Event Sequence After the Earthquake

June 28, 2011
ANS Annual Meeting, Hollywood, Fl., USA

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Sources

- http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety - The Accident at TEPCO's Fukushima Nuclear Power Stations - June 2011
- http://www.tepco.co.jp/cc/press/betu11_j/images/110618l.pdf 1F1 Tepco Press Release on the action taken immediately after the earthquake (in Japanese), June 18, 2011

- Reports from Tepco, NISA, NSC, etc
- AESJ Special Committee on Fukushima Accident
- USNRC Boling Water Reactor GE BWR/4 Technology, Technology Manual

Introduction

- March 11, 2011 M9 the Great East Japan Earthquake and Tsunami
- 15,365 dead + 8,206 missing as of June 5, 2011
- Almost 100,000 refugees from the quake and tsunami

- ~80,000 evacuees from Fuk-I NPS (within the radius 30 km)
- The earthquake caused:
  - The loss of off-site power initiating event
  - Severely hampering recovery activities because of the damage to the local infrastructure
  - Possible seismic damage to the piping systems and concrete that may never be known, in some cases, because of the damage caused by the tsunami and hydrogen explosions

- Tsunami “unforeseeable”?

Tsunami unforeseeable?

- NPP was unprepared for tsunami of 14 m high. As a result:
  - All power sources lost;
  - Most of the safety systems of all units damaged simultaneously (multi-unit effect); and

    subsequent events in one unit gave influences to other units (ex: H_2 migration and explosion; contaminated water into the other units)
- Long term Station Blackouts (SBO) was not assumed in a hope that the off-site power and/or DG would be restored soon
  - Insufficient safety considerations for severe accidents
- Was it a disaster that exceeded all worst-case scenarios?

"Yes" but the unexpected should have been expected

Defense-in-Depth should have been provided for the unexpected

What happened to Fukushima-Daichi NP Station – an outline

What went wrong and how likely was it

Focus on the events during the station blackout

DHR before Tsunami with AC power

- Shutdown upon the earthquake, followed by LOOP
- Main Steam Line Isolation Valves closed (loss of either AC power or DC triggers MSIV closure in Fuk-I units)
- With MSIV closed; DG started up (AC power available)

  (In case with MSIV open, the steam bypasses the turbine and condensed at the Feed Water Condenser)
- Added enthalpy (corresponding to decay power) pressurizes RPV
- For Unit-1, the vapor condenses at the Isolation Condenser (IC) and returns to RPV by natural circulation.
- For Unit-2 and -3, the vapor, after working at RCIC turbine, condenses in S/C
- Pressure Relief Valves (PRV) ~~or Automatic Depressurization System (ADS) valves~~ opened and the vapor produced by the added enthalpy in the core is moved to S/C
- **S/C water was pumped to and cooled by RHR heat exchanger; the heat was dumped to sea eventually**

Overview of the event sequence (after tsunami)

- After LOOP, SBO due to tsunami and subsequent loss of ultimate heat sink except for Unit-1 with IC
- Eventual loss of core cooling, still at a higher decay heat level, i.e., one day after SBO for Unit-1, ~2.5 days for Unit-3 and in ~3 days for Unit-2, resulted in:
  - Rapid loss of coolant;
  - Core exposure [tens of minutes];
  - Fuel melt;
  - Progression into core melt and meltdown, and possible melt-through

    All in less than a few hours
- Hydrogen explosions following the ventilation or due to leakage to RB, leading to release of radioactive materials (March 12, 14 and at max on March 15) and to damaging many countermeasures in place or in preparation
- All PCVs damaged and failed to confine radioactive materials [hrs]

Where did the decay heat go?

- Evaporation was the only mechanism to remove decay heat from the core
- Isolation Condenser (IC) removes the heat passively and returns the condensate to the core (Unit-1)
- RCIC pumps send the CST water into the main feed water line for make up and cooling the core (Unit-2 and -3)

- When RPV over-pressurized, the vapor released into S/C through Pressure Relief Valve (PRV) opened → (Note: ADS did not work)
- Decay heat transported to the S/C could not be transported to RHR (– service water line closed w/o DC power; no AC power to RHR pump): UHS loss

- All the decay heat stayed within PCVs; nowhere else (except for 1F1)
- Note: IC provides an ultimate heat sink outside PCV. This worked as evidenced in Unit-1. An improved Isolation Condenser system would be the key to survive the long term SBO and would be recommended to be equipped on the other BWRs. (as done for ESBWR)

∴ Require DHR w/o AC/DC power

- With DC power lost, termination of IC (or RCIC) resulted in a rapid core exposure and fuel melt ---- *Unit 1*
- With DC power continuously available (recharged or replaced or ..), the core would survive until RHR is restored (2F NPS) or until the S/C water starts boiling and eventually fuels start melting ---- *Units-2 and -3 of 1F*
- As RHR or other alternative heat removal system did not work even with DC and AC power recovery,

  decay heat removals (DHR) under the SBO condition require ***DHR systems that do not require electricity***

- Current GEN-III+ and SMRs meet this requirement; so do sodium cooled fast reactors ~~and SMRs~~
- One of the strong candidates to overcome the long-term SBO is Natural Circulation Decay Heat Removal (NCDHR) system
- NCDHR system should survive the earthquake and tsunami as the added defense in depth

Long term SBO
First three days at 1F NPS

How they could not cope with long-term station blackout

What went wrong and how likely was it

Daiichi vs Daini

Note:

Daiichi（第一）is No. 1 or First;   1F

Daini (第二）is No. 2 or Second;   2F

Ex. Unit-2 in Fuku-1   1F2

2F NPS

- Quick action saved the NPP (by an on-duty manager)
  - 3 out of 4 power lines failed at the quake
  - Off-site power taken away from one of four units under operation
  - Diesel generators at Daini were soaked by sea water
  - An on-duty manager quickly acted and distributed the remaining power line to the unit w/o power
- How was it saved?
  - Core cooling was made by RCIC without S/C cooling mode in 3 units (RHR not available at the beginning except for Unit-3)
  - Units-1, 2 and 4: Just in time before the water in S/C started boiling, **RHR was restored** and **so was the S/C cooling mode**. The decay heat removals to the sea was successful and NRx's have made a narrow escape from core damages

Where make-up water available for core cooling after tsunami?

