Development of irradiation technique with Satured temperature cappsule in the JMTR

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1.Introduction

The irradiation assisted stress corrosion cracking (IASCC) of in-core structural materials caused by the simultaneous effects of neutron irradiation and high temperature water environments has been pointed out as one of the major concerns not only for the light water reactors (LWRs) but also for the water-cooled fusion reactor, i.e,. ITER. The IASCC of the austenitic stainless steels or nickel base alloys has been studied for more than ten years under international efforts in the various projects for the plant life assessment and extension of LWRs. However its mechanism has not been clarified yet in spite of the extensive post-irradiation examinations. Under this situation, it is desired to perform irradiation tests under specially controlled conditions so that the effect of irradiation and high temperature water can be separately evaluated.

In the Japan Materials Testing Reactor (JMTR), irradiation technique with the saturation temperature capsule (SATCAP) was developed for irradiation of the materials in the water with high, but constant, temperature and applied to study the IASCC. The capability of the SATCAP was improved by enhancing the temperature controllability to irradiate materials even in a low gamma region in the JMTR core. The performance tests of the improved SATCAP carried out in the JMTR have proven its capabilities.

Based on experiences of the SATCAP, preliminary design study for the upgraded in-pile test facility are now underway in the JMTR. The test facility has a new test loop to achieve irradiate test simulated water environment of LWRs. The design, test results of the SATCAP and the design study of upgraded in-pile test facility are described in the following sections.

2. General description of the JMTR

The JMTR is a light water moderated and cooled tank in-pool type reactor with thermal power of 50 MW and maximum thermal and fast neutron flux of 4.0×10^{18} n/m^2·sec. The JMTR as a multi-purpose testing reactor has been contributing to research and development on nuclear field with a wide variety of irradiation for performing engineering test and safety research on fuel and component for light water reactor as well as fast breeder reactor, high temperature gas-cooled reactor etc., for research and development on blanket material for fusion reactor, for fundamental research, and for radio-isotope (RI) production. The cumulative operation cycles and thermal power since the first criticality in 1968 until August 1999 reached to 129 cycles and about 125,000 MWd, respectively.

The JMTR core is separated into four regions by the beryllium frame functioning as structural support, as reflector and as irradiation space. The core is loaded with the 22 standard fuel elements and 5 fuel followers coupled with each control rod. The JMTR core arrangement is shown in Fig. 1. The engineering data of the JMTR are listed in Table 1.

A lot of irradiation facilities are installed in the JMTR core as follows; about one hundred capsule irradiation holes, one shroud facility (OSF-1), two hydraulic rabbit irradiation facilities. Various kind of irradiation capsule are provided to meet the requirement of researchers such as,

- constant temperature control capsule which can keep specimens at desired temperature not only during reactor steady-state operation but also power up and shutdown period,
- creep capsule which can control tensile or compression load to the specimen at required temperature,
- spectrum controlled capsule which can adjust neutron energy spectrum,
- gas sweep capsule which has a carrier gas flow to recover gas element produced by neutron irradiation, and so on.

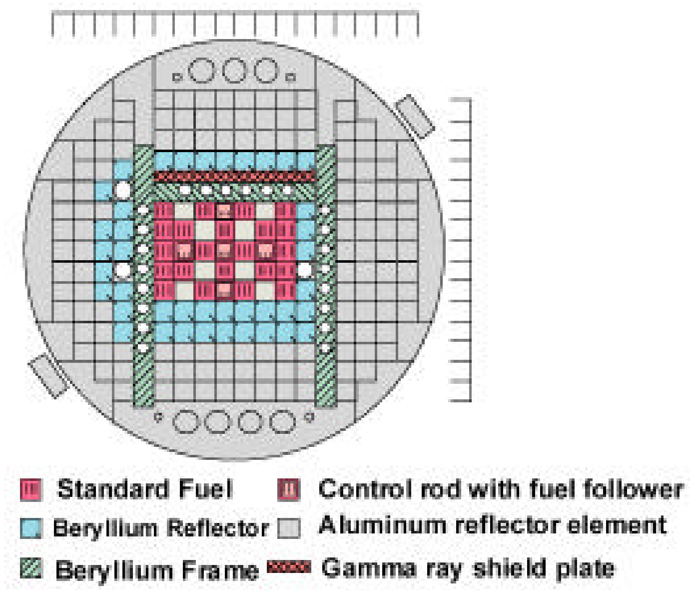
Utilizing OSF-1, power ramp tests on high burn-up fuel elements of power reactors have been carried out in BWR coolant condition.

