Structure, System and Component Designs of JSFR in relation to Sodium Chemical Reaction Issues

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Sodium Chemistry Related Exp.

- Operation Experiences & Experiments
  - Troubles, including sodium leaks and sodium-water reactions, had been experienced and solved from the early stage of SFR development ca. 1950'.
  - The troubles, incl. sodium-water reaction and sodium fire phenomena, had been thoroughly investigated, and the causes of such troubles were clarified.
- In JAEA:
  - Several sodium test facilities have/had been operated.
    - 50MW-scale SG test loop, CCTL & PLANDTL sodium loops, AtheNa facility, SWAT facilities (Sodium Fire)…
  - Technical results are considered in the SFR designs: Monju, JSFR

SDC related to Sodium Chemical Reaction

- Criterion 17: Internal and external hazards
  - **Internal hazards**: para. 5.16. The design shall take due account of internal hazards such as fire, explosion, flooding,…., and sodium chemical reaction with air, water and other materials, including associated pressure waves and product releases, e.g. hydrogen. Appropriate features for prevention and mitigation shall be provided to ensure that safety is not compromised.
- Criterion 42bis: Plant system performance of a sodium-cooled fast reactor
  - (e) Sodium is chemically active and opaque, and it is solid below 98 ºC.
  - (g) Due to chemical risk of sodium which burns in air and reacts with water, impact of such chemical reactions to items important to safety must be prevented.

SDC related to Sodium Chemical Reaction

- Criterion 47: Design of reactor coolant systems
  - Para. 6.14bis. Inert gas shall be used as a cover gas in sodium-filled components to prevent chemical reaction at the free surface of sodium,
  - Para. 6.14ter. Provisions shall be made to detect sodium leaks and to mitigate the consequence of sodium chemical reaction in case of postulated sodium leaks from the reactor coolant systems.
  - 6.16ter. Chemical reactions between sodium and water/steam or other working fluids shall be considered in the design of the secondary coolant system. Provisions to prevent and/or mitigate such chemical reactions shall be incorporated in the design:
    - (a) Provisions shall be made to detect leaks of working fluids,..
    - (b) A pressure relief system shall be employed in the secondary coolant system.
    - (c) The fundamental safety functions shall be maintained under postulated design extension conditions for severe chemical reactions between the sodium and the working fluid.

