrity of LBE target was guaranteed through the structural analysis on condition of beam current density bellows 30 μA/cm^2.
- Modifying the size and location of gap between the inner tube and the rectification lattice can effectively reduce the stagnant region in the inner tube.
- Adding flat-type flow guides can force the stagnant region move away from the center of beam window.

CFD analysis → **Particle Image Velocimetry (PIV)**
- ➢ Existence of stagnant region
- ➢ Effects of flow guides

□ Structural integrity diagnostic technique

- WDA technique was developed to enhance the differences between vibration signals.
- The vibration of target vessel is very depend on the size and depth of erosion damage.

Numerical simulation → **Water loop**
- ➢ Target material: acrylic
- ➢ With manually made damage

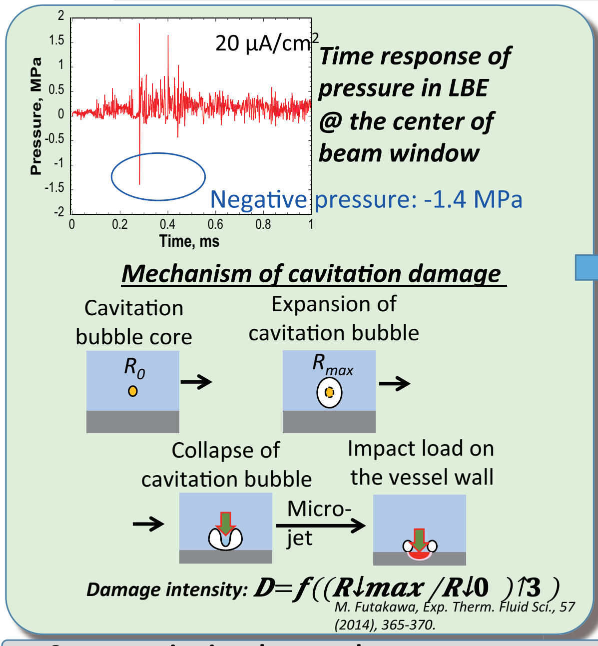
→ **Mockup loop**
- ➢ LBE flow
- ➢ High temperature

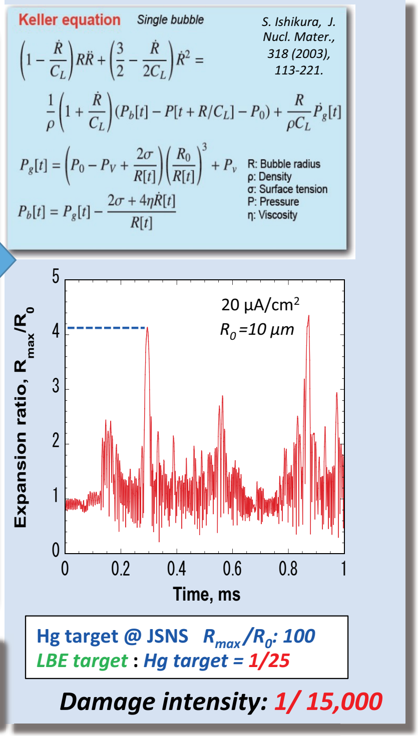
16

Thank you very much for your kind attention!

17

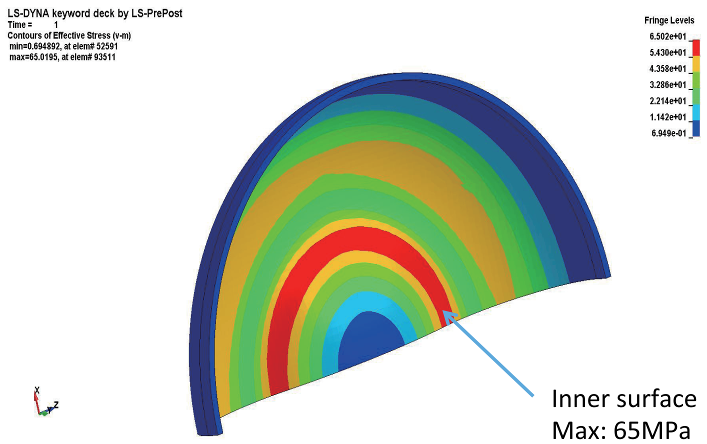
Possibility of cavitation damage





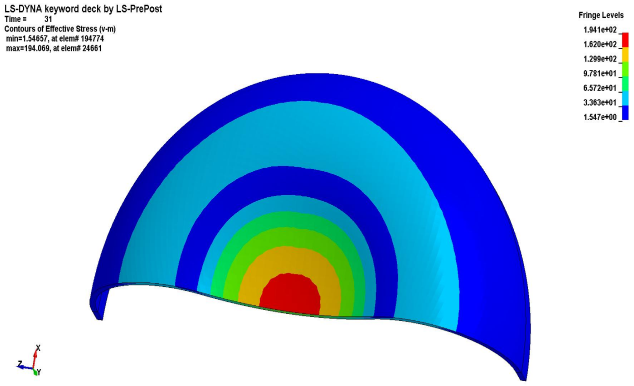
- **Severe cavitation damage due to pressure waves would likely not impose on the LBE vessel.**

- **Stress due to static pressure (0.3 MPa)**

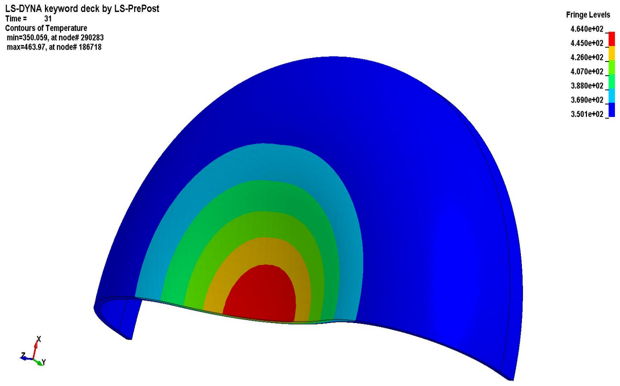


19

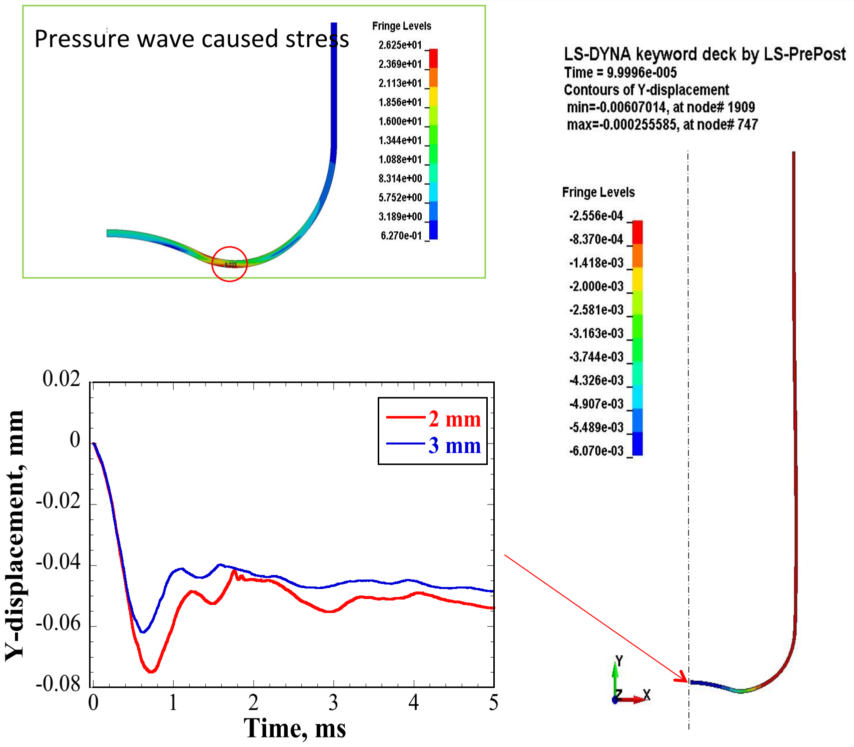
• Thermal stress



• Temperature



Dependency of displacement on target vessel thickness



5.4 Oxygen Sensor and Potential Control

Oxygen sensor and potential control

Takanori SUGAWARA, Kazushi YAMAGUCHI, Hironari OBAYASHI, Shigeru SAITO, Hidemitsu YOSHIMOTO and Toshinobu SASA

Target Technology Development Section, Nuclear Transmutation Division,

J-PARC Center, Japan Atomic Energy Agency

J-PARC is planning to build a Transmutation Experimental Facility (TEF) for R&D on volume reduction and mitigation of harmfulness of high-level radioactive waste by using an Accelerator-Driven System (ADS). In the ADS Target Test Facility (TEF-T) of the TEF, a liquid lead-bismuth eutectic (LBE) target will be irradiated with a high-power (250kW) proton beam, and irradiation effects on structural materials will be studied. It is supposed that LBE is the promising candidate material as the ADS's proton beam spallation target and core coolant because it has good neutron yield and is inactive chemically in comparison with other coolant materials (e.g., water, sodium). On the other hand, LBE is corrosive, so it is necessary to control oxygen concentration in LBE adequately to protect structural materials from the corrosion. In order to control the oxygen concentration in LBE, it is required to develop an oxygen sensor to measure the oxygen concentration.

J-PARC tried to fabricate two-types of oxygen sensors (platinum type and bismuth type). As the result, it was confirmed that output voltage of the platinum type sensors was adequate in a wide temperature range. For the platinum type sensor, it is known that there is a possibility of LBE leakage if the sensor would fail. To prevent the LBE leakage, a special structure was installed to the sensor itself. It was confirmed by experiments that this special structure was useful to prevent the LBE leakage.

The control of oxygen potential in LBE was also performed in static and flow conditions. In both condition, basic operation (oxidation and reduction) was performed, however it is necessary to comprehend the relationship between the change of oxygen concentration and the input of oxygen.

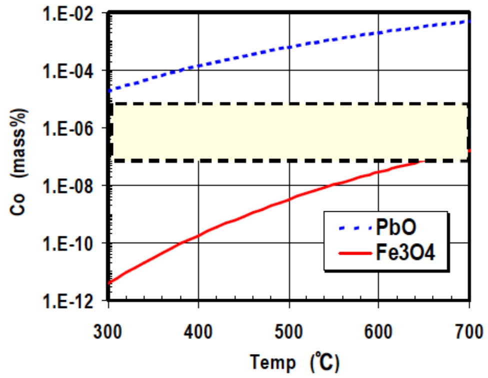
Oxygen Sensor and Potential Control

Takanori SUGAWARA, Kazushi YAMAGUCHI,
Hironari OBAYASHI, Shigeru SAITO,
Hidemitsu YOSHIMOTO and Toshinobu SASA
Japan Atomic Energy Agency

Introduction

- Accelerator-Driven System (ADS) investigated in JAEA employs **LBE** (Lead-Bismuth Eutectic) as coolant and spallation target material.
- TEF-T aims to perform R&D of LBE technology for the ADS.
- **LBE is corrosive** ← The control of the oxygen concentration (C_O) in LBE is one of the best solutions to prevent the corrosion of the structures.

Introduction



The target range of LBE temperature is 300-500℃.

→ The target range of C_O is $1x10^{-5}$ – 10^{-7} wt%.

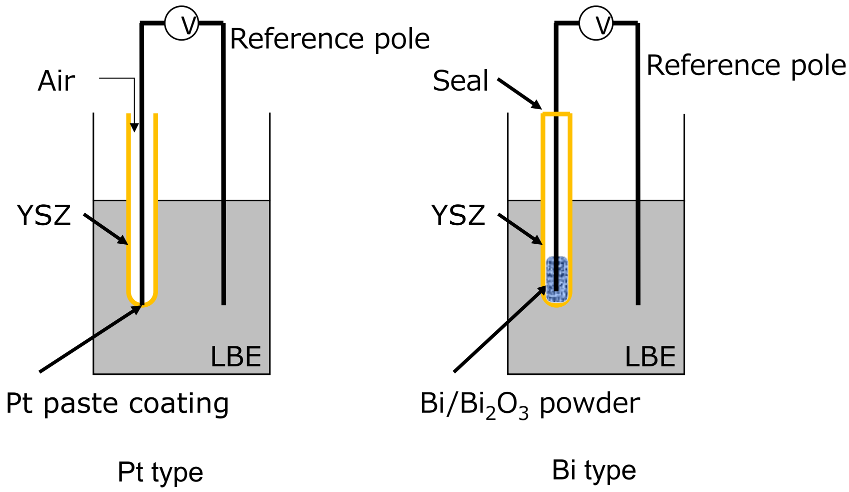
- The final goal is to control Co in the flow and irradiated condition.
- To control Co, it is required to measure Co.

Introduction

- Measurement
  - Fabrication of JAEA's original sensor
  - Measurement in static condition
- Control of Co
  - In static condition
  - In flow condition

Fabrication of Sensor

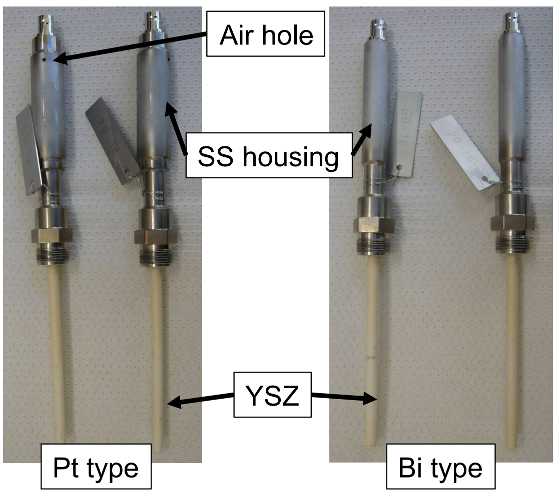
- Pt/Air and Bi/Bi_2O_3 sensors were fabricated.