Table 1 Engineering data of JMTR

Thermal Power (kW)		50,000 (50 MW)
Excess Reactivity (%Δ k/k)		15 (Max)
Thermal Neutron Flux (<0.683 eV,n/m^{2}sec)		$4.0\text{X}10^{18}$ (Max)
Fast Neutron Flux (>1 MeV,n/m^{2}sec)		$4.0\text{X}10^{18}$ (Max)
Power Density (kW/l)		500
Primary Coolant	Inlet Temperature (K)	322 (Max)
	Outlet Temperature (K)	about 329 (Max)
	Flow Rate (m^3/h)	about 6,000

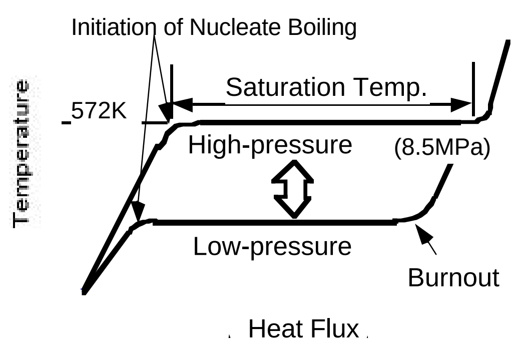
A gas sweep capsule is scheduled to be applied in the irradiation test on blanket of fusion reactors.

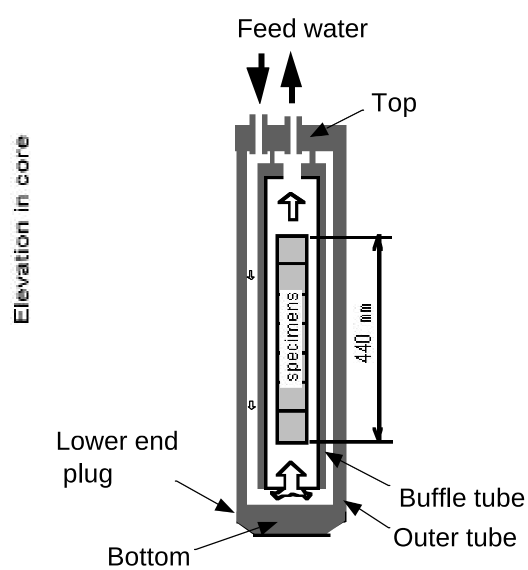
Fig. 1 JMTR core arrangement



3. Development of irradiation technique

One of the most significant problem for LWRs' core materials is the IASCC. Although it is clear that occurrence of the IASCC depends on neutron fluence and there is a neutron fluence threshold of 5×10^{24} m^{-2} by recent research, the mechanism of occurrence and preventive technique have not yet been clarified. Therefore irradiation tests of LWRs' core materials are needed under 563 K and high neutron fluence of 10^{26} m^{-2}. In order to obtain the high neutron fluence for few years, the irradiation must be carried out in high neutron flux area of the JMTR. However this area is of a high gamma heat generation. When an irradiation is carried out in this area by conventional temperature control capsules with electric heaters, the temperature of specimens rises beyond 873 K. Therefore, saturation temperature capsule (SATCAP) was developed to irradiate specimens at 563 K. Pressurized water is supplied into the capsule and gamma heating generated by capsule materials and irradiation specimens is utilized for irradiation temperature control. The relation between temperature and heat flux





generated by gamma heating in the capsule is shown in Fig. 2. As heat flux increase, the pressure water in the capsule starts nucleate boiling and reaches to film boiling. When heat flux is in the range between nucleate boiling and film boiling, temperature of water is kept nearly saturation temperature. This characteristic is applied to the SATCAP.

The capsule was designed to have double wall-structure that is composed of an outer tube and a buffle tube as shown in Fig. 3. The capsule is made of stainless steel (316). Water is pressurized and flows into the SATCAP through the pump, then flows downward between outer tube and buffle tube, turns upward at the bottom, flows around specimens, finally flows out of the capsule as shown in Fig. 4. The flow of pressurized water is once through.

