Major Influential Phenomena on the Accident Progressions of Fukushima Daiichi NPP

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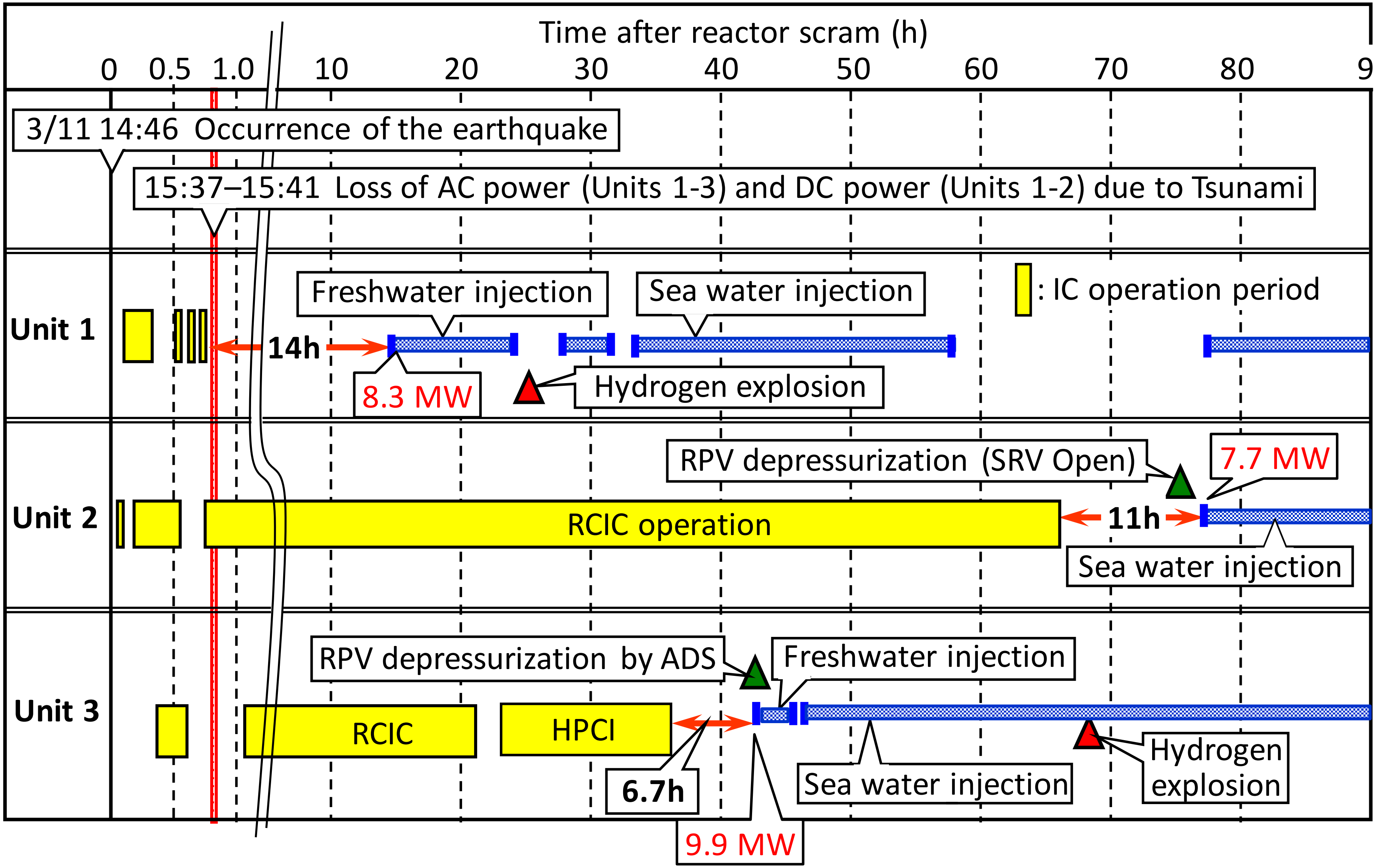
Introduction

- Core meltdowns occurred at Fukushima Daiichi NPP due to loss of AC powers at Units 1-3 and also loss of DC powers at Units 1 and 2.
- After the accident, the national project started to clarify the core status by means of simulation.
  - IAE: SAMPSON
  - Toshiba and Hitachi-GE: MAAP
    (as members of IRID: International Research Institute for Nuclear Decommissioning)
- Early phase of the accident at Fukushima Daiichi NPP has been analyzed by the SAMPSON code.
- For the accident analysis, the important issue is to define quantitatively the operative conditions of the plant equipment facilities during the accident.
- Primary analysis results could not reproduce the measured data at the plant, because some events and phenomena which have been deemed specific to the Fukushima Daiichi NPP did not modelled yet.
- New modellings for such events and phenomena was incorporated in the original SAMPSON.
- The analysis results with the improved SAMPSON code showed fairly good agreement with the measurements.

Time Line for Decay Heat Removal



Distinctive Phenomena of Fukushima Daiichi NPP Accident (1)

Direct steam release from RPV to D/W

(1) Buckling of ICM guide tube
(2) Leakage from SRV gasket, or
(3) Damage of MSL by creep

Leakage of D/W gas into reactor building

(4) Top flange gasket
(5) Equipment hatch
(6) Cable penetration

Increase of D/W, W/W pressure

(8) Thermal stratification and incomplete steam condensation in S/P
(9) H_2 generation due to Zr-H_2O reaction

