SEVERE ACCIDENT MODELING AND OFFSITE DOSE CONSEQUENCE EVALUATIONS FOR NUCLEAR POWER PLANT EMERGENCY PLANNING

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Abstract

We have investigated the roles of Firewater Addition System and Passive Flooder in ABWR severe accidents, such as LOCA and SBO. The results are apparent that Firewater System is vital in the highly unlikely situation where all AC are lost. Also in this paper, we present EPZDose, an effective and faster-than-real time code for offsite dose consequences predictions and evaluations. Illustrations with the release from our severe accident scenario show friendly and informative user's interface for supporting decision makings in nuclear emergency situations.

1. Introduction

Lungmen Nuclear Power Plant is an ABWR (Advanced Boiling Water Reactor) in Taiwan and expecting to begin initial fuel loading in about one year from now. Many investigations, such as benchmark studies against FSAR (Final Safety Analysis Report) and startup transient test prediction analysis are being conducted extensively. This paper studies two typical severe accidents and the effectiveness of the associated mitigation systems for Lungmen by PCTRAN [1]. The released activity of various radioactive nuclides from the output of PCTRAN is then read into EPZDose [2, 3, 4] to evaluate the offsite dose consequences in a nuclear emergency situation.

In order to provide long term core and primary containment vessel cooling, Lungmen has regular LPFL (Low Pressure Flooder) and RHR (Residual Heat Removal) systems. As an alternative, Lungmen also has ACIWA (AC Independent Water Addition) system. It is essentially a firewater addition system pumped by an independent AC system or a fire truck with pumping heads of around 2 – 2.5 MPa. The ACIWA mode of the RHR system allows the operator to manually tie the fire protection system into the RHR injection line. Such actions could prevent the core damage. The system also acts as a mitigation feature after core damage. It pours the water through the vessel, onto the corium on the floor of lower drywell. The system could also add water into the containment and increase the thermal mass to lower the containment loadings.

Another mitigation system when vessel fails is the Passive Flooder which can provide water from suppression pool to drywell. The path opens automatically when drywell gas temperature is high enough, around 533 K. The system contains no active subsystems, instrumentations, and controls. As a final protection of the possible containment failure, Lungmen ABWR has Containment Overpressure Protection System (COPS). The rupture disks open to the environment at a preset containment high pressure of around 0.72 MPa.

2. Loss of Coolant Accident

2.1 Accident Descriptions

Based on FSAR, a main steam line break inside drywell is assumed to be the initiating event in this case, along with failure of all ECCS (Emergency Core Cooling Systems), including Reactor Core Isolation Cooling System (RCIC), High Pressure Core Flooder (HPCF), and Low Pressure Core Flooder (LPFL) [1]. In a conservative view, feedwater system is also assumed to trip at the initiation of this case.

Right after the steam line break, high pressure steam dumps into containment, and the drywell pressure soon becomes high, and causes the Reactor Protection System (RPS) to scram the reactor. MSIVs (Main Steamline Isolation Valves) close because of low vessel pressure. Without ECCS, core could uncover in 3.2 minutes and cause fuel heatup. Finally, vessel would melt at around 1.5 hr.

Once the vessel fails, corium from the lower plenum relocates into lower drywell and is quenched by the water from lower plenum and condensed steam in the containment. The corium boils the water away and begins to heat up the air space of lower drywell. As the lower drywell gas temperature reaches 533K at 4.1 hours, Passive Flooder operates automatically drawing water from suppression pool into lower drywell to quench the corium again.

After the Passive Flooder operates, the steam generation in the lower drywell slowly pressurizes the containment. At 16.8 hours, the wetwell pressure finally reaches 0.72 MPa, and the rupture disk of Containment Overpressure Protection System (COPS) opens, cause the release of radioactive fission products.

2.2 Accident Modelling

To model this accident case using PCTRAN, one carries out the following settings:
Set all ECCS pumps to malfunction positions, shut off MSIV and feedwater valve, activate "Steam Line Break Inside Drywell" in the malfunction list and set 3850 cm^2 as the steam line failure cross section area. To model the operation of Passive Flooder, one manually presses "Drywell Flooder" button when drywell temperature reaches 533 K.

