# Development Status of FeCrAl-ODS Cladded Accident Tolerant Fuel for LWRs

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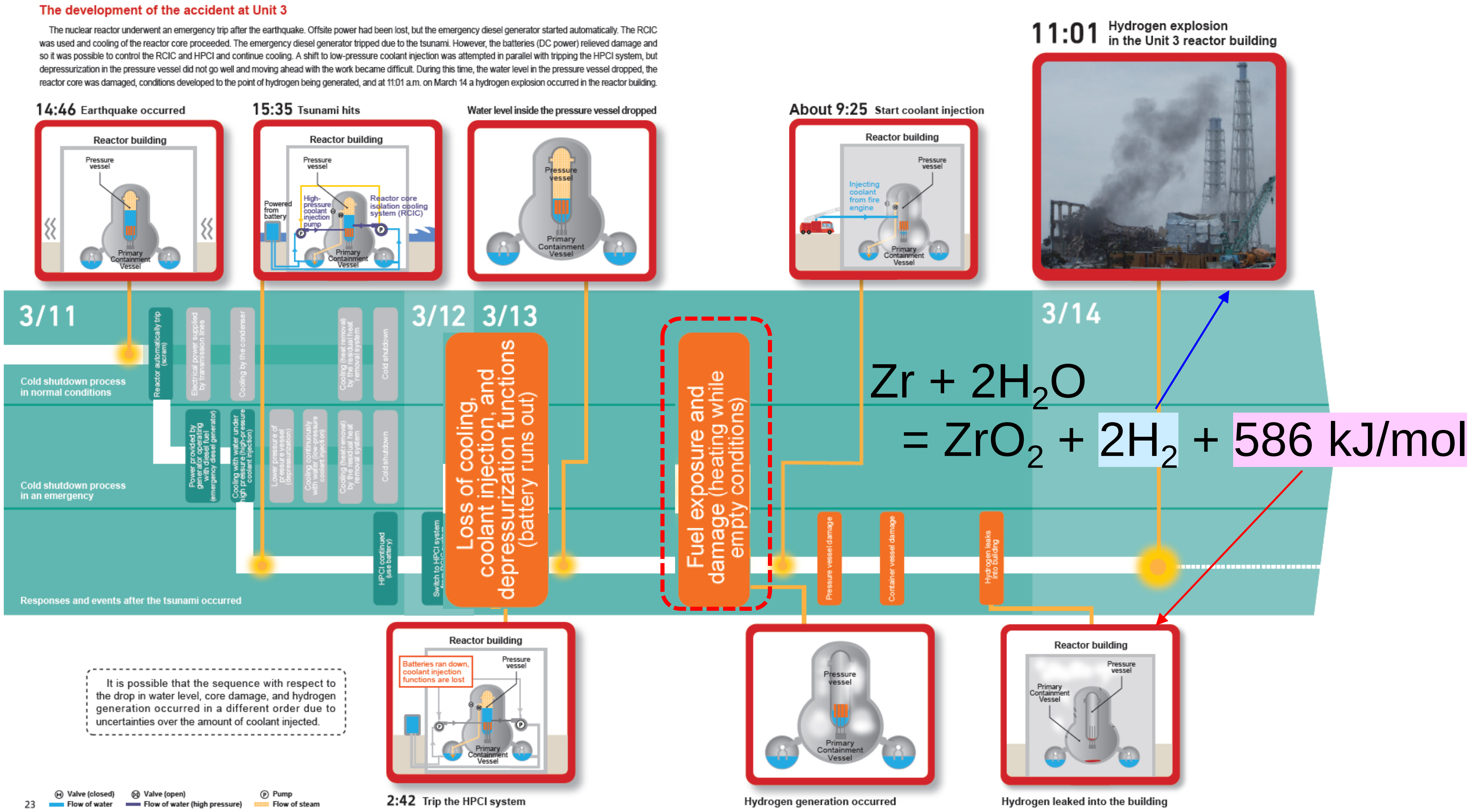
# Contents

- Background
- Concept of FeCrAl-ODS
- Current status:
  - Manufacturing technology development
  - Experimental study
  - Analytical study
- Challenges and data gaps

# Background (1)



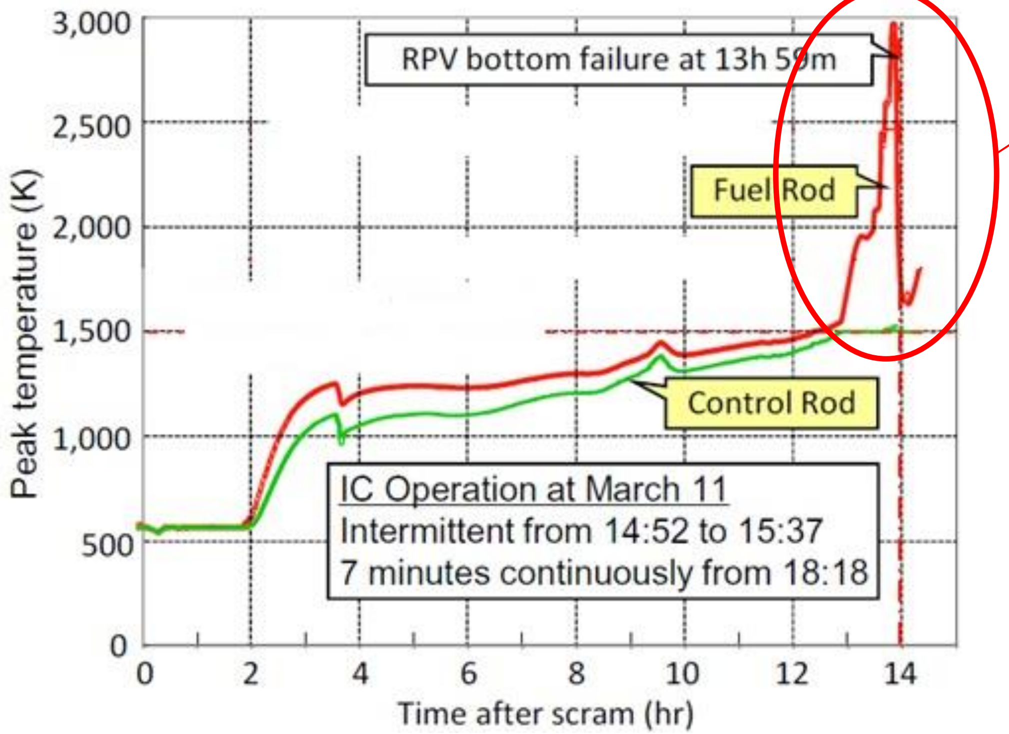

$$\mathrm{Zr} + 2\mathrm{H_2O} = \mathrm{ZrO_2} + 2\mathrm{H_2} + 586\ \mathrm{kJ/mol}$$

Reference: https://www.tepco.co.jp/en/wp-content/uploads/hd03-02-02-000-outline01.pdf

# Background (2)

- Requirements for ATF of LWRs*1
  - #1: High resistance to steam oxidation

*1: Light Water Reactors




Catastrophic temperature increase by zirconium oxidation

$$Zr + 2H_2O = ZrO_2 + 2H_2 + 586\ \text{kJ/mol}$$

Hydrogen explosion

Temp. escalation

Accident analysis of Fukushima-Daiichi unit 1 by SAMPSON code

Reference: M. Naito, et al. , Proc. Int. Mtg. on SA Assessment and Management, Paper 6005, San Diego, USA, November 11-15, 2012

# Background (3)

- Requirements for ATF of LWRs
  - #2: Applicability to existing (current) LWRs

ATF needs to fit the current fuel cycle system

- ☐ Manufacturing
- ☐ Normal operation, AOO*1, DBA*2
- ☐ Storage
- ☐ Recycling
- ☐ Disposal

*1: Anticipated Operational Occurrence
*2: Design Based Accident

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# Concept of FeCrAl-ODS (1)

