Development Plan of Accident Tolerant Control Rod

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OECD-NEA Meeting on Increased Accident Tolerance of Fuels for LWRs

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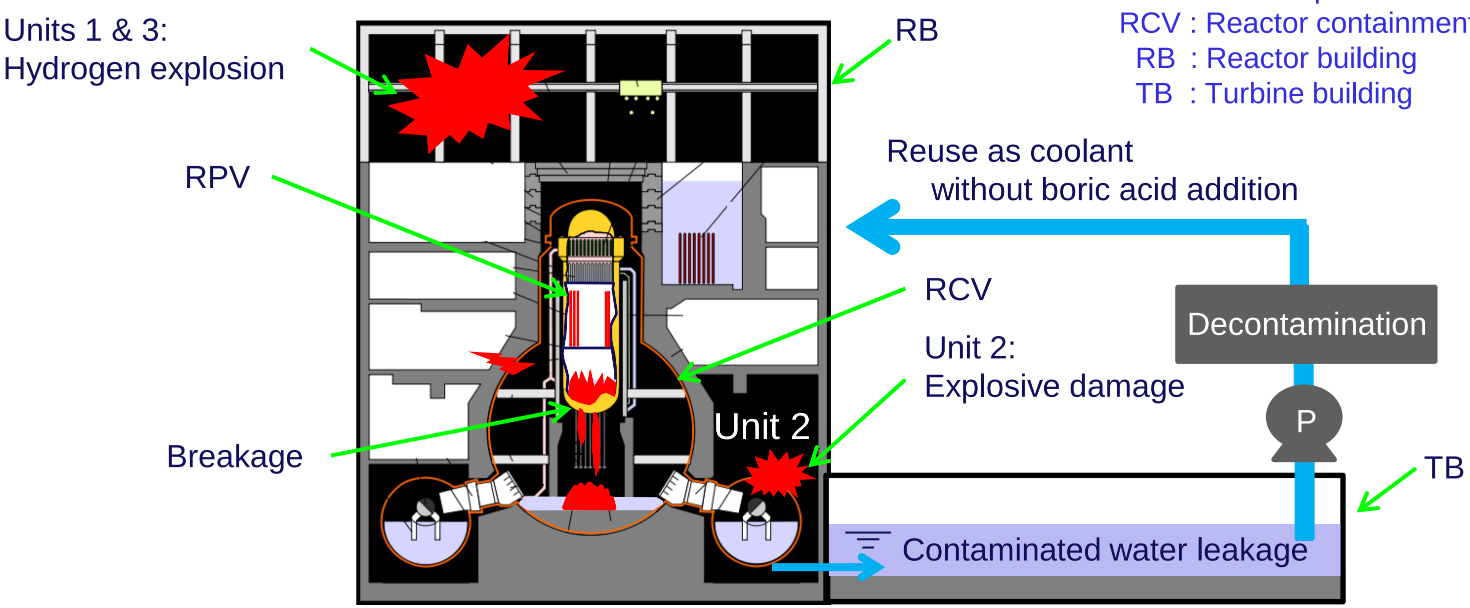
Background 1/2

◆Fukushima Daiichi NPP Accident

- Reactor core melted down due to loss of heat removal.
- Part of the molten fuel materials penetrated RPV and reached to RCV.
- At present, the reactors are stable in sub-critical condition.
    ⇐ Measurement of Iodine in leak water and Xenon in RCV
- However, the risk of re-criticality still cannot be excluded.

RPV : Reactor pressure vessel
RCV : Reactor containment vessel
RB : Reactor building
TB : Turbine building



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Background 2/2

◆Decommissioning work in the future

- Measures against water leakage and flooding in RCV are planned.

  Pure water will be injected to avoid corrosion of reactor equipment and piping by boric acid.

- In-reactor materials are recovered.

  Geometric conditions of fuel debris may drastically change during the recovery work.

