Workshop on Advanced Neutron Source and its Application

November 4-5, Aomori, Japan

Users' perspective on neutron sources for materials development

Takeo Muroga

National Institute for Fusion Science, Toki, Gifu, Japan

Outline of Presentation

1. Japanese fusion materials development program and neutron sources

2. The need for fundamental research

Japanese fusion materials development program and neutron sources

Outline of Japanese Fusion Structural Materials Development Program

1. Categorizes the candidate materials into Primary Option (RAFM) and Advanced Option (V-alloy, SiC/SiC, ODS-S)
2. Adopts staged developments corresponding to Decision Points DP1, DP2 and DP3.
3. Position D-Li neutron sources (near-term : A-FNS and long term : IFMIF) as key facilities for the development.
4. Emphasize the necessity of “standardization” of materials specifications and test technology as a crucial step toward DEMO design qualification.
5. Emphasize the necessity of establishing structural design criteria for the materials property requirements and standard specification of the structural materials.

Recent Reports from Japanese Fusion Community

The following documents were recently issued by Governmental Committees. Japanese DEMO development strategy is under reconstruction based on these documents.

1. Report by the Joint-Core Team for Establishment of Technology Bases Required for the Development of a Fusion DEMO Reactor

   1-1. Basic concept of DEMO and Structure of Technological Issues (19, January 2015)

   1-2. Chart of Establishment of Technology Base for DEMO (1, March 2015)

2. Action Plan toward DEMO Development (18, March 2016) – in Japanese

Joint-Core Team Report

In these reports “Material Development and Establishment of Codes and Standards” is one of the eleven technological issues.

DEMO Reference Concept and Important Decision Points (Joint-Core Team Report)

DEMO Reference Concept

Medium size steady state Tokamak, with availability reachable for commercialization and having T breeding to fulfil self-sufficiency.
(This does not preclude potential selection of non-Tokamak concepts for DEMO)

Three Important Decision Points (DPs)

Rescheduling is being made in 2017 according to the delay of ITER schedule, but is not yet official

(1) Intermediate Check and Review (DP1)

~2020 → ~2020 (DP1-1) and 2025~ (DP1-2)

(2) Decision of transition to DEMO (DP2)

~2027 → in 2030s

(3) Decision of DEMO construction (DP3)

in 2030s → in 2030~2040s

Primary and Advanced Materials Options

RAFM steel is widely accepted as primary materials option

Parallel efforts for developing advanced materials are being made

(1) Limited operation window of RAFM

Need advanced materials for advanced DEMO and fusion reactor options with high competitiveness relative to other energy options

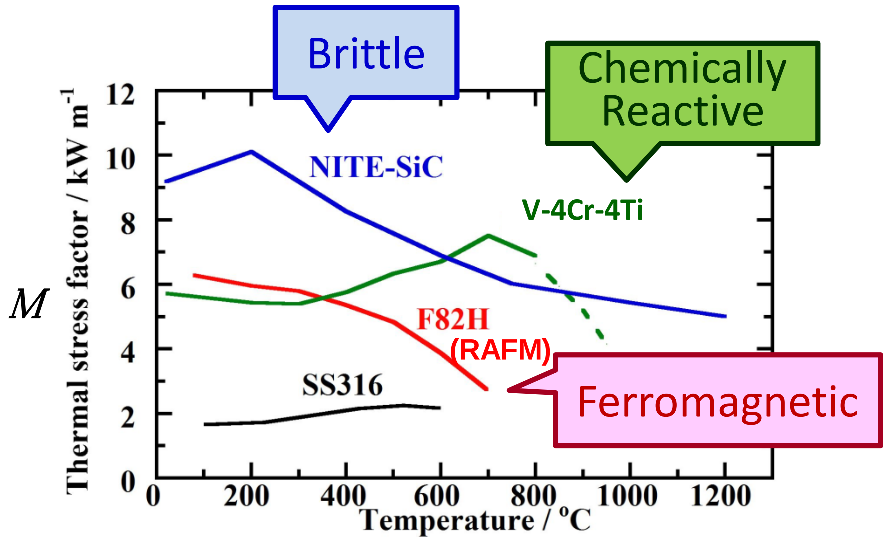
(2) Ferromagnetism issue of RAFM

Backup options of non-magnetic materials are necessary for risk mitigation

This talk focuses on RAFM development.

$$M = \frac{\lambda \sigma_{UTS}(1-\nu)}{\alpha E}$$

M : Thermal Stress factor
λ : thermal conductivity
σ : tensile strength
ν : Poisson ratio
α : thermal expansion coeff.
E : Young's modulus



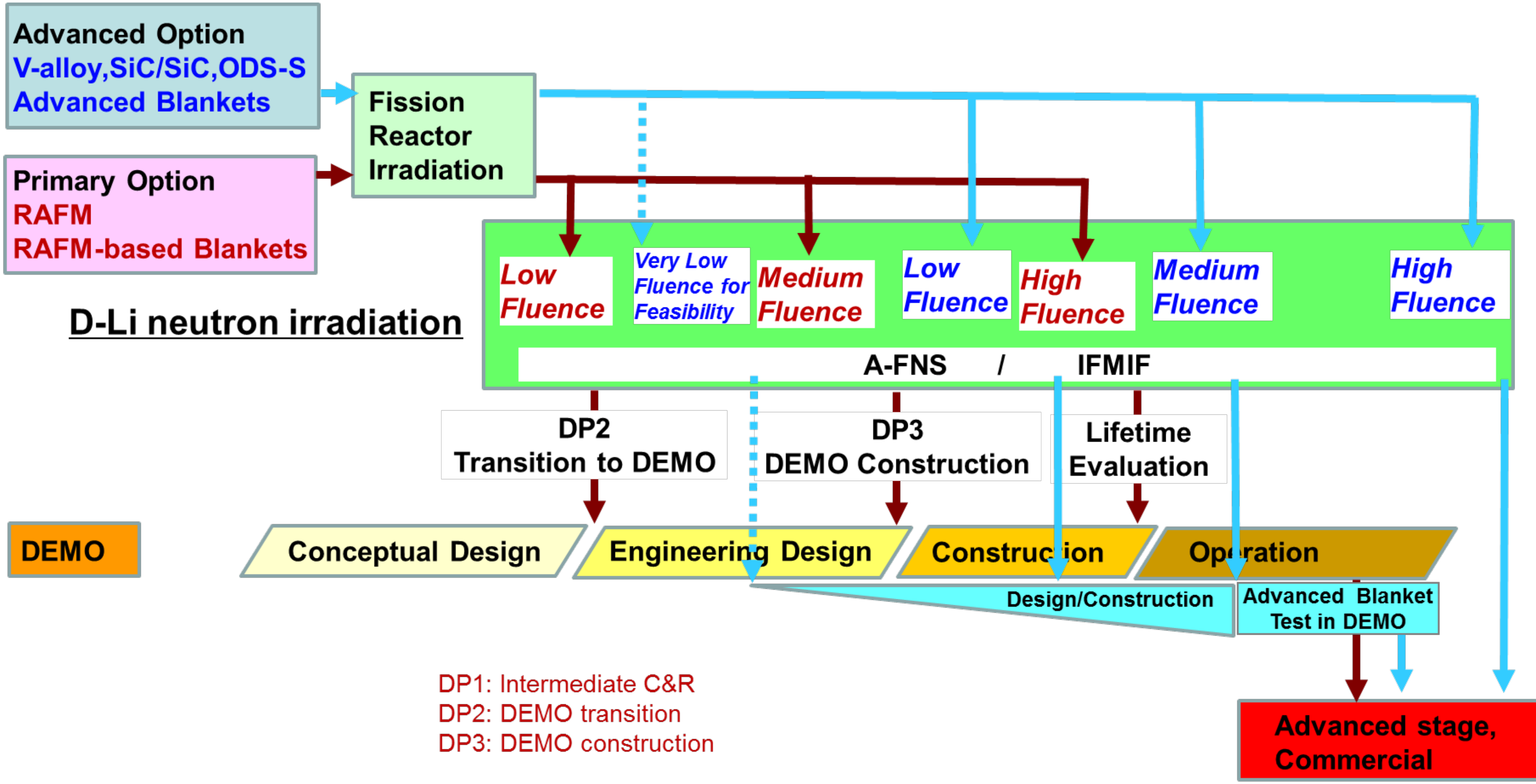
Heat flux tolerance of candidate materials

