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Adaptation of COSYMA and assessment of accident consequences for Daya Bay nuclear power plant in China

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Abstract

The program package COSYMA for assessing the radiological and economic consequences of nuclear accidents, developed with the support of the European Commission, was applied to investigate the health effects and risks from accidental releases of radioactive material from the Daya Bay nuclear power plant. Population distribution data in the range of 80 km around the site and hourly meteorological data for the year 1985 representative of accident consequence analysis were used. The results showed that early effects are more important at distances closer to the site, while the number of fatal cancers is closely related to the population density and the late effects are still important at distances larger than 50 km from the site. The mean annual expected values for early mortality and late mortality estimated for the population within a circle of 80 km around the Daya Bay nuclear power plant are 4.5×10^{-3} and $0.1\ yr^{-1}$, respectively.

Keywords: COSYMA; Consequence analysis; Nuclear accident; Health effects

1. Introduction

Since the commissioning of the Daya Bay Nuclear Power Plant in 1994, additional new nuclear power plants in Guangdong are under construction or are being planned,

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as China is gradually increasing its reliance on nuclear power to meet its future electricity demand. Due to the proximity of these plants, nuclear accident consequence analysis is needed to assess the impact of potential nuclear accidents on the public health of the nearby inhabitants.

COSYMA (CODE SYSTEM from MARIA) is a computer program package widely used in Europe for assessing the off-site radiological and economical consequences of accidental atmospheric releases of radioactive material. Thus, we decided to use this code for probabilistic accident consequence analysis after adaptation and customization to the local environment around Hong Kong.

COSYMA was developed jointly by Forschungszentrum Karlsruhe, Germany, and NRPB (National Radiological Protection Board, UK) as a part of the European Commission's MARIA project (Methods for Assessing the Radiological Impact of Accidents) during the late 1980s. Both the 95/1 mainframe version and the PC version of COSYMA were purchased by the City University of Hong Kong and installed on their computer system. An agreement on the use of software was also signed with the European Commission on this activity. The delivery of the source code for the PC COSYMA was agreed by the European Commission with the following understandings; (1) this activity is supported by Forschungszentrum Karlsruhe, (2) the work is done in close cooperation with colleagues from Forschungszentrum Karlsruhe and the Tsinghua University, Beijing, China, and (3) a special version of COSYMA for China/Hong Kong will be created by adaptation and customisation of models (in particular the food model) and databases for the specific situation of Hong Kong. In connection with the above, the NRPB also expressed their preparedness to modify the user interface as long as this requires only minor changes and effort.

The investigations presented in this paper concentrated on the estimation of the health effects and risks from accidental releases of radioactive material from the Daya Bay nuclear power plant in the population around the site. Therefore, only the health effects models implemented in COSYMA are described in detail. The COSYMA code used in the presented work was PC COSYMA (Version 2.01) (Jones et al., 1996) and all results presented in this paper refer to this version.

2. Health effects models in COSYMA

The description in this section is mainly extracted from the report by Jones et al. (1996) unless otherwise stated. The health effects were separated into deterministic effects and stochastic effects, which were referred to as early effects and late effects, respectively, in the PC COSYMA code.

2.1. Early effects

The early morbidity health effects considered in PC COSYMA included lung function impairment, hypothyroidism, skin burns, cataracts and mental retardation, while the early mortality health effects included pulmonary syndrome, haematopoietic syndrome, gastrointestinal syndrome, pre- and neonatal death and death from skin burns. In PC COSYMA, the risk R of early effects to an individual person was calculated using the hazard function H as

$$R = 1 - e^{-H}, \tag{1}$$

where

$$H = \ln 2 \times \left(\frac{D}{D_{50}}\right)^{S}. \tag{2}$$

D (Gy) is the dose received by a certain organ in the appropriate period, D_{50} (Gy) is the dose causing the effect in 50% of the exposed population, and S is the shape parameter characterizing the slope of the dose-risk relationship.

