28th IAEA Fusion Energy Conference (FEC 2020)
10-15 May 2021 (Virtual event)

TECH4-3 (#727)

Status and the challenge of Japanese materials property handbook to facilitate structural design criteria for DEMO in-vessel components

Takashi Nozawa[1], H. Tanigawa[1], T. Itoh[2], N. Hiyoshi[3], M. Ohata[4],

T. Kato[1], M. Ando[1], M. Nakajima[1], T. Hirose[1]

[1]National Institutes for Quantum and Radiological Science and Technology (QST)
[2]Ritsumeikan University
[3]University of Fukui
[4]Osaka University

This work was mainly supported by the Broader Approach activity under IFERC-T3PA04 and IFERC2-T2PA01.
Parts of this work were supported by the U.S. DOE and QST collaborative project under NFE-17-06547, with UT-Battelle, LLC.

Introduction

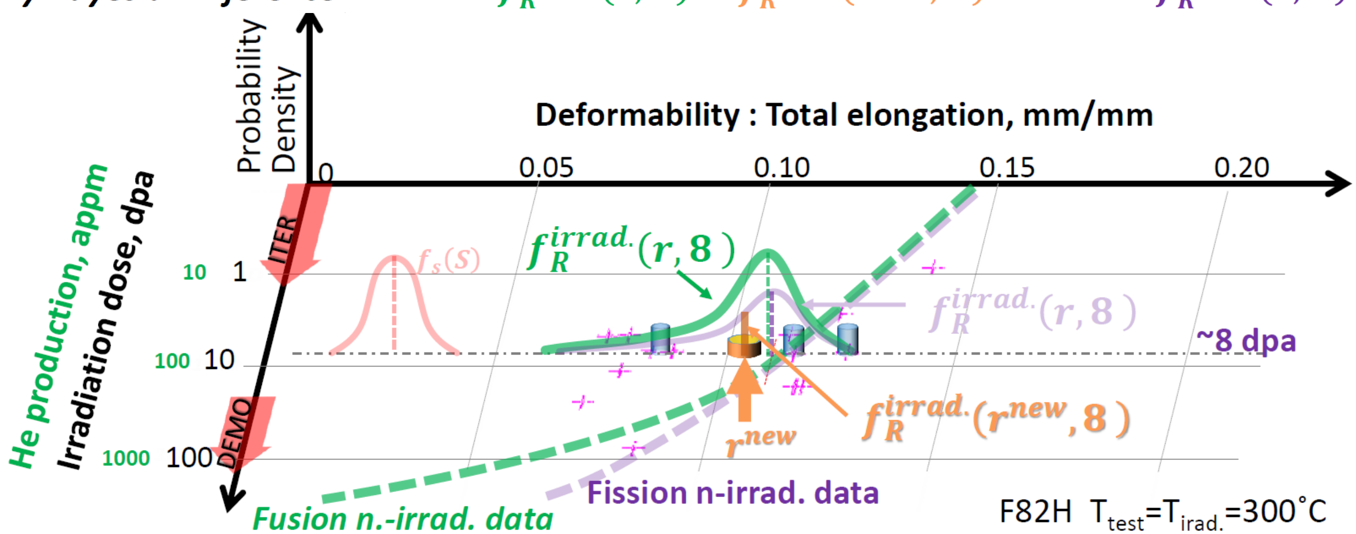
- Need to show sufficient structural integrity under normal and accident conditions.
- Need to complete the conceptual design without any experimental verification in the 14 MeV fusion at the timing of Japan's intermediate C&R in the mid-2020s, which will deliberate on the decision to move to the engineering design phase of the DEMO reactor.

  --> Basic strategy = Fission reactor irradiation data + modeling & simulation
- Need to establish a reasonable logic (e.g., fusion structural design criteria) to show the design feasibility specific to DEMO in-vessel components.

  --> To be discussed in BA Phase II (2020-2025) to provide a draft guideline

H. Tanigawa et al. IAEA-FEC 2018

By Bayesian inference: $\text{Fusion}\ f_R^{irrad.}(r,D) \propto f_R^{irrad.}(r^{new},D) \cdot \text{Fission}\ f_R^{irrad.}(r,D)$



Step 1: Obtain fission neutron irradiation data distribution, $\text{Fission}\ f_R^{irrad.}(r,D)$

Step 2: Obtain new data r^{new}, by fusion neutron source irradiation.

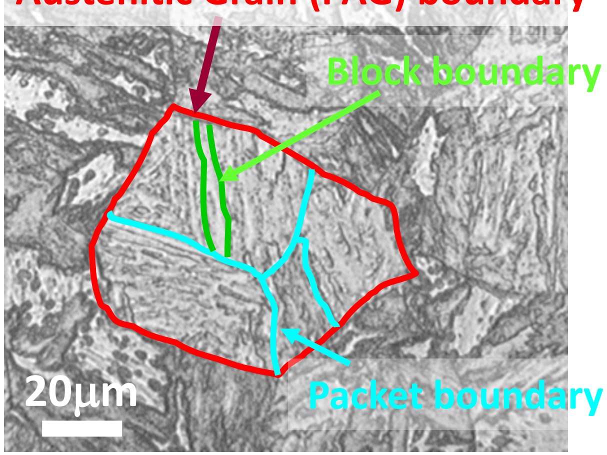
Step 3: Calculate probability to observe new data, r^{new}, $f_R^{irrad.}(r^{new},D)$ based on $\text{Fission}\ f_R^{irrad.}(r,D)$

