[Technical Meeting on the Benefits and Challenges of Fast Reactors of the SMR Type]

A Passive Safety Device for SFRs with Positive Coolant Temperature Coefficient

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September 26, 2019

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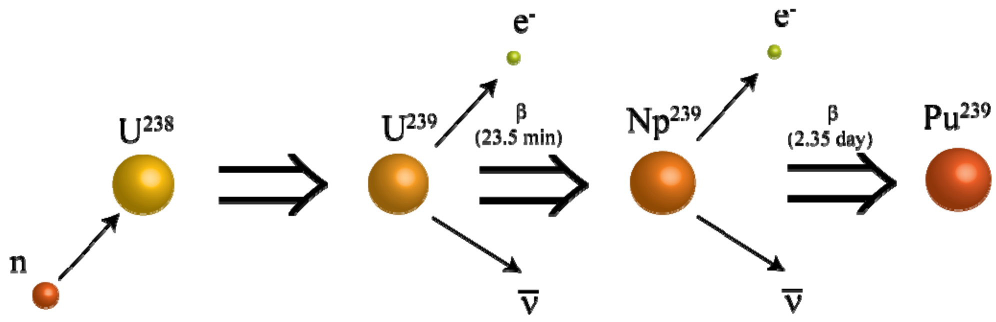
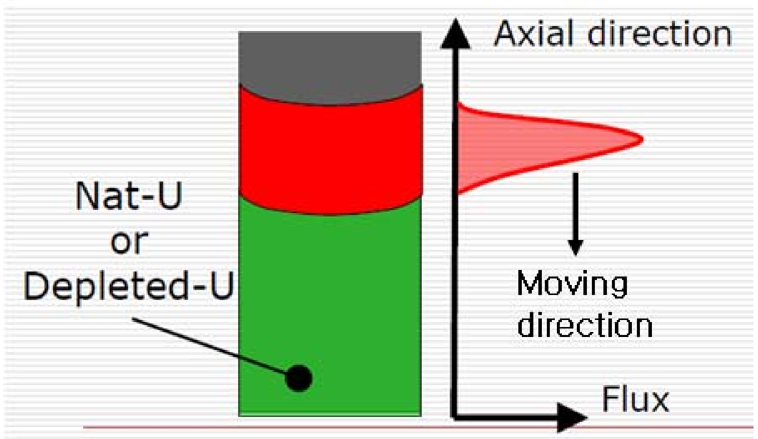
Breeding & Burn Reactor (B&BR)

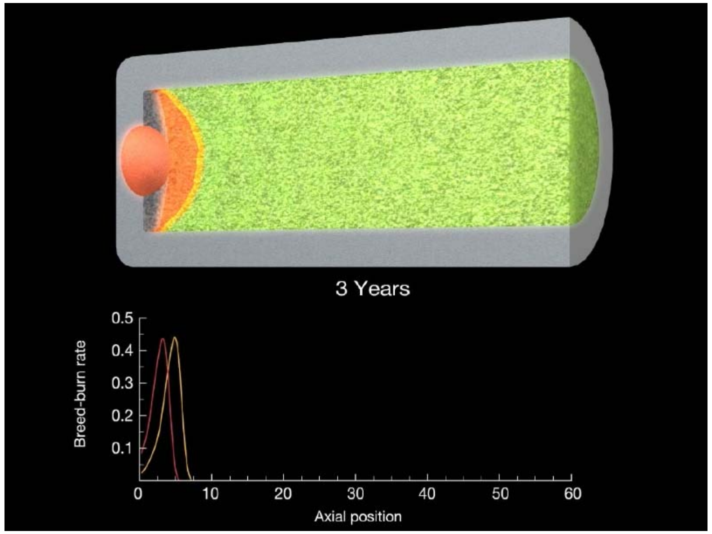
- **Breeding fissile and in-situ burn of the bred fuel**

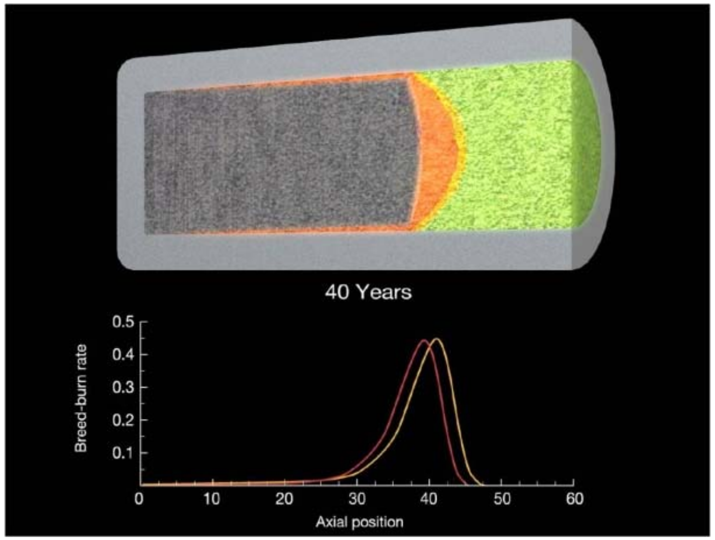




- No refueling over 50 years, very high burnup (> 40%), sustainable fuel cycle

- Tight-lattice & low-leakage (hardly achievable with coarse-lattice cores)



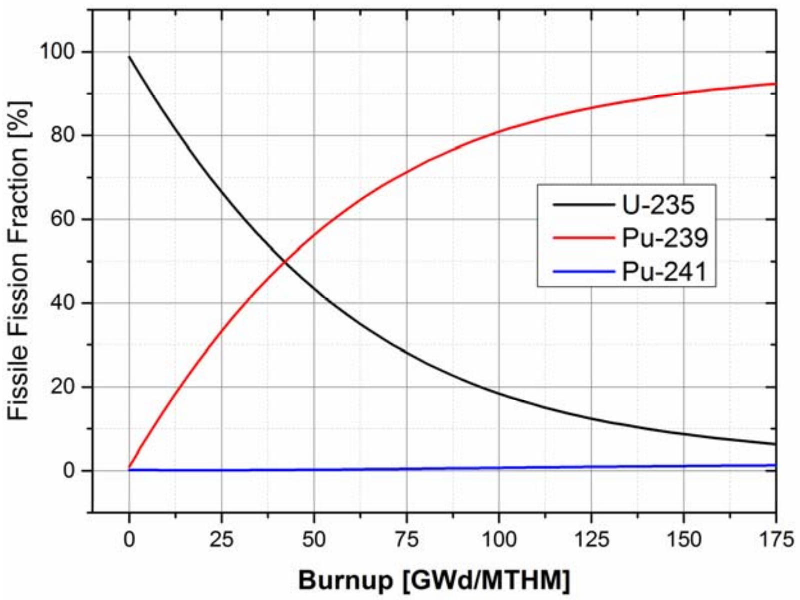


Linear B&BR or TWR (Traveling Wave Reactor) (CANDLE)

Introduction

A challenge in a ‘high-performance’ fast reactor : positive CTC and CVR.

- Neutron spectral hardening (major)
  - Reduced capture by U-238
  - More fission from TRUs
- Reduced absorption by coolant (minor).
- More positive in a low-leakage and a long-life SFR (e.g. B&BR).



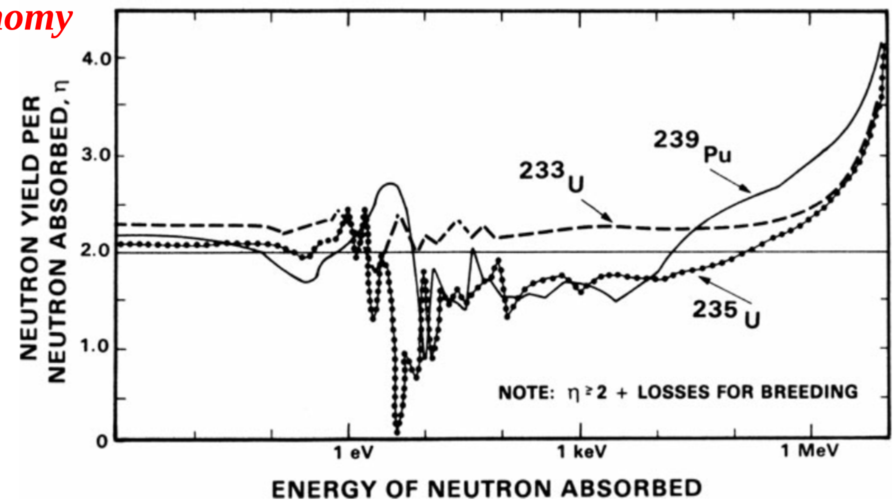
Existing ideas and concepts to improve the CVR and CTC:

- Heterogeneous core
- Softening neutron spectrum using moderator.
- Increasing neutron leakage e.g. pan-shape core.

→ *Complicated core design and/or reduced neutron economy*

An alternative solution is to use a passive safety device.

- ARC* (Autonomous Reactivity Control)
- FAST (Floating Absorber for Safety at Transient)
- SAFE (Static Absorber Feedback Equipment)



FAST (Floating Absorber for Safety at Transient)

- A guide thimble with a floating absorber rod inside
- The absorber and the void region is not attached.
- Installed by replacing pin or pins in a fuel assembly.
- To deal with positive void reactivity (originally)

- Absorber
  - 95% B-10 enriched B_4C

    : Buoyancy issue (mass reduction & absorption increment)