Water-fuel ratio (V_m/V_f) will change. → Possibility of re-criticality accident

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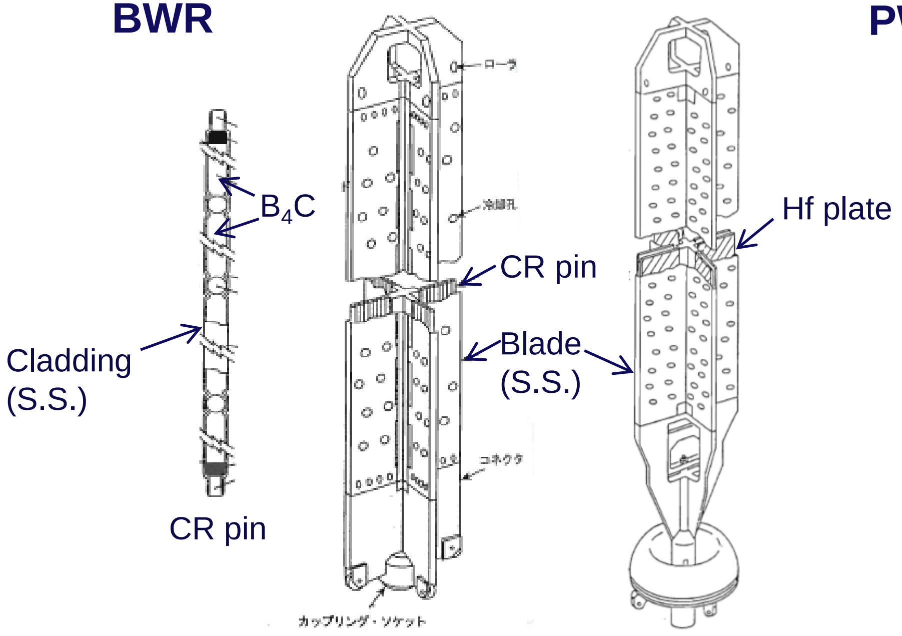
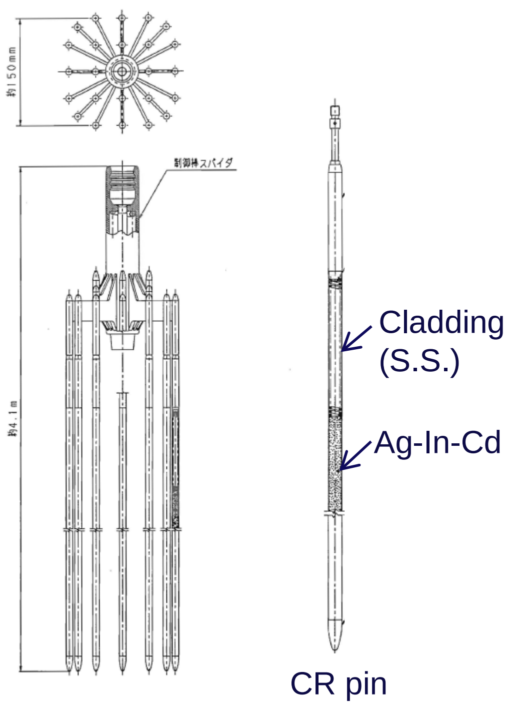
Conventional CR Design

- **BWR**: Boron carbide (B_4C) (with S.S. cladding)
  Metal hafnium (Hf) (with S.S. sheath)
- **PWR**：Silver - Indium - Cadmium (Ag-In-Cd=AIC) alloy (with S.S. cladding)
  Boric acid (H_3BO_3) water (as chemical shim)
- Structural material：S.S. (austenitic steel)

