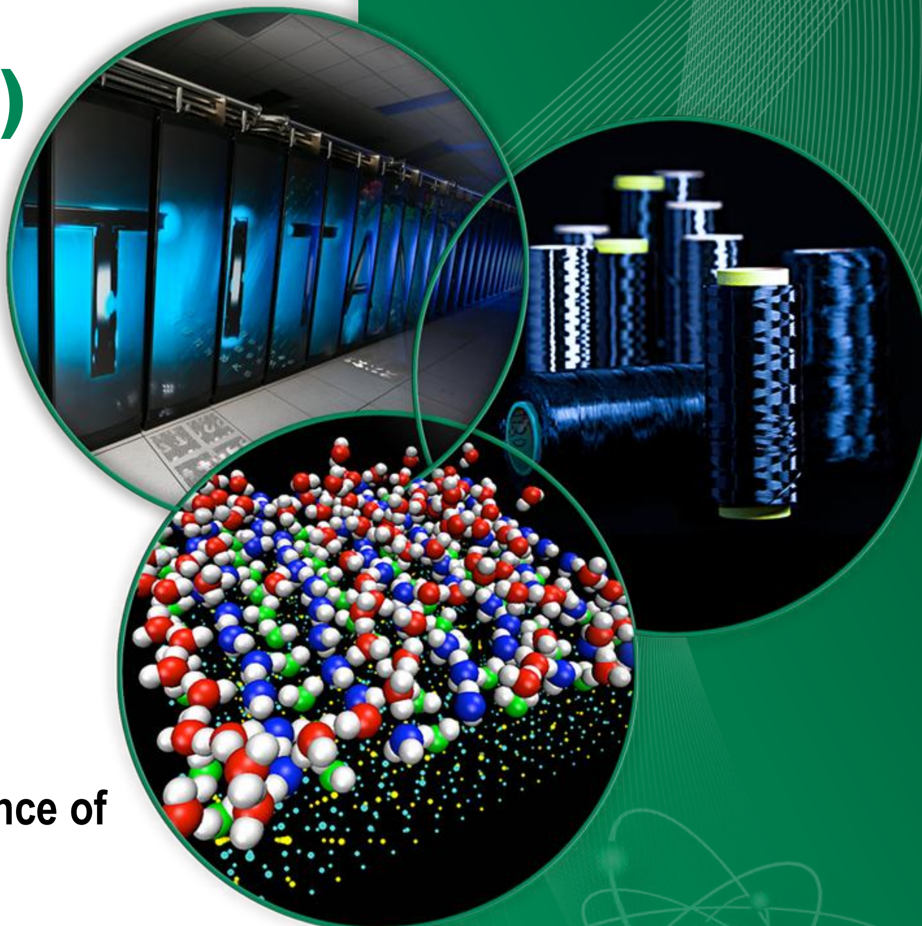
Accident Scenarios of Interest (TMI-2 / Fukushima ??)



Larry Ott
Reactor and Nuclear Systems Division
Oak Ridge National Laboratory

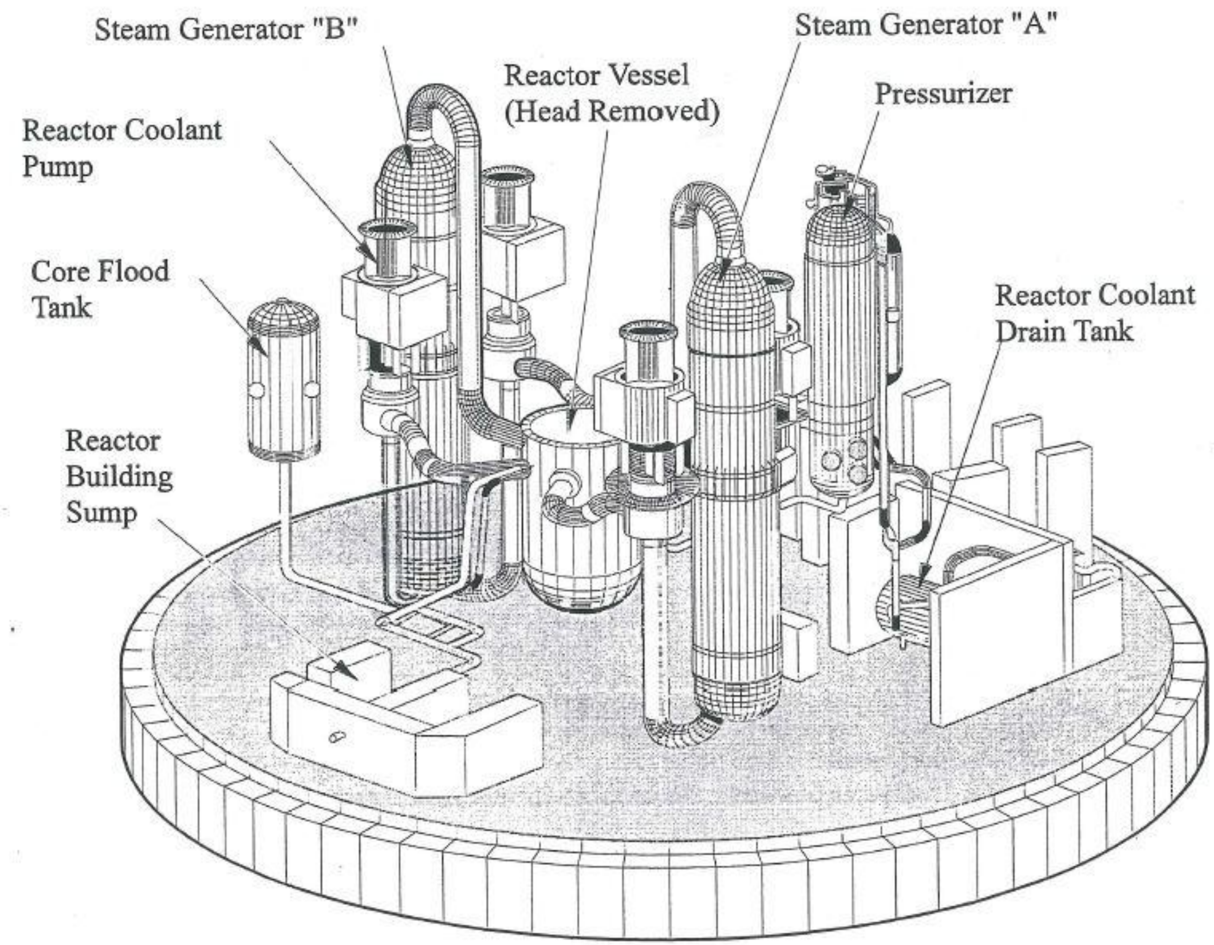
With input from B. Cheng (EPRI)
and S.Mizokami (TEPCO)

Second Meeting on Increased Accident Tolerance of Fuels for LWRs
NEA Headquarters
Issy-les0Moulineaux, France
29-29 October 2013

Common Platforms for Analysis
(TMI-2 / Fukushima ??)

Three Mile Island Units 1 and 2
March 28, 1979

Three Mile Island (TMI) NPS



Located near Middleton, PA

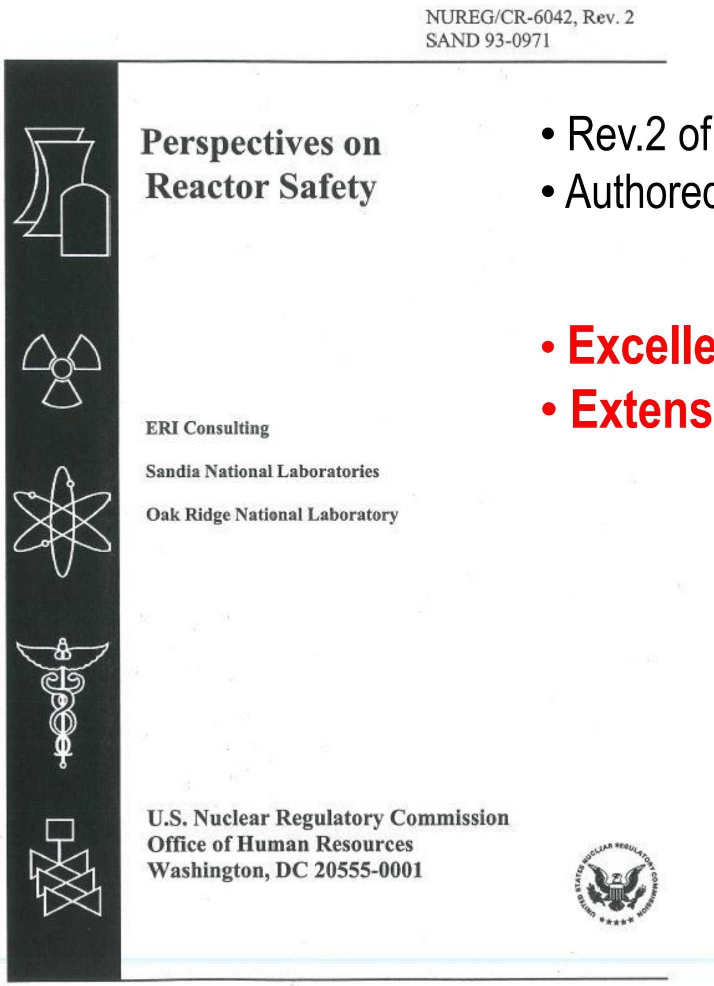
Babcock & Wilcox PWRs

Unit 1 rated at 792 Mwe
Unit 2 rated at 880 MWe

Three Mile Island Unit 2 History

- Reactor scram: 04:00 3/28/79
- Core melt and relocation: ~05:00 – 07:30 3/28/79
- Hydrogen deflagration: 13:00 3/28/79
- Recirculation cooling: Late 3/28/79
- Phased water processing: 1979-1993
- Containment venting 43Kci Kr-85: July 1980
- Containment entry: July 1980
- Reactor head removed and core melt found: July 1984
- Start defuel: October 1985
- Shipping spent fuel: 1988-1990
- Finish defuel: January 1990
- Evaporate ~2.8 M gallons processed water: 1991-1993
- Cost: ~$1 billion

TMI-2 Has Been a Significant Focus of the NRC's "Perspectives on Reactor Safety" Course Since Late 1990's


NUREG/CR-6042, Rev. 2
SAND 93-0971

Perspectives on Reactor Safety

ERI Consulting

Sandia National Laboratories

Oak Ridge National Laboratory

U.S. Nuclear Regulatory Commission
Office of Human Resources
Washington, DC 20555-0001

- Rev.2 of NUREG/CR-6042 published in March 2002
- Authored by F.E.Haskin, A.L.Camp, S.A.Hodge, and D.A.Powers

- **Excellent discussion of the TMI-2 accident**
- **Extensive chronology of the major TMI-2 accident events**

References:

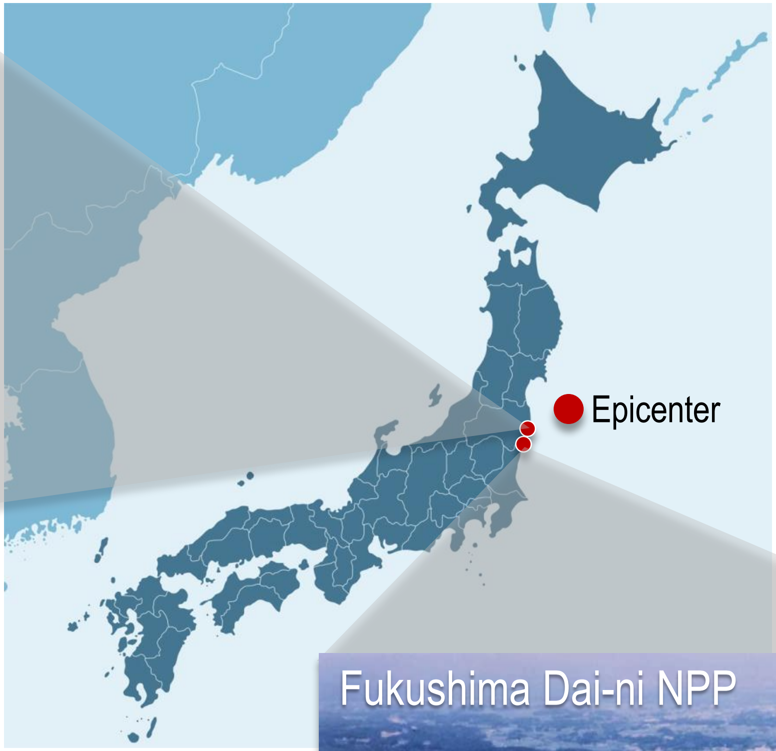
1. U.S. Nuclear Regulatory Commission, "Investigation Into The March 28, 1979 Three Mile Island Accident by Office of Inspection and Enforcement," NUREG-0600, Investigative Report No. 50-320/79-10, August 1979.
2. E. Rubinstein and J. F. Mason, "An Analysis of Three Mile Island," *IEEE Spectrum*, November 1979.
3. M. Rogovin, G. T. Frampton, et al., "Three Mile Island, A Report to the Commissioners and to the Public," U. S. Nuclear Regulatory Commission, NUREG/CR-1250, Volume II Part 2, January 1980.
4. U. S. Nuclear Regulatory Commission, "TMI-2 Lessons Learned Task Force" Final Report, NUREG-0585, 1980.
5. U. S. Nuclear Regulatory Commission, "NRC Action Plan Developed as a Result of the TMI-2 Accident," NUREG-0669, May 1980.
6. R. A. Knief, "The Accident at Three Mile Island Unit 2," Chapter 15 of *Nuclear Energy Technology - Theory and Practice of Commercial Nuclear Power*, Hemisphere Publishing, 1991.

The TMI-2 accident chronology is well documented and will not be repeated here BUT a summary of the chronology is included at the end of this presentation.

TMI-2 is obviously the accident scenario of choice for evaluating ATFs in PWRs

Fukushima Dai-ichi BDBA
(BWR Severe Accidents)

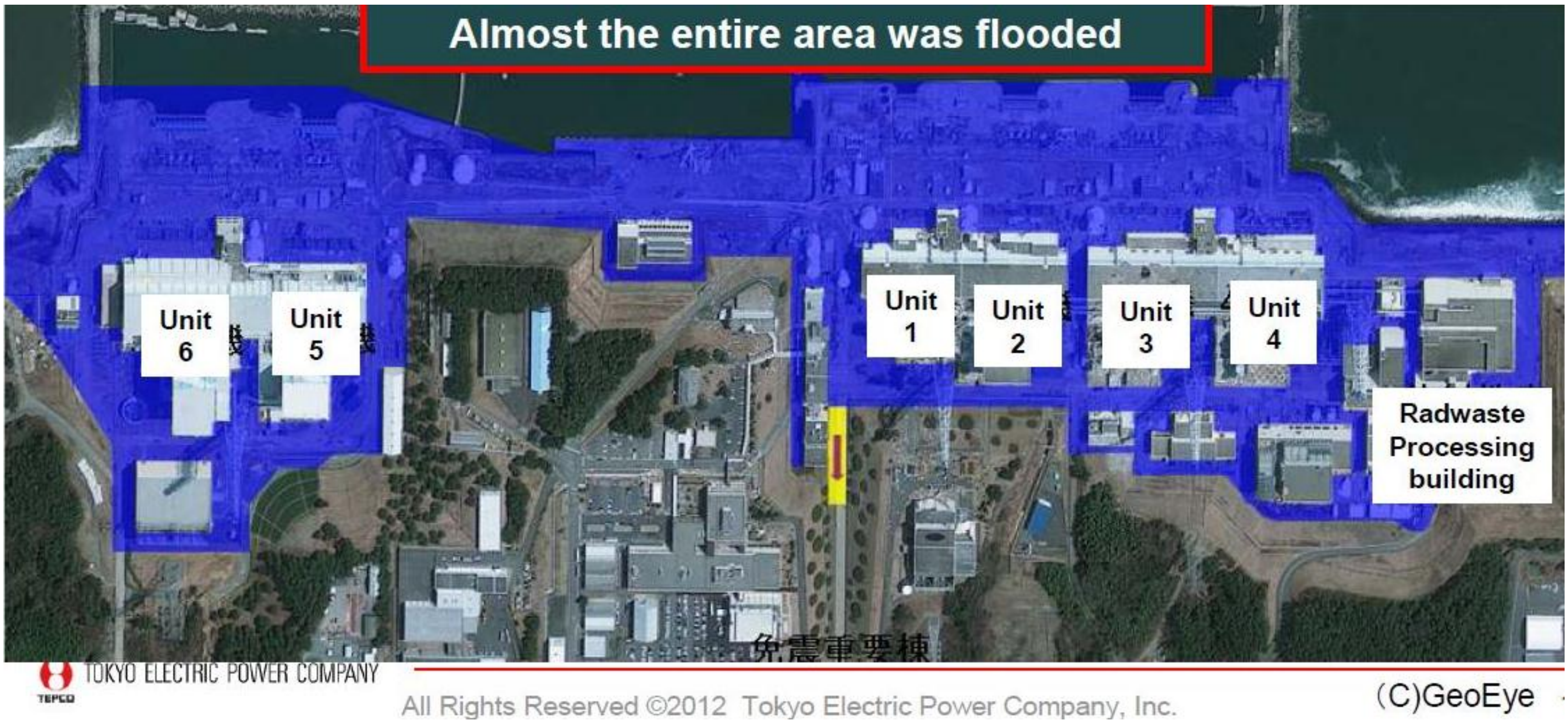
2011 Tohoku Pacific Earthquake



- Occurred 14:46 March 11, 2011
- Magnitude: 9.0 M
- Epicenter location: 130 km off the coast of Sanriku, 38°6”N and 142°51”E, and 24 km in depth
- The height of the tsunami that hit the Fukushima Dai-ichi NPS was more than 14 m

