2013.06.24-29
LAS-ANS Symposium
Buenos Aires, Argentina

POLITECNICO DI MILANO

Fukushima Dai-Ichi Nuclear Accident Analysis

How much do we know? After Fukushima Dai-ichi Nuclear Accident: Don’t let a crisis go to waste

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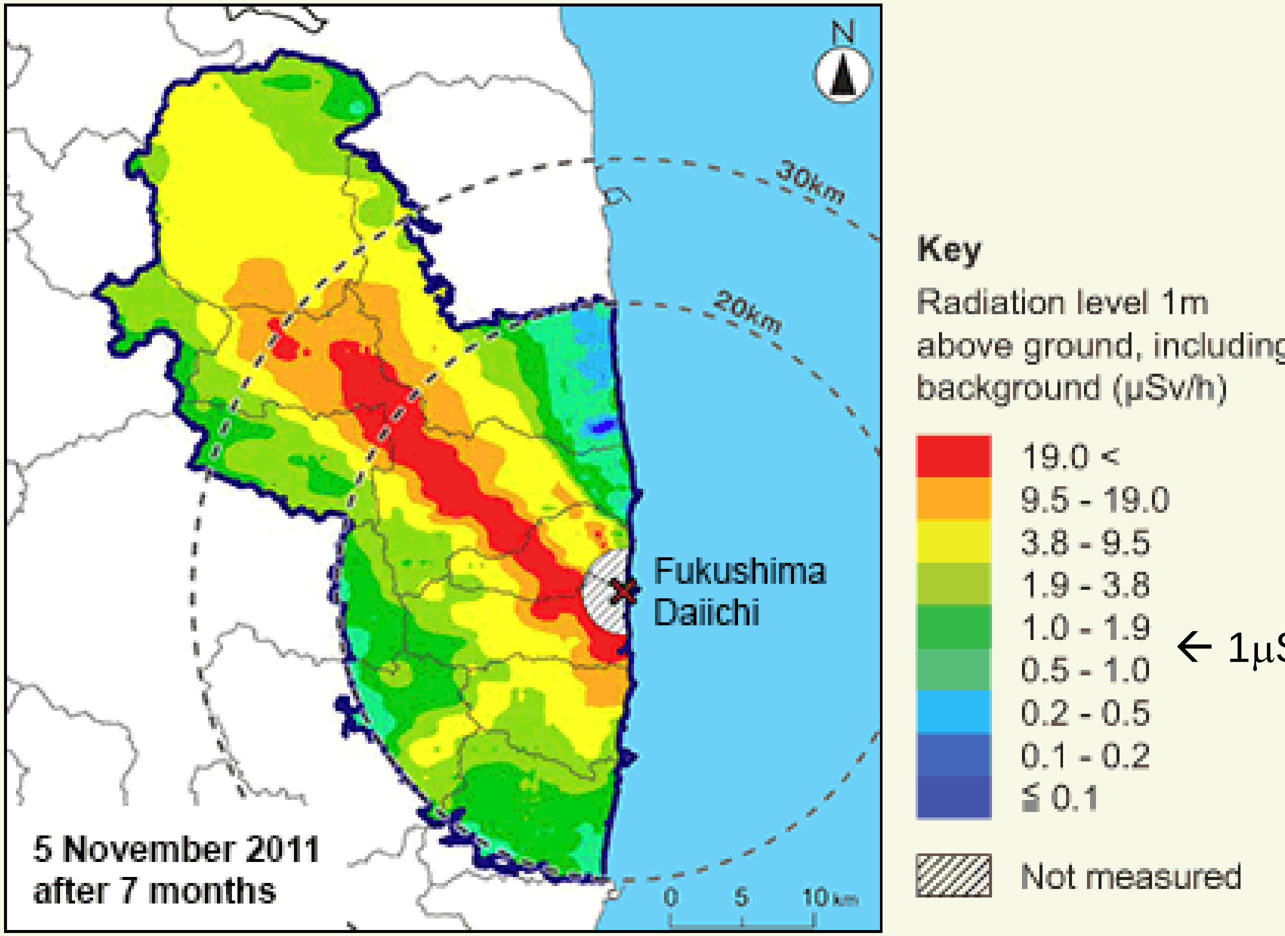
Sources

- Many publications in Japan including a NISA report (March 2012), Government reports, Congress reports, ….
- TEPCO reports
- NUTHOS, PSAM, NURETH conference proceedings
- ANS Fukushima special committee report
- INPO report
- …..
- Private communications with those who were involved in the accident

2011.03.11 – 2013.03.11

Radiation Decline in Evacuation Area



← 1μSv/hr~8.7mSv/y

Source: Nuclear Regulation Authority
Animation and translation: World Nuclear Association

Current status in 1F NPS

- Milestones and Schedule for decommissioning (from TEPCO)
- Observations and visual inspections; Endoscope, Robotics; PCV damage and leakage locations not yet identified
- 1F1~1F4; first, decontamination and clean-up;
- Fuel removal from SFP of the 1F4 unit;
- Stop contaminated waste water increase: underground water bypass

- No info on corium debris distributions
- High tech under development to observe below the bottom head under the extremely high radiation and high humidity environment

Current status in Japan

- In parallel, struggles for restarting nuclear operation (2 units in operation; 48 units idling)
- New regulatory authority; new tougher regulations set off effective July 8:
    - Check out for active faults under NPP
    - Set up emergency command centers
    - Install filtered vents,
    - SAM…, etc

  legally binding, not on a utilities voluntary basis; not necessarily safer

- Concerns are not on the technical but public perception; how the new regulation can get rid of the public fears over nuclear power would be more important in Japan

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All hopefully covered already so far in the Panel Sessions 1 & 2

Before Fukushima Dai-ichi Nuclear Accident

- Japanese NPPs were believed to be sufficiently safe

Because of:

- High quality assurance/control and high reliability
- More than sufficient safety assurance against design basis accidents;
- Extremely thick layers up to 3rd layer Defense-in-Depth against DBAs;

All within a realm of internal design-basis-events as well as for design-basis earthquakes --- evidenced by Onagawa NPPs and other NPPs

Before Fukushima Dai-ichi Nuclear Accident

[Afterthoughts] Less attentions to BDBAs and BDBEs, e.g., devastating tsunami on the NPP sites; then JNPPs **were:**

