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Reevaluation of the emergency planning zone for nuclear power plants in Taiwan using MACCS2 code

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Abstract

According to government regulations, the emergency planning zone (EPZ) of a nuclear power plant (NPP) must be designated before operation and reevaluated every 5 years. Corresponding emergency response planning (ERP) has to be made in advance to guarantee that all necessary resources are available under accidental releases of radioisotope. In this study, the EPZ for each of the three operating NPPs, Chinshan, Kuosheng, and Maanshan, in Taiwan was reevaluated using the MELCOR Accident Consequence Code System 2 (MACCS2) developed by Sandia National Laboratory. Meteorological data around the nuclear power plant were collected during 2003. The source term data including inventory, sensible heat content, and timing duration, were based on previous PRA information of each plant. The effective dose equivalent and thyroid dose together with the related individual risk and societal risk were calculated. By comparing the results to the protective action guide and related safety criteria, 1.5, 1.5, and 4.5 km were estimated for Chinshan, Kuosheng, and Maanshan NPPs, respectively. We suggest that a radius of 5.0 km is a reasonably conservative value of EPZ for each of the three operating NPPs in Taiwan.

Keywords: Emergency planning zone; Emergency response planning; MACCS2 code

1. Introduction

Since the NUREG-0396 report (Collins et al., 1978) introduced the concept of emergency planning zone (EPZ) as a basis for emergency response preparedness in a severe power reactor accident in 1978, this concept has been accepted all over the world. An EPZ is considered the area where actions should be taken first to protect the general public when a nuclear accident occurs. The corresponding emergency response planning (ERP) in the EPZ, therefore, has to be made in advance to ensure that all necessary resources are available to protect the population from radiation exposure. According to the government regulations revised in March 2005 in Taiwan, the EPZ of a nuclear power plant (NPP) must be designated again and reevaluated every 5 years according to the latest environmental data. Therefore, the EPZs of the three existing NPPs have to be reevaluated.

After the Reactor Safety Study (USNRC, 1975), the consequence modeling of accidental releases of radioactive materials has received widespread attention. A significant number of consequence models have been developed since then. Among these models, the Calculations of Reactor Accident Consequences Code (CRAC) was developed in support of the Reactor Safety Study to calculate the health and economic consequences of accidental releases to the atmosphere. The updated version CRAC2 released in 1982 (Ritchie et al., 1983) incorporated major improvements over the CRAC in terms of weather sequence sampling and emergency response modeling. Our institute (Institute of Nuclear Energy Research, Taiwan) had calculated the EPZs for the Chinshan, Kuosheng, and Maanshan nuclear power plants using the CRAC2 code during 1992

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(Chen et al., 1992; Yin, 1993). This code has some disadvantages; neither is it portable across computer platforms, nor is it sufficiently flexible for evaluation of other parameters in its model. The MELCOR Accident Consequence Code System (MACCS) (Jow et al., 1990) was, therefore, developed by Sandia National Laboratory (SNL) for replacing the CRAC code series. Subsequently, the MACCS2 (Chanin and Young, 1997) development effort was initiated in 1991. The purpose of this code was to develop a generally applicable analysis tool for use in assessing potential accidents at a broad range of reactor and nonreactor nuclear facilities.

Until now, there are three nuclear power plants operating in Taiwan; they are Chinshan, Kuosheng, and Maanshan; the fourth one, Longmen, is under construction. The previous EPZ results for these three operating NPPs obtained using the CRAC2 code were less than 5.0 km radius (3.6, 4.6, and 4.4 km, respectively). Therefore, the government set an EPZ of 5.0 km radius for all three plants. Nowadays, we have to reevaluate the EPZ for each plant using the MACCS2 code with the updated population distribution and meteorological data to fulfill the revised regulations. The effective dose equivalent and thyroid dose together with the individual risk and societal risk for each category of accidents were evaluated and then weighted to achieve the final outcome. By comparing the results with the Protective Action Guide (PAG) and the related criteria, a reasonable conservative EPZ was proposed for each plant.

