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THE STRATEGY OF FUSION DEMO IN-VESSEL STRUCTURAL MATERIAL DEVELOPMENT

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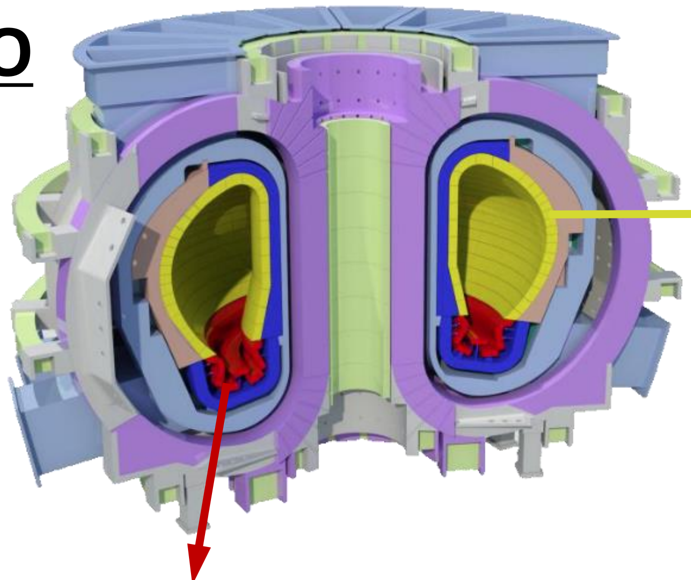
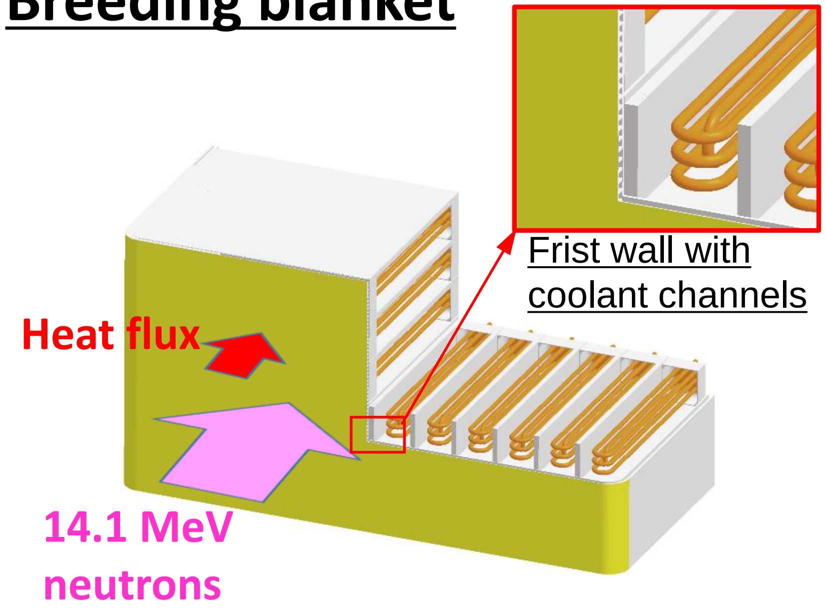
Use condition of Fusion DEMO in-vessel structural material

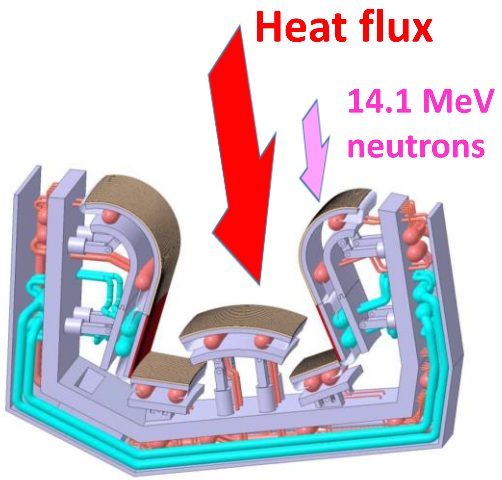
JA DEMO



Breeding blanket



Diverter



Plasma facing material (W)

Irradiation dose: 1.5 ~ 10 dpa

Heat flux: 10 MW/m^2

Temperature: 500 ~ 1000˚C

Coolant pipe material (Cu-alloy)

Irradiation dose: 6 ~ 10 dpa

Temperature: 200 ~ 350˚C

Structural material (FM Steel)

Irradiation dose: 20 ~ 80 dpa

Temperature: 280 ~ 550˚C

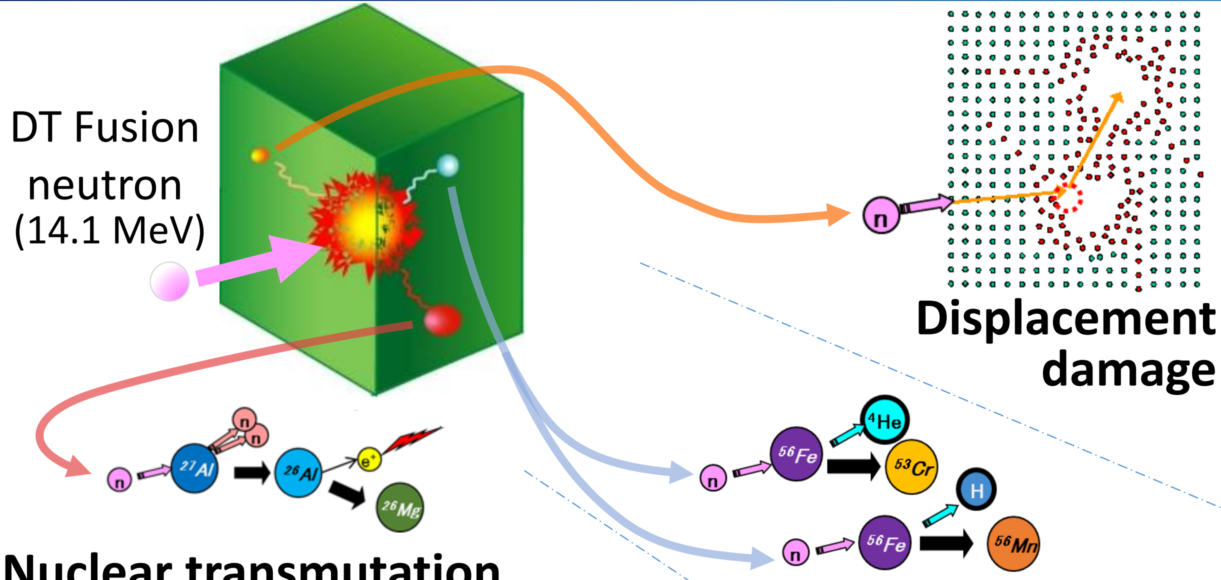
Plasma facing material of first wall (W)

Irradiation dose: 8 ~ 30 dpa

Heat flux: 0.5 MW/m^2

Temperature: 500 ~ 600˚C

Typical phenomena and general expectation

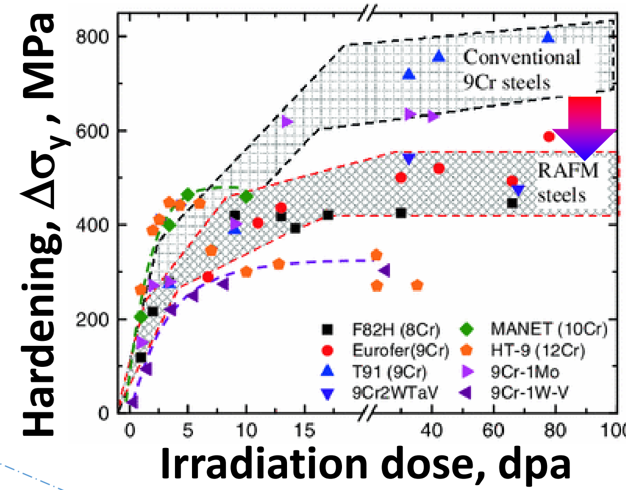


Displacement damage

Nuclear transmutation induced activation

Nuclear transmutation gas (He, H) formation

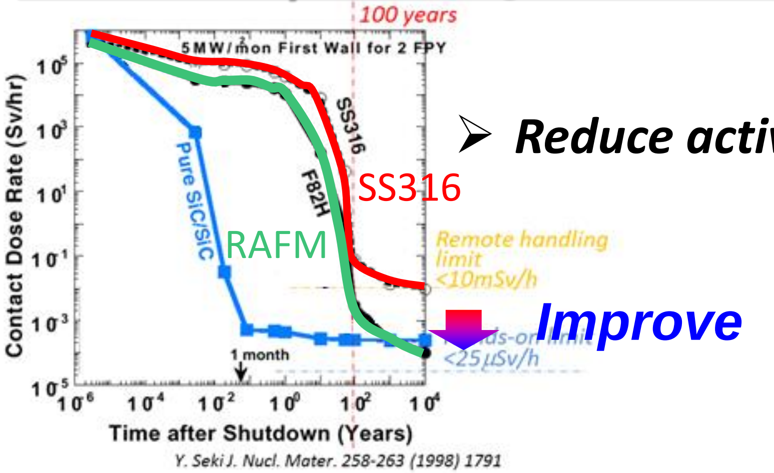
Property degradation (embrittlement)



