FAST and SAFE Passive Safety Devices for Sodium-cooled Fast Reactor

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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 this paper, two new concepts of passive safety devices are proposed. The devices are called FAST (Floating Absorber for Safety at Transient) and SAFE (Static Absorber Feedback Equipment). Their purpose is to enhance the negative reactivity feedback originating from the coolant in fast reactors. Both FAST and SAFE modules have been tested in an innovative Sodium-cooled Fast Reactor (iSFR), which is currently being developed at KAIST. A preliminary safety assessment for the iSFR was performed by using the balance of reactivity (BOR) method in order to identify the impact of the devices on the reactor safety.

2. Description of the Passive Safety Devices

2.1 FAST (Floating Absorber for Safety at Transient)

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 the guide thimble contains a neutron absorber rod, which is floating 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 can be low density 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.

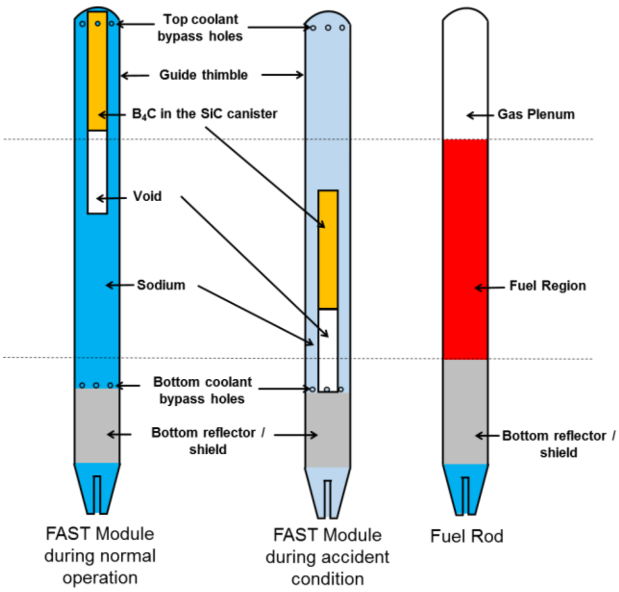

Fig. 1. FAST passive safety device concept.

FAST can be designed to respond to either any change in the coolant temperature or certain threshold change in coolant temperature. In this paper, the B_4C absorber section sinks into the active core only when the coolant temperature is increased by over 100 K from the nominal 100% power condition. 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.

2.2 SAFE (Static Absorber Feedback Equipment)

SAFE is inspired by the negative reactivity insertion mechanism of control element insertion due to thermal expansion of control element driveline. It consists of a long steel line holding an absorber rod in the tip as is shown in Fig. 2. The absorber rod consists of steel cladding and a neutron absorber such as B_4C. The absorber is located in the control element assembly by replacing some of the central absorber pins. Unlike the control assembly, the position of the holding line is fixed and the tip position of the absorber section is also fixed for the nominal conditions. When the coolant temperature increases, the steel holding line of the absorber will expand accordingly, become longer and thereby insert absorber a little bit more into the core to provide the negative reactivity feedback. The initial depth of the SAFE insertion is optimized so that it will not reduce the neutron economy too much but will still provide appropriate negative reactivity feedback when required. If necessary, the SAFE module can be placed in the central region of a fuel assembly.

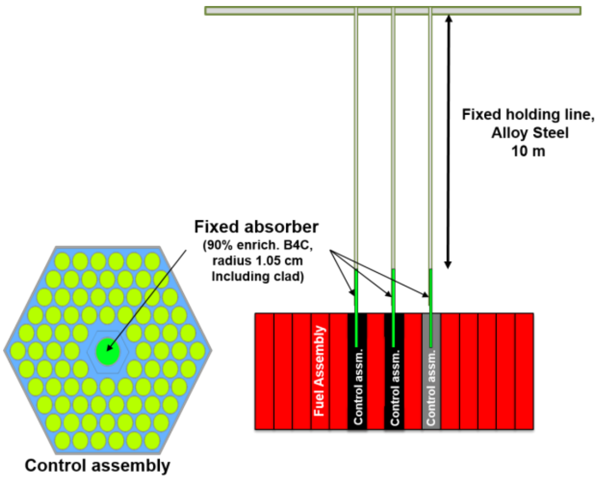

Fig. 2. SAFE passive safety device concept.