2. Method

2.1. Model description

The MACCS2 code version 1.12 was used to estimate radiological doses, health effects, and economic consequences that could be resulted from accidental releases of radioactive materials to the atmosphere. It includes three primary modules: ATMOS, EARLY, and CHRONC. The ATMOS module employs a Gaussian plume model with Pasquill–Gifford dispersion parameters to calculate the dispersion and deposition of materials released to the atmosphere as a function of downwind distance. The treated phenomena consist of building wake effects, buoyant plume rise, plume dispersion during transport, wet and dry deposition, and radioactive decay and ingrowth. The weather sampling method is modified from the one used in the CRAC2, which sorts weather sequences into categories and assigns a probability to each category according to the initial conditions (wind speed and stability class) and the occurrence of rainfall (intensity and distance). The outputs of ATMOS are then stored for later use by the EARLY and CHRONC modules.

The EARLY module performs all of the calculations pertaining to the emergency phase. The exposure pathways considered during this phase include cloudshine, groundshine, and resuspension inhalation. Two kinds of doses are calculated: acute dose used for the estimates of early fatalities and injuries, and lifetime dose commitment used for the estimates of associated excess cancer risks resulting from early exposure. The dose calculation for each exposure pathway is spatially variant and is the product of the following quantities: radionuclide concentration, dose conversion factors, duration of exposure, and shielding factors. Evacuation, sheltering, and relocation can be chosen as the protective actions in this module, but none of them was specified because the most conservative results were required.

The CHRONC module performs the calculations pertaining to the intermediate and long-term phases. The associated exposure pathways during the intermediate phase are groundshine and resuspension inhalation, and the pathways during the long-term phase are groundshine as well as food and water ingestion. The CHRONC module also calculates the economic costs of long-term protective actions, such as temporary interdiction and condemnation.

A polar-coordinate grid divided into 16 compass directions with an angle of 22.5° each is centered at the location of the release. The results outputted from the MACCS2 are stored subsequently on the basis of this spatial grid system. Fig. 1 shows the polar coordinate system built in the MACCS2 code and the numbering system associated with 16 compass directions.

2.2. Data source

To evaluate the EPZ of a nuclear power plant using the MACCS2 code, some specific data, such as source terms, meteorological data, and population distribution, are

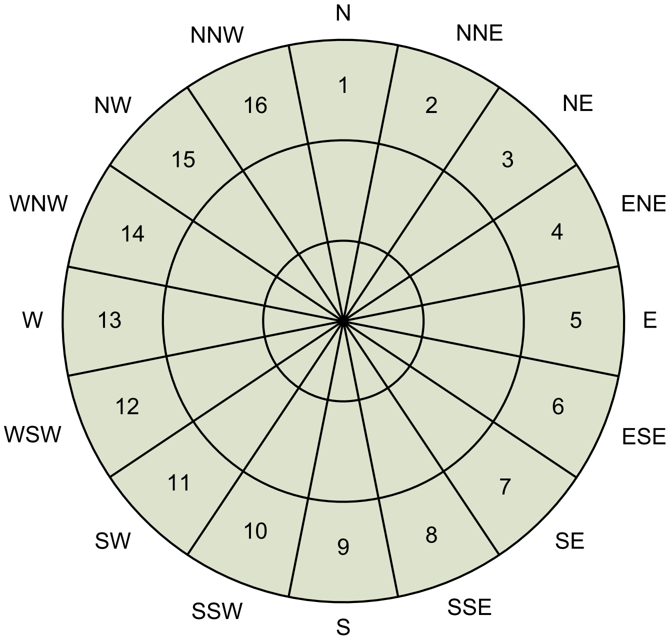

Fig. 1. The polar coordinate and the numbering system associated with 16 compass directions built in the MACCS2 code.

required. The source terms used in this reevaluation are identical to those used in our former evaluation using the CRAC2 in 1992, based on the preliminary design of the facility. For example, Table 1 shows some important parameters associated with 15 release categories for the Chinshan nuclear power plant, Table 2 shows the inventory of 60 radionuclides contained in that facility, and Table 3 shows the release fractions of nine radionuclide groups of the 60 radionuclides for each release category. The hourly meteorological data, including wind direction, velocity,

Table 1
Important parameters associated with 15 release categories for Chinshan NPP