- ***A "less" change in properties due to irradiation***

O. Anderoglu, et al., Metall Mater Trans. A 44 (Suppli 1) (2013) 70

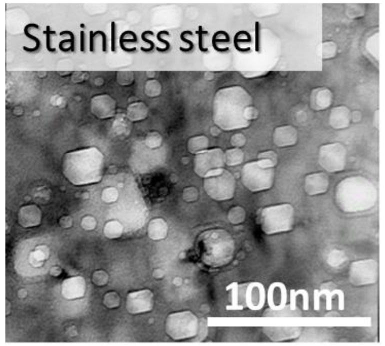
Radioactivity due to long-lived radionuclides

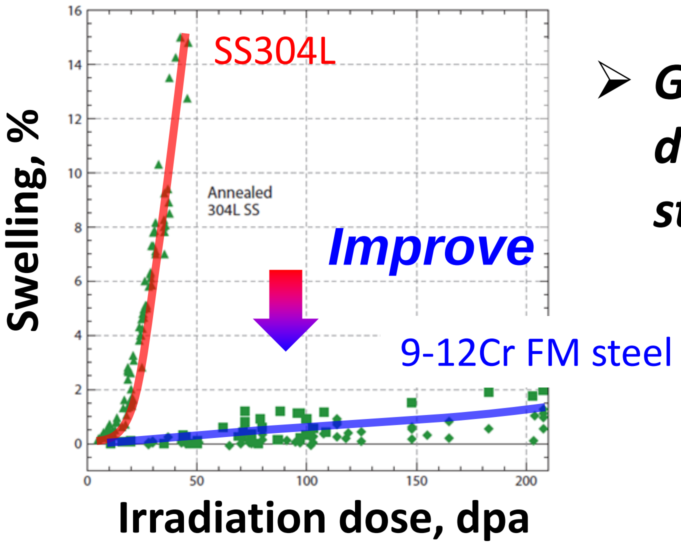


Y. Seki J. Nucl. Mater. 258-263 (1998) 1791

- ***Reduce activation***

Swelling





- ***Good dimensional stability***

S.J. Zinkle Acta Mater. 61 (2013) 735

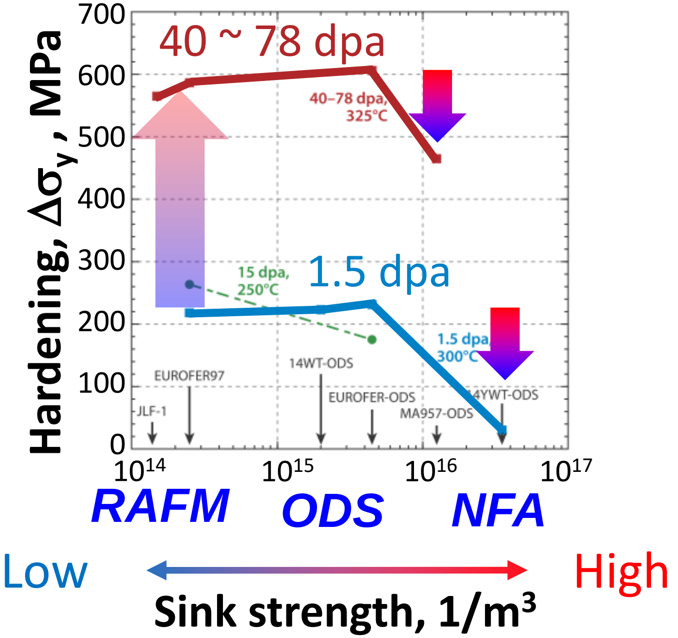
A common strategy and the near term approach

Materials for advanced performance

High sink strength materials

- ✓ Minimize irradiation effects by absorbing various defects by **various high density sinks** in material.

These are not yet mature as the "structural" material for design activity.



S.J. Zinkle, Annu. Rev. Mater. Res. 44 (2014) 241-267

Candidate material feasible for design activity

Reduced Activation Ferritic/Martensitic (RAFM) Steel

Fe - **8** ~ **9**Cr - **1**~**2**W - V, Ta (**F82H**, EUROFER, etc.)

- ✓ These steels have a sound technological background on their reproducibility and weldability.
- ✓ A certain level of irradiation resistance was demonstrated.
- ✓ Grain refining and heat treatment can improve the level of irradiation resistance or recover the degraded properties.
- ✓ **Irradiation induced property changes of RAFM steels are not negligible.**

It is essential to define how much irradiation induced property changes are allowed.

But, we have to define this

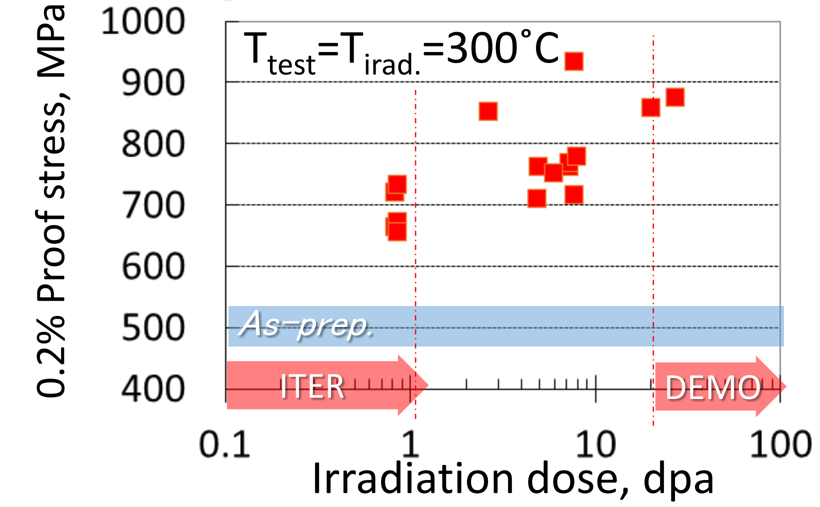
- ✓ ***Without (or with a very limited) experience of the real fusion in-vessel environment.***
- ✓ ***For DEMO construction.***

The typical irradiation effects on mechanical properties of RAFM

The data are inherent to ALL RAFM steels

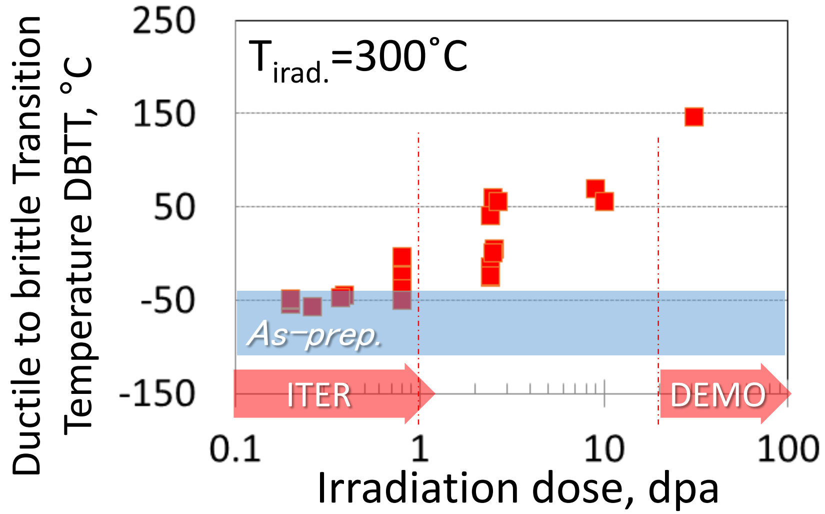
Irradiation effects observed in fission neutron irradiated F82H

