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RADAP–A PC Program for Real–Time Prediction of Doses Following a Nuclear Accident

Jae Won Park
Korea Power Engineering Company

Chang Sun Kang
Seoul National University

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RADAP-원자력 사고후 실시간 선량 예측용 PC 전산프로그램

박재원
한국전력기술주식회사

강창순
서울대학교

(1992. 8. 28 접수)

Abstract

A PC–computer program RADAP has been developed in this study to perform a quick real–time analysis of dose assessment following an accident in a nuclear facility. RADAP uses an interactive LKagrangian puff model in simulating the transport and diffusion of radioactive plume in the atmosphere. For real–time analysis, RADAP treats one or multiple puffs of ground–level releases, simultaneously. It is assumed to maintain a Gaussian distribution within the puff and the diffusion coefficients are computed using the USNRC's normal sigma curve method. The program, however, does not consider the spatial variations but the temporal variations in wind conditions. Whole body and thyroid doses for 3×31 grid are directed to output files, and they are also displayed through computer graphics on VGA or EGA color monitor. The results show that RADAP can be an excellent tool for quick estimation of accidental doses.

요 약

원자력시설의 사고에 따른 피폭선량 평가를 짧은 실시간에 대해 분석하는 PC 프로그램인 RADAP 을 개발하였다. RADAP 은 공기중 확산 및 수송에서 라그란지 puff 방법을 사용하고 있다. 실시간 분석을 위하여 한개 혹은 다중의 puff 를 동시에 취급할 수 있다. puff 내에서의 확산은 Gauss 분포를 가지며, 확산계수는 USNRC 의 normal sigma curve 방법을 사용하였다. 그러나 이 프로그램은 바람조건에서 시간적인 변화만 적용하고 위치에 따른 변화는 취급하지 않았다. 31×31

격자의 전신 및 갑상선 선량이 출력으로 나오며, EGA 및 VGA 모니터를 통하여 도상으로 표시된다. 결과에 의하면 RADAP은 사고후 짧은 시간동안의 선량을 평가하기 위한 좋은 도구라 할 수 있다.

1. Introduction

Dose assessment is a tool of quantifying the radiological impact to the general public due to radioactive effluent releases following an accident from a nuclear facility. The dose assessment, more specifically from airborne radioactive effluents calls for the prediction of radioactivity concentrations in the atmosphere at the specific locations around the release point. For real–time prediction of these concentrations, an atmospheric dispersion model is required to simulate the spatial and temporal variations of dispersion affecting the radioactive plume distribution in the air. For this purpose, the puff model is proposed, which permits temporal variations in radioactive source terms as well as both spatial and temporal variations in wind conditions.

In this study, a PC computer program RADAP has been developed for a quick assessment of doses following an accident. RADAP uses the puff model to simulate the real–time prediction of dose assessment following an accident. In order to simulate the transport and diffusion of the radioactive effluents released to the atmosphere, RADAP uses an interactive Lagrangian puff model as used in the computer code MESOI[1], which, however, only computes the air concentration of a single radionuclide. RADAP, meanwhile, computes the whole body and thyroid doses from multiple nuclides within the 120 km region from the release point. For real–time analysis, it also treats one or multiple puffs of ground–level release, simultaneously. Each puff is transported and diffused according to the time–dependent meteorological data. RADAP, however, does not incorporate the spatial variations but only the temporal variations in wind conditions since the spatial variation of wind condition requires an extensive amount of regional wind field data, which is very unrealistic at present. It is written in MS FORTRAN 5.0 for personal computers. The input data consist of time–dependent meteorological data at the release point, simulation time, release time of radioactive materials and spatial grid spaces. The computation output contains: 1) puff plot showing the movement of puffs, 2) screen display showing the 31x31 grid dose levels, and 3) two output files which contain cumulative whole–body and thyroid doses for 31x31 grid, respectively.

