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The Strategy of HTGR Fuel Development

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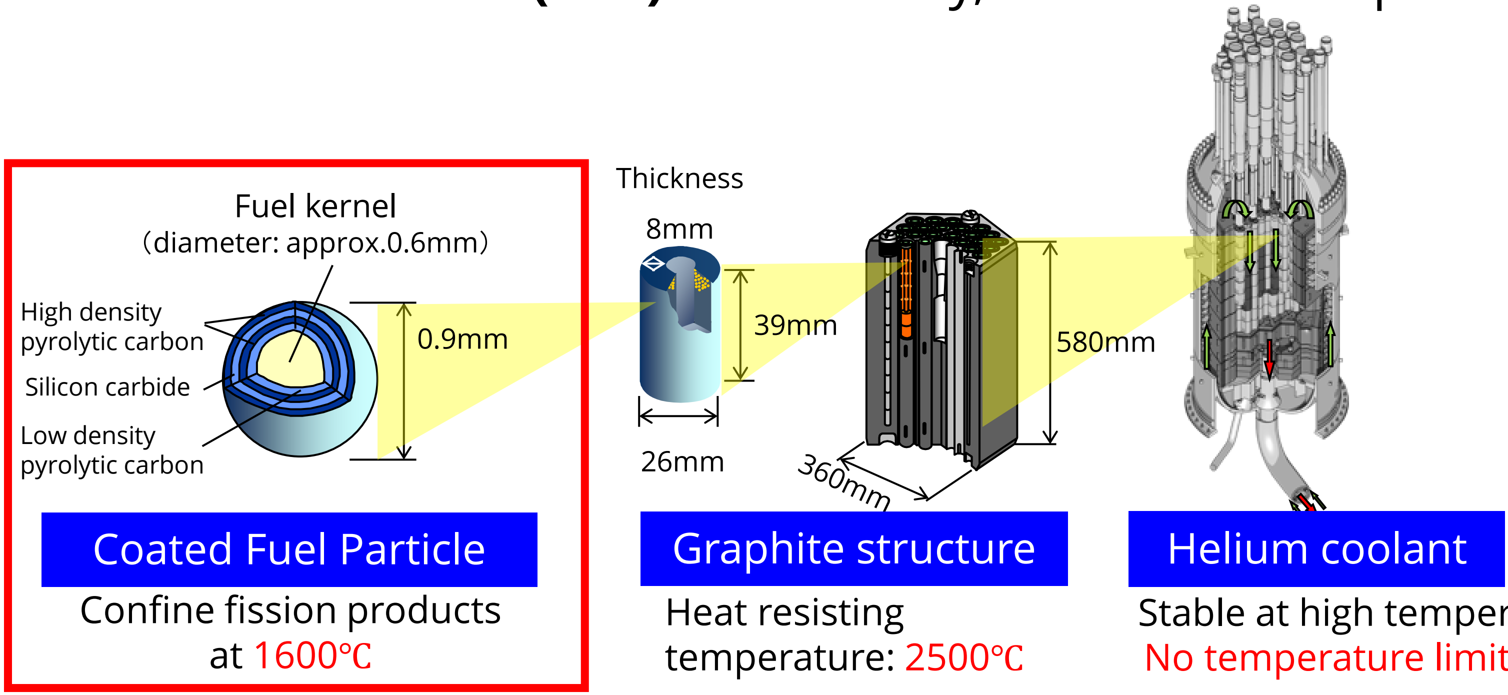
Contents

Overview - HTGR inherent safety features

- HTGR core cannot physically melt because of the inherent safety characteristics due to the following key elements.
  - **Helium coolant** – chemically inert
  - **Graphite structure** – high thermal conductivity
  - **Coated Fuel Particle (CFP)** – Refractory, contain fission products