A thermal calculation code was developed for evaluation of temperature distribution in the capsule. The supplied water temperature is calculated by the code. Secondary, out-of-the core

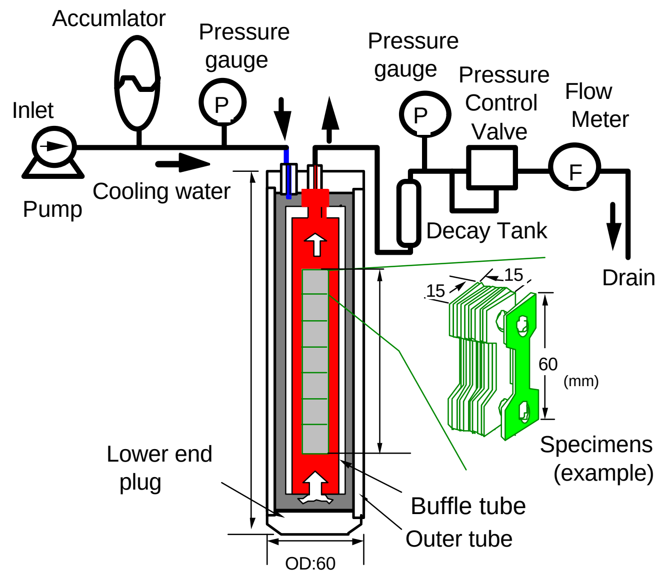


Fig. 4 Schematic of SATCAP

experimental facility to understand thermal-hydraulic was installed and utilized to verify validity of the calculation code. As shown in Fig. 5, calculated temperature distribution agreed well with the results of out-pile tests. All of the irradiated materials are heated by gamma rays. The gamma heating in the JMTR distributes in the form of a cosine curve in the vertical direction in the irradiation field (reference of Fig. 2). Inserted position of the SATCAP and specimens
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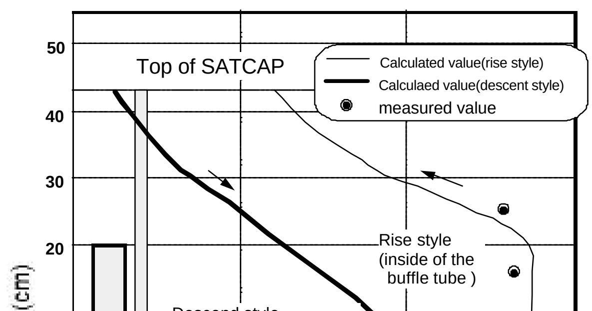
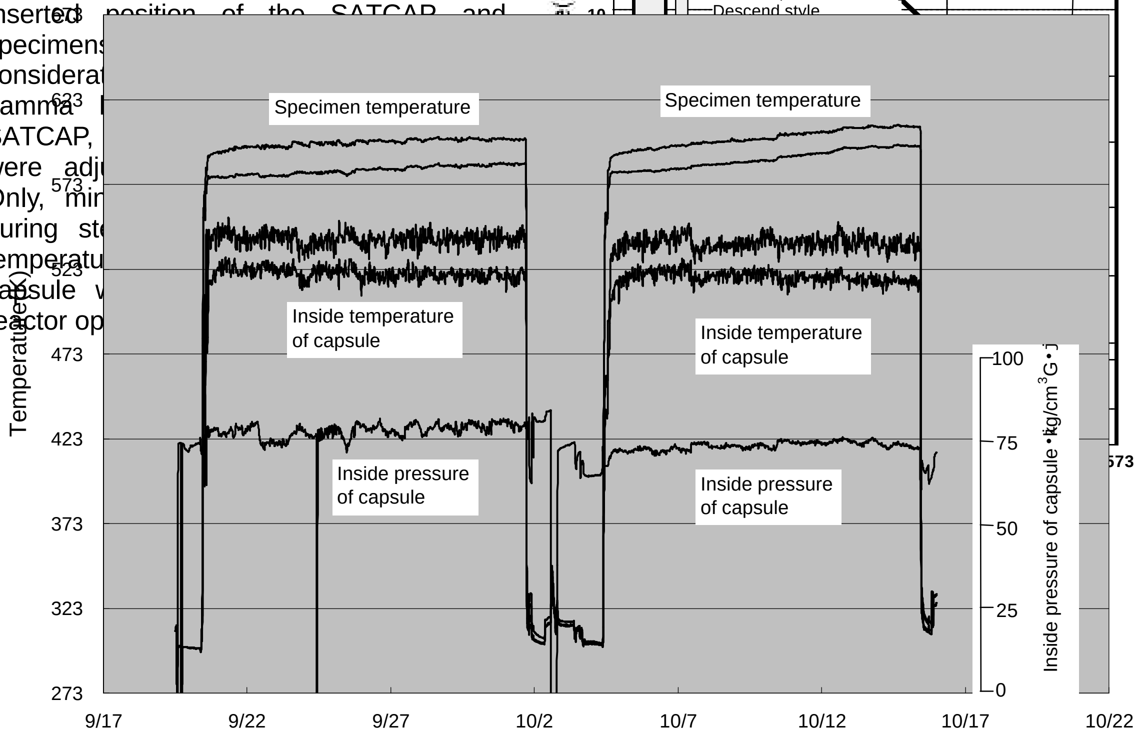
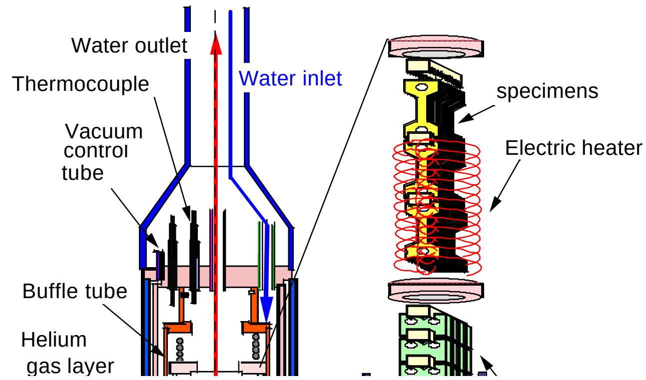




