Application of FAST Passive Safety Device in a Compact Breed-and-Burn Fast Reactor (B&BR)

Donny Hartanto, Chihyung Kim and Yonghee Kim*
Dept. of Nuclear & Quantum Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, South Korea
*Corresponding author: yongheekim@kaist.ac.kr

1. Introduction

The positive coolant temperature coefficient (CTC) and resulting coolant void reactivity (CVR) are a long standing issue in the sodium-cooled fast reactor (SFR). These are caused by several factors. The major factor is the impact of the neutron spectral hardening. The second factor that affects the CVR is reduced capture by the coolant when the coolant voiding occurs [1]. To improve the CVR, many ideas and concepts have been proposed, which include introduction of an internal blanket [2], spectrum softening [3,4,5], or increasing the neutron leakage [6]. These ideas may reduce the CVR, but they deteriorate the neutron economy. Another potential solution is to adopt a passive safety injection device such as the ARC (autonomous reactivity control) system [7], which is still under development.

In previous study, two newly developed concepts of passive safety devices called FAST (Floating Absorber for Safety at Transient) and SAFE (Static Absorber Feedback Equipment) have been proposed and tested in an innovative Sodium-cooled Fast Reactor (iSFR) [8]. It was shown that FAST could insert a strong negative reactivity feedback when the coolant temperature increases more than a set-point or when there is a loss of coolant accident takes place in the core. On the other hand, SAFE allows a low-leakage SFR to achieve a self-shutdown.

This paper shows the impact of only FAST passive safety device in the small and compact sodium-cooled Breed-and-Burn Fast Reactor (B&BR). SAFE is not considered because it decreases the neutron economy which is not favorable in a B&BR.

2. Description of the FAST Passive Safety Device

Figure 1 shows the concept of the FAST device. The FAST module is basically a guide thimble (fuel clad tube) filled with the coolant and a floating neutron absorber rod due to the buoyancy force. The top and bottom coolant holes allow the coolant to flow (very slowly) through the thimble during normal operation. The cylindrical neutron absorber rod is designed such that it can float when the sodium coolant fills the internal region of the guide thimble.

The FAST module uses an enriched B_4C neutron absorber enclosed in a SiC canister. For a higher buoyancy force, the B_4C absorber density can be lowered and the absorber rod can be supported by an empty SiC buoyancy can. Li-6 can be used as an alternative absorber material. A reflector or shield is loaded into the bottom of the FAST module to support the absorber when it sinks. The FAST module is designed so that the absorber section is fully out of the core during the normal operation and top of the absorber rod contact the upper cover of the thimble. The helium gas, resulting from B-10 depletion, can be vented to coolant through micro holes from the absorber rod.

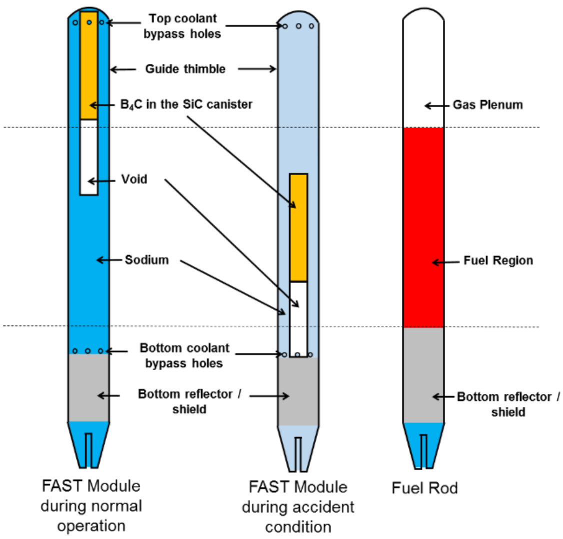

Fig. 1. FAST passive safety device concept.

FAST can be designed to respond to either any change in the coolant temperature or certain threshold change in coolant temperature. The B_4C absorber section starts to sink into the active core only when the coolant temperature is increased up to a set point temperature from the nominal 100% power condition. The upward coolant flow inside the guide tube is negligibly small and it will not interfere the sinking of FAST significantly. In the case of loss of coolant accidents, the absorber will passively drop into the core region due to gravity. In other words, the FAST can provide a strong negative reactivity in the case of coolant void.

The FAST module can be installed by replacing fuel pin or pins in a fuel assembly. The number of the FAST modules per fuel assembly depends on its requested reactivity worth. It is worthwhile to note that the FAST module will quickly respond to a coolant temperature increase at the bottom of the core. Therefore, FAST will be also very effective when an ULOHS (unprotected loss of heat sink) accident takes place and the coolant inlet temperature quickly increases. FAST will also be able to counteract partial blockage of coolant flow in a fuel assembly which results in a local coolant temperature increase.