2.3 Results and Discussions

The sequence of events is listed in Table 1. Accident begins at 60 seconds. High pressure steam flow into drywell cause the raise of pressure but soon decrease, due to condensation of the steam. Reactor scrams in 4 seconds due to low water-level signal in the vessel. Pressure variation in the vessel and drywell are shown in Figures 1 and 2 respectively. Without ECCS providing cooling water, core melts and falls into vessel bottom head at 4.1 hr, then vessel fails at around 6.4 hr. The remaining water in lower drywell boils away by the corium (as shown in Figure 3), and the drywell temperature starts to increase but not high enough to activate the Passive Flooder (as shown in Figure 4). Steam generation and non-condensable gas produced by core-concrete interaction in the lower drywell slowly pressurizes the containment. When the wetwell pressure reaches 0.72 MPa at 9.1 hr, COPS rupture disks open. Hydrogen concentration in the containment reaches 5% at about 2 hr, see Figure 5. Hydrogen detonation is highly possible.

In the case of all ECCS fail, firewater system can be used as an alternative way providing coolant injection either into vessel or containment through RHR piping. The firewater system components are outside the containment, including pumps and water source. To inject water into vessel, operator has to start the system manually while the vessel pressure is low. In this case, injection begins at 1 minute after the initiation of the accident while the vessel pressure is just below 1.96 MPa. Simulation shows that, by manually maintaining vessel water level between level 3 and level 8, core damage will not occur. Water in the vessel vaporizes into steam due to the decay heat, and the pressure in the containment increases vary slowly as shown in Figure 5. If RHR system can become available during this long period, then long-term cooling and containment heat removal can be accomplished successfully.

Table 1 The sequence of events for LOCA.

Time	Event
60 sec	Steam line break inside drywell
64 sec	Scram
120 sec	Vessel water level drops to TAF
4.1 hour	Fuel relocates
6.4 hour	Rx pressure vessel fails
9.1 hour	COPS rupture disk opens

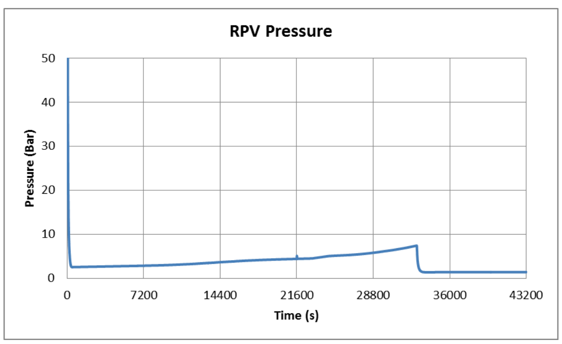


Figure 1 RPV pressure histories in LOCA.

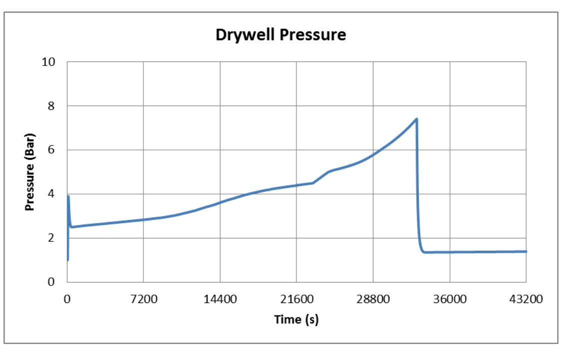


Figure 2 Drywell pressure histories in LOCA.

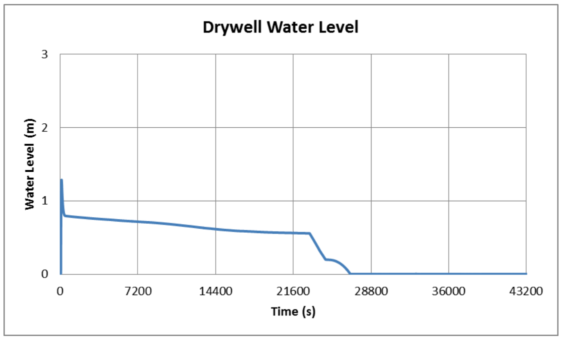


Figure 3 Drywell water level histories in LOCA.