Hardening

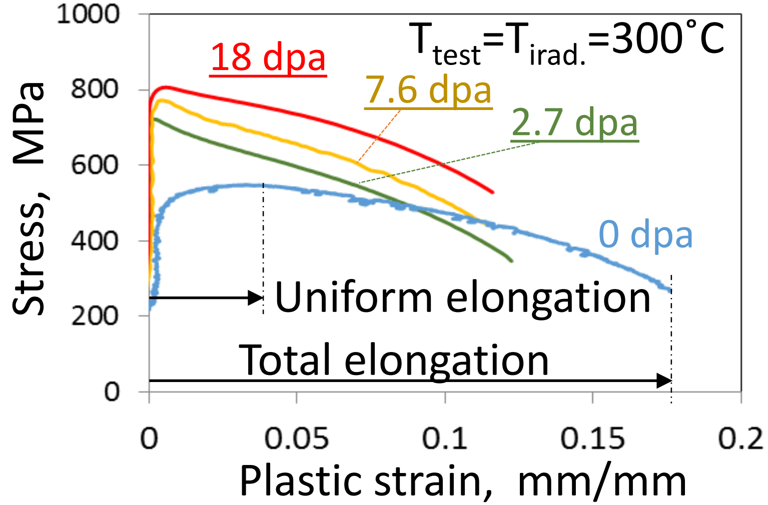


Hardening and embrittlement are well-known as the critical irradiation effects.

Embrittlement

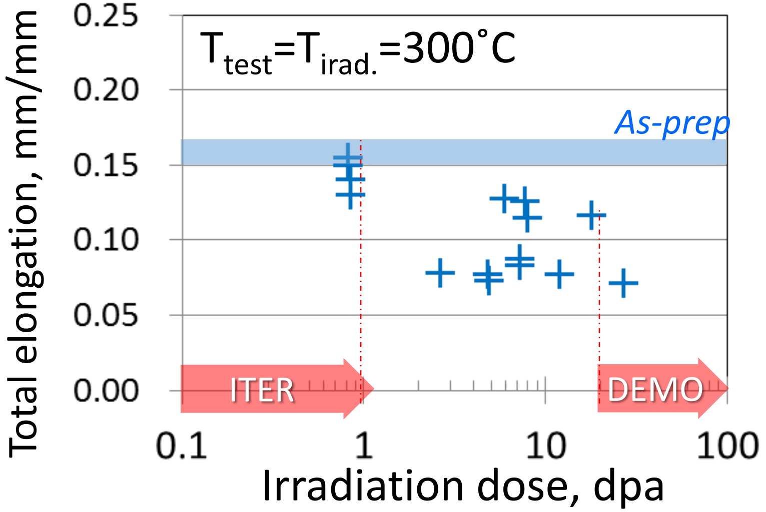


Typical tensile stress-strain curves



Deformability reduction which appeared as the loss of uniform elongation and the decrease of total elongation are also significant.

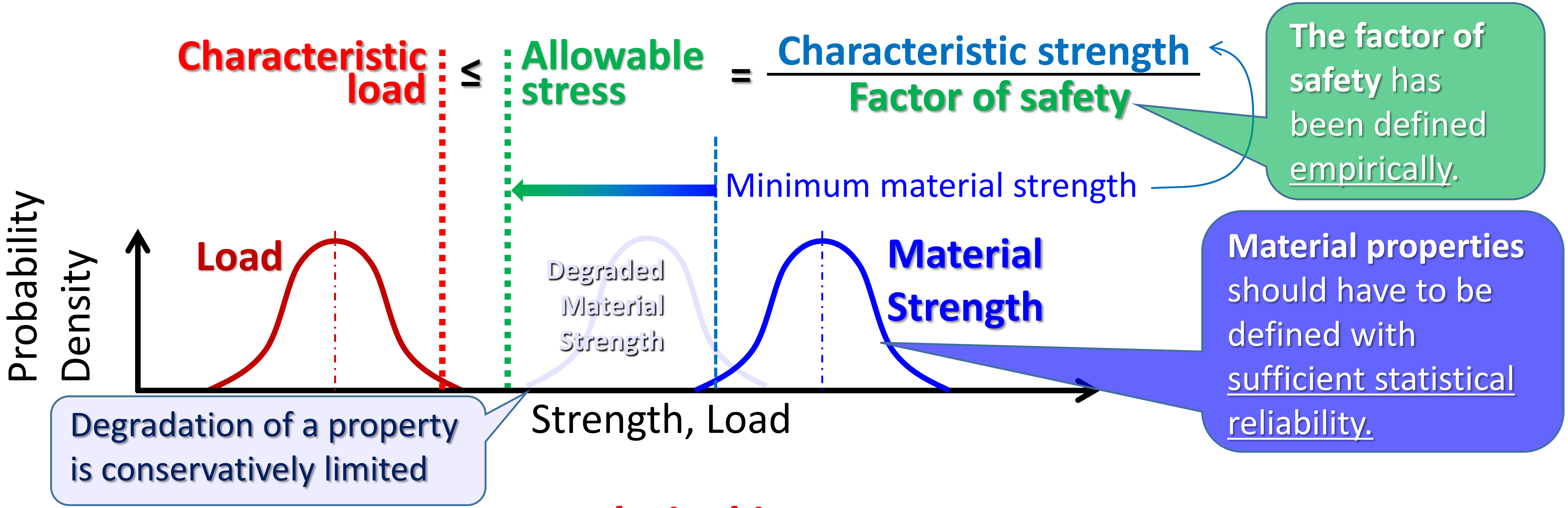
Deformability reduction



How to deal with property degradation?

The deterministic design method (Allowable stress design method)

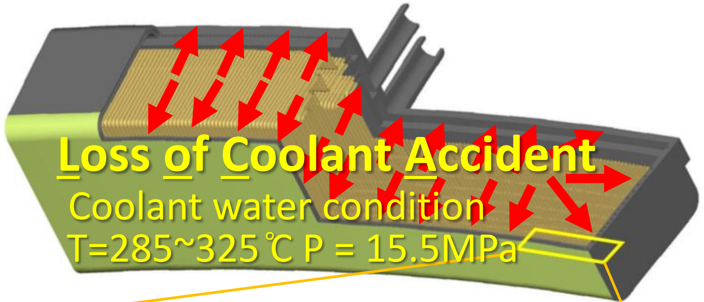
Basic strategy : Prevent plastic collapse by defining allowable stress level

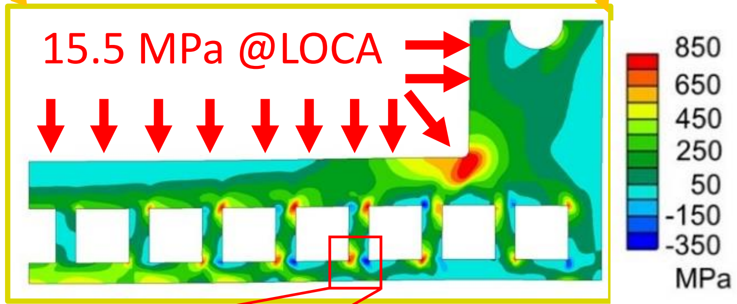


Technical issues

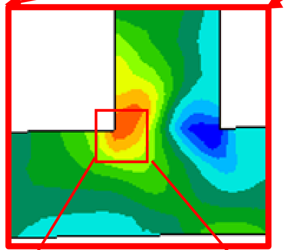
1. **Deformability decrease after irradiation.**
2. **Statistical reliability of irradiation data is limited.**
3. **"Empirical" approach is not feasible for fusion DEMO in-vessel components.**