2. Theory

2.1. Atmospheric Dispersion

The concentration of a given radioactive material at time t and location (x,y,z) in the atmosphere, is represented by the mass balance equation as follows:

$$\frac{\partial \chi}{\partial t} = -\nabla\cdot(\mathbf{v}\chi) + \nabla\cdot\underline{\underline{K}}\cdot\nabla\chi + S - \lambda\chi \qquad (1)$$

where,

χ (x,y,z,t) = airborne concentration of the radioactive material (Ci/m^3),

t = time after release (sec),

$\mathbf{v}$ = wind speed vector, $\mathbf{v} = iu + jv + kw$; u,v,w in (x,y,z,t) (m/sec),

K = diffusion coefficient dyadics, $K = iiK_x + jjK_y + kkK_z$; K_x, K_y, K_z in (x,y,z,t), m^2/sec,

S(x,y,z,t) = source function (Ci/m^3.sec), and

λ = nuclear transformation constant of the radioactive material (sec^{-1}).

If no external source exists in the atmosphere except the point source at the release point, the radioactive plume will move in the form of puff along the downwind direction. In a rectangular coordinate system of which the origin is the center point of the plume, the advective term can be eliminated since the puff moves with the coordinate system. And the radioactive decay of the plume in transit can be incorporated simply by multiplying a factor of exp($-\lambda$ x/u) after transport, where u is the average down wind speed along the distance x. In this case, the non-decaying material concentration is simply represented by:

$$\frac{\partial \chi}{\partial t} = \nabla\cdot K\cdot\nabla \chi$$

$$= \frac{\partial}{\partial x}(K_x\frac{\partial \chi}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial \chi}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial \chi}{\partial z}) \quad (2)$$

For an instantaneous puff release at t=0, the solution for the above equation becomes:

$$\chi(x',y',z',t) = \frac{Q_o}{(4\pi t)^{3/2}(K_{x'}\cdot K_{y'}\cdot K_{z'})^{1/2}}$$

$$\times \exp\left[-\frac{1}{4t}\left(\frac{x'^2}{K_{x'}} + \frac{x'^2}{K_{y'}} + \frac{x'^2}{K_{z'}}\right)\right] \quad (3)$$

where,

x',y',z'=x,y,z coordinates on the system in which the origin is located at the center point of the moving plume,

Q_o=inventory of the instantaneously released material (Ci), and

$K_{x'}$,$K_{y'}$,$K_{z'}$=diffusion coefficients (m^2/sec).

Using the standard deviations σ_i (i=x, y, z) in a Gaussian distribution and assuming constant K_i's, the concentration for the ground-level release becomes:

$$\chi(x,y,z,t)$$

$$= \frac{Q_o}{(2\pi)^{3/2}\sigma_y^2\sigma_z}\exp\left(-\frac{1}{2}\left[\frac{|r|^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right]\right) \quad (4)$$

where,

$\sigma_y = \sigma_x$ (lateral=longitudinal dispersions) (m),

$|r| = [(x-x_o)^2+(y-y_o)^2]^{1/2}$, and

x_o, y_o=position of the center of the puff (m).

2.2 Ground Reflection

When we assume the specular reflection of the airborne radioactive material by the surface of the ground, the specular reflection allows the addition of the imaginary radioactive plume which is formed by the release from an imaginary point source located at the ground surface. In this case, the concentration is given as follows:

$$\chi(x,y,z,t)$$

$$= \frac{2Q_o}{(2\pi)^{3/2}\sigma_y^2\sigma_z}\exp\left(-\frac{1}{2}\left[\frac{|r|^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right]\right) \quad (5)$$

3. Program RADAP

3.1. Diffusion Coefficients

Diffusion coefficients are functions of terrain conditions, distance from the release point and atmospheric stability conditions. The diffusion coefficients used in RADAP are based upon the USNRC's normal sigma curve method[2]. The effects of terrain conditions could be incorporated in this computer program through an appropriate selection of a set of diffusion coefficients which are specifically applicable to the specific terrain conditions.

