RAFM materials database, model data inputs and future developments toward DEMO

Takashi Nozawa[a*], Hiroyasu Tanigawa[a], Xiang (Frank) Chen[b], Masami Ando[a], Yoshiyuki Watanabe[a], Motoki Nakajima[a], Taichiro Kato[a], Yutai Katoh[b]

[a] *National Institutes for Quantum Science and Technology, Rokkasho, Aomori, Japan*
[b] *Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA*

***Corresponding author: nozawa.takashi@qst.go.jp**

ISFNT15
INTERNATIONAL SYMPOSIUM ON FUSION NUCLEAR TECHNOLOGY
10-15 SEPT 2023
AUDITORIO ALFREDO KRAUS
LAS PALMAS DE GRAN CANARIA, SPAIN

Contents

- Introduction
- RAFM materials database
- Model data inputs
- Future developments toward DEMO
- Summary

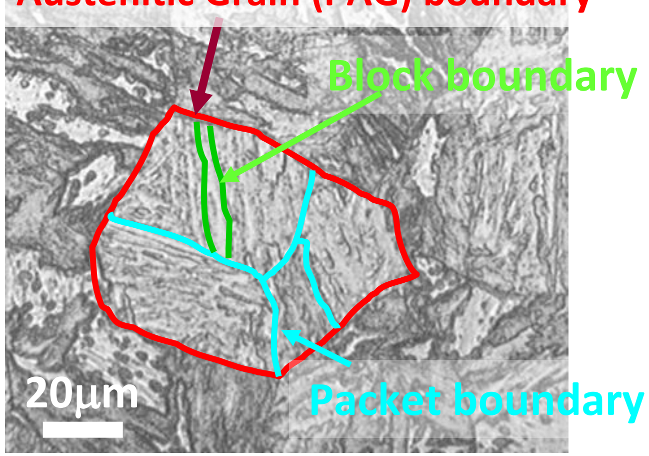
Reduced-activation ferritic/martensitic (RAFM) steel

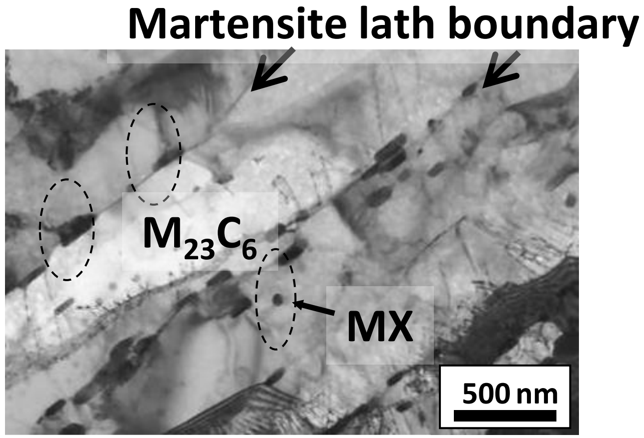
Specified chemical composition

wt%	F82H	EUROFER 97*
C	0.08 – 0.12 [0.10]	0.09 - 0.12 [0.11]
Cr	**7.5 – 8.5 [8.0]**	**8.5 - 9.5 [9.0]**
W	**1.6 – 2.2 [2.0]**	**1.0 - 1.2 [1.1]**
Mn	0.05 – 0. 5 (0.45)	0.20 - 0.60 [0.40]
V	0.15 – 0.25 [0.20]	0. 15 - 0.25
Ta	**0.01 – 0.10 [0.08]**	**0.10 - 0.14 [0.12]**
Si	<0.2 [0.1]	<0.05
N_2	**<0.025 [<0.01]**	**0.015 - 0.045 [0.030]**
P	< 0.02	< 0.005
S	<0.01	< 0.005
B	< 0.006 [0.001]	< 0.002 [ALAP]
O_2	< 0.005	< 0.01
Normalization	1040 °C	940-980 °C**
Tempering	740-750 °C	740-760 °C **
PWHT	720 °C	750 °C ***

*Gaganize et al. Fusion Eng. and Des. 135 (2018) 9–14
** RCC-MRx2015 Section III TOMEVI RM 243-3.43
*** Aubert J. Nucl. Mater..409 (2011) 156-162

Typical microstructure



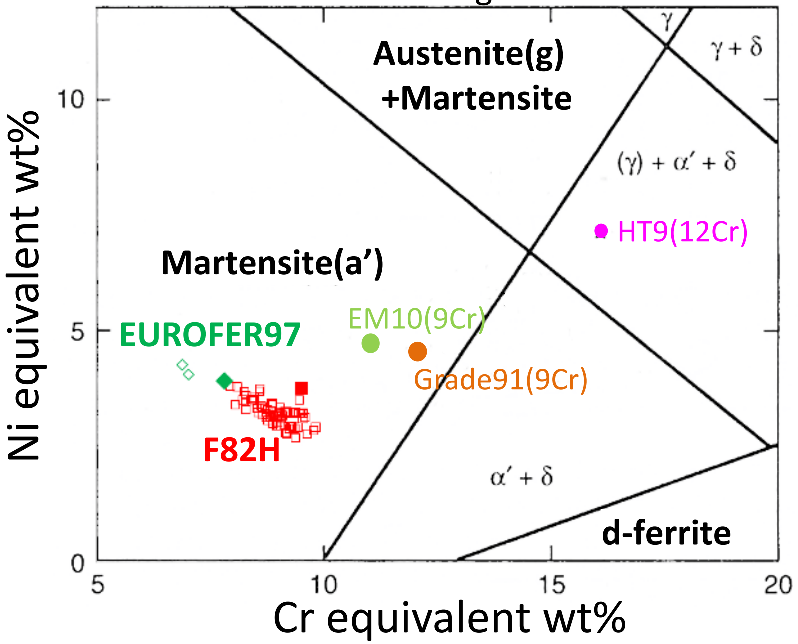


$M_{23}C_6$: M = Cr, Fe, W
MX : M=Ta, V, X= C, N

Expected phase

**Klueh and Harris, "High-Chromium Ferritic and Martensitic Steels for Nuclear Applications", ASTM Stock Number MONO3 (2001) ASTM

Schaeffler-Schneider diagram**



*Ni equivalent (wt%) = (%Ni) + (%Co) + **0.5(%Mn)** + 0.3(%Cu) + **30(%C)** + **25(%N)***

*Cr equivalent (wt%) = **(%Cr)** + 6(%Si) + 4(%Mo) + 11(%V) + 5(%Nb) + **1.2(%Ta)** + **1.5(%W)** + 8(%Ti) + 12(%Al) – 4(%Ni) – 2(%Co) – 2(%Mn) – (%Cu) – 40(%C) – **30(%N)***

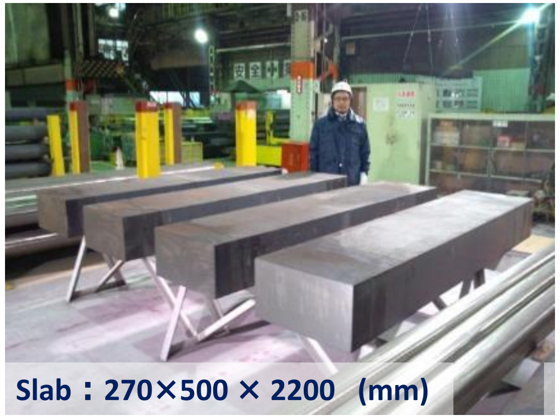
- ✓ F82H are predicted to be fully martensitic.
- ✓ Stability of precipitates is essential to the phase stability, which is the key to the excellent heat (and irradiation) resistance.

Manufacturing technologies of F82H

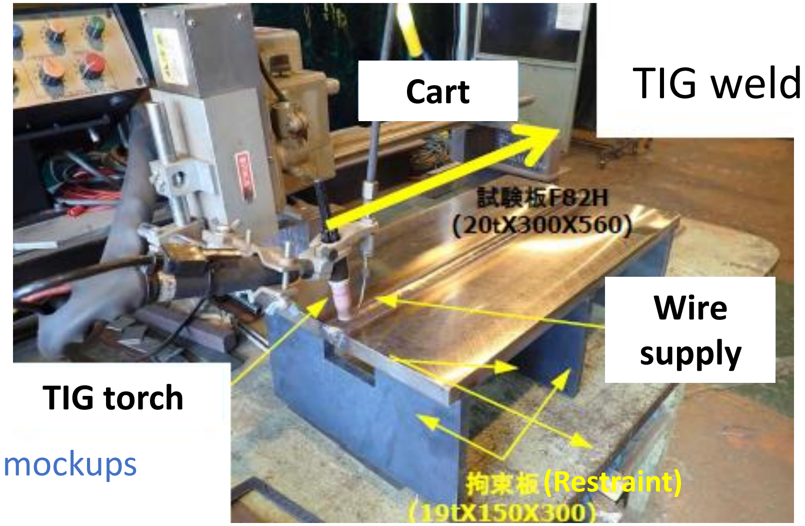
- **ITER-TBM: 1 ~ 2 t of RAFM to fabricate one module.**
- **DEMO: 5,000 ~ 10,000 t production to build one reactor.**

- 9 large heats (2 ~5 ton, including 20 ton) and various small heats (more than 20) has been made.
- Re-melting process, ESR (Electro slag re-melting), is effective to remove Ta-based inclusions (Ta oxides) which could decrease toughness and fatigue life.
- Fabrication of various parts (^{t}1.5 ~110 mm plates, ϕ_{out}11 to 76.3mm tubes, etc.) has been demonstrated.
- Good weldability has been demonstrated by the third party.

