Improved FAST Device (iFAST) for assuring the Safety of Oxide-fueled Sodium-cooled Fast Reactors during Anticipated Transients without Scram Events

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1. Introduction

In a fast spectrum reactor, the fission to capture ratio is much higher than that in a thermal neutron spectrum, and the number of neutrons produced per neutron absorbed (η) increase at harder neutron spectrum for PU-239. This leads to more excess neutrons available for breeding of fissile isotopes and transmutation of spent nuclear fuel. Meanwhile, the high fission to capture ratio in fast spectrum leads to less generation of higher actinides which simplifies the fuel recycling.

There are several fast spectrum reactor technologies that have been investigated for decades such as lead cooled fast reactors (LFRs), and sodium cooled fast reactors (SFRs). Lead is relatively heavy, and the lead coolant requires high pumping power. Thus, the power output of a LFR should be quite limited. Furthermore, due to corrosion and erosion problems caused by lead, there is a maximum allowable speed of the lead coolant. Therefore, the lattice should be rather coarse in LFRs. Spectrum hardening due to coolant loss is negligible in LFRs. Consequently, the coolant temperature coefficient (CTC) can be negative in the coarse lattice design of a LFR. Meanwhile, sodium has high thermal conductivity, low melting temperature, and good material compatibility. Accordingly, SFRs can operate at higher power density than LFRs. However, there are safety concerns of Na-water interactions, which require utilizing an intermediate heat exchanger in SFRs. In addition, the Na temperature increase will yield hardened neutron spectrum, less Na capture, and enhanced leakage. Furthermore, in a low leakage SFR design, coolant void reactivity (CVR), and CTC can be clearly positive at burned core condition.

In SFRs, the Doppler reactivity coefficient is more negative in an oxide fuel loaded core (OLC) than that in a metallic fuel loaded core (MLC). This is because the neutron spectrum is harder in a MLC. In addition, the oxide fuel has lower thermal conductivity, and it operates at higher temperature than a metallic fuel for the same power. The negative reactivity feedback from the axial fuel expansion is higher in a metallic fuel. However, in a MLC, the effects of the smaller fuel temperature, and a smaller Doppler reactivity coefficient lead to lower asymptotic temperatures after transients without scram (ATWS) than those in an OLC. Therefore, it is necessary to improve the safety of oxide fuel loaded SFRs.

Previously, a study was performed for FAST (Floating Absorber for Safety at Transient) as a solution of the positive CTC in SFRs. Studies were performed on the movement of the floating absorber module during the ATWS. The results showed promising potentials, however, oscillation behaviors of power and temperature due to refloating of FAST was observed during unprotected transient over power (UTOP) that may lead to core damage. In this work, an improved FAST device (iFAST) design is suggested to minimize the oscillation of power and temperatures during ATWS. In iFAST, a simple modification of the original design is introduced by imposing a constraint on the insertion limit of the absorber module. The modified design of FAST device is very effective in protecting the core at various ATWS scenarios: UTOP, unprotected loss of heat sink (ULOHS), and unprotected loss of flow (ULOF).

2. Methods

The iFAST device is designed to insert negative reactivity in case of coolant temperature rise or coolant voiding in an inherently passive way. The density of the absorber and volume of the void canister is determined to make the absorber module float (above the core) during normal operation. If coolant temperature rises, the coolant density decreases and absorber module in iFAST pin sinks down due to weakened buoyancy. In the original FAST design [1-2], the oscillation of the power may lead to core failure especially during UTOP. In iFAST, a restricted insertion region is optimized to minimize the power oscillation which is caused by the refloating of the absorber module. Figure 1 demonstrates the concept of iFAST device.