BWR



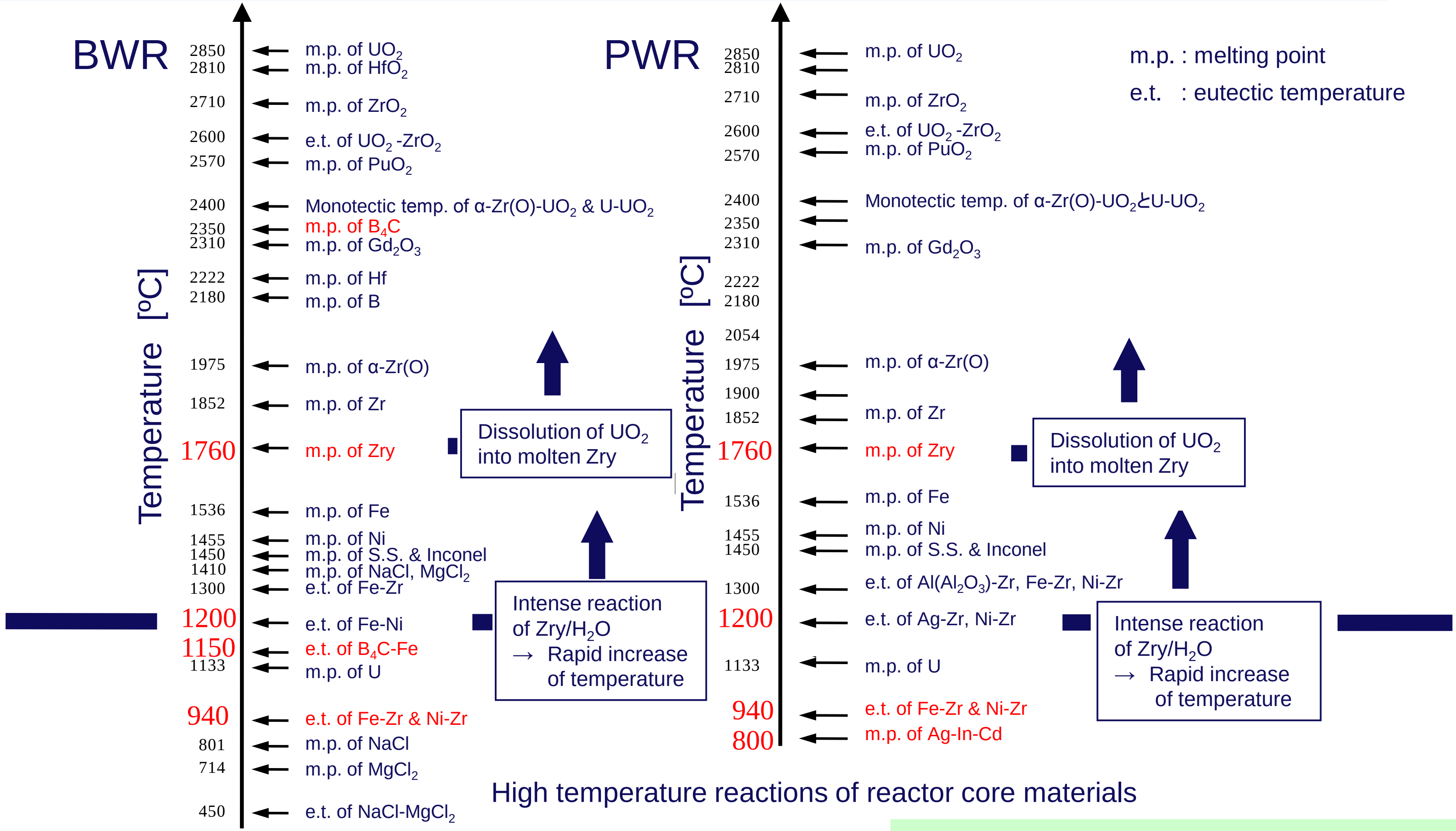
PWR



Overview of CRs for LWRs

Reference: http://www.rist.or.jp/

CR Behavior in Severe Accident 1/2



High temperature reactions of reactor core materials

e.t. of Fe/Zr (940ºC)
e.t. of B_4C/Fe (1150ºC)
m.p. of Ag-In-Cd (800ºC)

≦ Intense reaction of Zry/H_2O (~1200ºC)
m.p. of Zry (1760ºC) → Dissolution of UO_2

Prior to massive core damage, CR may melt and fall down from the core.

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CR Behavior in Severe Accident 2/2

Direct contact of B_4C and high-temperature water vapor

$$B_4C + 7H_2O(g) \rightarrow 2B_2O_3 + CO(g) + 7H_2(g)$$
$$B_4C + 8H_2O(g) \rightarrow 2B_2O_3 + CO_2(g) + 8H_2(g)$$
$$B_4C + 6H_2O(g) \rightarrow 2B_2O_3 + CH_4(g) + 4H_2(g)$$
$$B_4C + 6H_2O(g) \rightarrow 2B_2O_3 + C + 6H_2(g)$$

$$B_2O_3(l) \rightarrow B_2O_3(g)\uparrow$$
$$B_2O_3(l) + H_2O(g) \rightarrow 2HBO_2(g)\uparrow$$
$$B_2O_3(l) + 3H_2O(g) \rightarrow 2H_3BO_3(g)\uparrow$$

Volatilization of Cd／Separation of metal phases

High vapor pressure of Cd: 767ºC(1040K) ~1000hPa

Examinations of TMI-2 debris revealed ceramic phases and metal phases are separated.

Ceramic phases = UO_2, ZrO_2, etc.

Metal phases = Ag, Ag-In, Ag-In-Sn, Fe-Ni, Fe-Ni-Cr, Ni-Sn, etc.

⇒ Separation of CR materials from fuels

In the case of emergency injection of fresh- or sea-water without boric acid addition in LOCA, the reactor core without CR materials is re-flooded.

Apprehension for uncontrollable re-criticality accident!!

Requirements for Novel CR 1/2

Requirements for novel CR

1. Reactor shutdown margin is sufficiently ensured even at the severe accident (SA).

= <u>A</u>ccident <u>T</u>olerant <u>C</u>ontrol <u>R</u>od (ATCR)

① Strong neutron absorption effect

Gd(σ_a=1653b), Sm(σ_a=802b), Eu(σ_a=223b), Dy(σ_a=69b), etc.
B (σ_a=55b), Hf(σ_a=44b), Ag (σ_a=21b), In (σ_a= 52b), Cd (σ_a= 392b).