Fabrication of Sensor

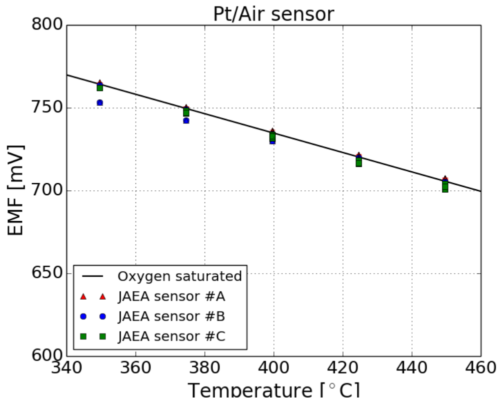
- Pt type: Air hole is prepared. To prevent LBE leakage by YSZ failure, freeze seal design was employed in housing.
- Bi type: No air hole

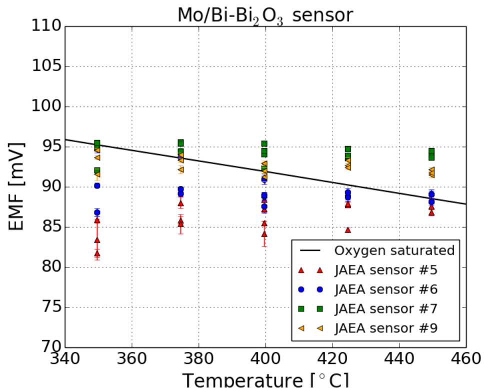
Length of sensor	240mm
Diameter of YSZ	6/4 mm (O/I)
Length of housing	140mm
For Pt type	Pt paste / SUS304 wire
For Bi type	Bi/Bi_2O_3=95:5 /Mo wire



Measurement in static condition

- Under oxygen saturated condition (2kgLBE)



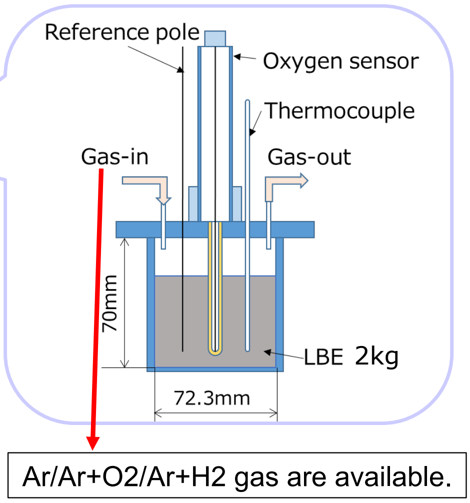


- Pt type: Good agreement with theoretical value ☺
- Bi type: Not good agreement ☹ → Need to improve

Asia ADS, 26-27, Oct, 2015 7

Control of Co in static condition

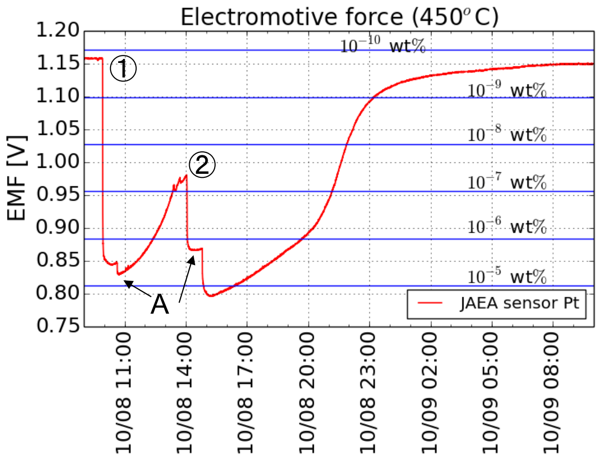
- Device



Asia ADS, 26-27, Oct, 2015 8

Control of Co in static condition

Result



①	Ar*1 37.5cc (25sccmx1.5min)
②	Ar 25cc（25sccm×1.5min）
A	Switching to Ar+4.5%H_2 gas

*1: 99.995%Ar

- Basic oxidation operation was performed by a tiny amount of oxygen in Ar gas.
- It is required to comprehend the relationship between change of Co and input of oxygen.
- #A is strange (Residual air?)

Control of Co in flow condition

Outline of JLBL-4

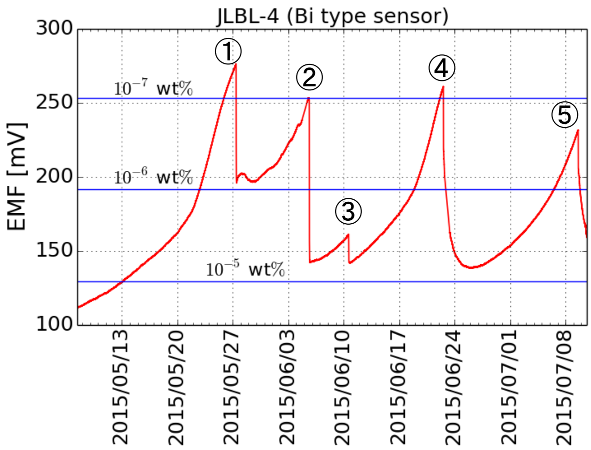
Specifications of JLBL-4

Main material	316SS
Inventory	20 L
Max. pressure	6 bar
Max. electrical power	7 kW heaters
Max. temperature	300 °C
Max. design temperature	500 °C
Flow rate of LBE	Max. 40 L/min
Flow rate of observation	EMF

O2 sensor	Bi type sensor (made by SCK/CEN)
LBE temperature	350℃
LBE flowrate	26L/min

Control of Co in flow condition

- Result



①	Ar continuous (2days)
②	Ar+O_2*1 150cc (50sccm×3min)
③	Ar+H_2*2 500cc (100sccm×5min)
④	Ar+O_2 150cc (50sccm×3min)
⑤	Ar+O_2 75cc (50sccm×1.5min)

*1: 20vol% O_2
*2: 4.5vol% H_2

- Basic oxidation operation was performed.
- It is required to comprehend the relationship between change of Co and input of oxygen.
- #③ is strange. (Residual air?)

Summary (1/2)

- Measurement

	Achievements ☺	Issues ☹
Fabrication of JAEA's original sensor	• Pt type sensor is good.	• Bi type sensor is not good. Need to improve. • Lifetime • Procedure to exchange in TEF-T
Measurement in static condition	• Measurement under oxygen saturated condition is good.	• Treatment of residual air.

Summary (2/2)

Control of Co

	Achievements ☺	Issues ☹
In static condition	● Basic operation (oxidation/reduction) was performed.	● Need to comprehend the relationship between change of Co and input of oxygen.
In flow condition	● Basic operation (oxidation) was performed.	● Need to comprehend the relationship between change of Co and input of oxygen. ● Long-term test is required. ● Auto control test

6. Activities in Kyoto University

6.1 Effect of Wall Surface Condition on Flow Structure in a LBE Two-phase Flow

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Effect of wall surface condition on flow structure in a LBE two-phase flow

Gen Ariyoshi[1)], Daisuke Ito[2)], Yasushi Saito[2)], Kaichiro Mishima[3)]

1) Graduate School of Energy Science, Kyoto University

2) Kyoto University Research Reactor Institute

3) Institute of Nuclear Safety System, Incorporated

To reduce amount of long-lived nuclide contained in high level radioactive wastes, an accelerator driven system (ADS) has been developed in many countries at present. However many technical issues have still remained. In particular, safety measures and estimations for severe accident in the ADS should be established to determine a safety design criteria as well as in existing nuclear reactors.

In reactor pool of the ADS filled with lead-bismuth eutectic (LBE) used as its coolant and spallation target, the flow channels in the fuel assembly and steam generator might be closed by impurities, such as lead oxides (PbO) and corrosion oxides of structural materials of the reactor. Then the cooling performance of the reactor would go down and finally meltdown might occur. To prevent this kind of accident, various thermal hydraulic studies on LBE have been conducted regarding the control of the dissolved oxygen in the LBE and the characteristics of corrosion/erosion effect caused by the LBE.

On the other hand, in case of piping rupture accident of steam generator, steam would leak into the hot LBE flow and an LBE two-phase flow might be formed in the ADS reactor. Having the density ratio between LBE and steam which is about 10 times larger than that of ordinary air-water two-phase flows, the characteristics of LBE two-phase flow might be different from that of air-water two-phase flows. Furthermore, if steam bubbles should come into the fuel region, the core reactivity might be strongly affected. Then fundamental characteristics of the LBE two-phase flow should be well understood to prevent and estimate this phenomenon. However, experimental data of flow structure of such LBE two-phase flow has not been accumulated enough because thermal hydraulic studies of LBE two-phase flows have not been conducted enough so far. Thus, in this study, fundamental characteristics of the LBE two-phase flow, such as liquid velocity fluctuation, turbulence intensity, void fraction, etc., were measured to make clear the flow structure of the LBE two-phase flow.

Figures 1 and 2 show measured liquid velocity and void fraction profiles (which were shown at previous meeting : The 12th International Work shop on Asian Network for ADS and NTT). Each profiles take maximum value near wall region. We considered that these results were caused by the wettability between the LBE and the wall. To verify this hypothesis, the liquid velocity and void fraction were measured again by using a channel with good wettability condition.

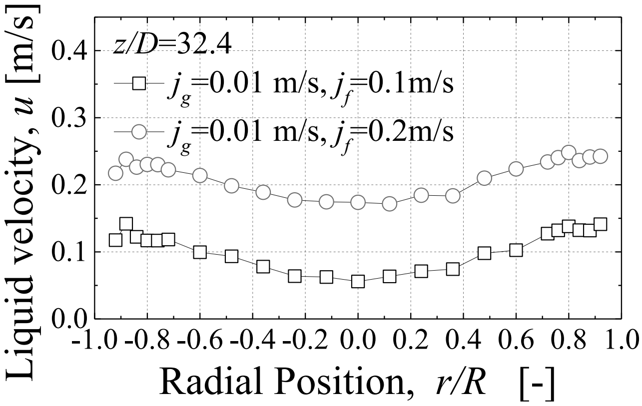


Fig.1 Local liquid velocity profiles.

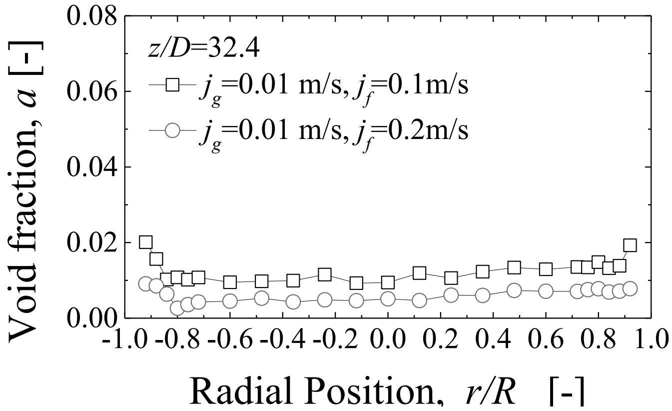


Fig.2 Void fraction profiles.

Effect of wall surface condition on flow structure in a LBE two-phase flow

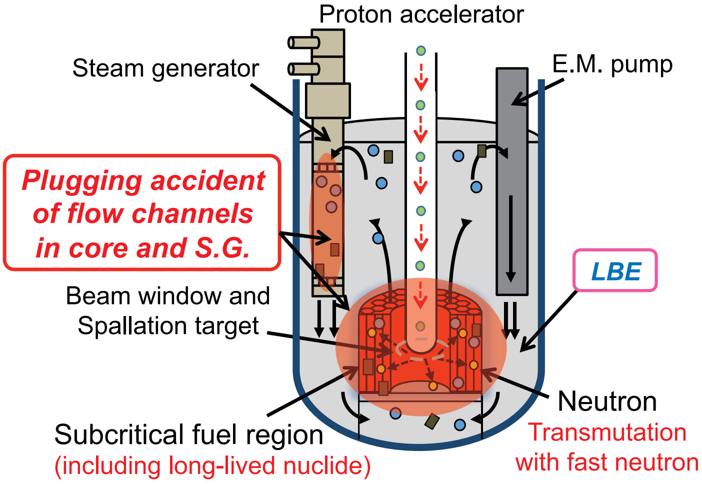
The First Topical Meeting on
Asian Network for ADS and NTT
Oct. 26th – Dec.27th , 2015,
J-PARC Center, Tokai, Ibaraki, Japan

○ [1)]Gen Ariyoshi, [2)]Daisuke Ito, [2)]Yasushi Saito and [3)]Kaichiro Mishima
[1)]Kyoto Univ., [2)]KURRI, [3)]INSS

Research Reactor Institute
Kyoto University

Table of Contents

1. Motivation Severe accidents in the ADS 1

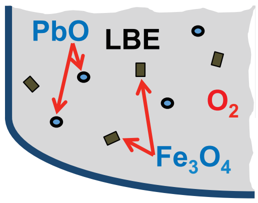


Heat generated in the target and fuel region should be removed by ***LBE single-phase flow***

At normal operation mode

LBE single phase flow will appear.

Chemical reaction in the ADS reactor pool

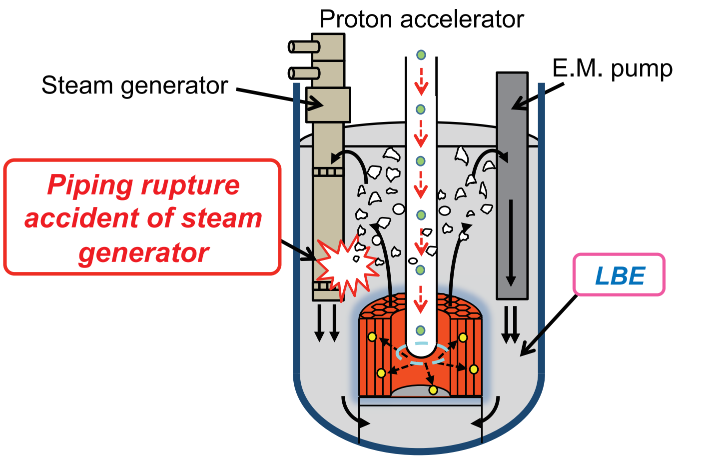


LBE and corrosion products (Fe, Cr, Ni) react with **dissolved O_2**

The flow channels in the core and S.G. might get blocked by **impurities (PbO, Fe_3O_4)**

So, **O_2 control** and characteristics of the **corrosion/erosion effect** should be well understood to prevent such accidents.

1. Motivation Severe accidents in the ADS 2



If the gas bubble comes into the fuel region, the core reactivity might be affected.

To develop an ADS,

The flow characteristics of LBE two-phase and single-phase flow also should be well understood to estimate the influence of such accidents.

In case of piping rupture accident of S.G. due to the corrosion/erosion effect of LBE on structural materials of the flow channel

Direct contact between LBE and water from the steam generator

At piping rupture accident of steam generator mode

LBE two-phase flow might appear, which would be one of the severe accidents of LBE-cooled ADS.

1. Motivation　Analytical models

Regarding the two-phase flow analysis, so far, the following analytical models for gas-liquid two-phase flow have been developed.