（thermal creep not considered）

Nagasaka 2012

Each candidate has its own inherent key feasibility issue

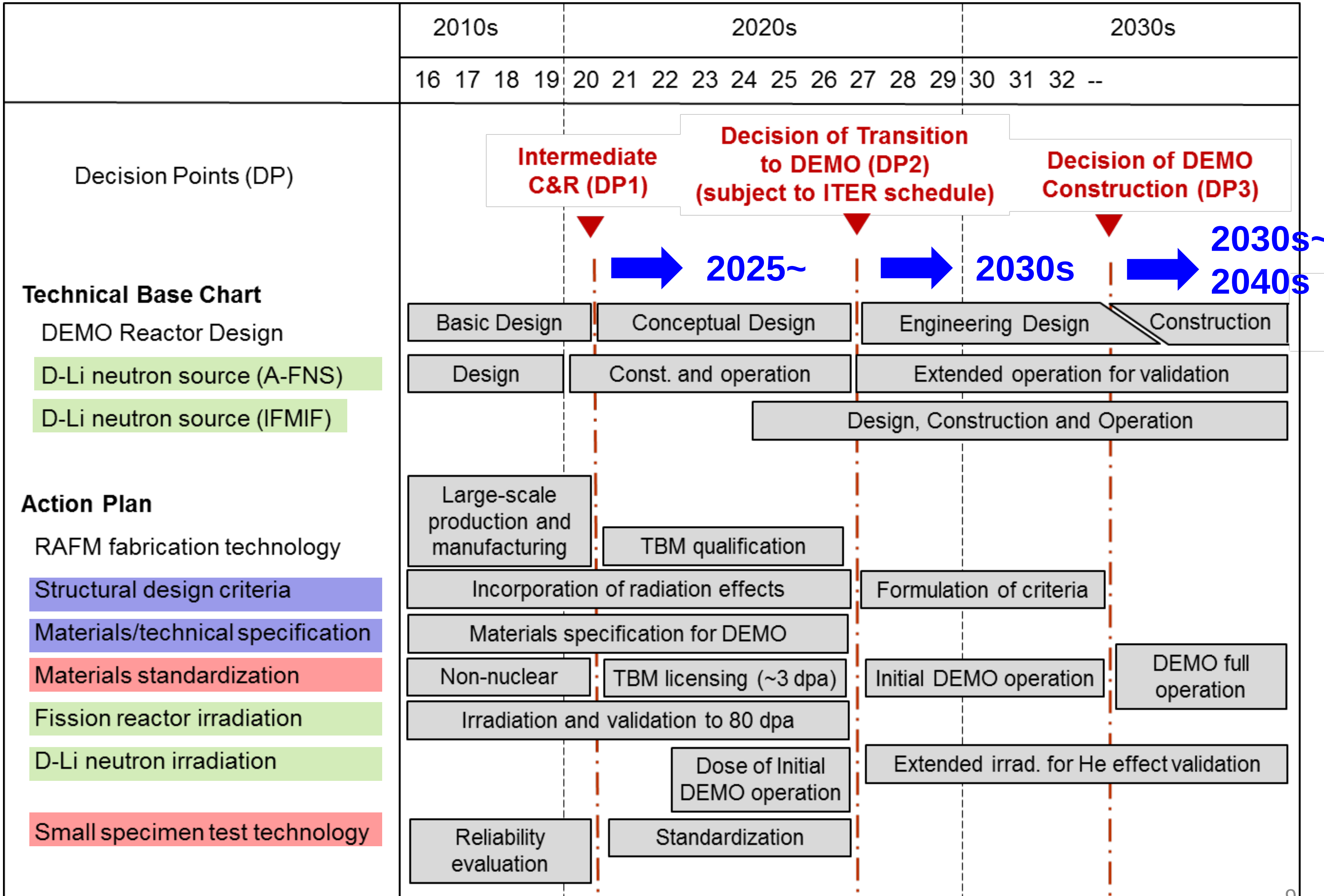
Primary and Advanced Materials Irradiation Tests and Development



Initial effort will be focused on RAFM and RAFM-based blanket systems for early realization of DEMO

Later efforts will shift to advanced materials and advanced high temperature blanket systems, toward development of advanced fusion systems

Basic Chart and Action Plan for RAFM Development



Irradiation Facility Options

Charged Particles

For fundamental studies and model prediction

Fission Reactors

Primary screening of candidates

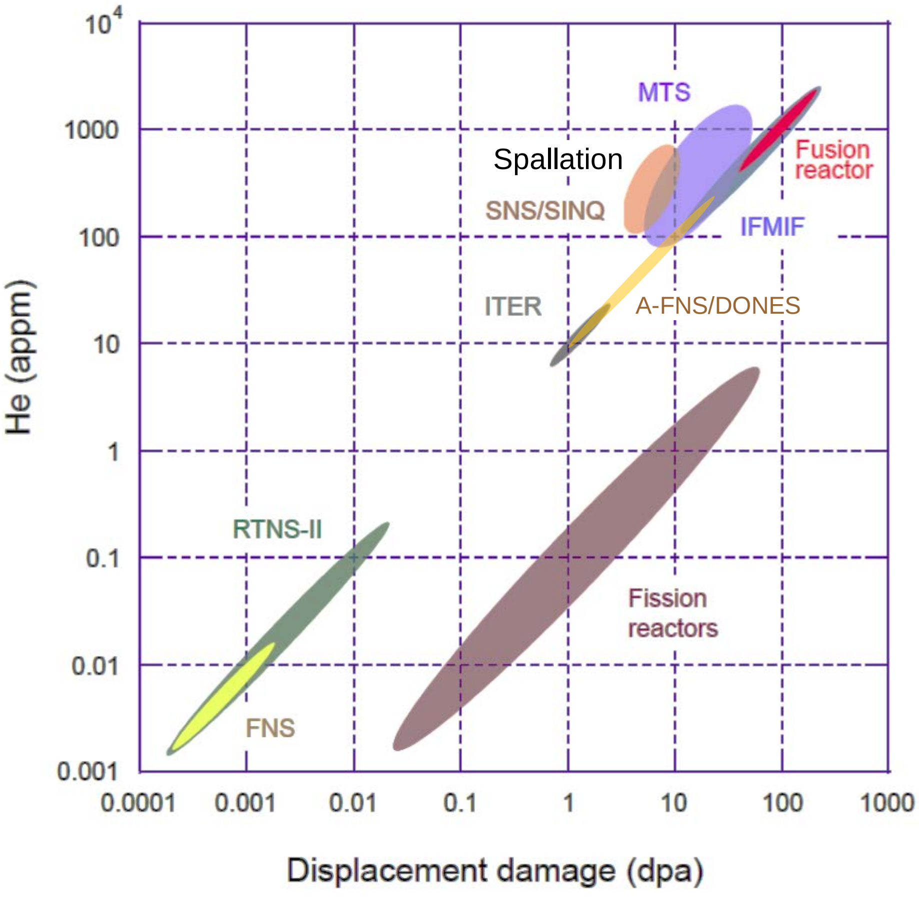
Difficult to simulation He effect

Near term D-Li neutron source (A-FNS)