3. Application of the FAST and SAFE Devices

These novel passive safety devices are installed in an innovative Sodium-cooled Fast Reactor (iSFR) and the impacts of devices on the core safety are evaluated in view of the balance of reactivity (BOR) analysis. In order to do this, the reactivity feedback coefficients should be calculated. This analysis provides a preliminary insight of the passive reactivity shutdown performance and self-controllability in response to several unprotected accidents such as loss of flow, pump over speed, failure of heat exchangers, chilled inlet, and transient overpower accidents [8].

The BOR analysis assumes that the reactor asymptotically approaches a new critical state after a limited transient, and the following the quasi-static reactivity balance equation should be satisfied:

$$\Delta\rho = (P-1)A + (\frac{P}{F}-1)B + \delta T_{in} C + \Delta\rho_{ext} = 0 \quad (1)$$

where P and F are normalized power and flow, δT_{in} is the change from the normal coolant inlet temperature, and $\Delta\rho_{ext}$ is externally-imposed reactivity. The constants *A*, *B*, and *C* are the integral reactivity parameters composed of the reactivity coefficients, as defined in Eqs. 2 to 4. The reactivity feedback from FAST is not considered because, in this work, the FAST is supposed to work only when the coolant temperature increment is higher than ~100 K or when there is a loss of coolant accident.

$$A = \alpha_{Doppler} \ \Delta\overline{T}_f \quad (2)$$

$$B = (\alpha_{Doppler} + \alpha_{Na} + \alpha_{Axial} + 2\alpha_{Radial} + \alpha_{CADL} + \alpha_{SAFE})^{\Delta T_C}/_{2} \quad (3)$$

$$C = (\alpha_{Doppler} + \alpha_{Na} + \alpha_{Axial} + \alpha_{Radial} + \alpha_{CADL} + \alpha_{SAFE}) \quad (4)$$

$\Delta\overline{T}_f$ is the increment in the average fuel temperature relative to the average coolant temperature. ΔT_C is the coolant temperature rise. The α values are various reactivity feedback coefficients of the iSFR.

By applying the quasi-static reactivity balance to the several possible unprotected accident scenarios, it was found that the asymptotic core outlet temperature is acceptable if the following criteria are met:

1. A, B, and C are negative.
2. $\frac{A}{B} < 1$ for passive control of pump and balance of plant-induced accident scenarios.
3. $1 < \frac{C\Delta T_c}{B} < 2$ for loss of flow, pump over speed, and chilled inlet accident scenarios.
4. $\frac{\Delta\rho_{TOP}}{B} < 1$ for transient overpower performance,

where $\Delta\rho_{TOP}$ is the multiplication of the 1st rod out interaction factor and the ratio of the burnup swing and the number of operational rods.

The iSFR is a 393 MWth, long-life (20 years) LEU-loaded reactor. The reactor core consists of 84 inner fuel assemblies, 60 outer fuel assemblies, 7 control assemblies, and 162 PbO reflector assemblies, as shown in Fig. 4. The inner fuel assemblies have lower enrichment than those of the outer fuel assemblies in order to flatten the radial power profile. The axial core configuration is depicted in Fig. 5. Table I shows the major design parameters of the iSFR. Three FAST modules are installed in each of the inner fuel assemblies only by replacing 3 fuel pins, as shown in Fig. 6. The FAST module uses 95% enriched B_4C neutron absorber enclosed in a SiC canister. Three radii of the absorber are considered i.e. 0.300 cm, 0.325 cm, and 0.350 cm, all much smaller than the inner radius of the guide thimble of ~0.43 cm. The SiC canister thickness is 0.01 cm. The length of the FAST absorber is 100 cm and the length of the void region is 70 cm. Meanwhile, the SAFE absorber is 90% enriched B_4C contained within 0.05-cm thick cylindrical cladding. In the SAFE device, total radius of the B_4C absorber and HT9 cladding is only 1.05 cm.