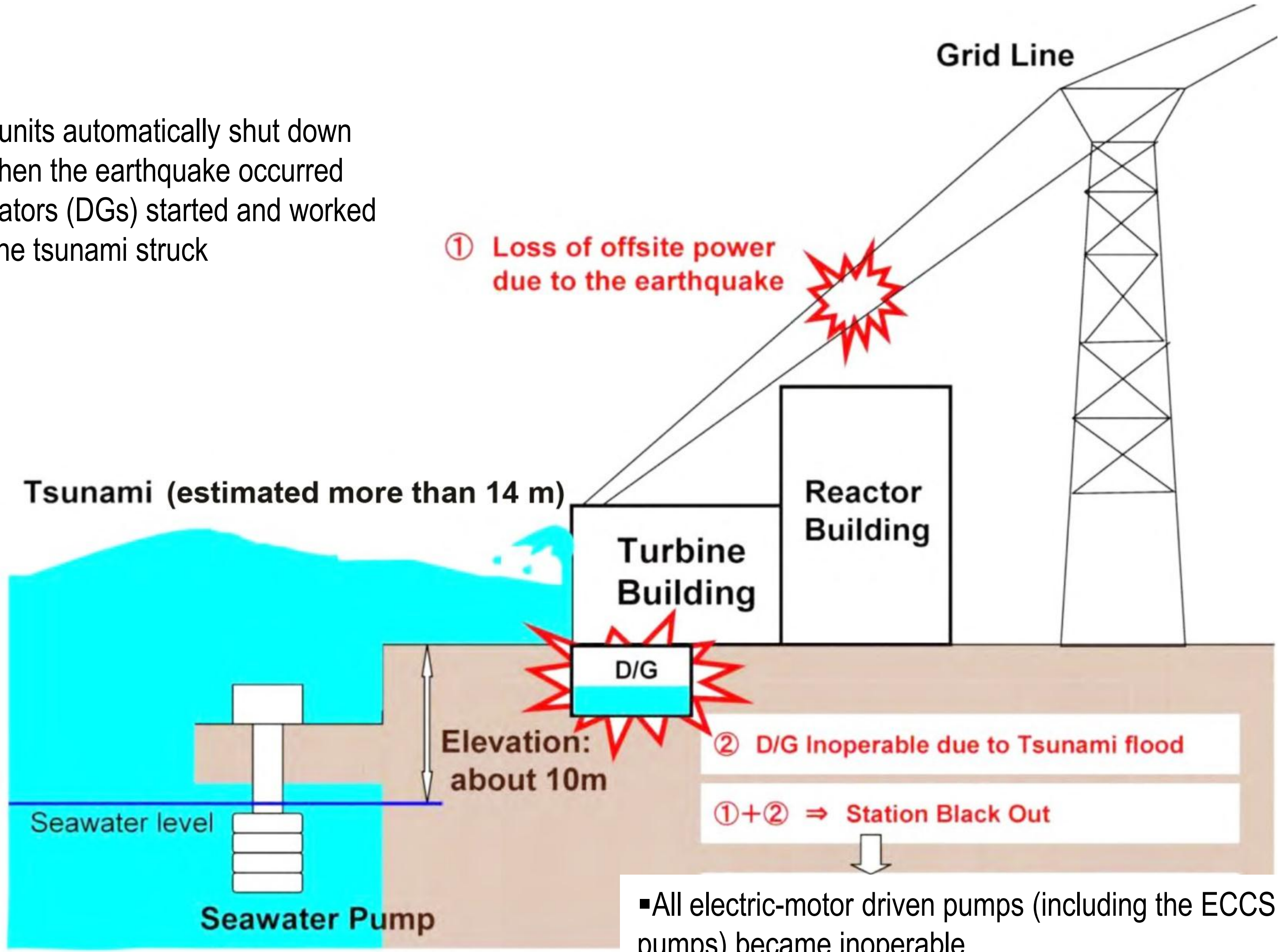
Fukushima Dai-ichi Nuclear Power Station

Tsunami Flooding at Fukushima Dai-ichi



The Tsunami Was the Primary Cause of the Accident on 3/11

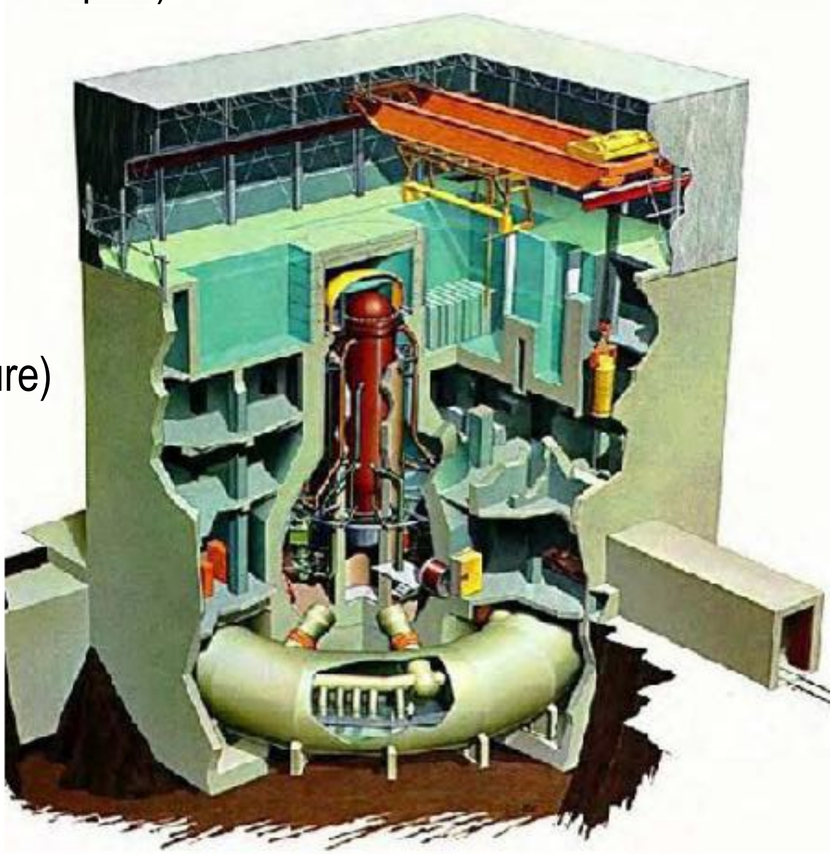
Note:
- All operating units automatically shut down (scrammed) when the earthquake occurred
- Diesel Generators (DGs) started and worked properly until the tsunami struck



- All electric-motor driven pumps (including the ECCS pumps) became inoperable
- The steam-turbine-driven pumps (RCIC and HPCI) were available

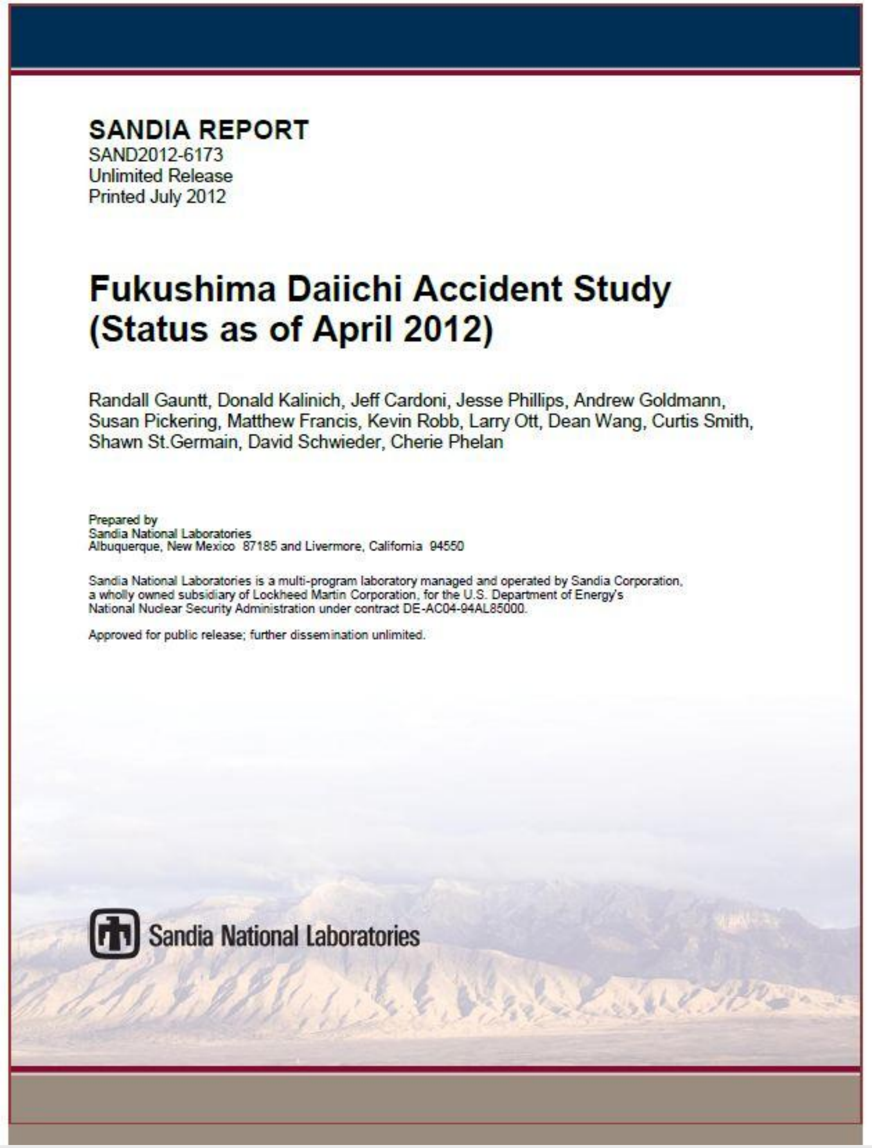
BWR/3, 4 Generation Plants

- BWR/3 (460 MWe, 1F1)
  - Mark 1 containment (drywell + torus-type suppression pool)
  - SFP on top floor of the R/B
  - Isolation condenser for passive core cooling (at high pressure)
  - Core spray system (at low pressure) after depressurization by SRVs
  - HPCI (high pressure core injection, at high pressure)
- BWR/4 (784 MWe, 1F2, 3, and 4)
  - Mark I containment (drywell + torus-type suppression pool)
  - SFP on top floor of the R/B
  - RCIC (reactor core isolation cooling) and HPCI (high pressure core injection) (at high pressure)
  - CS (core spray) and RHR/LPCI (at low pressure) after depressurization by SRVs



Event Progression

A Best-Estimate DOE/NRC Study (SNL/INL/ORNL) of the Fukushima Accident Published in July 2012


SANDIA REPORT
SAND2012-6173
Unlimited Release
Printed July 2012

Fukushima Daiichi Accident Study (Status as of April 2012)

Randall Gauntt, Donald Kalinich, Jeff Cardoni, Jesse Phillips, Andrew Goldmann, Susan Pickering, Matthew Francis, Kevin Robb, Larry Ott, Dean Wang, Curtis Smith, Shawn St.Germain, David Schwieder, Cherie Phelan

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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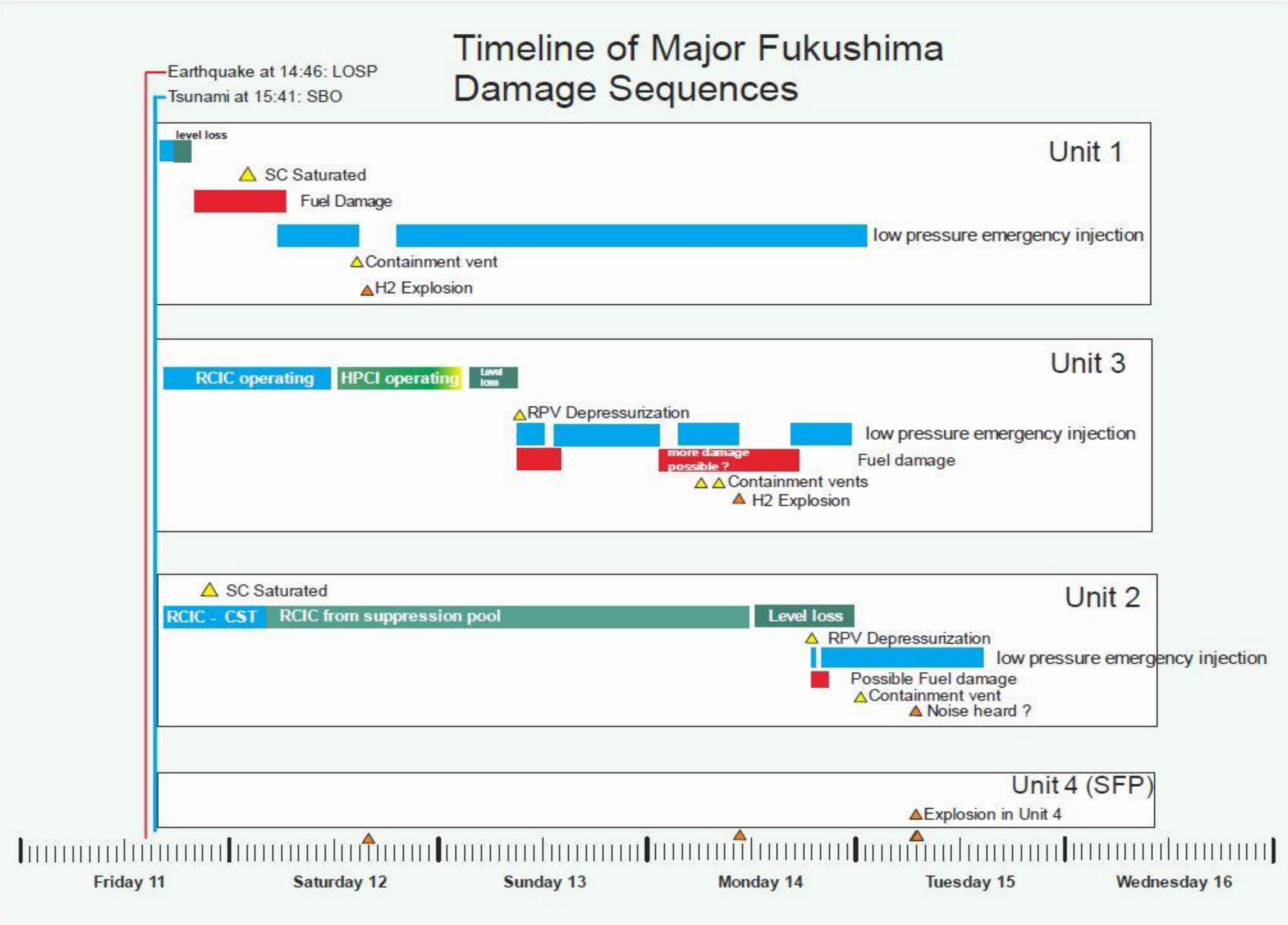
Approved for public release; further dissemination unlimited.

