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

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Abstract. This paper presents two novel passive safety devices for Sodium-cooled Fast Reactors (SFR): SAFE (Static Absorber Feedback Equipment) and FAST (Floating Absorber for Safety at Transient) to deal with the positive coolant void reactivity (CVR) and coolant temperature coefficient (CTC). It is well-known that the positive CVR and CTC limit the maximum performance of a SFR. Especially, CVR and CTC become more positive as the core average burnup of U-loaded SFR increases. Both FAST and SAFE can be easily introduced into an SFR core by replacing some fuel pins or control rods without any complicated core design changes. In this study, the optimum configurations of FAST and SAFE devices in an innovative Sodium-cooled Fast Reactor (iSFR), which is a small (393 MWth) and long-life (>20 years) SFR, are studied in terms of safety parameters and core lifetime. Moreover, time-dependent behavior of FAST module in transient situation is roughly analyzed by estimating the insertion speed and sinking depth.

Key Words: innovative SFR, Passive safety device, Void reactivity, Inherent safety

1. Introduction

As the core average burnup of U-loaded sodium-cooled fast reactor increases, the coolant void reactivity (CVR) and coolant temperature coefficient (CTC) become more positive due to high Pu content in the fuel. In this regard, those coefficients limit the maximum performance of a Sodium-cooled Fast Reactor (SFR). Various SFR core concepts have been suggested to make these coefficients negative or less positive, such as heterogeneous core design with internal blanket [1], core with softer neutron spectrum [2,3,4] or pancake core with high neutron leakage [5]. These core designs have relatively low CVR, but their performance is reduced because of bad neutron economy. To address the CTC and CVR problems, application of passive safety devices has been studied, such as LIM (Lithium Injection Module) [6], LEM (Lithium Expansion Module) [6], ARC (Autonomous Reactivity Control) [7], and our concepts: SAFE (Static Absorber Feedback Equipment) and FAST (Floating Absorber for Safety at Transient) [8].

In the previous study, the two newly developed concepts of passive safety devices: FAST and SAFE have been proposed and tested in an innovative Sodium-cooled Fast Reactor (iSFR) [8]. It was shown that FAST can effectively reduce the CVR about 4$ without reducing the core performance. Also, based on the quasi static reactivity analysis, it was found that the reactor self-shutdown could be achieved with SAFE device during anticipated transient without scram accidents. However, the CVR reduction of FAST at EOL was still positive, around 3$. In this work, further reduction of CVR with FAST in the iSFR is pursued by increasing the number of FAST module in the core. Neutronics analysis was performed by using McCARD (Monte Carlo code for Advanced Reactor Design and Analysis) [9] with ENDF/B-VII.0 nuclear data library.

2. Passive Safety Devices

2.1.Floating Absorber for Safety at Transient (FAST)

The FAST module is seemingly a fuel rod, but there are no fuel pellets inside as shown in Fig 1. It is filled with coolant and a neutron absorber rod. It should be noticed that this neutron absorber rod is designed such that it can float by the buoyancy force. There are several small holes at the top and bottom of the FAST module which allow the inflow and outflow of the coolant so that FAST module can be filled with coolant if there is coolant around it. However, vertical coolant flow within the FAST module is negligible. The absorber rod consists of neutron absorber, void and cladding, and they are made of enriched B4C, air and SiC/SiC, respectively. Buoyancy force of the absorber rod can be controlled by adjusting the length of void part, the diameter, and the density of absorber part. A 40cm-thick HT9 steel is loaded in to the bottom of the FAST module to support the absorber when it sinks. The FAST module is designed such that the absorber section is fully out of the core and top of the absorber rod contacts the upper cover of the thimble during the normal operation. The helium gas, resulting from B-10 depletion, can be vented to coolant through micro holes from the absorber rod.

The FAST can be designed to respond to any user-defined coolant temperature change. When the coolant temperature increases, the coolant density becomes lower and B4C absorber section sinks into the active core since buoyancy becomes weaker than gravity. In the case of loss of coolant accidents, the absorber will passively drop into the core region.