4. A new type capsule using saturation temperature

The capsule called “hybrid SATCAP” was developed to have the ability of irradiation materials in a low gamma region of temperature at various channels in the JMTR core by enhancing the temperature control mechanism. The hybrid SATCAP has Helium gas layer to adjust condition between inner and outer tubes as shown in Fig. 7. In order to supplement gamma heat, the electric heater was equipped along specimens in the buffle tube. The system of heater and Helium gas layer utilized the existing equipment of the normal SATCAP. The temperature distribution of the specimens and cooling water inside the SATCAP at low region of the gamma heating at 2.3 w/g is shown in Fig. 8.



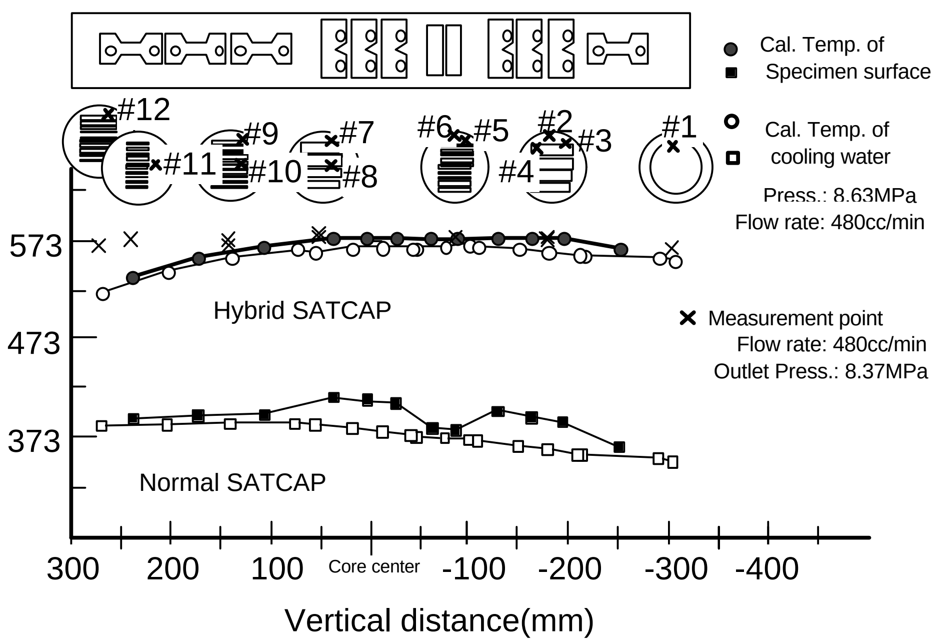


Fig. 8 Temperature distribution in hybrid SATCAP[1)]

Calculated temperatures of the specimens contained in the SATCAP are plotted, as well as the temperature was measured when the specimens were irradiated using the hybrid SATCAP. The measured temperatures agrees closely with calculated values and very close to the target temperature of 573 K. This shows that the hybrid SATCAP is effective for the irradiation even in the lower gamma heating region, because the temperature inside the hybrid SATCAP is about 200 K higher than that of the normal SATCAP and reaches saturation condition.

