Safety Analysis of Sodium-Cooled Fast Reactor and Innovative Numerical Approach

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Contents

- Safety analysis of sodium cooled fast reactor
  - ✓ Sodium fire
  - ✓ Sodium water reaction (SWR)
- Innovative numerical approach (ARKADIA*)

* Advanced Reactor Knowledge- and AI-aided Design Integration Approach through the whole plant lifecycle

Safety Analysis of Sodium-Cooled Fast Reactor

Safety analysis of innovative reactor caused by its specific characteristics is one of the key issue for a plant safety as well as a public acceptance.

[Sodium-cooled fast reactor (SFR)]

Chemical reactivity of liquid sodium with oxygen and/or water/water vapor is a key issue, although it may not cause a core disruptive accident (CDA) directly.

⇩

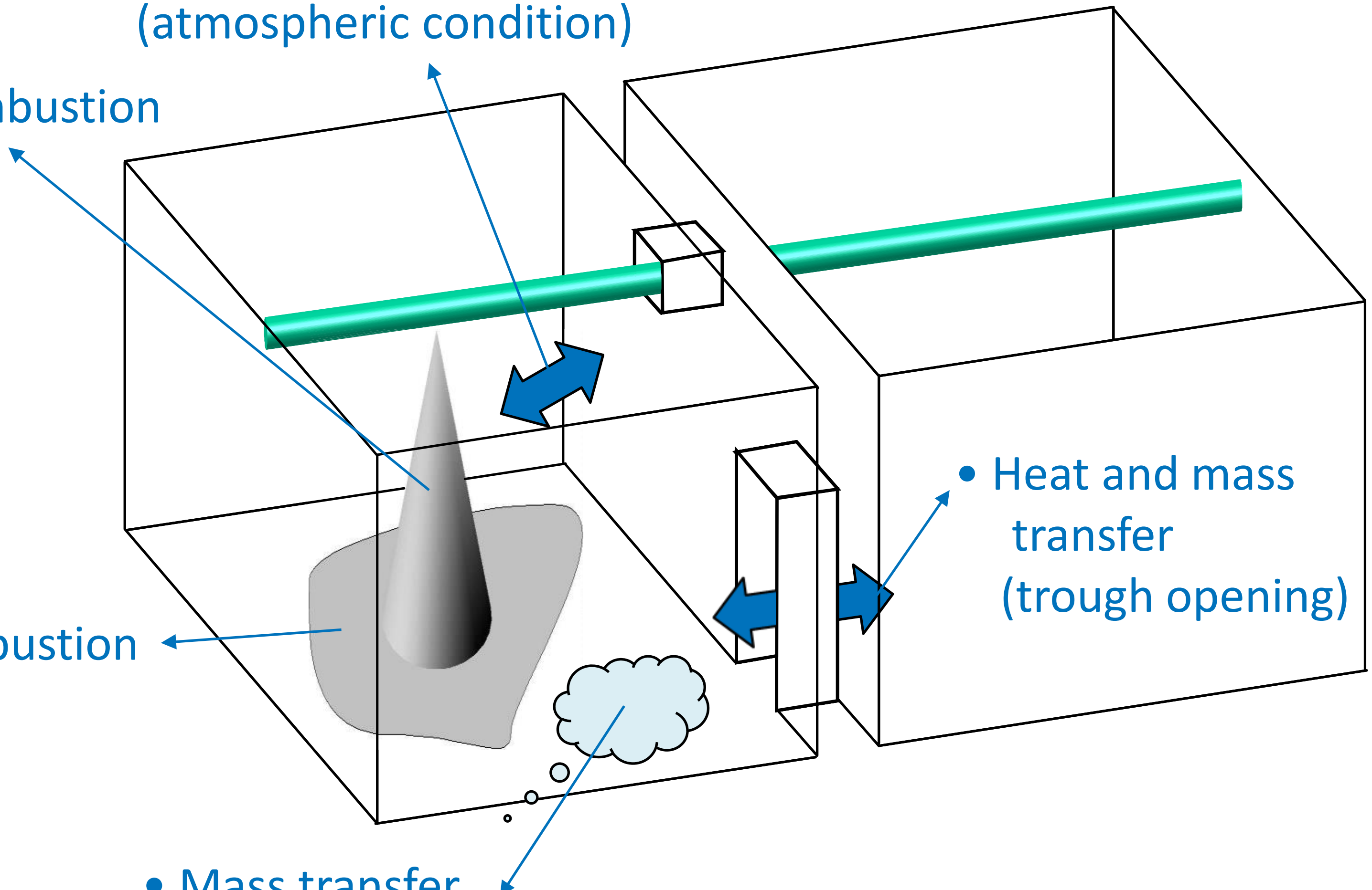
Both experimental and numerical researches have been conducted to understand the phenomena deeply and to predict an influence on plant safety.

- ✓ Sodium fire
- ✓ Sodium-water reaction (in steam generator)

Sodium Fire

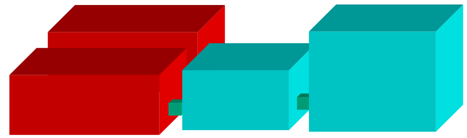
Key Physics in Sodium Fire

- Heat and mass transfer
  (to gas and structure)
- Chemical reaction
  (atmospheric condition)
- Spray combustion

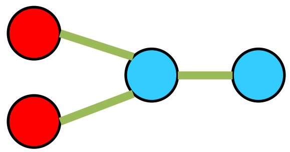


- Heat and mass transfer
  (trough opening)
- Pool combustion
- Mass transfer
  (water release from concrete)

Numerical Tools for Sodium Fire Analysis



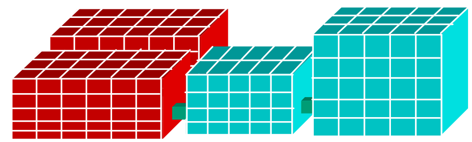
(Lamped mass)



Zone model

SPHINCS

(CFD)



Field model

AQUA-SF

- Chemical reaction (Stoichiometric calculation)

BISHOP

(Gibbs free energy minimization)
Na_2O, Na_2O_2, NaOH

- Aerosol behavior (agglomeration and adhesion)

ABC-INTG

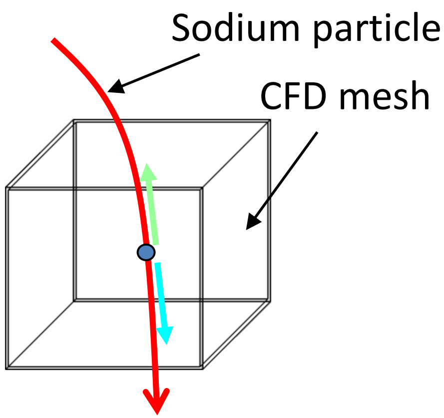
Those have been developed in Japan Atomic Energy Agency (JAEA).

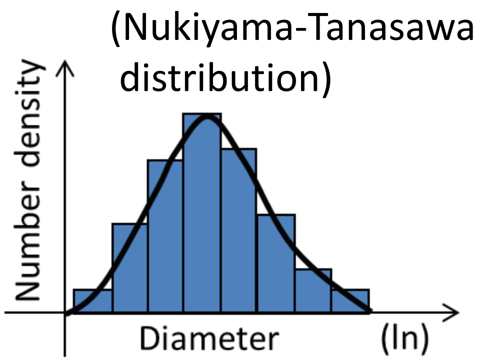
Sodium Fire Modeling

➢ Spray combustion

Particle tracking

Empirical combustion model is applied.





- ✓ Before ignition temperate

  Analogy of mass and heat transfer

$$\mathrm{Sh} = 2 + 0.6\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Sc}^{\frac{1}{3}}$$

- ✓ After ignition

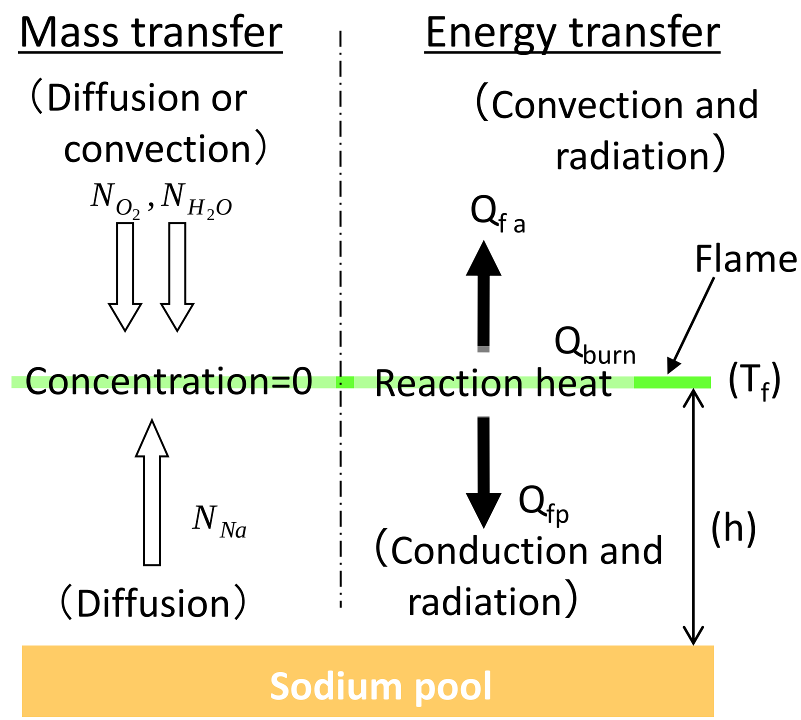
  D^2 law with convective effect

$$\dot{m}_b = \dot{m}_{D^2} \times \left(1 + 0.3\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}\right)$$

➢ Pool combustion

Infinity flame sheet concept

Governing equations are functions of flame temperature (T_f) and height (h).



PIRT* Analysis for Sodium Fire Phenomenon

M. Aoyagi et al., ID-93, FR17, 2017

*Phenomena Identification and Ranking Table

Category	Phenomenon	Atmospheric Pressure	Concrete Temperature	Component Temperature	Atmospheric Temperature	Steel Liner Temperature	Hydrogen Concentration	Aerosol Concentration
Related Concern**		1&2	1	2	2	1	1&2	2&3
Spray Combustion	1) Droplet Generation	H/L	M/L	M/L	H/L	M/L	L/L	H/M
	2) Spray Combustion	H/L	M/L	M/L	H/L	M/L	L/L	H/M
	3) Reaction Heat Transfer (spray)	H/L	M/L	M/L	H/L	M/L	L/L	L/M
Pool Combustion	4) Pool Enlargement	L/M	L/M	L/M	L/M	L/M	L/M	L/M
	5) Pool Combustion	L/M	L/H	L/H	L/M	L/H	L/M	L/M
	6) Reaction Heat Transfer (pool)	L/M	L/H	L/H	L/M	L/H	L/L	L/L
Heat Transfer	7) Heat Conduction	L/L	H/H	H/H	L/L	H/H	L/M	L/L
	8) Heat Convection	H/M	M/M	L/M	M/H	L/M	L/M	L/M
	9) Heat Radiation	M/M	M/M	L/M	M/M	L/M	L/M	L/L
Mass Transfer	10) Mass and Momentum Transfer	M/L	L/L	L/L	L/M	L/L	L/M	M/H
	11) Gas Species Transfer	L/L	L/L	L/L	L/L	L/L	H/H	M/M
	12) Aerosol Transfer	L/L	L/L	L/M	L/L	L/M	L/M	H/H
Chemical Reaction	13) Atmospheric Chemical Reaction	L/L	L/L	L/L	L/L	L/L	L/M	L/M
	14) Steel Liner Corrosion Wastage	L/L	L/L	L/L	L/L	H/H	L/L	L/L

**Concern about 1)Building Structure, 2)Components and 3)Circumference Enviroment

Early stage/Late stage

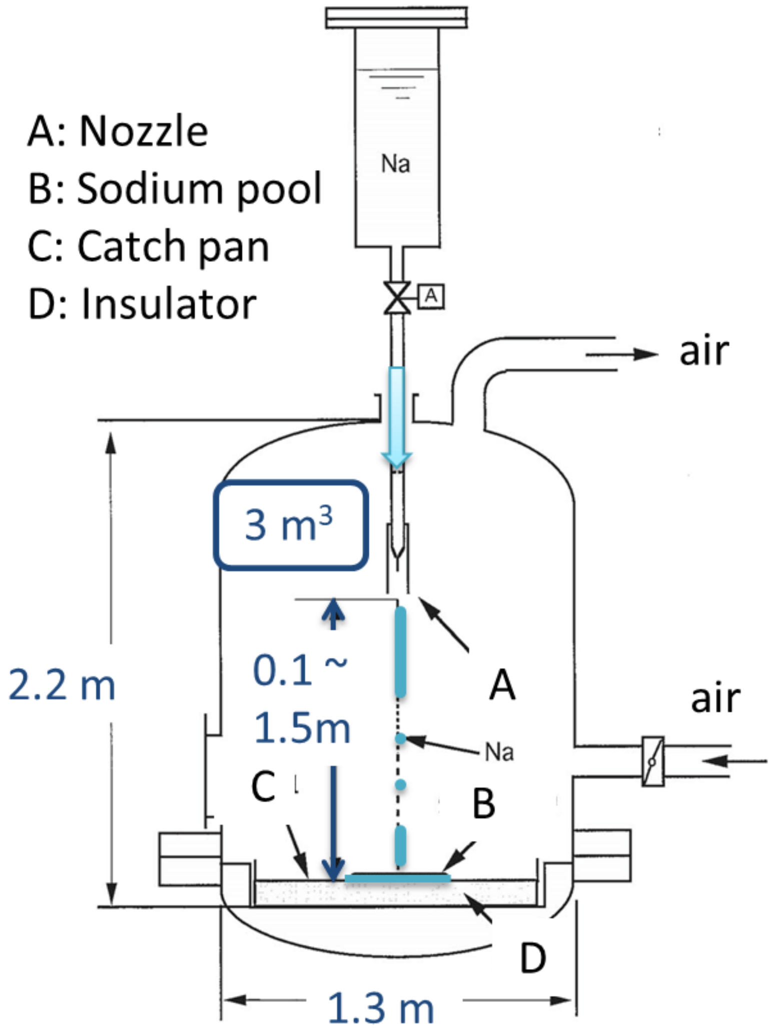
Validation Matrix

Phenomenon	Experiment (in JAEA)					
	Spray Fire		Pool Fire			
	Single Droplet (FD)	Spray (Run-E1)	Constant Pool Area (Run-D1)	Enlarging Pool Area (Run-F7)	Multi-cell Pool (Run-D3)	Integrated Mock-up (Run-D4)
1)Droplet Generation	-*4	-*4	-*4	-*4	-*4	-*4
2)Spray Combustion	✓	✓		n/a*5		n/a*5
3)Reaction Heat Transfer (spray)		✓		n/a*5		n/a*5
4)Pool Enlargement				✓		✓
5)Pool Combustion		n/a*5	✓	✓	✓	✓
6)Reaction Heat Transfer (pool)		n/a*5	✓	✓	✓	✓
7)Heat Conduction		✓*6	✓	✓	✓	✓
8)Heat Convection		✓*6	✓*6	✓	✓	✓
9)Heat Radiation			✓	✓*6	✓*6	✓*6
10)Mass and Momentum Transfer					✓	
11)Gas Species Transfer					✓	✓
12)Aerosol Transfer			✓	✓	✓	✓
13)Atmospheric Chemical Reaction						✓
14)Steel Liner Corrosion Wastage	-*4	-*4	-*4	-*4	-*4	-*4