The time dependence of diffusion coefficients is the result of the inherent relationship between distance and travel time and it is basically due to the temporal variation of atmospheric stability. If the actual distance were to be used, the puff shape would change at the instant of stability change and the change might be large. The resulting discontinuity would be unrealistic. In order to resolve this discontinuity problem, RADAP also adopted the concept of virtual distance as used in MESOI.

3.2. Time Integration

The output of RADAP is given in the form of cumulative dose matrices at various nodes of 31x31 grid. The time-integrated air concentration of radioactive puff j at the ground level (z=0), $E_j(x,y)$, is proportional to radiation exposure to person. Hence, for multiple puffs, the ground level time-integrated concentration at location (x,y) is given by:

$$E(x,y) = \sum_j E_j(x,y) = \sum_i \sum_j \chi_{ij}(x,y)\ \Delta T_i \qquad (6)$$

where χ_{ij} is the concentration for time interval i and puff j, which is defined by equation (5), as appropriate, and ΔT_i is the sampling interval. The summation over time (index i) in equation (6) starts at the beginning of the simulation and continues until the simulation is terminated or no active puffs remain on the computational grid. The other summation in equation (6) (index j) is over all puffs affecting the node. In RADAP, the time-integrated concentration is expressed in unit of Ci-hours/meter^3. In RADAP, it is assumed that the whole body dose is due to the direct external exposure from the radioactive clouds and the thyroid dose is due to internal exposure from inhalation of radioiodines. The doses from all contributing isotopes at the specific node are calculated:

1) for whole-body dose,

$$D^w(x,y) = \sum_k R_k \cdot E(x,y) \cdot (DCF)^w_k \qquad (7)$$

2) for thyroid dose,

$$D^t(x,y) = \sum_k R_k\ E(x,y) \cdot (BR) \cdot (DCF)^t_k \qquad (8)$$

where,

$D^w(x,y)$ = whole body dose (rem),

$D^t(x,y)$ = thyroid dose (rem),

R_k = ratio of isotope k to total inventory of released material,

BR = breathing rate (m^3/hour),

$(DCF)^w_k$ = whole-body dose conversion factor for isotope k ((rem/hr)/(Ci/m^3)),[4] and

$(DCF)^t_k$ = thyroid dose conversion factor for isotope k (rem/Ci).[4]

3.3. Organization of Program RADAP

RADAP is written in MS FORTRAN 5.0 and is developed for personal computers. It consists of a main program and 26 subroutines. Data transfers among program elements are achieved through 11 labeled common blocks that contain related variables and constants. User interaction, through a PC monitor, provides data for model initialization and controls the output of RADAP graphics at the end of each hour of simulation. Meteorological data are fed through input data file, OBSDAT .DAT which is prepared from observed data prior to running the program, or through the user interactive job such as in the case of using forecast data. Check points are read through data file, CHECK.DAT, which are used to inform the situation whenever the dose at a checkpoint exceeds the preset value. Whole body and thyroid doses for 31×31 grid are directed to output files, WHOCUM.DAT and THYCUM.DAT, respectively. The graphical output are shown directly through the PC monitor using VGA or EGA graphic adaptor.

Figure 1 shows the structure of the main program of RADAP. The two outer loops are indicated by the left branches from the decision points marked: "More Advection Steps this Hour?", and "More Hours?". The innermost loop is the left branch from the decision point marked: "More Puffs?".

