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Atmospheric Puff Model Developments in PCTRAN

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ABSTRACT

This study extended the capabilities of PCTRAN by including the Gaussian puff model and the basic numerical techniques, to efficiently calculate the radioactive effluent dispersion. PCTRAN is a PC based nuclear power plant simulation code, and capable of running faster than real time. Accident initiation events can be activated in the simulation software, and the radioactive materials are assumed to be released from the plant to the atmosphere at every time of interval. During a transient or an accident simulation, puffs are sequentially generated and dispersed in all directions governed by the Pasquill stability category, wind velocity and wind direction. The thyroid dose rate and whole body dose rate (as well as their accumulations) at every spatial location in the emergency planning zone (EPZ) are shown as a color-shaded plot. A postulated scenario was given in PCTRAN to demonstrate that the code predict the time-varying distributions of thyroid and whole body dose rates (and their accumulated dosages) efficiently. Therefore, the urgent decision-making on protective actions can be determined ahead of the accident time.

1. INTRODUCTION

Radioactive materials are produced in reactor operations, and may be released into the atmosphere if an accident occurs. The released radioactive materials could result in dangerous levels of radiation that could harm people and damage the environment. The importance of the Nuclear Emergency Response Plan has been examined by the U.S. Nuclear Regulatory Commission (NRC), and the plan must take the responsibility to protect the public in the vicinity of nuclear power plants. Therefore, before a plant is licensed to operate, the plant owner must confirm that his emergency response plan provides “reasonable assurance that adequate protective measures can and will be taken in the event of a radiological emergency”.

The Nuclear Emergency Response Plan includes on-site and off-site emergency response plans. Upon the occurrence of a nuclear accident, the on-site emergency response plan should be activated firstly. The plant owner must take actions to mitigate the accident, as well as evaluate plant conditions and recommend actions to the central and local government levels. If the emergency situation escalates from a small on-site problem to an emergency requiring off-site implication and assistance, prompt and effective protective measures, such as sheltering, distributing potassium iodide, evacuation and accommodation, and so on, are thus taken to protect the health and safety of the public. The central government level shall analyze, assess, manage the nuclear accident, as well as plan and supervise all other work [1]. Therefore, making rapid assessments of the potential magnitude and locations of radiological hazards is necessary to support decision-making in response to nuclear accidents [2].

This study was based on a simulation software, PCTRAN, which is a nuclear power plant transient and accident analysis code, and can be operated on a personal computer. Various accident initiation events are easily programmed by manipulating the graphical elements laid out on the interface, and the conditions of the plant, such as 1) important parameters: pressure, temperature, water level, 2) activation of control system: ECCS activation, control rod insertion, opening or closing of valves, and 3) production of fission products, are simulated as transient time progresses.

This work adopted the Gaussian puff model [3] and incorporated the basic numerical techniques to calculate the transport and dispersion of radioactive materials once they pass through the series of physical barriers. The releases of radioactive materials are treated as unsteady emissions in non-homogeneous dispersion conditions. The incorporation of PCTRAN with the Gaussian puff model also preserves the inherent characteristics and advantages of PCTRAN. Accordingly, the software is still easy to use and capable of running rapidly [4].

2. ANALYSIS TOOL

This paper is on the basis of the nuclear power plant transient and accident analysis code – PCTRAN. PCTRAN is a windows-based product, and the software provides a graphical user interface (GUI) to allow user-friendly manipulation. Important features (RCIC, HPCF, RHR, etc) and components (pumps, valves, pipes, etc) are programmed in the form of graphical images, and are laid out on the interface as the construction of a nuclear power plant, as shown in Fig. 1. These features and components can be disableed by users through directly interacting with the interface. In PCTRAN, a transient and/or accident can be run by easily selecting an initial condition and setting malfunctions, and the results are consequently shown during the transient. Such initiation events can be programmed to activate at a specified point of time beforehand, or interactively during a transient simulation [5]. Recently, the simulation software is developed to consider severe accidents.

PCTRAN evaluates the production of fission products, including noble gases (Xe and Kr), iodine isotopes (I) and others (Te, Sr, Ru, La, Ce, Ba, Co, Rb, Zr, Nb, Mo, Tc, Sb, Cs, Pr, Nd, Np, Pu, Am and

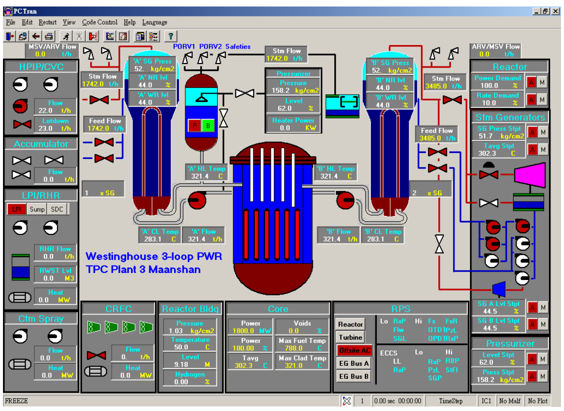


Fig. 1 Software Interface of PWR.