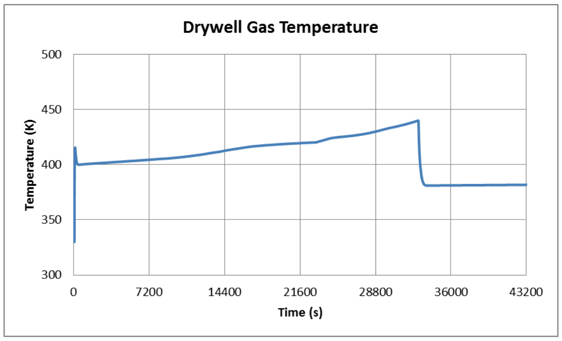


Figure 4 Drywell gas temperature histories in LOCA.

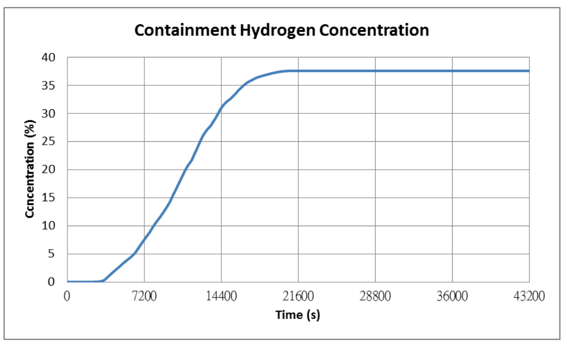


Figure 5 Containment Hydrogen Concentrations in LOCA.

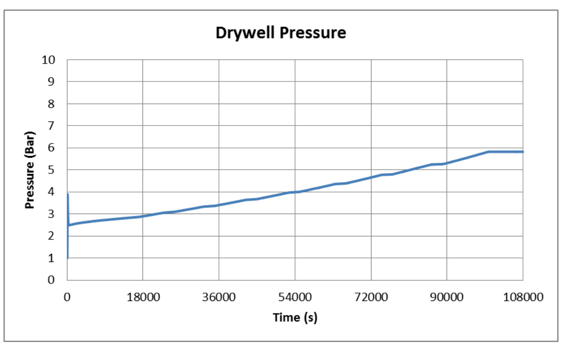


Figure 6 Drywell pressure histories in LOCA with firewater addition.

3. Station Blackout

3.1 Accident Descriptions

The Station Blackout (SBO) assumes the failure of all AC power, including all emergency diesel generators. Therefore, there are only RCIC and Firewater System available. By using batteries, RCIC system can provide core cooling for eight hours by design. After RCIC fails, the operator depressurizes the vessel and then there are two types of sequences to be considered. One sequence is that firewater will be injected into the vessel at the vessel pressure of 1.96 MPa. It can maintain core cooling to avoid RPV (Reactor Pressure Vessel) failure. When the wetwell pressure reaches 0.72 MPa, it will trigger the COPS. However, there is no release of fission products because the core stays intact. The other one is that firewater system is unavailable after RCIC fails, which will occur core damage. As a result, corium concrete interaction will cause the wetwell pressure to increase rapidly to 0.72 MPa and initiate COPS. Owing to core damage, it will release fission products to the environment. [1]

3.2 Accident Modelling

In Lungmen PCTRAN model, MSIV and feedwater valve are closed initially, and the malfunction, SBO, is active at the same time. RCIC will automatically start up and run for eight hours. Then, RCIC will be closed manually. Now, there are two types of sequences. One sequence is that according to the plant emergency operating procedures, we depressurize the vessel pressure by activating 1 ADS SRV (Automatic Depressurization Systems Safety/Relief Valves) when the vessel water level reaches the top of fuel. As the vessel pressure decreases to 1.96 MPa, we initiate the firewater system to maintain water level between Level 3 and Level 8. The other one is that we use 1 ADS SRV to depressurize the vessel when the water level reaches about two-thirds core height.

In Lungmen PCTRAN model, MSIV and feedwater valves are closed, and the malfunction, SBO, is active at 60 s. RCIC automatically starts at 190 s and fails at 8 hours.