- Very fragile against beyond-design-basis external events
- Almost defenseless against extremely low probability events < 10^{-4}/y but of high consequences: such as tsunami of 15 m high;

No water tight T/B (no protect EDG/batteries), Sea water Pump house --- if they are ….. ← afterthoughts;

as all safety functions were disabled completely (common cause failure from devastating tsunami)

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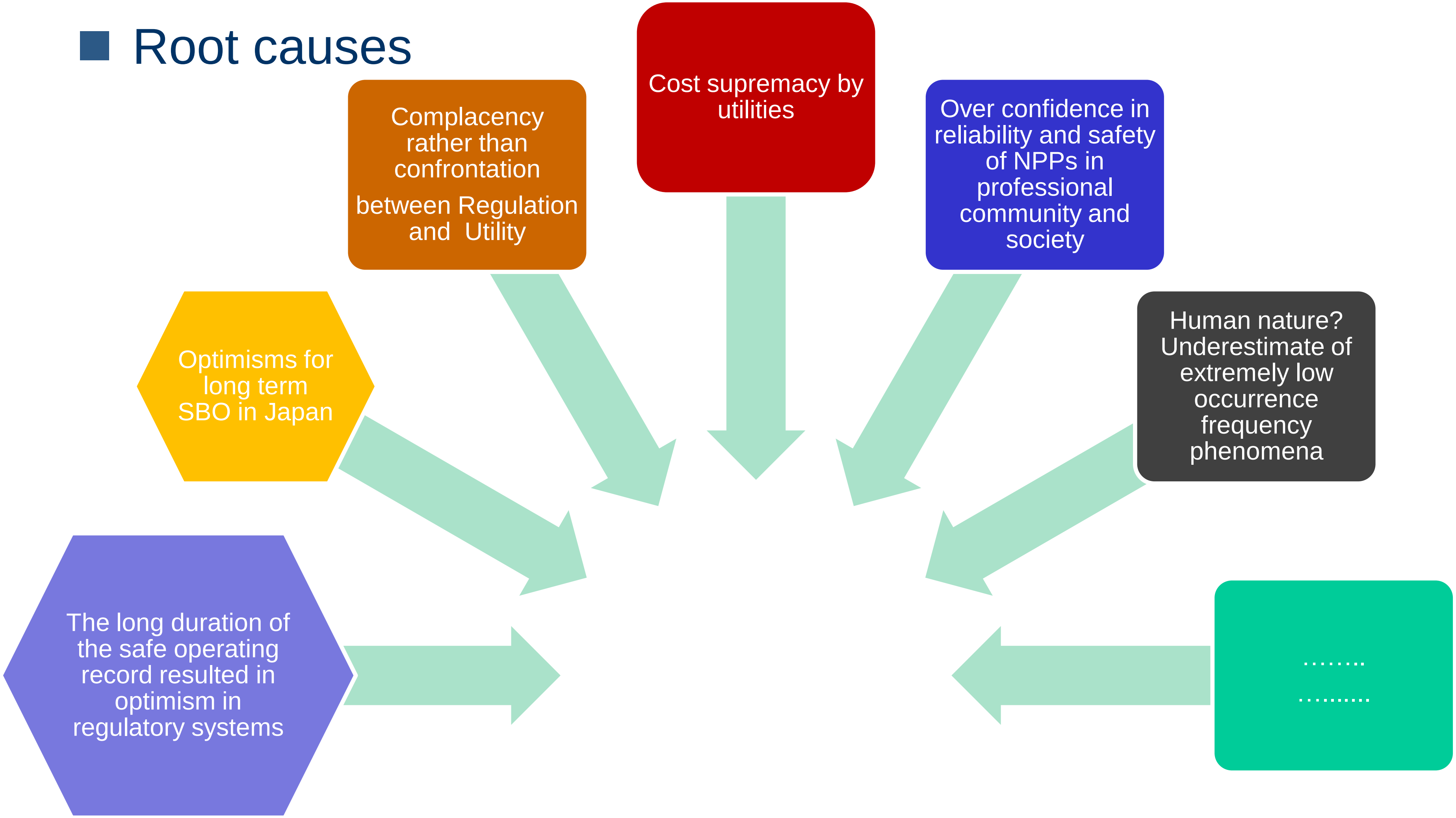
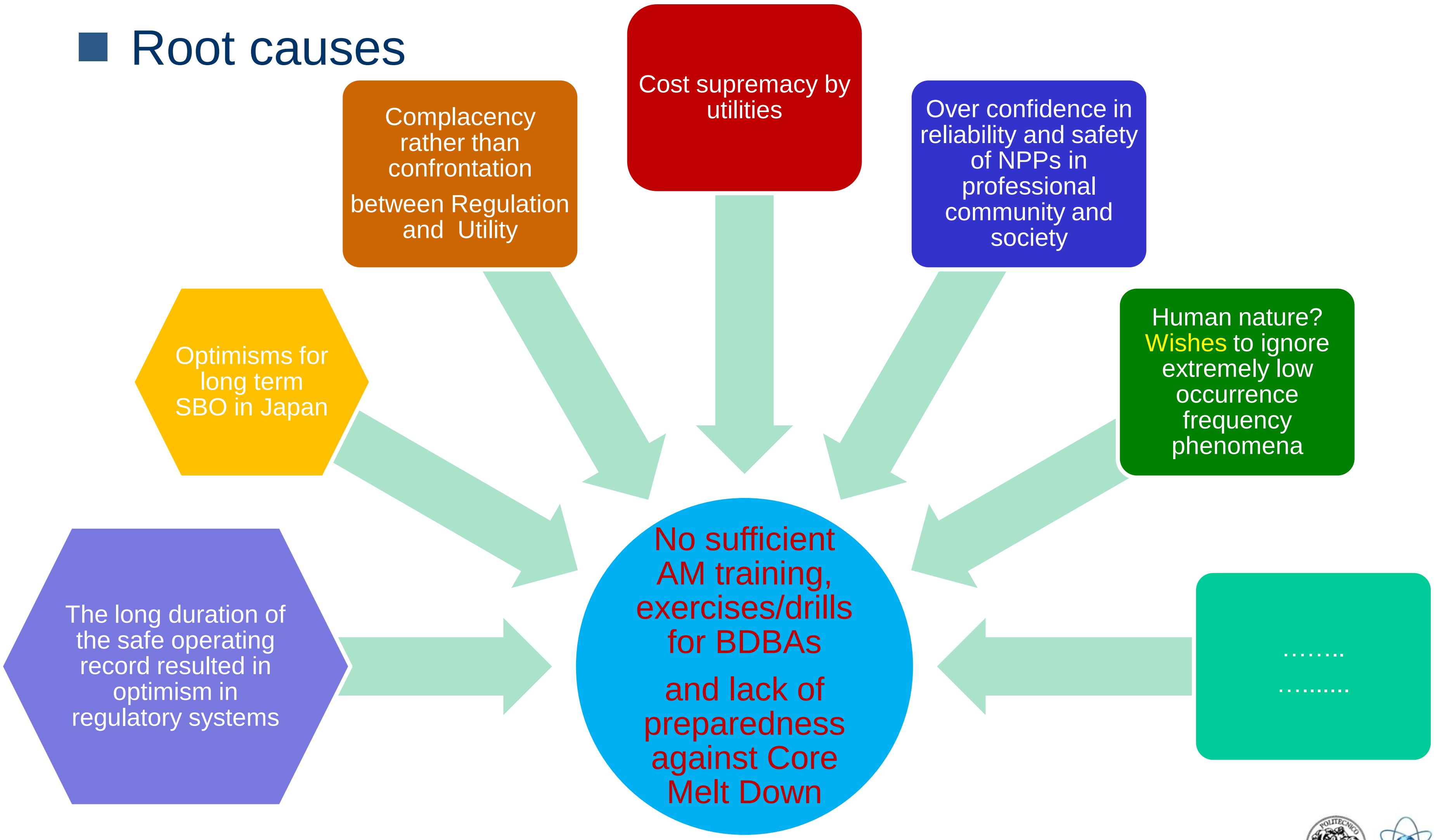
Introduction: Why unprepared for the BDBA?