Issue 1 : Impacts of deformability reduction

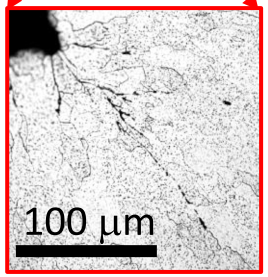




Max. principle stress



Stress concentration
at the corner of coolant channels



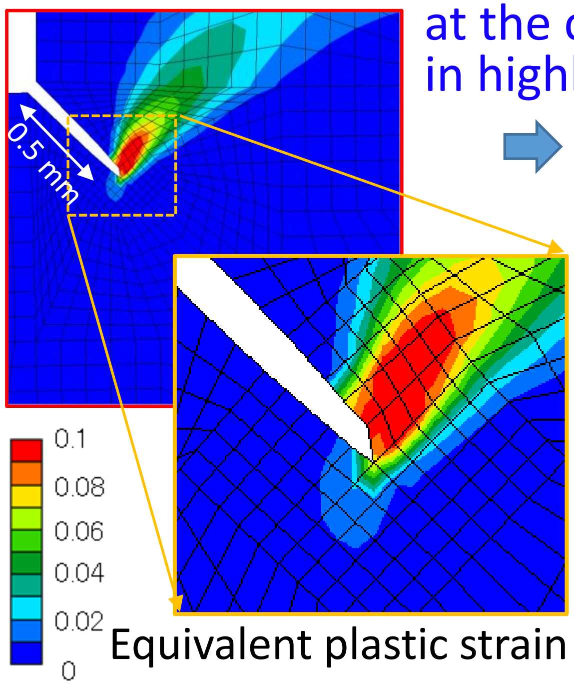
A possible flaw
Small crack occasionally observed at the corner of a rectangular tube

High deformability (ductility and plastic hardenability) is the basic presupposition for the allowable stress design method, to prevent plastic collapse

- *At the highly stress concentrated region of discontinuous parts*
- *Due to the presence of undetectably small flaws or defects*

Local deformation at the tip of a postulated crack

Unirradiated F82H

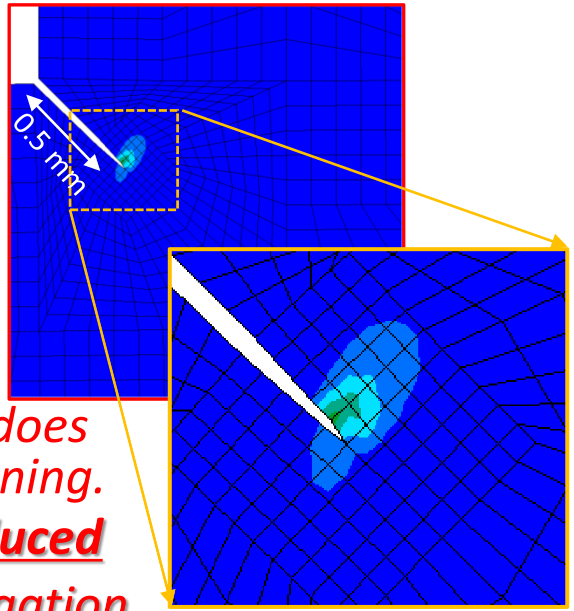


Equivalent plastic strain

Crack blunting and hardening at the crack tip can be expected in highly plastic material.

➡ *The crack propagation is not likely to occur.*

300˚C/20 dpa irrad. F82H

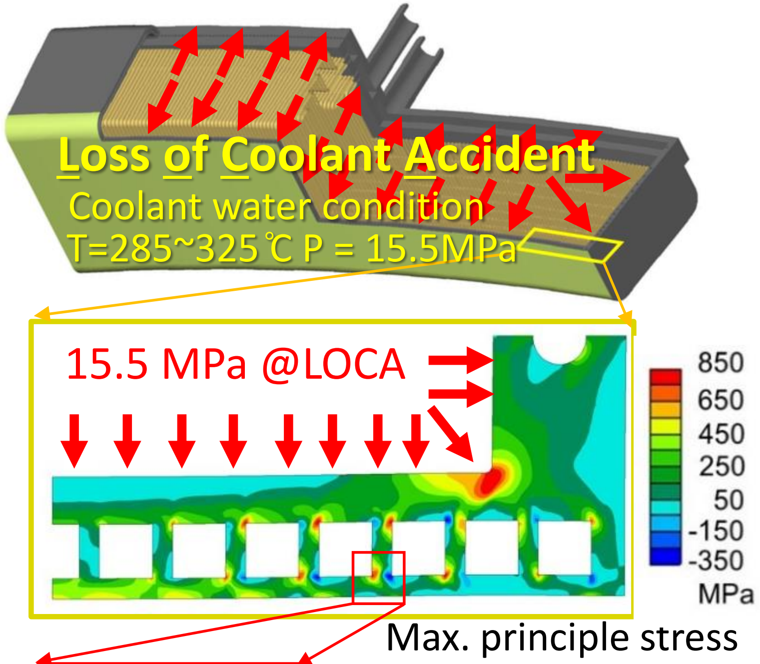


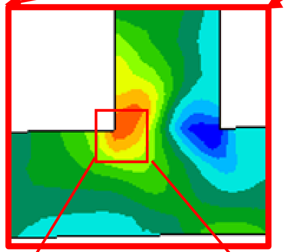
The crack tip blunting does not occur due to hardening.

+ Deformability reduced

➡ *The crack propagation could occur.*

Issue 1 : Impacts of deformability reduction





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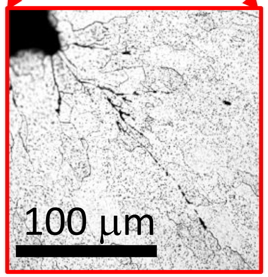

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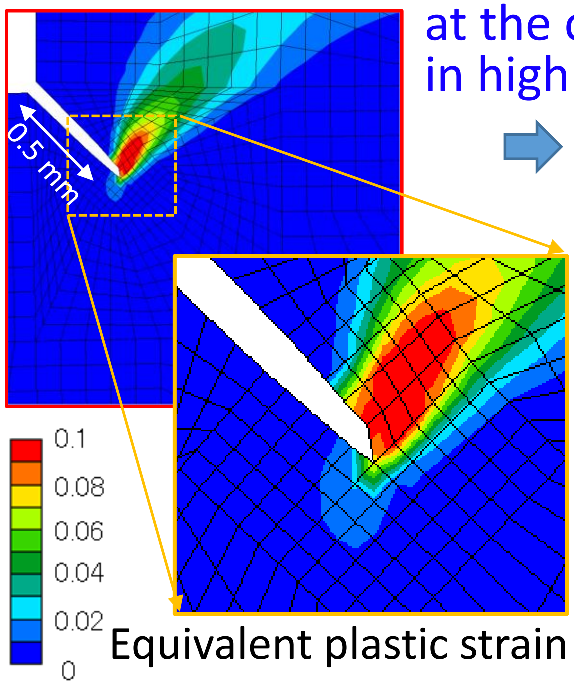
- ➤ *At the highly stress concentrated region of discontinuous parts*
- ➤ *... ly small flaws or defects*

The undetectably small crack becomes not negligible after irradiation due to deformability reduction.