Analytical models of gas-liquid two-phase flow	
Homogeneous flow model	The model is the simplest model which assumed that gas and liquid phase are uniform mixture.
Drift flux model	The model takes into account the relative velocity between gas and liquid phase.
Two-fluid model	The model proposes two sets of conservation equations for the gas and liquid phase, respectively.

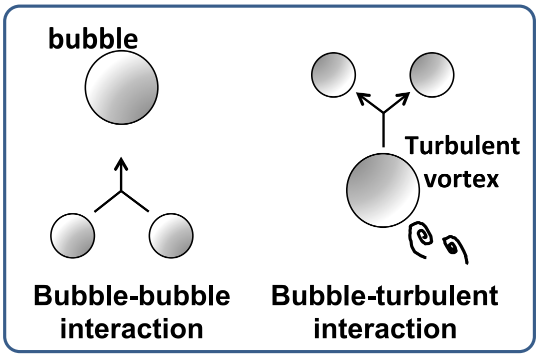
At present, the ***two-fluid model*** would be the most precise model for two-phase flow.

However, interaction between phases should be expressed by ***the interfacial transport term in the equations***.

1. Motivation　Analytical models

Example of dynamic behavior of bubbles

The interfacial area is affected by bubble coalescence and breakup.



- ✓ Generally, the interfacial area decreases by coalescence and increases by breakup.
- ✓ The coalescence and breakup are caused by **bubble-bubble interaction** or **bubble-liquid turbulence interaction**.

So, ***the interfacial area transport*** is linked strongly to the local flow structure of liquid phase. Therefore, not only the gas-phase distribution but also ***the local liquid flow structure should be measured*** to construct database and model for lead-bismuth two-phase flow.

1. Motivation　Purpose of this study

To develop a mechanistic model for LBE single-phase and two-phase flows

For this purpose, experimental database of LBE flows should be constructed not only for a two-phase flow at high void fraction condition but also for that at low void fraction and a single-phase flow.

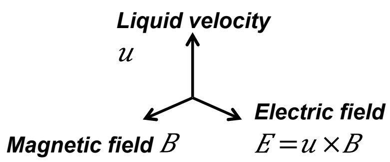
In this study, *the flow structure* and *turbulence characteristics* of lead-bismuth two-phase flows at low void fraction conditions and the single-phase flow were measured by using intrusive probe methods; such as single-sensor probe and electro-magnetic probe.

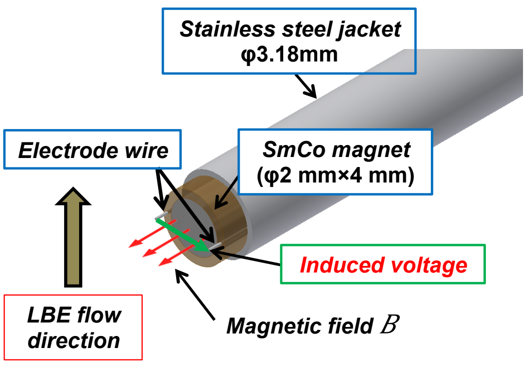
2. Experimental details
Measurement techniques of LBE flow

Electro-magnetic probe: EM probe

The EM probe consists of

- ***SmCo magnet*** **(φ2 mm×4 mm)**
- ***two electrode wires*** **(φ126μm)**
- ***stainless steel jacket*** **(φ3.06 mm)**



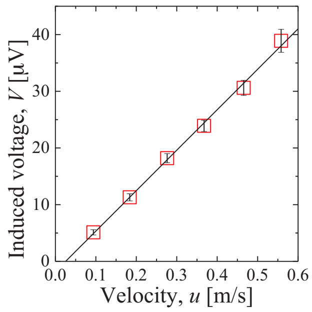


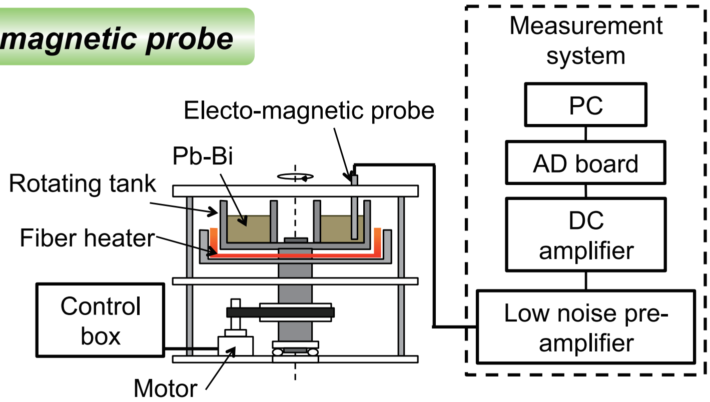
The EM probe is based on ***Faraday's law***.

To apply this kind of EM probe to a high temperature region, SmCo magnet was selected in this study, which has high Curie point of 800℃.

2. Experimental details
Measurement techniques of LBE flow

Calibration of electro-magnetic probe

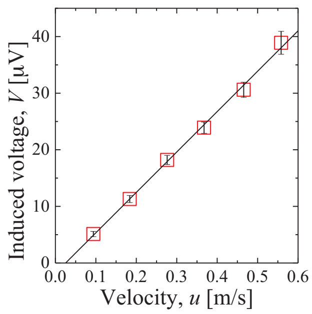


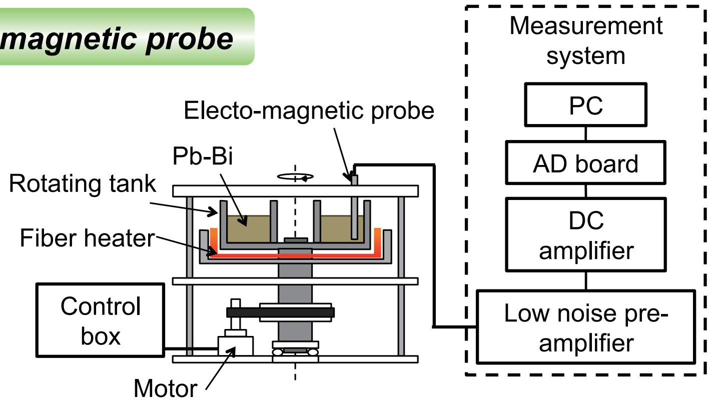


Circumferential velocity was calculated by assuming the rigid body rotation in the tank.

2. Experimental details
Measurement techniques of LBE flow

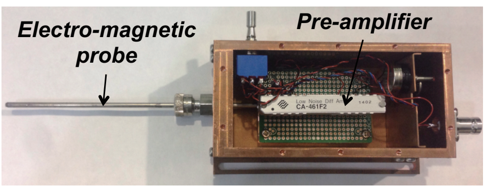
Calibration of electro-magnetic probe





So, it is important to suppress the electrical noise to signal path between signal source and the pre-amplifier.

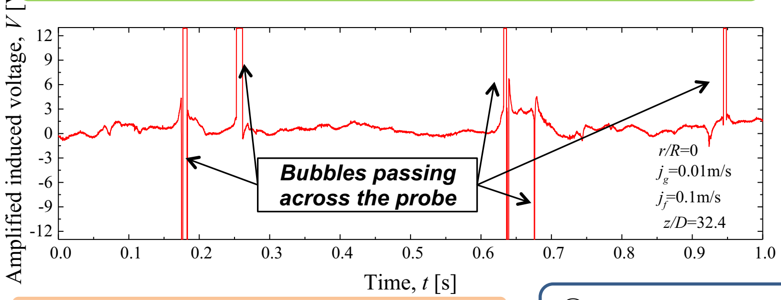
Combine the probe with pre-amplifier



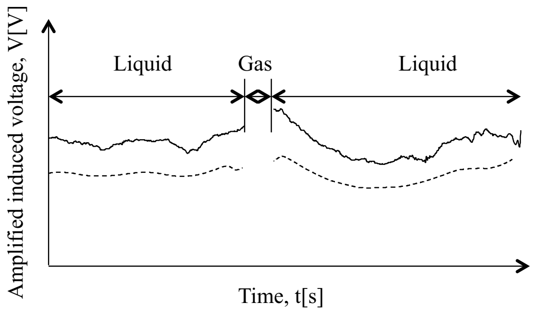
Electrical wirings can be shorter and the pre-amplifier can be covered by a metal shielding case resulting in better S/N ratio.

2. Experimental details
Measurement techniques of LBE flow

Signal processing for electro-magnetic probe



Scheme of present signal processing



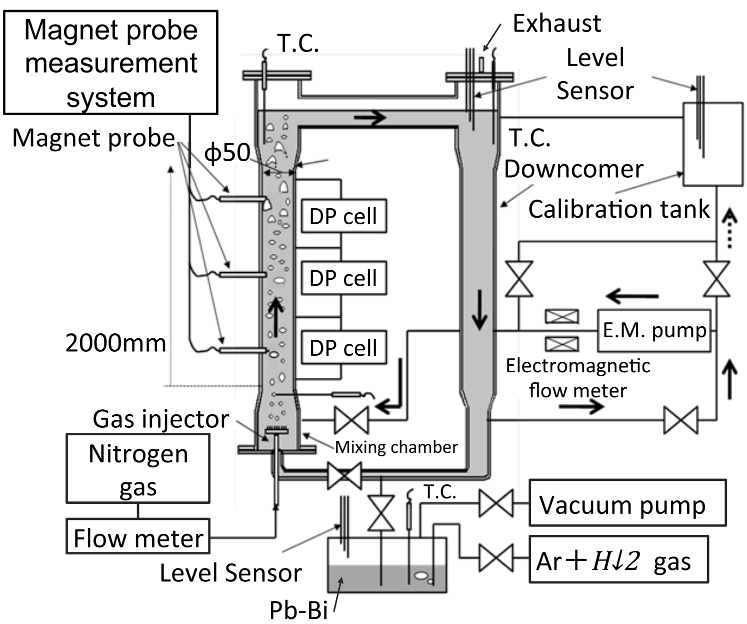
① The moving average values (dashed line) are calculated as the first threshold with a certain offset value for separating gas and liquid phase.

② The time derivative of the signal was estimated as second threshold value to adjust the precise interval between gas and liquid phase.

And then, **time-averaged liquid velocity** and **turbulence intensity** can be obtained

2. Experimental details　Experimental apparatus

Lead-bismuth test loop



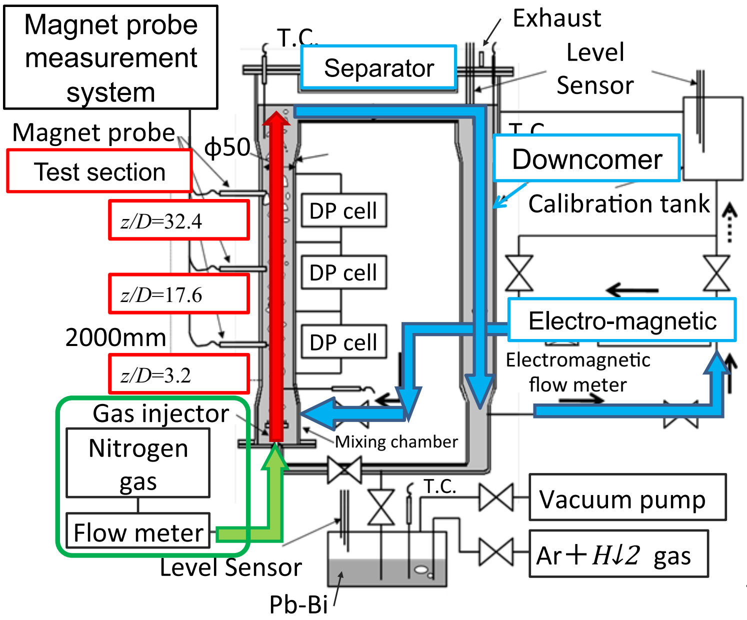
● *Test section*

Diameter : D=50 mm

Length : 2m

2. Experimental details　Experimental apparatus

Lead-bismuth test loop



We can get vertical upward flow in the test section.

●***Test section***
Diameter : D=50 mm
Length : 2m

●***Experimental conditions***
Working fluid :
LBE and Nitrogen gas

Liquid temperature : 200 ℃
Exhaust :
atmospheric pressure

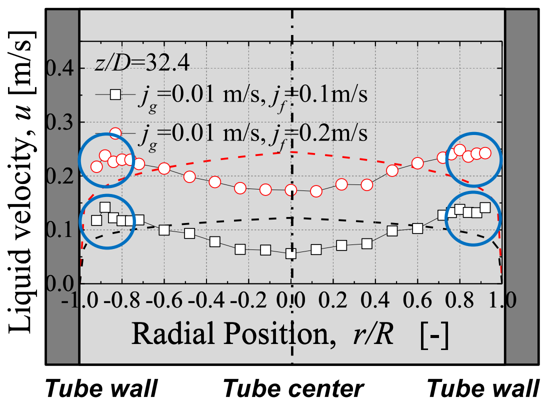
Superficial gas velocity :
0.01, 0.02, 0.04 m/s

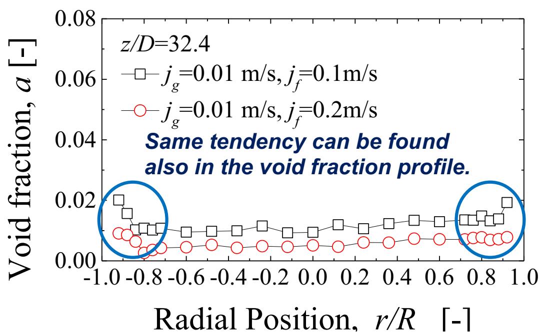
Superficial liquid velocity :
0.1, 0.2 m/s

●***Measurement conditions***
Sampling frequency : 10 kHz
Measurement time : 60 sec

3. Results and discussion

Measured liquid velocity and void fraction in LBE two-phase flow





Due to the non slip condition on the wall

The liquid velocity profile ➡ ***parabolic shape***

However, in case of low liquid velocity, the measured velocity profile takes *the maximum near the wall region*.

3. Results and discussion

Why do liquid velocity and void fraction increase near the wall?