- Root causes



■ Root causes



Cost supremacy by utilities
Complacency rather than confrontation between Regulation and Utility
Over confidence in reliability and safety of NPPs in professional community and society
Optimisms for long term SBO in Japan
Human nature? Wishes to ignore extremely low occurrence frequency phenomena
The long duration of the safe operating record resulted in optimism in regulatory systems
No sufficient AM training, exercises/drills for BDBAs and lack of preparedness against Core Melt Down
……..
……....

Introduction

Root causes

- Complacency rather than confrontation between Regulation and Utility
- Cost supremacy by utilities
- Over confidence in reliability and safety of NPPs in professional community and society
- Optimisms for long term SBO in Japan
- Subconscious wishes to ignore extremely low occurrence frequency phenomena
- The long duration of the safe operating record resulted in optimism in regulatory systems
- Difficult to perceive and prepare for the risk of Extrly Low P with High Q events. How can you expect the unexpected?.

Lack of the 4th layer Defense-in-Depth:

Not prepared for the unforeseen events

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Introduction

- Some nuclear advocates say “No more Fukushima topics. That’s enough. Let’s look forward to the future. It’s time to stop lament”.

- It is the reality that we look at.
- So far overall, most event sequences leading to the core meltdown and radiological release have been identified
- Still we need more TH investigations to understand the accident phenomena more clearly
- **To know more will result in preventing next accidents.**

Ex. INPO Lessons Learned Report

INPO® Special Report

INPO 11-005 Addendum
August 2012

Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station

Utility points of view

- Ensure that, as the highest priority, core cooling status is clearly understood and that changes are controlled to ensure continuity of core cooling is maintained.
- If core cooling is uncertain, direct and timely action should be taken to establish conditions such that core cooling can be ensured.
- Optimum accident management strategies and associated implementing procedures should be developed through communications, engagement, and exchange of information among nuclear power plant operating organizations and reactor vendors.
- On-shift personnel and on- and off-site emergency responders need to have in-depth accident management knowledge and skills to respond to severe accidents effectively.

Core cooling status

Toward the core meltdown

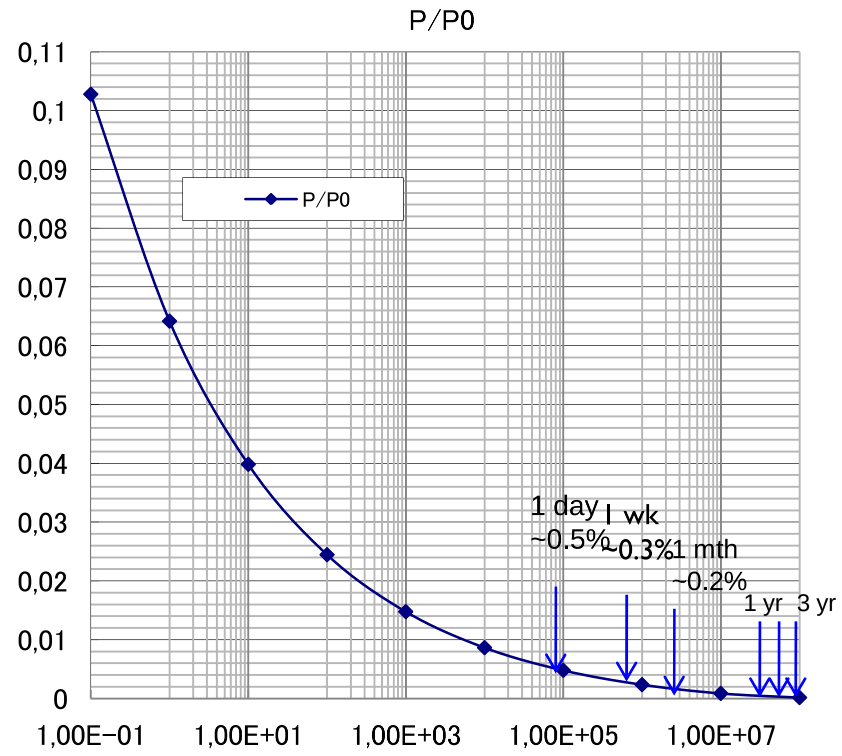
Failure in decay heat removals in 1 to 3 days

