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A MODEL OF PUBLIC EVACUATION FOR ATMOSPHERIC RADIOLOGICAL RELEASES

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ABSTRACT

A model of public evacuation is developed for use in evaluating the efficacy of evacuation as a protective measure in response to atmospheric releases of radioactive material. Differences between this model and the model of public evacuation previously developed for the Reactor Safety Study are described. Based on an analysis of available EPA evacuation data, ranges are suggested for the temporal parameters in the new model. The relative importance of the model parameters is also discussed.

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I. INTRODUCTION

If an accident should occur at a nuclear power reactor, significant quantities of radioactive material could be released to the atmosphere, requiring some form of emergency response for the protection of offsite individuals. Protection strategies to limit or mitigate the radiation exposures resulting from such a release are of prime concern to those responsible for radiological emergency planning and response. Potentially available protection strategies include sheltering, evacuation, and medical prophylaxis.

Significant atmospheric releases of radioactive material would in general be preceded by one or more hours' warning [1] and, depending on the wind speed following the release, several more hours might pass before the cloud of released radioactive material would reach a particular downwind population. Because of this available time period, evacuation* is given considerable attention as a public protective measure in most current radiological emergency preparedness programs in the United States. However, recent studies [2] support the view that it may be desirable to consider alternative or supplemental strategies to evacuation such as population sheltering followed by the selective and timely relocation of affected persons. To assist in the choice and design of appropriate response measures, a study, using a modified version of the consequence model of the Reactor Safety Study (RSS) [1], was conducted to evaluate the

*Evacuation is the expeditious movement of people to avoid exposure to the passing cloud of radioactive material.

relative merits of potential public protective measures, and to determine under what circumstances and over what areas they should be implemented. This report describes the model of evacuation developed for and used in the study of response measures. The effectiveness of evacuation and other protective measures, such as sheltering followed by relocation, is discussed in other papers [3,4,5].

II. BACKGROUND

Evacuation experience in the U.S. for the period from 1959 to 1973 is summarized in a report published by the U.S. Environmental Protection Agency (EPA) [6]. The report provides data on 64 evacuation events, most of which were in response to hazards from transportation accidents, floods or hurricanes. A simple evacuation model, based on a statistical analysis of this evacuation data, was included in the consequence model of the RSS for use in the calculation of public risks from reactor accidents. The statistical analysis performed for that study and the suitability of the EPA data for the modeling of evacuations in response to reactor accidents are discussed in Appendix VI of the RSS. The RSS evacuation model postulates that evacuated persons move radially away from the reactor at a constant "effective" speed immediately upon warning by nuclear facility personnel* of the impending

*No specific delay time is assumed for the notification of responsible authorities, the decision to evacuate, the time required by officials to notify people to evacuate, and the time required by people to mobilize and get underway.

release. Representative effective evacuation speeds were determined from the EPA data by dividing the recorded evacuated distances by the corresponding total time periods required to complete the evacuations. Because the total evacuation time periods include all delays as well as the travel time required to leave the affected areas, the "effective" speeds determined are considerably lower than the speeds actually attained while evacuating. Evacuated persons are assumed to continue moving outward from the reactor site until overtaken by the cloud of radioactive material. At the distance they are overtaken by the cloud, they are exposed to the entire duration of the cloud and to ground contamination for an assumed period of 4 hours. Constant shielding factors for exposure to airborne radionuclides and ground contamination and a constant breathing rate are uniformly applied to the entire evacuating population.