NFD
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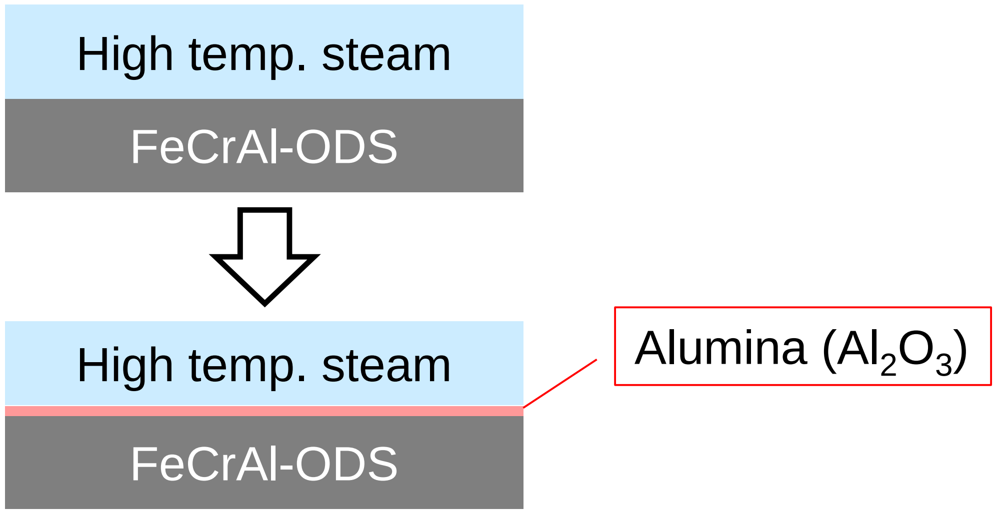
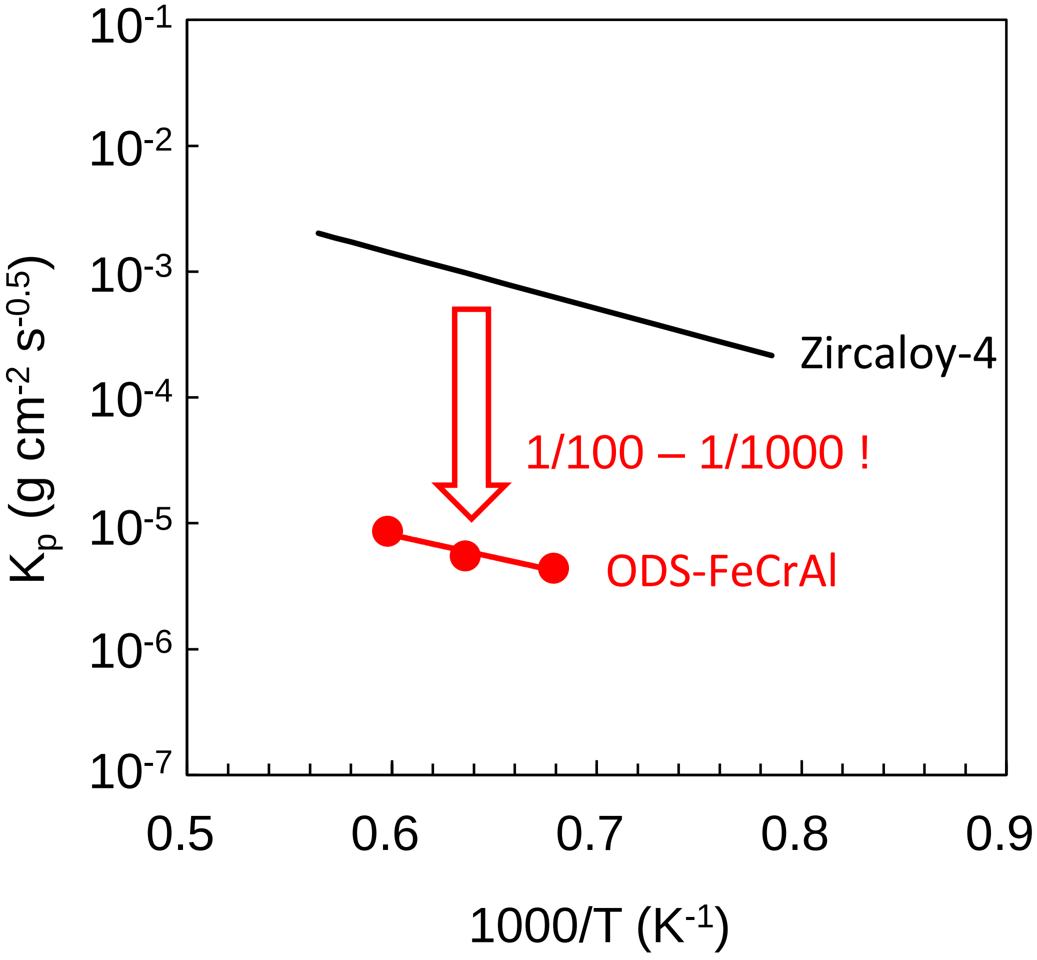
- Suppression of steam oxidation




Alumina layer suppresses steam oxidation by $10^2$ - $10^3$
→ Suppression of heat and hydrogen generation

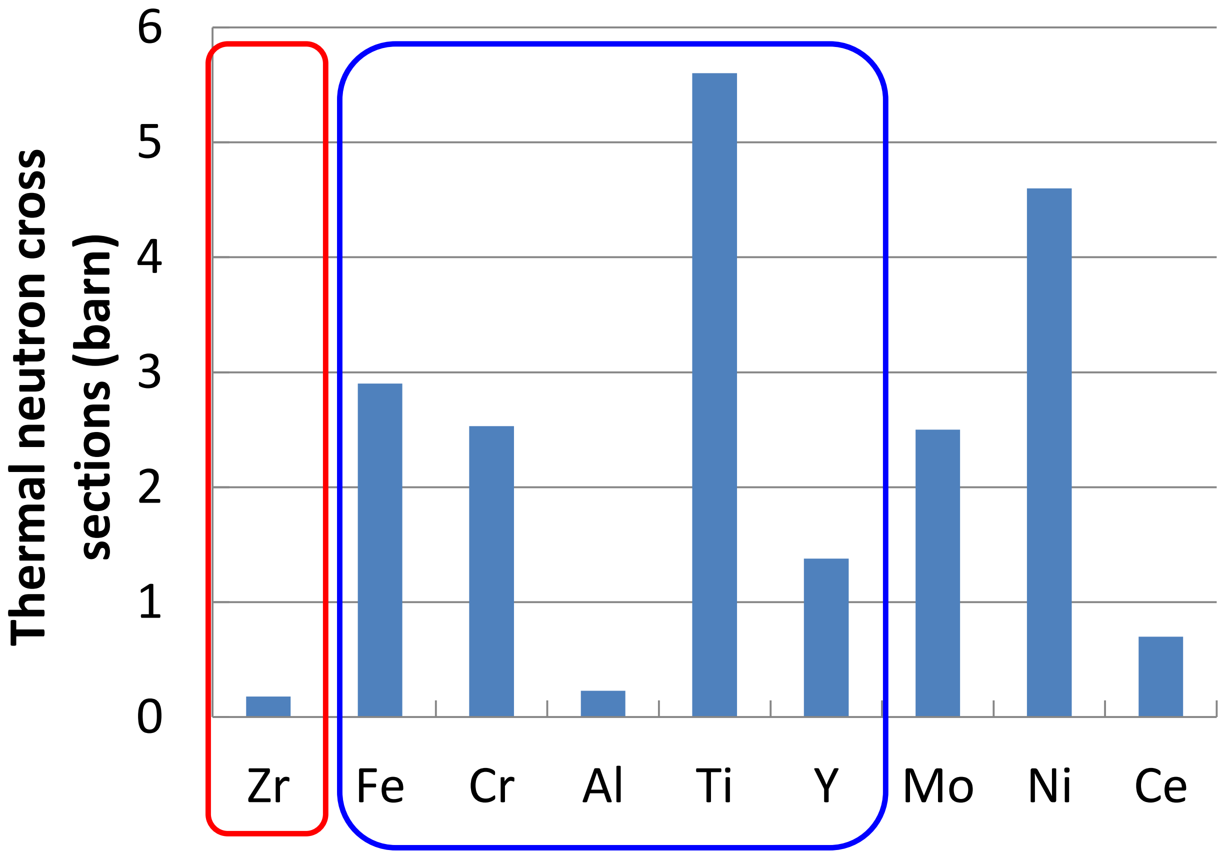



Oxidation rate of Zry-4 and FeCrAl-ODS

Reference: K. Sakamoto, et al. , Proc. Top Fuel 2018, 30 Sep. – 04 Oct. 2018, Prague, Czech Republic

# Concept of FeCrAl-ODS (2)

- Compensation of higher reactivity penalty (1)




Zircaloy:
Zr >98 mass%

FeCrAl-ODS:
Fe-12Cr-6Al-0.5Ti-0.4Zr-0.5$Y_2O_3$

Reduction of cladding material is essential to use in LWRs

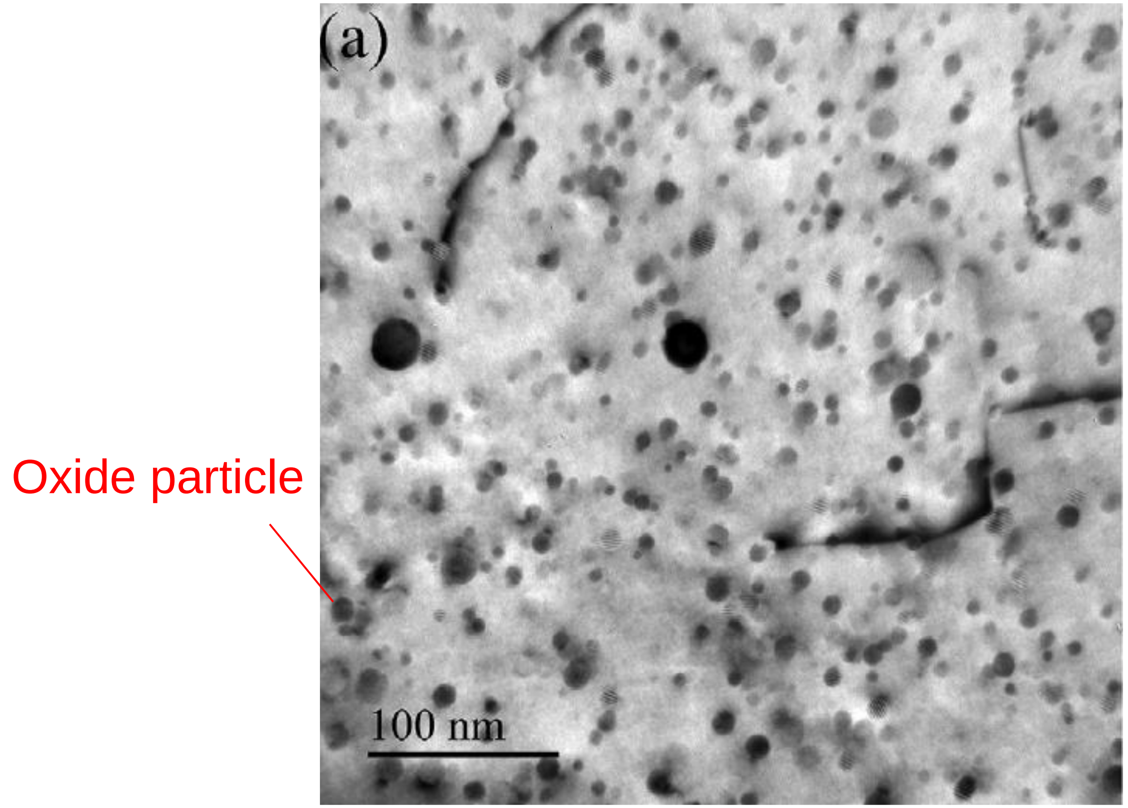
Comparison of thermal neutron cross sections