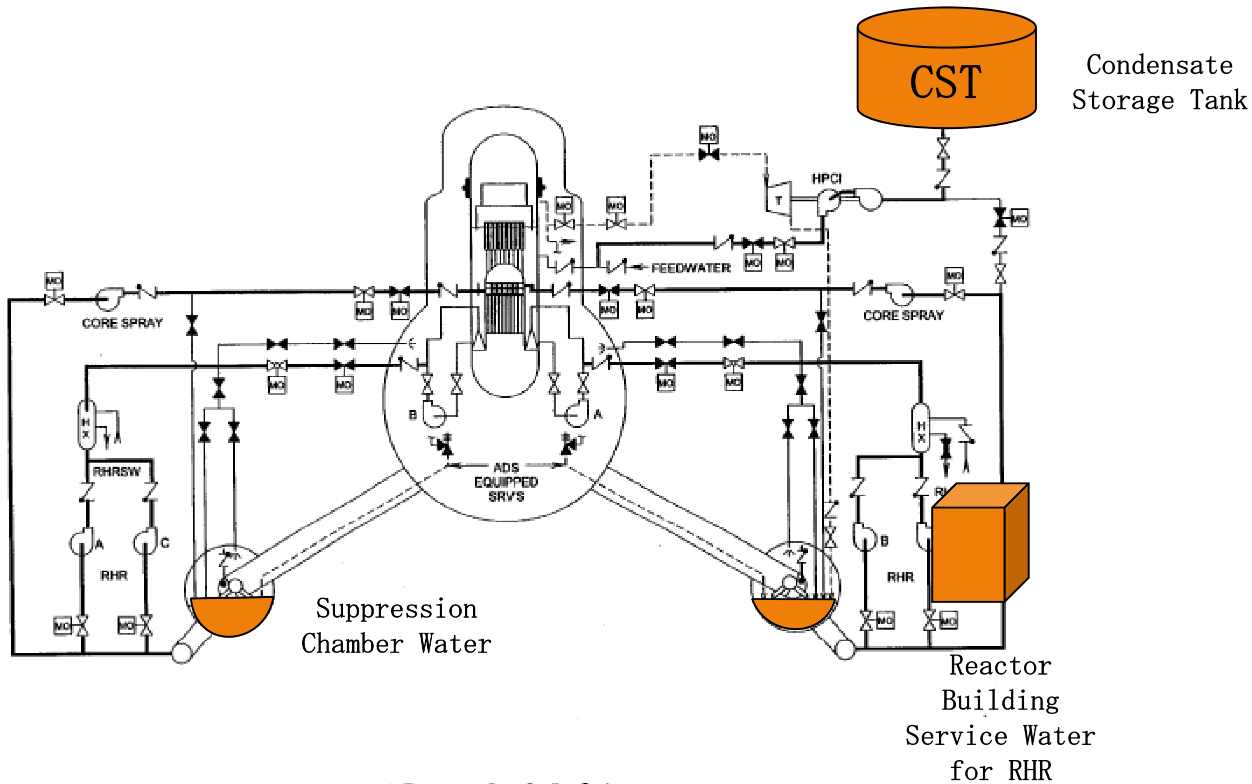


Figure 10.0-1 Emergency Core Cooling System

Source: USNRC Boling Water Reactor
GE BWR/4 Technology
Technology Manual

IC and RCIC

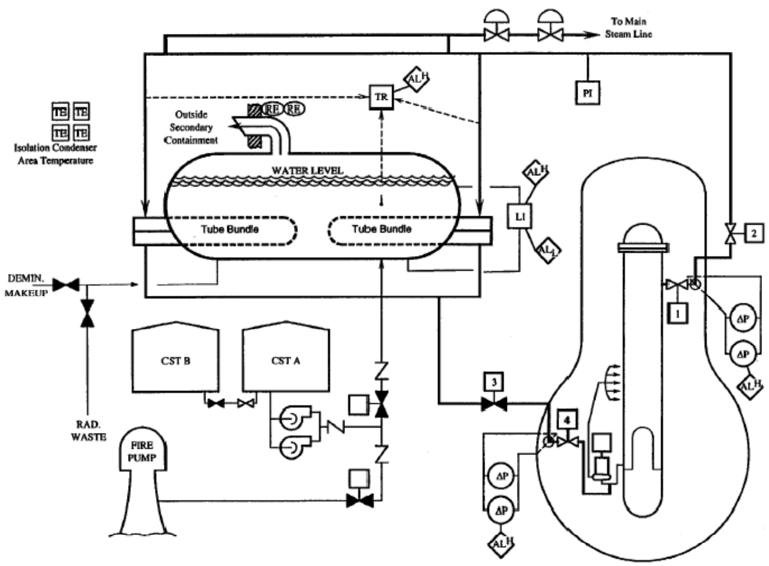
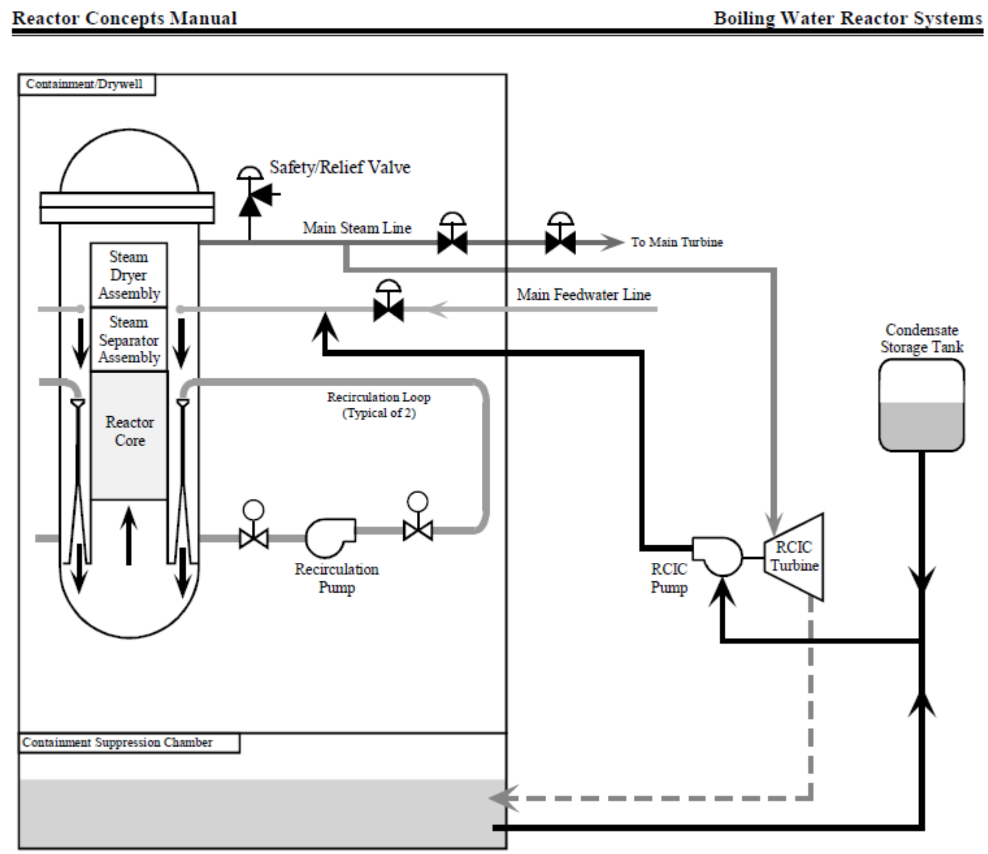


Figure 6.3-1 Isolation Condenser System (BWR/2/3)

Isolation Condenser



Reactor Core Isolation Cooling

Source: Boling Water Reactor (BWR) Systems
USNRC Technical Training Center

ECCS Available?