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 can be adjusted in accordance with requested reactivity worth. The FAST module will quickly respond to a coolant temperature increase at the bottom of the core so that it will be able to deal with ULOHS (unprotected loss of heat sink) accident that the coolant inlet temperature increases quickly. Furthermore, FAST is expected to be able to counteract partial blockage of coolant flow in a fuel assembly which results in a local coolant temperature increase.

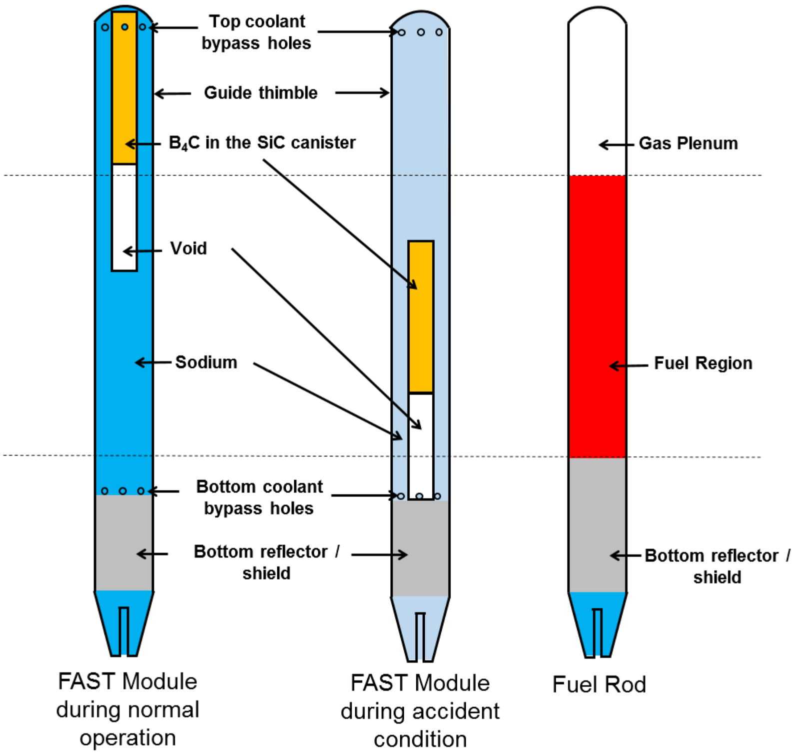

Fig. 1. FAST passive safety device concept.

2.2.Static Absorber Feedback Equipment (SAFE)

The SAFE is basically a long steel line holding a neutron absorber rod at the tip. 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. It should be noticed if it is necessary, SAFE also can be loaded by removing some fuel pins. The axial and radial position of the holding line absorber rod is fixed for the nominal conditions.