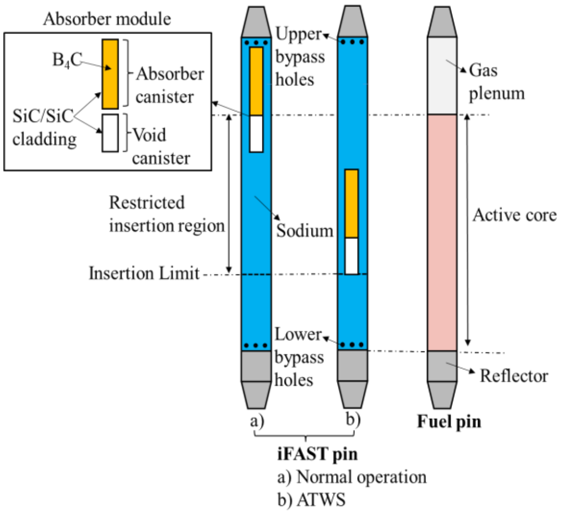

Fig. 1. Concept of the iFAST device

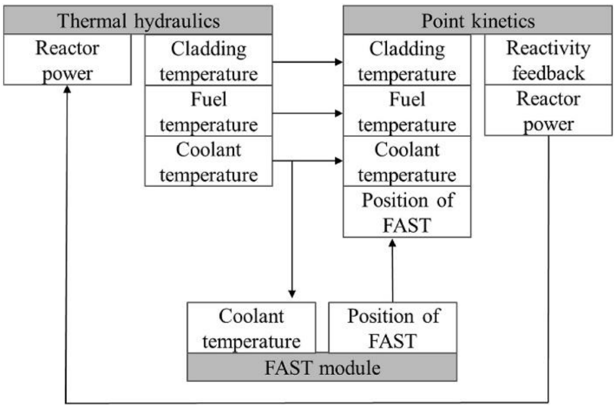

Fig. 2. Layout of system modeling including movement of the absorber module in iFAST

Table. 1. Kinetic parameters and reactivity feedback coefficients of the large-size oxide SFR ABR

Kinetic parameters (EOL)			**Reactivity Feedback coefficients (EOL)**	
G	**βg**	**λg**	**Parameters**	**Value**
1	5.36E-05	0.0124	Fuel temperature (pcm/K)	−0.372
2	5.73E-04	0.0305	Coolant temperature (pcm/K)	0.496
3	5.08E-04	0.111	Axial expansion (pcm/K)	−0.155
4	1.31E-03	0.301	Radial expansion (pcm/K)	−0.930
5	5.22E-04	1.14	Effective delayed neutron fraction	0.0031
6	1.33E-04	3.01	Prompt neutron lifetime (μs)	0.420

The iFAST device has the same dimensions as the fuel pins, and it can be easily installed in conventional SFRs by replacing some fuel pins. Compared to other passive-safety devices such as GEM (Gas Expansion Module) and ARC (Autonomous Reactivity Control) [3], iFAST is very unique in that it can improve the CTC in an extremely simple way, applicable without changes in the fuel assembly.

Figure 2 shows the layout of the model used. The point kinetics equation (PKE) with six delayed neutrons groups is used to determine the power (p) variation, as shown in Eq. 1. Meanwhile, Eq. 2 is used to update the net reactivity that is the summation of the initial reactivity, coolant reactivity feedback, radial core expansion reactivity feedback, axial fuel expansion reactivity feedback, excess reactivity, and iFAST reactivity feedback. It should be noticed that reactivity feedback from iFAST is a sort of external reactivity feedback that is inserted passively due to coolant temperature variation.

The 1000 MWth advanced burner reactor (ABR) core developed by ANL (Argonne National Laboratory) [4] is chosen as an oxide fuel-loaded reference core for the analysis of FAST behavior during the transient. Kinetic parameters and reactivity feedback coefficients listed in Table 1. Fig. 3 shows the axial temperature distribution in 1.067 m long active core region of ABR calculated by in-house thermal hydraulics code. It should be noted that chopped cosine-shaped axial power distribution is assumed. 1-D time-dependent energy and mass conservation in the axial direction. Velocity field of coolant surrounding the absorber module in iFAST is calculated using Navier-Stokes equation in cylindrical. Based on the calculated velocity, the position of the absorber module is calculated. The position-wise reactivity worth of the absorber module in iFAST is shown in Fig. 4.