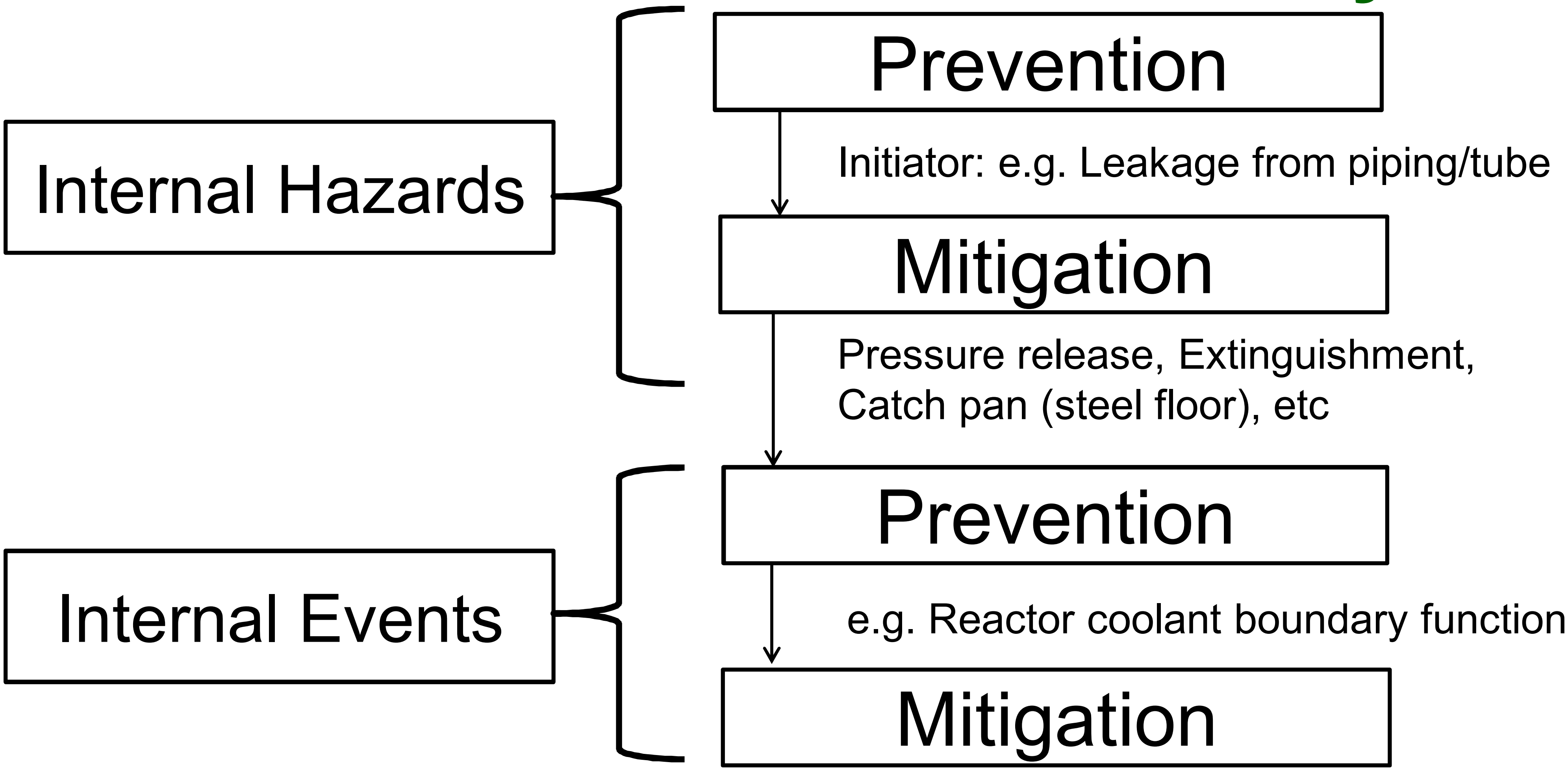
SDC related to Sodium Chemical Reaction

- Criterion 74: Fire protection systems
  - 6.54ter. Compartments with sodium components shall be protected from water ingress to prevent sodium-water chemical reactions, especially from water used in case of fire fighting in an adjacent compartment.

Safety Approach for Sodium-Chem.

- Fundamental Safety Approach
  - Sodium reaction after leakage – Internal Hazard
    - Anther points: “coolant inventory for cooling”, “containment function”
  - Prevent the progress of such effect to “safety functions” by minimizing the consequences of sodium water/air reaction
- Key for Gen-IV SFR system
  - To ensure reliability of sodium contained SSC, based on the operation experiences;
  - Prefer more “preventive” approach on sodium related hazard
  - Incorporate the progresses of knowledge & R&D results in the design & assessment on sodium-water reaction and sodium fire; especially Design Extension Conditions and hazard initiators/propagations

Image of Safety Approach for Sodium-Chemical Reactivity



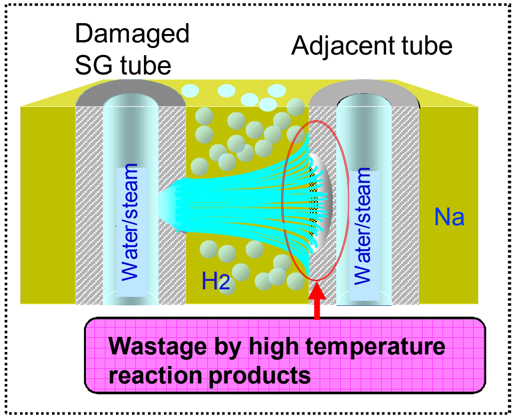
Sodium-Water Reaction

- Sodium reaction with water, producing H_2, heat, and corrosive products.
- Steam generator (SG) tube functions:
  - Boundary between water and sodium (of secondary coolant system)

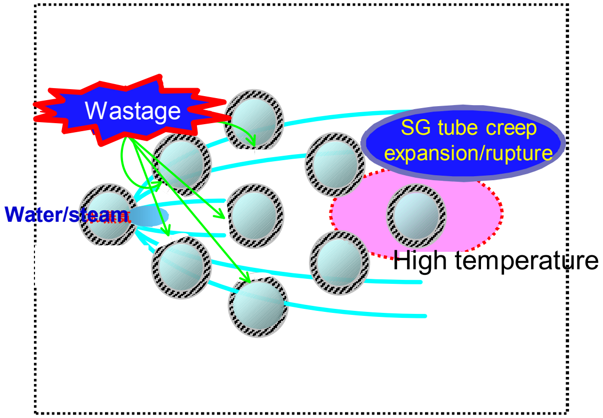
Major reactions $Na + H_2O \rightarrow NaOH + \frac{1}{2} H_2$ $\quad 2Na + H_2O \rightarrow Na_2O + H_2$

Three types of phenomena and propagation
- Categorized based on existing experiments and past accidents -

