Fukushima Event PCTRAN Analysis

Dr. LI-Chi Cliff Po

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1. Description of Event

The earthquake caused instant loss of offsite power. The scale-9 shock far exceeds plant design limit of scale 8.2. Onsite emergency diesel generators started to provide AC power for residual heat removal. But soon they were knocked out by the tsunami. There was limited DC battery power for valve control, etc. A complete station blackout (SBO) then followed without any means for coolant makeup and heat removal..

Fukushima Daiichi Unit 1 is a GE BWR-3 rated 460/1380 MW (electric/thermal). Units 2 to 5 are BWR4 rated at 784/2381 MW. There are two external recirculation pumps. Jet pumps inside the reactor downcomer enhance the core flow for better efficiency. They all have Mark I (steel liner plus concrete drywell and torus-shaped suppression pool) containments. The emergency core cooling systems contain passive Reactor Core Isolation Cooling (RCIC) and Core Spray (CS) systems. Their respective turbines are driven by steam extraction following Main Steam Isolation Valves (MSIV) closure. Centrifugal pumps draw water from the condensate storage tank initially. When the tank inventory is exhausted, water source can be switched to the suppression pool for extended period. On the active side, the diesel generator-powered High Pressure Coolant Injection (HPCI) turns on low reactor water level. It extracts water from the condensate or suppression pool as well. When the reactor pressure is lowered, low-pressure coolant injection (LPCI) system provides large flow to reflood the core. Figure 1 is the PCTRAN mimic during full-power steady state operation.

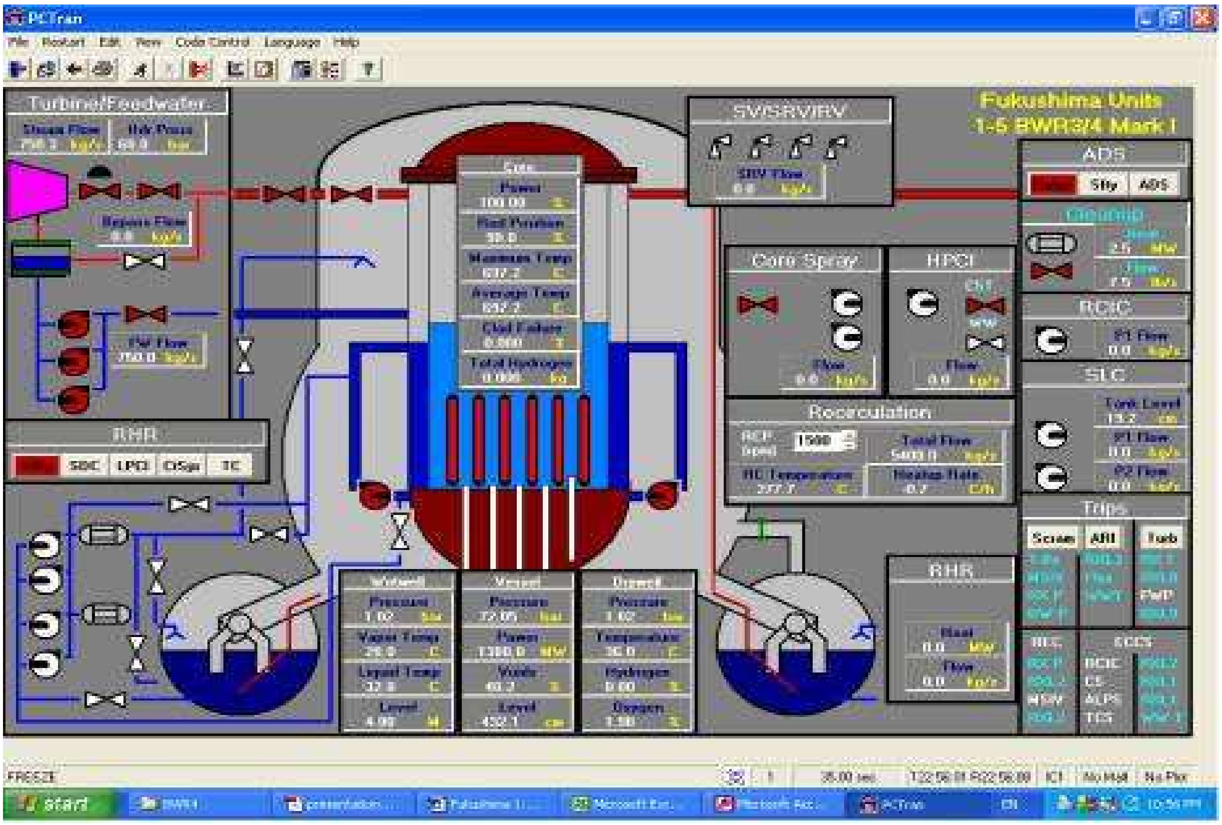


Fig. 1 Fukushima Unit 1 at 100% power 1380 MW thermal condition

Unit 6 of Daiichi and all four units in the neighborhood Daini site are BWR5 rated at 1110/3293 MW. Mark II containment has its suppression pool connected by vertical vent pipes underneath the drywell. The emergency core cooling system is different by using high-pressure core spray (HPCS) system instead of HPCI. Spray gets more uniform droplet distribution on top of the fuels than injection from the bottom.