RPV bottom break

(7) Earlier melt of ICM housing

S/P cooling

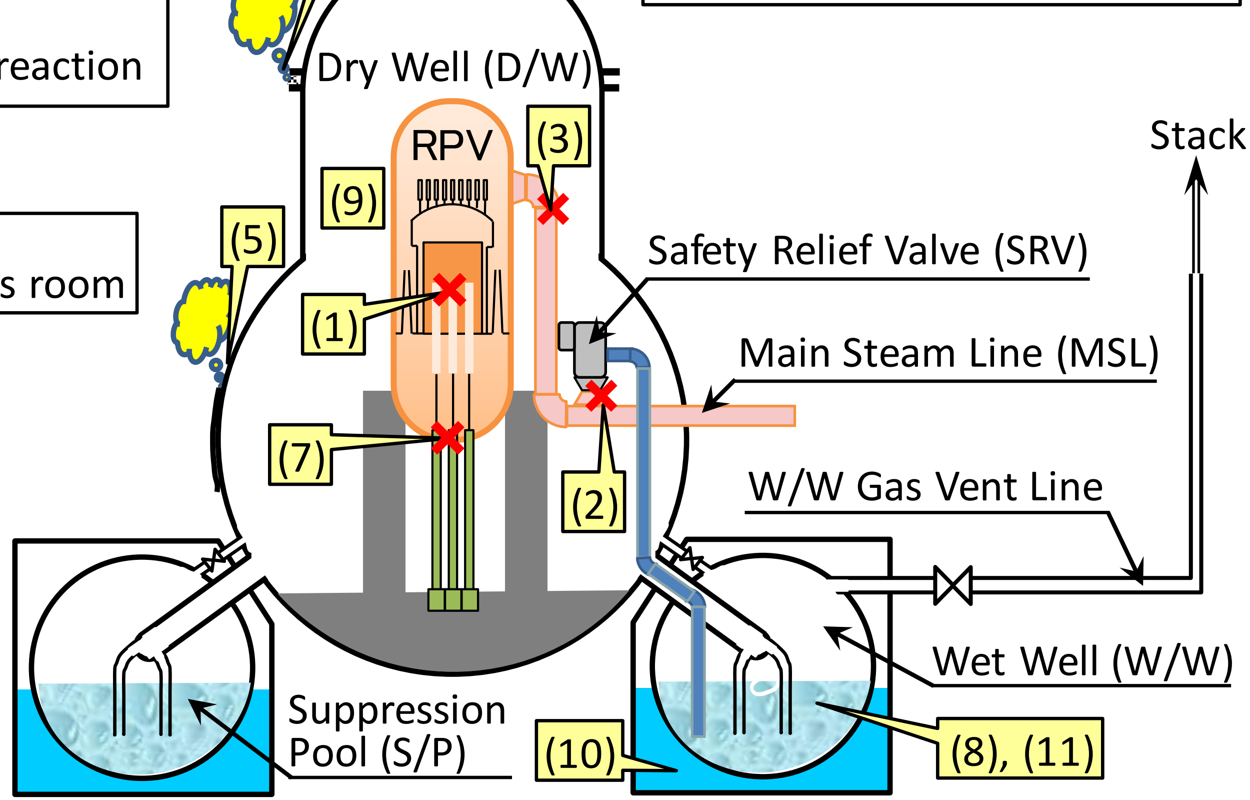
(10) Inflow of sea water into torus room

Not modeled in analysis yet

Decrease of scrubbing effect

(11) DF under high temperature

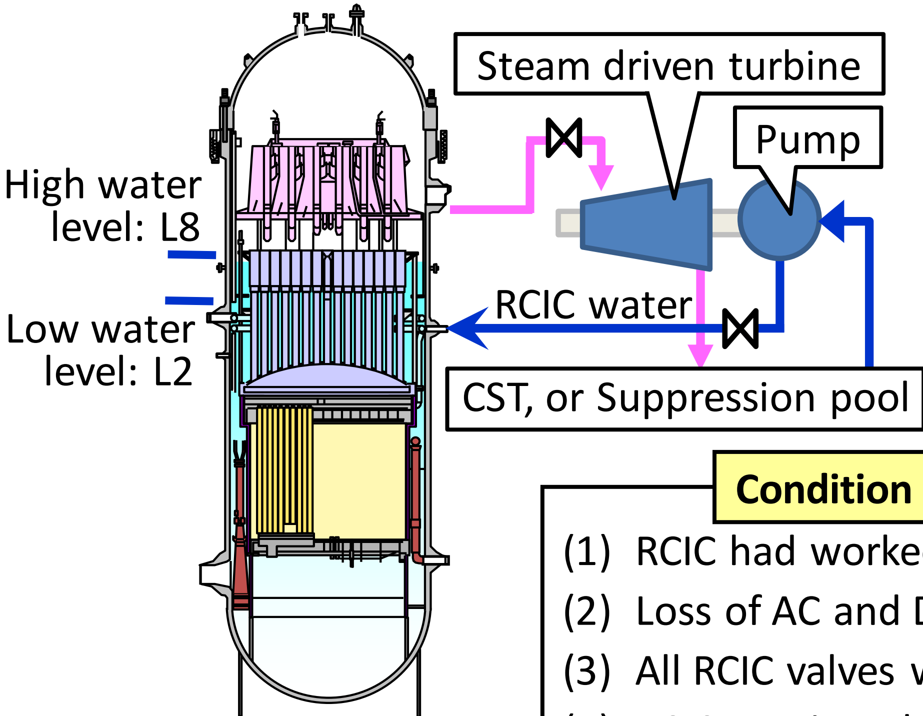
DF: Decontamination Factor



Distinctive Phenomena of Fukushima Daiichi NPP Accident (2)

- **RCIC of Unit-2 had worked for 66 hours after scram even under two-phase flow condition.**
- **RCIC Part load operation was modelled based on energy balance.**

RCIC: Reactor Core Isolation Cooling System



Original RCIC working logic
[Premise: Continuation of DC power supply]

(1) Transmission of L2 signal.
(2) Automatic start of RCIC.
(3) Transmission of L8 signal.
(4) Automatic stop of RCIC.

Condition during accident (No DC power supply)

(1) RCIC had worked until Tsunami. [RCIC valves were open.]
(2) Loss of AC and DC powers due to Tsunami.
(3) All RCIC valves were kept open. [No signal to close the valves]
(4) RCIC continued to operate without any control.
(5) RPV water level became higher than L8, reached MSL.
(6) RCIC had unexpectedly worked under two-phase flow condition.

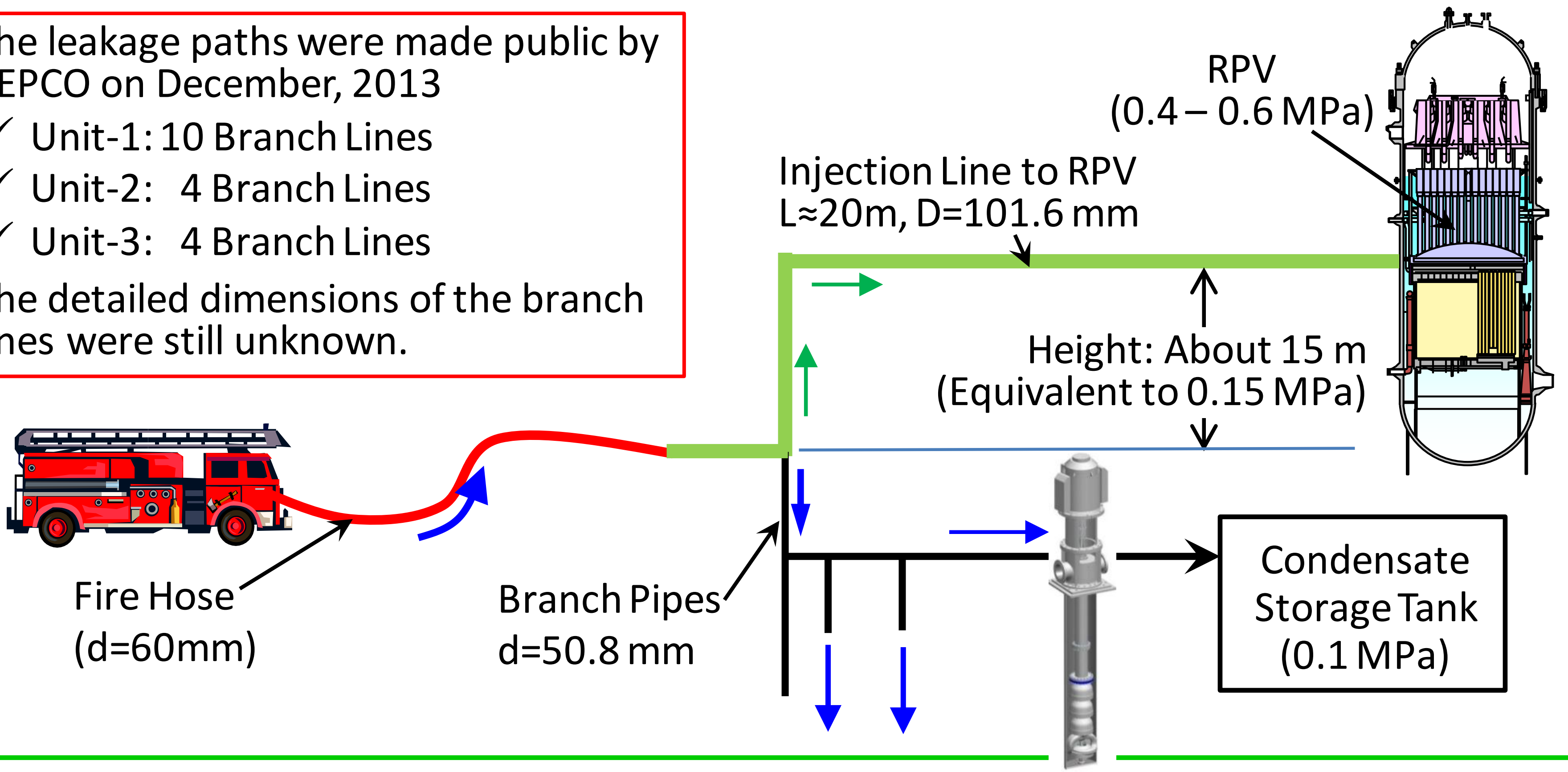
- **HPCI of Unit-3 had worked at around the lower limit of the design condition.**
- **It is still unknown whether it was stopped by operator's manual switch off or it stopped naturally when the pressure decreased to the lower design limit earlier than the operator's switch off.**