Local deformation at the tip of a postulated crack

Unirradiated F82H



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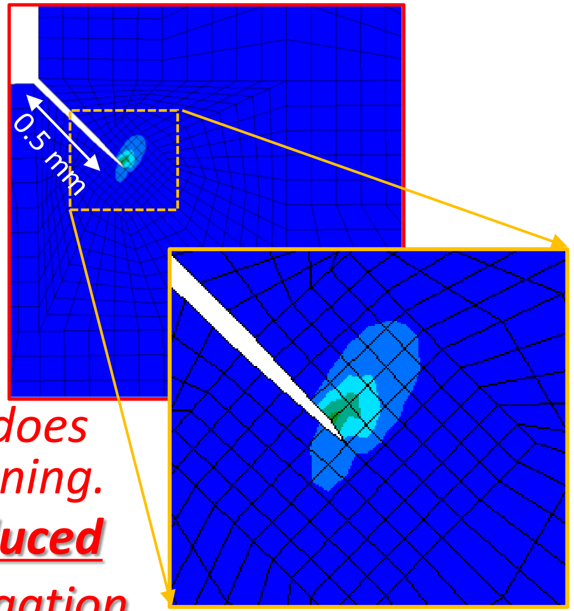

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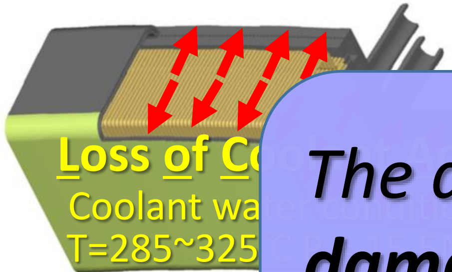
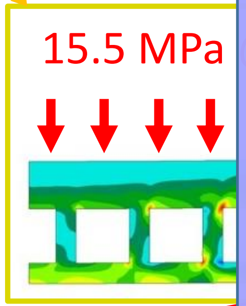
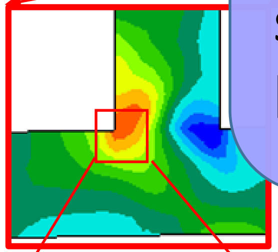
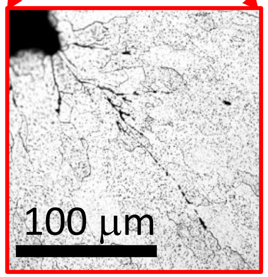




The development of ***design rule and methodologies for irradiation damaged fusion in-vessel components****, considering the* *irradiation induced deformability reduction**, would be required.*

This kind of phenomena is considered **in the Post Construction (PC) code** (e.g., API 579-1/ASME FFS-1), **as the degradation of fracture toughness,** but the structure of fusion in-vessel components are not simple, and the expected loads are complicated.





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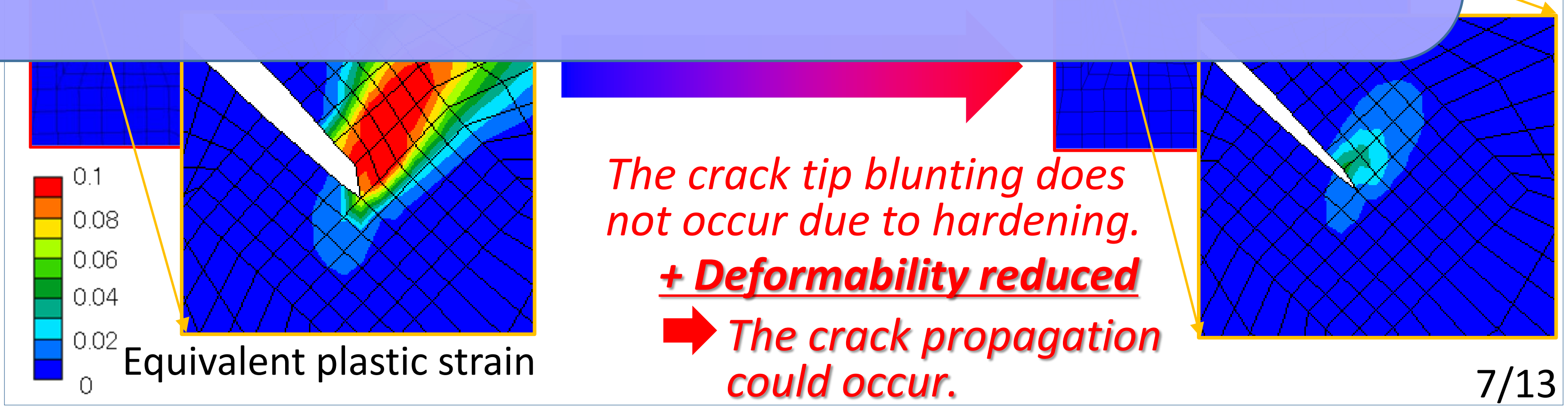

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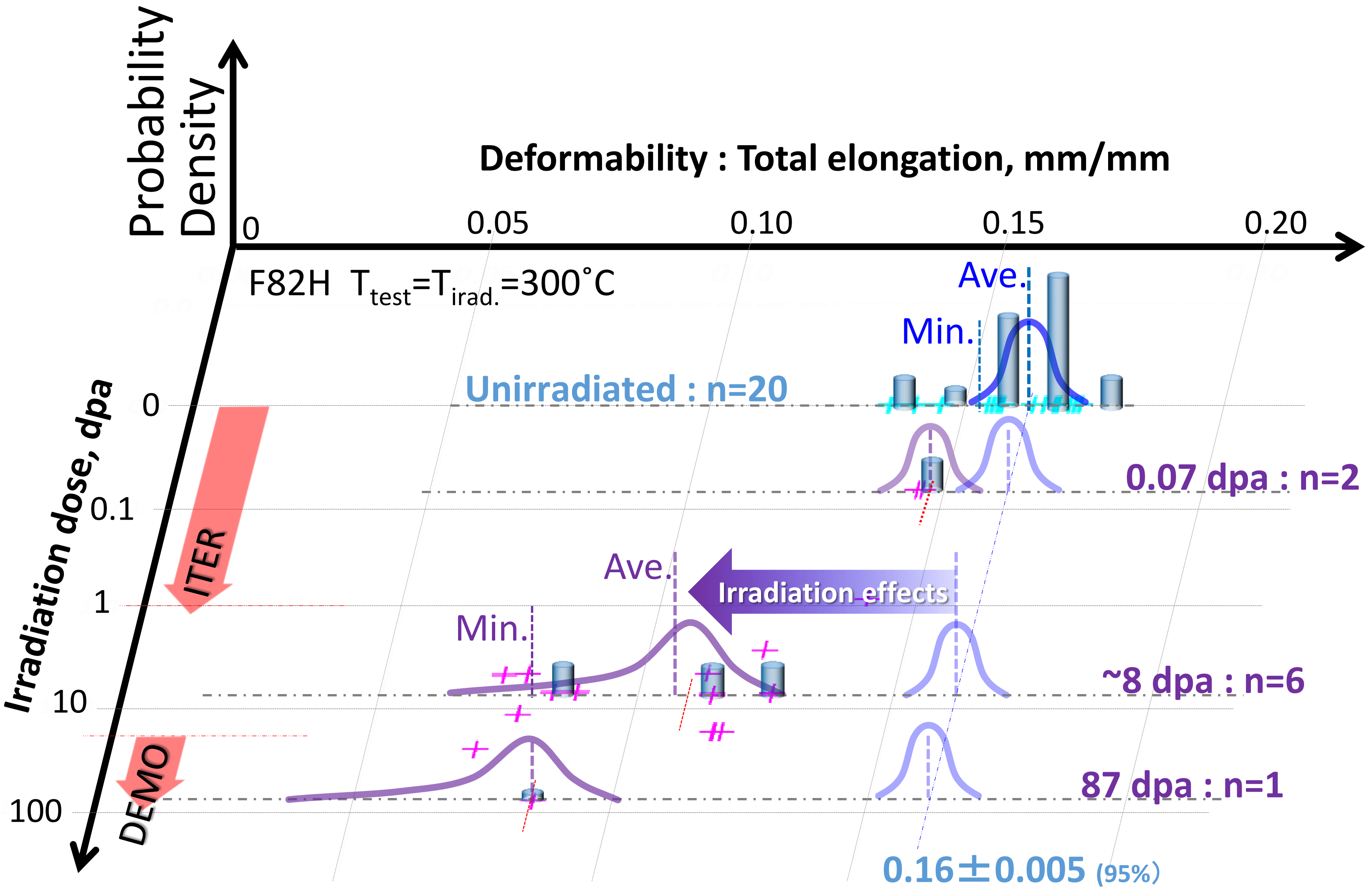
Issue 2 : Database and statistical reliability



- Most of the irradiation data consist of 1~3 data points per condition.
  - ✓ The number of irradiation data is too small to give a representative value (average, minimum value) with a statistical confidence.
- It is dangerous to assume **a normal distribution** to calculate a representative value from irradiated material property data, as the typical irradiation effects appear as embrittlement.