Reference: K. Kimura , Hoshasen data book (in Japanese), Chijin Syokan, 1958.

# Concept of FeCrAl-ODS (3)

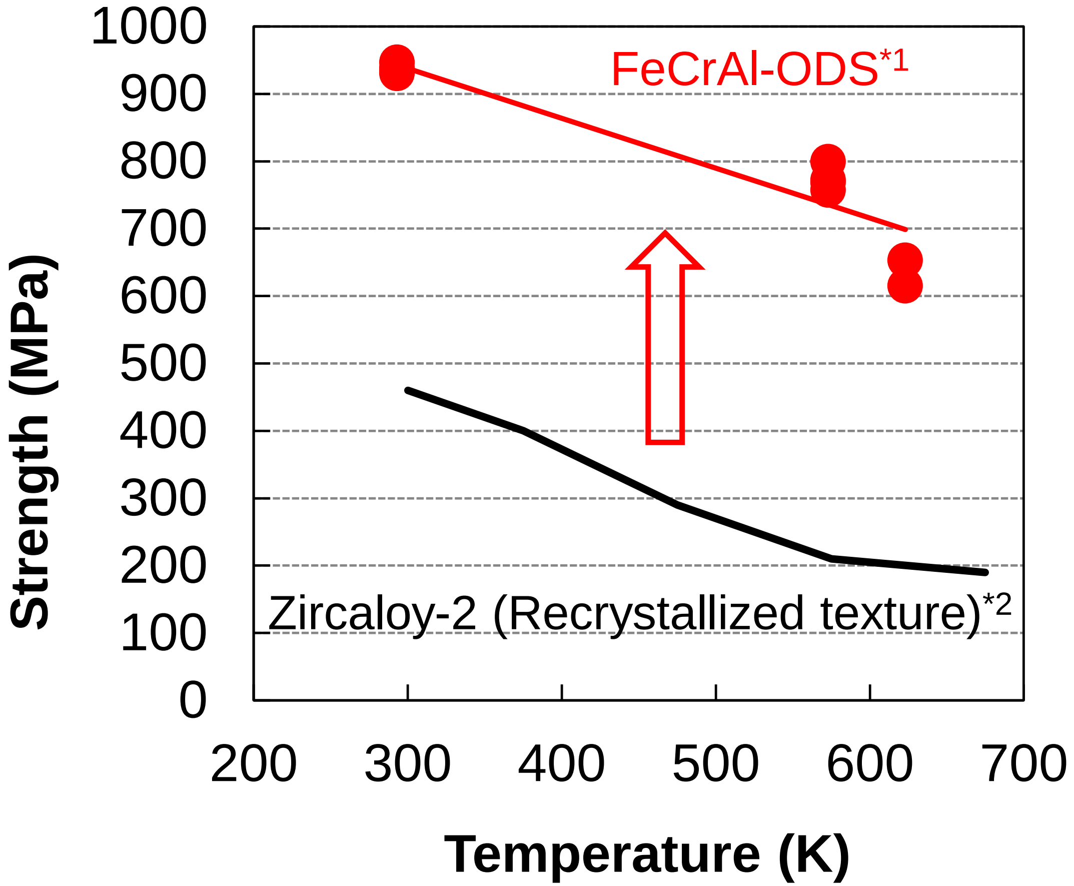
NFD Power the Future

- Compensation of higher reactivity penalty (2)




TEM observation of oxide particles

Reference: J. Gao et al., J. Nucl. Mater, 524 (2019) 1-8




Comparison of strength

Reference:
*1: K. Sakamoto, et al. , Proc. Top Fuel 2018, 30 Sep. – 04 Oct. 2018, Prague, Czech Republic
*2: Onchi et al., J. Nucl. Mater., 88 (1980) 226-235

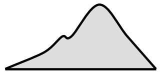
# Contents

# Manufacturing technology development (1)

- Chemical composition (in mass %)

| Material | Cr | Al | Ti | Zr | $Y_2O_3$ |
|---|---|---|---|---|---|
| FeCrAl-ODS tube | 12 | 6 | 0.5 | 0.4 | 0.5 |

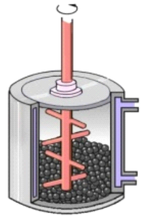
- Procedure (Tube fabrication)



**Alloyed powder**

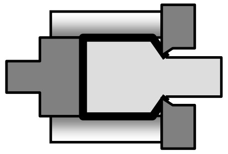
**$Y_2O_3$, $Fe_2O_3$ Powder**

Mechanical alloying



**Attritor**

Hot extrusion (1373 K or 1423 K)



Straightening (1323 K)

Annealing (1373 K or 1423 K)

Cold rolling & Annealing

Reference: K. Sakamoto, et al. , Proc. Top Fuel 2018, 30 Sep. – 04 Oct. 2018, Prague, Czech Republic

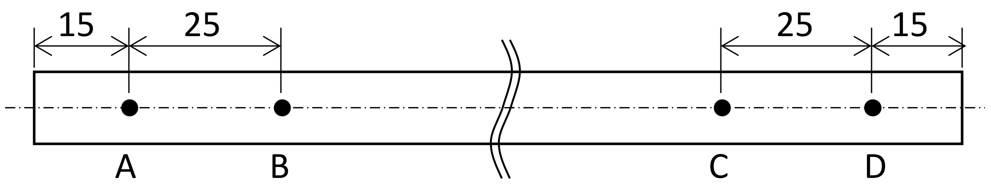
- Mechanical alloying and hot extrusion processes are needed
- Current cold rolling & annealing system can be adopted

# Manufacturing technology development (2)

## Flaw detection

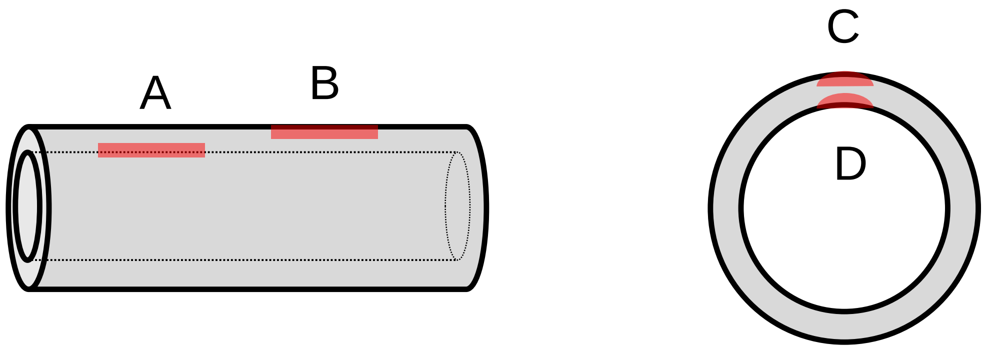
Fuel type: 10x10-type, Wall-thickness: 0.3 mm

Units: mm




| Location | Surface | Direction | Length (μm) | Width (μm) | Depth (μm) |
|---|---|---|---|---|---|
| A | Inner | Circumferential | 768 | 49 | 28 |
| B | Outer | Circumferential | 753 | 49 | 29 |
| C | Outer | Longitudinal | 767 | 48 | 30 |
| D | Inner | Longitudinal | 763 | 47 | 31 |