1-3)Spray and 4-6)Pool combustion
7-10)Heat and 10-12)Mass transfer
13-14)Chemical reaction

*4: Out of range in the present matrix
*5: Negligible small influence
*6: Assessable but indirect measurement

Pool Fire Experiment (Run-F7)



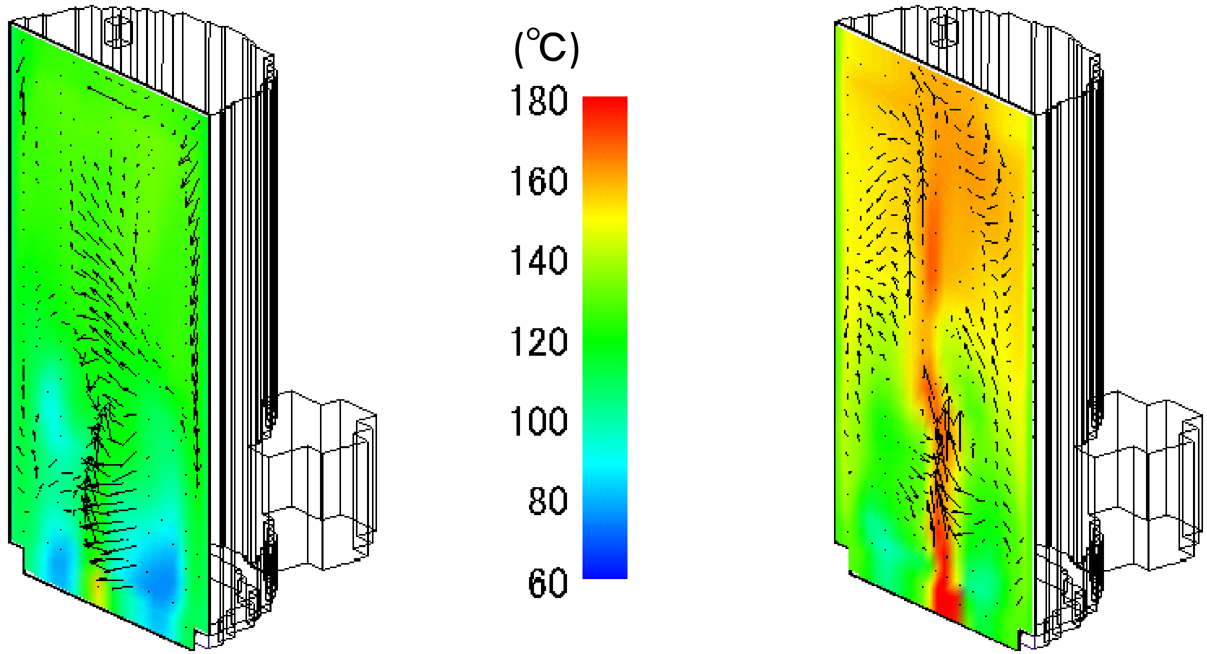
(Test section)

	Case 1	Case 2
Leakage rate	12 kg/hr	
Duration	25 min	
Sodium temperature	505 °C	
Leakage height	0.1 m	1.5 m

(Experimental condition)

(Sodium pool after test, Case 1)

Numerical Result (Gas Temperature)

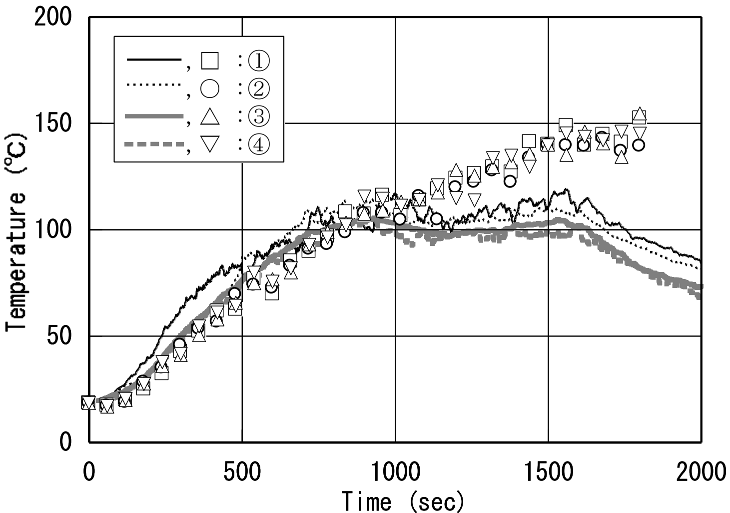


	Case 1	Case 2
Spray / pool combustion ratio	1:180	1:17
Average temperature of dropped sodium	532[°C]	731[°C]

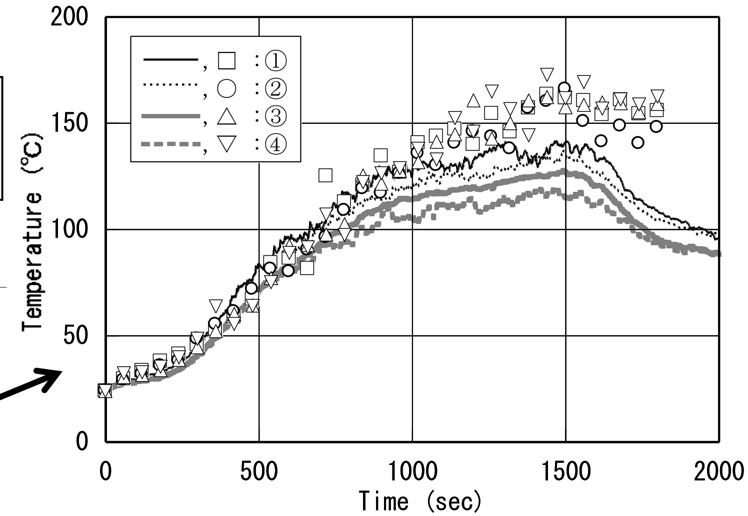
Case 1 (height: 0.1m)   Case 2 (height: 1.5m)

Comparison with Experiment

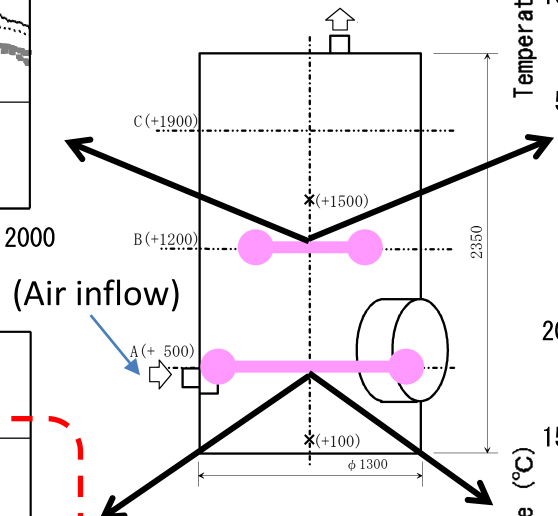
Case 1 (height: 0.1m)

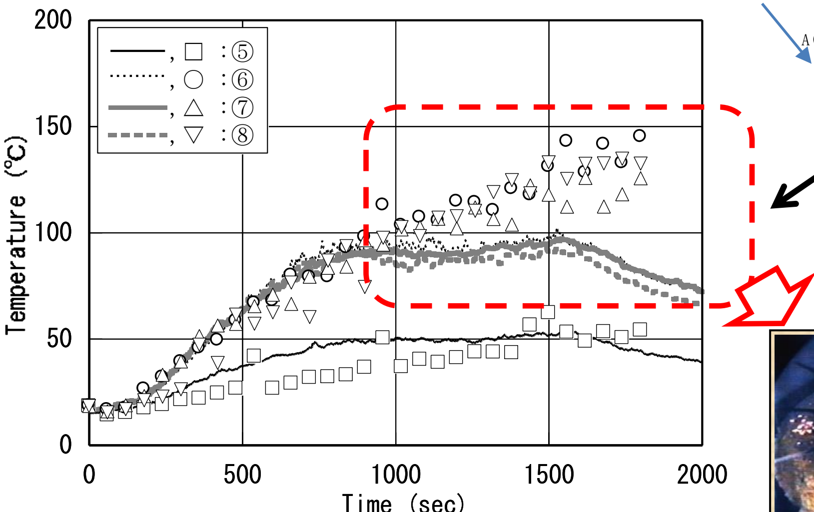


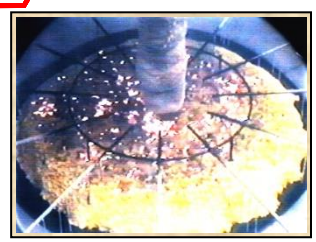
Case 2 (height: 1.5m)

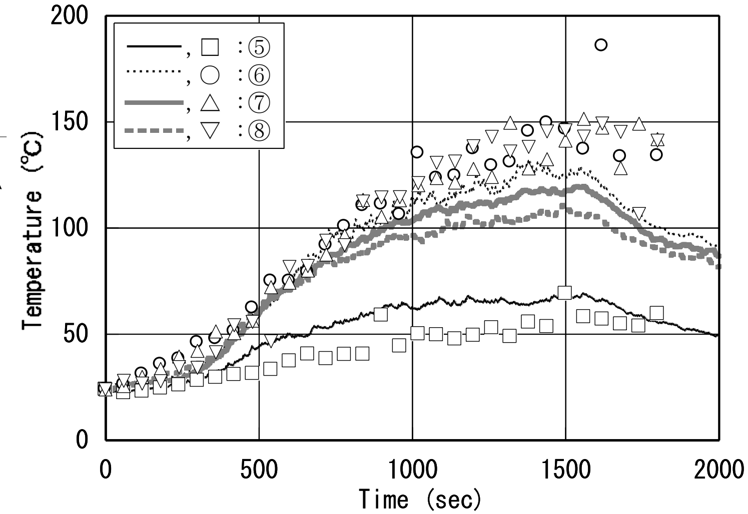


Symbol : Numerical results









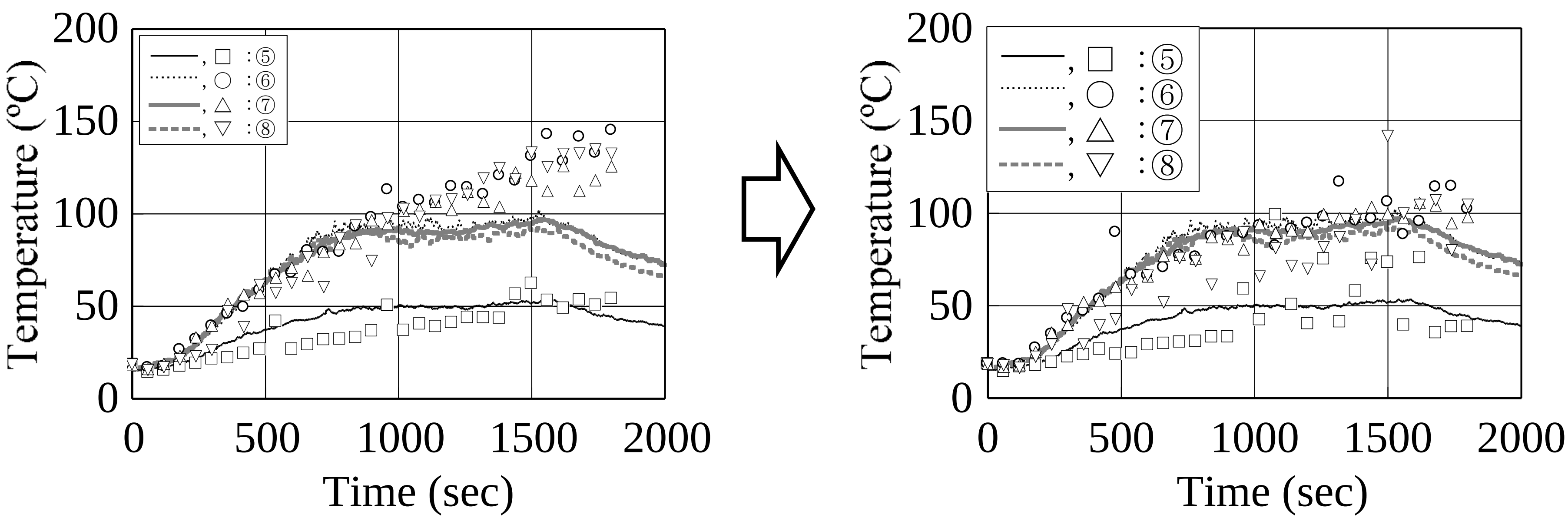
Suppression due to aerosol covering

Consideration of Suppression Effect

Simplified suppression model:

$$q'_{burn} = q_{burn} \times f$$

$$f = \frac{\text{Total weight of umburnt sodium in pool}}{\text{Total weight in pool (including dropped aerosol)}}$$

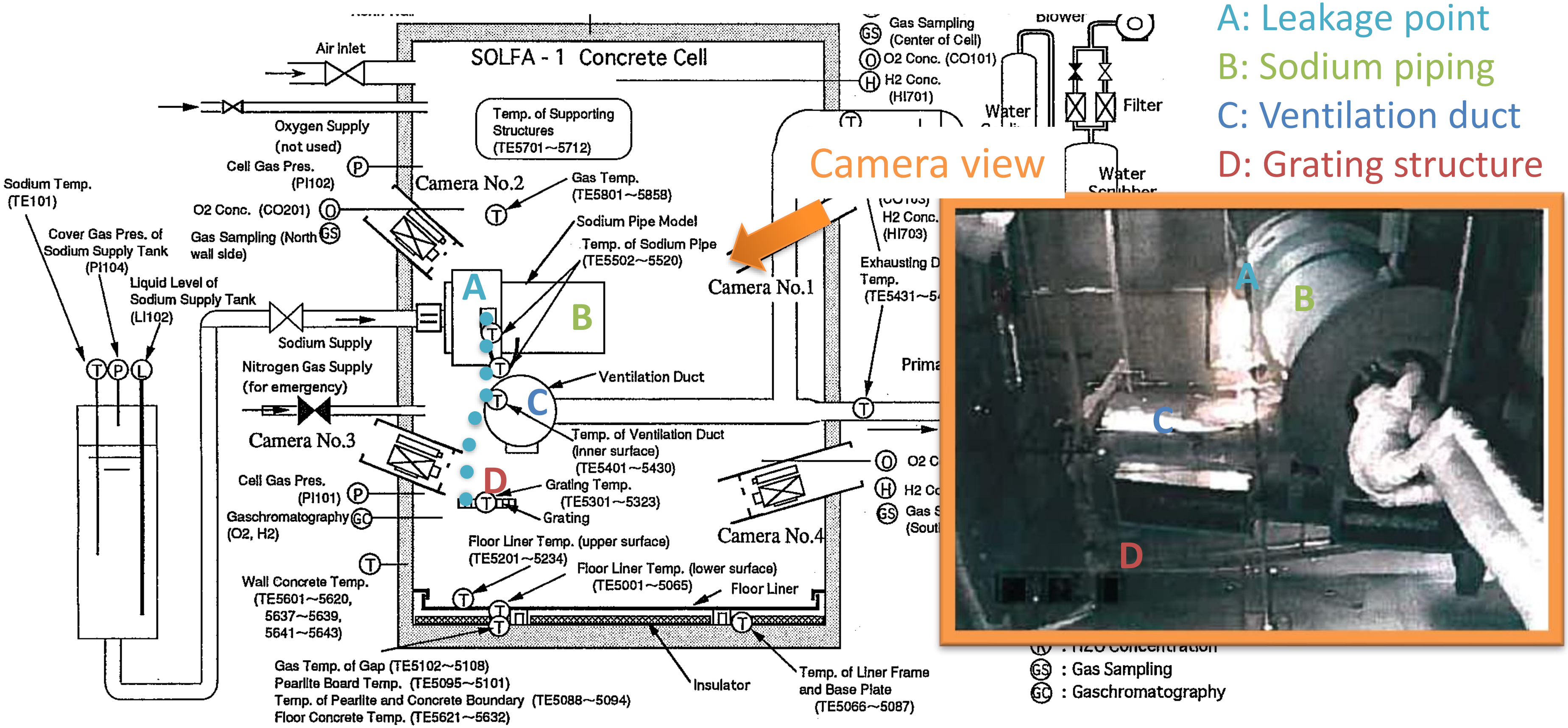


Since suppression effect has a large uncertainty, the model is not used for safety analysis currently.