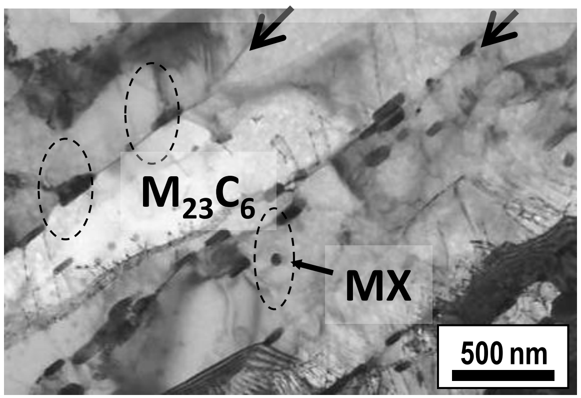
Step 4: Estimate fusion neutron irradiation data distribution, $\text{Fusion}\ f_R^{irrad.}(r,D)$

Japanese RAFM, F82H: Specification & variation

RAFM steel: Reduced-activation ferritic/martensitic steel

Typical microstructure





$M_{23}C_6$: M= Cr and W

MX : M=Ta, V, X= C, N

Key specification of F82H (wt%)

C	Cr	W	Mn	V	Ta	Si	B
0.08-012	7.5-8.5	1.6-2.2	0.05-0.5	0.15-0.25	0.02-0.10	<0.2	<0.006

N	Ti	Sol. Al	P	S	O	Fe
<0.025	<0.01	<0.04	<0.02	<0.01	<0.005	Bal.

Target composition of impurity elements (wt%)

Co	Ni	Cu	Mo	Nb
<0.01	<0.1	<0.05	<0.05	<0.001

- F82H-pre. IEA, F82H-IEA and F82H-BLK were 5 tons heats produced in Vacuum Induction Melting (VIM).
- F82H-BA07, F82H-BA10 and F82H-BA11 were molten in VIM followed by Electro-Slag-Remelting (ESR) as a secondary refinement.
- F82H-BA12 was molten in a 20 tons electric arc furnace followed by ESR.
- F82H-Mod3: modified steel as reference.

Billet : ϕ210 × 2600 (mm)

Slab : 270 × 500 × 2200 (mm)

F82H-BA12

Overview of MPH development in Japan

General approach

- Hazard analysis to comply with essential safety requirements (ESR) and essential radioprotection requirements (ERR)
- Identification of reference procurement specification with completion of material file
- Further update of DB/MPH including fission and fusion neutron irradiation

Key features of F82H MPH

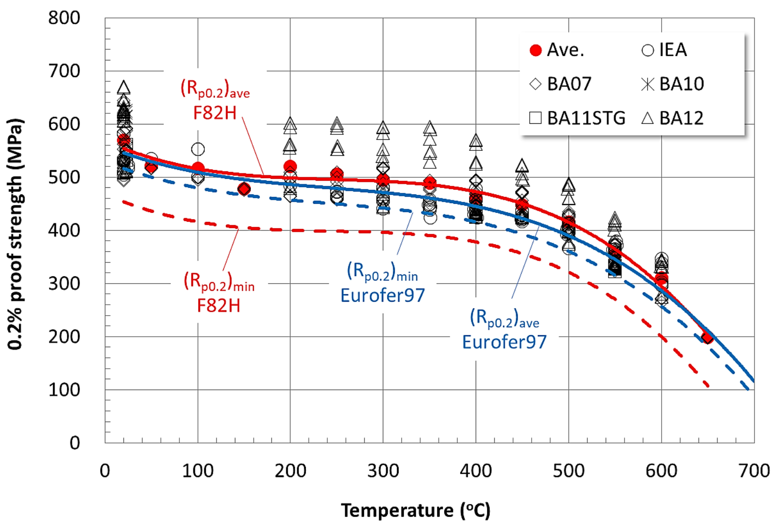
- Physical, thermal, electrical and mechanical props. + swelling & irradiation creep
- RT to 550°C for general.
- Addressing on base metal with welds/joints
- (Irradiation-induced) microstructure to be included
- Selected data (tensile: 394, creep: 222, fatigue: 51) available to facilitate material strength standards of non-irradiated F82H from massive database (several thousands of data)
- Irradiation database is being extensively developed in BA Phase II (2020-2025)

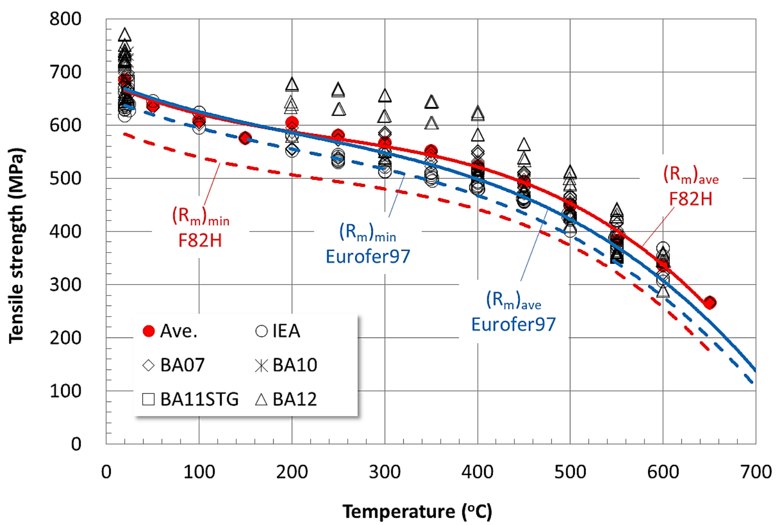
Material file (based on RCC-MRx 2018 edition)