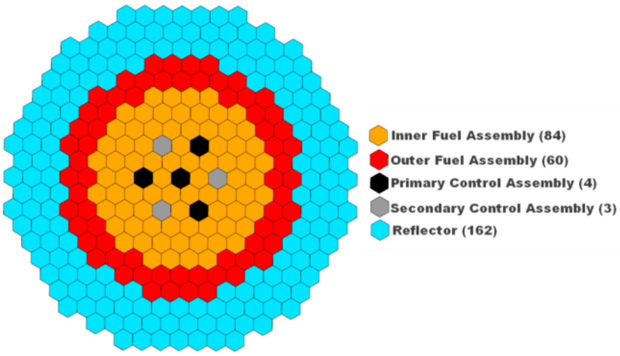

Fig. 4. iSFR radial core configuration.

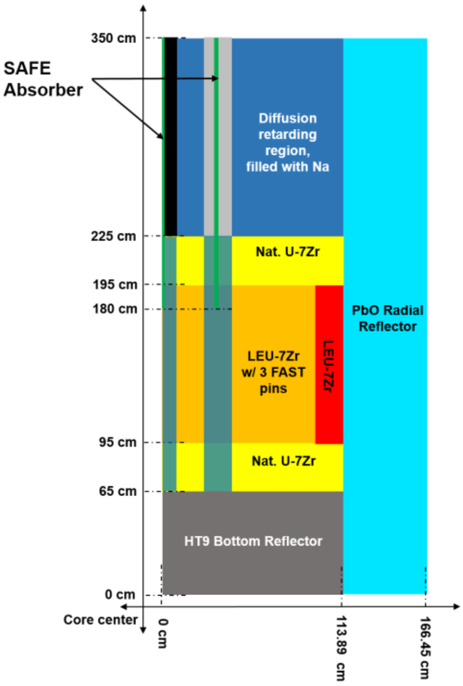

Fig. 5. iSFR axial core configuration.

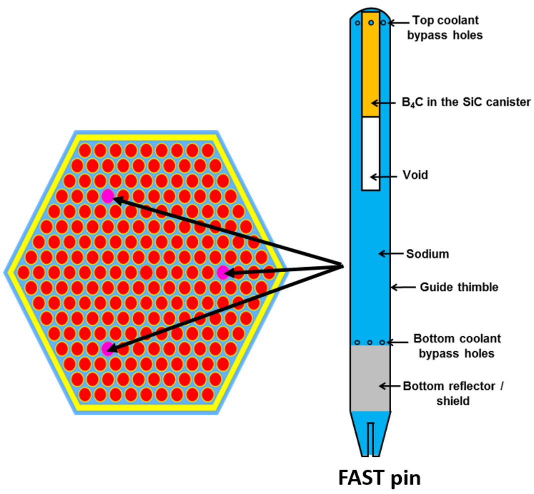

Fig. 6. FAST positions in the inner fuel assembly.

Table I: Core Design Parameters

Design Parameters	Value
Power, MWth	392.6
Active core height, cm	160.0
LEU core height, cm	100.0
Blanket core height each side, cm	30
Active core equivalent radius, cm	112.6
Whole core equivalent radius, cm	162.2
Power density, W/cc	64.09
Linear Power, kW/m	7.85
Coolant inlet temperature, ^{o}C	390
Coolant outlet temperature, ^{o}C	545
Coolant velocity, m/s	2.30
LEU mass, tons	21.26
Blanket fuel mass, tons	12.76

Table II summarizes the reactivity feedback coefficients of the iSFR core at BOL (beginning of life) and EOL (end of life), namely fuel temperature reactivity feedback coefficient ($\alpha_{Doppler}$), sodium temperature reactivity feedback coefficient (α_{Na}), sodium void reactivity feedback coefficient (α_{Void}), axial expansion reactivity feedback coefficient (α_{Axial}), radial expansion reactivity feedback coefficient (α_{Radial}), and control assembly driveline expansion reactivity feedback coefficient (α_{CADL}). These reactivity feedback coefficients were evaluated without considering the impacts of the two newly-introduced passive safety devices.