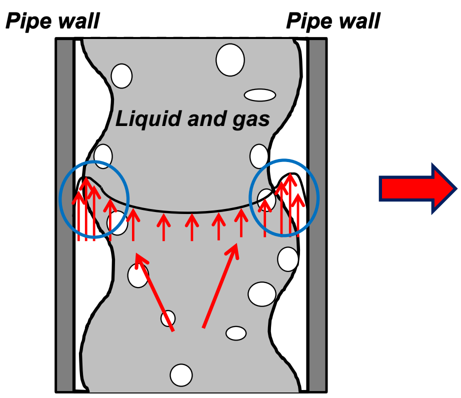
Possible causes of strange Liquid velocity and void fraction	
Effect of voltage induced by temperature drift of electro-magnetic probe	×
Effect of distribution of medium surrounding the tip of electro-magnetic probe	×
Effect of wettability between the LBE and the wall	○

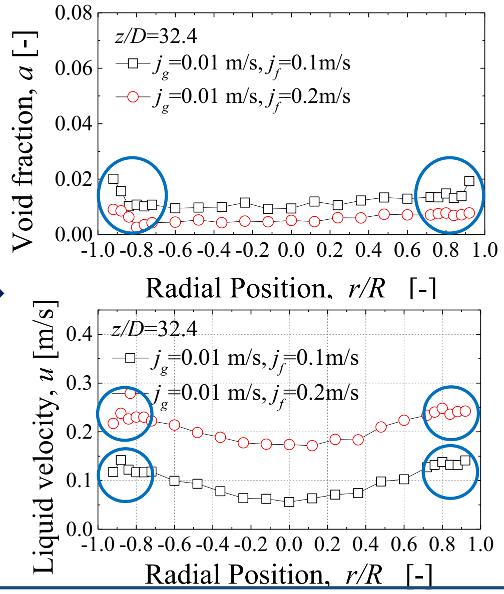
After various attempts, the measurement error was not severe due to the temperature drift or distribution of the medium.

3. Results and discussion

Why do liquid velocity and void fraction increase near the wall?

Poor wettability condition



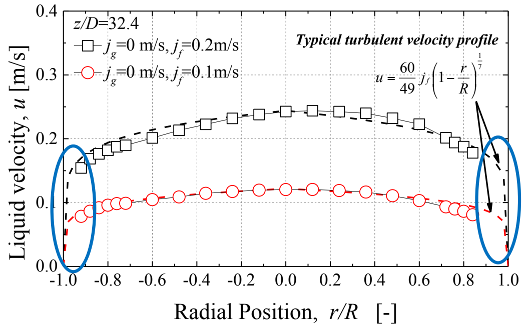


In case of poor wettability condition, many bubbles tend to be trapped in the wall region. ***Then, void fraction becomes high near the wall and the liquid phase is accelerated by the gas phase flowing along the wall.***

3. Results and discussion

Measured liquid velocity in LBE single-phase flow

To confirm the hypothesis, local liquid velocity fluctuation was measured also in LBE single-phase flow.



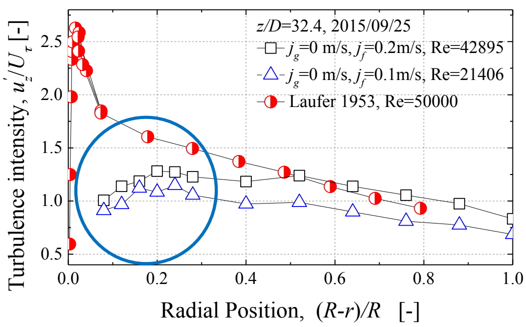
Measured velocity profiles seem to show good agreement with typical turbulent velocity profile.

However, it is difficult to conclude from the above results whether wall surface condition affects the liquid velocity profile or not **because liquid velocity was not measured enough at closer area to the wall surface.**

3. Results and discussion

Measured turbulence intensity in LBE single-phase flow

Turbulence intensity in fully developed pipe flow measured by Laufer (1953), which has good accuracy, was compared with the measured turbulence intensities.



Due to this comparison, it is found that **the measured turbulence intensity decreases at further area from the wall surface**.

The velocity fluctuations ➡ **LOW**

Then, at present our experimental condition, it is expected that ***less turbulence energy might be generated in the wall region due to the wall condition*** comparatively.

Finally, we can consider that the wall-shear stress is weaker than that of Laufer's experimental condition. ➡ ***Slip condition on the wall***

4. Conclusions

The following conclusions are obtained from measurement results of liquid velocity and void fraction in the LBE flows.

1. At the present experimental conditions, the liquid velocity and the void fraction in the LBE two-phase flow take the maximum near the wall region.
2. In poor wettability condition, many bubbles tend to be trapped in the wall region. Then, void fraction becomes high near the wall and the liquid phase is accelerated by the gas phase.
3. Wall wettability affects the void fraction and the liquid velocity profiles.
4. Effect of wall wettability on the liquid velocity profiles was confirmed also in case of LBE single-phase flow.

Thank you very much for your kind attention.

7. Activities for Japan Atomic Energy Agency

7.1 Oxygen Sensor Calibration Device

Oxygen sensor calibration device

Kazushi YAMAGUCHI
Target Technology Development Section,
Nuclear Transmutation Division, J-PARC Center, JAEA

Objectives of the device

- Performance tests of oxygen sensor in high temperature LBE alloy
  - Calibration before installing sensor to LBE loop equipment
  - Because of the sensor made by ceramic, certain number of sensor should be prepared to cope with quick replacement
  - Performance test for newly developed oxygen sensors
- Perform the experiments to control oxygen potential in LBE by various methods
- Experiment/tests using small amount of LBE

All the results and technologies will be transferred to LBE experimental loop and TEF-T Target loop.

T-TAC, 10-11, July, 2014 2

Outline of the device①

Electric furnace＆LBE pot

- **LBE pot**
  ・Material：316SS
  ・Capacity(Max)：0.3〔L〕
  ・Temp(Max)：600〔℃〕
  ・Design Press：0.5〔MPa〕
  ※ Sensor connection port×1
  Gas supply, exhaust, thermometer ×1

- **Electric furnace**
  ・Size：285×260×340〔mm〕
  ・Electrical power：1.0〔KW〕

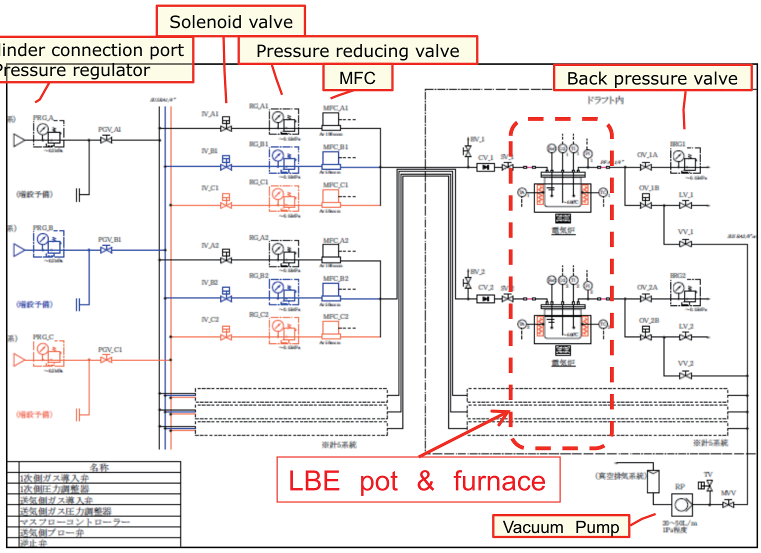
Electric furnace

LBE pot

Outline of the device ②

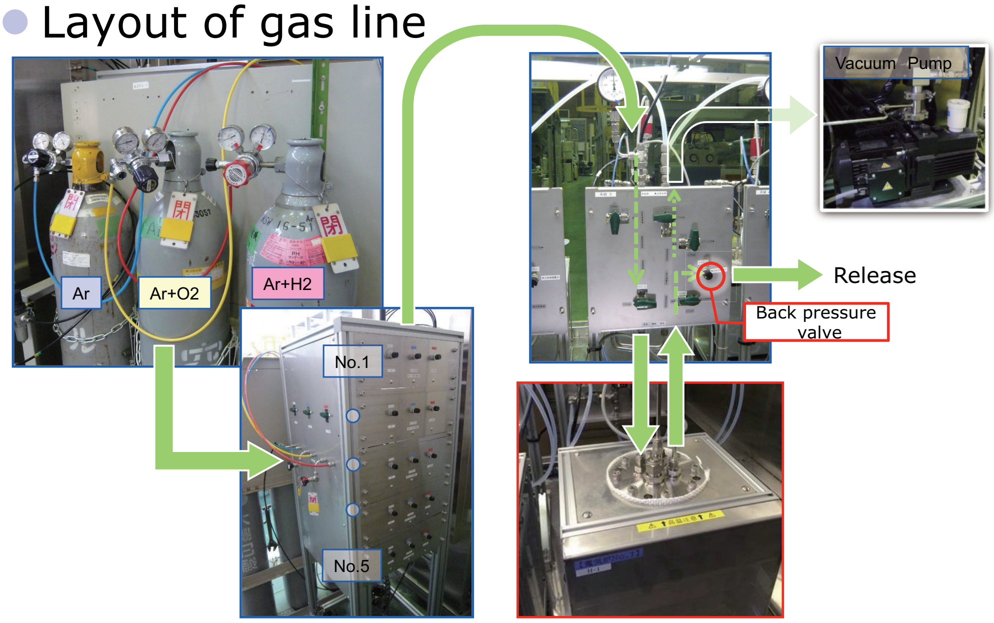
Layout of gas line

- Kinds of gas
  ・Ar
  ・Ar+H2(4%)
  ・Ar+O2(5%)
- Operation press：
  0.05~0.3(MPa)
- Flow control
  ・Ar：0~100(cc/min)
  ・Other ：0~50(cc/min)
- Vacuum Pump
  …Use the gas exchange in the pot



Outline of the device ③

- Layout of gas line



T-TAC, 10-11, July, 2014 5

Outline of the device ④

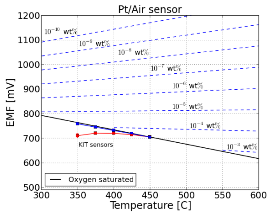
Easy to arrange & Small LBE capacity → Have the flexibility

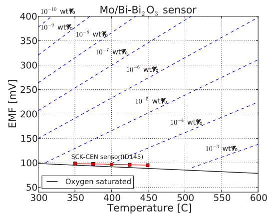
Can be used in various experiments

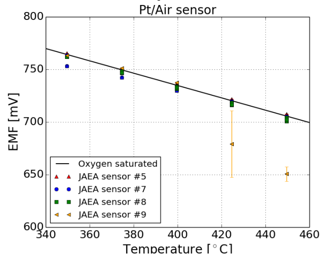
T-TAC, 10-11, July, 2014 6

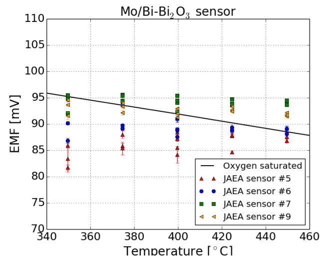
Result①

- O2 sensor development
  - Foreign-made O2 sensor operation test (KIT、SCK/CEN)
  - Domestic made O2 sensor development (Pt/Air＆Bi/Bi_2O_3 type





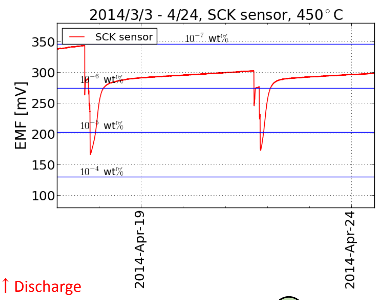


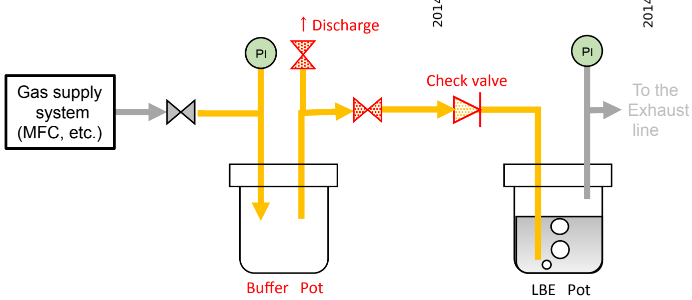


T-TAC, 10-11, July, 2014 7

Result②

- Oxygen concentration control technology development
  - ➢ Improvement of the gas control system (Change gas supply to bubbling manner)





T-TAC, 10-11, July, 2014

Summary

- Oxygen sensor calibration device was manufactured for
  - Oxygen sensor calibration
  - Development of oxygen control technique.
- This device is a flexible test bench for oxygen control techniques.

↓

- Improvement of oxygen control techniques will be performed using this flexible test bench.

T-TAC, 10-11, July, 2014 9

Future works

- Calibration of new oxygen sensor
- Establish techniques for effective oxygen potential control and develop new technologies (application of solid-lead oxide, oxygen pump, etc.)
- Stable supply of calibrated oxygen sensor to TEF-T and test loops
- Development of new measurement devices etc.

T-TAC, 10-11, July, 2014 10

7.2 TEF-T Target Mock-up Loop

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TEF-T Target Mock-up Loop

Hironari OBAYASHI[1)], Kazushi YAMAGUCHI[1)], Hidemitsu YOSHIMOTO[1)], Shigeru SAITO [1)], Toshinobu SASA[1)] and, Masaru HIRABAYASHI[2)]

1) Target Technology Development Section, Nuclear Transmutation Division, J-PARC Center, JAEA

2) Fast Reactor Technology Development Department, Advanced Fast Reactor Cycle System R&D Center, JAEA

ADS target experimental facility (TEF-T) is aimed for the acquisition of the irradiation data of candidate material of ADS. The target mock-up loop is a demonstration test loop with most of same performance of the lead-bismuth eutectic (LBE) spallation target in TEF-T. All component are actual scales, except a temperature conditioner simulating heat generation by the incidence of proton beam. The purposes of this loop are verification of dynamic behavior, confirmation of operation procedure, and integral test of individually developed components of LBE technologies. Its construction was finished at the end of 2014.

The inventory of LBE is 285 l. The maximum design temperature is 500°C, and maximum pressure is 0.5MPa. This loop is driven by an annular type of electro-magnetic pump (EMP), and maximum flow rate is 120 l/min. The flow rate is monitored by an ultrasonic flowmeter. To prevent the blockage caused by material deposition, it was designed so that a duct became as wide as possible.

Application test of ultrasonic flowmeter was performed by JLBL#4 loop. As the result, good followability by changing the flow rate was observed. In a constant flow rate condition, sufficiently stable flow rate was measured over 4,000hr. In a short run test of target mock-up loop, same type of ultrasonic flowmeter was successfully applied.