PHENOMENOLOGY FROM THE TH SPECIALIST VIEW

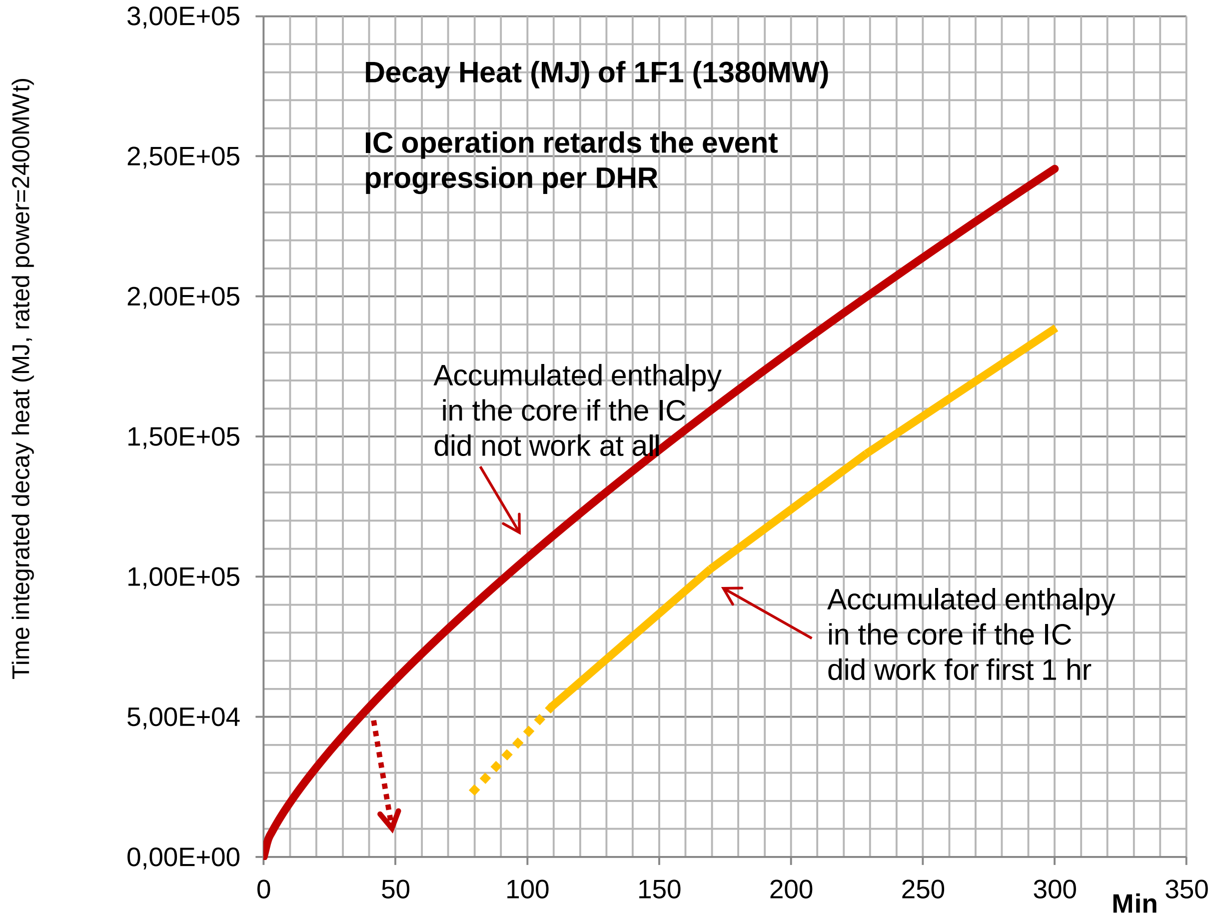
Decay Heat Removals

- 6 hours after the tsunami at **1F1**, Decay Heat generated is equivalent to vaporize 200~250 m^3 of water at 7MPa
- Close to RPV water volume at full inventory
- SRV opens to release high pressure vapor into the suppression chamber and prevents over-pressure of RPV
- Each time SRV opens, the water inventory decreases
- Possible whole core exposure w/o make-up
- Still, steam and super-heated vapor cooling could keep the core under low temperature profile

Note:
First 1 hour between earthquake – tsunami, the decay heat was removed successfully in all units



1F1 1 hour operation of IC



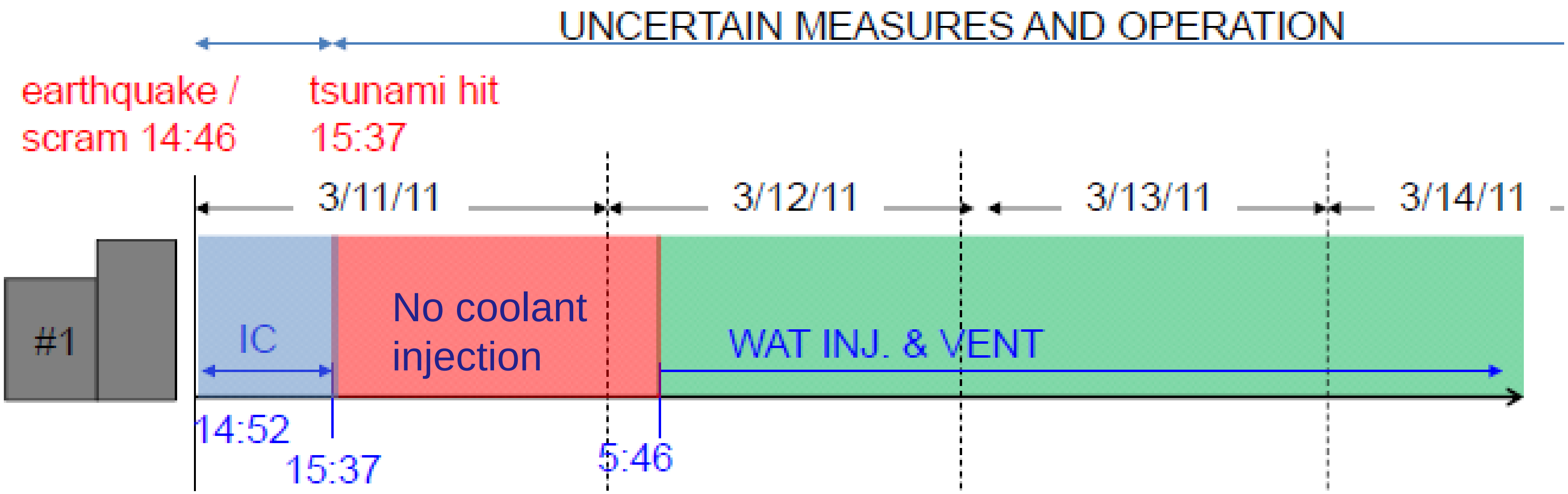
IC tank water decreased from 80% to 65%: ~50,000 to 60,000 MJ (a sum of latent and sensible heat)

