Status and The Challenge of Japanese Materials Property Handbook to Facilitate Structural Design Criteria for DEMO In-Vessel Components

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ABSTRACT

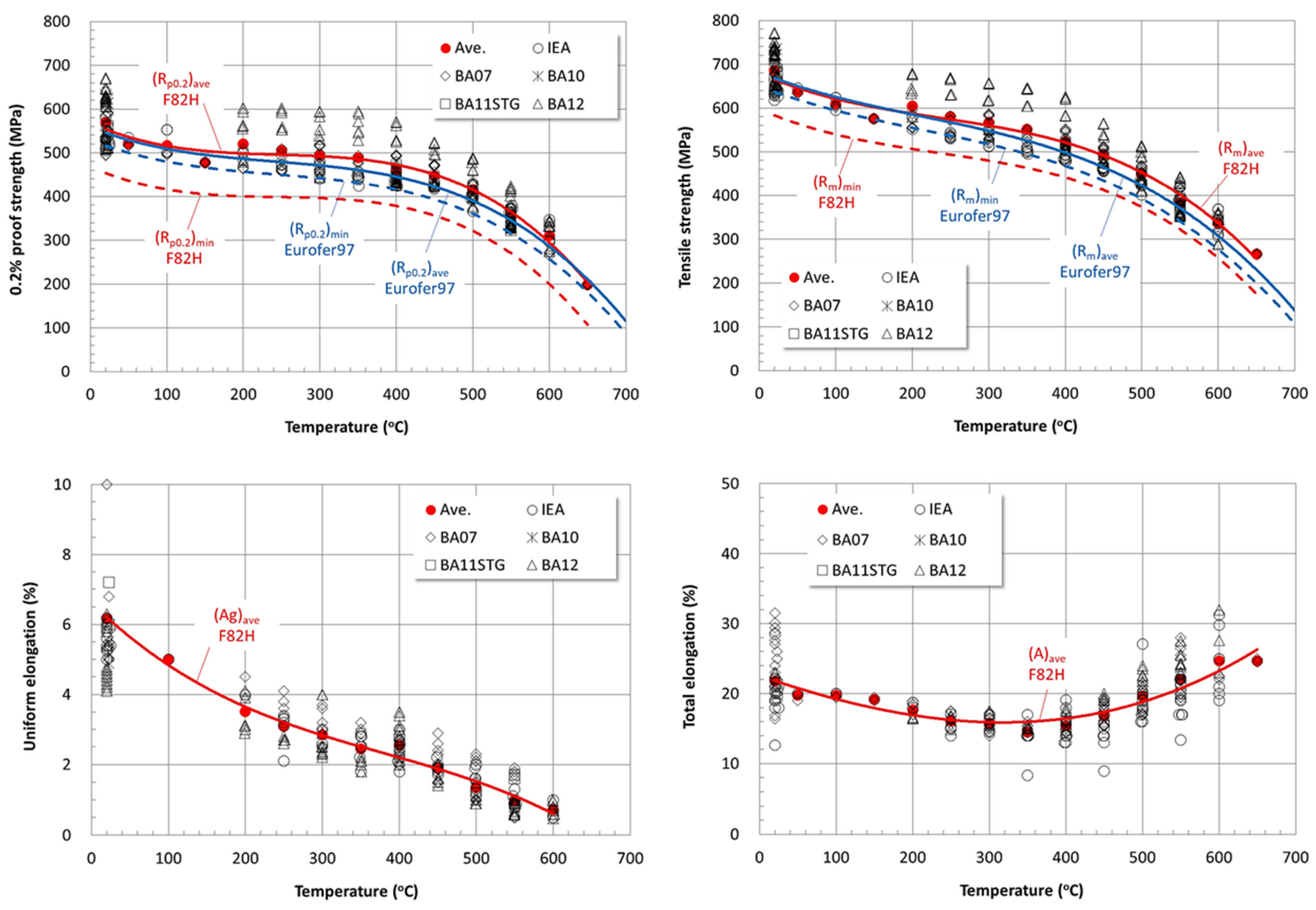
- The current status of the material property handbook for a structural design using Japanese reduced activation ferritic/martensitic (RAFM) steel F82H was summarized. In particular, the details of the material strength standards newly determined based on statistical data are shown.
  - ✓ The key structural parameters, e.g., time-dependent/independent design stresses and fatigue design curves, were determined following the French structural design code RCC-MRx.
  - ✓ Under the Japan-U.S. collaboration, tensile data were newly added to the benchmark heavy irradiation up to 80 dpa, as a critical input in the intermediate C&R in Japan.
- The status of structural material data and the near- and long-term issues were clarified by the evaluation using the attribute guides.
- Several structural design approaches which were newly introduced and extended to cope with the structural design issues under the complex environmental conditions peculiar to the DEMO were noted with the initial R&D results.
  - ✓ The multi-axial loading condition due to the complexity peculiar to the DEMO reactor as well as the coolant compatibility and the irradiation effect is mentioned. It is necessary to propose the basic concepts for handling these events step by step.
  - ✓ For instance in this paper, the multi-axial fatigue-creep using the modified universal slope method and the brittle/ductile fracture approaches are explained.
- The future work needs to address on the integration of microscopic irradiation effects to macroscopic evaluation of structural integrity.

