Accident Tolerant Control Rod Development in Japan

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Fuel & CR behavior in early stage of SA

Fuel Pin: H_2O / Zircaloy / UO_2

Oxidation reaction of Zry by high-temperature steam accelerates intensely at >1200ºC.

⇓

Fuel temperature increases sharply.

⇓

Zry cladding melts at ~1760ºC.

⇓

Fuel material, UO_2, dissolves in molten Zry.

Control Rod: Zircaloy, H_2O / S.S. / B_4C or Ag-In-Cd

Eutectic temperature of Fe / Zr = **940ºC**

Eutectic temperature of B_4C / Fe = **1150ºC**

Melting point of Ag-In-Cd = **800ºC**

In early stage of sever accident, CR potentially melt and fall down into lower part of core prior to fuel melt

Novel Control Rod Concept

Accident Tolerant Control Rod:

- to attain sub-criticality at any accidental conditions including SA.

① As sufficient neutron absorption effect as conventional CR materials.

② Higher melting & eutectic temperature than ~1200ºC. Or

②' Higher resistance to eutectic reaction

③ High miscibility with molten and solidified fuel materials.

Candidate Materials

Absorber: RE_2O_3(Sm_2O_3, Gd_2O_3, Eu_2O_3 …..), HfO_2, etc. (①, ②, ③)

Structure: Fe-Cr-Al ODS ferritic steel, etc. (①, ②')

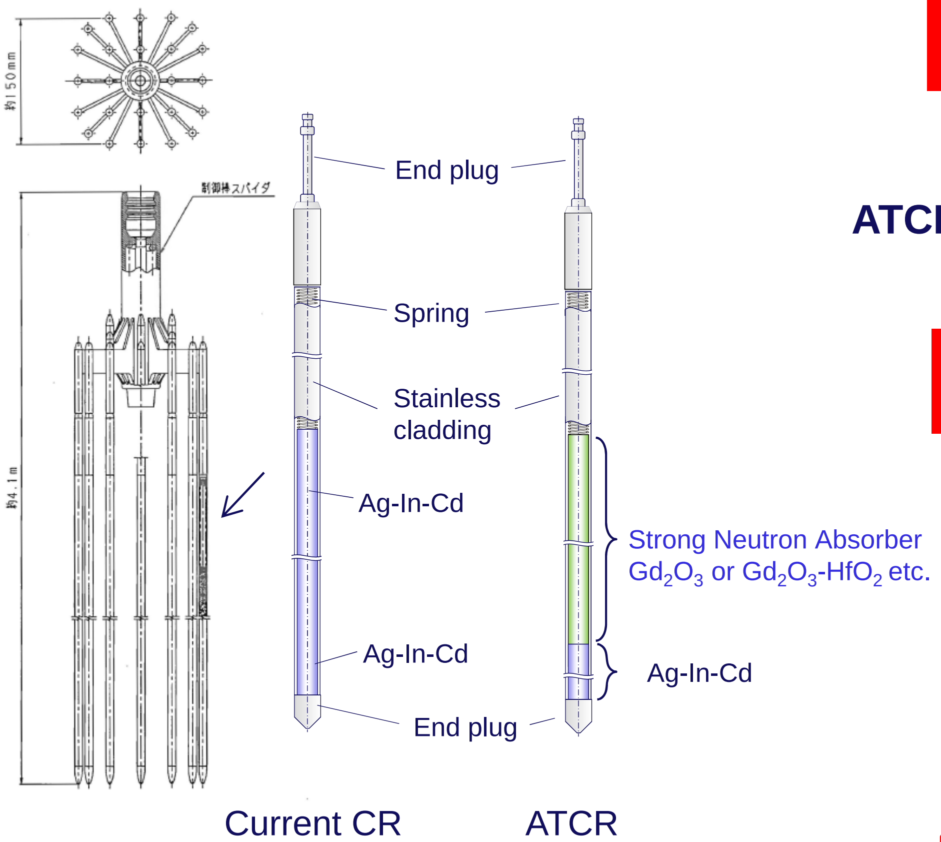
- to be applicable to current LWRs.