Cm). These radiation source terms may have an impact on the public when the radioactive materials are released to the environment through the series of physical barriers. PCTRAN also considers all possible pathways which allow radioactive materials leaving into the environment.

3. EFFLUENT DISPERSION AND DOSE DISTRIBUTIONS

Our earlier study extended the calculation capabilities of PCTRAN by including the Gaussian plume model [6]. In this study, we extended the calculation capabilities of PCTRAN by including the Gaussian puff model. The Gaussian plume model is used to assess the radioactive effluent dispersion for obtaining the construction permit and operating license. On the other hand, the Gaussian puff model is used to predict the time-varying dose distributions, and this kind of model shows more realistic predictions during emergencies, and thus is more practical in the emergency response.

3.1 Plume Model in PCTRAN

The Gaussian plume model in PCTRAN evaluates the whole body and thyroid dose rates and their accumulated dosages inside the EPZ [6]. The Gaussian plume model assumes that the emission is continuous and constant in steady-state meteorological conditions. The model describes the effluent dispersion in the horizontal and vertical directions according to the normal Gaussian distributions.

A postulated scenario is given to allow fission products leaving through the series of physical barriers during the simulation. Hence, the phenomena of the radioactive materials entering into the environment can be predicted by PCTRAN. This study assumes:

1) Fuel failure at power: 20 % of fuel failure;
2) Steam generator tube rupture: 4 full tube rupture;
3) Steam line break outside containment: break area of 400 cm^2.

Those malfunctions of components are easily set up through the GUI of PCTRAN, as shown in Fig. 2. The meteorological condition is assumed under the Pasquill stability category B (moderately unstable) with a southerly wind velocity of 1 m/s. Moreover, ground-level release is considered in the dose calculation.

Figures 3 and 4, respectively, show the distributions of the whole body and thyroid dose rate in the EPZ, as soon as the malfunctions are set up and meteorological conditions are given.

3.2 Puff Model in PCTRAN

The Gaussian puff model is used to simulate the dispersion of the unsteady radioactive effluent as they enter into the atmosphere. Let us consider the model

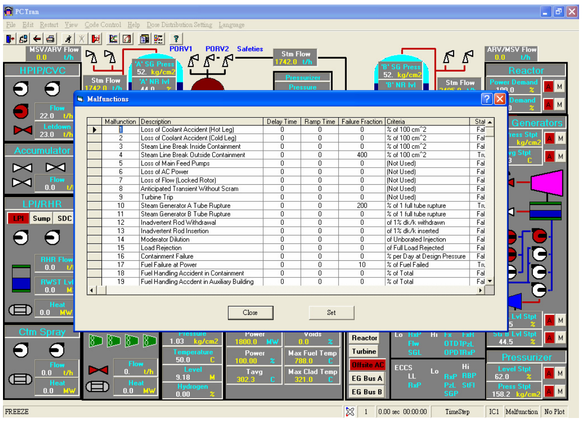


Fig. 2 The setting of malfunctions through the GUI of PCTRAN.

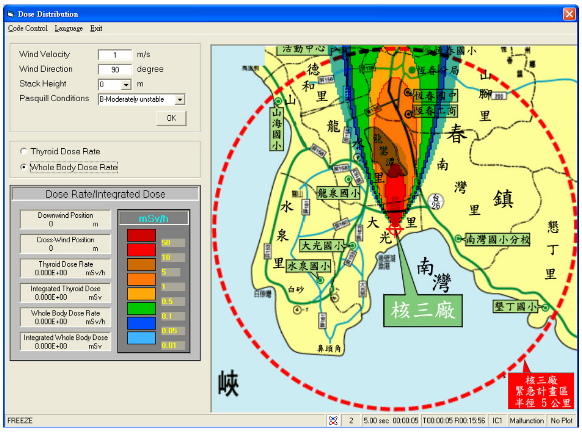


Fig. 3 Whole body dose rate distributions calculated by the plume model.