② Higher melting temperature than ~1200ºC, starting temperature of massive core damage

Gd_2O_3 ($T_{m.p.}$=2330ºC), Sm_2O_3 ($T_{m.p.}$=2330ºC), Eu_2O_3 ($T_{m.p.}$=2300ºC),
Dy_2O_3 ($T_{m.p.}$=2340ºC), HfO_2 ($T_{m.p.}$=2800ºC), etc.

③ High miscibility with molten and solidified fuel materials

High miscibility materials with UO_2 = Gd_2O_3, HfO_2, ·····, etc.

Requirements for Novel CR 2/2

2. Influences on normal operation conditions are minimized.

ATCR materials have different neutron absorption properties from conventional B_4C and Ag-In-Cd alloy.

Conventional materials are loaded in output adjustment part of CR.

⇒ Mitigation of influences on normal operation conditions

3. ATCR worth is maintained for a long term.

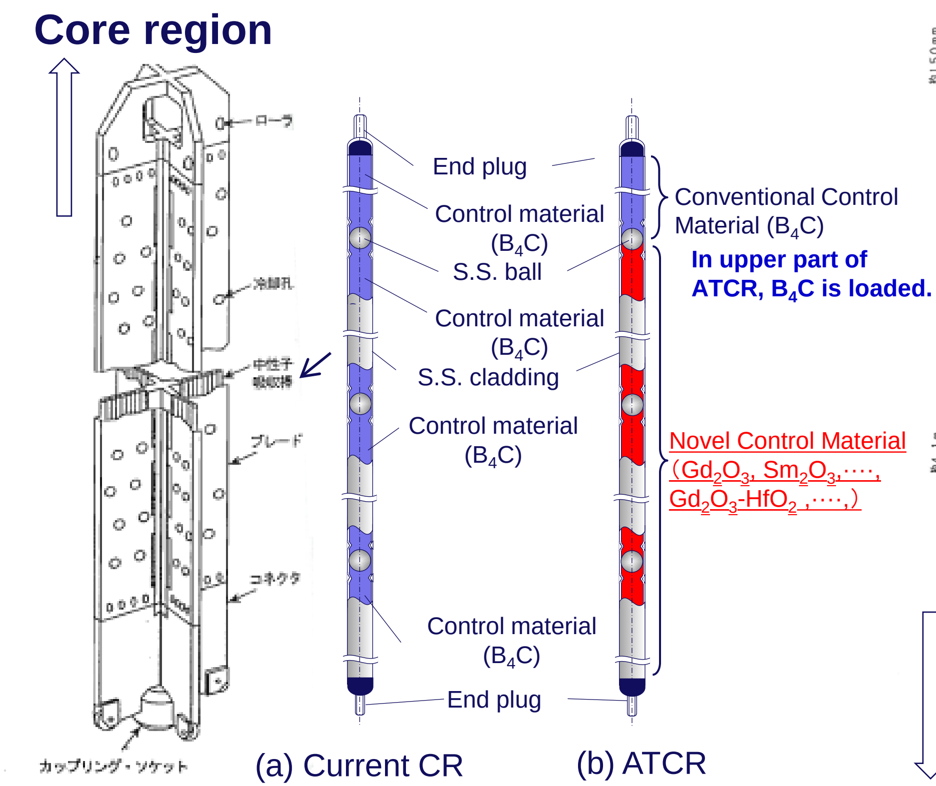
Strong neutron absorption materials are exhausted in a short term.

ATCR materials are loaded far from active region of reactor core.

