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《Original》

A Risk Evaluation Model Using On-Site Meteorological Data

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Abstract

A model is considered in order to evaluate the potential risk from a nuclear facility directly combining the on-site meteorological data. The model is utilized to evaluate the environmental consequences from the routine releases during normal plant operation as well as following postulated accidental releases. The doses to individual and risks to the population-at-large are also analyzed in conjunction with design of rad-waste management and safety systems. It is observed that the conventional analysis, which is done in two separate unaffiliated phases of releases and atmospheric dispersion tends to result in unnecessary over-design of the systems because of high resultant doses calculated by multiplication of two extreme values.

요 약

원자력 시설에서 방사선 방출에 의한 주거인구에 미치는 영향을 분석평가하는데 부지의 기상 조건을 직접 관련시키는 방법을 고려해 보았다. 이 방법은 정상가동시에 누출되는 방사능과 가상사고시의 누출로 부터 자연환경에 주는 영향을 보다 현실에 맞게 평가하는데 사용될 수 있다. 개개인이 받을 방사선량과 전체인구가 받을 피폭선량을 보다 논리적으로 계산함으로써 설비 설계에 반영하여 누출량과 대기내의 확산을 별도로 분석하여 평가하는 재래식 방법으로 부터 초래되는 필요 이상의 안전설계를 지양할 수 있다.

1. Introduction

Conventional analysis of the environmental impacts due to releases of radioactivity from nuclear facility, either routine releases during normal operations or unexpected releases during accident-conditions, are usually done in two separate and rather unaffiliated phases. The atmospheric dispersion patterns, either long-term or short-term, are first determined from on-site meteorological data; the calculation of the releases and the doses is then carried out with these thus-fixed atmospheric dispersion patterns.

The atmospheric dispersion patterns, commonly modeled as a diffusion process, are usually expressed as a probabilistic distribution of a set of atmospheric dilution factors $\frac{X}{Q}$'s, which are functions of location and time. There are several statistical reduction procedures for evaluating the $\frac{X}{Q}$'s (1 thru

5 and 11). Analyzing the atmospheric dispersion process independent from the pattern of radioactivity releases does not correctly evaluate the radiological consequences to the public, especially for the releases from the radioactive gas waste system and following a postulated accident. In particular, the conventional approach tends to overestimate the potential radiological consequences of the fairly extended releases associated with some postulated accidents; and certain unnecessary overdesigns of a nuclear facility may result. Furthermore, the conventional approach cannot be employed to correctly evaluate the risks to the population-at-large.

In this study, a method which directly incorporates on-site meteorological data into the evaluation of radiological consequences is proposed; a dosematrix, formulated by modeling the sequential behaviors of the radioactive plume on an hourly basis, is used to define the probabilistic distribution of radiological consequences. From this dose-matrix, the radiological consequences at any desired probability-level, as well as the associated risks, to individuals and the population-at-large can then be determined.

2. Description of Model

2.1. Formulation of Dose Matrix

The radiological consequence to an individual at the location (r,θ), due to a release of radioactivity $Q_i(t)$ and over a duration T, can be written as

$$D(r,\theta)=\sum_{i}^{\text{nuclides}}\varepsilon_i\int_0^T U(t)Q_i(t)\frac{X}{Q}(r,\theta,t)\,dt \tag{1}$$

where

$D(r,\theta)$ = dose to an individual at location (r,θ), rems.

ε_i = dose conversion facter for nuclide i, rem/hr per Ci/m³ for external exposures or rem/Ci for inhalation doses.

$U(t)$ = usage factor at time t; for external exposures, it is simply the occupancy-factor; for inhalation doses, it is the product of the occupancy-factor and the breathing-rate, m³/hr.

$Q_i(t)$ = release characteristics for nuclide i, Ci/sec.

$\frac{X}{Q}(t)$ = atmospheric dilution factor at location (r,θ) and at time t, sec/m³.