Table II: Reactivity Feedback Coefficients of iSFR

Reactivity Coefficient	At BOL	At EOL
$\alpha_{Doppler}$, ¢/K	-0.057 ± 0.002	-0.064 ± 0.003
α_{Na}, ¢/K	-0.008 ± 0.0004	0.206 ± 0.001
α_{Void}, ¢	17.051 ± 1.395	773.987 ± 2.541
α_{Axial}, ¢/K	-0.023 ± 0.002	-0.062 ± 0.003
α_{Radial}, ¢/K	-0.115 ± 0.003	-0.150 ± 0.004
α_{CADL}, ¢/K	-0.010 ± 0.005	-0.063 ± 0.008

Reactivity worth of the new passive safety devices were evaluated at both BOL and EOL conditions and are shown in Tables III and IV. The worth of FAST is evaluated with respect to sodium void reactivity coefficient (CVR) because FAST is designed to provide fast and sufficient negative reactivity feedback during a coolant loss accident. The CVR was calculated by coolant voiding in the active core region. From Table III, it is noticed that α_{Void} is reduced by about 2\$ ~ 3\$ at BOL and 4\$~5.5\$ at EOL, depending on the diameter of the absorber. The FAST absorber length is 100 cm and it covers only the LEU core region when it drops into the core. The FAST worth can be easily increased by installing them in the outer core region as well, if requested.

Meanwhile, the differential worth of the SAFE module was calculated for an initial depth of 45 cm from the top of the core. The linear expansion coefficient of the holding line steel is assumed to be about 15E-06 to 20E-06 /K. As shown in Table IV, the SAFE modules provide a strongly negative coolant temperature coefficient. It is noteworthy that the negative feedback by SAFE is rather comparable to the generic positive feedback at EOL from the coolant in Table II. It is also shown that the SAFE worth is larger than the α_{CADL} due to the initial insertion position. The fixed absorber of SAFE is initially located slightly inside the core region, while the control absorber assemblies are originally located at the top of the core.

Table III: Reactivity worth of FAST

Absorber diameter	α_{Void} at BOL, ¢	α_{Void} at EOL, ¢
0.300 cm	-205.321 ± 1.347	370.039 ± 2.086
0.325 cm	-244.822 ± 1.365	295.414 ± 2.029
0.350 cm	-288.606 ± 1.480	216.789 ± 1.983
Without	17.051 ± 1.395	773.987 ± 2.541

Table IV: Differential worth of SAFE

Worth at BOL	Worth at EOL
-9.15 ± 1.84 pcm/cm (-0.14± 0.03 pcm/K ~ -0.18 ± 0.004 pcm/K)	-8.79 ± 1.70 pcm/cm (-0.13 ± 0.03 pcm/K ~ -0.18 ± 0.03 pcm/K)

The BOR analysis results are summarized in Table V. The results indicate that the current iSFR core design satisfies the 4 requirements at BOL and EOL conditions only when the reactivity feedback from the passive SAFE module is accounted for. Without consideration of the SAFE, the third requirement is not satisfied at EOL condition due to the large positive sodium temperature reactivity coefficient.

Table V. Balance of Reactivity Analysis

Requirements	At BOL	At EOL
A	-1.755	-2.312
B	-26.880 (-25.373)*	-25.036 (-21.932)*
C	-0.232 (-0.213)*	-0.173 (-0.133)*
$\frac{A}{B} < 1$	0.065 (0.069)*	0.092 (0.105)*
$1 < \frac{C \Delta T_c}{B} < 2$	1.339 (1.229)*	**1.070 (0.938)***
$\frac{\Delta \rho_{TOP}}{B} < 1$	0.220 (0.233)*	0.106 (0.121)*

*without considering the reactivity feedback of SAFE.

4. Conclusions

Two unique passive safety devices named FAST and SAFE have been proposed to cope with the coolant void reactivity and the positive sodium temperature reactivity feedback in SFRs. FAST is designed to passively insert a strong negative reactivity when the coolant temperature increases more than a set-point or sodium coolant loss takes place in the core. Meanwhile, SAFE is derived to balance the positive reactivity feedback due to sodium coolant temperature increases. It has been demonstrated that SAFE allows a low-leakage SFR to achieve a self-shutdown and self-controllability even though the generic coolant temperature coefficient is quite positive and the coolant void reactivity can be largely managed by the new FAST device. It is concluded that both FAST and SAFE devices will improve substantially the fast reactor safety and they deserve more detailed investigations.

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