Integrated Mock-up Experiment (Run-D4)

Run-D4 experiment was mocked up Monju incident in 1995.

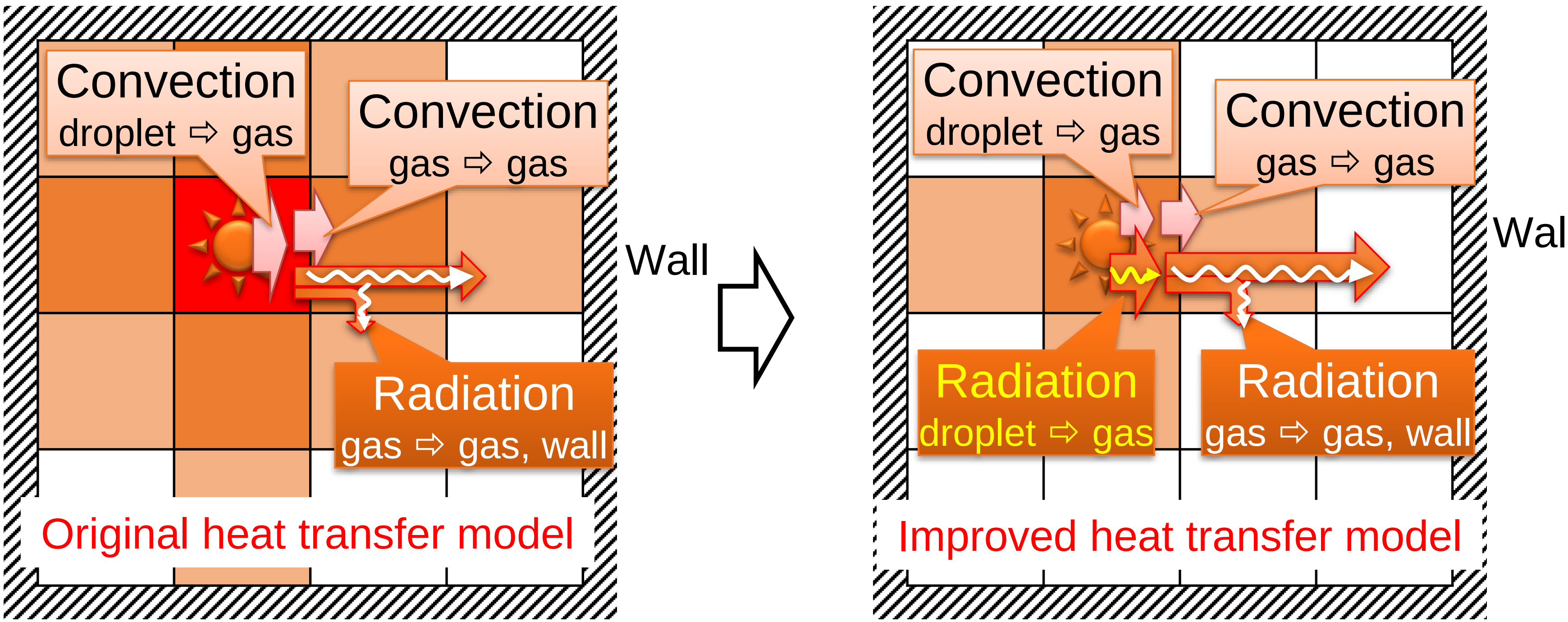
Leakage rate	54g/s (2-179min) -> 48g/s (179-192min) -> 39g/s (192-224min)
Sodium temperature	480 °C
Leakage height	3.6m



A: Leakage point
B: Sodium piping
C: Ventilation duct
D: Grating structure

Recent Topic for Model Improvement

Radiation heat transfer is considered in spray combustion model to Enhance code applicability in case of low aerosol concentration condition.



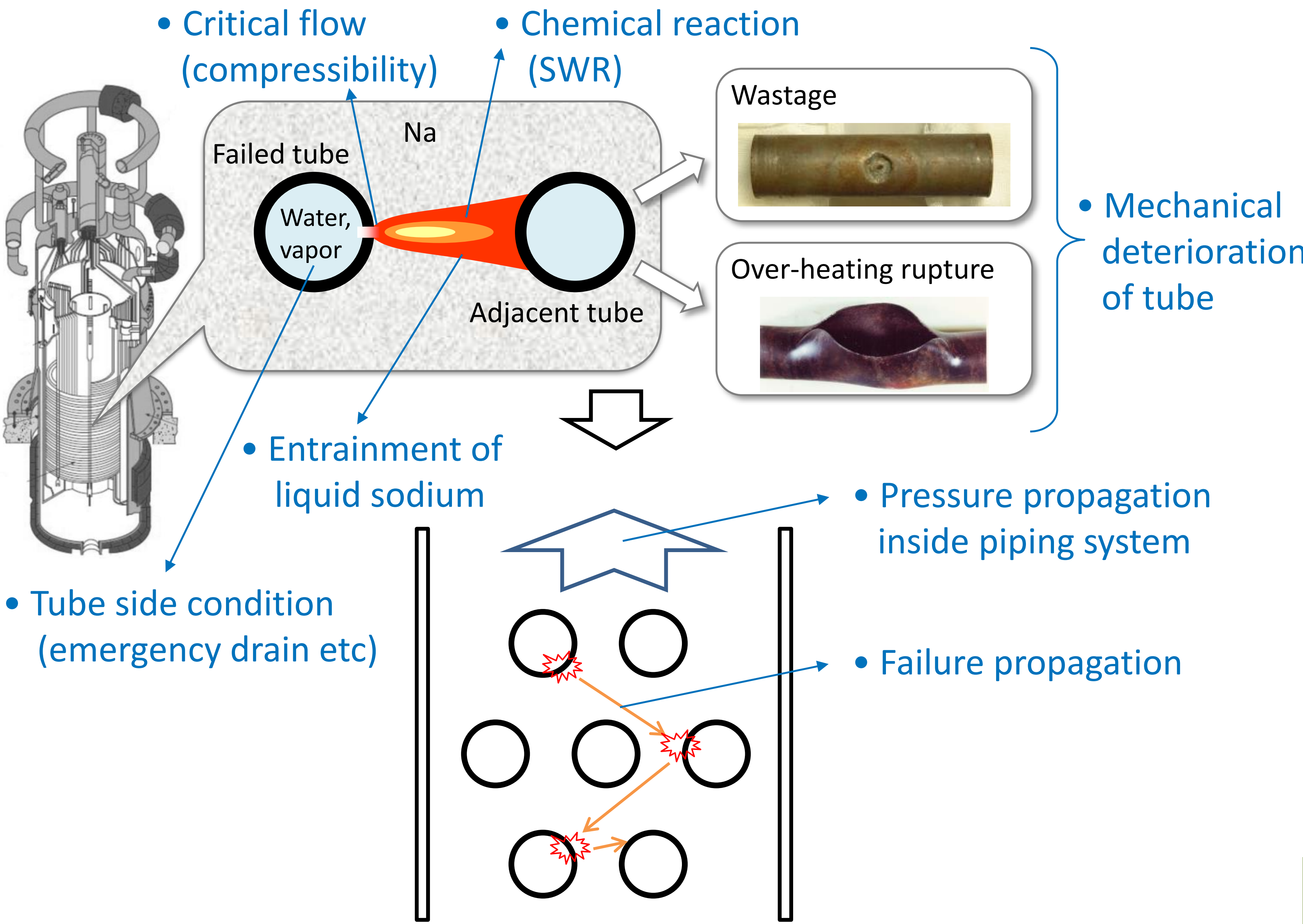
All reaction energy is released to gas firstly.

Reaction energy is released separately as radiation heat flux and gas phase.

M. Aoyagi, et al., NUTHOS-12, 974, China, 2018.

Sodium Water Reaction

Key Physics in Sodium-Water Reaction (SWR)



SWR Related Analytical Tools

Phenomena	Tool
• Critical flow • Chemical reaction • Entrainment of liquid sodium	SERAPHIM
• Mechanical deterioration of tube (detailed analysis)	TACT
• Mechanical deterioration of tube (Empirical) • Failure propagation	LEAP-III
• Pressure propagation inside piping system	SWACS
• Tube side condition	RELAP5

SWR Modeling

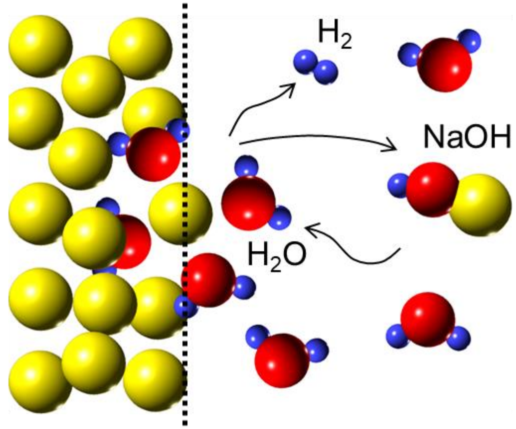
> *Le* : Lewis number, *H* : coefficient of heat transfer, C_p : specific heat,
> *Y* : mass fraction, *a* : interfacial area density

- **Surface reaction**

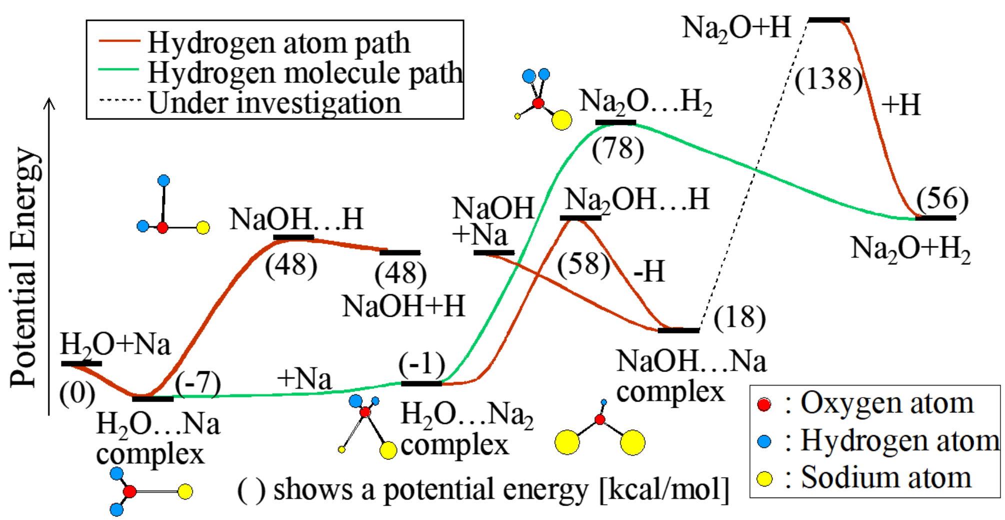
$$\gamma_j^{sf} = -Le^{b-1}\frac{H_{gl}}{C_{pg}}Y_j a$$

  - ✓ $Na + H_2O \rightarrow NaOH + 1/2H_2$
  - ✓ Infinite reaction rate
  - ✓ Reaction products → gas phase
  - ✓ Reaction heat → gas phase

- **Gas phase reaction**
  - ✓ Arrhenius law
  - ✓ Rate constant → MO* investigation



* Molecular Orbital method



Surface reaction >> gas phase reaction

Numerical Models and Experiments

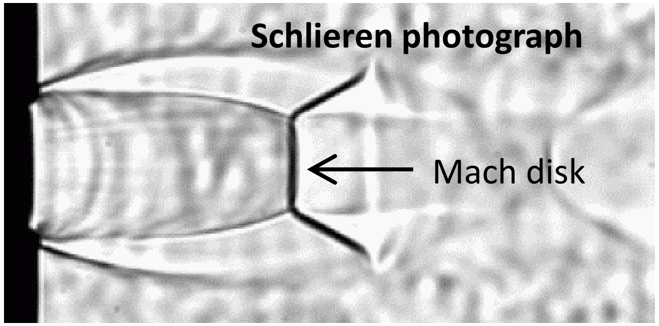
- Numerical models (for thermal-hydraulics)
  - ✓ Multi-phase model
    - ○ Multi-fluid model

      (Liquid sodium (continuous phase and droplets), water and multi-component gas)
    - ○ One-pressure model
  - ✓ Solution method
    - ○ HSMAC* with compressibility

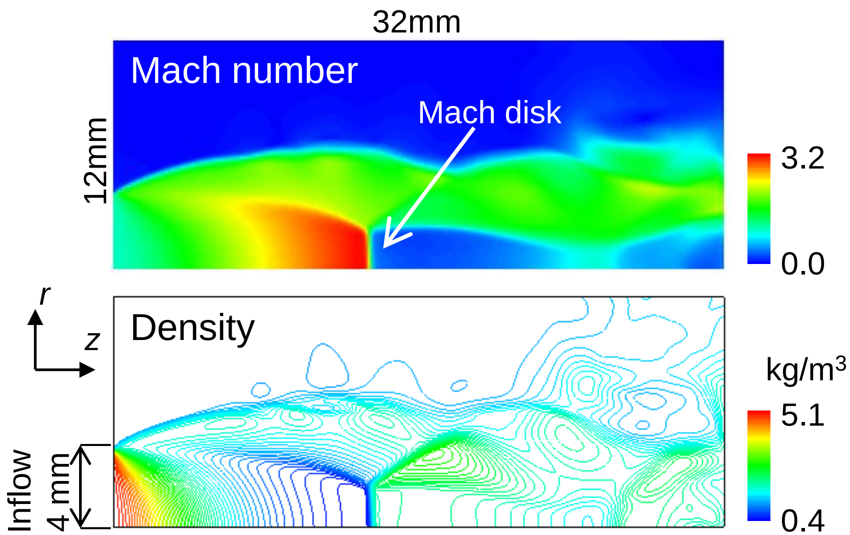
* Highly Simplified Maker And Cell

- Experiments for validation
  - ✓ Critical flow (under-expanded jet)
  - ✓ SWR with single target tube