Slabs and billets of F82H 20t heat (EAF+ESR)


Slab：270×500 × 2200 (mm)


Billet：ϕ210 × 2600 (mm)



PS2-38 T. Hirose, Functional tests for water cooled ceramic breeder blanket system using full-scale mockups

PS3-21 W. Guan, Weldability of F82H for WCCB TBM Application

Key directions in materials research toward DEMO

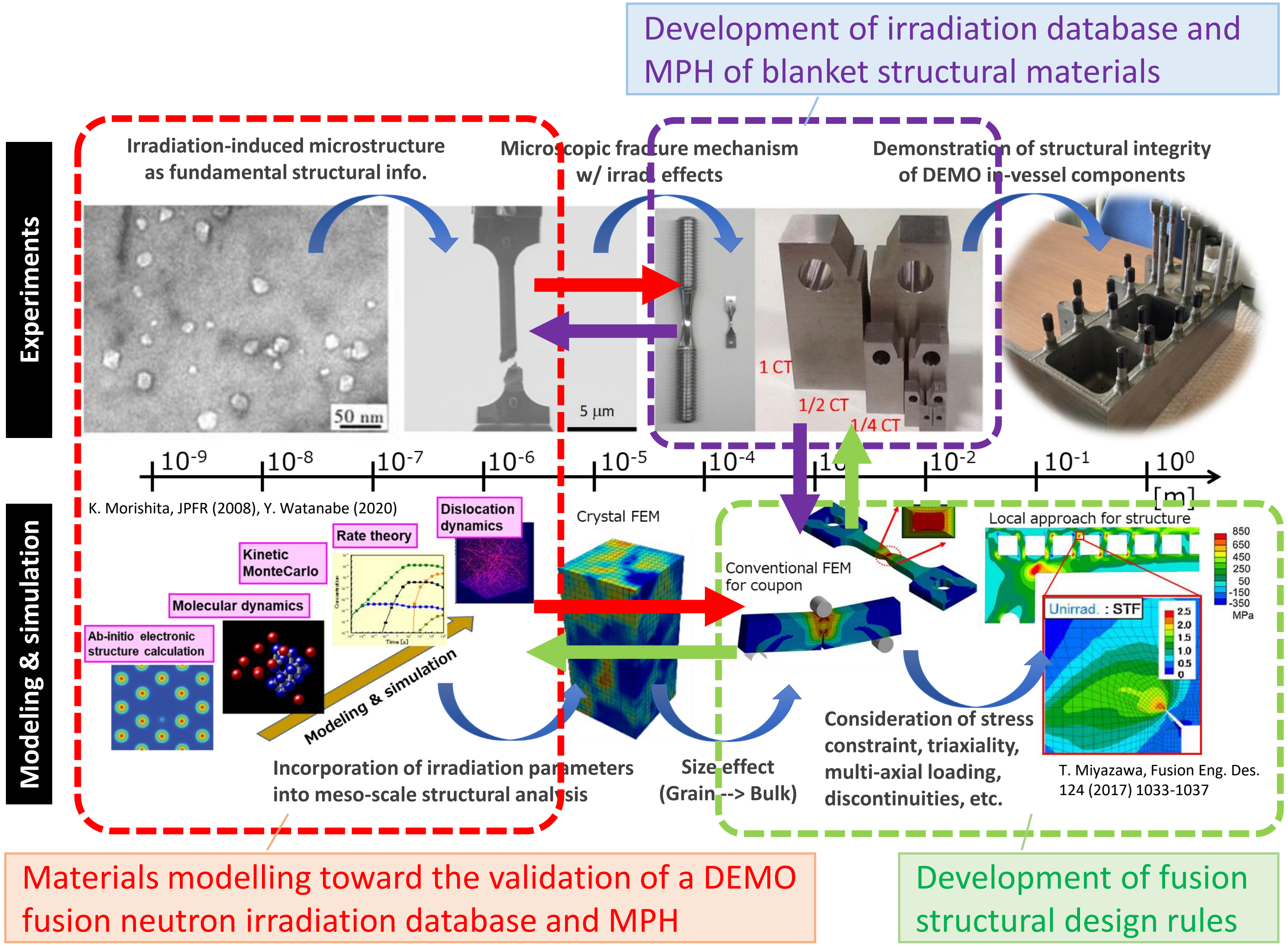
Material data for

- DEMO design
- Modelling & simulation
- Qualification

-->Staged approach

Issues:

- Mixed environments
- Multi-loading (multi-modes)
- **Multi-scale**
- …



Plans for obtaining material data by staged approach

■ *achieved,* ■ *major progress with important findings,* ■ *partly initiated*

TRL	System TRL	Status of F82H and targets
Level 1	Evidence from literature, Feasible material concept	Proposal of candidate concepts for DEMO materials and technologies based on assessment of basic principles
Level 2	Agreed target use	Clarification of the scope of realization and application of materials and technologies
Level 3	Materials' capability based on lab scale samples. Reference material.	Clarification of development issues and development goals required in engineering of the technology and proof of the range (upper limit) within which practical application can be achieved.
Level 4	Radiated and unirradiated design curves produced. Codification/handbook. Variability in properties	Establishment of design parameters for DEMO components.
Level 5	Methods for material processing and component manufacture	Establishment and verification of DEMO component fabrication and design techniques
Level 6	Validated via component and/or sub-element testing.	Final selection of DEMO candidate technologies.
Level 7	Evaluated in development rig tests	Completion of fabrication design of DEMO reactor components
Level 8	Full operational test	Proof of the finalized DEMO utilization conditions.
Level 9	Production-ready material	Utilization of DEMO materials in DEMO reactors based on the DEMO utilization conditions that are ultimately defined by technological development based on the unique attributes of the DEMO technology.

→ Feasibility

→ Material file (MF) for component design

→ Procurement spec.

→ Standardization & qualification

Contents

Overview of material file development in Japan

QST

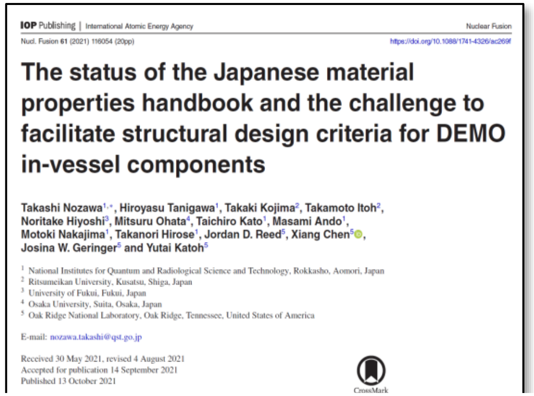
General approach

- Hazard analysis to comply with essential safety requirements (ESR) and essential radioprotection requirements (ERR)
- Reference procurement specification
- DB/MPH including fission and fusion neutron irradiation

Key features of F82H material file

- Base metal and welds/joints
- Thermo-physical and -mechanical props. + swelling & irradiation creep
- RT to 550°C for general.
- Selected data available to facilitate material strength standards of non-irradiated F82H from massive database (several thousands of data)
- Irradiation database is being extensively developed in BA Phase II (2020-2025)

MPH


IOP Publishing | International Atomic Energy Agency — Nuclear Fusion

Nucl. Fusion 61 (2021) 116054 (20pp) — https://doi.org/10.1088/1741-4326/ac269f

The status of the Japanese material properties handbook and the challenge to facilitate structural design criteria for DEMO in-vessel components

Takashi Nozawa[1,*], Hiroyasu Tanigawa[1], Takaki Kojima[2], Takamoto Itoh[2], Noritake Hiyoshi[3], Mitsuru Ohata[4], Taichiro Kato[1], Masami Ando[1], Motoki Nakajima[1], Takanori Hirose[1], Jordan D. Reed[5], Xiang Chen[5], Josina W. Geringer[5] and Yutai Katoh[5]

[1] National Institutes for Quantum and Radiological Science and Technology, Rokkasho, Aomori, Japan
[2] Ritsumeikan University, Kusatsu, Shiga, Japan
[3] University of Fukui, Fukui, Japan
[4] Osaka University, Suita, Osaka, Japan
[5] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States of America

E-mail: nozawa.takashi@qst.go.jp

Received 30 May 2021, revised 4 August 2021
Accepted for publication 14 September 2021
Published 13 October 2021