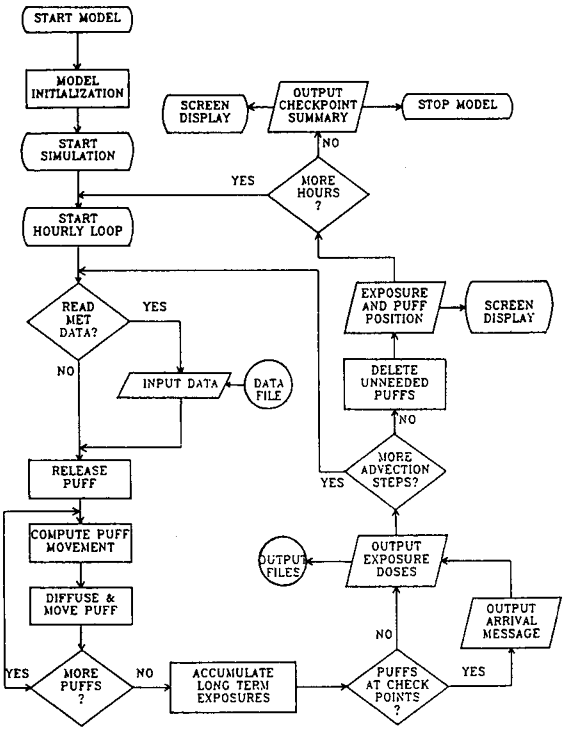


Fig. 1. Program Logic for RADAP Main Program

3.4. Applications

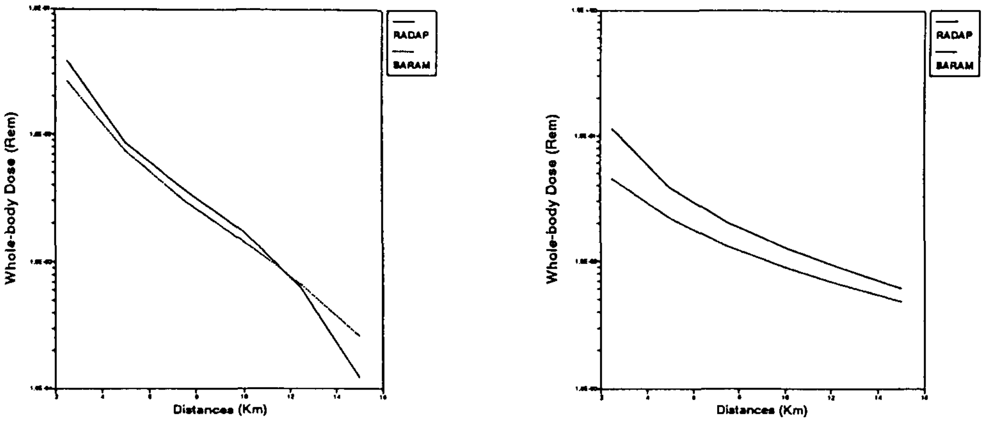
For code verification, the results of RADAP are compared with those calculated with BARAM[3] computer code for four different cases. The comparison results are presented in Figure 2.

The time-independent meteorological data are used for comparison, since the BARAM code uses the straight-line Gaussian model. Next, the 0–2 hour doses at the exclusion area boundary (700 m) are calculated following the design-basis accident as postulated in US Regulatory Guide 1.4[5]. In this calculation, 100 % noble gases and 25 % iodines of the total core inventory of Younggwang 3&4 are assumed to be released in the containment atmosphere instantaneously, and released to the environment with the containment leak rate of 0.1 %/day. The wind speed and atmospheric stability are assumed to be constant during the accident with the values of 1.5 m/sec and category D, respectively. The calculated whole body and thyroid doses are 1 rem and 145 rem, respectively, for 2 hour-period following the initiation of the accident.

For sample runs, a set of time-dependent meteorological conditions (wind direction, speed and stability) are applied in RADAP. The conditions chosen in these sample computations are summarized in Table 1 and the graphic results are presented in Figure 3 through 5.