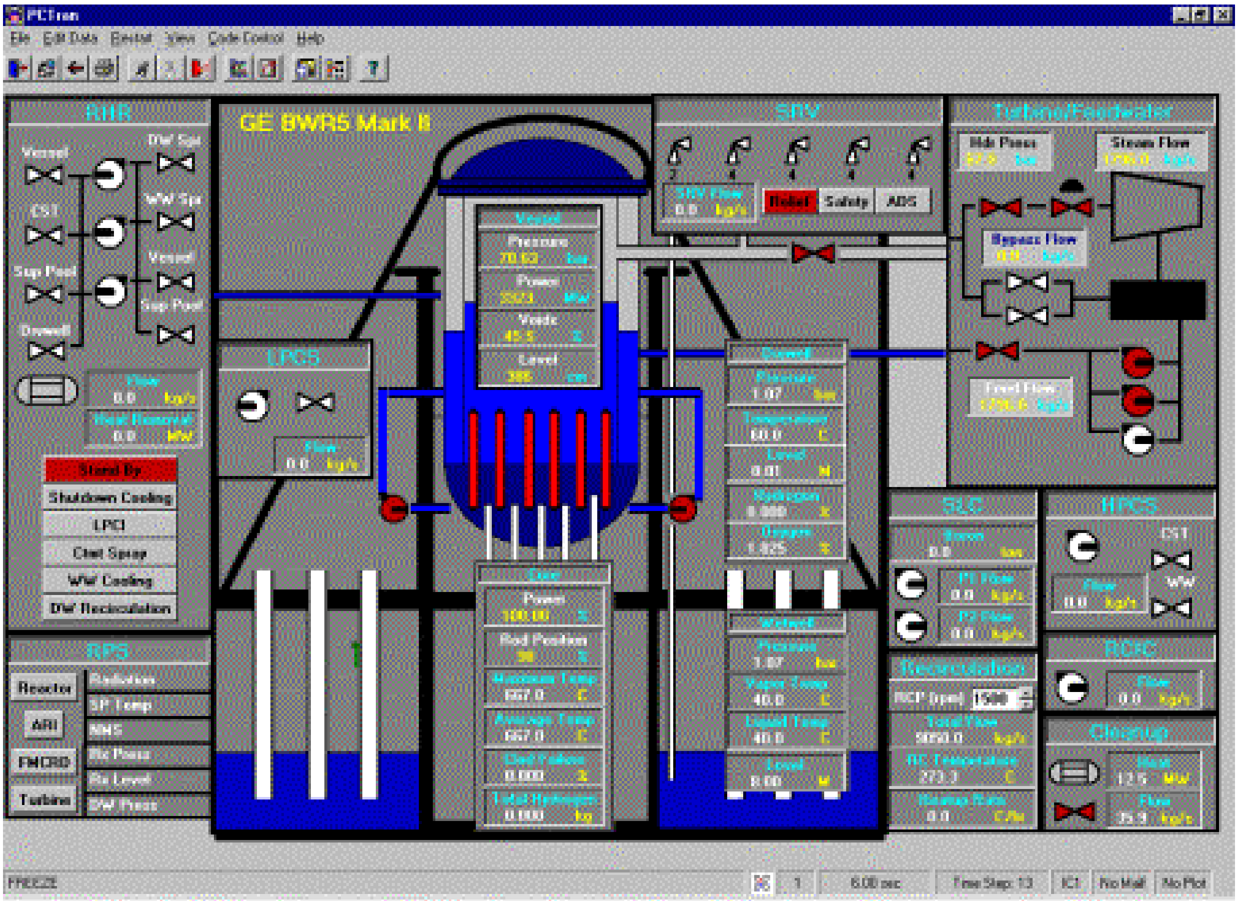


Fig. 2 PCTRAN BWR5 Mark II Mimic

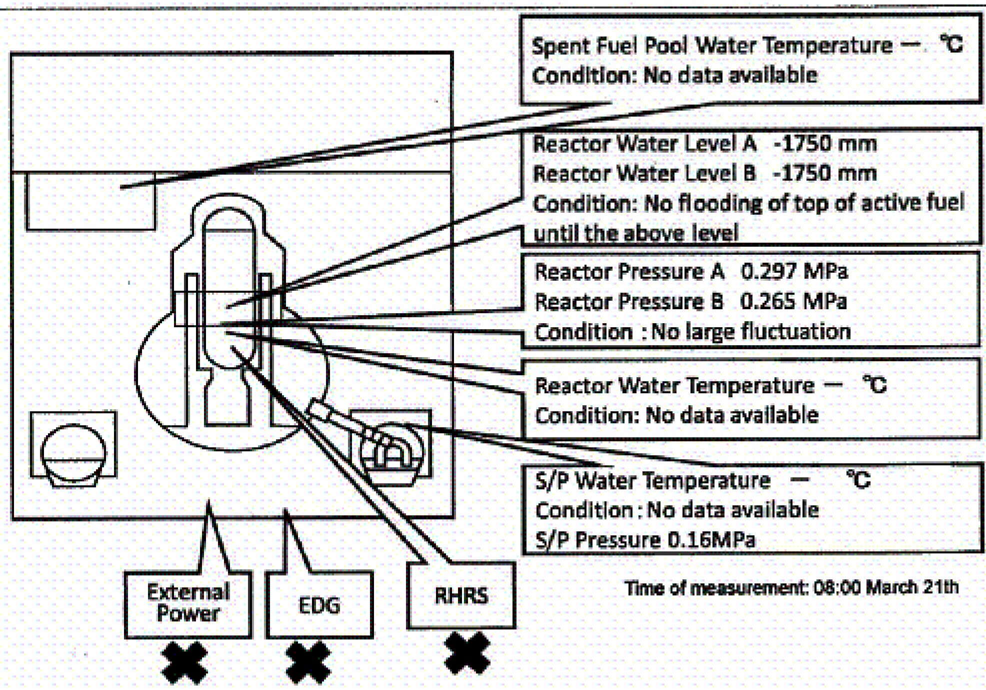
The following report provided by Mr. Seong-Deuk Jo of International Atomic Energy Agency was used in our study:

Tohoku Pacific Earthquake and the seismic damage to the NPPs

21 March 2011

Nuclear and Industrial Safety Agency
Japan

Conditions of Fukushima Dai-ichi Nuclear Power Station Unit 1
(As of 15:30 March 21th, 2011)



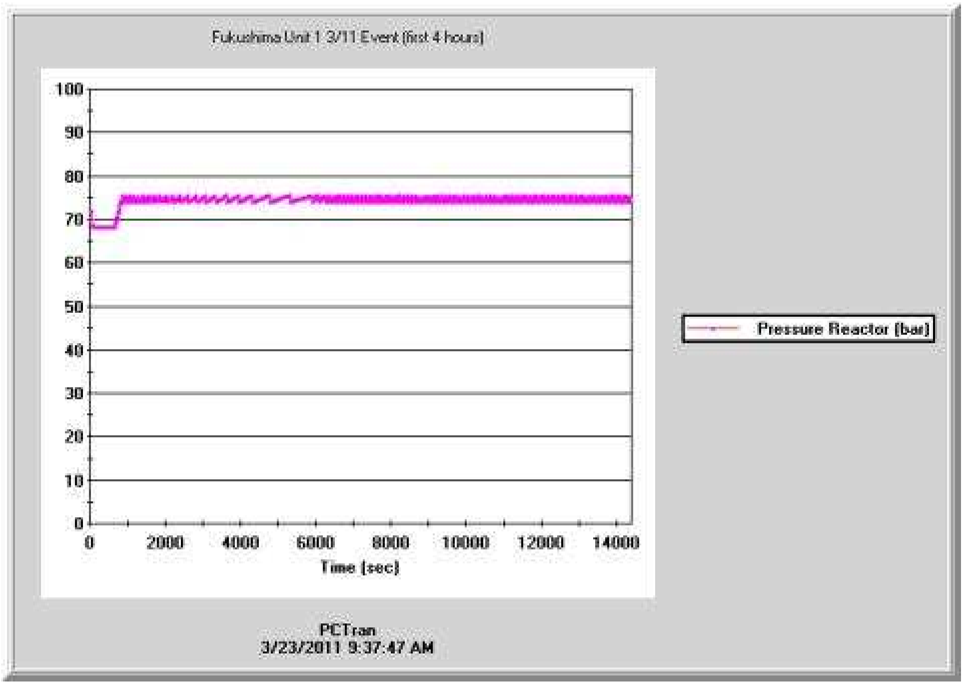
Conditions of Fukushima Dai-ichi Nuclear Power Station Unit 1
(As of 15:30 March 21th, 2011)

