Overview of Japanese Water Cooled Ceramic Breeder Test Blanket Module Manufacturing and Assembly Technologies

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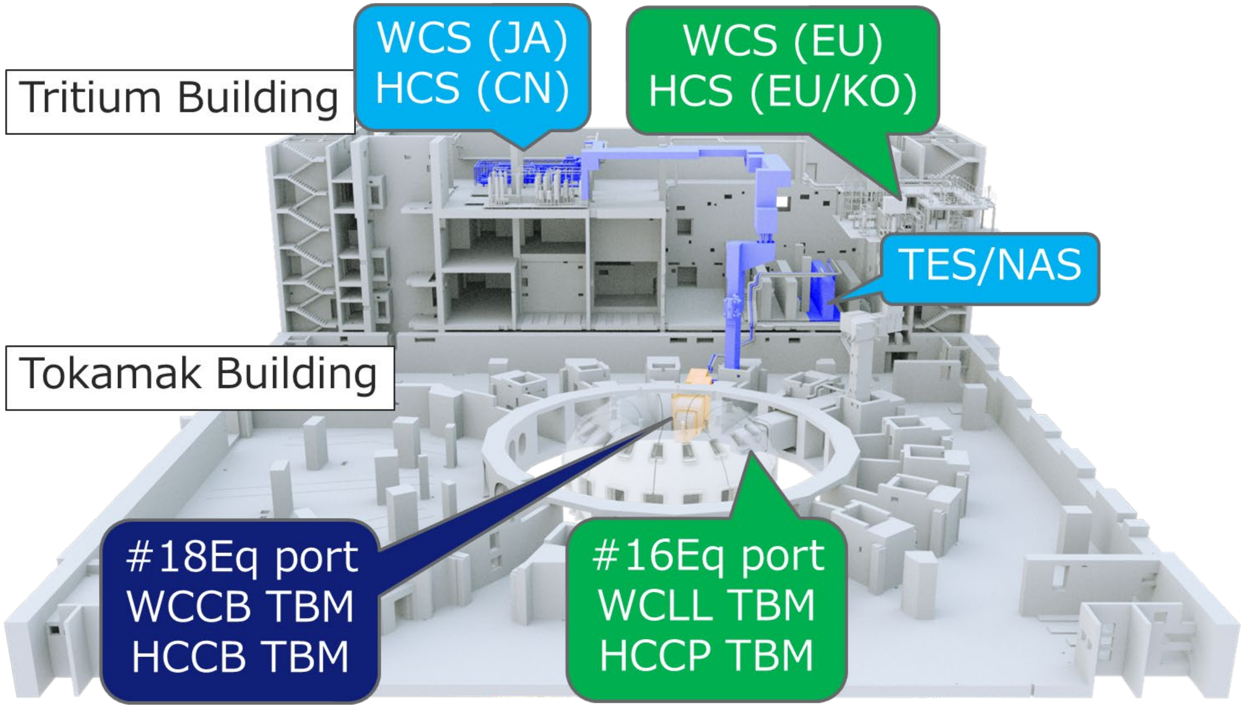
Contents

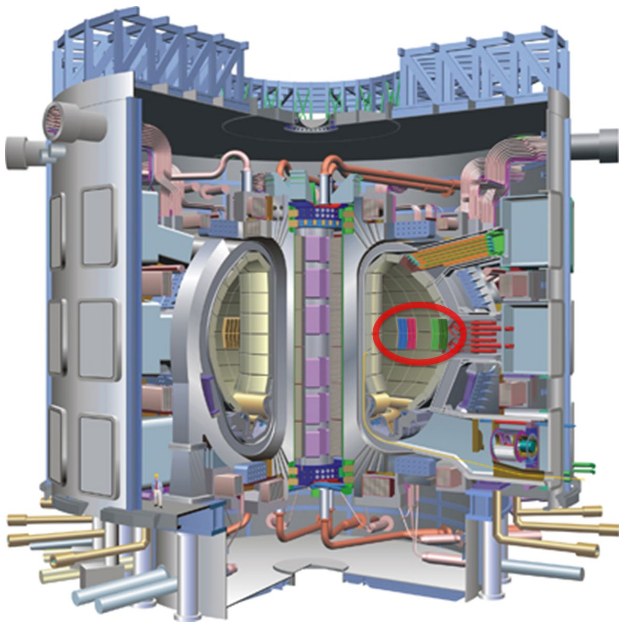
Background

- Breeding blankets are essential for tritium production and heat extraction in fusion reactors.
- The Water-Cooled Ceramic Breeder (WCCB) concept leverages PWR experience and known material behavior under neutron irradiation.
- Japan is developing a WCCB Test Blanket Module (TBM) for ITER to validate this concept experimentally.



Overview of Japanese WCCB-TBM Design

Water cooled ceramic breeder blanket	
Structural material	Reduced activation ferritic martensitic steel, F82H
Tritium breeder	Φ1 mm Li_2TiO_3 pebble
Neutron multiplier	Φ1 mm Beryllium pebble
Coolant	15.5 MPa / 280 °C water
Sweep gas	0.14MPa helium gas with 1% H_2



Cross-sectional schematic illustration of the TBM showing with material allocations and cooling channels.

https://doi.org/10.1016/j.fusengdes.2020.112050

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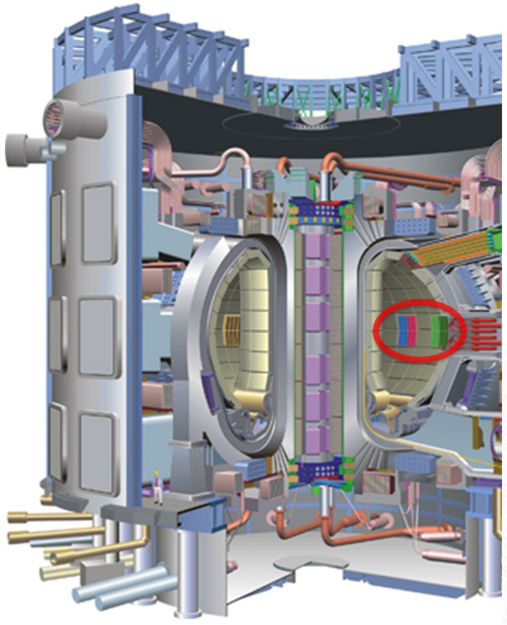