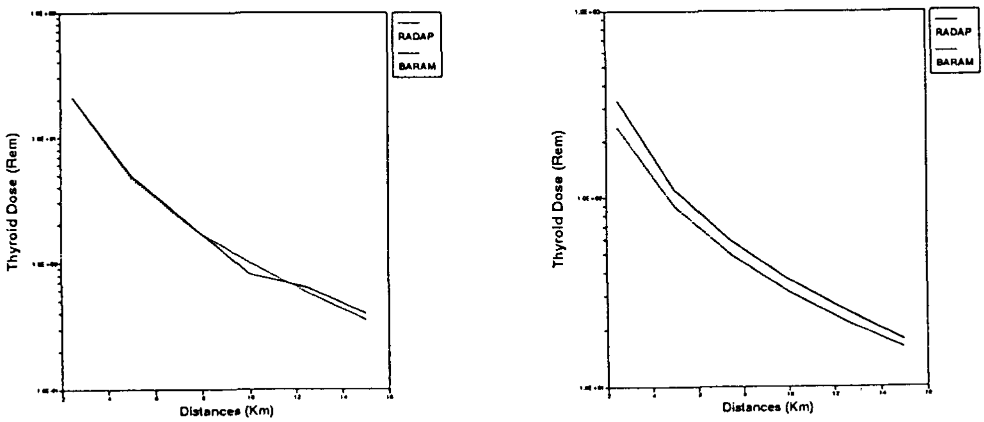
4. Conclusions and Recommendations

The objective of this study is to develop a PC program for quick real-time prediction of exposure dose following an accidental condition using puff model. This study was primarily focused on the atmospheric dispersion and transport of the released radioactive material using time-dependent meteorological data. As the result of effort, the computer program RADAP was developed for whole-body and thyroid dose calculations. RADAP, however, adopts the meteorological data which are only dependent on time at one location. RADAP could be an excellent tool for quick assessment of accidental dose since the space-dependent meteorological data are not much available at present. If 2-dimensional wind field data are available for at least 10 wind stations in the future, RADAP could be updated in order to incorporate the spatial changes of meteorological conditions. And the time-dependent source term, which is not treated in the present study, could be easily adopted in the program RADAP. RADAP needs the necessary improvements to deal with the space-dependent meteorological data. However, for the ground-level releases, RADAP is a fast responding and easy-to-use code which is available at the moment.



Isotope : KR 85 Release Rate : 500 Ci/s
Stability : C Release Duration : 5 Hr
Wind Speed : 1 m/s

Isotope : KR 85 Release Rate : 500 Ci/s
Stability : D Release Duration : 8 Hr
Wind Speed : 2 m/s



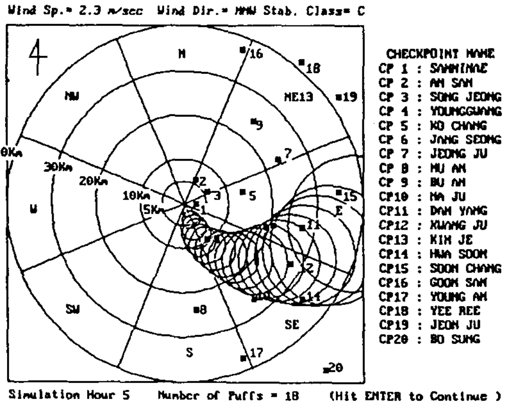
Isotope : I 131 Release Rate : 1 Ci/s
Stability : B Release Duration : 5 Hr
Wind Speed : 2 m/s

Isotope : I 131 Release Rate : 1 Ci/s
Stability : D Release Duration : 8 Hr
Wind Speed : 2 m/s