1F1

- It has been said that the whole core meltdown / melt-through took place in 6 to 10 hours after the tsunami at 1F1 (Unit #1)
- Is this correct? Probably yes, if RPV over-pressure was regulated to 7MPa by frequent SRV opening.
- If RPV leakage is assumed, which is very likely before starting core injection at 5:46am (13 hours later after tsunami) by the fire engine pumps, with much less frequent SRV opening, a melt fraction to be calculated would be sensitive to the timing, location and size of the leakage.
- So far, no affirmative core melt fraction 70~80%: could vary from 20% to 80%
- 1F2 and 1F3 also assume more or less similar uncertainties

1F NPS SBO Accident Time-Line

Source Marco Pellegrini (IAE): ICAPP2013



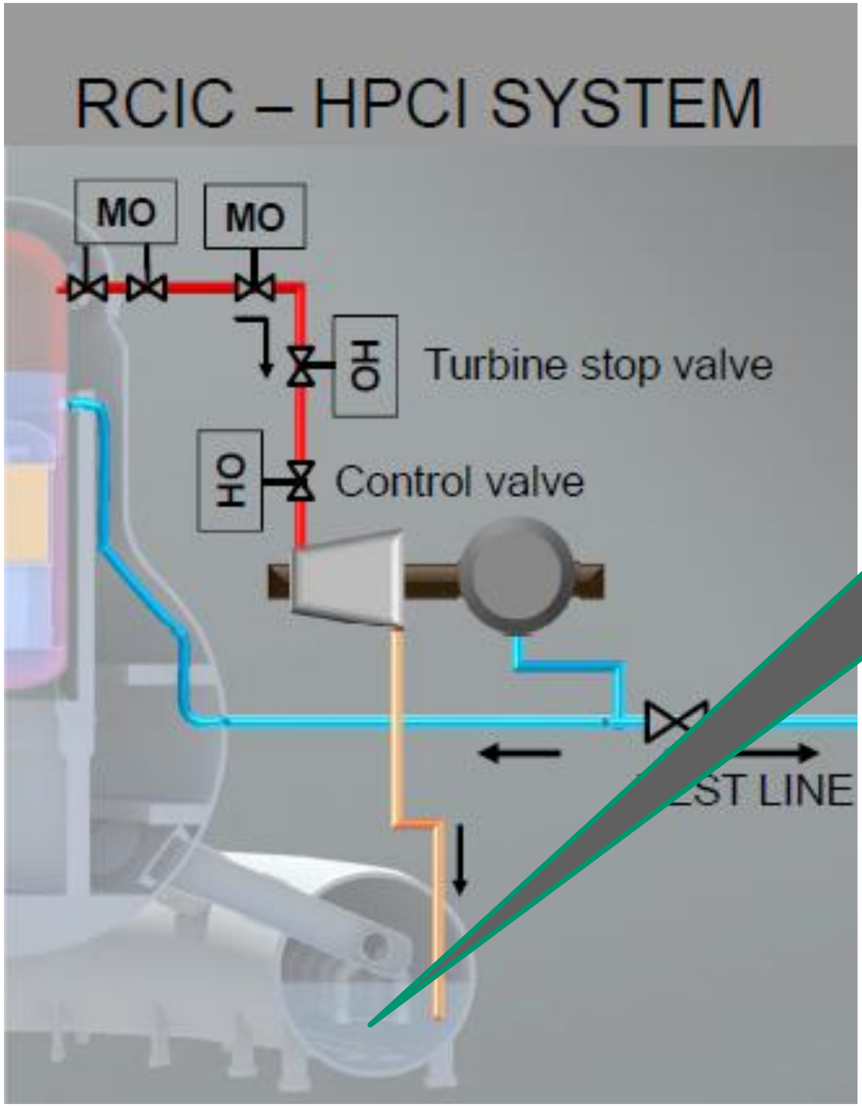
15:25 12:06 2:42 9:05

LOOP EDG

SBO→LUHS

PCV Isolation

After Tsunami SBO and LUHS [units 2 and 3]
Major components that do not require AC: RCIC/HPCI, SRV (but DC power needed)



- Enthalpy build up in S/C
  - Boiling; no condensation and no scrubbing
- PCV radiation level high
- PCV p and T high
- Need PCV venting

Unit #2 Performance of RCIC under the two-phase flow condition; MAAP ((*S. Mizokami, TEPCO, NURETH-15-536*), MELCOR, SAMPSON:
30 m^3/hr (vs 90 m^3/hr)

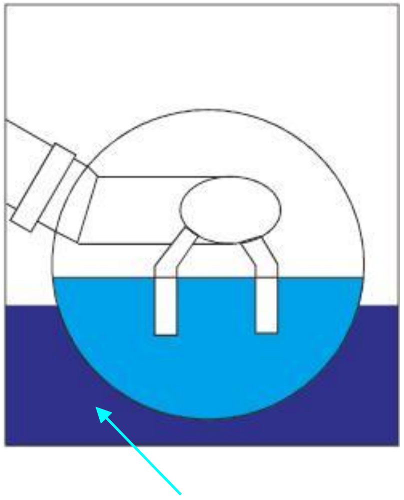
Unit #3 HPCI at < 1 MPa?

Core Meltdown --- Unit 2 (day 3/13-14)

- With deteriorated performance of RCIC under the two-phase flow condition; MAAP (*S. Mizokami, TEPCO, NURETH-15-536*), MELCOR, SAMPSON
- 3/14 9 am the water level started decrease (RCIC turbine thrust got weak?)
- 3/14 1100 The H2 explosion (unit 3) damaged much of the S/C vent line and fire engine injection line set ups
- **3/14 1325 RCIC termination after 72 hours of staggering operation**
- PCV pressure high; **no coolant make up until 19:54 for more than 6 hrs**
- 1F2 PCV pressure was better explained by including the S/C room flooded by sea water (H. Hoshi, JNES, NURETH-15, Right fig.)