Distinctive Phenomena of Fukushima Daiichi NPP Accident (3)

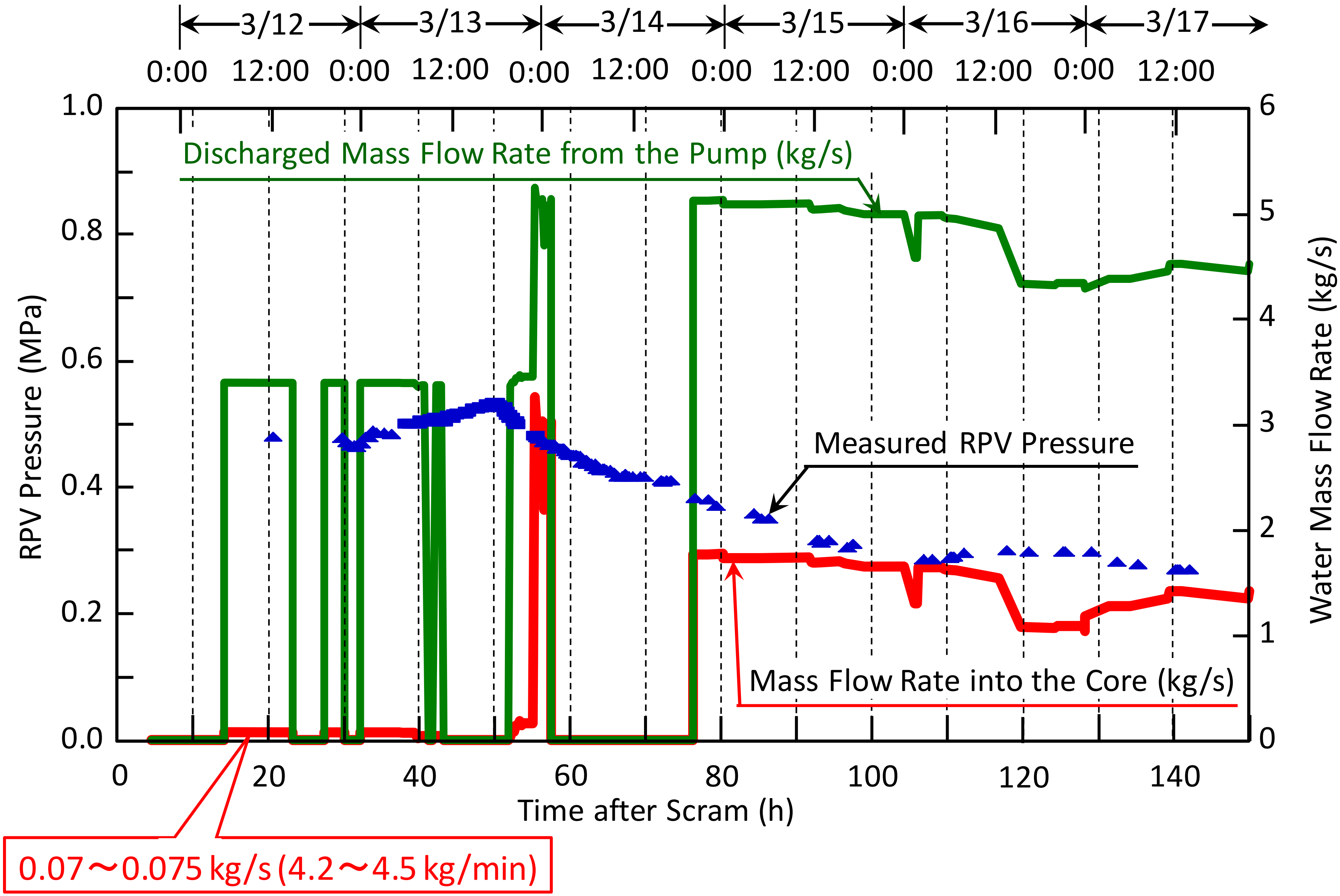
[Leakage of Alternative Water Injected by the Fire Pump]

- **The discharged mass flow rate from the fire pump was enough to remove decay heat, but a mass flow rate into the core was much less because of leakage from the branch pipes.**
- **A leak flow rate was calculated based on estimation of a pipe length, numbers of elbows, friction losses, and the pump Q-H curve. (Uncertainty still remains.)**