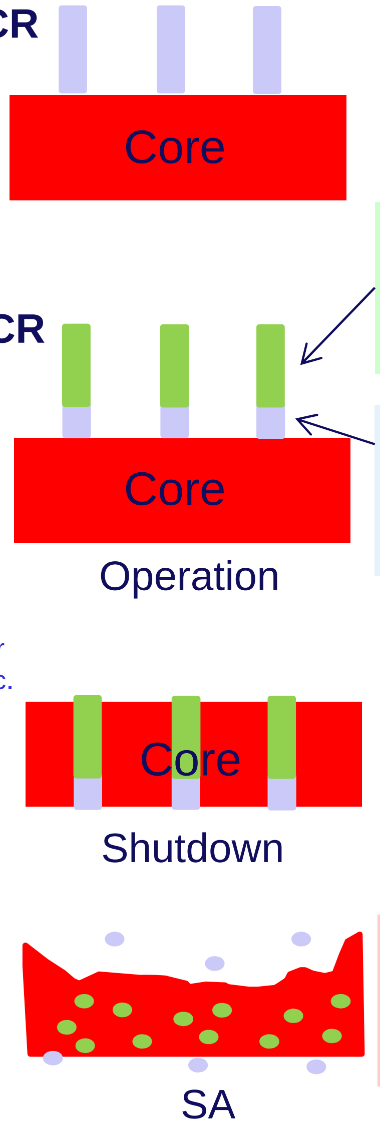
④ Influence on normal operation is minimized.

⑤ CR worth is kept for a long term.

Operation concept of ATCR – Absorber Modification –

Example in PWR





- Ag-In-Cd
- ATCR material
  RE_2O_3 or RE_2O_3-HfO_2 etc.

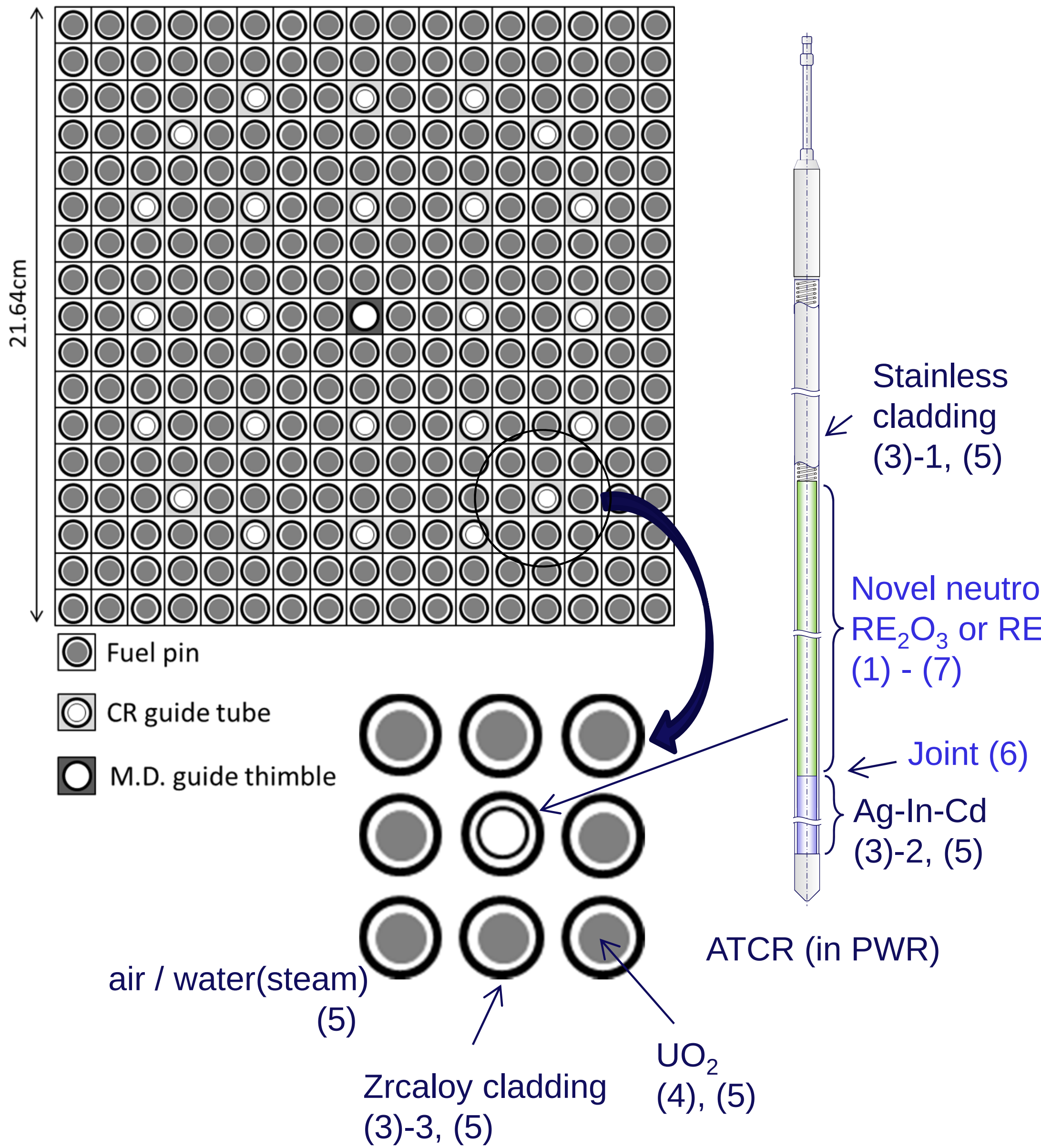
Low neutron leakage region:
RE_2O_3 or RE_2O_3-HfO_2
→ Minimum loss of neutron absorber

