Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Preliminary Design Evaluation of Control Rod for SFR with Metallic Fuel

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1. Introduction

By developing high TRU-bearing fuel, the volume and toxicity of spent fuel can be drastically reduced, and uranium can be recovered and recycled as a resource. Currently, preliminary design of control rod for Sodium-cooled Fast Reactor (SFR) with metallic fuel is in progress at KAERI. The control rod has important functions such as reactor power control and emergency reactor shutdown. In this study, the structure, design criteria, design evaluation method, and design evaluation results of control rod are presented.

2. Structure and Design Criteria

2.1 Design Description

The control rods are inserted into control rod assemblies to perform their respective functions. The control rods consist of the primary and secondary control rods. The primary and secondary control rods are identical except for the B-10 enrichment of the B_4C pellet.

The primary control rods simultaneously have the functions of reactor core excess reactivity control during power operation, and of emergency reactor shutdown during accidents. The secondary control rods are operated independently from the primary control rod assembly for diversity and redundancy during an emergency reactor shutdown.

The absorber used in the control rod is boron carbide, and the cladding and shroud material is Type 316SS. Boron carbide has excellent stability against neutron irradiation and is widely used not only for fast reactors but also as a control rod absorber in light water reactors (LWR). Type 316SS, a control rod cladding material, has excellent strength, creep resistance, corrosion resistance and dimensional stability under neutron irradiation, and exhibits suitable performance in fast reactors currently in operation.

Compared with control rods developed in various countries, upper filling type was selected [1]. The primary control rod consists of a plenum spring, the upper and lower seal plugs, a spacer, B_4C pellet, a sodium inflow tube, a vent tube, and a shroud. Fig. 1 shows the control rod design.

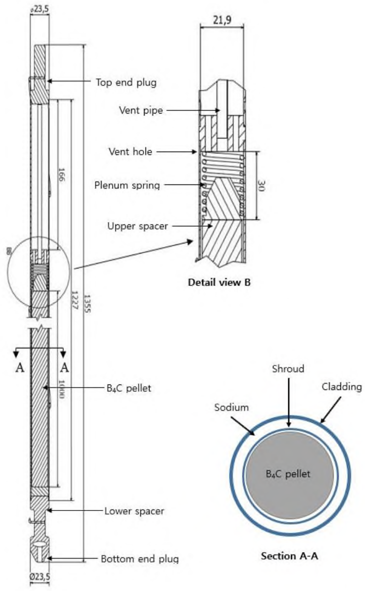

Fig. 1. Design configuration of the control rod

2.2 Design Criteria

The design criteria of the control rod is as follows. B_4C pellets shall not melt under conditions of 115 % overpower and 3σ uncertainty. The melting temperature of B_4C pellets is 2,450 °C [2]. The circumferential plastic strain of the cladding shall not exceed 1 %, taking into account the effect of B_4C pellet swelling and cladding creep.

3. Design Evaluation Results

3.1 Thermal Design Evaluation

The temperature of control rod for SFR is 200 ~ 300 °C higher than that of LWR. The most important factor of the thermal design of the control rod is the soundness of the B_4C pellet at high temperatures. To assess the soundness of the B_4C pellet, the centerline temperature of the B_4C pellet was evaluated.

The design temperature limit of B_4C pellet of the control rod is applied to 2,350 °C (100 °C of design margin at melting point). The B_4C pellet centerline temperature is obtained by successively calculating the temperature along the radial direction of the control rod. The B_4C pellet centerline temperature was evaluated with peak linear power density and peak cladding inner-wall temperature. The evaluation formulas are as follows:

$$\Delta T_{gap} = T_{c,i} - T_{sh,o} = q \cdot r_{c,i}^2 \frac{\ln\left(\dfrac{r_{c,i}}{r_{sh,o}}\right)}{2k_{gap}} \qquad (1)$$

$$\Delta T_{sh} = T_{sh,o} - T_{sh,i} = q \cdot r_{sh,o}^2 \frac{\ln\left(\dfrac{r_{sh,o}}{r_{sh,i}}\right)}{2k_{sh}} \qquad (2)$$