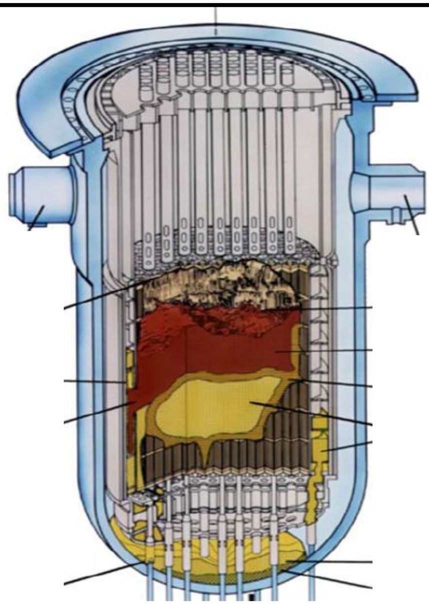
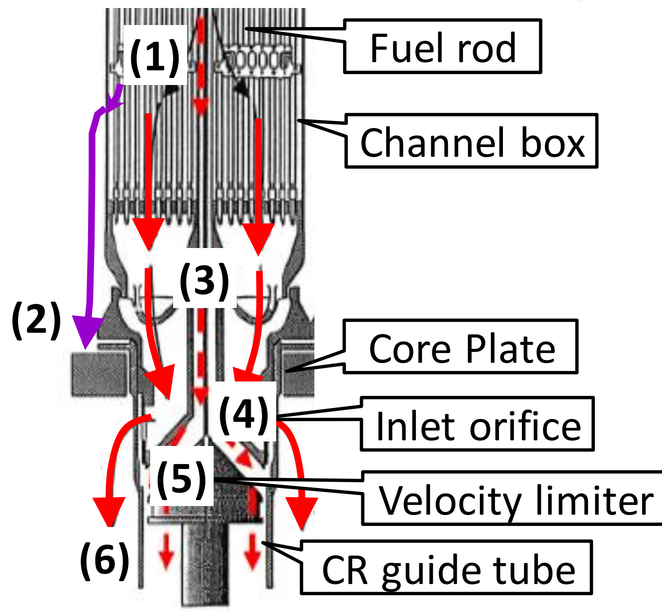
- The leakage paths were made public by TEPCO on December, 2013
  - ✓ Unit-1: 10 Branch Lines
  - ✓ Unit-2: 4 Branch Lines
  - ✓ Unit-3: 4 Branch Lines
- The detailed dimensions of the branch lines were still unknown.



Calculation of Mass Flow Rate of Water Injected into the Core (Unit-1)



Distinctive Phenomena of Fukushima Daiichi NPP Accident (4)-Debris Relocation Path

TMI accident	Fukushima Daiichi NPP accident
	
• Water level: above BAF [**Wet core**] • Melt surface was cooled by large steam generation in the core, resulting in formation of the dense crust.	• Water level: below BAF [**Dry core**] • Melt materials fall into the lower plenum through the continuous drainage pathways. • Some melts solidify on the core plate and on the velocity limiter.

Observed in the XR-test series at SNL*
*: *NUREG/CR-6527 (Aug. 1997)*

XR-2 Test Analysis with SAMPSON	Above Core Plate			Below Core Plate	
	(1)+(2)	(3)	(4)	(5)	(6)
Test	9%	11%	11%	37%	37%
Analysis	7%	15%	15%	28%	43%

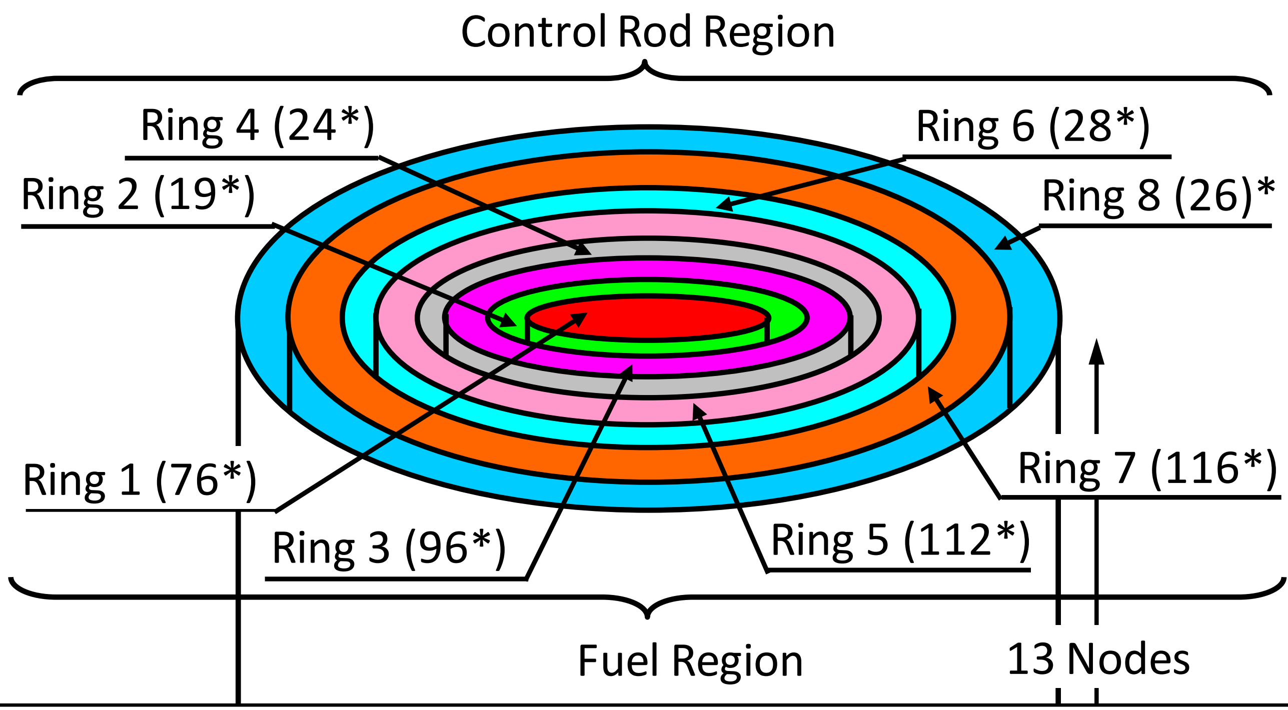
Note

Stainless steel, B_4C, and Zircaloy were used as melt materials in the test. (No UO_2 melt)

SAMPSON is a fully mechanistic code with modular structure.