On-site meteorological data are generally expressed, in compliance with Regulatory Guide 1.23[6], as an ordered sequence of hourly-averaged meteorological parameters. From these data, the hourly atmospheric dilution factors are calculated. Writing the hourly $\frac{X}{Q}$ during the hourly interval (t_j-t_{j-1}) as $\left(\frac{X}{Q}\right)_j(r,\theta_k)$

$$D(r,\theta_k)=\sum_{i}^{\text{nuclides}}\varepsilon_i\sum_{j=1}^{N_T}Q_{ij}\left(\frac{X}{Q}\right)_j(r,\theta_k) \tag{2}$$

and

$$Q_{ij}=\int_{t_{j-1}}^{t_j}U(t)Q_i(t)\,dt \tag{2-a}$$

where N_T is the number of hours within the period T, θ_k is the direction of sector k, $1\leq k\leq 16$.

For a full years' meteorological data with M valid hourly observations, a sequence of M hourly-averaged $\frac{X}{Q}$'s can be obtained for each of the 16 sectors-a lot of them may be zeros. The probabilistic distribution of radiological consequences can then be formulated by sequentially imposing the release function in terms of a 16×M dose-matrix $\underset{\sim}{D}$, whose element is of the form

$$D_{km}(r)=\sum_{i}^{\text{nuclides}}\varepsilon_i\sum_{j=1}^{N_T}Q_{ij}\left(\frac{X}{Q}\right)_{m'},\ (r,\theta_k)\quad(3)$$

where

$$m'=m+j-1,\ \text{for } m+j-1\leq M$$
$$m+j-1-M,\ \text{for } m+j-1\geq M\quad(3\text{-a})$$

From the dose-matrix $\underline{D}$, the individual doses and risks, as well as the population doses and risks, can then be determined.

2.2. Individual Doses

The dose-matrix $\underline{D}$ thus formulated defines the probabilistic distribution of radiological consequences to an individual, for any category of release of radioactivity. For routine and constant releases of radioactive effluents from a nuclear facility, the annual doses to an individual at the location (r,θ_k) are then

$$\overline{D}(r,\theta_k)=D_{k1}(r)=D_{k2}(r)=\cdots=D_{km}$$
$$\text{with } N_T=M\quad(4)$$

where $\overline{D}(r,\theta_k)$ is the annual individual-dose, rem/yr and Q_{ij}, used here for evaluating the matrix-elements, are just the average hourly releases of radioactivity. In this case, the dose matrix method becomes the same as the conventional way of dose calculation using the annual average $\frac{X}{Q}$ since the release function is constant with respect to time.

For short-term releases of radioactivity due to anticipated transients and postulated accidents or periodic intermittent releases, the dose-matrix $\underline{D}$ defines the probabilistic distribution of doses to an individual weighted by the time-dependent release function; each matrix-element represents one equally-probable value of the radiological consequences. From this matrix, the radiological consequences corresponding to any probability-level (e.g. 5%-level or 50%-level) can then be evaluated easily in a manner similar to that used conventionally for determining the 5%-level or 50%-level $\frac{X}{Q}$'s or in a stochastic approach.

For example, this method will yield slightly lower values for the 0-2 hours individual doses following a LOCA and significantly lower values for the 0-30 days individual doses, as compared with the conventional method. The 0-2 hour $\frac{X}{Q}$'s used in the conventional analysis, for any probability-level, are actually the hourly $\frac{X}{Q}$'s thus conservative in assuming that the limited meteorological conditions will persist during the second hour. In the 0-30 days analysis (conventionally divided into 0-8 hours, 8-24 hours, 24-96 hours, and 96-720 hours), the $\frac{X}{Q}$'s used actually correspond to the statistically reduced values for 0-8 hours, 0-16 hours, 0-72 hours, and 0-624 hours respectively; such an approach is completely unrelated to actual phenomena and will grossly overestimate the contributions from time-periods after the first one.