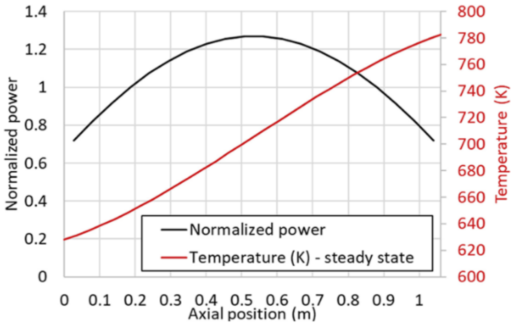

Fig. 3. Axial power distribution and coolant temperature rise

$$\dot{p}(t) = \frac{\rho(t)-\beta}{\Lambda} p(t) + \sum_k \lambda_k C_k(t), \qquad (1)$$
$$\dot{C}_k(t) = \frac{\beta_k}{\Lambda} n(t) - \lambda_k C_k(t).$$

$$\rho(t) = \rho_0 + \alpha_{fuel} \Delta T_{fuel} + \alpha_{coolant} \Delta T_{coolant} + \alpha_{radial\ expansion} \Delta T_{coolant} + \alpha_{axial\ expansion} \Delta T_{fuel} + \Delta\rho_{ex} + \Delta\rho_{FAST} \qquad (2)$$

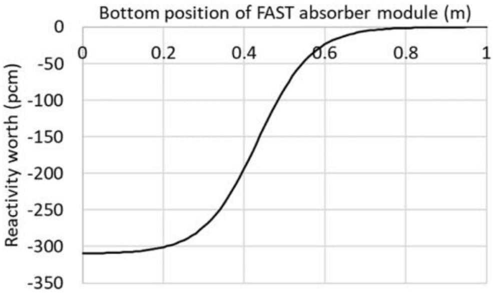

Fig. 4. Position-wise reactivity worth of the absorber module

3. Results and Discussions

For ATWS, the utilization of iFAST in the oxide fuel-loaded core aims at fast power decrease to protect the reactor core. In Fig. 5, ULOF is simulated with and without utilizing the iFAST. Clearly a faster power decrease is attained with iFAST and deeper insertion limit i.e. 0.1m measured from the bottom of the active core. In the ULOF scenario, we assume failure of all the coolant pumps in the primary system and the coolant mass flow rate decreases with pump halving time of 5s while 5% natural circulation is considered. Meanwhile, inlet coolant temperature remains unchanged. Figures 6 and 7 show that the maximum coolant and fuel temperatures during the ULOF is largely decreased by utilizing iFAST with deeper insertion limits.

Nevertheless, the insertion limit in iFAST must be optimized in the view of the reactor safety during the various ATWS. Especially because oscillations of the reactor power was previously reported for UTOP scenario with the old FAST design without optimized insertion limit. In the UTOP scenario, 50s of external reactivity insertion with a ramp rate of 0.02 \$/sec, while keeping the nominal coolant flow rate, and constant temperature drop in intermediate heat exchanger (IHX). Similar scenario is considered in this study for the oxide-loaded core. The iFAST device is utilized to passively protect the reactor core and various insertion limits are simulated.

