IAEA TM on Tritium Breeding Blankets and Associated Neutronics
Sep. 02-05, 2025, IAEA HQ, Vienna, Austria

Progress and Challenges in Structural and Functional Materials Development for Breeding Blanket in Korea

Yi-Hyun Park

on behalf of Blanket Engineering Group

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

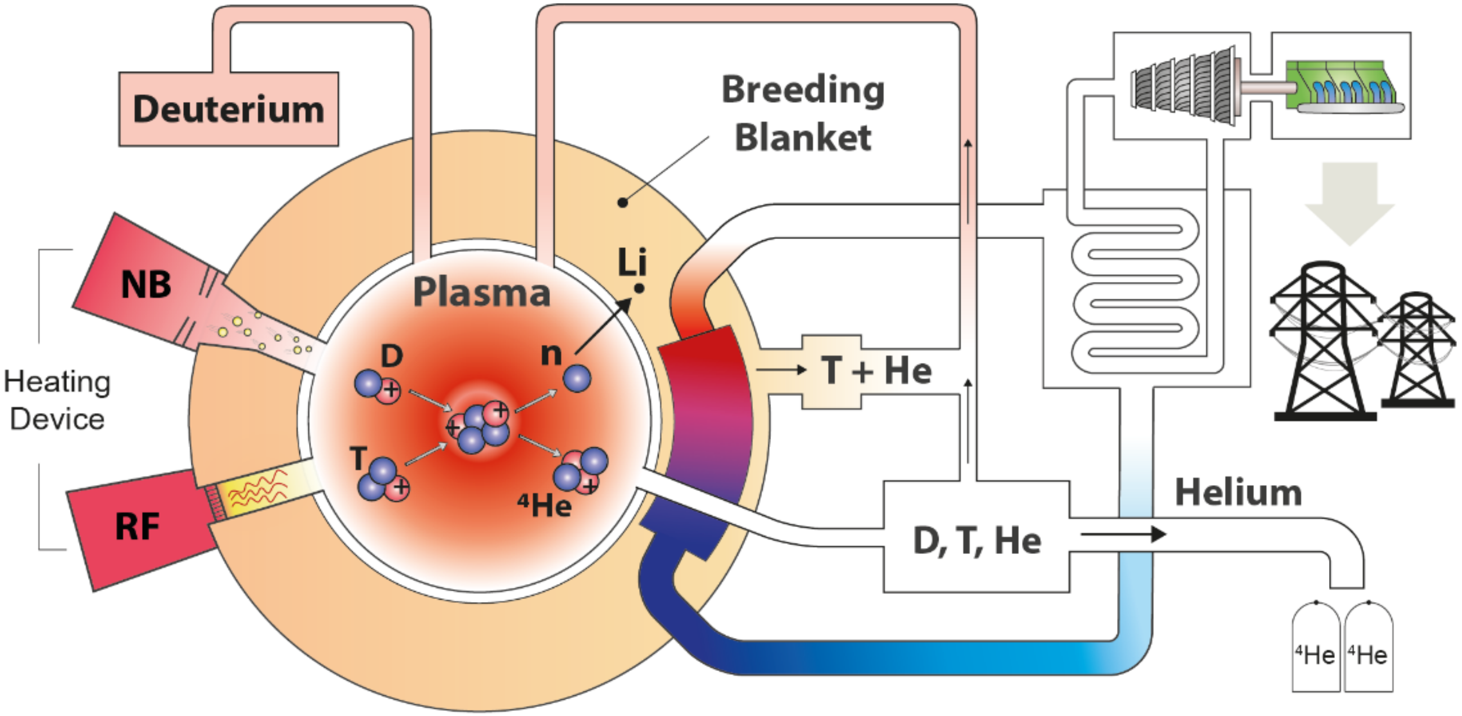
Table of Contents

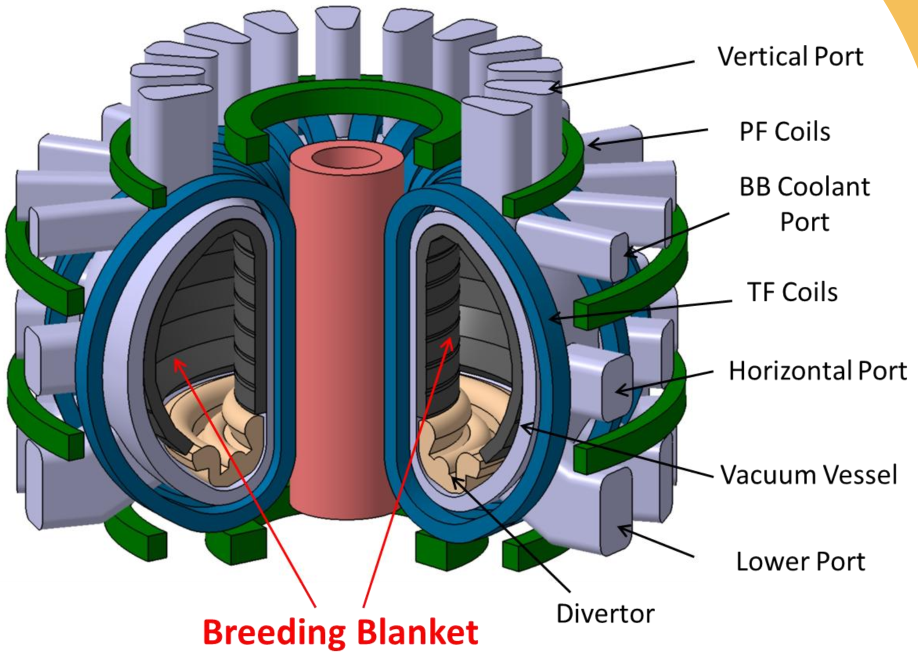
01

Background

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

Concept of Fusion Power Plant and Breeding Blanket





- in Fusion Core :

  D + **T** → 4 He + **n** + 17.6 MeV

- in Breeding Blanket :

  ^{6}Li + **n** → ^{4}He + **T** + 4.8 MeV

  ^{7}Li + n → ^{4}He + T + n' – 2.5 MeV

  ^{9}Be + n → ^{8}Be + 2n – 2.5 MeV

- Functions of Breeding Blanket
  - **Tritium Breeding** to ensure fuel self-sufficiency
  - **Heat Conversion and Extraction** for electricity generation
  - Neutron and Gamma-ray **Shielding**

ITER TBM Concepts and Materials

Main Characteristics for the 4 InCo TBMs and associated Ancillary Systems

TBS-1 – **WCLL-TBM** (proposed by EU) ▪ Eurofer Steel (structure), **Pb16Li** (multiplier/breeder). ▪ Coolant: **H_2O at 15.5 MPa, 280 /325°C**. ▪ T-removal gas (from Pb16Li): He at 0.4 MPa. ▪ Maximum Tritium production: 20-30 mg/day	TBS-2 – **HCCP-TBM** (joint KO/EU design) ▪ RAFM Steel (structure), Be pebbles (multiplier); **Li_4SiO_4 or Li_2TiO_3** pebbles (breeder). ▪ Coolant: **He at 8 MPa, 300/500°C**. ▪ Purge gas: Helium at 0.1/0.4 MPa. ▪ Maximum Tritium production: 20-30 mg/day
TBS-3 – **WCCB-TBM** (proposed by JA) ▪ F82H Steel (struct.), Be pebbles (mult.), **Li_2TiO_3** pebbles (breeder). ▪ Coolant: **H_2O at 15.5 MPa, 280 /325°C**; ▪ Purge gas: He at 0.1 MPa. ▪ Maximum Tritium production: 20-30 mg/day	TBS-4 – **HCCB-TBM** (proposed by CN) ▪ RAFM Steel (structure), Be-pebbles (multiplier), **Li_4SiO_4** pebbles (breeder) ▪ Coolant: **He at 8 MPa, 300/500°C**. ▪ Purge gas: He at 0.1/0.4 MPa. ▪ Maximum Tritium production: 20-30 mg/day

- ***The TBS Initial Configuration is expected to be operated for three ITER phases****, namely the last non-nuclear phase (PFPO-2) and in the first two nuclear phases (FPO-1 and FPO-2).*
- ***After FPO-2****, different TBSs could be operated, for example, Dual-Coolant Lithium-Lead (DCLL) TBS proposed by US and Helium-Cooled Solid Breeder (HCSB) TBS proposed by India.*
- *A decision on the TBS Second Configuration is expected around 2030.*

iter china eu india japan korea russia usa

L. Giancarli, ITER TBM Program, DPWS-8, 30 August-1st September 2022

13

Korean Breeding Blanket Concepts and Materials

Parameters	HCCR ITER TBM	HCCP ITER TBM	HCCR DEMO	HCCP DEMO
FW Heat Flux	0.3 MW/m^2	0.3 MW/m^2	0.5 MW/m^2	0.5 MW/m^2
Neutron Wall Loading	0.78 MW/m^2	0.78 MW/m^2	1.5 MW/m^2	1.5 MW/m^2
Armor Material (Plasma Facing)	n/a	n/a	Tungsten	Tungsten
Structural Material	**RAFM (ARAA)**	**RAFM (Eurofer/ARAA)**	**RAFM (ARAA)**	**RAFM (ARAA)**
Breeder Material	Li_2TiO_3	Li_4SiO_4/Li_2TiO_3	Li_2TiO_3	Li_4SiO_4/Li_2TiO_3
Neutron Multiplier Material	Be	Be	Beryllide	Beryllide
Reflector Material	Graphite	n/a	Graphite	n/a
Max. dpa (Lifetime of blanket)	3	3	20 / 50	20 / 50
Primary Coolant	Helium	Helium	Helium	Helium
Coolant Inlet/Outlet Temperature	300/500 ^oC	300/500 ^oC	300/500 ^oC	300/500 ^oC
Coolant Pressure	8 MPa	8 MPa	8 MPa	8 MPa
Purge Gas	He with 0.1% H_2	He with 0.1% H_2	He with 0.1% H_2	He with 0.1% H_2
Enrichment (^6Li)	70%	70%	90%	90%

02

Progress of **Structural Material** Development

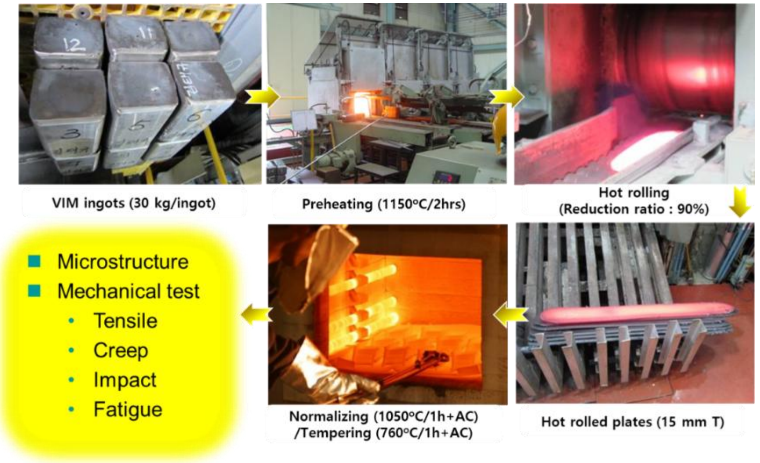
한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

Development of Korean RAFM Steel (ARAA)

- Advanced Korean RAFM Steel Development with:
  - Improved creep and impact resistances
  - Good irradiation resistance under neutron

ARaa™

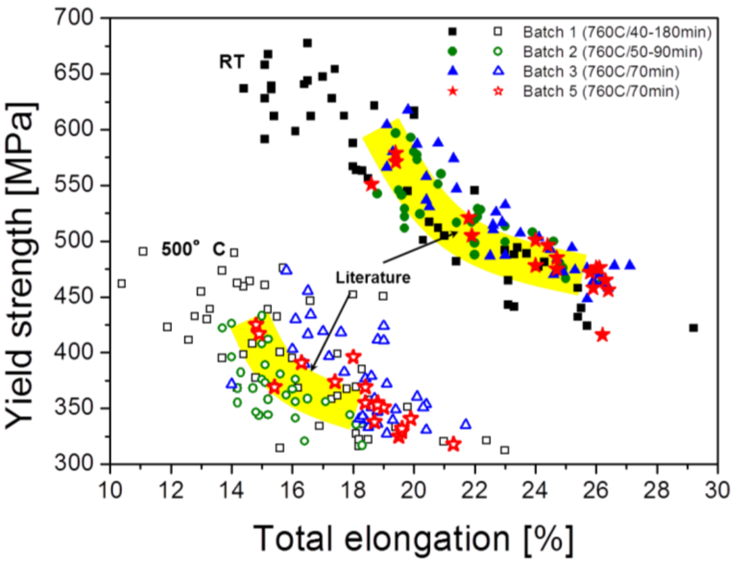
Advanced Reduced Activation Alloy

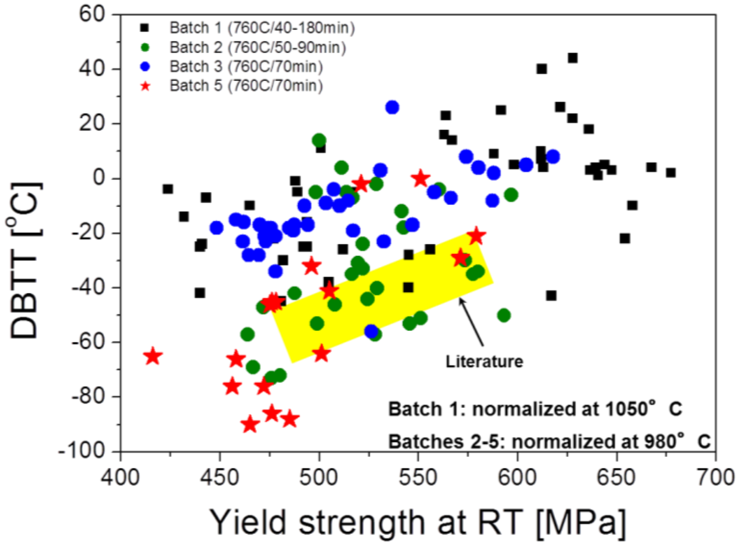


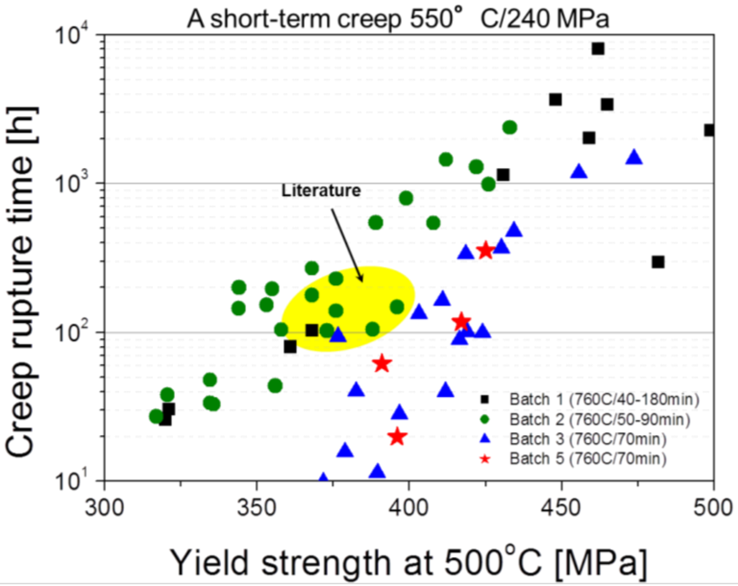
  - KFE and KAERI started R&D program on structural material for FUSION application in 2012.