For the same dose, a higher dose rate is more effective in causing early health effects. To reflect this, COSYMA divided the irradiation period into several periods, and replaced the ratio (D/D_{50}) by

$$\frac{D}{D_{50}} = \sum_{i} \frac{D^{i}}{D_{50}^{i}}, \tag{3}$$

where i specified the ith period of time, and

$$D_{50}^{i} = D_{\infty} + \frac{D_0}{X^{i}}, \tag{4}$$

where X^i is the average dose rate in the ith period, D_∞ the value of D_{50} at high dose rate and D_0 is a parameter (Evans, Moeller & Cooper, 1990).

PC COSYMA did not specify the threshold dose for individual early effects. Instead, when the value of R calculated using (1)–(4) was less than 1% (could be reset by the user), the corresponding dose was assumed to be below the threshold and R was set to zero.

2.2. Late effects

The late health effects considered in PC COSYMA included 11 cancers and the hereditary effects. The cancers were leukaemia, and cancers of the bone surface, breast, lung, stomach, colon, liver, pancreas, thyroid, skin and the remainder. Within these, the absolute risk (or additive model) was used for leukaemia and bone surface cancer while the relative risk (or multiplicative model) was used for the rest. Additive risk assumes that the excess mortality from cancer caused by a given dose of radiation is expressed as a constant number of extra cancer deaths per year, irrespective of the underlying spontaneous rate in the population; multiplicative risk assumes that excess mortality is expressed as a constant percentage of the underlying rate. The incidence of late effects was calculated in PC COSYMA using no-threshold linear dose-risk relationships.

As an example, the risk of a certain late health effect caused by external irradiation from material deposited on the ground could simply be expressed as

$$r = SF \times \sum_{k} (AG(k) \times ARC(k)), \tag{5}$$

where k specifies a particular radionuclide, SF is the mean shielding factor for external irradiation from materials deposited on the ground, $AG(k)$ the radionuclide concentration deposited on the ground (Bq m^{-2}) and $ARC(k)$ is the so-called "activity risk coefficient" ((Bq $m^{-2})^{-1}$). The risks of other late health effects caused by other exposure pathways were calculated with formulas similar to Eq. (5). There are at present two sets of dose risk coefficients. The first set was derived by Forschungszentrums für Umwelt und Gesundheit (GSF) (Paretzke, Stather & Muirhead, 1991) and the other was given in ICRP-60 (ICRP, 1991). In PC COSYMA used in these investigations, the ICRP set of dose risk coefficients was employed.

3. Basic input parameters

The surrounding area of the Daya Bay nuclear power plant with a radius of 80 km was subdivided into 13 concentric stripes and 16 sectors of 22.5°, with the plant located at the center of the concentric circles. The distances of the outer arcs of the concentric stripes from the center were 1, 2, 3, 4, 5, 10, 20 30, 40, 50, 60, 70 and 80 km, respectively. In numbering the sectors, the angles were calculated in clockwise sense with the north direction in the middle of the 1st sector. The concentric stripes intersected with the sectors to form a geographical grid as shown in Fig. 1.

The population distribution around the nuclear power plant was calculated for this grid from the existing population data. For Hong Kong, the 1996 census data from the Statistics Department of the Hong Kong Government were used. For regions

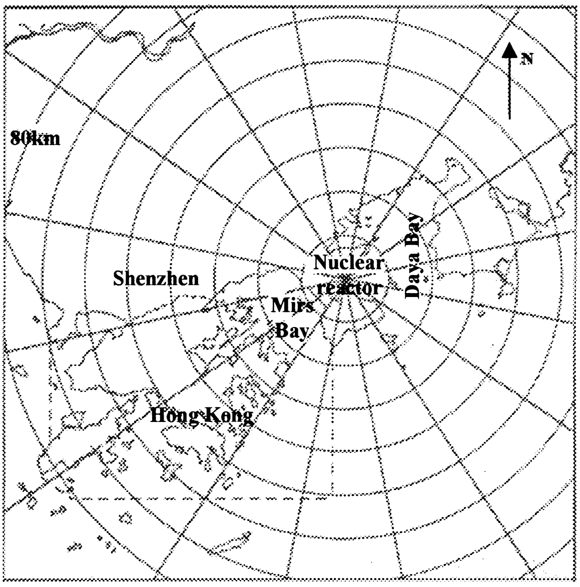

Fig. 1. Geographical grids assigned to the surrounding area of the Daya Bay nuclear power plant with a radius of 80 km.

outside Hong Kong, the population data were computed from the 1992 data (Tan, 1997) by assuming 10% annual increases in the population, which might have led to an overestimation of the population outside Hong Kong and thus of the collective risks.