The statistical analysis of the EPA data performed in the RSS showed that (1) a log-normal distribution can be suitably used to describe the distribution of effective evacuation speeds, (2) the likely effective speeds are small, (3) the range of likely effective speeds is large, and (4) the number of persons evacuated had no statistically significant effect on the effective speed of evacuation. Data for evacuations in response to transportation events, floods and hurricanes were analyzed both separately and together. However, the individual log-normal distributions of effective speeds for the three evacuation categories were shown to be significantly different. Therefore, because (1) transportation accidents often involve airborne releases of noxious gases, and (2) the warning times and evacuation movements are comparable to those that might be associated with a reactor accident, only data gathered for evacuations in response to transportation accidents were used in developing the descriptive model for reactor accidents. A chart of the data collected for transportation accidents is presented as Table 1. Because there is a large variation in effective evacuation speeds, the use of one "representative" speed was considered inappropriate. As explained in Appendix VI of the RSS, the distribution of evacuation speeds was therefore represented by three discrete values, 0, 1.2 and 7.0 mph, with probabilities of 30 percent, 40 percent, and 30 percent, respectively.

While the evacuation model described above is most likely sufficient for the calculation of aggregate public risks from potential reactor accidents, it is inadequate for use in evaluating evacuation as a radiological emergency protective measure for several reasons. Calculations which use effective evacuation speeds do not provide realistic descriptions of the spatial or temporal movements of evacuating persons, and are therefore difficult to interpret. The total time required to complete an actual evacuation will involve a delay time of some duration in addition to the actual travel time required to leave the affected area. The time required for notifying responsible authorities, interpreting data, deciding to evacuate,

Table 1. EPA Evacuation Data for Transportation Accidents (from Appendix VI of ref. 1)

Event Number	Location and Date	Type of Area Evacuated	Area Evacuated (sq. miles)	Number of Persons Evacuated	Distance Evacuated (Miles)	Evacuation Period (hrs)	Population Density (number per sq. mile)	Road and Conditions[a]	Weather	Time of Day	Evacuation Plans[b]	Remarks
12	Downington, PA; 2/5/73	Suburban	0.25	700 of 800	1.0	2.0	3200	Dry S	Cloudy	Night	PU	Private vehicles
16	Creve Coeur, MO; 8/1/61	Rural residential; suburban; urban	15	7,500	12	1.0	500	Dry S	Fog	Night	Pu	Private vehicles
18	Chadbourne, NC; 1/13/68	Suburban	0.5	350	1.0	5.0	700	Dry S	Cloudy	Dusk Night	NP	Private vehicles
33	Wetanka, OK; 4/4/69	Rural residential	3	2,000	25	8	667	Dry S	Cloudy	Day	PU	Private vehicles
[illegible]	Louisville, KY; 3/19/72	Urban	0.35	4,000	1	3	11,400	Wet U	Rain	Day	Pu	Private vehicles; chlorine barge; no chlorine release
35	Urbana, OH; 8/13/63	Suburban	3.1	4,000	0.75	3.5	1,300	Dry S	Clear	Dawn	N.D.	Private vehicles
36	Baton Rouge, LA; 8/65	Urban	8	150,000	10	2.0	19,000	Dry U, EU	Clear	Day	PU	Private vehicles chlorine barge; no chlorine release
38	Morgan City, LA; 1/19/73	Urban	1.8	3,000 of 3,300	2	4	1,800	Ice U	Snow	Day	PU	Private vehicles; chlorine barge; no chlorine release
39	Texarkana, TX; 8/27/67	Suburban	9.0	5,000	3	4	550	Dry U	Clear	Night	NP	Private vehicles
44	Glendora, MS; 9/11/69	Rural farming; rural residential suburban urban	1,200	35,000	20	4	29	Dry S	Cloudy	Night	P	Private vehicles

(a) Key: U - urban road;
S - suburban road;
R - rural road;
EU - express way (unlimited access);
EL - express way (limited access).