#	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-independent material strength standards

IEA, BA07, BA10, BA11STG, BA12

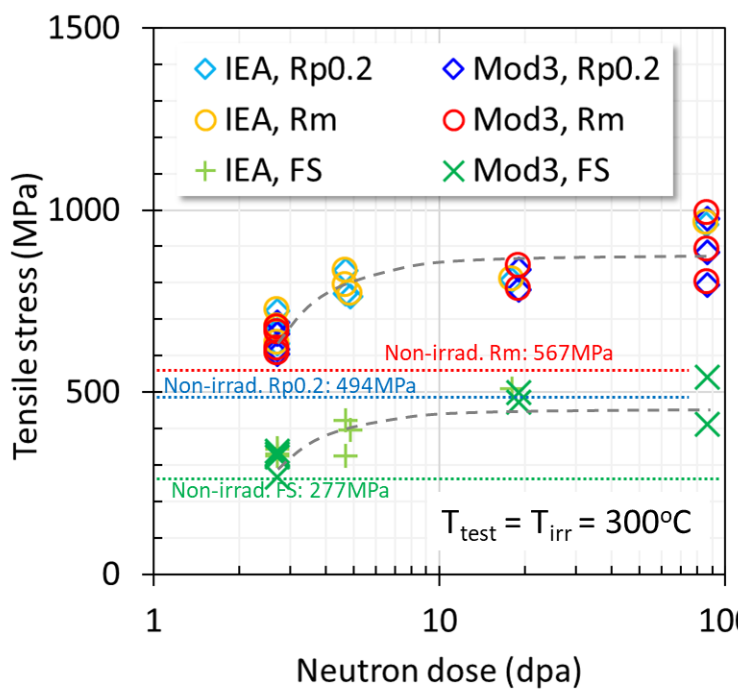




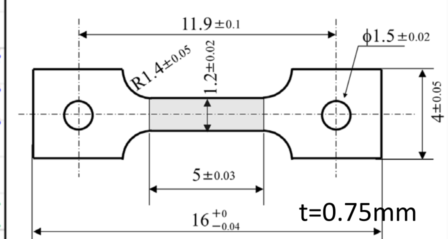
$(R)_{min} = (R)_{ave} - 1.96$ x (stdev. at RT)

- The minimum bound tends to be lower than Eurofer97 due to the relatively large data scatter among heats.
- Both $R_{p0.2}$ and R_m increased upon irradiation due to irradiation hardening and became almost constant with increasing neutron dose more than 5dpa.

  --> **<u>No deterioration by irradiation to 80 dpa</u>**.



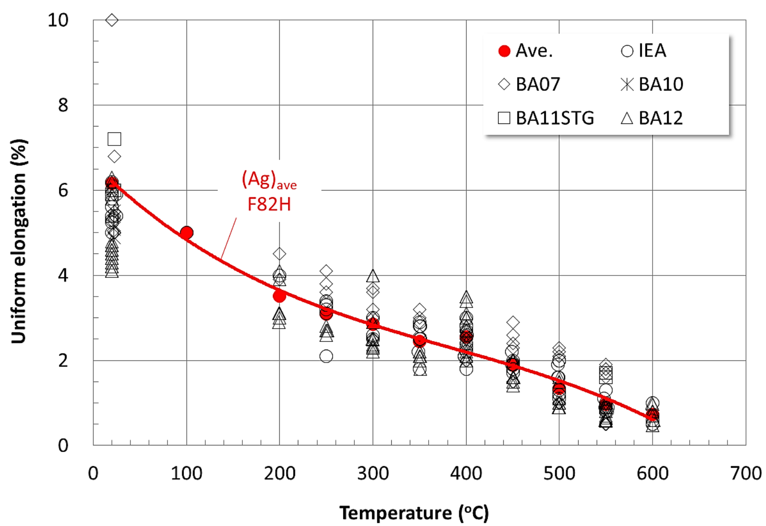
HFIR irradiation using SS-J3 miniature specimen