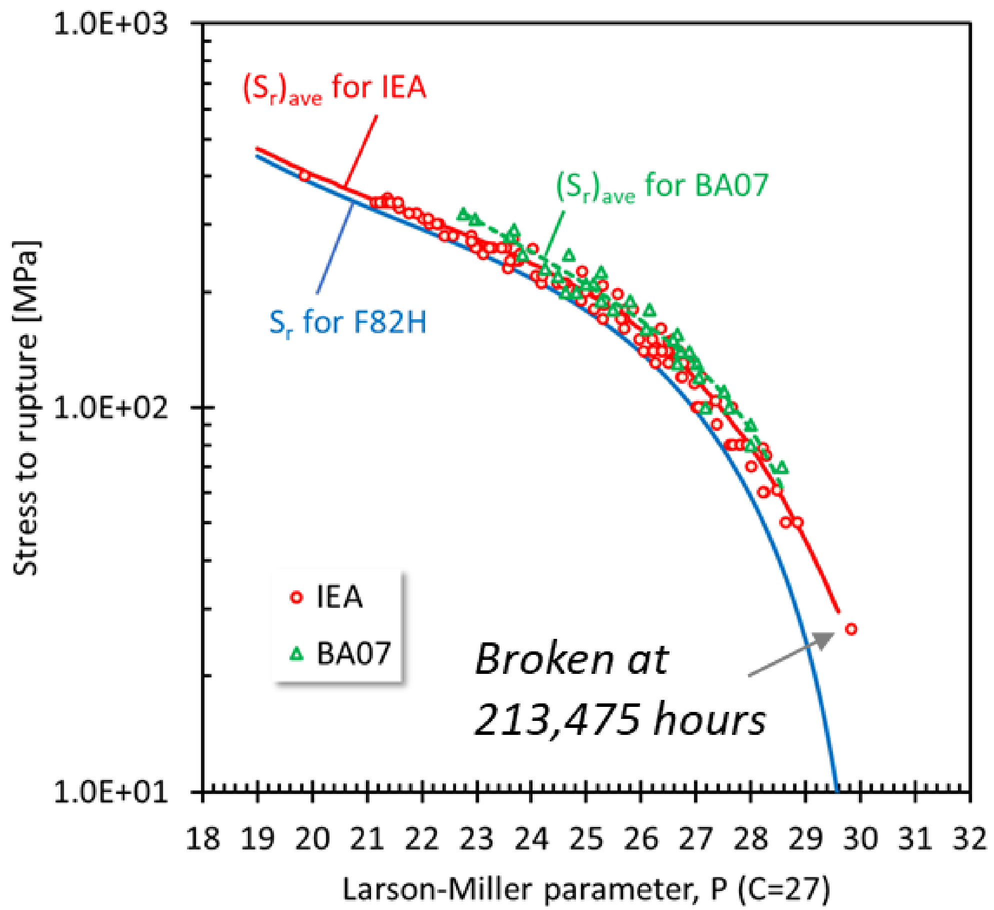
CrossMark

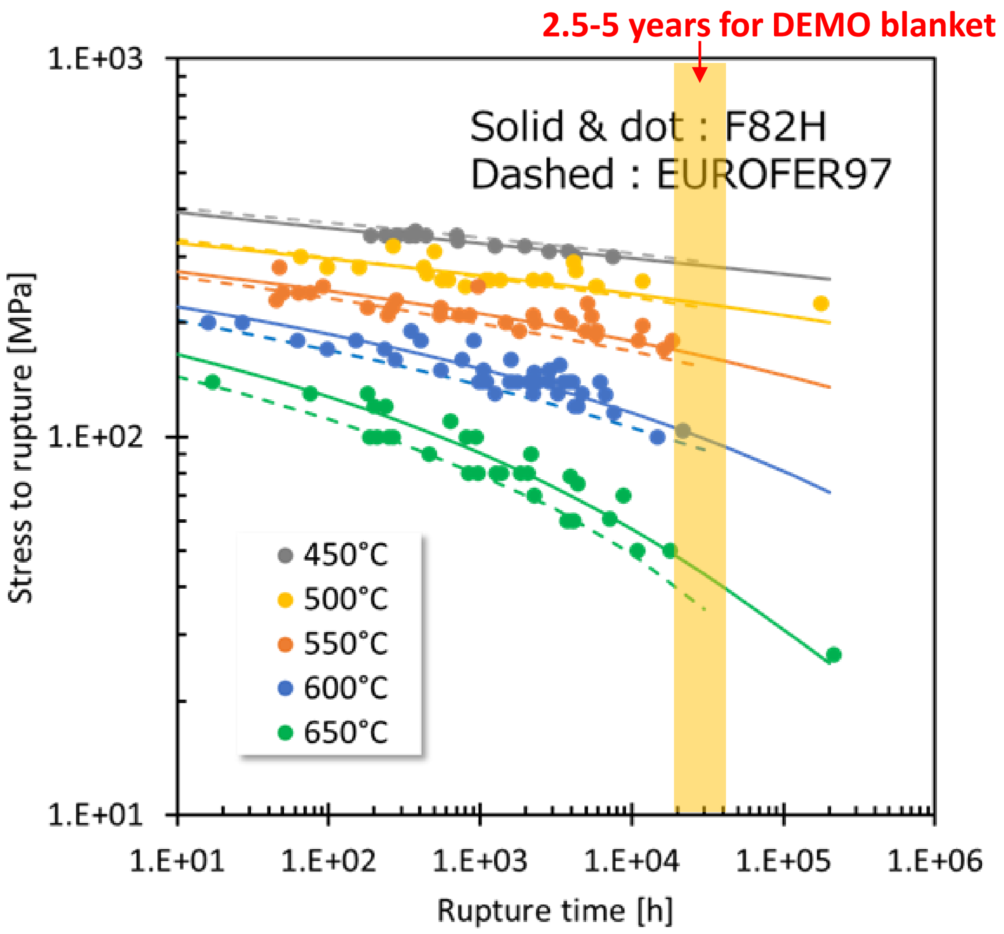
Nozawa et al. Nuclear Fusion 61 (2021) 116054.

Material file based on RCC-MRx 2018 edition

#	Contents (draft)
1	Introduction
1.1	Presentation of the grade(s)
1.2	Codes and standards covering these parts and products
1.3	Reference Procurement Specifications in Tome 2
1.4	Industrial applications and experience gained
2	Physical properties
3	Mechanical properties used for design and analysis (base metal and welds)
3.1	Justification of the applicability of the Design Rules (RB,C,D 3000) for the specified usage conditions
3.2	Basic mechanical properties
3.3	Mechanical properties when creep is significant
3.4	Mechanical properties when irradiation is significant
3.5	Guaranty of the consistency between the properties of the final part laid-on the plant and the material properties used to design the component
4	Manufacturing
4.1	Industrial experience
4.2	Metallurgy
5	Fabrication
5.1	Industrial experience
5.2	Forming operation ability
6	Welding
6.1	Weldability
6.2	Industrial experience gained during welding procedure qualifications
7	Controllability
8	In-service behavior (Thermal ageing, corrosion, erosion-corrosion, irradiation, …)
9	Conclusion

Time-dependent mechanical properties

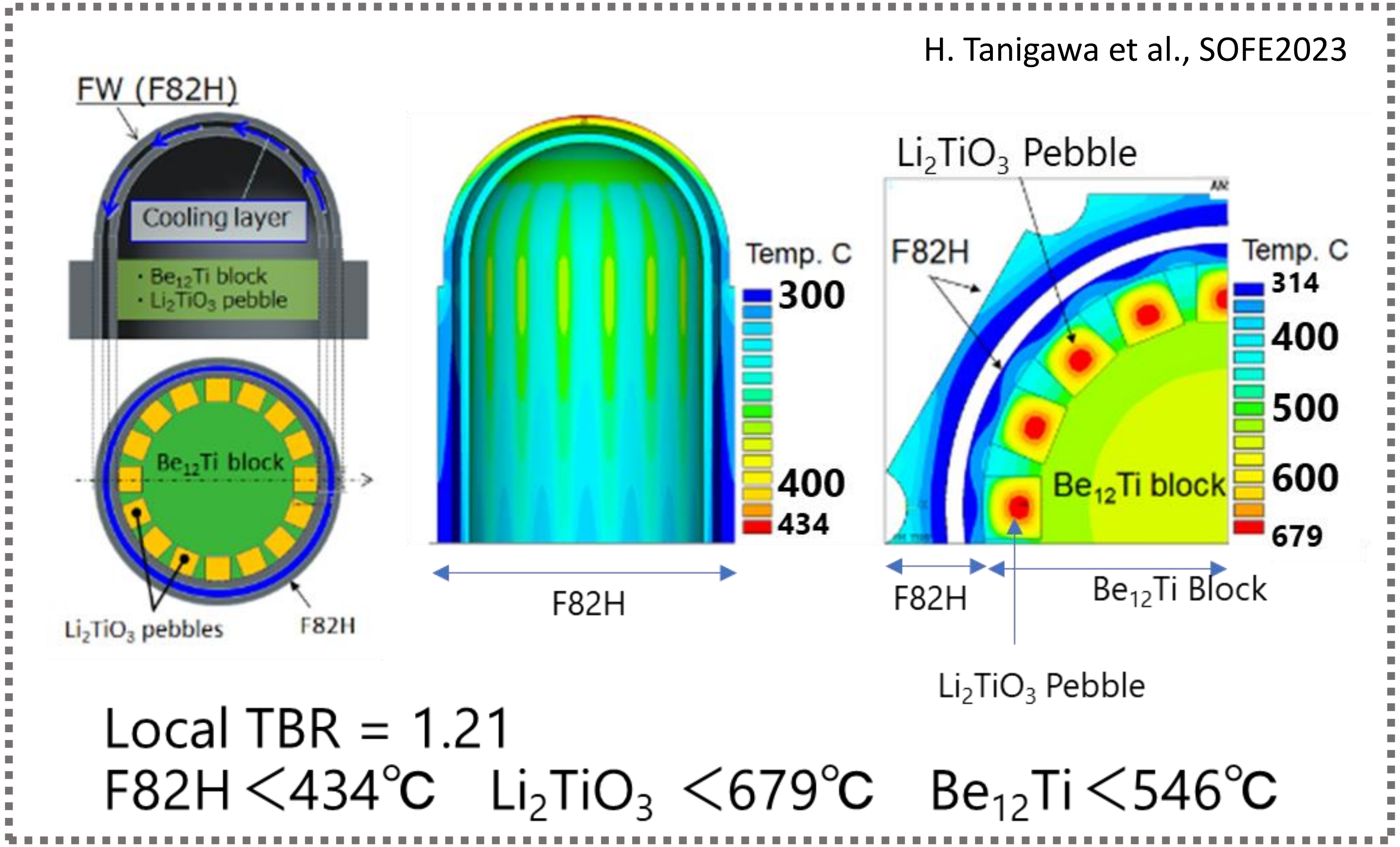


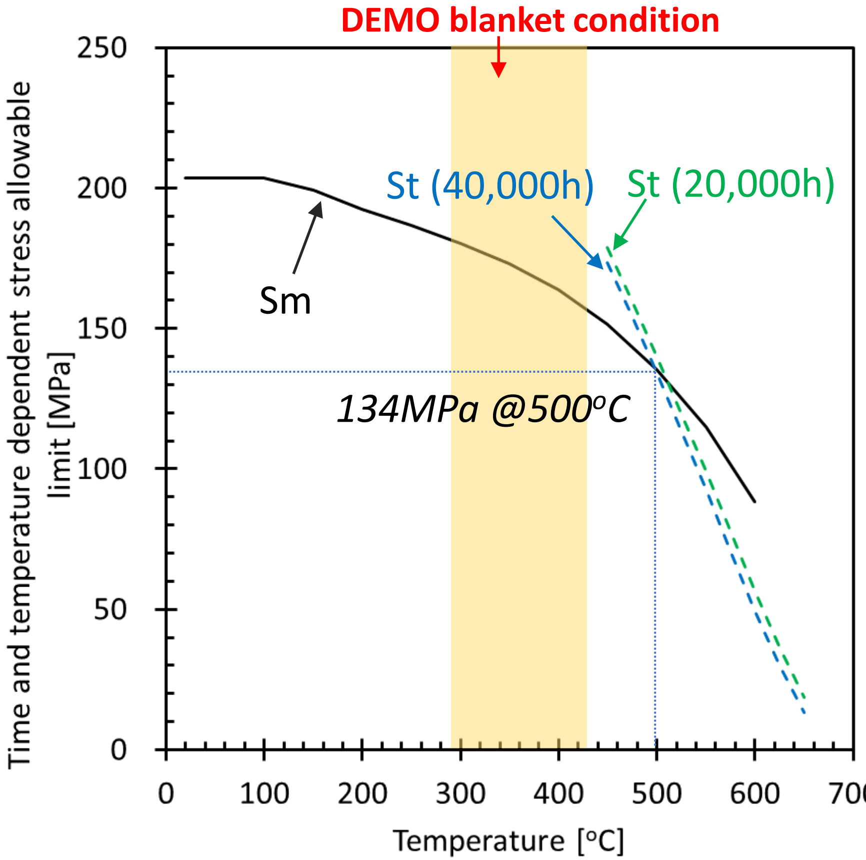


- Increased reliability when predicting creep lifetime due to >200k hours creep data.