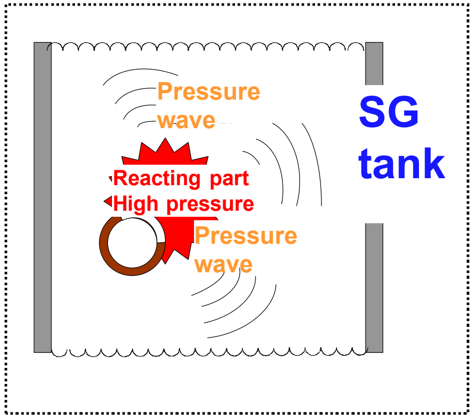
〈Target wastage〉



〈Multi-wastage via propagation〉

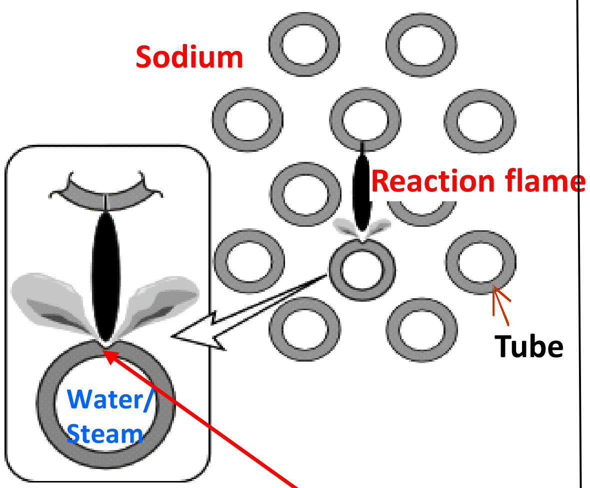


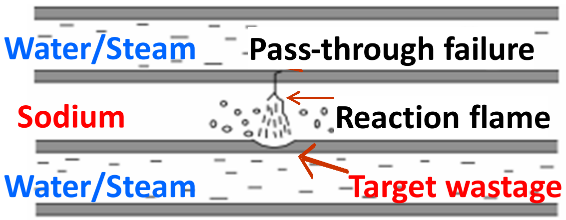
〈Pressure wave [pulse]〉

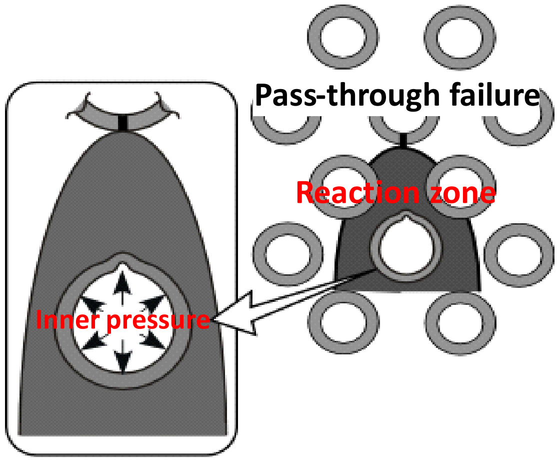


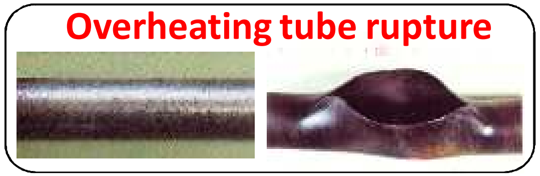
Sodium Leak Rate and Phenomena & Propagation

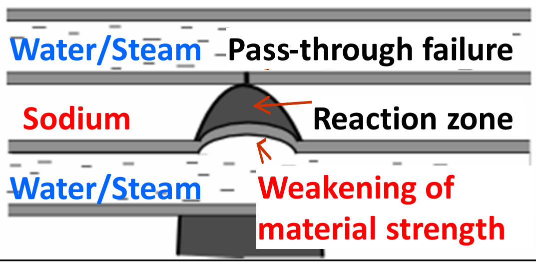
Small-scale Water Leakage (Water leak rate: e.g. 0.1 ~ 10 g/s)	Mid-scale Water Leakage (Water leak rate: e.g. 10 g/s ~ Several kg/s)	Large-scale Water Leakage (Water leak rate: more than several kg/s)
Adjacent tube damaged by erosion and corrosion in reaction flame	Several tubes damaged by high-temperature during longer period	Accumulated gas zone No wastage and overheating rupture