INTRODUCTION

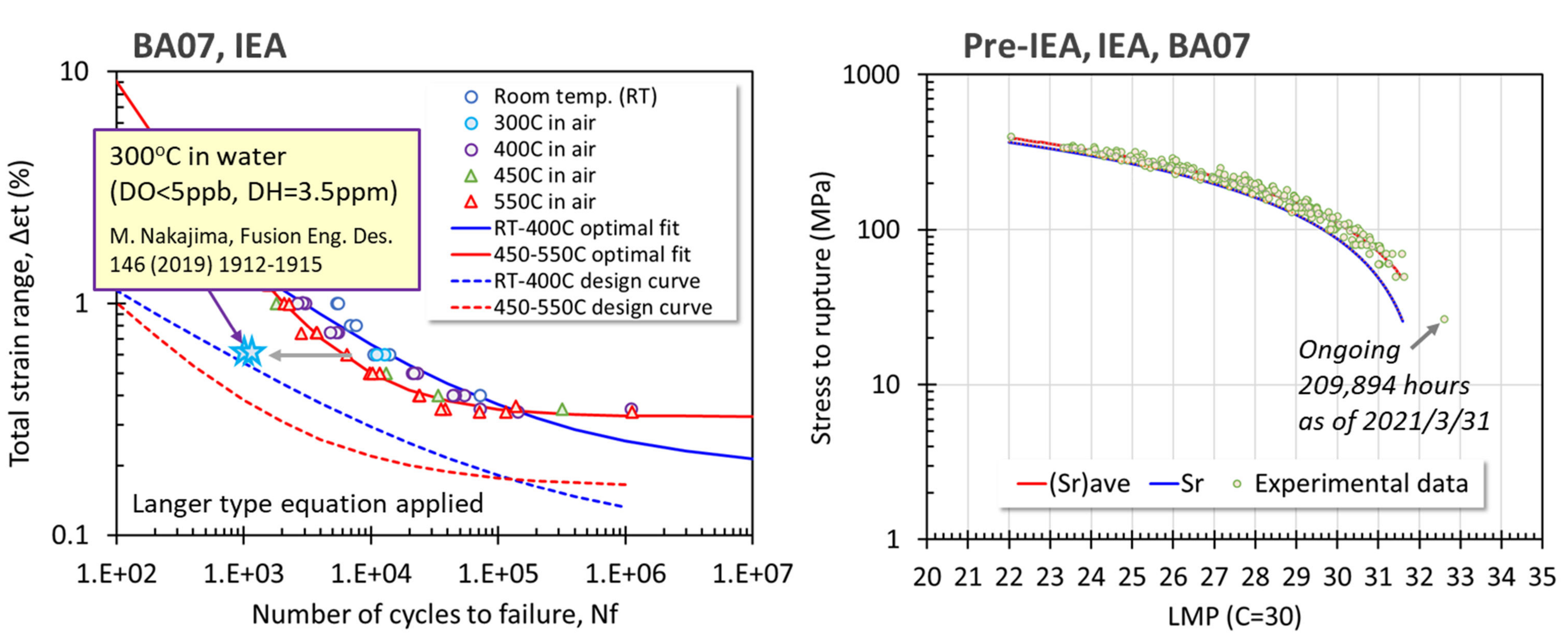
- DEMO in-vessel components need to show sufficient structural integrity not only under normal conditions but also under accident conditions.
- It is necessary to complete the conceptual design without any experimental verification in the 14 MeV fusion at least at the timing of Japan's intermediate C&R 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
- It is also necessary to establish a reasonable logic (e.g., fusion in-vessel 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