H. Tanigawa et al., “Phase stability of long-term creep-tested F82H and its correlation with irradiation resistance” to be presented in ICFRM-21

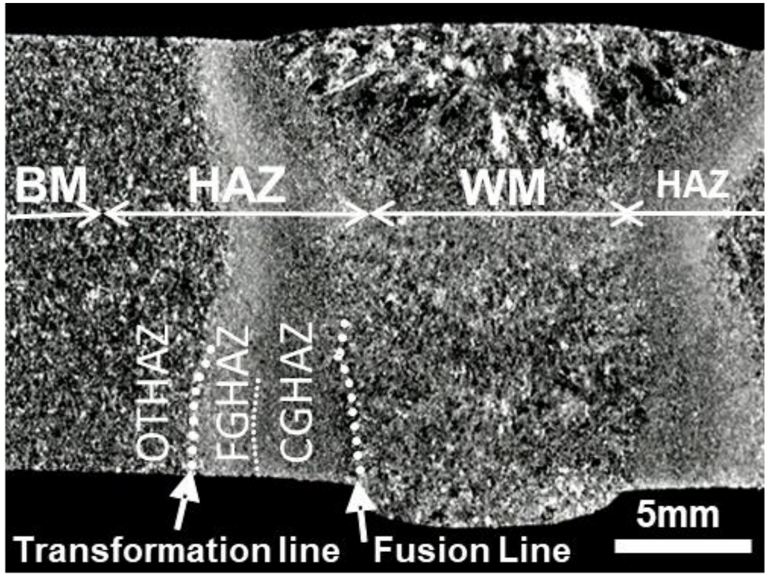
Time-dependent mechanical properties



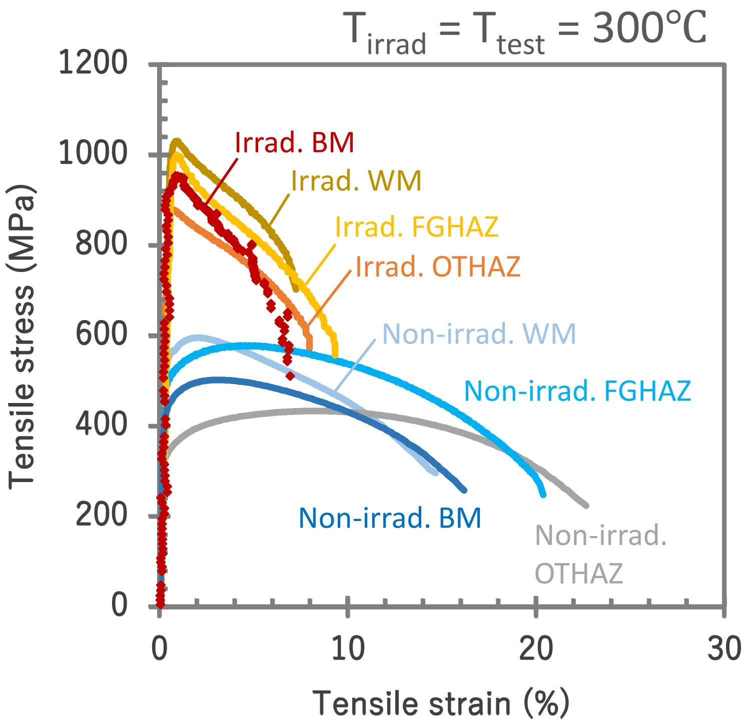


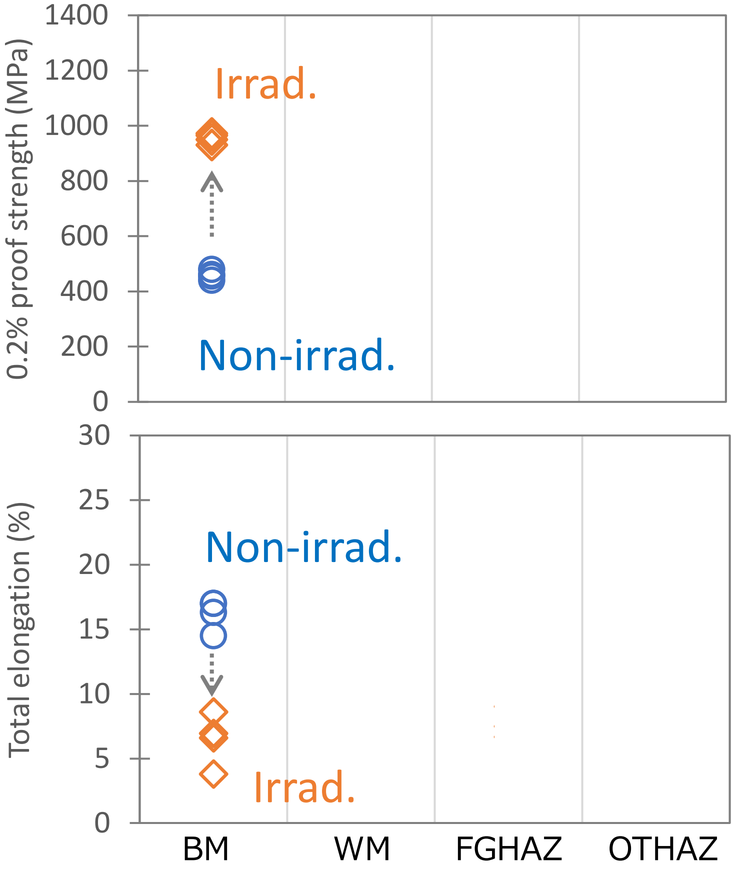
- Thermal creep is not a major parameter in operation of the DEMO blanket (<450°C).

Neutron irradiation (50dpa@300ºC) on F82H TIG welds



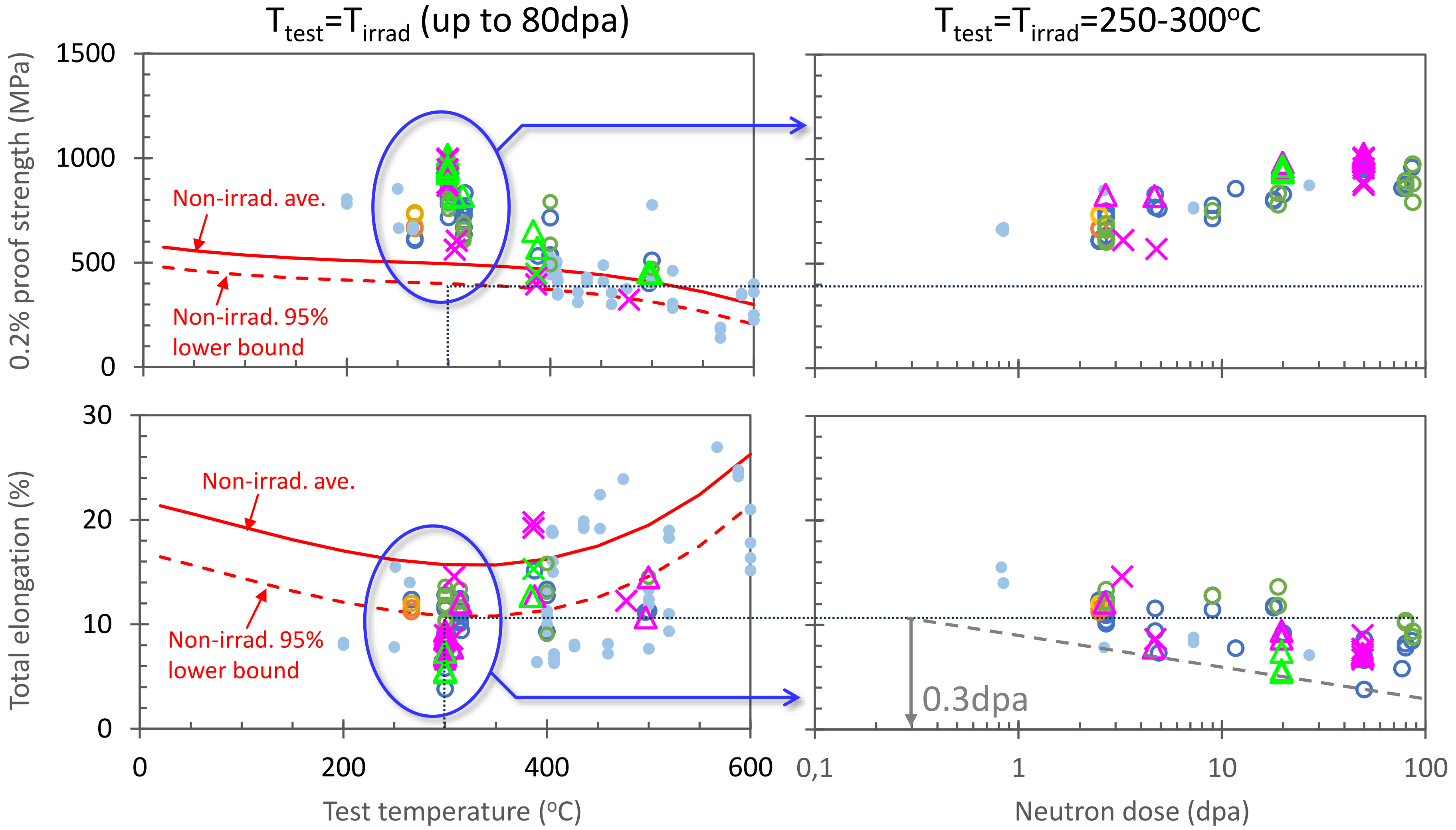
BM: Base metal
WM: Weld metal
CGHAZ: Coarse-grained heat-affected zone
FGHAZ: Fine-grained heat-affected zone
OTHAZ: Over-tempered heat-affected zone

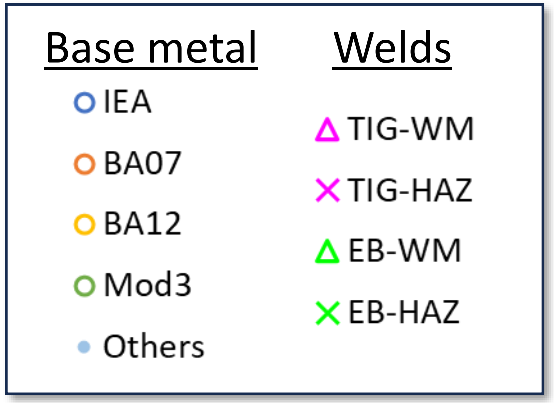




- WM and HAZ undergo hardening and loss of ductility to the base metal level by irradiation

Summary of neutron irrad. on tensile props. of F82H





- No heat variation
- Welds: similar trend
- Negligible irradiation dose judged by the significance level of the loss of ductility

T. Nozawa et al., "Reference standard strength for neutron-irradiated reduced activation ferritic/martensitic steel F82H toward DEMO design" to be presented in ICFRM-21

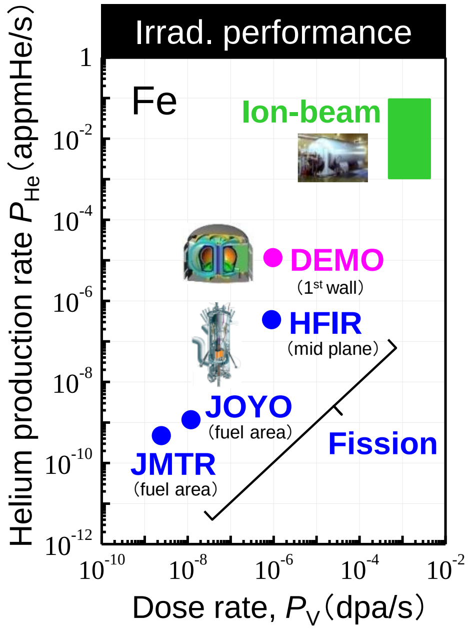
Contents

Toward prediction of fusion neutron irradiation effects

QST

- Fusion DEMO reactor shall be designed within the range that irradiation effects of “FUSION neutron” are not too different from those of “FISSION neutron.”
- With theoretical understanding of material behaviors under various irradiation conditions, a prediction tool of irradiation effects in the fusion DEMO environment is necessary.

The critical conditions of fusion neutron irradiation effects appearance should be predicted for important phenomena (e.g., microstructures, yield strength and volumetric swelling).