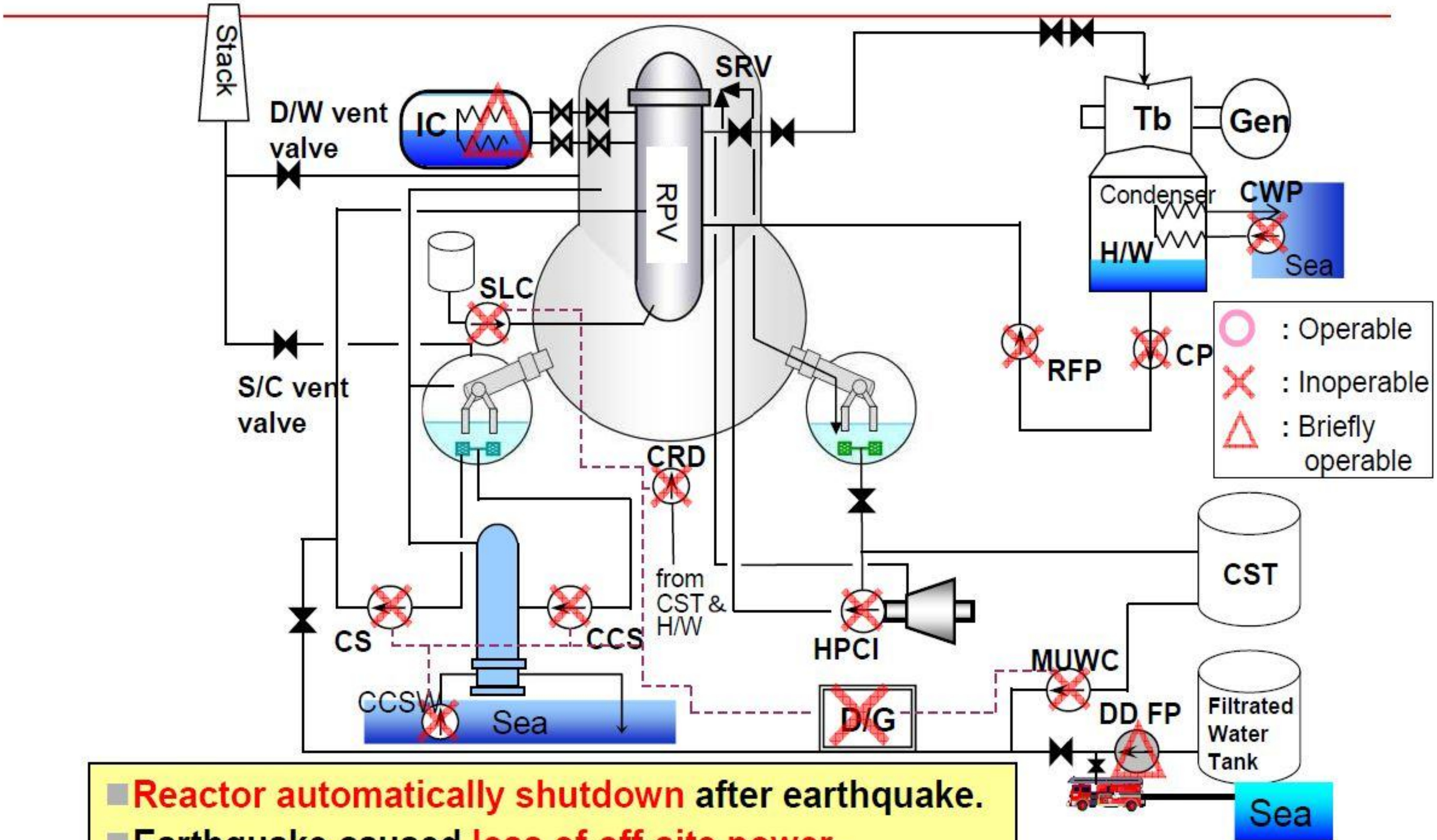
Sandia National Laboratories

- Data Portal (INL) : available data, information, timelines, etc on the accidents
- Accident TimeLines
- Analyses of the Reactor Accidents for Units 1-4 – (SNL and ORNL)
  - Model descriptions, input, assumptions
  - Analyses and results

Fukushima Dai-ichi Accident Timelines



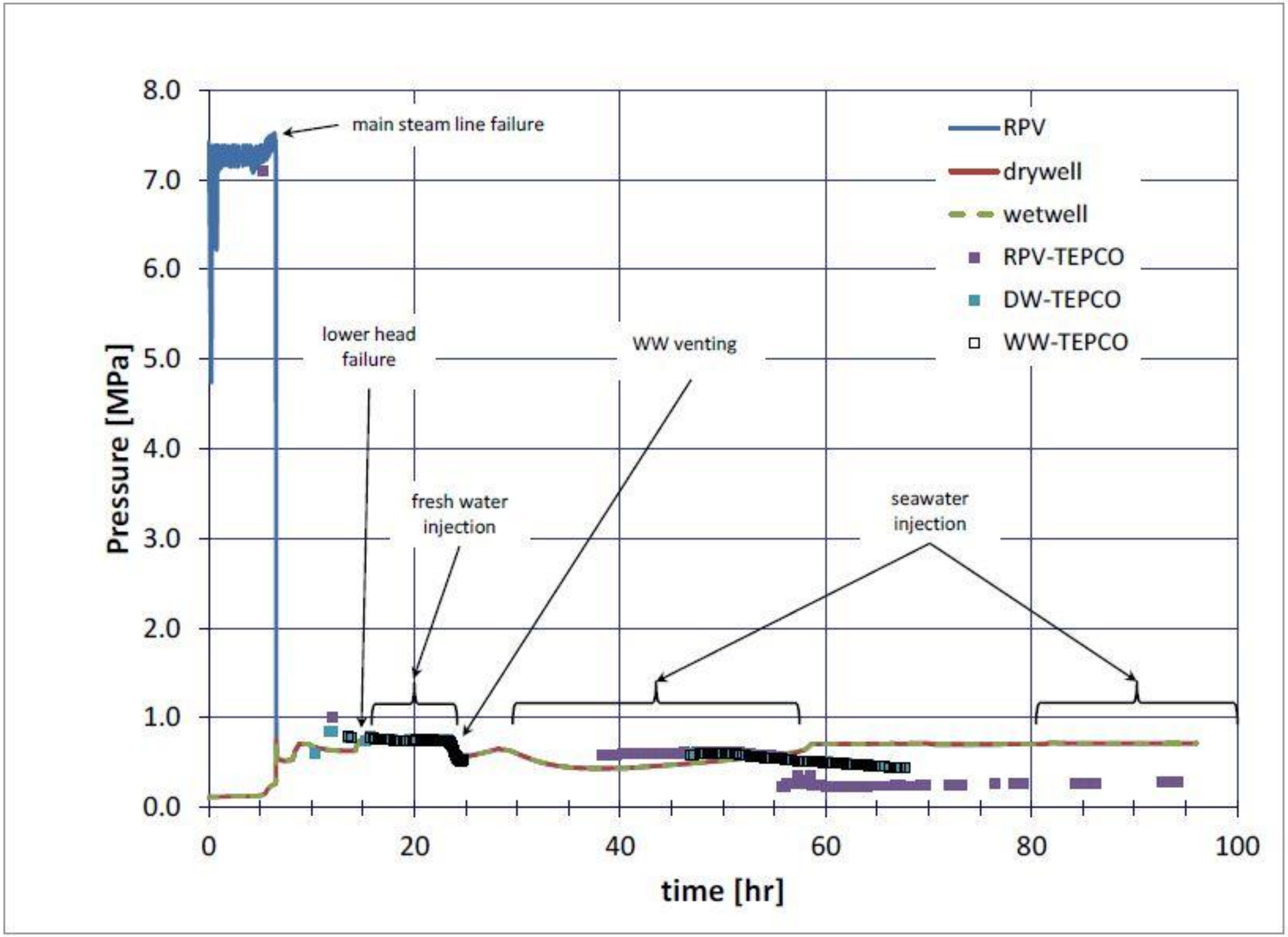
1F Unit 1 Schematic System Diagram (Post-Tsunami Status)



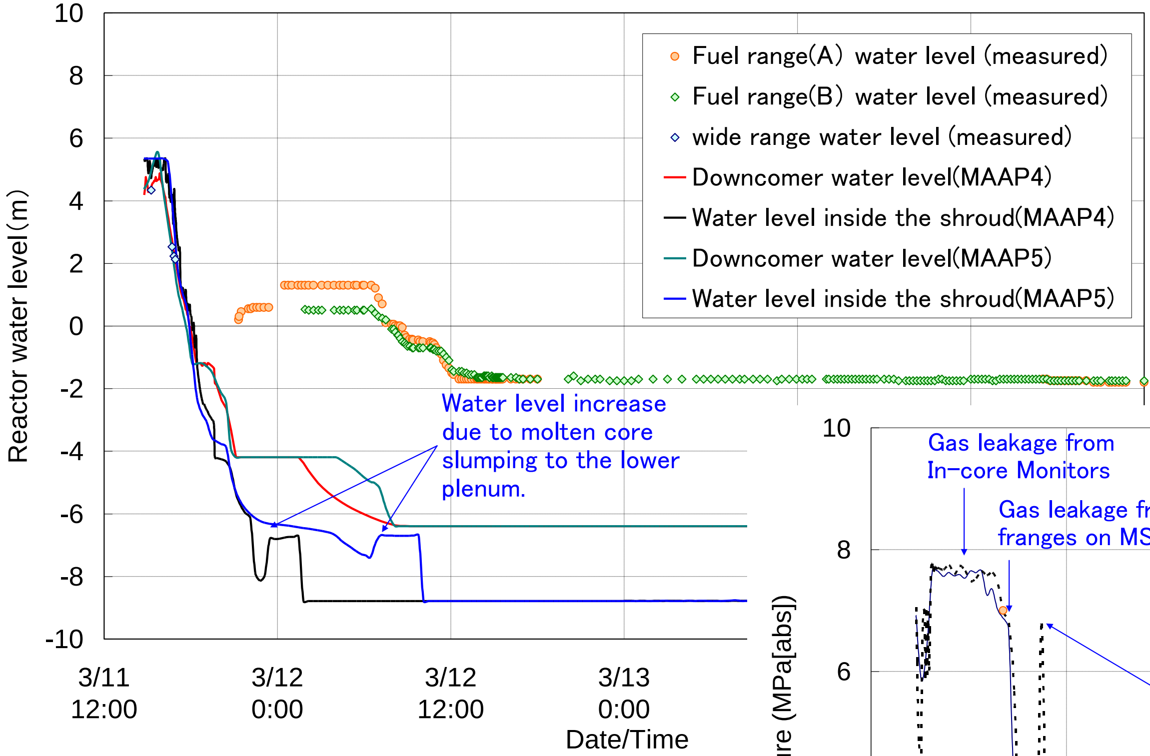
- Reactor automatically shutdown after earthquake.
- Earthquake caused loss of off-site power.
- Tsunami caused loss of all emergency power, rendering most safety systems inoperable.

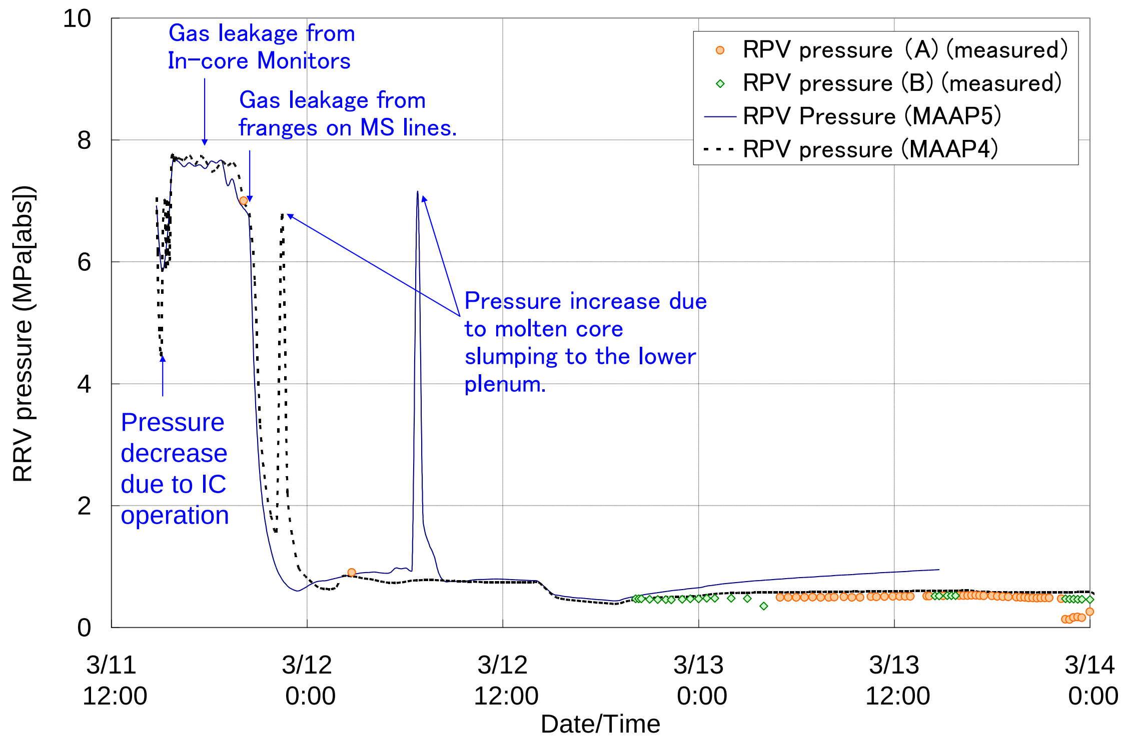
TEPCO

MELCOR RPV and Containment Pressure Predictions (SNL) Compared to TEPCO data (Unit 1)