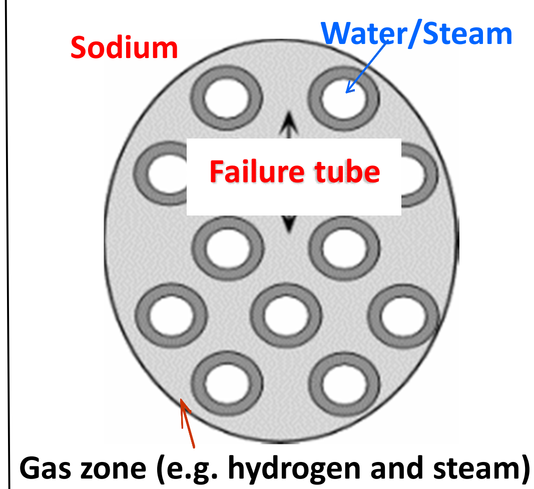


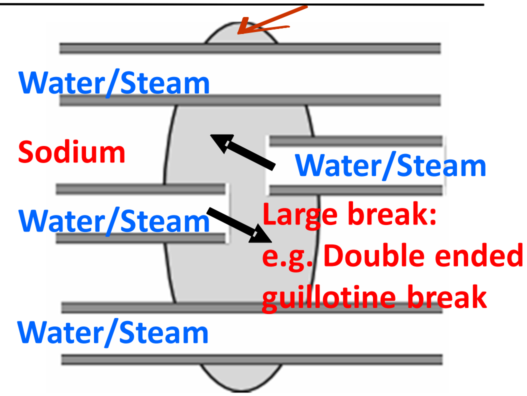












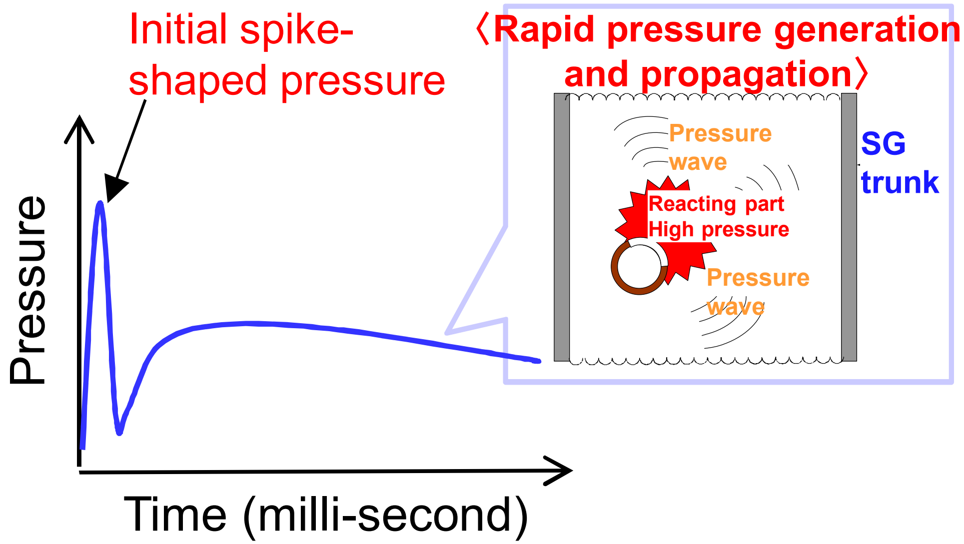
Effects on Secondary Coolant System

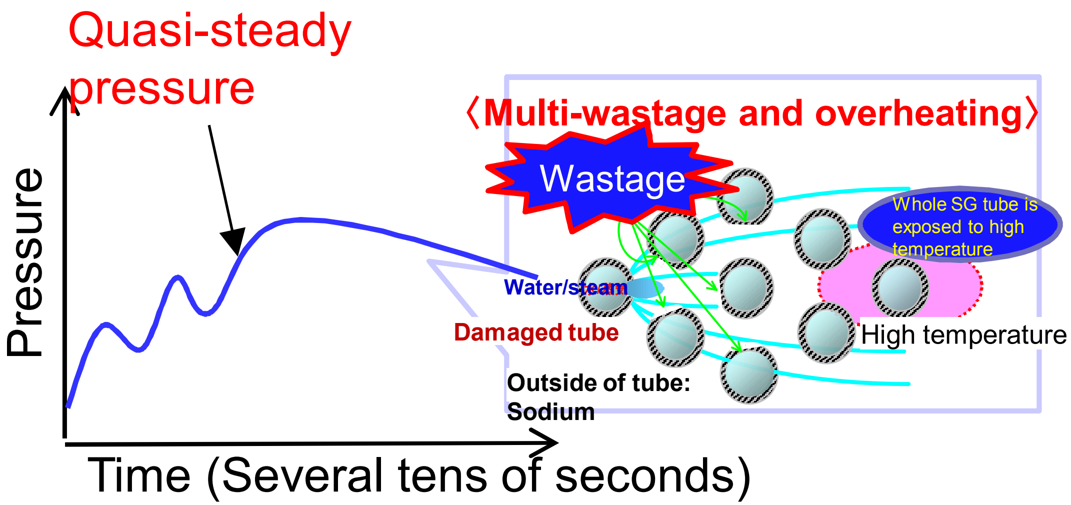
（1）Damage progression (Thermal and chemical effects)

- Effect on adjacent tubes due to high temperature and corrosive water jet.
- Need to immediate control for termination, not to the failure propagate to adjacent and spread.

（2）Mechanical effects on the secondary coolant system & components

- Initial spike-shaped pressure wave in a very short time, and quasi-steady pressure due to hydrogen and heat generation if sodium-water reaction continues.
- These pressures potentially become a risk to secondary coolant system and components, e.g. secondary main pipes, intermediate heat exchanger (IHX) tube.