    → void can + porous absorber

    : He-4 production (n, α) of B-10
  - Li-6

    : Low density

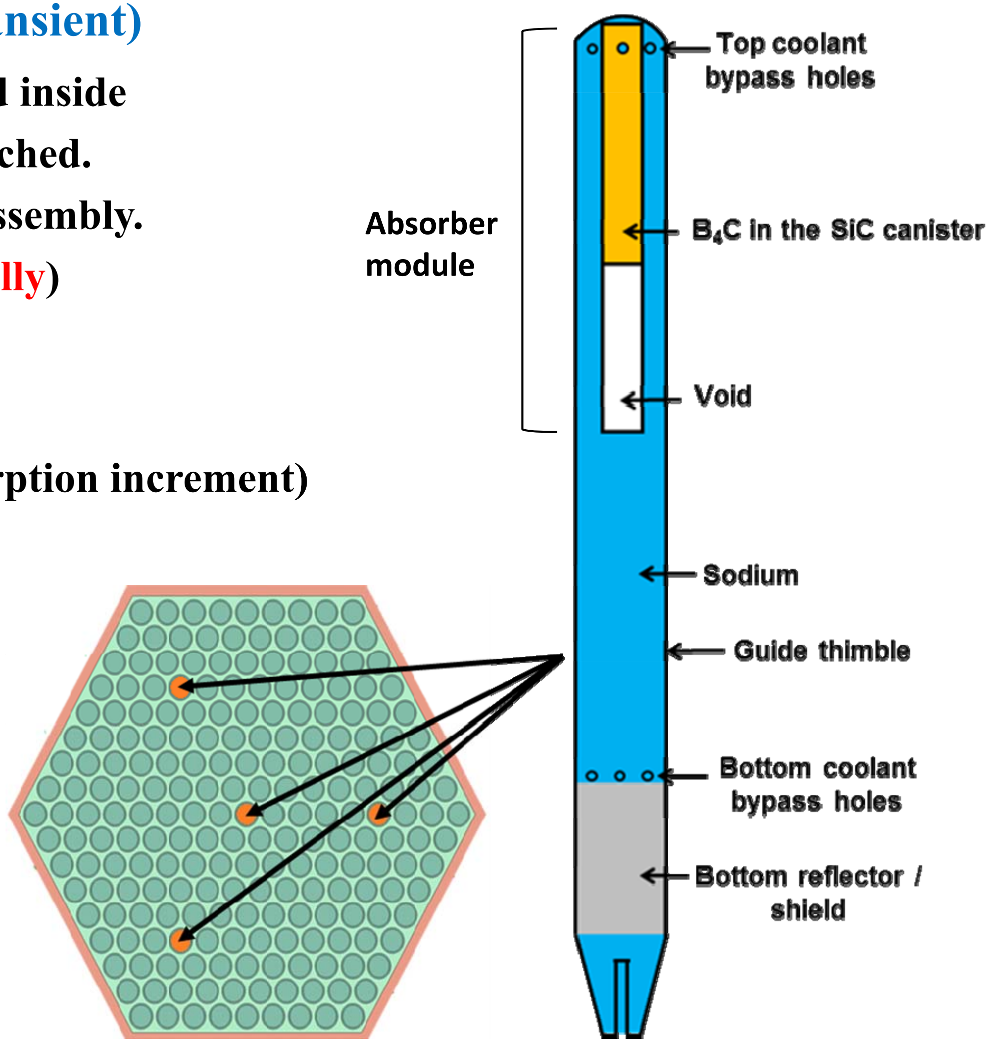
    : low reactivity worth in fast spectrum

- Cladding
  - SiC/SiC composite

    : Helium permeable

    : Long life in fast neutron environment

    (neutron irradiation resistance)

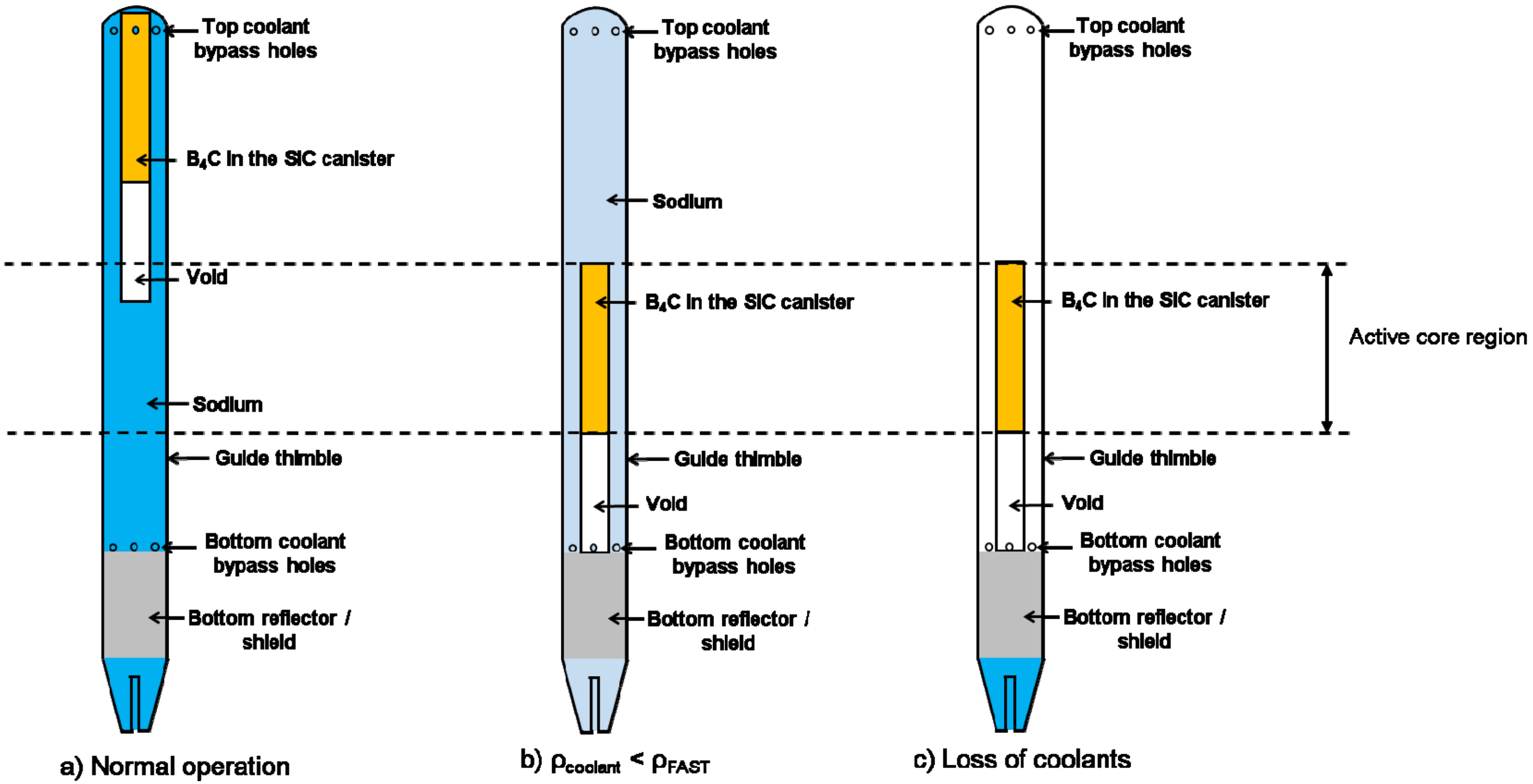


Introduction

How the (original) FAST works:

- Floats above the active core during normal operating condition.
- Sinks into the core as the coolant temperature reaches a set-point temperature (nominal + 100K).
- During the coolant loss accident, it is passively inserted into the core.
- Quickly responds to a temperature increases at the bottom of the core

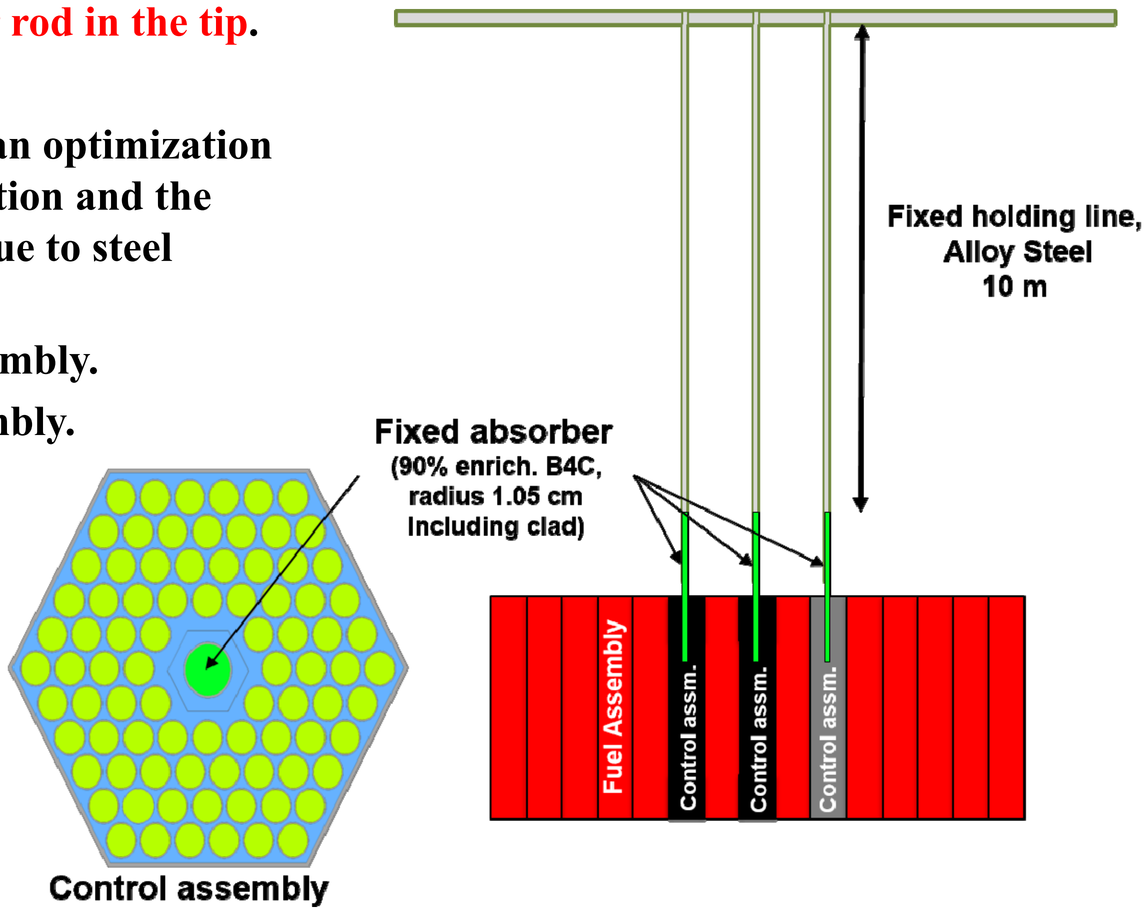
  e.g. ULOHS and partial coolant blockage.



Introduction

SAFE (Static Absorber Feedback Equipment)

- Inspired by the negative reactivity insertion mechanism of control rod driveline thermal expansion.
- Long steel line holding an absorber rod in the tip.
- Absorber is also enriched B_4C.
- The insertion depth of absorber is an optimization between reactivity loss due to insertion and the negative reactivity feedback gain due to steel expansion.
- Located in the control element assembly.
- Also can be placed in the fuel assembly.