The specimens was irradiated by the hybrid SATCAP for three operation cycles. During the second and third cycle, stable irradiation condition was also achieved. During this irradiation, coolant pressure in the SATCAP was regulated at 7.95 MPa with saturation temperature of 570 K. In the stable operation period, cooling water flow rate and the gas pressure were controlled as 640

Table 2 The irradiation temperature during the third cycle[1)]

Measurement point	95% distribution term (K)	Min. (K)	Max. (K)
#1 (Water temp.)	558 ± 13	543	575
#2 (Water temp.)	565 ± 10	552	576
#3 (Spe. surface)	565 ± 10	552	576
#4 (Spe. inside)	568 ± 8	556	575
#5 (Spe. surface.)	570 ± 5	561	585
#6 (Water temp.)	570 ± 5	561	575
#7 (Spe. surface)	572 ± 3	566	575
#8 (Spe. surface)	575 ± 1	572	577
#9 (Spe. surface)	565 ± 7	553	574
#10 (Spe. surface)	568 ± 5	557	574
#11 (Water temp.)	567 ± 5	557	572

cc/min and 0.01 torr, respectively, while the heater was not used. The results of the temperature measured in the third cycle are shown in Table 2.

To utilize hybrid SATCAP, corrosion rate of zircaloy under irradiation was carried out by AC impedance method [2].

5. Upgrade in-pile test facility for the IASCC study of LWR core materials

Based on experiences of the SATCAP, preliminary design study for the upgraded in-pile test facility for the IASCC study of LWR core materials is now underway.
The main purpose of the new test facility is to carry out irradiation test under the simulated water environment of LWR, especially BWR.