Major Events after the earthquake

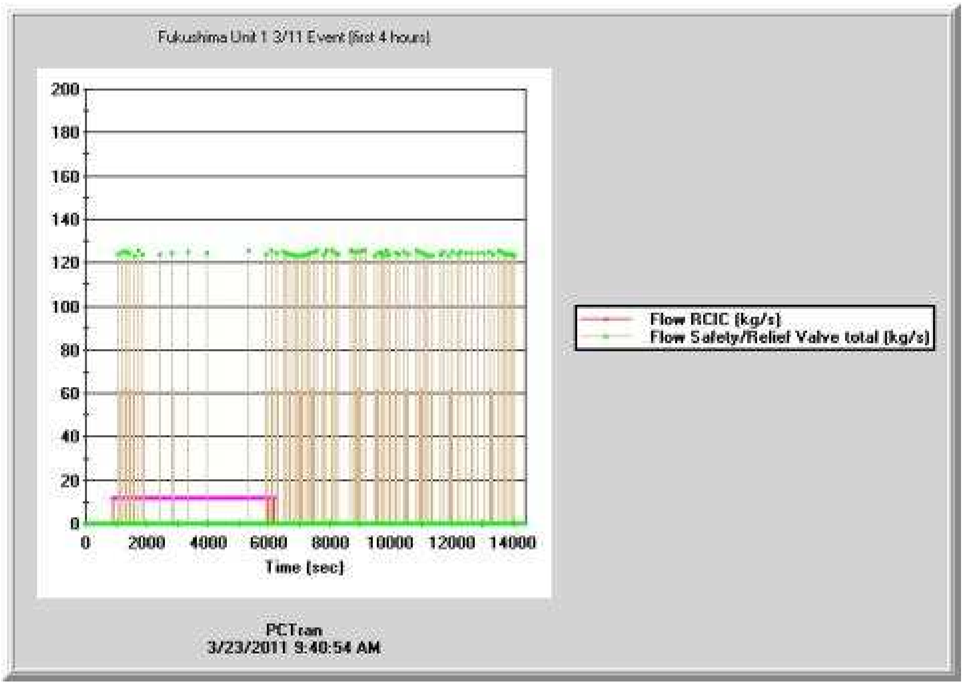
11th 14:46 Under operation, Automatic shutdown by the earthquake
11th 15:42 Report of the Article 10 (loss of A/C power)
11th 16:36 Occurrence of the Article 15 event
(Loss of water injection function)
12th 0:49 Occurrence of the Article 15 event
(unusual increase of PCV pressure)
12th 14:30 Start to vent
12th 15:36 Sound of explosion
12th 20:20 Start of injection of seawater and borated water to the core

2. PCTRAN Analysis of Unit 1 Chronicle - Part 1 Station Blackout to Loss of All Core Cooling (first 5 hours)

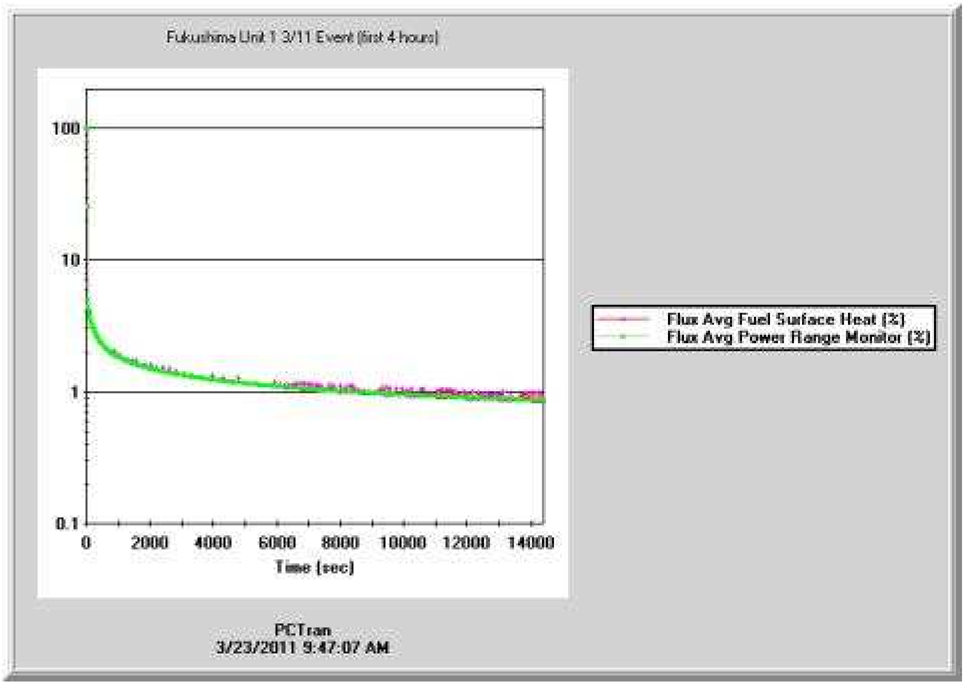
Time	Seconds from earthquake	Event reported	Event conduct on PCTRN simulation
11th 14:46	0	Reactor automatic shutdown	Reactor Manual scram, trip both recirculation pumps, all MFW pumps,
	> 600	Tsunami hit plant loss of diesel	Isolate turbine bypass valve on loss of condenser vacuum, RCIC starts on Rx water level < L2
11th 15:42	3,360	Report loss of AC, loss of AC article 10 event	
11th 16:36	6,600	Loss of water injection Article 15 event	Stop RCIC
11th 18:46	14,400	End of Part 1	End of Part 1 = Beginning of Part 2



