Accident Tolerant Control Rod

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Current control rod in LWRs

**BWR**: Boron carbide ($\text{B}_4\text{C}$) powder (with stainless steel cladding)
   Metallic Hafnium (Hf) (with Stainless sheath)

**PWR**: Silver – Indium – Cadmium (Ag-In-Cd) alloy (with stainless steel cladding)
Boric acid ($\text{H}_3\text{BO}_3$) (= chemical shim)

Main structure material: Austenitic Steel
Behavior of current control rod at SA

Eutectic of Fe-Zr (940°C)
Eutectic of Fe-B₄C (1150°C)
Melting of Ag-In-Cd (800°C)
Rapid Zircaloy oxidation by H₂O (~1200°C)
Melting of Zircaloy (1760°C)

⇒ Control materials would melt and fall down before severe core damage.
⇒ Injecting pure (sea) water into core would lead to dilution of boric acid concentration.
TMI-2 relocation

Borac acid

Molten metal and ceramic

Upper debris bed

Control, structural, and cladding material solidified between fuel rods

Fig. 12. Hypothesized configuration of core at 224 min (just prior to major core relocation).
Accident Tolerant Control rod (ATC)

1. To keep enough shutdown margin at sever accident.
   Neutron absorber materials should have following properties:
   1) Higher neutron absorption than current control rod
      Gd, Sm, Eu, Dy etc.
   2) Higher melting or eutectic point than ~1200°C where rapid Zircaloy oxidation occurs
      Gd$_2$O$_3$, Sm$_2$O$_3$, Eu$_2$O$_3$, Dy$_2$O$_3$ etc.
   3) High miscibility with molten fuel materials
      Miscible with UO$_2$ = Gd$_2$O$_3$, HfO$_2$ etc.

2. To minimize the influence on the operation conditions of reactors, and
   To keep control rod worth for a long-term.
   4) High neutron flux regions, loading current control rod (B$_4$C or Ag-In-Cd).
      Mitigate the effect on reactor control in operation
   5) Low flux regions, loading ATC materials.
      Increase of shutdown margin & Long-term use of control rod
      ※ ATCR materials are reused.
**Concept of ATC**

- **BWRs**
  - **Current control rod**
  - **ATC under operation**
  - **ATC during shutdown**
  - **Sever accident**

- **PWRs**
  - **ATC under operation**
  - **ATC during shutdown**

- **Absorbers: Gd$_2$O$_3$ / HfO$_2$**
  - To keep burnable poison (Gd$_2$O$_3$) for a long-term
  - To minimize the influence on reactor operation.

- **Vicinity of core: current materials**
  - Higher shutdown margin than current control rod
  - Restrictive loss of burnable poison

- **Reusable**
  - B$_4$C or Hf
  - Ag-In-Cd
  - Gd$_2$O$_3$ or Gd$_2$O$_3$-HfO$_2$ etc.

- Remaining in the core material at SA or overheating
  - Gd$_2$O$_3$ / HfO$_2$ would mix with core debris
Structure of ATC

BWRs

(a) Current control rod
(b) ATC
Upper part is same as Current CR structure

PWRs

(a) Current control rod
(b) ATC
Lower part is same as Current CR structure
Future works

To improve the accident tolerance without significant effect on reactor control in operation, we will confirm

(1) Neutron absorption worth of ATC materials,
    \( \text{Gd}_2\text{O}_3 \) or \( \text{Gd}_2\text{O}_3 - \text{HfO}_2 \)

(2) Life time of ATC,
    Loading position

(3) Melting behavior of ATC materials,
    Compatibility with structural materials,
    \( \text{Gd}_2\text{O}_3, \text{Gd}_2\text{O}_3 - \text{HfO}_2, \text{Gd}_2\text{O}_3 - \text{Fe}, \text{Gd}_2\text{O}_3 - \text{Zr} \) etc.

(4) Miscibility with molten core materials.
    \( \text{UO}_2 - \text{Gd}_2\text{O}_3, \text{UO}_2 - \text{HfO}_2, \text{ZrO}_2 - \text{Gd}_2\text{O}_3 \), \( \text{Gd}_2\text{O}_3 - \text{Fe} \) etc.