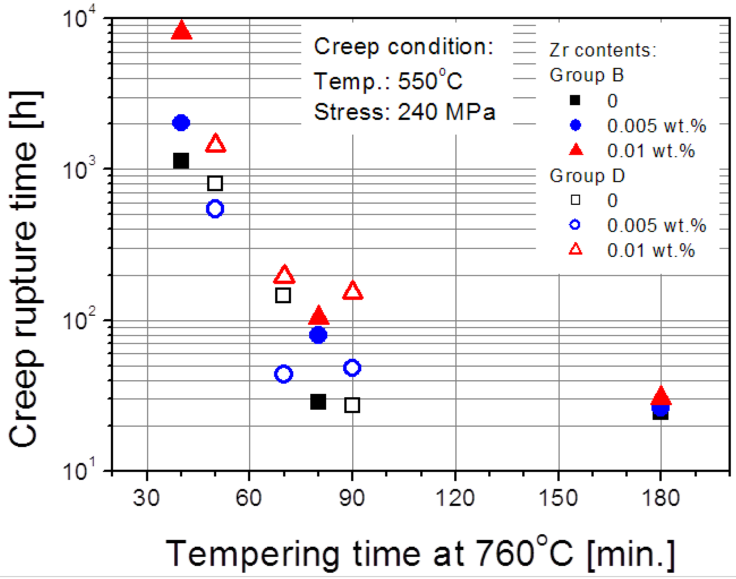
- Alloy Design : Strategy
  - Basic guidelines
    - 8~9 Cr – 1~2 W base (good resistance to irradiation embrittlement)
    - Minimized induced-activity: (Nb, Mo, Ni, Co, Cu, Al)-free
    - Full-martensitic structure (delta-ferrite free)
  - Approaches
    - Optimal combination amounts of alloying elements commonly used in the RAFM steels : Cr, W, Ta, V, Ti, …
    - Addition of new alloying elements : Zr or Sc, or both

Evaluation of ARAA Model Alloys







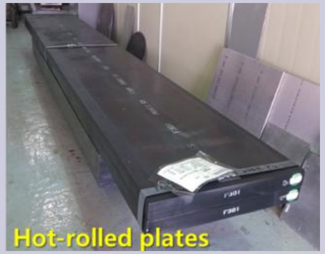


Optimized ARAA Alloy

Country	Name	C	Si	Mn	Cr	W	V	Ta	N	Ti	Zr
Japan	F82H	0.1	0.1	0.2	8	2	0.15	0.02	0.04	-	-
Japan	JLF-1	0.1	0.05	0.5	9	2	0.2	0.07	0.05	0.001	-
EU	Eurofer97	0.11	0.05	0.4	9	1.1	0.2	0.07	0.05	0.01	-
US	9Cr-2WVTa	0.1	0.25	0.4	9	2	0.25	0.07	0.003	0.01	-
Russia	Rusfer EK181	0.15	0.4	0.7	11	1.2	0.6	0.2	0.1	-	-
India	Indian-RAFM	0.1	0.09	0.5	9	1	0.2	0.07	0.02	0.005	-
China	CLAM	0.1	0.01	0.45	9	1.5	0.2	0.15	0.02	-	-
China	CLF-1	0.11	0.05	0.5	8.5	1.5	0.5	0.1	0.02	0.01	-
Korea	**ARAA**	**0.1**	**0.1**	**0.45**	**9**	**1.2**	**0.2**	**0.07**	**0.01**	**0.01**	**0.01**

- Characteristics of ARAA
  - Cr (9 wt.%) : for Good Corrosion Resistance, Minimum DBTT before & after Irradiation
  - W (1.2 wt.%) : for Decrease in the Possibility of Laves Phase Precipitation,
    Balance between High-temp. Strength and Impact Properties
  - Zr (0.01 wt.%) : for Improvement of Creep and Impact Resistance
- Optimized Heat Treatment Conditions of ARAA
  - (Normalizing) 1000 ^{o}C / 40 min. / AC, (Tempering) 750 ^{o}C / 70 min. / AC

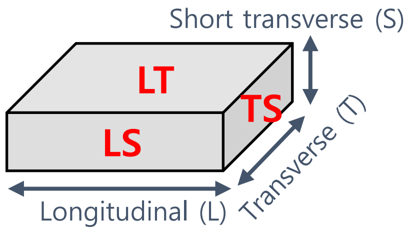
Large-scale Productions of ARAA

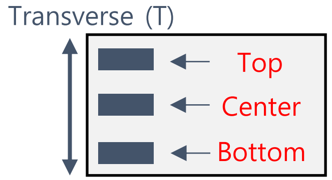
Production Year		2014	2015	2017			2025
Heat No.		RC4416	WA77	VB27	WB63	WB65	
Heat Scale (ton)		5	6	6	6	6	3 x 6 heats
Manufacturer		POSCO Specialty Steel	KPCM	KPCM	KPCM	KPCM	HVM
Melting & Refining		VIM + ESR	VIM + VAR	VIM + VAR	VIM + VAR	VIM + VAR	VIM + VAR
Material DB	Un-irrad.	Done	Done	Done	Done	Done	
	Irrad.		In progress	Scheduled			
ARAA Plates		 Hot-rolled plates	 Tempered plates	 Forged Bar		 Hot-rolled Plates	

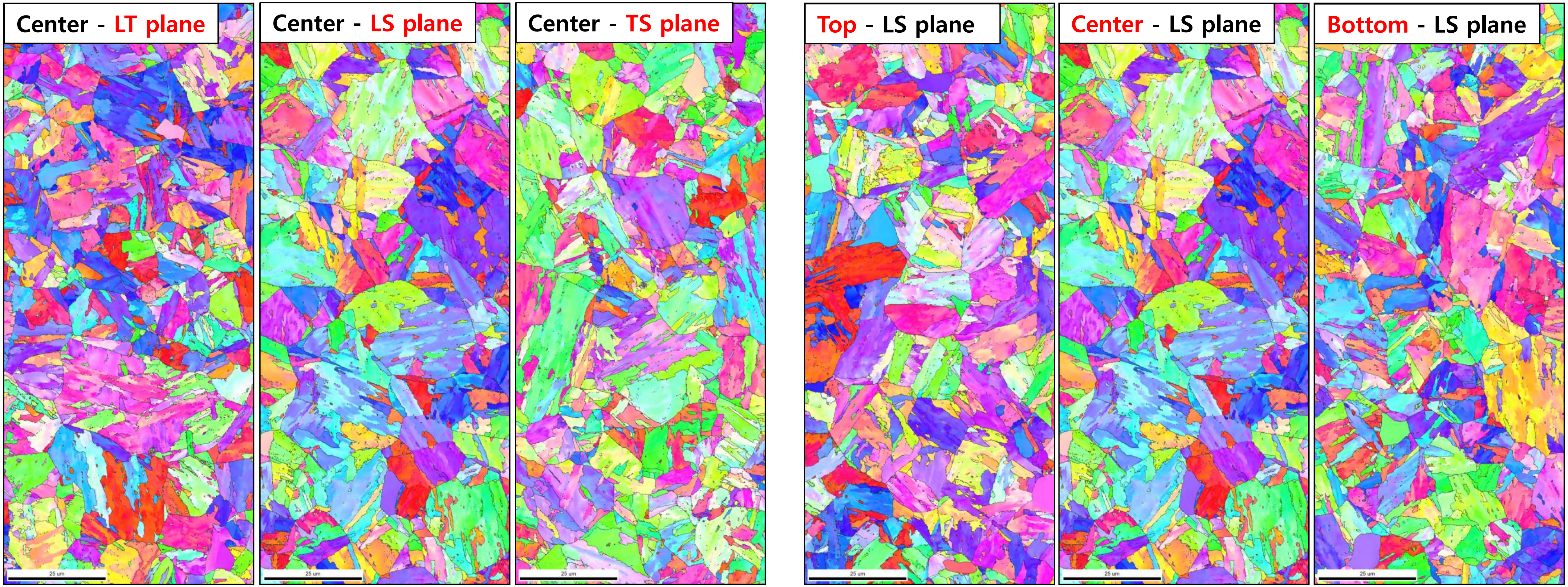
- The large-scale products have been used for …
  - Development of Material Properties DB and Welding Technology
  - Fabrication of Mock-up for Parts of Breeding Blanket

Uniformity of Hot-rolled Plate

- 20T ARAA (Heat #. VB27) – EBSD Analysis



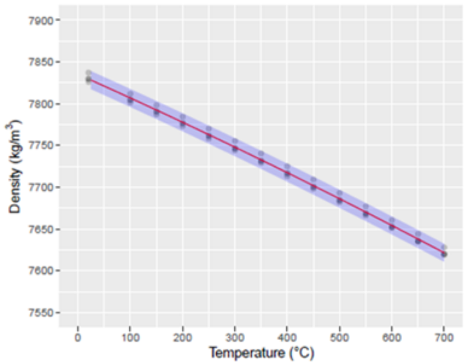




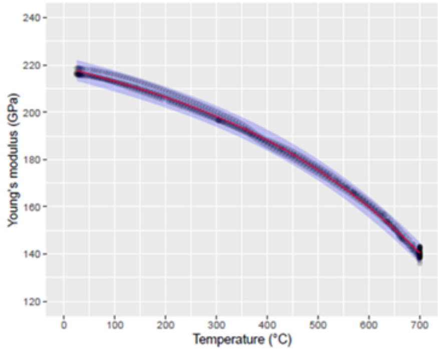
Material Properties of ARAA

KFE

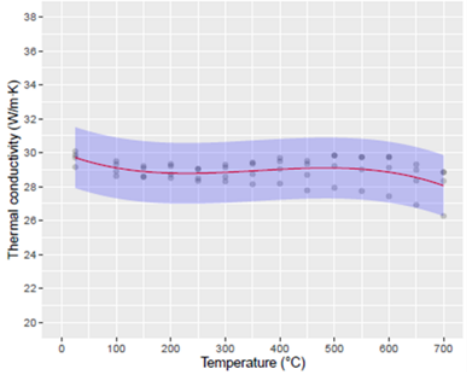
Density



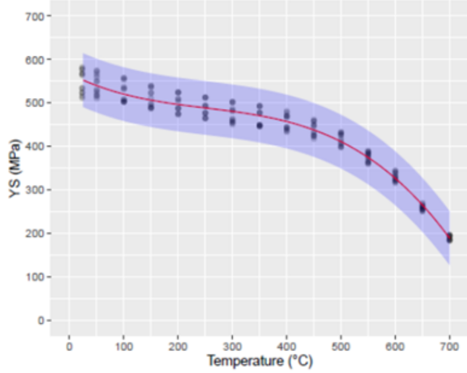
Young's Modulus



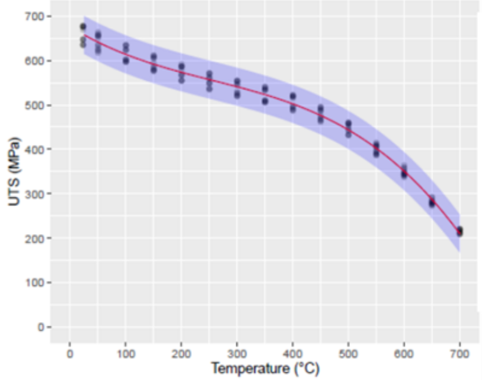
Thermal Conductivity



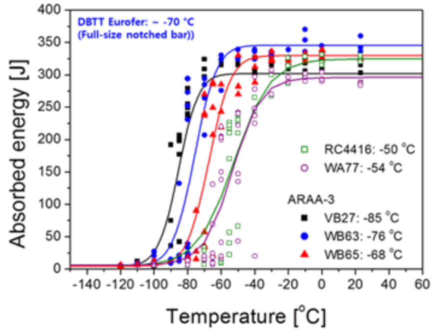
Yield Strength



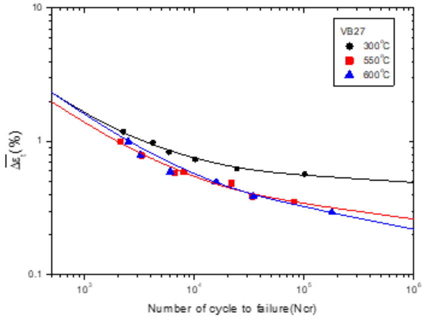
Tensile Strength



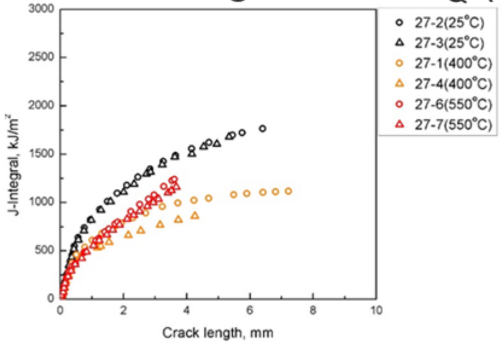
Impact Toughness



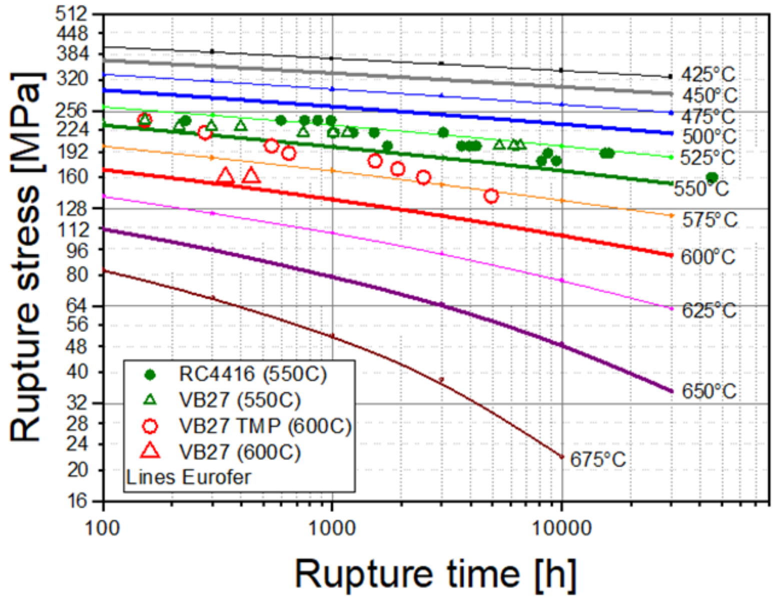
Low Cycle Fatigue



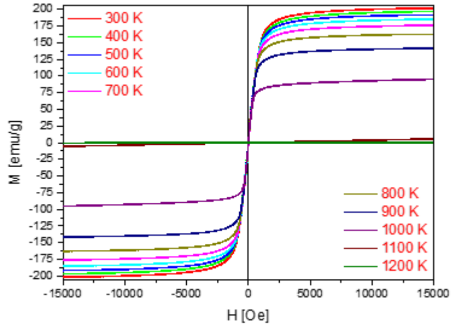
Fracture Toughness – J_Q (kJ/m^2)