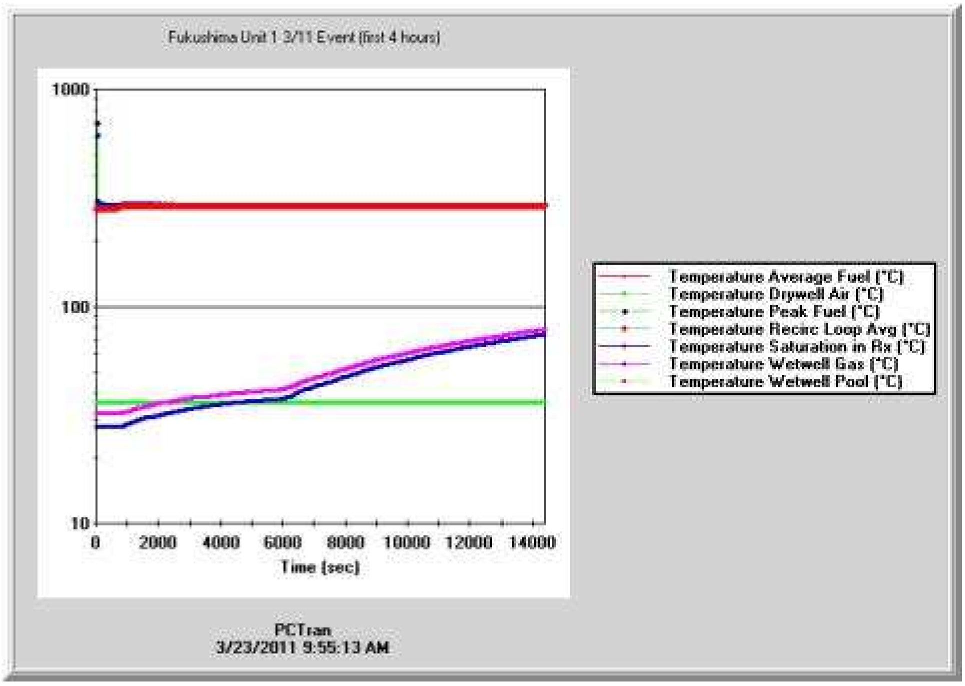
Reactor pressure vessel pressure - pressure cycled around 1st SRV set point of 75 bar



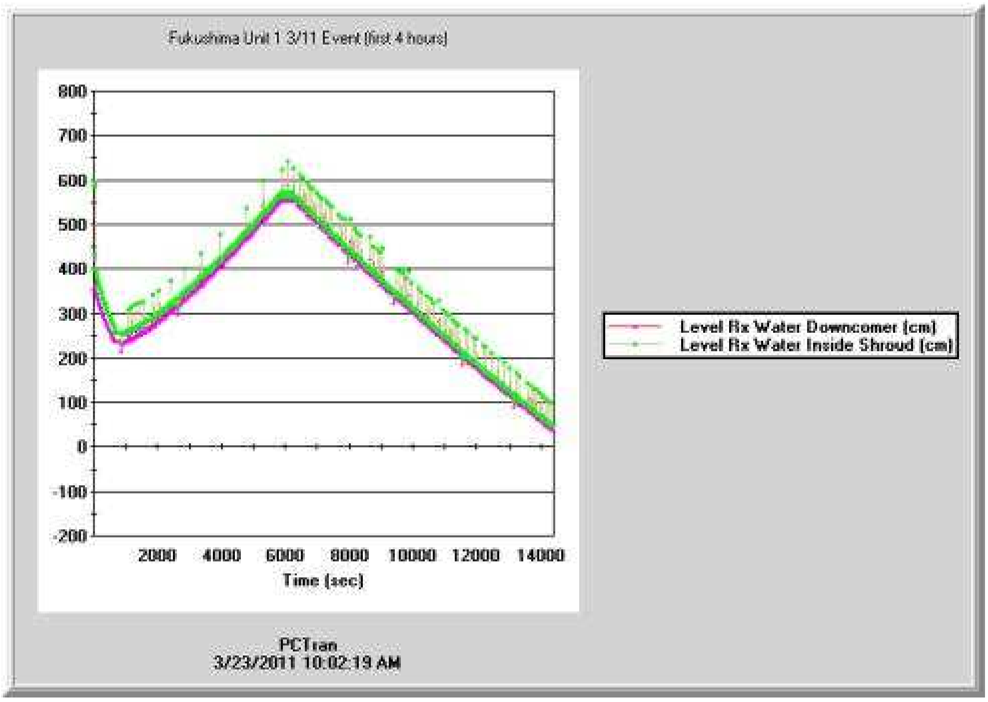
RCIC flow and SRV discharge flow – RCIC was lost around 6,000 sec by the tsunami
damage or running out of DC battery. Article 15 event declared.



Core decay heat.



Fuel and reactor coolant temperatures stable after reactor trip; suppression pool and air temperatures heated up by SRV steam discharge; drywell air temperature increased slightly by flipping of the vacuum breaker between drywell and wetwell.



Reactor water level above top of active fuel – RCIC started at 600 sec to makeup SRV loss; terminated around 6600 seconds so the level dropped.

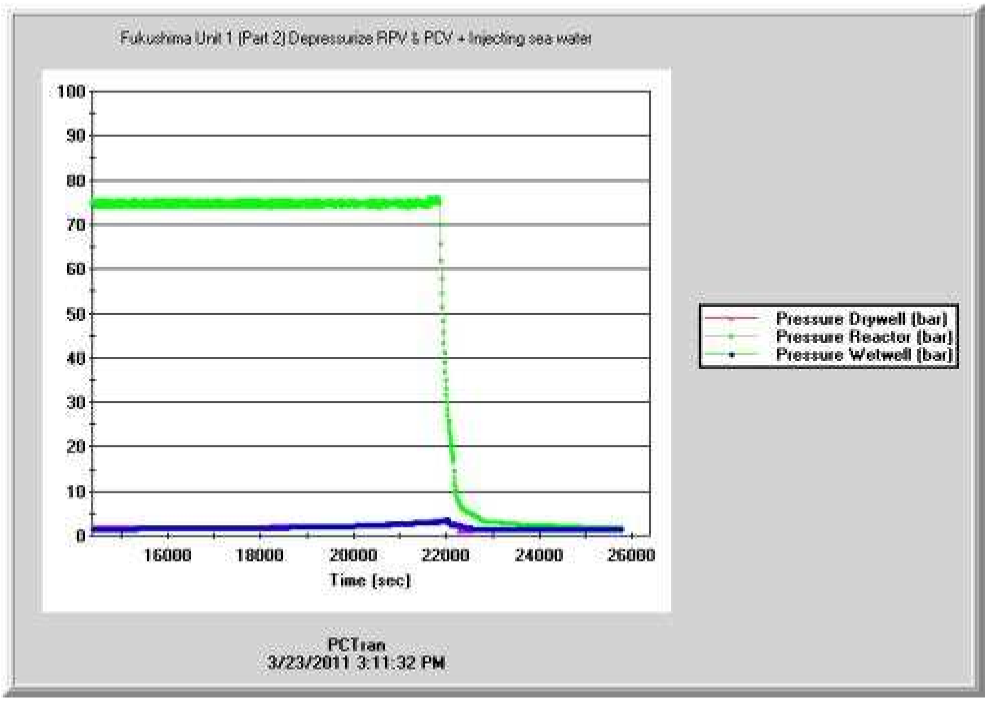
3. Simulation Part 2 – Vent CPV and Injecting Sea Water into Core

The extent of core damage from the later part of Day 1 (March 11) till the 2nd day none was unknown. The operators noticed the Containment Pressure Vessel (CPV) pressure was unbearably high to face failure. They decided to depressurize the CPV. Soon a sound of hydrogen explosion from the Reactor Building was heard.

