# ATWS Responses of Sodium-cooled Fast Reactor with a FAST (Floating Absorber for Safety at Transient) Device

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## 1. Introduction

Floating absorber for safety at transient (FAST) is a passive safety device for sodium-cooled fast reactors, which inserts negative reactivity in case of coolant temperature rise or coolant voiding [1]. Previous studies showed that FAST can effectively insert the negative reactivity to the core in case of coolant voiding [2]. In this study, FAST is slightly modified to be sensitive to the coolant temperature change and the response and stability of FAST at transient in B&BR with high neutron economy are analyzed in this study. Monte Carlo code SERPENT2 [3], in conjunction with ENDF-B/VII.0 library [4], and in-house developed thermal hydraulics coupled point kinetics based transient code are used for the analysis.

## 2. Floating Absorber for Safety at Transient (FAST)

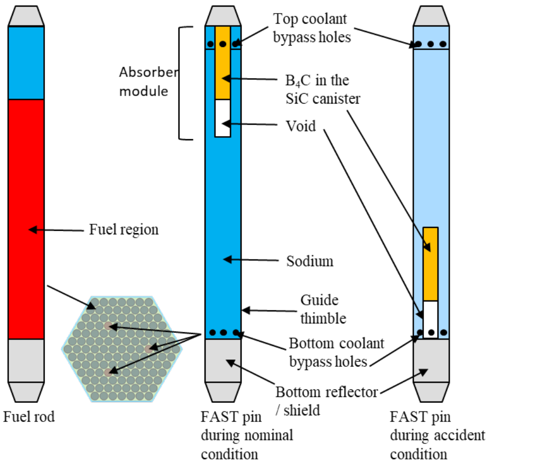


Figure 1. Floating absorber for safety at transient (FAST)

FAST apparently has the same geometry as the fuel rod, but it does not contain the fuel inside as shown in Fig 1. The inside of the FAST is filled with coolant and the neutron absorber module is located in the coolant. The axial position of the absorber module is determined by the balance of buoyancy and gravity. There are several holes at the top and bottom of the FAST pin to allow the inflow and outflow of the coolant. The absorber module consists of the absorber and void canister to adjust the magnitude of buoyancy force. The absorber part is $B_4C$ enclosed in a SiC/SiC composite cladding and void part is filled with noble air. SiC/SiC composite is helium permeable so that the helium produced by (n,α) reaction of B-10 can be vented out through the cladding to release the internal pressure [5]. It is noteworthy that void part and absorber part are not attached to each other to increase the freedom of drop path in case of fuel pin or assembly bowing. One can also consider the separation of absorber part of absorber module in several pieces.

## 3. Reference Core: Advanced Compact B&BR

400MWth advanced compact B&BR core developed by KAIST is chosen as a reference core for the analysis of FAST behavior during the transient [6]. The radial and axial core configurations are shown in Fig 2. Core average burnup of advanced compact B&BR is about 160 GWd/MTHM, equal to 52.3 years of operation without refueling. The maximum excess reactivity is about 1 $ during the reactor operation. Reactivity feedback coefficients of the reference core listed in table 1 are used for the transient analysis.

In advanced compact B&BR, three FAST pins are installed in each fuel assembly replacing fuel pins. This study borrows the configuration of FAST in reference core except the density of absorber module. Detailed FAST configuration used in this study is described in section 4.4.

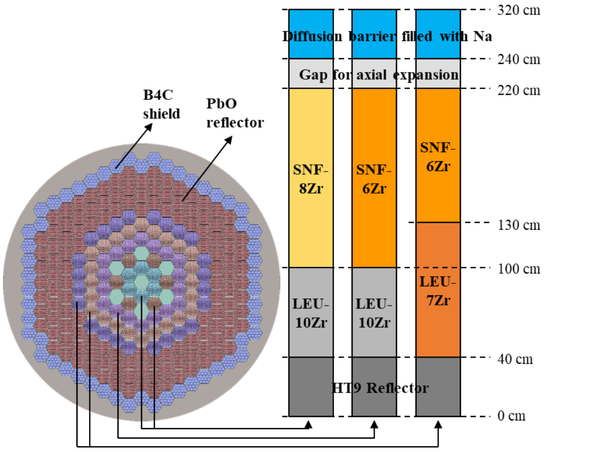


Figure 2. Core configuration of advanced compact B&BR

Table 1. Reactivity coefficients of reference core at EOL

| Reactivity feedback coefficients | Value |
|---|---|
| $\alpha_{Doppler}$ (¢/ K) | -0.045 ± 0.003 |
| $\alpha_{Na}$ (¢/ K) | 0.263 ± 0.001 |
| $\alpha_{Axial}$ (¢/ K) | -0.067 ± 0.003 |
| $\alpha_{Radial}$ (¢/ K) | -0.155 ± 0.003 |
| $\alpha_{CEDL}$ (¢/ K) | -0.024 ± 0.007 |