High neutron leakage region:
Ag-In-Cd
→ No influence on operating conditions

High neutron absorption
→ High shutdown margin

High melting or eutectic temperature
Miscibility with fuel materials
→ Remaining in the core material

Technical Issues & Development Plan
– Absorber Modification –



(1) Reactivity worth analysis

(2) Lifetime evaluation of ATCR,

(3) High-temperature compatibility observation with structural materials,
   1. RE_2O_3 - Fe,
   2. RE_2O_3 - AIC (or B_4C) - Fe,
   3. RE_2O_3 - Zr ···

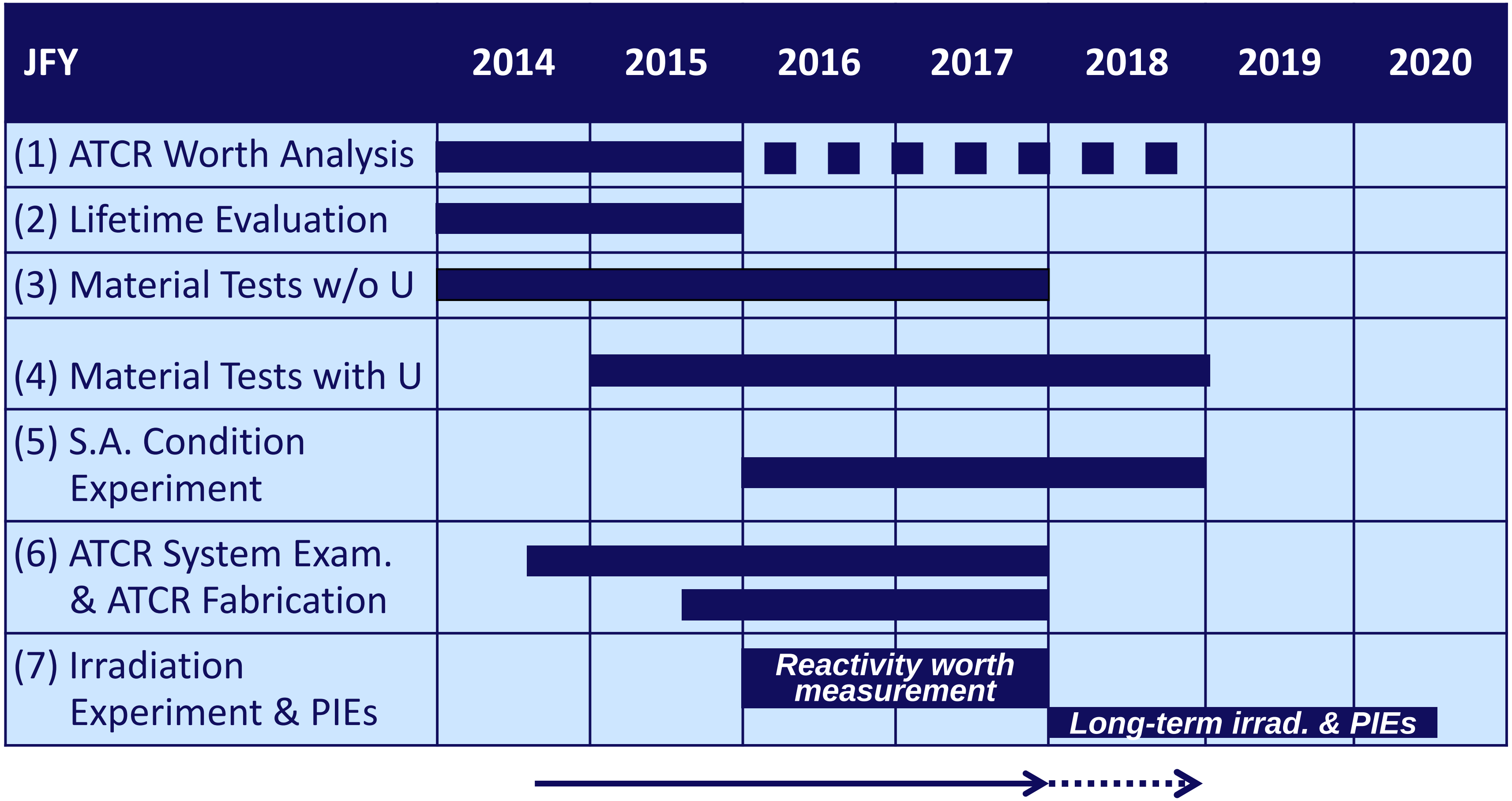
(4) Confirmation of miscibility with fuel materials, RE_2O_3-UO_2

(5) SA condition experiment,
   UO_2 - Zr(Zry) - Fe(S.S.) - RE_2O_3 etc.
   in air / water(steam)

(6) Structure design & fabrication
   RE_2O_3 / Ag-In-Cd(B_4C)

(7) Irradiation experiment

Development Schedule of ATCR
– Absorber Modification –



ATF development project is discussed.

High temperature stability of ATCR

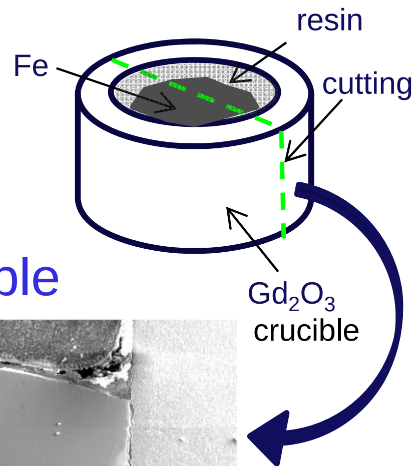
Experimental apparatus
High temperature furnace
: Induction heating
Available Temp. > 2700ºC
Atmosphere = Vacuum, Inert gases