(b) Key: P - plan available (not used);
PU - plan used
NP - no plan
N.D. - no data

directing people to evacuate, and for people to mobilize and get underway [7] may result in significant delays. Actual speeds attained while evacuating may be considerably higher than the calculated effective speeds. This could significantly affect the total time of exposure to ground deposited radioactive material. Responsible planning authorities will have some understanding of these delay components and the likely speeds attainable on routes leaving the evacuated area. The assumption that evacuating persons overtaken by the radioactive cloud are exposed to the entire cloud duration and to ground contamination for a constant 4 hours is also an unrealistic description of the public's exposure to radiation during evacuation. In addition, rather than remaining constant during the total time of evacuation, shielding factors and breathing rates may be markedly different during the delay and transit periods. Therefore, a revised model of public evacuation was developed for use in examining evacuation as a protective measure and is presented in the next section. Representative values for the temporal parameters in the revised treatment are determined based on a reinterpretation of the EPA data [6], as explained in Section IV of this report. It should be noted that the concepts enumerated in the proceeding discussions are applicable in general to emissions of airborne toxicants.

III. DESCRIPTION OF EVACUATION MODEL AND PARAMETERS

The new evacuation model was designed for use in the RSS consequence model and is therefore similar in some respects to the RSS evacuation model described in the previous section. However, significant differences do exist between the two models and these differences are detailed here. In lieu of the effective evacuation speeds assumed in the RSS evacuation model, the revised treatment incorporates a delay time before public movement, followed by evacuation radially away from the reactor at a higher constant speed.* Both the assumed delay time and evacuation speed are required as input to the model. Different shielding factors and breathing rates are used while stationary or in transit. As assumed previously, all persons within the designated evacuation area move as a group with the same delay time and evacuation speed. Therefore, the possibility that some people may not leave the evacuated area is ignored. This latter assumption results in upper bound estimates of evacuation effectiveness, given a specific delay time and speed.** Unlike the RSS model in which persons continue evacuating until they are either overtaken by the cloud or leave the model grid, all evacuating persons in the new model travel a designated distance from the evacuated area and then are removed from the problem. This treatment allows for the fact that after traveling outward for some distance, people may learn their position relative to the cloud and be able to avoid it.

*The speed is higher than the previously assumed effective speed since the total evacuation times (delay plus travel time) must be the same.

**The evacuation effectiveness would decrease linearly with an increasing nonparticiating fraction of the population. In actual evacuations, Civil Defense personnel have observed a nonparticipating minority of approximately 5% [6].

The new model also calculates more realistic exposure durations to airborne and ground deposited radionuclides than the RSS evacuation model. The RSS consequence model employs an exposure model for an instantaneous point source [8] and thus all releases have zero effective lengths. Because of this, evacuating persons overtaken by the cloud in the RSS evacuation model are exposed to the entire cloud at the point the cloud initially reaches them. In reality, however, a released cloud of radioactive material would have a finite release duration and a length that depends on the wind speed during and following the release of the radioactive material from the reactor containment building. A person overtaken by the front of the cloud might still escape before being passed by the entire cloud and thus receive only a fraction of the full cloud exposure.* The revised evacuation model assigns the cloud a finite length which is calculated using the assumed release duration and wind speed during the release. To simplify the treatment, the cloud is assumed to remain of constant length following the release (i.e., the front and back of the cloud travel at the same speed), and the concentration of radioactive material is assumed to be uniform over the length of the cloud. The radial position of evacuating persons, while stationary and in transit, is compared to both the front and the back of the

*It is also possible that an evacuating person may travel under the cloud for a long time and thus receive more exposure than if he had remained stationary during the passage of the cloud.

cloud as a function of time to determine a more realistic period of exposure to airborne radionuclides.

The revised treatment calculates the time periods during which people are exposed to radionuclides on the ground while they are stationary and while they are evacuating. Because radionuclides would be deposited continually from the cloud as it passed a given location, a person while under the cloud would be exposed to ground contamination less concentrated than if the cloud had completely passed. To account for this, at least in part, the new model assumes that persons are exposed to the total ground contamination concentration, calculated to exist after complete passage of the cloud, when completely passed by the cloud, to one half the calculated concentration when anywhere under the cloud, and to no concentration when in front of the cloud. A graphical description of the people/cloud interactions treated in this model is included in Appendix A.