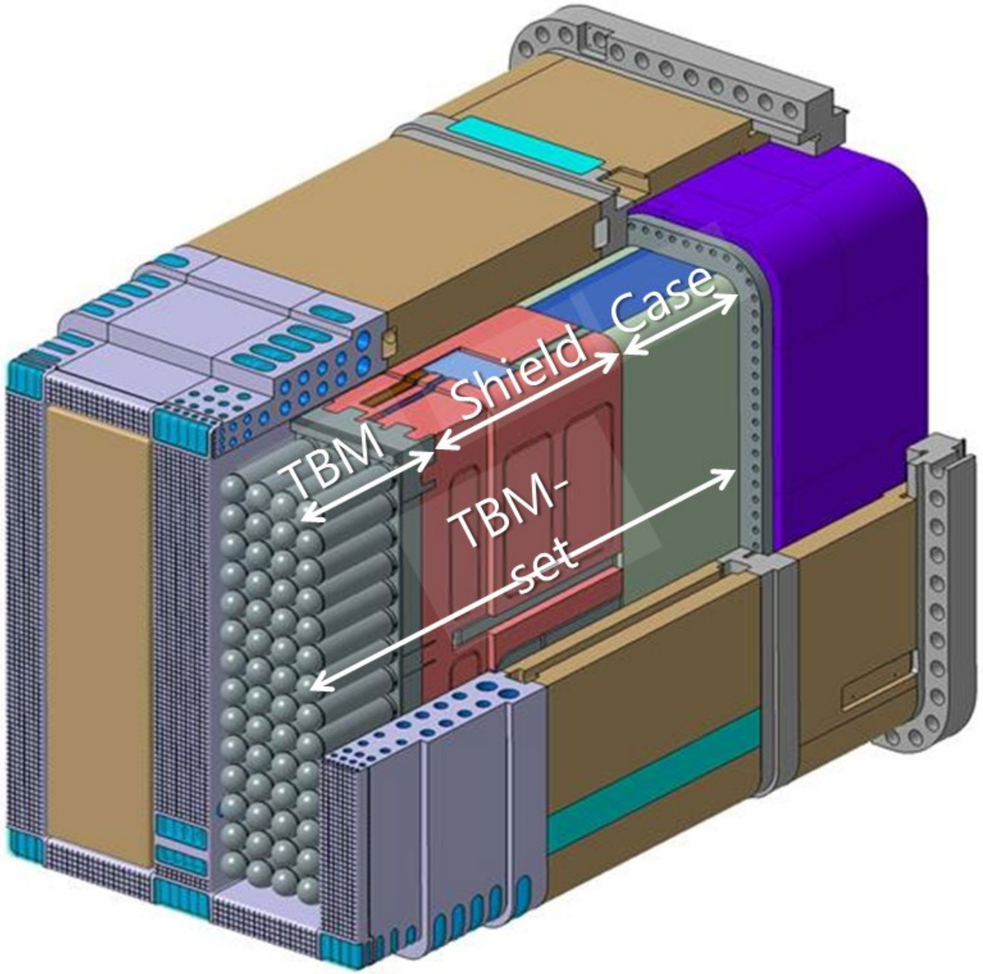

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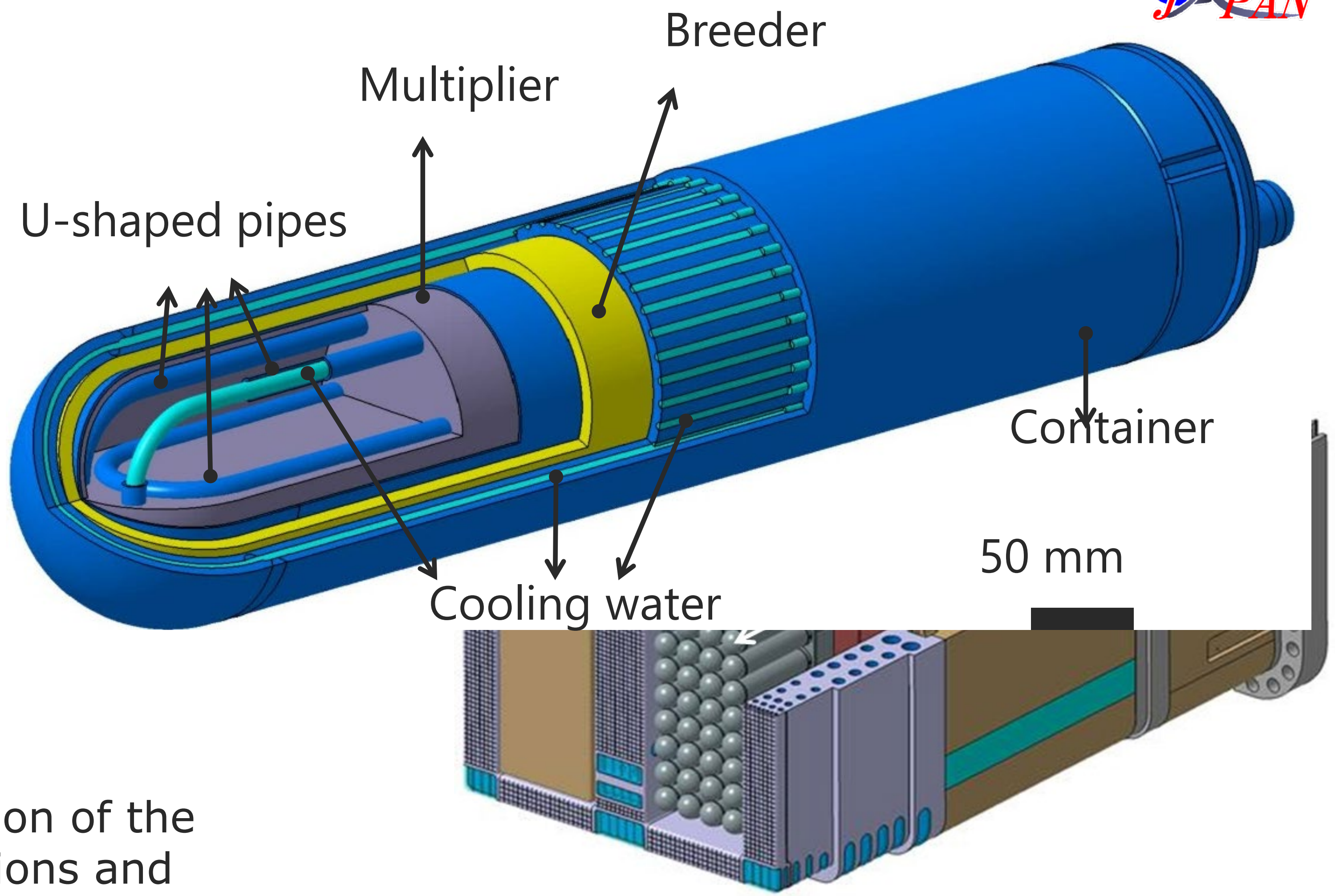

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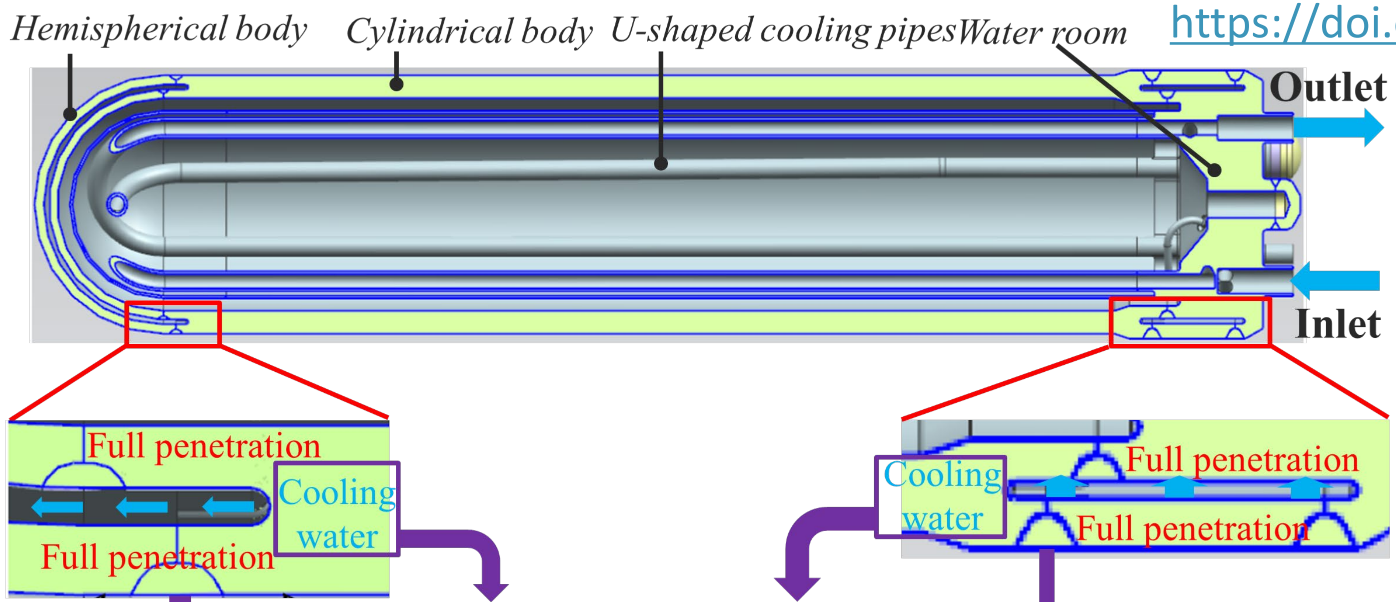


https://doi.org/10.1016/j.fusengdes.2023.113637

Design conditions	
Pressure [MPa]	Temperature [°C]
17.0	343

Pressure boundary

No harmonized standard defining material properties and **weldability** for **F82H in RCC-MRx**.

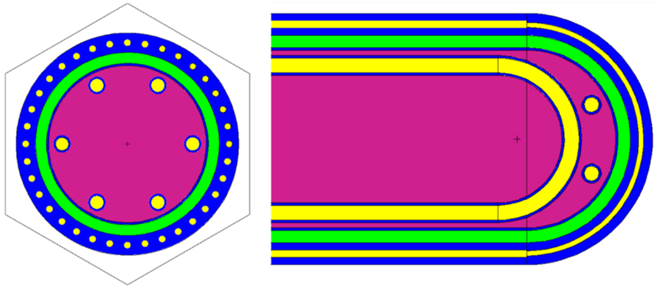
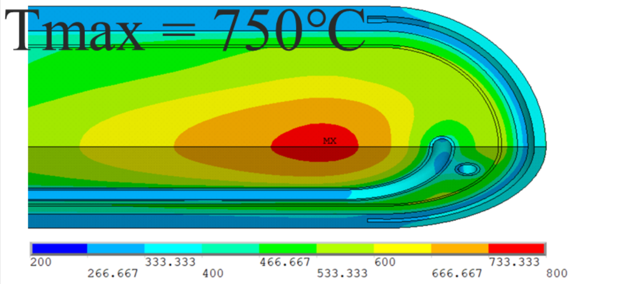
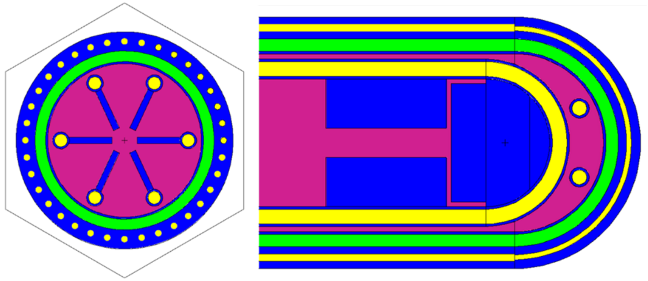
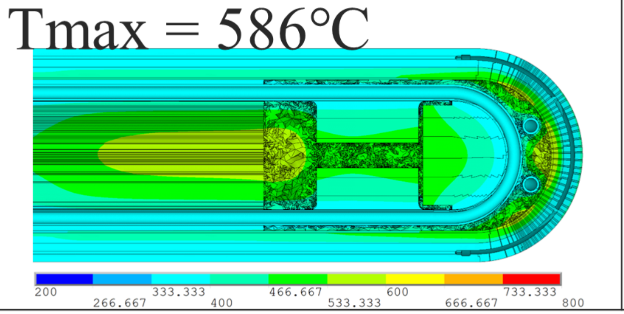
\+

Third party validation (**N2 ESPN CAT. IV** is applied to WCCB TBM)

- Coolant manifold locates at the back, and distributed to container and internal cooling pipes.
- Helium gas flows into breeder layer to sweep out produced tritium.
- The cylindrical submodule remains within the elastic range under the expected loading conditions in ITER, and the cyclic loads are kept below the fatigue limit.