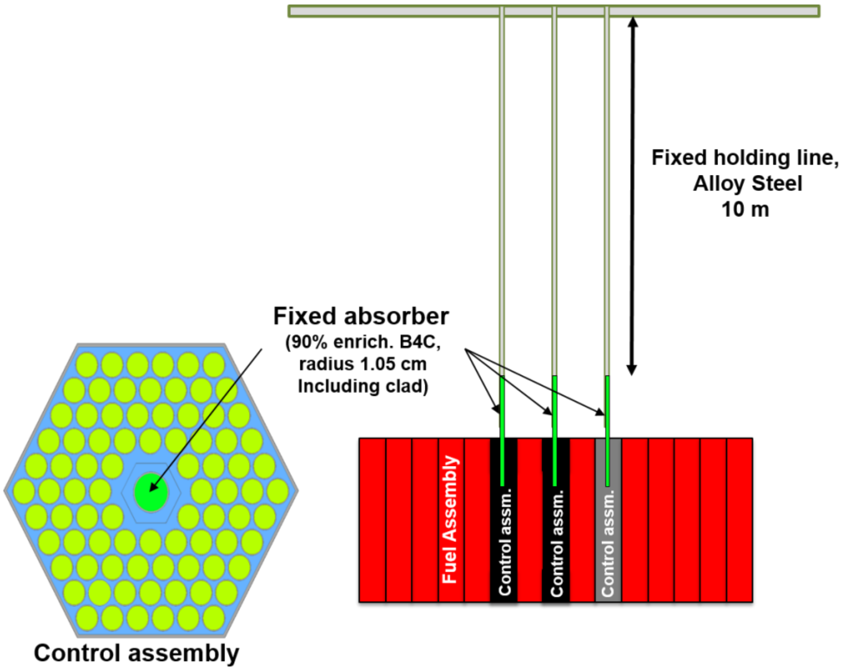

Fig. 2. SAFE passive safety device concept.

When the coolant temperature increases, the steel holding line of the absorber will expand and thereby absorber tip is inserted a little bit deeper into the core, which provides the negative reactivity feedback. The initial depth of the SAFE insertion should be optimized by compromising negative reactivity feedback and neutron economy loss.

3. Analysis Method

3.1.Balance of Reactivity (BOR)

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:

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

where P and F are normalized power and flow, $\delta T_{in}$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.

$$\mathrm{A} = \alpha_{\mathrm{Doppler}}\Delta\overline{T_f} \qquad (2)$$

$$\mathrm{B} = \left(\alpha_{\mathrm{Doppler}} + \alpha_{Na} + \alpha_{Axial} + 2\alpha_{Radial} + \alpha_{CADL} + \alpha_{SAFE}\right)\Delta T_c/2 \qquad (3)$$

$$\mathrm{C} = \left(\alpha_{\mathrm{Doppler}} + \alpha_{Na} + \alpha_{Axial} + \alpha_{Radial} + \alpha_{CADL} + \alpha_{SAFE}\right) \qquad (4)$$

$\Delta\overline{T_f}$ is the increment in the average fuel temperature relative to the average coolant temperature. ΔT_c is the coolant temperature rise. α 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. $\frac{\mathrm{A}}{\mathrm{B}} < 1$ 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.

3.2.innovative Sodium-cooled Fast Reactor (iSFR)

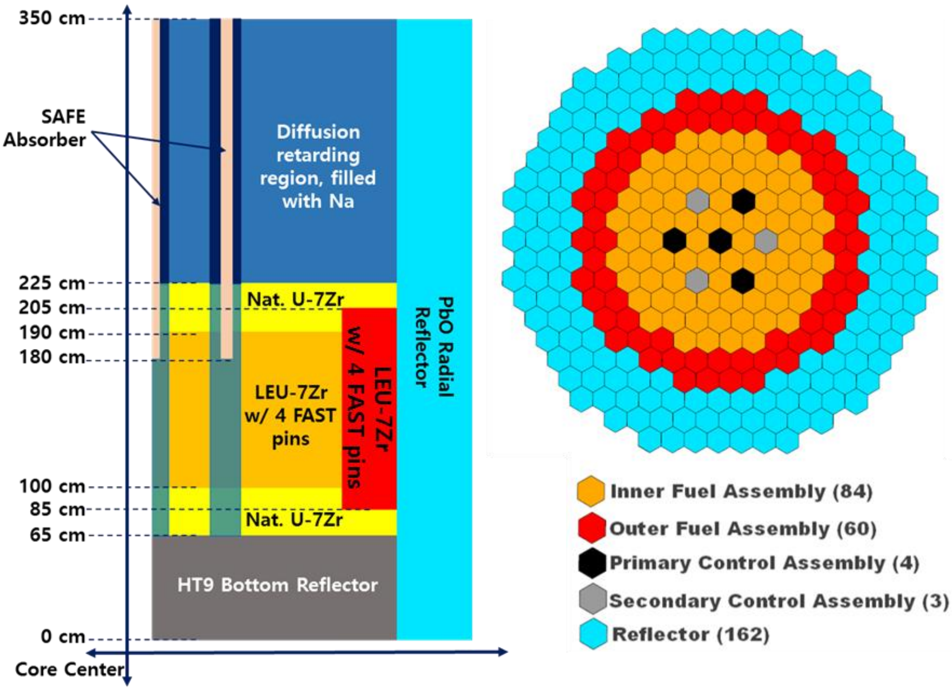

Fig. 3. iSFR core configuration.