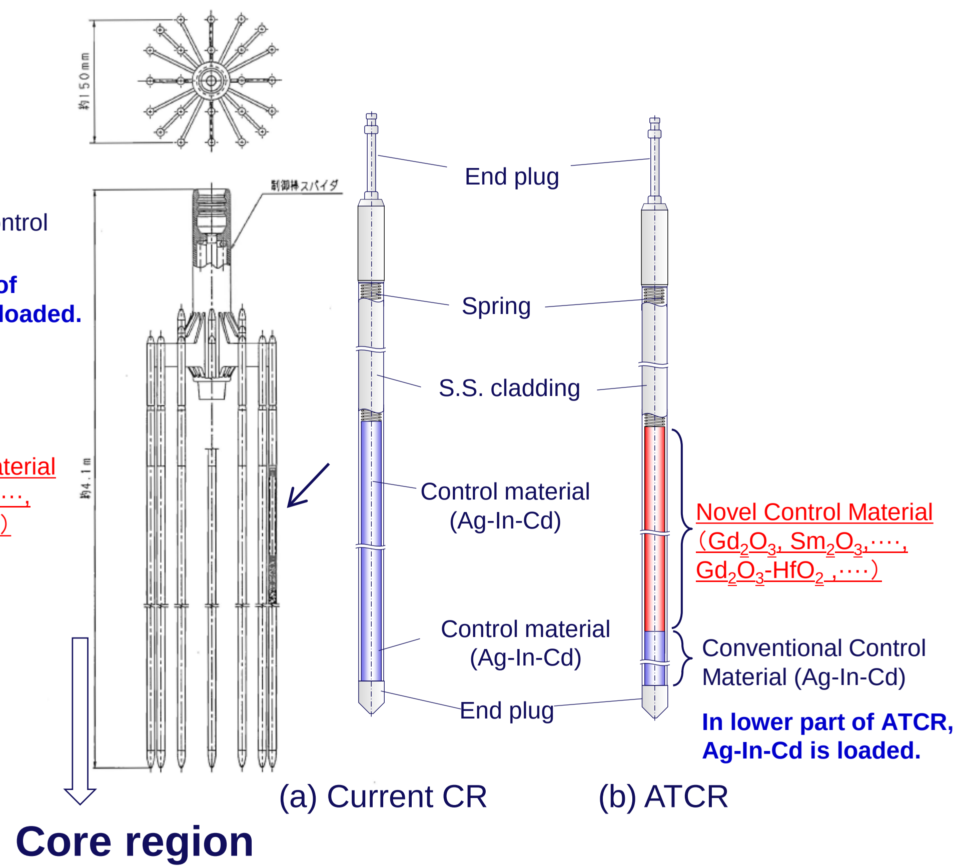
⇒ Large shutdown margin & Extension of CR lifetime