Normal distribution

Weibull distribution.

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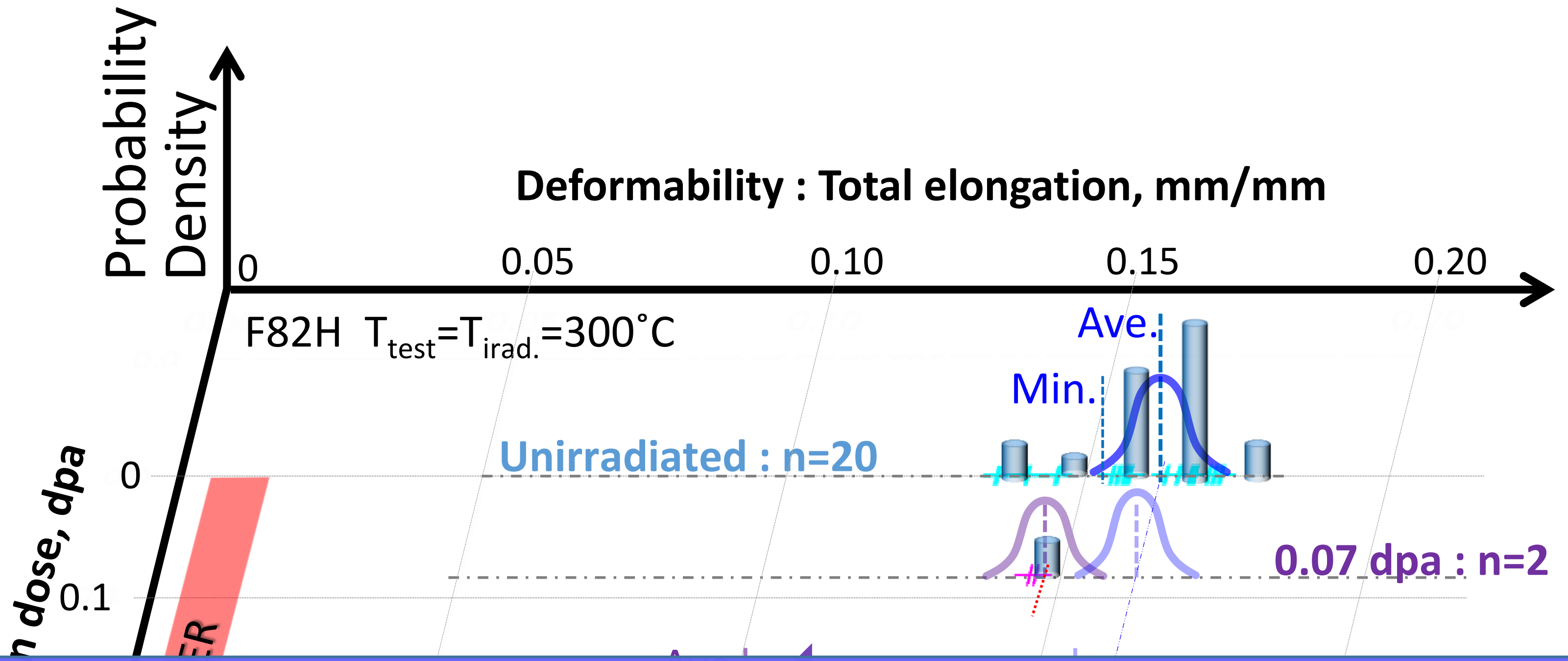

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Normal distribution

↳ **Weibull distribution.**

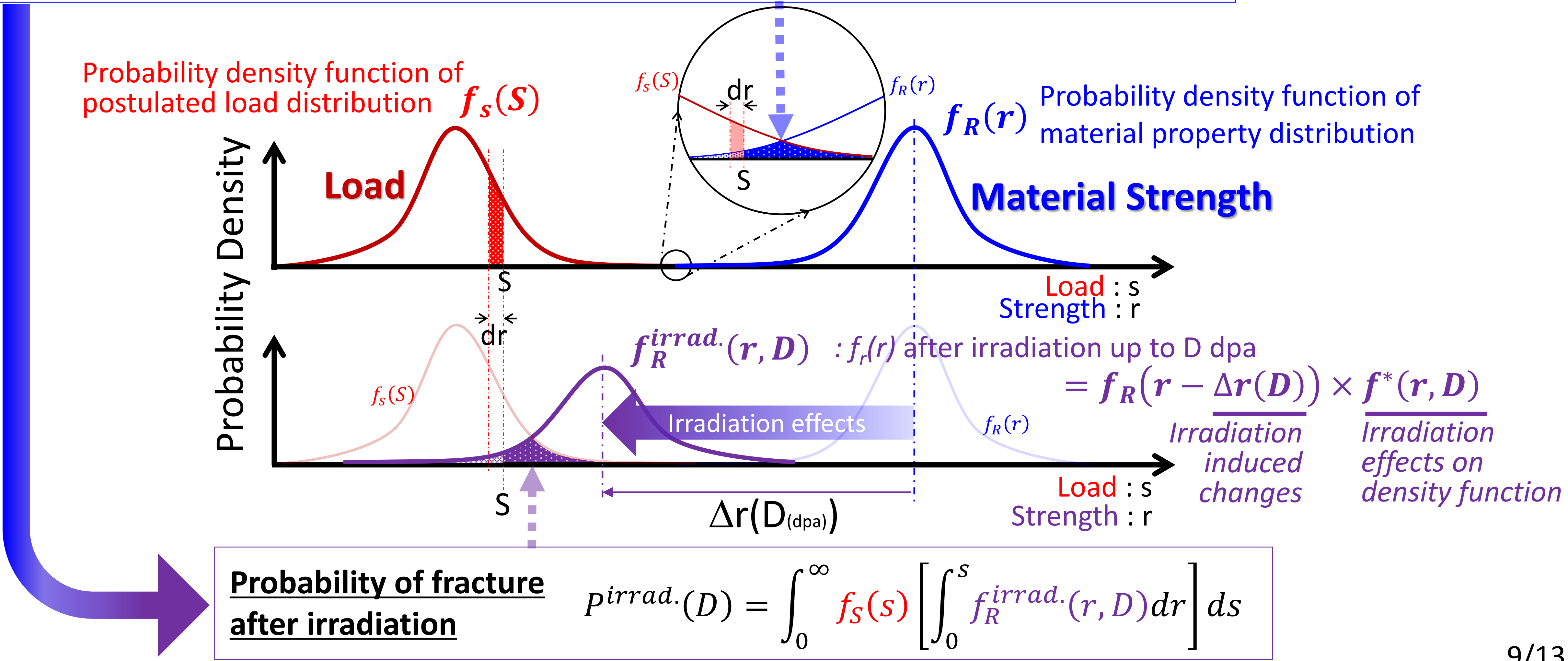
If there is **a tendency to obtain a extremely low value** (i.e. the data distribution suggest a **Weibull distribution**) ,

Minimum number of data will be **n=20** per one irradiation condition (dose, temperature).