The iSFR is a 393 MWth, long-life (20 years) LEU-loaded reactor. Metallic fuel U-7Zr is used to maximize the neutron economy. 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. 3. The inner fuel assemblies have lower enrichment than those of the outer fuel assemblies in order to flatten the radial power profile. The height of inner core (IC) LEU region is 90 cm but that of outer core (OC) LEU region is 120 cm. Because of this unique fuel arrangement, power distribution can be more flat and reactivity swing can be reduced. Table I shows the major design parameters of the iSFR.

TABLE I: Core Design Parameters

Design Parameters	Value
Power, MWth	392.6
Active core height, cm	160.0
Uranium enrichment (IC/OC), %	11.75/12.8
LEU core height (IC/OC), cm	90/120
Blanket core height each side (IC/OC), cm	35/20
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, °C	390
Coolant outlet temperature, °C	545

Coolant velocity, m/s	2.30
LEU mass, tons	21.64
Blanket fuel mass, tons	12.10

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}), *CVR*, 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 passive safety devices.

TABLE II: Reactivity Feedback Coefficients of iSFR

Reactivity Coefficient	At BOL	At EOL
$\alpha_{Doppler}$, ¢/K	-0.072 ± 0.003	-0.082 ± 0.005
α_{Na}, ¢/K	-0.007 ± 0.0004	0.221 ± 0.001
CVR, ¢	-49.890 ± 0.396	623.317 ± 1.257
α_{Axial}, ¢/K	-0.027 ± 0.002	-0.068 ± 0.002
α_{Radial}, ¢/K	-0.103 ± 0.002	-0.239 ± 0.004
α_{CADL}, ¢/K	-0.003 ± 0.0016	-0.051 ± 0.007

3.3.Application of the FAST and SAFE Devices

To check the applicability of FAST to the iSFR, the core radial temperature distribution with coolant flow orificing is first analyzed since FAST should not be inserted in the normal operating condition. Fig. 4 show the coolant temperature after optimized orificing flow results. The working temperature of FAST is about 700°C which is around 100K higher than the nominal 100% power condition coolant temperature. The maximum coolant exit temperature in the hottest fuel assembly is around 600°C. Based on these results density of absorber and height of buoyancy can is determined as shown in table. III. In the simulation, average coolant temperature is used.