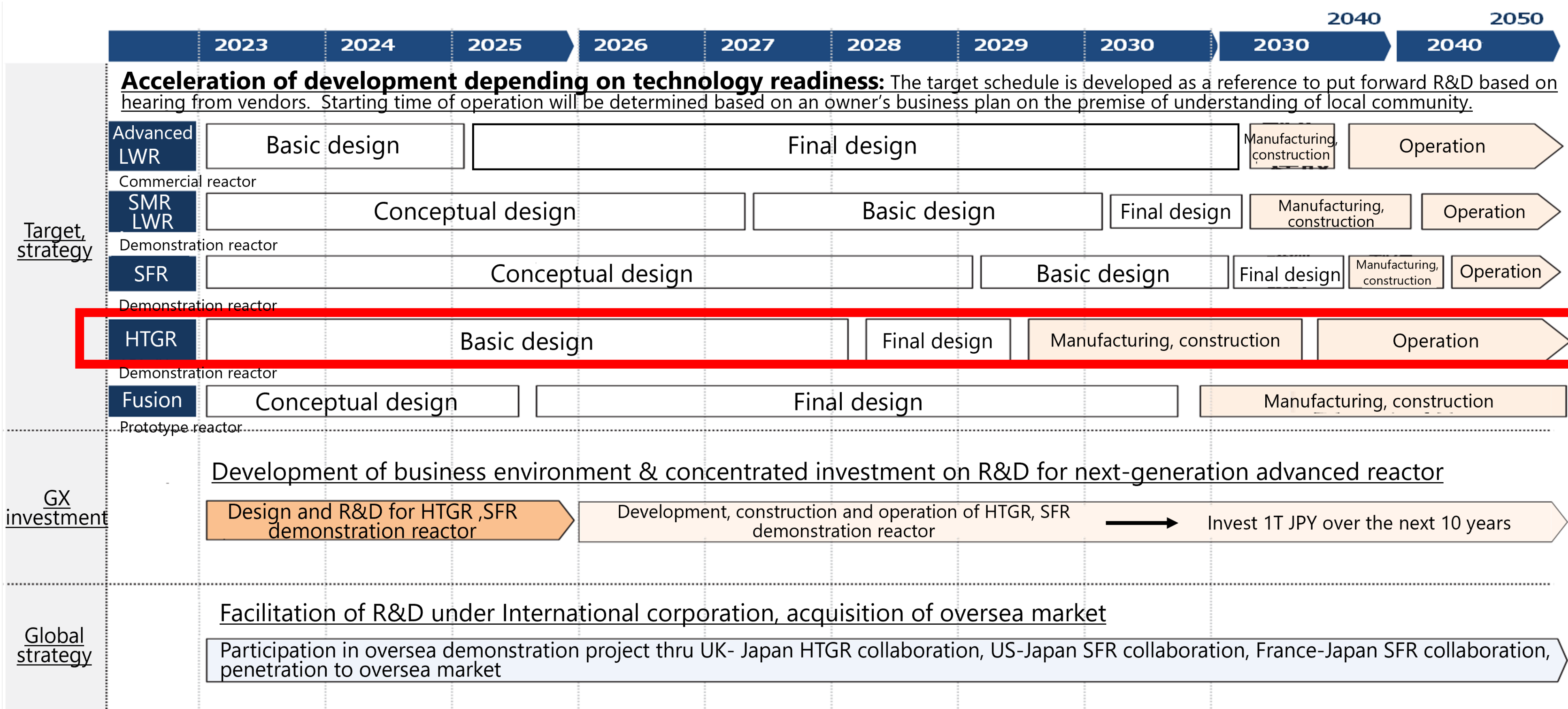
CFP is at heart of the unique features of the HTGR.

Reliable and economical CFP development is the key issue.

Sakaba, 18th Annual Symposium of the JAEA's Activities (2023).

Overview - toward the demonstration reactor

- HTGR has attracted significant attention toward carbon neutrality.
  - ➢ "Basic Policy for the Realization of GX" outlines a roadmap for the HTGR demonstration reactor starting operation in late 2030s.
- To meet demonstration reactor schedule, it is necessary to draw up fuel development roadmap.
  - ➢ Make the most of HTTR licensing data to minimise development elements.



The Basic Policy for Realization of GX Reference Materials, https://www.cas.go.jp/jp/seisaku/gx_jikkou_kaigi/pdf/kihon_sankou_en.pdf, (accessed on May 23, 2025).