Temperature distribution and TBR in WCCB-TBM sub-module

✓ The container's structural integrity including LOCA condition has been confirmed according to RCC-MRx Edition 2018 criteria.

	Submodule structure	Temperature distribution	TBR
U-shaped cooling pipes			1.12
Cooling pipes w/ fins			1.09

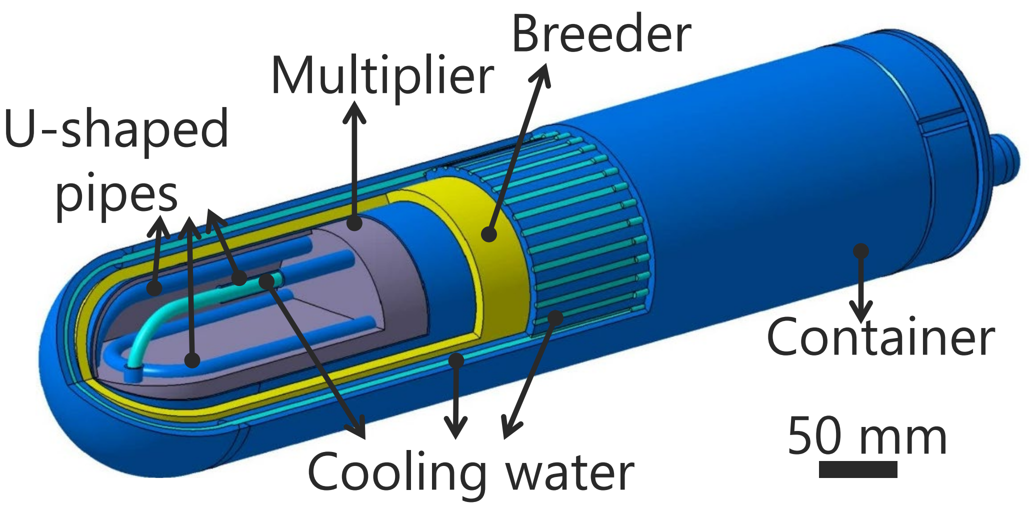
➢ Cooling fin was applied to decrease multiplier temperature to avoid temperature excursion due to Beryllium – water reaction in case of LOCA.

https://doi.org/10.1016/j.fusengdes.2023.113637

Structural Design of Container

❑ Radial-axis cylindrical structure ensures:

- Stable containment of high-pressure coolant
- Efficient heat dissipation to vacuum vessel in case of failure
- Even when cooling water leaks into its interior, the cylindrical container remains within the elastic range of F82H.

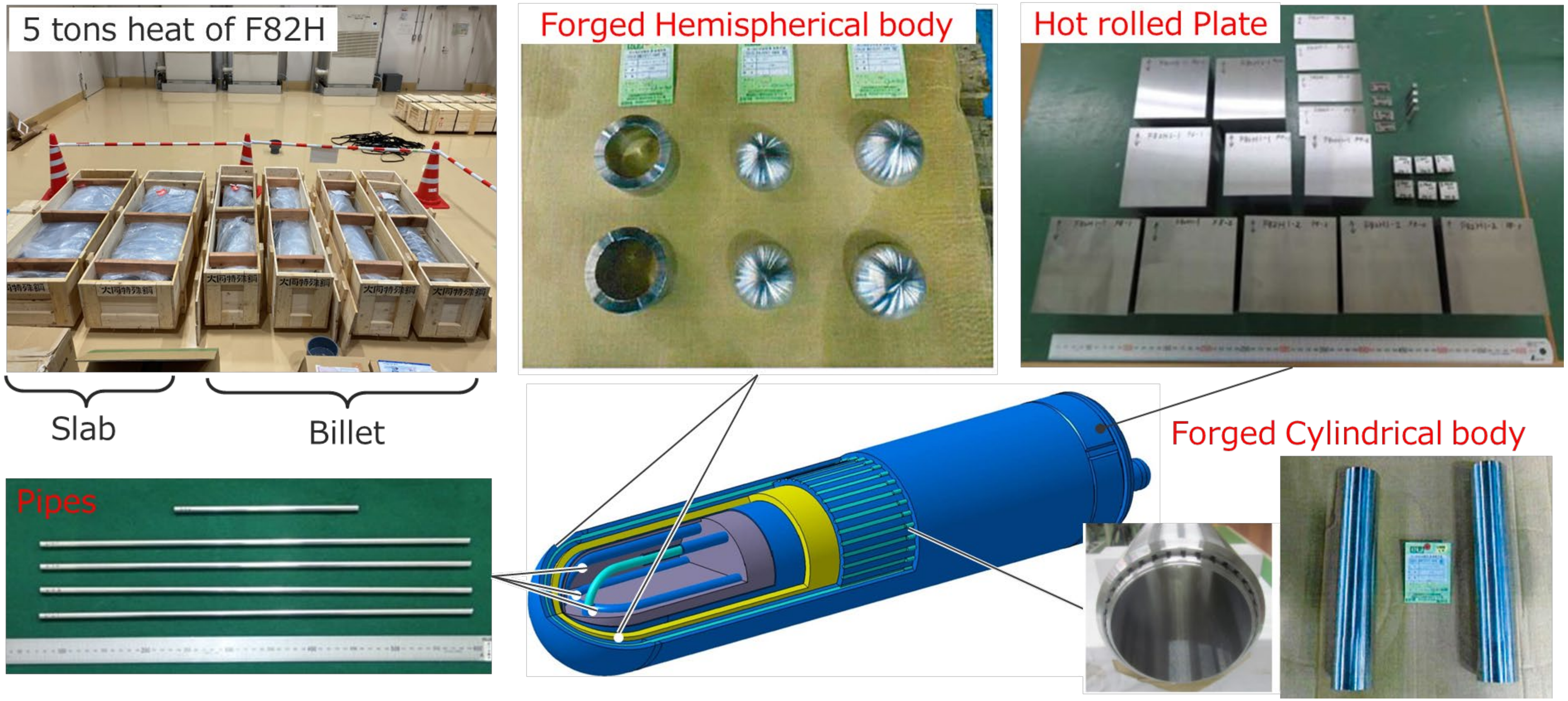


https://doi.org/10.1016/j.fusengdes.2018.04.105

MANUFACTURING AND ASSEMBLY

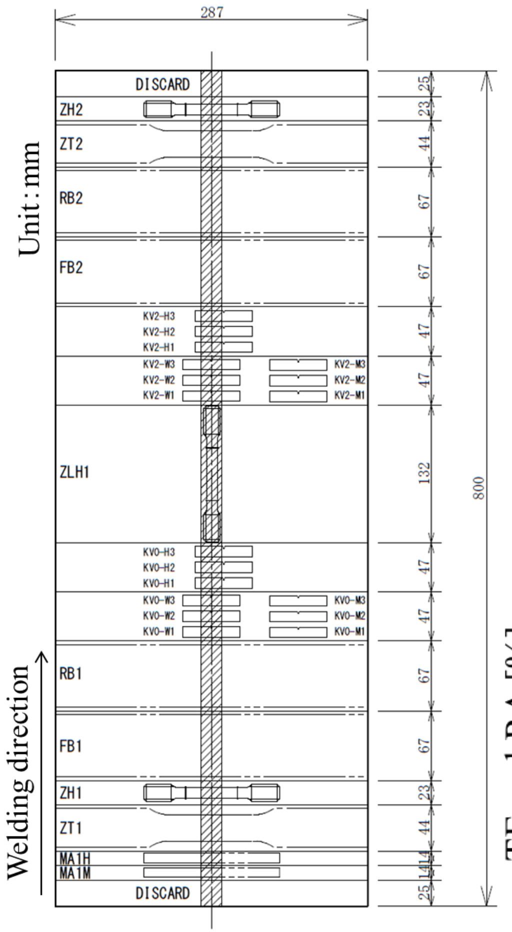
Structural material, F82H

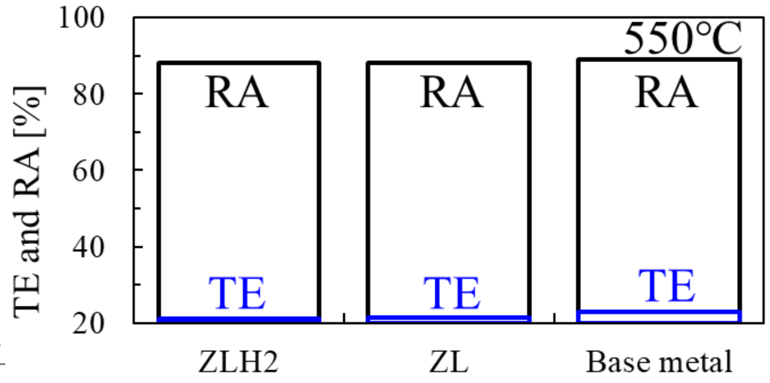
DOI: 10.1088/1741-4326/ac269f



- 5 tons heat of F82H has been produced taking account for European harmonized standard.
- F82H is to be used as TBM using NPMA without registering RCC-MRx.
- Material properties including long term properties were summarized as material file.