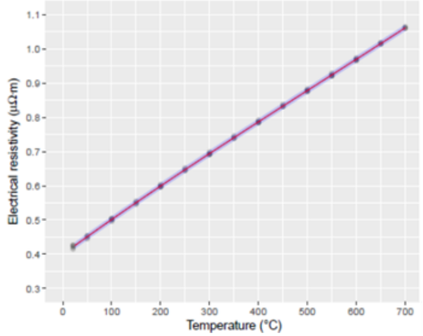
Creep Properties



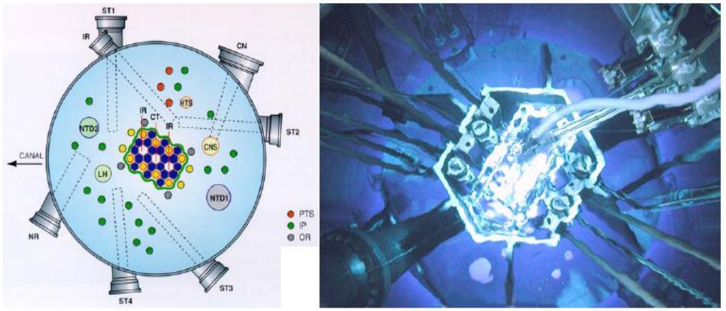
B-H Curve



Specific Electrical Resistivity

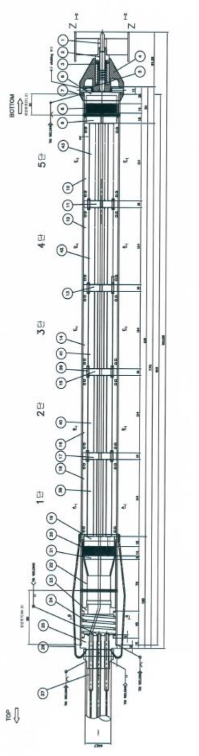


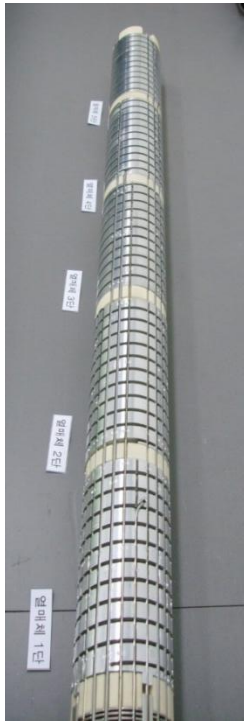
Neutron Irradiation Test



Location	Hole		Inside Dia. (cm)	Neutron Flux (n/cm^2 . sec)		Remarks
	Name	No.		Fast (>0.82 Mev)	Thermal (<0.625 ev)	
Core	CT	1	7.44	2.10 x 10^{14}	4.39 x 10^{14}	Fuel/material irradiation, isotope production
	IR	2	7.44	1.95 x 10^{14}	3.93 x 10^{14}	
	OR	4	6.00	2.23 x 10^{13}	3.36 x 10^{14}	
Reflector	LH	1	15.0	6.62 x 10^{11}	9.77 x 10^{13}	Fuel/material irradiation, Isotope production
	HTS	1	10.0	9.44 x 10^{10}	47.97 x 10^{13}	
	IP	17	6.0	1.45 x 10^{9} ~ 2.20 x 10^{12}	2.40 x 10^{13} ~ 1.95 x 10^{14}	

<HANARO Research Reactor and Irradiation Capsule for ARAA>





<ARAA Specimens for Irradiation Test>

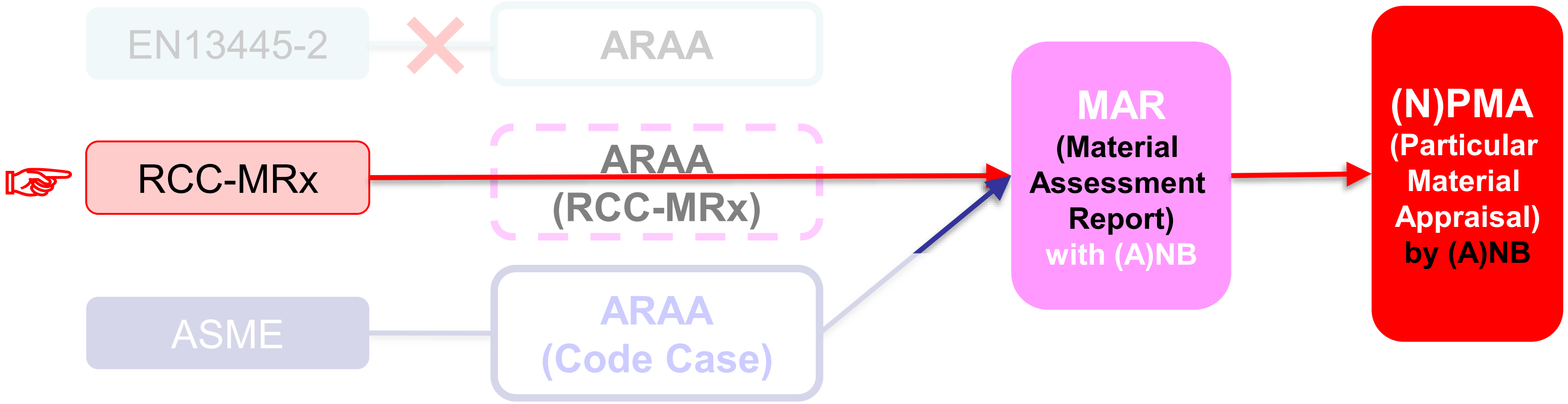
- ARAA samples (impact, tensile, hardness, thermal conductivity, microstructure, et al.) for base metal and TIG welded metal are located in the core (CT Hole) of the HANARO research reactor.
- The irradiation test up to 1.0 dpa at 320 ^{o}C has been done in Mar. 2025, and PIE will be started in Sep. 2025.
- The 3.0 dpa test of ARAA base metal and TIG welded metal is planned to be carried out at the end of 2025.

Newly Developed Structural Material for ITER TBM

PED, Annex I, Essential Safety Requirements

- 4.2 b)
  - the manufacturer must provide in his technical documentation elements relating to compliance with the materials specifications of the Directive in one of the following forms:
    – by using materials which comply with **harmonized standards**,
    – by using materials covered by a **European approval of pressure equipment materials** in accordance with Article 11,
    – by a **particular material appraisal**;

Selection of Design and Construction Code for ITER TBM



DB List for ARAA

o : Done

	Material property	Base Metal (Heat No.)				Welded/Joined Metal			
		WA77	VB27	WB63	WB65	TIG	EB	Laser	HIP
Physical Properties	1. Chemical composition	O	O	O	O	-	-	-	-
	2. Density	O	O	O	O	-	-	-	-
	3. Melting point	O	O	O	O	-	-	-	-
	4. Poisson's ratio	O	O	O	O	-	-	-	-
	5. Young's modulus	O	O	O	O	-	-	-	-
Thermal Properties	6. Coefficient of thermal expansion	O	O	O	O	-	-	-	-
	7. Specific heat	O	O	O	O	-	-	-	-
	8. Thermal diffusivity	O	O	O	O	-	-	-	-
	9. Thermal conductivity	O	O	O	O	-	-	-	-
Mechanical Properties	10. Yield strength	O	O	O	O	O	Planned	Planned	In Progress
	11. Tensile strength	O	O	O	O	O	Planned	Planned	In Progress
	12. Stress-strain curve	O	O	O	O	O	Planned	Planned	In Progress
	13. Ductility	O	O	O	O	O	Planned	Planned	In Progress
	14. Reduction of area	O	O	O	O	O	Planned	Planned	In Progress
	15. Impact toughness	O	O	O	O	O	Planned	Planned	In Progress
	16. Cyclic curve, Hysteresis curve	300 °C O	300 °C O	300 °C O	300 °C O	Planned	Planned	Planned	Planned
	17. Low cycle fatigue	550 °C O -	550 °C O 600 °C O	550 °C O 600 °C O	550 °C O 600 °C O	Planned	Planned	Planned	Planned
	18. J-R Curve	-	RT O 400 °C O 550 °C O	RT O 400 °C O 550 °C O	RT O 400 °C O 550 °C O	Planned	Planned	Planned	Planned
	19. Creep Curve	-	In Progress			Planned	Planned	Planned	Planned
	20. Creep-Fatigue interaction	-	Planned			-	-	-	-
Magnetic Prop.	21. B-H Curve	O	O	O	O	-	-	-	-
Electrical Prop.	22. Specific Electric Resistivity	O	O	O	O	-	-	-	-
Environmental Properties	23. Irradiation Properties	In Progress	In Progress			In Progress	Planned	Planned	Planned
	24. Thermal Aging	-	In Progress			-	-	-	-
	25. Compatibility with CP	-	In Progress			-	-	-	-

DB established by Statistical Analysis

Poisson's Ratio

Poisson's Ratio (ν) of ARAA

$\nu = 0.3$ (within the elastic range)

Melting Point

Sample	WA77	VB27	WB63	WB65	Average
Melting point(℃)	1,514	1,523	1,525	1,527	1,522

Density

Density(ρ) of ARAA

$$\rho = \beta_0 + \beta_1 T + \beta_2 T^2$$

β_0=7.835e+03

β_1=-2.798e-01

β_2=-3.603e-05

$25℃ \le T \le 700℃$

Specific Electrical Resistivity

Specific Electrical Resistivity (ρ_e) of ARAA

$$\rho_e = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$$

β_0=3.996e-01

β_1=1.040e-03

β_2=-2.408e-07

β_3=1.519e-10

$25℃ \le T \le 700℃$

Thermal Conductivity

Thermal Conductivity (k) of ARAA

$$k = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$$

β_0=3.000e+01

β_1=-1.263e-02

β_2=4.054e-05

β_3=-3.780e-08

$25℃ \le T \le 700℃$

Young's Modulus

Young's Modulus (E) of ARAA

$$E = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$$

β_0=2.191e+02

β_1=-5.756e-02

β_2=-1.132e-05

β_3=-9.567e-08

$25℃ \le T \le 700℃$

Yield Strength

Yield Strength (YS_{min}) of ARAA

$$YS_{min} = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$$

β_0=5.056e+02

β_1=-6.352e-01

β_2=1.922e-03

β_3=-2.553e-06

$25℃ \le T \le 700℃$

Tensile Strength

Ultimate Tensile Strength (UTS_{min}) of ARAA

$$UTS_{min} = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$$

β_0=5.056e+02

β_1=-7.765e-01

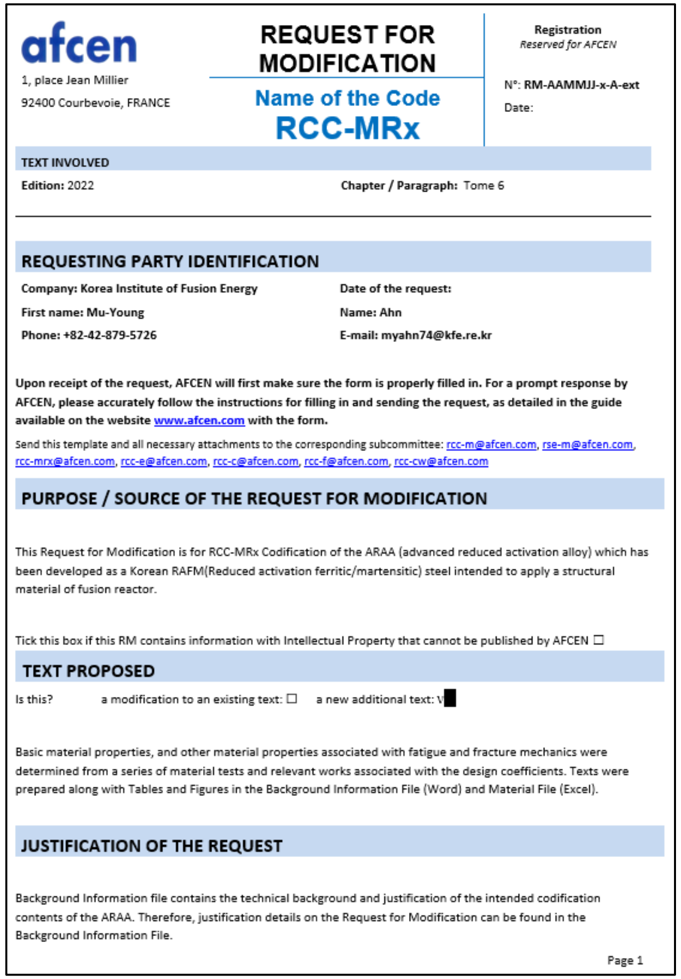
β_2=1.787e-03

β_3=-2.325e-06

$25℃ \le T \le 700℃$

Codification of ARAA in RCC-MRx

- The modification request with material file, background information, RPS and RPP for codification of ARAA was submitted to RCC-MRx subcommittee in Feb. 2025.



afcen

1, place Jean Millier

92400 Courbevoie, FRANCE

REQUEST FOR MODIFICATION

Name of the Code

RCC-MRx

Registration
Reserved for AFCEN

N°: RM-AAMMJJ-x-A-ext

Date:

TEXT INVOLVED

Edition: 2022 **Chapter / Paragraph:** Tome 6

REQUESTING PARTY IDENTIFICATION

Company: Korea Institute of Fusion Energy	Date of the request:
First name: Mu-Young	Name: Ahn
Phone: +82-42-879-5726	E-mail: myahn74@kfe.re.kr

Upon receipt of the request, AFCEN will first make sure the form is properly filled in. For a prompt response by AFCEN, please accurately follow the instructions for filling in and sending the request, as detailed in the guide available on the website www.afcen.com with the form.

Send this template and all necessary attachments to the corresponding subcommittee: rcc-m@afcen.com, rse-m@afcen.com, rcc-mrx@afcen.com, rcc-e@afcen.com, rcc-c@afcen.com, rcc-f@afcen.com, rcc-cw@afcen.com

PURPOSE / SOURCE OF THE REQUEST FOR MODIFICATION

This Request for Modification is for RCC-MRx Codification of the ARAA (advanced reduced activation alloy) which has been developed as a Korean RAFM(Reduced activation ferritic/martensitic) steel intended to apply a structural material of fusion reactor.