Critical Flow

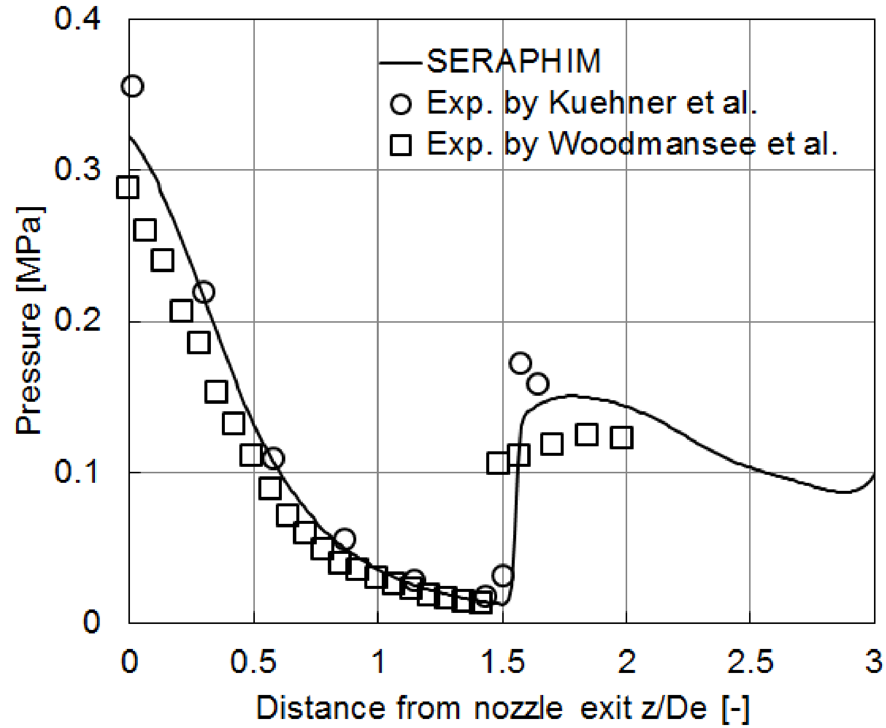


Exp. by Lee (p_0=0.7MPa, R_e=4mm)



SERAPHIM (p_0=0.7MPa, R_e=4mm, second-order TVD, 0.125mm cell)

p_0: Stagnation pressure

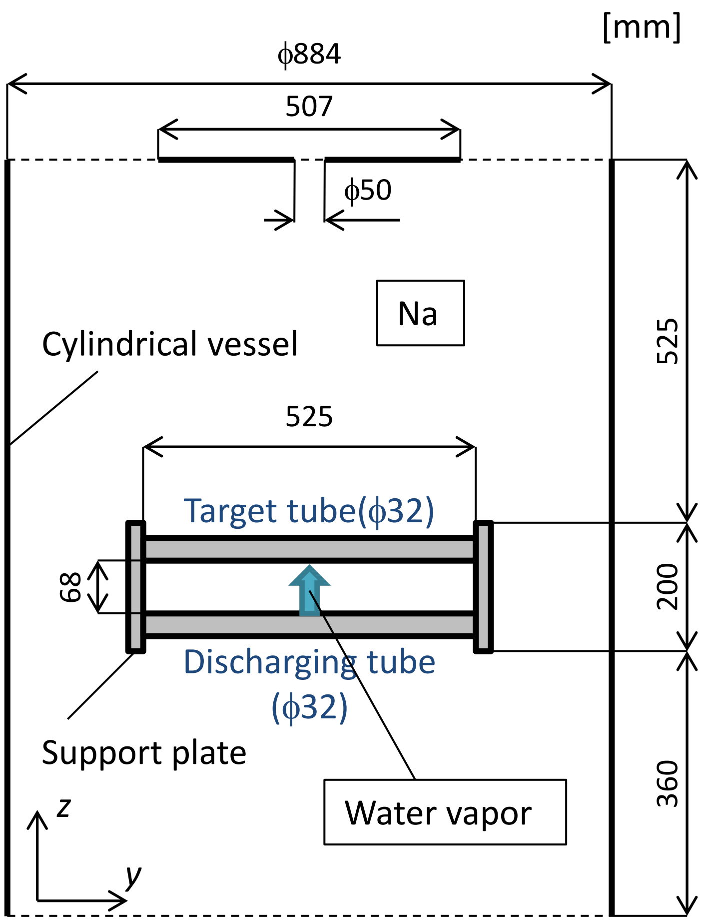


Pressure along centerline of jet (p_0=0.617MPa, p_e/p_a=3.3, R_e=5mm, second-order TVD, 0.125mm cell)

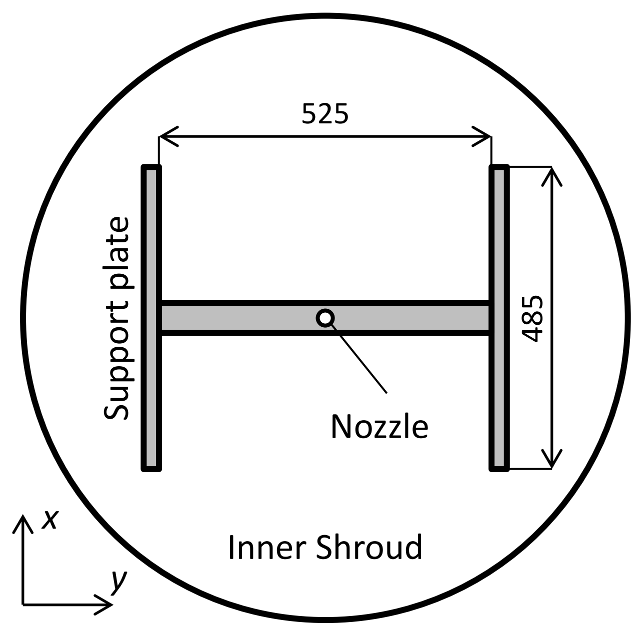
K. H. Lee, Ph. D. thesis, Saga University, Japan, 2004. (from Saga University Digital Library: http://www.dl.saga-u.ac.jp/z3950/hkshi/search_e.html
J. P. Kuehner, et al., AIAA 2002-2915, 2002.
M. A. Woodmansee, Ph. D. thesis, University of Illinois, USA, 1999.

SWR with Single Target Tube

- Pressure of water vapor (nozzle): 17.17 MPa
- Temperature of water vapor (nozzle): 374.4 ºC
- Pressure of sodium: 0.15 MPa
- Initial temperature of sodium: 522 ºC
- Inner diameter of nozzle: 8.2 mm
- Leak rate: about 1.0 kg/s



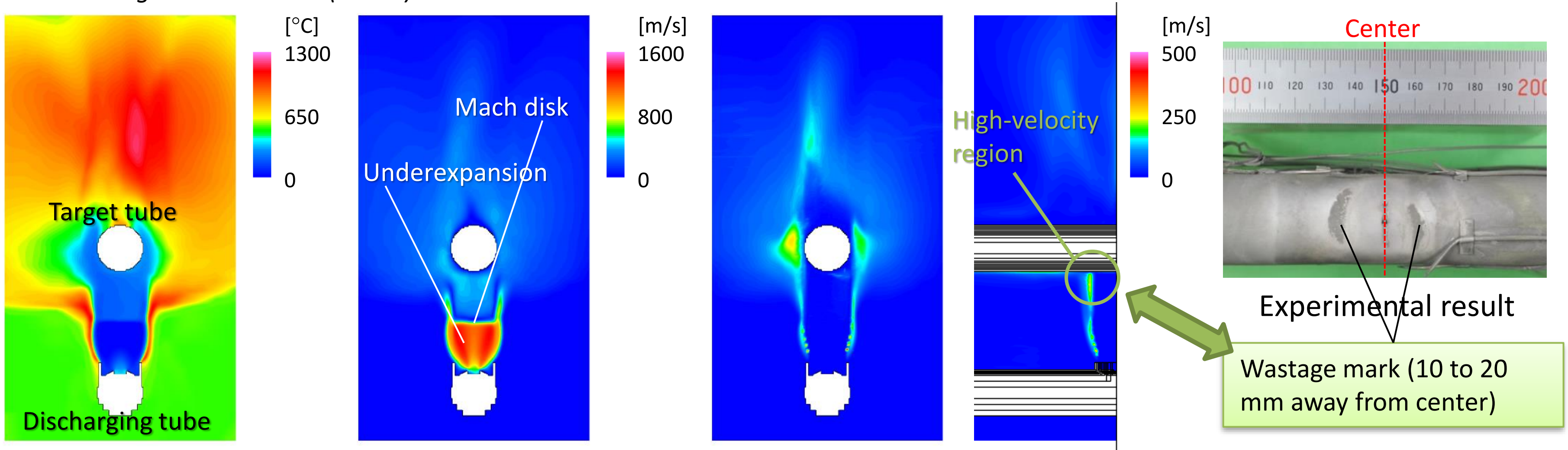
Vertical sectional view of computational domain



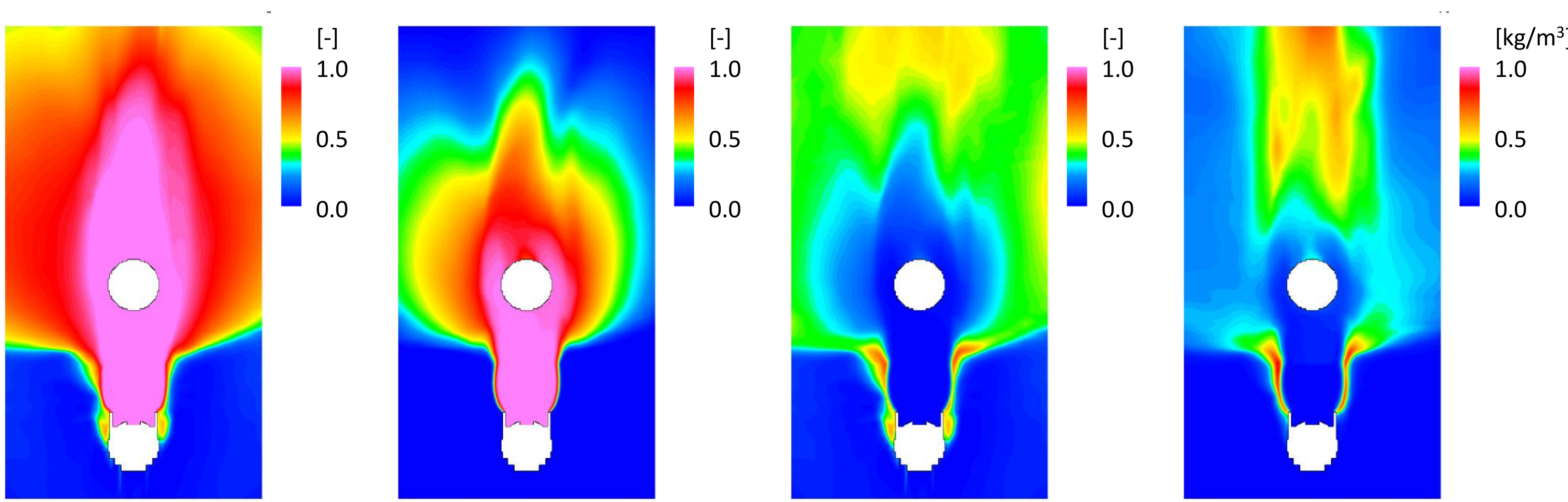
Horizontal sectional view

Computational result

Time-averaged distributions (50 ms)



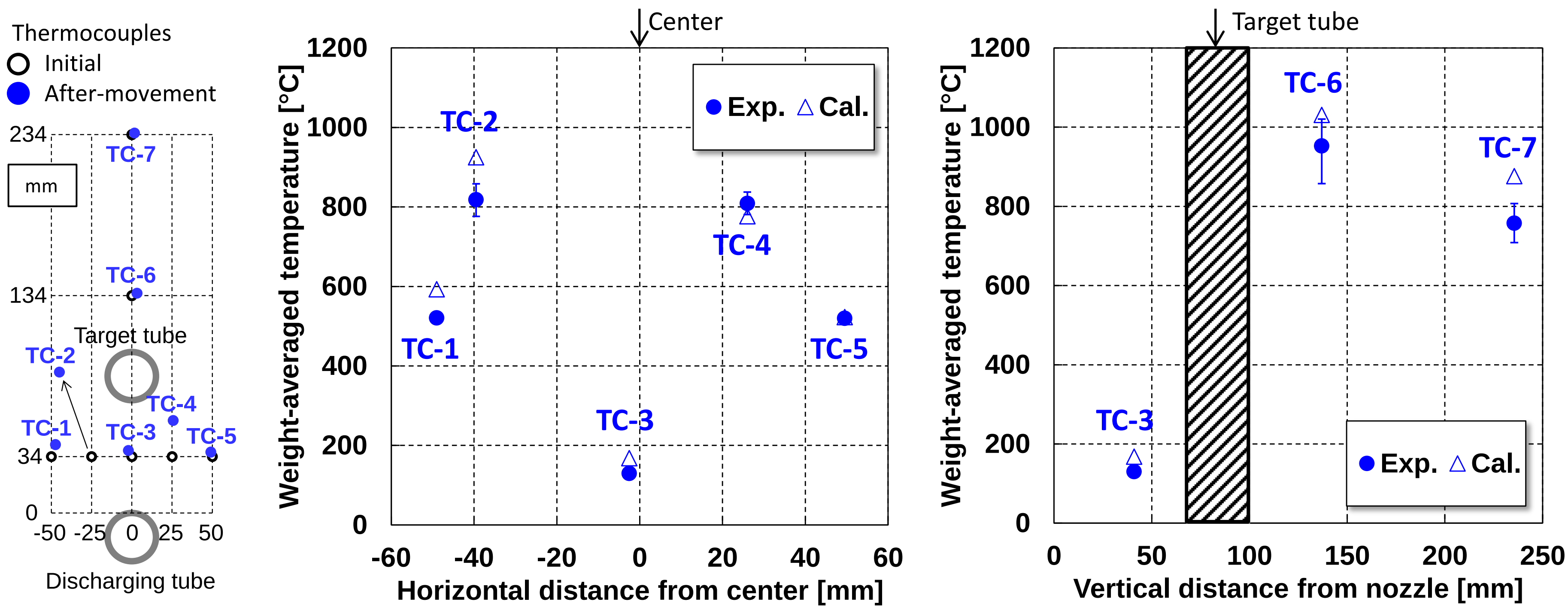
Gas-phase temperature | Gas-phase velocity | Liquid droplet velocity



Void fraction | Volume fraction of water vapor | Volume fraction of hydrogen | Mass concentration of NaOH