3.3 Results and Discussions

Station Blackout with Firewater System

The vessel water level reaches the top of fuel at 10.1 hr and causes 1 ADS SRV to open (Figure 7). Afterward, the vessel pressure decreases to 1.96 MPa at 10.4 hr and the firewater starts to inject (Figure 8). The fuel cladding failure rate is about 0.025%, and the vessel structure integrity is maintained. Finally, although the COPS is triggered at 18.7 hr, the fission product releases are still negligible. It should be noted that no core damage is predicted in FSAR. Furthermore, to raise the vessel water level to Level 8 with firewater, we need ten hours of operation in PCTRAN, but it takes only three in FSAR.

Station Blackout without Firewater System

The sequence of events is listed in Table 2. When the vessel water level reaches about two-thirds core height at 10.5 hr, we initiate 1 ADS SRV to depressurize the system (Figure 9). The vessel finally fails at 16.5 hr and causes the Corium Concrete Interaction (Figure 9). It increases the wetwell pressure rapidly to trigger COPS at 16.6 hr (Figure 10) and starts to release the fission products to the environment. According to FSAR, the drywell temperature reaches 533 K and trigger the Passive Flooder, but the drywell temperature in PCTRAN is too low (434 K) to activate the Passive Flooder (Figure 11). Hydrogen concentration in the containment reaches 5% at about 12 hr, see Figure 12. Hydrogen detonation is highly possible by then.

Results and Conclusions

In general, the trend of the results from PCTRAN is consistent with those from FSAR. Obviously, we can observe that the drywell water level drops down while corium falls (Figure 13), and we can easily distinguish the differences with and without the introduction of the firewater. In the future, the sensitivity of the firewater flow rate and the drywell temperature will be developed in a more satisfactory way.

Table 2 The sequence of events for SBO.

Time	Event
60 sec	Loss of all AC power
64 sec	Scram
190 sec	RCIC starts
8 hour	RCIC fails
10.5 hour	Vessel water level drops to two-thirds core height
16.5 hour	Rx pressure vessel fails
16.6 hour	COPS rupture disk opens

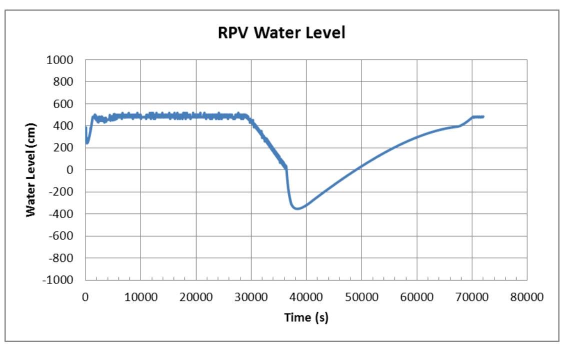


Figure 7 RPV water level histories in SBO with firewater addition.

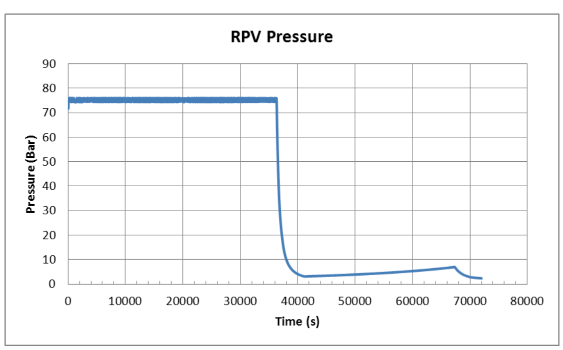


Figure 8 RPV pressure histories in SBO with firewater addition.

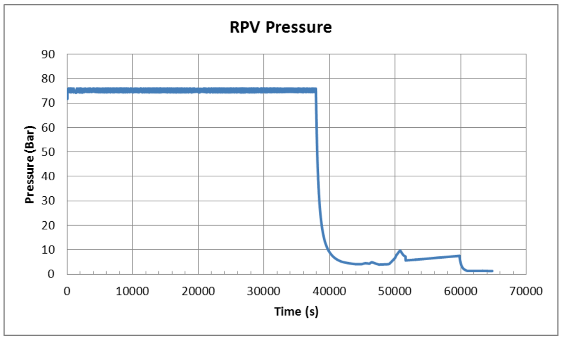


Figure 9 RPV pressure histories in SBO without firewater addition.