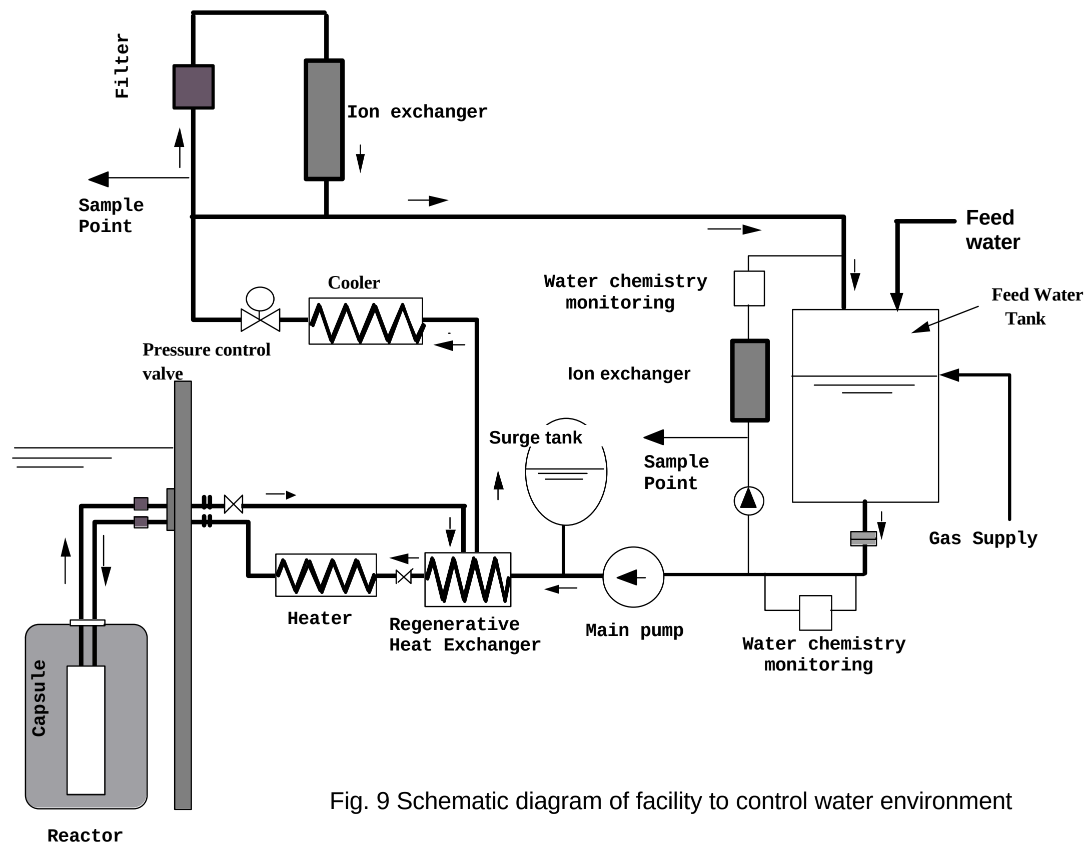


Fig. 9 Schematic diagram of facility to control water environment

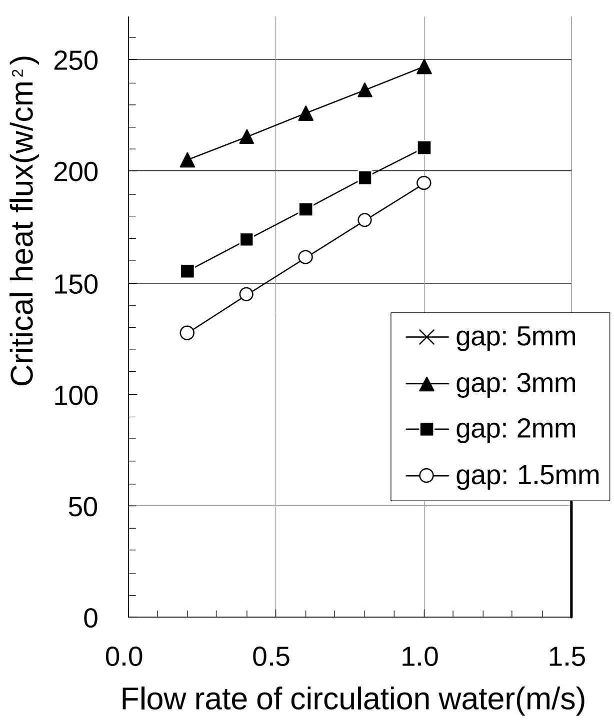
Major points to be considered in the new test facility design are as follows.

1. control and measure water chemistry under irradiation
2. increase of flow rate

In order to attain following concrete object, design study is going to be carried out about the measurement and control of the water chemistry.

- Electric conductivity < 0.1 μS/cm
- Dissolved oxygen (DO) concentration several - 200 ppb
- SO_4 concentration < 5ppb
- pH 5.5 - 7.0
- Electro-chemical potential (ECP): +200 to -400 SHE

A system of hydrogen addition is



being studied to achieve required DO and ECP level. The schematic diagram of the in-pile test facility is shown in Fig. 9. In order to control and maintain these water quality, whole cooling water passed through the reactor core is purified by ion exchanger.

Also there is a possibility that the water quality changes locally by activated reaction and/or chemical reaction in the reactor core if flow rate is too small.

The subjects to increase flow rate are as follows.

1) there is the limit on flow velocity for feed and drain tubes from the view point of piping design.
2) Water channel should be small enough to increase flow velocity along specimens.
3) It is required to secure thermal safety margin to prevent film boiling on the specimen surface by flow and pressure fluctuation.

Inner diameters of the feed and drain tubes for circulating water are both 10.2 mm. In the viewpoint of piping design, flow velocity in these tubes have to be about 2 – 3 m/s at the maximum. If flow velocity is 1 m/s in the feed and drain tubes, then flow velocity around test specimens is 0.3 m/s.