In general 1F1, 1F2 behaviors are relatively well understood

RCIC: Reactor Core Isolation Cooling
RPV: Reactor pressure vessel
PCV: Primary containment vessel



Radiological consequences

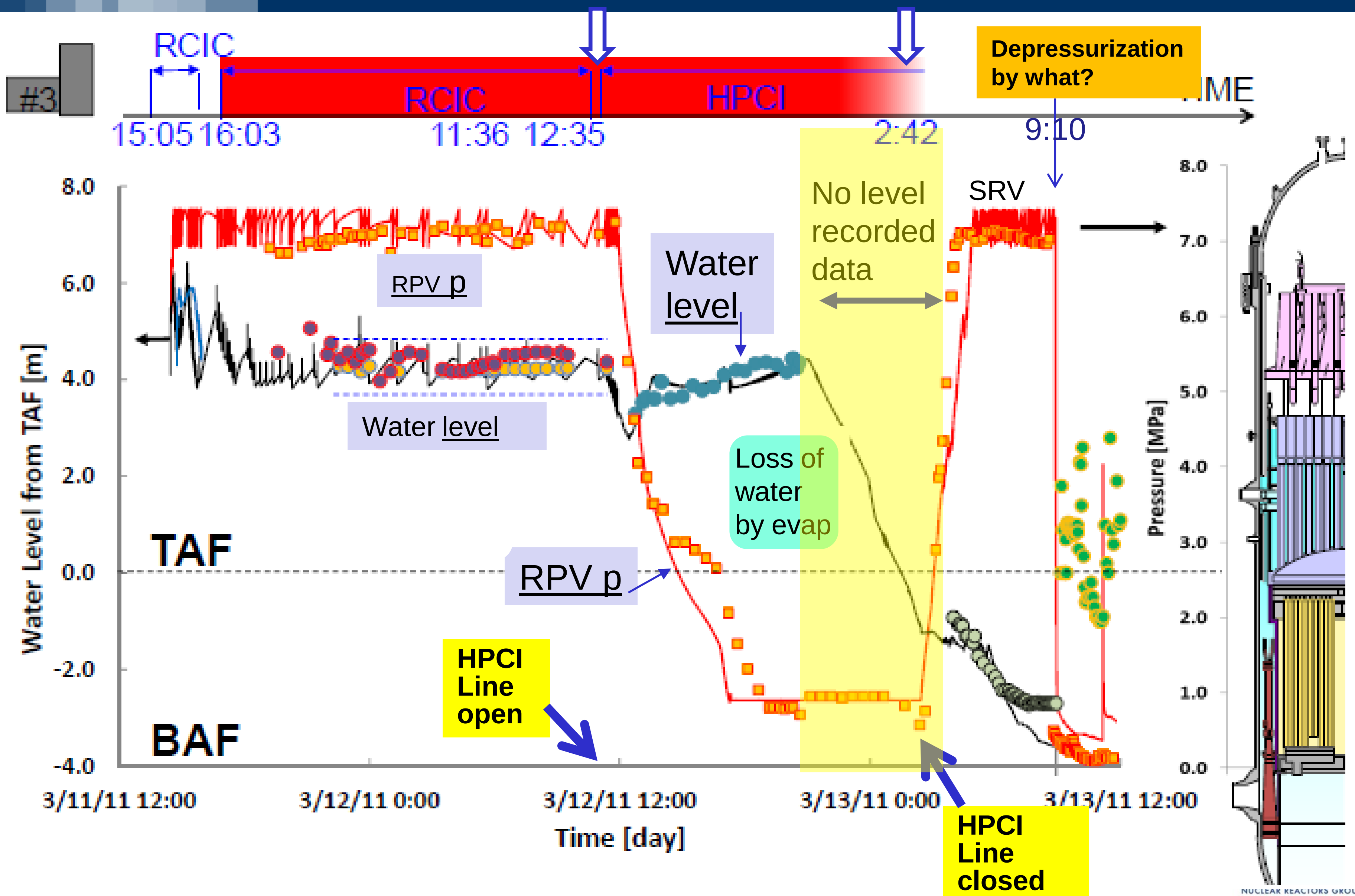
- Long duration of RCIC line open (w/o DC); S/C saturated, high radiation atmosphere in the drywell
- Either leakage from PCV or the drywell vent or both were supposed to be responsible for a large amount of release
- The largest release March 15 in the morning

Most uncertainties lie in:

UNIT #3

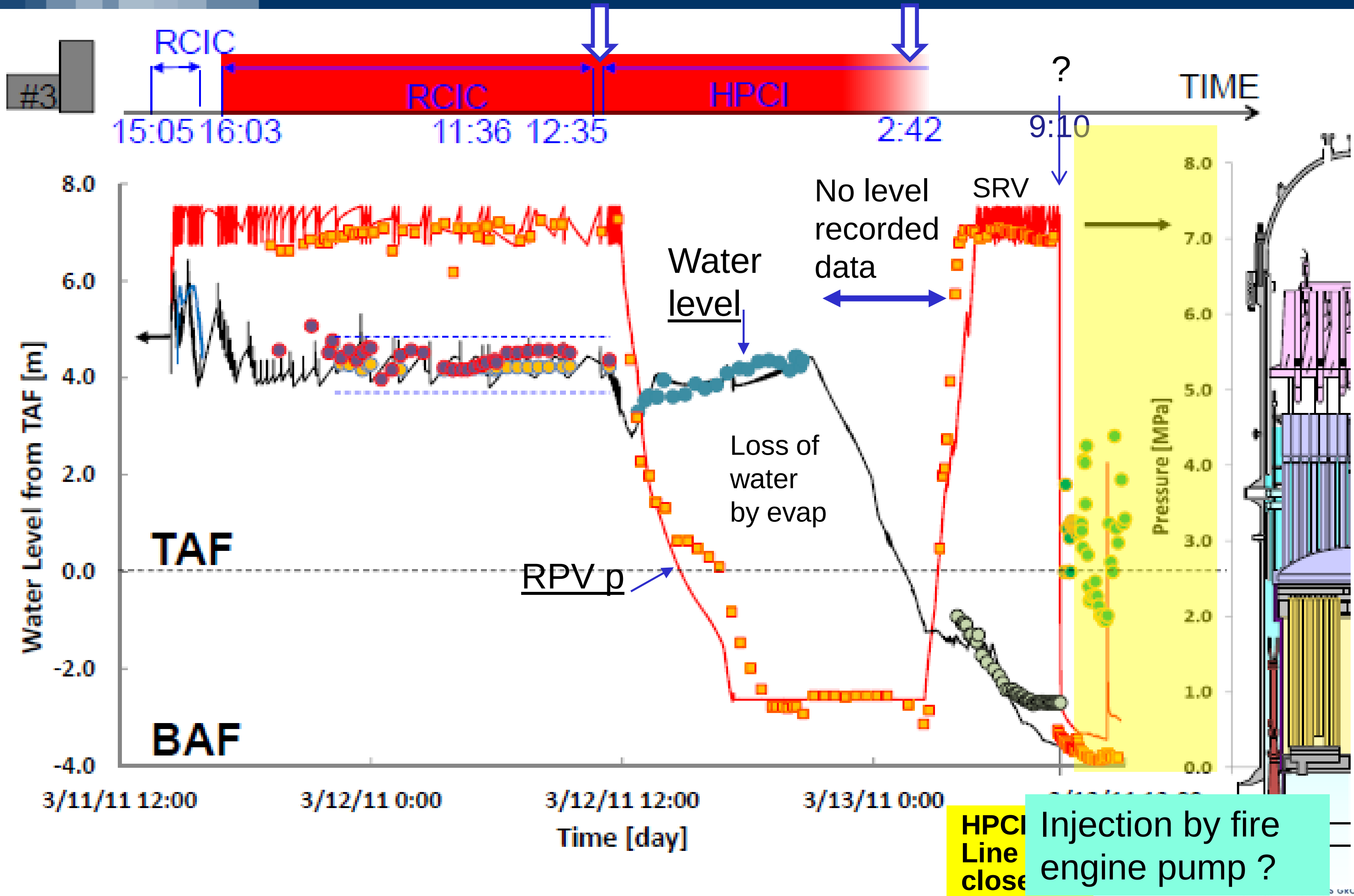
Unit #3 (1F3) water level and RPV pressure

Source Marco Pellegrini (IAE): ICAPP2013



Unit #3 (1F3) water level and RPV pressure

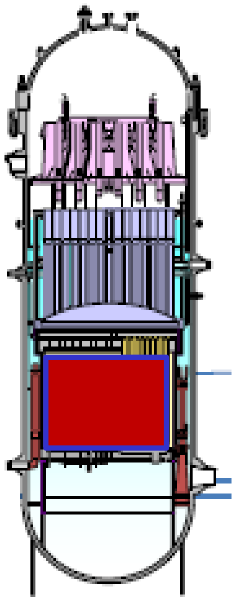
Source Marco Pellegrini (IAE): ICAPP2013



1F3 Core melt likely early afternoon, March 13

Comments from Marco Pellegrini, IAE, SAMPSON, NURETH-15

- Before the reactor depressurized (March 13th around 9:00AM), as measurements show, the water level is **already at BAF** (= Bottom of Active Fuel).
- After 9:10 depressurization, the water level jumps down of couple of meters
- 3/13 ~9:25am Borated fresh water injection (~ 12:20): might not have entered RPV; near BAF
- *Most likely, bypassed to the condenser (through the pump seal water line*: *NHK)*
- 3/13 1300~ possibly **below BAF** and not recovered

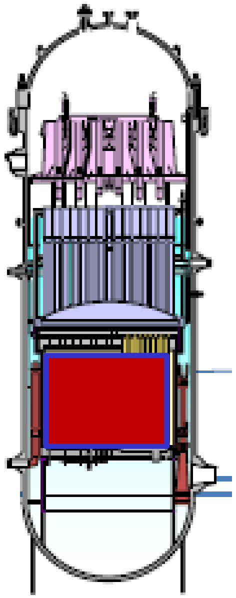


- 20~25m^3 of water are necessary just to reach BAF.

1F3 Core melt likely early afternoon, March 13

Comments from Marco Pellegrini, IAE, SAMPSON, NURETH-15

- Assuming that water injection from fire engine started right after RPV depressurization and with an optimistic nominal value of 10 kg/s directly to PRV, it will take about **40 min** just to fill the lower plenum to the BAF.
- Fuel temperature increase *w/o vapor convection cooling*:
  - 1K/s from 600 K to1500 K temperature increase
  - Higher than 1500K ,10 K/s (because of Zr oxidation and hydrogen generation)
- It will take roughly 20 min to melt. << **40 min**
- Given the delay in injection and the likely reduced mass flow rate, it is likely that melting was already in advance when the water reached BAF, (assuming that RPV did not fail before).



Fire engine injection as AM

- In spite of 12 hours of sea water injection efforts, ERC recognized water level was kept below TAF

← Circumferential evidence for RPV failures

- RPV failure in unit 3 (due to molten corium) is a big unknown

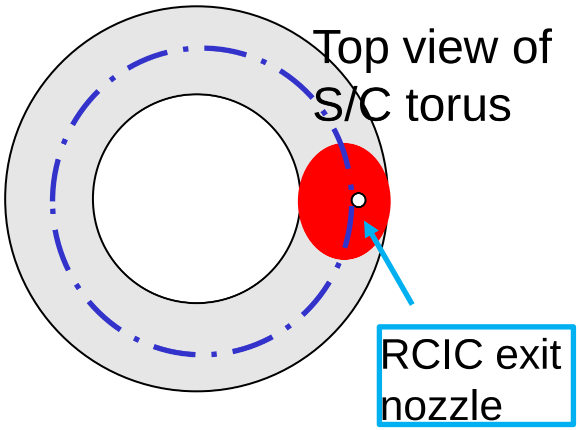
In Summary, melt % and RPV integrity

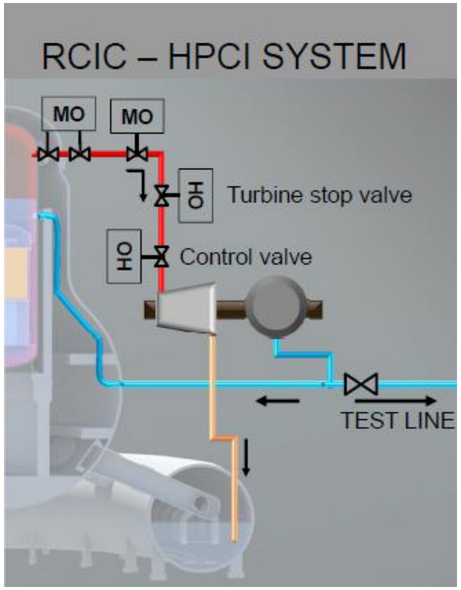
	1F1	1F2	1F3
Fuel support structure failure (melt attack)	Y	Y	Y
RPV failure (melt through)	Y	Y or N Unknown	N But big unknown
Core melt fraction	??%	~?? 50%?	~??20%?
H2 generation	~??710 kg	~??560 kg	~??900 kg