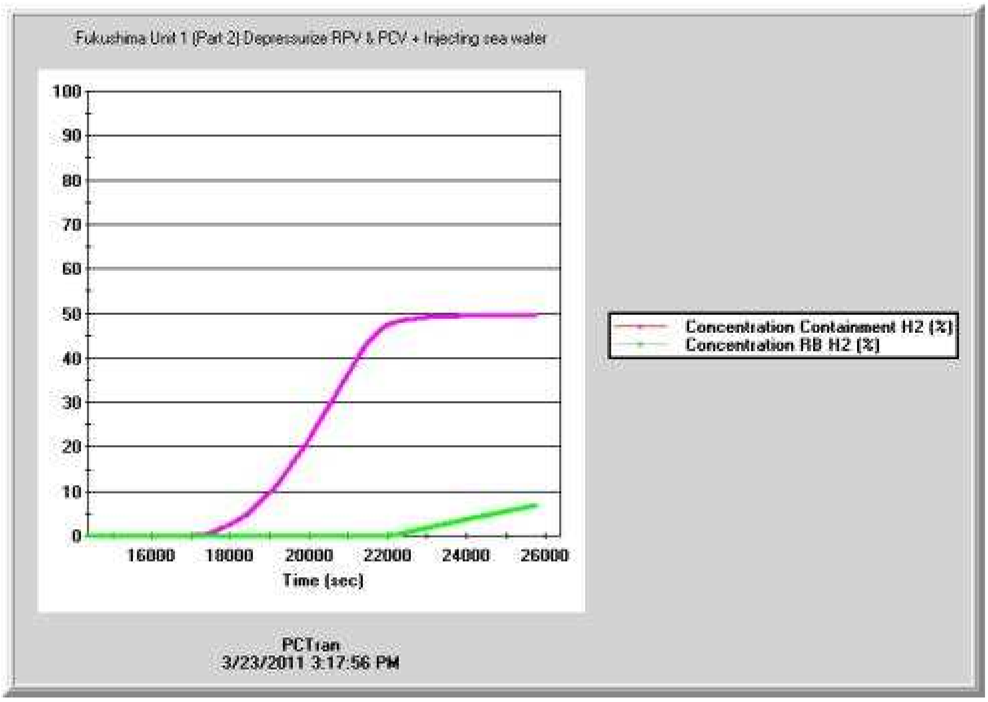
Time	Seconds from earthquake	Event reported	Event conduct on PCTRN simulation
12th 0:49	36,180	Increase of PCV pressure Article 15 event	After the fuel shows signs of exposure and failure, PCTRAN analysis moved ahead to the end of Part 1 for calculation continuity
12th 14:30	85,440	Start to vent (from PCV to reactor building)	Vent at 22,000 seconds
12th	89,400	Sound of explosion	Hydrogen concentration in Rx

15:36			Bldg > 5%, explosion assumed at 24,000 seconds
12th 20:20	106,440	Start injecting sea water to core	25,000 seconds.

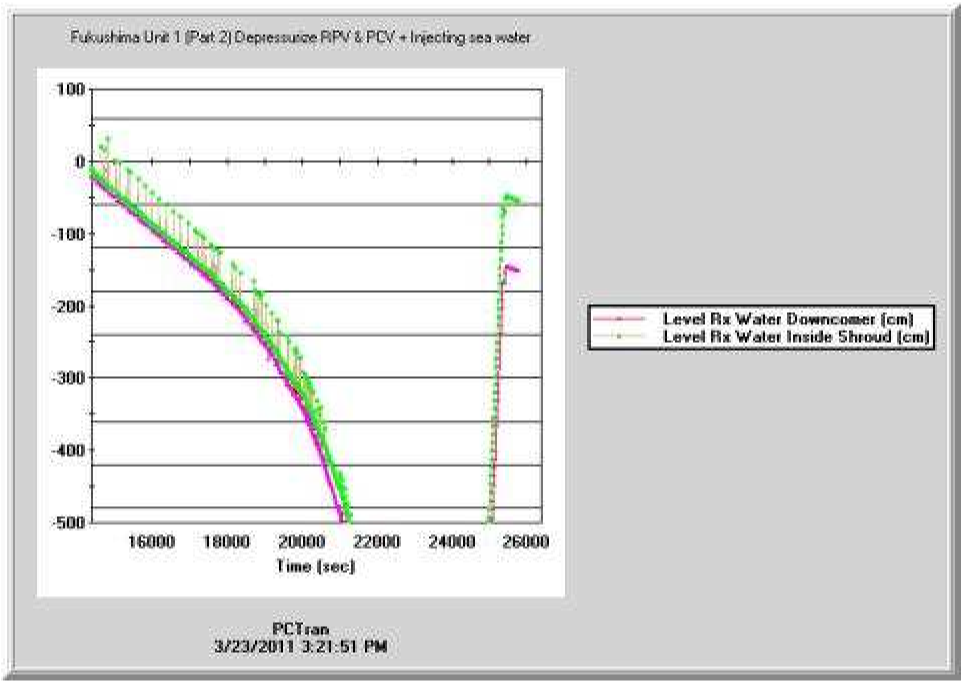
- Operator depressurize RPV and Containment
- Hear Hydrogen Explosion in the Reactor Building
- Injecting Sea Water to Core