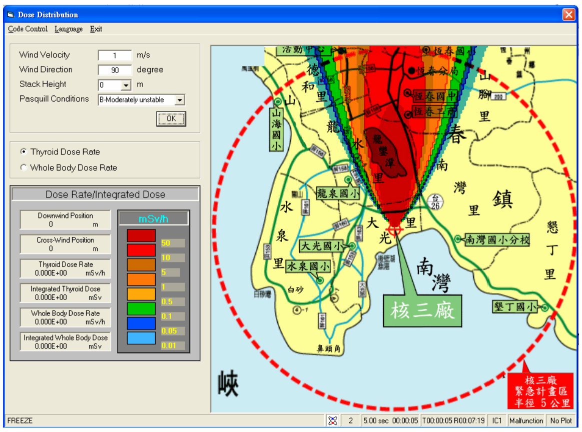


Fig. 4 Thyroid dose rate distributions calculated by the plume model.

in a discrete time series and assume the activity release with a time-varying source strength. To save the computational burden and to enhance the accommodation of PCTRAN in the application of plant emergency response, the concentration of the activity (in Ci/sec) before being released outside the nuclear power plant is accumulated for a period of time t. For precise concentration integration, the time period t is further divided into M sub-intervals as Δt_n (n=1, 2,…,M), and the activity of radioactive materials at each time point Δt_n is $\dot{Q}_n^{\,i}$. Therefore, for the i^{th} successive release, the activity in a puff is

$$Q^i = \sum_{n=1}^{M} \dot{Q}_n^{\,i} \cdot \Delta t_n \tag{1}$$

where Q^i is the activity in a successive released puff (Ci); t is the accumulation time for a puff (sec).

When the simulated nuclear power plant experiences a transient or an accident from time T_{init} to T_{tran}, $(T_{tran} - T_{init})/t$ puffs are released. The travel time for the i^{th} released puff is

$$t^{ia} = T_{tran} - \sum_{k=1}^{i} t^k = T_{tran} - t \cdot i \tag{2}$$

According to the wind velocity U and wind direction θ (e.g. θ=0 means wind blows from the west to the east; θ=90° means wind blows from the south to the north), the center of the i^{th} released puff reaches

$$\begin{cases} x_p = U \cdot t^{ia} \cos\theta \\ y_p = U \cdot t^{ia} \sin\theta \\ z_p = 0 \end{cases} \tag{3}$$

The consequent thyroid dose rate and whole-body dose rate at the receptor (x_r, y_r, z_r) due to the i^{th} released puff located at (x_p, y_p, z_p) can be computed

$$DT^i(x_r, y_r, z_r; T) = BRTH \cdot CONV \cdot \frac{Q^i}{(2\pi)^{3/2}\sigma_y^2\sigma_z} \cdot \exp\left[-\frac{1}{2}\left(\frac{x_p - x_r}{\sigma_y}\right)^2\right] \cdot \exp\left[-\frac{1}{2}\left(\frac{y_p - y_r}{\sigma_y}\right)^2\right] \cdot \left[\exp\left(-\frac{1}{2}\left(\frac{z_p - z_r}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z_p + z_r}{\sigma_z}\right)^2\right)\right] \tag{4}$$

$$DW^i(x_r, y_r, z_r; T) = 0.247 \cdot E_\gamma \cdot \frac{Q^i}{(2\pi)^{3/2}\sigma_y^2\sigma_z} \cdot \exp\left[-\frac{1}{2}\left(\frac{x_p - x_r}{\sigma_y}\right)^2\right] \cdot \exp\left[-\frac{1}{2}\left(\frac{y_p - y_r}{\sigma_y}\right)^2\right] \cdot \left[\exp\left(-\frac{1}{2}\left(\frac{z_p - z_r}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z_p + z_r}{\sigma_z}\right)^2\right)\right] \tag{5}$$

where DT^i is the thyroid dose rate caused by the i^{th} released puff (Rem/hr); *BRTH* is the breathing rate (m^3/hr); *CONV* is the dose rate conversion factors

(Rem/Ci); DW^i is the whole-body dose rate caused by the i^{th} released puff (Rem/hr); E_γ is the average gamma energy (MeV); and σ_y and σ_z are dispersion coefficients in the lateral and vertical directions, respectively.

The identical postulated scenario given in Section 3.1 is also simulated by the puff model in PCTRAN. The consequent whole body dose distributions varying with time are plotted on the map, as shown in Fig. 5, and the time-varying thyroid dose distributions are illustrated in Fig. 6.

