A Passive Safety Device for SFRs with Positive Coolant Temperature Coefficient

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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$_4$C
    : 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.

![Diagram of FAST operation at different conditions:](image-url)
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 B₄C.
– 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.
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

*(Sungmin Lee, Development of analysis code for behavior of passive safety device in innovative sodium-cooled fast reactor, MA thesis, KAIST (2018)*
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
  \[
  \frac{F}{A} = \mu \frac{\Delta V_{coolant}}{\Delta r}
  \]
  \[
  F_D = \mu \frac{\Delta V_{coolant}}{\Delta r} \Delta A_{FAST_{side}} \quad \text{(For 1 finite node)}
  \]

- Pressure force
  \[
  F_p = (\Delta P_{contraction} + \Delta P_{friction} + \Delta P_{expansion}) \times A_{FAST_{front}}
  \]
Methodologies

Governing Equations for Coolant Heating

1. Energy Conservation
   - Neglect viscous dissipation term and pressure work term*
   - Average volumetric heat source \( (q^{'''} = \text{Conductive heat source from the cladding}) \)

   \[
   \rho c_p \frac{\partial T_{\text{coolant}}}{\partial t} + \rho c_p \nu \frac{dT}{dz} = q^{'''}
   \]

2. Mass Conservation

   \[
   \frac{d\rho}{dt} + \nu \frac{d\rho}{dz} + \rho \frac{dv}{dz} = 0
   \]

3. Conduction in fuel & FAST pin region

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

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

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.

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

\[
\dot{\zeta}_k(t) = -\lambda_k \zeta_k(t) + \beta_k p(t), \quad k = 1, 2, \ldots, 6
\]

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

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

\(\alpha_f\) = fuel temperature coefficient, \(\text{C}^{-1}\)
\(\alpha_c\) = coolant temperature coefficient, \(\text{C}^{-1}\)
\(\rho_{ex}\) = external reactivity
\(\rho_{FAST}\) = 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

![Diagram of a nuclear reactor system]

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

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

- **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.

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

Compact B&BR

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

<table>
<thead>
<tr>
<th>Reactivity feedback coefficients</th>
<th>BOL</th>
<th>MOL</th>
<th>EOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel temperature, $\dot{\epsilon}$/ K</td>
<td>-0.093 ± 0.001</td>
<td>-0.054 ± 0.002</td>
<td>-0.045 ± 0.003</td>
</tr>
<tr>
<td>Coolant temperature, $\dot{\epsilon}$/ K</td>
<td>-0.025 ± 0.001</td>
<td>0.170 ± 0.001</td>
<td>0.263 ± 0.001</td>
</tr>
<tr>
<td>CVR w/o FAST, $\dot{\epsilon}$</td>
<td>-13.956 ± 1.451</td>
<td>632.634 ± 2.591</td>
<td>945.603 ± 3.418</td>
</tr>
<tr>
<td>CVR w/ FAST, $\dot{\epsilon}$</td>
<td>-565.433 ± 1.859</td>
<td>-405.612 ± 2.678</td>
<td>-36.174 ± 2.529</td>
</tr>
<tr>
<td>Axial expansion, $\dot{\epsilon}$/ K</td>
<td>-0.025 ± 0.002</td>
<td>-0.051 ± 0.003</td>
<td>-0.067 ± 0.003</td>
</tr>
<tr>
<td>Radial expansion, $\dot{\epsilon}$/ K</td>
<td>-0.133 ± 0.002</td>
<td>-0.162 ± 0.005</td>
<td>-0.155 ± 0.003</td>
</tr>
</tbody>
</table>

![Effective Full Power Years](image)

![Excess reactivity vs. Burnup](image)

![Core height vs. Normalized axial fission power](image)
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power (MWth)</td>
<td>400</td>
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<tr>
<td>Fuel material</td>
<td>U-Zr (driver)</td>
</tr>
<tr>
<td></td>
<td>SNF-Zr (blanket)</td>
</tr>
<tr>
<td>Average power density of active core (W/cm³)</td>
<td>57.1</td>
</tr>
<tr>
<td>Coolant inlet/outlet temperature (K)</td>
<td>633 / 783</td>
</tr>
<tr>
<td>Average discharge burnup (GWd/MTHM)</td>
<td>160</td>
</tr>
<tr>
<td># of batches / cycle length (month)</td>
<td>1 / 624</td>
</tr>
</tbody>
</table>

Reactivity Coefficients

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel temperature (pcm/K)</td>
<td>-0.163</td>
</tr>
<tr>
<td>Coolant temperature (pcm/K)</td>
<td>0.952</td>
</tr>
<tr>
<td>Radial expansion (pcm/K)</td>
<td>-0.561</td>
</tr>
<tr>
<td>Axial expansion (pcm/K)</td>
<td>-0.243</td>
</tr>
<tr>
<td>Delayed neutron fraction</td>
<td>0.00362</td>
</tr>
<tr>
<td>Prompt neutron lifetime (µs)</td>
<td>0.34</td>
</tr>
</tbody>
</table>
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
Reference FASTs

Design parameters

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactivity worth, $</td>
<td>Metallic B&amp;BR</td>
</tr>
<tr>
<td>Absorber / void height, cm</td>
<td>90 / 50</td>
</tr>
<tr>
<td>B$_4$C density, g/cm$^3$</td>
<td>1.178</td>
</tr>
<tr>
<td>Absorber module average density, g/cm$^3$</td>
<td>0.832</td>
</tr>
<tr>
<td>Absorber module radius, cm</td>
<td>0.3</td>
</tr>
<tr>
<td>FAST radius, cm</td>
<td>0.95</td>
</tr>
<tr>
<td>Guide thimble thickness, cm</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Reactivity worth: explicitly calculate (B&BR), typical control rod insertion-like (Burners)
Transient Responses with the FAST Device
Unprotected Loss of Flow (ULOF)

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

ATWS Analysis

Unprotected Loss of Flow (ULOF)

- Reactor power

- Maximum temperatures of fuel and coolant

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

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

- Maximum temperatures of fuel and coolant
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

- Maximum temperatures of fuel and coolant

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

- Maximum temperatures of fuel and coolant

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!