Category	Prob. (year^{-1})	RT (h)	RD (h)	WT (h)	HR (cal/s)	RH (m)
1	2.00×10^{-6}	6.97	48.00	9.54	1.80×10^{7}	240.00
2	7.60×10^{-9}	0.07	0.83	0.70	7.20×10^{6}	29.80
3	6.40×10^{-6}	34.20	1.83	23.70	2.80×10^{7}	29.80
4	7.70×10^{-6}	1.63	0.83	1.25	5.20×10^{7}	29.80
5	1.10×10^{-7}	2.09	1.92	1.92	1.20×10^{6}	29.80
6	3.10×10^{-7}	2.09	1.92	1.92	1.20×10^{6}	29.80
7	4.30×10^{-6}	15.40	0.38	5.50	1.80×10^{7}	29.80
8	5.70×10^{-5}	15.40	0.38	5.50	1.80×10^{7}	29.80
9	2.10×10^{-5}	19.50	0.50	9.54	1.80×10^{7}	29.80
10	4.10×10^{-6}	19.50	0.50	9.54	1.80×10^{7}	29.80
11	1.50×10^{-7}	2.20	0.38	1.55	8.20×10^{6}	240.00
12	1.90×10^{-6}	6.97	0.42	6.21	5.40×10^{6}	240.00
13	3.00×10^{-5}	19.50	48.00	9.54	1.80×10^{7}	29.80
14	1.60×10^{-6}	1.06	1.50	1.32	8.60×10^{5}	29.80
15	1.90×10^{-8}	0.26	1.07	0.67	4.10×10^{6}	29.80

RT = Time between reactor shutdown and radioactive material release, RD = Duration of release, WT = Time between notification of the public and release, HR = Sensible heat rate, RH = Release height.

Table 2
Inventory of 60 radionuclides contained in Chinshan NPP

No.	Isotope	Group	Inventory (Bq)	No.	Isotope	Group	Inventory (Bq)
1	Co-58	6	1.005E+16	31	Te-131m	4	2.509E+17
2	Co-60	6	1.203E+16	32	Te-132	4	2.452E+18
3	Kr-85	1	1.646E+16	33	I-131	2	1.695E+18
4	Kr-85m	1	5.983E+17	34	I-132	2	2.491E+18
5	Kr-87	1	1.088E+18	35	I-133	2	3.558E+18
6	Kr-88	1	1.468E+18	36	I-134	2	3.895E+18
7	Rb-86	3	9.208E+15	37	I-135	2	3.350E+18
8	Sr-89	5	1.822E+18	38	Xe-133	1	3.563E+18
9	Sr-90	5	1.289E+17	39	Xe-135	1	8.468E+17
10	Sr-91	5	2.368E+18	40	Cs-134	3	2.777E+17
11	Sr-92	5	0.000E+00	41	Cs-136	3	7.446E+16
12	Y-90	7	1.381E+17	42	Cs-137	3	1.662E+17
13	Y-91	7	2.223E+18	43	Ba-139	9	0.000E+00
14	Y-92	7	0.000E+00	44	Ba-140	9	3.236E+18
15	Y-93	7	0.000E+00	45	La-140	7	3.302E+18
16	Zr-95	7	2.926E+18	46	La-141	7	0.000E+00
17	Zr-97	7	3.014E+18	47	La-142	7	0.000E+00
18	Nb-95	7	2.770E+18	48	Ce-141	8	2.939E+18
19	Mo-99	6	3.194E+18	49	Ce-143	8	2.860E+18
20	Tc-99m	6	2.755E+18	50	Ce-144	8	1.906E+18
21	Ru-103	6	2.419E+18	51	Pr-143	7	2.799E+18
22	Ru-105	6	1.614E+18	52	Nd-147	7	1.251E+18
23	Ru-106	6	6.583E+17	53	Np-239	8	3.761E+19
24	Rh-105	6	1.206E+18	54	Pu-238	8	2.594E+15
25	Sb-127	4	1.526E+17	55	Pu-239	8	6.573E+14
26	Sb-129	4	5.303E+17	56	Pu-240	8	8.230E+14
27	Te-127	4	1.478E+17	57	Pu-241	8	1.417E+17
28	Te-127m	4	1.990E+16	58	Am-241	7	1.440E+14
29	Te-129	4	4.976E+17	59	Cm-242	7	3.803E+16
30	Te-129m	4	1.307E+17	60	Cm-244	7	2.052E+15

Table 3
Release fractions of nine radionuclide groups for each of the 15 release categories