Structure of Accident Tolerant Control Rod

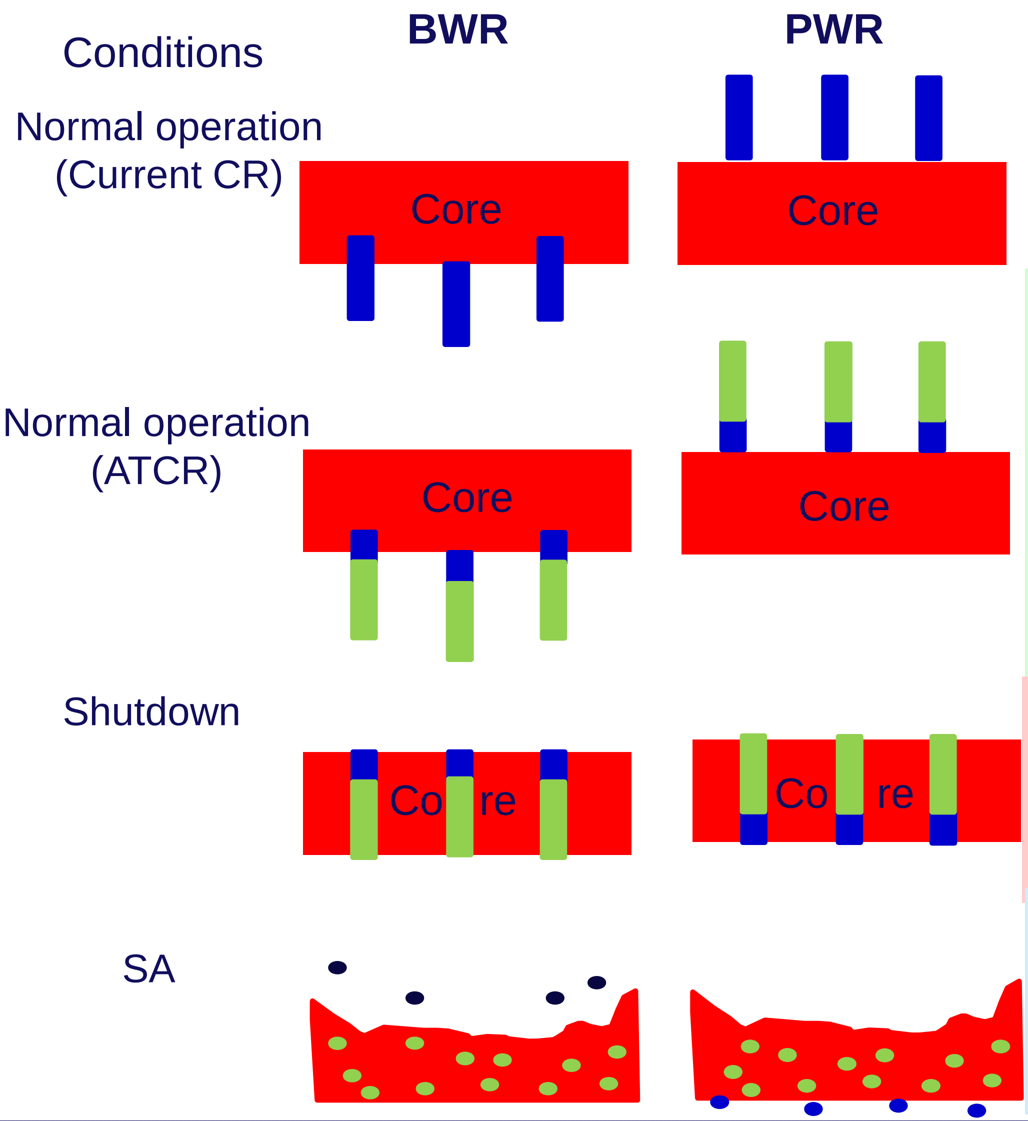
BWR



PWR



Concept of Accident Tolerant Control Rod



- Conventional control material
  B_4C or Hf (BWR)
  Ag-In-Cd (PWR)
- Novel control material
  Gd_2O_3 or Gd_2O_3-HfO_2 etc.

- Alternation of control material to Gd_2O_3/HfO_2
- Conventional material is loaded near the core to minimize influences on operation condition, and to extend ATCR lifetime.
  → applicable to current LWRs
- Few Gd_2O_3/HfO_2 is consumed.
  → repeatedly useable for long term

- Sufficient shutdown margin is ensured by strong neutron absorbent insertion
- Prevention of early collapse of CRs in SA condition

- Novel control material dissolved in and coexists with molten and solidified fuel materials.
→ Risk elimination of re-criticality accident

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Technical Issues & Development Plan

The following evaluations and examinations are planned to develop ATCR.

(1) Reactivity worth analysis of ATCR at normal & SA conditions
RE_2O_3 or RE_2O_3-HfO_2 mixture, (RE= Gd, Sm, Eu, Dy, ·····)

(2) Lifetime evaluation of ATCR
Required length of conventional control material section,
Loading position of novel control material

(3) High-temperature compatibility observation between novel control materials and structural materials
Liquid phase formation of Gd_2O_3 - HfO_2, Gd_2O_3 - Fe, Gd_2O_3 - Zr, ·····

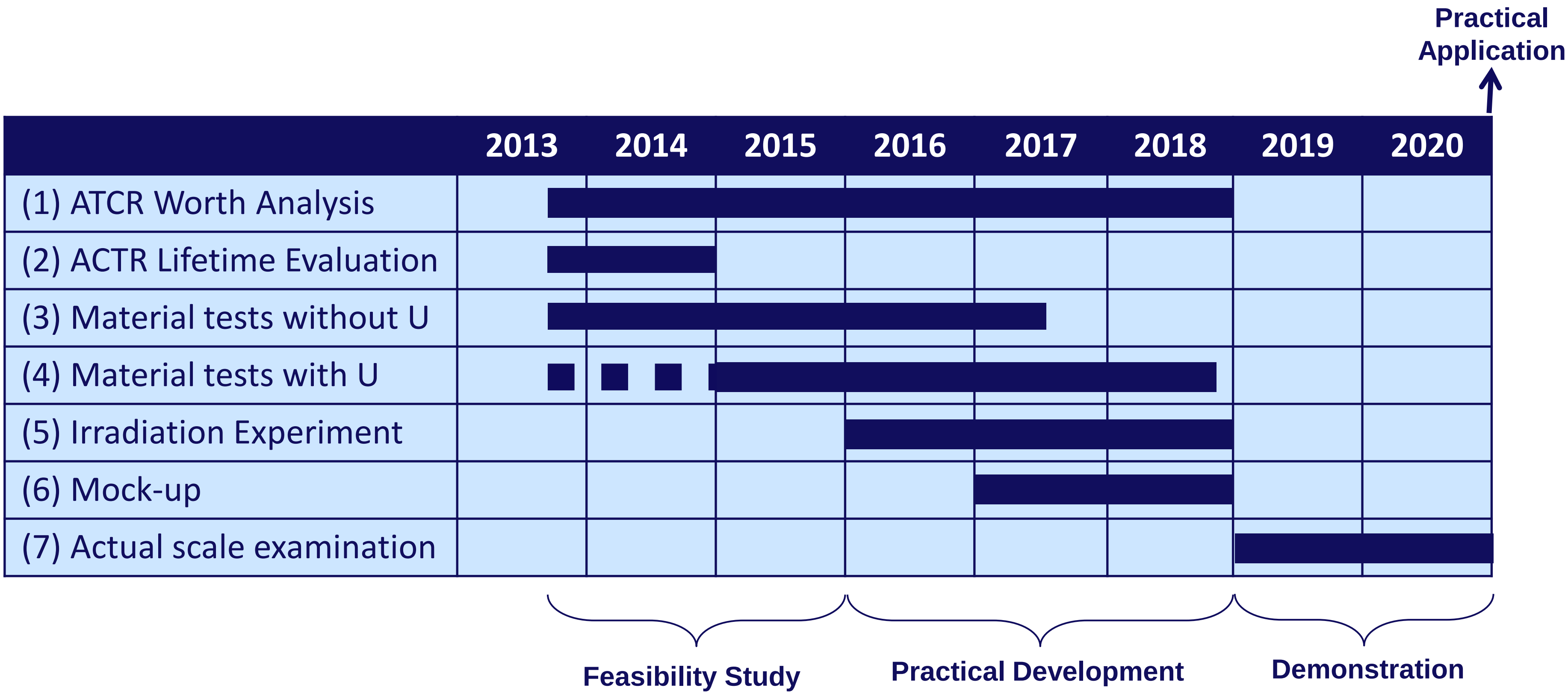
(4) Confirmation of miscibility with molten core materials
UO_2 - Gd_2O_3, UO_2 - HfO_2, ZrO_2 - Gd_2O_3, ·····