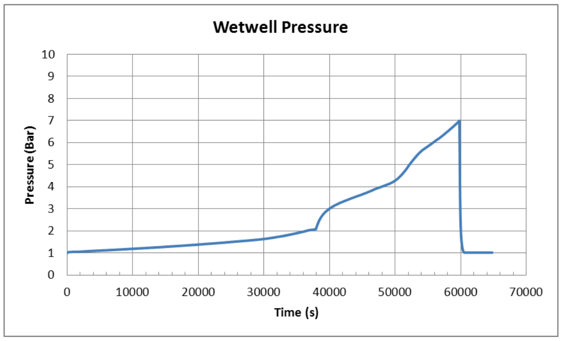


Figure 10 Wetwell pressure histories in SBO without firewater addition.

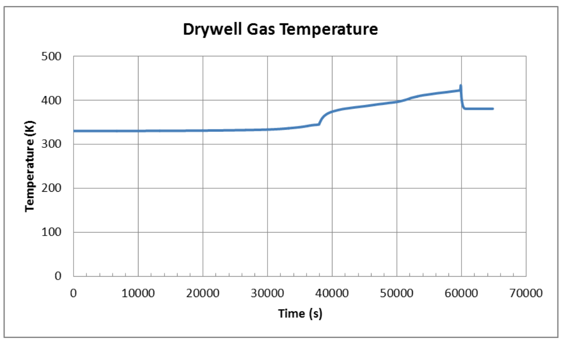


Figure 11 Drywell gas temperature histories in SBO without firewater addition.

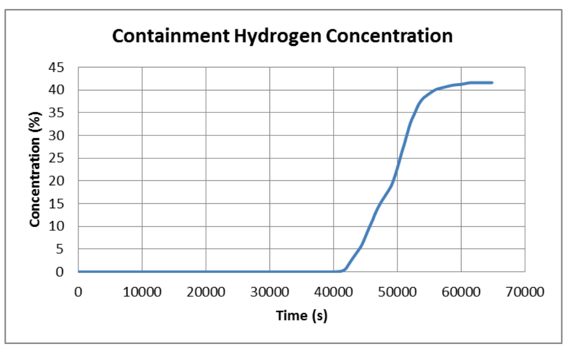


Figure 12 Containment Hydrogen Concentration in SBO without firewater addition.

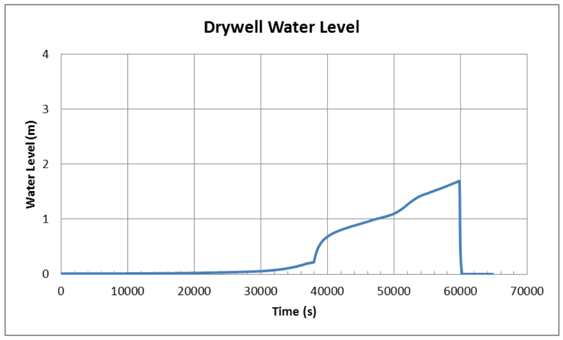


Figure 13 Drywell water level histories in SBO without firewater addition.

4. Offsite Dose Consequences Evaluations

4.1 Code Descriptions

The function of EPZDose is to simulate and display the dose distributions around a nuclear power plant from the release of radioactive materials in a nuclear power plant accident. EPZDose is developed using visual studio 2008, with multi-language capabilities (Chinese/English). [2,3,4] The theory of its kernel computing module is based on modified Gaussian puff models. Equipped with visual user interface, friendly operation and fast prediction capability, EPZDose can assist the authorities in preparing the emergency response planning and achieving proper resource distribution. It could help to reduce the impact of the accident and improve the efficiency of the emergency response planning. Its input data, output data and operating features are given as follows.

(a) Input data for simulation function, see Figures 14 and 15.

- Radioactivity of materials released from the power plant.

  The time variations of more than 50 different radio-nuclides released from the nuclear power plant can be saved as local Access files when PCTRAN performs simulations of the nuclear power plant incidents. Besides, the information of the time variation can be saved simultaneously into the MySQL database in a remote server if the MySQL database is accessible by the network. Therefore, the EPZDose users can retrieve the radioactivity of released materials either from the local Access files or from the MySQL database. Both PCTRAN and EPZDose can synchronize to perform simulations. EPZDose reads data at fixed intervals and if no updated data is available, EPZDose pauses and stands by automatically. After reading the updated data, EPZDose restarts to perform calculations and plot.