The atmospheric conditions are a critical factor in determining the spatial and temporal distributions of the dispersed radionuclides. The hourly synoptic data for the whole year of 1985 measured near the nuclear power plant were employed and formatted as required by PC COSYMA (Tan, 1997). Basically, there were 8760 weather sequences. Stratified sampling (Jones et al., 1996) was used to carry out probabilistic calculations. Thereby, sequences likely to give similar consequences were combined into groups (COSYMA allowed a maximum of 144 groups). A probability was calculated for each group according to the ratio of the number of sequences in the group to the total number of 8760 sequences. A sequence was then randomly selected from each group as representative, each bearing the corresponding probability of their group. By summing the consequences of all group representatives weighted by their probabilities, the annual average consequences could be obtained.

In the present work, a total of 120 groups of conditions were identified. Among these, 5 groups were extremely rare and did not have the corresponding sequences. Therefore, 115 groups were actually used in the calculations.

The use of meteorological data measured at the Daya Bay nuclear power plant for estimating consequences within the whole 80 km area might not be fully appropriate and thus might cause some uncertainties. For example, the annual rainfall in Hong Kong is larger than that in Shenzhen by 15%. The Daya Bay nuclear power plant was not built before 1986, so the ground surface around the Da Kang meteorological station was less complex and relatively flat, i.e. the distributions of wind speed and wind direction were similar to those at other stations such as Hong Kong, Wagnan Island and Shenzhen. As regards the medium distances (or areas), the meteorological data between September 1984 and August 1986 were more representative. Therefore, the choice of the meteorological data for the whole year of 1985 for our calculations should be the most appropriate. For more information, the readers can refer to Chen (1989) and Ruming and Zhongmin (1986).

The segmented plume model MUSEMET incorporated in COSYMA (Panitz, Matzerath & Päsler-Sauer, 1989) was employed for the calculations; it is an improved linear Gaussian plume model, which assumes that the meteorological conditions (wind direction, wind speed, dispersion category and rain intensity) are known and constant in subsequent time intervals of 1 h. It uses the plume information at the end of the kth time interval as the point source for calculations in the $(k+1)$th time interval under new meteorological conditions. Reduction of the radioactive material due to dry and wet deposition is considered during the dispersion process, which is referred to as the source depleted model (Hanna, Briggs & Hosker, 1982).

The wind speed at a height Z was calculated using $u(Z) = u_o(Z/Z_{ref})^p$ where Z_{ref} was the measurement height of the wind speed taken to be 10 m, u_o was the wind speed at Z_{ref} and p was the wind profile index. A roughness length $Z_o \geqslant 1$ m was assumed in the calculations, so the p values corresponded to those of a rough terrain (Panitz et al., 1989) as shown in Table 1.

Table 1
The wind profile indices p for different dispersion categories

Dispersion category	A	B	C	D	E	F
p	0.07	0.13	0.21	0.34	0.44	0.44

Table 2
The coefficient a and the index b for the washout coefficient λ (s^{-1}) ($\lambda = a \cdot i^b$) where i is the rainfall intensity (mm hr^{-1}) (adopted from Schwarz (1986))

Category	Aerosol	Elemental iodine	Organic iodine
a	8×10^{-5}	8×10^{-5}	8×10^{-7}
b	0.8	0.6	0.6

The dry deposition velocities were adopted from Shi and Wei (1994) as follows; aerosols: 0.001 m s^{-1}; elemental iodine: 0.01 m s^{-1}; organic iodine: 5×10^{-4} m s^{-1}. The washout coefficient λ (s^{-1}) describes the wet deposition velocity and is calculated from $\lambda = a \cdot i^b$ where i is the rainfall intensity in mm h^{-1}. The coefficient a and the index b were adopted from Schwarz (1986) as shown in Table 2.