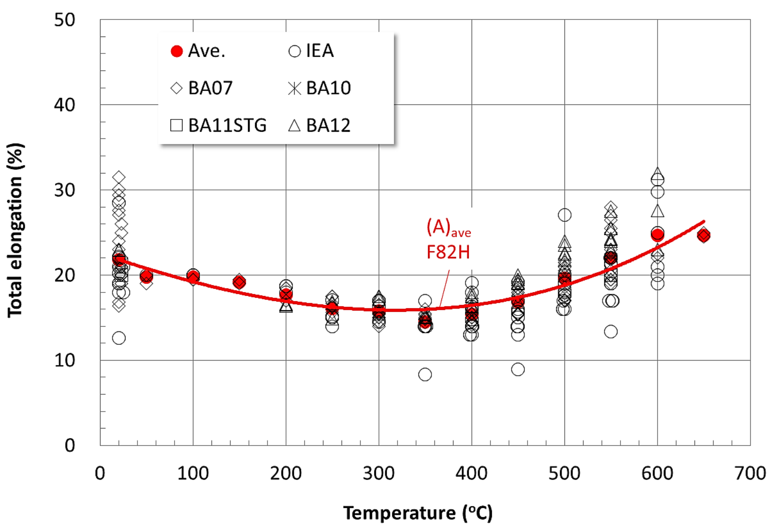


$R_{p0.2}$: 0.2% proof strength
R_m: Tensile strength
FS: Fracture strength

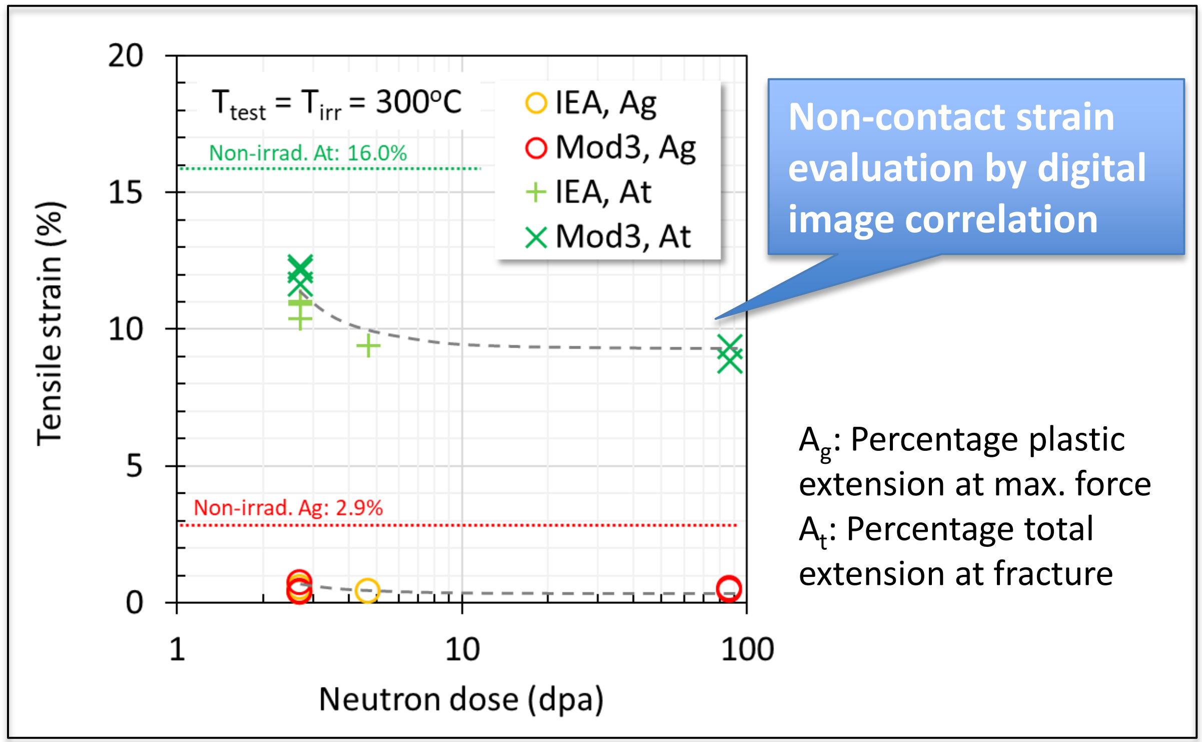
Time-independent material strength standards