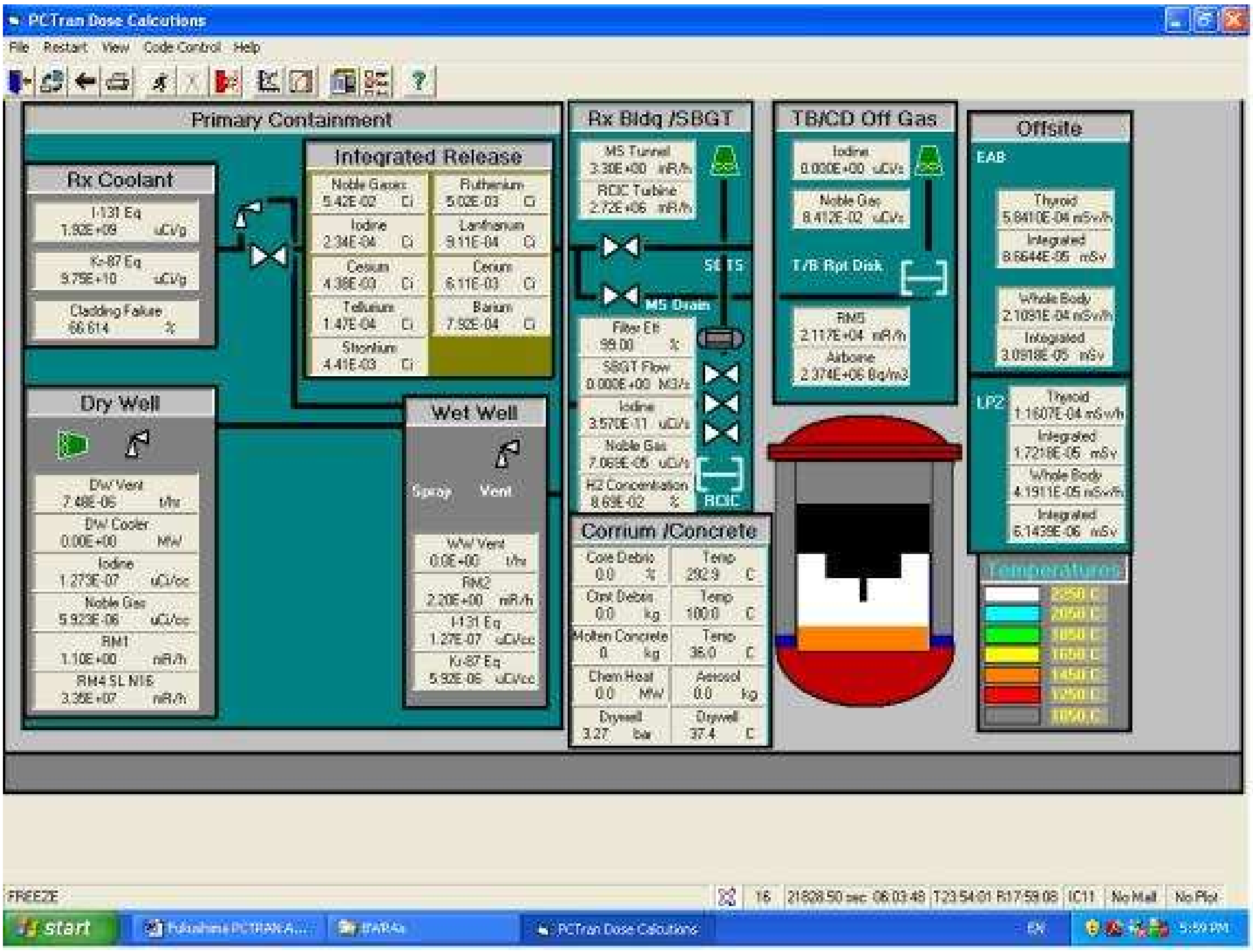
Operator depressurize the RPV and PCV to vent hydrogen



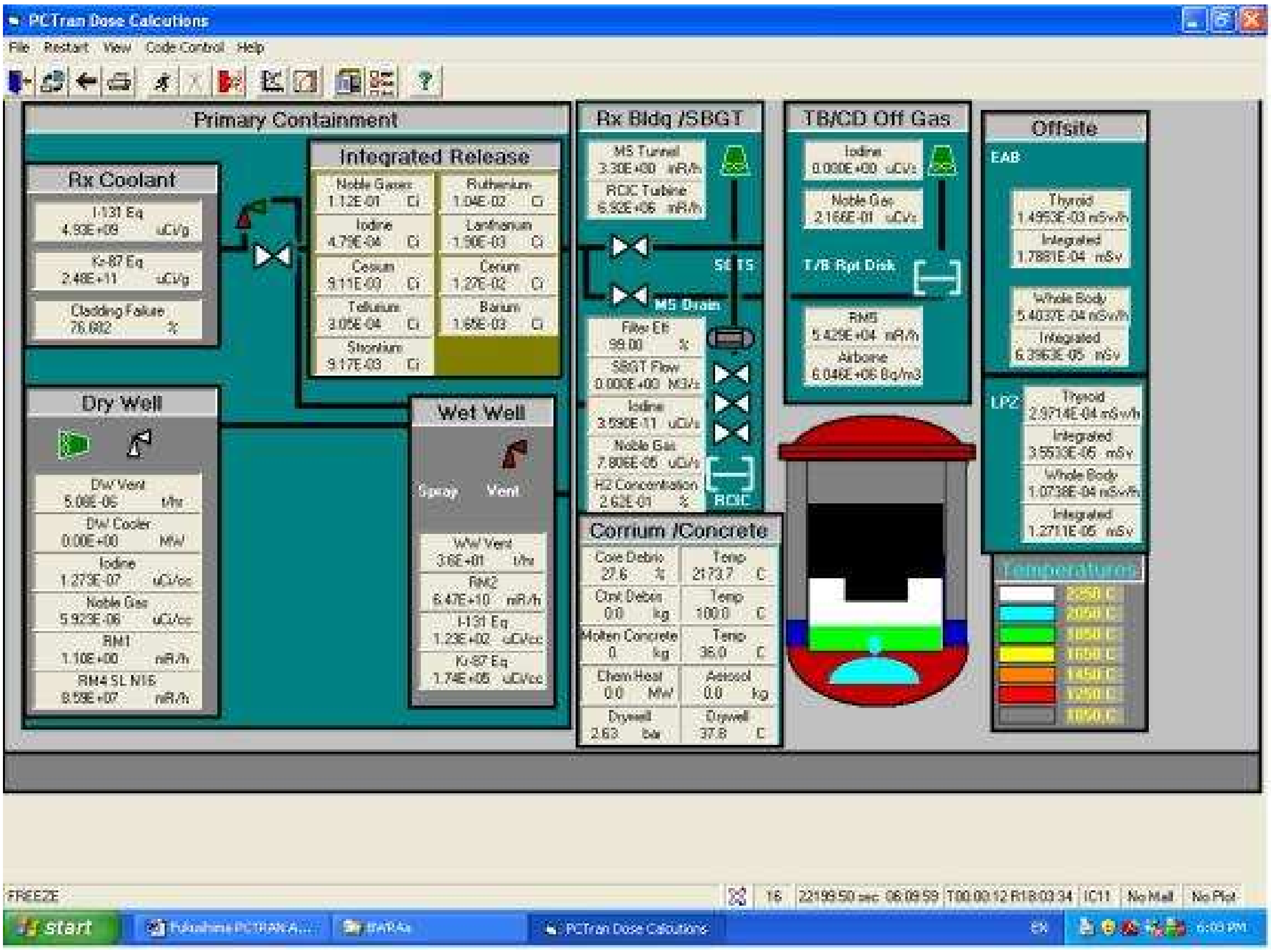
Hydrogen in the Reactor Building reached detonation point (5%) and exploded.



Water level (above top of active fuel) in the RPV; sea water and borated water was used to recover the core.



Containment and radiological release mimic displays core-melt condition



Containment and radiological release mimic displays core collapsed condition; note operators have open the wetwell vent valve (color in red) to vent the containment.

4. Station Blackout for PWR

An immediate question is whether a PWR is more resilient to an earthquake/blackout than a BWR. By using our PCTRAN PWR models it is quantitatively analyzed in great details. We may conclude an affirmative “yes” - but not by much - just buy you a few more hours to resume onsite power supply. After that the consequence is the same.