Ref:
MAAP by TEPCO (NUTHOS-9, NURETH-15) and
SAMPSON results by M. Pellegrini (ICAPP2013, NURETH-15)

TH issues common to 1F2/1F3

- S/C pool TH (condensation, mixing and stratification) + pool scrubbing capability
- RCIC/HPCI performance under low pressure or two-phase flow conditions
- Core melt fraction, relocation and redistribution process: 3D multi-component multi-phase flow problems would be desired
- Molten core and RPV thermal interactions – melt-through fraction
- RPV depressurization – uncontrolled
- How effective was the AM fire pump injection to prevent core damage and its progression, and mitigation?





Controversy comments
Conclusions

AFTERTHOUGHTS

Nuclear Power Core Damage Frequency

- At this time, there are about 435 operating commercial nuclear power units (some on and some off line);
- Let us assume that the average availability is about 70% per year and that their average CDF is ***conservatively*** 1.0^{-4}/RY;

  Sensitive issue ---
- This means that we could expect a core damage accident about once every 33 years ($435*70\%*1.0^{-4} = 3.05^{-2}$);
- Coincides with two events, i.e., TMI and Fukushima in a ~30 years interval and agrees with the public perception ---
- Chernobyl is excluded in this crude statistics
- Should 1FNPS be included in this category of 10^{-4}/RY, if the 1FNPS CDF was lower than the frequency of the "Tsunami" of such magnitude at the site?

Nuclear Power Core Damage Frequency

- Another way of looking at this is to say that in a lifetime, a person should expect to see about 2 core damage accidents
- But is this appropriate when we face the public?

Is this acceptable to people and to nuclear power advocates?

"No" from both sides.

- *Anti-nuclear fanatics*
- *The 10e-4 has been replaced constantly by smaller numbers.*
- *The situation (Nuclear crisis ← Nuclear energy refusal ← Fukushima) → energy crisis*
- *This crisis cannot be ruled out IF NO IMPROVEMENT in the current CDF IS ASSUMED*
- Problem is the sense of feeling or perception

Don’t let the crisis go to waste

- The new NPPs are of much lower CDF as of now already
- Continuous efforts should be made to improve the current CDF: e.g.,
  - Back-fits
  - Replacement of old NPPs with GEN-III or GEN-III+, like Hamaoka #6 unit replacing #1 and #2 (toward decommissioning process).
- All in the category of DBA and its Design Extension Condition (DEC) or Design Enhanced (safety) Condition (G. Apostolakis)

- Preparedness against external events beyond imagination would be the key *(natural hazards as well as sabotage)*
- Hence, more probabilistic regulation (risk-informed basis)

- Several countries don’t show eagerness in the lessons, probably for political reasons or also due to over-confidence in their technology and safety culture -- “NOT IN MY COUNTRY” attitude

- Further efforts should be directed towards building a thicker 4th layer of the defense-in-depth. It is not expensive.
- The efforts should be continued not to let the crisis go to waste

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Gracias
Thanks





The Fukushima nuclear accident should be taken as a chance to make big and necessary changes

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August 30-September 5, 2015

Chicago, Illinois, USA

NURETH-16

16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics

The 10th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-10)

Dec. 14-18, 2014 Okinawa, Japan

Sponsored by

Atomic Energy Society of Japan

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Conference place

Okinawa Convention Center
4-3-1 Mashiki, Ginowan, Okinawa 901-2224, Japan
http://www.oki-conven.jp/en/

Key deadlines (tentative)

Submission of abstracts:	March 31, 2014
Notification of acceptance:	April 30, 2014
Full manuscript due for review:	May 31, 2014
Notification of acceptance:	July 31, 2014
Camera ready manuscript:	Sep. 30, 2014
Pre-registration:	Oct. 31, 2014
Conference:	Dec. 14-18, 2014

	3/11	3/12		3/13		3/14		3/15
	Earthquake/ tsunami	AM	PM	AM	PM	AM	PM	AM/PM
1F1	IC on (A & B) 1503off man'lly 1830 Open-close 17~1800 TAF 2130 No access to IC Core melt (before mdngt)	Rad level high in RBs 3am RPV failure ? 5am PCV failure? Prep vent	1430 Vent successfuil? 1536 H2 expl.			S/C temp high (sat) PCV pres high – rupture level set too high; difficult to vent and open SRV PCV failure expcted due to excess temp		Highest rad level at the main gate
1F2	1502 RCIC on w/o DC power RCIC valves not compl closed? Car batteries for instrumen-tation and to open SRVs	(20 hours)	(>70 hours) (14 hours)	11am try PCV venting (not success)	(21 hours)	Alternate water injection line (CRD pump, SLC pump lines) and PCV vent lines damag'd by H2 *No coolant injection !*	1325 RCIC off PCV p high No makeup until 1954 1730 TAF 1802 SRV op 1830 Whole core uncov. Makeup was delayed until 1954	600 H2 expl? Near S/C or #4 Large scale release of rad-active materials 2000 a large portion of the core melt down to bottom head (est)
1F3	1506 RCIC on RPV p falls down due to possible ADS open or RPV failure – high peak p pulse: by MFCI ? Not likely but still under debate	1136 RCIC off	1230 HPCI on *No coolant injection !*	0242 HPCI off 700TAF then Core metldown started 841 PCV vent (insufficient) 908 SRV open 925 sea water injection	S/C temp too high (no condensatn) 1312 Sea water inject (for ~12 hrs: ***insufficient***)	1100 H2 explosion		PCV venting was higher priority at TEPCO

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Birdseye View Of Fukushima Dai-ichi NPPs (1F) Before the 3/11 tsunami

Cf. http://cryptome.org/eyeball/daiichi-npp2/daiichi-photos2.htm