Unit	#1	#2	#3
IC	Y	-	-
RCIC	-	Y	Y
HPCI	N	N	Y
LPCI	NA	NA	NA

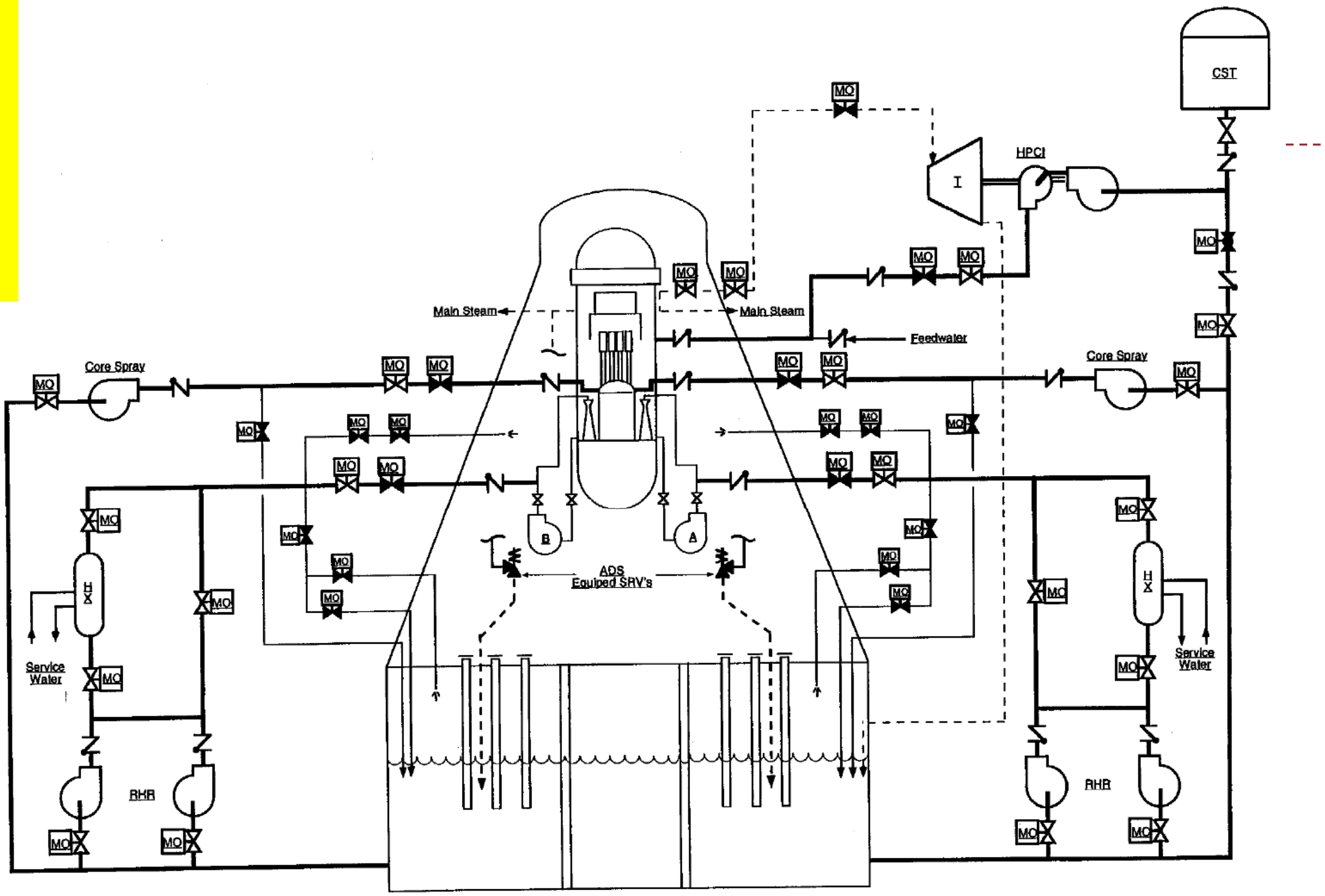


Figure 10.0-1 Emergency Core Cooling Systems

RHR

Source: USNRC Boling Water Reactor
GE BWR/4 Technology
Technology Manual

Core cooling after tsunami:
A summary of the system responses until core melt

Unit	#1	#2	#3
DC source	**Lost in tsunami** Battery charger; panels -- unavailable	**Lost in tsunami** (but not all; DC power available for RCIC)	Battery survived tsunami (dead after ~10 hrs)
Make-up water:	IC feeds the condensate into the RPV; (IC shell side from service water. With fire pumps @ 6 am~ 3/12: 80 ton in 9 hrs)	RCIC from CST	RCIC from CST
Condensation at:	IC tube side	S/C	S/C
Coolant injection and core cooling chronology :	IC automatic startup (two trains); Manual stop ~330PM [-100° C/hr] (then tsunami; activated later – results unknown; refill water at night)	3/11 1502 RCIC on ← in spite of the battery lost; with backup batteries plugged? *Lasted ~70 hours by (est) good on-off battery management*!	3/11 1506 RCIC on 3/12 1136 RCIC off 1230 HPCI on
Core cooling lost and major events that followed:	3/11 IC unknown (~1930 TAF uncovered: est) (~2000-2100 core melt starting: est) 3/12 5 am (radiation ext high in RB and TB) PCV vent delayed --- PCV failure 6 am core meltdown suspected 1430 First vent 1536 H_2 explosion	3/14 1325 RCIC off 1800 TAF uncovered 1900 whole core exp fuel melting; (21 hrs to core meltdown) 3/15 6 am (H_2 expl? near S/C) 2000 a large fraction of the core meltdown to the RPV bottom head (est)	3/13 0242 HPCI off ~ 7 am TAF uncovered (20 hrs to core melt d) 3/14 ~ 3 am whole core melt down ~ 11 am H_2 detonation

1F1 Timeline: Isolation Condenser 1

1503 IC (two trains A and B) terminated following the operation manual. Tepco decided to operate just the Train A. Single train operation was considered sufficient to depressurize and cool the core and RPV.

1537 SBO: Right after the tsunami, Tepco confirms that DC source was not available for the two trains of IC.

The highest priority was put on recovery of DC power for instrumentation and control of IC. Efforts were made to look for batteries and cables on the site.

Availability of batteries for IC and HPCI was unknown until 1818. On-site power source vehicles were operated and connected to power panels of Unit-2, but not to Unit-1 since the power panels of Unit 1 and 3 are soaked by tsunami water. No chance for the batteries to be recharged.

1818 Found the control panel IC lamp was on. DC power came back (temporarily?) available for IC; then, opened the MO-V (Motor Operated Valve) and then 7 minutes later, 1825: closed for some reasons. It was closed until 2130.

(It was estimated that fuel damage started around 1930~ but not likely yet)

1F1 Timeline: Isolation Condenser 2

1730 Diesel pump for fire protection was in stand-by position

Valves on core spray line were opened by hands to reduce RPV pressure to 0.69MPa before 1730

2019 Water level +200mm TAF

2007 RPV pressure back to 6.9MPa

2119 RPV Water level indicator (Unit-1) became readable +200mm top of the active fuel (TAF)

2130 IC MO-V was open again. Steam was found to rise from the reactor building (RB).

Speculation: IC was working until midnight as there is no report on closing the valve or any damages to the IC system.

Loss of the IC function would be a key to understand onset of core degradation and at this moment, there is no sufficient information on when it was lost. This should be a highlight in the investigation.

2200 Tepco found the water level of Unit-1 core is still above TAF region by +550 mm (if the reading was trustable.)

1F1 Timeline: venting order and water injection

2300 However, radiation level of turbine building (TB) was getting higher and higher. This implies the fuels are damaged seriously by this timing.

2350 PCV pressure 0.6MPa (D/W)

<u>3/12</u>

0006 Prepare for PCV venting

0245 RPV pressure low at 0.84MPa

0455 Radiation level at the main gate was high (0.069 μSv to 0.7 μSv in 20 minutes)

PCV failure was noted.

0546 Water injection started using the Fire Protection Line by Fire Pump; 80 tons until 14:53

1453 Water injection ended. AC power vehicle source was connected to the SLC (Stand-by Liquid Control) line and borated water injection was ready but the SLC line was destroyed by H_2 explosion 1536

Seawater injection order was made immediately but took 4 hours to start injecting seawater at 1904. 3 fire engines in series to increase the pumping power.