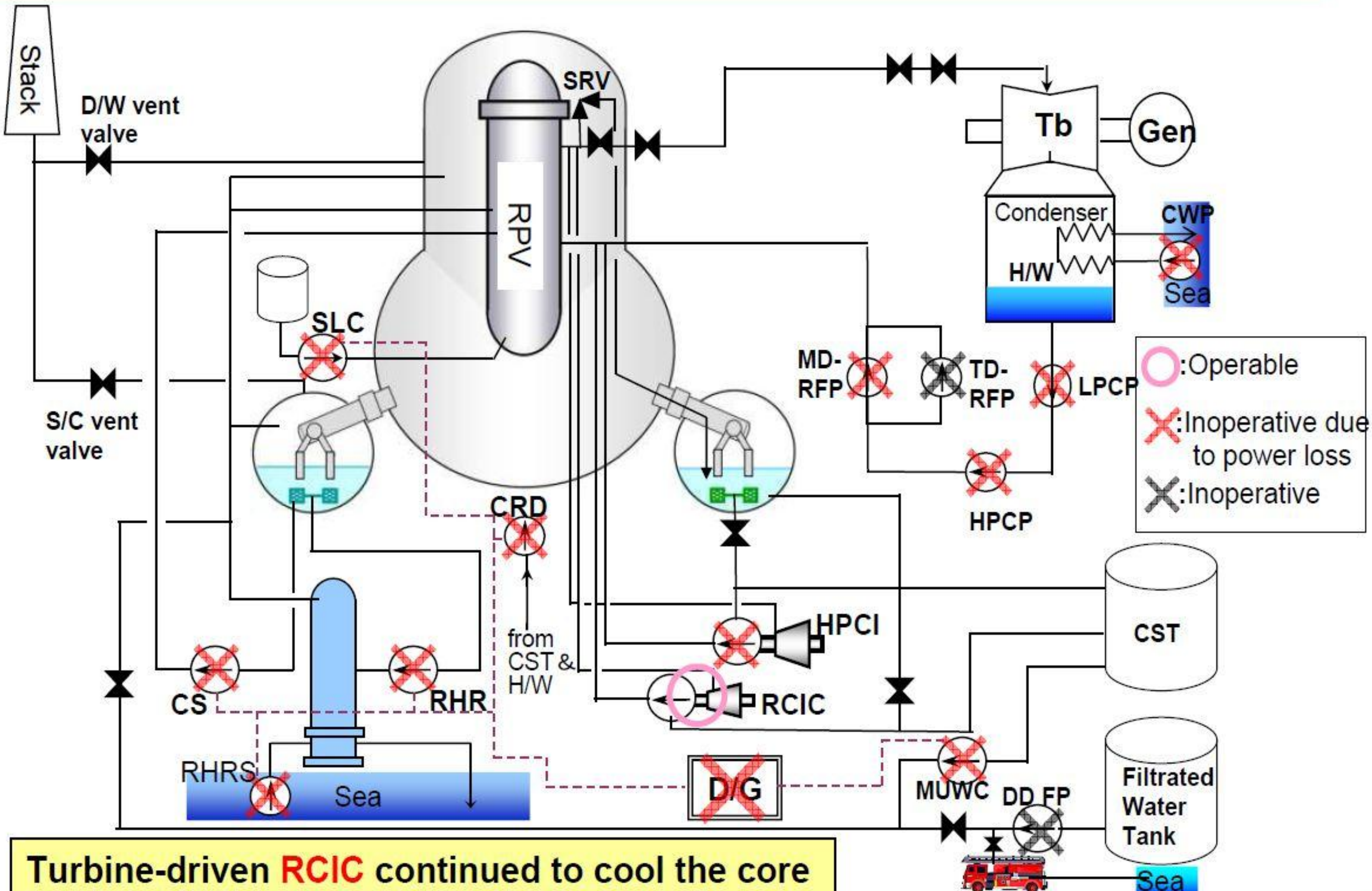


Shinya Mizokami (TEPCO) MAAP Analyses of Fukushima Dai-ichi Unit 1



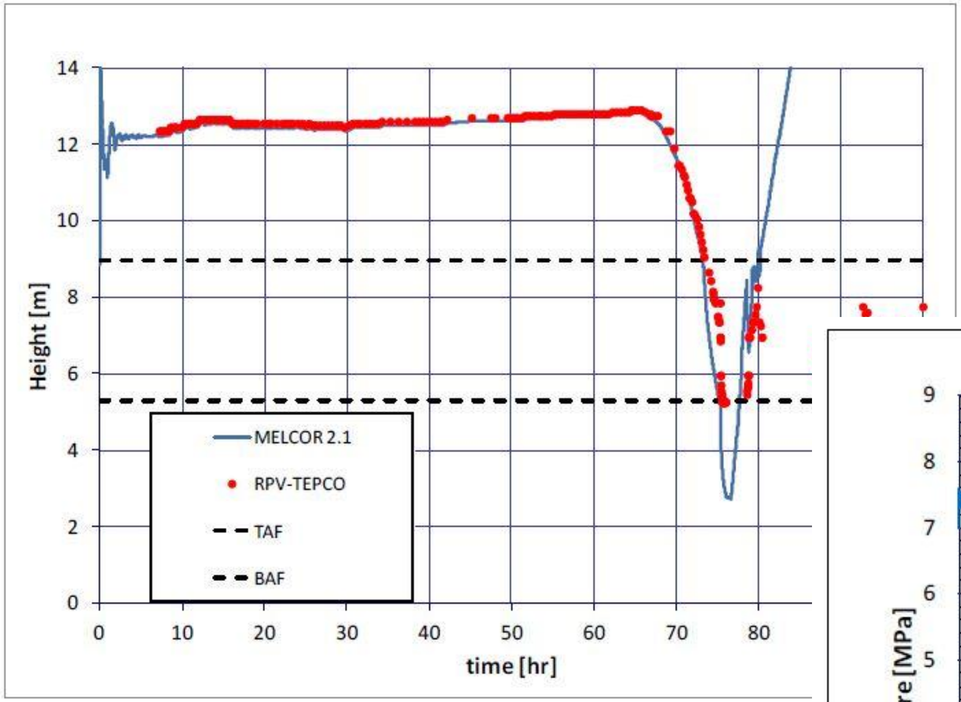


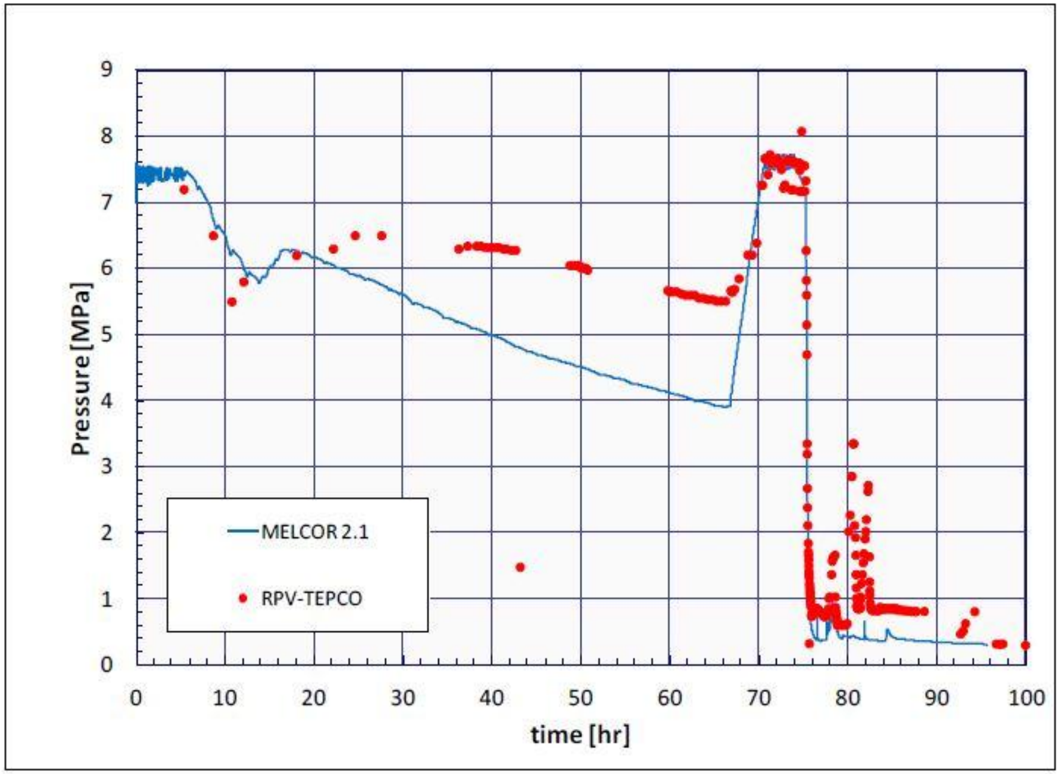
1F Unit 2 Schematic System Diagram (Post-Tsunami Status)



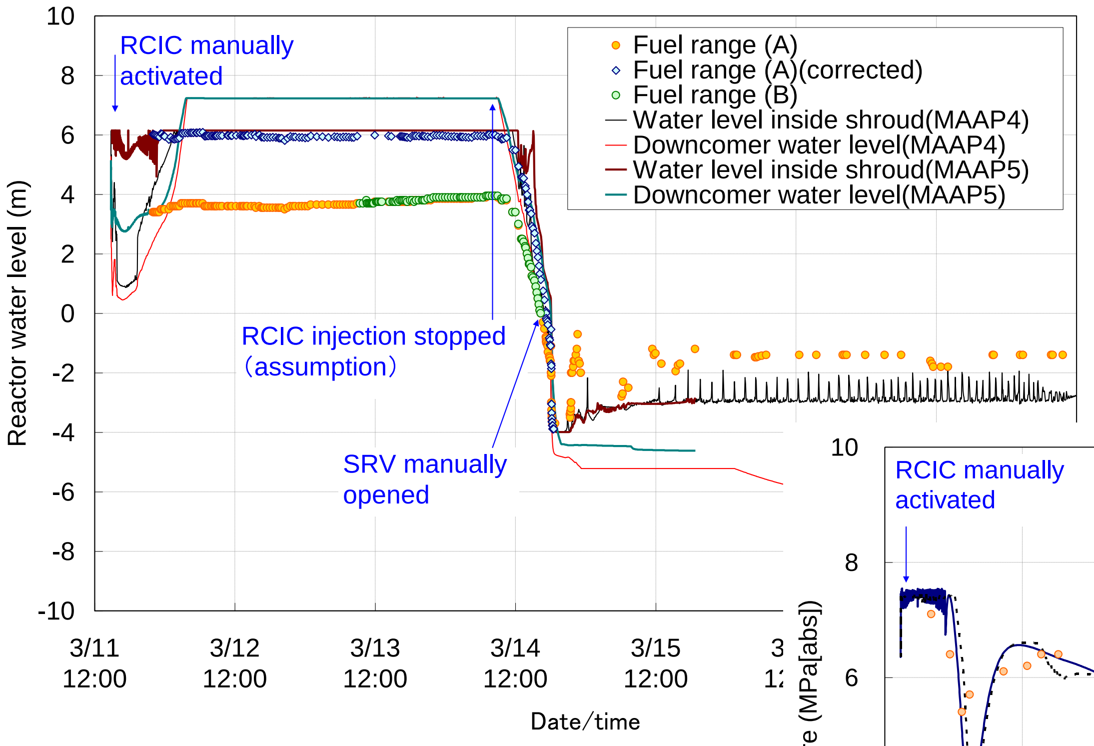
Turbine-driven RCIC continued to cool the core for about 3 days.

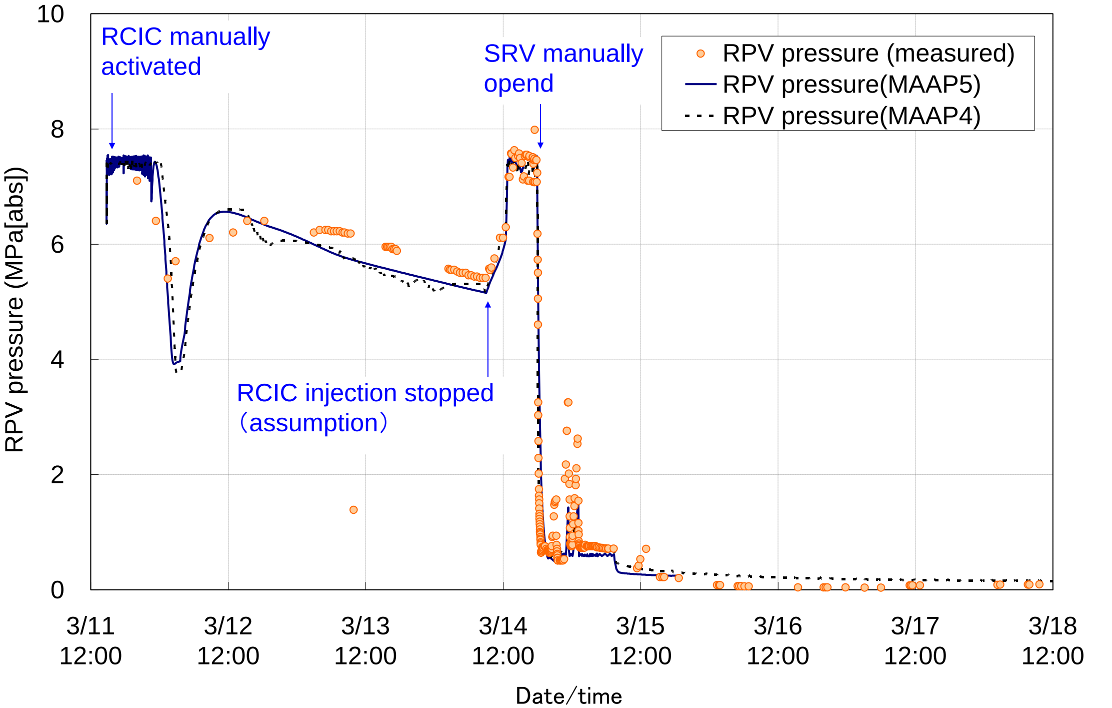
MELCOR RPV and Containment Pressure Predictions (SNL) Compared to TEPCO data (Unit 2)



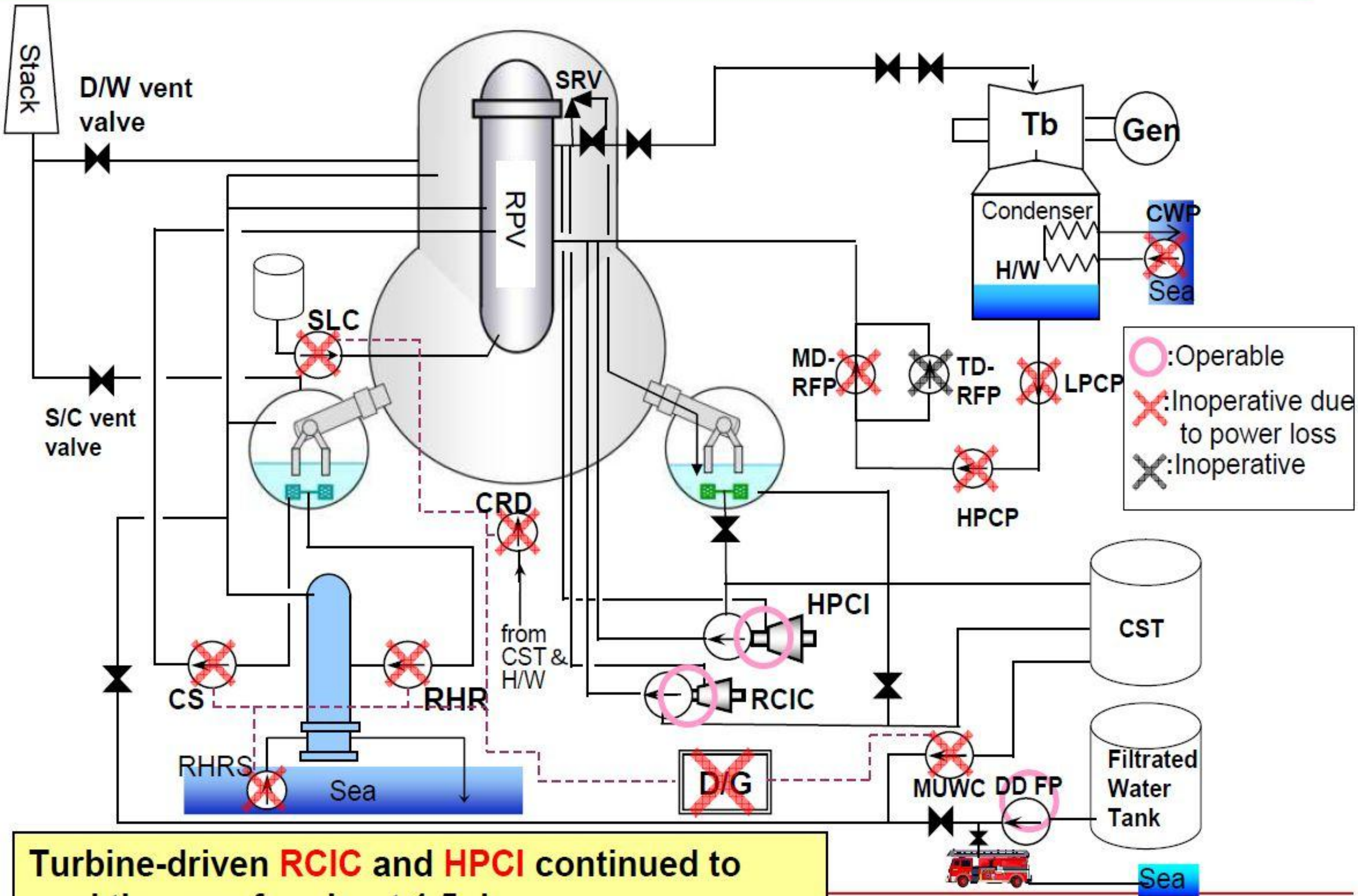


Shinya Mizokami (TEPCO) MAAP Analyses of Fukushima Dai-ichi Unit 2





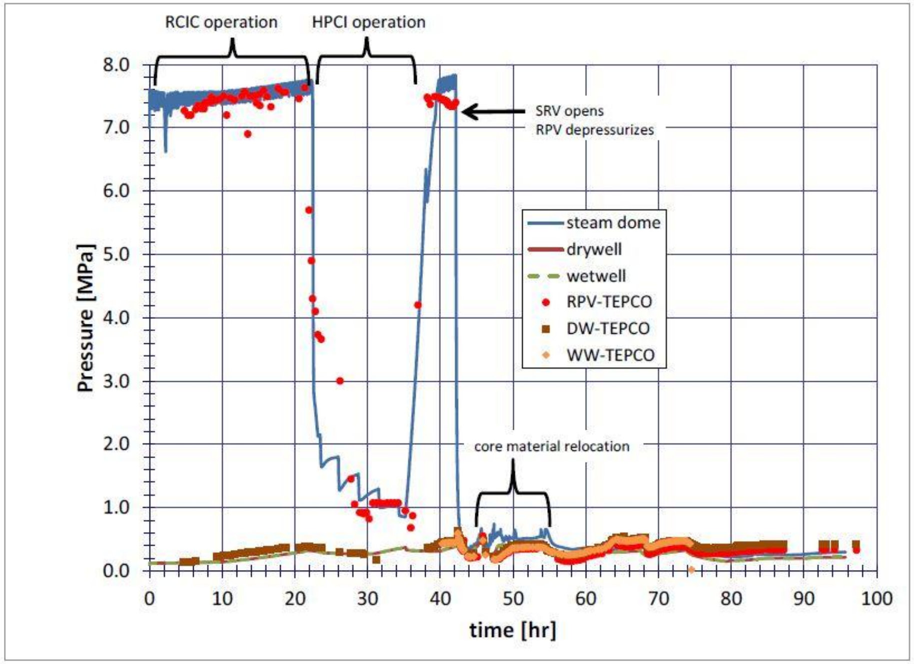
1F Unit 3 Schematic System Diagram (Post-Tsunami Status)



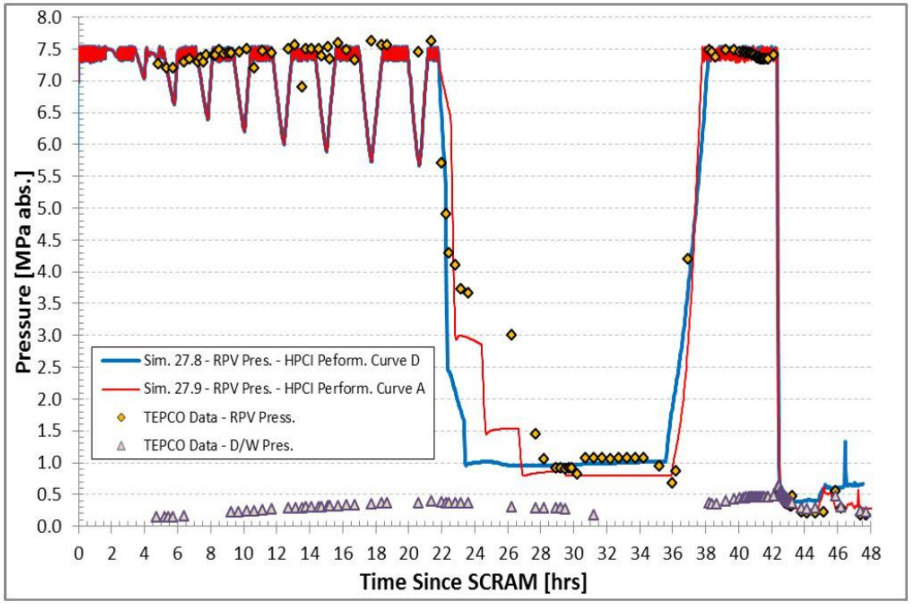
Turbine-driven RCIC and HPCI continued to cool the core for about 1.5 days.