Fig. 2. Comparison Results Between RADAP and BARAM

Table 1. Source Term and Meteorological Data for RADAP Simulation

Site	Younggwang Nuclear Site			
Source Term	Release Rate	Xe–133 : 500 Ci/sec I–131 : 10 Ci/sec		
	Release Duration	5 hours		
Atmospheric Conditions	TIME	WIND SPEED	WIND DIR.	STABILITY
	0 : 00–0 : 15	2.7 m/sec	SW	D
	0 : 15–0 : 35	2.9 m/sec	SW	C
	0 : 30–1 : 00	3.1 m/sec	WSW	C
	1 : 00–1 : 15	3.5 m/sec	WSW	B
	1 : 15–1 : 45	3.5 m/sec	W	B
	1 : 45–2 : 15	3.0 m/sec	W	C
	2 : 15–2 : 30	2.8 m/sec	W	C
	2 : 30–2 : 45	2.7 m/sec	WNW	C
	2 : 45–3 : 15	2.5 m/sec	WNW	D
	3 : 15–3 : 30	2.3 m/sec	NW	D
	3 : 30–4 : 00	2.0 m/sec	NW	D
	4 : 00–4 : 15	1.8 m/sec	NNW	E
	4 : 15–4 : 35	2.0 m/sec	NNW	D
	4 : 30–5 : 00	2.3 m/sec	NNW	C
	5 : 00–	2.3 m/sec	NNW	C

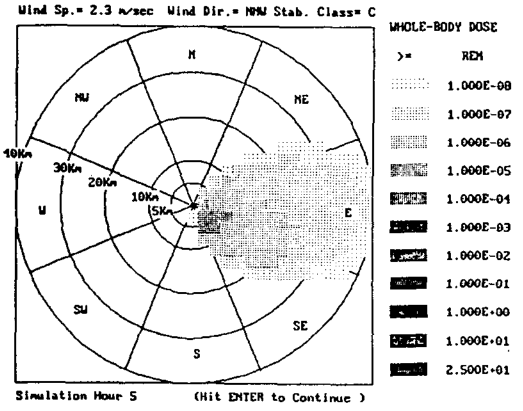


```
Wind Sp.= 2.3 m/sec  Wind Dir.= NNW Stab. Class= C
```

```
CHECKPOINT NAME
CP 1 : SAMHINAE
CP 2 : AN SAN
CP 3 : SONG JEONG
CP 4 : YOUNGGWANG
CP 5 : KO CHANG
CP 6 : JANG SEONG
CP 7 : JEONG JU
CP 8 : MU AN
CP 9 : BU AN
CP10 : NA JU
CP11 : DAM YANG
CP12 : KWANG JU
CP13 : KIM JE
CP14 : HWA SOON
CP15 : SOON CHANG
CP16 : GOOM SAN
CP17 : YOUNG AM
CP18 : YEE REE
CP19 : JEON JU
CP20 : BO SUNG
```

```
Simulation Hour 5    Number of Puffs = 18    (Hit ENTER to Continue )
```

Fig. 3. RADAP Output Showing Puff Movement



```
Wind Sp.= 2.3 m/sec  Wind Dir.= NNW Stab. Class= C
```

```
Simulation Hour 5          (Hit ENTER to Continue )
```

Fig. 4. RADAP Output Showing Whole–body Doses at 31×31 Grids

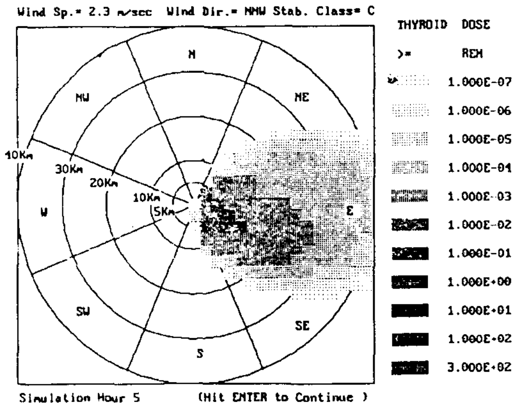


Fig. 5. RADAP Output Showing Thyroid Doses at 31×31 Grids

References

1. J.V. Ramsdell, et al., *MESOI Version 2.0* (1983)
2. Eimutis and Konicek, *Normal Sigma Curves Used In the NRC* (1972)
3. KAERI, *BARAM* (1986)
4. USNRC, *Regulatory Guide 1.109*
5. USNRC, *Regulatory Guide 1.4*