IEA, BA07, BA10, BA11STG, BA12

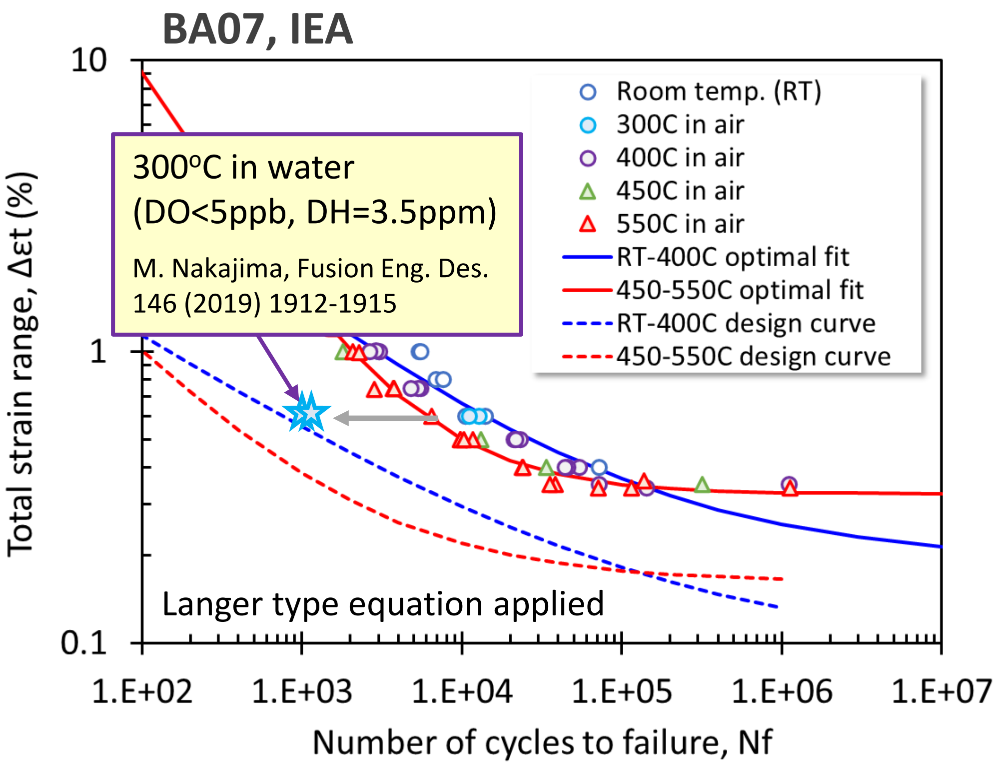


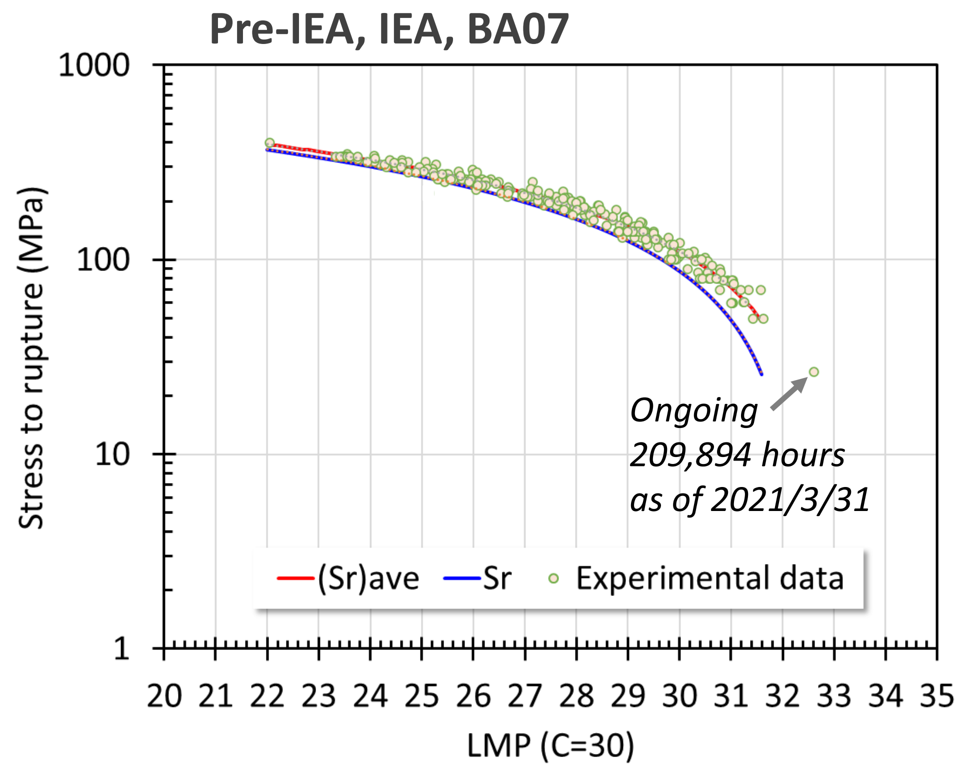


- A total elongation of >14% at room temperature is identified considering 95% confidence level.
  --> **<u>Satisfying ESPN requirement</u>**.
- Loss of ductility was pronounced at the beginning of irradiation (within a few dpa)
  --> **<u>Need to identify negligible irradiation</u>**



Time-dependent material strength standards





- Two characteristic fatigue design curves : **one for 20-400°C** and **another for 450-550°C**.
- Creep design values S_r and S_t are available in [Sakasegawa, Fusion Eng. Des. 161 (2020) 111952].

--> Need increased data for other F82H heats to demonstrate reproducibility

Other issue: Marked reduction of lifetime due to corrosion fatigue (1/19 of air condition)

QST

Summary of F82H MPH by attribute guides

Status and challenges in development of MPH

		Non-irradiated	Reactor irradiation（T_{irr}=300、400、500℃）			14MeV neutron irradiation
		0dpa	~5dpa (N=1~3)	~80dpa (N=1~3)	~20dpa (N>10)	~20dpa and more (N>10)
Physical properties	Thermal expansivity	(green)	(orange)	(white)	(white)	(red)
	Young's modulus	(green)	(orange)	(orange)	(blue)	(red)
	Poisson's ratio	(green)	(orange)	(orange)	(blue)	(red)
	Density	(green)	(white)	(white)	(white)	(white)
	Thermal conductivity	(green)	(white)	(white)	(white)	(white)
	Electrical resistivity	(green)	(orange)	(white)	(white)	(red)
	Magnetic properties	(orange)	(red)	(white)	(white)	(red)
	Swelling	n/a	(orange)	(white)	(white)	(red)
Mechanical properties	Tensile	(green)	(orange)	(orange)	(blue)	(red)
	Fatigue	(orange)	(red)	(white)	(white)	(red)
	Thermal ageing	(green)	n/a	n/a	n/a	n/a
	Creep	(green)	n/a	n/a	n/a	(red)
	Fatigue-creep	(blue)	n/a	n/a	n/a	(red)
	Ratchet	(white)	(white)	(white)	(white)	(white)
	Toughness	(orange)	(orange)	(blue)	(blue)	(red)
	Impact properties	(green)	(white)	(white)	(white)	(white)
	Irradiation creep	n/a	(orange)	(white)	(white)	(red)