(5) Irradiation experiment of ATCR
Reactivity measurement, Neutron streaming effect, ·····

(6) Mock-up examination using large-scale equipment
UO_2 - Zr(Zry) - Fe(S.S.) - Gd_2O_3 - HfO_2 etc. in H_2O

(7) Demonstration
Actual scale fabrication, Long term Irradiation, ···

Development Schedule of ATCR



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Ex.1) Neutron Absorption

	Candidate mats.					Conventional mat.	
	Gd_2O_3	Sm_2O_3	Eu_2O_3	Dy_2O_3	HfO_2	B_4C	Ag-In-Cd
Density [g/cm^3]	7.4	8.4	7.4	7.8	9.7	2.5	9.9
Atom number density [$\times 10^{22}$ cm^{-3}]	0.70	1.44	1.27	1.26	2.77	2.78	5.63
Macroscopic neutron capture cross section [cm^{-1}]**	40.5	23.1	5.6	1.7	1.2	6.2	2.5

*:100%TD, **:ORLIBJ40, PWR41J40.LIB

Gd_2O_3 , Sm_2O_3, and mixtures (Gd_2O_3 - HfO_2, Sm_2O_3 - HfO_2, etc.) are promising.

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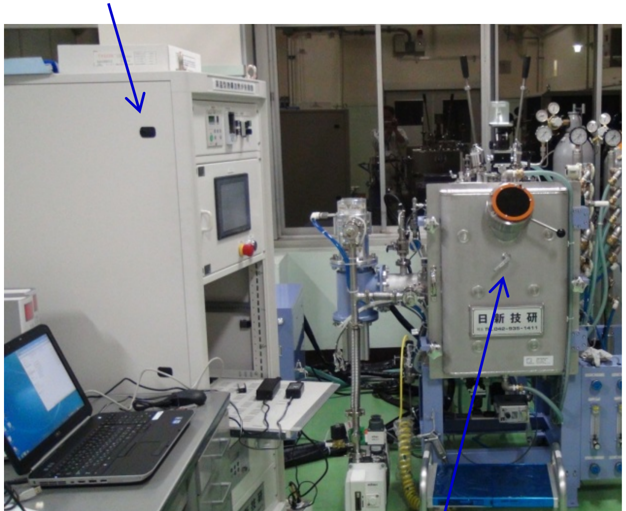
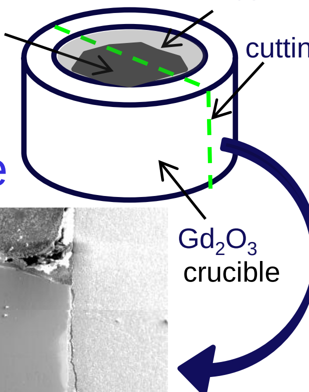
Ex.2) High temperature stability of ATCR