The source terms of nuclear accidents also affect significantly the assessment of accident consequences. The source terms include the amount and form of radionuclides released into the environment, start time and duration of the release, release energy rate, release height and temporal change of release condition, etc. Since the severe accident probabilistic assessments for the Daya Bay nuclear reactor (which was a French design) have not yet provided the required data, the WASH-1400 data (Rasmussen, 1975) for pressurized water type reactors as shown in Table 3 were used. The released radionuclides were separated into 7 groups, and organic iodine and elemental iodine were assigned to the same group. The release fraction of iodine was based on that of elemental iodine, which inevitably overestimated the release of organic iodine except in category PWR6. Nevertheless, this could be remedied by adjusting the fraction of organic iodine within all types of iodine, which was taken to be 1%. The activities of radionuclides in a 290 MW pressurized water reactor at the end of a fuel change cycle were assumed to be the radioactive inventory of the Daya Bay nuclear power plant.

The source term data of WASH-1400 were obtained from probabilistic safety analyses based on the operation experience of the PWRs in USA. The source terms were more conservative and the calculated doses relatively large. Theoretically, the source terms for the PWR1 to PWR9 accidents were not aimed at being source terms for determining the radius of the contingency planning areas. According to the French approach, the source terms S1, S2 and S3 should be used, with S1 similar to but slightly less serious than PWR1 (Liu & Zhang, 1991; Shi & Yang, 1992). The French approach also uses S3 as the source term to determine the size of the contingency planning area. The released fractions of various radionuclides in the S3 source term

Table 3
Source terms for different categories of accidents. (After Rasmussen, 1975)

	Annual probability	Time release starts (h)	Duration (h)	Release height (m)	Release Energy rate (MW)	Release fractions						
						Group 1 Xe–Kr	Group 2 I[b]	Group 3 Cs–Rb	Group 4 Te–Sb	Group 5 Ba–Sr	Group 6 Ru[c]	Group 7 La[d]
PWR1	9×10^{-7}[a]	2.5	0.5	25	5.86; 152	0.9	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR2	8×10^{-6}	2.5	0.5	0	49.81	0.9	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR3	4×10^{-6}	5.0	1.5	0	1.758	0.8	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR4	5×10^{-7}	2.0	3.0	0	0.293	0.6	0.09	0.04	0.03	5×10^{-3}	3×10^{-3}	4×10^{-4}
PWR5	7×10^{-7}	2.0	4.0	0	0.088	0.3	0.03	9×10^{-3}	5×10^{-3}	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR6	6×10^{-6}	12.0	10.0	0	0	0.3	8×10^{-4}	8×10^{-4}	1×10^{-3}	9×10^{-5}	7×10^{-5}	1×10^{-5}
PWR7	4×10^{-5}	10.0	10.0	0	0	6×10^{-3}	2×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-6}	1×10^{-6}	2×10^{-7}
PWR8	4×10^{-5}	0.5	0.5	0	0	2×10^{-3}	1×10^{-4}	5×10^{-4}	1×10^{-6}	1×10^{-8}	0	0
PWR9	4×10^{-4}	0.5	0.5	0	0	3×10^{-6}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0

[a] PWR1 was separated in to PWR1A and PWR1B. The annual probability and released energy were $4\times10^{-7}\ yr^{-1}$ and 5.86 MW for PWR1A, respectively, and $5\times10^{-7}\ yr^{-1}$ and 152 MW for PWR1B, respectively.

[b] I only refers to elemental iodine, since the release fraction of iodine put into COSYMA was based on the elemental iodine.

[c] Including Mo, Rh, Tc, Co, Ru.

[d] Including Nd, Y, Ce, Pr, La, Nb, Am, Cm, Pu, Np, Zr.

are: Xe–Kr: 0.75; I: 0.08; Cs–Rb: 6×10^{-4}; Ba–Sr: 6×10^{-5}; Ru:0; La: 0. When compared to the source terms of WASH-1400, S3 is approximately equivalent to PWR4 or PWR5. The objective of this study was to estimate the health hazards under hypothetical accidents at the Daya Bay nuclear power plant, but not to decide on the size of the contingency planning area.