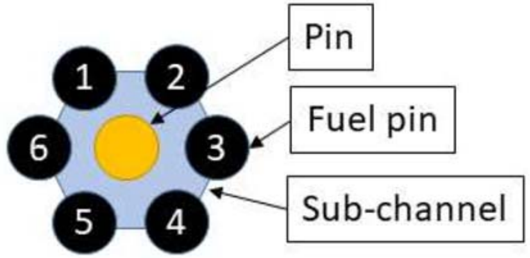


Introduction

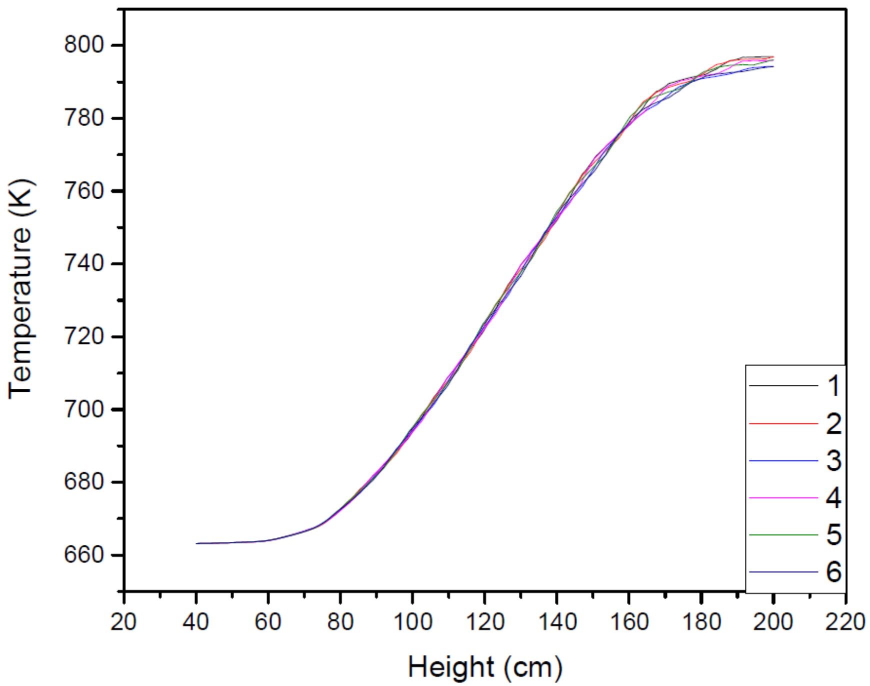
Can FAST be also effective in reducing CTC?

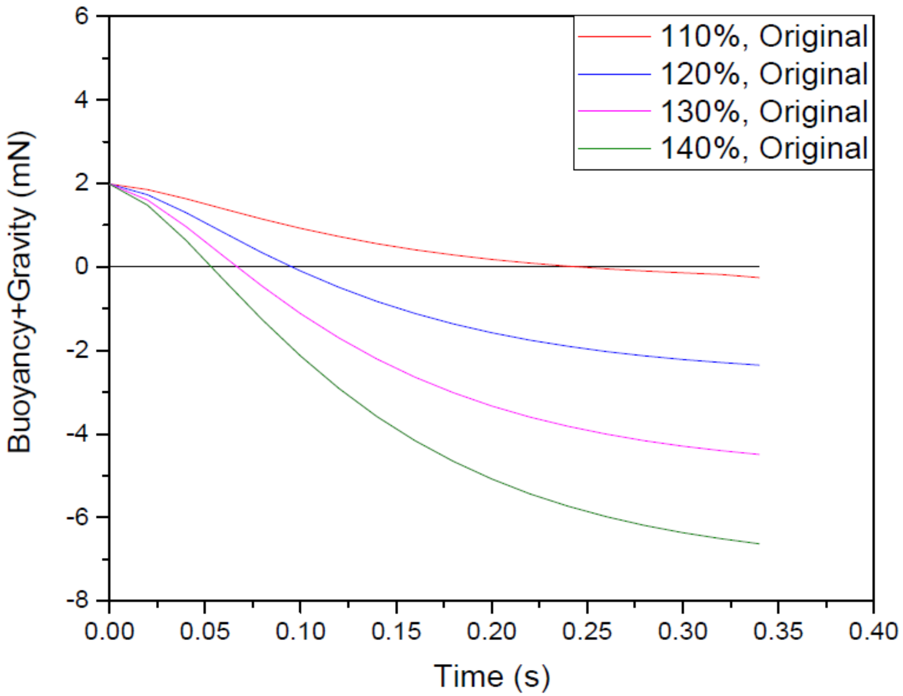
→ **Short response time is shown in previous study done by Lee*.**

- **FAST is expected to deal with positive CTC effectively with a short response time (lower working set point ~ 3K above nominal).**
- **Detailed analysis of FAST considering time-dependent power change is required.**



- Step heat flux change





Methodologies

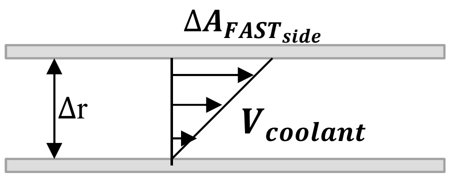
Methodologies

Governing Equations for FAST Movement

– **Forces acting on the FAST**

- **Gravity** = $\rho_{FAST} Volume_{FAST} \times g$
- **Buoyancy** = $\int_V \rho_{coolant}(z) g dV$
- **Drag force**

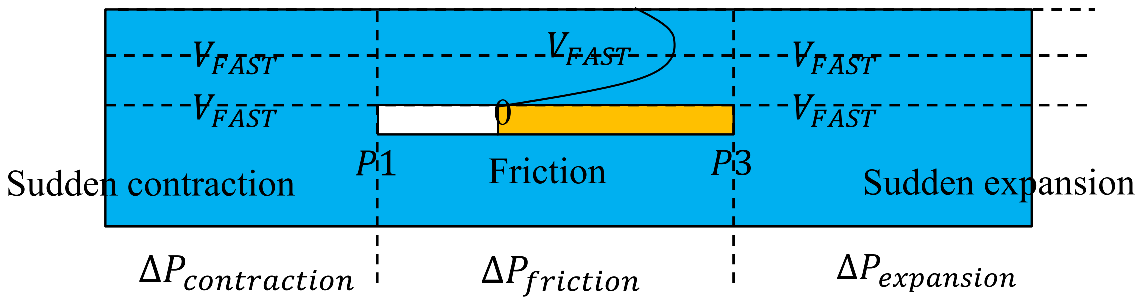
$$\frac{F}{A} = \mu \frac{\Delta V_{coolant}}{\Delta r}$$



$$\mathbf{F_D} = \mu \frac{\Delta V_{coolant}}{\Delta r} \Delta A_{FAST_{side}} \text{ (For 1 finite node)}$$

- **Pressure force**

$$\mathbf{F_p} = (\Delta P_{contraction} + \Delta P_{friction} + \Delta P_{expansion}) \times A_{FAST_{front}}$$



Methodologies

Governing Equations for Coolant Heating

1. Energy Conservation

- **Neglect viscous dissipation term and pressure work term***
- **Average volumetric heat source (q''' = Conductive heat source from the cladding)**

$$\rho c_p \frac{\partial T_{coolant}}{\partial t} + \rho c_p v \frac{dT}{dz} = q'''$$

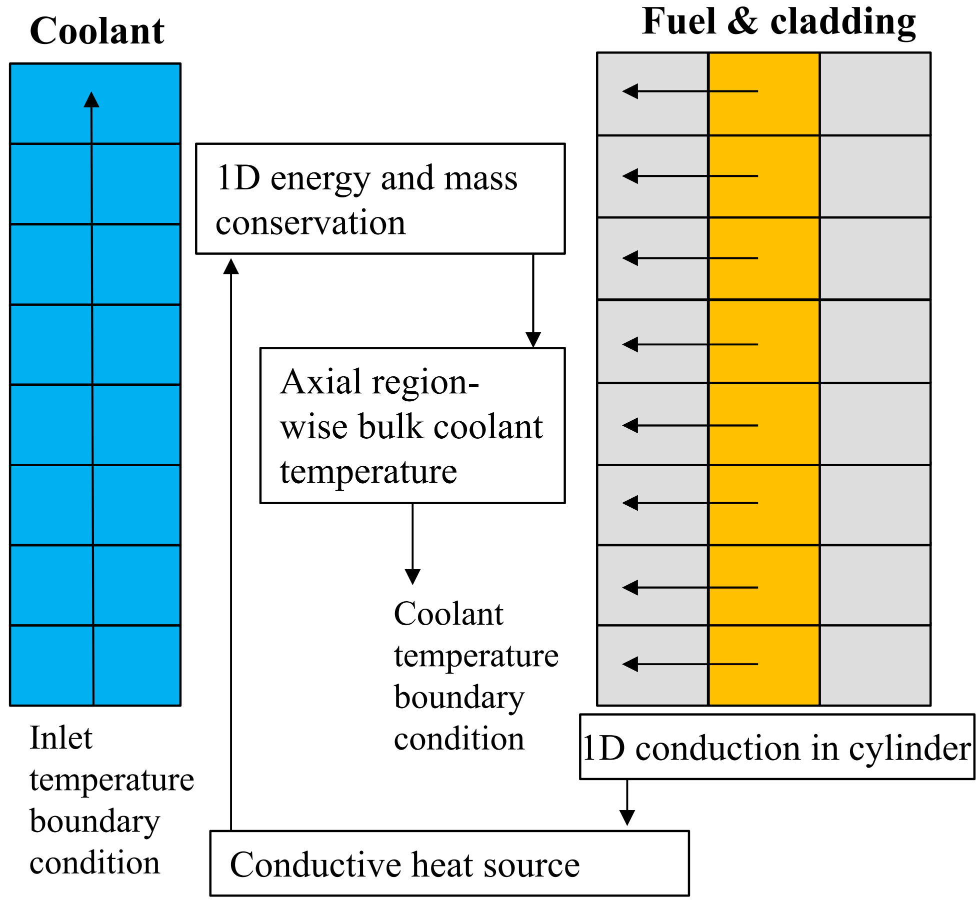
2. Mass Conservation

$$\frac{d\rho}{dt} + v\frac{d\rho}{dz} + \rho\frac{dv}{dz} = 0$$

3. Conduction in fuel & FAST pin region

$$\rho c_p \frac{\partial T_{fuel}}{\partial t} = \frac{1}{r}\frac{d}{dr}\left(kr\frac{dT_{fuel}}{dr}\right) + q'''$$

$$\rho c_p \frac{\partial T_{clad}}{\partial t} = \frac{1}{r}\frac{d}{dr}\left(kr\frac{dT_{clad}}{dr}\right)$$



*Anglart, H., Thermal-hydraulics in nuclear systems, Warszawa: Institute of Heat Engineering, Warszaw University of Technology (2013)

Methodologies

Point Kinetics Equation

- **Tightly coupled = neutron flux is more nearly separable in space and time.**
- **Small power distribution change during the transient in fast reactor**
- **Difficult to consider the core expansion reactivity feedback practically**

1. Governing equation is solved by simple FDM.

$$\dot{p}(t) = \frac{\rho(t) - \beta(t)}{\Lambda} p(t) + \frac{1}{\Lambda} \sum_k \lambda_k \zeta_k(t)$$

$$\dot{\zeta}_k(t) = -\lambda_k \zeta_k(t) + \beta_k p(t),\ k = 1,2,..,6$$

2. Reactivity components

- **Reactivity coefficients and reactivity worth of FAST is explicitly calculated by SERPENT**
- **Average temperatures are considered to calculate the reactivity feedback**