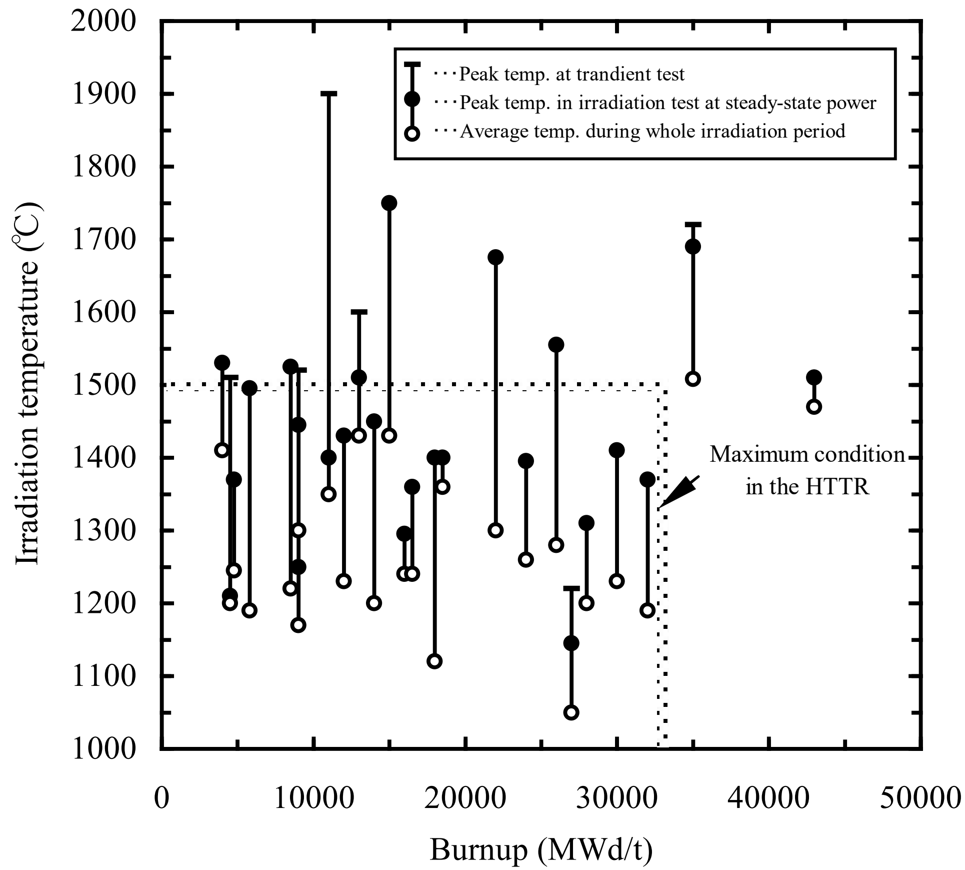
HTTR licencing data (1/2)

- For the licencing of HTTR, fuel integrity was confirmed up to 43GWd/t burn-up under normal operation condition through experiments.
- In terms of fuel integrity, **three phenomena** during operation shall be considered.

- **Internal pressure failure**

➢ As irradiation proceeds, internal pressure of CFP is increased due to production of gaseous fission products and CO gas.

➢ Regarding internal pressure failure, HTTR fuel integrity up to 43GWd/t burn-up was confirmed by the experiments.

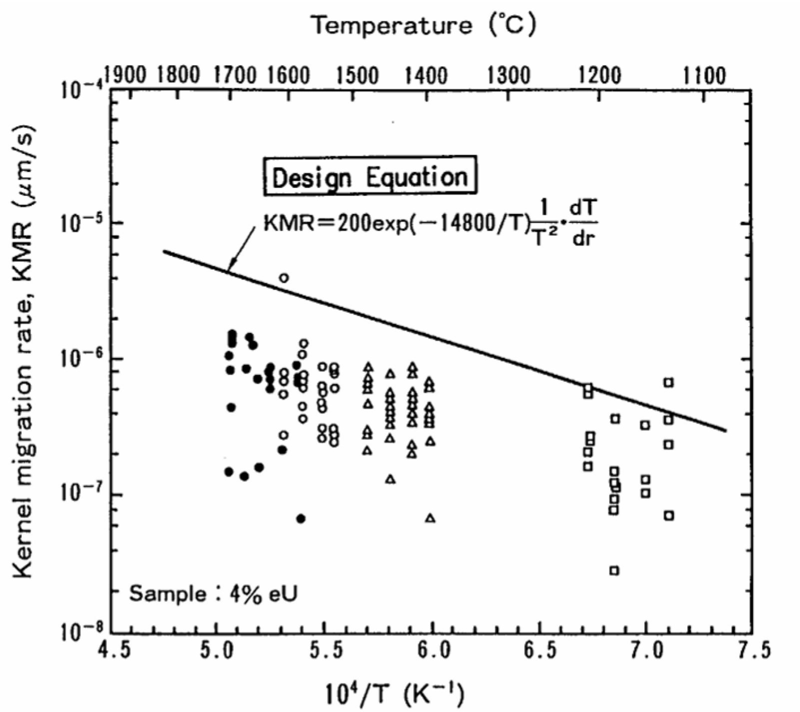


Irradiation result in JAEA

Saito, et al., JAERI-1332 (1994).