The stack height was taken to be 52.3 m, the height and width of the reactor building were set at 57 and 39 m, respectively. Consideration of the wake was necessary. The calculations assumed no countermeasures. The other input parameters were based on those from Tan (1997) or default values in the COSYMA code. Other adopted parameters included the following: fraction of contaminated skin: 10%; integration time for late skin dose: 10,000 d; integration time for early individual dose: 7 d; half life of radioactivity deposited on skin: 30 d; radioactivity concentration deposited on skin is equal to that deposited on the ground.

4. Results and discussion

The effects of atmospheric sequences on the health effects under category PWR1 type A (referred to as PWR1A in the following) are discussed first. Within the 115 selected weather sequences, two were most significant for the early health effects for Hong Kong inhabitants, leading to 20,560 and 18,350 early mortalities, respectively, and constituting more than 99% of the total number of the early mortalities for all the sequences combined. However, the annual probabilities of these two sequences were only $9.24\times10^{-4}\,yr^{-1}$ and $1.5\times10^{-3}\,yr^{-1}$. Considering the annual probability of PWR1A of $4\times10^{-7}\,yr^{-1}$, the expected number of early mortalities among Hong Kong inhabitants from PWR1A accidents was only $1.88\times10^{-5}\,yr^{-1}$. The two most important sequences for late mortalitities in Hong Kong were different from those identified above. They constituted 79% of the total number of late mortalities for all the sequences combined. Considering their probabilities of $2.54\times10^{-3}\,yr^{-1}$ and $1.96\times10^{-2}\,yr^{-1}$, and taking into account the annual probability of PWR1A, the expected number of late mortalities among Hong Kong inhabitants from PWR1A accidents was $4.86\times10^{-5}\,yr^{-1}$, which was higher than that of early mortalities.

Fig. 2 shows the variation with distance up to 80 km of the numbers of early morbidity, early mortality and fatal cancers in the population for a PWR1A accident at the Daya Bay nuclear power plant. It can be seen that the variations for early and late effects were different. Most early effects, in particular early mortality, occurred in regions relatively close to the site, and rarely occurred beyond 50 km. On the other hand, the late mortality rate was still high at relatively large distances, and the maximum reached 1.328×10^{4} people in the range of 40–50 km. The difference could be explained as follows. Threshold values existed for early effects which could not be exceeded at large distances. Late effects, however, were calculated assuming linear dose risk relationships without thresholds and there were finite probabilities of occurrence of late effects even at large distances although the dose values were small. The number of cancer incidences were obtained from the product of the probabilities and the population in a region, so the number was closely related to the population density. The population was 4,011,453 in the range of 40–50 km, which included the majority of the densely populated Hong Kong Island and the Kowloon Peninsula, and the late mortality reached 1.082×10^4 in this range.

Figs. 3 and 4 show the complementary cumulative frequency distributions (CCFDs) of early morbidity and early mortality, respectively. Each point on a CCFD curve represents the probability of having results larger than or equal to a consequence value (in the present case, the number of health effects). It can be seen that the skin effects dominated the early effects, and in particular the early morbidity effects. The early morbidity effects in descending importance were skin effects, cataracts, hypothyroidism and lung function impairment, and the early mortality effects in descending importance were death from skin burns, haematopoietic syndrome, pulmonary syndrome and gastrointestinal syndrome.

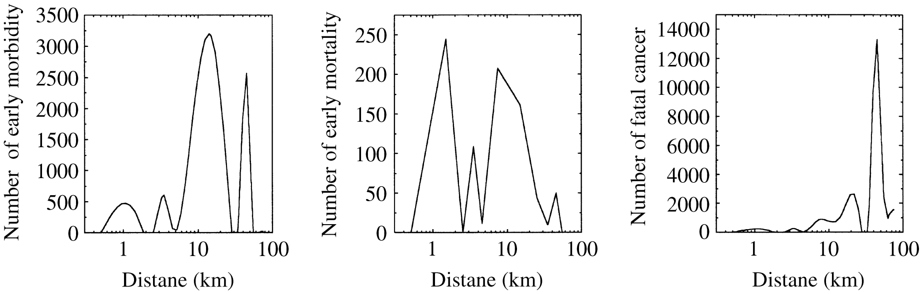

Fig. 2. Variation of the numbers (yr^{-1}) of early morbidity, early mortality and fatal cancer with distance in the population within a circle of 80 km for a PWR1A accident.