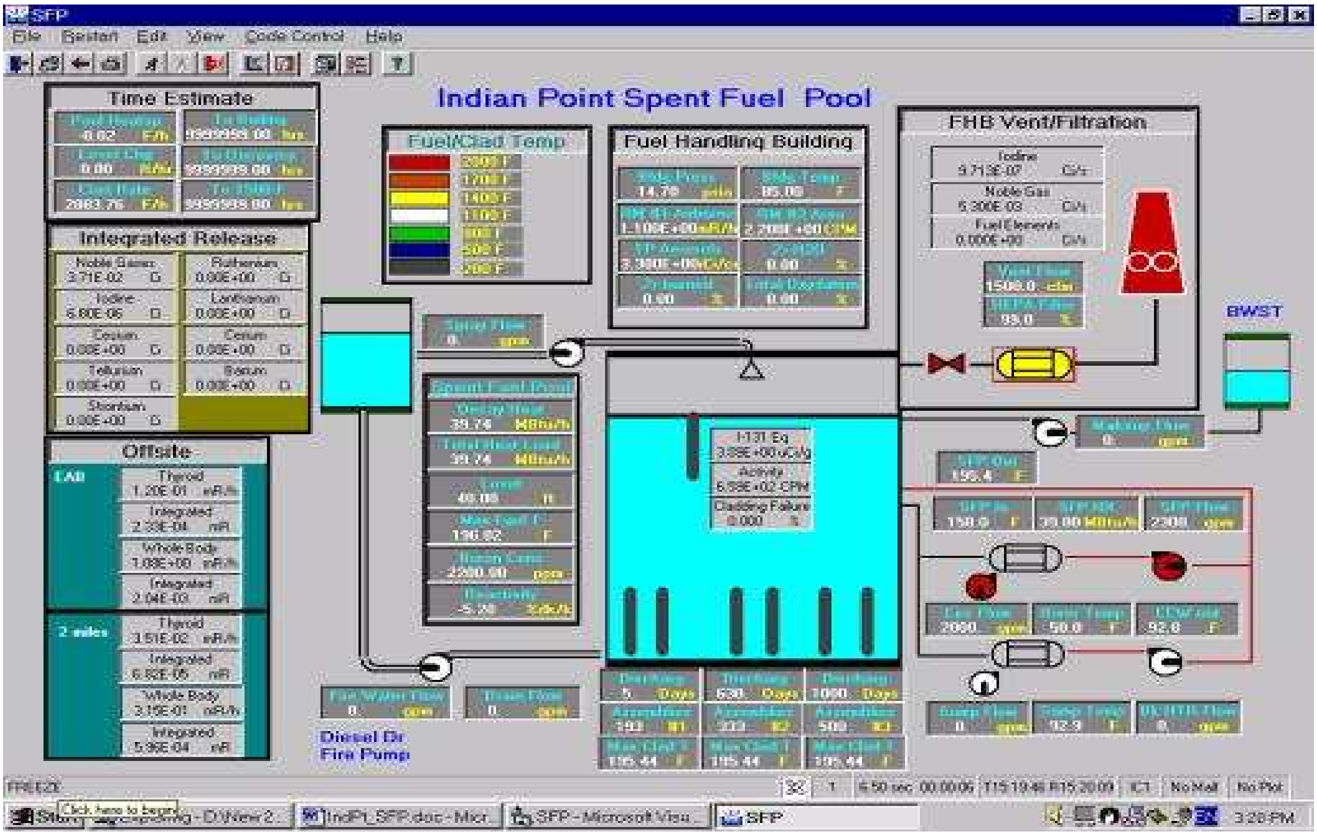
PWR has its own steam generator secondary water inventory. It provides a heat sink for the core decay heat from about 30 minutes to a couple hours. PWR containment is in average four times larger than a BWR’s; so that after emergency depressurization of the primary coolant system, the containment is less likely to elevate to its breach level.

This does not mean all PWR's are safe enough and nothing should be further examined. Close review and inspection of all passive and active emergency systems are still necessary.

5. Impact to Spent Fuel Pool

Another significant event is loss of cooling/coolant at Fukushima Unit 4's spent fuel pool that has caused clad oxidation and radiological release. Micro-Simulation has another simulation product "**SFP**". Since 2004 we have advocated that spent fuel pool safety was overlooked and an independent hardened cooling system is necessary. Unfortunately what happened at Fukushima Unit 4 on March 18 has proven our points.

Shown below is SFP software's main mimic during normal operation. The pool is filled with freshly unloaded and previous cycles' discharged fuels. Their combined decay heat is removed by the cooling systems.



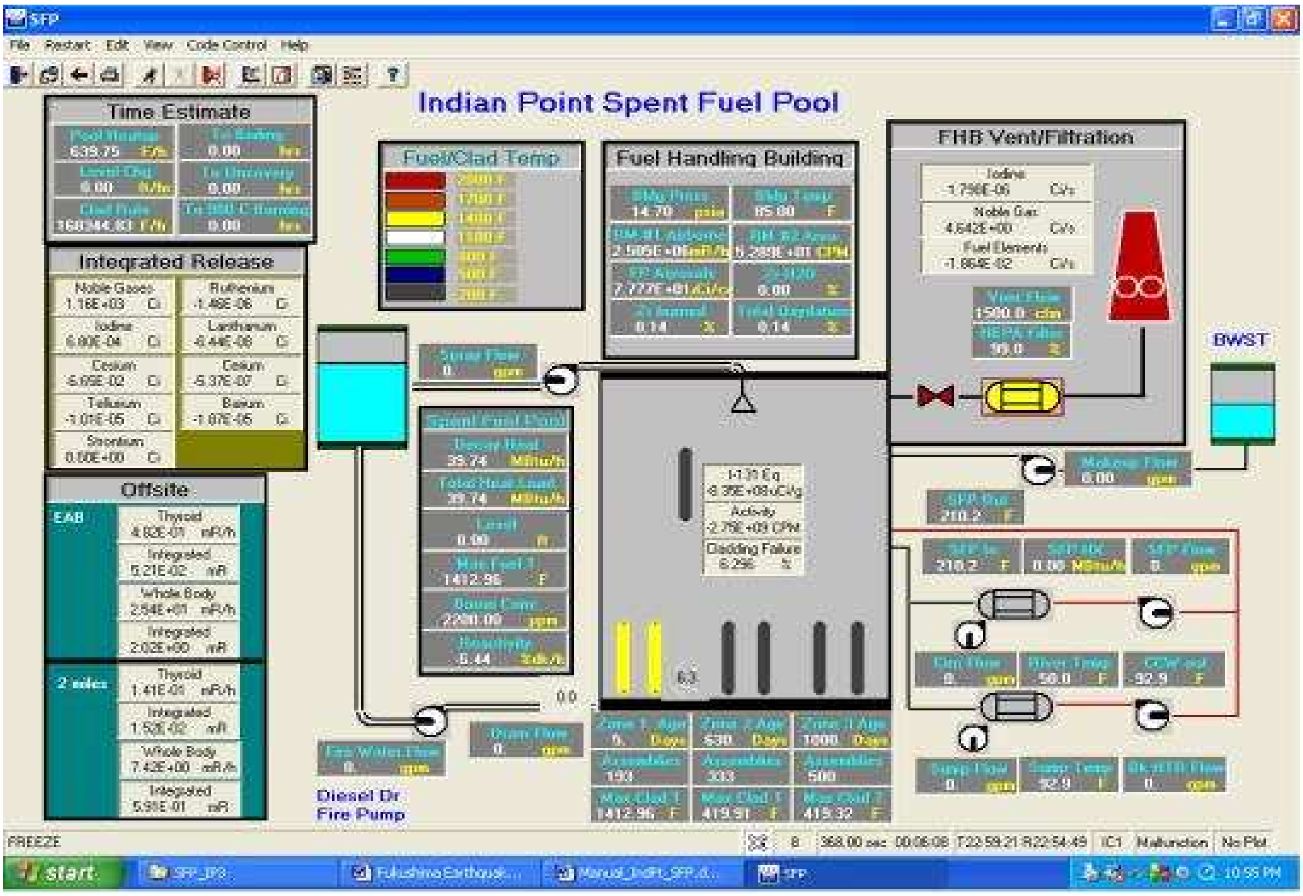
Spent Fuel Pool Simulator – normal condition.