IV. REINTERPRETATION OF EPA EVACUATION DATA

The EPA evacuation data [6] for transportation accidents presented in Table 1 was used to determine representative effective evacuation speeds for use in the RSS evacuation model. The revised model of public evacuation described in this report requires as input estimates for both a delay time before public movement and an evacuation speed while in transit. While the data recorded for the evacuation events listed in Table 1 includes the total evacuation period or time, the delay and transit times are not given. However, sufficient information is available for the separation of delay and transit times if a specific actual evacuation speed is assumed. The transit time for each evacuation event can be estimated by dividing the recorded evacuated distance by the assumed evacuation speed. Subtracting the estimated transit time from the recorded evacuation period results in the appropriate delay time for that event. Performing this calculation for each of the ten evacuation events listed in Table 1 for selected assumed evacuation speeds leads to the following estimates of the mean and range of corresponding delay times.

Assumed Evacuation Speed (MPH)	Mean Delay Time (hours)	Range of Delay Times (hours)
10	2.8	0 - 5.5
20	3.2	0.4 - 6.8
30	3.3	0.6 - 7.2
40	3.4	0.7 - 7.4

Statistical analysis of the data suggests that for each assumed evacuation speed, the distribution of delay times calculated may be satisfactorily represented by a normal distribution. Using a normal distribution for each of the assumed speeds suggests the following 15-85 percent range of delay times.

Assumed Evacuation Speed (MPH)	15-85% Range of Delay Times (hours)
10	0.9 - 4.7
20	1.2 - 5.2
30	1.3 - 5.3
40	1.4 - 5.4

As indicated by the information above, the mean and likely range of delay times suggested by the EPA data are relatively insensitive to the evacuation speed assumed. Regardless of what speed is assumed the mean, 15 and 85 percent delay times are approximately 3, 1 and 5 hours, respectively.

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APPENDIX A

Graphical Description of Evacuation Model

This appendix graphically illustrates the possible space/time interactions of evacuating persons and the cloud of radioactive material as treated by the revised evacuation model. Figure 1 shows the radial position of the radioactive cloud as a function of time following warning of the impending release. The warning is assumed to occur at time = 0, and t_w is the time available after warning and before the start of the release. t_r is the duration of release. The positions of both the front and back of the cloud are indicated, and for simplicity the speed of the cloud (windspeed) is assumed constant in this figure. In actual computations performed using the consequence model, the speed of the cloud can vary downwind distance interval. Also, both in the model and the figure, the speeds of the front and back of the cloud are assumed to be identical (i.e., the cloud has a constant length).

Figure 2 shows the radial position of evacuating people initially located at d_o as a function of time following warning. Again, the warning is assumed to occur at time = 0, and t_o is the delay time before people begin to move away from the reactor. Evacuating persons are assumed to move radially away from the reactor with a constant velocity, v_p. The distance functions of the cloud and people are given by:

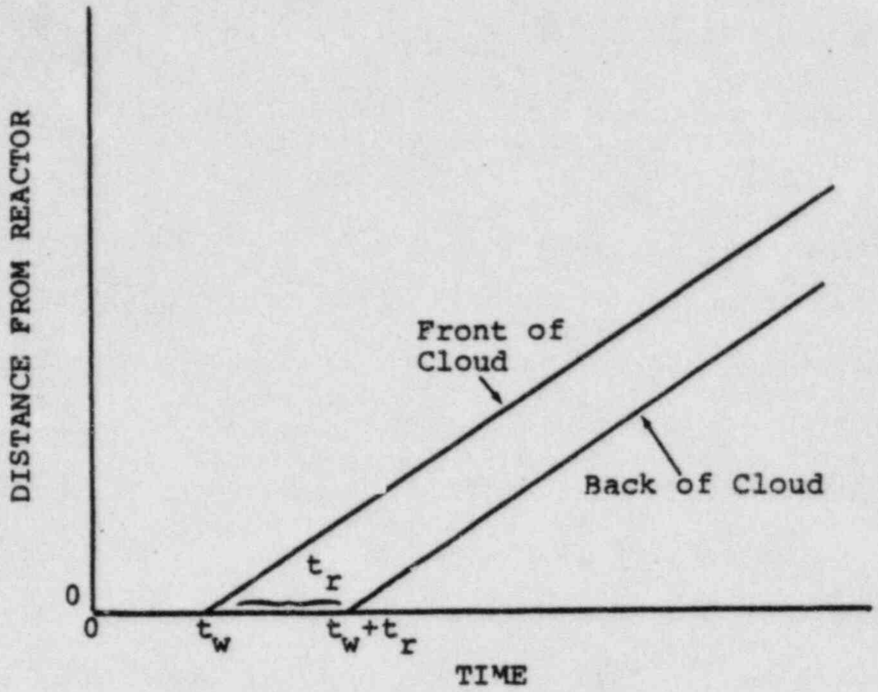


Figure 1. Radial Position of Cloud as a Function of Time

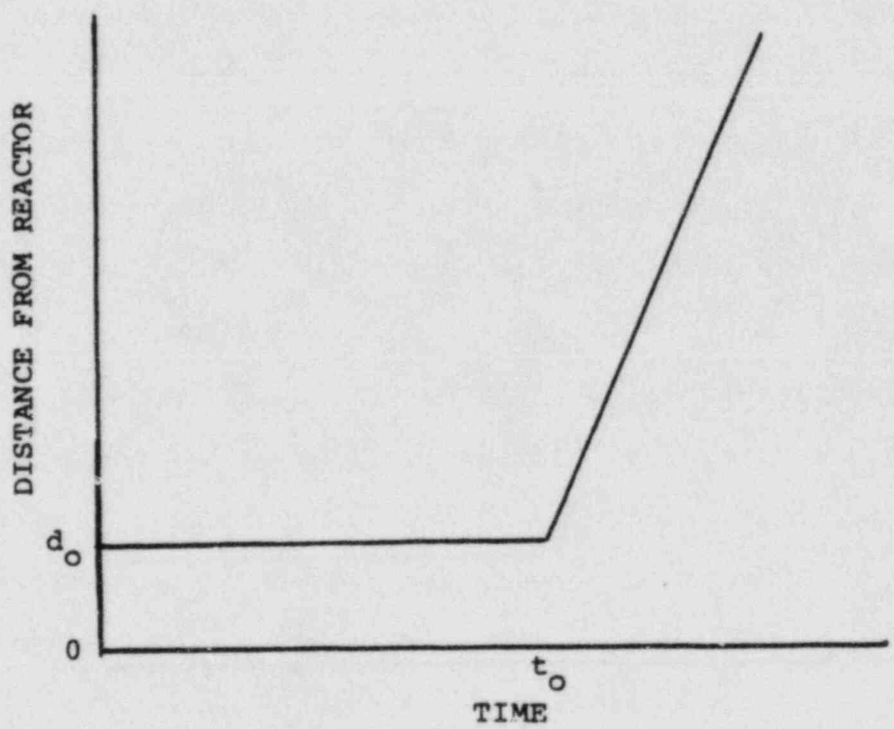


Figure 2. Radial Position of Evacuating People as a Function of Time

People:

$$d_p(t) = \begin{cases} d_o & , t \leq t_o \\ v_p(t-t_o) + d_o & , t > t_o \end{cases} \quad (A.1)$$

Front of Cloud:

$$d_{c_f}(t) = \begin{cases} 0 & , t \leq t_w \\ v_c(t - t_w) & , t > t_w \end{cases} \quad (A.2)$$

where v_c = average cloud velocity up to $d_{c_f}(t)$.