Tick this box if this RM contains information with Intellectual Property that cannot be published by AFCEN ☐

TEXT PROPOSED

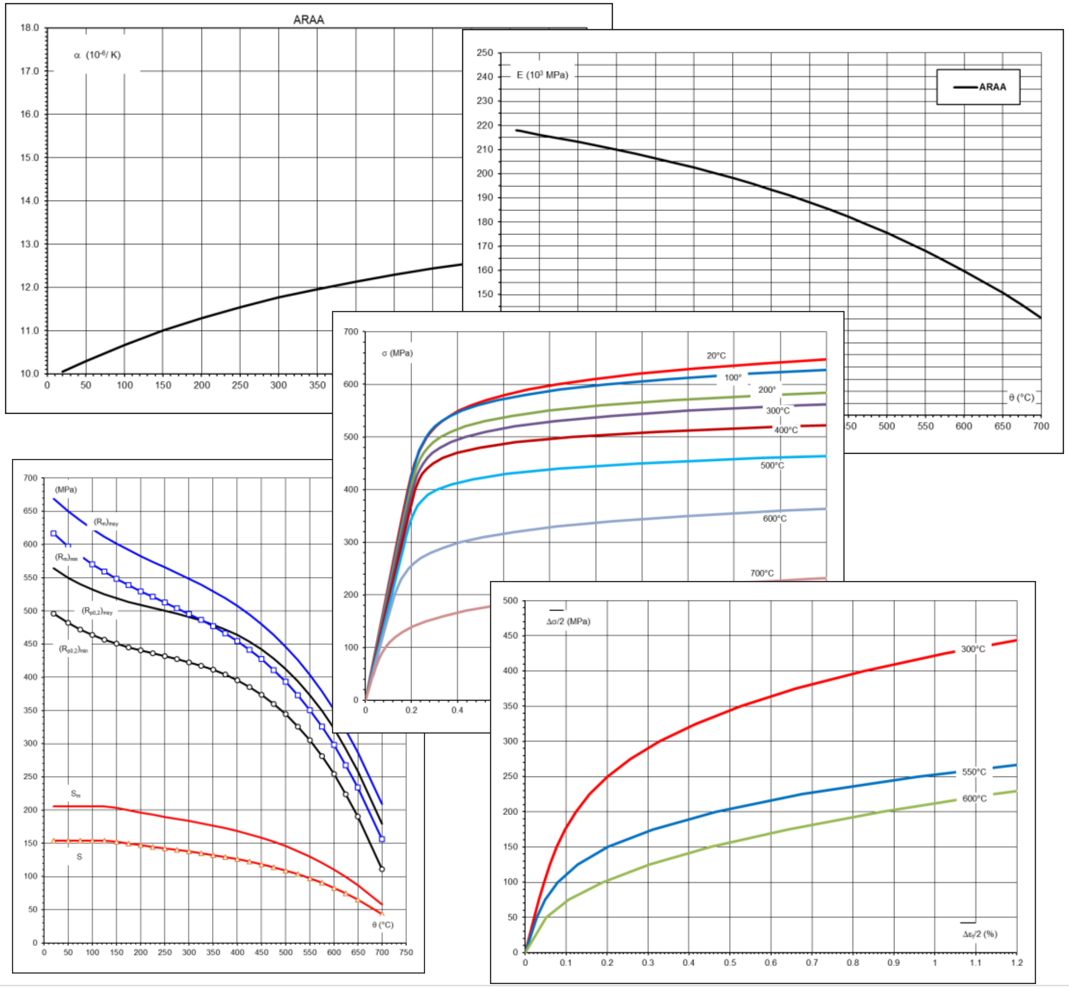
Is this? a modification to an existing text: ☐ a new additional text: V

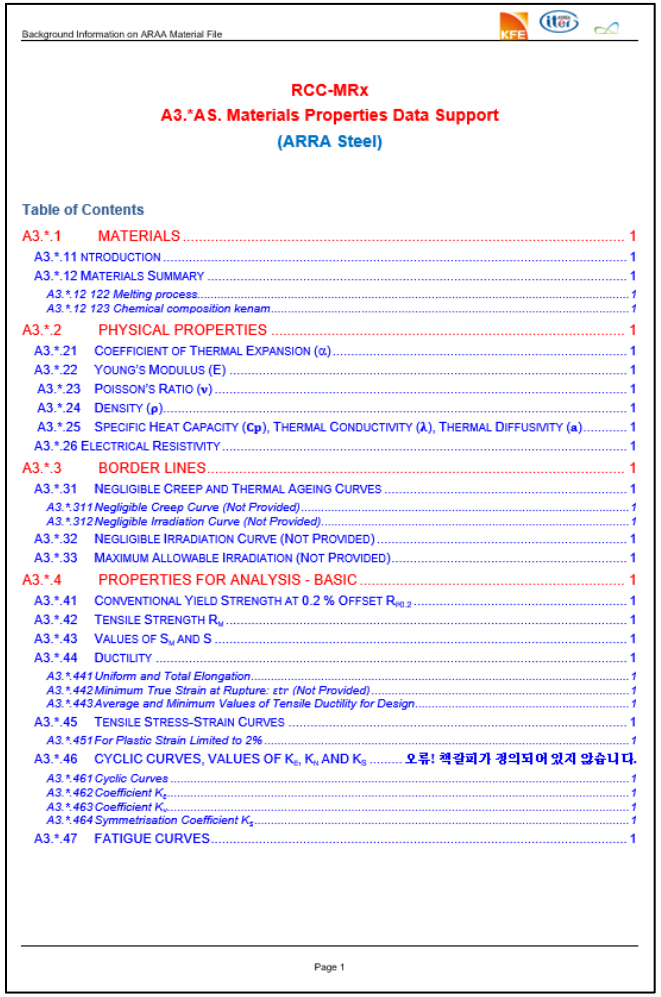
Basic material properties, and other material properties associated with fatigue and fracture mechanics were determined from a series of material tests and relevant works associated with the design coefficients. Texts were prepared along with Tables and Figures in the Background Information File (Word) and Material File (Excel).

JUSTIFICATION OF THE REQUEST

Background Information file contains the technical background and justification of the intended codification contents of the ARAA. Therefore, justification details on the Request for Modification can be found in the Background Information File.

Page 1





Background Information on ARAA Material File

RCC-MRx

A3.*AS. Materials Properties Data Support

(ARRA Steel)

Table of Contents

Page 1

Draft Document of ARAA for RCC-MRx_Tome 6_2025 Ed.

afcen RCC-MRx Draft document – RPP on ARAA RAFM STEEL

The following document has still to be validated by the RCC-MRx Sub Committee.

RPPXX-2025-ARAA ARAA RAFM

RPPxx - Purpose of change

This rule introduces the possibility of using the denominated ARAA chromium, 1.2% tungsten and 0.01% zirconium. This rule includes a **Appendix A3** which covers the mechanical properties associated tests or methods which comply with the other rules in the Code. Mis must be collected so as to review the rule's probationary classificatio

In addition, the following aspects of the material file must also be co
- Justification of applicability of the Design Rules for the specified
- Manufacturing: industrial experience, metallurgy
- Fabrication: industrial experience, formability, etc.
- Welding: weldability (RS 1300), feedback on qualification of we repair processes involving welding
- Ease of monitoring
- In-service behaviour: thermal ageing, corrosion, erosion-corrosio

Furthermore, due to the lack of data, some characteristics have introduction of the proposed rules into the code, specific charact characteristics are as follows:
- Instantaneous Coefficients of thermal expansion (α_i),
- Negligible creep and thermal ageing curves,
- Negligible irradiation curve,
- Maximum allowable irradiation,
- Symmetrisation coefficient K_s,
- Fatigue-creep interaction diagram,
- Fatigue crack growth da/dN,
- Regarding R_p and R_m values, justification of the consistency betw

RPPxx - Modification status

The chapters for these rules are in addition to the rules currently ava

RPP Araa

afcen RCC-MRx

RPPxx - Text - Part 1

RM 243-4 G-RPS: X10CrWVTaZr9-1 ARAA A THICK, N2Rx AND N3Rx

RM 243-4.1 Purpose and scope

Specification **RM 243-4** covers weldable chromium-tungsten-vanad denominated ARAA, which are 20 to 60 mm thick. If the absence of significant creep (negligible creep) conditions defined report defined in **RM 015-0** shall be prepared by the Supplier. These p *Specification.*

RM 243-4.1 Melting process

The alloy shall be made using an electric furnace or any other technical the manufacturing process must be provided.

RM 243-4.3 Chemical composition

RM 243-4.31 Required chemical composition

Chemical composition, as determined by ladle and product analyses, sl 4.31.

Table RM 243-4.31: chemical con

Elements	GradeX10CrWVTaZr9-1 Ladle and product (%)
Carbon	0.08 – 0.12
Manganese	0.25 to 0.65
Phosphorous	< 0.005
Sulphur	< 0.005
Silicon	0.05 – 0.15
Nickel	< 100 ppm
Chromium	8.7 – 9.3
Molybdenum	< 50 ppm
Vanadium	0.15 – 0.25
Tantalum	0.05 – 0.13
Tungsten	1.0 – 1.4
Titanium	0.004 – 0.015
Copper	< 100 ppm
Niobium	< 50 ppm
Aluminium	< 100 ppm
Nitrogen	0.003 – 0.015
Boron	< 0.002
Cobalt	< 100 ppm
Zirconium	0.003 – 0.02
Oxygen	< 0.02
Magnesium	< 50 ppm
Potassium	< 10 ppm
Calcium	< 50 ppm
Arsenic	< 100 ppm
Zinc	< 50 ppm
Silver	< 50 ppm
Stannum	< 50 ppm
Lead	< 50 ppm
Antimony	< 100 ppm
Hydrogen	< 10 ppm

RPP Araa Page 2/22

afcen RCC-MRx Draft document – RPP on ARAA RAFM STEEL

RM 243-4.5 Mechanical properties

RM 243-4.51 Required values

Mechanical properties requirements to comply with, for both as-delivered tests and Simulated Stress-relieving Heat Treatment tests, are given in **table RM 243-4.51.**

Table RM 243-4.51: mechanical properties

Test type	Test temperature (°C)	Characteristics	Required va
Tensile test	Room	$R_{p0.2}$	≥ 530 MP
		R_m	≥ 640 MP
		A (5d)	≥ 15 %
	450	$R_{p0.2}$	≥ 408 MP
	550	$R_{p0.2}$	≥ 339 MP
Charpy V-notch impact	0	KV (Average value on 3 test specimens)	≥ 250 J
		KV (individual value) **(1)**	≥ 200 J
	-20	KV (Average value on 3 test specimens)	≥ 200 J
		KV (individual value) **(1)**	≥ 150 J
	+20	KV (Average value on 3 test specimens)	≥ 250 J
		KV (individual value) **(1)**	≥ 200 J

(1) In each series of 3 tests, only one value less than the minimum required average value accepted.

RM 243-4.52 Sampling requirements

Test samples shall be taken:
- from the top end of each rolled sheet or strip weighing 3000 kg or less,
- from the top and bottom ends of each rolled sheet or strip weighing more than 3000 kg.

The samples shall be cut after the strip has undergone Heat Treatment for Mechanical Propert appropriately identified and the final rolling direction marked.
The size of test samples shall be such that they can provide enough test specimens for all tests a
Test samples shall be taken at half the distance between the edge of the plate and its centreline from the quenched end of the plate equal to at least the thickness of the plate.
To meet this last condition, the Supplier shall be allowed to protect the end of the plate with a weld over the whole thickness of the plate.

RM 243-4.521 Tension tests specimens

The longitudinal axis of the tension test specimens shall be perpendicular to the final rolling dire direction), at mid-thickness.

RM 243-4.522 Impact test specimens

The longitudinal axis of the V-notch impact test specimens shall be perpendicular to the fina (transverse direction).
Test specimens shall be taken from the skin and at mid-thickness.
The notch axis of impact test specimens shall be perpendicular to the rolling skin.

RM 243-4.523 Bend test specimens

The longitudinal axis of the test pieces for bending tests shall be perpendicular to the final rol specimen is taken from the skin.

RM 243-4.53 Testing of samples

RM 243-3.531 Number and content of the test series

The number of tests to be performed, the sampling directions and test temperatures are shown 4.531.
Test specimens shall be taken from:

RPP Araa

afcen RCC-MRx Draft docu

- representative as-delivered test samples, which were not subjected to heat trea
- samples taken from the plate after it has undergone Heat Treatment for Mecha **RM 243-4.52** and subjected to Simulated Stress-relieving Heat Treatment acc **RM 016-1.**

Table RM 243-4.531: number and content of tests

Test type	Test temperature (°C)	Top Transverse Skin	Top Transverse Within thickness (2)	Bottom Tran Skin
(HTMP) As-delivered tests				
Tensile test	Room		1	
	450 (3)		2	
	550 (3)		2	
Bend test	Room	1		1
Charpy V-notch impact	0	3	3	3
	- 20	3	3	3
	+ 20	3	3	3
(HTMP + SSHT) Tests performed after simulated stress-relieving heat treatment				
Tensile test	Room		1	
	450 (3)		2	
	550 (3)		2	
Charpy V-notch impact	0	3	3	3
	- 20	3	3	3
	+ 20	3	3	3

HTMP = Heat Treatment for Mechanical Properties
SSHT = Simulated stress-relieving heat treatment
(1) Test at bottom if weight of rolling sheet or plate is more than 3000 kg.
(2) See **RM 243-4.521** and **RM 243-4.522**
(3) Test temperature given by the *Equipment Specification.*

RM 243-4.532 Test Procedure

RM 243-4.5321 Tensile test at room temperature

- **Test pieces**
  Test pieces shall have a circular section. Normally, their nominal diameter shall be as specified in **RMC 1211**.
  For plates less than 20 mm thick, the cylindrical test specimen may be replaced by section, as stipulated in **RMC 1211**.
- **Test Method**
  The tensile test shall be performed as specified in **RMC 1211**.
  The following values shall be recorded:
  - $R_{p0.2}$: proof strength, 0.2% plastic extension (MPa),
  - R_m : tensile strength (MPa),
  - A : percentage elongation after fracture,
  - Z : percentage reduction of area after fracture.
- **Results**
  The test results shall meet the required values given in **table RM 243-4.51** (perc recorded for information purposes only).
  If this is not the case and the test specimen has a physical defect (which does n product) or if unsatisfactory test results are due to incorrect mounting of the sp malfunction, the test shall be repeated using another specimen. If the results of th the lot shall be accepted; if not, the following paragraph shall apply.
  Where unsatisfactory results cannot be attributed to any of the above-mentioned performed for each unsatisfactory result obtained. The second set of test specimen which were defective.
  If the results of the retests are satisfactory, the lot shall be accepted; if not, it shall be rejected (RM 243-4.54).

RPP Araa Page 5/22

afcen RCC-MRx Draft document – RPP on ARAA RAFM STEEL

RPPxx - Text - Part 2

A3.20AS.1 INTRODUCTION

The Properties Group A3.20AS shall be applied to products and parts made in low activation alloy steel with around 9% chromium and 1% tungsten, under normalised and tempered conditions.
Interpolations shall be carried out according to the provisions given in **A3.GEN.12**.

A3.20AS.2 PHYSICAL PROPERTIES

A3.20AS.21 COEFFICIENTS OF THERMAL EXPANSION

The properties of **A3.18AS.21** can be used.

A3.20AS.22 YOUNG'S MODULUS

Young's modulus E is given as a function of the temperature θ by the **formula A3.20AS.22**, the **table A3.20AS.22** and the **figure A3.20AS.22**.

- **Formula A3.20AS.22:**

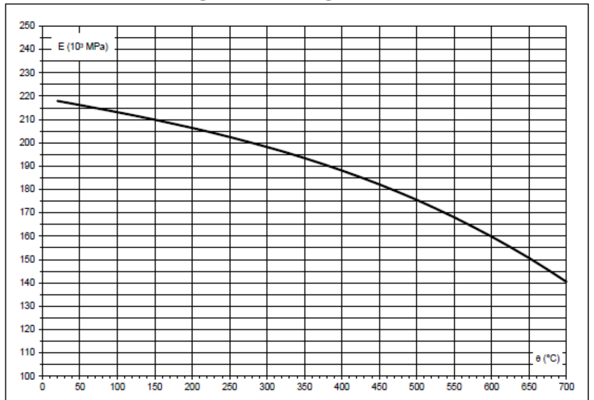
$$E = 2.191 \times 10^5 - 57.56\,\theta - 1.132 \times 10^{-2}\,\theta^2 - 9.567 \times 10^{-5}\,\theta^3 \qquad (20°C \leq \theta \leq 700°C)$$

In this formula, E is expressed in MPa and θ in °C.