General weldability of F82H





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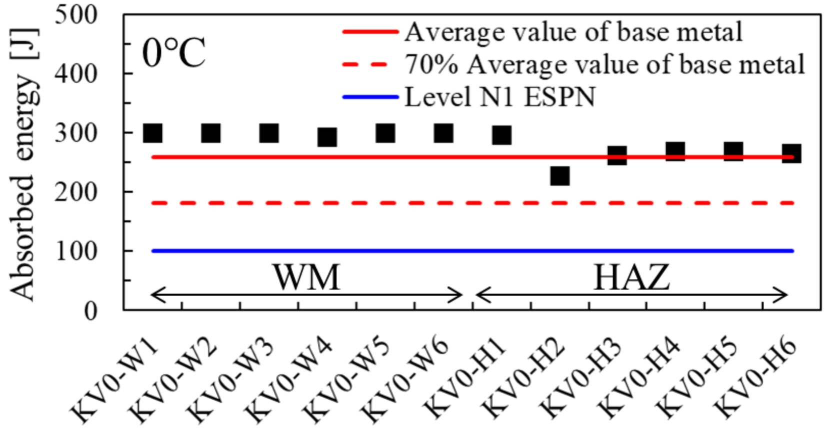
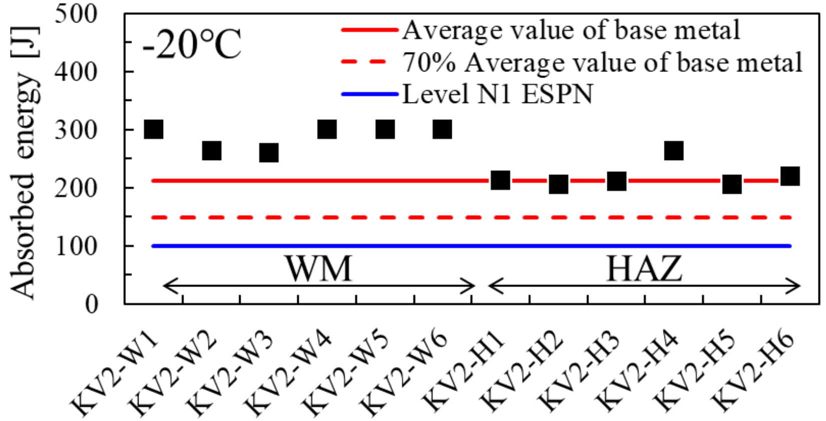
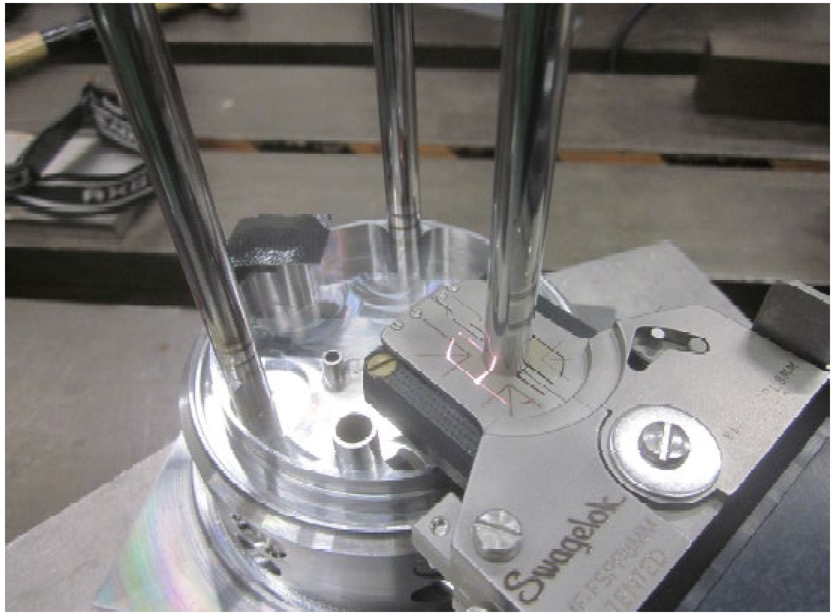




- General weldability of F82H was assessed with a third party inspector according to European harmonized standard. **No show stopper was found.**

Welding procedure for TBM manufacturing



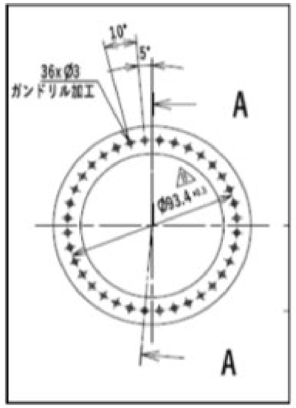
WPS-R1006S
TIG welding between U-shaped pipe and manifold
OD: 8 mm
Thick: 1 mm, I-butt weld w/o filler
Single path w/ pure argon gas for backing and shield

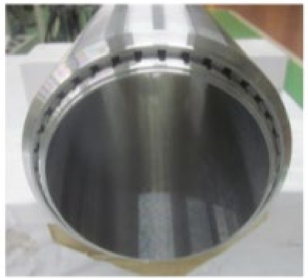
https://doi.org/10.1016/j.fusengdes.2024.114227

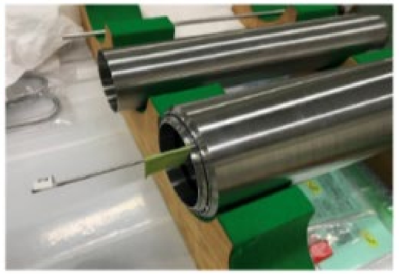
Material	Thick (mm)	Filler	Note
F82H	3.3	Φ1.2	Cylindrical body / Inner hemisphere
F82H	1	n/a	Cylindrical body / Separator
F82H	1.9	Φ1.0, 1.2, 1.6	Cylindrical body / Inner hemisphere, Backing
F82H	5.6	Φ1.2	Cylindrical body / Outer hemisphere
F82H	**1**	**n/a**	**U-shaped pipe / manifold**
F82H	0.35	n/a	U-shaped pipe / manifold, fillet
F82H	0.7	n/a	Sweep gas line
F82H	0.2	Φ1.0, 1.2, 1.6	Plug, fillet
F82H	0.35	Φ1.0, 1.2, 1.6	Plug & manifold, fillet
F82H	1	n/a	U-shaped pipe / manifold
F82H	5	Φ1.2	Cylindrical body / manifold
F82H	5.6	Φ1.0, 1.6, 2.0	Cylindrical body / manifold
F82H	5.6	Φ1.0, 1.6, 2.0	Cylindrical body / manifold
F82H/Inconel	1	n/a	Pipes
Inconel/SS316L	1	n/a	Pipes

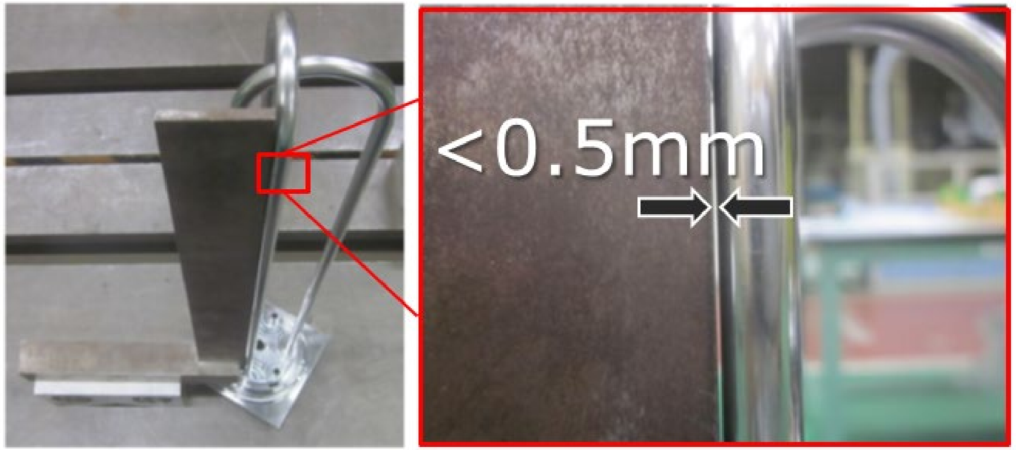
TIG welds were applied. Full-penetration was achieved at the pressure boundaries.