Back of Cloud:

$$d_{c_b}(t) = \begin{cases} 0 & , t \leq (t_w + t_r) \\ v_c\left[t - (t_w + t_r)\right] & , t > (t_w + t_r) \end{cases} \quad (A.3)$$

Figure 3 combines Figures 1 and 2 as an example of the people/cloud interaction possibilities treated in the evacuation model. In the hypothetical situation indicated, the entire cloud passes by the population located at d_o before they begin to move. However, once the population begins

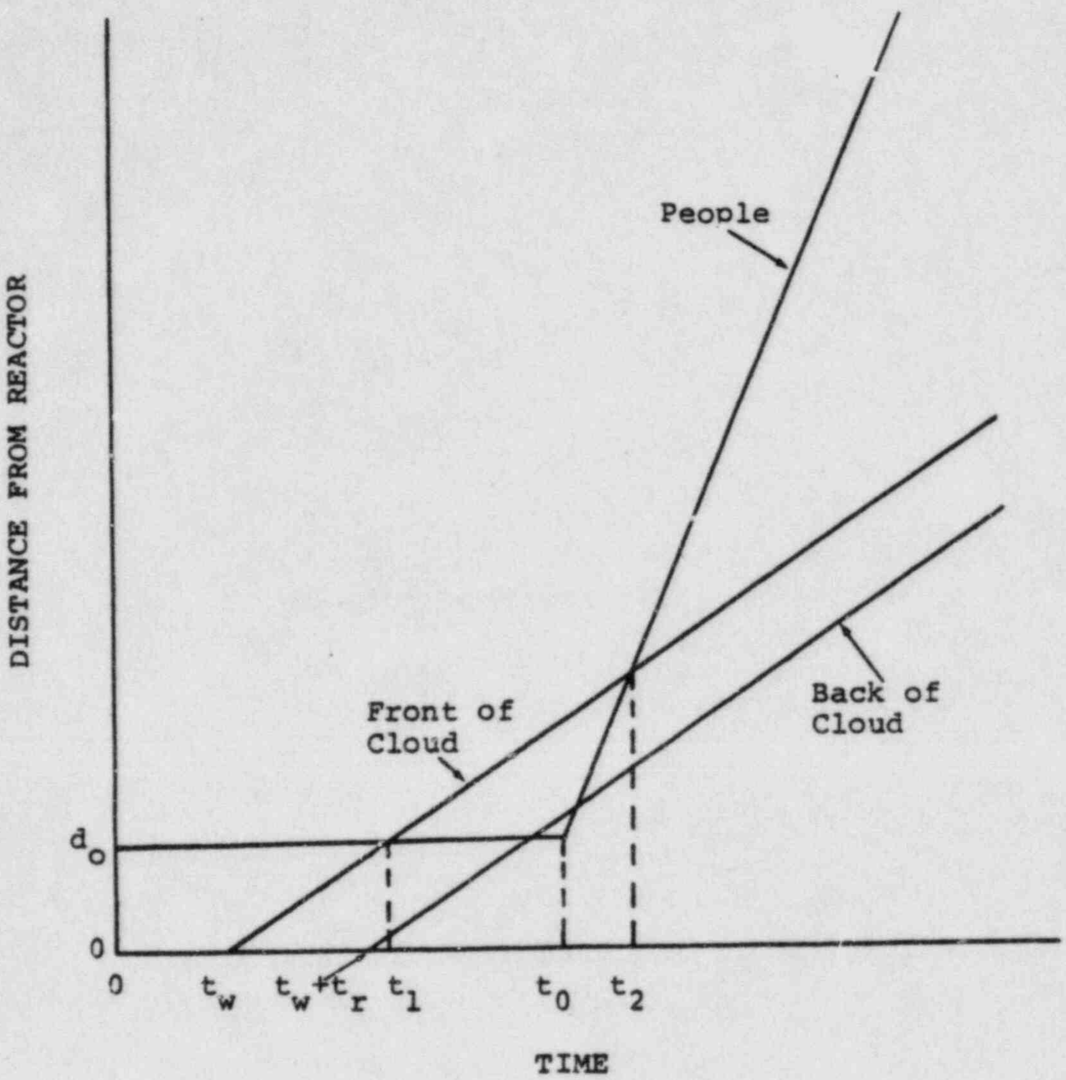


Figure 3. One Example of the Interaction of Evacuating People and Cloud as a Function of Time.

moving away from the reactor, they rapidly overtake and escape the cloud.