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

α_f = fuel temperature coefficient, C^{-1}

α_c = coolant temperature coefficient, C^{-1}

ρ_{ex} = external reactivity

ρ_{FAST} = external reactivity inserted by FAST

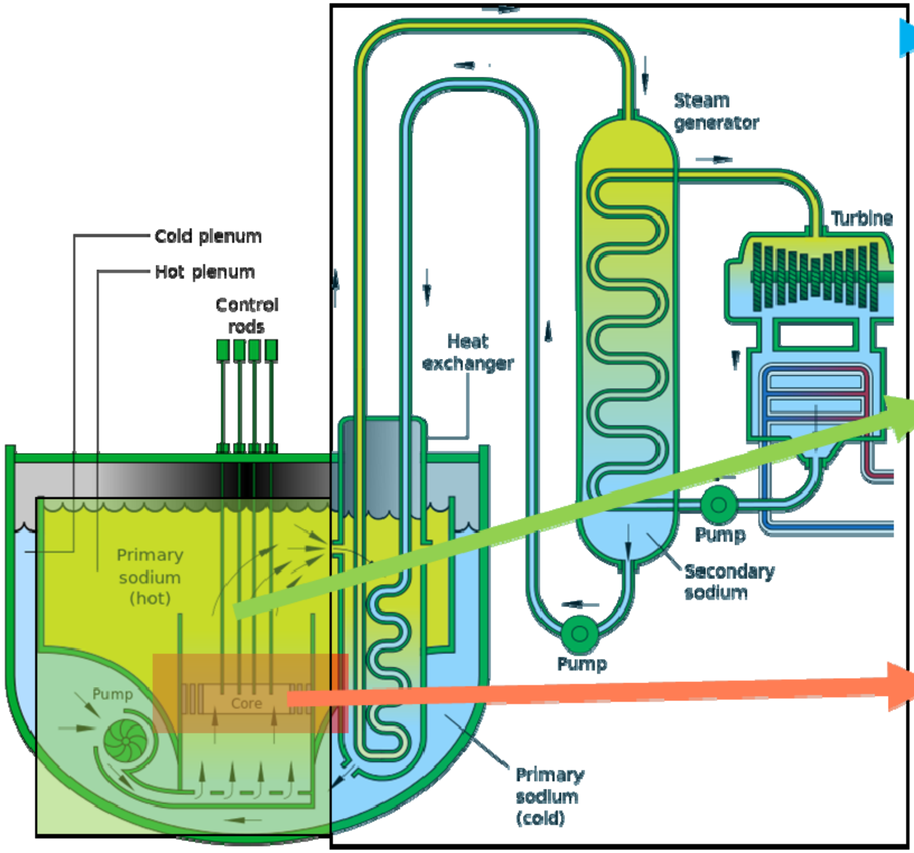
$\Delta T_f = T_f(t) - T_{f0}$, fuel temperature change from the initial one

$\Delta T_c = T_c(t) - T_{c0}$, coolant temperature change from the initial one

Methodologies

System simplification for ATWS simulations

- **The primary side is only modeled.**
- **Arbitrary heat removal scenario in IHX during the ATWS**
  - **Simplification for feasibility study**
  - **System model is required for the realistic simulation**



Lumped IHX

- ULOF: Constant inlet temperature
- ULOHS: No heat removal
- UTOP: Constant heat removal (nominal power)
  : Constant inlet temperature

Core exit coolant temperature ↑ | Core inlet coolant temperature ↓

Primary system

- Axial 1D heat transfer in coolant
- Radial 1D heat conduction in fuel pin

Heat generated in fuel region ↑ | Temperature of core components ↓

Reactor core

- Point reactor model
- Explicitly calculated feedback coefficients and kinetic parameters by SERPENT2

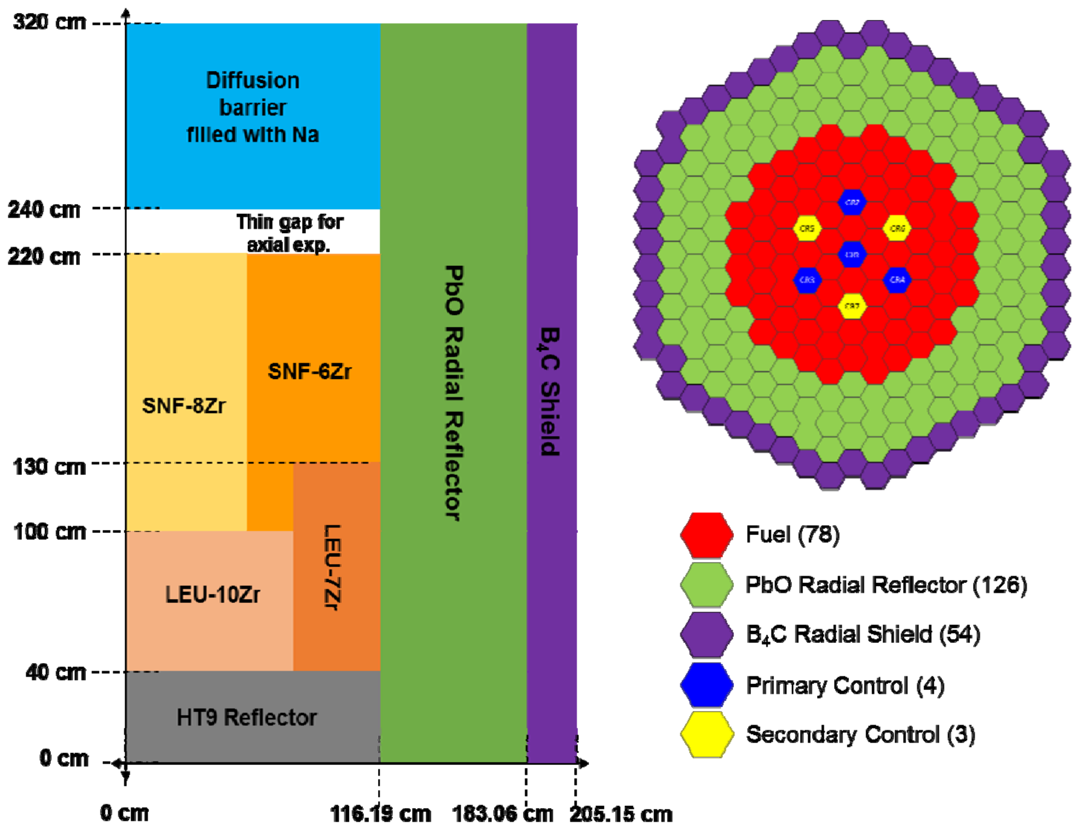
Reference Cores & FAST Configurations

Reference Core

Compact B&BR

- LEU driver fuel and SNF axial blanket (no radial blanket)
- Pan-shape initial core → minimization of excess reactivity.
- Zr-zoning core → flattened radial power distribution.
- PbO reflector → improved neutron economy.

Design Parameters	Value
Power, MWth	400
Core height, cm	180
Initial core height (IC/OC), cm	60 / 90
Active core equivalent radius, cm	116.19
Whole core equivalent radius, cm	205.15
Coolant inlet temperature, °C	360
Coolant outlet temperature, °C	510
Power density, W/cc	90.149
Discharge burnup, GWd/MTHM	160
Core lifetime, EFPYs	52
Peak Cladding DPA	700

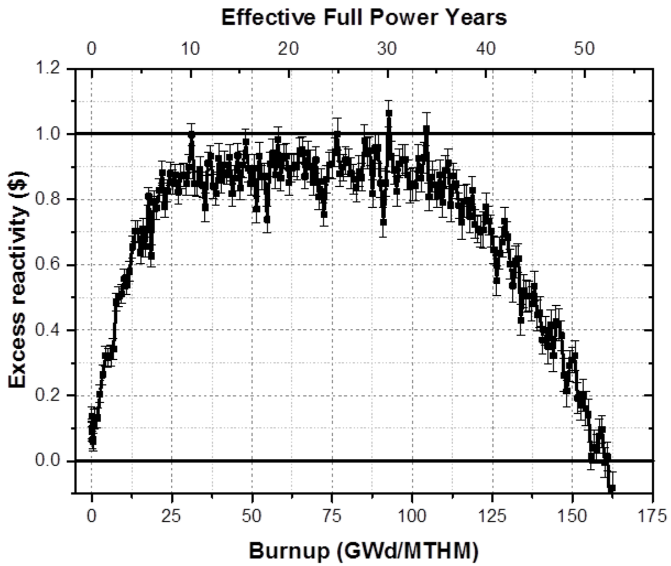


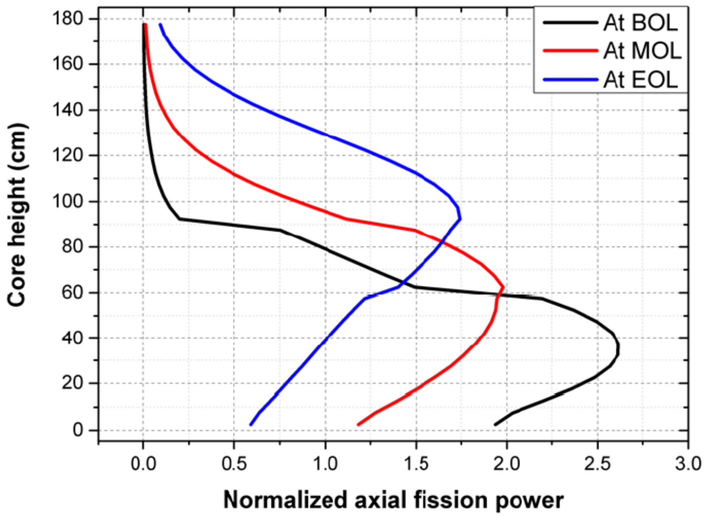
Reference Cores

Compact B&BR

- Lifetime ~ 50 years with 150GWd/MTHM of burnup
- Extremely small excess reactivity over ~50 year → Generic prevention of reactivity-induced accident
- Positive CVR and CTC at MOL and EOL

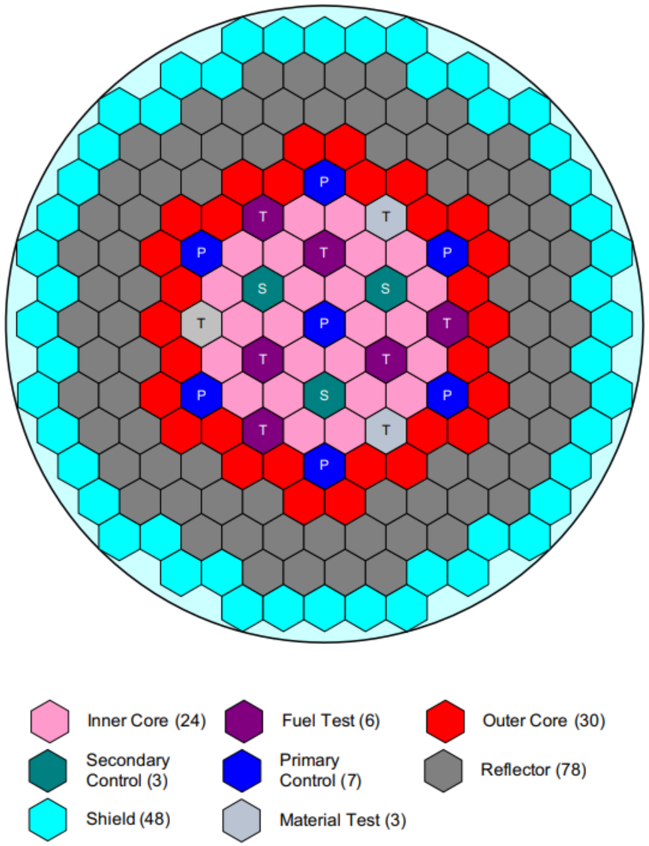
Reactivity feedback coefficients	BOL	MOL	EOL
Fuel temperature, ¢/ K	-0.093 ± 0.001	-0.054 ± 0.002	-0.045 ± 0.003
Coolant temperature, ¢/ K	-0.025 ± 0.001	0.170 ± 0.001	0.263 ± 0.001
CVR w/o FAST, ¢	-13.956 ± 1.451	632.634 ± 2.591	945.603 ± 3.418
CVR w/ FAST, ¢	-565.433 ± 1.859	-405.612 ± 2.678	-36.174 ± 2.529
Axial expansion , ¢/ K	-0.025 ± 0.002	-0.051 ± 0.003	-0.067 ± 0.003
Radial expansion, ¢/ K	-0.133 ± 0.002	-0.162 ± 0.005	-0.155 ± 0.003