- Meteorology conditions.

  The conditions include wind velocity, wind direction and Pasquill stability conditions, which can be changed with unlimited times according to simulation scenarios or real situations.

- Stack height, plant name, radius of simulation region.

  These three items can’t be changed after initial setting is done. Plant name and simulation radius are selected by radio buttons. Simulation radius has two options, 1 km and 5 km. Once selected, EPZDose will automatically display the corresponding map as a base map for the dynamic dose distribution map.

- Output configurations.

  There are two options for output data storage, one is to save into the local Access files and the other one is to save into a MySQL database, which can be multiply selected. The storage path has to be set when the first one is selected. If a previously analyzed file exists under the storage path, the user is prompted to overwrite it or not.

(b) Output data

EPZDose displays the simulated region and progress of radioactivity dispersion by the dynamic dose distribution map. Concurrently, the numerical data of the simulation results is outputted and saved as the input data for the replay function. Items of the output data are listed as follows:

- Four regional distributions of dose (whole body dose rate/thyroid dose rate/integrated whole body dose/integrated thyroid dose) are recorded at fixed time intervals. They are calculated based on standard dose conversion factors for different radioactive nuclides.
- Records of changes of meteorology conditions during the simulation period.
- Plant name and radius of simulated region.

(c) Operating features

- The code can speed up, speed down and pause during simulation. The simulation speed can be made at least 60 times faster than the real times.
- The code can change the dose category of the dynamic dose distributions among the four categories (whole body dose rate/thyroid dose rate/integrated whole body dose/integrated thyroid dose) during simulation.
- At the click of the mouse on any location in the map, its direction and distance from the plant and levels of the dose categories will be displayed in a panel inside the application window for user's reference.
- PCTRAN and EPZDose both provide two kinds of output modes, the local Access and the MySQL database. For the viewpoint of event management, it’s better to select the MySQL database mode. However, equipped with these two modes, EPZDose is ensured to be still functional if the server (for MySQL database) cannot be accessed by the network.
- Integrated into EPZDose itself is the replay function of the simulated results. It takes the outputs of the simulated results either in text formats or in MySQL database. After the data entry is completed, the map, records of meteorology condition and times when levels of dose rates or accumulated doses are updated will be displayed in the window. Users can select the starting time point of playback, and pause or stop the playback process at any time.

4.2 Results (SBO without firewater for illustration purposes)

For the illustration purposes, the radioactive release (source term) from the above mentioned station blackout without firewater addition is adopted. An emergency planning zone of 5 km radius is considered. The wind velocity is 1 m/sec and is blowing from southeast. The Pasquill's condition is taken as stable at F. Remember that COPS opens at about 60000 sec. As shown in Figure 16, one can see the progressions of the affected area under radioactive plume as consecutive radioactive puffs are being released and dispersed throughout the area near the plant. Such information is vital for the authority to come up with a plan on when and where and how an evacuation should be effectively conducted.