Comparison of Temperature

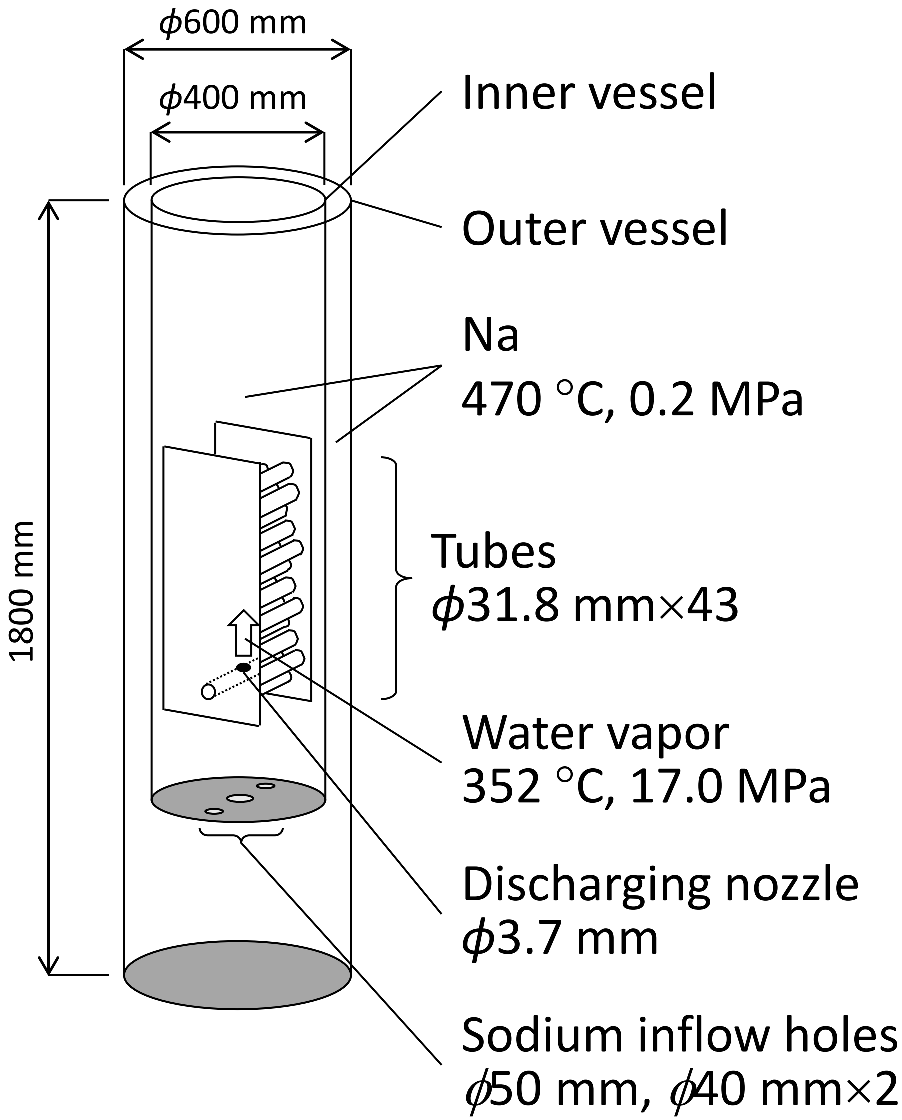
Computational temperature : mass weighted average of gas and liquid phases



The numerical analysis reproduced the tendency of the experimental result.

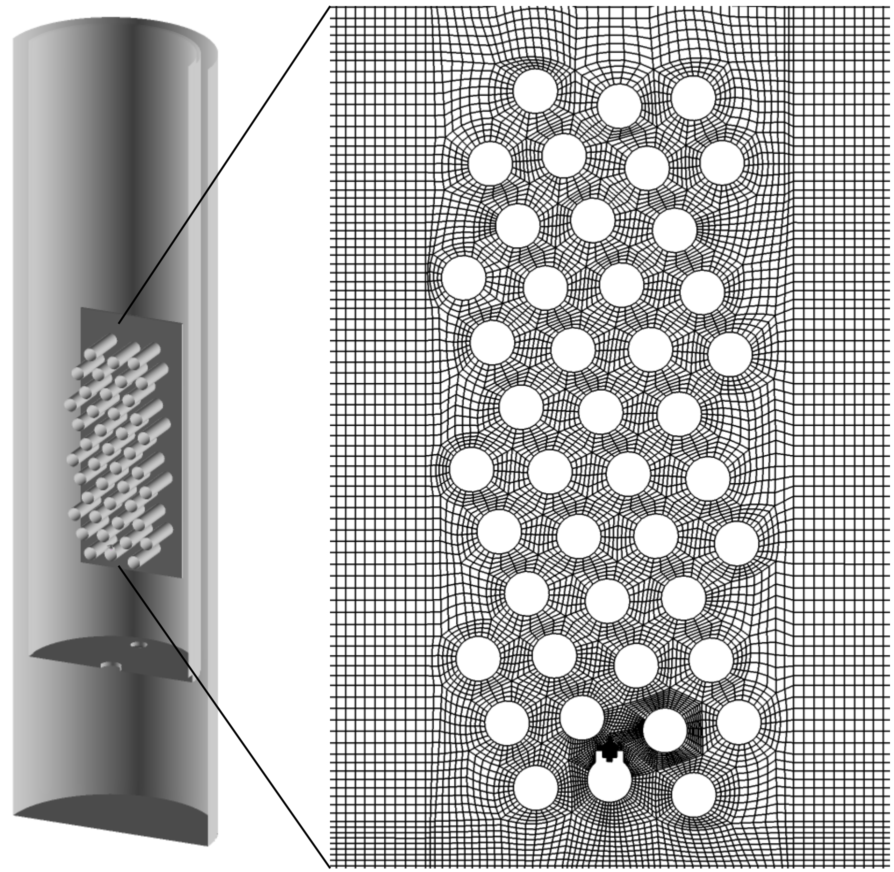
Recent Topic for Applicability Improvement

Extended to unstructured mesh arrangement*



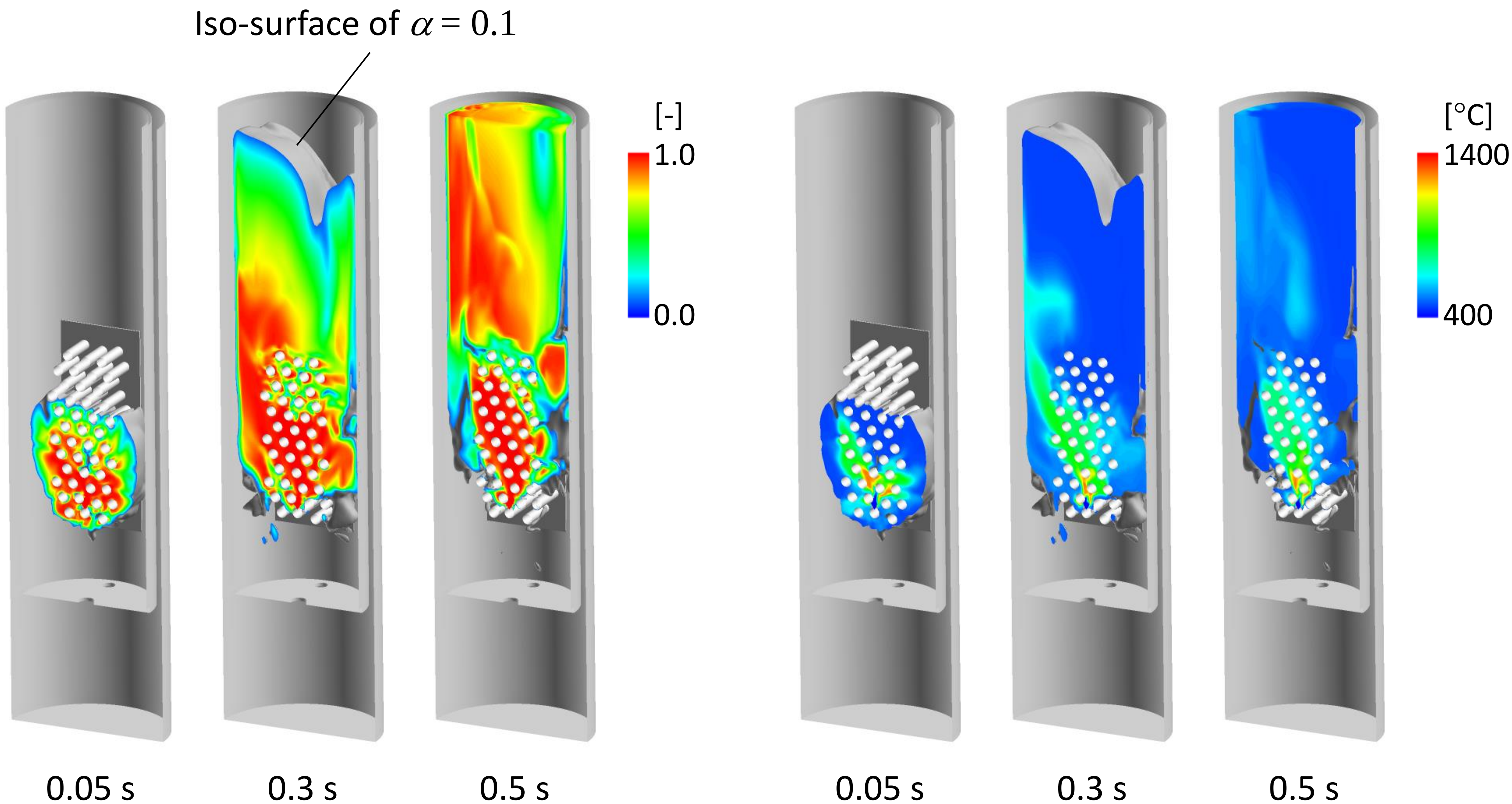
Experiment on SWR with tube bundle

* Uchibori, et al, NURETH-19, 35562 (2022)



Unstructured mesh

Computational Result by Unstructured Mesh



(a) Void fraction

(b) Gas-phase temperature

Innovative Numerical Approach (ARKADIA)

What is ARKADIA ?

Advanced Reactor Knowledge- and AI-aided Design Integration Approach through the whole plant lifecycle

- Knowledge base that stores insights from past nuclear reactor development projects and R&D
- State-of-the-art computational methods linked with the knowledge base and AI*

↓

Automatic optimization of plant design including safety measures from various perspectives such as safety and economics

* Artificial Intelligence

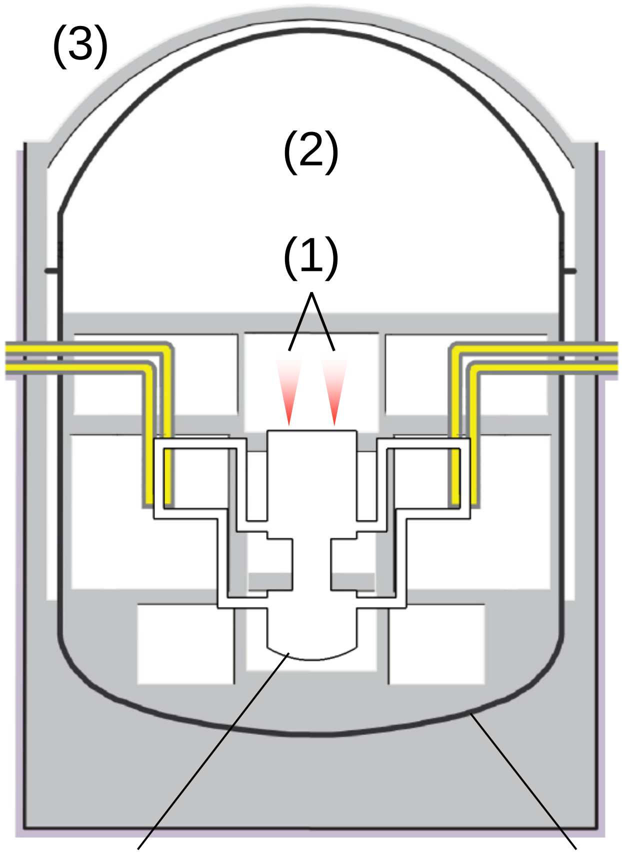
Motivation

- Support evaluation of various innovative reactor concepts represented by SFRs
- Optimize plant lifecycle of advanced reactors automatically by using state-of-the-art simulation technologies and knowledge
- Keep and transfer technology bases including knowledge
- Develop human resources

Example of Optimization Problem

Postulated event during Severe Accident (SA)

(1) Sodium leakage and combustion
(2) Increase of temperature and pressure
(3) Failure of containment vessel



Reactor vessel (RV)   Containment vessel (CV)

Optimization of CV design considering SA

Size	Measures against sodium fire
Size A	Measure 1
Size B	Measure 2
…	…

⇨ Design parameters

Constraint condition

Satisfy requirements on safety and economics

Objective

Find best solutions (minimize objective function)

Optimization Flow

Start

Step (1)
- Define objective function

  $object = e_1 + e_2 \mid e_1 < 1 \, and \, e_2 < 1$

  e_1: safety elemental function

  e_2: economics elemental function

Step (2)
- Collect required information

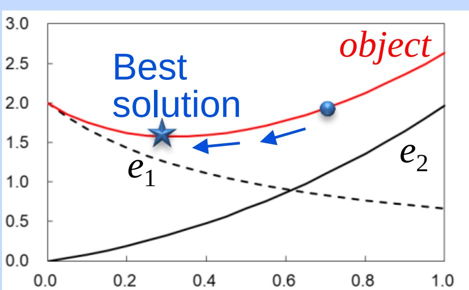
  Ex) specifications and cost data of CV
- Evaluate e_2
- Select analysis condition

Step (3)
- Perform an analysis of CV response
- Evaluate e_1

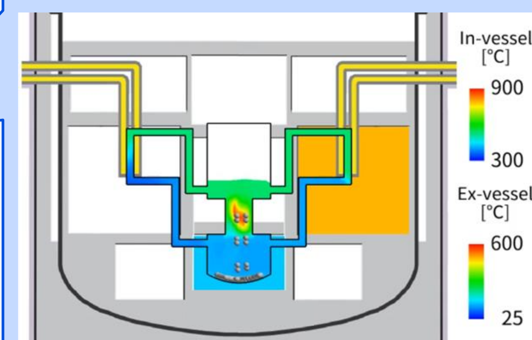
Step (4)
- Confirm achievement of objective

Finish

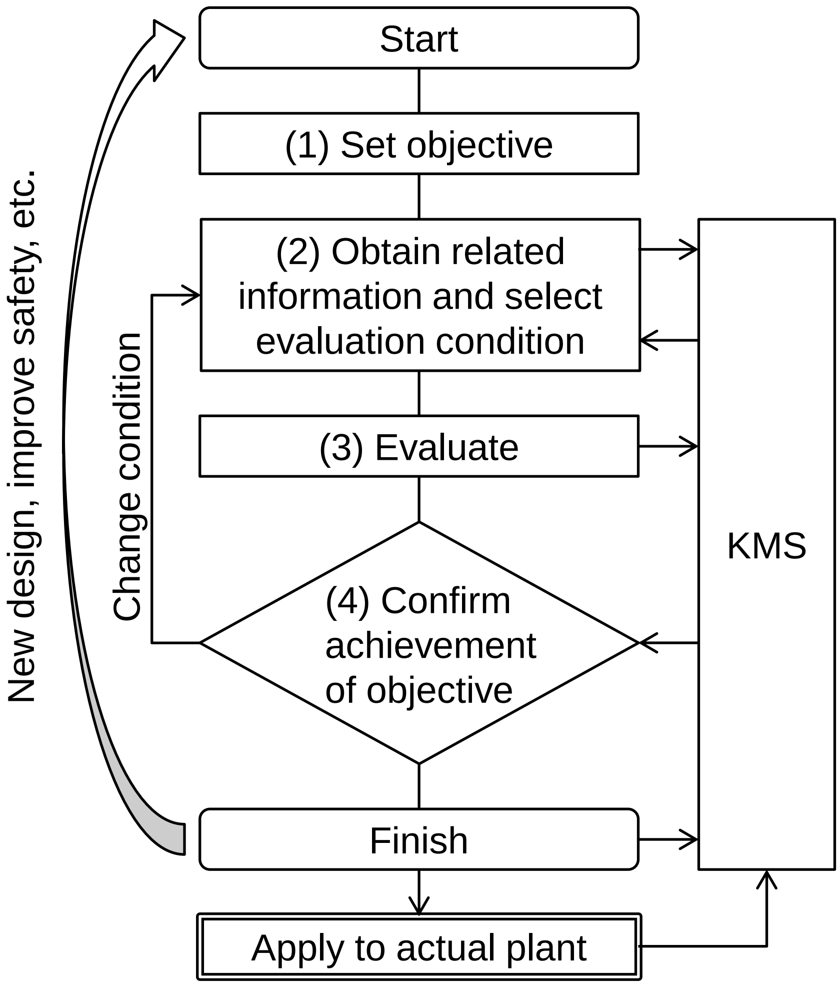
Change analysis condition
(find best solution by AI)