(*) 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,　N: number of valid data

--> **Extendedly applied to welds/joints in the next step**

Important to find out the color code of "white (blank)" items that cannot be classified due to the lack of clear materials for judgment

Recognize and remove potential showstoppers at an early stage

Near-term issues:
- post-irradiation magnetic properties and fatigue data.
- Fatigue-creep and ratcheting

Long-term issues:
- Establishment of the remote-controlled test technique using miniature specimens
- Establishment of the irradiation techniques such as homogeneous dose and temperature control in 14 MeV neutron irradiation.

Issues and challenges for DEMO structural design

- DEMO in-vessel components are subjected to steady-state stresses such as thermal stresses, Maxwell stresses, and irradiation-induced stresses during normal operation, and instantaneous Lorentz stresses during failure.
- Transient loading conditions and their mixtures need to be more important to be considered.
- Structural integrity needs to be verified under the water corrosive environment especially for JA DEMO
- Understanding the material strength at structural discontinuities (welds and dissimilar joints) is an important issues.
- Developing the material testing method is necessary.

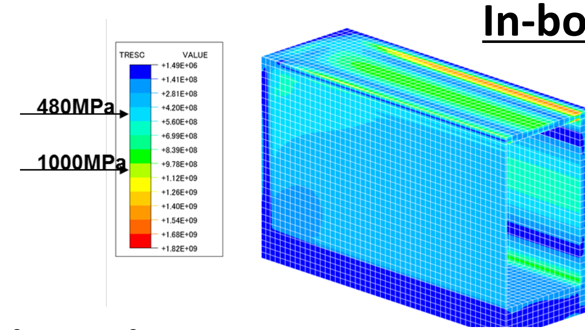
--> <u>**Important to establish a rational and comprehensive structural design rule considering multi-axial loading conditions to cope with various DEMO scenarios**</u>

Irradiation damage gradient

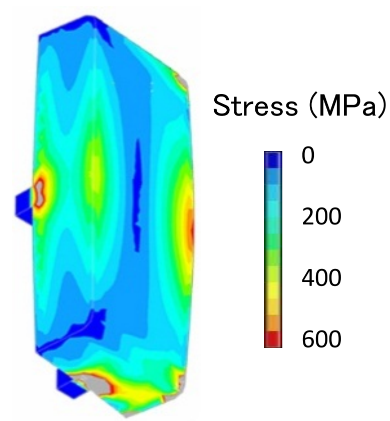
Transmutation He / H (appmHe / appmH)

Neutron damage (dpa)

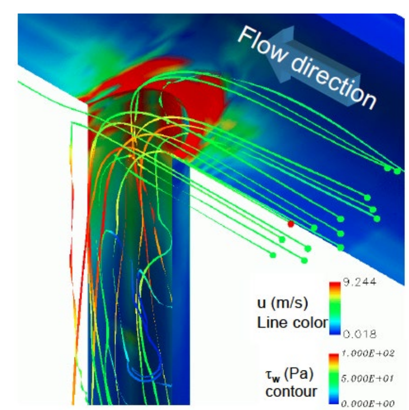
In-box LOCA



Disruption



Corrosion/erosion



Multi-axial fatigue testing and evaluation

Key issue: Non-proportional multi-axial loading

- The direction of principal stress and principal strain varies with time, resulting in reduction of the failure life.
- With the modified universal slope method, it is possible to evaluate the creep-fatigue failure life under non-proportional multi-axial loading within a factor of 2.

Modified universal slope method

学校法人立命館

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

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

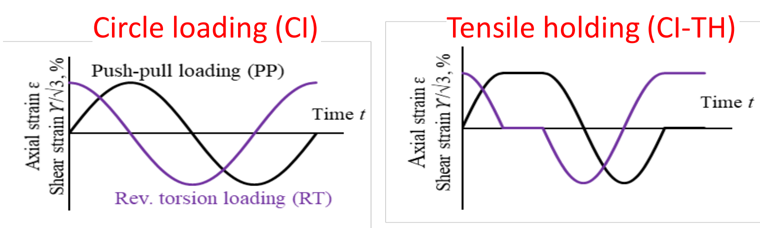
α : Coefficient for material dependence of non-proportional loading effects

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

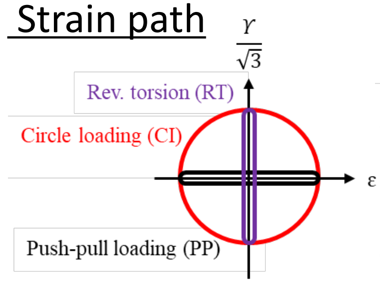
Creep ⇒ K_S : Parameter considering the decrease in non-proportionality due to stress relaxation