Inspection during assembly









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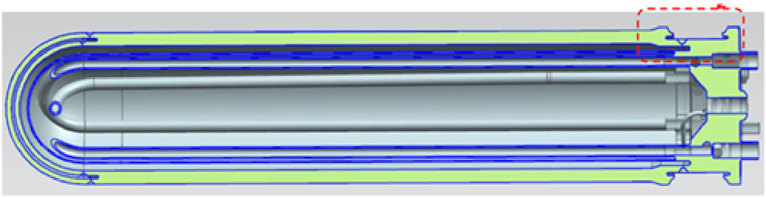
Inspection	Interest	Results
Penetrant tests	Elbow in the U-shaped tubes	No indication
	Welds	No indication
Dimensions	Drilled cooling channels	Insert angle< 5/100°
		Position in cylinder thickness <±0.2 mm
Square	U-shaped tube	< 0.5 mm
Ovalization	U-shaped bend	$(d_{max}-d_{min})d_e < 7\%$ where d_e: outside diameter before bending
Distortion	Welds	Max. 2.2 mm in radial direction. Needs to be compensated by parts dimensions

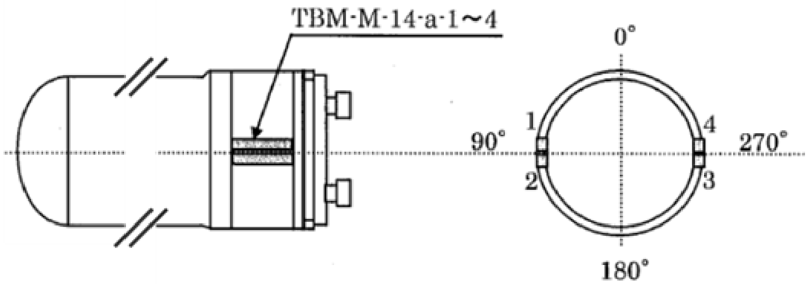
Through the prototyping process, we obtained data on the dimensional tolerances and welding deformations of components that should be taken into account in the design and fabrication of the actual equipment.

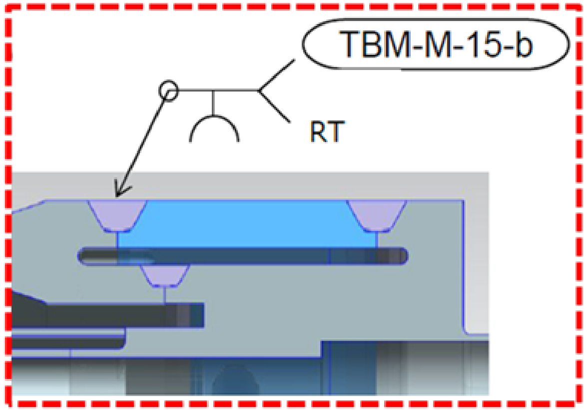
Inspection on welds

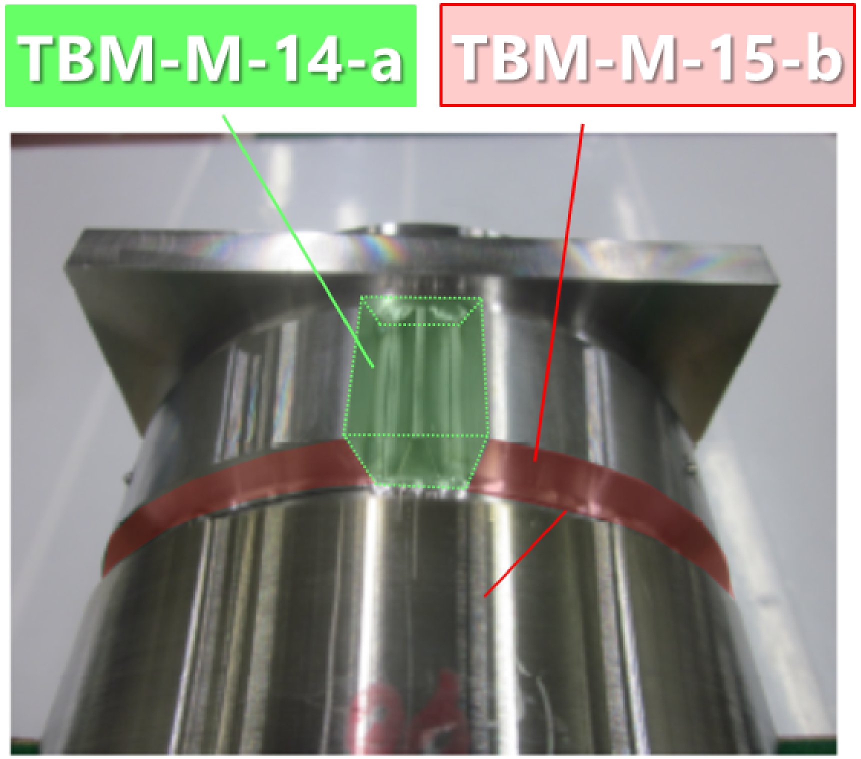
https://doi.org/10.1016/j.fusengdes.2024.114227

ID	Part	Thick. (mm)	Note
TBM-M-14-a	Coolant separator / Manifold	5.6	Hardly distinguish the weld from contents inside. According to RCC-MRx, alternative inspection is to be investigated.
TBM-M-15-b	Cylindrical body / Manifold	5.6	





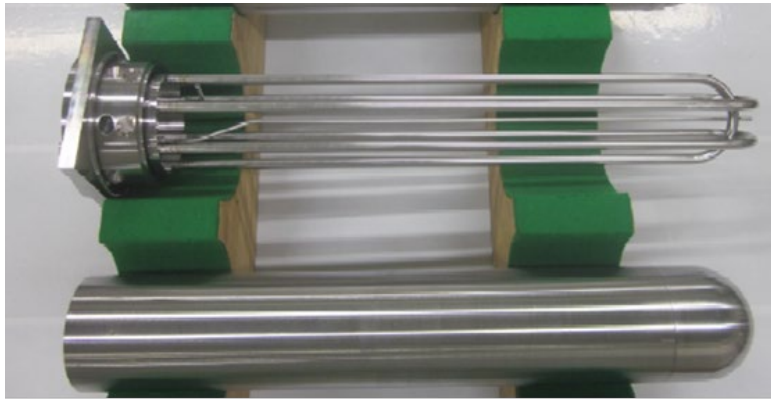


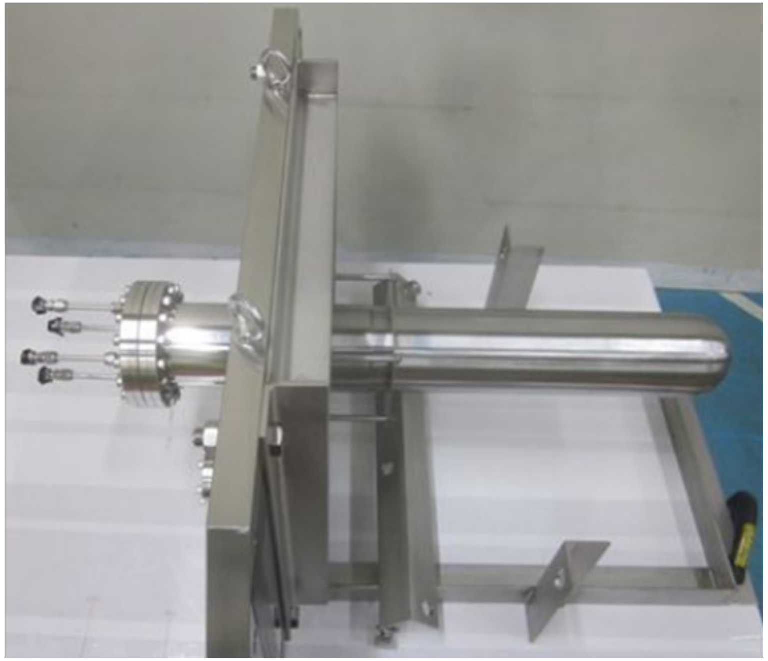


- ➢ The pressure resistance of the cooling water channel was confirmed by a 25.8 MPa hydraulic test with no leakage observed.

Findings from the first cylindrical TBM mockup

https://doi.org/10.1016/j.fusengdes.2024.114227



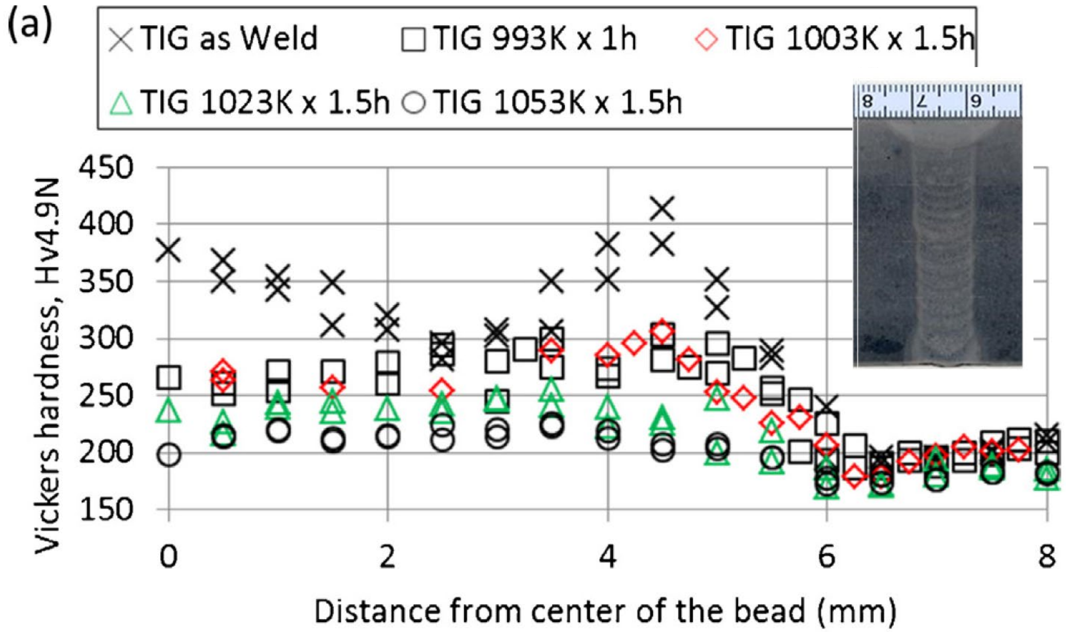


- ✓ Welding Procedure Specification have been developed for the manufacturing
  - It was identified the weld joints that are hardly radiographically inspected due to internal components, alternative inspection is to be investigated: ex) penetrant tests per layer, pressure test with bigger margin
  - Tolerance due to assembly and welding distortion have been assessed and it can be controlled by the dimensions of parts
- ➤ This first mock-up is being tested at EB high flux testing machine for its cooling capability.