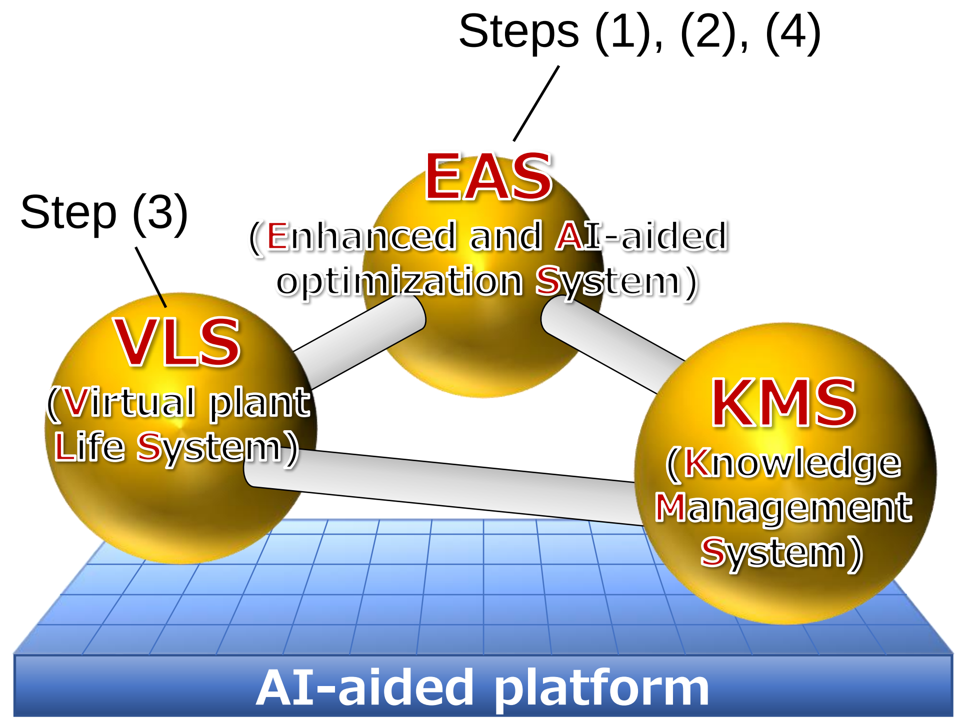
Numerical simulation



Procedures and System Structure



Generalized evaluation flowchart

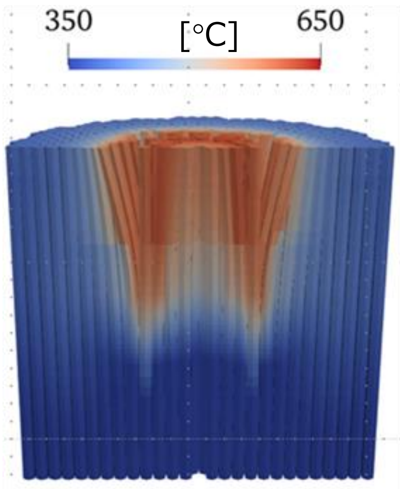


Three systems that comprises ARKADIA

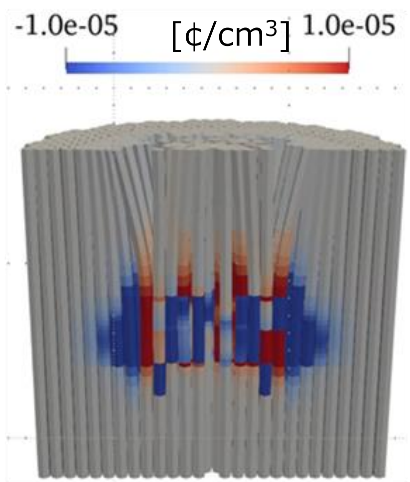
ARKADIA-Design

optimizes core design, plant structure design, and maintenance program

Example coupled simulation by VLS (Neutronics, thermal hydraulics, structure)



Core temperature

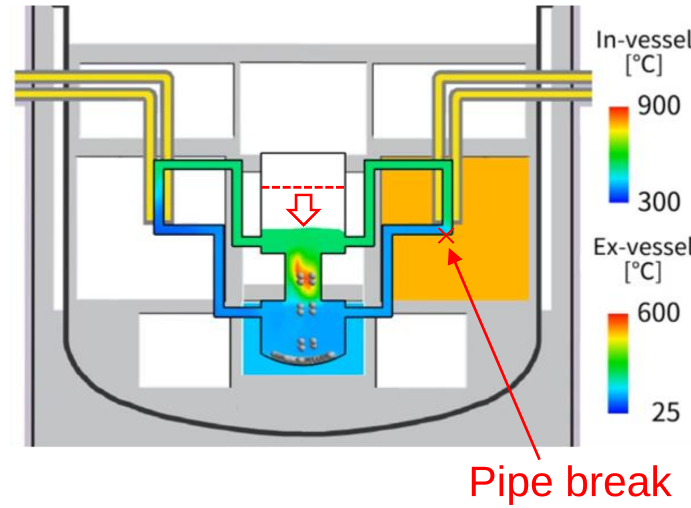


Core reactivity

ARKADIA-Safety

provides design satisfying requirements of safety and economics from SA simulation

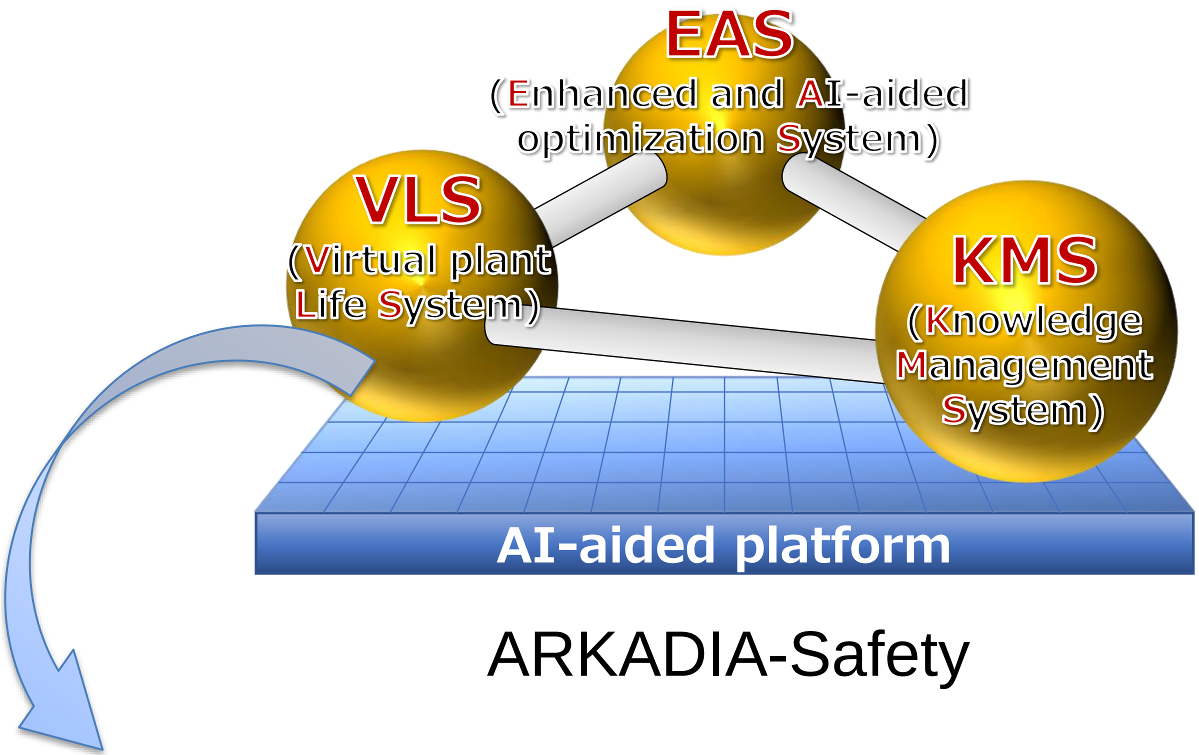
Example SA simulation by VLS (hypothetical condition)



Coolant and atmosphere temperature during loss of reactor level event

- Individual development in the first phase
- Integration into a single system in the second phase

SPECTRA code as base of VLS

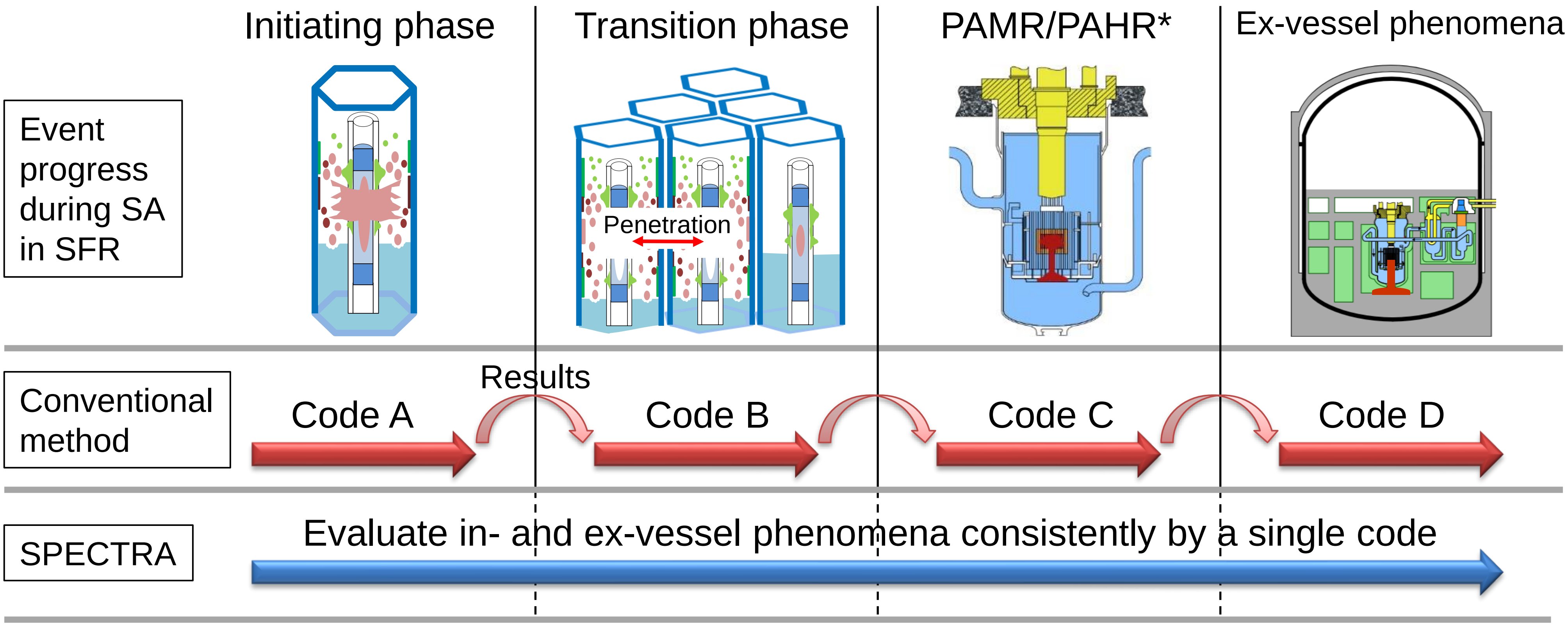


ARKADIA-Safety

SPECTRA code for integrated analysis of in- and ex-vessel phenomena during SAs in SFRs

(Severe-accident PhEnomenological Computational tool for TRansient Assesment)

Motivation for SPECTRA Development



- Completion of evaluation of multiple SA scenarios and parametric analyses by this single code
- Optimization of a plant design from safety evaluation

* Post-Accident-Material-Relocation/Post-Accident-Heat-Removal

Selected phenomena during SA

- ☐ (red) : In-vessel
- ☐ (blue) : Ex-vessel
- ● : Already incorporated into the code