Database for decision of transition to DEMO

IFMIF or equivalents

Database for decision of DEMO construction and operation period



Damage and helium production of surrogate neutron irradiation facilities

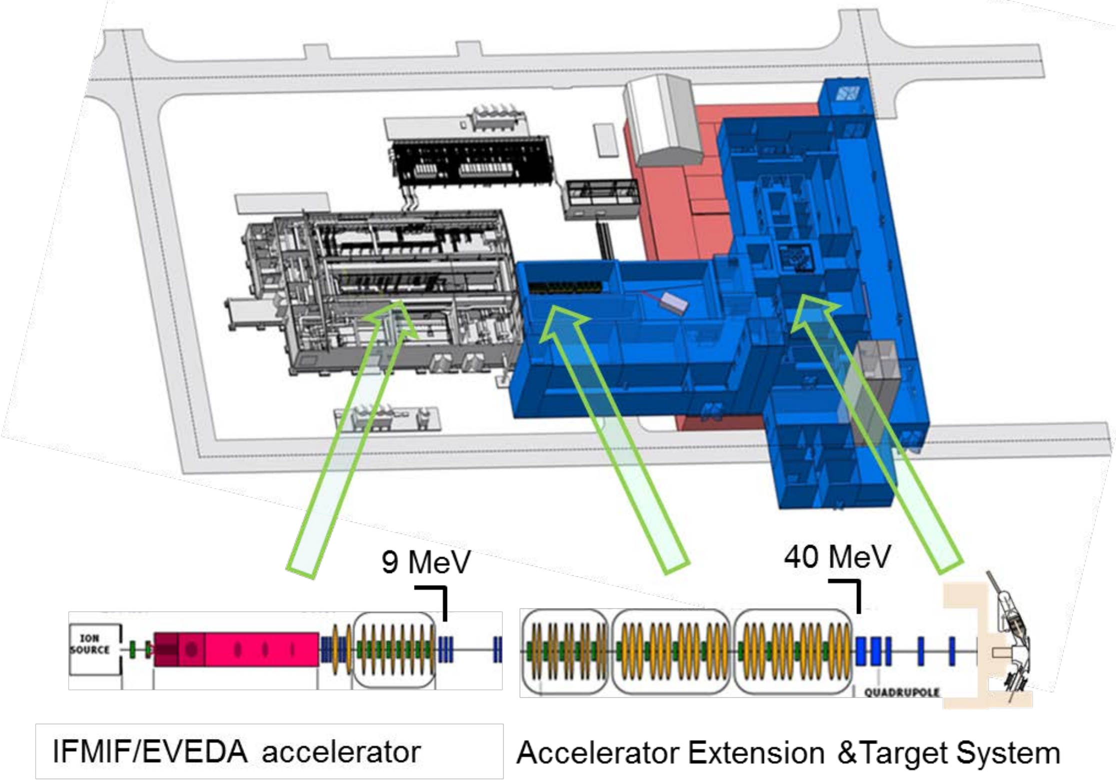
Knaster, Moeslang, Muroga (2015)
Modified from S.J. Zinkle and L.L. Snead (2014)

IFMIF/EVEDA and A-FNS

IFMIF/EVEDA accelerator tests (~9 MeV d⁺) will be completed in 2019. → 2020~2025

A-FNS (~ 40 MeV d⁺) is being planned as post-EVEDA project. → 2025~

A-FNS is expected to contribute to DP2 and DP3.



Layout of A-FNS

D-Li Neutron Source Development

Name	Accelerating Voltage	d^+ beam current	Objective
IFMIF/ EVEDA (LIPAC)	9 MeV	125 mA	Engineering validation (no neutron)
A-FNS	40 MeV	125 mA	Medium Fluence 14 MeV neutron Irradiation
IFMIF	40 Mev	250 mA	High Fluence 14 MeV neutron Irradiation

DP1: Intermediate C&R
DP2: Transition to DEMO
DP3: DEMO construction

Courtesy of K. Ochiai (QST)

Characterization of Neutron Irradiation Facility

Purposes	Candidate Selection	Model Validation	Lifetime Evaluation
Required Characteristics	Timely availability	Precise Control	High Fluence
Fission Reactors	Timely use possible Difficult to simulate He effect	Difficult to simulate He effect	Difficult to simulate He effect
A-FNS	Limited timely use	Low fluence validation	Medium fluence evaluation
IFMIF	Not timely	Medium fluence validation	High fluence evaluation

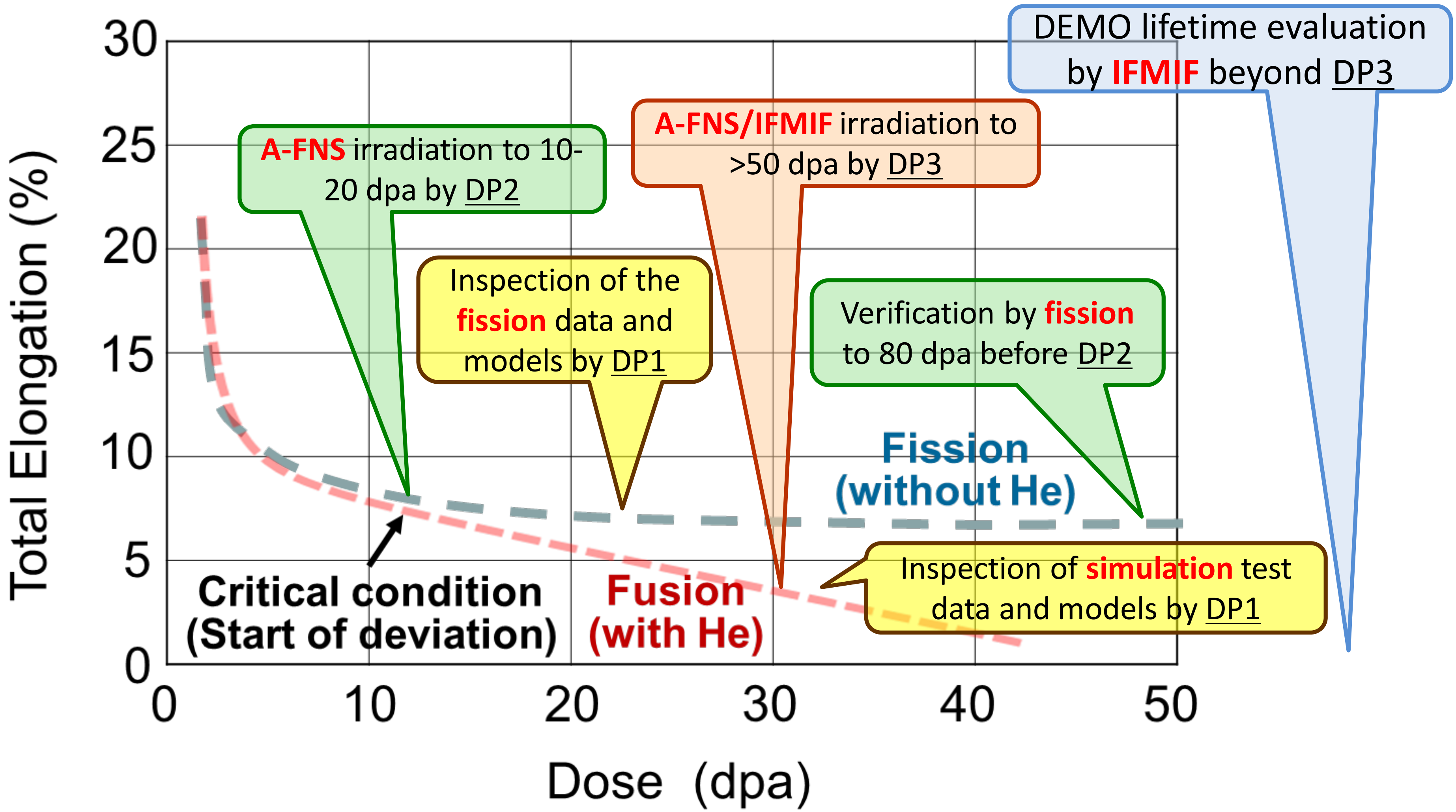
DP1-DP2 emphasis

DP2-DP3 emphasis

Beyond DP3

DP1: Intermediate C&R
DP2: Transition to DEMO
DP3: DEMO construction

Irradiation Test Strategy to Quantify Loss of Ductility of RAFM



Prediction of loss of elongation of RAFM by irradiation and strategy of testing

DP1: Intermediate C&R
DP2: Transition to DEMO
DP3: DEMO construction

Modified from H. Tanigawa et al., Nucl. Fusion 2017

Materials Development for DEMO Licensing

Establishing a philosophy for ensuring safety of the plant

Establishing structural design criteria

interactive

Materials property requirements

interactive

Establishing irradiation database
1. Fission Rectors
2. A-FNS
3. IFMIF

Standardization of test technology including SSTT

Standard materials specifications (non-nuclear)