Potential Effects on Primary Coolant System

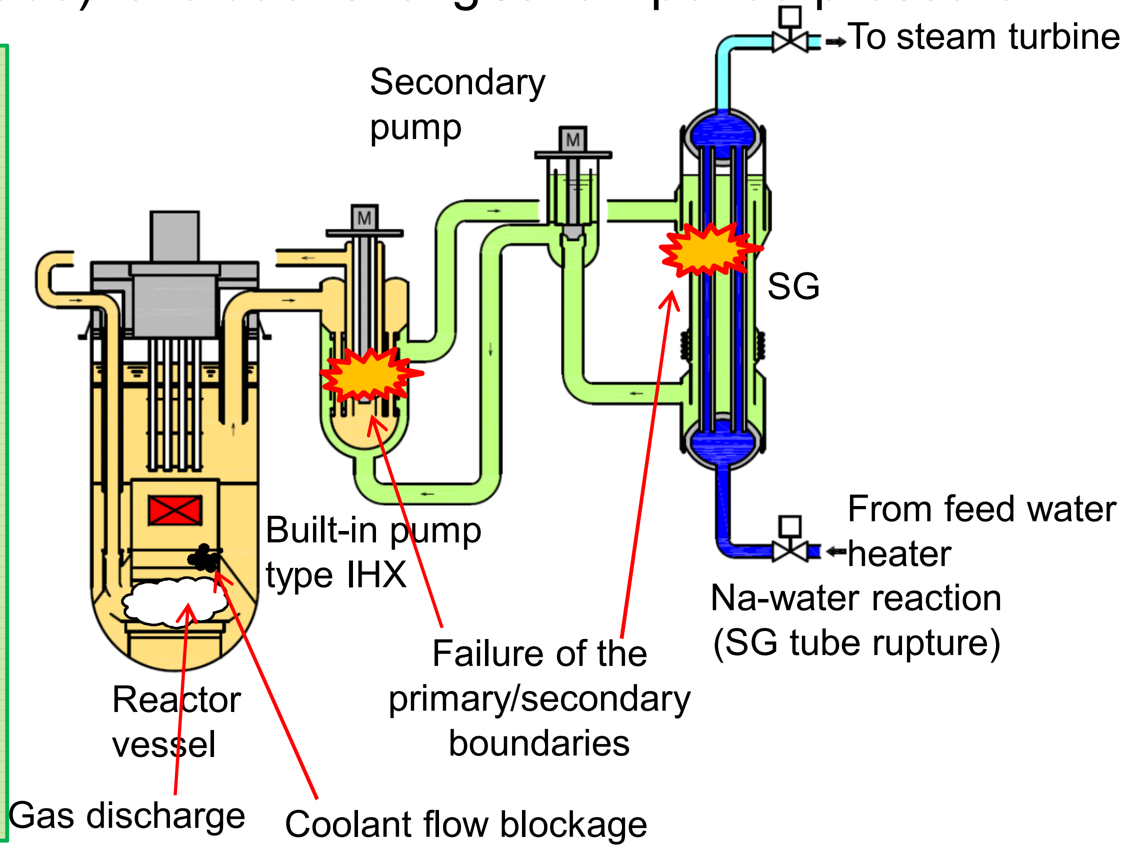
(1) Progression to In-vessel event

- Potential effect on safety function via chemical, structural and neutronic effects, just in case that boundary between primary and secondary coolant system boundaries (e.g. IHX tube) fails due to long-/short-period pressure

✓Gas ingress to the core region
Could lead to reactivity insertion.

✓Reaction products in primary coolant system
Could lead to coolant flow blockage
Could lead to material corrosion.

✓If IHX is located near the core (e.g. pool type), pressure wave
Could lead the configuration change of the reactor core

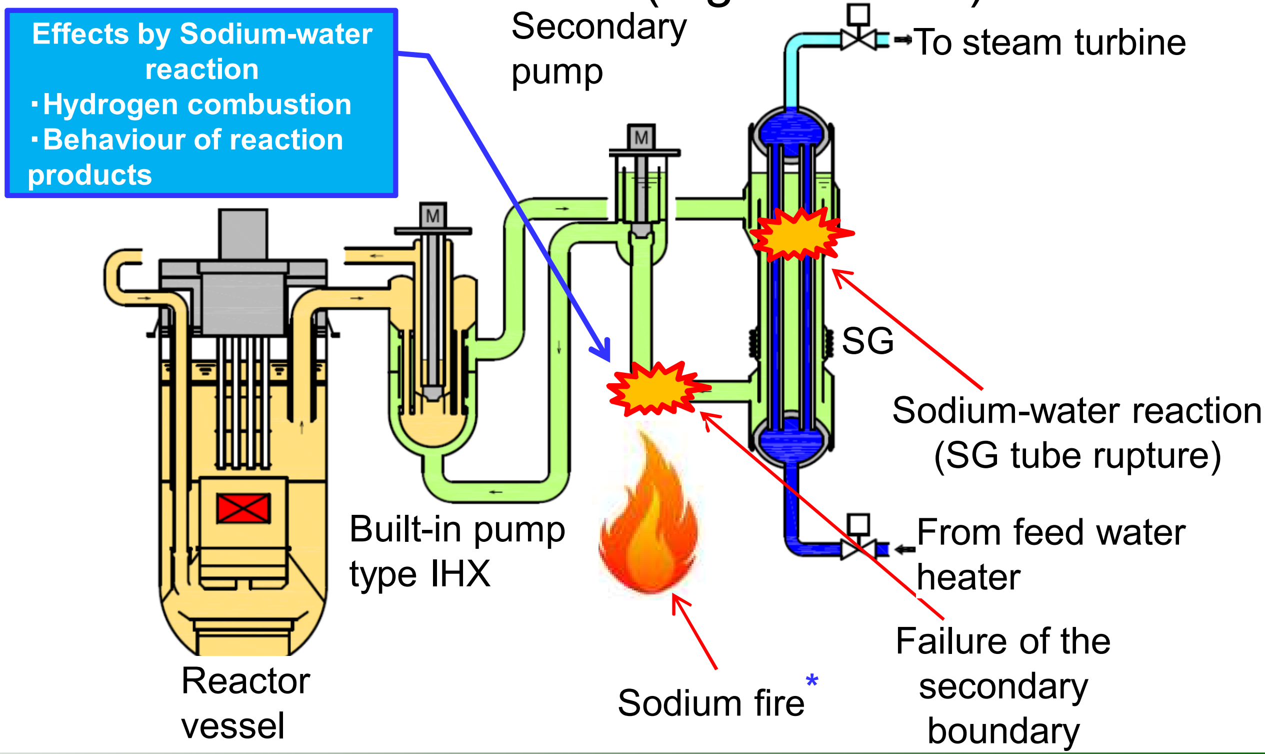


Potential Effects on Containment

（2）Progression to In-/Out-Containment

- Via Thermal, chemical and mechanical effects
- Potential sodium fire, if the secondary coolant system & components damaged by e.g. pressure increase
- Potential contact of sodium and structural material (e.g. concrete)

Note]
An enclosure is applied so that sodium fire would not occur.
Leaked liquid sodium is retained by the enclosure with inert atmosphere.