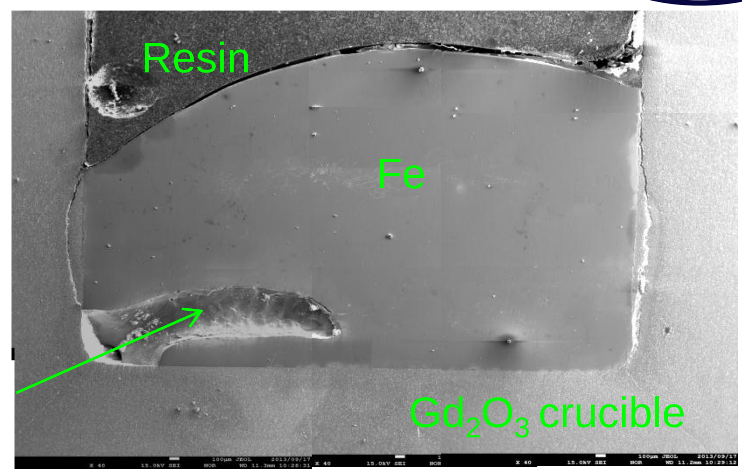
Experimental device
- High temperature furnace : Induction heating
- Avail. Temperature > 2700ºC
- Atmosphere = Vacuum, Inert gases



Compatibility of Fe-Gd_2O_3
- Heating of Gd_2O_3 crucible containing Fe
- Temperature = 1600ºC (> m.p. of Fe)
- Holding time = 1 hr.
- Atmosphere = Ar



Cross section of test sample



- Significant reaction was not found between molten Fe and Gd_2O_3 at 1600ºC.
- Slight migration of oxygen into Fe was observed.

Summary

1. ATCR concept was proposed.
    - Shutdown margin is sufficiently ensured even at the SA condition.
    - Influences on normal operation conditions are minimized.
    - CR worth is maintained for a long term.

2. R&D of ATCR for practical utilization in current LWRs were launched.
    (1) Some candidate materials were selected considering requirements for ATCR.
        Single or mixed substance(s) of Gd_2O_3, Sm_2O_3, Eu_2O_3, Dy_2O_3, HfO_2, etc.

    (2) For the most promising material of Gd_2O_3, a preliminary experiment was performed.
        High-temperature compatibility with Fe was confirmed to 1600ºC.
        (Massive core damage is started at ~1200ºC.)

3. Development schedule of ATCR was prepared.
    - Feasibility study is planned for 2 years.
    - Introduction target ~ 2020.

Thank you for your attention.

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Neutron Absorption Cross-section

Isotopes	Nat. abundances	Absorption Cross-sections [barn]
^{10}B	19.9%	278.60
^{11}B	80.1%	4.07E-4

Isotopes	Nat. abundances	Absorption Cross-sections [barn]
^{152}Gd	0.2%	69.23
^{154}Gd	2.2%	13.17
^{155}Gd	14.8%	2005.00
^{156}Gd	20.5%	3.49
^{157}Gd	15.7%	8627.00
^{158}Gd	24.8%	2.01
^{160}Gd	21.9%	0.46

Isotopes	Nat. abundances	Absorption Cross-sections [barn]
^{174}Hf	0.2%	41.59
^{176}Hf	5.2%	19.83
^{177}Hf	18.6%	186.40
^{178}Hf	27.3%	20.43
^{179}Hf	13.6%	14.87
^{180}Hf	35.1%	1.72

Isotopes	Nat. abundances	Absorption Cross-sections [barn]
^{107}Ag	51.8%	5.09
^{109}Ag	48.2%	37.43
^{113}In	4.3%	5.62
^{115}In	95.7%	54.41
^{110}Cd	12.5%	1.90
^{111}Cd	12.8%	1.90
^{112}Cd	24.1%	0.50
^{113}Cd	12.2%	3203.0
^{114}Cd	28.7%	0.52

Isotopes	Nat. abundances	Absorption Cross-sections [barn]
^{144}Sm	3.1%	0.18
^{147}Sm	15.0%	26.06
^{148}Sm	11.3%	1.57
^{149}Sm	13.8%	5600.00
^{150}Sm	7.4%	13.96
^{152}Sm	26.7%	88.43
^{154}Sm	22.7%	1.67

Neutron Absorption Cross-section

Isotopes	Nat. abundances	Absorption Cross-sections [barn]
^{151}Eu	47.8%	406.00
^{153}Eu	52.2%	55.09
^{156}Dy	0.1%	29.33
^{158}Dy	0.1%	8.51
^{160}Dy	2.3%	32.96
^{161}Dy	18.9%	63.93
^{162}Dy	25.5%	91.23
^{163}Dy	24.9%	43.31
^{164}Dy	28.2%	91.39

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