## 4. Methodologies for Transient Analysis of FAST

### *4.1. Heat transfer model*

Assuming radial temperature distribution of coolant is flat, heat transfer by the coolant flow can be modeled by 1-D time-dependent energy and mass conservation in axial direction:

$$\rho c_{p_{coolant}} \frac{\partial T_{coolant}}{\partial t} + \rho c_{p_{coolant}} v_{coolant} \frac{\partial T_{coolant}}{\partial z} = q''' \quad (1)$$

$$\frac{\partial \rho_{coolant}}{\partial t} + v_{coolant}\frac{\partial \rho_{coolant}}{\partial z} + \rho_{coolant}\frac{\partial v_{coolant}}{\partial z} = 0 \quad (2)$$

Heat transfer in the fuel pin and FAST pin is treated as a radial 1-D heat conduction in cylindrical coordinate since axial heat conduction in the fuel rod is negligible compared to the radial heat conduction:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{dr}\right) + q''' \quad (3)$$

Specific heat of the coolant is treated as a constant since it is almost constant between 600 K and 900 K [7]. The heat source term for each axial node in the fuel region is calculated by considering the axial power distribution at EOL of the reference core and reactor power determined by the point kinetics equation. It is assumed that the power distribution does not change during the transient since power distribution hardly changes in fast reactor. Figure 3 shows the axial power distribution of reference core at EOL.

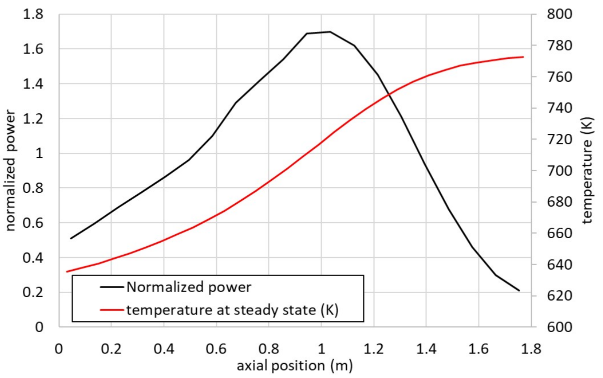


Figure 3. Axial power distribution of reference core at EOL

### *4.1. FAST movement model*

Assuming that the fluid is incompressible, irrotational and fully developed, velocity field of coolant surrounding the absorber module ($V_{coolant}$) in FAST pin can be derived by steady-state N-S equation in cylindrical coordinate [8].

$$0 = -r\frac{dp}{dz} + \mu\frac{d}{dr}\left\{r\left(\frac{dV_{coolant}(r)}{dr}\right)\right\} \quad (4)$$

$$B.C.:\ V_{coolant}(r_{FAST}) = V_{FAST},\ V_{coolant}(r_{pin}) = 0$$

The equations for forces acting on FAST are tabulated in Table 2. It should be noted that steady-state assumption and pressure gradient correction technique guarantee the accuracy of the solution with very small time step size.

Table 2. Mathematical formulation of forces acting on FAST

| Force type | Equation |
|---|---|
| Gravity | $F_g = \rho_{FAST} Volume_{FAST} g$ |
| Buoyancy | $F_b = \int_V \rho_{coolant}(z) g dV$ |
| Drag | $F_D = \int \mu \frac{dV_{coolant}}{dr} dA_{FAST\_side}$ |
| Pressure | $F_p = \Delta p \times A_{FAST\_front}$ |

### *4.3. Point kinetics model*

The standard point kinetics model is considered to simulate the change of reactivity in accordance with the temperature change of core components and insertion of the FAST. Kinetic parameters of reference core are estimated using Monte Carlo code SERPENT2. The PKE is solved by the simple finite difference method and the reactivity change is calculated by the equation (5).

$$\rho(t) = \rho_0 + \alpha_f \Delta T_f + \alpha_c \Delta T_c + \Delta\rho_{ex} + \Delta\rho_{FAST} \quad (5)$$

### *4.4. Reference FAST Design*

Detailed design parameters of reference FAST are tabulated in Table 3. Modified FAST is used for the following analysis and position-wise reactivity worth of FAST absorber module is calculated by Monte Carlo code SERPENT2.

Table 3. Reference FAST design parameters

| Design parameters | Value |
|---|---|
| Absorber height, cm | 90 |
| Void height, cm | 50 |
| Absorber density ($B_4C$), g/cc | 1.178 |
| Absorber module average density, g/cc | 0.831 |
| Absorber module radius, cm | 0.66 |
| Absorber module cladding thickness, cm | 0.01 |
| FAST pin radius, cm | 0.95 |
| FAST pin cladding thickness, cm | 0.06 |

## 5. Transient Analysis of FAST

Three representative anticipated transient without scram (ATWS) scenarios at EOL of the reference core are considered in this study: unprotected loss of flow (ULOF), unprotected loss of heat sink (ULOHS) and unprotected transient overpower (UTOP). Instead of modeling the secondary system, accident scenarios are simulated by varying inlet coolant temperature, inlet coolant velocity and external reactivity.