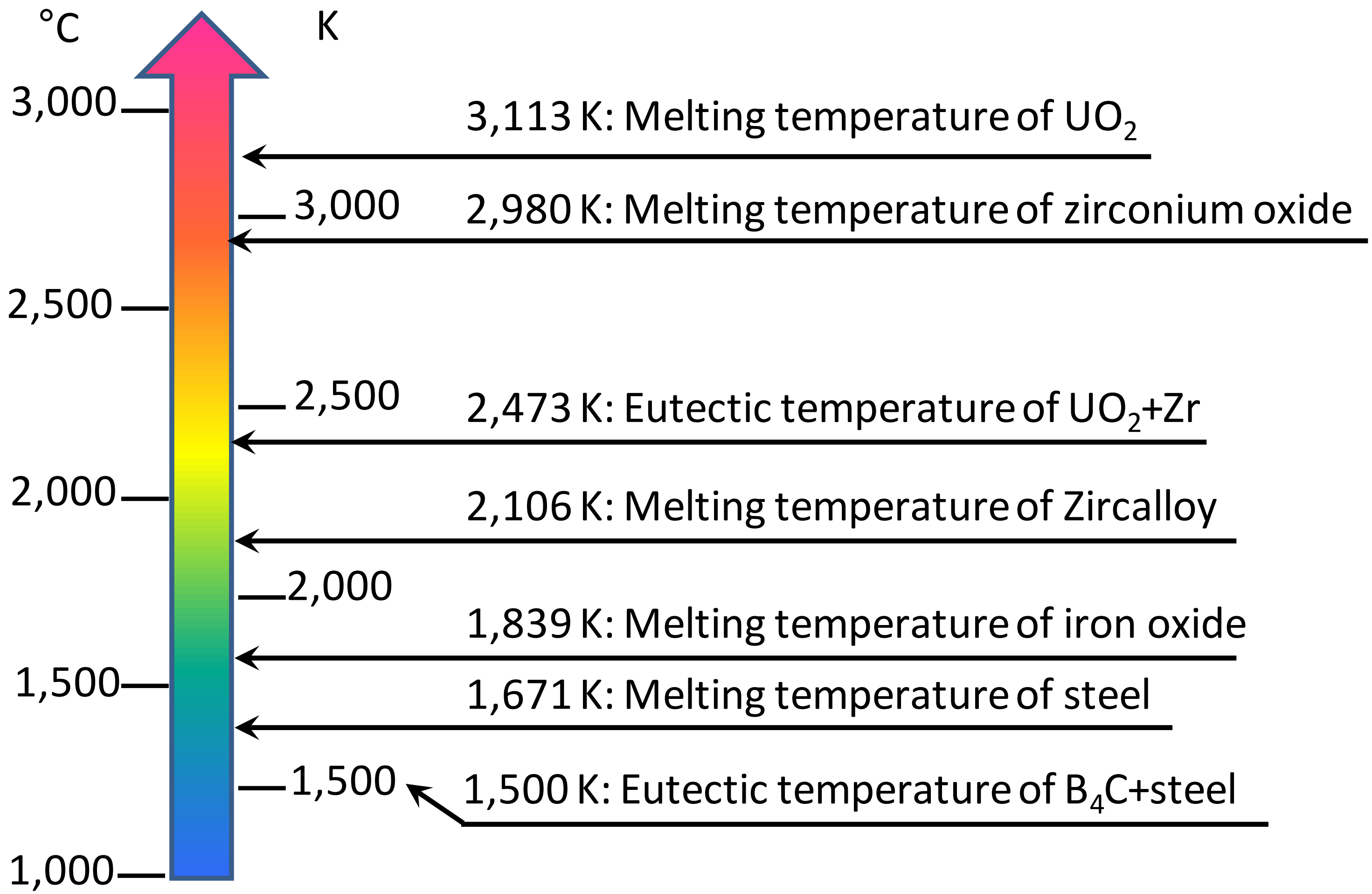
Node Division in Core Region

- *r-z* 2D coordinates
- Radially 8 rings and axially 13 nodes
  - 4 rings for the fuel region and 4 rings for the control rod region.
  - Axially 10 nodes were allocated to the active fuel region.

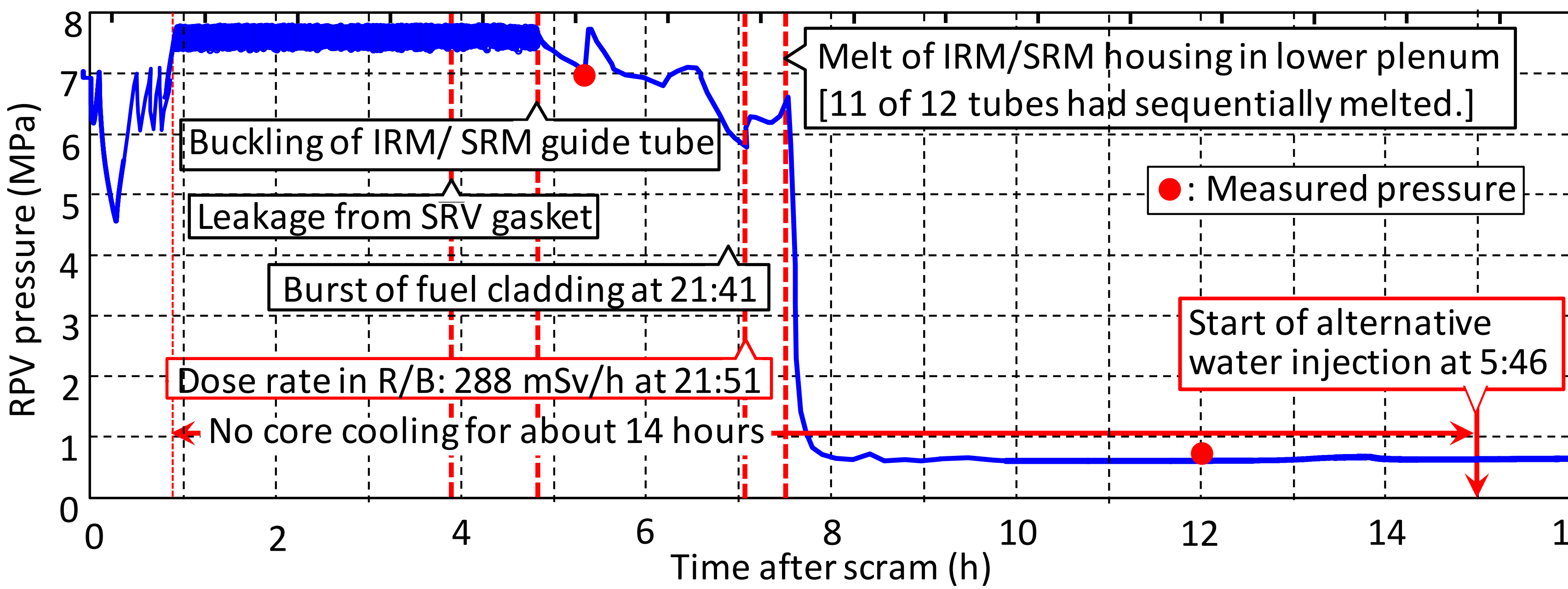


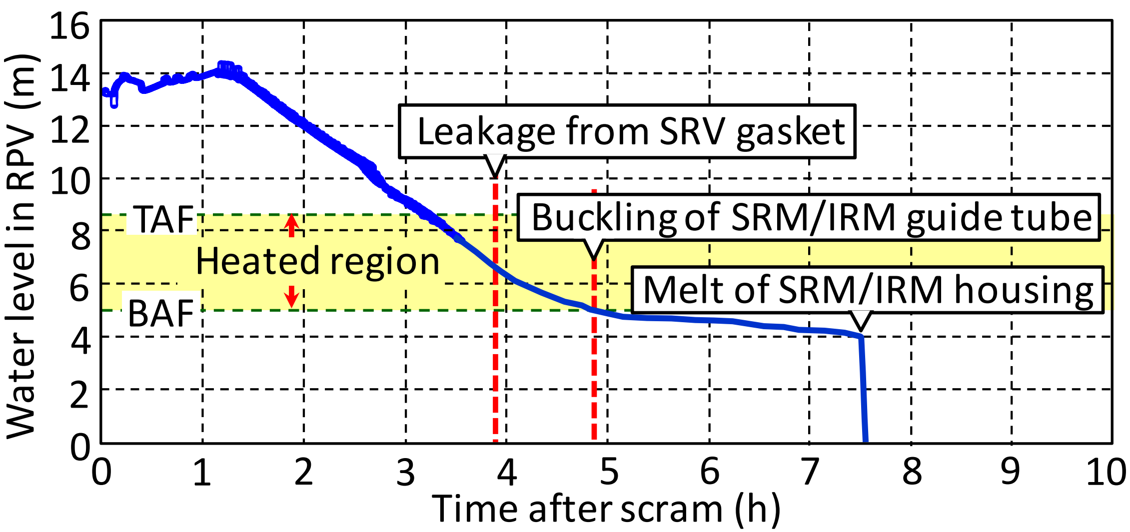
*: Number of fuel bundles or control rod blades included in each ring for Unit-1