Research issue	Input data	Method / Analysis	Output data
Theoretical understanding of microstructure evolution for different irradiation fields	• Irradiation temperature • Dose rate & He production rate • Primary defect distribution • Defect energies (for migration and thermal stability) • Dislocation density, sink strength, etc.	Reaction rate theory / KMC analysis / CRA	• Number density & size distribution of defects: cavities(voids/bubbles), dislocation loops, black dots, etc. • Correlation of microstructures for different irradiation fields
Prediction of mechanical properties and dimensional changes due to microstructure evolution	• Number density & size distribution of defects • Elastic stress-strain for defects	FEM/CP-FEM MD/DD	• Elastic stress-strain distribution • Yield strength • Volumetric swelling / Void swelling

New indicator: Fracture strength by μ-tensile testing

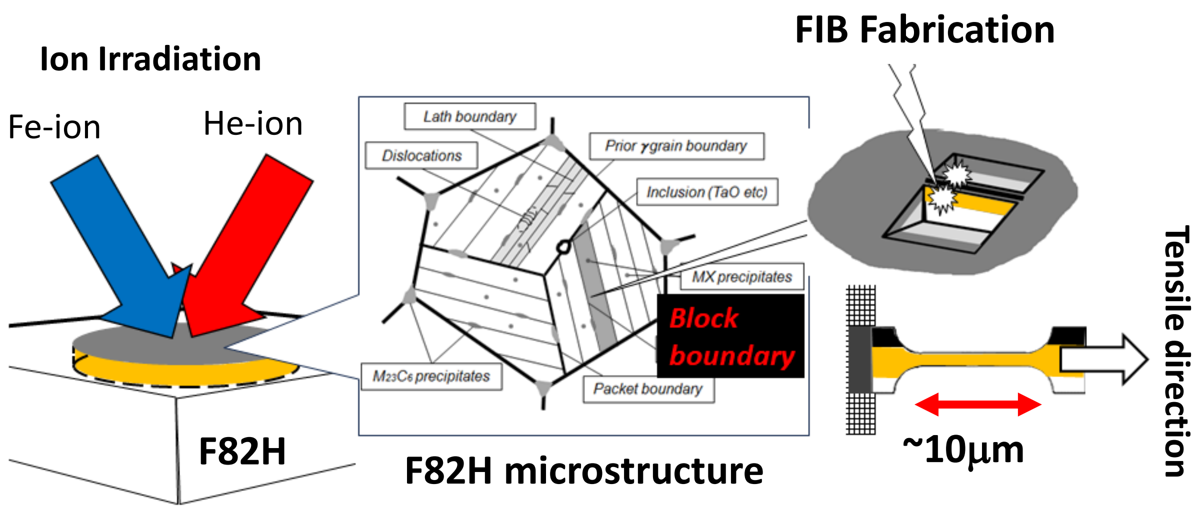
Important to evaluate the effects of **damage** and **transmutation helium**.
(Difference point is described as **critical point**)

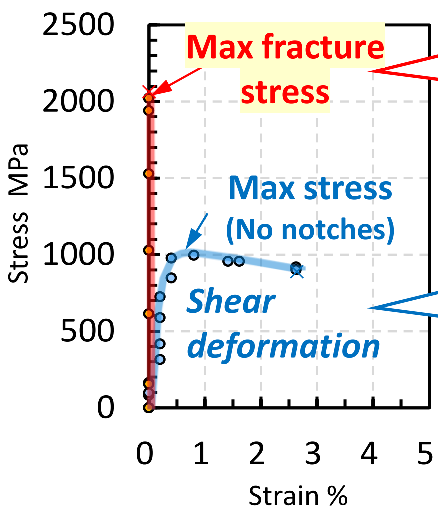
Ion irradiation beneficial to estimate the **critical point**.
… Limited applicability (damaged layer = small volume)

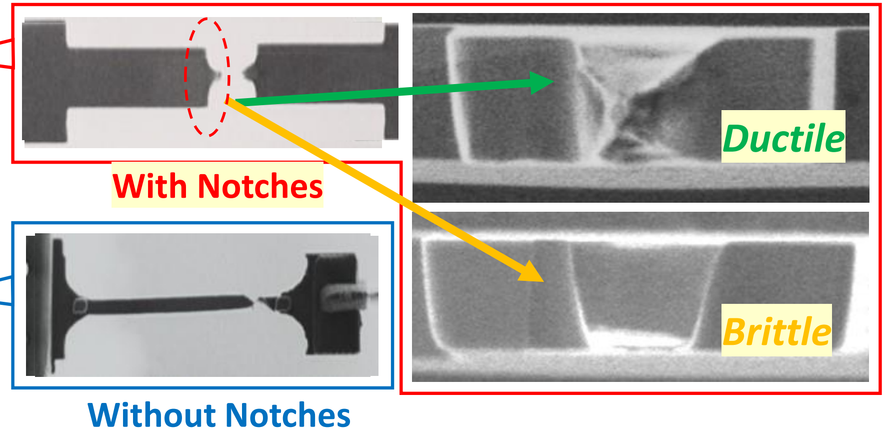
Conventional indicators

	TEM observation	Nano-indenter
Evaluation item	Cavity microstructure (Density, Size)	Nano-hardness
Indicator	Void swelling	Irradiation hardening (∝UTS)

--> Develop a fracture strength evaluation for small areas as a NEW indicator by applying μ-tensile testing technology



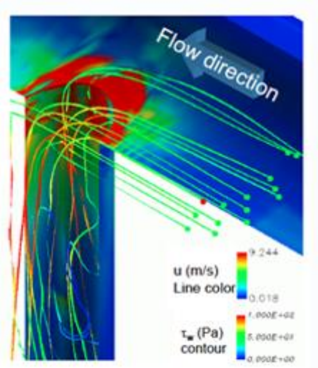


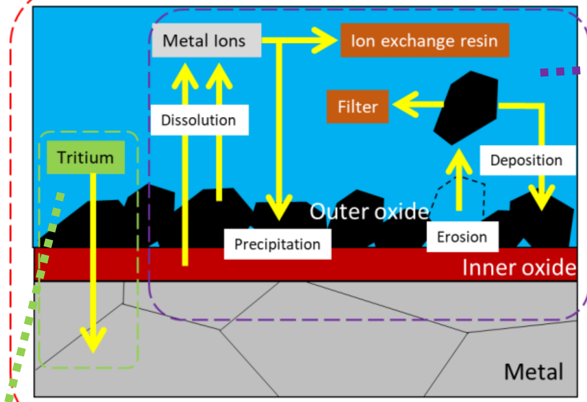


Toward prediction of activated corrosion products (ACPs)