Standard materials specifications (nuclear) and design qualification and licensing
1. TBM
2. DEMO construction and initial operation
3. DEMO operation extension to full specification

SSTT : Small Specimen Test Technology

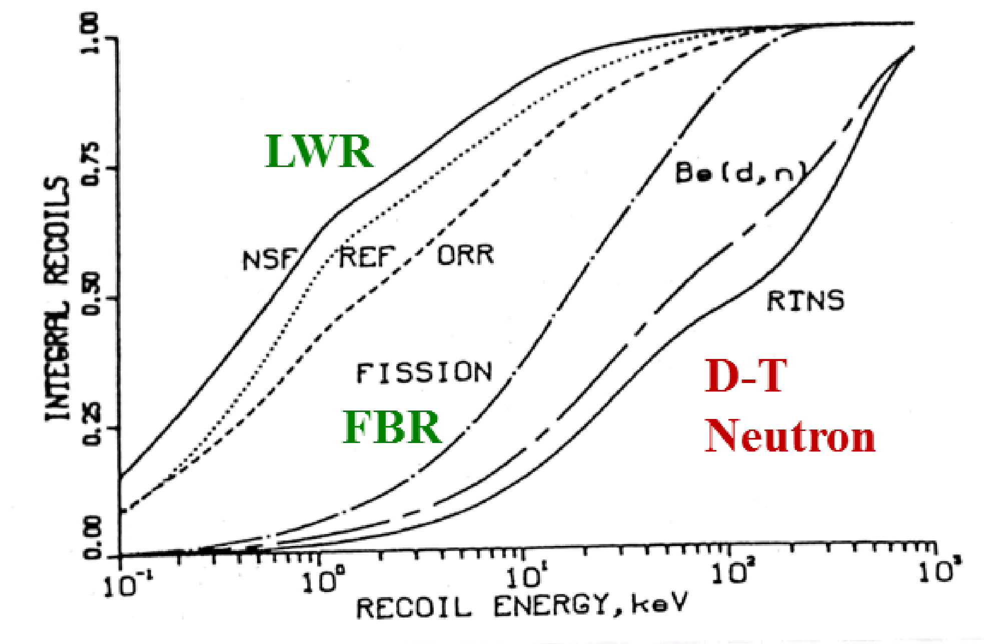
In reality, the standardization and reactor design must be carried out without sufficient materials irradiation data.

Careful manipulation of the schedule in the development of irradiation facilities, acquisition of irradiation data, and auxiliary fundamental/modeling efforts are essential.

T. Muroga and H. Tanigawa, Fusion Tech. 2017

Need for Fundamental Research

PKA Energy Spectra



Weighted Integral PKA Energy Spectra

Greenwood (1983)

PKA energy spectra was considered for correlating different kind of irradiations

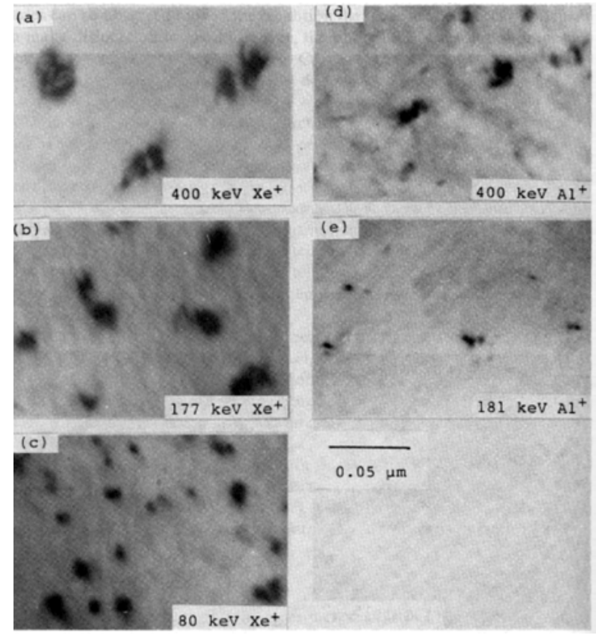
PKA spectra weighted with displacements can be the effective correlation measure

Average or weighted average PKA spectra was used as correlation parameters

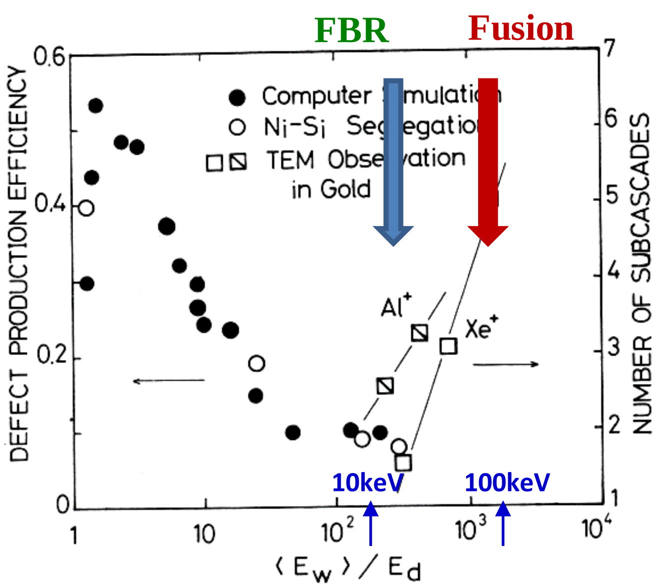
Effects of PKA Energy Spectra

Effects of PKA energy spectra have been investigated

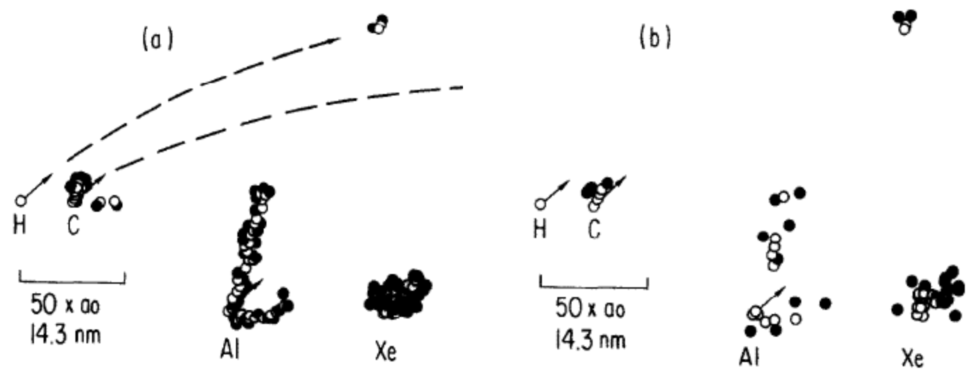
Collision cascades were separated into sub-cascades above ~10keV, whose performance does not change