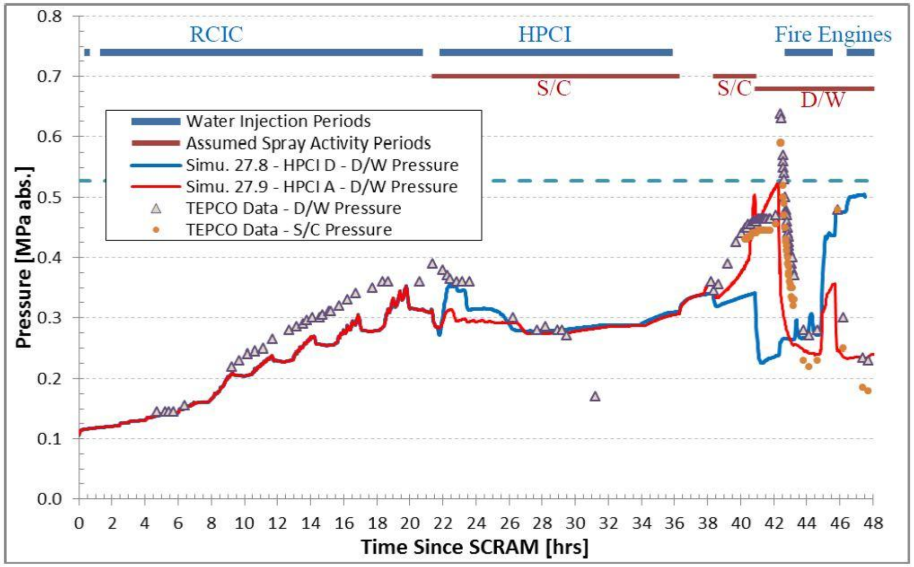
MELCOR Predicted RPV and Containment Pressures Compared to TEPCO Data (Unit 3)

SNL

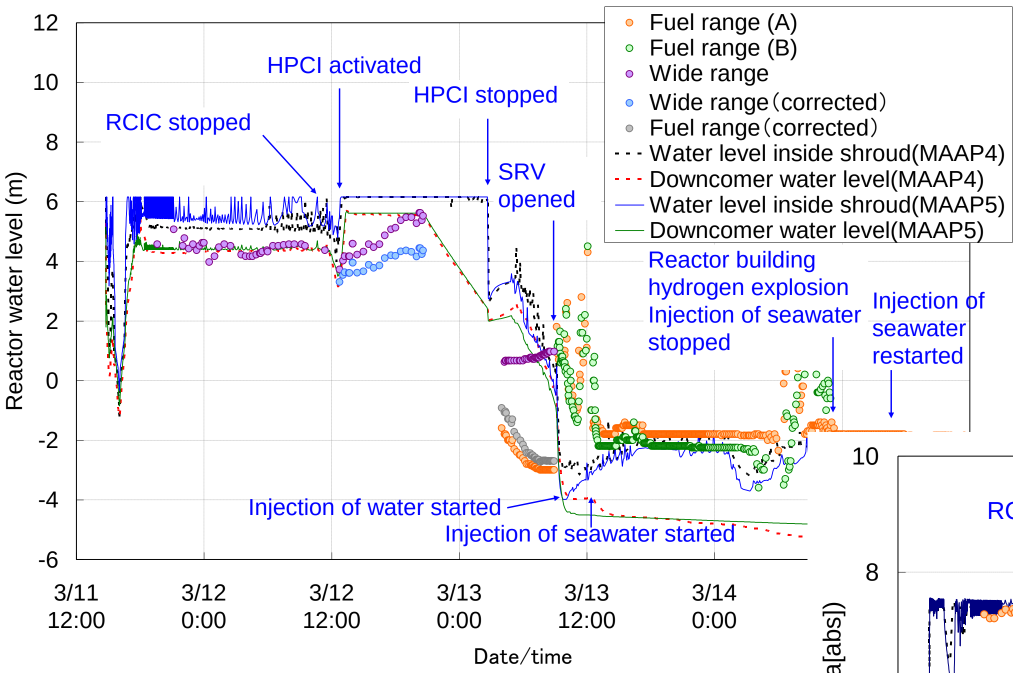


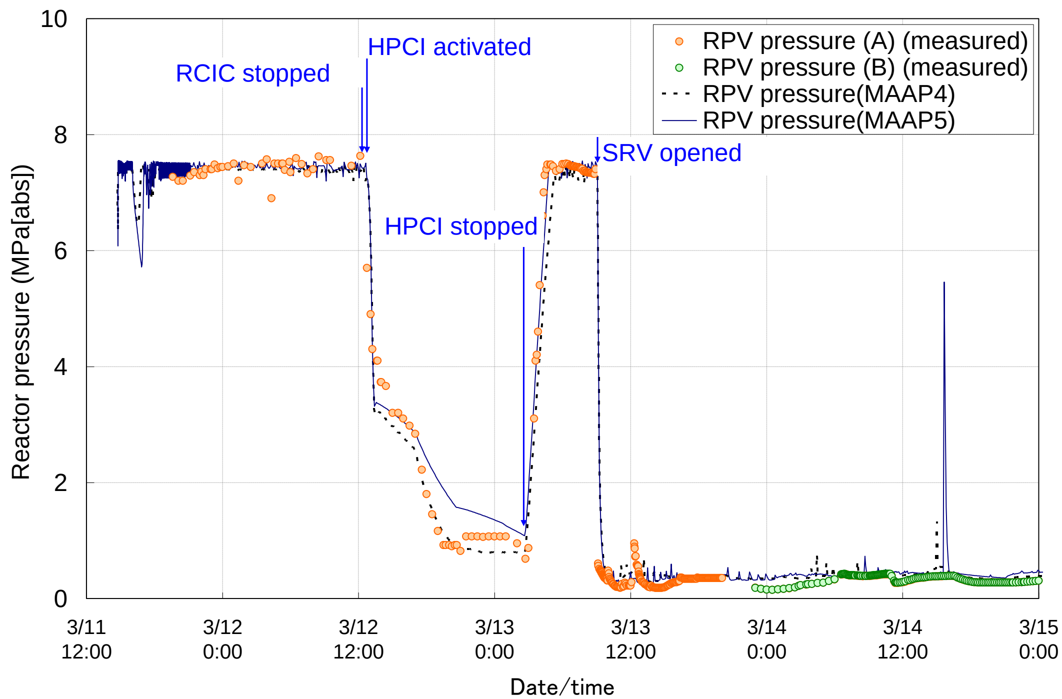
ORNL





Shinya Mizokami (TEPCO) MAAP Analyses of Fukushima Dai-ichi Unit 3





Fukushima Base Case for Analysis
Unit 1 ? 2 ? Or 3 ?

Unit 1 ?

- Cons:
  - How and where RPV failed ?
  - There is NO possibility to prevent a melt-down, even if there is no energy generation by the water-Zr reaction
  - An ATF design probably would not have prevented the melt-down
  - Inadequate TEPCO plant data early in the accident
- Pros:
  - Simpler to model (no RCIIC or HPCI activation, no sprays)
  - Fewer uncertainties (of operator actions)
  - Bottom head failure within 15 hours (reasonable computation time)
  - High probability of core on the floor (can incorporate effects of ATFs on ex-vessel phase of the accident)

Unit 2 ?

- Cons:
  - At least 66 hours of transient would have to be simulated – this is a significant computation time for our SA codes, especially if multiple runs are made
  - Uncertainty in RCIC operation (intermittent, operator trim, and/or degradation of pump output)
  - How and where RPV failed ?
  - Problems in WW modeling (saturation and local overheating/boiling)
- Pros:
  - There is a possibility to prevent the melt-down, if there is no energy generation by the water-Zr reaction
  - An ATF design may have prevented the melt-down
  - Adequate TEPCO plant data

Unit 3 ?

- Cons:
  - At least 50 hours of transient would have to be simulated – this is a significant computation time for our SA codes, especially if multiple runs are made
  - 1F3 is difficult to model even before core degradation starts:
    - Uncertainty in RCIC operation (intermittent or operator trim of pump output)
    - After RCIC failure and the initiation of the HPCI, RPV pressure dropped significantly (**DUE** to the steam demand of the HPCI steam turbines), some codes may not be able to model this phenomena
    - HPCI performance degrades with dropping RPV steam pressure [**SO**, how much water was pumped into the RPV is uncertain]
  - After HPCI failure, the RPV repressurizes and boiloff starts [this probably started earlier with the degradation in the HPCI pumping performance]
    - DW/WW pressures increase significantly (noncondensable gas generation or local WW saturation/boiling)
    - DW sprays initiated (uncertainties in delivery ammount and efficiencies)
    - How and where RPV failed ?
  - Problems in WW modeling (saturation and local overheating/boiling) noted in SAND2012-6173
- Pros:
  - There is a possibility to prevent the melt-down, if there are no energy generation by the water-Zr reaction
  - An ATF design may have prevented the melt-down
  - Adequate TEPCO plant data

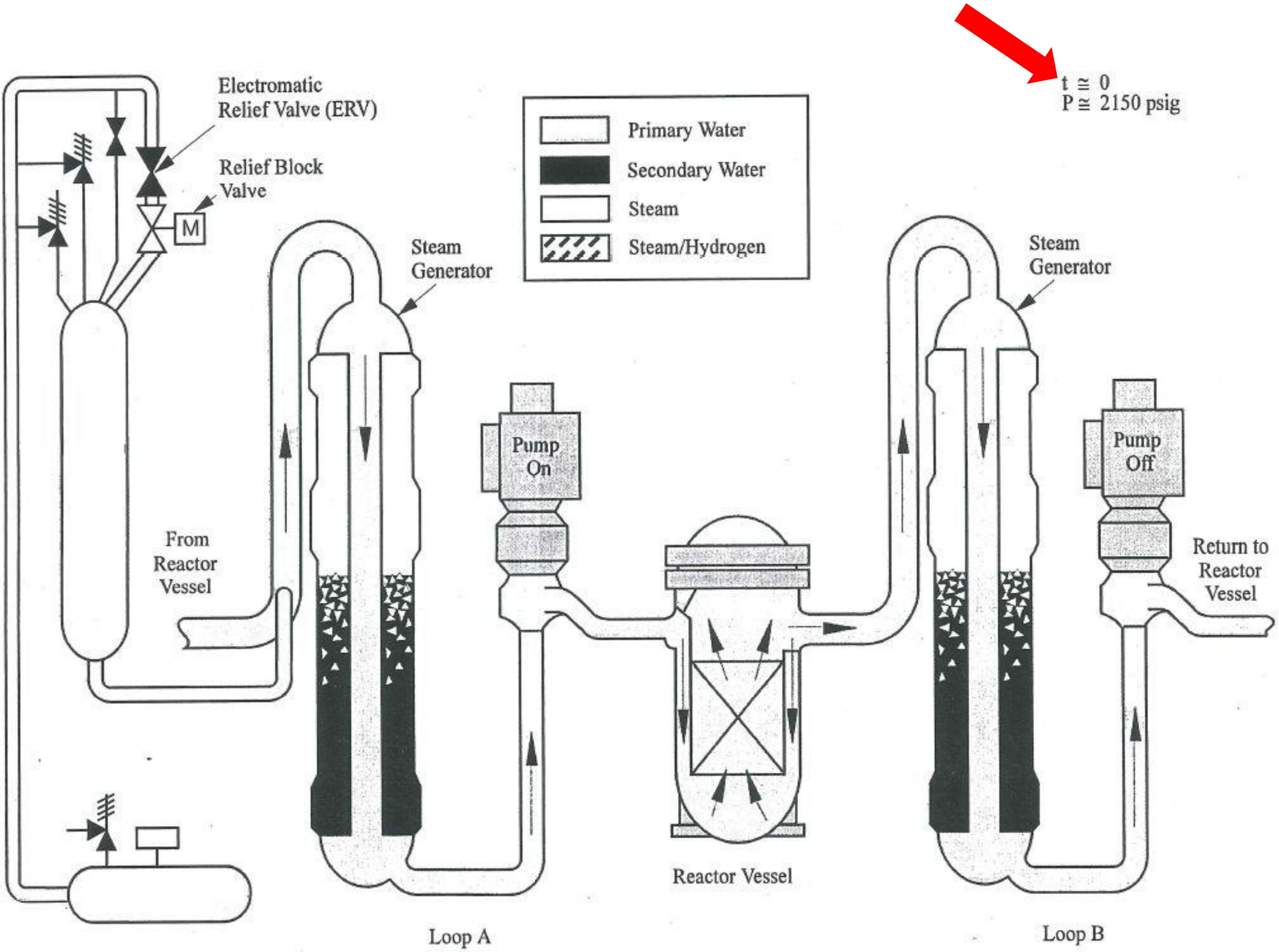
Questions ??