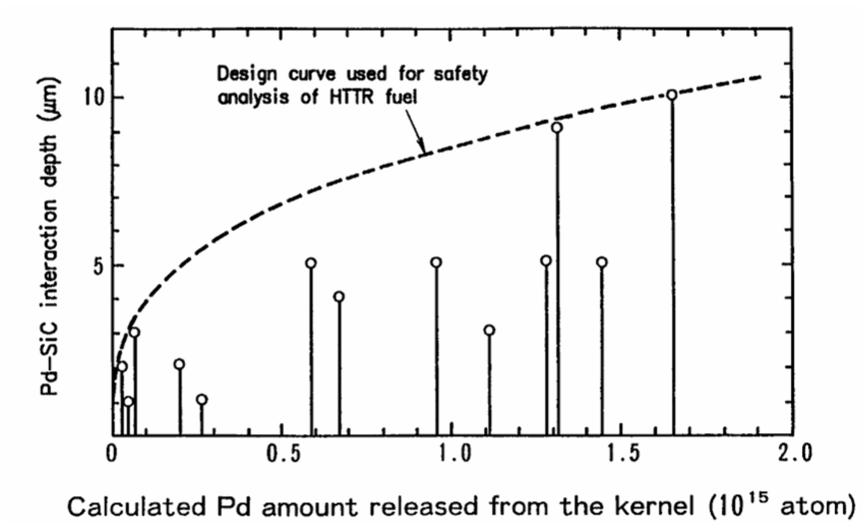
HTTR licencing data (2/2)

- **Ameba effect**
  - Ameba effect is a phenomenon in which the fuel kernel migrates into the coating layer.
  - Using design equation, the integrity of HTTR fuel to 70GWd/t burn-up was confirmed.



Relation between kernel migration rate and fuel temperature

- **Pd-SiC corrosion**
  - Pd-SiC corrosion is a phenomenon in which Pd, fission product, corrodes SiC layer. This affects the integrity of the coating layer.
  - Regarding the HTTR fuel design, evaluation curve up to 50GWd/t burn-up was confirmed.



Relation between Pd corrosion depth and the amount of released Pd

Saito, et al., JAERI-1332 (1994).

Basic concept of fuel development plan (1/2)

Demonstration reactor ~late 2030s

- Maximise the HTTR' s achievements, minimise development elements and improve the economics by increasing the burn-up.
  - ➢ The burn-up of 1st loaded fuel shall be 40GWd/t to utilise HTTR licensing database.
  - ➢ The burn-up of 2nd loaded fuel shall be 60GWd/t by acquire missing data from additional test to improve the economics.
  - ➢ UO_2 kernel with proven fuel design in HTTR are used.

Commercial reactor ~2050s

- Incorporate the elements necessary for further improvements in economic efficiency and safety to strengthen competitiveness.
  - ➢ The burn-up of the fuel shall be 160GWd/t by further improving safety.
  - ➢ Develop UO_2 kernel with ZrC coating.

	Burn up	**Kernel**
HTTR	40 GWd/t	UO_2
Demo reactor	60 GWd/t	
Commercial reactor	160 GWd/t	UO_2 + ZrC coating

Basic concept of fuel development plan (2/2)

Action items

Demonstration reactor

- Newly manufacture the fuel up to 40GWd/t burn-up and confirm fuel integrity through irradiation test.
- Acquire irradiation data up to 60GWd/t burn-up regarding Pd-SiC corrosion and heat transient.

Commercial reactor

- Manufacture the fuel up to 160GWd/t burn-up with ZrC coating and confirm fuel integrity through each irradiation test.

	GWd/t	Fuel load	Irradiation test	Duration
Demonstration reactor	40	Late 2030s	Irradiation for confirming soundness	3 years
	60	2040s	Irradiation for confirming kernel soundness: Pd-SiC interaction	2 years
			Irradiation of heat transient condition	8 years
Commercial reactor	160	Late 2040s	Irradiation for confirming kernel soundness: Pd-SiC interaction, Ameba effect	6 years
			Irradiation of steady and heat transient condition	8 years

Action items for development of HTGR fuel are identified.