Category	1 Xe–Kr	2 I–Br	3 Cs–Rb	4 Te–Sb	5 Sr	6 Co–Mo	7 La–Y	8 Ce–Pu	9 Ba
1	9.96×10^{-1}	3.50×10^{-5}	2.30×10^{-5}	7.30×10^{-6}	2.60×10^{-7}	4.40×10^{-10}	3.30×10^{-11}	0.00	4.30×10^{-6}
2	8.50×10^{-1}	8.60×10^{-2}	8.00×10^{-2}	2.80×10^{-2}	5.20×10^{-5}	9.50×10^{-8}	7.70×10^{-9}	0.00	9.70×10^{-4}
3	9.94×10^{-1}	1.80×10^{-2}	1.70×10^{-2}	1.20×10^{-2}	1.77×10^{-1}	1.20×10^{-7}	6.30×10^{-3}	4.20×10^{-3}	9.90×10^{-2}
4	9.96×10^{-1}	1.46×10^{-1}	1.28×10^{-1}	9.38×10^{-1}	2.46×10^{-1}	7.40×10^{-10}	6.50×10^{-3}	8.00×10^{-3}	1.62×10^{-1}
5	9.81×10^{-1}	2.30×10^{-2}	3.30×10^{-2}	2.20×10^{-2}	6.30×10^{-4}	2.10×10^{-7}	3.10×10^{-5}	4.10×10^{-6}	2.20×10^{-3}
6	9.81×10^{-1}	3.97×10^{-1}	3.20×10^{-2}	2.27×10^{-1}	2.58×10^{-1}	1.10×10^{-6}	8.60×10^{-3}	1.20×10^{-2}	1.80×10^{-3}
7	9.29×10^{-1}	4.40×10^{-3}	5.80×10^{-3}	1.20×10^{-3}	2.50×10^{-2}	2.50×10^{-8}	2.70×10^{-3}	8.30×10^{-4}	1.20×10^{-2}
8	9.29×10^{-1}	6.10×10^{-3}	5.90×10^{-3}	7.70×10^{-3}	2.39×10^{-1}	6.90×10^{-8}	8.60×10^{-3}	9.20×10^{-3}	1.23×10^{-1}
9	9.07×10^{-1}	3.50×10^{-5}	2.40×10^{-5}	7.30×10^{-6}	2.60×10^{-4}	4.40×10^{-10}	3.30×10^{-11}	0.00	4.30×10^{-6}
10	9.70×10^{-1}	1.10×10^{-4}	8.50×10^{-5}	1.90×10^{-3}	3.50×10^{-2}	5.50×10^{-9}	3.40×10^{-4}	4.80×10^{-4}	1.80×10^{-2}
11	9.94×10^{-1}	7.10×10^{-3}	4.00×10^{-3}	4.50×10^{-2}	1.82×10^{-1}	3.80×10^{-8}	6.30×10^{-3}	4.50×10^{-3}	1.06×10^{-1}
12	9.94×10^{-1}	1.50×10^{-4}	1.00×10^{-4}	2.50×10^{-3}	4.00×10^{-3}	2.30×10^{-8}	8.50×10^{-5}	7.40×10^{-5}	2.40×10^{-3}
13	1.99×10^{-3}	7.10×10^{-8}	4.70×10^{-8}	1.50×10^{-8}	5.10×10^{-10}	8.80×10^{-13}	6.60×10^{-14}	0.00	8.70×10^{-9}
14	9.78×10^{-1}	8.40×10^{-2}	8.30×10^{-2}	1.12×10^{-1}	3.13×10^{-1}	8.70×10^{-8}	1.00×10^{-2}	1.70×10^{-2}	2.00×10^{-2}
15	9.99×10^{-1}	9.46×10^{-1}	9.56×10^{-1}	2.78×10^{-1}	3.39×10^{-1}	6.00×10^{-7}	8.20×10^{-3}	1.30×10^{-2}	2.25×10^{-1}