Atmospheric chemical reaction

Transport of fission products

●Ex-vessel thermal hydraulics

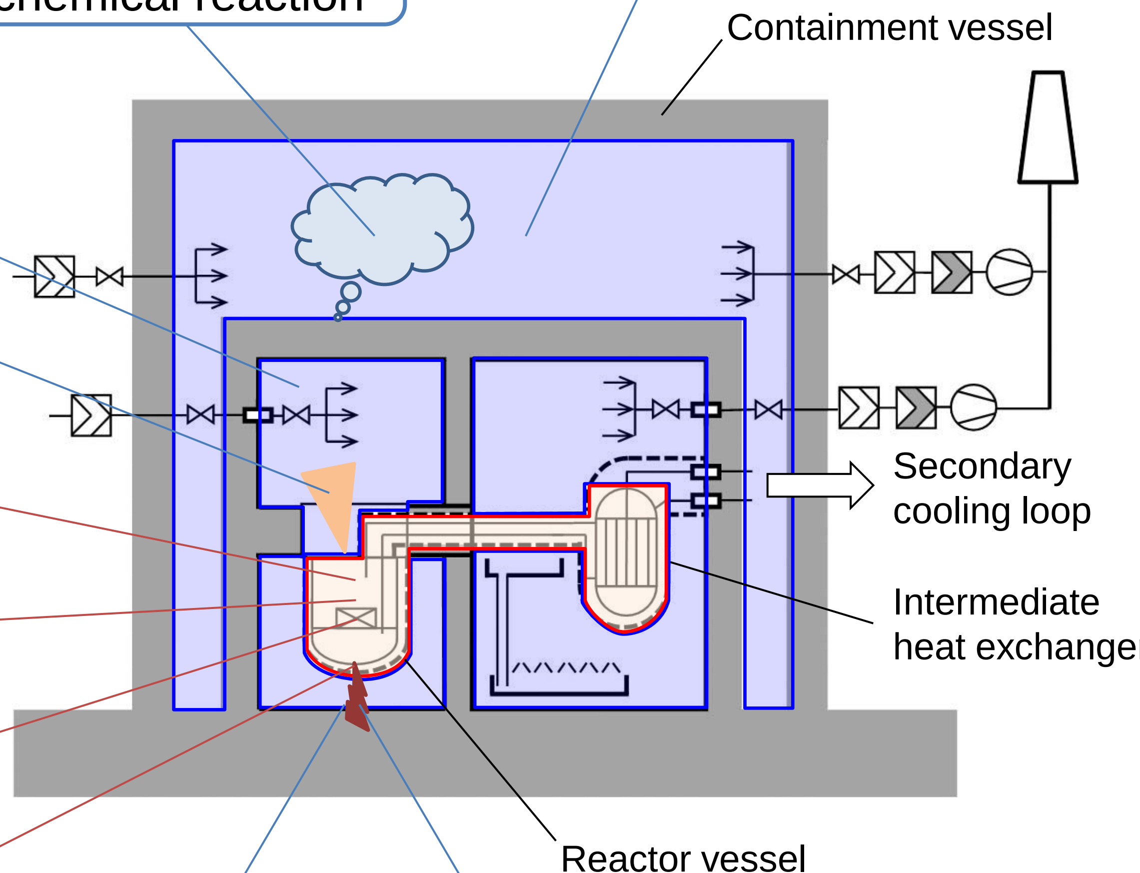
●Sodium fire

●In-vessel thermal hydraulics

Transport of fission products

Neutronics and core disruption

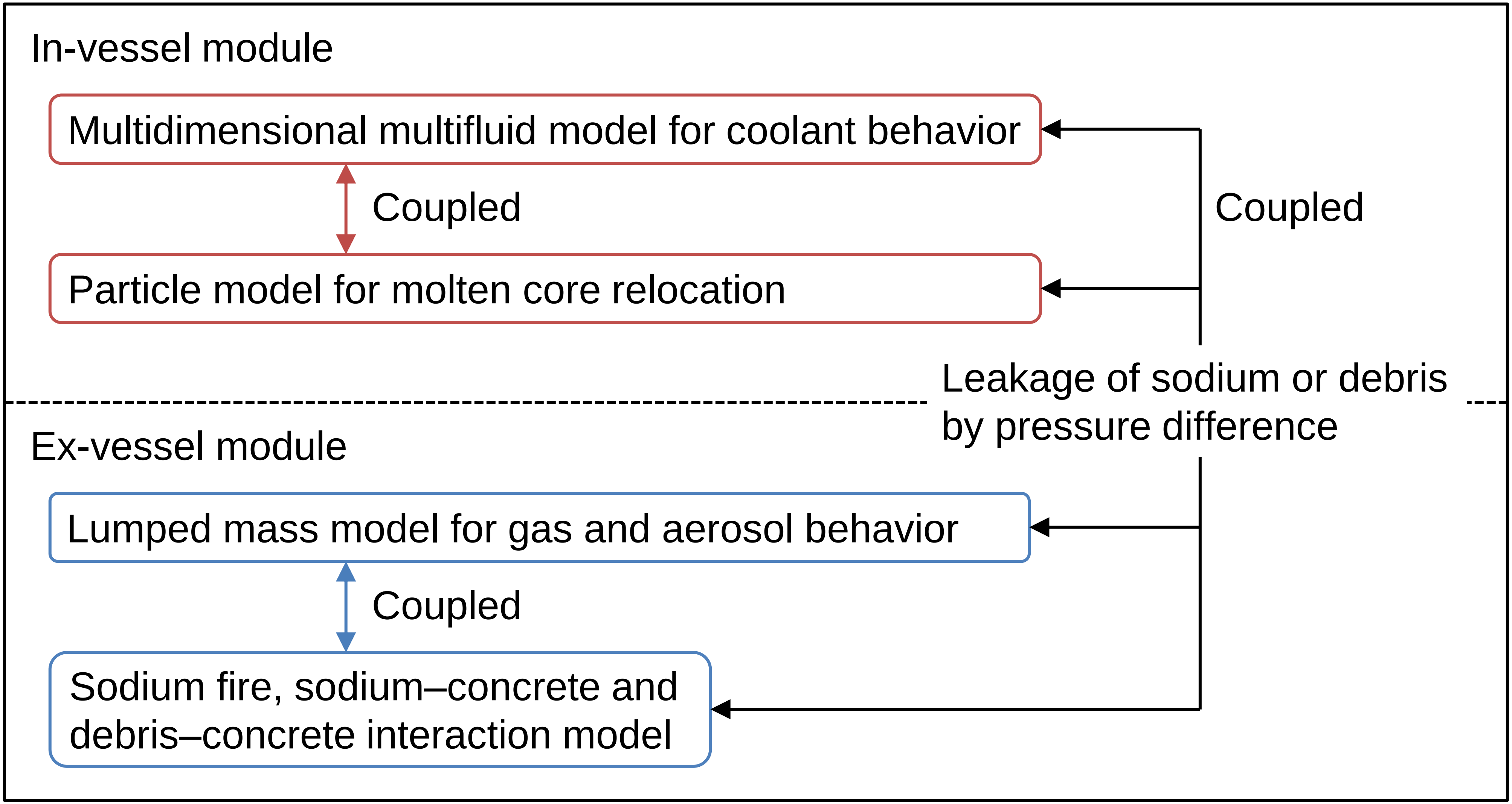
●Molten core relocation



●Sodium-concrete interaction

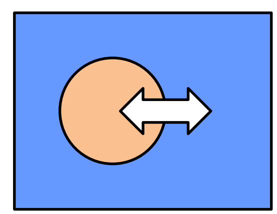
●Debris-concrete interaction

Current Structure of SPECTRA



Analytical Models in In-Vessel Module

- Behavior of coolant (base model)
  - Fully-implicit, single-pressure, multi-component, multi-fluid model
- Molten core relocation
  - Dissipative Particle Dynamics (DPD) method
    - ✓ Low computational load
    - ✓ Useful for simulating molten core both in liquid and solid state
    - ✓ Empirical parameters for particle-particle interaction
- Coupling of Computational Fluid Dynamics (CFD) and DPD
  - Porosity and permeability in CFD
  - Exchange of momentum and energy

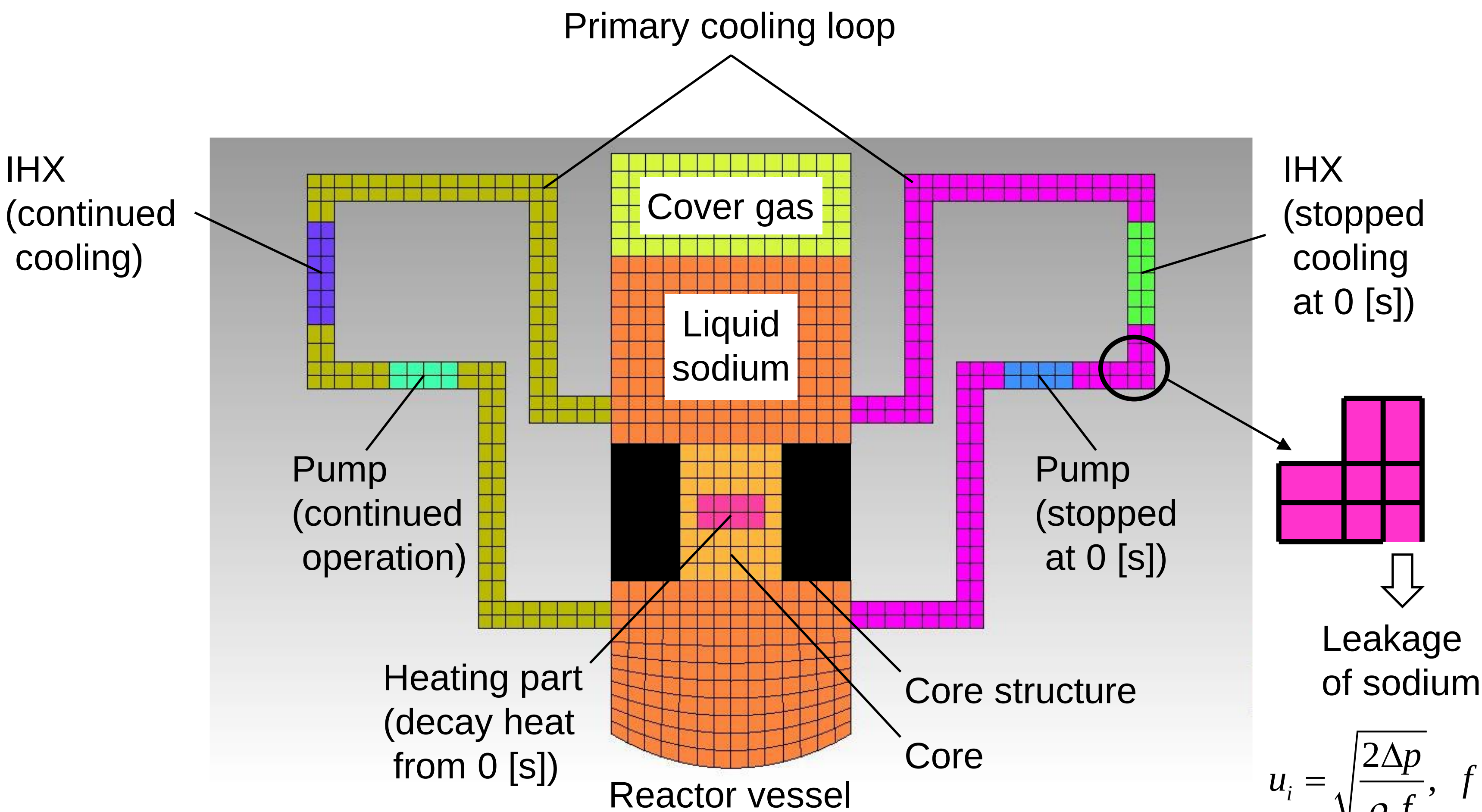


Analytical Models in Ex-Vessel Module

- Behavior of multi-component gas and aerosol (base model)
  - Lumped mass model considering compressibility and buoyancy
  - Volume change of atmosphere by accumulation of leaked sodium
  - Fully implicit method
- Sodium fire
  - Spray and pool fire models from SPHINCS and AQUA-SF
- Sodium-concrete interaction
- Debris-concrete interaction

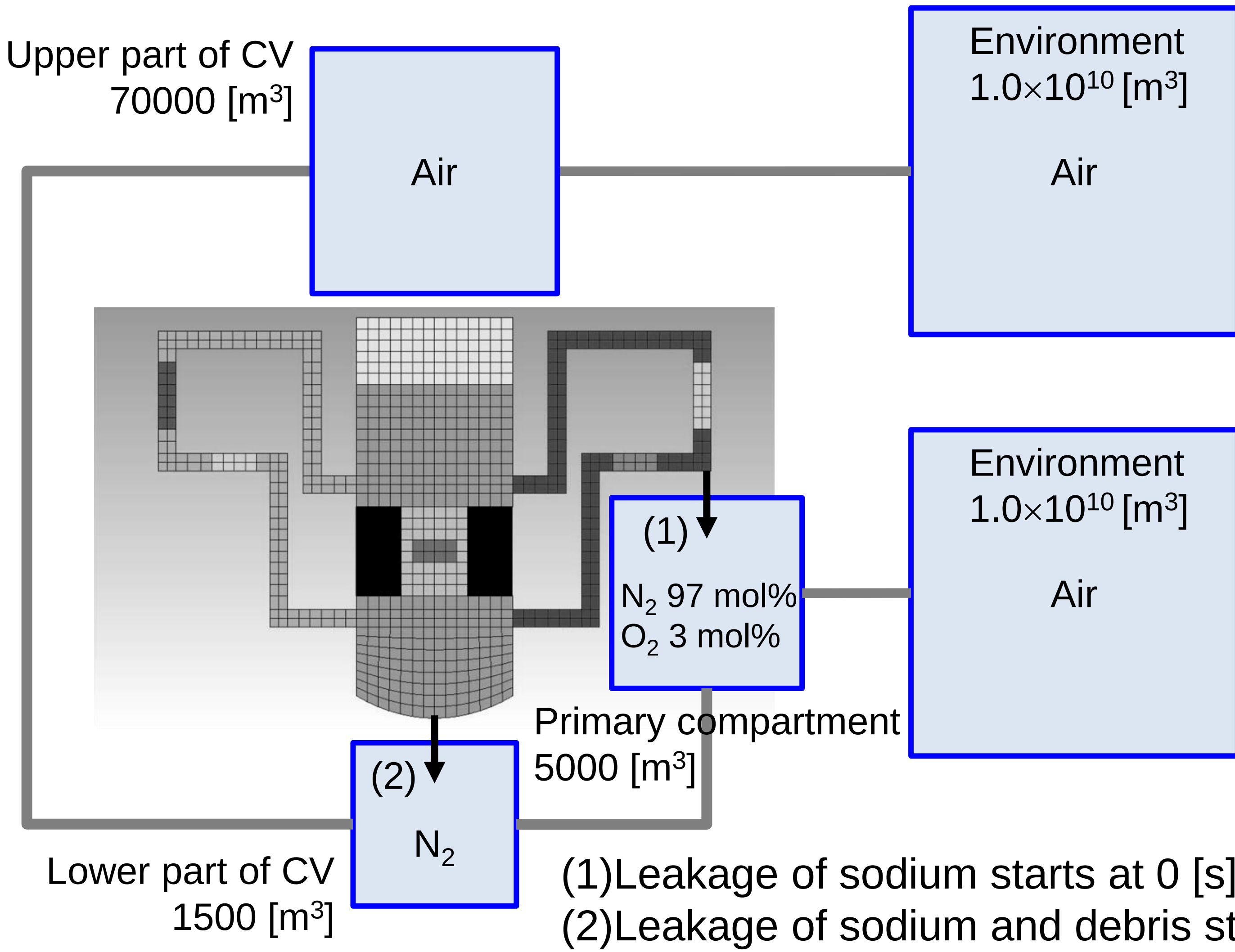
Analysis of LORL event (1/4)