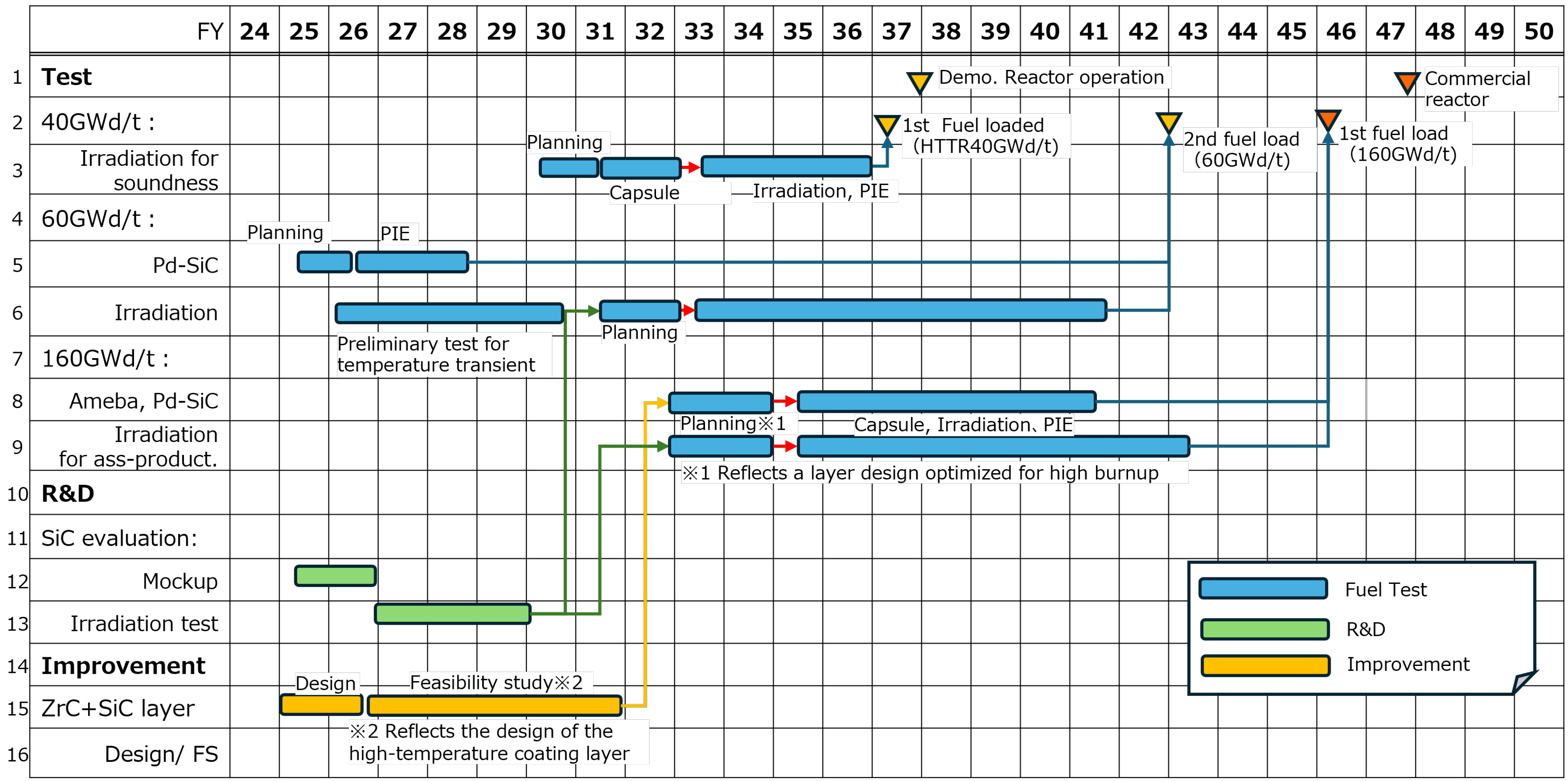
Fuel development roadmap

Demonstration reactor ~late 2030s

- Confirm 1st loaded fuel integrity by irradiation test from 2030.
- Acquire 2nd loaded fuel data through the preliminary irradiation test by 2030.

Commercial reactor ~2050s

- Acquire irradiation data up to 160GWd/t burn-up from early 2030s, utilising the outputs of R&D and other improvements.