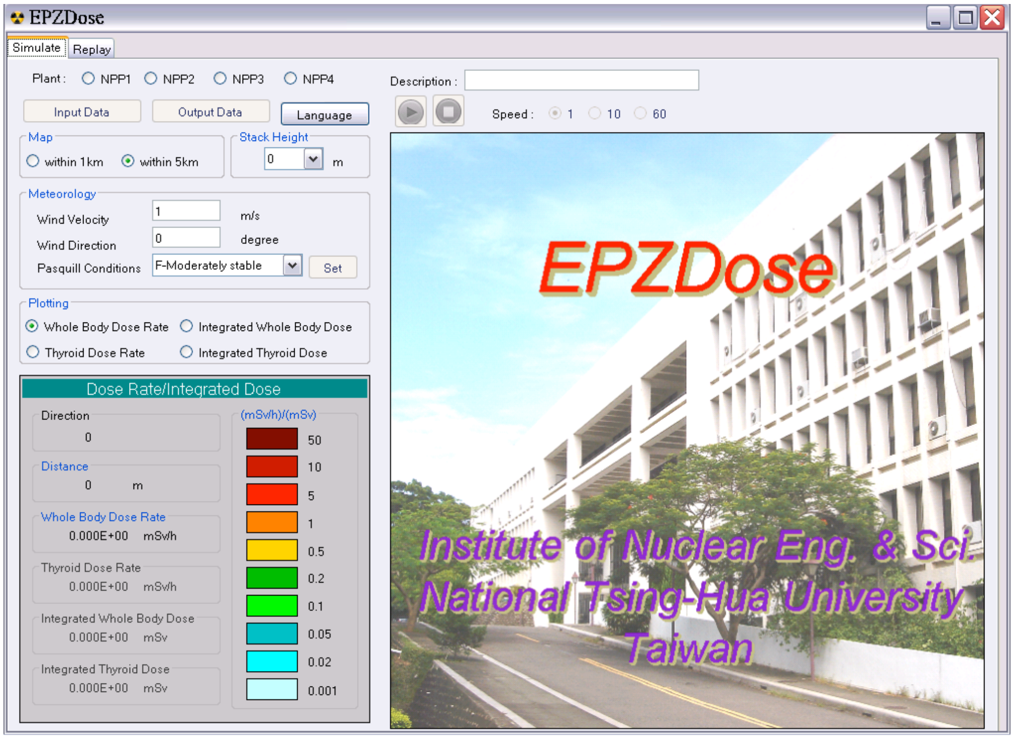


Figure 14 Simualtion function window in EPZDose.