Table A3.20AS.22: Young's modulus E

θ (°C)	20	50	100	150	200	250	300	350	400	450	500	550	600	650	700
E (10³ MPa)	218	216	213	210	206	203	198	193	188	182	176	168	160	151	140

Figure A3.20AS.22: Young's modulus E



RPP Araa Page 9/22

03

Progress of
Tritium Breeder Material Development

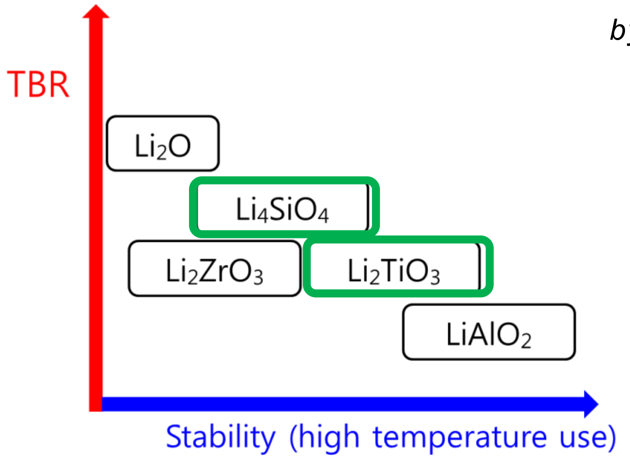
한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

Tritium Breeder Ceramics

Candidates of Solid Type of Tritium Breeder

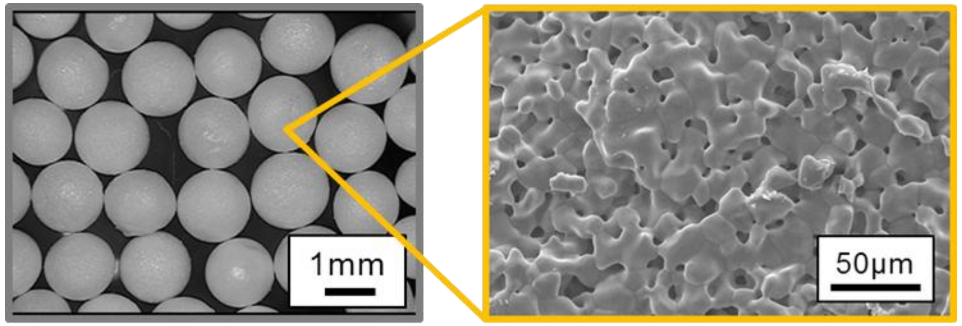
	Li_2O	Li_2AlO_2	Li_2ZrO_3	Li_4SiO_4	Li_2TiO_3
Li Vaporization (in additional H_2)	> 600˚C	> 900˚C	> 800˚C	> 700˚C	> 800˚C
Long period use (2 years)	Instability (Li vaporization)	Stability	Instability (crack)	Instability (Li vaporization)	Instability (Reduction of Ti)
Tritium release (easy release)	> 400˚C	> 400˚C	> 400˚C	> 350˚C	> 300˚C
Optimum operating temp.	400 - 600 ˚C	400 - 900˚C	400 - 800˚C	350 - 700˚C	300 - 800˚C
Tritium breeding ratio (TBR)	High	Lower	Middle	Middle	Middle
Thermal conductivity	High	Middle	Middle	Middle	Middle

by Dr. Hoshino, CBBI-16, 2011



Shape of Tritium Breeder Ceramics : **Pebble**

- Strength
- Packing Phenomenon
- Thermal Conductance
- Modeling and Analysis
- …



(Li_2TiO_3 Pebbles)

by Y.-H.Park et al, JNM 455 (2014), 106

Manufacturing Process for Ceramic Pebble (by Sintering)

Mixing

- Raw Powder (Li_2TiO_3 or Li_4SiO_4)
- Binder Materials
- Solvent

Shaping

- Wetting Process (Dropping, Emulsion, …)
- Drying Process (CM, PIM, 3D Printing, …)

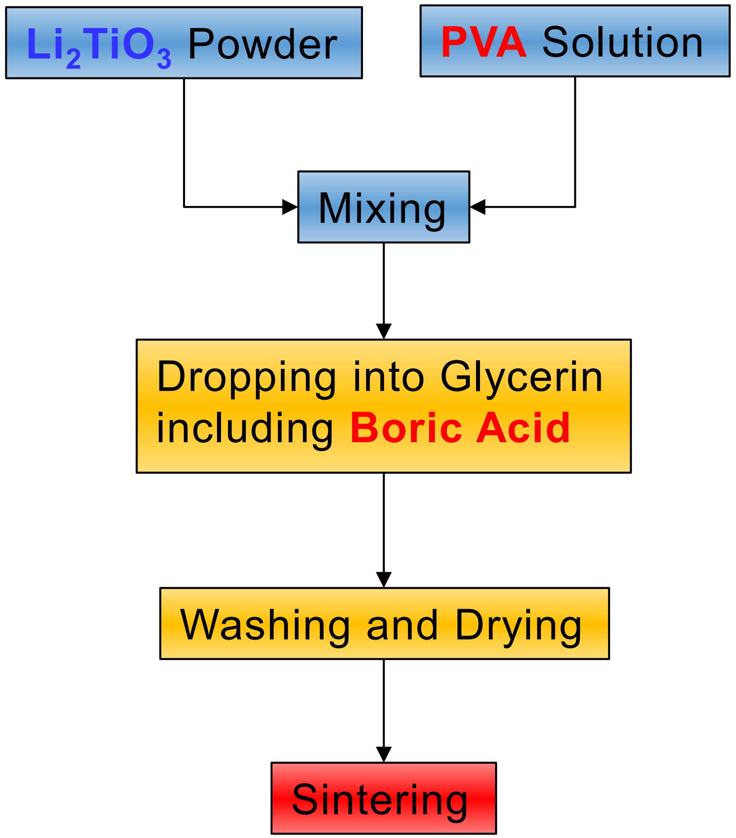
Sintering

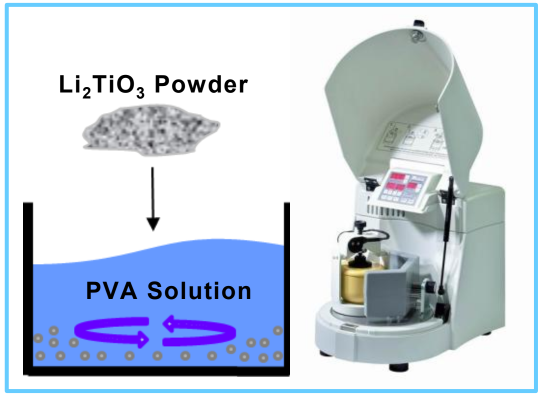
- Temperature
- Time
- Atmosphere

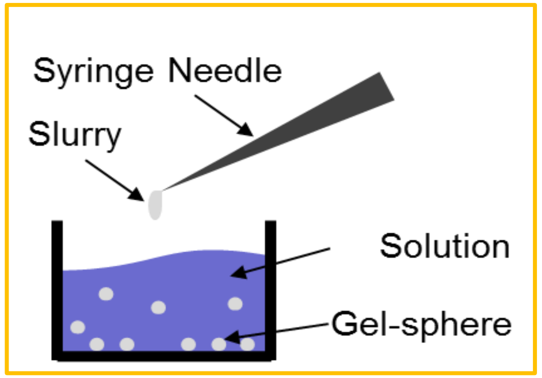
Development of Manufacturing Process for Li_2TiO_3 Pebbles

- **Slurry Droplet Wetting Method** based on the Cross-linking Reaction between PVA and Boric-acid

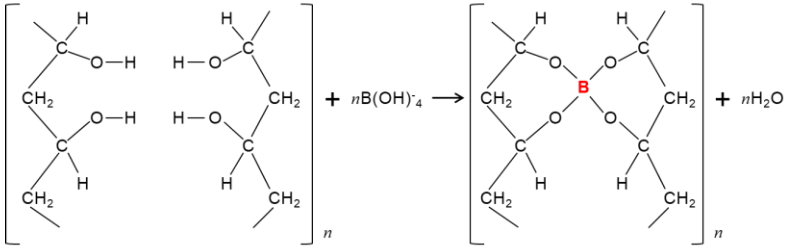
Fabrication Process







Cross-linking Reaction :

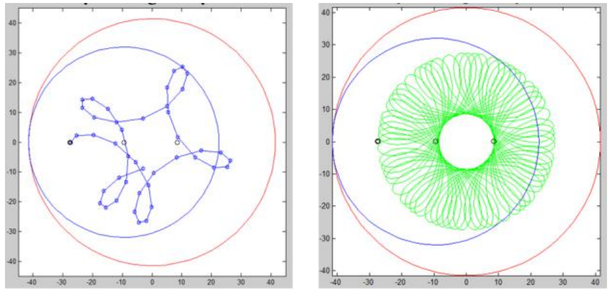


Mass-production System for Slurry Droplet Wetting Method

- Automatic Slurry Dispensing System

Dispensing Unit

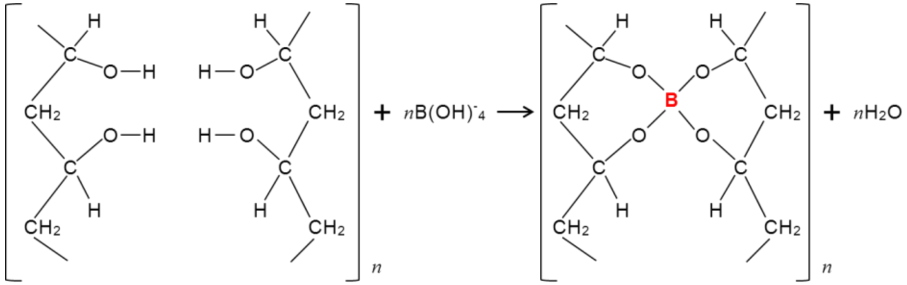
; for instillation of Li_2TiO_3 slurry

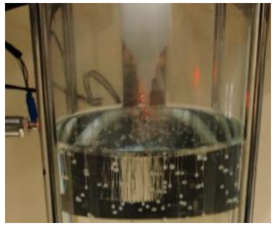


Trace of Drop Point through the Moving Needle

Glycerin Bath

; for hardening of droplets



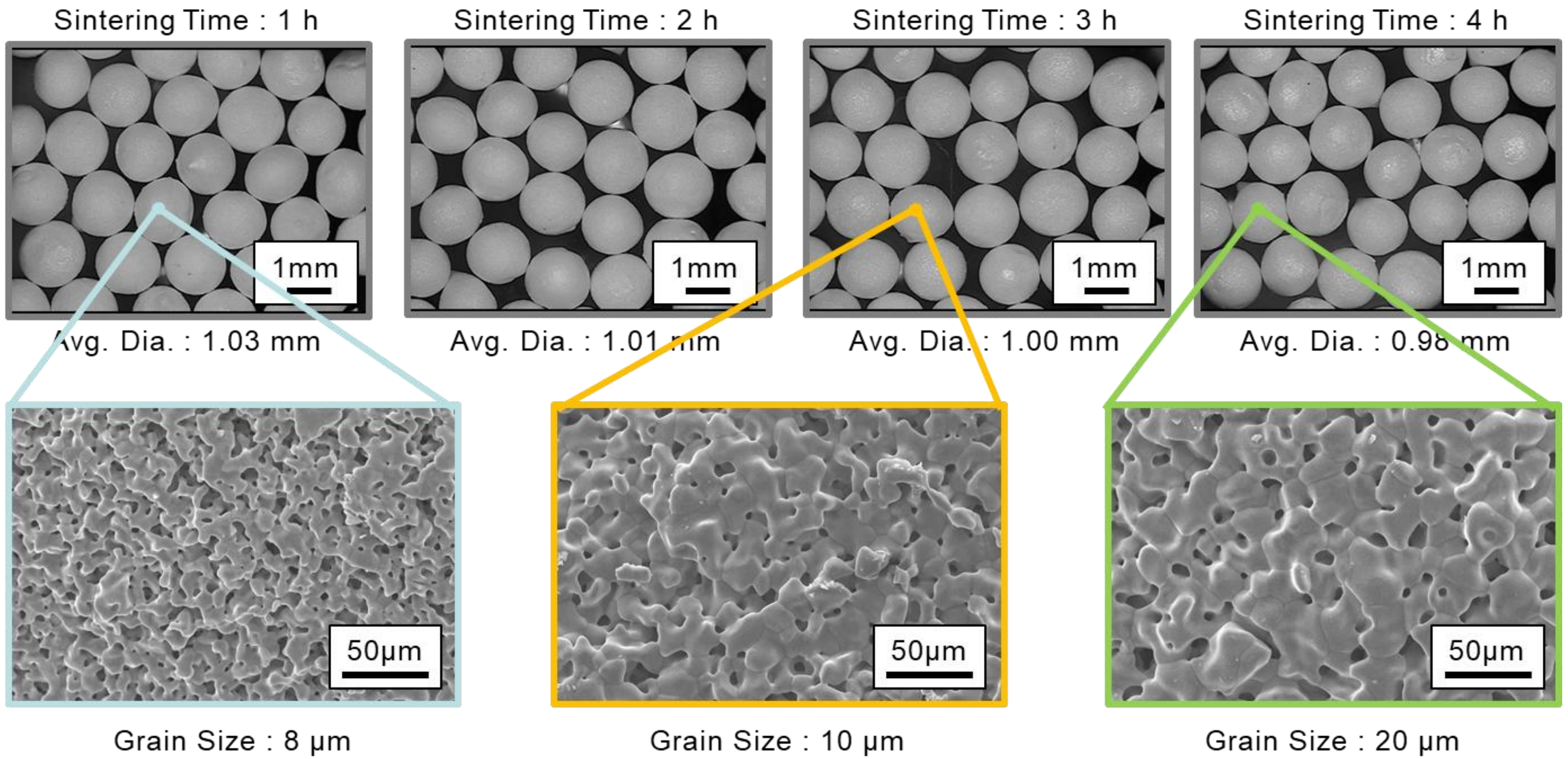


Automatic maintaining Unit

; for constant distance between syringe needle and glycerin surface

Parametric Study on Sintering for Li_2TiO_3 Pebbles

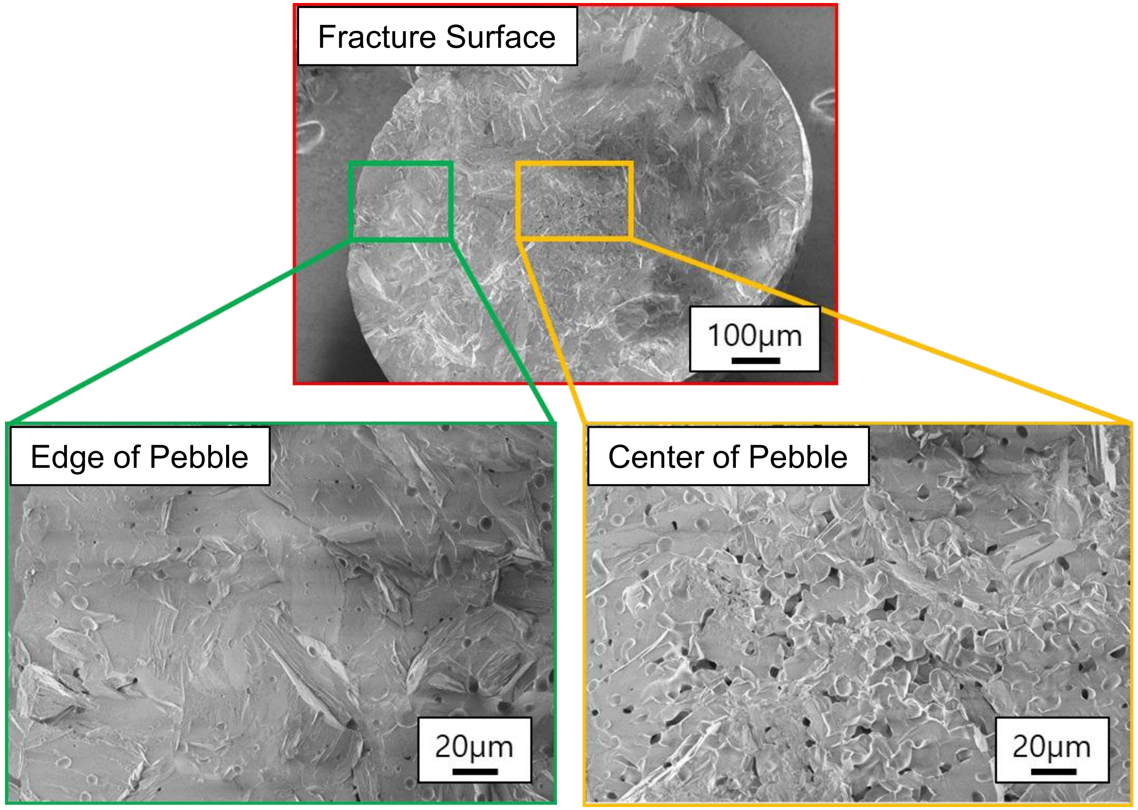
- Effect of Sintering Time (1200 °C, Air atmosphere)



- Grain size was increased with increasing sintering time.
- The whole pore of the sintered pebble was open type.
- The open porosity was about 10 %. (Sintering Time : 3 h)

Shortcoming of Slurry Droplet Wetting Method

- **Ununiformed Microstructure** of Sintered Pebbles caused by Wetting Process
  - Difference of hardening speed in edge and center of the green pebbles during shaping process
    → Grain Size, Porosity, and so on.