~10% of wall-thickness



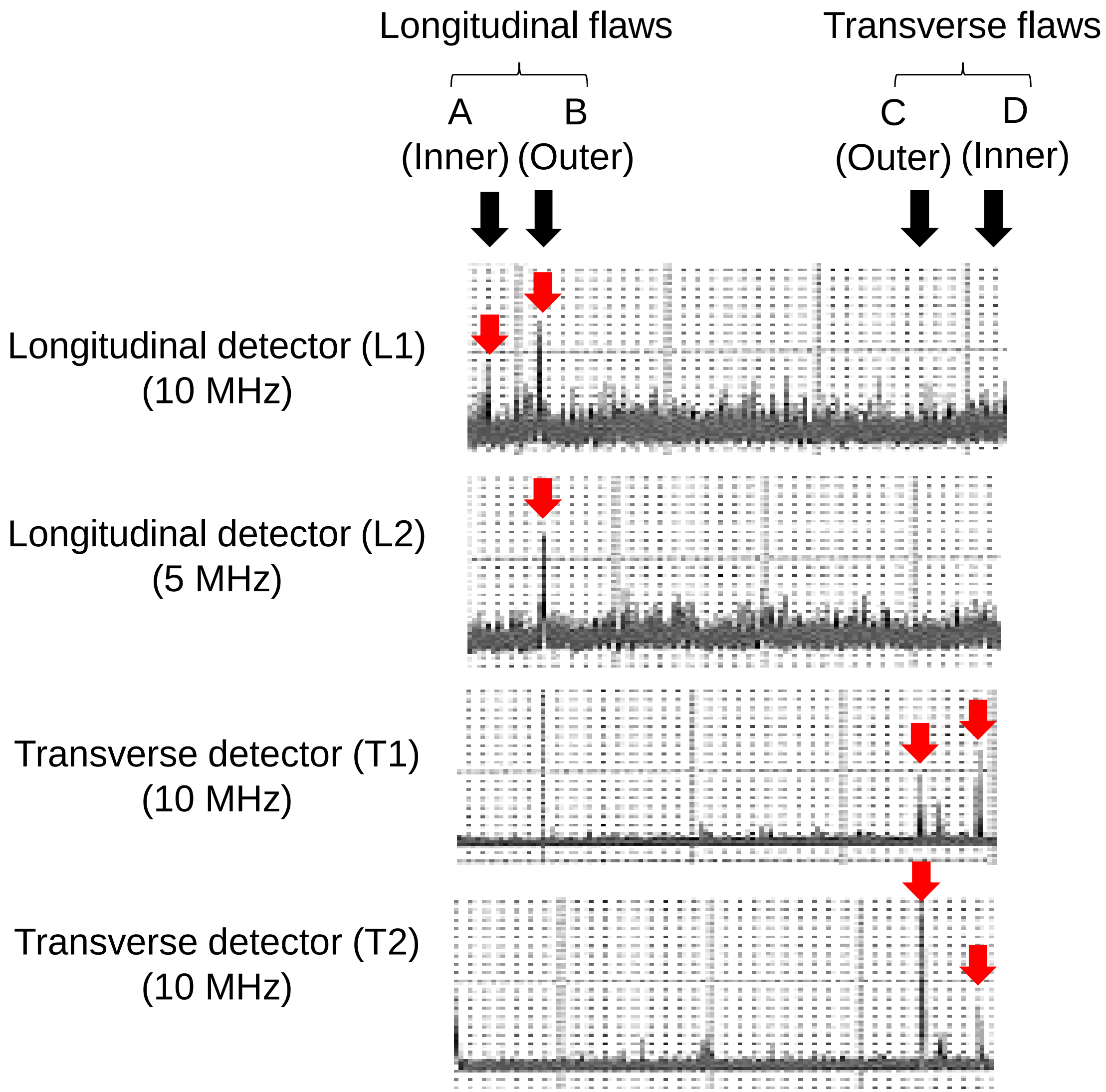

## Ultrasonic detection methods

- Inspection in water
- 4 detectors (2 for transverse and 2 for longitudinal (axial) flaws)
- Ultrasonic angle beam method at 10 MHz or 5 MHz

Reference: K. Sakamoto, et al., Proceedings of TopFuel2021, Santander, Spain, October 24-28, 2021,

# Manufacturing technology development (3)

Power the Future




- All four artificial flaws with ~ 30 $\mu$m depth (~ 10 % of wall-thickness) were successfully detected
- S/N ratio in detection of longitudinal flaws was worse than that of transverse flaws(→anisotropic shape of crystal grains in FeCrAl-ODS tube)
- A change of frequency was required for L2 from 10 MHz to 5 MHz

- Ultrasonic flaw detection method would be applicable to the inspection of FeCrAl-ODS tubes
- Further optimization is clearly needed for the practical application

Reference: K. Sakamoto, et al., Proceedings of TopFuel2022, Raleigh, NC, October 9-13, 2022, 161-169

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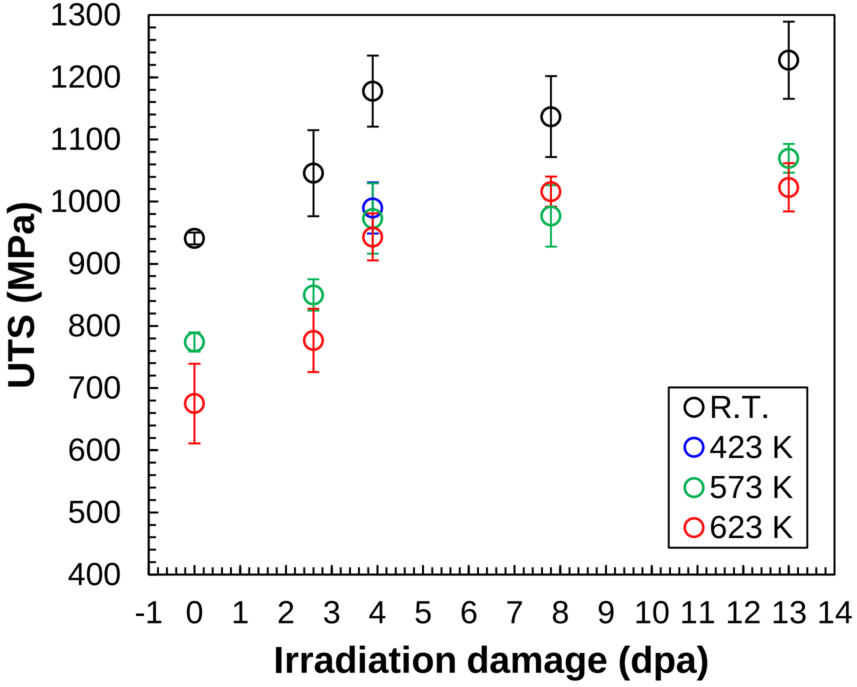
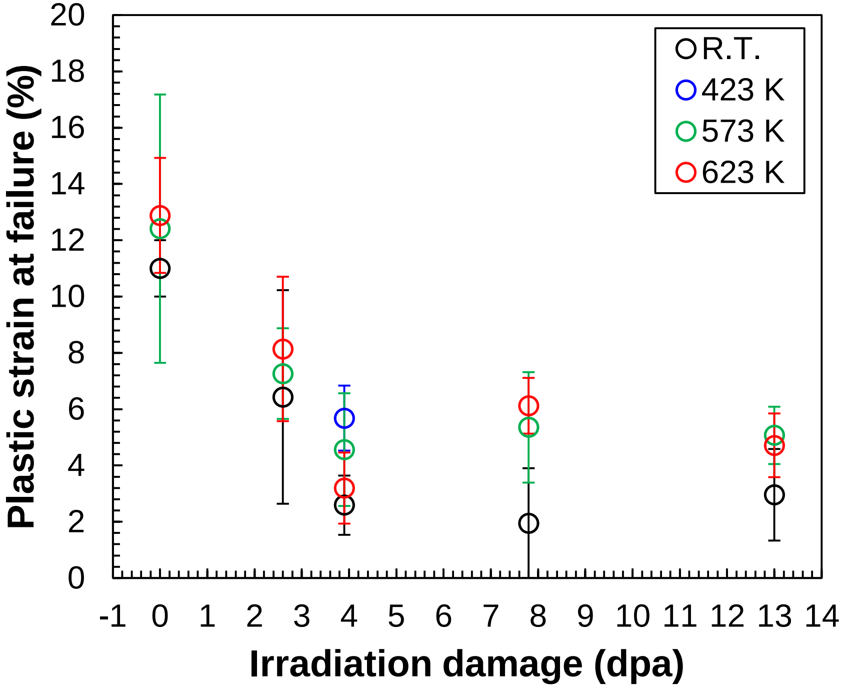
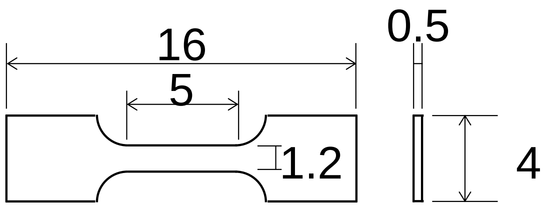
# Experimental study (1)

- Effect of neutron irradiation on mechanical properties
  - SS-J2 type specimens
  - Irradiated in ORNL HFIR at 573 K up to 13 dpa




(Unit: mm)