1st TM Asia ADS & NTT
27-29, Oct., 2015

TEF-T Target Mock-up Loop

○H.Obayashi, K.Yamaguchi, H.Yoshimoto, S.Saito, T.Sasa
J-PARC Center, JAEA
M.Hirabayashi
Fast Reactor Technology Development Department, JAEA

1

Contents

1. Outline
2. Status of developed components & Roadmap of Mock-up loop
3. Application test of ultrasonic flowmeter
4. Summary

2

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Outline of TEF-T Target Mock-up Loop

Target Mock-Up loop is a demonstration test loop with most of same configuration/ components of the primary cooling system of TEF –T target.

Most of component are actual scales, except a temperature conditioner simulating heat generation by the incidence of proton beam.
Construction of this loop was finished at the end of JFY2014.

Purpose of mock-up loop

1. Dynamic behavior of heat removal
2. Confirmation of operation procedure
3. Integral test of individually developed components of LBE technologies (including EMP & HX)
4. Production of control sample for PIE of TEF-T irradiation sample

3

Hironari OBAYASHI TEF-T Target Mock-up Loop

Nuclear Transmutation Division, J-PARC Center, Japan Atomic Energy Agency

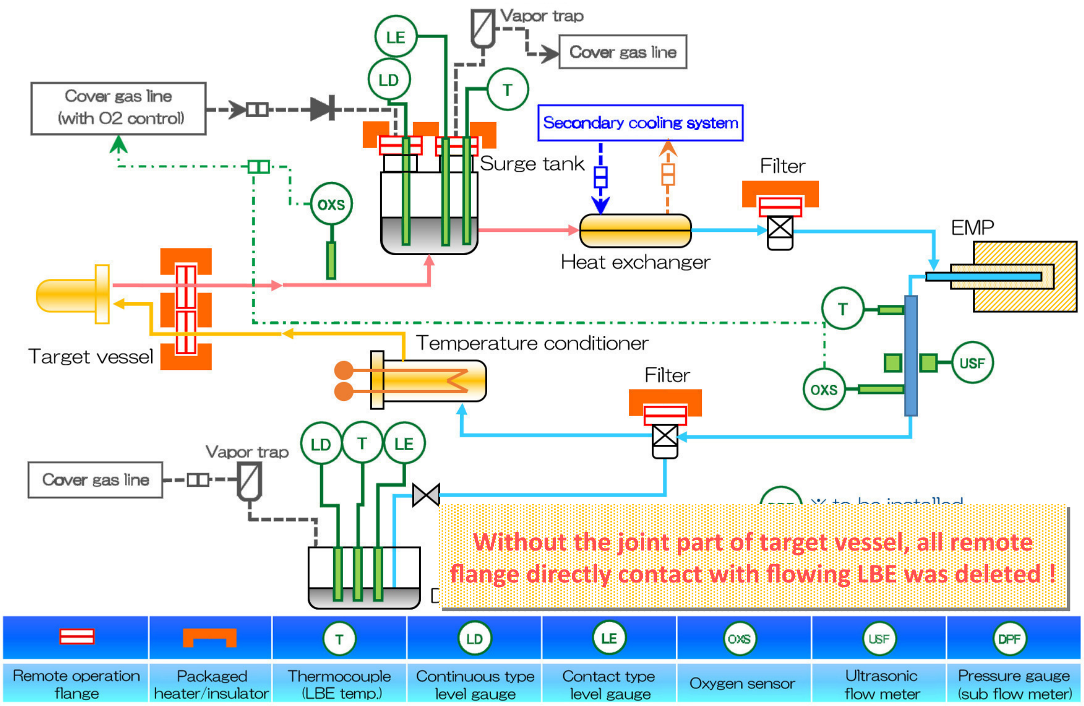
Contents

1. Outline
2. Status of developed components & Roadmap of Mock-up loop
3. Application test of ultrasonic flowmeter
4. Summary

4

Hironari OBAYASHI TEF-T Target Mock-up Loop

Diagram of TEF-T Target Mock-up Loop



Specifications of Target Mock-up Loop

Specifications	Target Mock-up Loop	TEF-T
Max. temperature	500 ˚C	500 ˚C
Temperature difference ΔT	100 ˚C	100 ˚C
Max. Flow rate	120 liter/min	120 liter/min
Heat deposition by proton beam	-	200 kW
Power of temperature conditioner	67 kW :to simulate heat generation (about 1/3 of heat deposition)	< 10 kW :to control inlet temp. only
Amount of heat exchanger	Design 200 kW Working 67 kW	200 kW
Inventory of LBE	≈ 290 liter	≈ 290 liter
Main piping	i.d. 69.3 mm	i.d. 69.3 mm ⇒ i.d. 42.6 mm
Main material	316 SS	316 SS / T91
Flow monitoring system	Ultrasonic flowmeter	Ultrasonic flowmeter
Oxygen Concentration (OC) control system	Available (Pt/Air type sensor)	Available (Pt/Air type sensor)
Liquid pressure gauge	To be installed	Available
Freeze seal type of drain valve	To be installed	Available

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Piping & Flange (1/2)

Design Requirements from LBE handling

- Result of JLBL-1: The blockage of flow channel (schedule pipe 20A, o.d. 27.2ϕ, t=2.5) was observed. (No control condition of oxygen concentration)

⇒ To prevent the blockage and the extremely fast LBE flow(>2m/s) , sufficiently wide flow channel should be secured.

- To exchange the target vessel, the remote-controllable joint device should be installed.

Answers

Mock-up Loop design

- Schedule pipe 65A(o.d. 76.3ϕ, t=3.5) was applied to main piping.

・65A size was determined by minimum standardized remote flange of MLF.

・LBE velocity at 120l/min ≈ 0.53 m/sec ⇒ **OK**

- MLF type remote flange (65A) & packaged heater/ insulator system were applied to the joint part of target vessel.

Remote flange

Packaged system

Hironari OBAYASHI TEF-T Target Mock-up Loop

Nuclear Transmutation Division, J-PARC Center, Japan Atomic Energy Agency

Piping & Flange (2/2)

Latest revised design for TEF-T

- To prevent the risk of LBE leakage, **all remote flange directly contact with flowing LBE will be replaced remote cutting/welding system.**
- Schedule pipe 40A(o.d. 48.6ϕ, t=3.0) will be applied to TEF-T target.

・Size was determined by Max. pipe size for automatic welding machine & pipe cutter.

・ LBE velocity at 120l/min ≈ 1.4 m/sec ⇒ **OK**

R&D by Other LBE apparatus

Remaining issues at Mock-up loop

- Evaluation of blockage generation
- Evaluation of burning of remote bolt/nut & burning reducing method (remote flange for exchanging filter)
- Evaluation of inclination angle of main piping for LBE drain
- Design & operation procedure to prevent the generation of gas accumulating region after push-up operation

Hironari OBAYASHI TEF-T Target Mock-up Loop

Full scale model of target vessel (1/2)

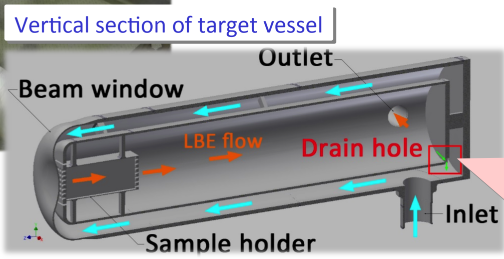
Purpose

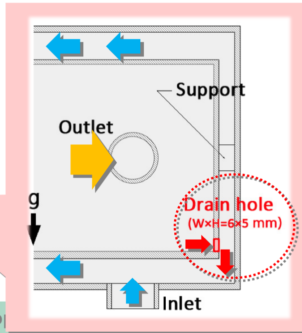
A) Confirmation of manufacturing method
B) Confirmation of the residual LBE after drain operation
C) Structural durability in non-irradiation condition (erosion/corrosion)
D) Confirmation of dynamic behavior
(LBE flow, heat transfer, flow vibration)

Confirmed by long-run test & flow visualization

Result of A) & present design of B)

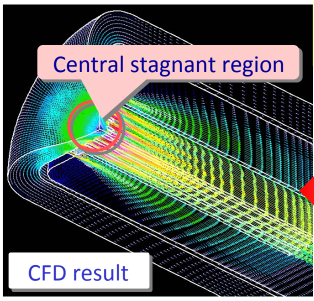
A) BW(2mm thick) part was made by shaving from ingot, and successfully manufactured.
B) To reduce residual LBE, drain hole (6(W)×5(H)mm) was provided at the end of inner pipe.



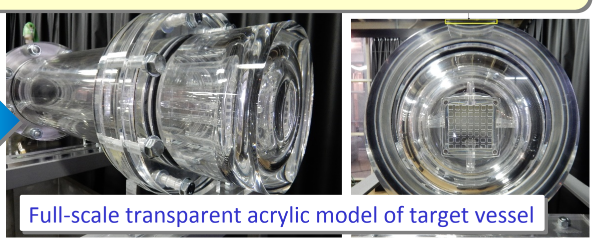


Full scale model of target vessel (2/2)

D) Confirmation of dynamic behavior (LBE flow, heat transfer, flow vibration)



Estimation of the instability of central stagnant region is important issue for TEF-T target.



Purpose of flow visualization experiment

- To verify the simulated LBE flow (In particular instability of central stagnant region)
- Confirmation of the effect of planned guide fin (to remove the central stagnant region)
- Experimental data acquisition to verify the fluid analysis result for upgrade of target vessel

Status

Full-scale flow visualization model and Hi-speed PIV system were prepared.
Experiment will be started from Nov. 2015.

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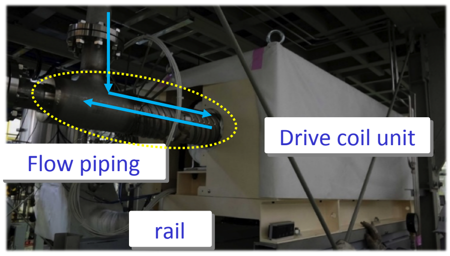
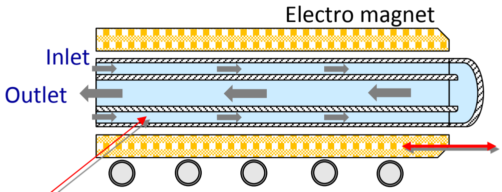
Electro Magnetic Pump (EMP)





Design

- To reduce the radioactive waste

⇒ Return flow type of coaxially annular flow channel was applied.

⇒ Drive coil unit is installed on the rail in order to realize the extracting operation.

- To prevent the blockage of flow channel

⇒ Gap of annular region was increased to about 22 mm.

(Old annular type used in JLBL-2 = 3 mm)

Parameters	Specification
Type	Annular flow channel type
Material	316SS
Design temperature	450 °C
Design pressure	0.5 MPa
Flow rate	Max. 120 liter/min
Delivery pressure	Max. 0.2 MPa
Operation temperature	200-450 °C

- **Performance test (Max. flow rate) ⇒ OK**
- **Durability (including the evaluation of gap width) will be confirmed by long run test (Aug, 2016)**

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Heat exchanger

Parameters	Specification
Type	Fin-tube type
Exchange duty	67 kW
Design Exchange duty	200 kW (depending on 3rd system)
Primary/Secondary medium	LBE/Pressurized water
Flow rate of LBE/Pres. Wat.	Max. 120/300 liter/min
Temperature of secondary medium	In 150 / out 200 °C
Pressure LBE/Pres. Wat.	0.5/2.0 MPa

Experience from old LBE loop

To prevent the erosion caused by the disturbed flow, it is desirable for the primary flow channel to be the single pipe structure with no channel reduction/expansion.

⇒Fin-tube type (air cooling) was applied to old LBE loop(JLBL-1), and it worked well.

Design

- Heat exchanger of fin-tube type was applied and its primary flow channel made with schedule pipe same as main piping (65A).
- To prevent the enlargement of HX, pressurized water (<2.0MPa) was applied to the secondary medium.

(Saturated pressure of pressurized water at 200°C is about 1.45 MPa)

- **Performance test will be started from December, 2015.**
- **Durability test will be started from August, 2016.**

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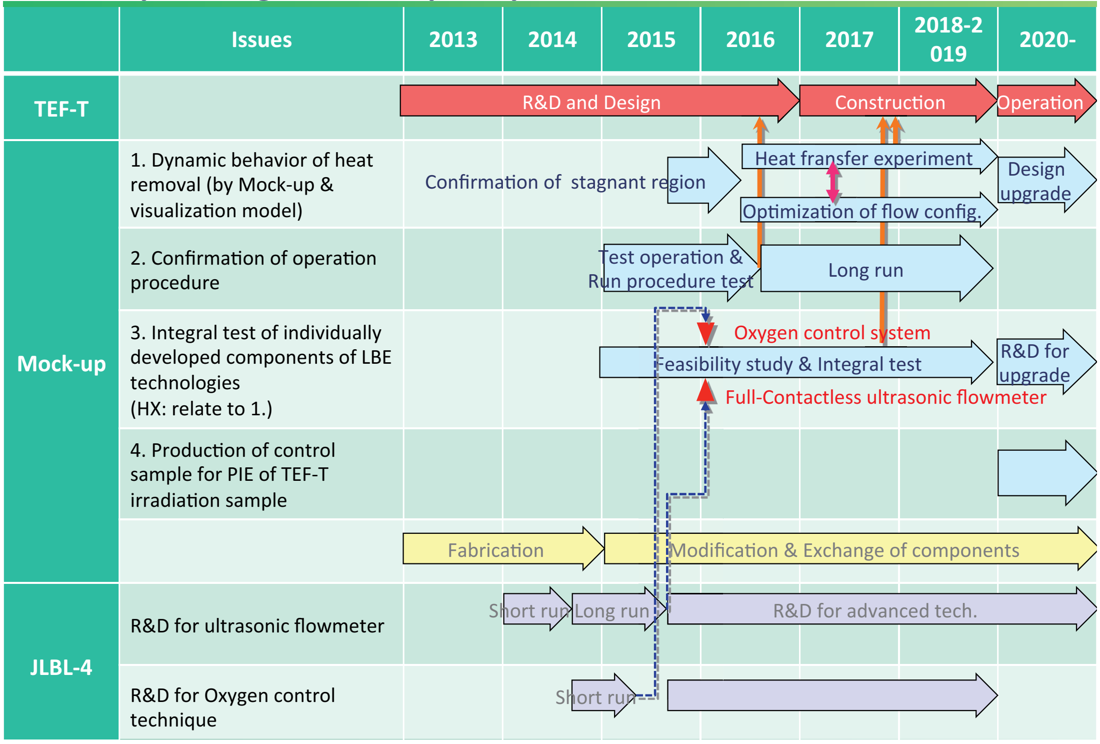
Roadmap of Target Mock-up Loop