Cascade splitting into subcascades in gold by Xe and Al ions



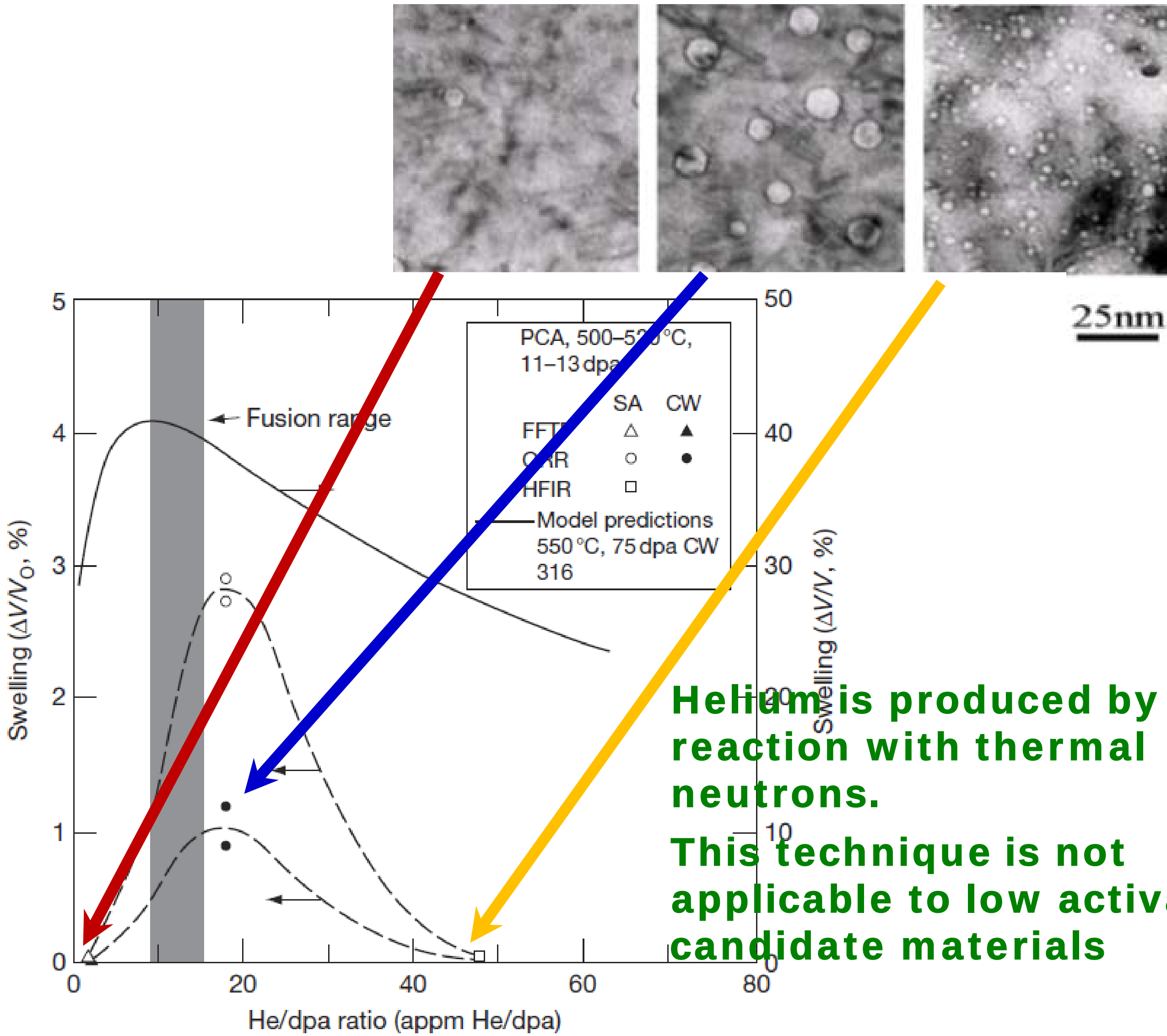
Correlation by Weighted Average PKA Spectra



After cascade **After thermal annealing**

Muroga (1985)

He/dpa Dependence



Helium is produced by Ni's reaction with thermal neutrons.

This technique is not applicable to low activation candidate materials

He effect in an austenitic steel

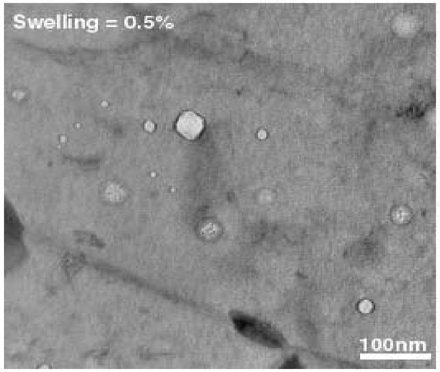
Efforts to Evaluate He Effects

<u>Boron addition</u>

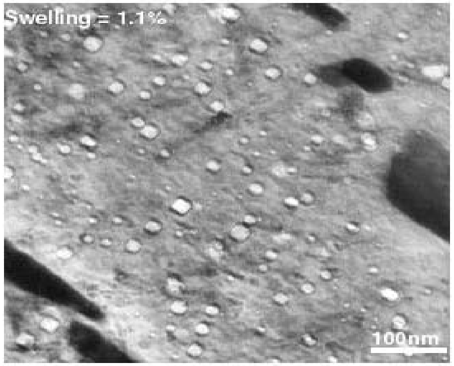
$^{10}B + n\ (thermal) \rightarrow\ ^{4}He +\ ^{7}Li$

^{10}B addition enhanced swelling and embrittlement
Boron addition can change the steel properties (chemical effects)

^{10}B /^{11}B ratio control tests showed ^{10}B can enhance DBTT shift
However, it was also shown that Li can enhance cavity formation and enhance DBTT shift.
It is quite difficult to evaluate He effects explicitly

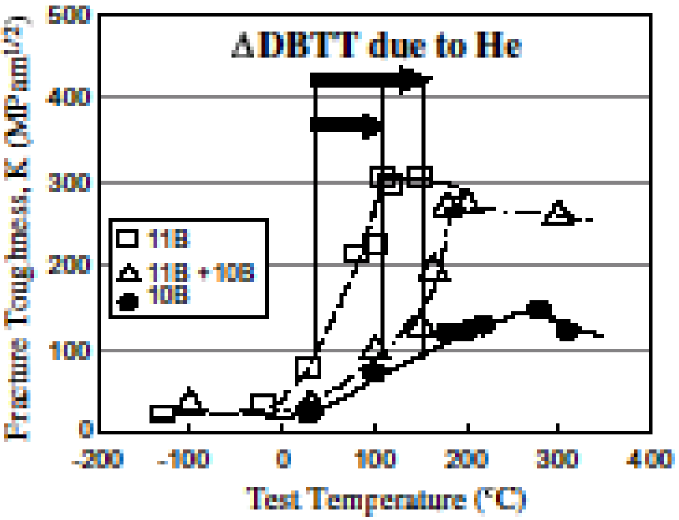


F82H (36 appmHe)



^{10}B-doped F82H (330 appmHe)

^{10}B addition enhanced cavities(HFIR 673K, 51dpa)