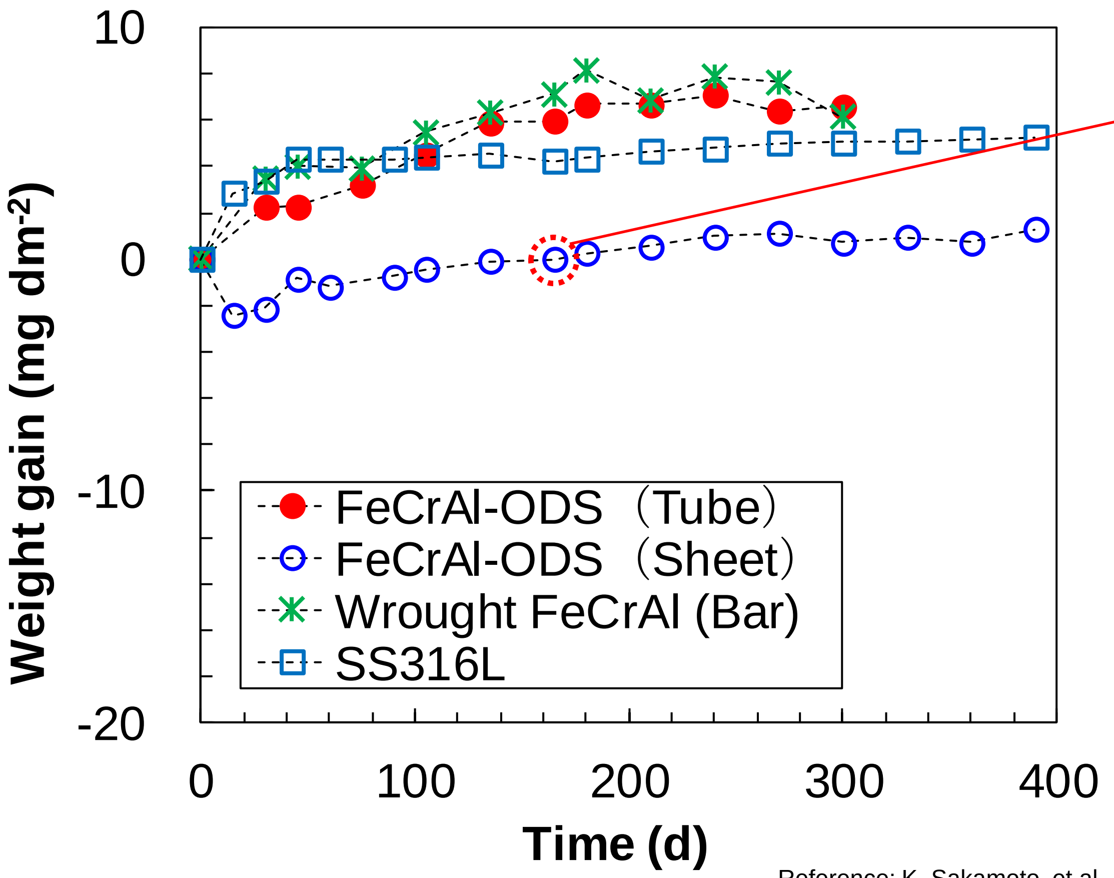


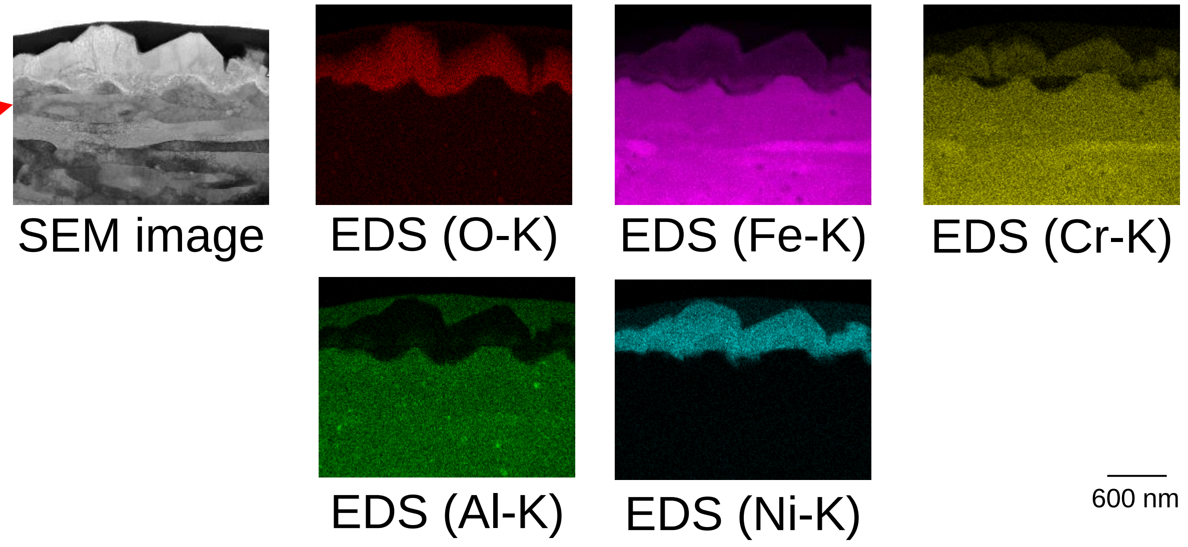

Reference: K. Sakamoto et al., Proceedings of the 2023 Water Reactor Fuel Performance Meeting, WRFPM2023, July 17-21, Xi'an, China, pp. 20-28, 2024

- Strength increases and ductility decreases with irradiation damage up to 3.9 - 7.8 dpa and is almost at saturation value at higher irradiation damage levels

# Experimental study (2)

- Corrosion property
  - ➢ Corroded in autoclave with circulation pure water at 563 K, ~ 8MPa and 6 ppmDO (563 K)



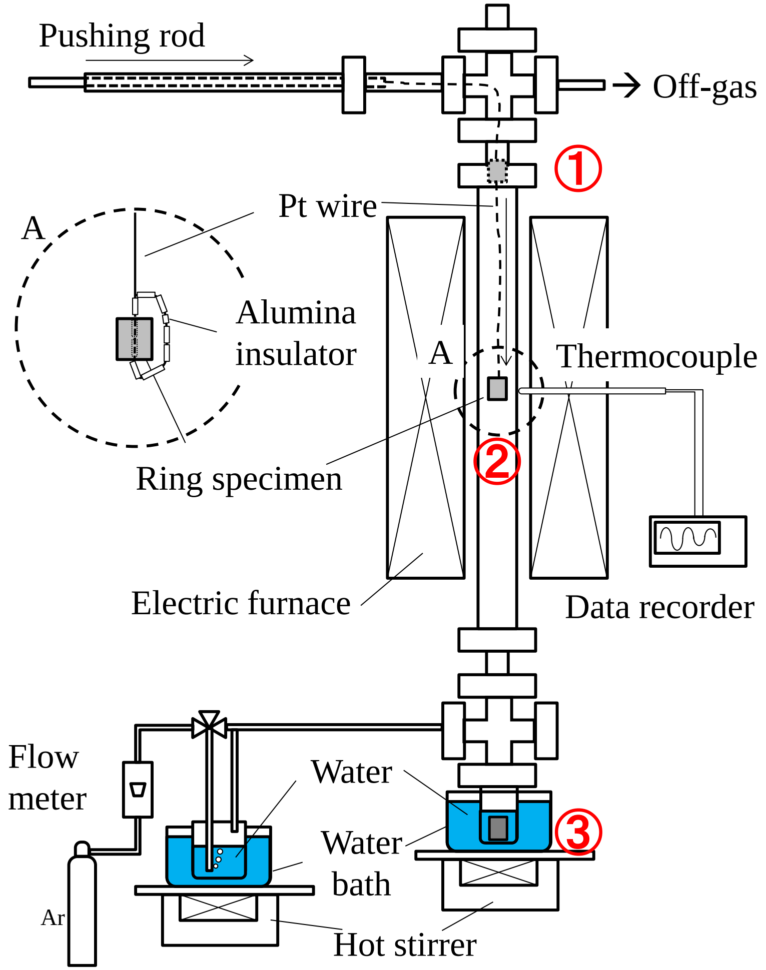

Thickness reduction due to dissolution ~ 0.3 μm

- Stable corrosion resistance
- Very limited dissolution to coolant water

Reference: K. Sakamoto, et al. , Proc. Top Fuel 2018, 30 Sep. – 04 Oct. 2018, Prague, Czech Republic

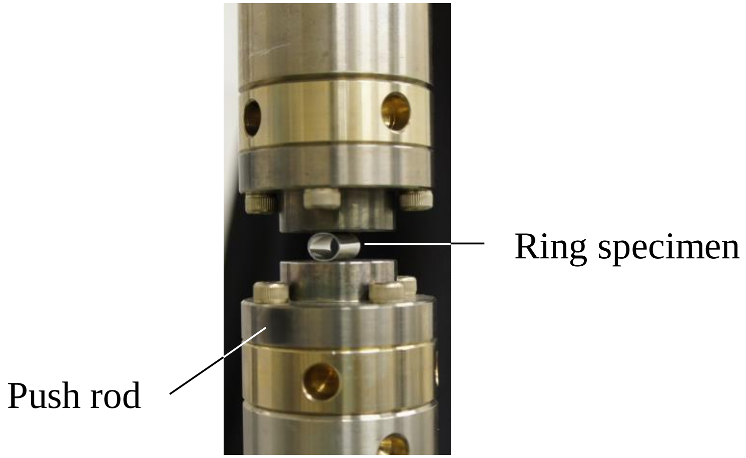
# Experimental study (3)