Post Weld Heat Treatment on F82H

- F82H should be PWHTed at 720℃+15/-0 for 60 min.
- Higher temperature or longer duration cause softening.

https://doi.org/10.1016/j.fusengdes.2015.06.133



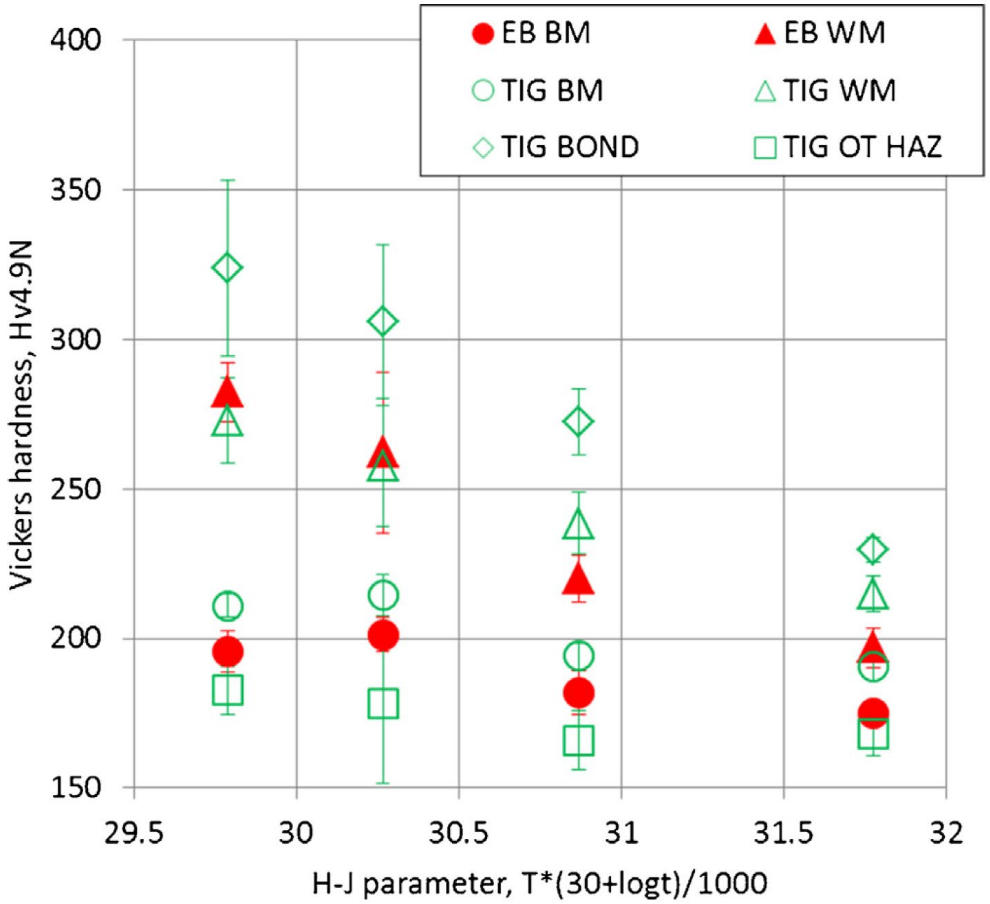


Fig. 5. PWHT effects on the hardness of F82H welds.

PWHT after packing of Breeder/Multiplier materials

https://doi.org/10.1016/j.jnucmat.2008.12.273

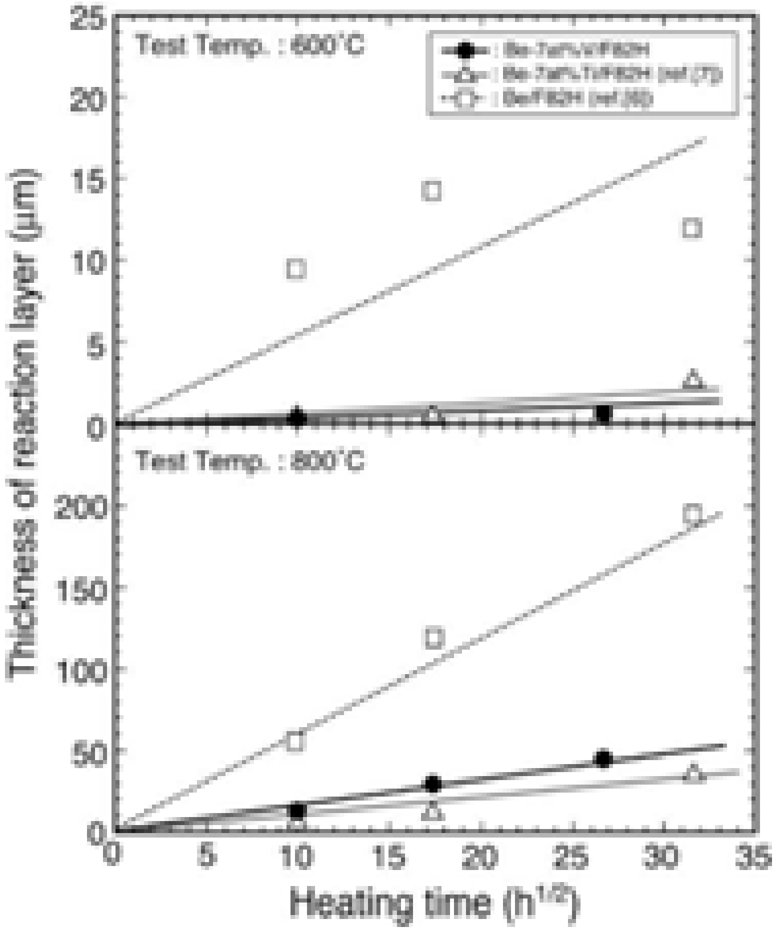


Fig. 5. Change in thickness of the reaction layer at the surface of F82H with annealing time in compatibility tests between Be-7 at.%V and F82H.

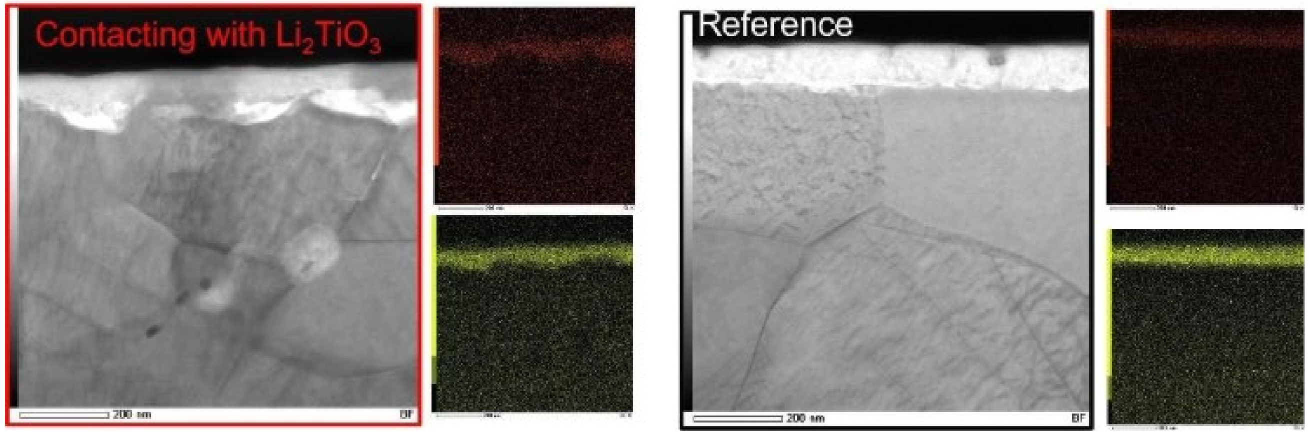


Figure. 9 TEM images of F82H contacting Li_2TiO_3 under PWHT conditions (left) and reference (right)

- ❑ Thickness of reaction layers of Beryllium and Li_2TiO_3 are 3.6μm and <0.2 μm, respectively.
- ✓ Post-weld heat treatment (PWHT) is not required for sealing the pebble filling ports by welding, as the material used is either Inconel or 316L stainless steel.

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Summary

- The Japanese WCCB-TBM has demonstrated robust structural integrity and manufacturability under ITER-relevant conditions.