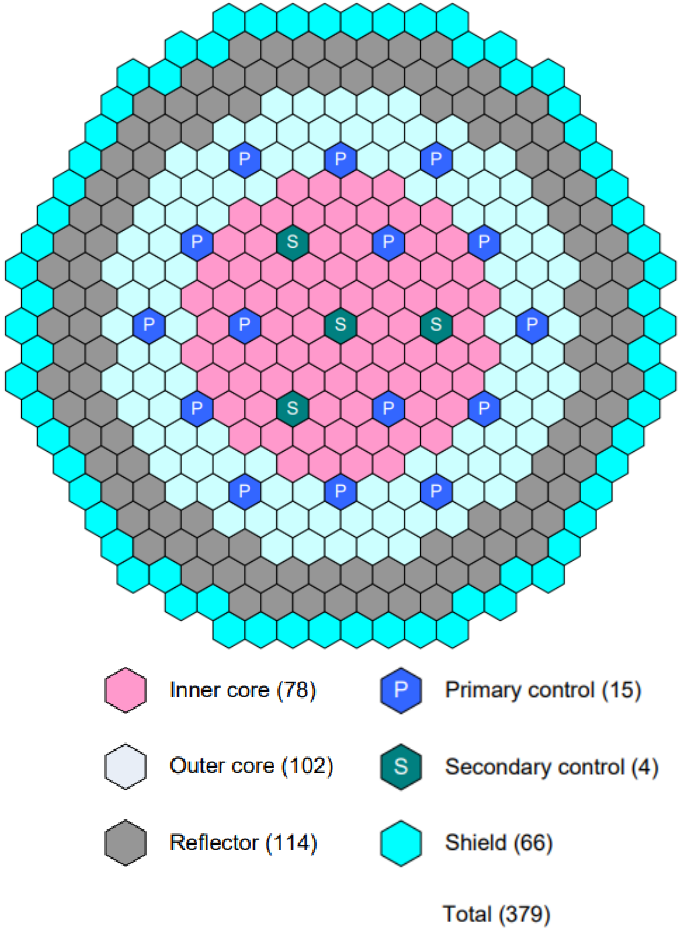


Reference Cores

Advanced Burner Test Reactor (ABTR) & Advanced Burner Reactor (ABR), ANL



Advanced Burner Test Reactor (ABTR)
- 250 MWth
- Metallic fuel



Advanced Burner Reactor (ABR)
- 1,000 MWth
- Mixed oxide fuel

Reference Cores

Reference cores

- Metallic B&BR - Compact B&BR (KAIST): High discharge burnup, low leakage
- Metallic SFR - Advanced Burner Test Reactor (ANL): typical burner SFR with metallic fuel
- Oxide SFR - Advanced Burner Reactor (ANL): typical burner SFR with oxide fuel

Design parameters

Parameter	Value		
	Metallic B&BR	Metallic SFR	Oxide SFR
Thermal power (MWth)	**400**	**250**	**1000**
Fuel material	U-Zr (driver) SNF-Zr (blanket)	U-TRU-Zr	TRU/SNF oxide
Average power density of active core (W/cm^3)	57.1	258	231
Coolant inlet/outlet temperature (K)	633 / 783	628 / 783	628 / 783
Average discharge burnup (GWd/MTHM)	160	97.7	111
# of batches / cycle length (month)	1 / 624	(12/15/12)* / 4	5 / 12

Reactivity Coefficients

Parameter	Value		
	Metallic B&BR	Metallic SFR	Oxide SFR
Fuel temperature (pcm/K)	-0.163	-0.33	-0.372
Coolant temperature (pcm/K)	0.952	0.099	0.496
Radial expansion (pcm/K)	-0.561	-1.947	-0.93
Axial expansion (pcm/K)	-0.243	-0.198	-0.155
Delayed neutron fraction	0.00362	0.0033	0.00264
Prompt neutron lifetime (µs)	0.34	0.33	0.59

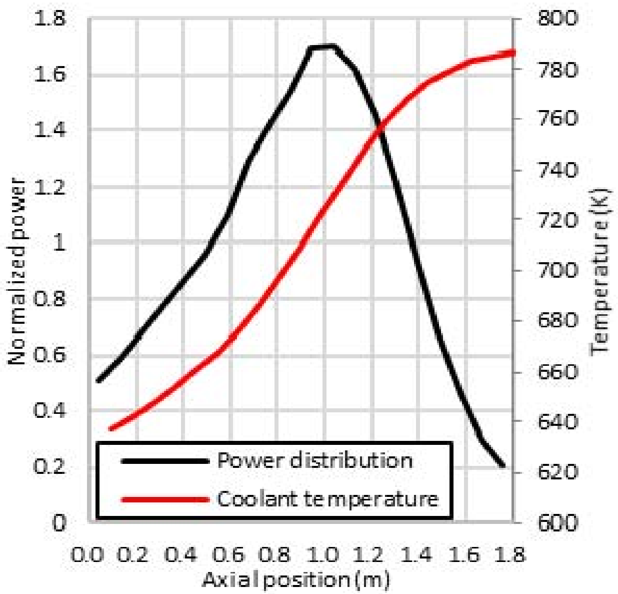
Reference Cores

Reference cores

- Metallic B&BR - Compact B&BR (KAIST) : High discharge burnup, low leakage
- Metallic SFR - Advanced Burner Test Reactor (ANL): typical burner SFR with metallic fuel
- Oxide SFR - Advanced Burner Reactor (ANL): typical burner SFR with oxide fuel

Power distribution

- Explicitly calculate axial power distribution for metallic B&BR
- Chopped cosine shape for typical SFRs
- EOL condition



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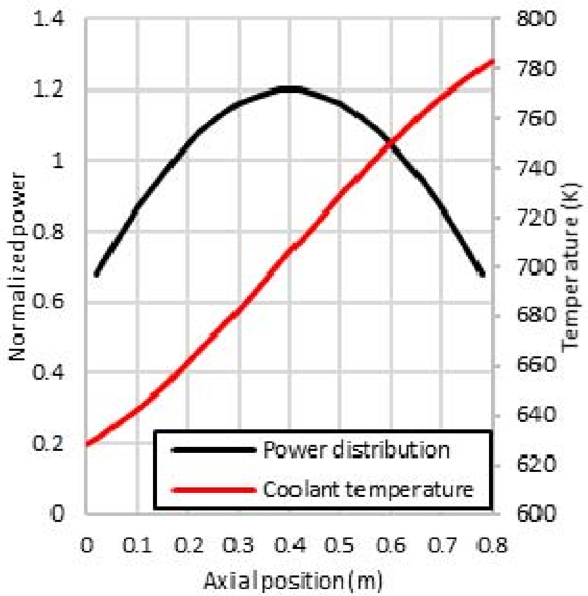

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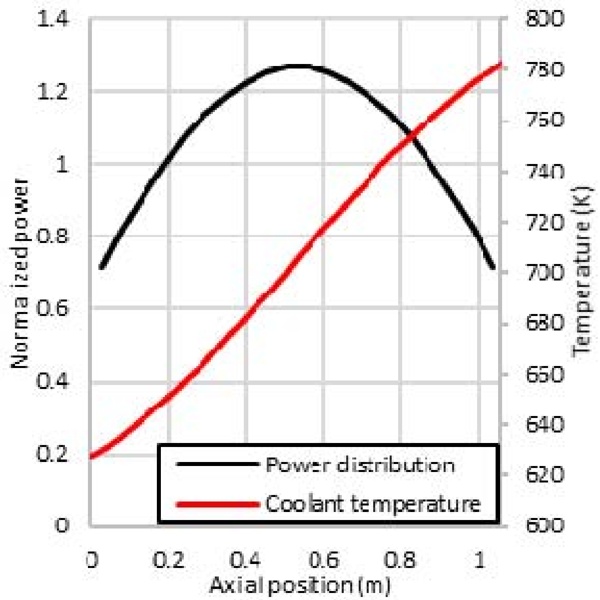
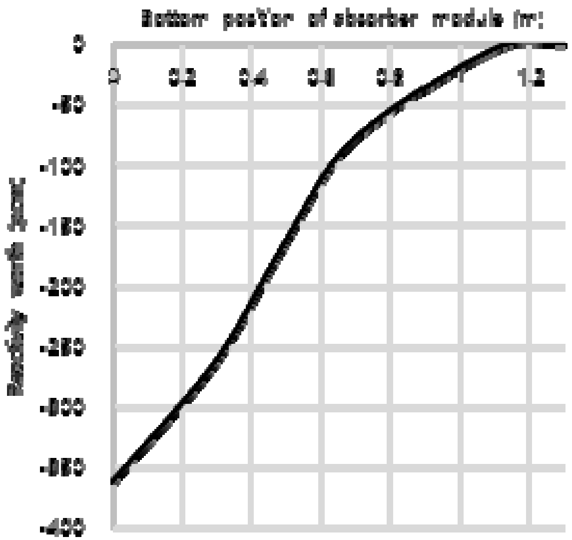


<Oxide SFR>

Design parameters

Design parameters	Value		
	Metallic B&BR	Metallic core	Oxide core
Reactivity worth, $	1	1	1
Absorber / void height, cm	90 / 50	40 / 20	60 / 20
B_4C density, g/cm^3	1.178	1.248	1.109
Absorber module average density, g/cm^3	0.832	0.832	0.832
Absorber module radius, cm	0.3	0.2	0.2
FAST radius, cm	0.95	0.4	0.3775
Guide thimble thickness, cm	0.06	0.052	0.05

Reactivity worth: explicitly calculate (B&BR), typical control rod insertion-like (Burners)