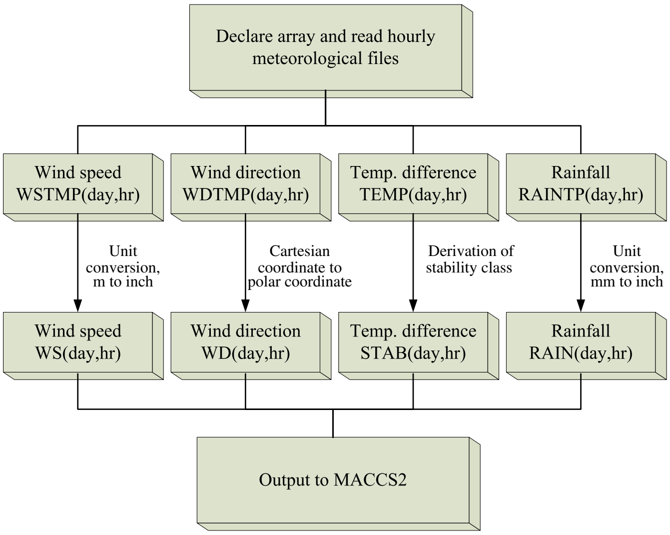

Fig. 2. The flowchart of the METRAN preprocessor.

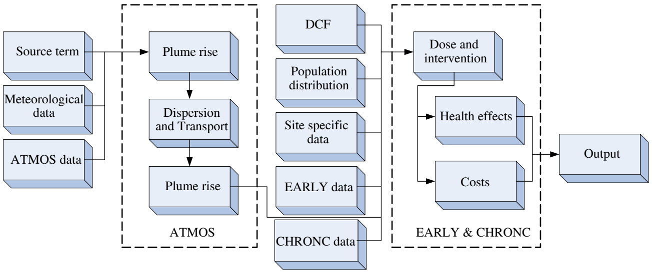

Fig. 3. The diagram of the MACCS2 code.

and stability, were collected at the weather towers 10 m from the ground inside each plant during 2003. A preprocessor, the Meteorological Transformation (METRAN) code, was developed to transform the 8760 hourly records into the formatted input file of the MACCS2 code. Fig. 2 shows the flowchart of the METRAN preprocessor. Moreover, the population distribution data were obtained from the Household Registration Office and rearranged to 16 compass sectors of 0.5 km width.

Dose conversion factors (DCFs) of the 60 radionuclides considered important for NPP releases are required as input data for the MACCS2 code. For the exposure pathways of cloudshine and groundshine, the DCFs were extracted from the DOE database (ICRP, 1979), and for the pathways of inhalation and ingestion the DCFs were adopted from the Federal Guidance Reports 11 and 12 (Eckerman et al., 1988; Eckerman and Ryman, 1993). Fig. 3 shows the diagram of the MACCS2 code with corresponding data files required as input.

2.3. Safety criteria

The MACCS2 code itself is only a consequence modeling code. For the purpose of EPZ calculation, some safety criteria should be provided as a reference to achieve conservative and reasonable results. According to the regulations, the following four guidelines were proposed as basis:

- The risk of prompt fatality to an individual or to the population in the vicinity of a NPP that might result from reactor accidents should not exceed 0.1% of the sum of prompt fatality risks resulting from all other causes.
- The risk of cancer fatality to an individual or to the population in the vicinity of a NPP that might result from reactor accidents should not exceed 0.1% of the sum of cancer fatality risks resulting from all other causes.
- The anticipated whole body dose and thyroid dose beyond the EPZ should not exceed the PAG levels in

the design base accidents and most of the core-melt accidents.

- There is no prompt fatality beyond the EPZ even if the most severe accident occurs.

According to these guidelines and the prompt and cancer fatality data collected from other accidents in Taiwan, the safety criteria for calculating the boundary of an EPZ can be derived as follows:

- The individual risk is less than 6.41×10^{-7} per year.
- The societal risk is less than 2.18×10^{-6} per year.
- The probability of the whole body dose exceeding 0.1 Sv is less than 3.0×10^{-5} per year.
- The probability of the thyroid dose exceeding 1.0 Sv is less than 3.0×10^{-5} per year.
- The probability of the whole body dose exceeding 2.0 Sv (prompt fatality dose) is less than 3.0×10^{-6} per year.

By comparing the consequences of individual risk, societal risk, whole body dose, and thyroid dose versus distance to the corresponding safety criteria listed above, we can then propose a reasonably conservative suggestion for the EPZ of each of the three NPPs.