### *5.1. Unprotected Loss of Flow (ULOF)*

In the ULOF scenario, failure of all the coolant pumps in the primary system is assumed. During the ULOF transient, 2.94 m/s of the nominal coolant flow rate linearly decreases to 0.5 m/s over 5 seconds. It should be noted that the inlet coolant temperature boundary condition is kept same as the nominal state.

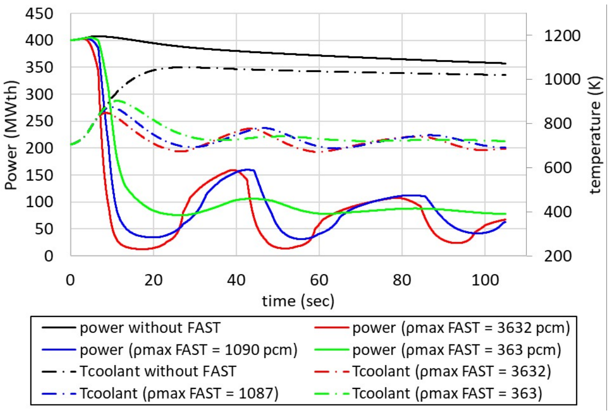


Figure 4. Time evolution of the core power in ULOF

Figure 4 compares the transition of core power and coolant temperature with and without FAST. The power and the temperatures of fuel and coolant decreased sharply in the presence of FAST. However, oscillation of power level and temperature is observed due to the movement of the FAST absorber module. As shown in Fig 5, reactivity worth of FAST absorber dominates the overall reactivity and drastic reactivity perturbation by movement of FAST absorber module results in an oscillation of the power. On the other hand, it is clearly shown that FAST with low reactivity worth is preferable for the stable mitigation of ULOF transient at EOL.

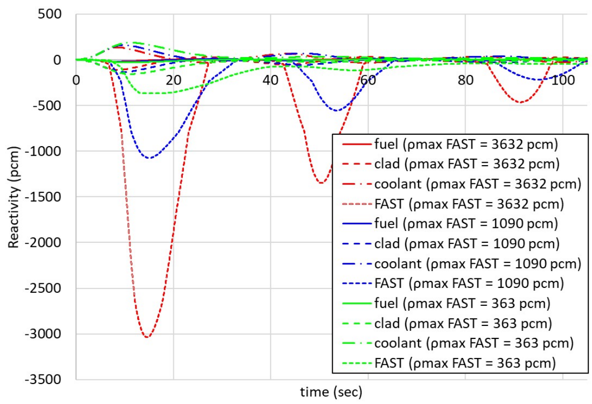


Figure 5. Time evolution of the reactivity and its components in ULOF

### *5.2. Unprotected Loss of Heat Sink (ULOHS)*

In the ULOHS scenario, the rise of the inlet coolant temperature due to the failure of heat removal is assumed and a linear temperature rise of 167K is considered over 20 seconds. The flow rate of the coolant on the primary circuit is kept equal to the nominal state.

Figure 6 compares the transient progress of with and without FAST in ULOHS scenario. In the presence of FAST, power decrease at ULOHS is more rapid and therefore, the temperature rise of the core components is much less than that without FAST. Oscillation of power and temperature is not observed with any reactivity worth of FAST during the ULOHS transient because the rise of the coolant inlet temperature only causes insertion of the FAST absorber module. The reference core with FAST quickly shutdown by insertion of negative reactivity by FAST as shown in Fig 7.