RECENT UPDATES OF F82H MPH

TIME-INDEPENDENT MATERIAL STERNGTH STANDARDS



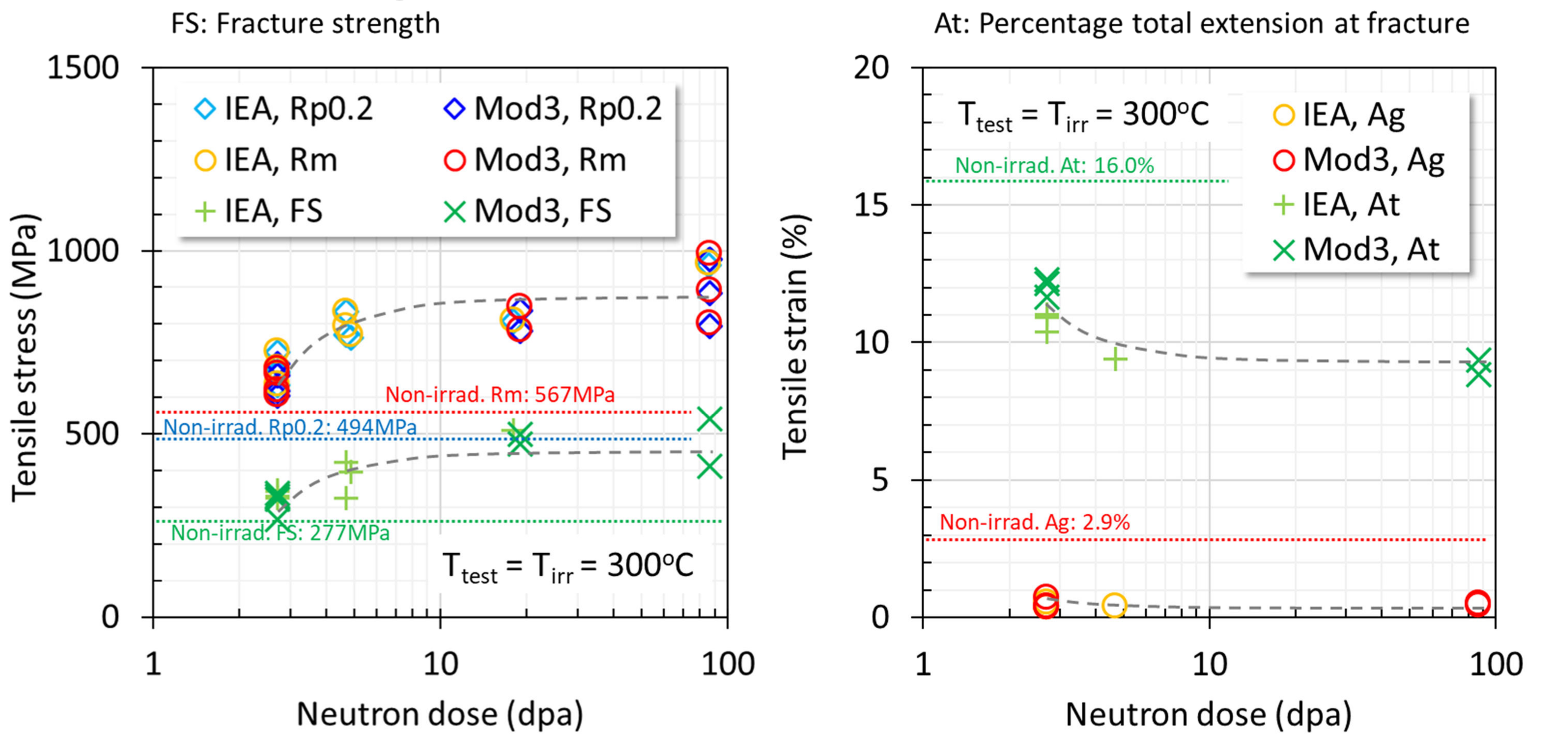
TIME-DEPENDENT MATERIAL STERNGTH STANDARDS