3. Results and discussion

Using the MACCS2 code, we estimated the radiological doses and the associated risks that could result from each postulated accidental release category. The consequences were then summed up by the probability weighting factor of each category. The complementary cumulative distribution function (CCDF) was used to analyze the probability that could exceed the safety criteria. Figs. 4–6 plot the CCDFs of whole body dose of 0.1 Sv, whole body dose of 2.0 Sv, and thyroid dose of 1.0 Sv versus distance for the three NPPs, respectively. The results showed that the whole body dose of 2.0 Sv was the most critical dose criterion and hence should be selected for the conservative purpose. The resulted EPZs for the Chinshan, Kuosheng, and Maanshan nuclear power plants with respect to dose criteria were less than 1.5, 1.5, and 3.5 km, respectively. Compared with the

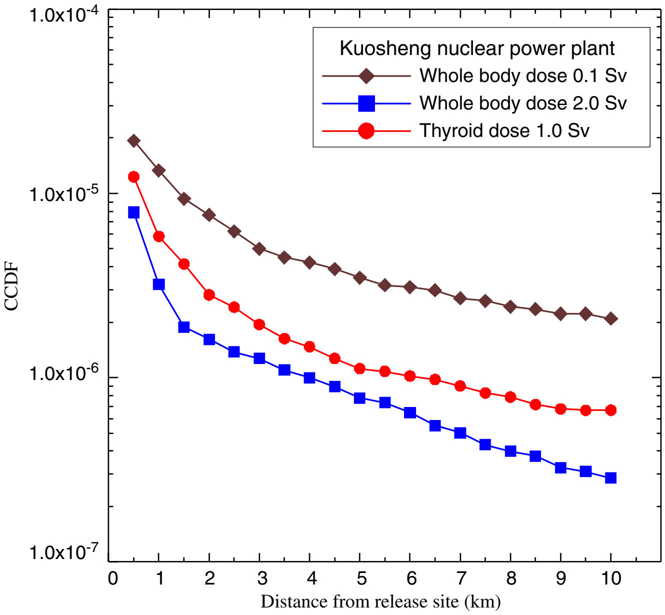

Fig. 5. The CCDF of whole body dose of 0.1 Sv, whole body dose of 2.0 Sv, and thyroid dose of 1.0 Sv versus distance for the Kuosheng NPP.

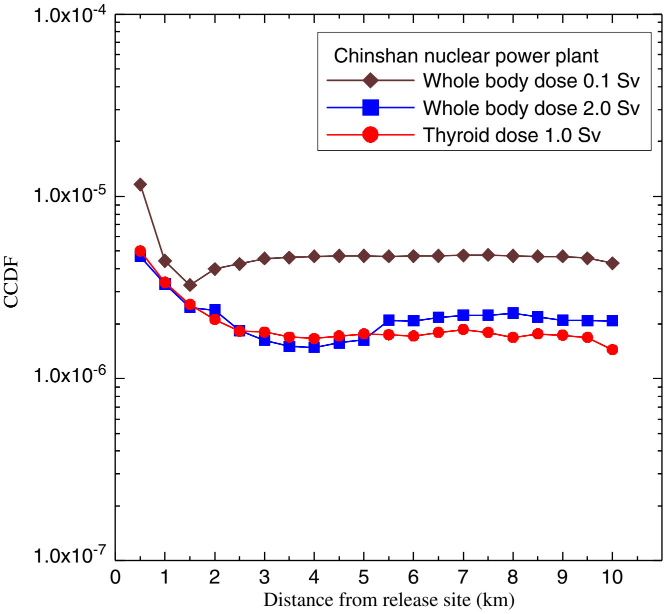

Fig. 4. The CCDF of whole body dose of 0.1 Sv, whole body dose of 2.0 Sv, and thyroid dose of 1.0 Sv versus distance for the Chinshan NPP.