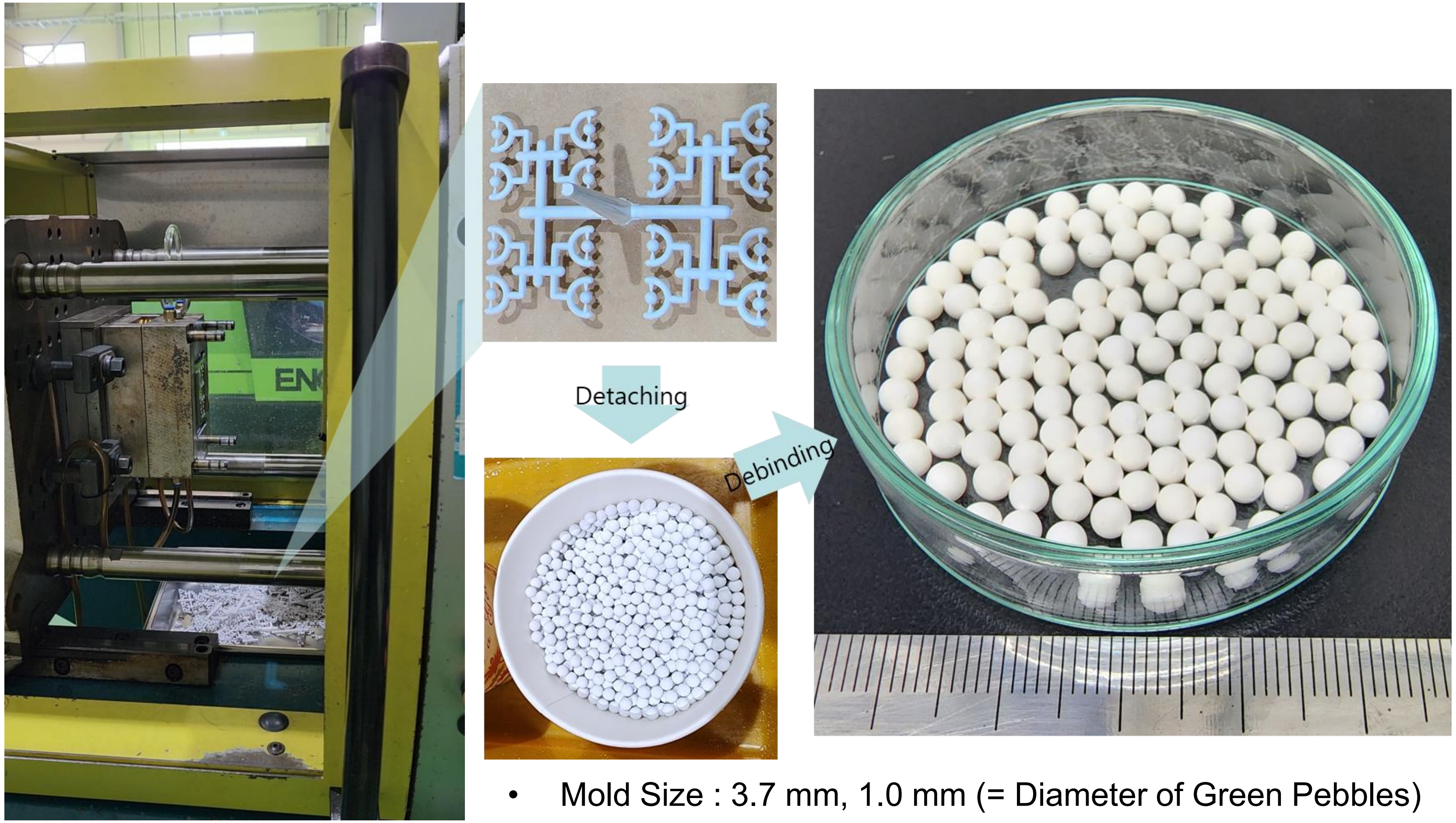


[Microstructure of Sintered Li_2TiO_3 Pebble after Crush Test]

Development of Manufacturing Process for Li_2TiO_3 Pebbles

- Li_2TiO_3 green pebbles have been successfully fabricated by using **Powder Injection Molding (PIM) process**

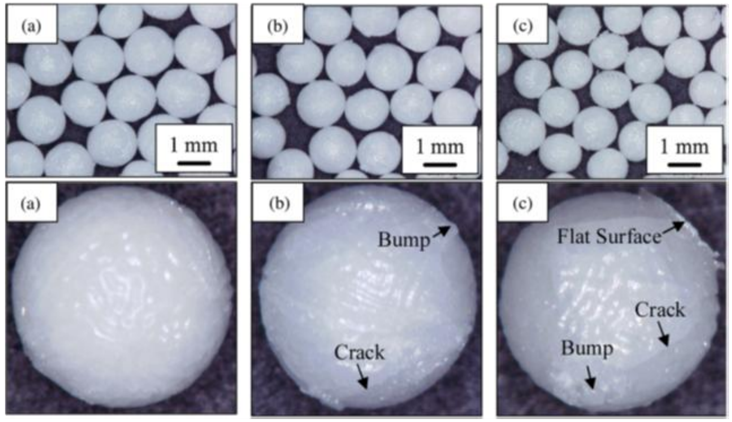
Li_2TiO_3 Powder + Binder → Injection Molding → Detaching → Debinding → Sintering



- Mold Size : 3.7 mm, 1.0 mm (= Diameter of Green Pebbles)
- Amount of Binder : 48 %
- Debinding Conditions : 800 ^oC, 1 h

Improvement of Sintering Process for Breeder Pebbles

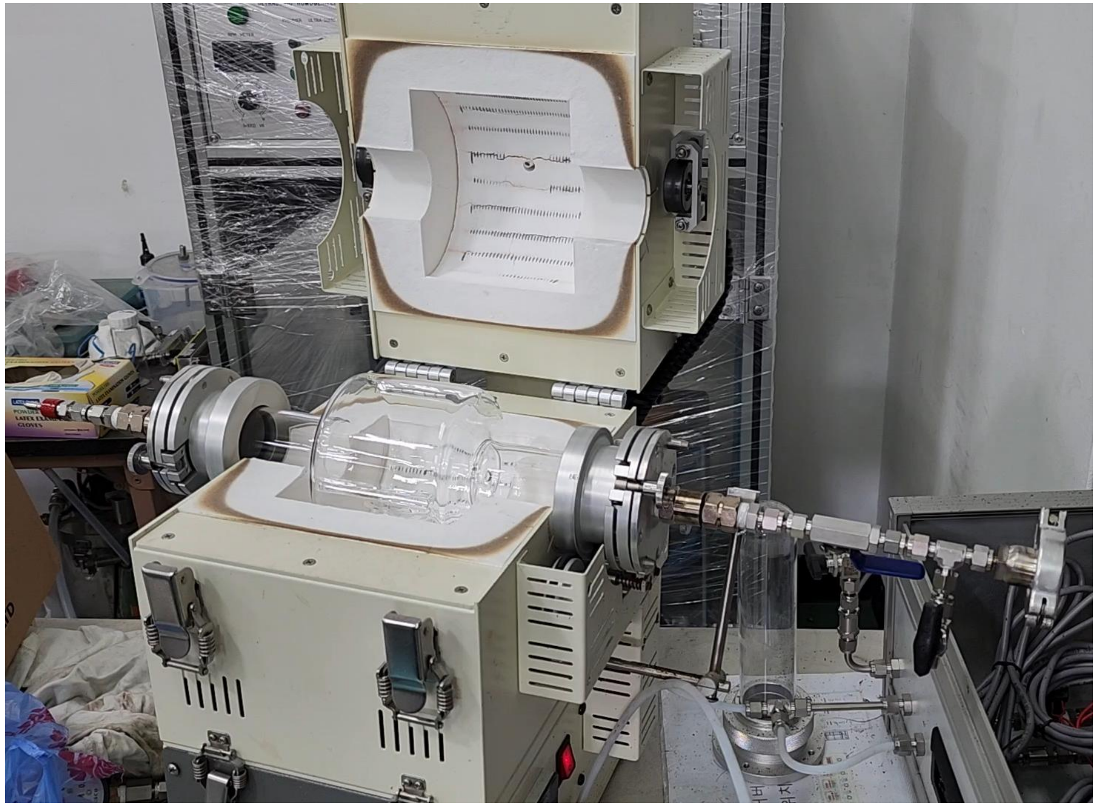
- **Formation of Defects** caused by Batch Process
  - Sintering between the neighbored pebbles
    → Crack, Bump, Flatted Surface, and so on.



by Y.-H.Park et al, FED 109-111 (2016), 443

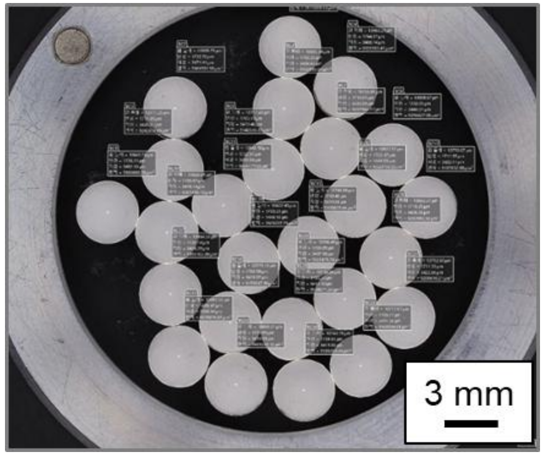
Improvement

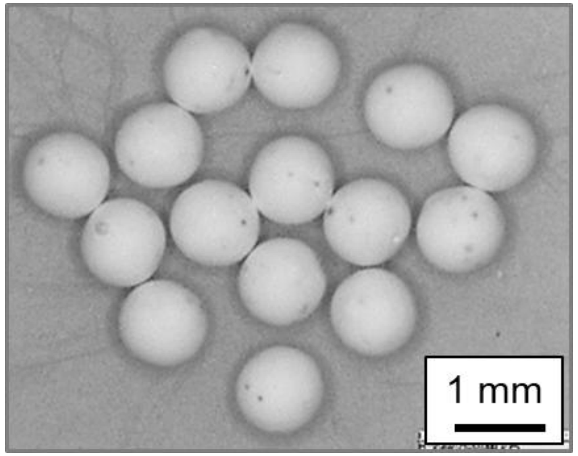
- **Rotating Sintering System** was adopted to avoid the sintering between neighbored pebbles in the crucible.



- Sintering Temperature : 1000 ^{o}C
- Sintering Time : 3 h
- Atmosphere : Air

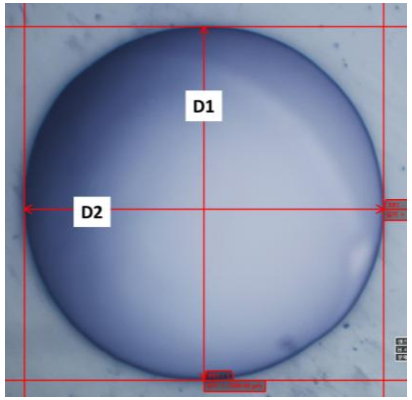
Morphology of Li_2TiO_3 Pebbles manufactured by PIM Process





Value	Item	Value
3.70 mm	Mold Size	1.00 mm
3.43 mm	Average Diameter	0.96 mm
< 1.01	Average Sphericity	< 1.01
16 %	Volume Shrinkage Ratio	15 %

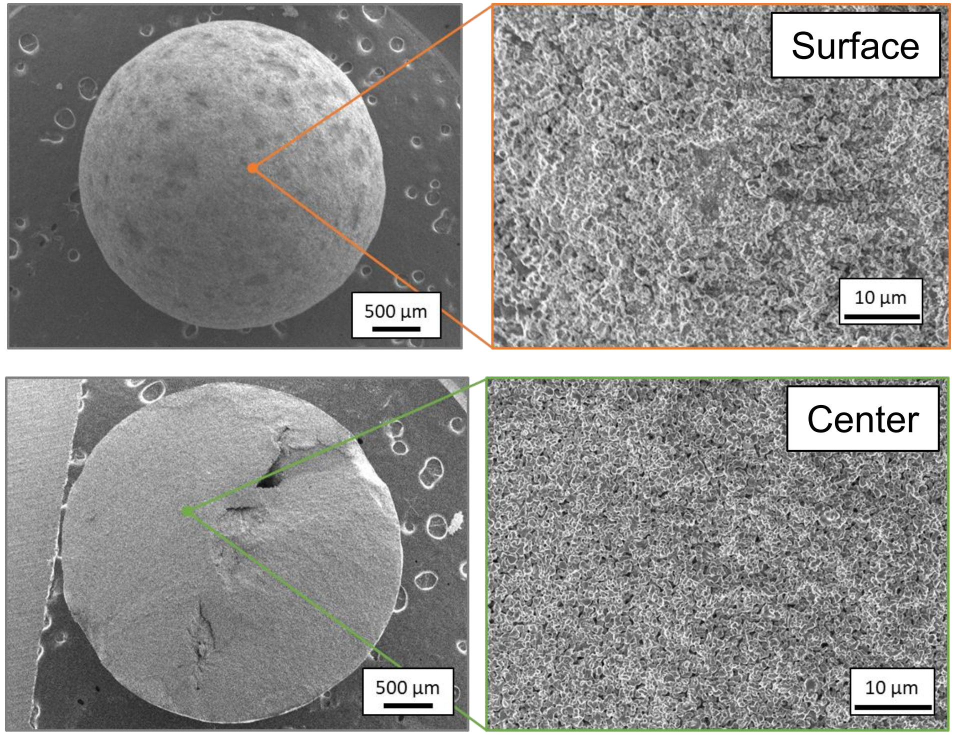
Sphericity = D1 / D2, (D1 > D2)