IRRADIATION EFFECTS

Rp0.2: 0.2% proof strength
Rm: Tensile strength
FS: Fracture strength

Ag: Percentage plastic extension at maximum force
At: Percentage total extension at fracture



ASSESSMENT 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

MULTI-AXIAL FATIGUE-CREEP 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)

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

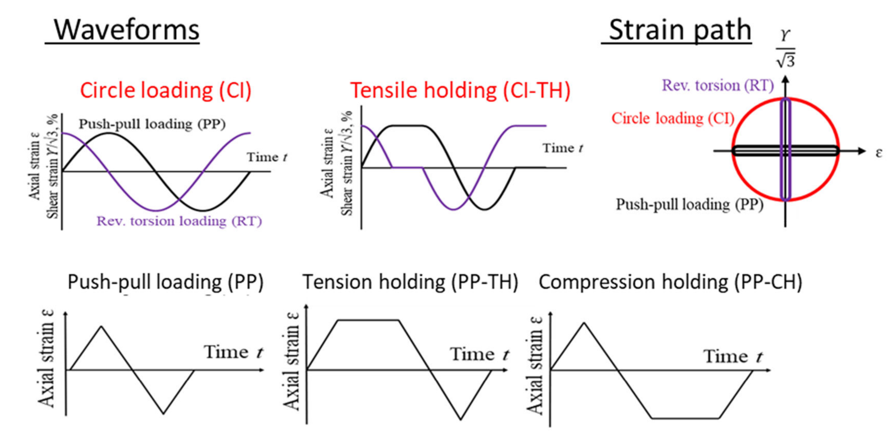
Non-proportionality ➡ $(1+\alpha f_{NP})$

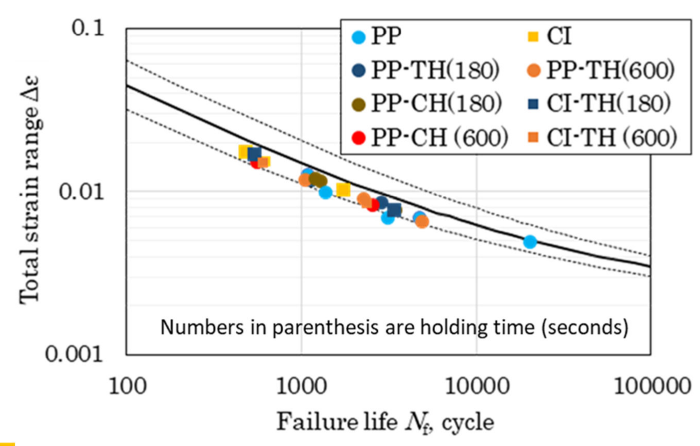
α : Coefficient for material dependence of non-proportional loading effects

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

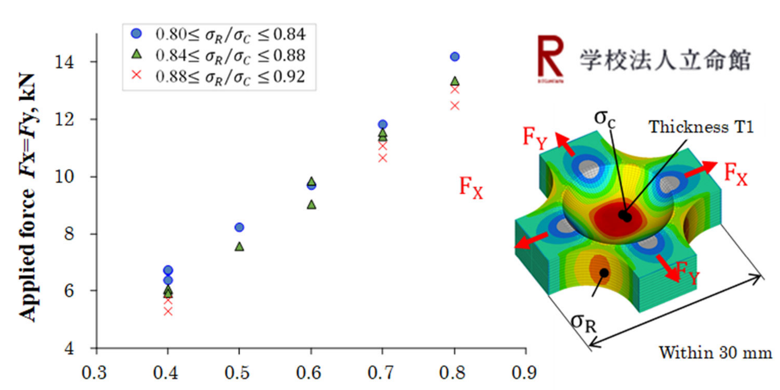
Creep ➡ K_S : Parameter considering the decrease in non-proportionality due to stress relaxation