3. Compact B&BR Concept

The radial and axial core configurations of the 400 MWth B&BR are shown in Fig. 3. The fuel, reflector, and shield assemblies are arranged in a 10-ring hexagonal core. There are 78 fuel assemblies, 128 reflector assemblies, 54 shield assemblies, 4 primary control assemblies and 3 secondary control assemblies. At the bottom of the core, a 40 cm axial HT-9 reflector is located. Above the fuel region, there are 20 cm gap for the fuel expansion and 80 cm Cs and I diffusion retarding region which is assumed to be filled with Na. The fuel region height is 180 cm. The LEU-Zr region is a pan-shape configuration to achieve maximum core excess reactivity less than 1.0$ during operation [9].

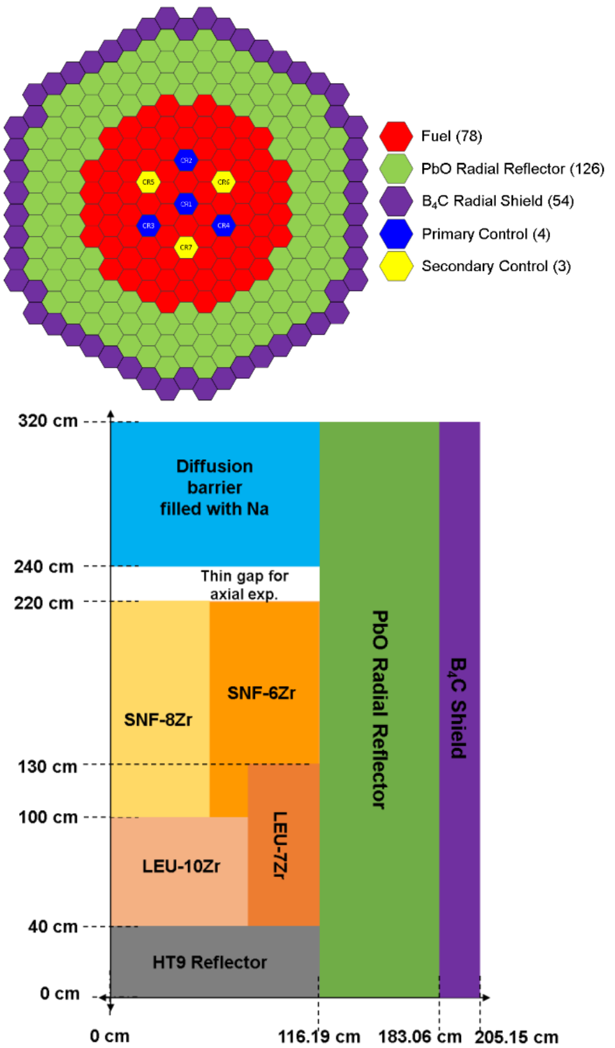

Fig. 3. B&BR radial and axial core configuration

In the fuel assembly, the fuel, structure, coolant volume fractions are about 63.34%, 14.01%, and 22.65%, respectively. Slightly higher fuel volume fraction is adopted to improve the neutron economy. In the reflector, the PbO reflector, structure, and coolant volume fractions are 64.38%, 16.9%, and 18.71%, respectively.

The FAST device is located inside the 3 non-fuel tubes in the fuel assemblies. The height of the absorber rod and the buoyancy can is 90 cm and 50 cm, respectively. The radius of the module is 0.66 cm. The thickness of the SiC/SiC composite canister is 0.01 cm. The absorber material is 95% enriched B_4C and the density is 1.13396 g/cc. The schematic concept of the FAST passive safety device in the B&BR is shown in Fig. 4. The FAST working temperature is about 630℃. This temperature was determined by using a sub-channel temperature analysis code MATRA-LMR [10]. From the sub-channel analysis, the maximum coolant exit temperature of the tube is about 611.52℃ as shown in Fig. 5.