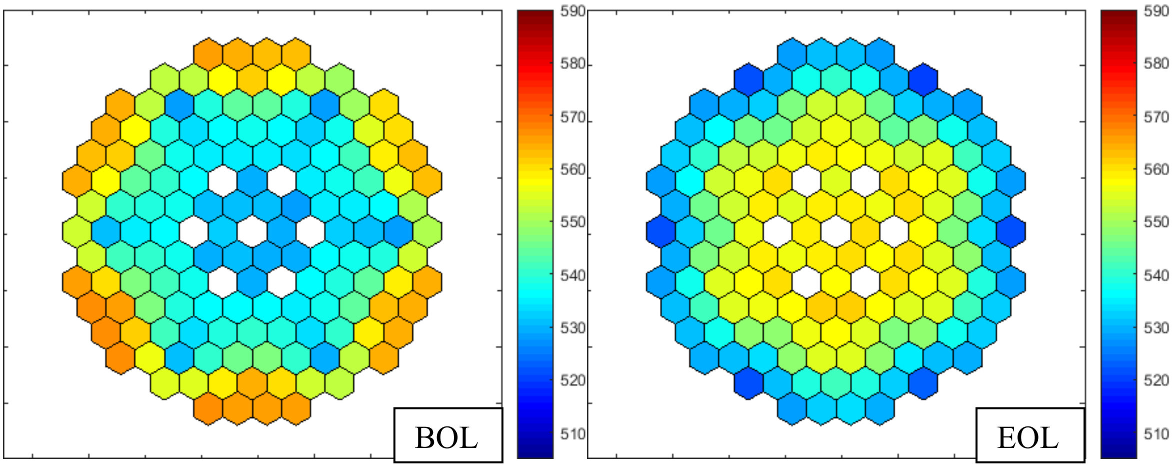

Fig.4. Radial temperature distribution with orifice at BOL and EOL

Four FAST modules are installed in all fuel assemblies by replacing 4 fuel pins, as shown in Fig. 5. Fig. 6 shows the lifetime of the cores with and without FAST modules. It is noteworthy that core lifetime is just slightly reduced even though noticeable number of FAST modules are loaded replacing fuel pins. However, for the core with FAST, the enrichment of outer core is increased to 13.2% to achieve the initial criticality. The FAST module uses 95% enriched B_4C neutron absorber enclosed in a SiC/SiC canister. Table III shows the two design variations of the FAST module. Two radii of the absorber are considered i.e. 0.300 cm and 0.325 cm, all much smaller than the inner radius of the guide thimble of ~0.43 cm. The SiC/SiC canister thickness is 0.01 cm. The lengths of the FAST absorber void canister are determined to balance the buoyancy force and gravity. 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.

TABLE III: Design variations of FAST module

Structure	Material	Radius (cm)	Height (cm)	Density (g/cc)
Absorber	B_4C	0.3	80	1.102
Void	Ar	0.3	55	--
Absorber	B_4C	0.325	85	1.102
Void	Ar	0.325	55	--

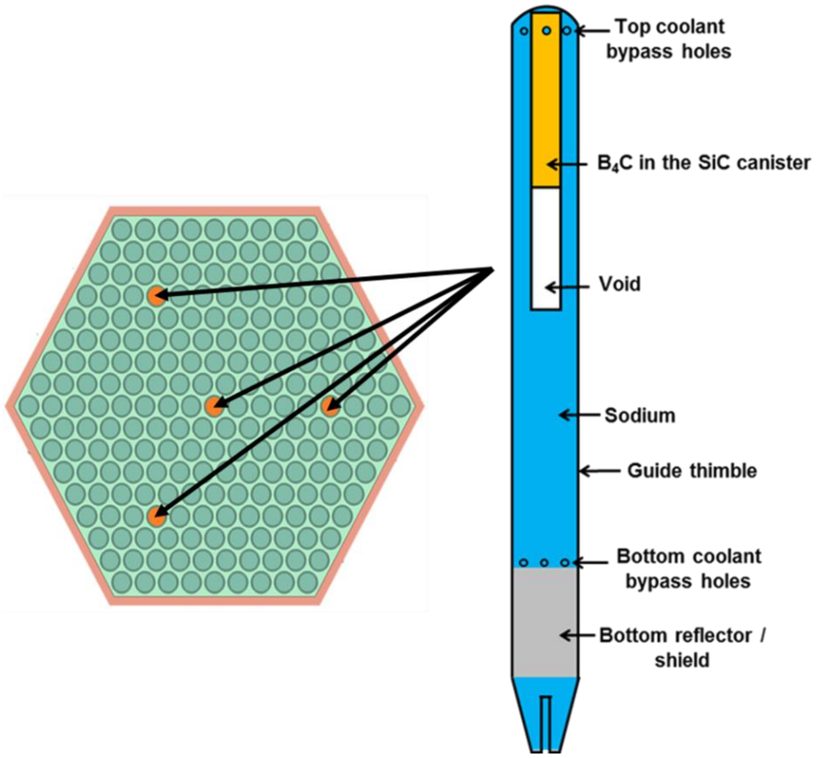

Fig. 5. FAST positions in the fuel assembly.