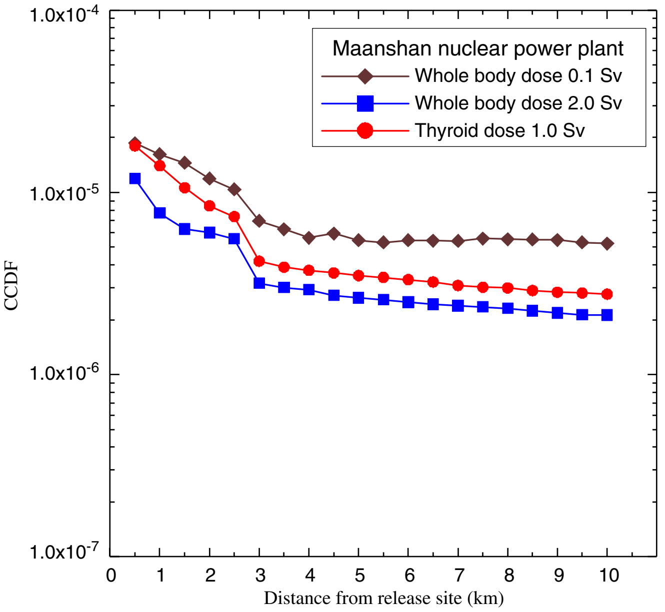

Fig. 6. The CCDF of whole body dose of 0.1 Sv, whole body dose of 2.0 Sv, and thyroid dose of 1.0 Sv versus distance for the Maanshan NPP.

results of Kuosheng and Maanshan NPPs, the CCDF of Chinshan tended to decrease first and then increase. This is because the Chinshan NPP has two release paths with different heights of 29.8 and 240 m, which are indicated as RH in Table 1.

Figs. 7–9 show the individual risk and societal risk for these three NPPs. From the aspect of risks, the estimated EPZs for the Chinshan and Kuosheng NPPs were equal or less than the results estimated by dose criteria. The EPZ for the Maanshan NPP estimated by societal risk, however, was larger than that calculated by dose criteria, and consequently the result of 4.5 km was chosen for the conservative reason. Again, the risk pattern for the Chinshan NPP shown in Fig. 7 had a different trend compared with other NPPs due to the two release paths, high and low chimneys.

Table 4 lists the EPZs calculated using the MACCS2 code in this study and using the CRAC2 estimation in 1992. The estimates with respect to dose criteria were generally less than those calculated by the CRAC2 code. This is probably because the model used in the ATMOS

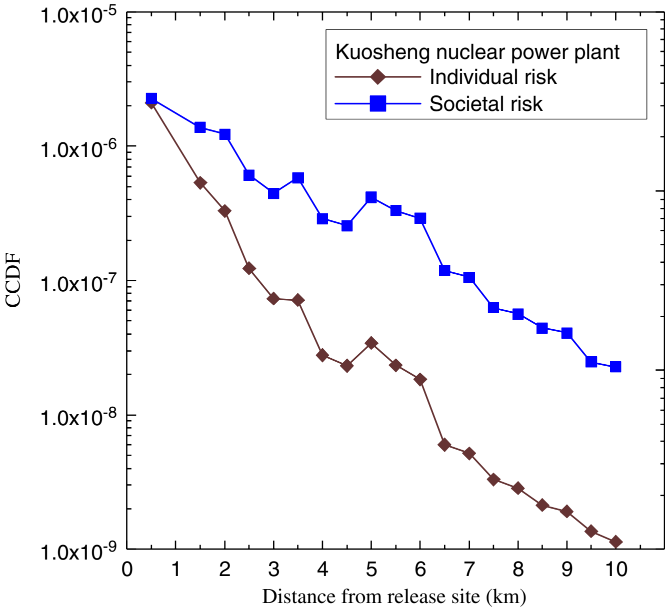

Fig. 8. The individual risk and societal risk estimated for the Kuosheng NPP.