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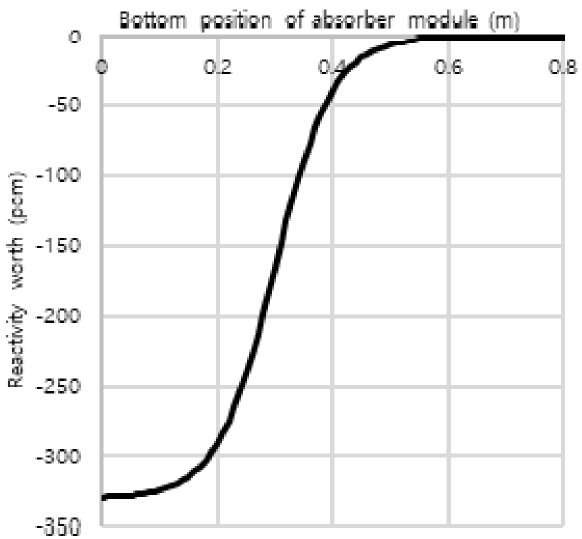

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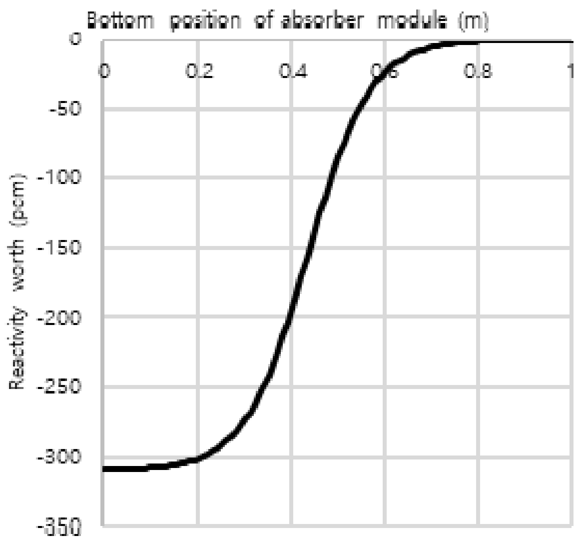


<Oxide SFR>

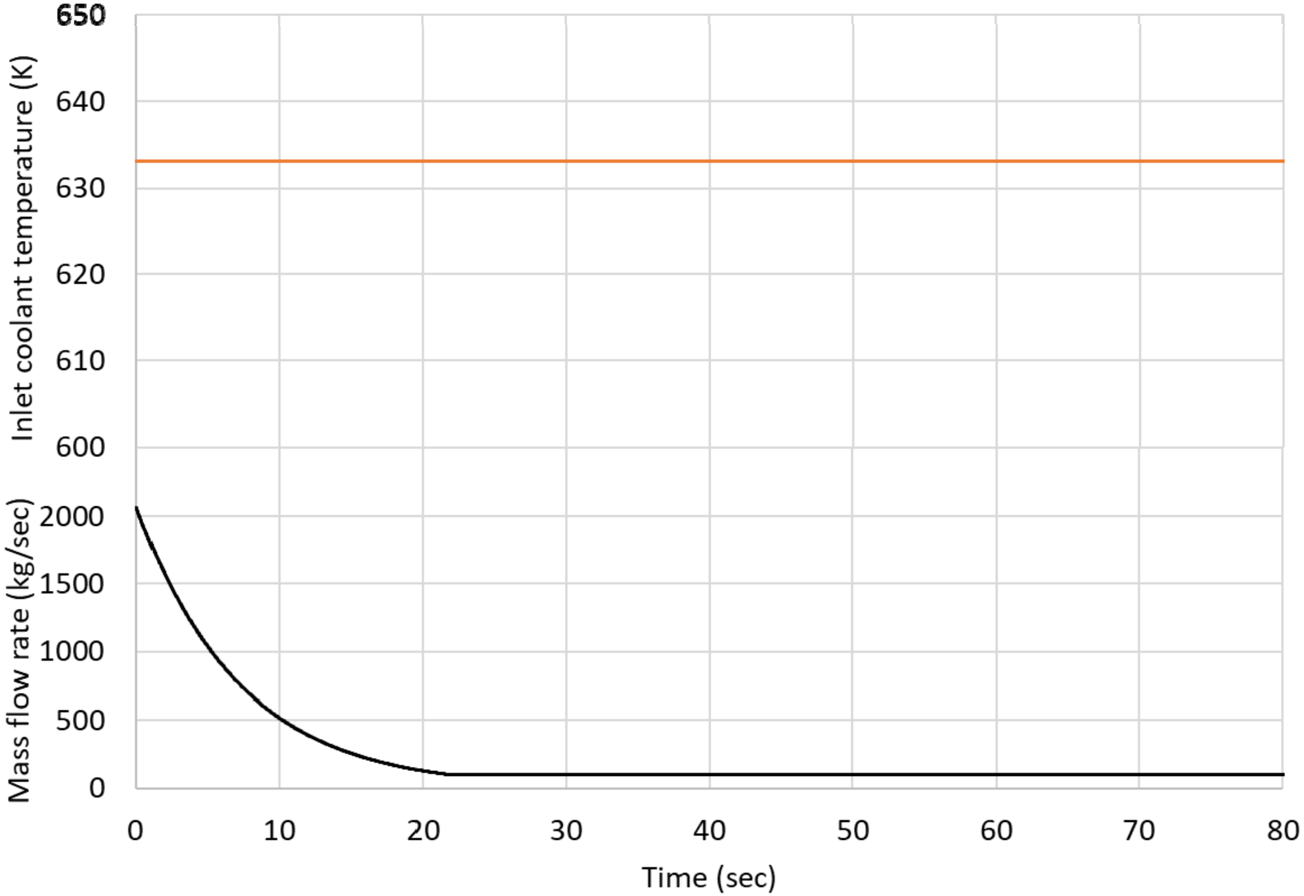
Transient Responses with the FAST Device

Feasibility of FAST – Results

Unprotected Loss of Flow (ULOF)

– **Inlet velocity ramp down**

- **Constant inlet temperature***
- **Exponential pump ramp down (halving time = 5 sec)**

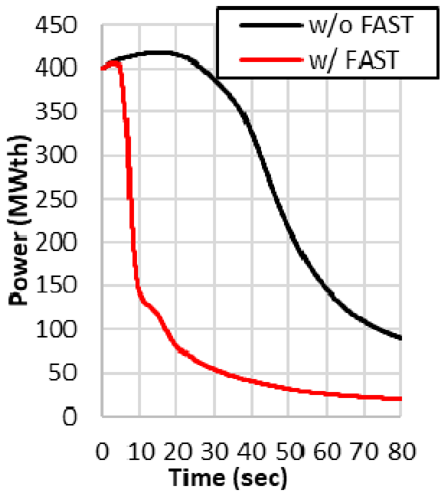


*Housiadas, C., Simulation of loss-of-flow transients in research reactors. Annals of Nuclear Energy, 27(18), 1683-1693 (2000).

ATWS Analysis

Unprotected Loss of Flow (ULOF)

– **Reactor power**



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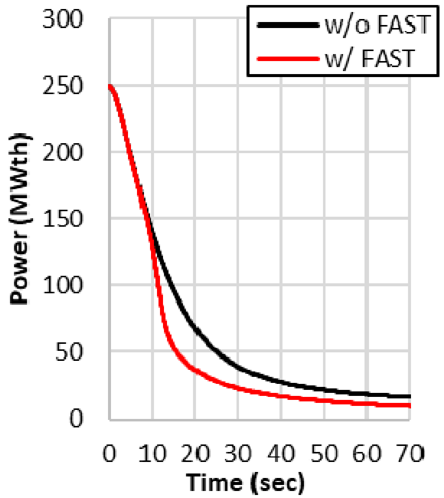

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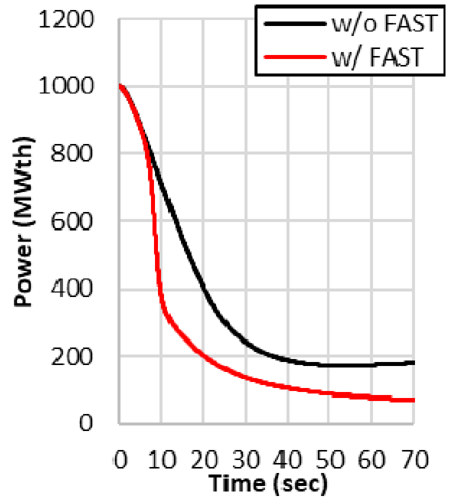

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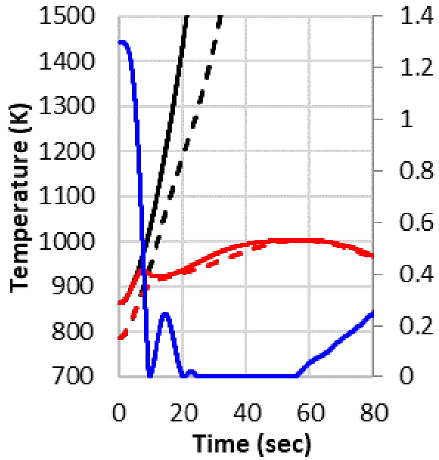
– **Maximum temperatures of fuel and coolant**



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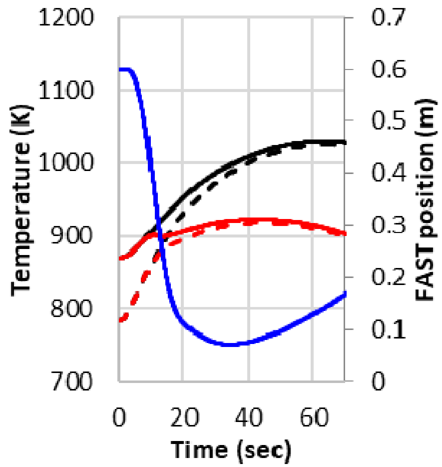

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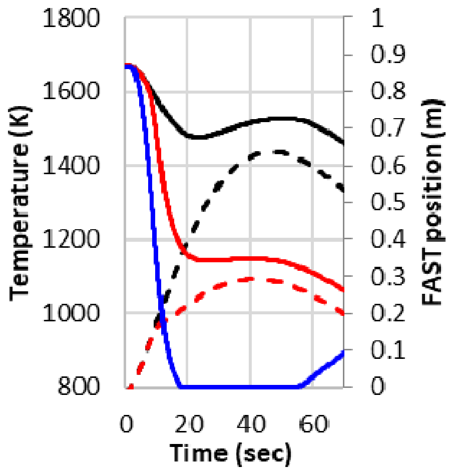


<Oxide SFR>

Maximum temperature of coolant **quickly exceed the failure limit without FAST!!**