Issue 3 : Lack of sufficient empirical evidence

A new strategy : Probability based design method (Reliability design method)

Probability of fracture $P = P_f[Strength < Load] = \int_0^{\infty} f_S(s)\left[\int_0^{s} f_R(r)dr\right]ds$



Probability of fracture after irradiation $P^{irrad.}(D) = \int_0^{\infty} f_S(s)\left[\int_0^{s} f_R^{irrad.}(r, D)dr\right]ds$

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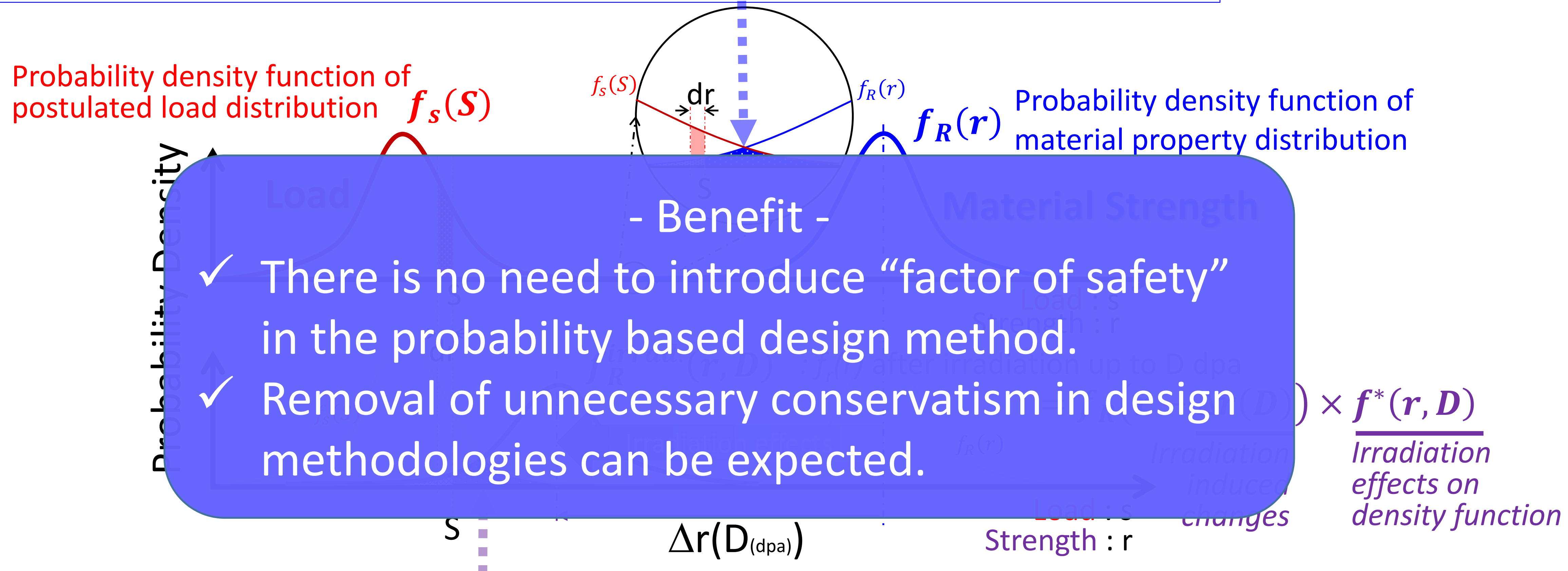


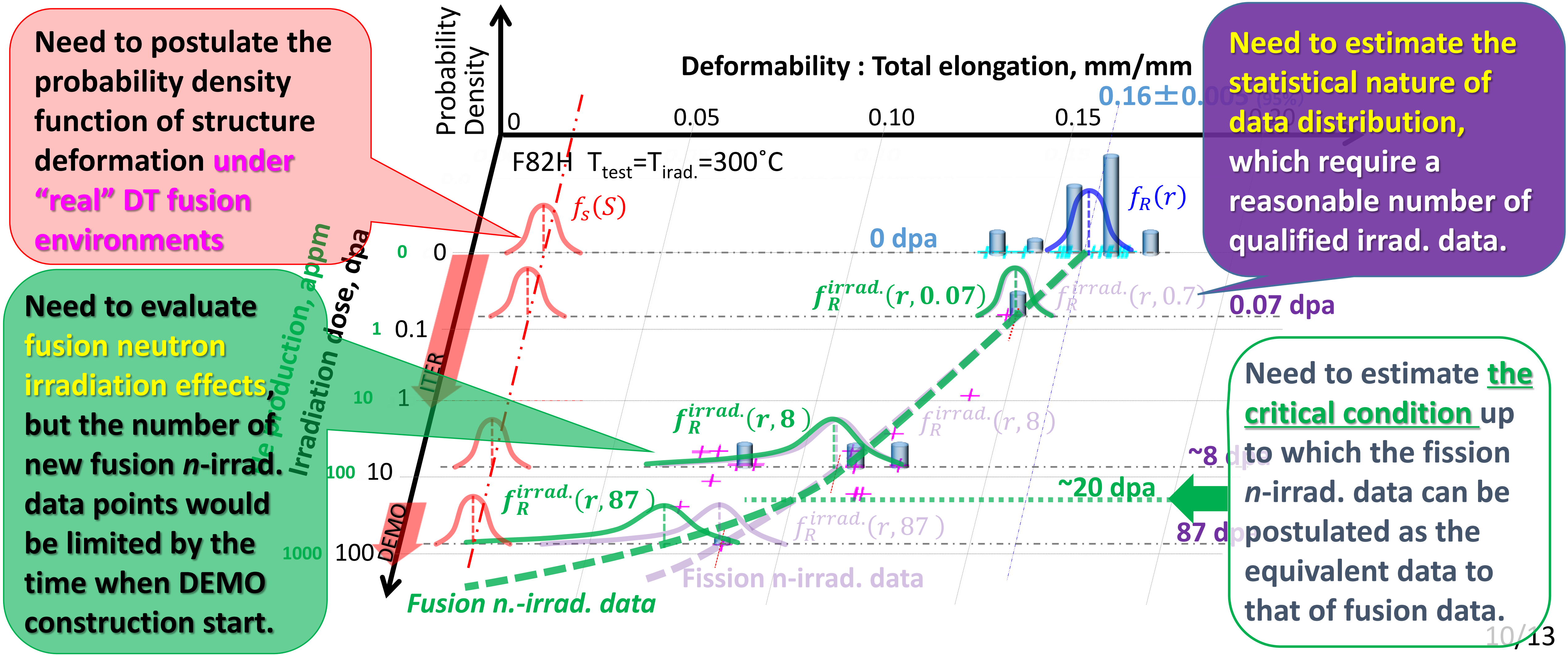
- Benefit -

- ✓ There is no need to introduce "factor of safety" in the probability based design method.
- ✓ Removal of unnecessary conservatism in design methodologies can be expected.

Probability of fracture after irradiation $P^{irrad.}(D) = \int_0^{\infty} f_S(s)\left[\int_0^{s} f_R^{irrad.}(r, D)dr\right]ds$

Issues in adopting probability based design method

A great deal of effort is needed to postulate the probability density function of operation/load conditions of structure and property changes of structural materials.



How to estimate the fusion *n* irradiation effects with a limited number of fusion *n* irrad. data?