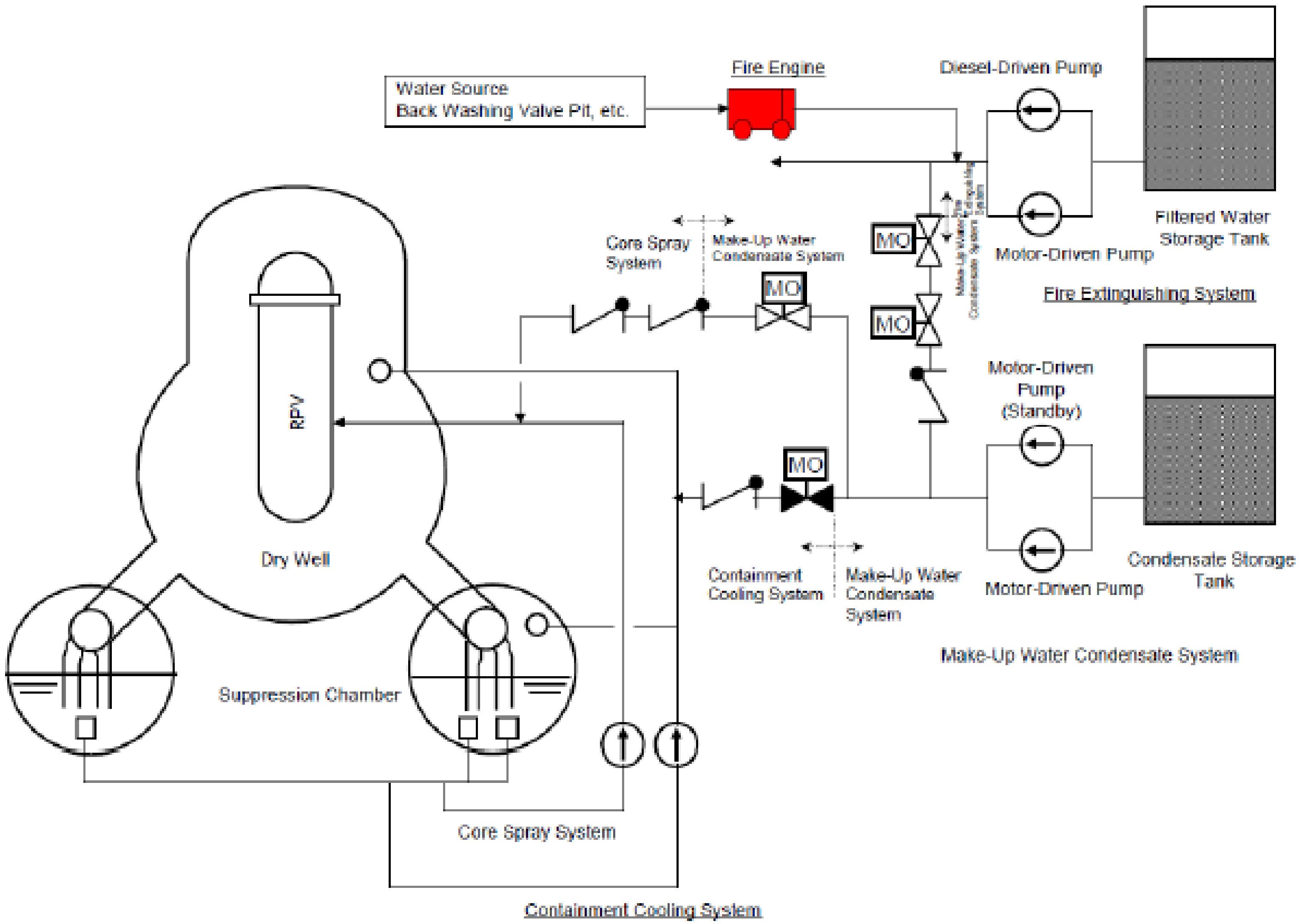


Figure IV-4-1 Conceptual Diagram of Alternative Water Injection Using Fire Engines

1F1 Timeline: Venting delayed

The venting order was delayed until 6.50 am and then didn't succeed until 14:30

3/12

0006 Prepare for venting

Needed to struggle with high levels of radiation

0230 D/W pressure 0.84MPa abs (.74 MPa gauge >> 0.427MPa gauge)

0903 Confirmed evacuation completed (O-kuma town)

0924 Head for the Torus where S/C AOV is located

Manually open the AOV

1017 ?

1023 ?

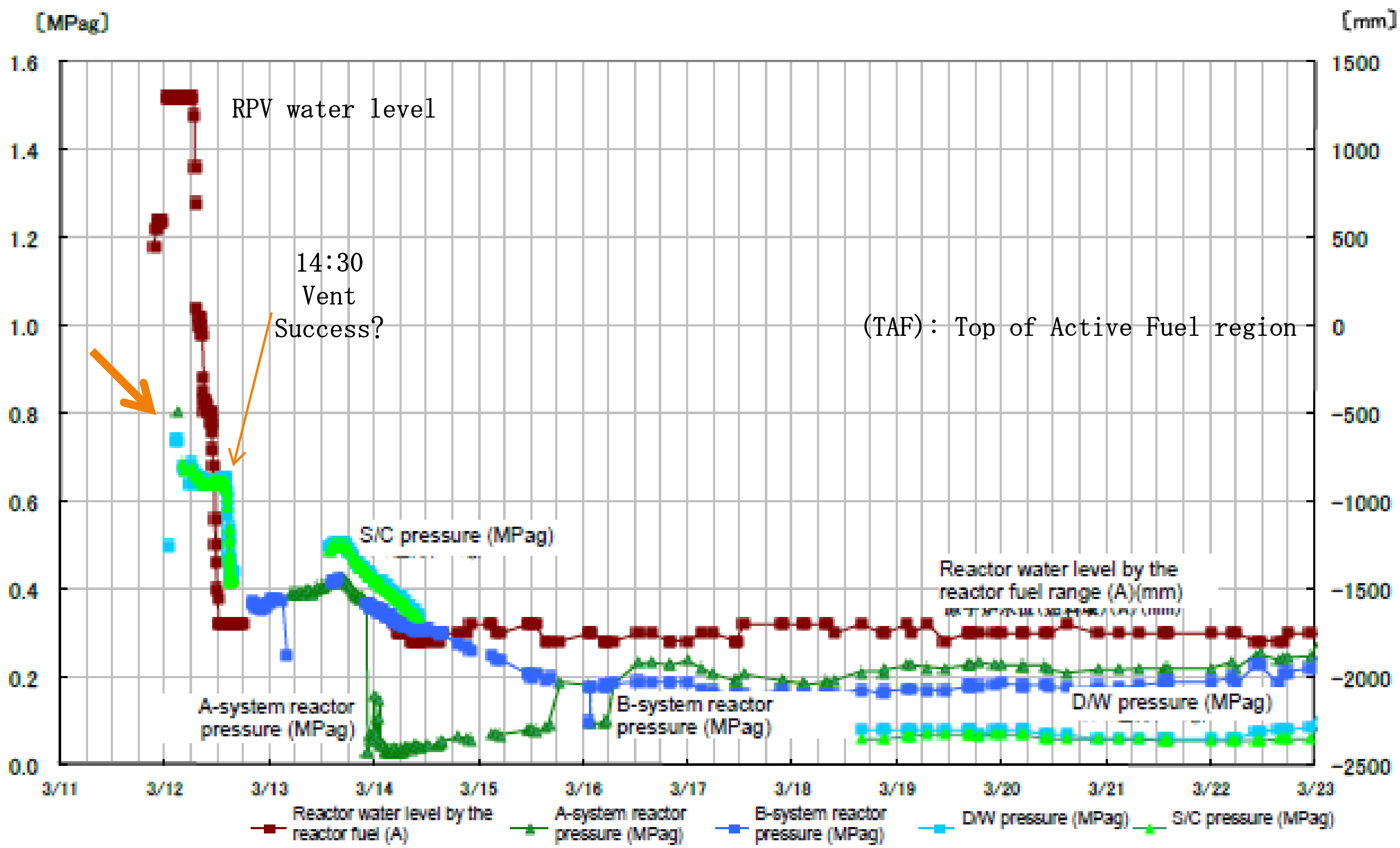
1024 ?

1400 Compressor connected

1430 D/W pressure decresed from 0.75MPa to 0.58MPa (still > 0.43MPa)

1536 H2 explosion (H2 maigrated to RB 4th floor through CV flange/airlock, or SGTS – RB vent line?)

1F1 Water level and S/C and D/W pressure



1F1 Temperatures (March 21~)