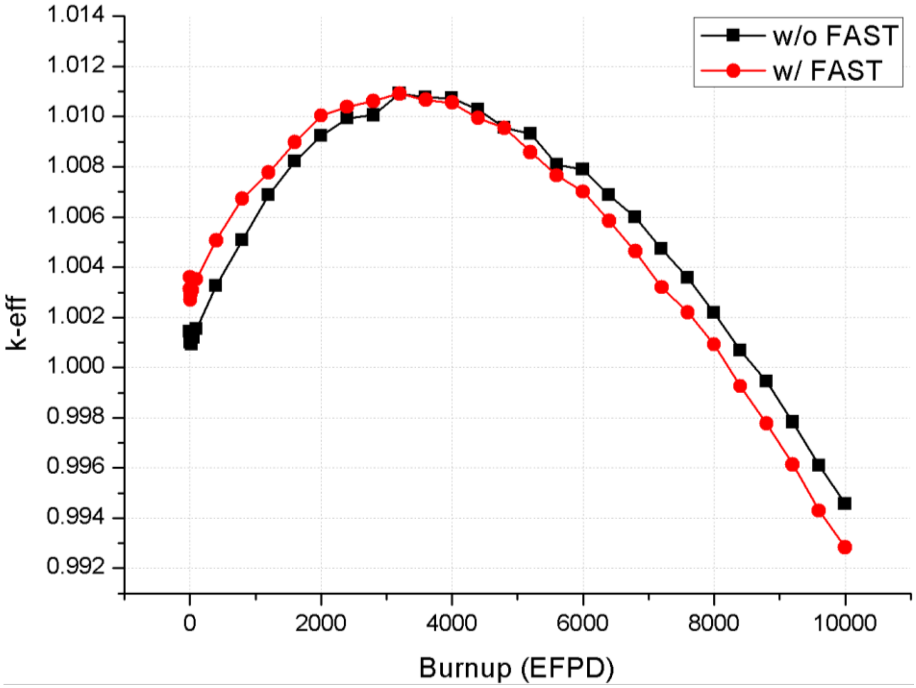

Fig. 6. Core lifetime with FAST modules

4. Analysis Results

4.1.Impact of FAST Passive Safety Device

The worth of FAST device is analyzed with respect to CVR. The CVR is conservatively evaluated by considering the voiding of fuel region instead of whole core voiding. All calculations are done considering less than 20 pcm statistical error of k-eff. Table IV summarizes the CVR with FAST modules. It is shown that CVR could be consistently negative at BOL and EOL if radius of absorber in FAST module is 0.325 cm.

TABLE IV: Design variations of FAST module

Absorber Radius, cm	CVR at BOL, ¢	CVR at EOL, ¢
0.300	-271.30 ± 3.63	76.51 ± 4.27
0.325	-346.12 ± 3.61	-191.12± 4.21

To estimate the response time of the FAST module, time-dependent position of FAST module is calculated assuming 100K rise of outlet temperature. Stokes’ law, which is about the sinking of sphere-shaped material, is used to simplify the calculation, while the shape of FAST module is cylinder. The axial temperature distribution of the core is assumed to be linear and FAST is located at above 20 cm from the top of the active core during the normal operation.