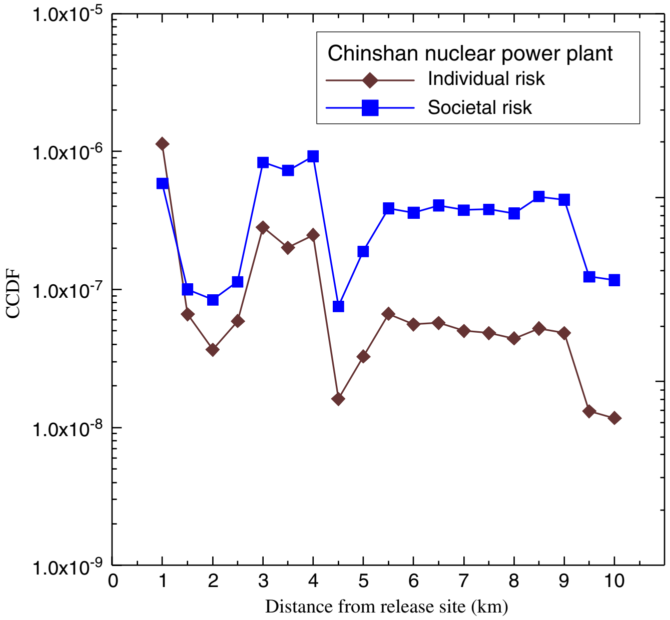

Fig. 7. The individual risk and societal risk estimated for the Chinshan NPP.

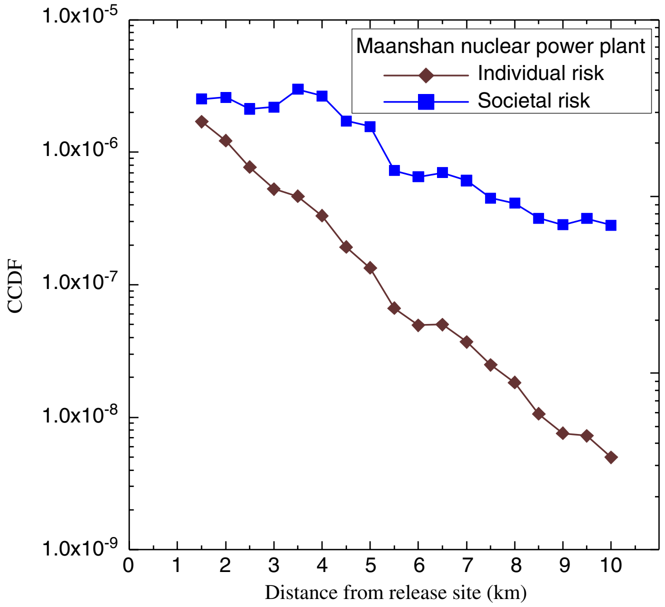

Fig. 9. The individual risk and societal risk estimated for the Maanshan NPP.

Table 4
The comparison of EPZs calculated by using MACCS2 and by using CRAC2

Safety criteria	Chinshan		Kuosheng		Maanshan	
	CRAC2 (km)	MACCS2 (km)	CRAC2 (km)	MACCS2 (km)	CRAC2 (km)	MACCS2 (km)
P (whole body dose > 0.1 Sv) < 3.0×10^{-5}	1.5	0.5	4.6	0.5	4.4	0.5
P (whole body dose > 2.0 Sv) < 3.0×10^{-6}	3.6	1.5	3.6	1.5	4.1	3.5
P (thyroid dose > 1.0 Sv) < 3.0×10^{-5}	0.5	0.5	0.5	0.5	3.5	0.5
Societal risk	2.0	1.5	1.0	1.5	1.5	3.0
Individual risk	1.0	1.0	1.0	1.5	1.0	4.5

module includes the dispersion of the plume in the horizontal (crosswind) direction, which is not considered by the CRAC2 code. Note that the individual risk and societal risk of the Maanshan NPP were higher than those estimated in 1992. The main reason for this difference is the population distribution within 10 km in the vicinity of the plant. By definition, the individual risk at a given radius *R* from the plant is the ratio of acute fatality to total population within *R*, and the societal risk is the ratio of latent cancer fatality to total population within *R*. Compared with the data collected from the Household Registration Office in 1992 and in 2003, the population drops from 35,178 to 11,057 within a radius of 10 km. Therefore, the corresponding risks and EPZ tend to increase when the total population decreases. Following these results, we conclude that a radius of 5.0 km is still a conservative value of EPZ for each of the three operating NPPs in Taiwan.

4. Conclusion

This study has proposed using the MACCS2 code to reevaluate the EPZs for the three operating NPPs, Chinshan, Kuosheng, and Maanshan in Taiwan. The latest meteorological data and population distribution collected in 2003 were used to ensure the accuracy of consequence modeling. According to government regulations, five safety criteria were derived from four guidelines and the updated individual and societal risks. The estimates suggest that 5.0 km radius is still a conservative value for the EPZ of the three NPPs in Taiwan, and their corresponding emergency response plans are still practicable.

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