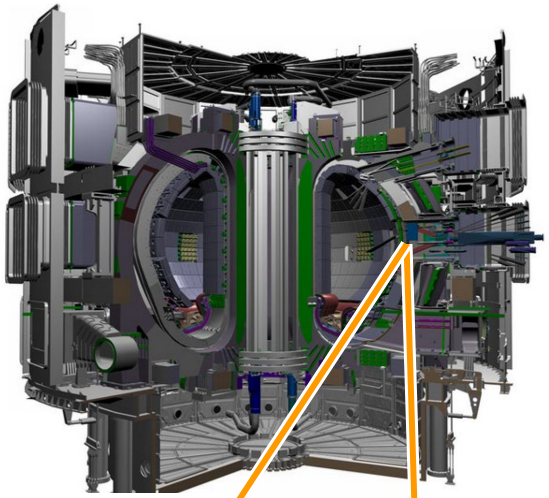
- Key technologies such as welding, heat treatment, and precision assembly have been studied through mock-up fabrication and testing.

Final remark

- While nuclear performance remains a central focus in the development of breeding blanket technologies, it is equally vital to ensure manufacturability, inspectability, and compliance with regulations and corresponding standards.

- These aspects are not merely supporting factors—they are essential for realizing reliable and deployable fusion components. Our work demonstrates that a balanced approach integrating design, fabrication, and qualification is key to advancing toward practical fusion energy systems.

Breeding Blanket Module with box shape

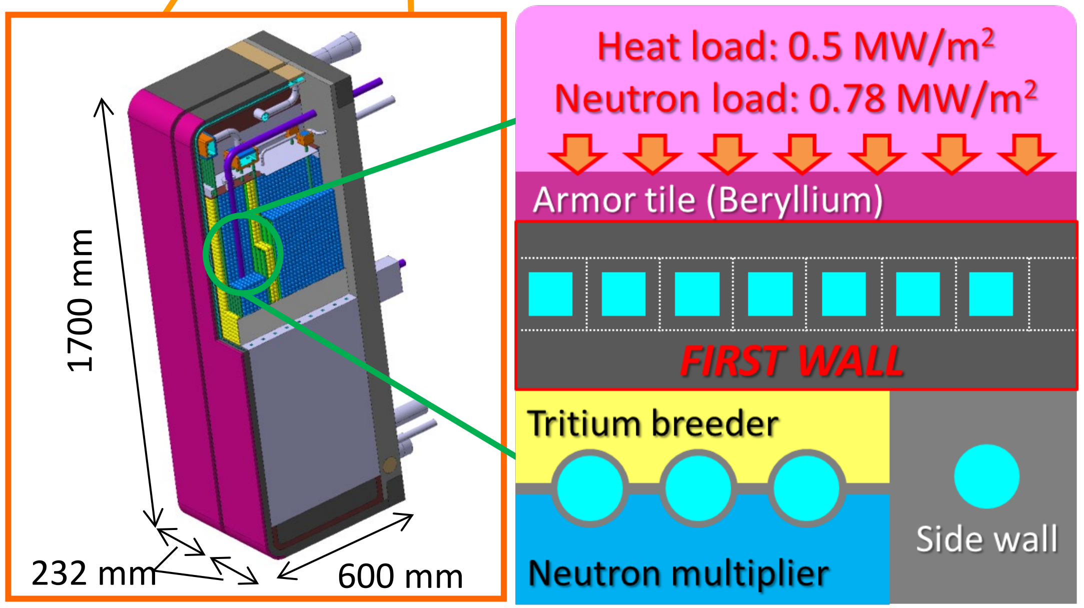


ITER
http://www.iter.org

ITER Test Blanket Module (TBM) is tested to validate functions of Blanket in the fusion environment

- Production of Fuel Tritium
- Energy Conversion
- Structural Integrity

Armor tile = Beryllium for high heat flux.
First Wall = Ferritic/Martensitic Steel, F82H (Fe-8Cr-2W) for irradiation damage.



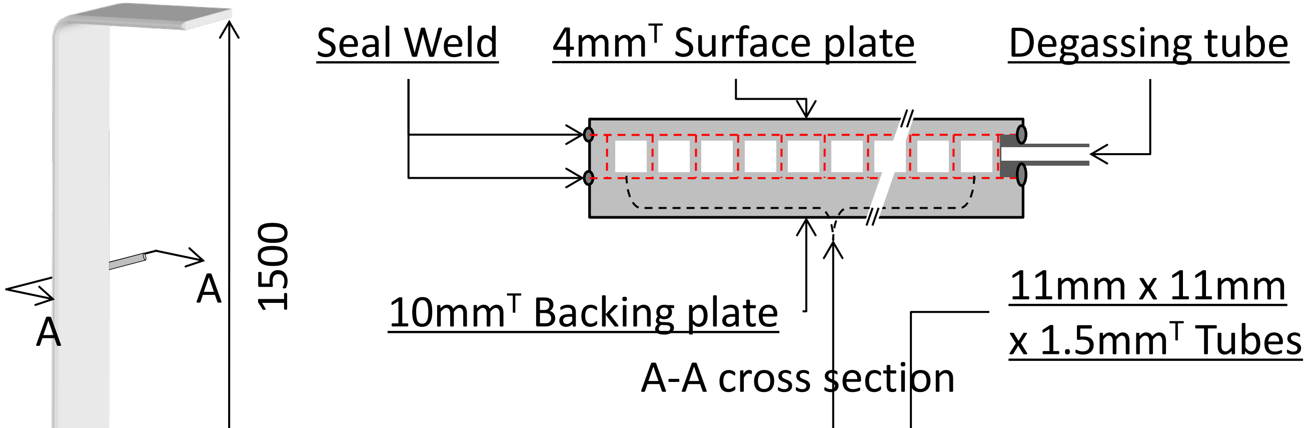
Water Cooled Solid Breeder (WCSB) Blanket

HIP has been developed as the most promising process for FW fabrication.

-U-Shaped First Wall with built-in cooling channels at 1100°C/150MPa

-Dissimilar metal joint between Be and RAFM at 750°C/160MPa

Fabrication Procedure of the FW



Seal Weld

Bracing with grid

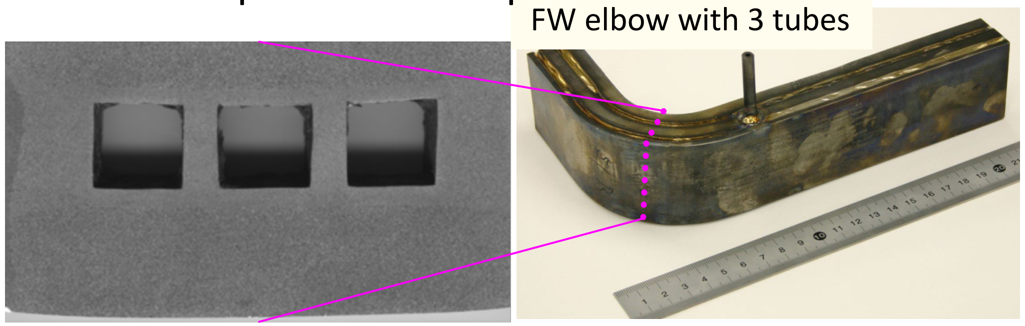
Fabrication Procedure of FW

1. F82H, tubes and plates
2. Acid washing to remove oxide
3. Bending to FW shape
4. Assembly with welding
5. Degassing at 600°C to reduce oxygen
6. HIP at 1100 °C x 150 MPa
7. Heat treatment at 960°C and 750°C to obtain fine-grained microstructure

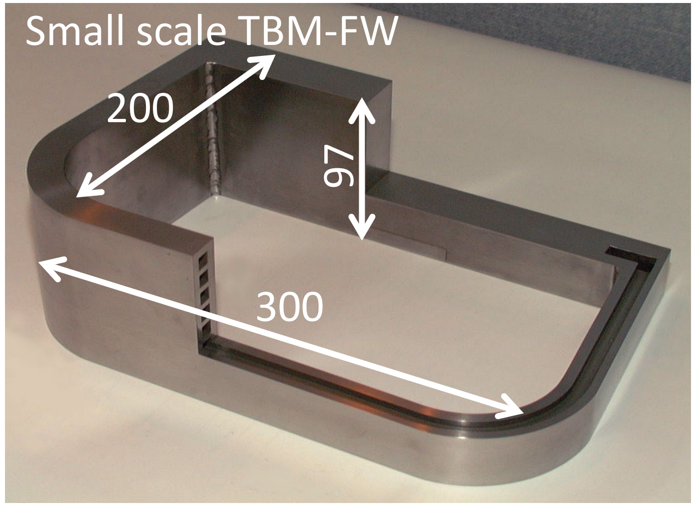
- HIP conditions are within limit of the available HIP units.
- Assembly gap is controlled below 0.5mm due to machining accuracy.
- Bracing successfully suppressed deformation during HIP process.