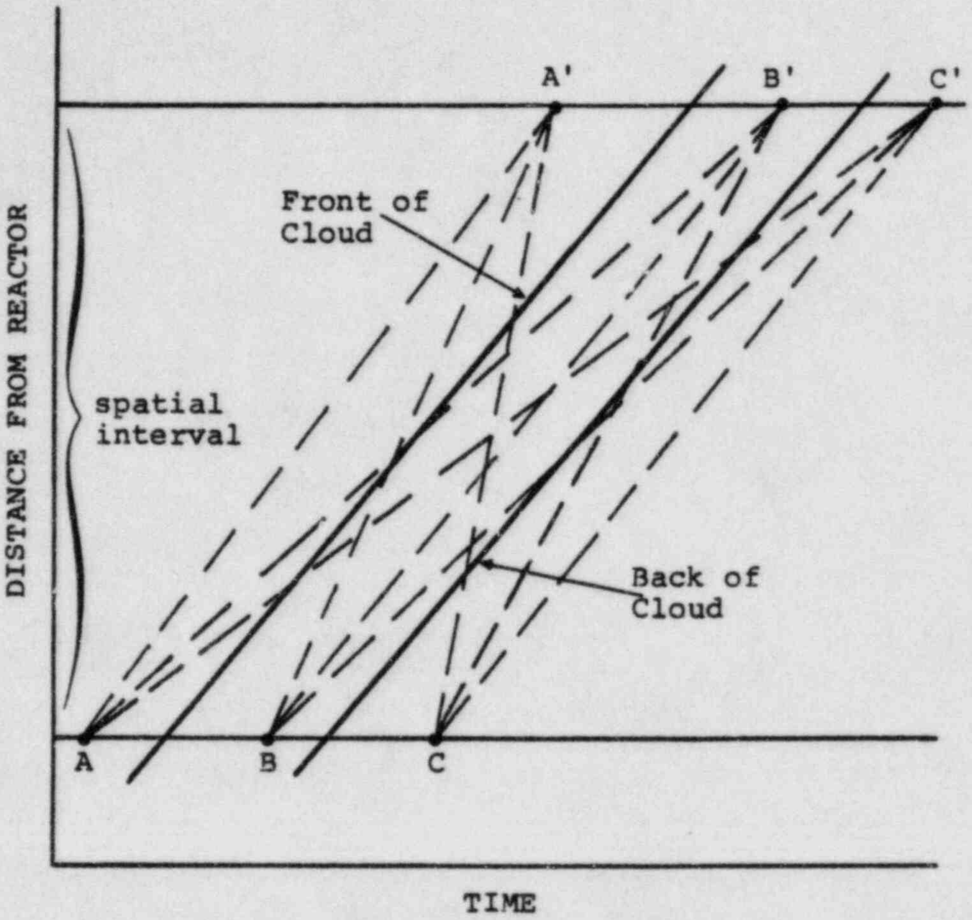
Exposure implications:*

i) people are exposed to cloud twice: once while stationary, once in transit

ii) people are exposed to ground contamination for $(t_o - t_1)$ while stationary and for $(t_2 - t_o)$ while in transit

The exposure history of downwind populations is calculated on a distance interval basis in the consequence model [1]. As people evacuate through each interval, there are nine possible people/cloud interactions, all of which are treated by the evacuation model. The following figure schematically illustrates these situations.

*Shielding factors and breathing rates may be different while stationary and in transit.



1) (A, A'): People travel in front of cloud
2) (A, B'): Cloud overtakes people
3) (A, C'): Cloud overtakes and passes people
4) (B, A'): People escape from under cloud
5) (B, B'): People travel under cloud
6) (B, C'): Cloud passes people
7) (C, A'): People overtake and pass cloud
8) (C, B'): People overtake cloud
9) (C, C'): People travel behind cloud

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