Control system

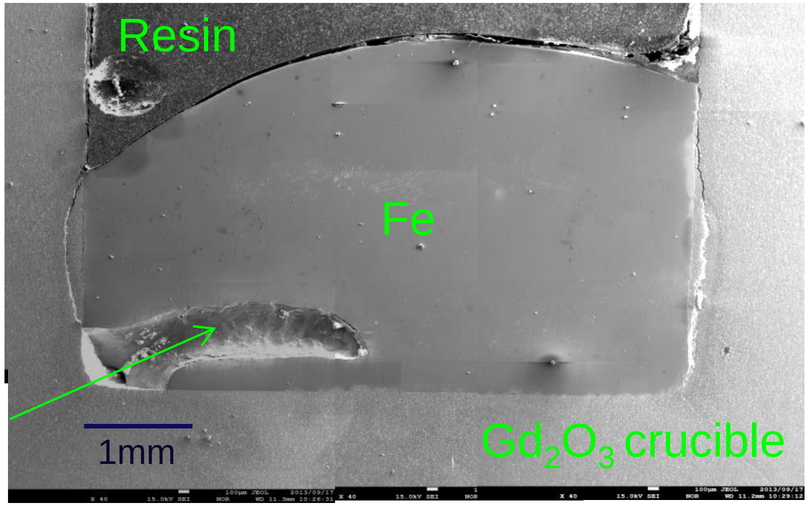
Record PC

Furnace chamber

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

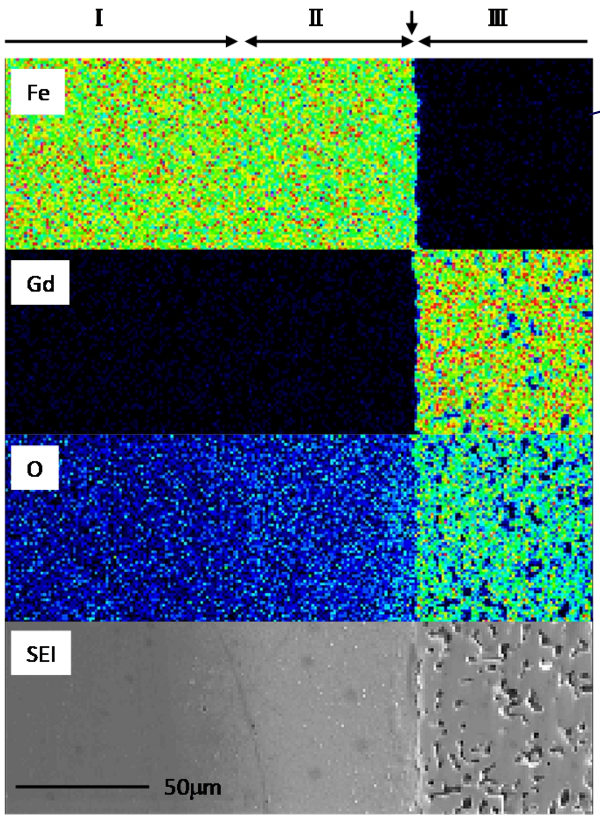


Cross section of test sample

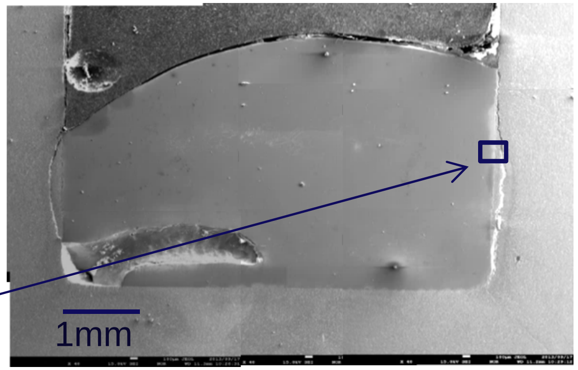


Void

Reaction between molten Fe and Gd_2O_3



Distributions of Fe, Gd and O around Fe/Gd_2O_3 reaction boundary



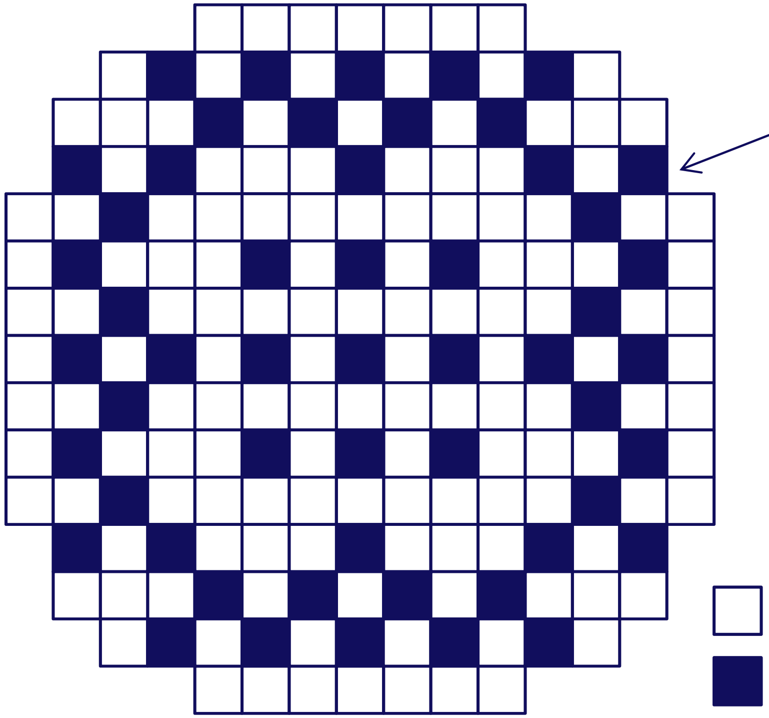
Preliminary composition analysis results [mol%]

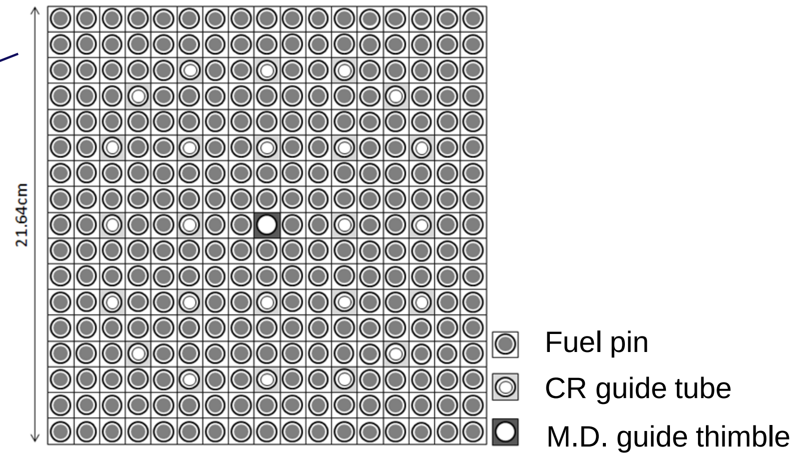
Area	Fe	Gd	O
I	98	N.D.	2
II	93	N.D.	7
III	N.D.	47	53

← boundary

- No significant reaction was found between molten Fe and Gd_2O_3 at 1600ºC.
- Slight migration of oxygen into periphery of Fe was observed.

Preliminary analysis of CR worth





Large scale PWR core configuration

CR worth analysis using MVP code

	Sm_2O_3	Eu_2O_3	Gd_2O_3	HfO_2	AIC
Reactivity worth of CR [%Δk/kk']	5.2	**6.3**	5.1	4.6	5.1

$\mathbf{Eu_2O_3} > Sm_2O_3 \cong AIC \cong Gd_2O_3 > HfO_2$

Summary

1. ATCR-concept proposed from CRIEPI, Japan.

- Sub-criticality attained at any accidental conditions including SA.

  Candidate Materials

  Absorber: RE_2O_3(Sm_2O_3, Gd_2O_3, Eu_2O_3 …..), HfO_2, etc.

  Structure: Fe-Cr-Al ODS ferritic steel, etc.

- Applicability to current LWRs is promising.

  Influences on normal operation conditions potentially kept minimized.

  CR worth potentially kept maintained for a long term.

2. R&D of ATCR were launched.

(1) Material tests initiated.

High-temperature compatibility between Gd_2O_3 and Fe was confirmed to 1600ºC.

(2) An available CR reactivity preliminarily analyzed for candidate absorber materials.

$Eu_2O_3 > Sm_2O_3 \cong AIC \cong Gd_2O_3 > HfO_2$

(3) Details about structure design, fabrication & irradiation experiments being discussed.

(4) Development of alternative structural materials (Fe-Cr-Al ODS, etc.) has started by collaborating industries.

⇒Details will be presented in the near future.

3. Outlook of ATCR development

- ATF development project for application of current LWRs start being discussed.
- CRIEPI wants to introduce ATCR in ~ 2020.