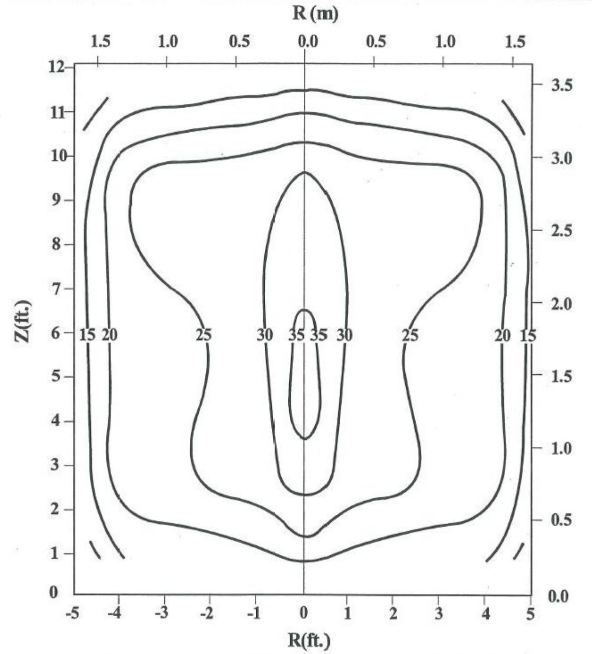
TMI-2 Chronology

Chronology of Major TMI-2 Accidents Events – p.1

Elapsed Time h:min:s	Event or Condition
-0:00:01	Condensate pump 1A and condensate booster pumps trip.
0:00:00	Feedwater pumps trip, turbine trips.
0:00:03	PORV opens at 2255 psig.
0:00:08	Reactor trip (control rods dropped) at 2355 psig.
0:00:13	PORV failed to reclose at 2205 psig.
0:00:15	Indicated pressurizer level peaked at 256 inches and began a rapid decrease.
0:00:14	Auxiliary feedwater pumps achieved normal discharge pressure.
0:00:15	Steam generator levels indicate 74 inches (startup range).
0:00:30	PORV and pressurizer safety valve outlet temperatures alarmed high.
0:00:38	Steam generator A water level at 23.8 inches. Auxiliary feedwater valves open as level decreases below 30 inches and give dual indication on panel.
0:00:40	Steam generator B water level at 23.7 inches and decreasing.
0:00:41	Operator manually started one of the three makeup pumps (pump 1B).
0:00:54	Pressurizer level reached lowest level (158 inches) and started to rise.
≥0:01:00	NRC estimate of onset of steam void formation.
≥0:01:45	Steam generators A and B boiled dry.
0:02:01	High pressure injection initiated (1000 gpm) when reactor coolant pressure fell below 1600 psig setpoint.
0:03:12	Reactor coolant drain tank relief valve began opening intermittently.
0:03:13	Operators bypassed the high pressure injection system.
0:03:28	Pressurizer high level alarm.
0:04:38	Operator throttled high pressure injection isolation valves and stopped makeup pump 1C.
0:04:52	Second let-down cooler put in service to allow increased letdown.
0:05:00	Pressurizer level reached 377 inches and continued to rise.
0:05:15	An operator restarted condensate pump 1A.

TMI-2: Initial Condition – Standby Operation at 97% Power





Distribution of fuel rod rating (kW/m) in the core

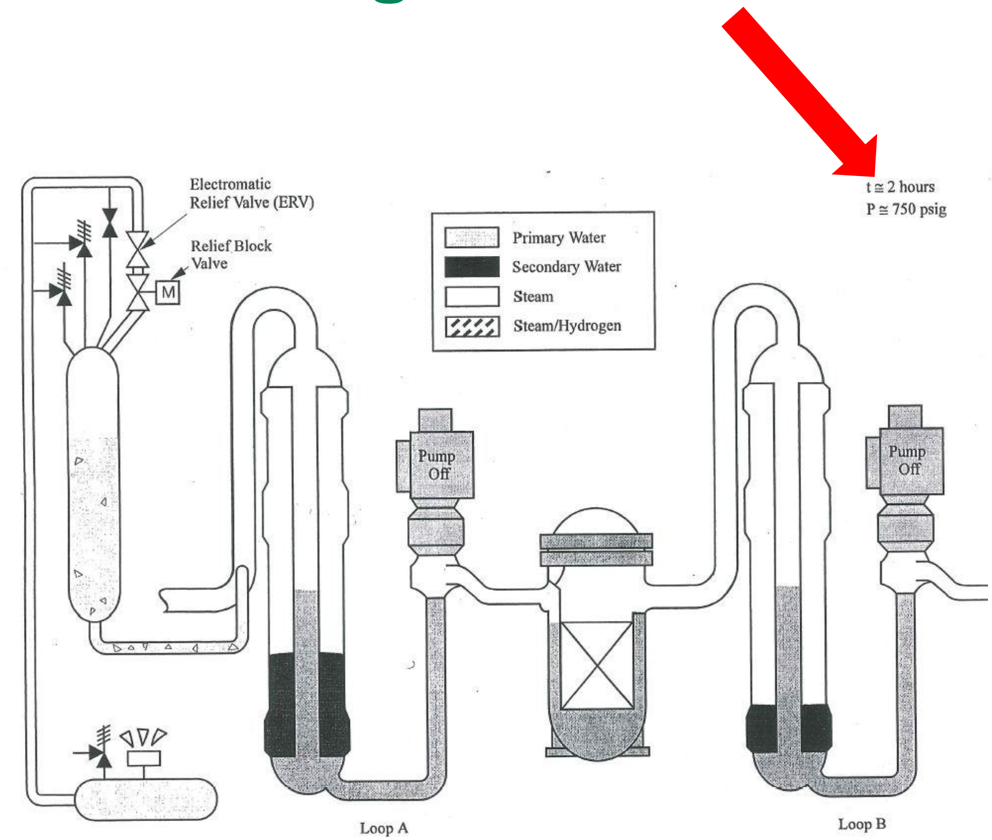
Chronology of Major TMI-2 Accidents Events – p.2

Elapsed Time h:min:s	Event or Condition
>0:05:15	Operators tried to restart condensate booster pump 2B but it tripped.
0:05:30	Saturated conditions indicated. Indicated reactor coolant temperature (T_h=582°F) and pressure (1340 psig) reached saturation.
0:06:00	Pressurizer steam bubble lost.
0:07:29	Reactor building sump pump 2A started (140 gpm).
0:08:00	*Figure 2.4-5. Expansion/Saturation Due to LOFW/LOCA.*
0:08:18	Operator opened auxiliary feedwater block valves.
0:10:19	Second reactor building sump pump (2A) started.
0:10:48	High (5.65 ft) reactor building sump level alarm. Sump soon overflowed (6 ft).
0:11:43	Pressurizer level indication came back on scale and dropped rapidly (20 inches in 1 min..) as reactor coolant loop temperatures continued to decrease from the heat being removed by the steam generators.
0:14:48	Reactor coolant drain tank rupture disk blows.
≥0:14:50	Reactor coolant pump alarms sound.
0:18:00	Waste exhaust monitors showed a small increases in radioactive iodine. Reactor building exhaust showed a tenfold increase in reading of radioactive emissions.
0:22:00	Abnormal out-of-core source-range neutron flux behavior.
0:24:58	PORV outlet temperature was 285.4°F. Safety valve outlet temperature was 270°F.
0:28:00	Operators have been dispatched to the auxiliary building to confirm pressurizer level indication and/or determine source of water that has filled pressurizer.
>0:30:00	Emergency diesel generators shut off.
~0:36:00	Auxiliary feedwater pump 2B turned off.
0:38:10	Reactor building sump pumps turned off.
~0:40:00	Increasing count rate continued on the source range neutron detector.

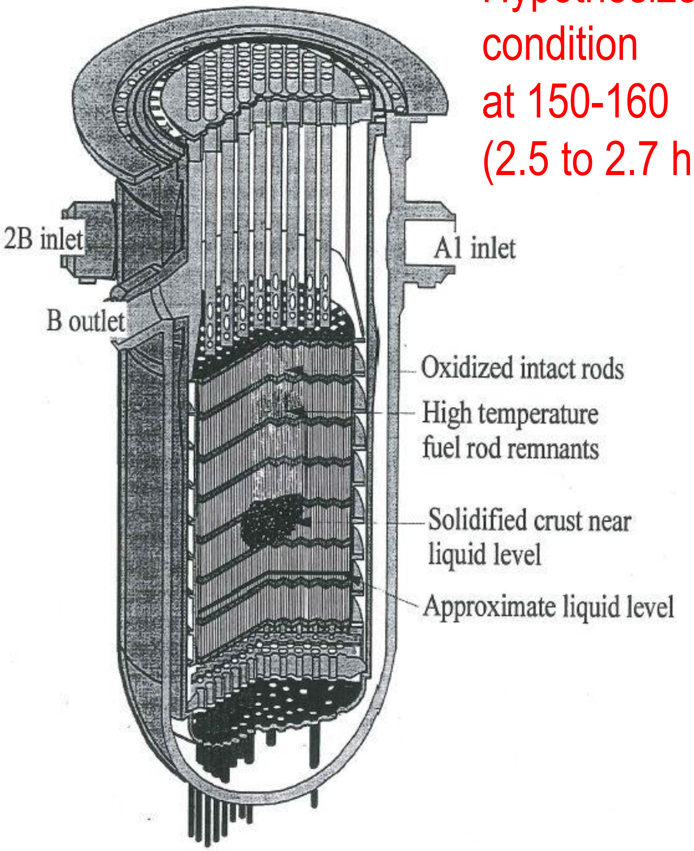
Chronology of Major TMI-2 Accidents Events – p.3

Elapsed Time h:min:s	Event or Condition
0:46:23	Letdown cooler monitor count rate began increasing. It would increase by a factor of 10 within the next 40 minutes.
~0:50:00	Operators called on-call operating engineer to the site.
1:00:00	*Figure 2.1-7. Reactor Coolant Voids Increasing.*
1:11:00	Operators initiate reactor building cooling.
1:13:40	Loop B reactor coolant pumps turned off. Loop A pumps kept on to retain pressurizer spray capability.
>1:14:00	Sample of reactor coolant indicates low boron concentration (700 ppm).
1:20:00	An operator had the computer print out the PORV (283°F) and pressurizer safety valve (211°F and 219°F) outlet temperatures.
1:27:00	Operators isolate steam generator B.
1:30:00	*Figure 2.1-8. Loop-B Stagnates After Pumps Shut Off.*
~1:30:00	Reactor coolant sample indicated 400-500 ppm boron and 4 μCi/ml.
1:40:40	Loop A reactor coolant pumps turned off.
1:42:30	Excore source-range detectors indicated increasing neutron flux levels. Emergency boration initiated.
1:51:00	Loop A and B hotleg (T_h) temperatures were increasing (eventually went off-scale high - 620°F). Cold leg temperatures were decreasing.
2:00:00	*Figure 2.1-9. Further Voiding After Loop-A Pumps Shut Off.*
2:00:00	Conference call.
2:14:23	Reactor building air sample particulate radiation monitor went off scale.
2:18:00	Fifteen to twenty people in control room at this time.
2:19:00	PORV block valve closed, loss of coolant halted.
2:20:00	Vessel water level had dropped to about midcore.
2:29:00	Hotleg temperature indications passed the high end of the instrument scale, 620°F.
2:30:00	1 R/h reported in makeup tank area of auxiliary building.

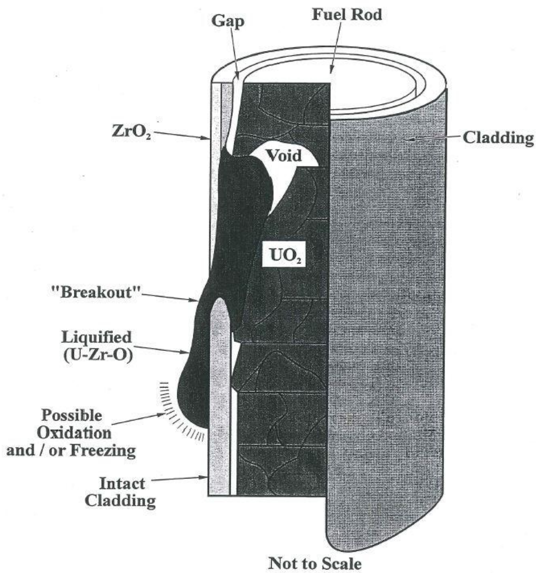
TMI-2 : all pumps off, reactor core drying out and heating up, superheated steam flowing to pressurizer and to one steam generator and condensing



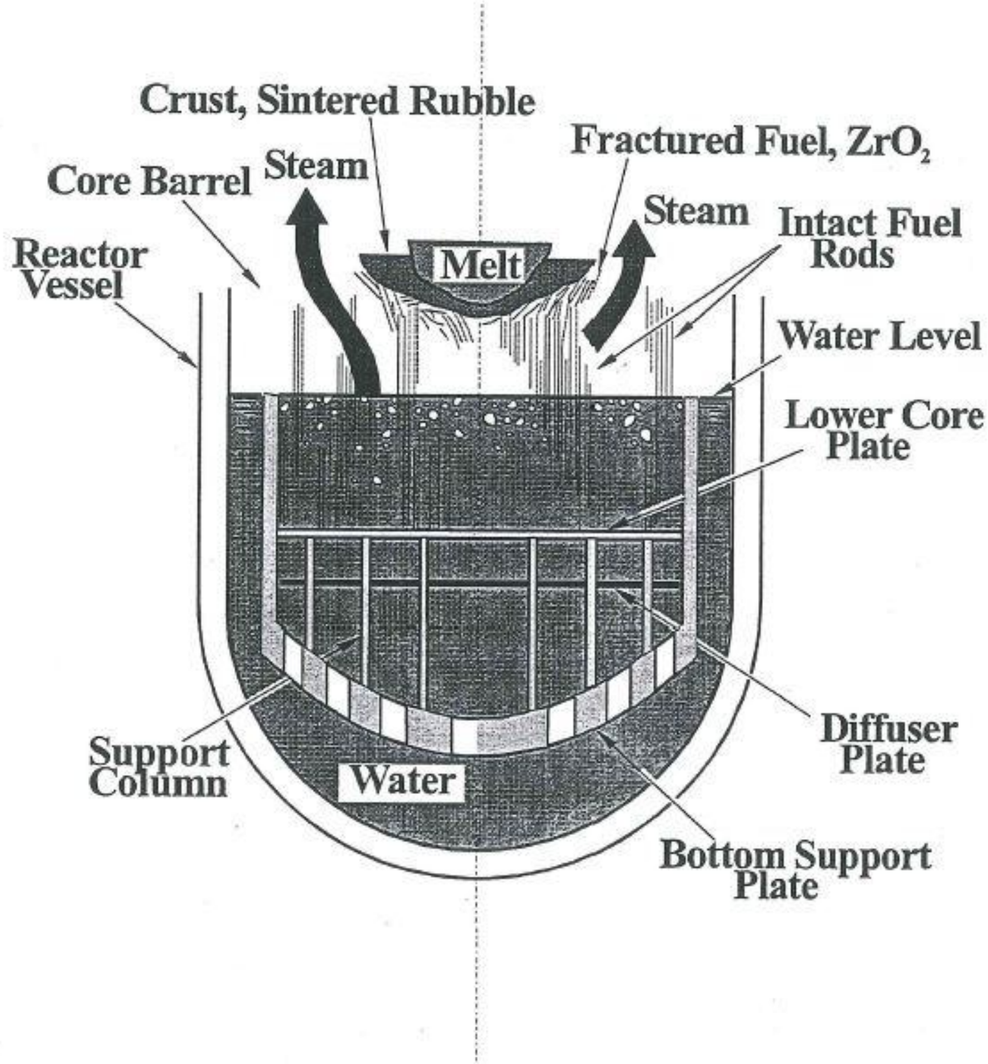
Hypothesized core condition at 150-160 mins (2.5 to 2.7 h)



TMI-2 : Initial core degradation



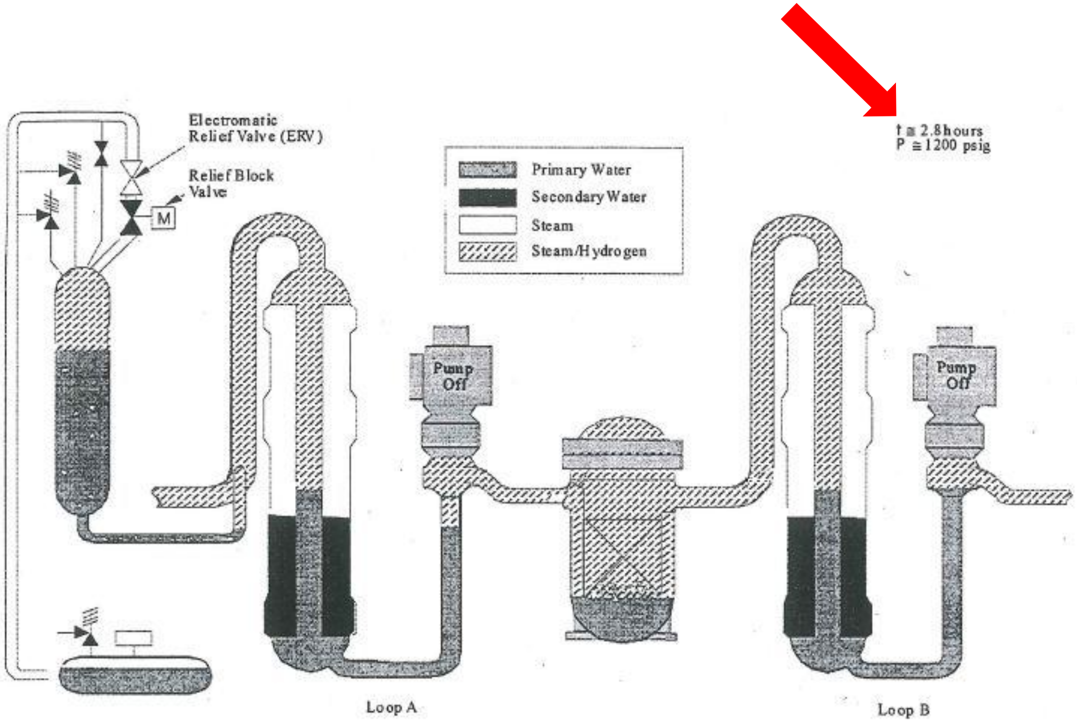
Possible mode of initial fuel liquefaction and downward flow