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Contents

1. Outline

2.Status of developed components & Roadmap of Mock-up loop

3.Application test of ultrasonic flowmeter

4.Summary

14

Hironari OBAYASHI TEF-T Target Mock-up Loop

Purpose of ultrasonic flowmeter

Purpose

- Flow rate (velocity) of LBE is directly related to the cooling performance of target vessel

Stable & accurate monitoring of LBE flow rate is very important

Ultrasonic flowmeter

- R&D of ultrasonic flowmeter with the plug-in type transducer has been performed.
- And it **worked well at short run(≤1,000hr) test.**

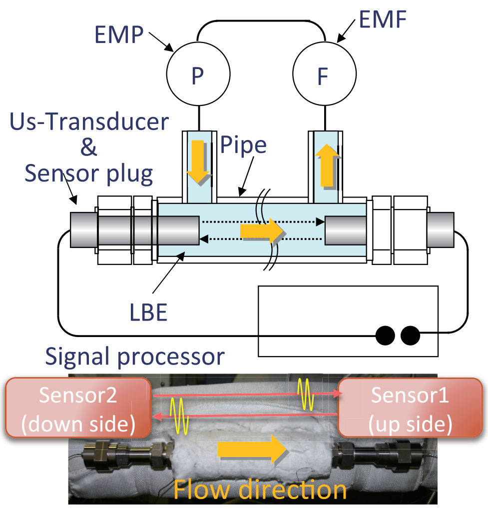
(Plug-in type: top of plug is contact to LBE)

Requirement for flowmeter

- Heat resistance over 300-500˚C ⇒ OK
- Application to flowing LBE ⇒ OK
- Radiation-resistant ⇒ OK
- Remote operability ⇒ under consideration with the other sensor
- Measurable method in re-wetted condition & Durability

Test configuration at JLBL-4

- Test configuration for plug-in type of ultrasonic flowmeter



Test conditions	
Transducer (TDX)	Plug-in type
Frequency	4 MHz
Wave number	1 cycle
Length of Flight path	115 mm
Num. of TDX couple	1
Time resolution	0.5 sec
LBE temperature	350 ˚C
LBE flow rate	0-30 liter/min (0-0.4 m/sec)
Control of oxygen concentration	Until halfway of long run

Testing items

- LBE drain is necessary for scheduled maintenance

⇒Application test for re-wetted condition

- Durability test in long run operation (≤ 5,000 hr)

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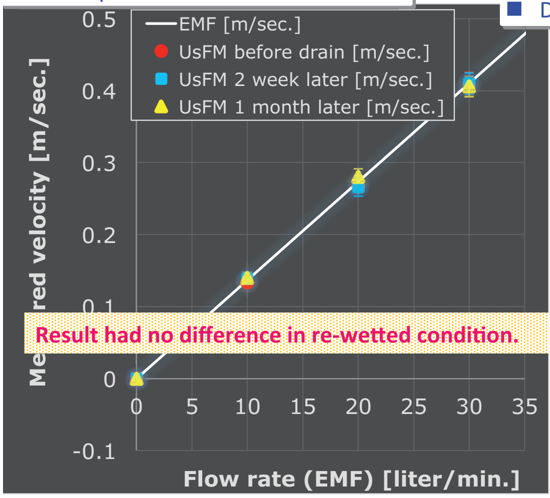
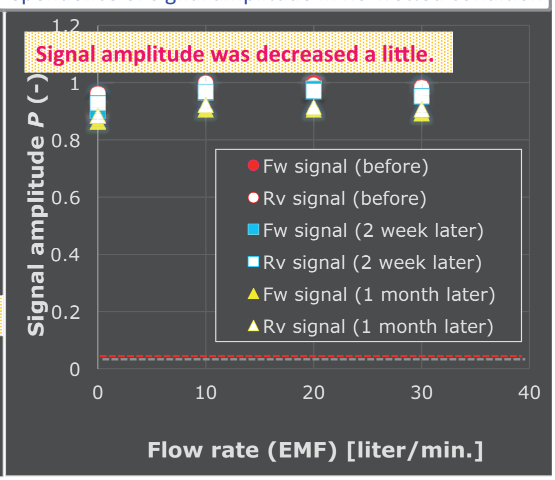
Result of Application test for Re-wetted condition

Measurement① (before drain)	Drain & shutdown (Push-up LBE 2 week later)	Measurement② (2 week later)	Drain & shutdown (Push-up LBE 1 month later)	Measurement③ (1 month later)

■ Comparison between UsFM &EMF



■ Dependence of signal amplitude in Re-wetted condition



Plug-in type of Ultrasonic flowmeter can apply to re-wetted condition.

Hironari OBAYASHI TEF-T Target Mock-up Loop

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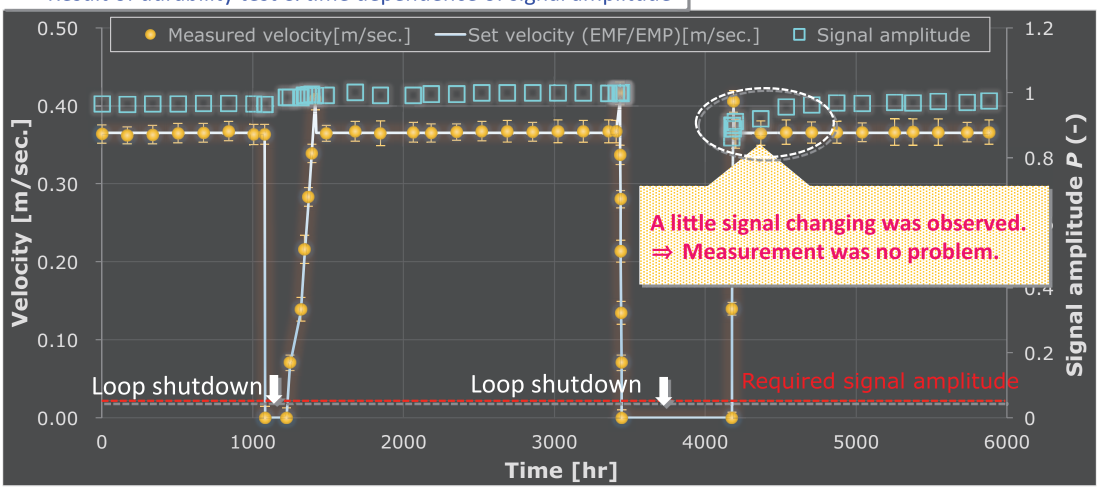
Durability experiment of ultrasonic flowmeter

- LBE flow rate: 26.8 liter/min.

  ≈ 0.37m/sec : same velocity of TEF-T piping (65A) at rating flow rate

■ Result of durability test & time dependence of signal amplitude



Measurement time will reach 5,000 hr at the end of Oct.
UP to the present, extremely stable measurement result is provided.
Durability of ultrasonic flowmeter is no Problem!

Contents

Summary

- **JAEA designed and built TEF-T Target Mock-up Loop to confirm following issues.**

1. Dynamic behavior of heat removal
2. Confirmation of operation procedure
3. Integral test of individually developed components of LBE technologies (including EMP & HX)
4. Production of control sample for PIE of TEF-T irradiation sample

The experiment for each issue will be started in this year.

- **The plug-in type of ultrasonic flowmeter showed sufficient performance.**

End

Thank you for your kind attention.

21

Monitoring system

Parameter	Device	Purpose	Mock-up	TEF-T
Temperature	Thermocouples	Temp. monitoring/control of each component Management of LBE temp.	O	O
Flow rate	Us. Flowmeter	Monitoring of LBE flow rate (Main) Detection of blockage (sub)	O	O
LBE pressure	Liquid pressure gauge	Monitoring of LBE flow rate (sub) Detection of blockage (Main)	2016-	O
Liquid level	Continuous/point Level gauge	Management of liquid level Detection of LBE leakage (continuous)	O	O
Leak-detector	Resistor type	Detection of LBE leakage	X	O
Oxygen concentration	Oxygen sensor (Pt-Air) & control system	Control of oxygen concentration of LBE	2015-	O
Cover gas pressure	Gas pressure gauge	Management of cover gas pressure Detection of gas leakage	O	O
Radiation detector	Radiation gas monitoring system	Detection of radiation gas leakage	X	O
Parameters for secondary system	TC, Gas Pres. gauge, Flowmeter	Management of secondary system	O	O

22

◆ **Each device are connected to the interlock system**

7.3 LBE High Temperature Material Corrosion Test (HTC) Loop

LBE High Temperature material Corrosion test (HTC) loop

Shigeru SAITO, Hironari OBAYASHI, Kazushi YAMAGUCHI and Toshinobu SASA

Target Technology Development Section, Nuclear Transmutation Division, J-PARC Center, JAEA

To realize TEF-T and ADS, corrosion data at 400-550℃ under oxygen concentration controlled and flowing condition are necessary. To obtain the corrosion data at the higher temperature, JAEA designed and built High-Temperature material Corrosion test (HTC) loop. The loop was composed of two test sections, a surge tank, contact type liquid level gauges, oxygen sensors and an oxygen control unit, heaters, a cooler, a filter, an electromagnetic pump (EMP), an ultrasonic flow meter and a drain tank. A typical flow rate is 20 liters/min. Operating temperature range is 200-550℃and maximum ΔT is 100℃. Piping materials of the high temperature part is T91 (Mod.9Cr-1Mo) and low temperature part is SS316L. There are two high temperature test sections at the lower part of the expansion tank. A specimen holder will be set into the test section from a sample exchange box set on the expansion tank. The specimen holder was made of T91 tube with a pair of grooves at the upper and lower parts of the inner surface. The specimens will be set in the grooves straightly.

Construction of the loop has been completed in March 2015. Conditioning operation without LBE and some modifications are processing. Oxygen control test will be started next April and corrosion test will be started in 2016.

LBE High Temperature material Corrosion test (HTC) loop

Shigeru SAITO

Target Technology Development section,

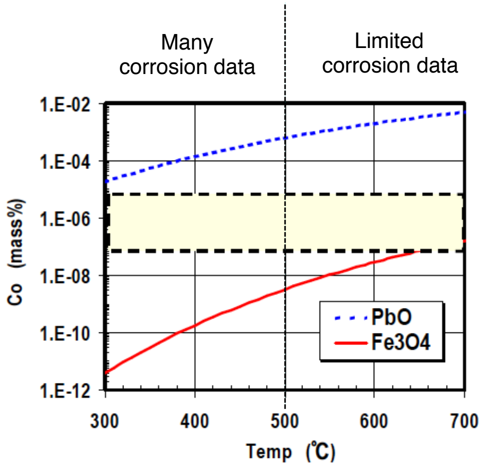
J-PARC Center, JAEA

Contents

1. Purpose of the HTC loop
2. Specification of the HTC loop
3. Testing plan
4. Summary

1. Purpose of the HTC loop

To realize TEF-T and ADS, corrosion data at 400-550°C under oxygen concentration controlled and flowing condition are necessary.



JAEA designed and built High-Temperature material Corrosion test (HTC) loop to obtain the corrosion data at higher temperature.

1. Purpose of the HTC loop

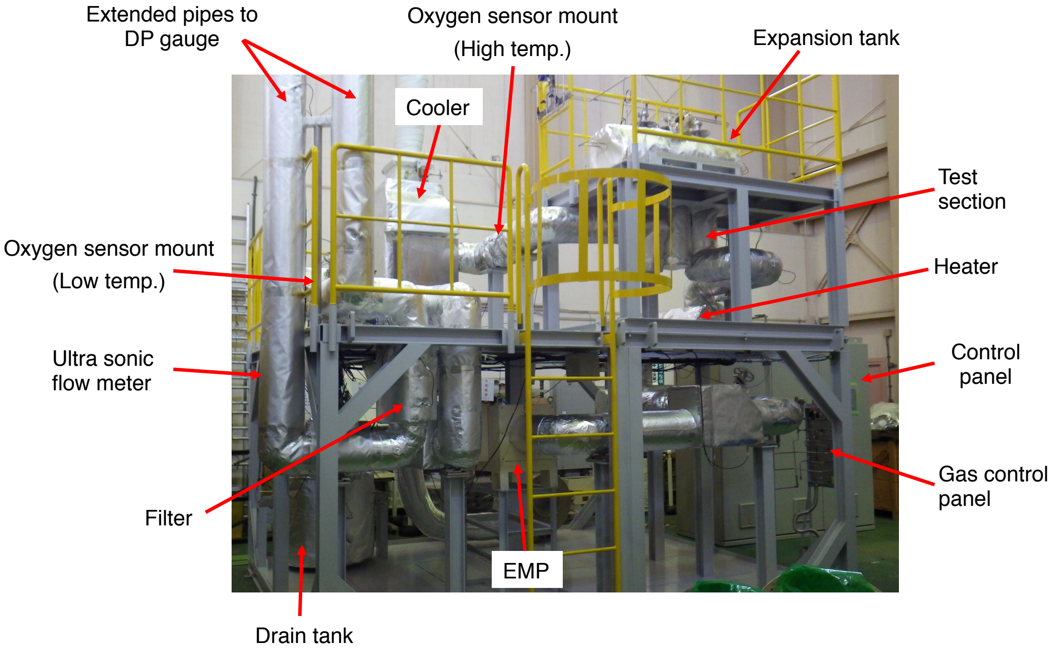
Purpose

- Fundamental study for future ADS development
- Corrosion data collection for PIE on TEF-T irradiated materials.
- Development of filtering system

Design concept

- High temperature (>500°C) corrosion test
- Multi test section
- Non-contact type flow meter
- Oxygen sensor, oxygen concentration control system
- Purification system of LBE
- Exchange test-piece without drain (to keep oxygen concentration)
- Decrease flange

1. Purpose of the HTC loop

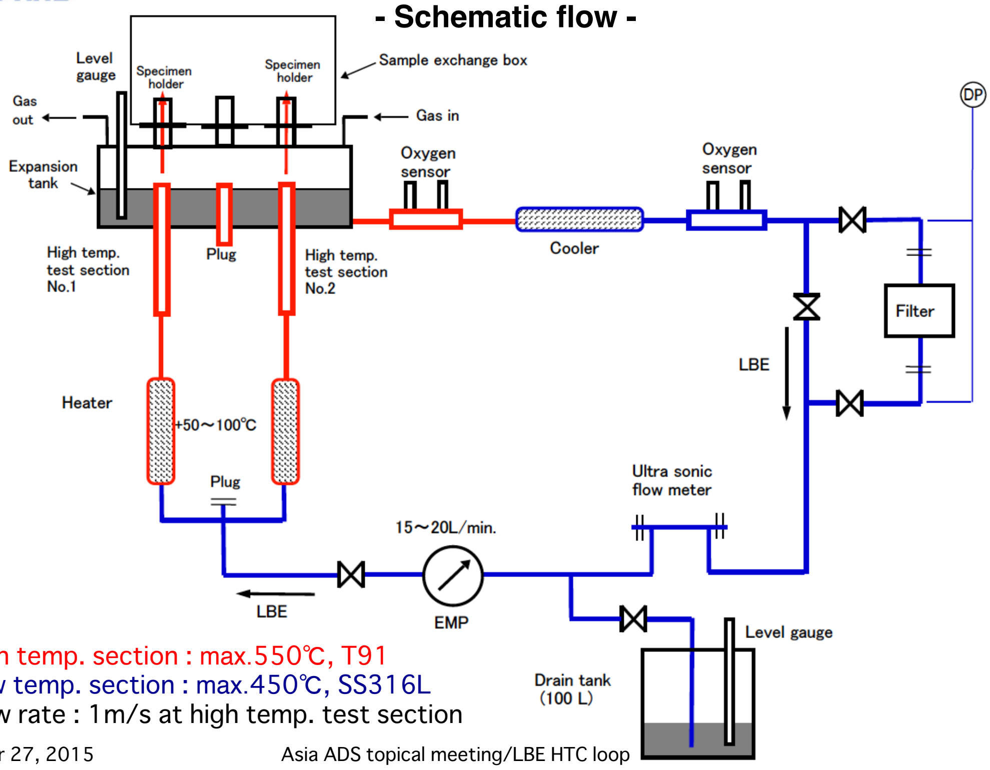


The loop was installed in this March.