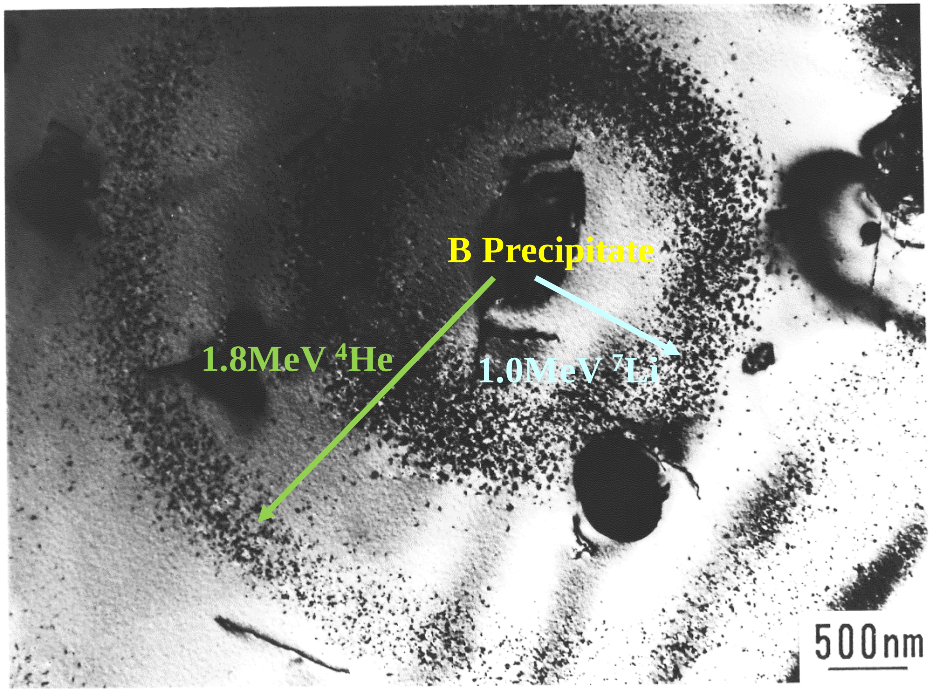


DBTT shift by isotope-controlled boron addition (JMTR 473K) **(Wakai)**

^{4}He, ^{7}Li ejection from ^{10}B

B doped austenitic steel has B rich precipitates, whoing double ring damage structure

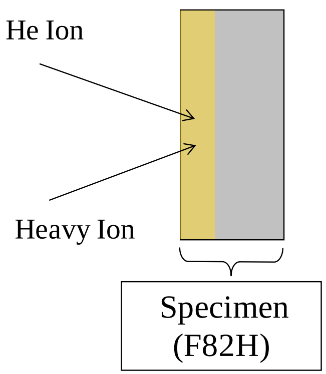
Both ^{7}Li and ^{4}He depositing enhance loop and canity formation



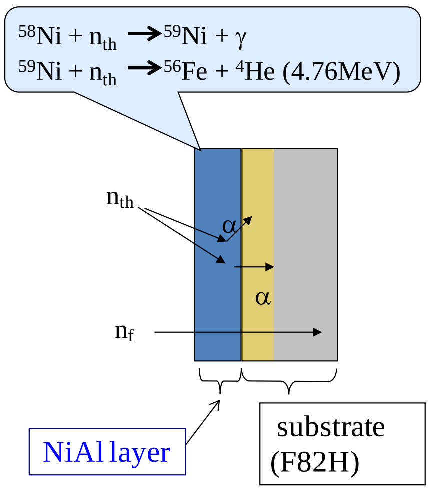
JMTR 400°C, 5.5x10^{23}n/m^{2} (E>1MeV), JPCA

Helium Injection in HFIR

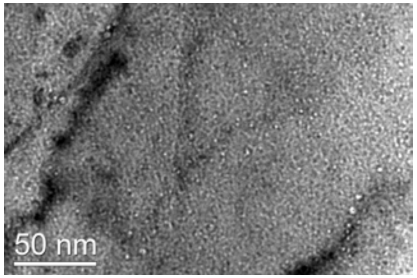
Helium injection to F82H during irradiation

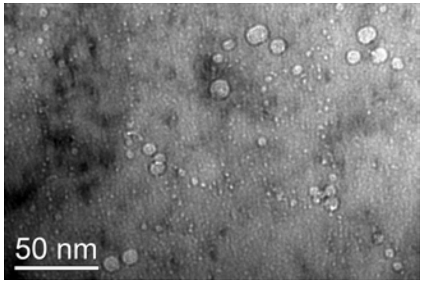


Dual beam irradiation (Kyoto U.)



He injection during neutron irradiation in HFIR using Ni reaction with thermal neutrons





10 dpa, 380 appm He **（Yamamoto）**
Different microstructure with the same dpa and He level

Both ion irradiation and helium injection can produce fusion relevant He/dpa only near-surface area

The difference in microstructure may be attributed to the extreme difference in damage rate (10 dpa by some hours and some months)

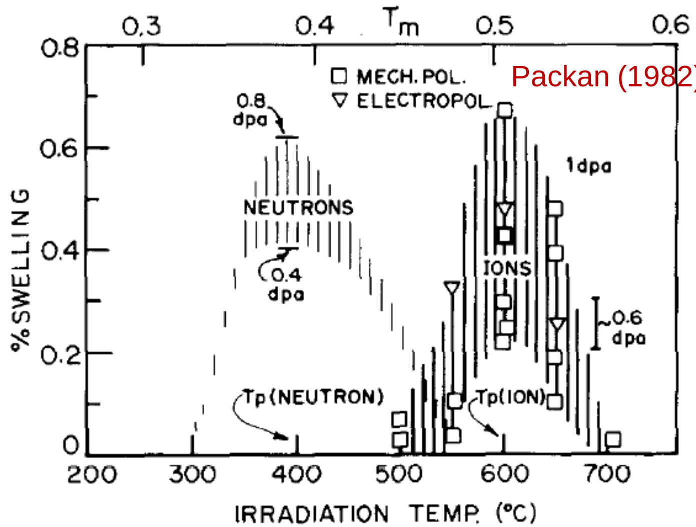
Effects of Accelerated Irradiation

Most irradiation tests are "accelerated" tests

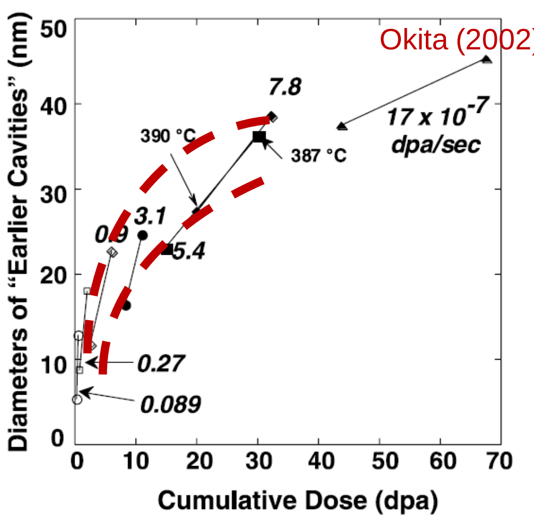
Acceleration can induce very different materials performance, especially when multiple mechanisms with different activation energies operates.