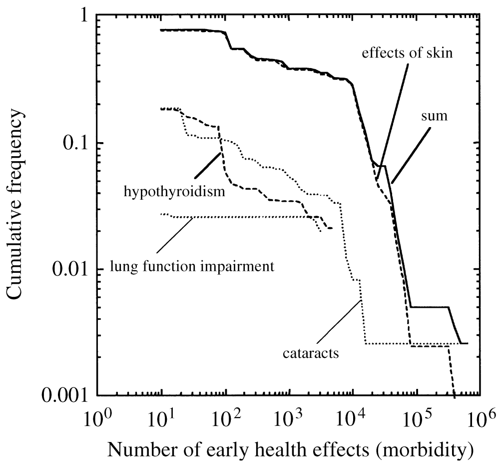

Fig. 3. Complementary cumulative frequency distribution (CCFD) (yr^{-1}) of early morbidity in the population within a circle of 80 km for a PWR1A accident. The CCFD curve represents the probability of health effects larger than or equal to the corresponding number on the abscissa.

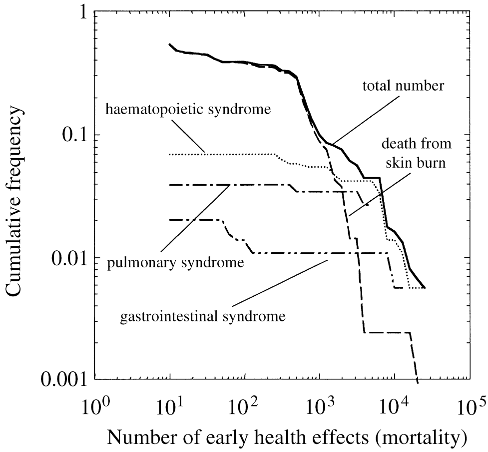

Fig. 4. CCFD for early mortality (yr^{-1}).

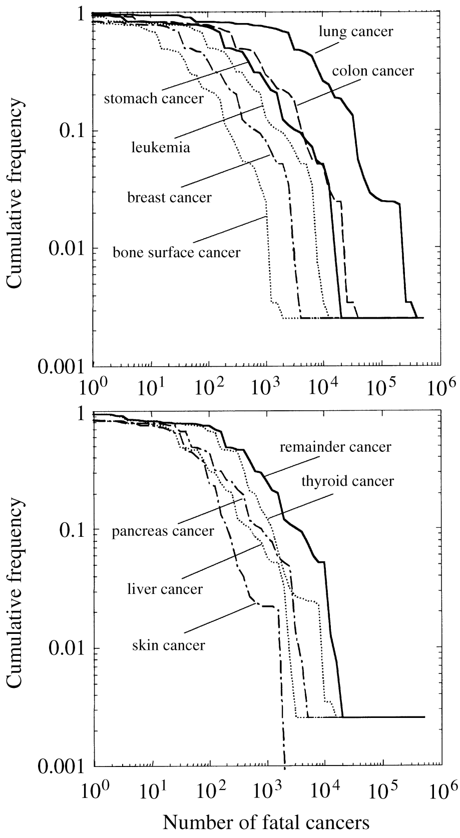

Fig. 5. Annual frequency (yr^{-1}) of different late fatal cancers for the PWR1A release.

Fig. 5 gives the annual frequency of different late fatal cancers under the PWR1A release. The probability of lung cancer was the largest, while those for skin cancer and bone surface cancer were the smallest. In other words, skin effects were very important for deterministic effects but much less important for stochastic effects.