K_v : Parameter considering the strain rate

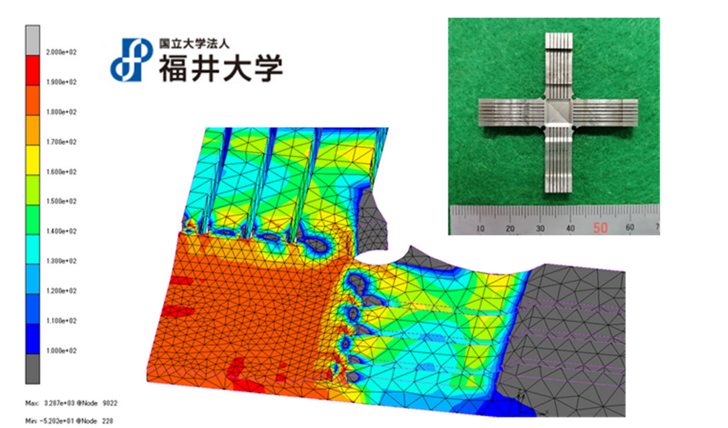




Key issue: SSTT development for DEMO-material data-basing



Relationship between applied load and thickness of the gauge part of the cruciform specimen.



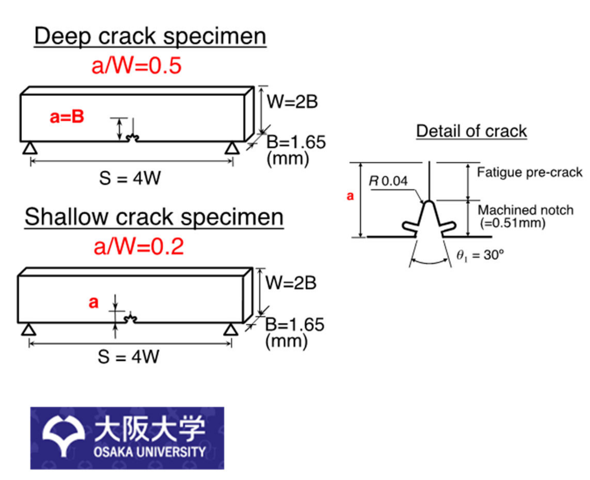
Example results of finite element analysis for the miniature cruciform specimen (equivalent von Mises stress distribution at Px = Py = 2 kN, 500 hours loading)

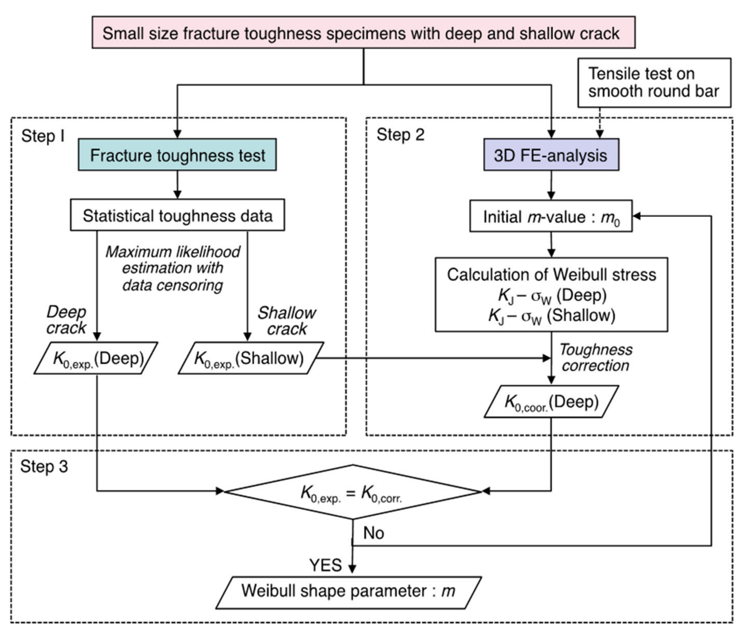
BRITTLE AND DUCTILE FRACTURE TESTING AND EVALUATION

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

- 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.
- Important to integrate microscopic irradiation process to macroscopic structural design toward practical DEMO design

ACKNOWLEDGEMENTS

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