Melting Temperature of Core Constituent Materials Considered in SAMPSON



SAMPSON Result for UNIT-1 – Pressure and Water Level

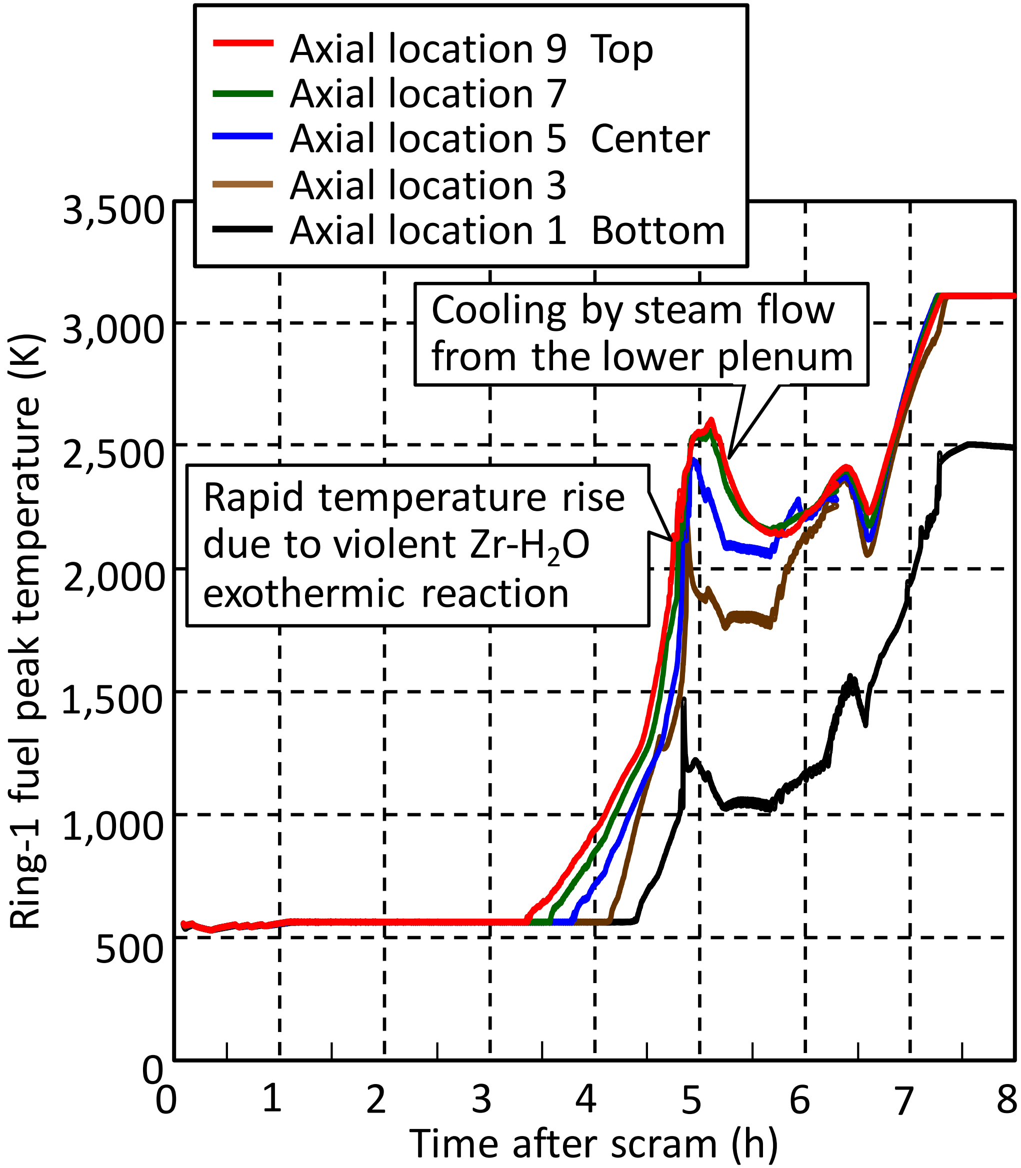




- MSL creep damage was not modelled in SAMPSON, but melt behavior of ICM housings was.
- IRM and SRM are In Core Monitors.

  IRM: Intermediate Range Monitor
  SRM: Source Range Monitor

SAMPSON Result for UNIT-1 – Core Melt and Relocation



Fuel Temperature Transient in the Ring-1

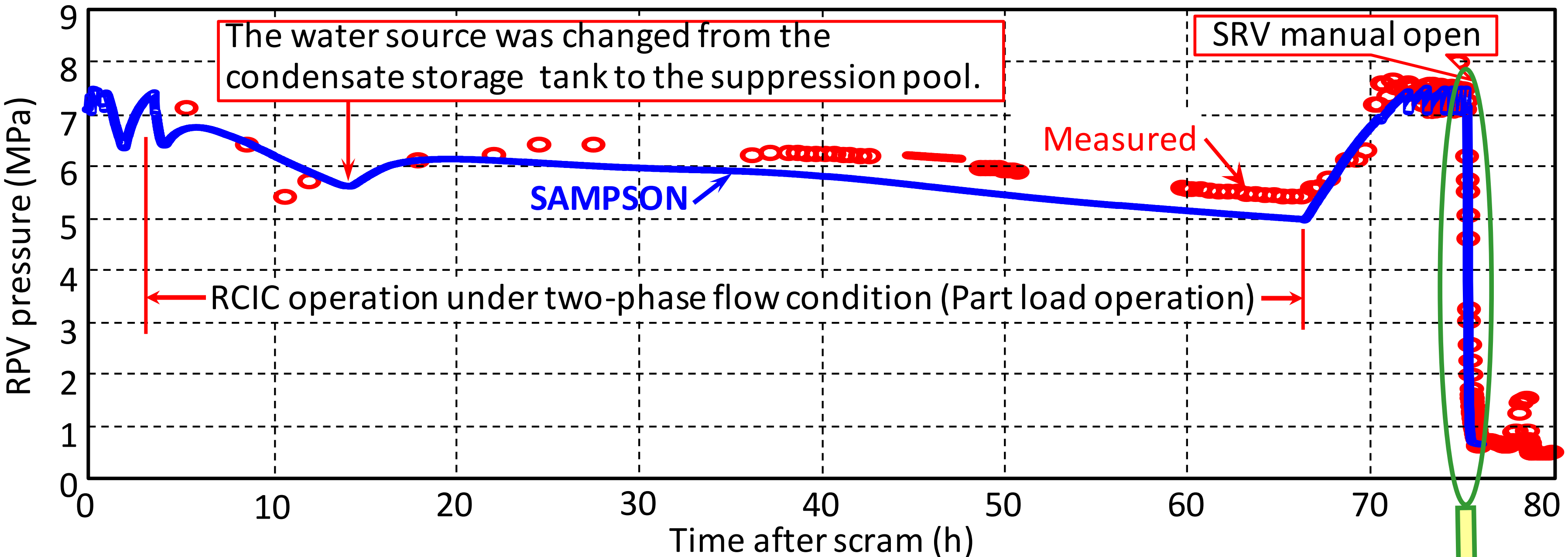
- Molten materials had already fell down on the pedestal at the start time of the alternative water injection, 15 hours after scram.
- Constituent of molten materials in the pedestal at 15 hours after scram