Figs. 6–8 compare the CCFDs of the health effects in the population within 80 km of the Daya Bay nuclear power plant (total population) and Hong Kong inhabitants for all categories of accidents (PWR1 to PWR9): Fig. 6 shows the CCFD for early morbidity, Fig. 7 for early mortality (excluding prenatal deaths) and Fig. 8 for late fatal cancers (excluding hereditary effects). It can be observed that the early effects for Hong Kong inhabitants were relatively unimportant when compared

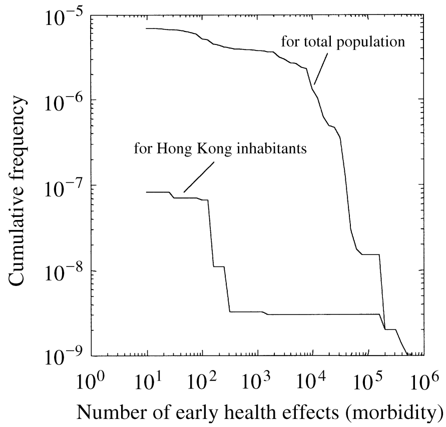

Fig. 6. CCFD for early morbidity (yr^{-1}) in the population within 80 km of the Daya Bay nuclear reactor for all categories of accidents (PWR1 ~ PWR9).

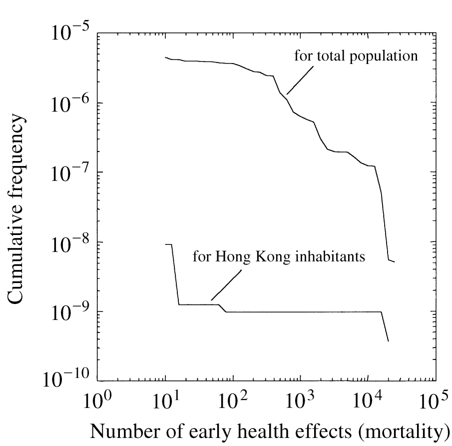

Fig. 7. CCFD for early mortality (excluding prenatal deaths).

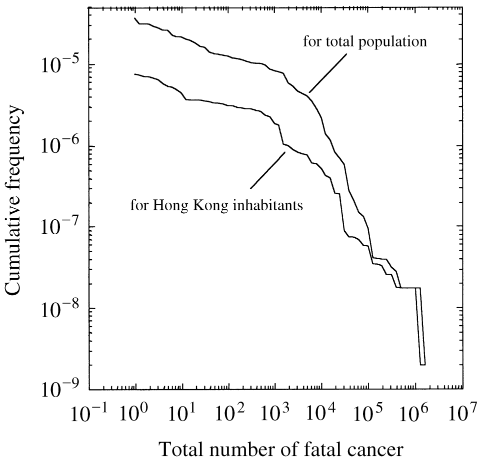

Fig. 8. CCFD for late fatal cancers (excluding hereditary effects).

to those for the total population; this could be explained by the large distances of Hong Kong inhabitants from the site (even the shortest distance was more than 10 km). However, the late effects for Hong Kong inhabitants become much more important, which could be explained by the very high density of the Hong Kong population although the Hong Kong population was mainly confined to the 12th and 13th sectors. From these CCFD curves, the annual expected values for early morbidity, early mortality and late mortality were obtained as 0.046, 4.5×10^{-3} and $0.10\ \text{yr}^{-1}$, respectively, for the total population within 80 km of the Daya Bay nuclear reactor, and 1.18×10^{-3}, 1.92×10^{-5} and $4.73 \times 10^{-2}\ \text{yr}^{-1}$, respectively, for the Hong Kong population. These figures were lower than the baseline cancer incidences and deaths from traffic accidents by 3–5 orders of magnitude.

All the above calculations assumed no countermeasures. If countermeasures such as sheltering or distribution of stable iodine tablets were enforced, the early individual dose and mortality risk could be considerably reduced.

5. Conclusions

Probabilistic accident consequence assessments performed for a PWR1A accident at the Daya Bay nuclear power plant clearly showed that early health effects are more important in the vicinity of the site. The number of fatal cancers is closely related to the population density; they are still important at distances larger than 50 km from the site. The annual expected values for early mortality and late mortality were obtained as 4.5×10^{-3} and $0.10\ \text{yr}^{-1}$, respectively, for the population within a circle of 80 km around the site, which is significantly smaller than the baseline mortality risk.

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