PCTRAN Analysis of Fukushima Event

Li-Chi Cliff Po[a] and Juyoul Kim[b*]
[a]*Micro-Simulation Technology, 10 Navajo Court, Montville, NJ 07045, USA,*
[b]*Gyeongju Branch of FNC Technology, Dongguk University, Gyeongju, 780-714*
**Corresponding author: gracemi@fnctech.com*

1. Introduction

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 and 2 are the PCTRAN mimic during full-power steady state operation.

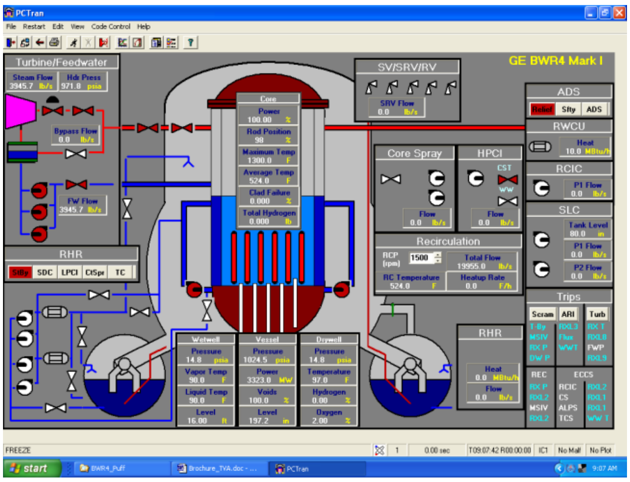

Fig. 1 PCTRAN BWR3,4 Mark I Mimic

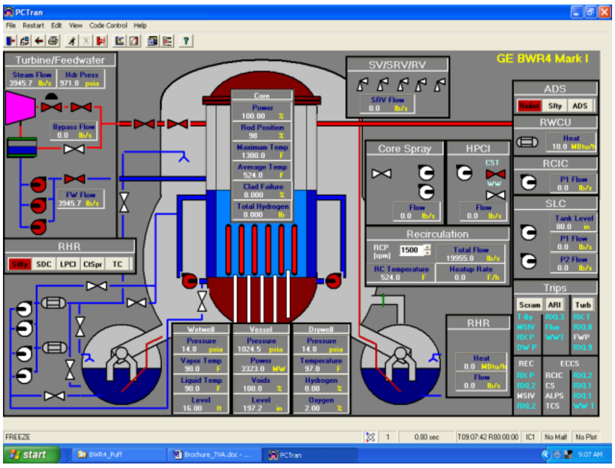

Fig. 2 PCTRAN BWR5 Mark II Mimic

2. PCTRAN/BWR Analysis

During the March 11 event, the RCIC and CS lines were either destroyed by the earthquake or soon exhausted their water supply. Since no onsite AC power available, HPCI and LPCI were never initiated. When the core water lowered to expose the core, clad damage and hydrogen generation was observed. The operators decided to depressurize the reactor vessel by opening the Safety Relief Valves. Coolant was further boiled off from the reactor to expose more fuels. Sea water was used to cool the core. A mixture of steam, hydrogen and fission gas pressurized the primary containment (i.e. the drywell and suppression pool). Since BWR4's containment is typically inerted below 4% of oxygen content, in principle there is no chance for hydrogen explosion regardless of the hydrogen concentration. However, because the containment pressure might have exceeded its 4-atmosphere design pressure, leakage from the pressure boundary cracks might have occurred. The gas mixture then filled the external Reactor Building. Detonation condition has reached and then explosions occurred. These happened at Units 1, 3 and 4. The Reactor Building roof is an ordinary structure so it was blown off. Later water spray on top of the Reactor Buildings by either helicopters or fire engines had limited effect since water has difficulties to reach the damaged core. All above sequence of events can be simulated by PCTRAN/BWR4 and 5 with quantitative accuracy.

Upon a SBO the reactor is tripped successfully and all recirculation pumps and main feedwater pumps are tripped. RCIC and CS then start on low reactor water level signal. Both systems work for a while and later disabled on assumption of damaged piping or exhausted water supply. The dome pressure then increases to lift the Safety Relief Valves (SRV) and cycle around their lowest band set point around 76 bar (1,100 psia). Both HPCI and LPCI are never available since the diesel generator has failed. The transient results are shown in Figure 3. The reactor dome pressure cycles around the SRV's set point by discharge the steam into the suppression pool. The operator decided to depressurize the vessel about 17,000 seconds prior to its failure.