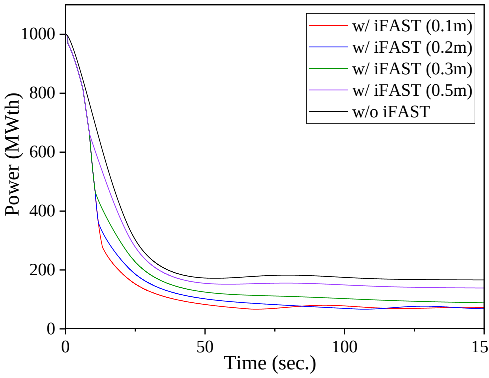

Fig. 5. Core power during ULOF

Figure 8 shows the reactor power during UTOP for various insertion limits in the iFAST device. For insertion limit at 0.1m, clear oscillations of the reactor power occurs due to refloating of the absorber module in iFAST as shown in Fig. 9. This leads to oscillations of maximum fuel and coolant temperatures for 0.1m insertion limit as shown in Figs. 10 and 11, respectively.

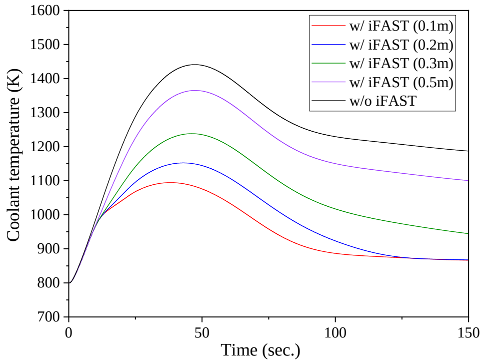

Fig. 6. Maximum coolant temperature during ULOF

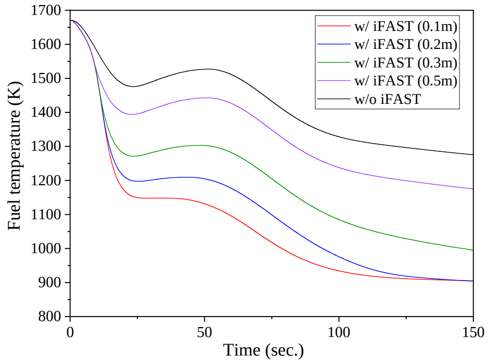

Fig. 7. Maximum fuel temperature during ULOF

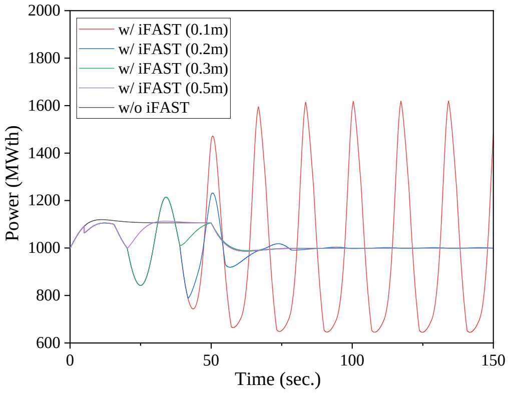

Fig. 8. Core power during UTOP

It is also clear from Figs. 10 and 11 that utilizing iFAST with optimized insertion limit can effectively reduce the maximum fuel and coolant temperature variations even during severe UTOP accident. This is because iFAST inserts relatively large negative reactivity in case of coolant temperature rise. For example, Fig. 12 demonstrates the reactivity components during from Doppler reactivity, core expansion and axial fuel expansion reactivity feedback, coolant reactivity feedback, and the passively induced reactivity feedback from the iFAST device with insertion limit at 0.2m. In addition, the utilization of the iFAST device also effectively reduce the core temperatures during the

ULOHS. Figure 13 shows the variation of the maximum fuel temperature during for ULOHS over 20s.