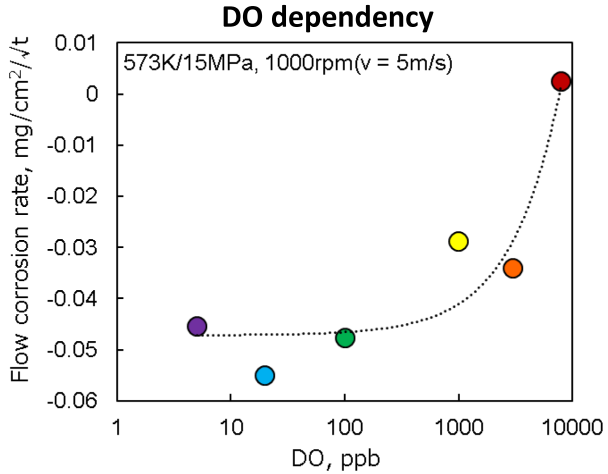
PS1-66

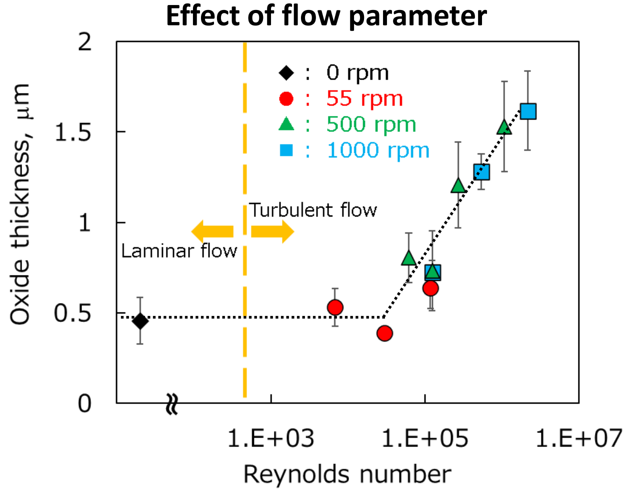
ACP model development

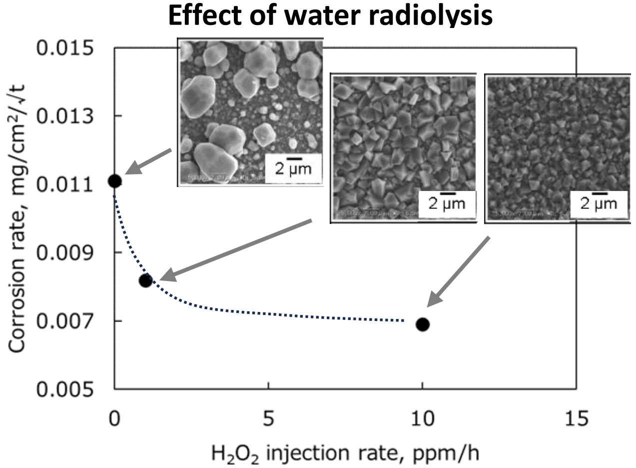


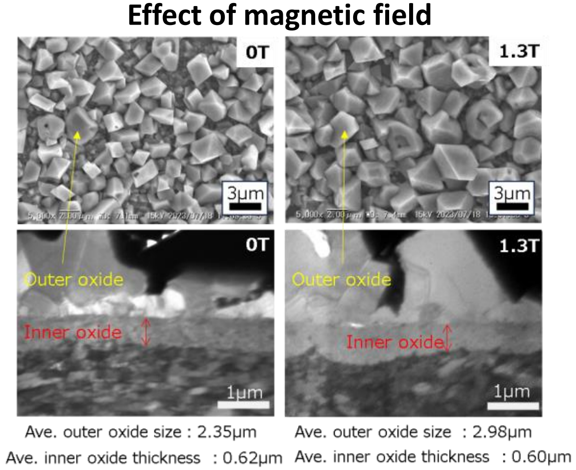


Corrosion/erosion handbook

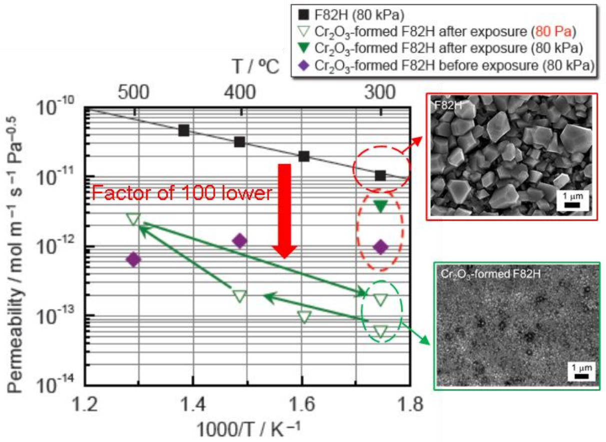








Tritium behavior DB



National University Corporation Shizuoka University

KINDAI UNIVERSITY

UNIVERSITY OF TOYAMA

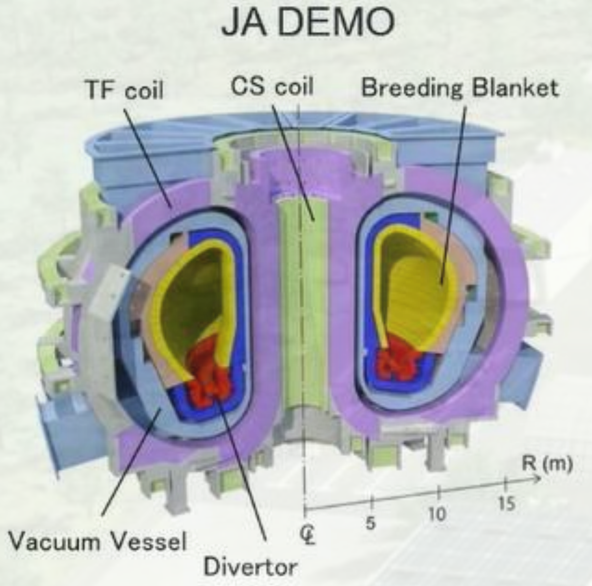
- Deuterium permeability of Cr_2O_3-formed F82H after exposure to high-temp. water
- Tritium permeability test is ongoing

M. Nakajima et al., “Status and issues of high-temperature and high-pressure water corrosion research of fusion structural materials” to be presented in FEC2023
T. Chikada et al., “Deuterium permeation and retention in F82H after exposure to pressurized water” to be presented in ICFRM-21

Contents

- Introduction
- RAFM materials database
- Model data inputs
- Future developments toward DEMO
- Summary

Fatigue is more important under the new JA DEMO strategy



R_p: 8.5m
a_p: 2.42m
P_{fus}: 1.5GW
P_{gross}: 0.64GW
B_{T0}: 6T
I_p: 12.3MA
P_{aux}: < 100MW
β_N: 3.4
n_e/n_{GW}: 1.2
HH_{98y2}: 1.3
PWR water condition
Availability: ~70%
Steady-state operation
TBR: 1.05

Consideration of "bringing forward the implementation date of fusion power generation"

- Based on the integration strategy of JT-60SA and ITER to DEMO in line with Action Plan (AP), consider the implementation timing of power generation by DEMO to be brought forward.
  - Define the 1st phase (power generation demonstration) and the 2nd phase (rated power generation demonstration) as the phased improvement of DEMO performance (expansion of the operation area).
  - Phase 1 is set as a "milestone" to demonstrate power generation by breeding blanket (BLK) at an early stage, while ensuring that the Phase 2 target can be achieved promptly.
- AP update: Activities after the 2nd C&R will be considered after the review of the same.
- Fusion energy innovation strategy will promote 1) developing the Fusion industry, 2) developing Fusion Technology, and 3) framework for promoting fusion energy innovation strategy.

Pulse operation will be adopted in phase 1

https://www8.cao.go.jp/cstp/fusion/230426_strategy.pdf

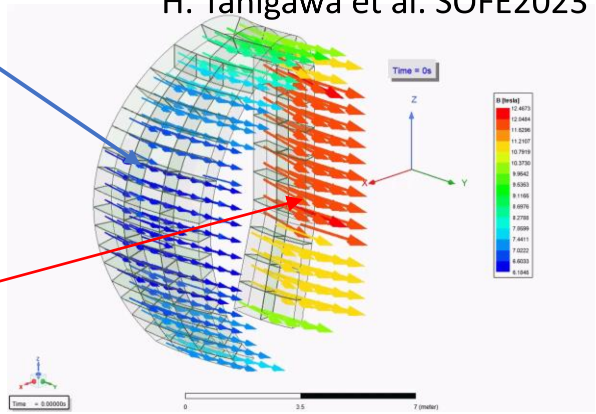
Electromagnetic (EM) force also affects structural integrity

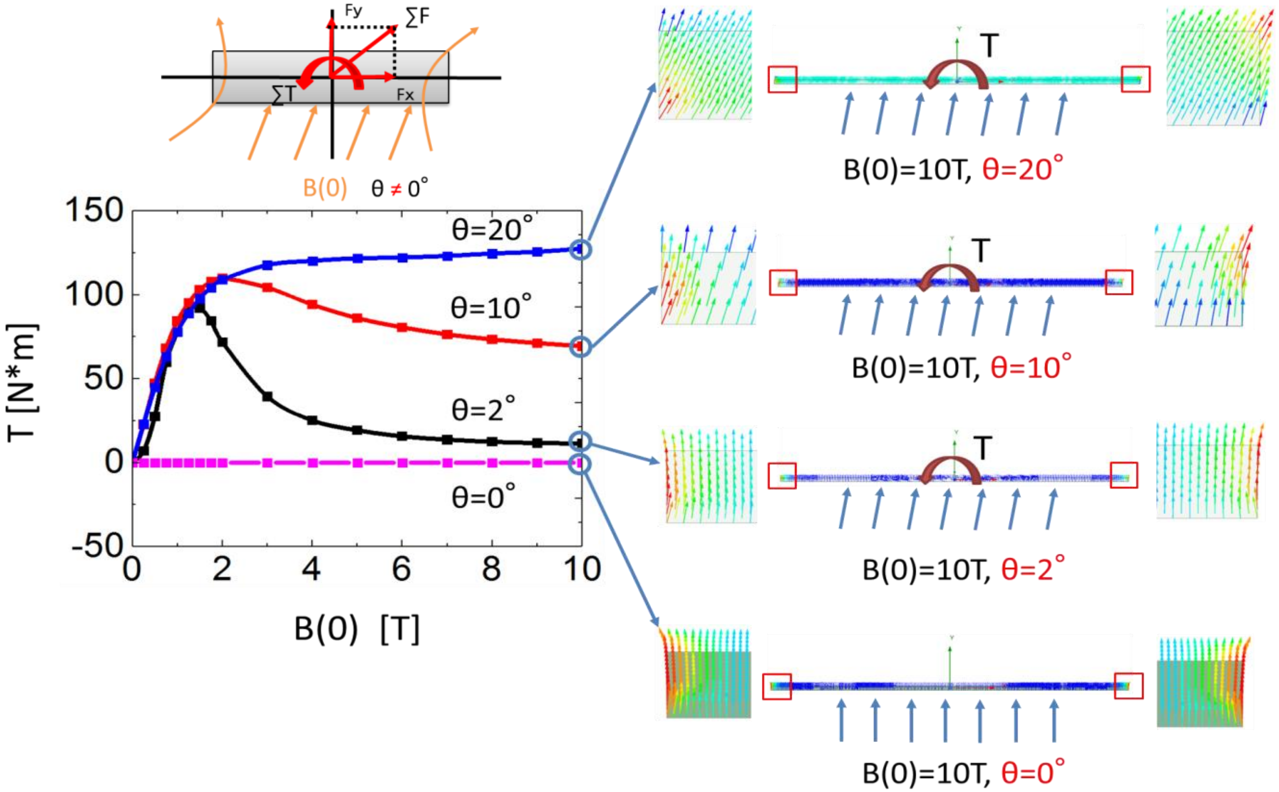
The Maxwell forces will be applied as a primary stress on the ferromagnetic structure.

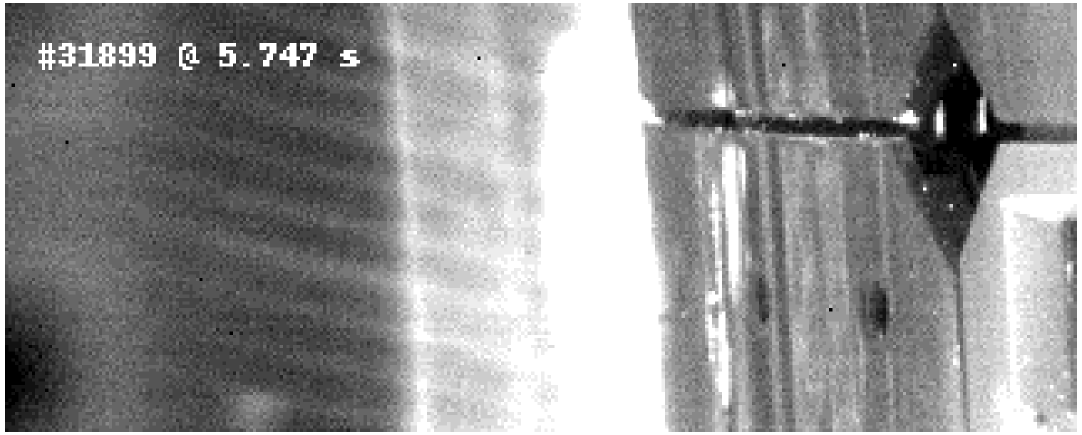
Outboard position
- ✓ 4.3T~ 4.7T

Inboard position
- ✓ Magnetic field gradient : 8.7T~ 9.5T
- ✓ Vector change : ~15 degree

H. Tanigawa et al. SOFE2023





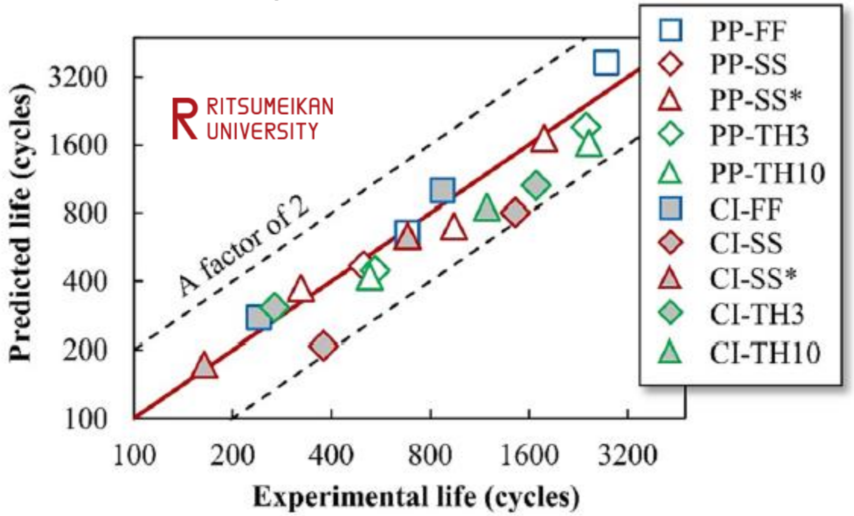


I. Zammuto et al. FED 124 (2017) 297

- Possible torque generation due to dynamic directional change of the magnetic field
- **Does F82H property change in magnetic field?**