October 27, 2015 Asia ADS topical meeting/LBE HTC loop 5

2. Specification of the HTC loop

- Schematic flow -



High temp. section : max.550℃, T91
Low temp. section : max.450℃, SS316L
Flow rate : 1m/s at high temp. test section

October 27, 2015 Asia ADS topical meeting/LBE HTC loop 6

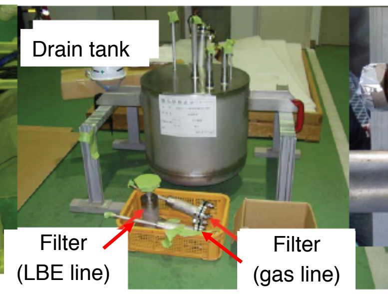
2. Specification of the HTC loop

Expansion tank

Oxygen sensor mount
(High temp.)

Cooler

Heater

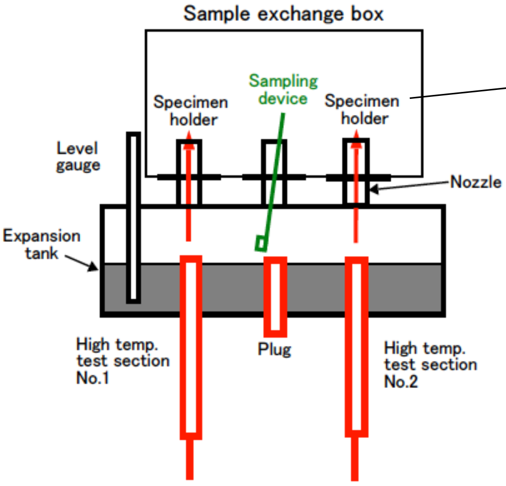


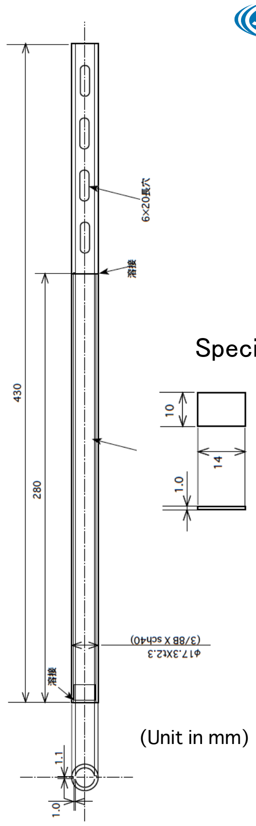
Ultra sonic flow meter

October 27, 2015 Asia ADS topical meeting/LBE HTC loop 7

Specification of the HTC loop
- Design of the test section -

Test section	:T91(3/4B, ϕ27.2 X t2.9 mm)
Specimen holder	:T91(3/8B, ϕ17.3 X t2.3 mm)
Specimen	:plate (10 X 14 X t1.0 mm)
Material	:T91, 316SS, various steels





Specimen

(Unit in mm)

October 27, 2015 Asia ADS topical meeting/LBE HTC loop 8

2. Specification of the HTC loop

Specification

-Maximum temp. : 550°C, ΔT=100°C
-Material : T91(Mod.9Cr-1Mo), SS316L
-Test section : 2
-Flow rate : 1 m/s at high temp. test section
-Ultra sonic flow meter
-Oxygen sensor (to be installed)
-Oxygen concentration control system (Ar-H_2, Ar-O_2) (to be installed)
-Filter **:** stainless steel mesh, bypass line
Differential pressure gauge to detect blockage
-Sample exchange box (to be installed)

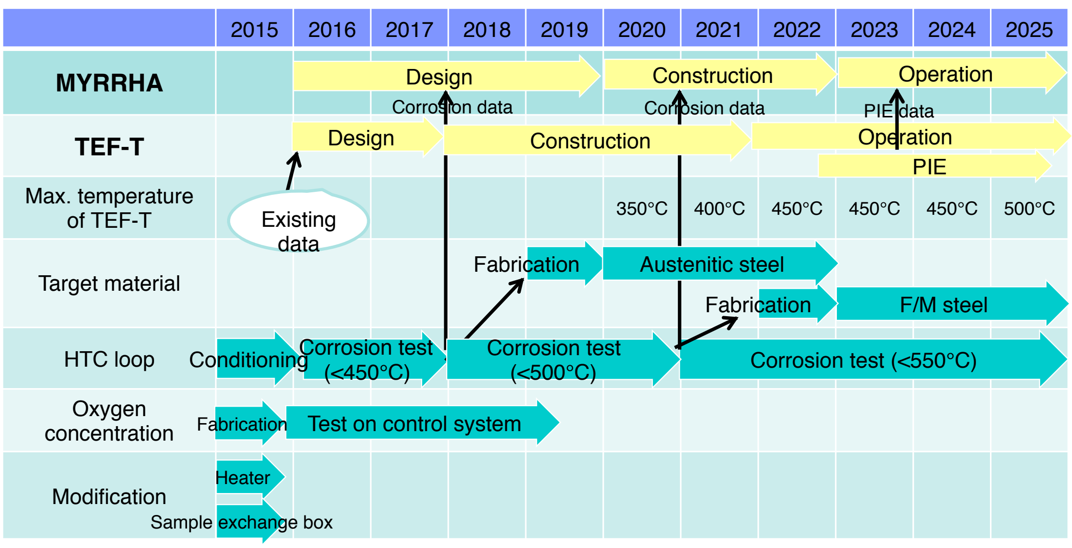
Status

Conditioning operation without LBE, modification of heaters and sample exchange box.

Oxygen sensor and oxygen concentration control system are to be installed until next March.

3. Testing plan

-Schedule-



- TEF-T will be designed based on the existing corrosion data.
- Results of corrosion test (<450°C and <500°C) will be reflected to the design of Austenitic steel target and F/M steel target, respectively.
- These corrosion data will be reference of MYRRHA design.

3. Testing plan

Proposal testing plan of HTC loop including experimental conditions (temperature, oxygen concentration and LBE flow rate) was made.

		2016	2017		2018		2019		2020		2021		2022	
Phase		1 (Proof test)	2 (Corrosion test, benchmark)		3 (Corrosion test)		4 (Corrosion test, reproducibility)		5 (Corrosion test, long run test))		6 (Corrosion test)		7 (Corrosion test, reproducibility)	
Oxygen concentration (wt.%)		10^{-5} – 10^{-7}	←	←	←	←	←	←	←	←	←	←	←	←
LBE flow rate		1m/s	←	←	←	←	←	←	←	←	←	←	←	←
ΔT(℃)		100	←	←	←	←	←	←	←	←	←	←	←	←
Test section No. 1	Temp.(℃)	450	450	450	500		500	500	500		550	550	550	
	Time	3,000h	1,000h	3,000h	5,000h		1,000h	3,000h	5,000h(10,000h)		1,000h	3,000h	5,000h	
Test section No. 2	Temp.(℃)	450	450		500	500	500		500	500	550		550	550
	Time	3,000h	5,000h		1,000h	3,000h	5,000h		1,000h	3,000h	5,000h		1,000h	3,000h
Specimen		Austenitic F/M steel	Austenitic, F/M steel, welds, coating, ODS, etc.		←		←		←		F/M steel, welds, coating, ODS, etc.		←	

October 27, 2015 Asia ADS topical meeting/LBE HTC loop 11

4. Summary

JAEA designed and built High-Temperature material Corrosion test (HTC) loop to obtain the corrosion data at higher temperature.

- Conditioning operation, modifications are processing.
- Oxygen sensor and oxygen concentration control system are to be installed.
- Oxygen control test will be started next April.
- Corrosion test will be started within next year.

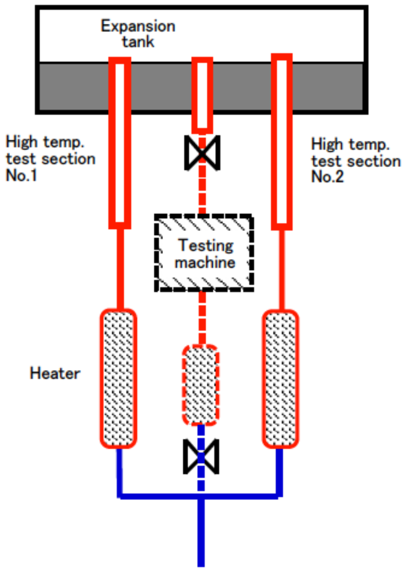
Issues

- Oxygen control
- Life time of oxygen sensor
- Purification of LBE

October 27, 2015 Asia ADS topical meeting/LBE HTC loop 12

Future plan

As a future plan, installation of a mechanical testing machine in the 3rd test section of HTC loop is under considering.



7.4 Elemental Technologies for LBE Loop

Elemental Technologies for LBE loop

Toshinobu Sasa, Shigeru Saito, Hironari Obayashi, Hidemitsu Yoshimoto, Kazushi Yamaguchi and Takanori Sugawara

Target Technology Development Section, J-PARC Center, Japan Atomic Energy Agency

The elemental technologies for LBE loop were developed to realize ADS Target Test Facility (TEF-T) in J-PARC. As previous experiences in JAEA, Pb-oxides were produced and wedged to the seal of mechanical valve. Then, slow-leakage of LBE occurs and it decreases primary coolant amount and finally, the circuit will be aborted by loss of coolant. On the other hand, automatic drain mechanism of irradiated LBE is desirable by the safety point of view not only for public but also for workers. So, freeze-seal valve was manufactured experimentally and tested. From the experimental results, water-cooled type valve was selected by the time response for freezing. Because of the high irradiation of proton, LBE loop in TEF-T should be fully handled by remote operation. Several tests were performed to manage the LBE loop with the intention of remote handling. Automatic welding system, package type preheater and remote operation flange that are used in mercury target loop in J-PARC were tested. Through the experiments using master-slave manipulator, some issues were recognized and detail design should be improved according to the experiences.

Elemental Technologies

27, Oct. 2015
1st Topical Meeting on Asian Network for ADS and NTT

T. Sasa, S. Saito, H. Obayashi,
H. Yoshimoto, K. Yamaguchi, T. Sugawara
Target Technology Development Section, J-PARC Center

Contents

- Results of Functional Tests for LBE-loop elemental technologies
  - Freeze-seal Valve
  - Automatic Pipe Welding
  - Remote operation tests
    - Package Heater
    - Joint by Flange
- Summary

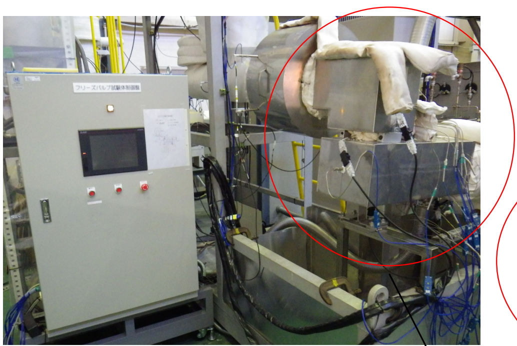
Freeze-seal Valve

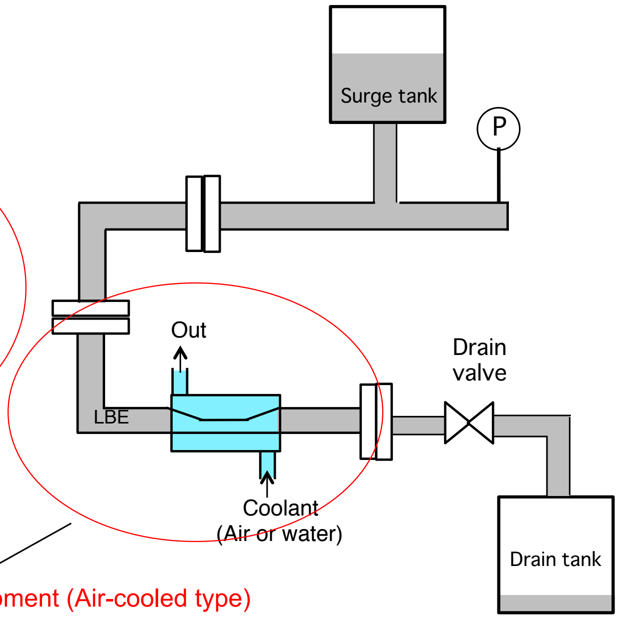
Objective

- Due to the production of Pb-oxides and those are wedged to the seal of mechanical valve, slow-leakage of LBE occurs and it decreases primary coolant amount and finally, the circuit will be aborted by loss of coolant.
- In the case of Station Black Out, automatic drain mechanism is desirable (it is not a legal recommendation), by the safety point of view not only for public but also for workers.
- Two types of coolant (Water, Air) was tested.