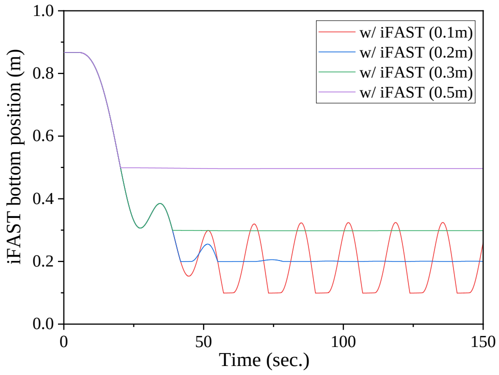

Fig. 9. Position of the absorber module in iFAST during UTOP

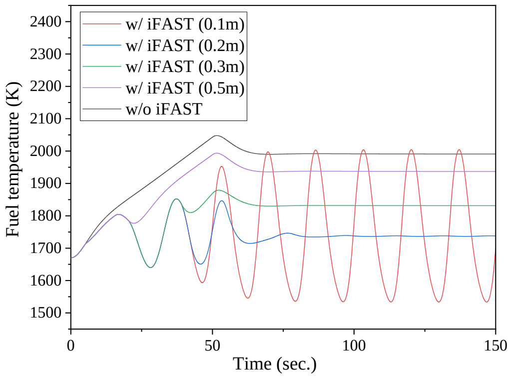

Fig. 10. Maximum fuel temperature during UTOP

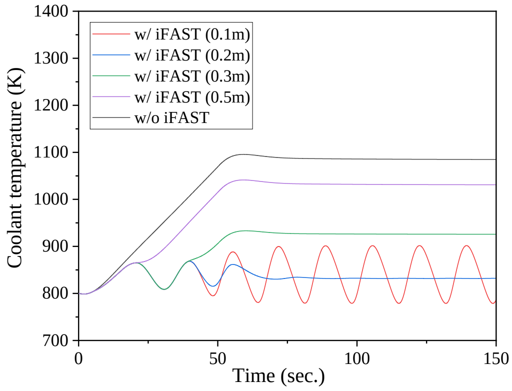

Fig. 11. Maximum coolant temperature during UTOP

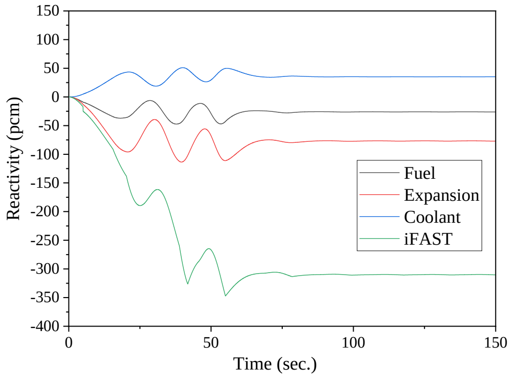

Fig. 12. Reactivity feedback components during UTOP with insertion limit at 0.2m

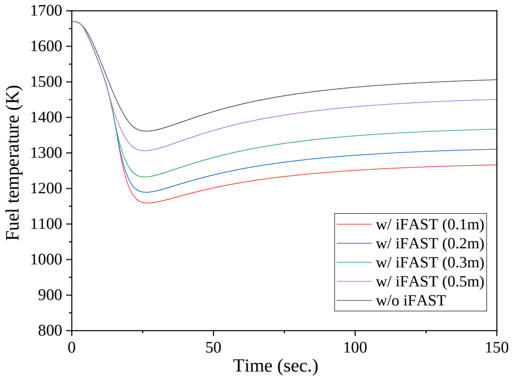

Fig. 13. Maximum fuel temperature during ULOHS

4. Conclusions

Improved FAST device (iFAST) design is proposed. It imposes a constraint on the sinking (insertion) limit of the absorber module in FAST. This provides a simple solution of the oscillation of power that was previously noticed during UTOP. For the original FAST design, the oscillation of the power may lead to core failure especially during UTOP. The insertion limit in the iFAST device controls both the maximum worth and the refloating region of the absorber module. Optimizing the insertion limit shows effective impact on reducing the power oscillation during UTOP in the large-size oxide fuel-loaded core ABR, therefore it protects the reactor core. The study also demonstrates that iFAST device has high potentials in protecting the oxide-loaded SFR core in the cases of ULOF and ULOHS.

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