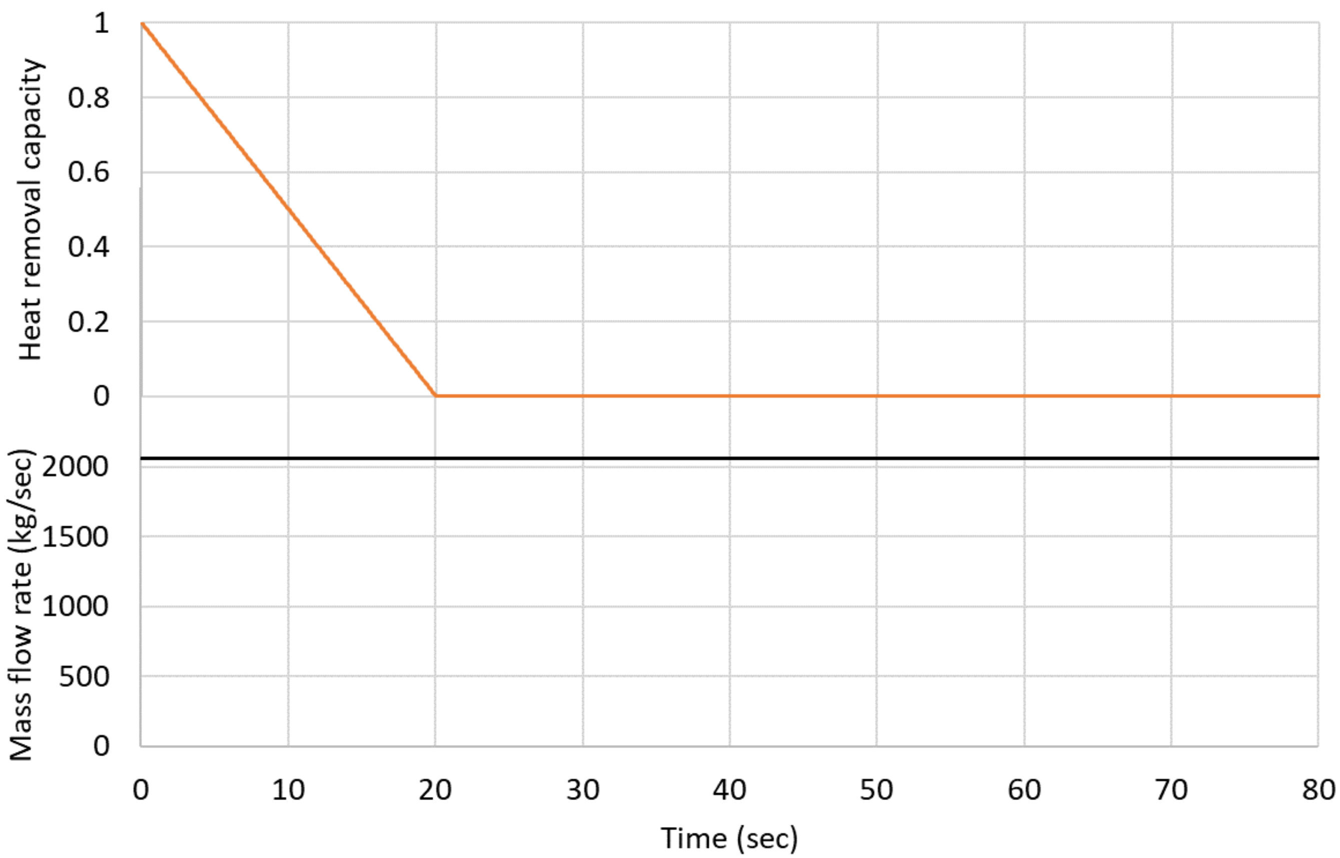
- Fuel - w/o FAST
- Coolant - w/o FAST
- Fuel - w/ FAST
- Coolant - w/ FAST
- FAST position

ATWS Analysis

Unprotected Loss of Heat Sink (ULOHS)

– **Complete loss of heat removal capacity in IHX**

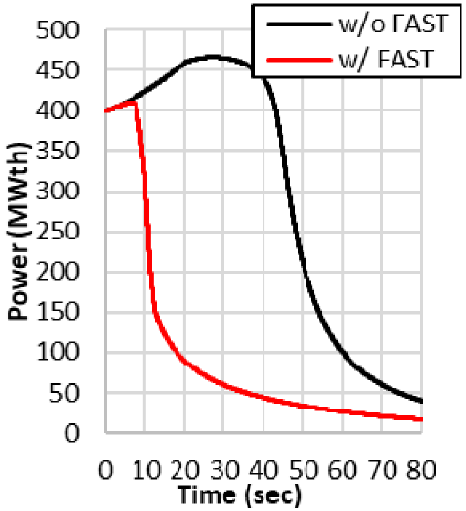
- **Linear decrease of heat removal in IHX from 100% to 0% over 20 seconds**



ATWS Analysis

Unprotected Loss of Heat Sink (ULOHS)

– **Reactor power**



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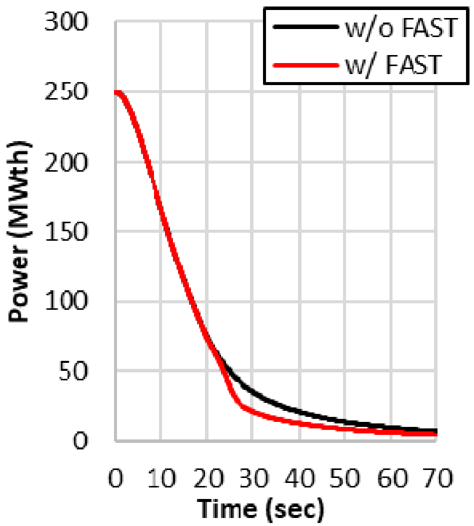

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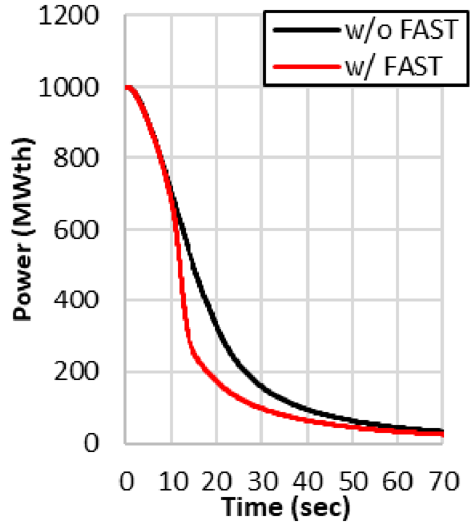

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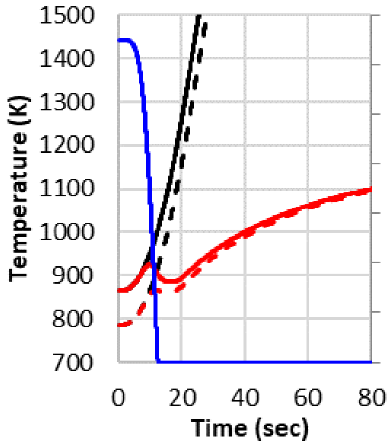
– **Maximum temperatures of fuel and coolant**



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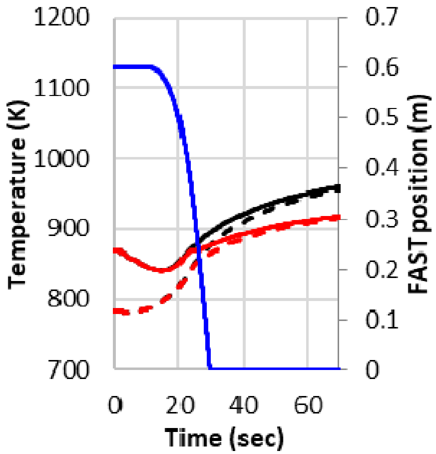

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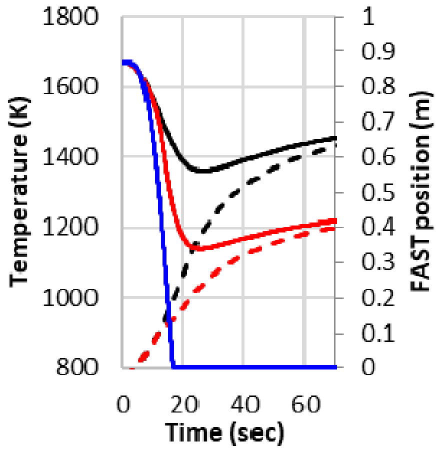
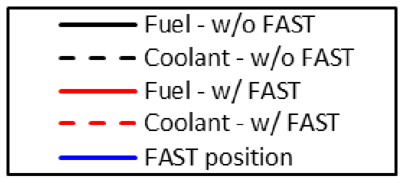


<Oxide SFR>

Quick power suppression by FAST and **moderate increase of temperatures** in case with FAST

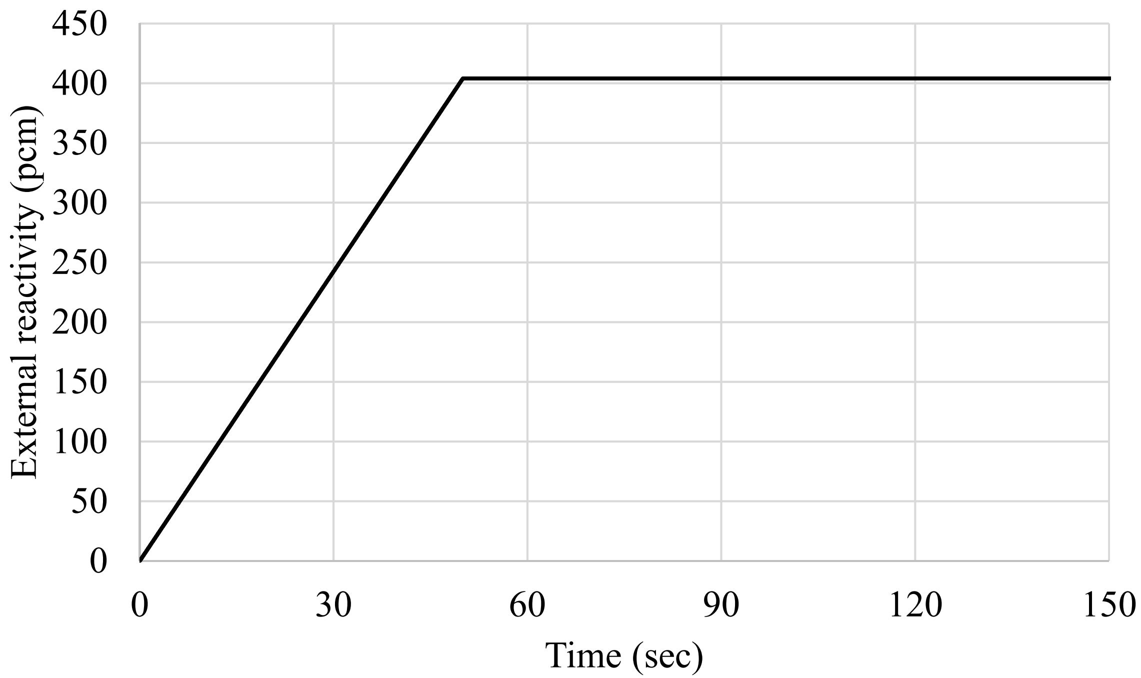


ATWS Analysis

Unprotected Transient Overpower

– **External reactivity = 1$ (ramp up rate = 0.02 $/sec)**

: Impractical in B&BR



– **Keep nominal inlet coolant velocity (2.94 m/s)**

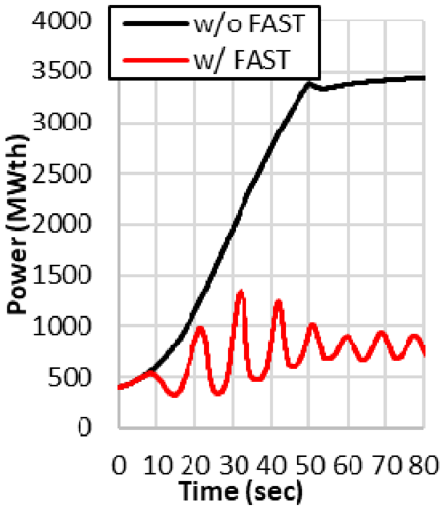
– **Two simple IHX models**

- **Constant core inlet coolant temperature**
- **Constant temperature drop in IHX**