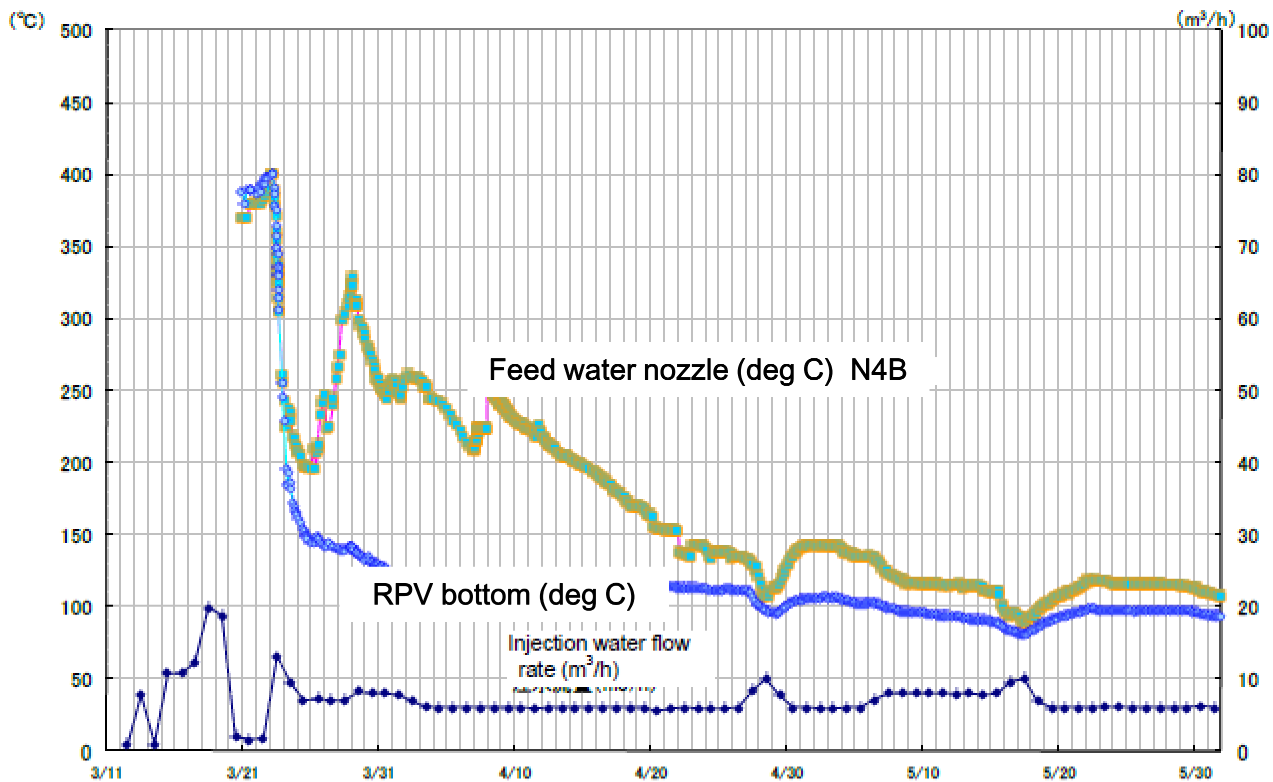
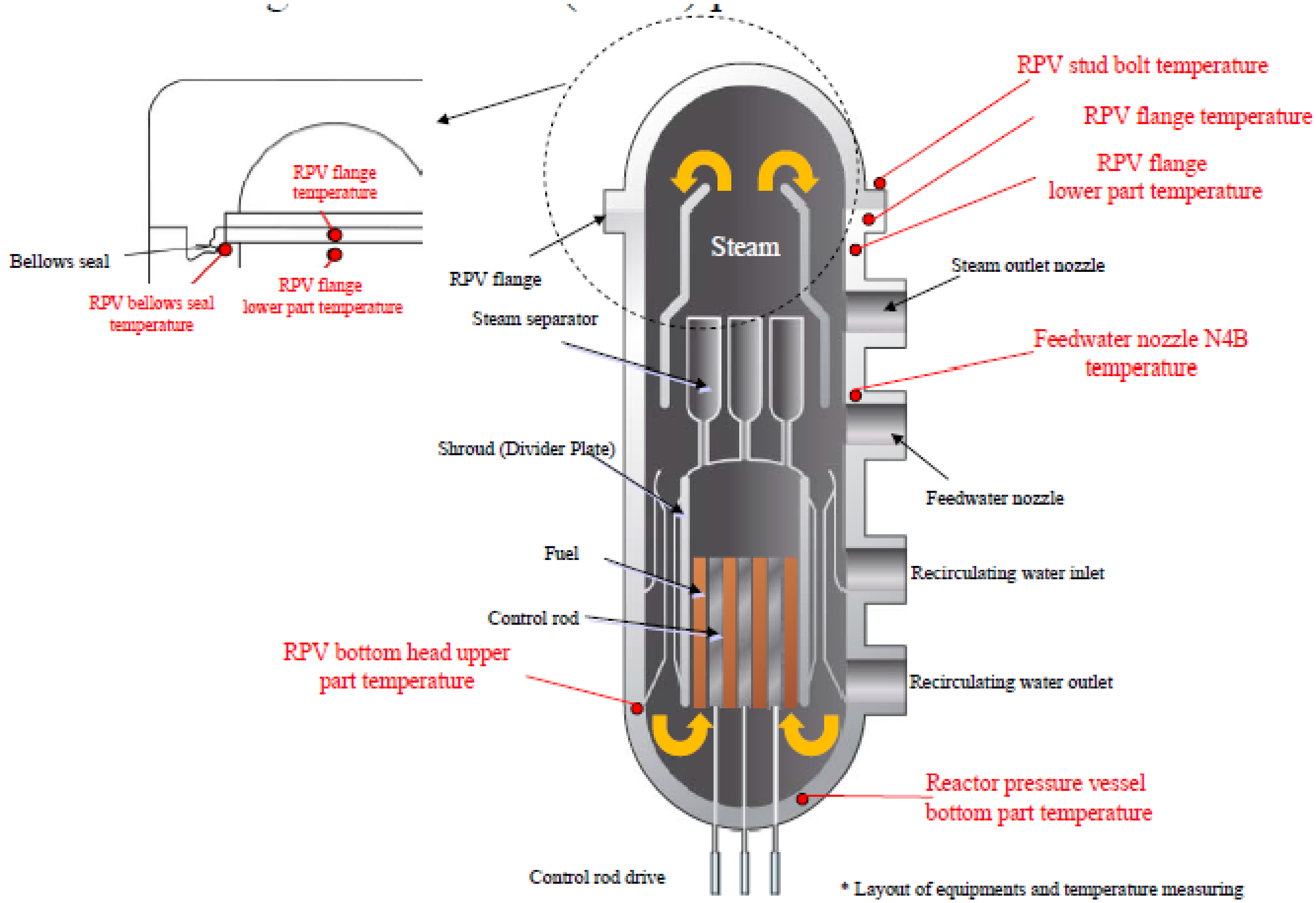


Figure IV-5-1 Changes in major parameters [1F-1] (From March 11 to May 31)

1F1 Temperature measurement



* Layout of equipments and temperature measuring positions are notional.

1F2 showed different behaviors from other two units

Survived 70 hours possibly due to battery management?

1F2 Timeline: Rector Core Isolation Cooling 1

3/11

1450 RCIC started but tripped1451 (Water level too high)

1502 RCIC reactivated and tripped 1528

1535 Tsunami

1539 Activated RCIC on

1541 SBO

No instrumaentation signals available in the control room

One of the power centers (panel) was available (other M/C and P/C were soaked); Stand-by Liquid Control (SLC) line could be used for water injection

2200 +3400 mm TAF

3/12

0255 Confirmed RCIC on

1536 H2 explosion in Unit-1 damaged SLC line and the high voltage power unit

1730 Prepare for venting

3/13

1F2 Timeline: Rector Core Isolation Cooling 2

3/13

1015 Vent order

1100 Vent line ready; 20-30km range in-house waiting order by PM

1205 Prepare for seawater injection following the AMG

3/14

1101 H_2 explosion in Unit-3 caused AOV (S/C vent line) to close; damaged seawater injection line and fire engines

1230 S/C: 0.486MPa and 149 Deg C ---- (no condensation in S/C with SRV open)

(Therefore venting should be done before SRV opening ---- but no venting was done)