The drywell and suppression pool pressures increased gradually due to SRV discharge. At 17,000 seconds when operators decided to depressurize, the containment pressure surged above its design (about 4 atm) and failed at about 7 atm. The fuel was exposed around 3,000 seconds into the event. Temperatures of the fuel and cladding increased rapidly to the melting point in about 10,000 seconds. Hydrogen was generated when the cladding temperature exceeded 900℃. It reached a maximum at about 15,000 seconds. Its leakage into the reactor building caused explosions in all four units.

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.

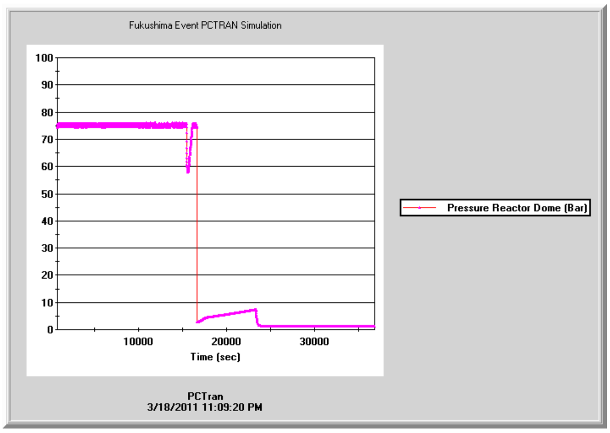

Fig. 3 Reactor dome pressure vs. time

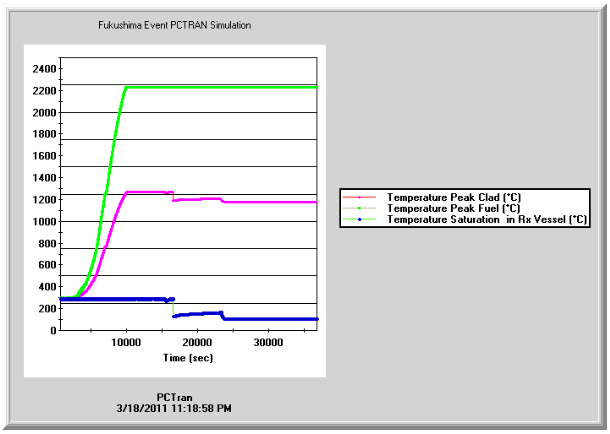

Fig. 4 Fuel and clad temperature vs. time

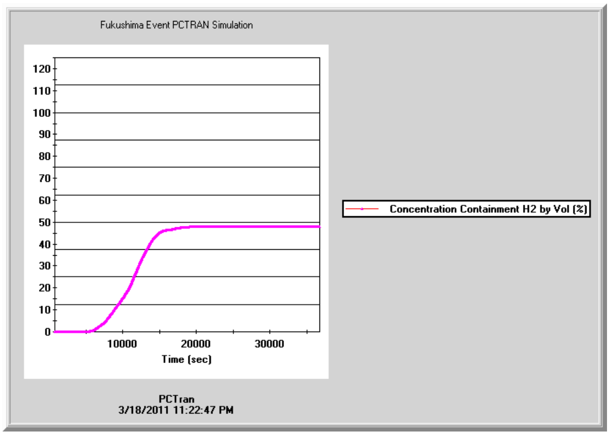

Fig. 5 Hydrogen concentration in the containment

3. Conclusions

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

REFERENCES

[1] L. C. Po and Jouyoul Kim, "PCTRAN/KSNP1000 – A PC-based Simulator for KSNP1000", Trans of the Korean Nuclear Spring Mtg *Pyeongchang*, Korea, May 27-28, 2010.
[2]] L. C. Po and Jouyoul Kim, "PCTRAN/APR1400 – A PC-based Simulator for APR1400", Trans of the Korean Nuclear Autumn Mtg *Jeju*, Korea, October 21-22, 2010.