4. RESULTS AND DISCUSSIONS

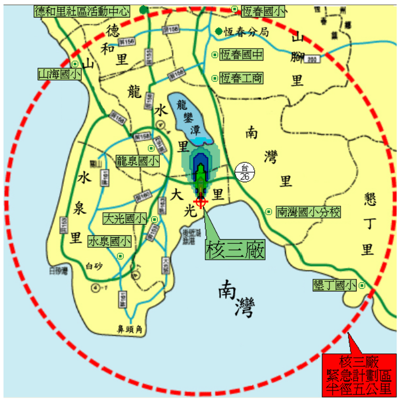
For the postulated accident studied above, radioactive materials are released into the environment without any on-site response measures for demonstrating the whole body and thyroid dose rates and their accumulated doses in the EPZ. PCTRAN has a natural ability to execute rapid reactor transient and accident analysis. The simulation in this study is run on a Pentium 4 / 1.90 GHz PC with 512 MB RAM. Figures 7 and 8, respectively, reveal the variations of whole body and thyroid dose accumulations at the downwind locations of 250 m, 500 m and 1000 m. These figures also have the accident time and CPU time in their x-axis. CPU time is the amount of time that CPU spends on the calculation, while accident

(a) Time=10 min

(b) Time=20 min

Fig. 5 Time-varying whole body dose distributions.

(a) Time=10 min



(b) Time=20 min

Fig. 6 Time-varying thyroid dose distributions.

time is the time during the postulated accident. These figures demonstrate that PCTRAN can run faster than the real accident time. Therefore, the need for making rapid assessments of the potential magnitude and locations of radiological hazards that the plant owner and the central government level should accomplish can be done in a short time.

In more detail, intervention levels are the level of dose at which a particular measure should be taken. Intervention levels in nuclear emergency situations are expressed in terms of avertable dose. Avertable dose means the dose that can be averted if a protected action is induced. Referring to Figs. 7 and 8, the accumulated dose during an accident is obtained during the simulation. Hence, the avertable dose, which is regarded as the guided value of protective actions, can be easily determined if protective actions are decided to be taken at a certain time.

5. CONCLUSIONS

This study extended the capabilities of PCTRAN to include the Gaussian puff model, and demonstrated its ability of efficient prediction of the consequences of a nuclear accident. We studied a scenario that allows radioactive materials to be released into the

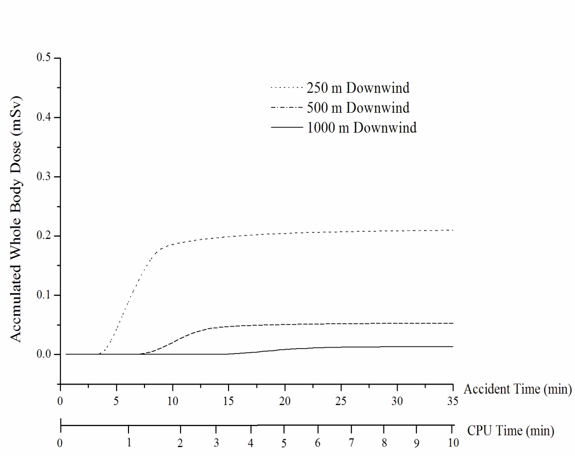


Fig. 7 Accumulated whole body dose relative to accident time and CPU time.

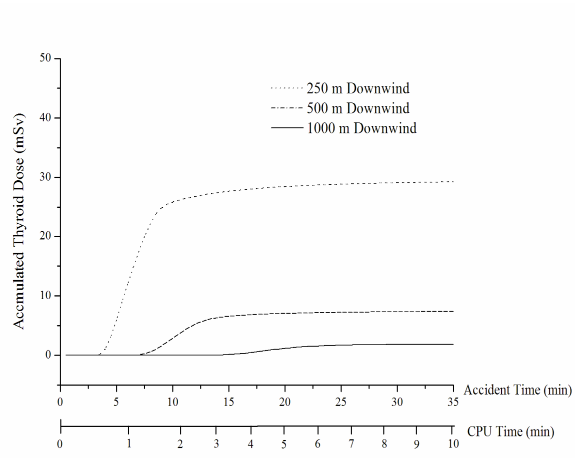


Fig. 8 Accumulated thyroid body dose relative to accident time and CPU time.

environment. The radioactive materials are thus released at every predetermined interval of time, and the movement of these materials is governed by the Gaussian puff model. The consequent whole body and thyroid dose rates and their accumulated dosages are obtained much earlier than the real accident time. The prompt and effective actions that should be taken are clearly identified following the simulation results. This study facilitates the potential applications of PCTRAN in nuclear emergency response.

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