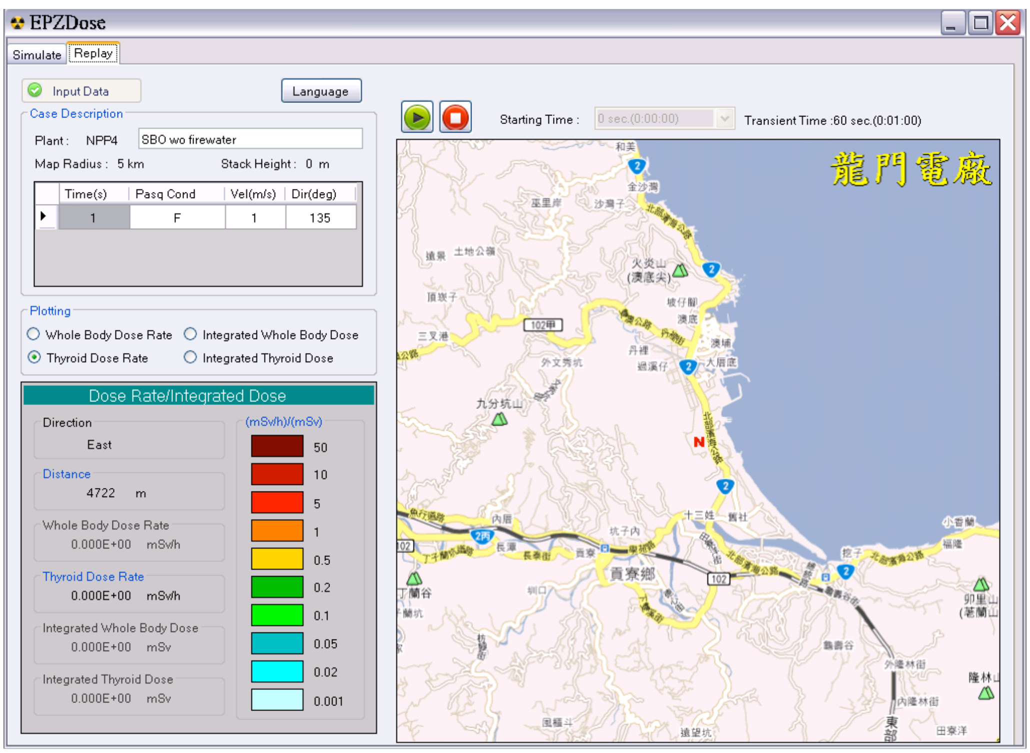
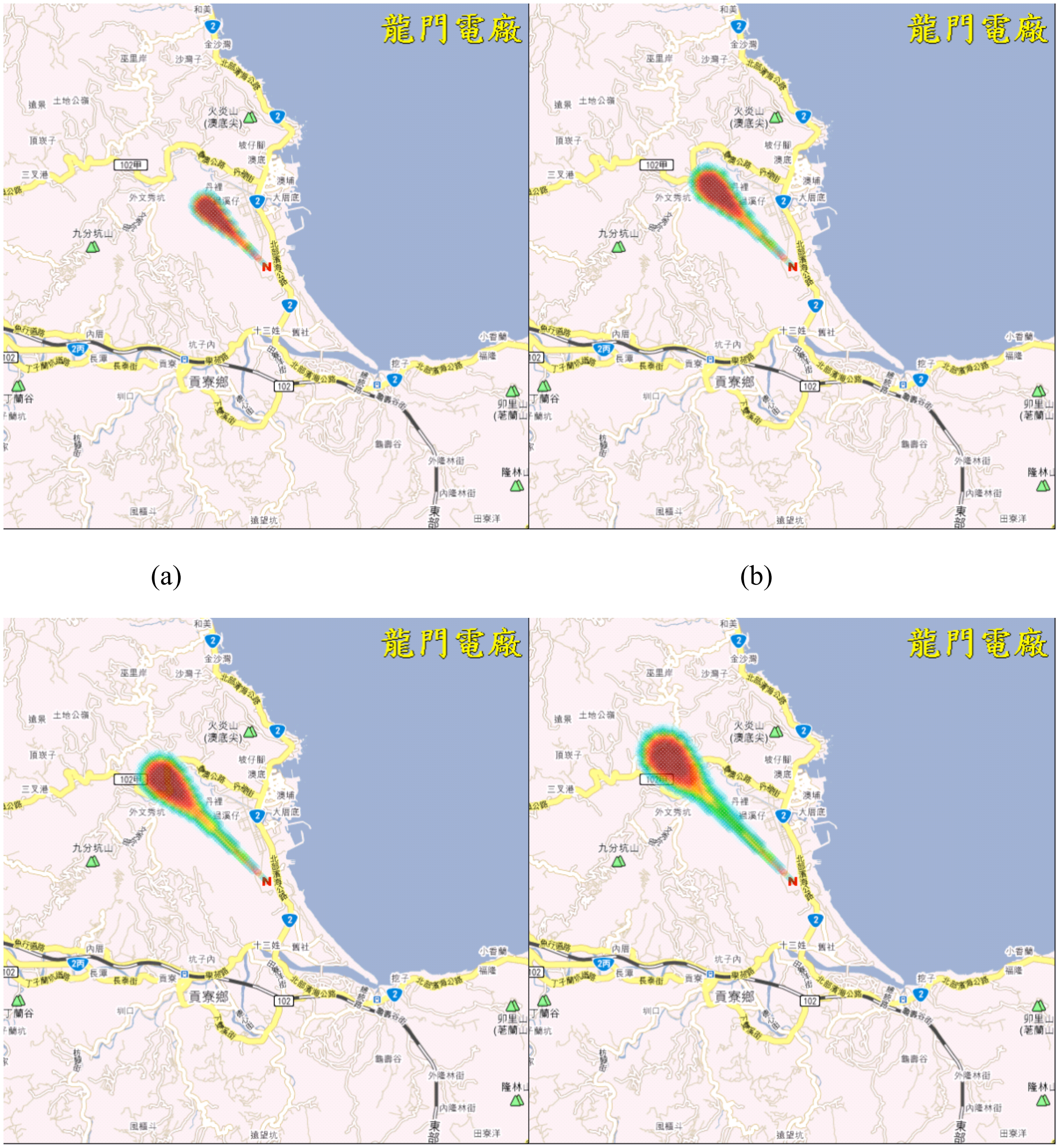


Figure 15 Replay function window in EPZDose.



(a) (b)

(c) (d)

Figure 16 The thyroid dose rate distributions at times (a)17:05, (b)17:15, (c)17:25, (d)17:35 in hh:mm after the initiation of SBO. Refer to the color bar in Figure 14 or 15.

5. Conclusions

We have demonstrated and summarized the role of firewater in severe accidents such as loss of coolant (LOCA) and station blackout (SBO). People have also realized its importance after the tragedy at Fukushima Daiichi Plant. In order to provide enough and valuable information concerning the radioactive consequences around the plant for an effective evacuation plan, faster-than-real time evaluation tools such as EPZDose is a proper solution.

6. References

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