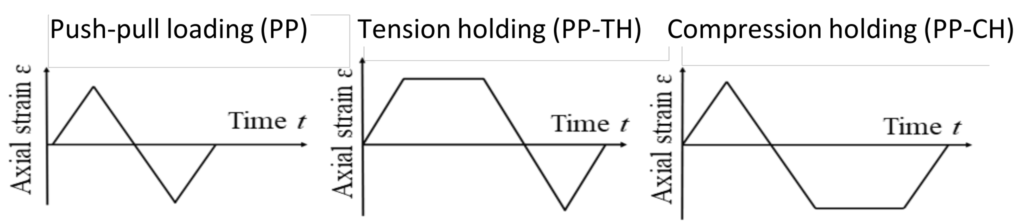
K_v : Parameter considering the strain rate

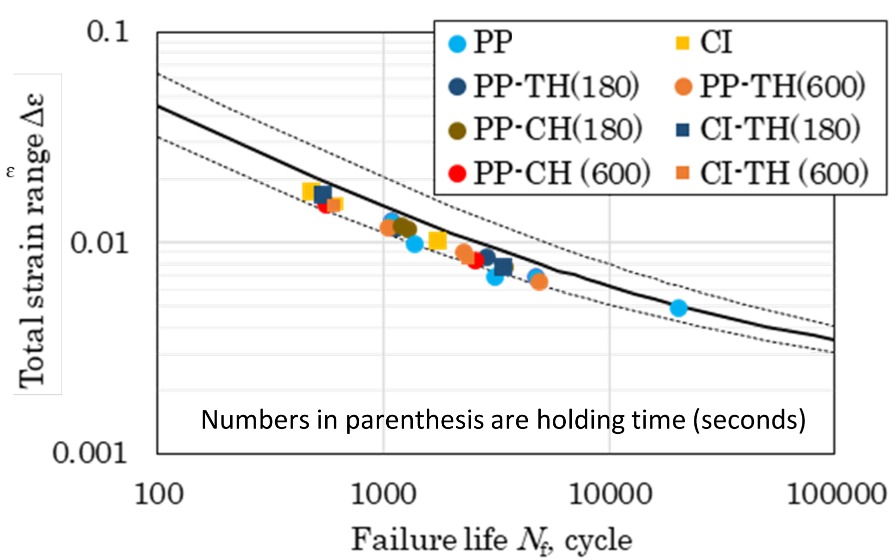
Waveforms



Strain path







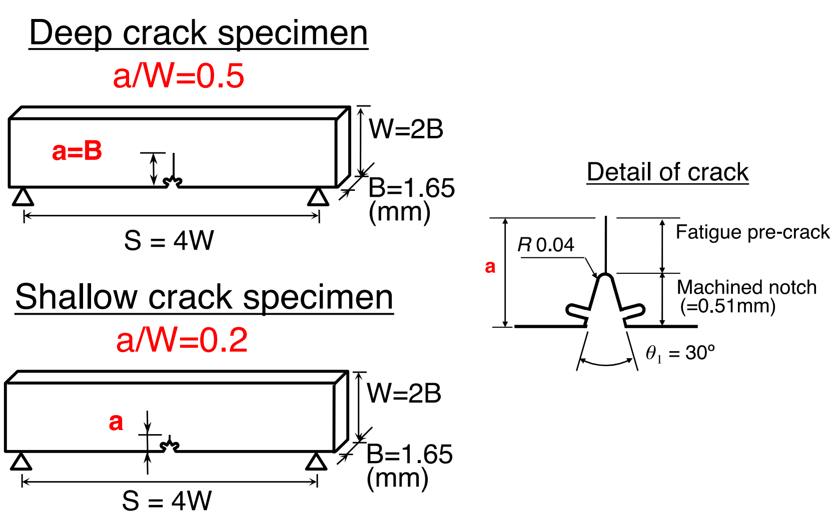
Numbers in parenthesis are holding time (seconds)