- Resistance to high temperature oxidation followed by water quenching




- Steam oxidation at 1473 K
  - Heating of electric furnace (Position ①)
  - Moving down to center zone of electric furnace (Position ②)
  - Dropping down to water (Position ③)

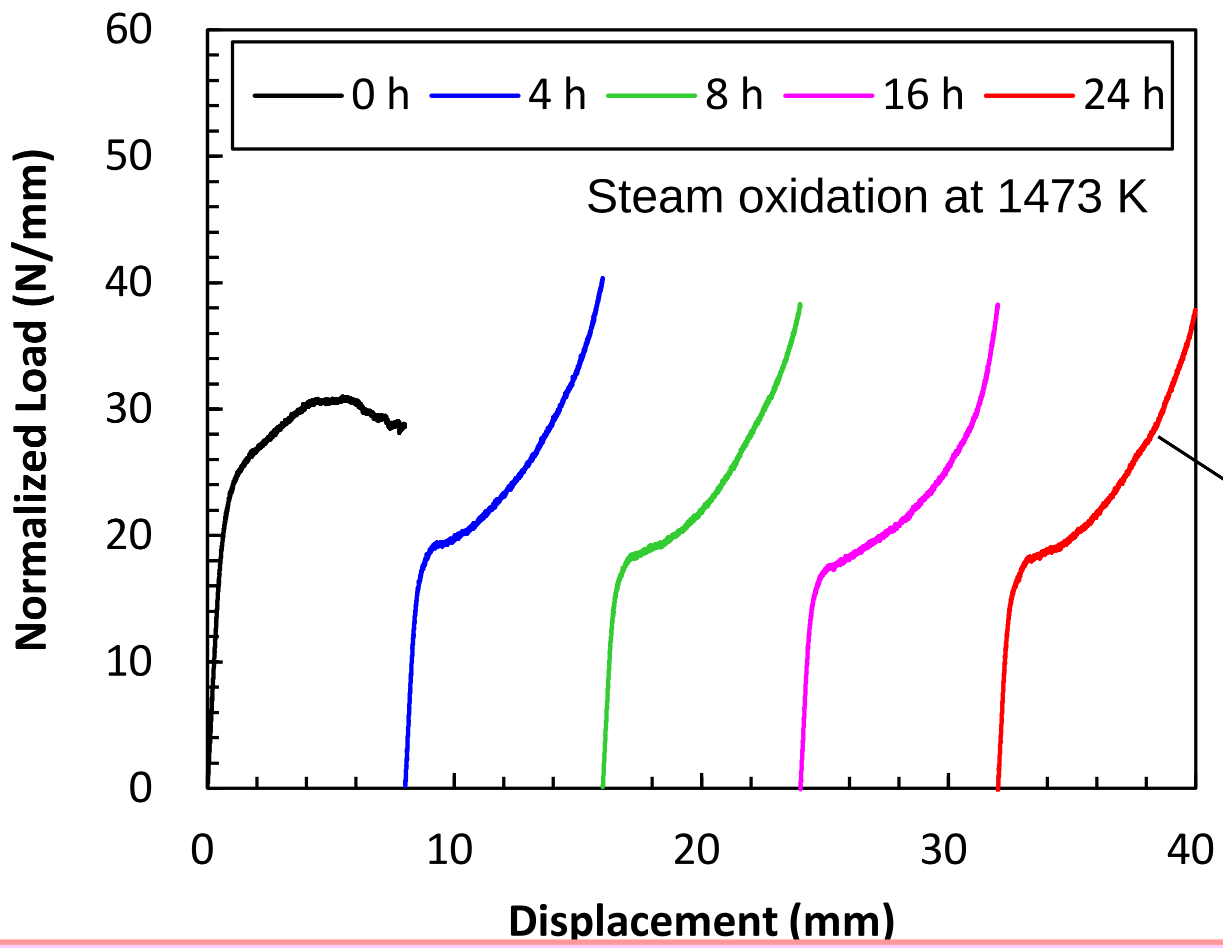
- Ring compression test at RT

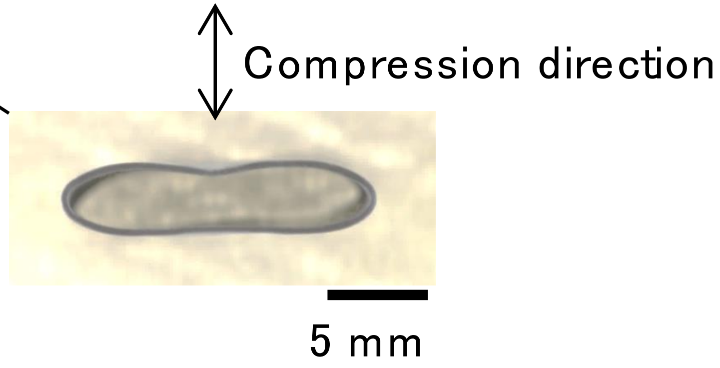



Reference: K. Sakamoto et al. , Proc. ICAPP2017, 24-28 April, 2017, Fukui and Kyoto, Japan

# Experimental study (4)

- Resistance to high temperature oxidation followed by water quenching



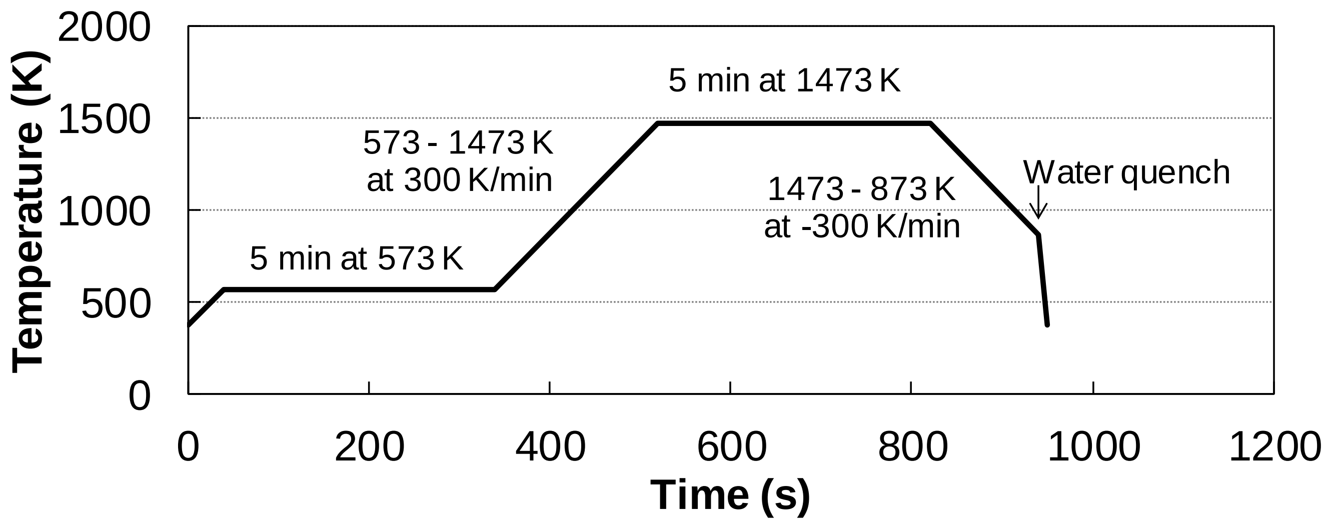



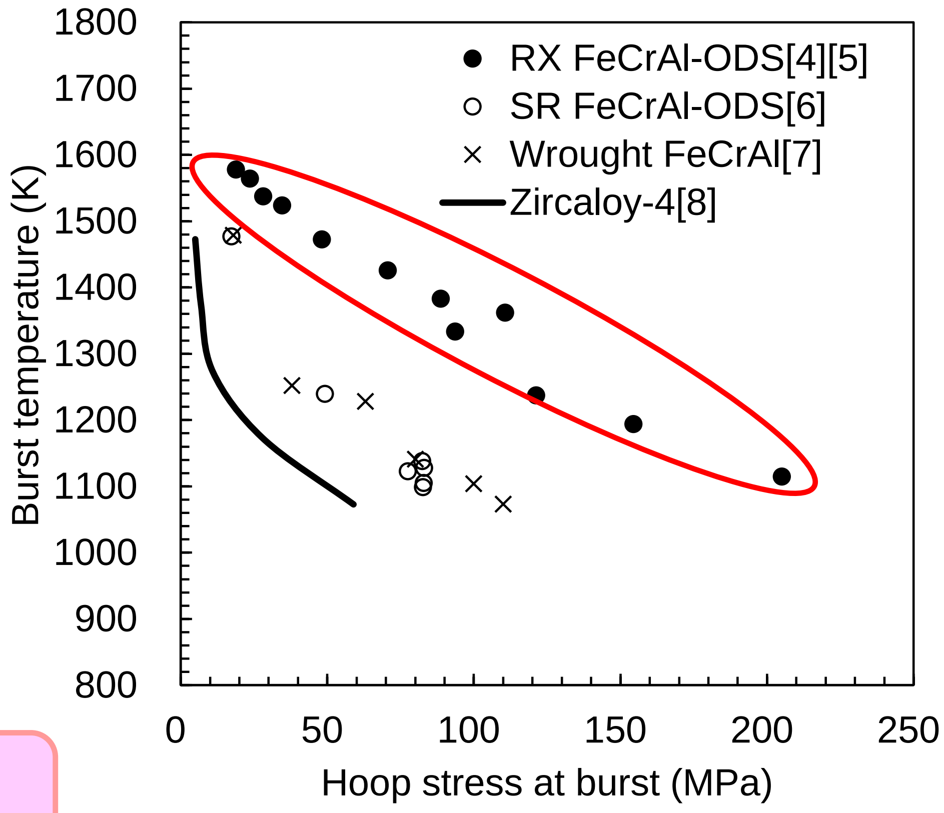

Reference: K. Sakamoto et al. , Proc. ICAPP2017, 24-28 April, 2017, Fukui and Kyoto, Japan