ATWS Analysis

Unprotected Transient Overpower (UTOP) < **Constant core inlet** coolant temperature >

– **Reactor power**



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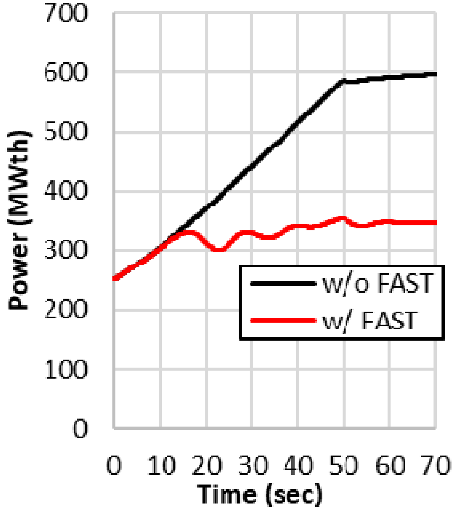

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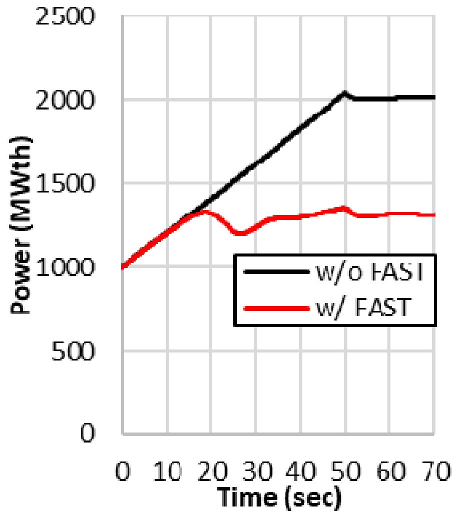

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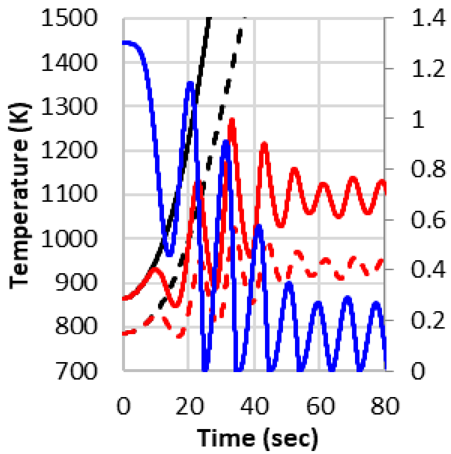
– **Maximum temperatures of fuel and coolant**



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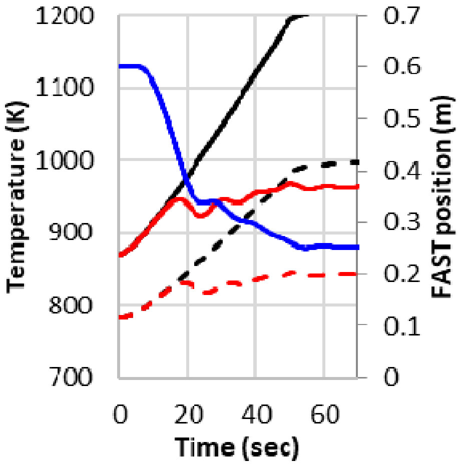

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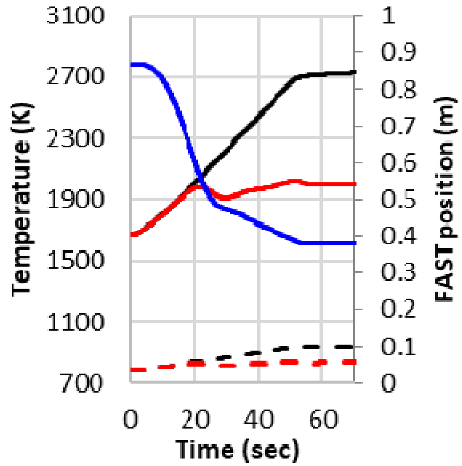


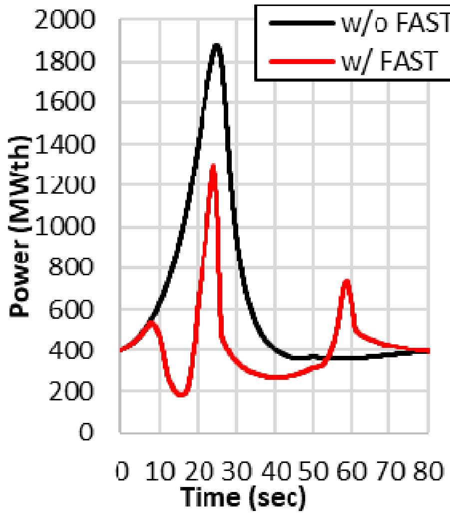
<Oxide SFR>

Quick initial decrease of temperature by FAST and **oscillation** due to the refloating of absorber module caused by power and temperature suppression

ATWS Analysis

Unprotected Transient Overpower (UTOP) < **Constant temperature drop** in IHX >

– **Reactor power**



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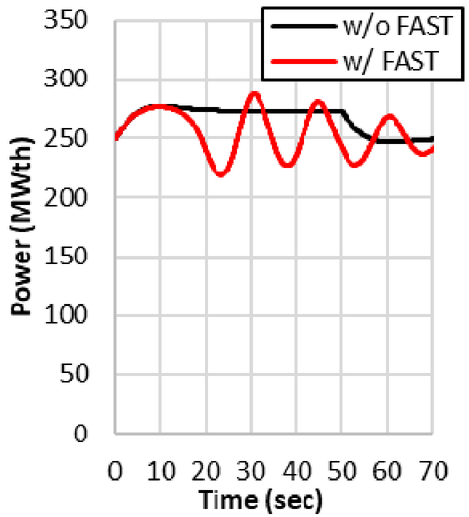

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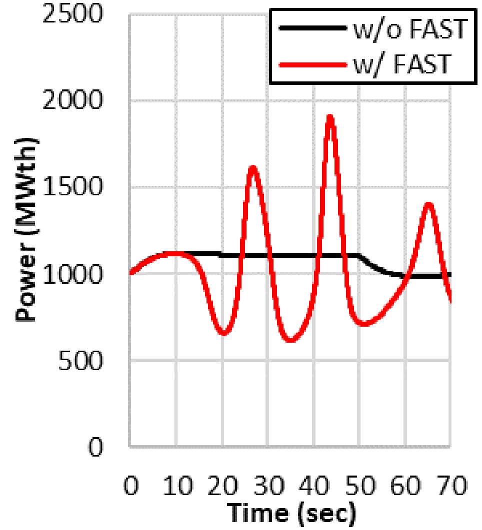

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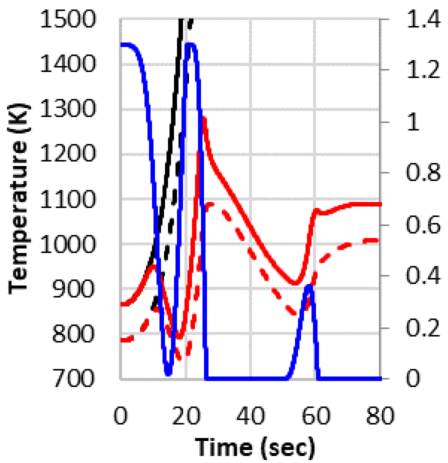
– **Maximum temperatures of fuel and coolant**



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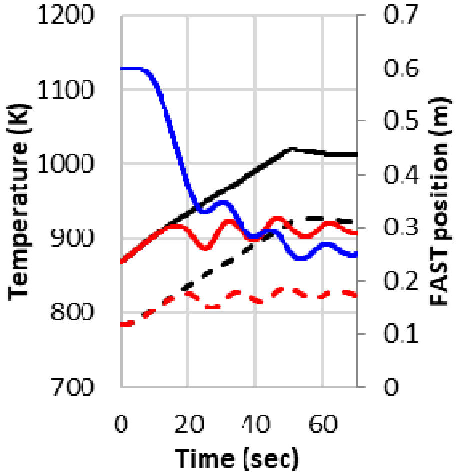

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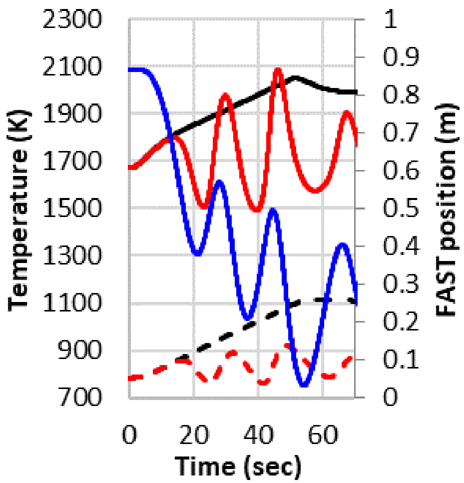
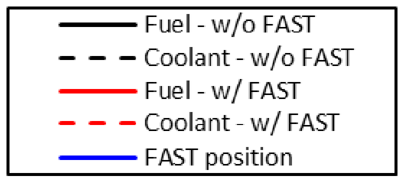


<Oxide SFR>

Quick initial decrease of temperature by FAST and **different oscillation tendency** depending on IHX modeling scenario



Conclusions and Future Works

Conclusions

- **Performance of FAST**
  - **It is possible to directly apply the FAST to deal with the positive CTC.**
  - **FAST effectively and successfully mitigates consequence of the ATWS (Anticipated Transient W/o Scram) scenarios. → Early failure of core during any ATWS is effectively prevented.**
  - **Inherent safety of SFRs can be improved substantially with the FAST device.**

Future Works

- **Realistic transient analysis with system model**
- **Consideration of locking device for FAST absorber module to prevent the possible oscillation.**

Thank you!