Fabrication of TBM-FW Mock-Up

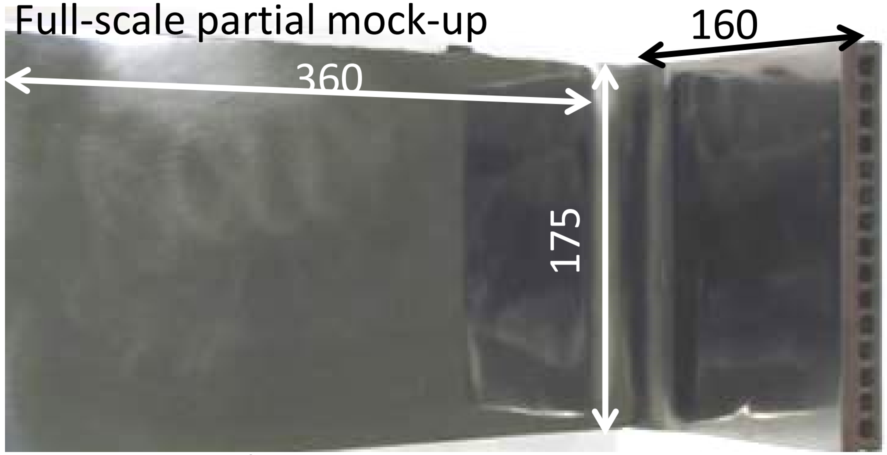
Small scale partial mock-up



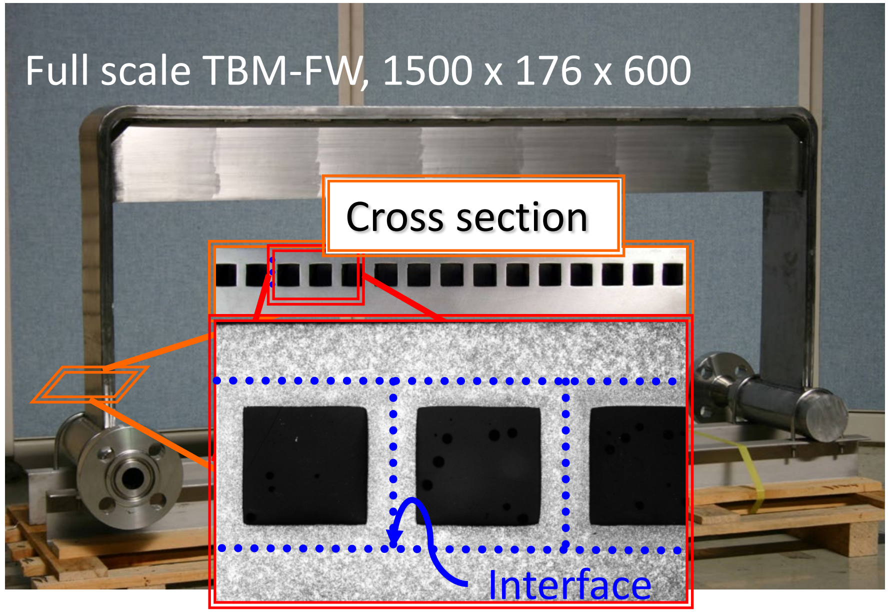
Small scale partial mock-up



Full-scale partial mock-up

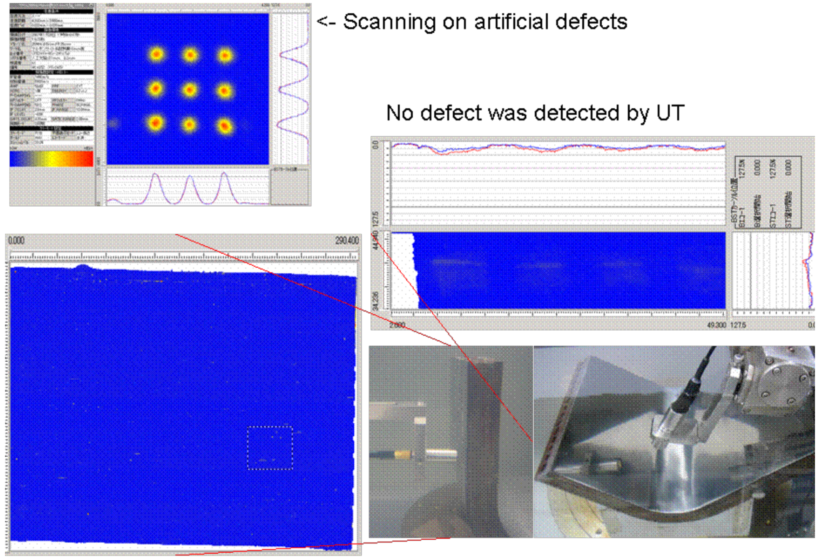


Destructive / non-destructive inspection

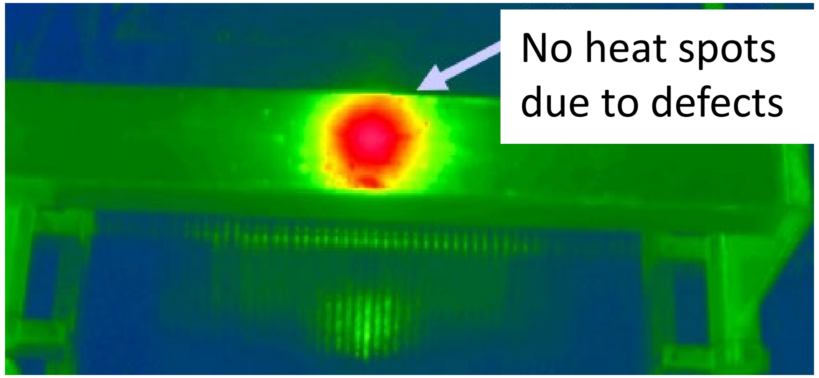


Fabrication of the TBM-FW was successfully validated in an industrial scale.

Inspection of the HIP Joint for TBM-FW

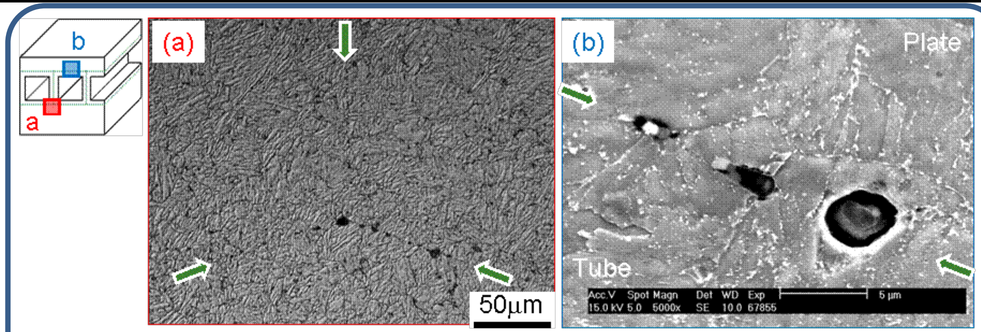


Ultrasonic inspection did not detect defects on the HIP interface.

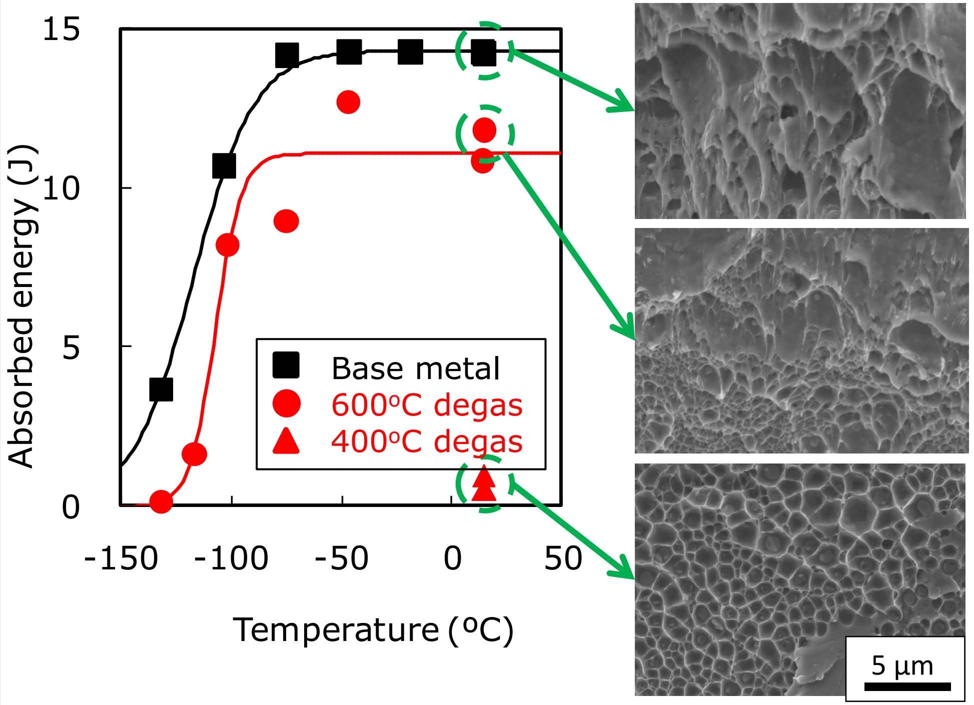


High Heat Flux testing did not indicate defects.

IR image of high heat flux test using H+ ion.
Heat flux: 0.5MW/m^2, coolant: 15MPa/30^{o}C water



Oxides on the HIP interface in the full-scale FW



Charpy impact properties at the HIP interface

Non detectable defects degrade the toughness at HIP interface

Optimization of HIP Conditions for TBM-FW

- Upper-Shelf-Energy (USE) in Charpy impact test is very sensitive to the quality of joint.
- Surface finishing is to remove surface layer including oxides and to improve contact ondition.
- Degassing suppressed oxidation at the HIP interface.
- The USE after electrolytic polishing are very similar to that of base metal (BM).
- On the other hand, mirror like finishing does not improve the toughness without electrolytic polishing.