1325 Possible termination of RCIC (water level going down low)

1634 RPV 7MPa

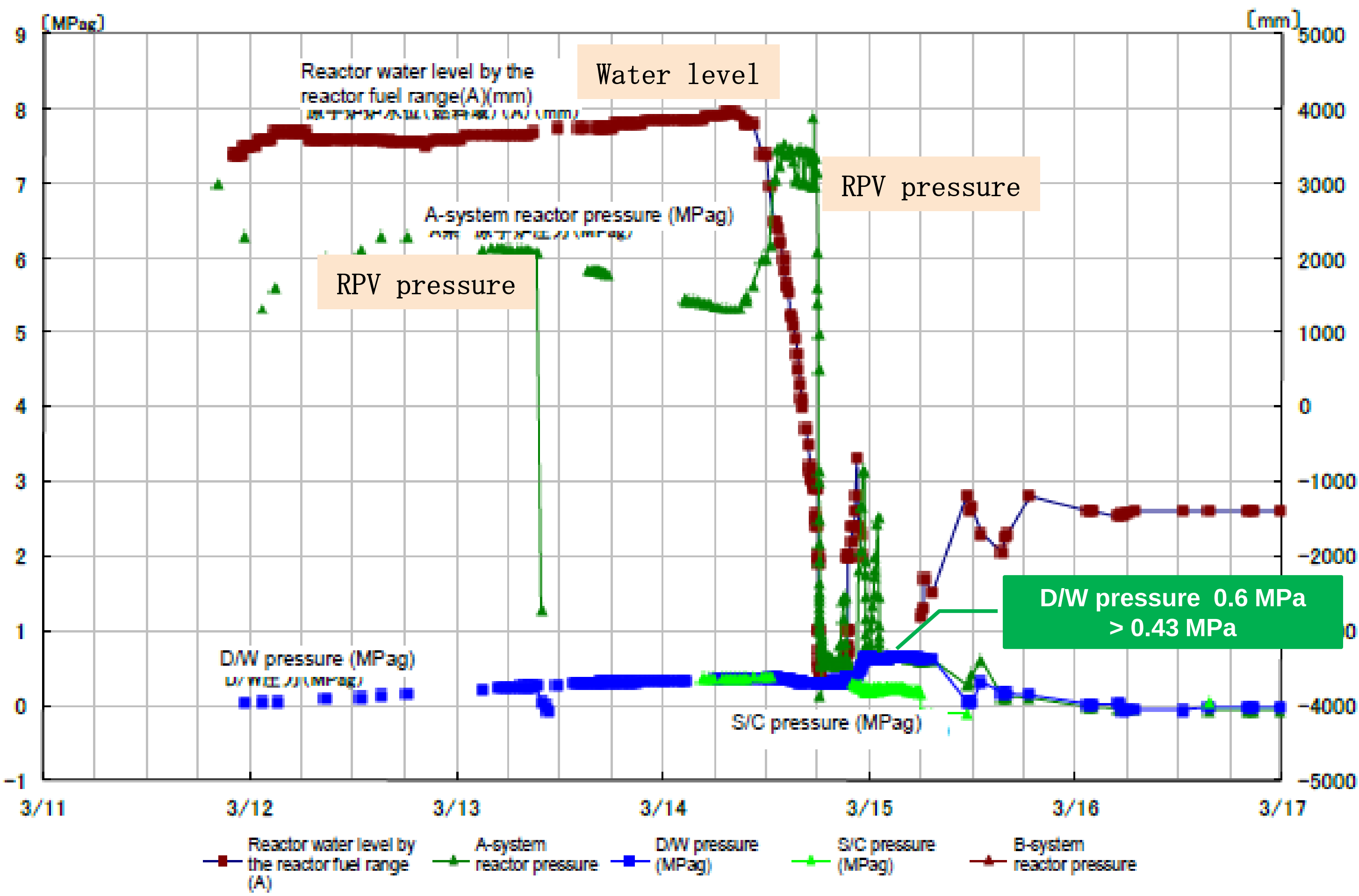
1717 Water level 0.0 TAF

1800 Depressurization by opening Safety Relief Valve (SRV) with car batteries (done before venting)

1803 RPV 6.1MPa to 0.63MPa in 1 hr

1822 Water level -3,700 mm -TAF

1F2 Water level, RPV/DW pressures



1F2 Timeline: water injection

3/14

1822 Water level -3,700 mm -TAF

1954 **Started seawater injection** using the FP line

2100 Ready for venting; D/W < 0.427MPa --- waiting

2130 **TAF -3,000mm**

2250 D/W pressure > .427MPa

3/15

0002 Ready for venting; D/W pressure 750kPa abs stabilized; rupture disk did not rupture; **no venting so far**

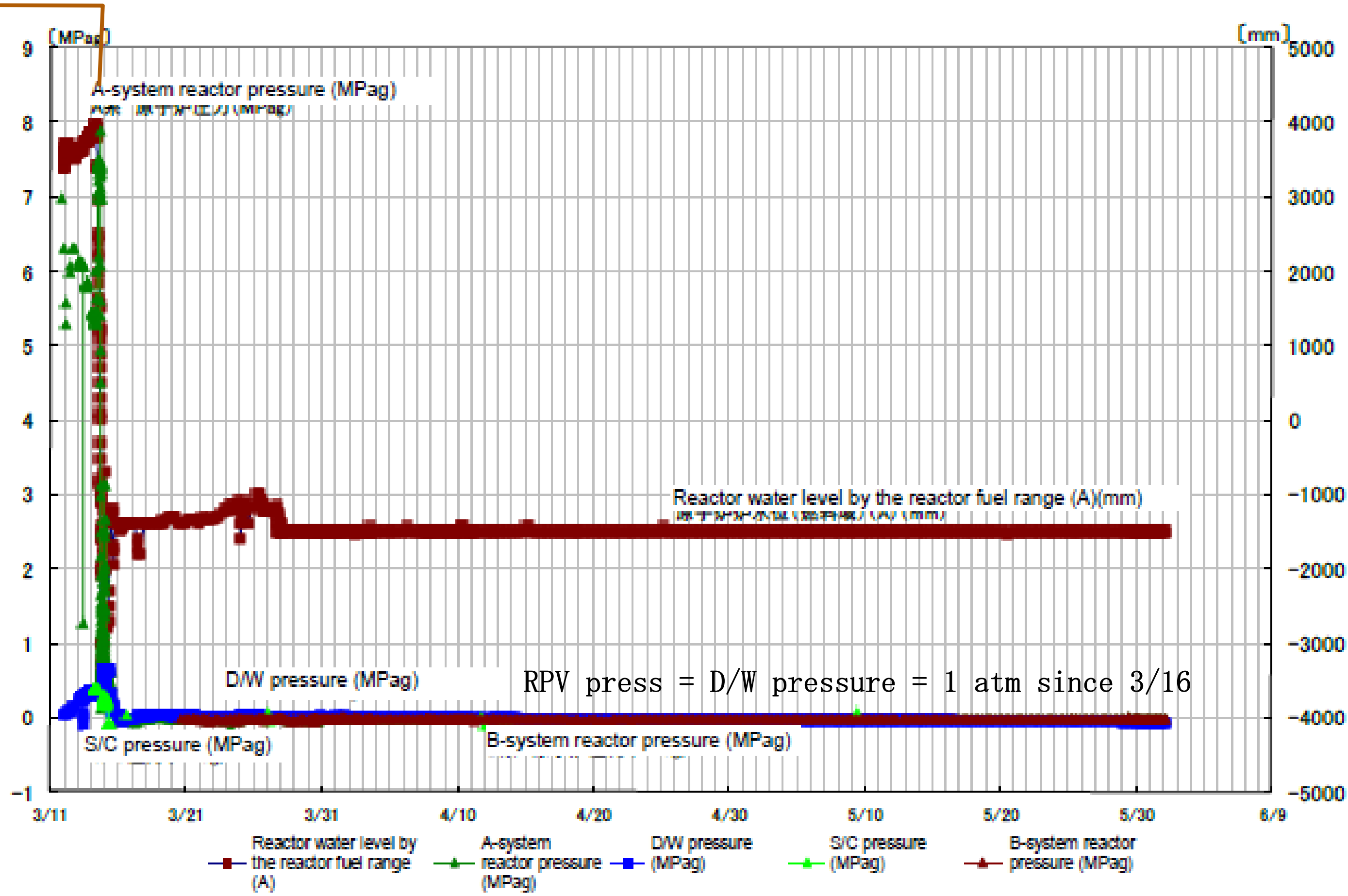
0600 **Explosion? Near S/C**

0650 High radiation level 583.7 μSv/hr at the main gate

0811 **807 μSv/hr at the main gate**

1F2 Water level and pressures (long term)