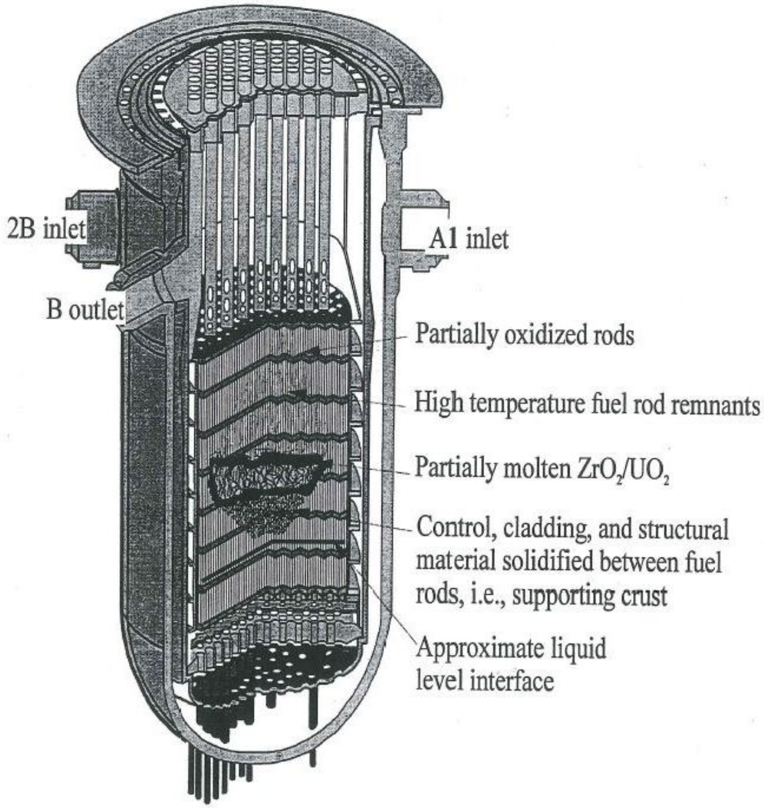


Chronology of Major TMI-2 Accidents Events – p.4

Elapsed Time h:min:s	Event or Condition
2:38:23	Letdown cooler A radiation monitor went offscale high.
2:39:23	Two samples indicated the boron concentration in the reactor coolant was 400 ppm. Emergency boration was started to avoid a reactor restart.
2:47:00	Alarm typewriter indication showed self-powered neutron detectors responding to high temperature down to 4 foot level of the core. 90% of the core exit thermocouples >700°F.
2:48:00	*Figure 2.1-10. Hydrogen Generation.*
2:50:00	Start of melting, downward relocation, and crust formation.
2:54:00	Reactor coolant pump 2B was restarted and operated for 17 min.
2:56:00	Site emergency declared.
2:57:00	Fifty to sixty people are in control room; attempting to resolve the crisis.
3:00:00	*Figure 2.1-11. Effects of Loop-B Pump Restart.*
3:12:00	PORV block valve opened to control reactor coolant pressure.
3:20:00	Engineered safeguards actuated, makeup pump 1C started, HPI flow increased.
3:21:00	Excore neutron instrumentation indicated a sharp decrease (reflood). Reactor building dome radiation monitor read 8 R/h.
3:23:23	General emergency declared.
3:29:00	PORV block valve reclosed.
3:30:00	*Figure 2.1-12 Vessel Refilled.*
3:32:00	The makeup tank radiation level was at about 3 R/h, and the auxiliary building basement was reported flooded with airborne radioactivity. Spent-fuel demineralizer monitor read 250-900 mr/h. Source range monitor count rate shows increase by a factor of three.
3:37:00	Operators tripped makeup pump 1C.
3:42:00	PORV block valve again opened.
3:44:00	Molten pour.

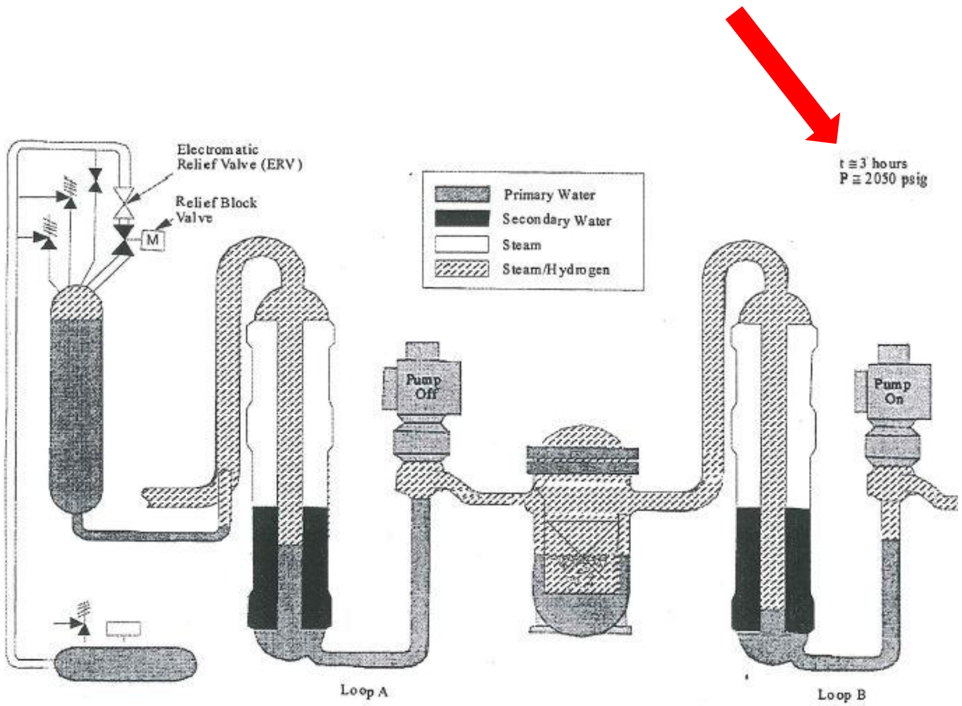
TMI-2 : Core Dryout and Heatup continuing, hydrogen generation via steam/Zr reaction in hotter core regions

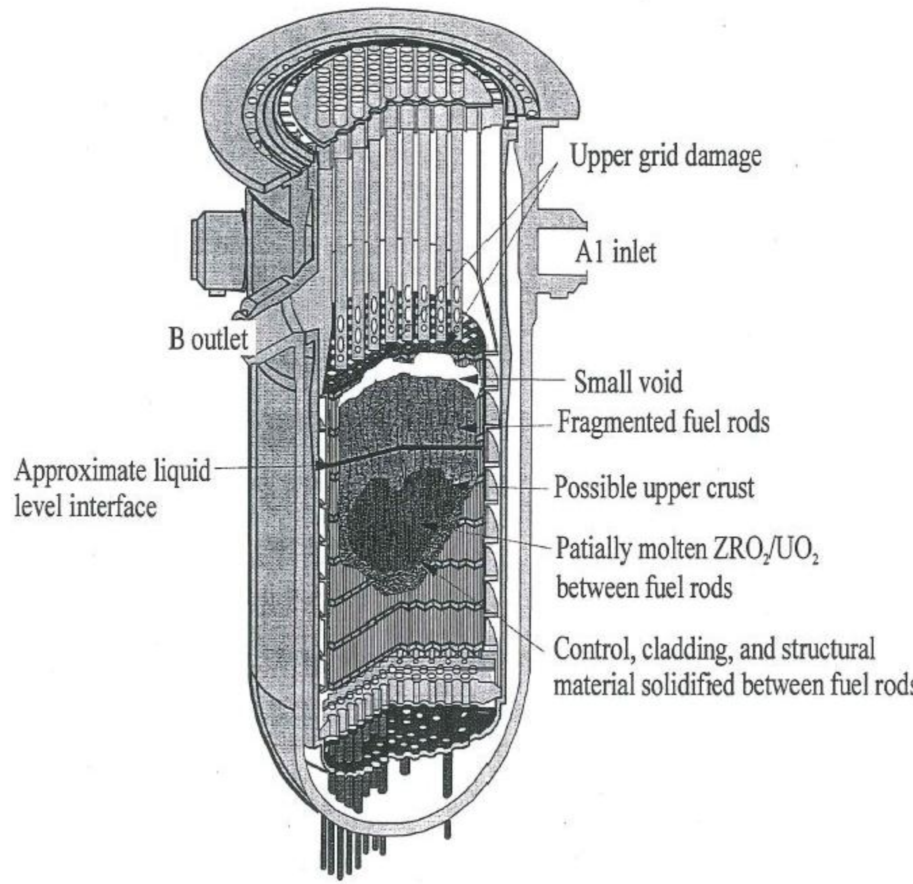




Hypothesized core condition at 173 mins (~2.8 h)

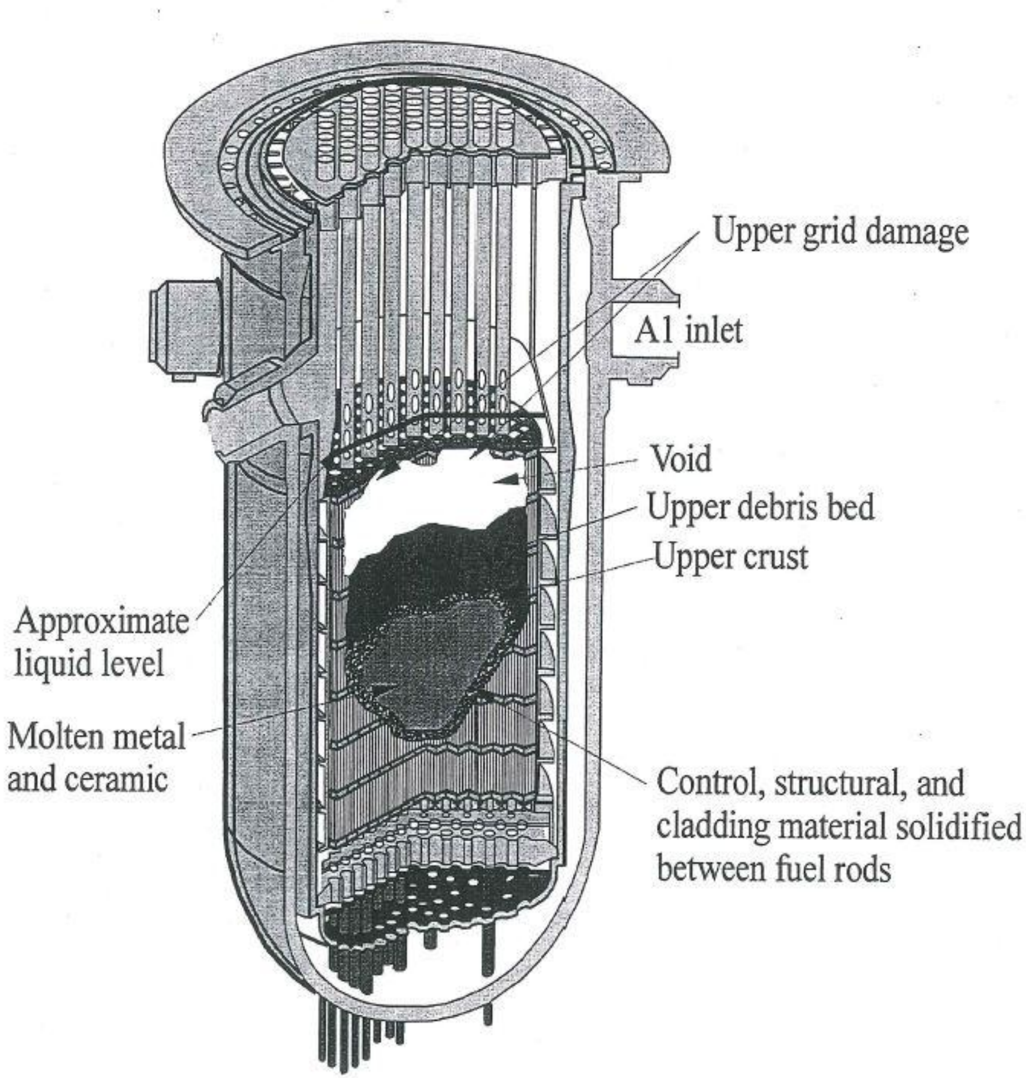
TMI-2 : core partially quenched by fluid during loop B pump start, heatup resumes





Hypothesized core configuration between 174 and 180 mins (2.8 to 3.0 h)

TMI-2 : Hypothesized core configuration at 224 mins (3:44:00) – just prior to molten pour



Chronology of Major TMI-2 Accidents Events – p.5

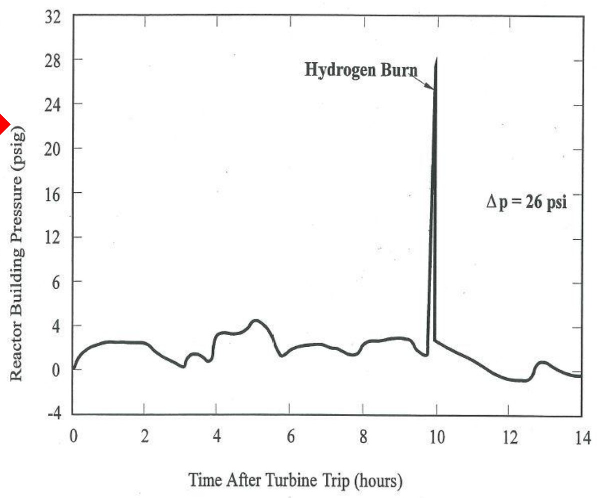
Elapsed Time h:min:s	Event or Condition
3:55:39	Reactor building automatically isolated on high (>4 psig) pressure. Makeup pump 1C started automatically.
>4:00:00	Over the next 90 minutes, core exit thermocouple readings were manually obtained ranging from 217 to 2580°F.
4:18:00	Makeup pumps 1A and 1C tripped. Operator attempted to restart pump 1A. Switch was then placed in "Pull to Lock."
4:20:00	Reactor building dome radiation monitor records 600 R/h.
4:22:00	Makeup pump 1B was started.
4:26:00	Sustained high pressure injection after this time.
~4:30:00	Condensate system completely shut down. Problems with the condensate system were continuing. The condenser had been steadily losing vacuum. It was necessary to maintain steam to the main turbine seals in order to operate the condenser at a vacuum. When main steam is not available, seal steam is provided by the oil-fired auxiliary boiler. The auxiliary boiler broke down, so that seal steam could not be maintained. It was, therefore, necessary to shut down the condensate system completely.
4:40:00	Reactor building dome radiation monitor records 1000 R/h.
4:42:00	Auxiliary feedwater was turned off. Only a small amount of heat could be removed by the steam generator because the upper part of the primary system was filled by a mixture of steam and hydrogen gas. The water level on the secondary side was rising because more auxiliary feedwater was coming than was leaving as steam. At 4 hours 42 minutes, auxiliary feedwater was shut off.
~5:00:00	Reactor building dome radiation monitor reaches 6000 R/h.
5:15:00	Initial repressurization began, PORV block valve shut.
5:29:00	Emergency diesel fuel racks reset.
5:35:00	NRC Region 1 inspector reports no consideration of offsite evacuation, since utility reports no significant leakage, and there has been no significant off-site radioactivity yet.