R&D items - SiC layer fracture strength evaluation

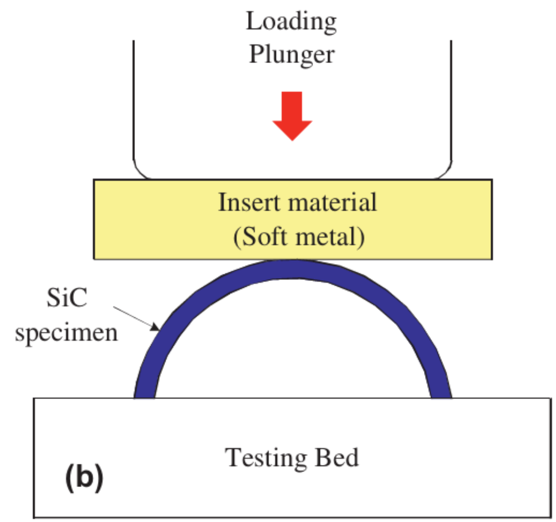
- To predict the internal pressure failure, it is necessary to obtain SiC layer strength data.
- There are some issues in current internal pressure failure prediction model.
  - ➢ SiC strength data is only two data (2).
    - ✓ SiC strength is underestimated in the evaluation of high burn-up fuel.
  - ➢ The effect of the volume of the SiC layer should be considered (1).

- Acquire SiC layer fracture strength data considering fast neutron fluence and SiC layer size.
  - ➢ It is necessary to prepare SiC hemispherical shell samples.

$$f(t) = 1 - \exp\{-\ln 2 \times \left(\frac{\sigma(t)}{\sigma_0}\right)^m \times V_{SiC}\} \qquad (1)$$

$$\sigma_0 = 834 - 88\phi \qquad (2)$$

Where,
f(t) : probability of failure for SiC layer in time t
$\sigma(t)$: tensile stress [MPa]
σ_0 : fracture strength of SiC layer [MPa]
m : Weibull modulus
V_{SiC} : Volume of SiC layer [m^3]
Φ : Fast neutron fluence [$10^{25}/m^2$]



SiC layer fracture strength test as developed by ORNL

Sawa, et al., Journal of Nuclear Science and Technology, 33, 9, 712-720 (1996).

Hosemann, et al., Journal of Nuclear Materials, 442, 133-142 (2013).

Summary

- Importance of CFP development
  - ➢ HTGR core cannot physically melt because of inherent safety characteristics and CFP plays on important role by confining FPs at 1600℃.
  - ➢ Therefore, reliable and economical CFP development is the key issue.

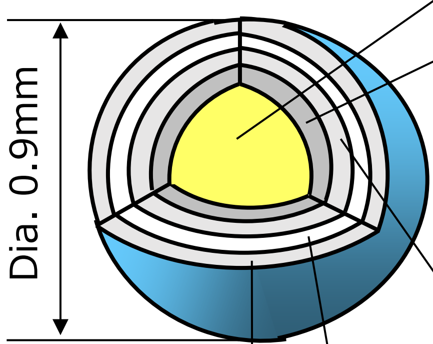
- Past performance of fuel design
  - ➢ Three phenomena during operation shall be considered as internal pressure, ameba effect and Pd-SiC corrosion.
  - ➢ Fuel irradiation test and PIE have been performed to design HTTR fuel and confirmed fuel integrity against phenomena mentioned above.

- Draw up HTGR fuel research and development plan
  - ➢ By maximum making use of experience, development plan and roadmap have been drawn up to meet demonstration and commercial reactor requirements.
  - ➢ SiC layer fracture strength evaluation has been identified as R&D to achieve high burn-up fuel such as 160 GWd/t.

JAEA promotes fuel development toward HTGR commercialization.

Appendix

Appendix: Coated Fuel Particle



Fuel Kernel

Porus Carbon Buffer

Absorb the kinetic energy of fission fragments ejected from fuel kernel surface and to provide space for the accumulation of gaseous fission products and carbon monoxide. Protects the IPyC layer from recoil fission fragments and fuel-core swelling.

Inner Pyrolytic Carbon（IPyC)

Protects the kernel from corrosive gases liberated during the SiC coating process.

First load-bearing barrier and provides structural support for the SiC layer.

Protects the SiC layer from fission products and CO during operation by retaining gaseous fission products.

Silicon Carbide (SiC)

Structural strength of the particle. Provides diffusion barrier for internal fission gases and impermeability to metallic fission products.

Outer Pyrolytic Carbon（OPyC)

Protects the fuel particle during formation of the fuel compact. Provides structural support for the SiC layer and acts as additional barrier to the release of gaseous fission products in the event of SiC failure.

Source: PNNL-31427