Summary of L.L. from the Superheater (SG) accident in PFR

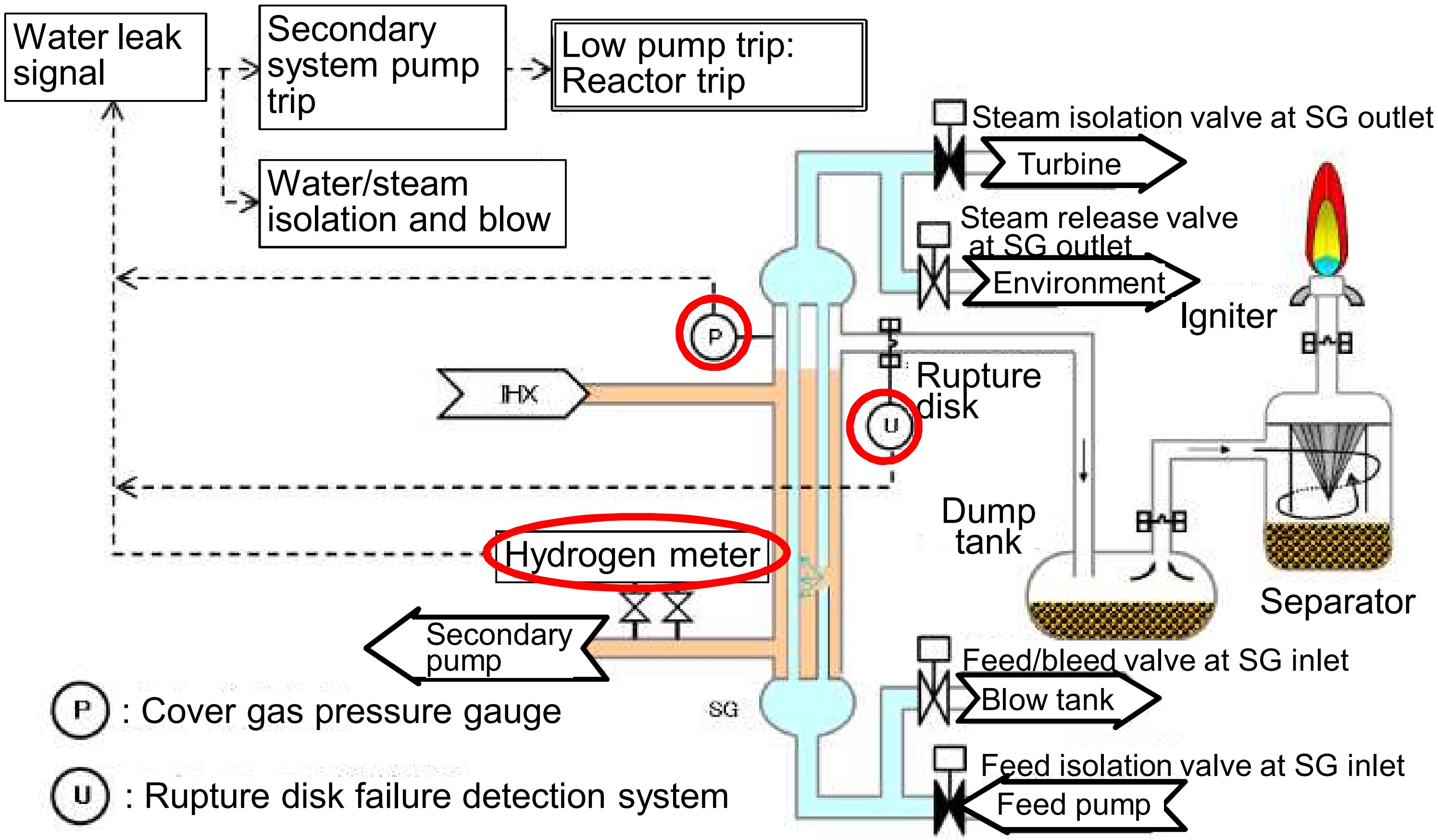
- PFR
  - Pool type, 600MWt / 3 loops of Secondary circuit
  - Superheater tube rupture propagation, 27th February 1987
  - Initial failure (small trans-axial crack) in one tube, then subsequent tube failure by “sodium-water reaction jet”

Related SSC	Causes/Conditions	Example of design resolutions
Flow-induced vibration of tubes	Leak flow through gaps of central baffle	No gap design (e.g. welding)
Fast steam dump system	Not installed in superheater	Install in all Sodium-steam heat exchanger
Hydrogen detection system	Out of order	Operation rules (e.g. No operation if out-of-order)

Design Measures

- Abnormality detection, mitigation measures (e.g., reactor trip, water blow), pressure release (control) are essential.

Diagram of example of measures for sodium-water reaction in JSFR



Approach to DBA & DEC

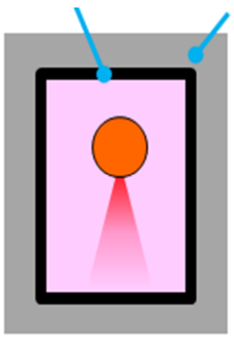
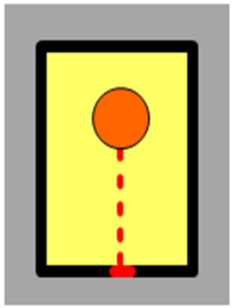
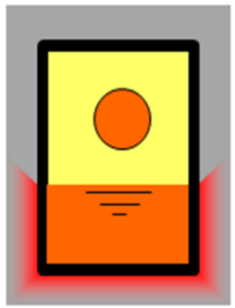
- Design Basis Accident (DBA)
  - Prevent failure of boundary between sodium and water
    - Margin to external force by external hazards (i.e. earthquake)
  - Mitigate measures to avoid a propagation
    - e.g. “flow vibration”, “thermal transient”, “aging degradation”, “steam and water pipe whip”…
  - Postulated initiator
    - Random failure of tube = single tube failure in SG
- Design Extension Condition (DEC)
  - Multiple failure (DBA + a loss of mitigation function)
    - Object: Confirmation of no cliff edge effect.