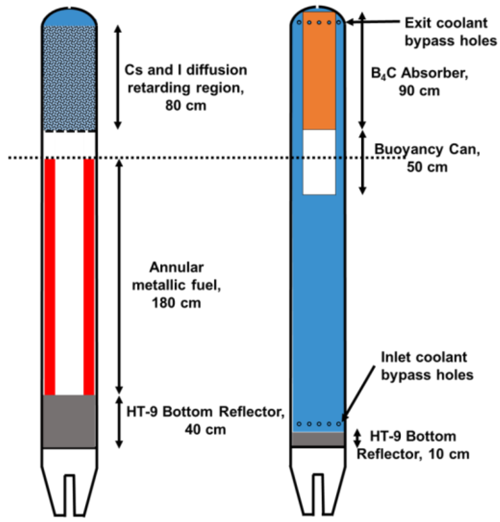

Fig. 4. FAST device configuration in B&BR

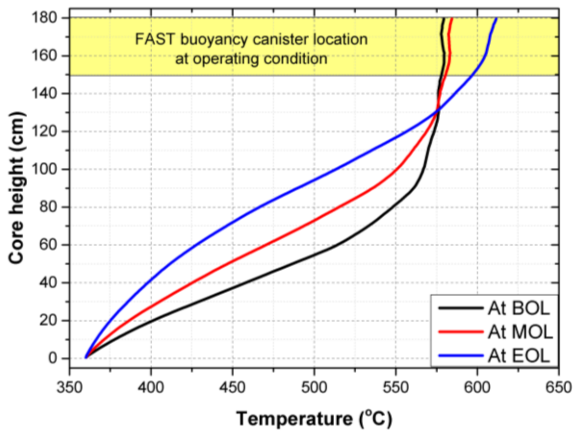

Fig. 5. FAST tube maximum coolant exit temperature in B&BR.

4. Impact of FAST Passive Safety Device

Table I summarizes the reactivity feedback coefficients of the B&BR at BOL (Beginning of Life), MOL (Middle of Life), and EOL (End of Life), namely the fuel temperature reactivity coefficient ($\alpha_{Doppler}$), sodium temperature reactivity coefficient (α_{Na}), sodium void reactivity coefficient (α_{Void}), axial expansion reactivity coefficient (α_{Axial}), radial expansion reactivity coefficient (α_{Radial}), and control assembly driveline expansion reactivity feedback coefficient (α_{CEDL}). These reactivity feedback coefficients were evaluated without considering the impact of FAST.

Table I. Reactivity feedback coefficients

Coefficient	BOL	MOL	EOL
$\alpha_{Doppler}$ (¢/ K)	-0.093 ± 0.001	-0.054 ± 0.002	-0.045 ± 0.03
α_{Na} (¢/ K)	-0.025 ± 0.001	0.170 ± 0.001	0.263 ± 0.001
α_{Void} (¢/)	-13.956 ± 1.451	632.634 ± 2.591	945.603 ± 3.418
α_{Axial} (¢/ K)	-0.025 ± 0.002	-0.051 ± 0.003	-0.067 ± 0.003
α_{Radial} (¢/ K)	-0.133 ± 0.002	-0.162 ± 0.005	-0.155 ± 0.003
α_{CEDL} (¢/ K)	-0.001 ± 0.004	-0.002 ± 0.006	-0.024 ± 0.007

The $\alpha_{Doppler}$ is consistently negative at both BOL, MOL, and EOL conditions. The α_{Na}, which is calculated by considering the non-fuel region, is slightly negative at BOL and becomes significantly positive at MOL and EOL. Meanwhile α_{Void} is conservatively evaluated by partially voiding the fuel region only instead of global core voiding as in the α_{Na} calculation so that a lower neutron leakage is obtained. The value is found to be slightly negative at BOL, becomes positive at MOL, and even more positive at EOL. This is reasonable since these values strongly depend on fuel compositions. At BOL, the core is a uranium-dominated core, which results in near zero α_{Na} and α_{Void}. At MOL and EOL, however, the core is plutonium-dominant, which deteriorates the α_{Na} and α_{Void} values. The fission to capture ratios of Pu-239 and minor actinides increase as neutron spectrum hardens.

The α_{Axial} and α_{Radial} values are negatives at BOL and more negative as the burnup increases. A similar trend was also observed for α_{CEDL}, which is directly affected by the axial blanket compositions. At BOL, the axial blanket was basically neutron absorbers, essentially limiting the active core region to the LEU zones only. At EOL, the blanket also generates neutrons, effectively widening the active core region. As the active core becomes wider, the expansion coefficients become more negative with burnup. Also due to the wider active core, the slight insertion of the control assemblies' tips will produce a more negative α_{CEDL} at EOL.

The worth of the FAST device at BOL, MOL, and EOL is shown in Table II. It was evaluated with respect to the sodium void reactivity coefficient. It was discovered that α_{Void} becomes negative when FAST is inserted into the core. It is clear that a FAST can bring the reactor to subcritical condition when an accident occurs.

Table II. Coolant Void Reactivity when FAST is inserted

Coefficient	BOL	MOL	EOL
α_{Void} (¢/)	-565.433 ± 1.859	-405.612 ± 2.678	-36.174 ± 2.529

5. Conclusions

In a high-performance U-loaded B&BR providing a high fuel burnup, positive coolant void reactivity can be strongly positive due to its low neutron leakage and high Pu content in the fuel. In this study, a simple and novel passive safety device is introduced. To cope with the large positive void reactivity, FAST passive safety devices have been installed in the B&BR. It is shown that the FAST will ensure the reactor safety by bringing the core to a subcritical state when any uncontrolled accident occurs.

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