Sometimes misleading

Modeling is critically important

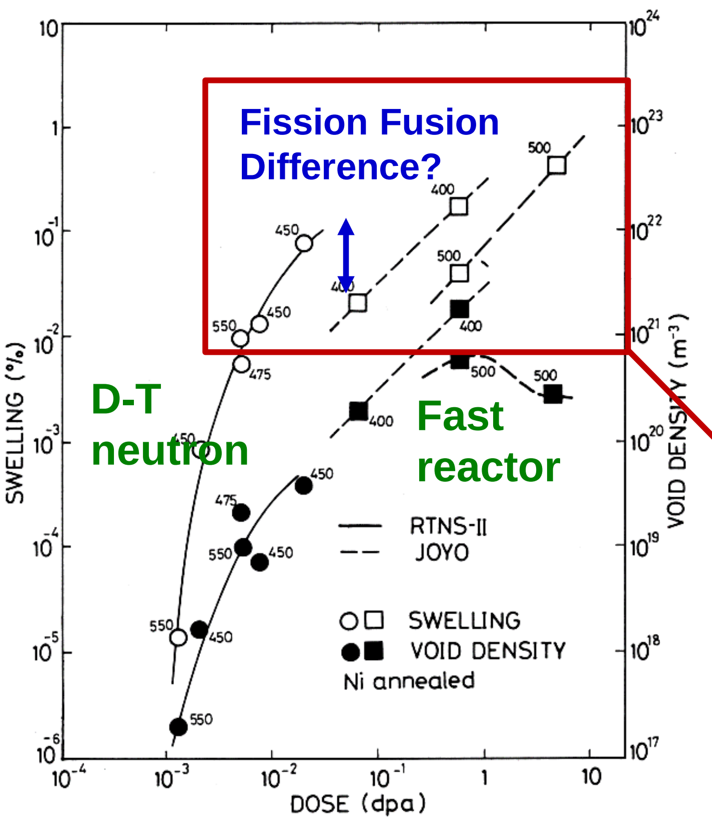


Temperature shift of swelling in Ni



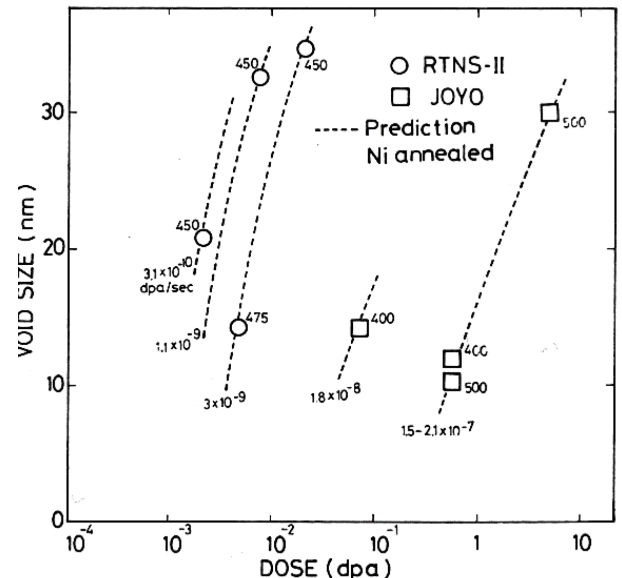
Void size evolution in austenitic steels

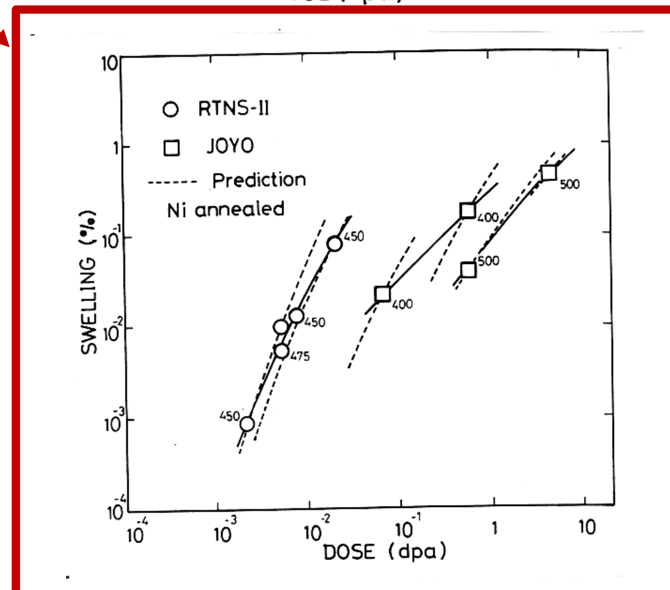
An Example is Misleading Fission-Fusion Correlation



Void swelling and density in Ni

Muroga (1988)

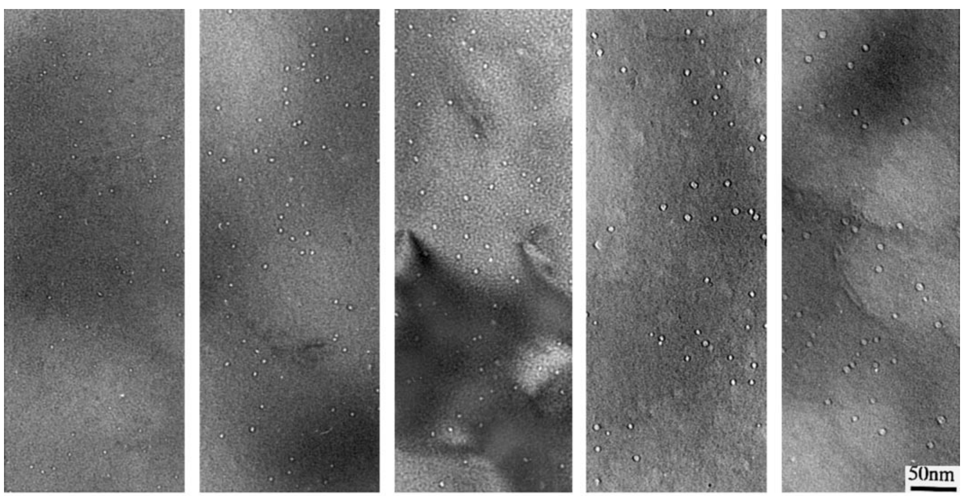




Damage rate effects dominate over fission-fusion difference

Irradiation Rig Development for JMTR

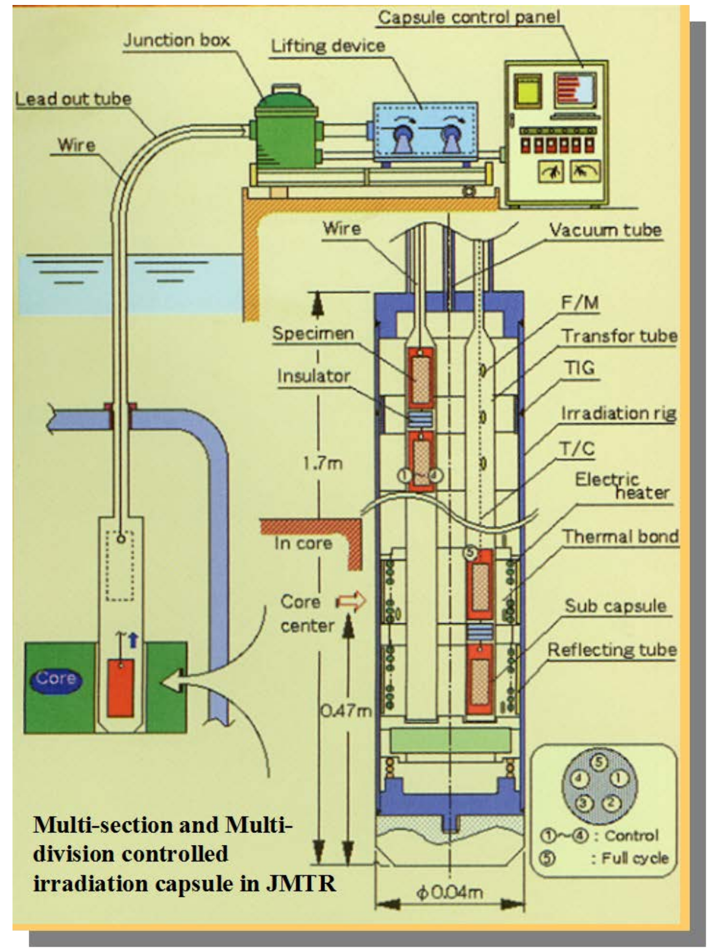
- In-situ resistivity
- Intentional temperature variation during irradiation
- Specimen pulling out during irradiation.