Multi-axial fatigue, creep and fatigue-creep

L. Xu et al. Int. J. Fatigue 170 (2023) 107555



$$\Delta\varepsilon = \frac{\left[0.0266{\varepsilon_f}^{0.155}\left(\frac{\sigma_B}{E}\right)^{-0.53}{N_f}^{-0.56} + 1.17\left(\frac{\sigma_B}{E}\right)^{0.832}{N_f}^{-0.09}\right]}{(1+\alpha k_s f_{NP})k_v}$$

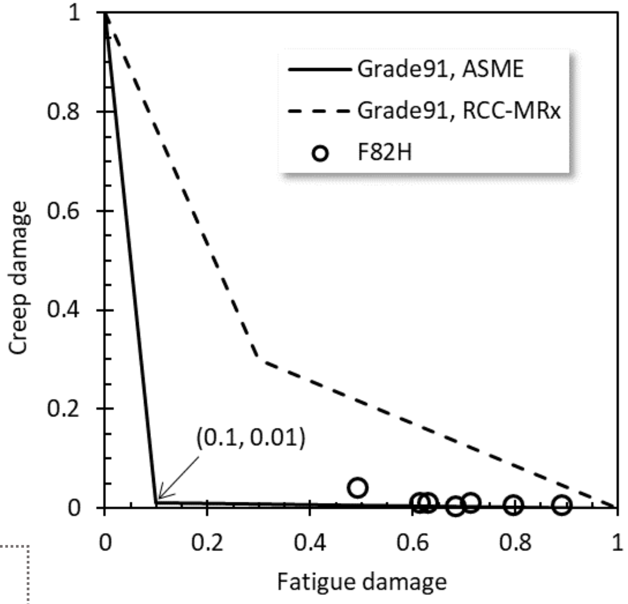
Non-proportionality ➡ $(1+\alpha f_{NP})$

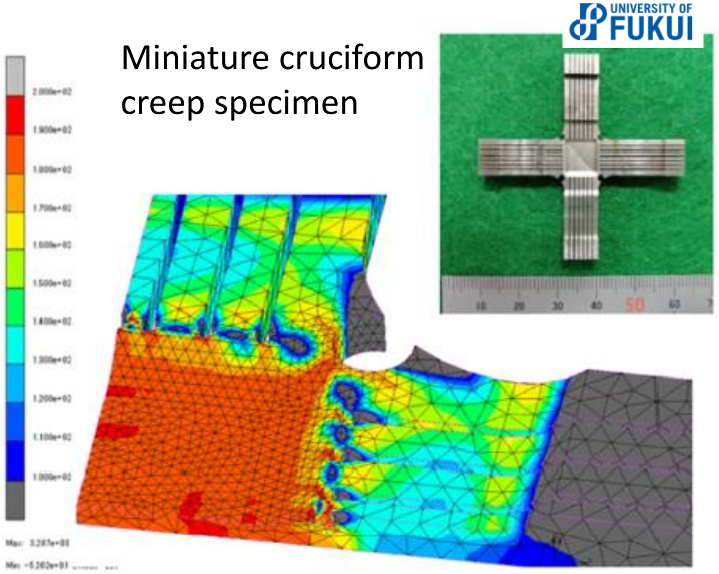
α : Coefficient for material dependence of non-proportional loading effects

f_{NP} : Coefficient indicating the intensity of the non-proportionality

Creep ➡ K_S : Parameter considering the decrease in non-proportionality due to stress relaxation

K_v : Parameter considering the strain rate



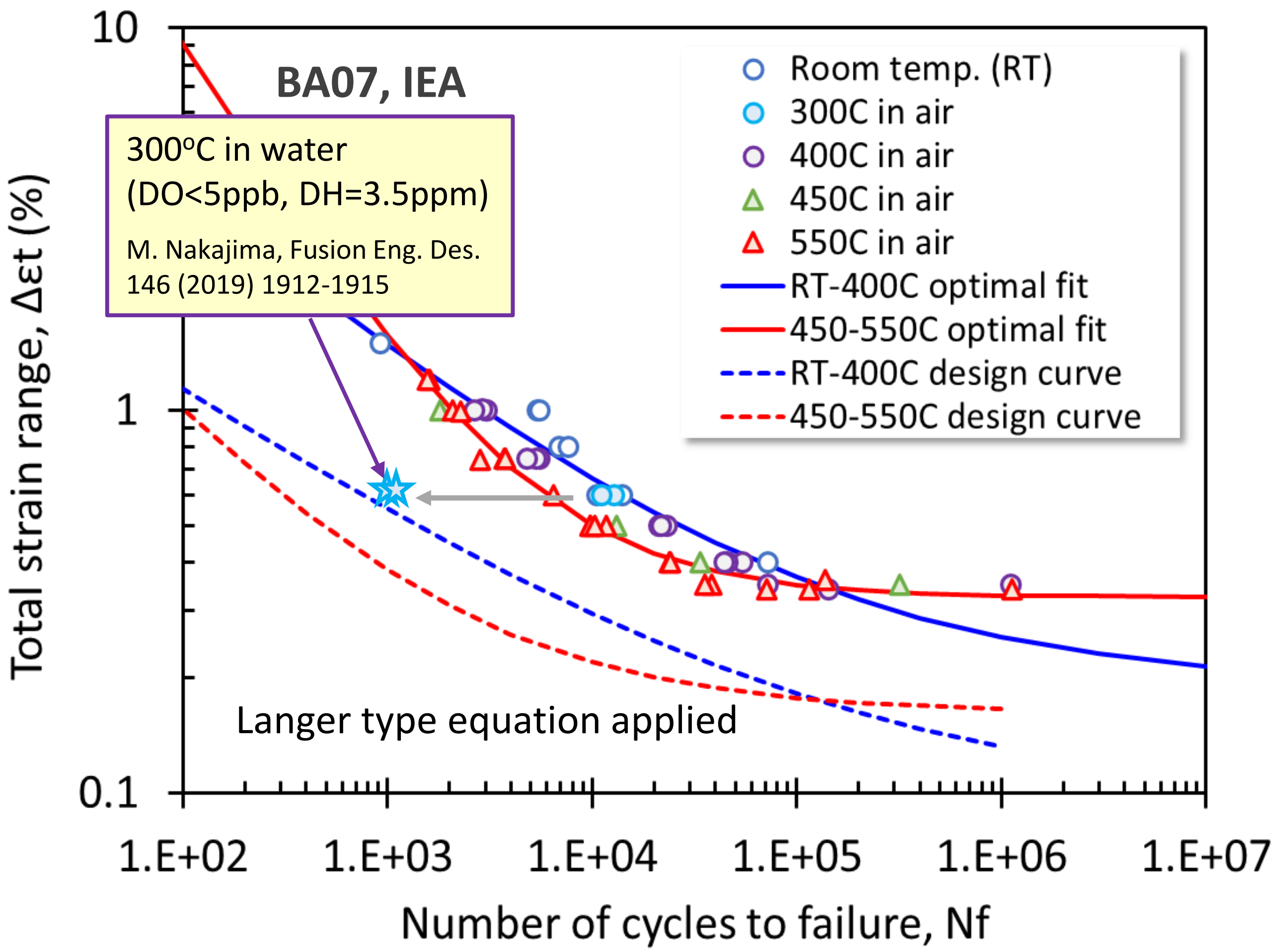


Nozawa et al. Nuclear Fusion 61 (2021) 116054.

- Well described by the modified universal slope method
- Temporarily okay to use fatigue-creep diagram of ASME Grade 91
- More important to adopt multi-axial creep testing approach with varied triaxiality

*** Challenge to consider irradiation creep together**

Corrosion fatigue under high-temp. high-pressure water



- Two characteristic fatigue design curves : **one for 20-400ºC** and **another for 450-550ºC**
- **Marked reduction of lifetime due to corrosion fatigue (1/19 of air condition)**

--> Need more data to demonstrate reproducibility

Summary

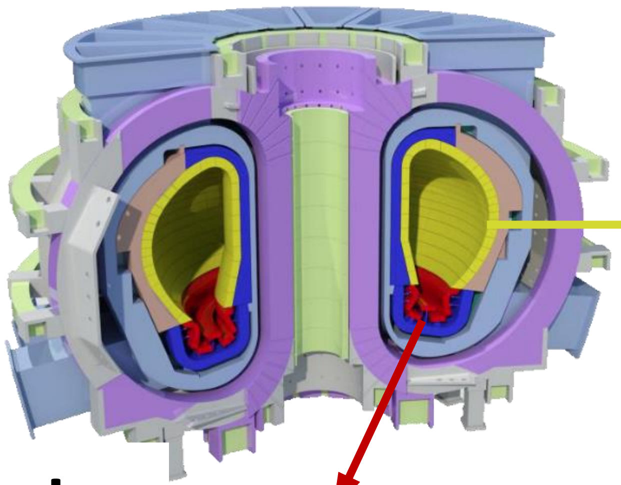
- **Establishing the material file is the essential in design, modeling & simulation, and qualification toward DEMO realization.**
  - >200,000h thermal creep data was added, suggesting no negative impact on the structural integrity.
  - The first set of high-dose neutron irradiation data of welds was provided, suggesting a good consistence with the base metal data.
- **In the engineering phase (TRL4-5), understanding the multi-physics, e.g., mixed environment, multi-mode loading, and multi-scale is more emphasized.**
  - Impact of the electromagnetic force on structural integrity needs to be clarified. Probable change of material property under the magnetic field is also of our interest.
  - Remained issues: Corrosion fatigue, multiaxial creep, fatigue, and fatigue creep for the pulse operation of the early DEMO (+ Irradiation creep).