Assessment and Criteria

- Assessment
  - Key point: “Spike-shaped pressure wave”, “Quasi-steady pressure state”, “Propagation of tube failure”.
  - DBA] Conservative + Single Failure
    DEC] Best Estimate + Multiple failure
- Criteria [Same for DBA & DEC
  - Integrity of boundaries (e.g. SG tube) between the primary and secondary coolant systems.
  - Prevent significant damage of components in secondary coolant system.
  - Integrity of reactor core and primary coolant system

Sodium Fire Type & Potential effect on CV

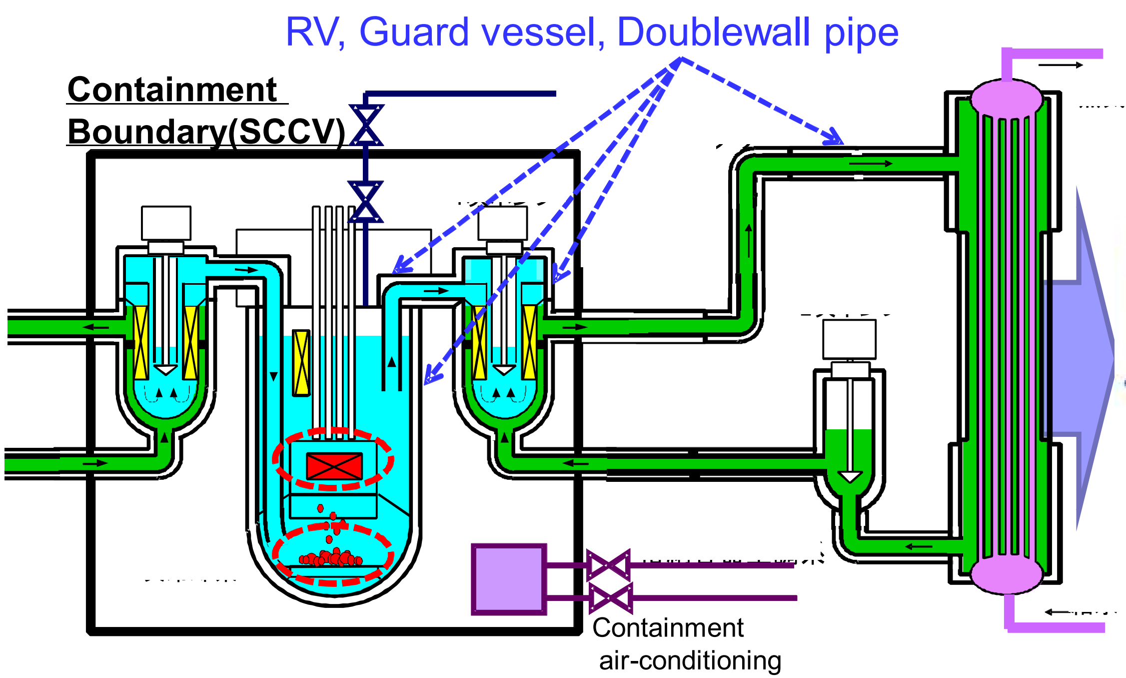
Challenge to CV	Assessment parameter	Mode of Sodium leakage and fire
Overpressure failure of containment boundary	Pressure in CV	Large spray fire
Local failure of containment boundary and following hydrogen deposition and combustion	Temperature of CV steel	Small/medium/large fire
Aging degradation of CV	Temperature of CV	Large pool fire

	Large spray fire	Small fire	Large pool fire
Sodium leakage mode	 Rapid temperature increase of CV atmosphere ⇩ Rapid pressure increase of CV atmosphere	 Local and long-time heating of CV steel ⇩ CV steel failure (Sodium-concrete reaction)	 Temperature increase of CV concrete ⇩ Loss of integrity of containment building
Assessment parameter	Pressure in CV	Temperature of CV steel	Temperature of CV concrete and duration time

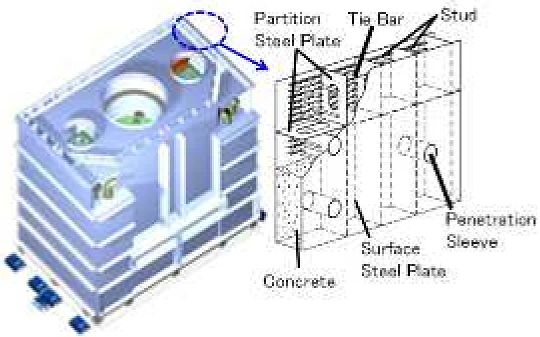
Measures to Sodium Fire

- Prevention of Hazard
  - Sodium Coolant Boundary – Double wall
    - Primary Circuits for Loop type, Secondary Circuits for Loop & Pool types
    - Limiting the break area in hypothetical guillotine break
    - Operational issues still considered – small leaks protected by steel liner, leak detection
- Mitigation of Hazard
  - Early detection is indispensable (for primary & secondary circuits)
  - Reduce/Eliminate the combustion
    - Inner gas environment or injection in sodium-piping rooms and/or containment
  - Reduce the amount of sodium leak
    - Early Sodium Dorian (Cooling capability still to be assessed)
  - For DEC, multi-failure to be considered