Freeze-seal Valve

Experimental Apparatus

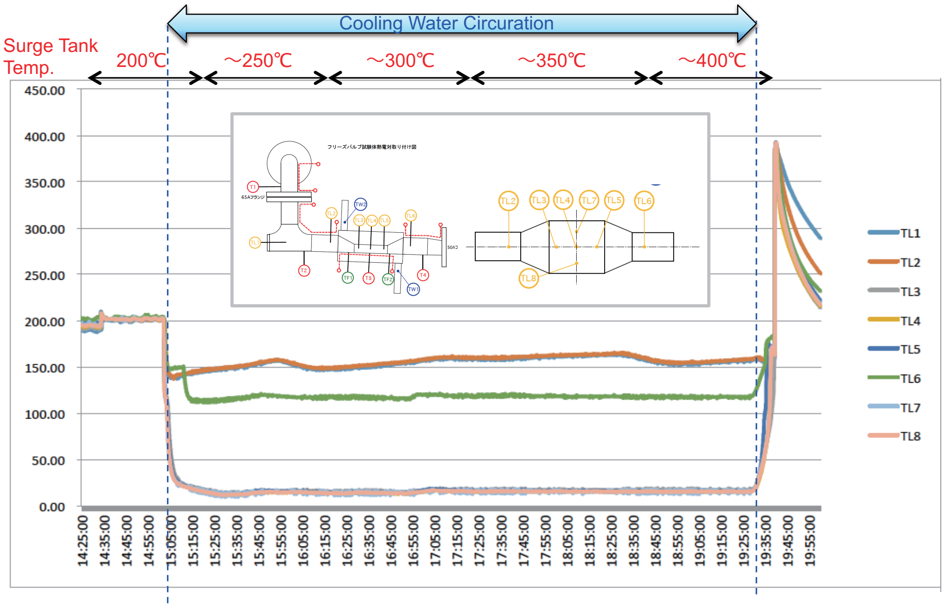




Test Equipment (Air-cooled type)

Freeze-seal Valve

Experimental Results



27/10/2015 Topical Mtg for Asian Network for ADS & NTT 5

Freeze-seal Valve

Experimental Results

Coolant Type	Freezing Time	Melting Time with Heater	Melting Time without Heater
Air	30 min	10 min	20 min
Water	2 – 3 min	10 min	20 min

- Selection of coolant
  - By the time response for freezing, we selected water-cooled type.
- Issues
  - Stress tests for thermal shock should be needed.

27/10/2015 Topical Mtg for Asian Network for ADS & NTT 6

Automatic Pipe Welding

Objective

- From our experiences, some difficulties are exist to handle the flange connection.

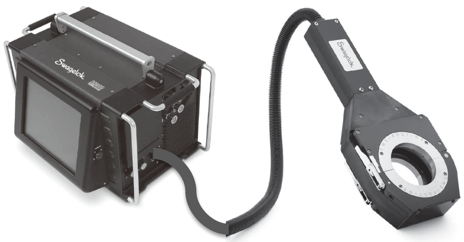
- Automatic welding machine (Swagelok)
  - Preset parameters for stainless steel
  - No needs for pre-processing
  - Low cost (Machine, Operation)

✓ Allowable pipe size is limited.

✓ Need parameter adjustment for T91 connection

Automatic Pipe Welding

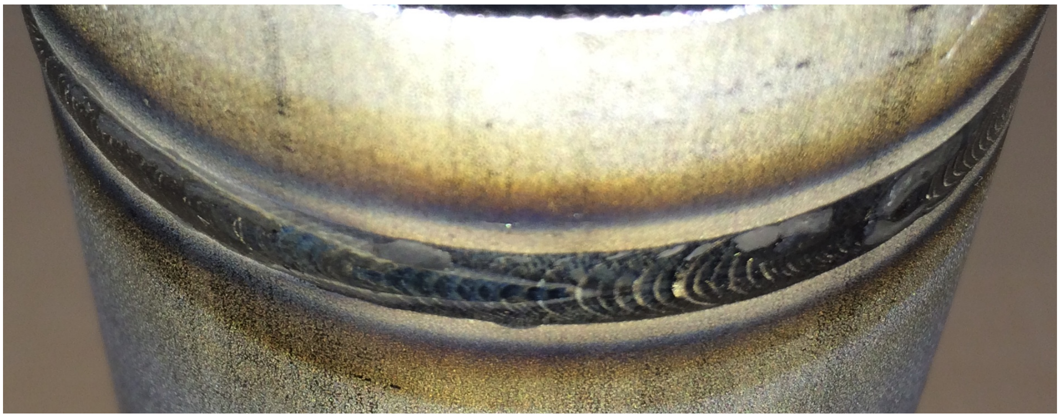
Welding Machine and Results

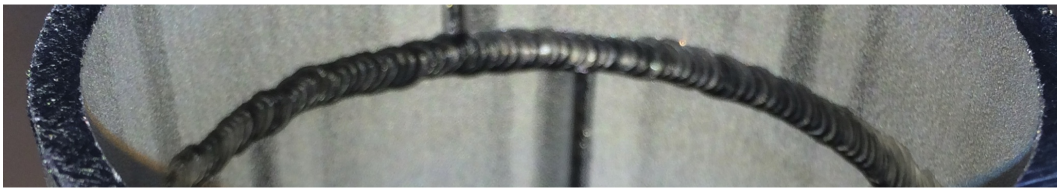


- Issues
  - Minimizing airborne dust
  - Treatment of residual LBE in piping
  - Method of inspection on welded parts by remote op. ...

Automatic Pipe Welding

Detail View of Welding position





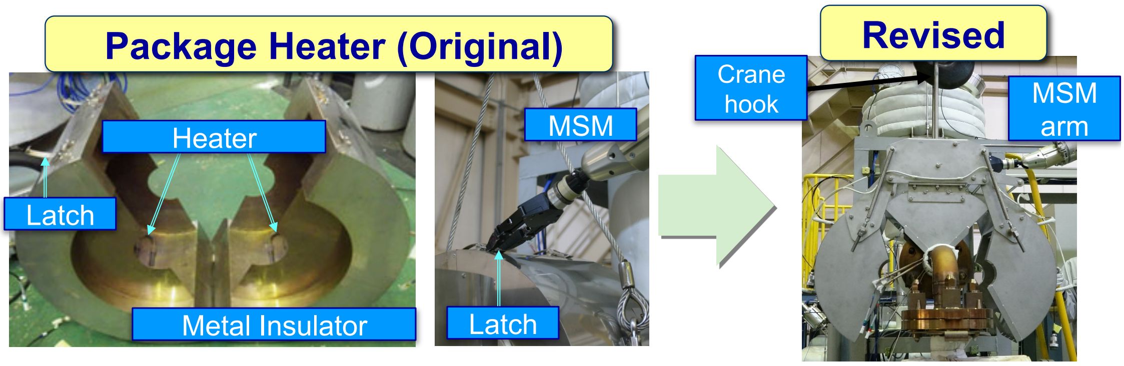
Remote Operation Tests

Package Heater

- Requirement of pre-heating of LBE is one of the big difference from our existing liquid metal spallation target in J-PARC.
- All pipes should be changed because the corrosion issues are still unclear, components including preheater should be handled by remote operation.
- As applying Fast Reactor technologies of JAEA, we built "Package Heater" which can be handled by remote machine with small modifications.

Remote Operation Tests

Package Heater



- Results
  - Revised heater gives satisfying results for remote operation by MSM.
- Issues
  - Heater for long piping should be designed and tested.

Remote Operation Test

Remote Flange (MLF type)

- Even though, we change the connection not by flange but welding, several periodic replacement parts, such as oxide filter and oxygen sensor, should be replaced easier.

- We remain the remote flange at the position, that swerve the LBE mainstream.

- So, we tried the functional tests for remote operation of remote flange using MSM.

Remote Operation Test

Remote Flange (MLF type)

- It's observed that the operation can be done with specific combination of MSM and PM.
- Reduction of burning in high radiation field should be solved (radiation resistant inhibitor).

Summary

- Elemental technologies for LBE loop have been developed using experimental devices.
- Some issues were recognized even preliminary experiments so far done.
- Detail design will be improved according to our experiences.

- Various issues to be solved has been cleared up.

8. Summary and Future Collaboration

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SUMMARY DISCUSSION
THE FIRST TOPICAL MEETING ON ASIAN NETWORK FOR
ACCELERATOR-DRIVEN SYSTEMS AND NUCLEAR TRANSMUTATION TECHNOLOGY
J-PARC Center, Japan Atomic Energy Agency
Tokai, Ibaraki, JAPAN


Group Photo

10/26 AM

LBE application in Europe (Invited talk by J. Konys [KIT])

- Long and deep research activities in KIT
- R&Ds toward the MYRRHA project
- Oxide potential control to form the film layer is a key to use LBE.

Development of LBE technology and related facilities in China (S. Gao [INEST])

- Steady progress toward the establishment of CLEAR reactor series
- Various research using existing equipment and development of attractive devices

10/26 PM-1

Current Status of the Development of Electromagnetic Pumps in Korea (Prof. H. Kim [UNIST])

Studies for sodium cooled fast reactors

Large flow amount pump are preparing for commercial rectors.

Preliminary core design analysis of a subcritical dedicated burner loading thorium-based oxide fuel (Ms. J. Lee [SNU])

Spent nuclear fuel management is serious issues for Korea.

MA Transmutation by ADS with Thorium is proposed for the solution.

10/26 PM-2

TEF-T Target Station design and maintenance (H. Obayashi)

LBE primary loop and target trolley design (H. Yoshimoto)

Target Analysis and monitor system (T. Wan)

Oxygen sensor and potential control (T. Sugawara)

Research toward establishment of Transmutation Experimental Facility

10/26 PM-3

Effect of Wall Surface condition on flow structure in a LBE two-phase flow (G. Ariyoshi [KURRI])

- Study for thermal-hydraulics of LBE for accidental case
- Treatment of boundary condition between liquid and solid
- Electromagnetic Probe was developed for measurement.
- Further experiments are planned.

10/27 AM

Oxygen sensor calibration device (K. Yamaguchi)

TEF-T Target Mockup Loop (H. Obayashi)

High Temperature Corrosion Test Loop (S. Saito)

Elemental Technologies (T. Sasa)

- Experimental devices and related technologies are developed for TEF construction.

Things to do

- Safe application of LBE for ADS and/or FRs
- Common Knowledge
  - Formation of oxide layer is a key
- However, issues are still exists…
  - Stable formation of oxide layer
  - Oxygen potential management for real-scale ADS/FR
  - Film formation on fuel cladding
  - Thermal conductivity of oxide film

Next meeting in 2016

- - Next meeting (ADS+NTT; general meeting) will be held in Japan
- -> Around (before or after) TCADS-3 meeting,

  which is held on 6th to 9th Sep. 2016 at Mito

We will provide you detailed information soon.

Appendix

Conference Agenda

The First Topical Meeting on Asian Network for Accelerator-driven Systems and Nuclear Transmutation Technology

Date: Oct. 26-27, 2015

Venue: Main Conference Room, J-PARC Center Research Building 2F, Tokai, JAEA

<u>Oct.26 (Mon)</u>

8:30 Bus transport from the Hotel Terrace inn Katsuta to J-PARC/JAEA

9:30 Welcome (N. Saito [J-PARC], Chair: F. Maekawa [J-PARC])

9:45 LBE application in Europe (Invited talk by J. Konys [KIT])

10:30 Break and group photo

11:00 LBE application activities in China (Chair: H. Kim [UNIST])
Development of LBE technology and related facilities in China (S. Gao [INEST])

12:00 Lunch

13:00 LBE application activities in Korea (Chair: S. Gao [INEST])
Current Status of the Development of Electromagnetic Pumps in Korea (Prof. H. Kim [UNIST])
Preliminary core design analysis of a subcritical dedicated burner loading thorium-based oxide fuel (Ms. J. Lee [SNU])

14:00 LBE Application activities for J-PARC TEF (Chair: Y. Saito [KURRI])
TEF-T Target Station design and maintenance (14:00-14:30, H. Obayashi)
LBE primary loop and target trolley design (14:30-14:50, H. Yoshimoto)
Target Analysis and monitor system (14:50-15:10, T. Wan)
Oxygen sensor and potential control (15:10-15:30, T. Sugawara)

15:30 Break

16:00 LBE application activities in Kyoto Univ. (Chair: T. Sasa [J-PARC])
Effect of Wall Surface condition on flow structure in a LBE two-phase flow (G. Ariyoshi [KURRI])

16:30 Adjourn

16:45 Bus transport to the Hotel Terrace Inn Katsuta

18:30 Dinner (near the Katsuta Station)

<u>Oct. 27 (Tue)</u>

8:30	Bus transport from the Hotel Terrace Inn Katsuta
9:30	LBE Experimental Equipment in JAEA (Chair: C. Pyeon[KURRI])
	Oxygen sensor calibration device (9:30-9:50, K. Yamaguchi)
	TEF-T Target Mockup Loop (9:50-10:15, Obayashi)
	High Temperature Corrosion Test Loop (10:15-10:40, S. Saito)
	Elemental Technologies (10:40-11:00, T. Sasa)
11:00	Discussions and future collaborations (Moderator: T. Sasa [J-PARC])
12:00	Lunch
13:30	Site tour (LBE equipment, Guide: H. Obayashi [J-PARC])
15:00	Adjourn
15:15	Bus transport to the Hotel Terrace Inn Katsuta

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度 [(a)]，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率 [(b)]	（数字の）1	1
比透磁率 [(b)]	（数字の）1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン [(b)]	rad	1 [(b)]	m/m
立体角	ステラジアン [(b)]	sr [(c)]	1 [(b)]	m^2/m^2
周波数	ヘルツ [(d)]	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度 [(e)]	℃		K
光束	ルーメン	lm	cd sr [(c)]	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能 [(f)]	ベクレル [(d)]	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト [(g)]	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で”radioactivity”と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ s\ A$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ s\ A$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	$1\ ha=1\ hm^2=10^4 m^2$
リットル	L，l	$1\ L=1\ l=1\ dm^3=10^3 cm^3=10^{-3} m^3$
トン	t	$1\ t=10^3\ kg$

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1\ eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1\ Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1 u=1 Da
天文単位	ua	$1\ ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100\ kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)^2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St=1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb=1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}=10^4lx$
ガル	Gal	$1\ Gal=1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウエル	Mx	$1\ Mx=1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G=1Mx\ cm^{-2}=10^{-4}T$
エルステッド [(a)]	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R=2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	$1\ \gamma=1\ nT=10^{-9}T$
フェルミ		1 フェルミ=1 $fm=10^{-15}m$
メートル系カラット		1 メートル系カラット= 0.2 g = $2\times10^{-4}kg$
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ \mu=1\mu m=10^{-6}m$

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