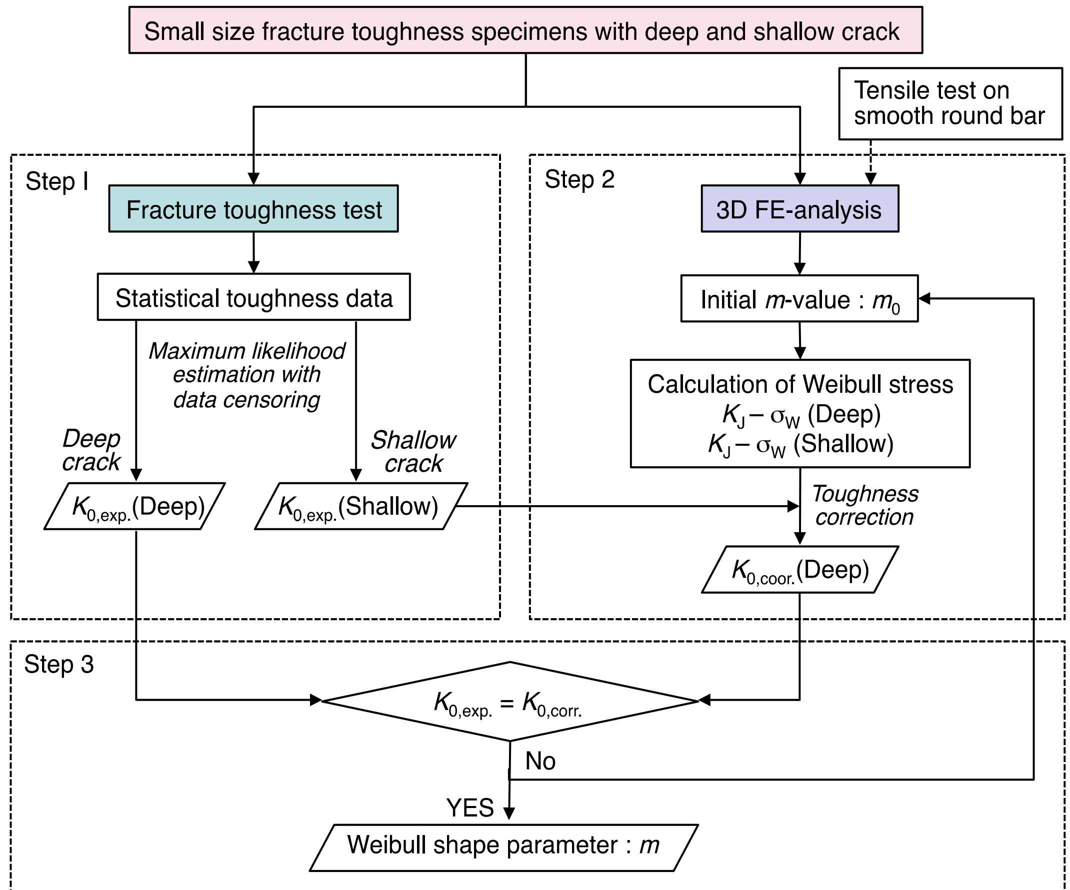
Brittle and ductile fracture testing and evaluation

Key issue: Irradiation embrittlement accompanied by a decrease in ductility

- Weibull stress concept to evaluate the effect of plastic constraint on the limit of brittle fracture
- Numerical simulation by applying the ductile damage model as a method to evaluate the effect of plastic constraint at the ductile fracture limit

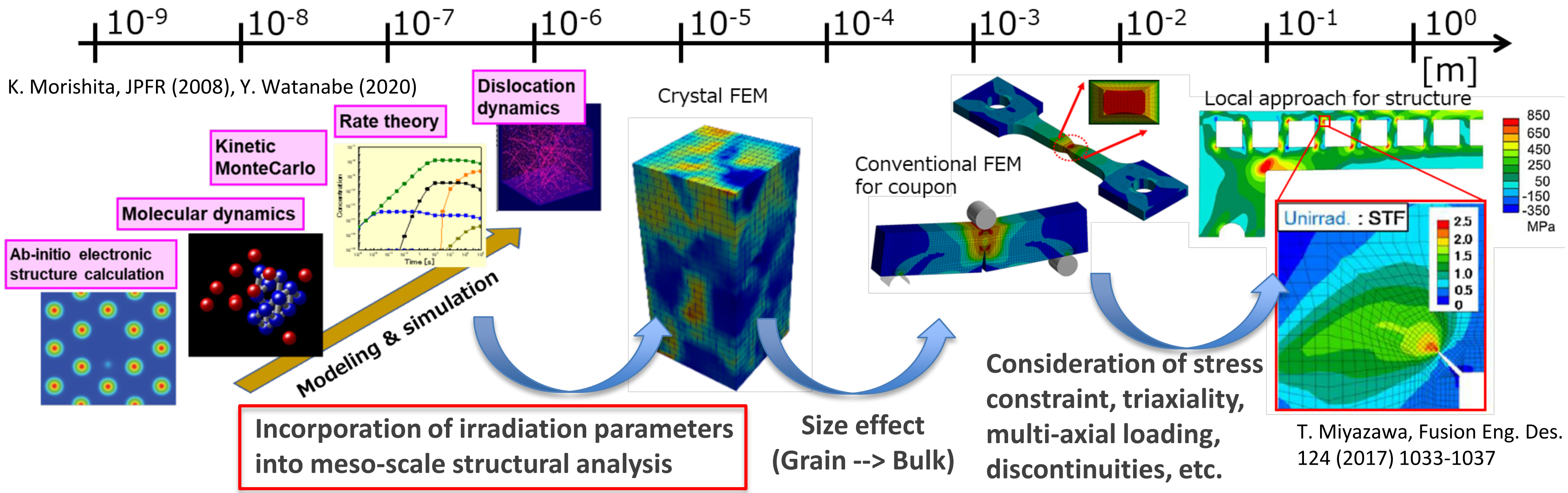
Local Approach using small size toughness specimen for brittle fracture evaluation





Summary and future work

Multi-scale material issues in structural integrity demonstration toward DEMO



- The material strength standards were updated with increased statistical data.
- Status of MPH with the near- and long-term issues was clarified with the attribute guides.
- Several structural design approaches were newly introduced to consider non-proportional multi-axial loading and brittle/ductile fracture of the structure.

--> <u>**Important to integrate microscopic irradiation process to macroscopic structural design**</u>