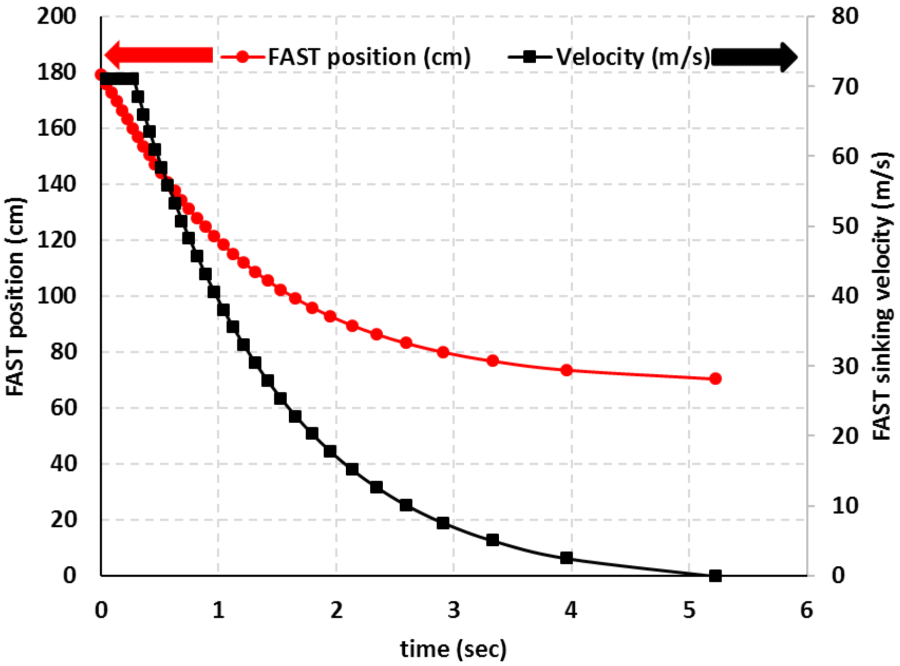

Fig. 7. Time-dependent position of FAST modules

Fig. 7 shows the time-dependent position of FAST module. Initial position of the FAST module is assumed to be 20 cm above the top of the active core. Since the temperature of the upper part of the core is almost constant at the core outlet temperature, FAST sinks at a constant speed. From the top of the core, 160 cm, the sinking speed decreases gradually due to the gradual increase in buoyancy. Total insertion depth of FAST is around 89.6 cm, and the time required for FAST to sink from the initial position to the maximum insertion position was estimated to be approximately 5.3 seconds. One can easily infer from this result that FAST module will respond to the transient faster as the scale of core temperature rise is bigger since the density of coolant becomes lower in higher temperature.

4.2.Impact of SAFE Passive Safety Device

The differential worth of the SAFE module was calculated assuming the SAFE is located just above the active 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 V, the SAFE module provides 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. The BOR analysis results are summarized in Table VI. 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

TABLE V: Differential worth of SAFE

Worth at BOL	Worth at EOL
-6.99 ± 1.84 pcm/cm (-0.10± 0.03 pcm/K ~ -0.14 ± 0.04 pcm/K)	-8.80 ± 1.70 pcm/cm (-0.13 ± 0.03 pcm/K ~ -0.18 ± 0.03 pcm/K)

TABLE VI: BOR analysis of the core with SAFE

Requirements	BOL	EOL

A < 0	-2.221 ± 0.087	-2.986 ± 0.181
B < 0	-25.867 ± 0.544	-38.547 ± 1.163
C < 0	-0.231 ± 0.006	-0.259 ± 0.013
$\frac{A}{B}<1$	0.086 ± 0.004 (0.091 ± 0.004)*	0.077 ± 0.005 (0.084 ± 0.005)*
$1<\frac{C\Delta T_C}{B}<2$	1.385 ± 0.047 (1.346 ± 0.034)*	**1.040 ± 0.059** **(0.958 ± 0.053)***
$\frac{\Delta\rho_{TOP}}{\lvert\beta\rvert}<1$	0.071 ± 0.001 (0.075 ± 0.001)*	0.008 ± 0.0002 (0.009 ± 0.0003)*

* Values in bracket are not considering the reactivity feedback of SAFE.

5. Conclusions

FAST and SAFE passive safety devices have been introduced and the impacts of them are evaluated. It is shown that CVR can be negative by adopting FAST device at both BOL and EOL without reducing the core lifetime. Also, the SAFE device could effectively deal with the positive coolant temperature reactivity coefficient. Also, it is shown that safety criteria in terms of accident scenario can be satisfied by applying SAFE device. In brief, it can be concluded that both FAST and SAFE devices can practicably improve the inherent safety of fast reactors minimizing the sacrifices such as core lifetime or neutron economy.

Optimum shape, material or location of FAST and SAFE should be further studied by coupling neutronics with thermal hydraulics codes. Working temperature of the FAST should be carefully calculated based on the results of thermal hydraulics code, especially core outlet temperature distribution. Also, transient response of FAST is needed to be analysed considering response time and reactivity worth. .

6. References

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7. Acknowledgment

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