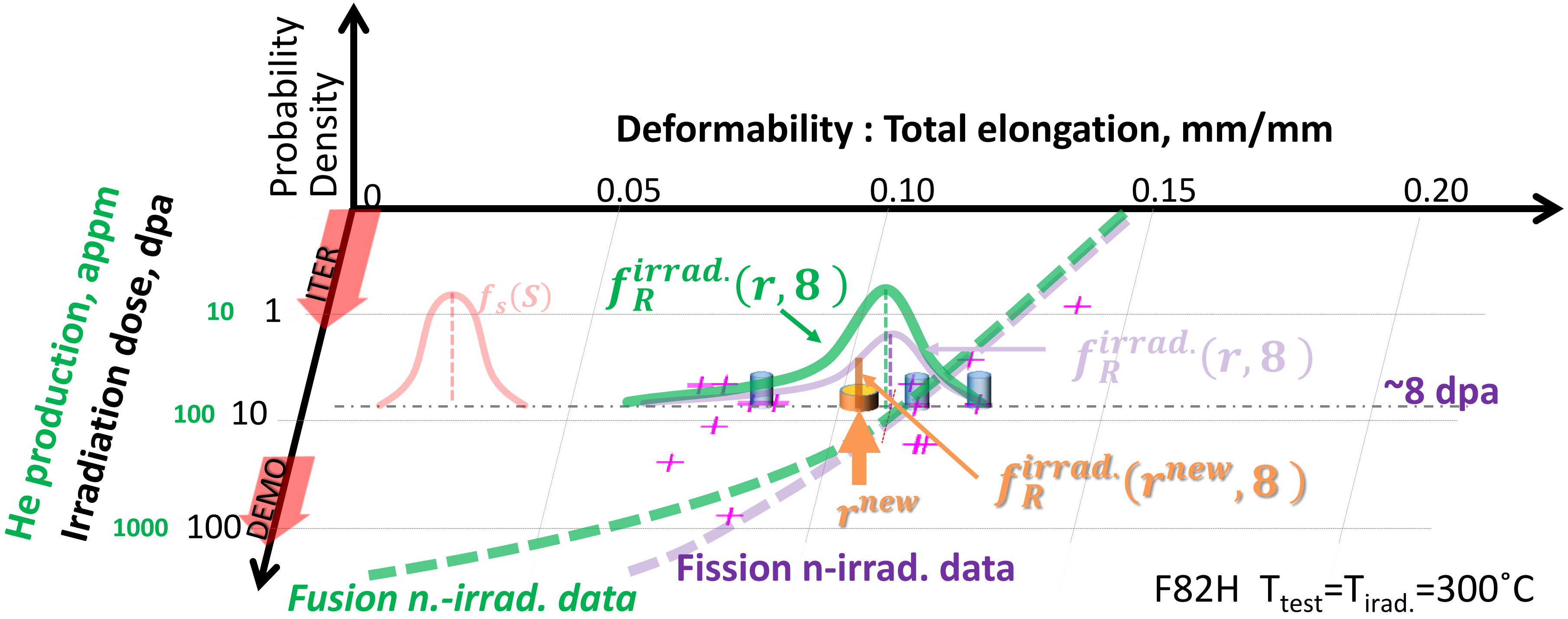
Step 1: Obtain fission *n* irradiation data distribution $Fission\ f_R^{irrad.}(r, D)$

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 $Fission\ f_R^{irrad.}(r, D)$

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

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



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It is important to estimate **an appropriate function** for the original property data distribution $\boldsymbol{Fission\ f_R^{irrad.}(r, D)}$, to update the function to $\boldsymbol{Fusion\ f_R^{irrad.}(r, D)}$ for fusion n irradiation data.

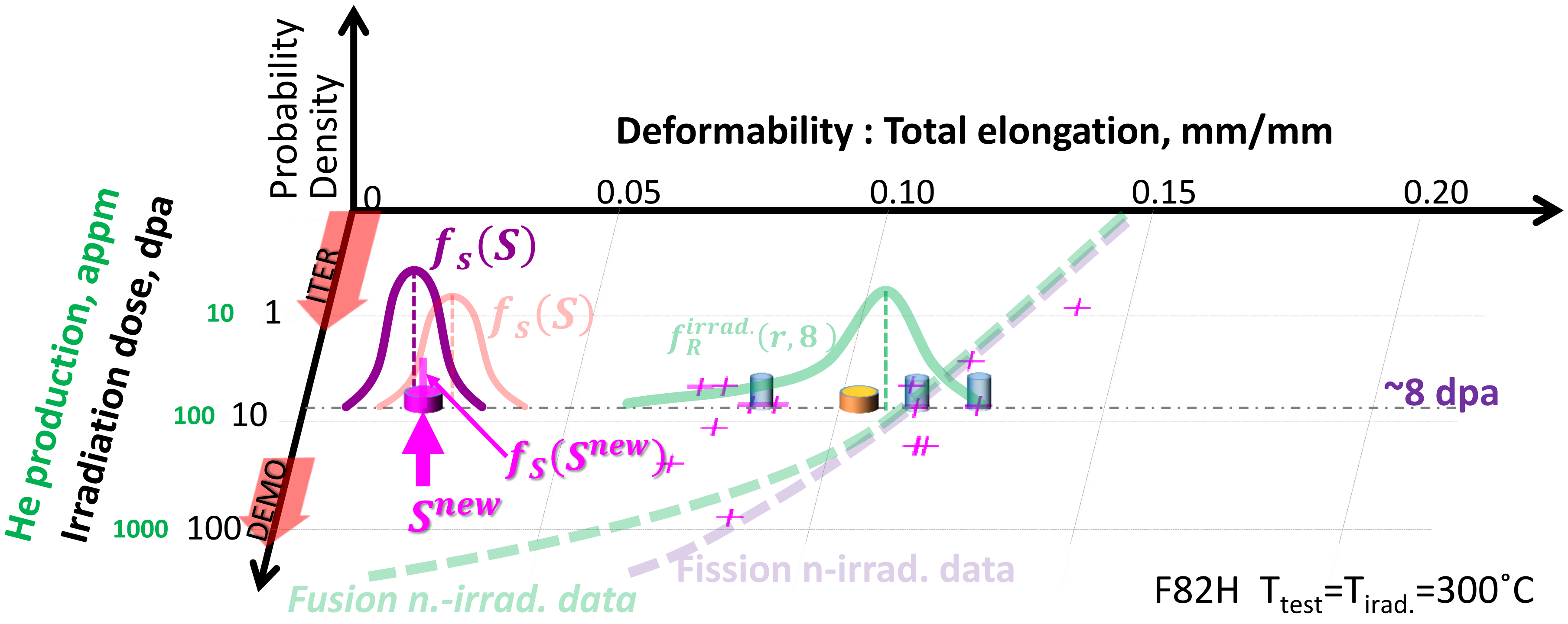
*Essential to have **theoretical understandings on irradiation effect** to select **an appropriate function type** to make Bayesian inference work.*

[NOTE] This approach is applicable up to "the critical condition" up to which we may assume fission data is expected to be similar to that of fusion data.

How to postulate the load conditions under DT ?

1. Obtain load distribution $f_S(S)$ in a similar environment (JT-60SA, JET, etc.)
2. Observe new load condition S^{new}, **obtained in a real DT environment.**
3. Calculate probability **to observe load condition, S^{new}, $f_S(S^{new})$**, based on $f_S(S)$
4. Postulate load distribution of in-vessel structure under DT operation $f_S(S)$,

By Bayesian inference: $DT\ operation\ f_S(S) \propto f_S(S^{new}) \cdot Similar\ enviroment\ f_S(S)$



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$f_S(S)$

- ✓ To **define the probability density function of load conditions** and to **validate the design method**, it is essential to accumulate relevant data* of in-vessel component tested in non-DT burning plasma machines (JT-60SA etc.)
  ** loaded stress variation, failure rate, fracture rate, crack initiation/propagation rate, etc.*
- ✓ **Development of inspection methodology** for tested (and irradiated) component is indispensable to endorse this approach and to mitigate the uncertainty of these estimations.
- ✓ ITER DT operation (ITER-TBM, Divertor) is a precious opportunity to **update the function** for DEMO operation to secure availability and inspection period.

Fusion n.-irrad. data

F82H $T_{test}=T_{irad.}=300^\circ C$

Summary

The strategy of fusion in-vessel structural material development toward fusion DEMO is addressed with special emphasis on the lack of irradiation data available and limitations on confidence levels in concluding on allowable performance limits.

Technical issues under the existing design code regarding irradiation effects were indicated.

- The impact of deformability reduction due to irradiation was discussed.
  - ✓ Need to develop design rule and methodologies considering the impact of the deformability and/or fracture toughness reduction.
- The limitation of irradiation data reliability was indicated.
  - ✓ Required to obtain a reasonable amount of fission neutron irradiation data to define its statistical nature, in order to estimate the “real” fusion data, up to "the critical irradiation dose level".
- Difficulty to define an appropriate "safety factor" without "empirical” approach, was suggested.
  - ✓ A new strategy based on probabilistic approaches was proposed.

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The strategy of fusion in-vessel structural material development toward fusion DEMO is addressed with special emphasis on the lack of irradiation data available and limitations on confidence levels in concluding on allowable performance limits.

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The issues and requirements described in this presentation will be the target of new phase of international collaborations.

Japan - EU : Broader Approach Phase 2
Japan - US : QST/DOE collaboration under the implementing agreement between MEXT and DOE

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  - ✓ Need to develop design rule and methodologies considering the impact of the deformability and/or fracture toughness reduction.
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