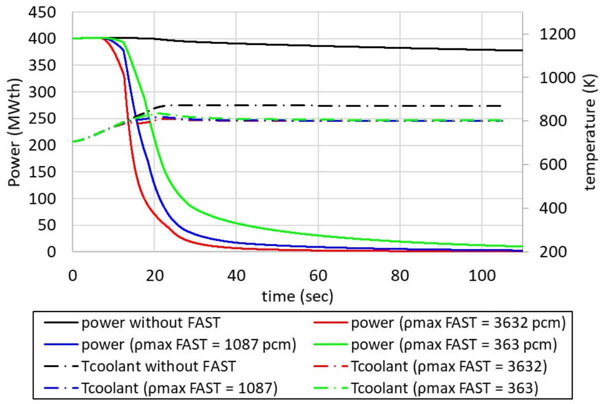


Figure 6. Time evolution of the core power in ULOHS

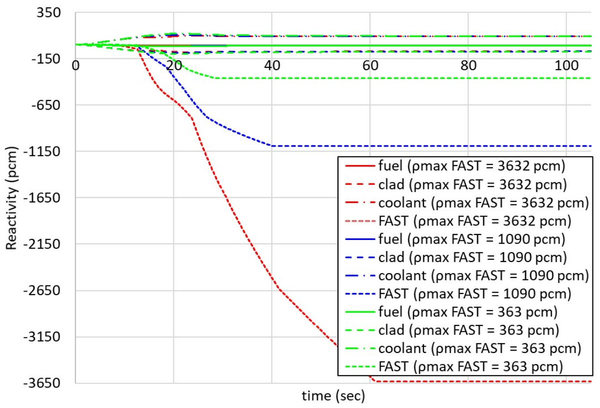


Figure 7. Time evolution of reactivity and its components in ULOHS

### *5.3. Unprotected Transient Overpower (UTOP)*

UTOP, in which positive external reactivity is inserted into the core, is one of the most dangerous accident scenarios which can lead to a sudden rise in power and hence a rise in temperature of core components. The UTOP scenario in this study assumes 50 seconds of external reactivity insertion with a ramp rate of 0.02 $/sec, while keeping flow rate and inlet temperature of the coolant same as the nominal state.

Time evolution of power and temperature during the UTOP transient is shown in Fig 8. In the absence of FAST, the power of the core increases sharply due to positive external reactivity insertion, while the increase of power and temperature is much less drastic in the presence of FAST.

Similar oscillatory behavior as that in ULOF is observed during the UTOP transient in cases with FAST. This is because the coolant temperature rapidly increases or decreases due to the sudden power change caused by insertion or withdrawal of the FAST absorber module with large reactivity worth as shown in Fig 9. One can clearly note the less oscillation of power and temperature with low reactivity worth of FAST absorber.

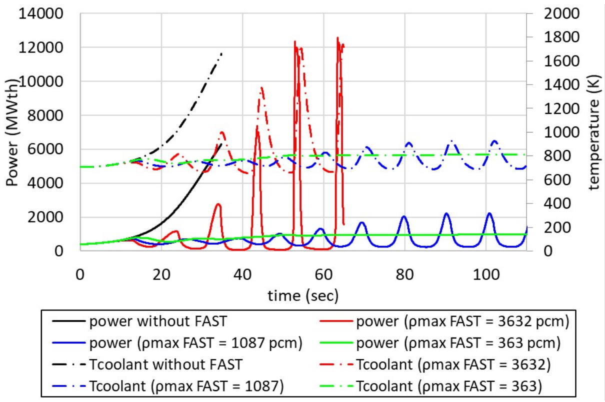


Figure 8. Time evolution of the core power in UTOP

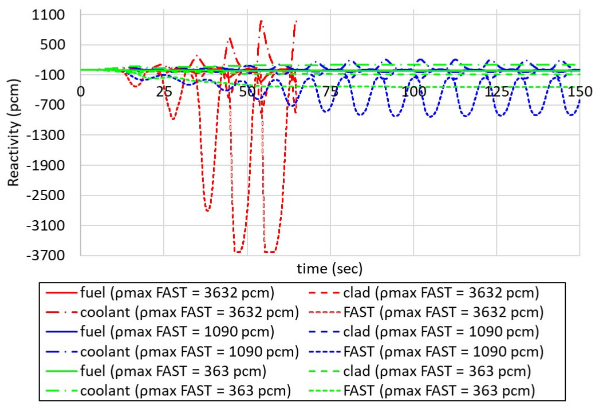


Figure 9. Time evolution of the reactivity in UTOP

## 6. Conclusions

The feasibility of direct application of the FAST to deal with the positive CTC in core with low leakage is confirmed in this study. FAST effectively and successfully mitigates consequence of the ATWS (Anticipated Transient without Scram) scenarios including ULOF, ULOHS and UTOP at EOL of the reference core. In particular, temperature increasing rate of reactor components can be much more moderate in transients with FAST. As a result, it is expected that inherent safety of SFRs can be improved substantially with the FAST device.

Oscillation of power and temperature in case of ULOF and UTOP can be minimized by adjusting the reactivity worth of FAST absorber and largely positive CVR issue can be simply resolved by installing another type of FAST with large reactivity worth and high working temperature in each assembly. Future works may contain detailed optimization methodologies for FAST considering radial power distribution, cladding material, and so on. Moreover, for the linear B&BR whose position and height of the active core changes during the burnup, the behavior of FAST at various burnups should be also further investigated. In particular, it should be noted that the reactivity worth of FAST and reactivity feedback coefficients of the core are highly dependent on the burnup of the linear B&BR and affect the behavior of FAST by varying the temperature profile during the transient.

## Acknowledgement

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