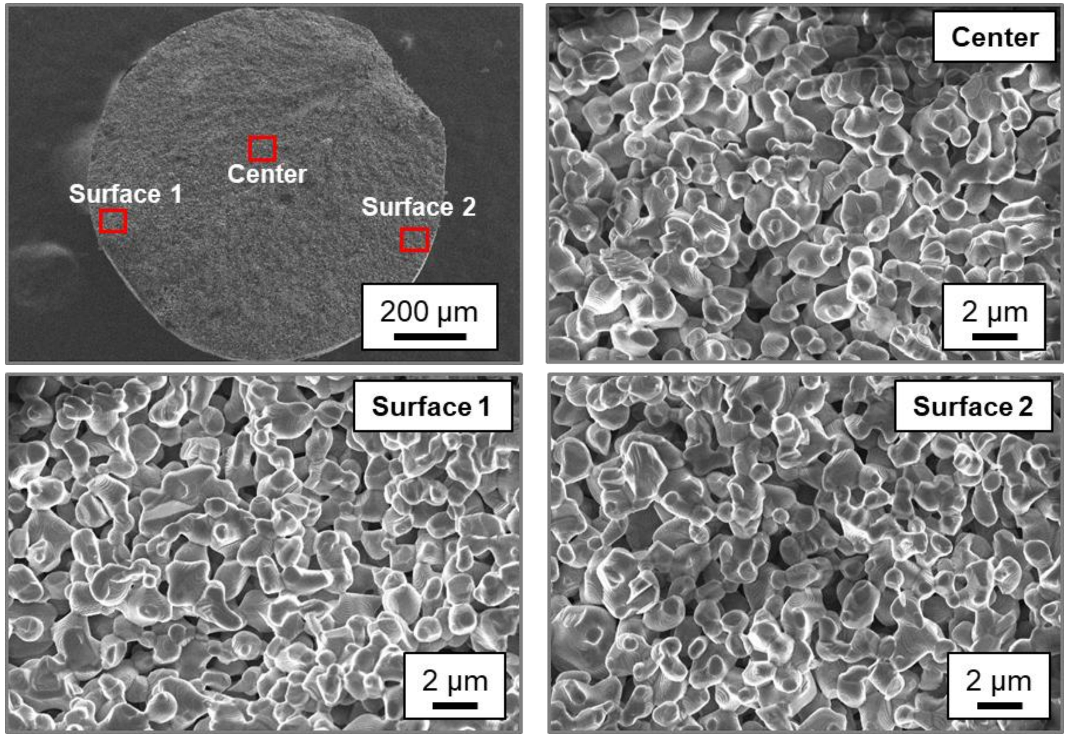
- Combined pebbles were not observed due to the pebble moving in the rotating tube during sintering process.
  - Defects (crack, bump, flatted surface, and so on) were not formed at the surface of sintered pebbles.
- The shrinkage ratio can be used as a parameter to design the mold in order to control the pebble diameter.

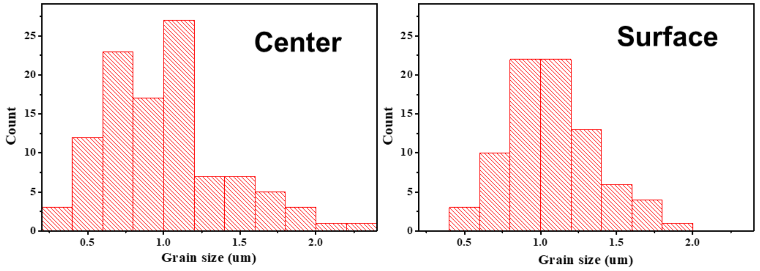
Microstructure of Li_2TiO_3 Pebbles manufactured by PIM Process

Diameter : 3.43 mm

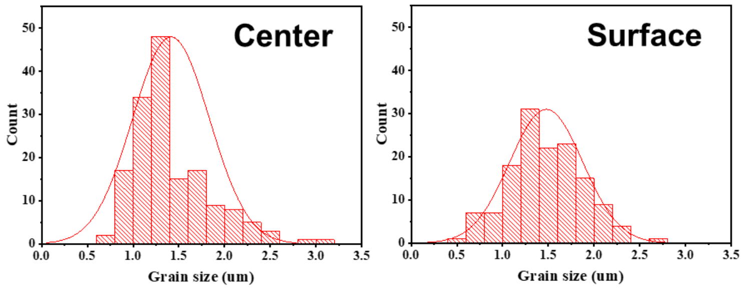


Diameter : 0.96 mm





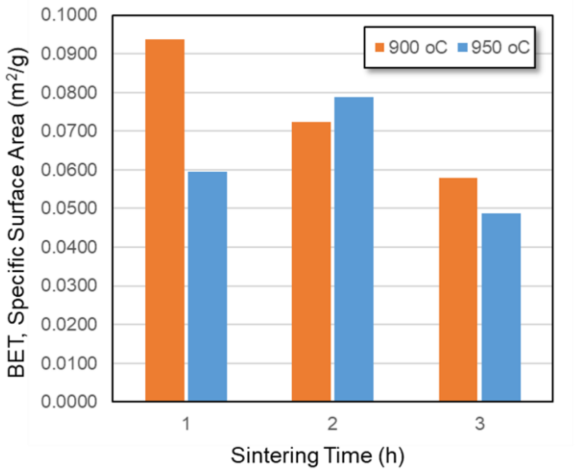
Value	Item	Value
1.00 µm	Grain Size	1.35 µm
39.7 %	Porosity	34.2 %

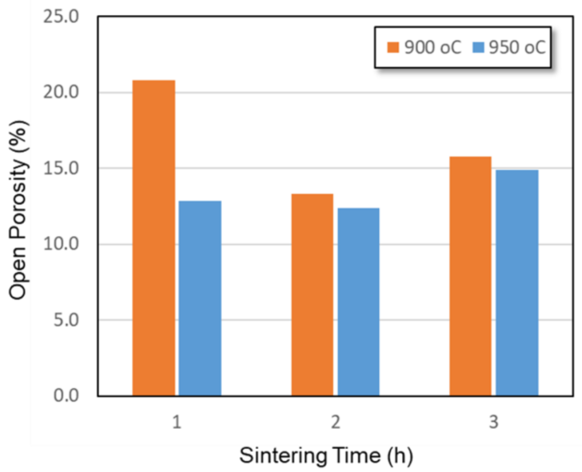


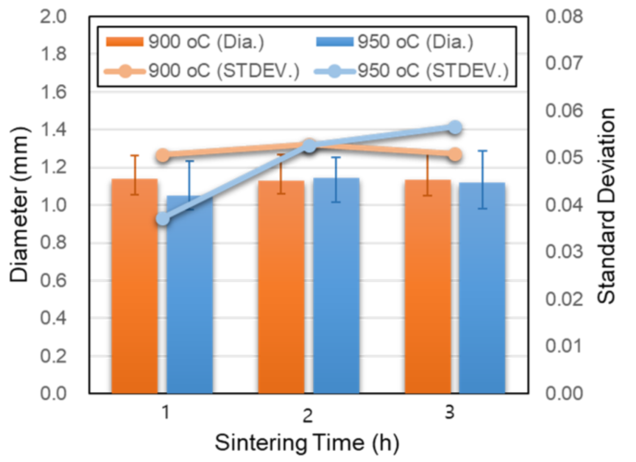
- The uniform microstructure with open pores in surface and inside of the sintered pebbles was confirmed.

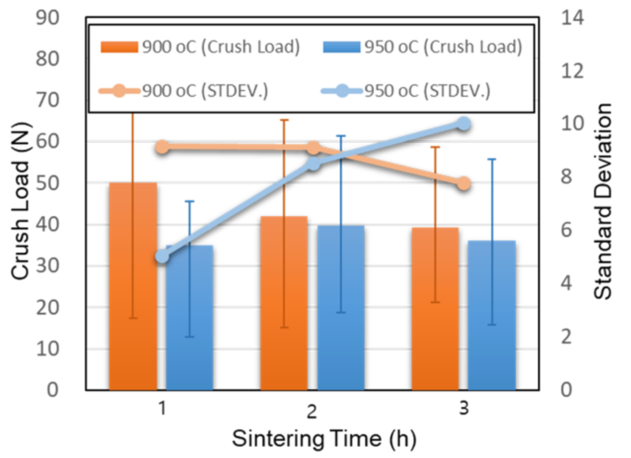
Establishment of DB for Li_2TiO_3 Pebbles and Pebble Bed

- Physical and Mechanical Properties of Li_2TiO_3 Pebbles and Pebble Bed

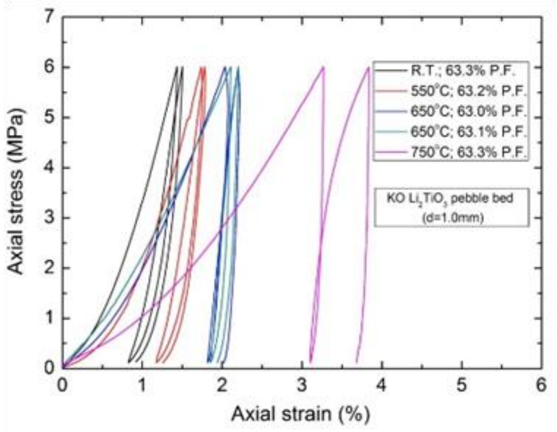




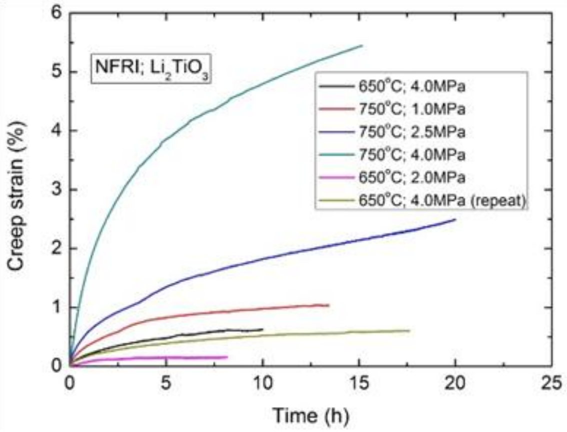




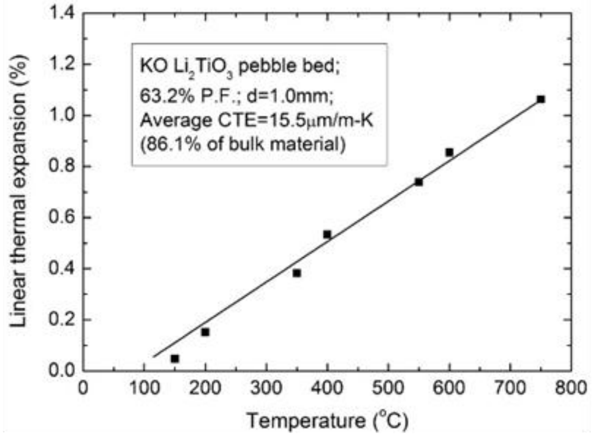
Stress-strain



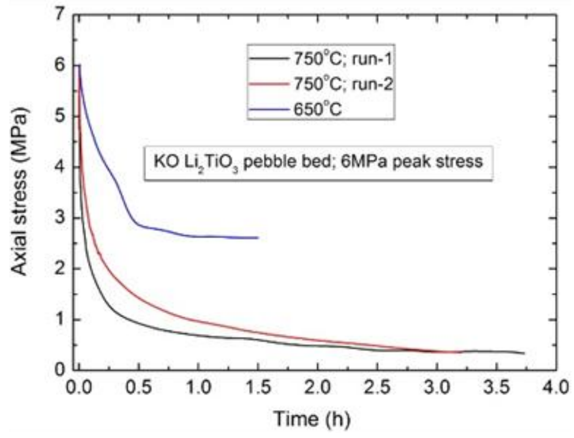
Creep Strain



CTE



Stress Relaxation

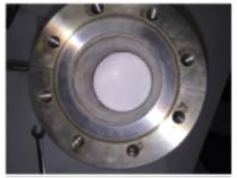


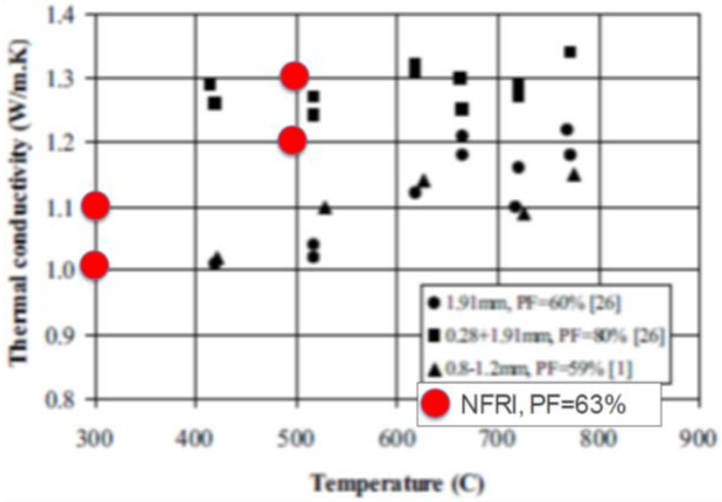
Establishment of DB for Li_2TiO_3 Pebbles and Pebble Bed

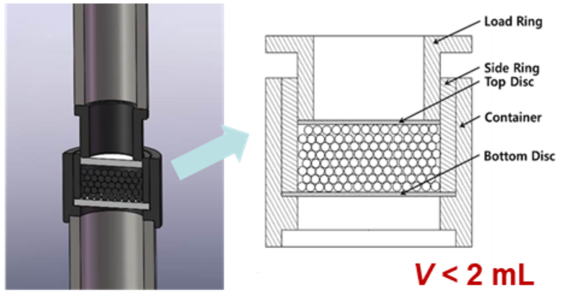
- Effective Thermal Conductivity of Li_2TiO_3 Pebble Bed
  - Effective thermal conductivity of the pebble bed was measured by transient hot wire method at UCLA and laser flash method at KFE.
  - Effects of axial compression load on the effective thermal conductivity of the pebble bed has been investigated.