Upon a loss of cooling or coolant event, the pool will heat up to boiling. Continued boiling exposes top of the fuels. Heat-up of the exposed fuel may turn into cladding oxidation and radiological gas release. The scale of a pool's radiological inventory could be even more serious than a plant's, since a pool contains much more assemblies than a core.

Since cracks can be developed at bottom of a pool – especially for Mark I and II containment the pool is located high above ground. A supplemental system should be a spray from atop of the pool with its own water storage and lines to outside makeup. Its piping and power supply should be independent and hardened to assure effectiveness in adversity. Having this you would never need helicopters or fire engines.

So, one of the lessons learned from Fukushima spent fuel pool release is:

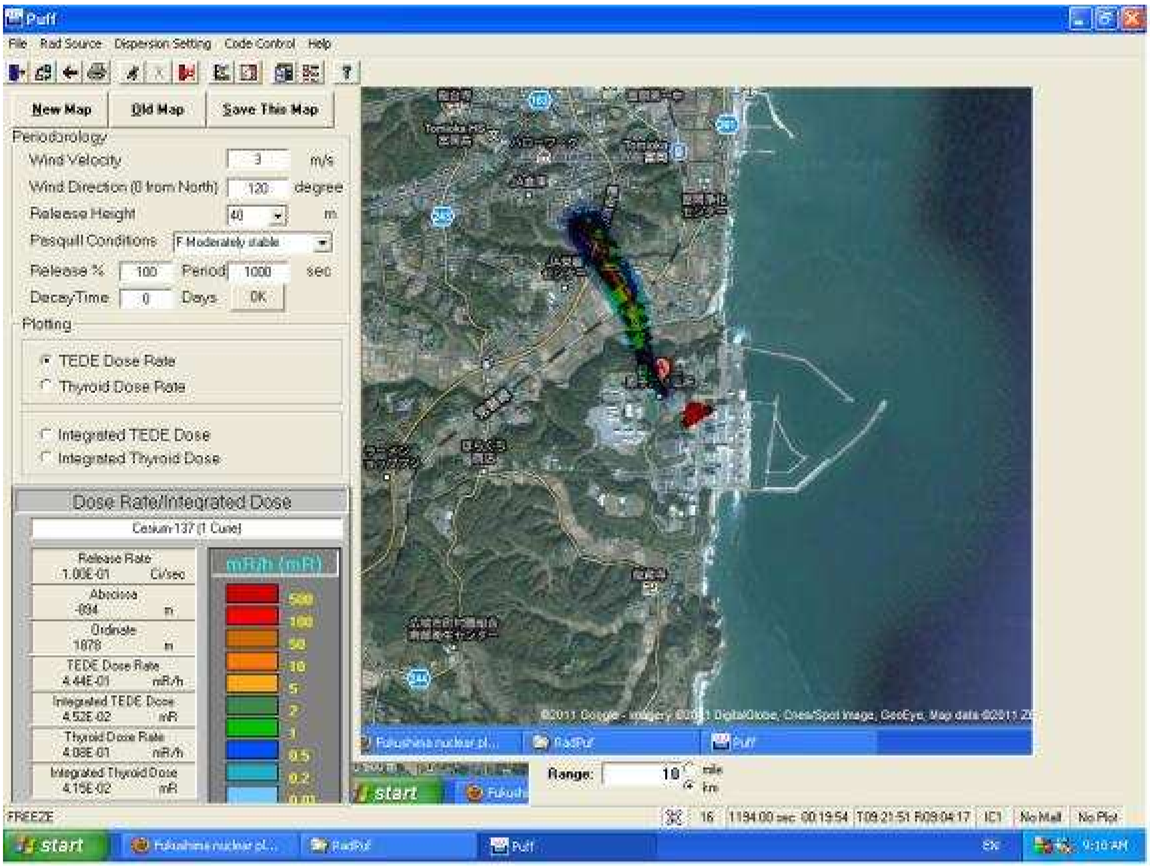
<u>Every nuclear power plant in the world (both PWR and BWR) should add a hardened spray cooling system.</u>



Spent Fuel Pool accident – after loss of coolant or cooling water boiled off. Note, a supplement pool spray system on top of the pool could keep the fuels cooled to present radiological release.

6. Dose Dispersion

Iodine and noble gases release source term is used by another MST product RadPuff for dose dispersion. Mostly southeast wind prevailed in the next couple days, so the plume was projected into the northwest direction.



RadPuff projection of dose dispersion following radiological release from the Fukushima site, southeast wind was assumed.

7. Conclusion and Recommendations

The Fukushima event was unprecedented because it exceeded historical maximum in the region. The succeeding tsunami aggregated the damage that knocked out crucial cooling systems and disabled all diesel generators. Given the initiating conditions PCTRAN is able to reproduce the plant behavior and radiological consequence. Our specific observation/recommendations are:

1. All existing power plants' passive emergency cooling systems (BWR's RCIC and PWR's turbine-driven auxiliary feedwater system) should be inspected and reinforced to assure their reliability during adverse condition. Onsite emergency generators should be further protected.

2. PWR is more resilient than BWR because of its steam generator secondary water inventory and size of containment. This gives larger margin to core damage and containment failure. Further review is still necessary to improve the safety level.

3. Spent fuel pool safety has been grossly overlooked. A hardened and independent top spray system is necessary for all nuclear power plants.