JSFR Designs



■ Adoption of SCCV

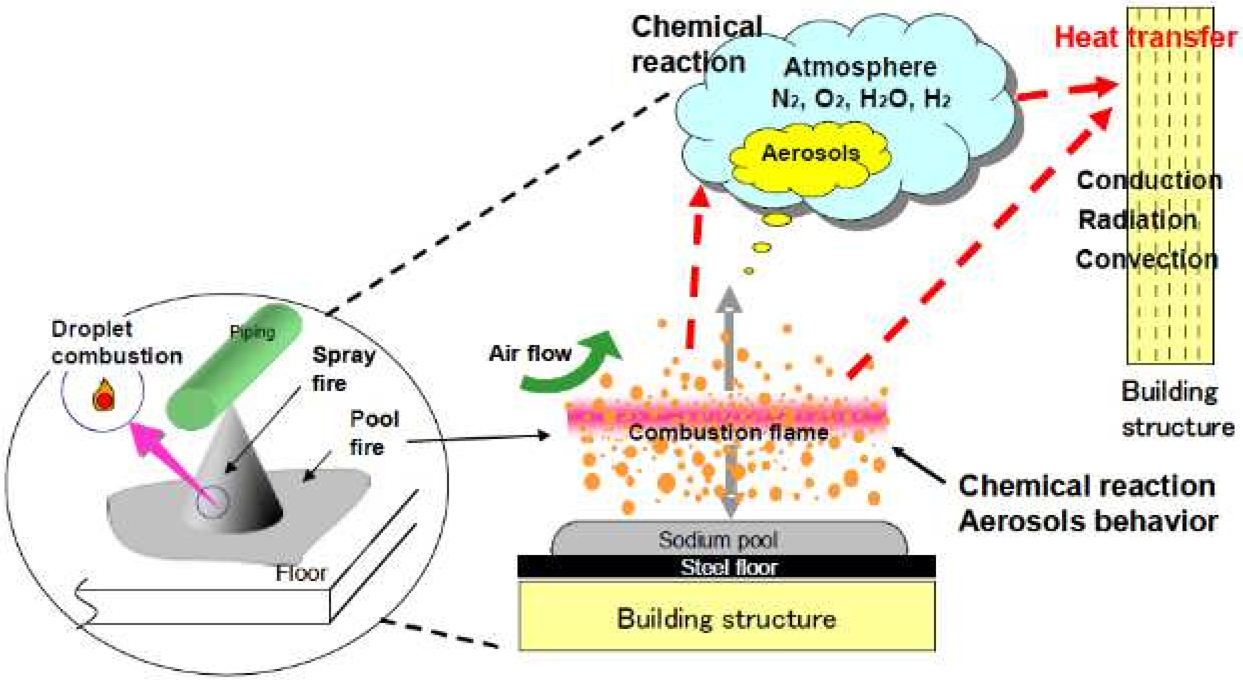


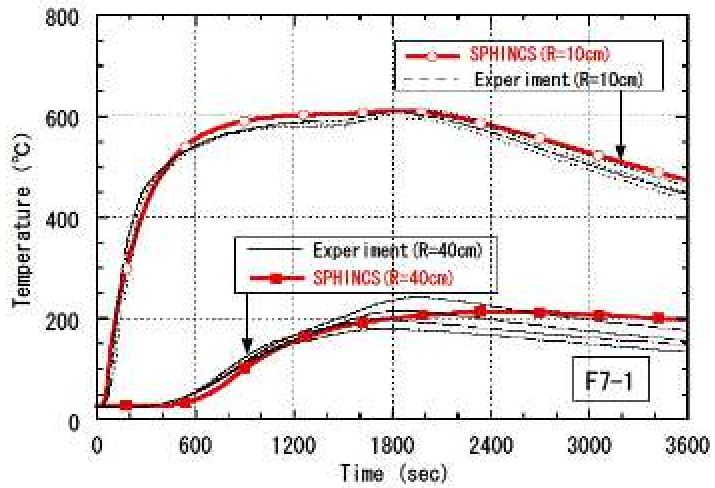
■ Air atmosphere

- Prevent sodium leak accident,
- Prevent deflagration/detonation of accumulated hydrogen which may be produced by sodium-concrete reaction
- Double boundary concept (double-walled primary & secondary pipes, a guard vessel for a reactor vessel) is adopted.

Assessment: SPHINCS Code

- Sodium combustion evaluation was carried out by the SPHINCS code developed by JAEA.
- SPHINCS code is based on mechanical / phenomenological models to deal with sodium spray and pool combustion simultaneously.





Code Validation with experiment
(3m^3 steel vessel, leak rate of 12 kg/h)

Assessment & Measures against Sodium Fire in JSFR

- Sodium Fire Assessments
  - Sodium Leakage from Primary Coolant System in Containment
  - Sodium Leakage from Secondary Coolant System in Containment/Reactor Building
- Candidate measures against Sodium Leakage from Secondary Coolant System
  - Double tube

  or

  - Sodium Drain + Nitrogen Gas Injection + Catch pan etc.

Remarks

- Approach to Sodium Chemical Reaction
  - Sodium reaction after leakage – Internal Hazard
  - Prevent the progress of the effects on “safety functions” by mitigating the consequences by sodium water/air reaction
- Key for Gen-IV SFR system
  - Ensure reliability of sodium contained SSC
  - More “preventive” approach to hazard occurrence
  - Incorporate progresses of knowledge & R&D results;
    - Hazard initiator, Hazard propagation…
  - DEC (i.e. multiple-failure)