https://www.qst.go.jp

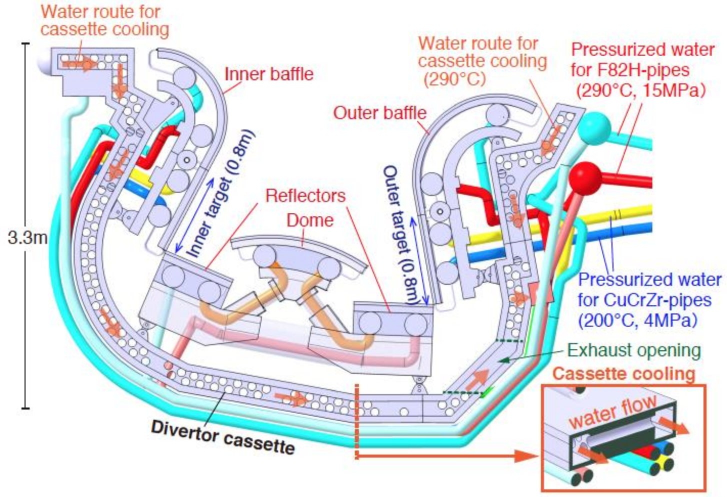
Thank you for your kind attention

JA fusion DEMO breeding blanket & divertor

JA DEMO



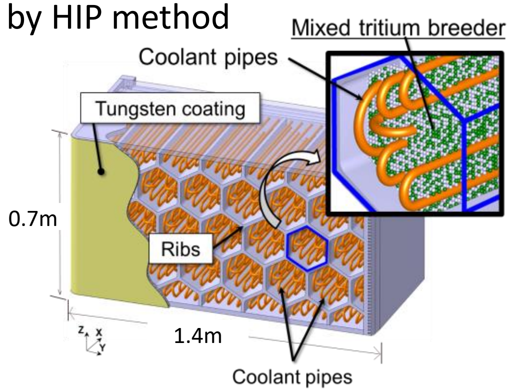
Divertor



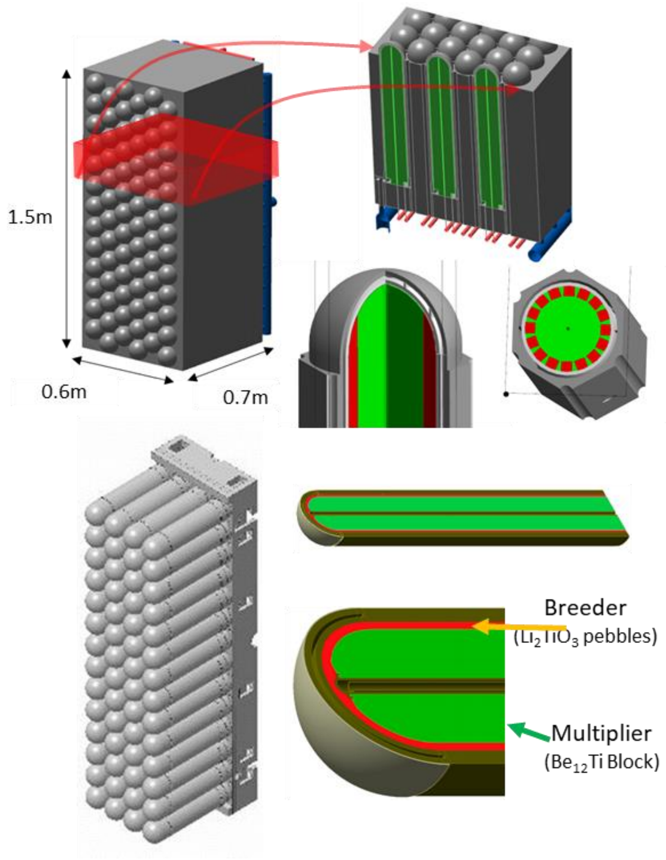
Breeding blanket

DEMO design – Water cooled / solid breeder blanket (with W as PFM)

Mixed breeder/multiplier pebbles
Fabricated by HIP method

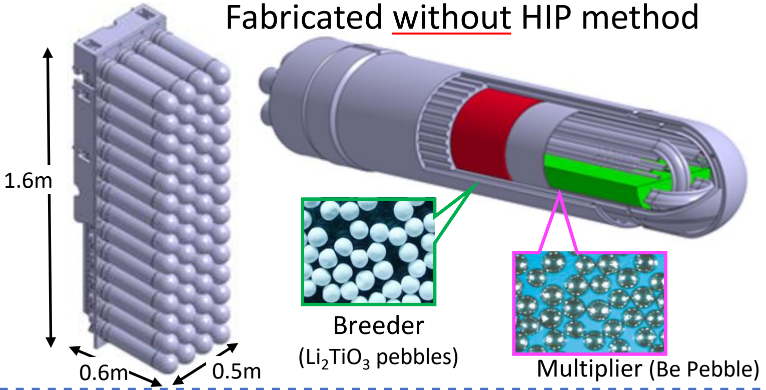


Pebble breeder/ **Beryllide Block multiplier**
Fabricated without HIP method



ITER-WCCB TBM design (wo W as PFM)

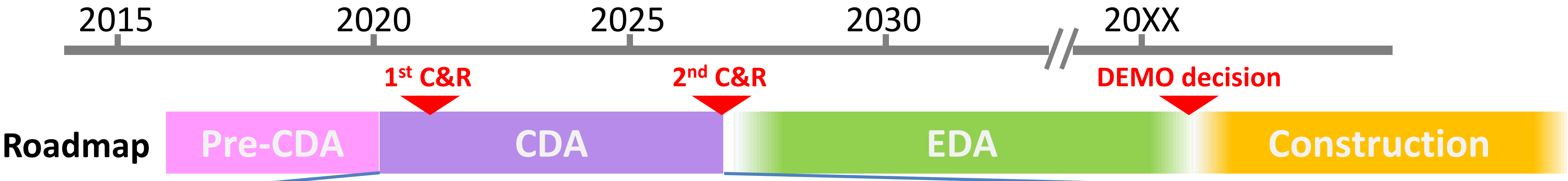
Pebble breeder/ Pebble multiplier
Fabricated without HIP method



Material R&Ds toward the engineering design phase (TRL5+)

QST

Material file --> Structural design rules --> Properties & technologies verification



Project	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027+
ITER-TBM			★PDSA		★PDRW	★PDR		• Procurement & qualification • Continuous safety evaluation
	Hazard analysis							
				Nuclear Particular Material Appraisal (NPMA)				
	MPH development for base metal, verification of manufacturability, machinability, weldability, controllability							
				+ MPH development for welds				
	Activated corrosion products evaluation, safety demonstration							
BA Phase II	Preparatory work							• Statistical DB • Validation of design rules • Prediction of post irrad. properties, critical dose • Irrad. DB of corrosion • ACP codes
	T2 : DMEO materials (F82H, DIV materials)	Draft MPH, SSTT (including irrad. experiments)		Updated MPH, SSTT guideline, statistical DB (including irrad. experiments)				
		Theories & models for modelling & simulation		Guideline of prediction method for fusion neutron irradiation				
		Draft design rules for BLK & DIV structures		Guideline of design rules for irradiated BLK & DIV structures				
	T4 : Corrosion DB (BLK, DIV)	Draft handbook of material corrosion		Handbook of material corrosion				
		Draft DB for ACP & H isotope behavior		ACP evaluation model based on H isotope behavior				
HFIR irrad.	80dpa irrad. data							• Validation of heavy neutron irrad. data • Statistical irrad. DB
		Detailed evaluation of 80dpa irrad. data						
		Heavy irradiation data for reproducibility evaluation						
IAEA CRP	Phase 1 (2017-21): Draft guideline (size & shape effects)		Phase 2 (2022-26): Updated guideline (high-temp. & hot cell technologies)					• SSTT standardization

Assessment of F82H MPH status by attribute guides

QST

	Contents	Base metal				Weld/Joint			
		Non-irrad.		Irrad.		Non-irrad.		Irrad.	
		As-received	Aged	Ion & LWR	FNS	As-received	Aged	Ion & LWR	FNS
1	**INTRODUCTION**								
2	**GENERAL INFORMATION**								
3	**SPECIFICATION OF MATERIAL**								
3.1	Material production method	TBM	n/a	n/a	n/a	TBM/BA	n/a	n/a	n/a
3.2	Chemical composition	TBM	n/a	n/a	n/a	TBM/BA	n/a	n/a	n/a
3.3	Metallurgy		domestic	BA (HFIR)	FNS	TBM/BA	domestic	BA (HFIR)	FNS
4	**PHYSICAL PROPERTIES**								
4.1	Coefficient of thermal expansion		n/a	BA (HFIR)	FNS	(blank)	n/a	BA (HFIR)	(blank)
4.2	Elastic properties		n/a	BA (HFIR)	FNS	(blank)	n/a	(blank)	(blank)
4.3	Density		n/a	(blank)	(blank)	(blank)	n/a	(blank)	(blank)
4.4	Thermal properties		n/a	(blank)	(blank)	(blank)	n/a	(blank)	(blank)
4.5	Electrical resistivity		n/a	BA (HFIR)	FNS	(blank)	n/a	BA (HFIR)	(blank)
4.6	Magnetic properties		n/a	BA (HFIR)	FNS	(blank)	n/a	(blank)	(blank)
4.7	Melting temperature	BA	n/a	n/a	n/a	n/a	n/a	n/a	n/a
4.8	Sputtering	(blank)	(blank)	(blank)	(blank)	(blank)	(blank)	(blank)	(blank)
5	**MECHANICAL PROPERTIES**								
5.1	Hardness		domestic	BA (HFIR)	FNS	TBM/BA	domestic	BA (HFIR)	FNS
5.2	Tensile properties		domestic	BA (HFIR)	FNS	TBM/BA	domestic	BA (HFIR)	FNS
5.3	Impact strength		domestic	TBM	(blank)	TBM/BA	domestic	TBM	(blank)
5.4	Fracture toughness	BA	domestic	BA (HFIR)	FNS	BA	domestic	BA (HFIR)	FNS
5.5	Fatigue	BA	(blank)	BA (TBD)	FNS	TBM/BA	(blank)	BA (TBD)	FNS
5.6	Creep		(blank)	n/a	FNS	TBM/BA	(blank)	n/a	FNS
5.7	Creep-fatigue	TBM	(blank)	n/a	FNS	TBM/BA	(blank)	n/a	FNS
5.8	Ratcheting	(blank)	(blank)	(blank)	(blank)	(blank)	(blank)	(blank)	(blank)
6	**FUSION-SPECIFIC PHENOMENA**								
6.1	Swelling	n/a	n/a	BA (HFIR)	FNS	n/a	n/a	(blank)	(blank)
6.2	Irradiation creep	n/a	n/a	BA (HFIR)	FNS	n/a	n/a	(blank)	(blank)
7	**ENVIRONMENTAL PROPERTIES**								
7.1	Corrosion	TBM/BA	n/a	(blank)	FNS	TBM/BA	n/a	(blank)	(blank)
7.2	Compatibility	TBM	(blank)	(blank)	(blank)	TBM	(blank)	(blank)	(blank)

(*) color code :

- ✓ White (blank) for properties not addressed, lack of data
- ✓ Black : potential showstopper identified
- ✓ Red : lack of data and potentially challenging
- ✓ Blue : lack of data, NOT challenging
- ✓ Orange : data available, results not good enough, further optimization needed
- ✓ Green : data available, results are good, concept is mature

n/a : not applicable

Key R&D issues remained

- Creep-fatigue diagram
- More toughness data
- Fatigue and fatigue crack growth test data
- Corrosion test data under irradiation
- Magnetic properties at higher doses
- etc.