In- and ex-vessel integrated analysis for Loss Of Reactor Level (LORL) event



$$u_i = \sqrt{\frac{2\Delta p}{\rho_i f}}, \quad f = 1.5$$

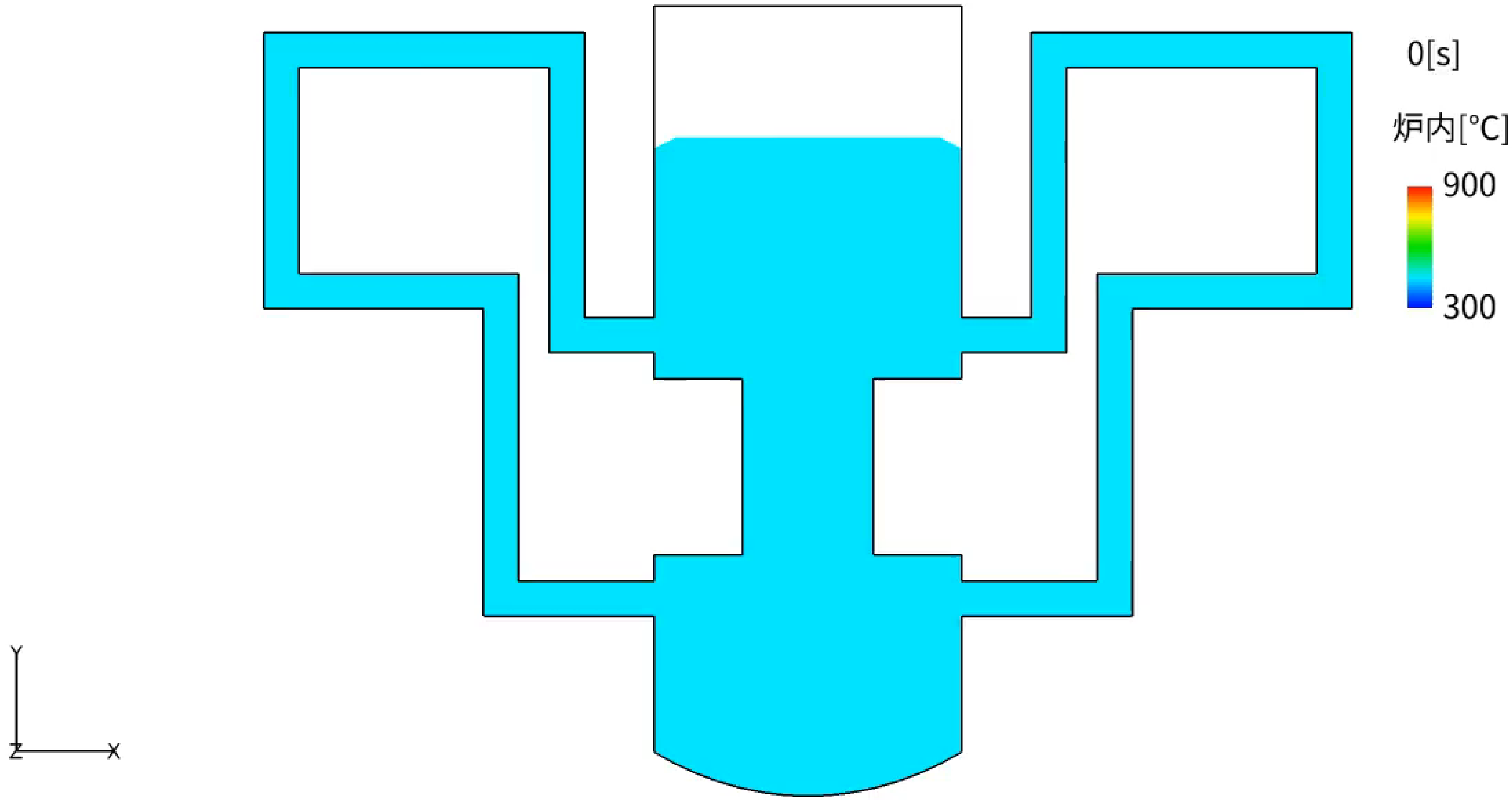
In-vessel condition (two-dimensional)



(1)Leakage of sodium starts at 0 [s]
(2)Leakage of sodium and debris starts at 200 [s]

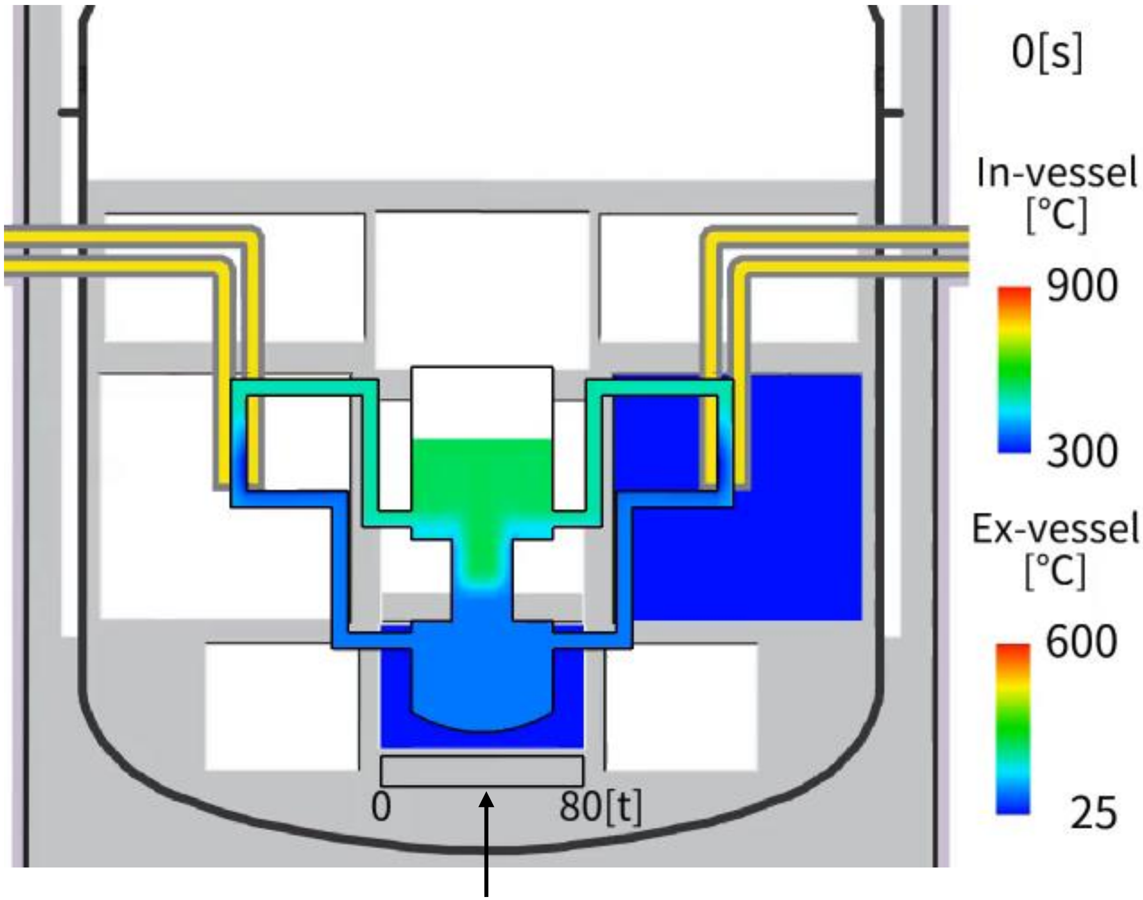
Ex-vessel condition (five cells)

Analysis of LORL event (3/4)



- This analysis starts from the condition of a uniform temperature.
- The liquid surface fluctuation and the temperature change disappeared within a certain time.
- The reached steady-state was used as an initial condition of LORL analysis.

Analysis of LORL event (4/4)



Total mass of leaked debris

In-vessel

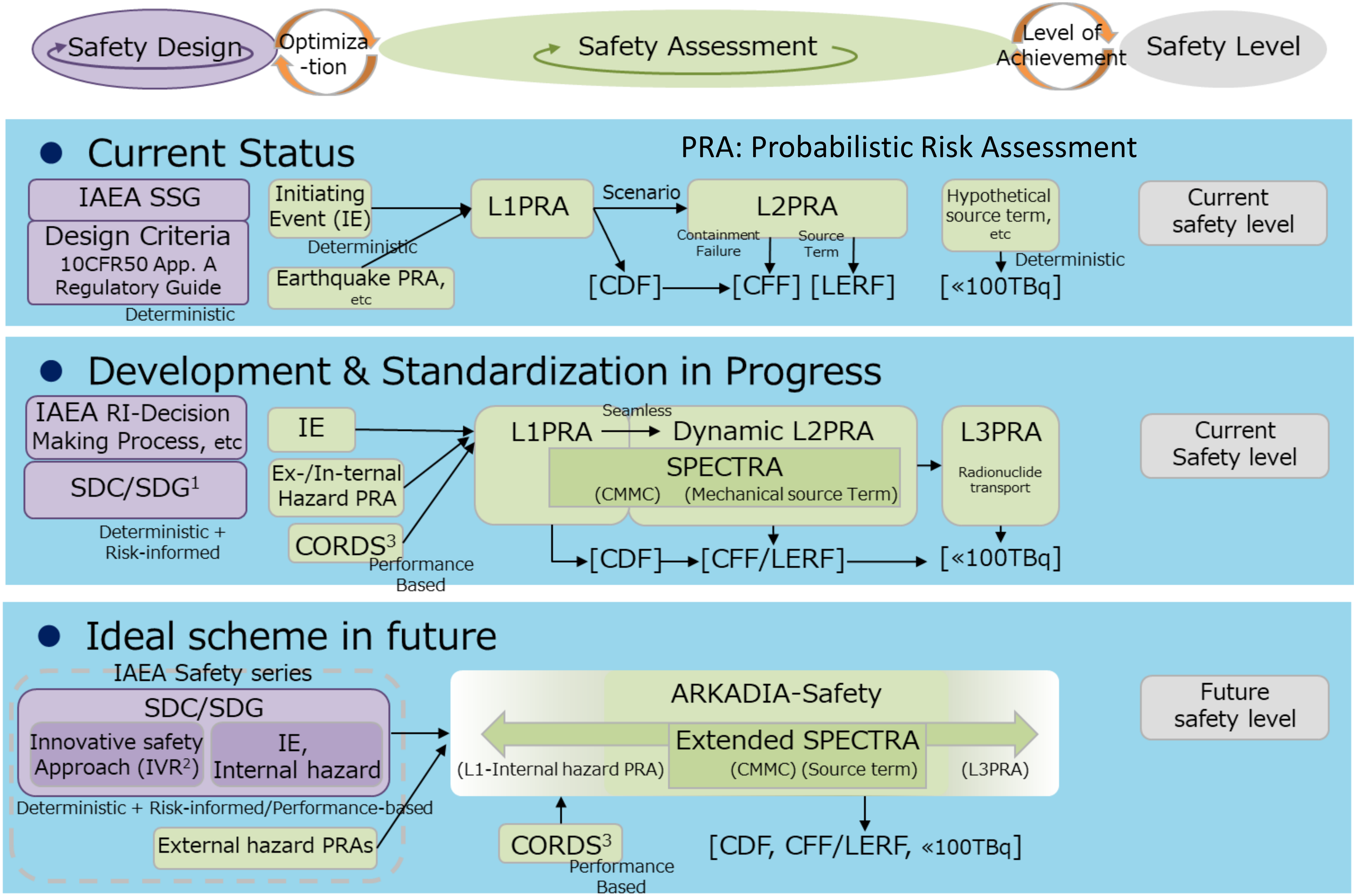
- Coolant level drops
- Temperature in core region rises and molten core falls
- Cooling path fails completely, and coolant temperature rises

Ex-vessel

- Atmosphere temperature rises due to sodium fire and sodium-debris-concrete interaction

The SPECTRA code can evaluate the overall complex thermal hydraulics phenomena.

Target Range on Safety Assessment

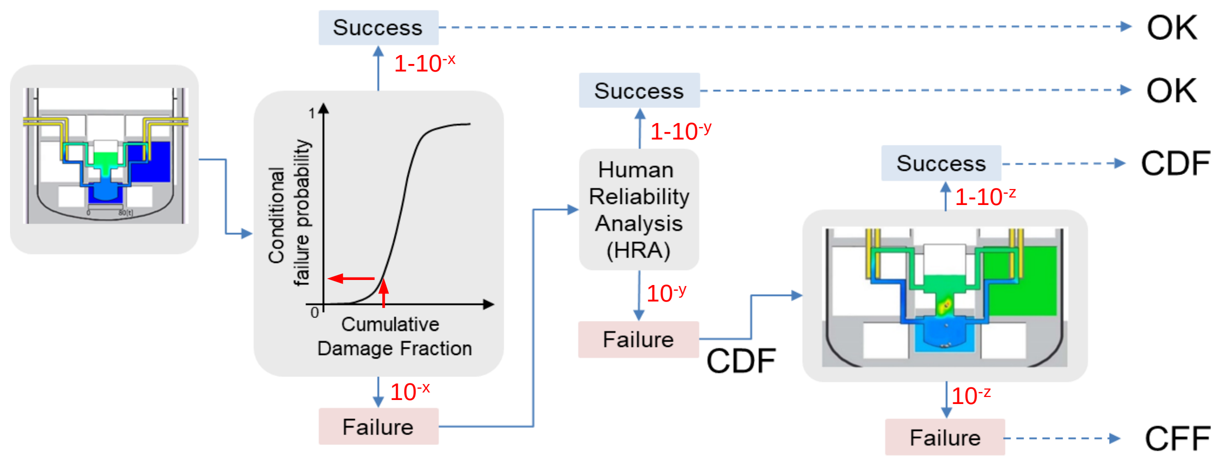


1: Safety Design Criteria/Guideline, 2: In-Vessel Retention, 3: Component reliability database

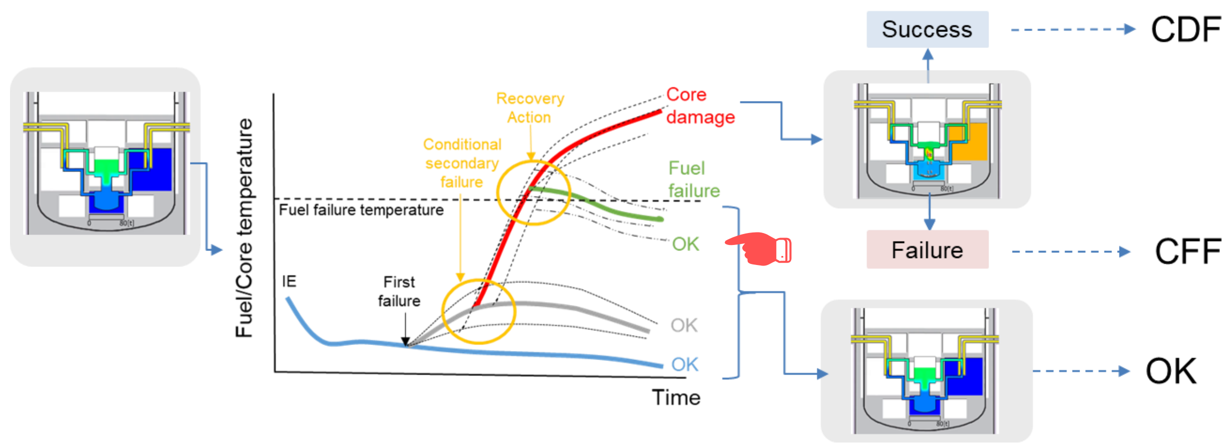
PRA on Success Criteria & Source term

Level 1 PRA			Level 2 PRA		End State
Initiating Event	Primary Coolant System	Recovery Action	Cooling	Containment	
Leakage in primary coolant system	Fragility of lower elevation part	e.g. Siphon Break	e.g. GV air cooling	e.g. compartment isolation	

- ✓ PRA on focused scenario with given branch probabilities



- ✓ Dynamic PRA on wide-rage scenario with on-demand branch probabilities



Summary

- Safety analysis of SFR

Thermal-hydraulics with sodium chemical reactivity is key issue for plant safety of SFR. From Verification and Validation's (V&V) viewpoint, an international collaboration will play important role in near future.

- Innovative numerical approach (ARKADIA)

ARKADIA has the state-of-the-art computational methods linked with the knowledge base (so called a digital triplet) and AI.

This system will realize automatic optimization of a plant design based on safety evaluation including PRA, and thus it realizes an improvement of development efficiency of innovative reactors.

Thank you for your kind attention!!