- Excellent resistance to high temperature steam and water quenching

# Experimental study (5)

- Resistance to LOCA events (Integral LOCA tests)
  - Cooperative research activity under U.S. – Japan CNWG
  - Integral LOCA furnace module at ORNL SATS (Severe Accident Test Station)





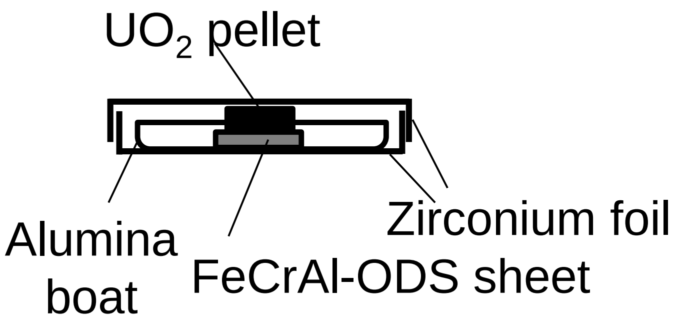
[4] K. Sakamoto et al., J. Nucl. Mater., 557 (2021) 153276
[5] K. Sakamoto et al., Proceedings of TopFuel2022, Raleigh, NC, October 9-13, 2022, 161-169
[6] T. Narukawa et al., J. Nucl. Mater., 582 (2023) 154467
[7] S.B. Bell et al., J. Nucl. Mater., 557 (2021) 153242
[8] M. Ishikawa and S. Shiozawa, J. Nucl. Mater., 95, 1-2, (1980) 1-30

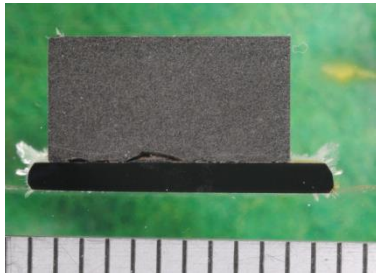

Reference: K. Sakamoto et al., Proceedings of the TopFuel 2024, September 29-October 3, Grenoble, France, pp. 63-69, 2024

- No apparent embrittlement after water quenching
- Higher resistance to fracture (burst) than Zircaloy

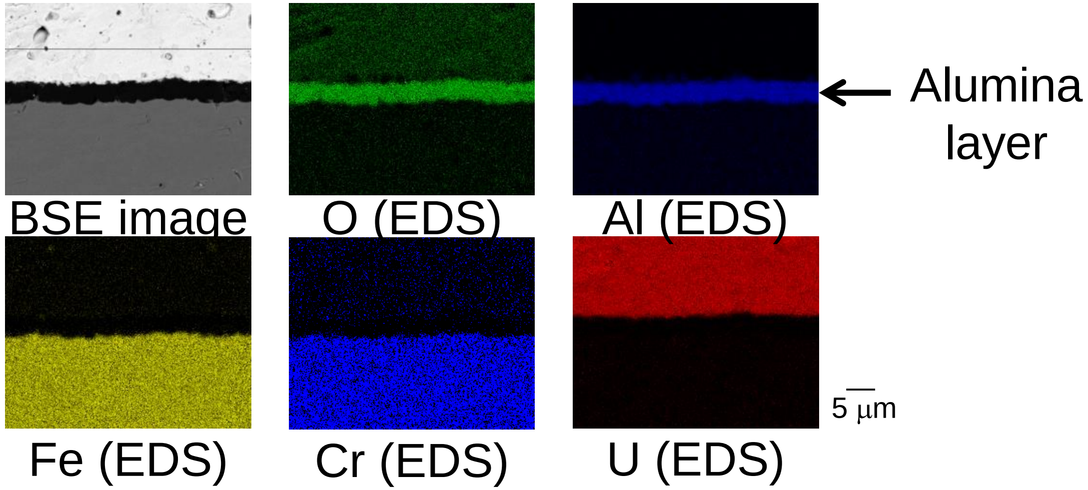
# Experimental study (6)

- Compatibility with $UO_2$ fuel
  - ➢ Sheet material was attached with $UO_2$ at 1723 K up to 25 h in inert-gas atmosphere



Optical image
(1723 K x 25 h)




Reference: K. Sakamoto, et al. , Proc. Top Fuel 2018, 30 Sep. – 04 Oct. 2018, Prague, Czech Republic

- Excellent resistance to fuel at high temperatures

# Contents

# Analytical study (1)

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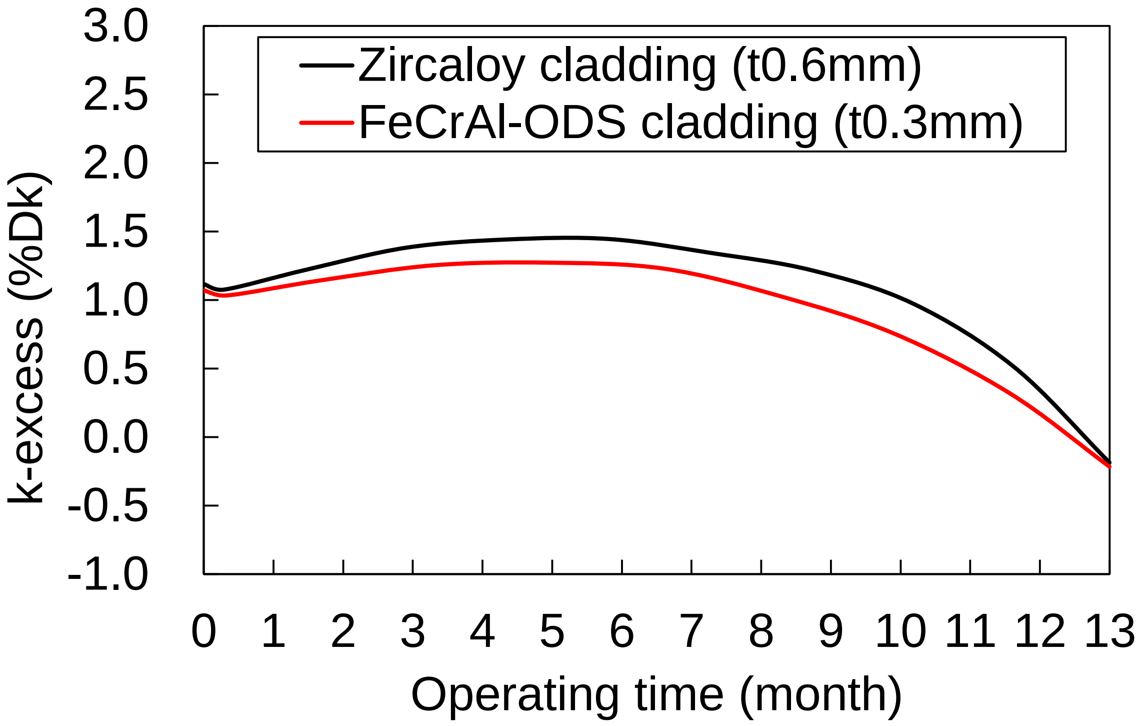
- Analytical evaluation of core characteristics

➢ Analysis condition

| | | |
|---|---|---|
| Core (ABWR) | Rated thermal power | 3926 MW |
| | Number of bundles | 872 |
| | Operating term | 13 month |
| Fuel type | 10 x 10 | |

➢ Core reactivity




- Reactivity penalty (due to Fe and Cr) can be compensated
- No unacceptable core characteristic degradation

* Reference: K. Sakamoto et al., J. Nucl. Mater., 557 (2021) 153276

# Analytical study (2)

- Analytical evaluation of fuel behavior in severe accidents
  - ATF performance was evaluated during SA of BWRs with and w/o accident management (AM) by MAAP5.05β

| Item | Analysis conditions |
|---|---|
| Analysis code | MAAP5.05β * |
| Plant type | ABWR |
| Fuel type | 9×9 (StepIII) |
| Cladding and channel box materials | Zry, ODS**, and SiC |
| Accident sequence groups | TQUV (high/low pressure water injections failure), and TB (Station blackout) |
| Analysis range | Until fuel cladding failure * |