3/14 RCIC/HPCI stopped



1F2 RPV support skirt temperature

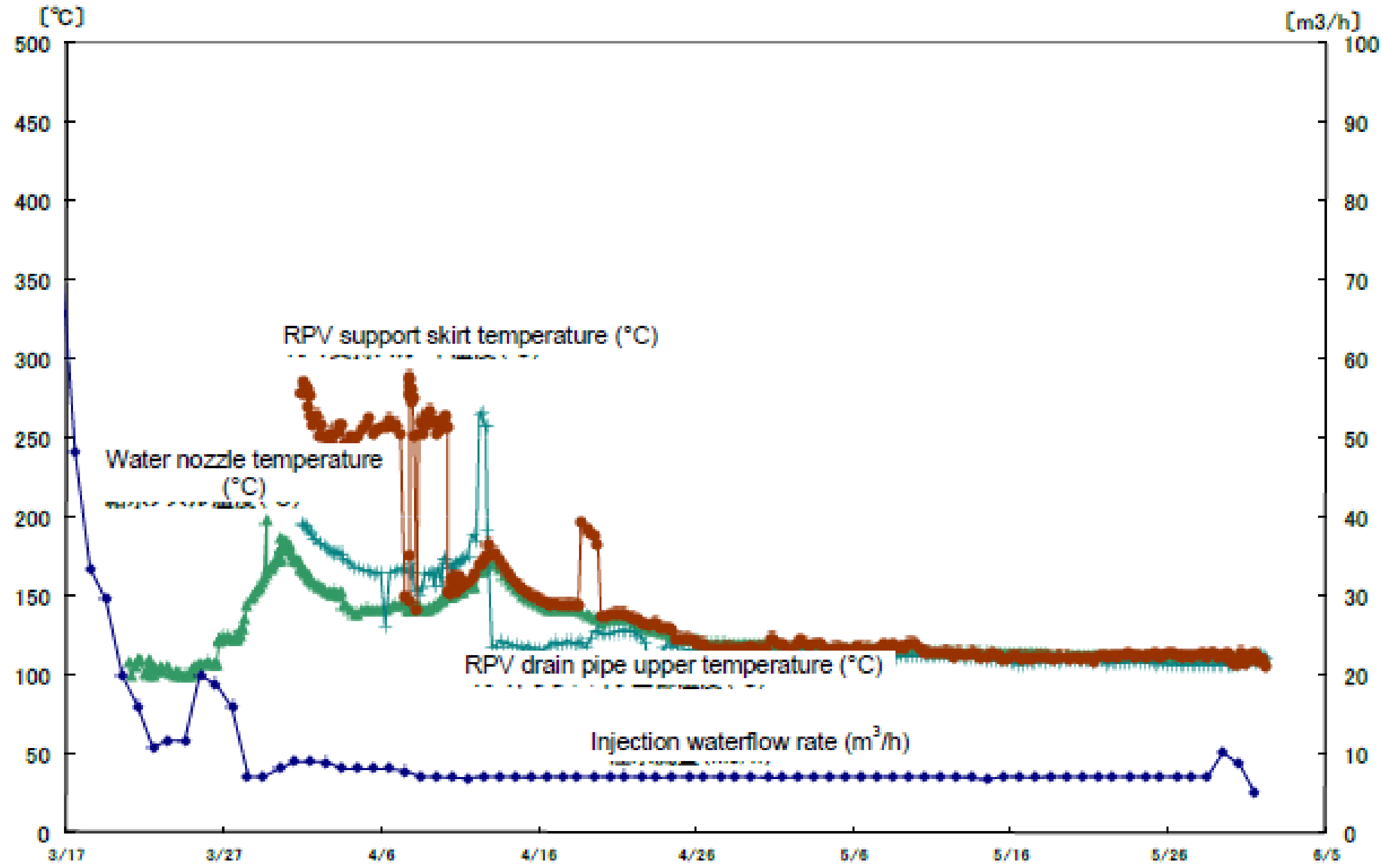


Fig. IV-5-6 Changes in key parameters [1F-2] (From March 17 to May 31)

1F3 Timeline

Unit #3 behaviors were fairly understandable

3/11

1538 SBO

1603 **RCIC on**

3/12

1136 **RCIC trip**

1235 **HPCI on due to reactor level low**

1730 Vent order

3/13

0242 **HPCI stopped**

0515 Prepare Vent line

0841 Vent line ready

0908 SRV open to depressurize RPV with car batteries

0925 Borated water injection started (~1220)

0936 Carry out venting (D/W pressure low);

1320 Start seawater injection through the FP line

3/14

0110 Seawater injection terminated

0200 D/W 0.265MPa abs → 0.315 MPa abs

0320 Seawater injection restarted

0520 Venting

0610 Confirmed a vent valve open

1101 **H_2 explosion**

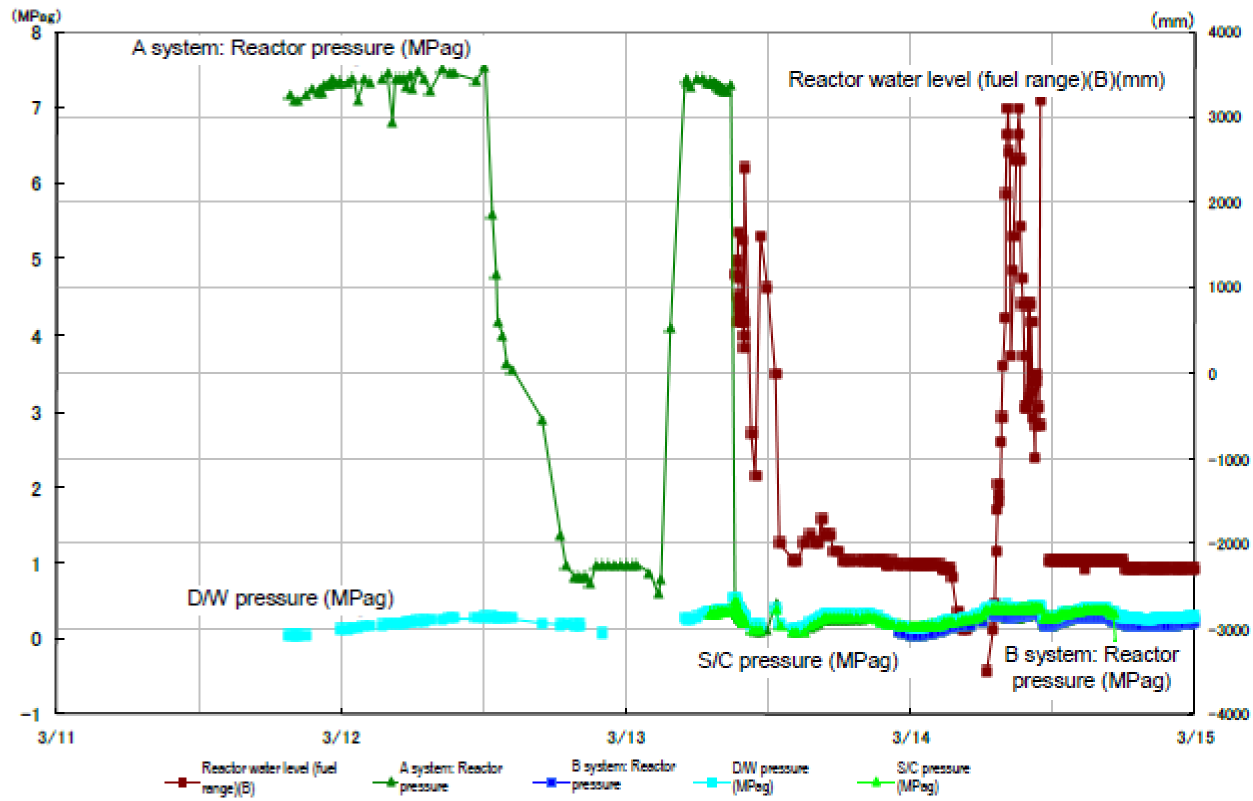
After RCIC and HPCI stopped, attempts were made to restore. Not possible

Diesel pump (D/D) fire pump was tried but RPV pressure was too high (4MPa) to inject make up water

SLC line was not restored in time due to frequent aftershocks

Seawater injection was judged inevitable

1F3 RPV and D/W pressures, water level



1F3 RPV and D/W temperatures, water level (long range)