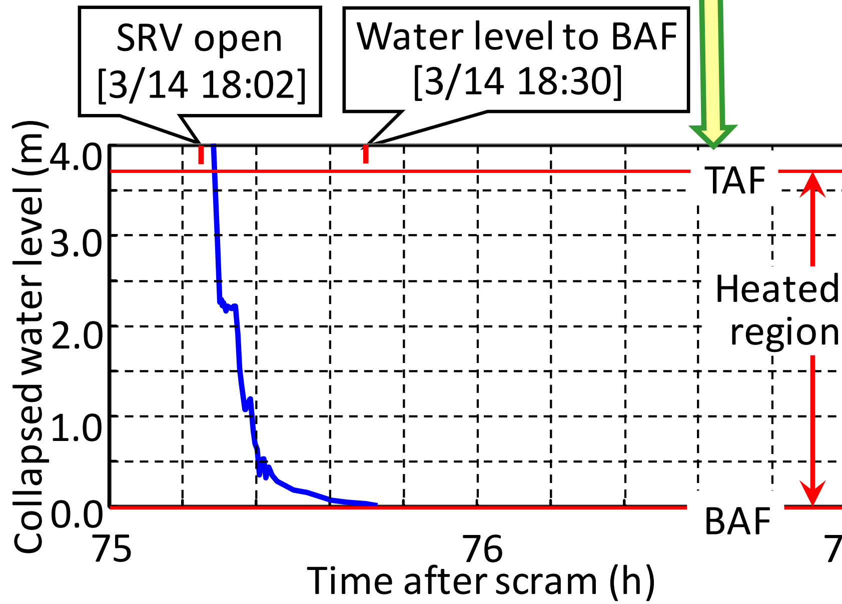
Fuel (UO_2)	56.5 ton (69%)
Zr	9.53 ton
ZrO2	11.4 ton
Steel	18.4 ton
Steel Oxide	2.69 ton
B4C	0.53 ton
Total	99.05 ton (77%)

Percentage means the ratio to the original mass at the time of scram.

- About 30% of fuel (UO_2) has remained in the peripheral region of the core

SAMPSON Result for UNIT-2 – Pressure and Water Level



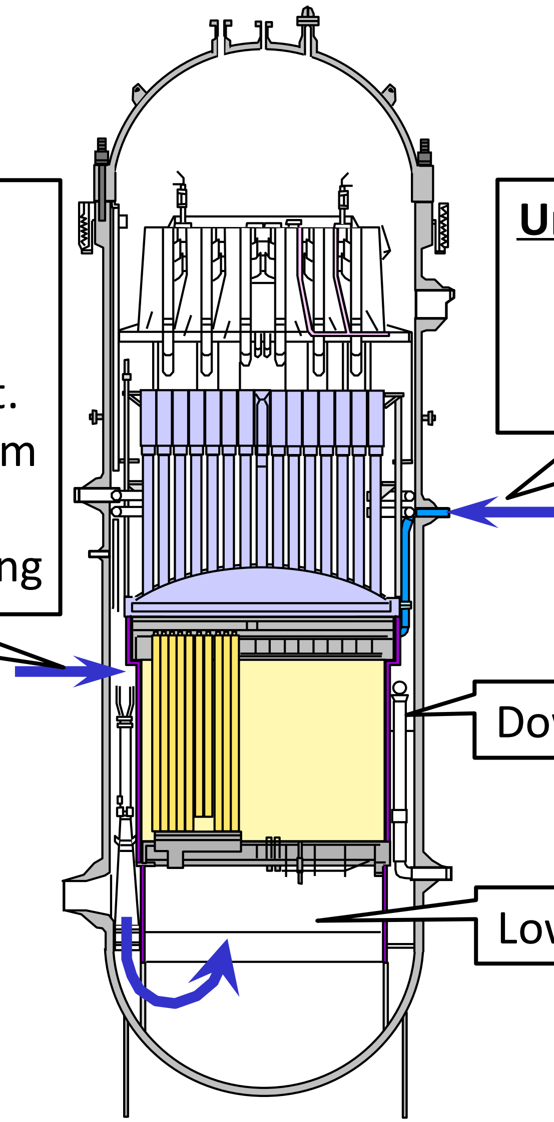


- 77.1 h after scram: Initiation of sea water injection
- 77.5 h after scram: Initiation of fuel cladding burst [FP release]
- 77.7 h after scram: Initiation of UO_2 melt by eutectic reaction with Zr
- Since the sea water was injected into the down-comer region, the lower plenum was filled up first and then the core was cooled by bottom flooding. This caused time delay for effective core cooling.

Route of Alternative Water Injection into the Core

<u>Units-2 and -3</u>

- ✓Water injection through the down-comer region.
- ✓The lower plenum was filled up first.
- ✓Then, the core was cooled by bottom flooding
  - ⇨ Time delay for effective core cooling