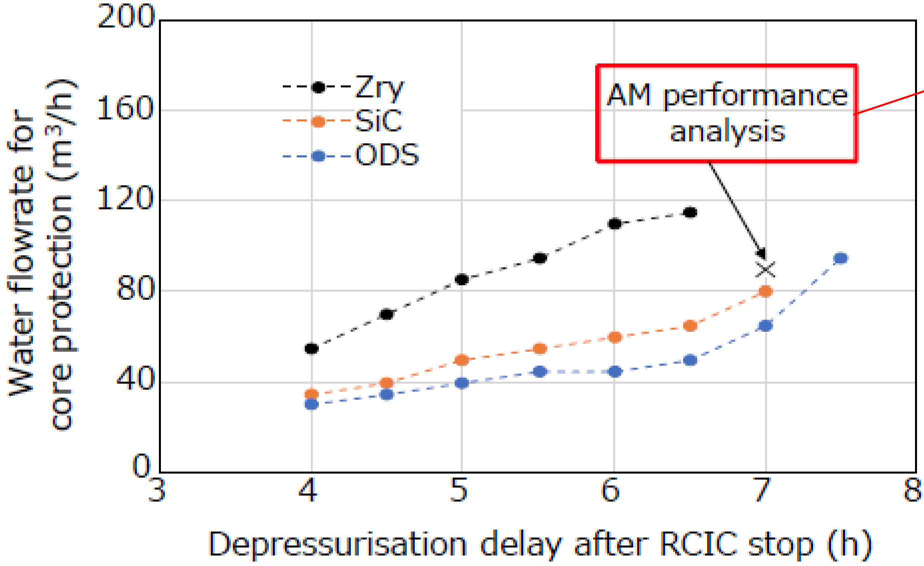
*: MAAP5.05 beta version has the limitation that it can handle ATF behaviour only inside the core.

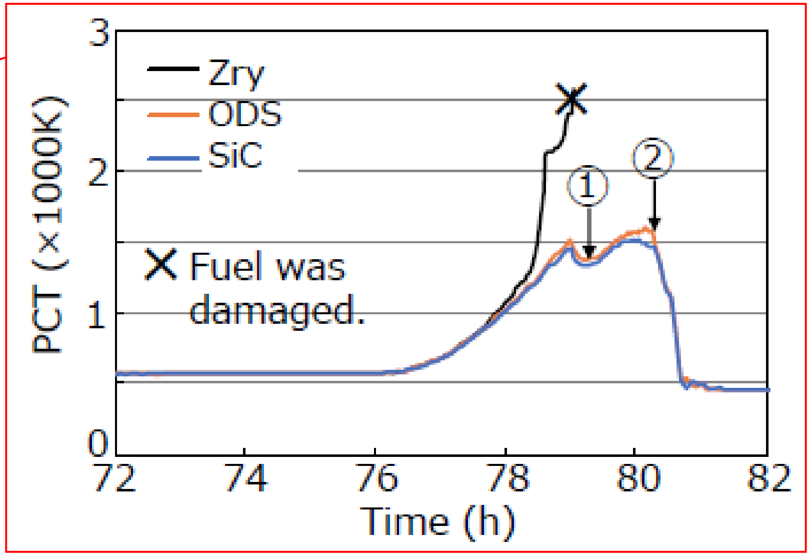
**: Thin-walled fuel was applied for ODS in consideration of neutron economy.

Reference: T. Ikegawa, et al. , Proc. Top Fuel 2018, 30 Sep. – 04 Oct. 2018, Prague, Czech Republic

# Analytical study (3)

- Merit of ATF was evaluated with long term TB scenario
- "Grace time to depressurization" and "Minimum flow rate" to prevent fuel damage were analyzed




PCT (Peak clad temperature)

- ATF can increase "Grace time" and/or reduce AM capacity/resources

Reference: T. Ikegawa, et al. , Proc. Top Fuel 2018, 30 Sep. – 04 Oct. 2018, Prague, Czech Republic

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# Challenges and data gaps (1)

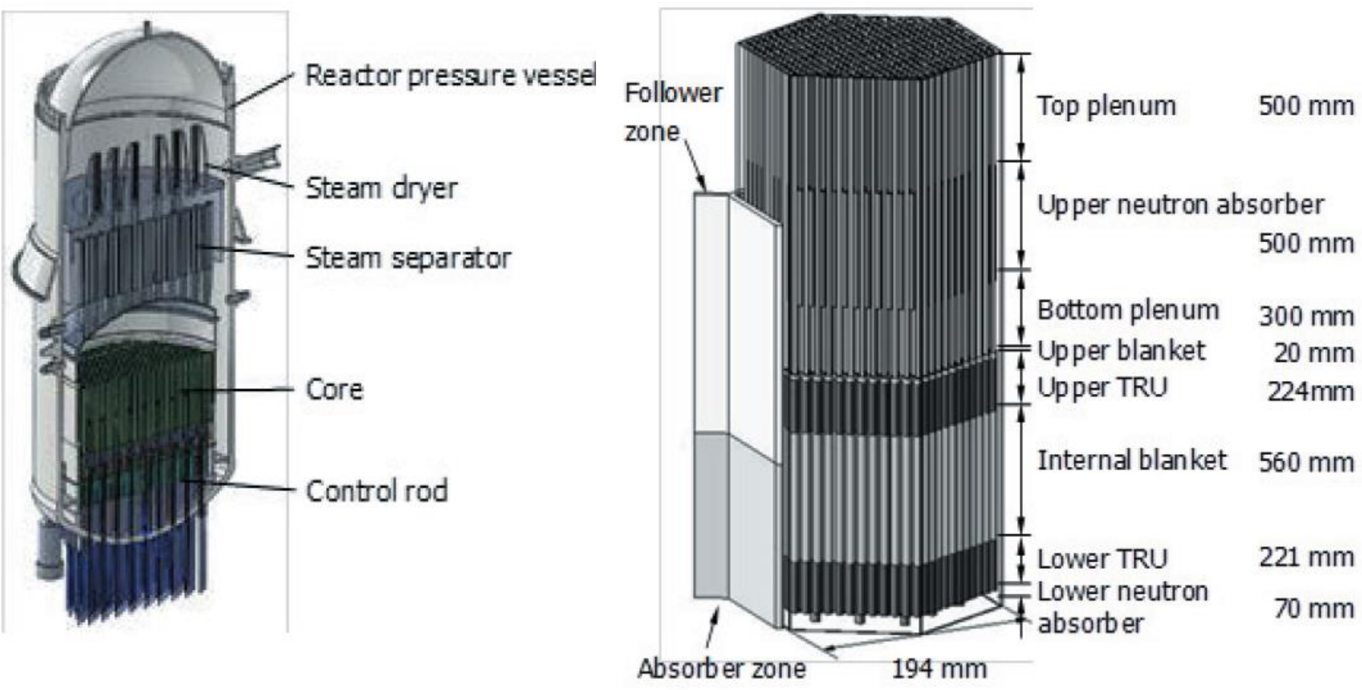
- R&D status is now TRL 3-4

- Short-term challenges:
  - Measurement of fuel behavior in a test reactor
  - Validation of thermal-mechanical code predictions

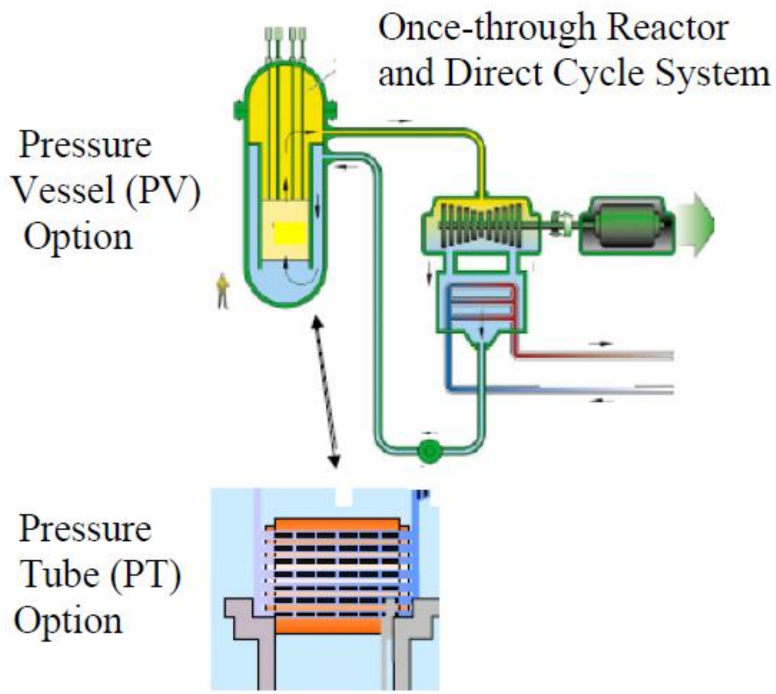
- Short-term data gap:
  - Irradiation creep
  - Mechanical property changes with neutron irradiation
  - Heat transfer characteristics
  - ….

# Challenges and data gaps (2)

- Other applications
  - FeCrAl-ODS can bring “safety” to the next generation NPPs using water
  - Application to FBR-like LWRs are favorable due to much less reactivity penalty




Resource-renewable BWR (RBWR)




SuperCritical-Water-cooled Reactor (SCWR)

Reference: T. Mitsuyasu. Sakamoto et al. , Proc. ICAPP2017, 24-28 April, 2017, Fukui and Kyoto, Japan

Reference: T. Schulenberg et al. , IAEA-CN-164-5S06, 2009

# Acknowledgments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