0.026 0.062 0.13 0.24 0.40 dpa

Microstructural evolution of Ni at low dose with a constant dose rate

Yoshiie 2000



Specimen pulling-out during irradiation using sectioned capsules

Issues for fundamental understaning

1. He effects in fusion conditions still need validation

    Fundamental studies

    Modeling prediction

    Validation by A-FNS/IFMIF

2. Dose and dose rate effects are mixed in most cases

    Compilation of single-variable experiments is essential

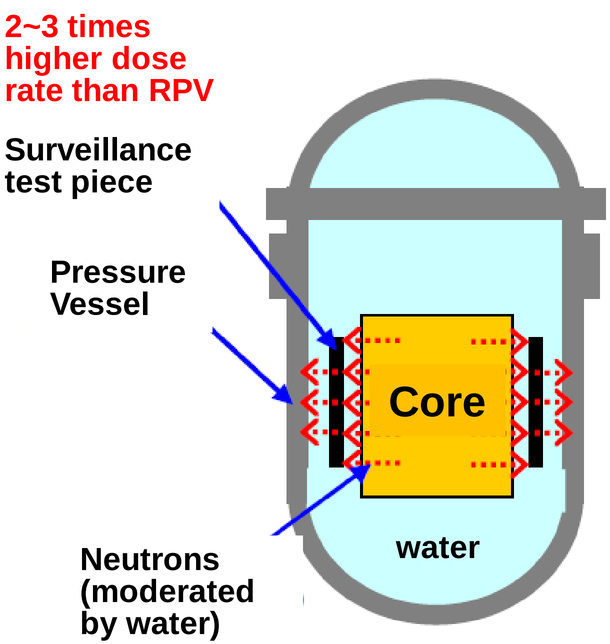
    Property change vs dose with constant dose rate

    Property change vs dose rate with constant dose

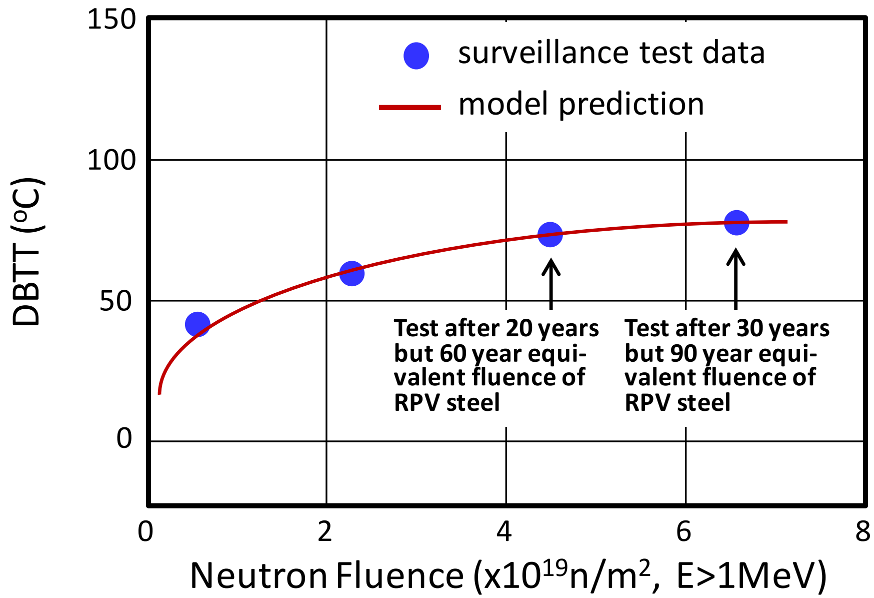
    Fission reactors have limitation in performing controlled experiments because of limited accessibility

Current issue – fission power reactor and materials

Surveillance test in LWR



Surveillance test in LWR



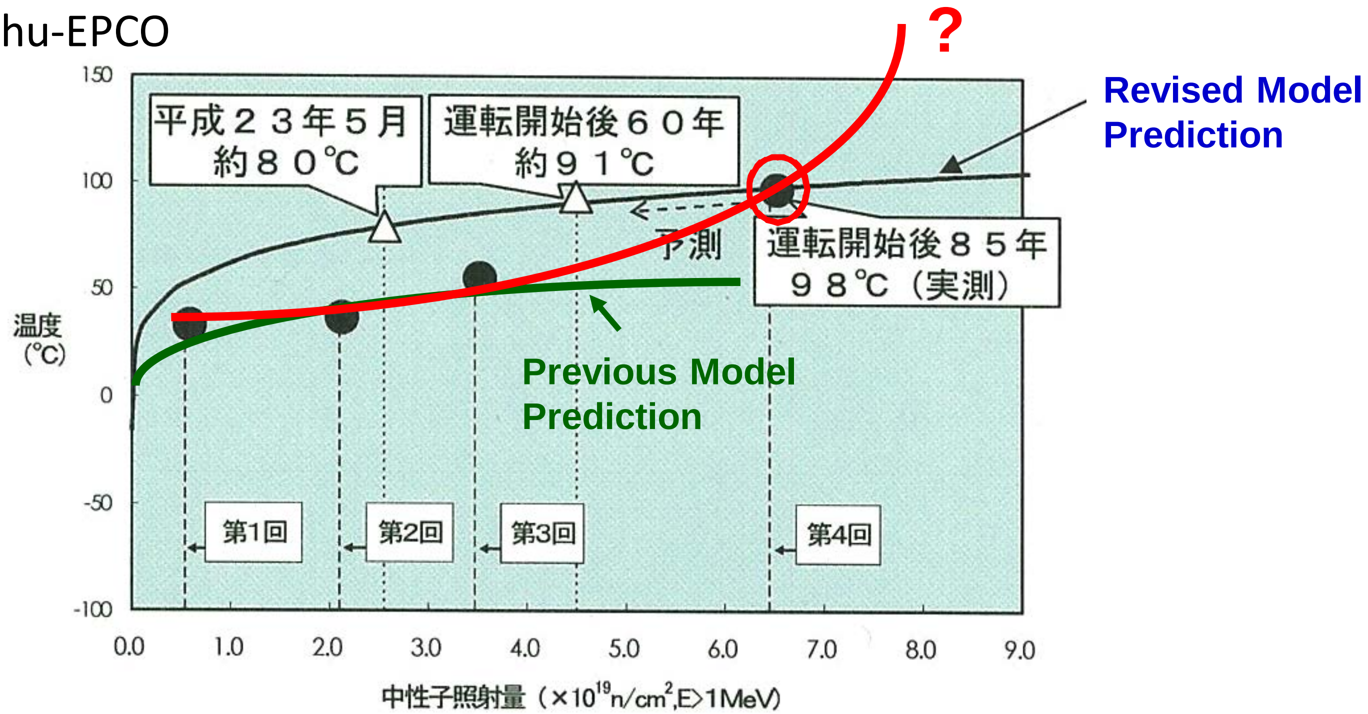
Concept of Surveillance test

Surveillance test data can predict future performance of PV

Prediction is based on an embrittlement model

Anomalous DBTT Shift in Surveillance of Genkai-1 Power Plant

After HP of Kyushu-EPCO



Criticism emerged toward the model revision.

1. Model is wrong (should have a different fluence dependence).
2. Surveillance (accelerated simulation) is misleading. (impact of flux effects)

Had seriously negative effects on the discussion of extended operation of the present power plants

This is clearly showing a lesson we should learn.

Fundamental understanding on materials performance in fusion condition is crucial even in the stage of commercial operation

Future neutron sources must contribute to enhancing fundamental understanding of radiation effects as well as constructing database

- High controllability
- Single variable experiment capability

Summary (1)

Recently, Japanese fusion community issued some reports on the strategy for technological developing toward DEMO. Japanese DEMO development strategy is under reconstruction based on these documents.

Three decision points (DPs) were scheduled allowing a staged development toward DEMO.

DP1 : Intermediate C&R ~2020, ~2025

DP2 : Transition to DEMO phase in 2030s

DP3 : DEMO construction ~2040s

The standard materials specifications are recognized as a crucial step toward DEMO design qualification and licensing. For this purpose, the materials property requirements to be derived by establishing the structural design criteria is necessary as well as establishing irradiation database.

Summary (2)

The challenges in this process includes that the reactor design must be carried out without sufficient materials irradiation data.

Thus, careful manipulation of the schedule in the development of irradiation facilities, acquisition of irradiation data and auxiliary basic and modeling research efforts are essential for materials development toward DEMO.

Recent controversy in Reactor Press Vessel performance clearly shows necessity for fundamental understanding of materials performance under irradiation in every stage of reactor development, including licensing phase and commercial operation phase. The materials irradiation facilities need to have capability to carry out fundamental researches such as single-variable experiments.