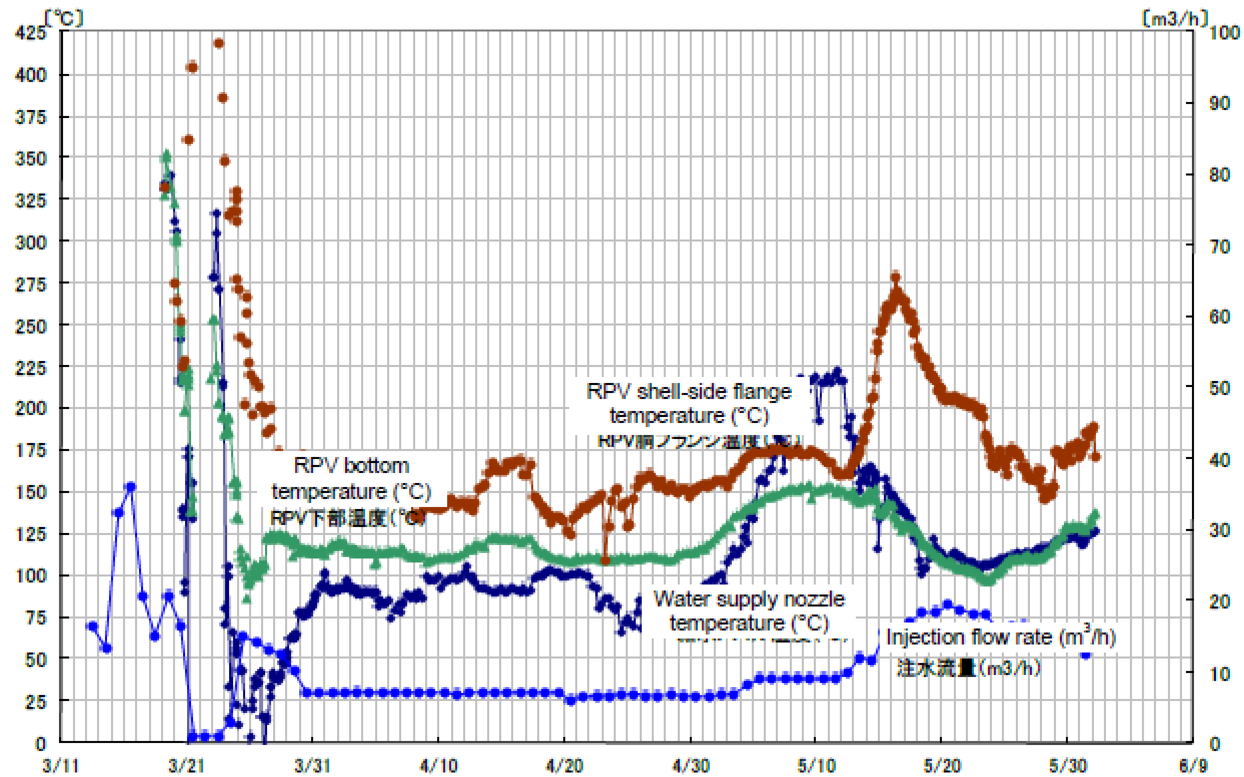


Figure IV-5-7 Changes of Main Parameters (1F-3) (March 11 to May 31)

Other topics that were skipped

- Chronology after March 15 ----
- Spent fuel storage pool issues
- Unit-5 under annual inspection since Jan 3, 2011; core -- fully loaded standby
- Unit-6 under annual inspection since Aug 14, 2010; core -- fully loaded standby; one EDG available (air cool EDG)
- Roadmap to the cold stand by of all units 1 to 3 and control of on-site radioactive materials

- IAEA report
- TEPCO, NISA reports

What went wrong in a first few days 1

- DC power supply: necessary to keep cooling and make-up; Note: however, to avoid core melt, need to have RHR restored or countermeasures to be put in place
- Reactor core cooling:
  - Termination of IC for Unit-1 due to failure in re-opening a MO-valve
  - Termination of RCIC due to loss of DC power for logic circuits, control valve opening, etc
- IC for Unit-1to the atmosphere worked: but difficult to control
  - After LOOP, auto start-up; ~ -100ºC/hr (too rapid vs. - 55ºC/hr); manually stopped following the operation manual, w/o knowing tsunami coming
  - After tsunami, not usable (?) in spite of the efforts to resurrect the IC, refilling the water by fire pumps
- 3/11 midnight: ~ A number of mobile power units were summoned but arrival delayed due to traffic jam. Most could not make access to the NRx units because of rubbles and drifts of tsunami; some of them made it but with connection mismatch. One mobile AC line was connected but the pump did not start work
- Fire pumps: available but RPV pressure reduction was the first thing to do; later useful to fire protection lines

What went wrong in a first few days 2

- Depressurization and makeup were difficult after IC or RCIC/HPCI stopped functioning and after the core was uncovered
- Venting should have been made immediately to protect PCV
- PCV flooding should have been initiated prior to the core melt and prevent RPV failures by cooling the outer RPV wall. Problems foreseen are:
  - No powerful pumps were available
  - Flooding the Mark-I PCV would have taken much longer time than the time from the loss of core cooling to core melt
  - The timing was too late to prevent core melt but maybe not too late to prevent the RPV failure
  - Flooding disables the suppression capabilities at S/C
  - PCV might not stand the self-weight and dynamic load during a big aftershock
- PCV flooding was “carried out” since the mid March, although not intentionally but with the RPV leak
- Flooding has never been attained because the water injected into RPV kept leaking out of PCV to the Reactor Building to Turbine Building, spreading the contamination

What went wrong in a first few days 3

- The on-site duty manager was not given the authority; waiting for the PM's authorization
- The delay in venting caused the PCV failure and possibly H_2 explosions
  - Tepco decided to vent 1:30am 3/12 and preparation was ordered
  - The central government command center authorized (acknowledged) the vent while the evacuation must be completed; vent order was delayed; issued 6:50am <u>(ventilation should be notified to the public)</u>
  - Frequent aftershocks and tsunami warnings at the site
  - No instruction manual for MO-valve opening by hands; no experience before; started working on the MO-valve 9:40am
  - Already radiation level was high
  - Finally vent was said successful 2:30pm: 13 hours after the Tepco's midnight decision
- Delays in injecting water/seawater were due partly to technical problems and to complicated lines of command and communication problems; this has created useless mishaps later among Cabinet, Tepco, …

Status as of June, 2011

- Status of 1F1 ~ 1F3 unit
  - Decay power level at ~ 0.15~0.2%
  - 500 tons water/day poured into RPVs = make up for the evaporation + leakage
  - More than 100,000 tons of highly contaminated water (710k TBq) accumulated in the basement of reactor buildings as well as turbine buildings
  - The water level in the basement and trench is increasing everyday due ~~not only~~ to core cooling water ~~but to the under-ground water flowing in~~
  - All units look stabilized but far from stable while overall risks to the environment and workers are still high
  - 6 – 12 months of "feed & bleed" before establishing cooling loop and containment for cold shutdown (Tepco's Road Map)

END

For specific lessons, visit the following web-site:

Atomic Energy Society of Japan

http://www.aesj.or.jp/en/release/gbcom_kyokun_EN_20110530.pdf

Nuclear Safety Regulation System in Japan

Licensee

Application for Establishment Permit

Application

Regulatory Bodies

Nuclear and Industry Safety Agency (NISA) for NPPs

Technical supports

Japan Nuclear Energy Safety Organization (JNES)

Ministry of Education, Culture, Sports and Science and Technology (MEXT) for RRs

Inquiry

Report

Cabinet Office **Nuclear Safety Commission (NSC)**

- Secondary Review: "Double check"
- Supervise and audit the regulatory bodies
- Receive and respond to reports on accidents and problems

NISA :

- Issue license for NPPs and related facilities
- Approve construction and suitability of safety program and pre-service inspection
- Conduct periodic inspections of facilities, suitability of safety inspection, emergency preparedness

MEXT :

- The same function as NISA for test and research reactor facilities

JNES :

- Inspection and cross-check analysis, etc. for NPPs
- Investigations and tests to be reflected onto the safety regulations

Subsequent Regulation

(NISA/JNES and MEXT)

Construction phase
Approve design, ---
Operation Phase
Periodic inspections etc
Others
Periodic inspections etc

Periodic Report

Supervise & Audit

(NSC)
Review subsequent regulation