2.3. Population Doses

Based upon the dose-matrix $\underline{D}$ thus formulated, the probabilistic distribution of population doses can then be expressed in terms of the M-dimensional dose-vector $\overrightarrow{H}$, whose elements are of the form

$$H_m=\sum_{l}^{\text{distance}}\sum_{k}^{\text{sectors}}\left(D^{l}_{km}P^{r}_{kl}+D^{l}_{km}P^{s}_{klm}\right)\quad(5)$$

where H_m is the population dose, man-rems $D^{l}_{km}\equiv D_{km}\left(\frac{1}{2}(r_l+r_{l+1})\right)$, element of matrix $\underline{D}$, P^{r}_{kl} is the residential population in sector k, between the distances r_{l-1} and r_l; P^{s}_{klm} is the seasonal population in sector k, between the distances r_{l-1} and r_l, during the m^{th} time-interval.

Assuming no seasonal change in population distribution, for routine releases of radioactive effluents from a nuclear facility, the annual doses to the population-at-large are then:

$$\overline{H}=H_1=H_2=\cdots=H_M, \text{ with } N_T=M \quad (6)$$

where $\overline{H}$ is the annual population dose, man-rems/yr.

For short-term or periodic releases of radioactivity, the probabilistic distribution of population doses is represented by the dose-vector $\vec{H}$; each element of $\vec{H}$ then represents an equally probable value of the population doses. From this dose-vector $\vec{H}$, the population doses corresponding to any probability-level (e.g. 50%-level) can be then be easily obtained.

For the areas of large seasonal change of populations and meteorological conditions around a nuclear facility, this method is expected to yield slightly different results for the population doses, as compared with the conventional method due to its more precise treatment of the seasonal population.

In accordance with Regulatory Guide 4. 2[7], the applicant of a nuclear facility is required to evaluate the radiological consequences of nuclear accidents to the population-at-large. In the conventional analysis, the doses are first evaluated as functions of distance, using the 50%-level $\frac{X}{Q}$'s; the resultant doses are then integrated over the population distribution, and weighted by the wind-frequencies in the sectors, to yield the population doses. However, the population doses analyzed by this method does not physically correspond to the radiological consequences to any probability-level. At best, this method may provide an educated guess about the order-of-magnitude of the mean value of the population doses. The dose-vector $\vec{H}$, thus formulated in this study, describes the entire spectrum of the radiological consequences of a nuclear accident to the population-at-large. From this distribution, the values of the population doses corresponding to any desired probability-level, as well as the mean value, can be easily obtained. More important, this dose-vector $\vec{H}$, can be used for the evaluation of the population risks while the conventional method is not applicable.

3. Application of Model

As an illustration of this approach to assess radiological consequenes, the off-site wholebody doses due to a Loss-of-Coolant-Accident (LOCA) type of release of radioactivity are analyzed with this method and compared with the conventional method. The meteorological parameters are based on one years' on-site data for a potential site in the Southern United States. The results are shown below in Table 1; the assumptions used in the analysis are given in Table 2.

Table 1. Individual Doses Due to LOCA-Type Release

	wholebody doses, in rems	
	Dose-Matrix Method	Conventional Method
0-2 hours at 500 meters		
5%-level	21.0	28.7
50%-level	2.25	2.63
0-30 days at 2 miles		
5%-level	0.920	2.17
50%-level	0.155	0.415
Overall Zero-Dose Probability		
0-2 hours	90.8%	N/A
0-30 days	0.291%	N/A

From the results of the analysis, it is seen that the 0-2 hour doses are fairly close for both methods; however, the 0-30 day doses are quite different for the two methods. The conventional method yields results more than twice as large. These results can be understood by examining closely the behavior of the radioactive plume.