Fig. 10 Relationship among flow gap, flow velocity and critical heat flux

Although the flow gap around specimen is prefer to be small in order to obtain higher flow velocity under a given flow rate, necessary safety margin to film boiling should be maintained even in case of unexpected flow disturbance. Calculated results for the relationship among flow gap, flow velocity and critical heat flux is shown in Fig. 10. Critical heat flux to burnout is calculated by equation of Bernath[3)]. Supposing that heat flux on surface of test specimen is 50w/cm^2, calculated result shows that safety margin is more than 3.0 when the gap is larger than 2.0 mm and flow velocity is more than 0.2 m/s. These can be basic condition for thermal-

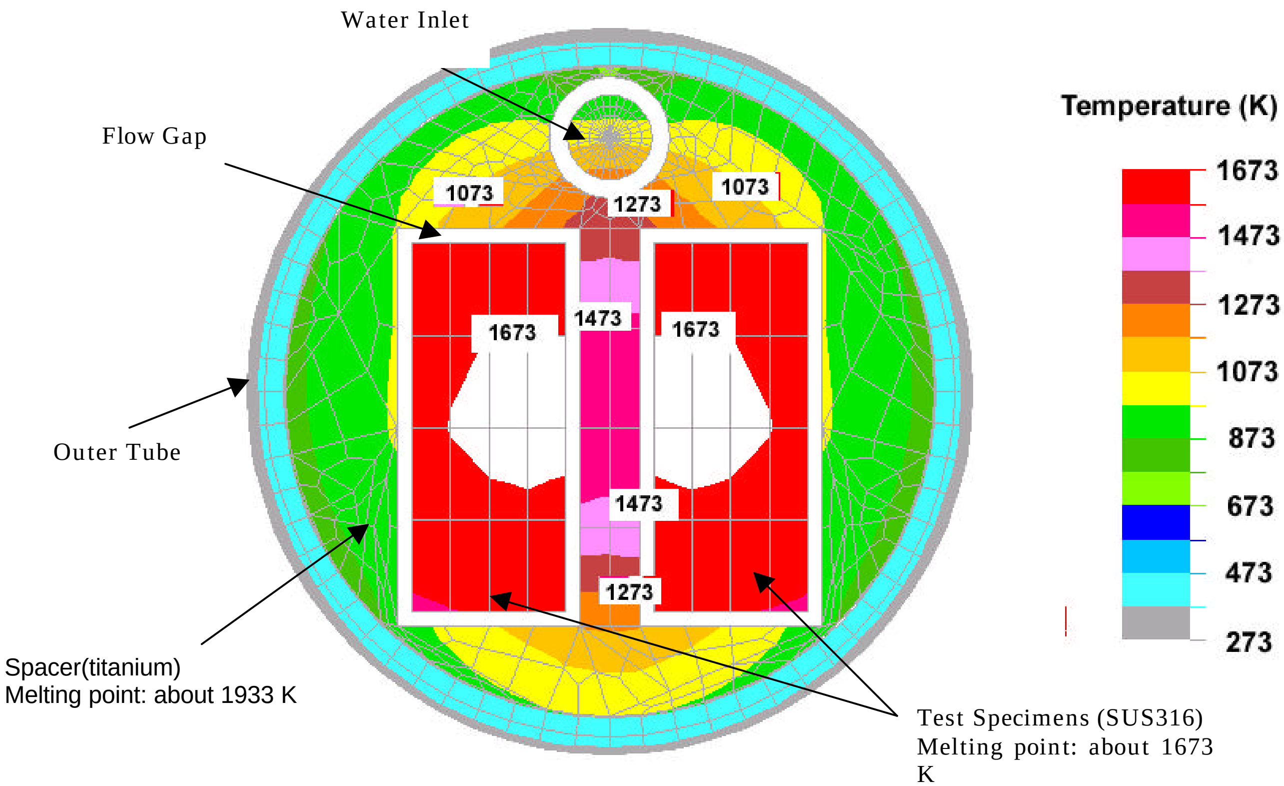


Fig. 11 Temperature distribution in postulated loss of cooling water

hydraulic designing of the facility.

Temperature distribution inside the capsule in loss of cooling water is computed by three-dimensional thermal calculation code for an accident condition of loss of cooling. The result of calculation is shown in Fig. 11. Although center temperature of the specimen exceeds the melting temperature, outer part of the specimen and other component of the capsule is kept under the melting point.

6. Summary

In the JMTR, the irradiation capsule utilizing saturation temperature was developed and has been used for study on LWR core structure materials.

After successful irradiation of the SATCAP, electric heater and vacuum control system were incorporated in the SATCAP in order to improve its controllability even in the irradiation in the low gamma heating area.

Based on experiences of the SATCAP, preliminary design study for the upgraded in-pile test facility for the IASCC study of LWR core materials is now underway.

References

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