$$\Delta T_{B_4C} = T_{p,c} - T_{p,s} = q \cdot r_p^2 \left(\frac{1}{4k_p}\right) \qquad (3)$$

where T : temperature, q : B_4C pellet heat generation, r : radius, k : thermal conductivity, subscript *gap*: gap between cladding inner-wall and shroud outer-wall, subscript *c,i*: cladding inner-wall, subscript *sh,o*: shroud outer-wall, subscript *sh,i*: shroud inner-wall, subscript *p*: B_4C pellet, subscript *p,c*: B_4C pellet centerline, and subscript *p,s*: B_4C pellet surface.

Peak heat generation of the B_4C pellet and peak cladding inner-wall temperature is 128 W/cm^3 and 553 °C, respectively. The centerline temperature of the B_4C pellet calculated by applying eqs. (1)-(3) is 2,193 °C. Therefore, the soundness of the B_4C pellet is maintained because the centerline temperature of B_4C pellet is lower than 2,350 °C.

3.2 Mechanical Design Evaluation

The B_4C pellet is swelled by neutron irradiation. ACMI (Absorber material Cladding Mechanical Interaction) is caused by B_4C pellet swelling. The mechanical life of the control rod can be reduced by ACMI. A shroud tube is installed in the control rod to restrict the generation of ACMI by restraining the B_4C pellet [3,4].

ACMI generation time of the control rod with the shroud tube is evaluated by calculating onset time of contact between cladding inner-wall and shroud tube outer-wall due to B_4C pellet swelling. The evaluation formula is as follows:

$$\frac{\Delta D}{D} = \frac{1}{3}\left(0.159 \cdot Bu + 3.093\right) \qquad (4)$$

where $\Delta D / D$: radial swelling (%), and Bu : burnup (×10^{26} cap/m^3).

When the B_4C pellet swelling of the control rod is 5.6 %, the gap between the shroud tube and cladding is closed. At this time, ACMI generation burnup is estimated to be 85×10^{26} cap/m^3 (Fig. 2).

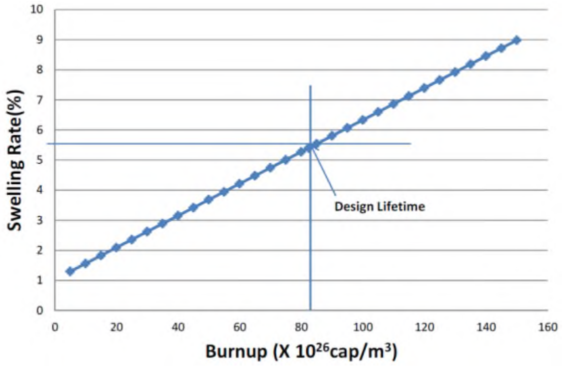

Fig. 2. ACMI design evaluation results

4. Conclusions

The structure, design criteria, design evaluation method, and design evaluation results of control rod for SFR with metallic fuel were presented. The thermal design is to maintain the soundness of the B_4C pellet at high temperature. Thermal design evaluation result showed that the centerline temperature of the B_4C pellet met the design limit temperature of 2,350 °C. The mechanical design evaluation considering ACMI showed that ACMI design life of control rod was estimated to be 85×10^{26} cap/m^3. In the future, thermal and mechanical design evaluation of the control rod with more detailed irradiation history data will be performed.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT and Future Planning).

REFERENCES

[1] T. Soga and et als, “The Improvement of Control Rod in Experimental Fast Reactor JOYO”, JNC TN9400 99-052, June, 1999.

[2] I.S Han, “Non- Fuel Rod Design Report”, SFR-FP-S62-006, KAERI, 2016.12.26

[3] Ph. Dunner, H.-J Heuvel and M. Horle, “Absorber Materials for Control Rod Systems of Fast Breeder Reactors”, Journal of Nuclear Materials 124 (1984) 185-194.

[4] Tadashi Maruyama, Onose Shoji, et al, “ Joyo post-irradiation examination of the MK-Ⅱ control rod - irradiation behavior evaluation of absorbing pin", PNC TN9410 97-077 (1997).