Chronology of Major TMI-2 Accidents Events – p.6

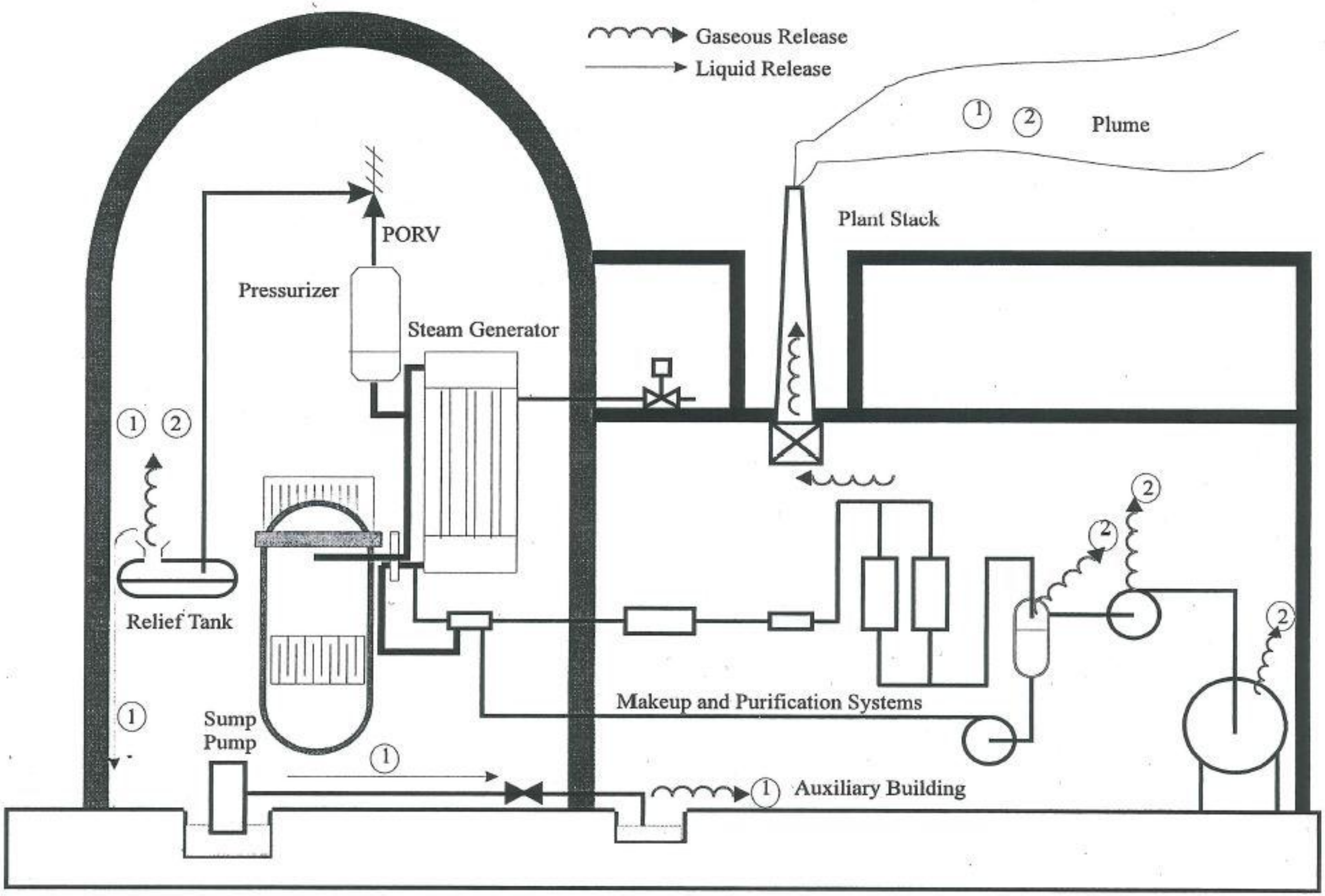
Elapsed Time h:min:s	Event or Condition
5:43:00	By cycling the PORV block valve, reactor coolant pressure was maintained in the 1865-2150 psig range during the next 2 hours.
6:00:00	*Figure 2.1-13. Repressurized, Attempting to Collapse Vapor Bubble.*
6:04:00	Commenced filling steam generator A (to 97%) using condensate pumps.
6:10:00	Airborne radiation levels in Unit 2 control room require evacuation of all but essential personnel.
6:17:00	Unit 2 personnel put on masks to protect against possible radiation.
6:27:00	Everyone, except essential personnel, started moving to Unit 1 control room.
6:52:00	People leaving the Unit 2 control room fail to close the door properly, possibly compromising the recirculation ventilation system.
7:00:00	Communications in the Unit 2 control room were hampered by respirators. Communications problems led some personnel to remove respirators for short periods.
7:00:00	A tour of the auxiliary building found 10 R/h at the radiation waste panel, water standing on the floor in areas with floor drains, and the auxiliary building sumps full.
7:08:00	Auxiliary feedwater pump 2A was started. Level in steam generator A reached 100% (operating range).
7:38:54	Depressurization initiated to actuate core flood system.
7:40:00	Region 1 inspector reports that utility believes there will be no radioactive release to the surrounding area.
8:00:00	*Figure 2.1-14. Depressurizing, Releasing H_2.*
8:30:00	The power-operated emergency main steam dump valve was closed at the request of corporate management.
8:41:00	Core flood tanks initiate, little flow.
9:04:00	Makeup pump 1C was shut off (concerned with borated water storage tank inventory).
9:10:00	Initial depressurization halted.

Chronology of Major TMI-2 Accidents Events – p.7

Elapsed Time h:min:s	Event or Condition
9:50:00	*Figure 2.1-15. Second Depressurization Initiated, Hydrogen Burn.* High pressure injection actuated. Reactor building sprays actuated.
9:50:30	Makeup pump 1C was stopped.
9:57:00	Reactor building spray pumps were stopped.
10:26:15	Loop A T_h<620°F. Stays on scale 10 minutes.
10:30:00	*Figure 2.1-16 Reactor Coolant Pressure Near Minimum (400 psig).*
11:06:00	Pressurizer level decreased to 180 inches in the next 18 minutes. Loop A temperature was increasing.
11:08:00	Second depressurization attempt ends.
13:00:00	*Figure 2.1-17. Steam Generators Blocked By Hydrogen.*
≥13:00:00	About 13 hours after turbine trip, the auxiliary boiler was brought back into operation. Steam for the turbine seals was now available and it was possible to hold a vacuum on the condenser. Two condenser vacuum pumps were started. It was the operator's belief that the main condenser would soon be available.
13:20:00	Repressurization began.
14:35:00	NRC Region 1 inspector reported that there still appeared to be a bubble in loop B.
15:00:00	*Figure 2.1-18. Repressurized, Flow Blocked by Hydrogen.*
15:33:00	Operator started reactor coolant pump 1A started, ran it for 10 seconds, then tripped it.
15:45:00	The station superintendent directed operators to start a reactor coolant pump.
15:50:00	Operator started reactor coolant pump 1A and let it run continuously.
16:00:00	*Figure 2.1-19. Forced Circulation Reestablished.*

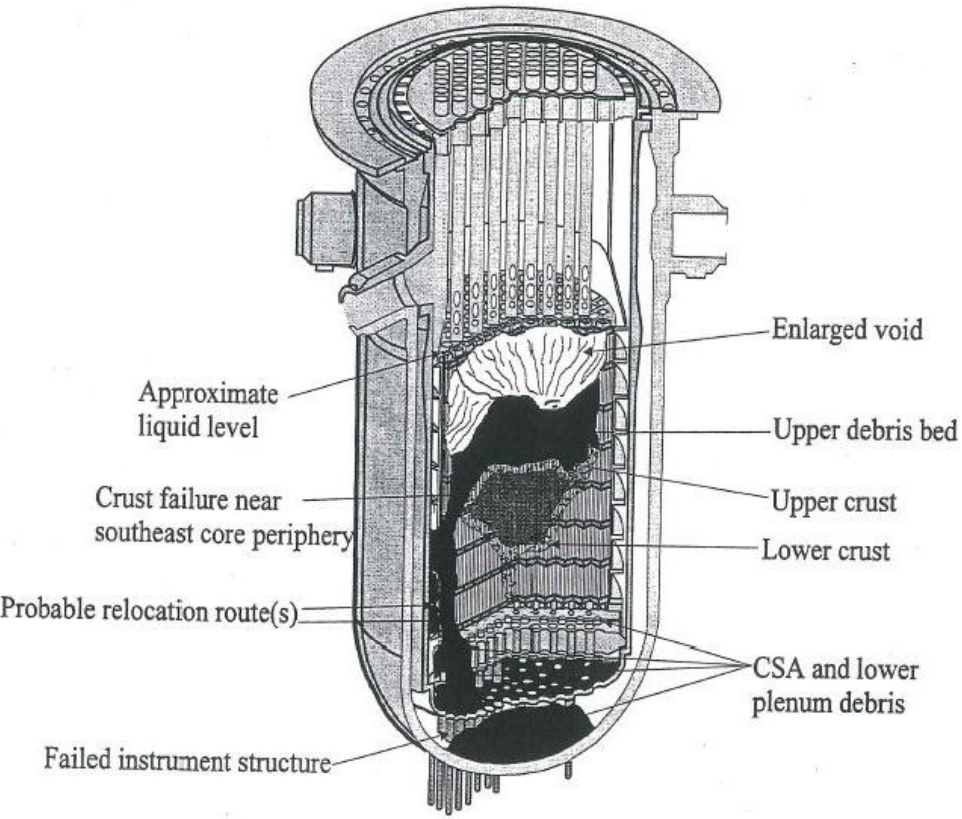


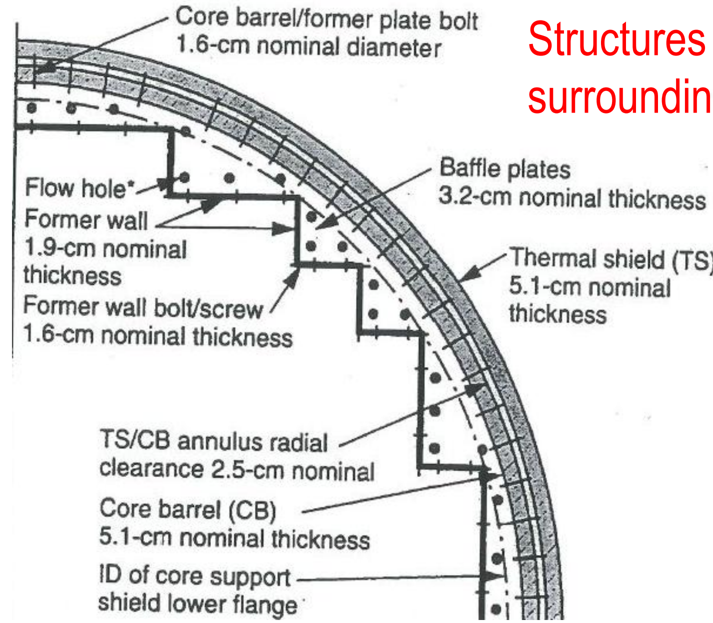
TMI-2 : Accident Radioisotope Release Pathways



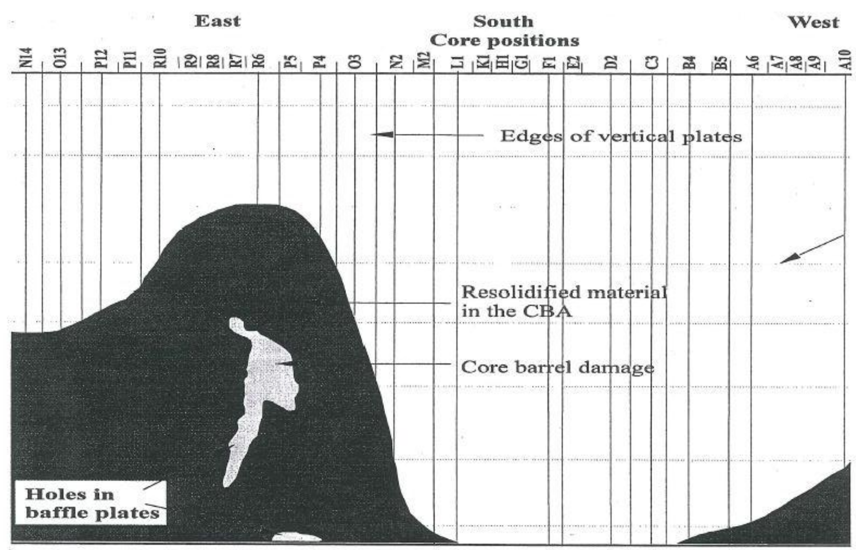
1. Early (first 38 minutes) before core damage, normal coolant only, sump pump operation
2. After core damage, leakage from makeup and purification system was the source of most of the release

TMI-2 : Final debris configuration



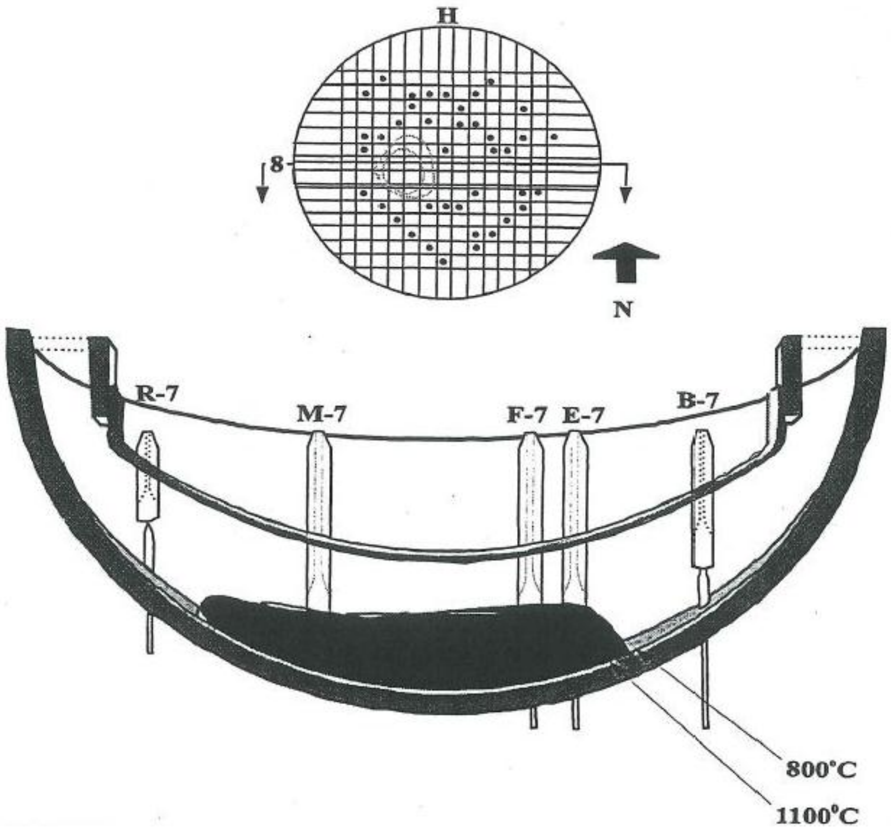


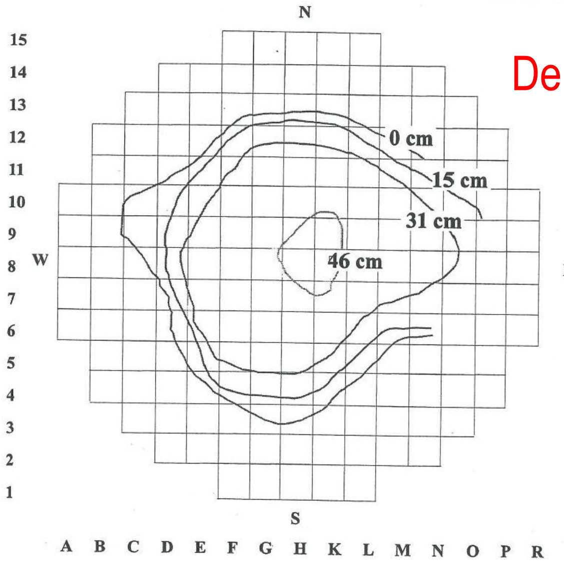
Structures surrounding core



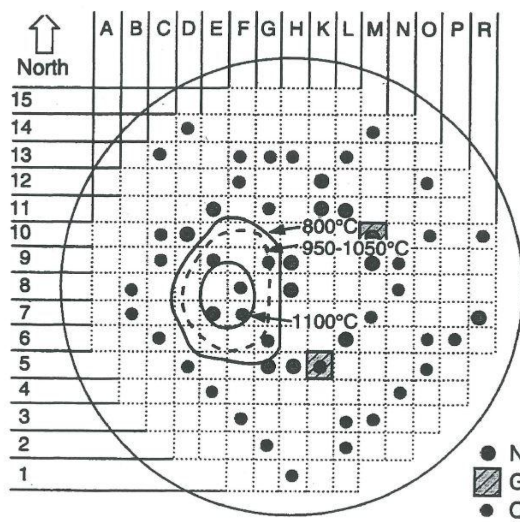
Debris inside core barrel

TMI-2 : Lower head cross-section of hard debris





Debris depth



Lower-head hot spot