<u>Unit-1</u>

Water injection through the core spray line, directly into the core

Downcomer Region

Lower Plenum

SAMPSON Result for UNIT-2 – Core Melt and Relocation

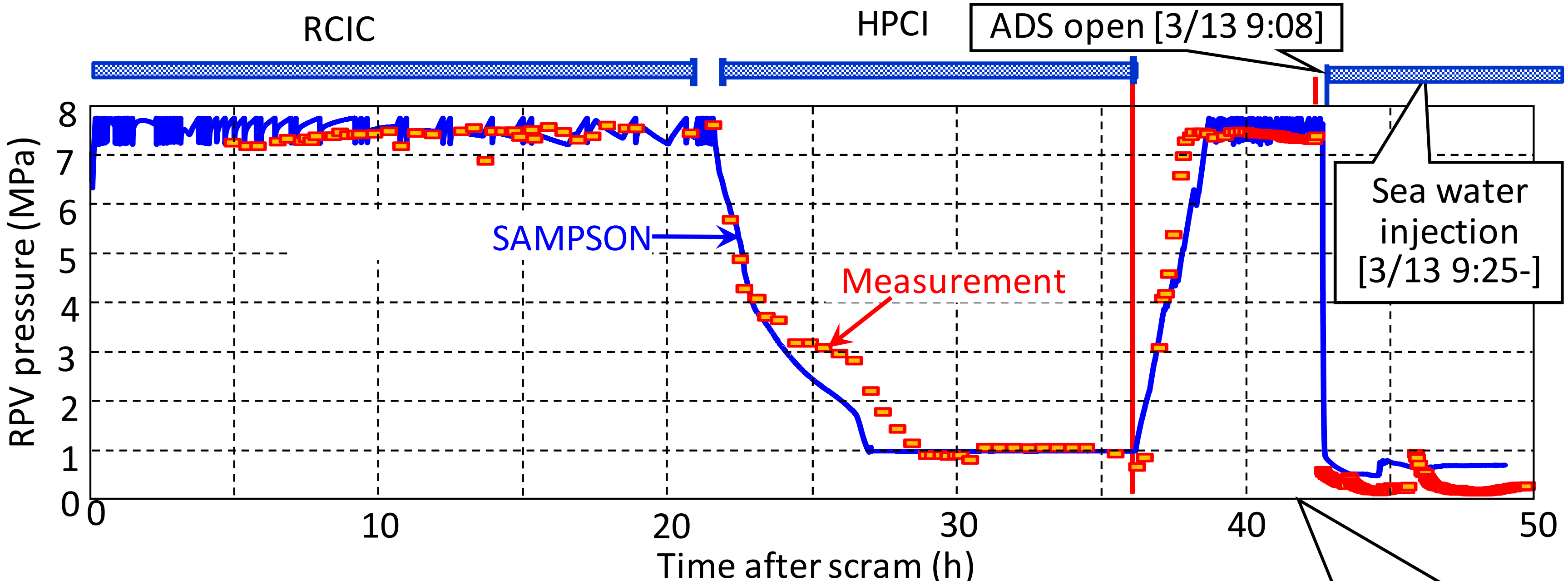
- After the core was completely reflooded at about 105 h by the sea water injection, the fuel temperature decreased to almost the saturation temperature of water.
- Since the RPV bottom was not damaged, all the melt materials accumulated in the lower plenum of the RPV.
- Constituent of molten materials in the lower plenum at 105 hours after scram

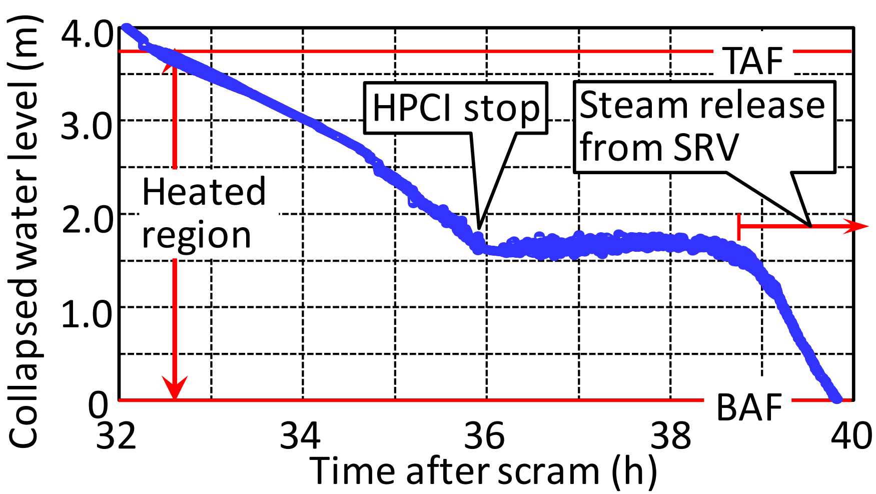
	In the Core	In the Lower Plenum	Total
Fuel (UO_2)	0.22 kg	6,271 kg (5.6%)	6,272 kg (5.6%)
Zr	0.39 kg	6,450 kg	6,451 kg
ZrO2	2.22 kg	18,103 kg	18,105 kg
Steel	801 kg	3,490 kg	4,291 kg
Steel Oxide	1,530 kg	4,877 kg	6,407 kg
B4C	276 kg	744 kg	1,020 kg
Total	2,610 kg (1.5%)	39,935 kg (23%)	42,546 kg (25%)

- There still are uncertainties which affect very much the melt behaviors.
  - Node division in core region [Finer node division, especially in *r*-direction, is required.]
  - Mass flow rate of sea water injected into the core

    Possible RPV bottom damage (IRM/SRM melt) if the mass flow rate would be slightly less than the current estimation.
  - Time delay for effective core cooling (water injection into the downcomer region resulting in bottom reflooding)
  - RCIC part load performance under two-phase flow condition

SAMPSON Result for UNIT-3 – Pressure Transient





At about 3/13 9:00
(just before the ADS open):

- ✓ Neutrons by spontaneous fission of ^{242}Cm were detected near the front gate of the site.
- ✓ This meant the occurrence of fuel cladding burst or core melt-down before this timing.

- **The water mass flow rate by HPCI under low pressure condition is very sensitive to the melt behavior.**

SAMPSON Result for UNIT-3 – Accident Progression

- 39.8 h after scram: Water level to BAF
- 41.7 h after scram: Initiation of fuel cladding burst [FP release]
- 41.8 h after scram: Initiation of melt of UO_2 eutectics
- 42.2 h after scram: Detection of neutrons
- 42.6 h after scram: Initiation of sea water injection
- 44.3 h after scram: RPV bottom break [IRM/SRM housing melt]
- Since the sea water was injected through the downcomer, effective core cooling was delayed.
- After the RPV bottom break, the injected water leaked through the breaks.
- Finally, all the core materials had melted down onto the pedestal.

  - It is still unknown whether HPCI was stopped by operator’s manual switch off or it stopped naturally when the pressure decreased to the lower design limit earlier than the operator’s switch off.
  - The injected water mass flow rate by HPCI under low pressure condition and by the fire pump are very sensitive to the melt progression, especially to the timing of the RPV bottom break and the amount of melts.

Conclusions

1. Distinctive phenomena of Fukushima Daiichi NPP accident
   (1) Direct steam release from RPV to D/W
   (2) Leakage of D/W gas into reactor building
   (3) Increase of D/W and W/W pressure
   (4) Cooling of S/P by torus flooding
   (5) RPV bottom break by earlier melt of ICM housing
   (6) Part load operation of RCIC of Unit-2 and HPCI of Unit-3
   (7) Leakage from branch pipes of discharged water from the fire pump
   (8) Decrease of scrubbing effect under high pool temperature

2. SAMPSON Results

<table>
<tr><th></th><th>Unit-1</th><th>Unit-2</th><th>Unit-3</th></tr>
<tr><td>RPV Bottom Break
Debris Relocation</td><td>Yes
70%
in Pedestal</td><td>No
25%
in RPV Lower Plenum</td><td>Yes
100%
In Pedestal</td></tr>
<tr><td rowspan="2">Major influential Factors
In-Vessel</td><td rowspan="2"></td><td colspan="2">✓ Water mass flow rate into the cores by the fire pumps
✓ Time delay for effective core cooling</td></tr>
<tr><td>✓ RCIC performance</td><td>✓ HPCI performance</td></tr>
<tr><td>Ex-Vessel</td><td colspan="3">✓ MCCI ✓ Leakage from PCV (Drywell and Wetwell) to R/B</td></tr>
<tr><td>Source Term</td><td colspan="3">✓ Large uncertainty (Chemical forms of fission products, Scrubbing effect, Deposition on wall, Integrity of components</td></tr>
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