Table 2. Assumptions* for Evaluating Wholebody Doses Due to LOCA-Type Release

Radioactivity Inventory in Core	PSNH-PSAR[8], Table 15.4-2
Releases into Containment	Instantaneous
Noble Gases	100%
Iodines and Solids	not considered
Containment Leakage	0.1%/day (for the duration of the accident)
Radioactive Decay inside Containment	only simple decays considered: no parent-daughter transitions considered
Radioctive Decay in Flight	not considered
Deposition, Rain, etc.	not considered

The dose-matrix method as formulated in this study traces the statistical behaviors of the plume very closely, accounting for any change in atmospheric stability or wind-speed as well as any shifting in wind direction, on an hourly basis. Thus, this method closely simulates the real-life situations.

In the conventional method, the 0-2 hours $\frac{X}{Q}$'s used are actually the hourly $\frac{X}{Q}$'s, at any given probability-level. This does not have any provision for meteorological changes dnring the second hour of the time-period. With the initial hourly $\frac{X}{Q}$'s defined at the $\alpha\%$-level, the conventional 0-2 hours $\frac{X}{Q}$'s actually correspond to a probability-level lower than the $\alpha\%$-level. Thus, the conventional method tends to slightly overestimate the 0-2 hours doses.

The 0-30 days $\frac{X}{Q}$'s used in the conventional analysis are actually the $\frac{X}{Q}$'s for the time intervals 0-8 hours, 0-16 hours, 0-72 hours and 0-624 hours; each of these $\frac{X}{Q}$'s is individually determined at the same $\alpha\%$ probability-level. However, the atmospheric diffusion sequence resulting from the combination of these $\frac{X}{Q}$'s corresponds to a probability-level much lower than the intended $\alpha\%$-level. Thus, the conventional method tends to be overly conservative in evaluating the 0-30 day doses.

In this study, the zero matrix-elements in $\underline{D}$ are first dropped, and only the distribution of non-zero elements is used for the determination of the radiological consequences for various probability-levels. This is consistent with the traditional way of determining the $\alpha\%$-level $\frac{X}{Q}$'s. However, it is interesting to note that the 0-2 hours zero-dose probability for this case is evaluated to be as high as 90.8%. By defining the $\alpha\%$-level dose as the value which is only exceeded $\alpha\%$ of the time during the period of release in all sectors (i.e. including the zero-elements in the dose-distribution), the resultant 5% 0-2 hours wholebody dose is 1.80 rems at 500 meters, and the corresponding 50%-level value is zero.

4. Discussions

It is recognized that no radioactive decay in flight has been considered in the present formulation of the dose-matrix. Also, environmental removal-mechanisms such as deposition and rainout have not been considered in the present formulation. This may lead to overestimates of the impacts due to releases of radioactivity, especially the population exposures. It is simple in conception to modify the formulation of the dose-matrix to incorporate these processes. However, these processes are functions of the wind-speed as well as the atmospheric stability-classes, which may vary from one hour to another. Thus, such modifications may cost significant increases in computer running

* These assnmptions are common for both models.

time. It is recommended that future efforts are to be made to include modifications, which should correctly and efficiently account for these processes, in a more generalized formulation of the dose-matrix.

In the present formulation of the dose-matrix, a full years' meteorological data with a high percentage of recovery (90% or better) is assumed. However, questions can be raised about whether reasonable estimates can be made without 90% data recovery or a full years' data. SRP 2.3.3[9] and Regulatory Guide 1.23[6] infer that at least one full years' meteorological data with 90% data-recovery should be achieved in order to provide an adequate assessment of the site diffusion conditions. In practice, this may not be easy to achieve; natural events such as windstorms, icestorms and lightning usually stress severely the capacity of present-day meteorological equipment. For some sites, only six months worth of data may be available for making design decisions. A study by Woodard[10], surveying the meteorological data from ten different nuclear reactor sites, suggested that the average deviation from the values based on a full years' data is about 4% for nine months' worth of data, and about 10% for six months' worth of data; these estimates were made for the 5%-level $\frac{X}{Q}$'s. However, besides dependent upon the distribution of the initial meteorological states, the sensitivity of the dose-matrix is also dependent upon the transition-probabilities of these meteorological states into one another. It is thus recommended that future efforts are to be made to investigate the sensitivity of the dose-matrix in this respect.

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