UCLA Design

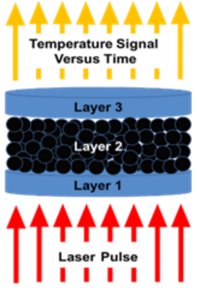
- $V = 578\ mL$
- $m = \rho \cdot V \cdot (.63) = 1153g$



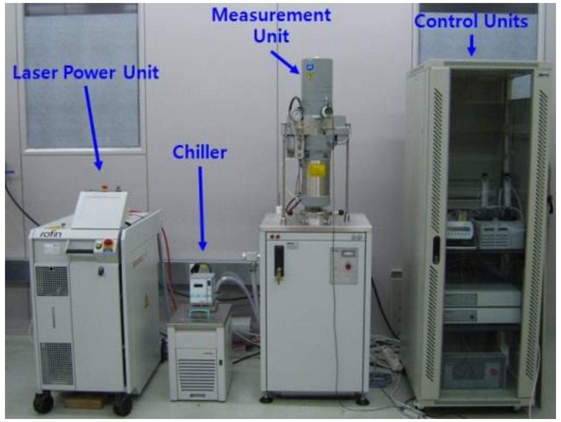




[Special Designed Pebble Holder]



[3-layer Method]



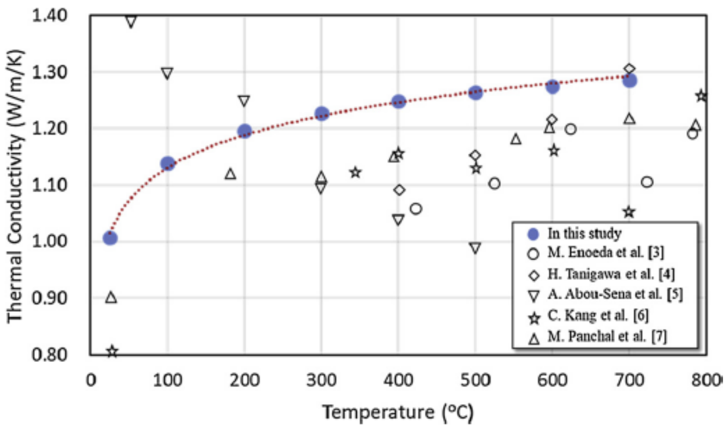
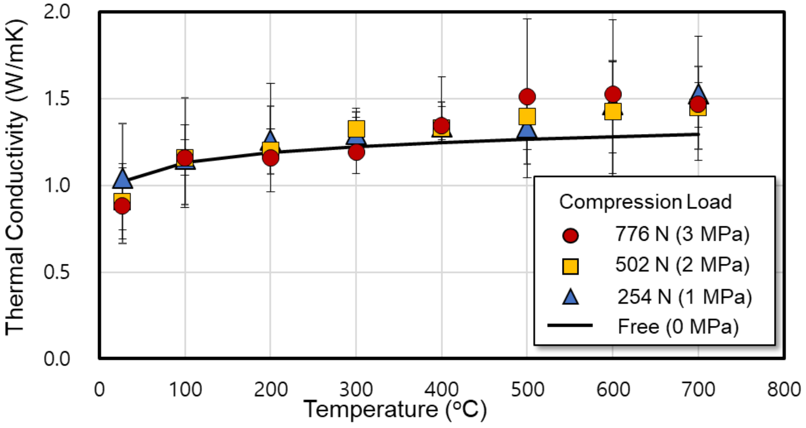


Fig. 6. Thermal conductivity of Li_2TiO_3 pebble bed.

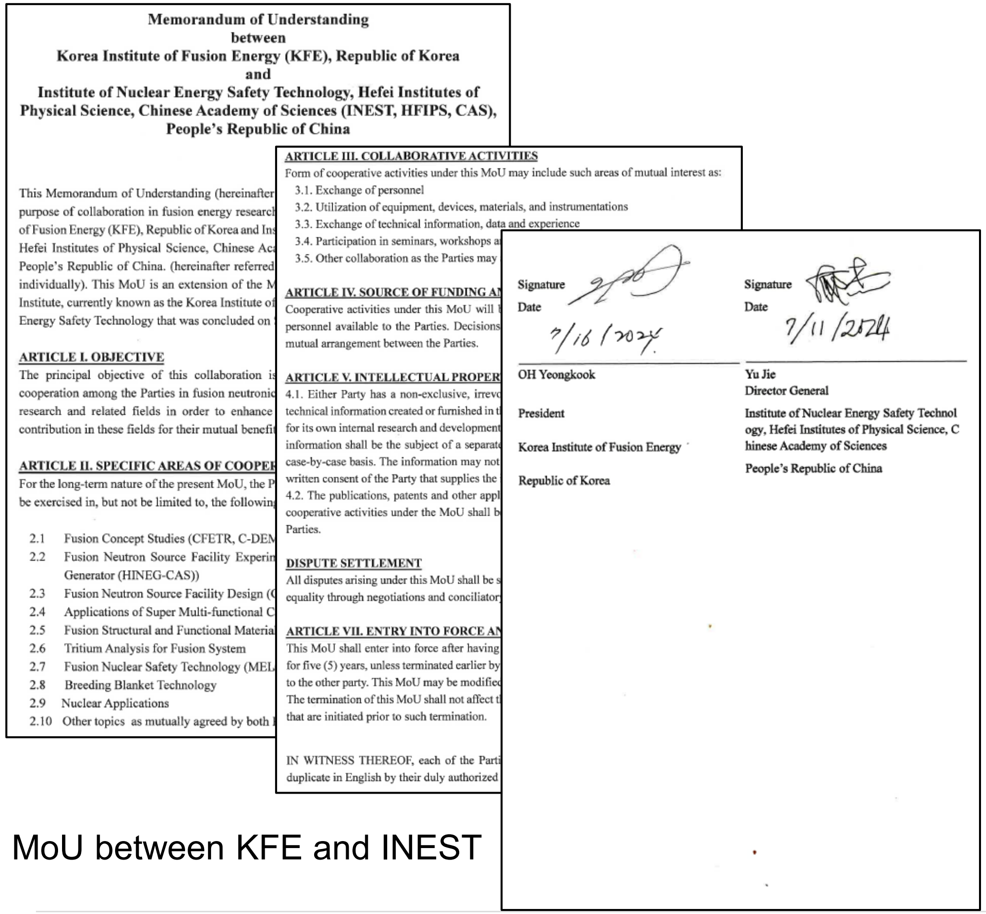
by Y.-H.Park et al, Fusion Eng. Des. 146 (2019), 950



by Y.-H.Park et al, Fusion Eng. Des. 194 (2023) 113728

Neutron Irradiation Test : KO-CN International Collaboration Program

- Tritium Breeding Research on Li_2TiO_3 Pebbles using D-T Fusion Neutron Source Facility
  - Phase 1 : 2021.10 ~ 2023.10
  - Phase 2 : 2024.12 ~ 2026.12



Memorandum of Understanding
between
Korea Institute of Fusion Energy (KFE), Republic of Korea
and
Institute of Nuclear Energy Safety Technology, Hefei Institutes of Physical Science, Chinese Academy of Sciences (INEST, HFIPS, CAS), People's Republic of China

This Memorandum of Understanding (hereinafter ... purpose of collaboration in fusion energy researc... of Fusion Energy (KFE), Republic of Korea and Ins... Hefei Institutes of Physical Science, Chinese Ac... People's Republic of China. (hereinafter referred... individually). This MoU is an extension of the M... Institute, currently known as the Korea Institute of... Energy Safety Technology that was concluded on ...

ARTICLE I. OBJECTIVE
The principal objective of this collaboration is... cooperation among the Parties in fusion neutronic... research and related fields in order to enhance... contribution in these fields for their mutual benefit...

ARTICLE II. SPECIFIC AREAS OF COOPER...
For the long-term nature of the present MoU, the P... be exercised in, but not be limited to, the following...

2.1 Fusion Concept Studies (CFETR, C-DEM...
2.2 Fusion Neutron Source Facility Experi... Generator (HINEG-CAS))
2.3 Fusion Neutron Source Facility Design (...
2.4 Applications of Super Multi-functional C...
2.5 Fusion Structural and Functional Materia...
2.6 Tritium Analysis for Fusion System
2.7 Fusion Nuclear Safety Technology (MEL...
2.8 Breeding Blanket Technology
2.9 Nuclear Applications
2.10 Other topics as mutually agreed by both ...

ARTICLE III. COLLABORATIVE ACTIVITIES
Form of cooperative activities under this MoU may include such areas of mutual interest as:
3.1. Exchange of personnel
3.2. Utilization of equipment, devices, materials, and instrumentations
3.3. Exchange of technical information, data and experience
3.4. Participation in seminars, workshops a...
3.5. Other collaboration as the Parties may ...

ARTICLE IV. SOURCE OF FUNDING AN...
Cooperative activities under this MoU will ... personnel available to the Parties. Decisions ... mutual arrangement between the Parties.

ARTICLE V. INTELLECTUAL PROPER...
4.1. Either Party has a non-exclusive, irrevo... technical information created or furnished in t... for its own internal research and development... information shall be the subject of a separate... case-by-case basis. The information may not... written consent of the Party that supplies the ...
4.2. The publications, patents and other appl... cooperative activities under the MoU shall b... Parties.

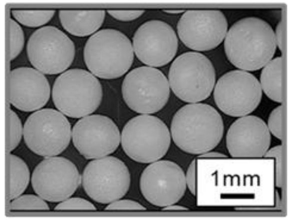
DISPUTE SETTLEMENT
All disputes arising under this MoU shall be s... equality through negotiations and conciliatory...

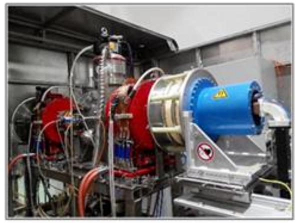
ARTICLE VII. ENTRY INTO FORCE AN...
This MoU shall enter into force after having ... for five (5) years, unless terminated earlier by... to the other party. This MoU may be modified... The termination of this MoU shall not affect t... that are initiated prior to such termination.

IN WITNESS THEREOF, each of the Parti... duplicate in English by their duly authorized...

Signature	Signature
Date 7/16/2024	Date 7/11/2024
OH Yeongkook	Yu Jie
President	Director General
Korea Institute of Fusion Energy	Institute of Nuclear Energy Safety Technology, Hefei Institutes of Physical Science, Chinese Academy of Sciences
Republic of Korea	People's Republic of China

MoU between KFE and INEST





Irradiation Exp. Data

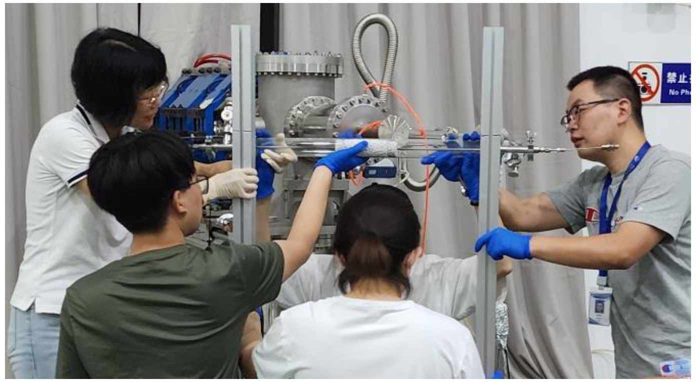
(KFE) Li_2TiO_3 Breeder Pebbles
- Synthesis of Li_2TiO_3 Raw Powder
- Fabrication of Li_2TiO_3 Breeder Pebbles
- Evaluation of un-irradiated Li_2TiO_3 Pebbles

(HFIPS) D-T Neutron Source
- Neutron Irradiation on Li_2TiO_3 Pebbles
- Measurement of Bred Tritium
- Evaluation of irradiated Li_2TiO_3 Pebbles

Li_2TiO_3 Breeder Pebbles

1^{st} Neutron Irradiation Test on Li_2TiO_3 Pebbles

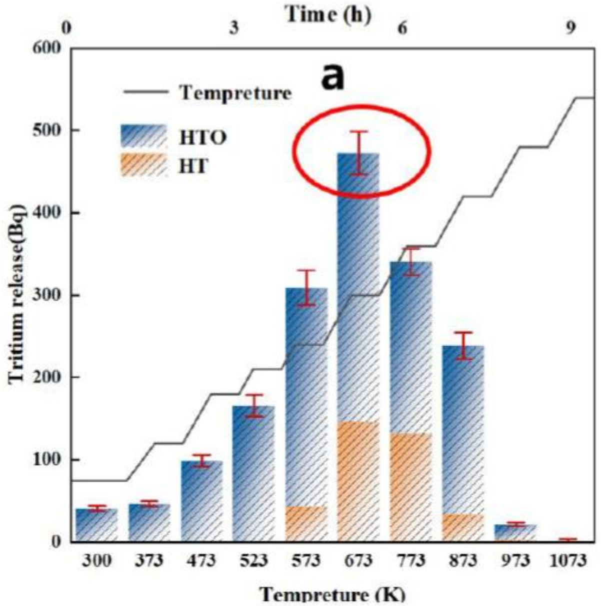
- Date : 2023.06
- Neutron Source : HINEG-CAS
  - Neutron Energy : 14 MeV
  - Neutron Yield : ~ 10^{12} n/s
- Irradiation Test Conditions
  - Duration Time : 6 hrs.
  - Total Number of Neutron : 1.104 x 10^{15} n
  - Neutron Fluence at Pebble : 9.96 x 10^{11} n/cm^2
- Tritium Breeder Sample
  - Material : Li_2TiO_3 Pebbles
  - Diameter : 3.4 mm
  - Sphericity : < 1.01
  - Porosity : 40 %



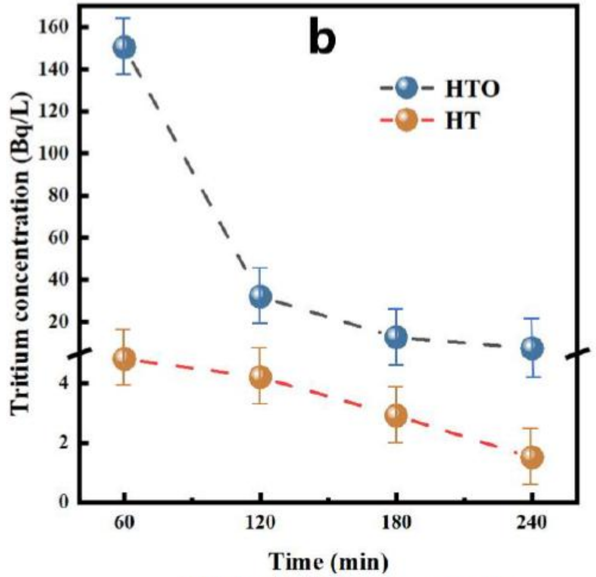
Tritium Release Test from Irradiated Pebbles

- Test Conditions
  - Purge Gas : He + 1 % H_2
  - Flow Rate of Purge Gas : 100 ml/min
  - Humidity Level : < 15 ppm
  - Tritium Release Temperature : R.T. ~ 1073 K
  - Tritium Measurement : LSC + Bubbler Method (Lower Detection Limit : 0.7 Bq/L)

by W. Wu et al,
Int. J. Hydrogen Energy 68 (2024), 1393



Distribution curves of tritium release at different temperature



Tritium measurement results at 1073 K for 4 h

- The total radioactivity of release tritium from the irradiated Li_2TiO_3 pebbles with 274 g in weight was about 1866.4 Bq.
- The ratio between HTO and HT at 400 ^oC was about 79.3 % to 20.7 %.
- The tritium radioactivity was decreased to background level after 4 h at 800 ^oC.

04

Summary

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

Summary

- Structural Material
  - Korean Reduced Activation Ferritic/Martensitic (RAFM) steel, ARAA, has been successfully developed.
  - Neutron irradiation test of ARAA is on-going in the core of HANARO research reactor, and PIE will be stared in Sep. 2025.
  - Draft document for ARAA codification in RCC-MRx_Tome 6 (2025 Ed.) is under review.

- Tritium Breeder Material
  - Manufacturing processes for Li_2TiO_3 pebbles, slurry droplet wetting method and PIM method, with the rotating sintering system have been successfully developed.
  - Material Property Database of Li_2TiO_3 pebbles and pebble bed is being established by domestic program and international collaboration program.
  - Neutron irradiation test and tritium release test of Korean Li_2TiO_3 pebbles is on-going under the KO-CN international collaboration program.

Thank you for your kind attention !!!

Yi-Hyun PARK

yhpark@kfe.re.kr

한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY