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Protective Action Evaluation Part II

The Effectiveness of Sheltering as a Protective Action Against Nuclear Accidents Involving Gaseous Releases

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PROTECTIVE ACTION EVALUATION

PART II

THE EFFECTIVENESS OF SHELTERING AS A PROTECTIVE ACTION AGAINST NUCLEAR ACCIDENTS INVOLVING GASEOUS RELEASES

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FOREWORD

The Office of Radiation Programs carries out a national program designed to evaluate the exposure of man to ionizing and nonionizing radiation, and to promote the development of controls necessary to protect the public health and safety and assure environmental quality.

Office of Radiation Programs technical reports allow comprehensive and rapid publishing of the results of intramural and contract projects. The reports are distributed to groups who have known interests in this type of information such as the Nuclear Regulatory Commission, the Department of Energy, and State radiation control agencies. These reports are also provided to the National Technical Information Service in order that they may be readily available to the scientific community and to the public.

Comments on this report, as well as any new information, would be welcomed; they may be sent to the Director, Environmental Analysis Division (AW-461), Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, D.C. 20460.

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PREFACE

The material contained in this report was sponsored by the U.S. Environmental Protection Agency under the technical guidance of Mr. J. Logsdon of the Office of Radiation Programs, Environmental Analysis Division. Based on a study to assess the application and utility of sheltering and evacuation as specific protective measures in the event of accidental releases of gaseous radioactive material from nuclear power plants, this report is the first of two that deal specifically with the effectiveness of public shelter structures.

The second report evaluates both sheltering and evacuation protection measures from the standpoint of providing technical guidance in formulating emergency planning procedures.

The purpose of this contract report is to provide a technical basis for EPA to develop guidance with regard to actions to protect the public from accidental airborne releases of radioactive material from nuclear power facilities. The information in this report should not be construed as guidance from EPA to State and local officials in development of their radiological emergency response plans. Such guidance will be published in the "Manual of Protective Action Guides and Protective Actions for Nuclear Incidents," currently under development by the EPA Office of Radiation Programs. The Environmental Protection Agency is making this report available as a source of technical information.

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I. INTRODUCTION

Both evacuation and sheltering can provide protection for the public against exposure to gaseous radioactive fission products released during a nuclear power plant incident. The degree of protection that could be provided by shelter structures available to the public is limited by inherent structural characteristics. Evacuation, on the other hand, is potentially 100-percent effective, depending on temporal and logistic considerations.

This report attempts to develop initial technical guidance information that will quantitatively define important considerations and pertinent parameters that may affect the recommendation of an appropriate course of emergency protective action. To that end, the effectiveness of evacuation and sheltering are compared against a common operational time-frame for variations in temporal parameters based on idealized model representations and parameter ranges of source release and operational logistics.

The means of estimating sheltering effectiveness, or dose reduction factor (DRF), are described in the first report of this study [1]. DRF is based on a computational model that considers small structure (SS) and large structure (LS) shelter categories, including particular physical features that determine their protection characteristics, which together with access-timing characteristics define to what extent their protection potential can be realized.

In this report, evacuation effectiveness estimates are based on a simplified computational model that considers the various possible exposure-time increments over a time-frame determined by the source release and cloud-exposure duration, estimated time of cloud arrival at the point of interest, and information and procedural delay times. The model also assumes that evacuation takes place in a representative vehicle (a passenger car or bus) over a transit period for which it is assumed that a somewhat reduced exposure to the airborne cloud and ground-fallout source occurs while leaving a vicinity enhazarded by the radioactive gaseous fission-product release.

Evacuation and sheltering evaluations are based on comparing calculated model estimates of their respective DRF values to make recommendations for the course of emergency protective actions. Both whole body (WB) and thyroid doses may occur during a gaseous fission-product release, but not necessarily equal protection for WB and thyroid exposure would be provided for either evacuation or sheltering, and a protective-action recommendation must be based on which type of exposure is the most important insofar as expected dose reduction is concerned.

This report describes a procedure that provides guidance in using evacuation and sheltering effectiveness information that includes identifying which exposure (WB or thyroid) is the most important for the development of emergency-action plans that would form the basis of a decision to take appropriate action at the time of the accident. Also discussed are the advantages of combination emergency protection actions of sheltering and evacuation, particularly for the sequence of initial sheltering followed by evacuation.

Appendix A (pp. 57-58) lists the special terms used in this report.

II. ANALYSIS

A large portion of the technical material used in the analysis of the effectiveness of evacuation and sheltering protective measures for the public is presented and discussed in an earlier report [1], which deals specifically with sheltering. For example, Ref. 1 includes nuclide source data, shielding attenuation, finite source-geometry correction, air change rate, and derivations of analogous dose equations. Therefore, the following discussion focuses primarily on evacuation, with frequent referral to Ref. 1 for continuity.

RADIONUCLIDE SOURCE

Table 1 gives the radionuclides and associated data used in this study to simulate a fission-product release of the rare gases Xe and Kr and the significant radioiodines. The Xe, Kr, and I radionuclide sources and parameters shown are essentially the same as those given in WASH-1400, Appendix VI [2], with the exception of Xe-133m and Xe-135m, which have been added for completeness only, since they would not affect results significantly.

Fission-product source inventory data based on ORIGEN Code calculations [3] were used to estimate the Xe-133m and Xe-135m sources listed in Table 1, based on a 550-day irradiation period (same as Ref. 2). Since the decay half-life of Xe-135m decaying to Xe-135 is short (15.6 min) considering the times of interest (hours) in this study, the estimated shutdown zero-time Xe-135m inventory was added to the Xe-135 source on a mass basis and converted to Xe-135 on an activity basis, which increases to 0.27 Ci instead of 0.26 Ci given for Xe-135 in Ref. 2. The metastable decay half-life for Xe-133 is by comparison appreciable, and no similar adjustment for the Xe-133 source inventory was made.

The average decay gamma energies listed in Table 1 for the metastable Xe radionuclides were taken from Ref. 4 (pp. 32-33); the whole-body (WB) cloud gamma-dose factors, from Ref. 2, Appendix D. These dose factors for the ground-γ (surface deposition source) do not take ground roughness into effect (such as a factor of 2). The estimated effectiveness values

Table 1

RADIONUCLIDE SOURCE DATA

Nuclide	Half-Life (hr)	Source (Curies ÷ 10^8) (Q)	Average Gamma Energy (MeV) (E)	Dose Factors			
				Cloud-γ $\frac{\text{rem}}{(\text{ci-sec/m}^3)}$	Ground-γ $\frac{(\text{rem/hr})}{(\text{Ci/m}^2)}$	WB Dose (50-yr) (rem/Ci)	Thyroid (50-yr) (rem/Ci)
Kr-85	93,600	0.006	0.0	0.0	0.0	0.0	0.0
Kr-85m	4.32	0.26	0.16	0.036	↓	↓	↓
Kr-87	1.27	0.52	0.82	0.36			
Kr-88	2.78	0.76	2.21	0.42			
Xe-133	127	1.7	0.08	0.007			
Xe-133m	55.2	0.04[a]	0.23[b]	0.0075[c]			
Xe-135	9.12	0.27[a]	0.26	0.06			
Xe-135m	0.27	0.27[a]	0.52[b]	0.0972[c]			
I-131	193	0.85	0.39	0.09	2.8	2,600	1.47×10^6
I-132	2.4	1.2	2.3	0.55	17	130	5.3×10^4
I-133	21	1.7	0.63	0.12	3.7	570	3.96×10^5
I-134	0.864	2.0	2.4	0.6	16	40	2.5×10^4
I-135	6.72	1.5	1.45	0.42	12	290	1.23×10^5

[a] Based on Refs. 2 and 3.

[b] Ref. 4.

[c] Ref. 5

in terms of a dose reduction factor (DRF) would not be affected significantly whether or not the ground roughness adjustment were included, as the effect would be the same both inside and outside the shelter structure.

An estimate of the average gamma decay energy was made for the source nuclides to serve as a guide in 1) estimating gamma-ray attenuation factors for shelter structures and vehicles; and in 2) making estimated adjustments for finite source geometries for interior shelter and vehicle cloud-source volume, since the dose factors for cloud-γ apply to infinite source geometries. The average gamma decay energy was estimated to be $\sim$1.2 MeV, based on the following simple weighting relationship:

$$\langle E \rangle = \frac{\sum_j Q_j E_j \mu_e(E_j)}{\sum_j Q_j \mu_e(E_j)} ,$$

where Q_j and E_j are the radionuclide source activities and gamma energies, respectively, listed in Table 1, and $\mu_e(E_j)$ is the gamma-ray linear energy absorption coefficient as a function of energy for air given in Ref. 6. The estimate of the average gamma ray energy was based on a summation over all the radionuclides shown in Table 1, with the exception of Xe-135m--again because of its short half-life for the times of interest in this study. The gaseous radionuclide data in Table 1 are used to estimate evacuation and sheltering effectiveness in dose reduction by summing each nuclide contribution (assuming single radionuclide decay) to obtain the unprotected and protected dose. Design basis assumptions (DBA) are made for the source release--100 percent of the noble gases and 25 percent of the iodines available for release.

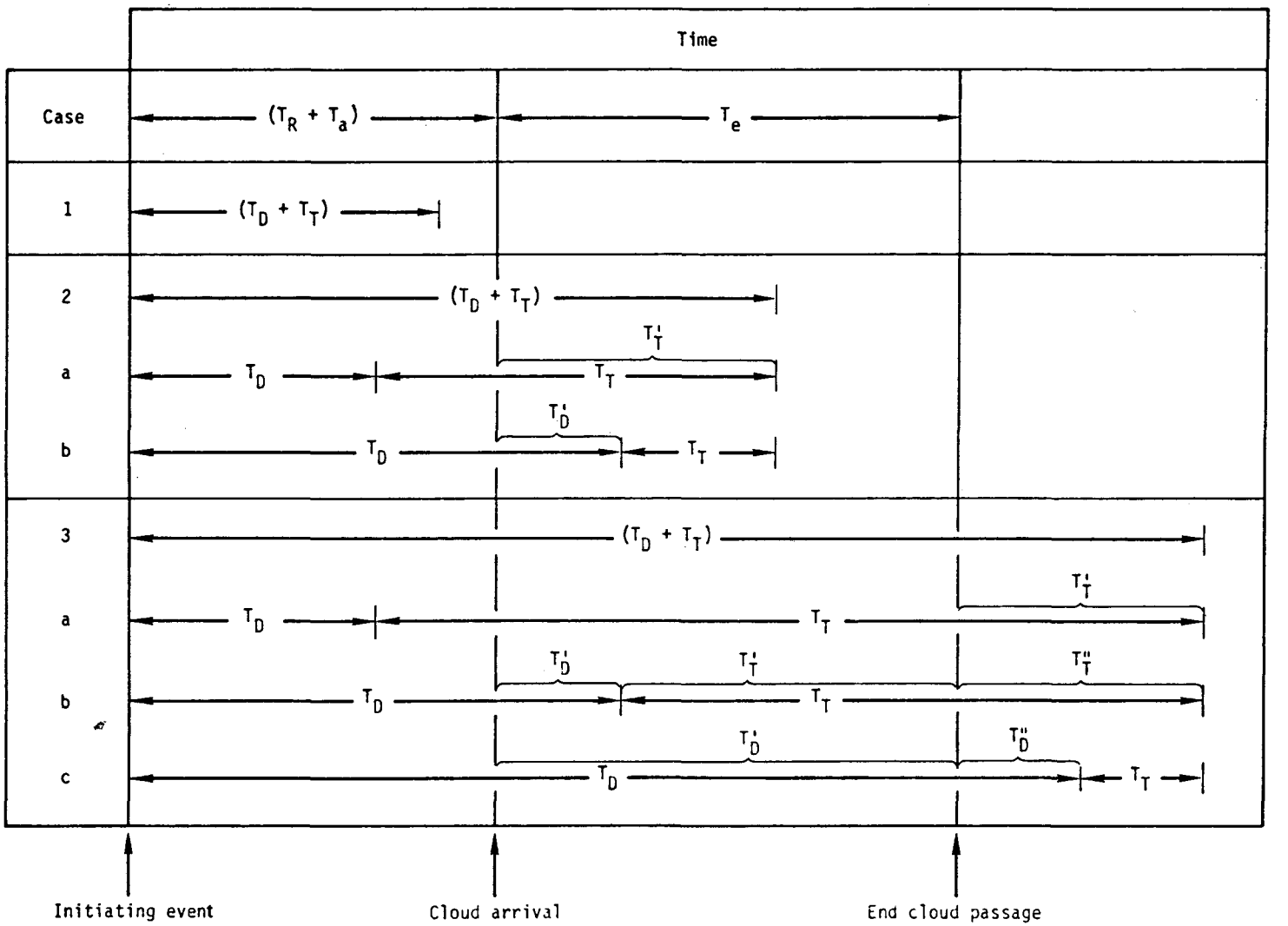
TIME-FRAME MODEL

The effectiveness of sheltering and evacuation as measures for protection from airborne radioactive material accidentally released from a nuclear power plant is primarily dependent upon the time required for individuals either to gain entry into a protective structure or to move

away from the vicinity of the radioactive airborne and ground fallout material. Reference 1 discusses details of timing considerations for sheltering primarily, whereas this report emphasizes evacuation.

Figure 1 gives the time-frame considerations of the dose computational model. The source release time, T_R (time duration from initiating event to commencement of source release at the facility), plus the cloud arrival time, T_a (time for source to travel from facility to downwind reference position, $x = \bar{u}T_a$), determine the expected delay time when radiation exposure commences measured from the initiating reactor accident event. T_e is the cloud-passage time duration of the reference point, a distance $x = \bar{u}T_a$ downwind from the facility. That is, measured from initiation of a possible incident, (T_R+T_a) is the estimated time-of-arrival of the lead portion of a radioactive cloud. T_R, measured from incident initiation, may vary from about 1.5 to 9 hr for the more severe accident categories [2]. Values of T_R from 1.5 to 3 hr were considered to be of more interest for sheltering, whereas longer times might be more applicable to evacuation considering the possibly greater time requirements to effect evacuation than sheltering.

Based on siting data given for 76 nuclear power plants [7], the average low-population zone (LPZ) distance is 3.4 mi. Assuming the cloud arrival time $T_a = x/\bar{u}$, T_a would range from 20 min to 1.5 hr for wind speeds ranging from 11 to 2 mph, respectively. The time required for evacuation from incident initiation is shown in Fig. 1 as (T_D+T_T), where T_D is the delay-time duration from the initiating event to the evacuation order, and T_T is the actual time increment spent in evacuating (while being exposed to the airborne radioactive material). Delay-time estimates (T_D) have been discussed by the EPA [8] with regard to evacuation that may also be somewhat applicable to sheltering, since the time components of T_D are similar or may in fact be one and the same in terms of a local decision process. In Fig. 1, T_D represents the total delay time from initiation of an event to onset of physical movement. For evacuation, the EPA estimates this delay time as being from 0.9 to 4.5 hr [8]. Also, for evacuation, the EPA estimate for T_T



T_R = source release time
T_a = cloud arrival time
T_e = cloud passage time

T_D = delay time from initiating event to evacuation alert
T_T = actual time spent evacuating while being exposed to radiation sources

Fig. 1--Evacuation time-frame

is from 0.2 to 1.5 hr, which may be excessive for sheltering. (Reasonable sheltering times may be anywhere from a few minutes to half an hour.)

The cloud passage time, T_e, would depend on source release duration (T_s) and wind persistence time (direction and speed). T_s may range from 0.5 to 4 hr for accidental release events [2], i.e., periods of time where shelter may be effective. For cloud passage periods of more than about 6 hr, shelter would be less attractive and evacuation may offer a greater protective advantage. Estimates of wind persistence time should be based on particular site meteorology. In terms of protective action by the public (i.e., taking shelter or evacuating), the wind-persistence time estimates made at the time of and during post-incident phases of an accident are among the most important parameters affecting the effectiveness of protective action. Ideally, of course, the best situation is to base protective action recommendations on real-time wind-trajectory data. Normally, however, local wind forecast information would be available from local weather service sources. Short of that, useful information on persistence for making protective action decisions would be an estimate of the mean or expected wind-direction persistence time--given a particular time of the day and that a particular direction has been maintained up to that point. This latter type of predictive ability would have to be formulated from a detailed statistical analysis of site meteorological data of record requiring frequent observations (perhaps every 15 min) over an adequate period of time. A means of computing source-cloud trajectory based on real-time analysis of site and regional meteorological data is described as a feature of the ARAC program currently being developed at the Lawrence Livermore Laboratory [9]. This kind of capability would obviously be very useful in planning emergency public actions such as sheltering and evacuation.

For this study, exposure time, T_e, is equal to the shorter of either release duration, T_s, or the wind persistence time. The three time cases in Fig. 1 compare assumed values of (T_D+T_T) with (T_R+T_a) and $(T_R+T_a+T_e)$, and the subcases are in turn determined by the values of T_D and T_T.

Case 1, for example, corresponds to DRF = 0, in which evacuation is accomplished prior to cloud arrival and all exposure is avoided--i.e., $(T_D+T_T) \leq (T_e+T_a)$. On the other hand, case 3c corresponds to a situation in which evacuation does not physically commence until after cloud passage, and the overall dose reduction would be limited--since only some relatively small degree of protection would be offered against only ground fallout deposition, assuming individuals leave the contaminated area within a reasonable amount of time (i.e., within an hour or so).

Case 2 corresponds to the situation in which evacuation is not completed until some time after cloud arrival, which divides into subcases a and b, where actual physical movement commences before and after cloud arrival, respectively. In subcase 2b, an individual is assumed to be exposed to radioactive material without protection during the period T_D'; and protected within the confines of an evacuation vehicle over the periods T_T' and T_T for subcases 2a and 2b, respectively.

Subcases 3a and 3b are essentially time extensions of subcases 2a and 2b, respectively, in which again, T_D and T_T vary for $(T_D+T_T) \geq (T_R+T_a+T_e)$. Similarly, the T_D (and T_D-primes) correspond to unprotected exposure, and T_T (and T_T-primes) correspond to protected exposures within the confines of an evacuation vehicle.

In terms of the time-frame model, the evacuation effectiveness is defined as the ratio of the dose received under combined unprotected and protected conditions to that received under wholly unprotected conditions over the interval of cloud passage and evacuation. The time-frame model is thus formulated to include the effects of the time parameters on evacuation effectiveness. The effectiveness estimates in this study are mainly concerned with times commencing at cloud arrival, (T_R+T_a), in which simple radioactive decay by each source isotope is considered over (T_R+T_a). Note also that the time-frame model assumes an abrupt boundary at both the leading and trailing edges of the radioactive cloud material. In reality, of course, this is not true, as it is well known that turbulent diffusion in the atmosphere gives rise, on the average, to continuously changing airborne source boundaries--whose dimensional scales, however, are such that the above model would be a reasonable approximation, considering the source release intervals of interest (excluding an instantaneous puff).

EVACUATION VEHICLE

Effectiveness estimates of evacuation (i.e., DRF) in this study assume that evacuation takes place inside a vehicle transporting individuals away from the vicinity of airborne and ground-fallout radioactive material. Of course, individual evacuation may take place by any means--e.g., by bicycle or even on foot, which may be very effective if completed prior to cloud arrival. Obviously, however, vehicular evacuation is much more effective, if carried out according to plan, because of transit-time advantage and some degree of protection provided by the vehicle where radioactive sources are present. The following discussion of the calculation model considers vehicular protection.

A variety of vehicle types could be used for transporting individuals in emergency situations. Although varying degrees of protection could be realized, the relative variations would not approach those inherent in building structures. For convenience of analysis, the numerical calculations of this study assume a representative vehicle (passenger car or bus).

During vehicular evacuation, WB dose would result from vehicle penetration of gamma radiation from the airborne radioactive cloud and the ground fallout during cloud passage (and from only ground fallout after cloud passage) and from the inhalation exposure of airborne radioactive material that would infiltrate the moving vehicle during transit. Any dose from interior vehicle surface contamination (e.g., fallout) is assumed negligible and therefore neglected for the purposes of WB-dose calculation. The inhalation exposure of radioiodine inside the vehicle is, of course, assumed for purposes of thyroid-dose calculation.

Since the DRF for evacuation is also based on unprotected doses as well as dose estimates incurred in the vehicle during evacuation, WB exposure from cloud, fallout, and inhalation exposures is taken into account for unprotected individuals as well as the inhalation of radioiodine for the unprotected thyroid dose.

Assuming an evacuation vehicle, Burson and Profio [10] estimate that steel and glass used in automobiles and small trucks average roughly 2 gm/cm^2 of shielding thickness for gamma radiation from an airborne cloud source. From Fig. 3 of Ref. 1, this thickness corresponds to an attenuation of only about 0.95 (the value assumed in this analysis). For heavier vehicles (e.g., large commercial buses), the gamma attenuation may be 0.8 to 0.9--still not appreciable. Also assuming an effective vehicle enclosure radius of about one meter gives a source-geometry correction factor for WB gamma exposure of about 0.003 (Fig. 5, Ref. 1) for the contaminated airborne material in the vehicle.

Gamma ray attenuation in automobiles and small trucks is 0.5 for contaminated 50-ft-wide roads (Table 4, Ref. 1). Values estimated by Burson, based on experimental measurements [11], were from 0.5 to 0.67. An average value of 0.6 is assumed in this analysis.

Air change rates for automobiles under various conditions of operation have been determined by Peterson and Sabersky [12]. Their results (Fig. 2) are from measurements made of pollutants (O_3, CO, NO, and NO_X) inside a stock Chevrolet automobile with an air-conditioning unit. The exchange rate is relatively high. In fact, the passenger compartment is not intended to be airtight; and even in the maximum air-conditioning mode, a small fan draws outside air into the compartment. Without this ventilation, the rates can probably be reduced by a factor of 5 without difficulty. The single point marked by an arrow in Fig. 2 was taken when, with the windows closed, the vehicle's air conditioning was turned off but the engine left running. Under these conditions, a fan still draws in outside air. At higher speeds and with the same settings, f/v (air change rate) would be expected to approach the values obtained with the air-conditioning unit in operation. This expectation is based on the assumption that general leakage rather than the fan is the dominant factor determining f/v at these speeds. A value of 0.5 min^{-1} (30 hr^{-1}) was chosen for this analysis, which corresponds to $\sim$35 mph when general leakage is the dominant factor for f/v. Penetration of gaseous fission products into the evacuation vehicle was assumed to be 100 percent for the rare gases and 80 percent for radioiodines,

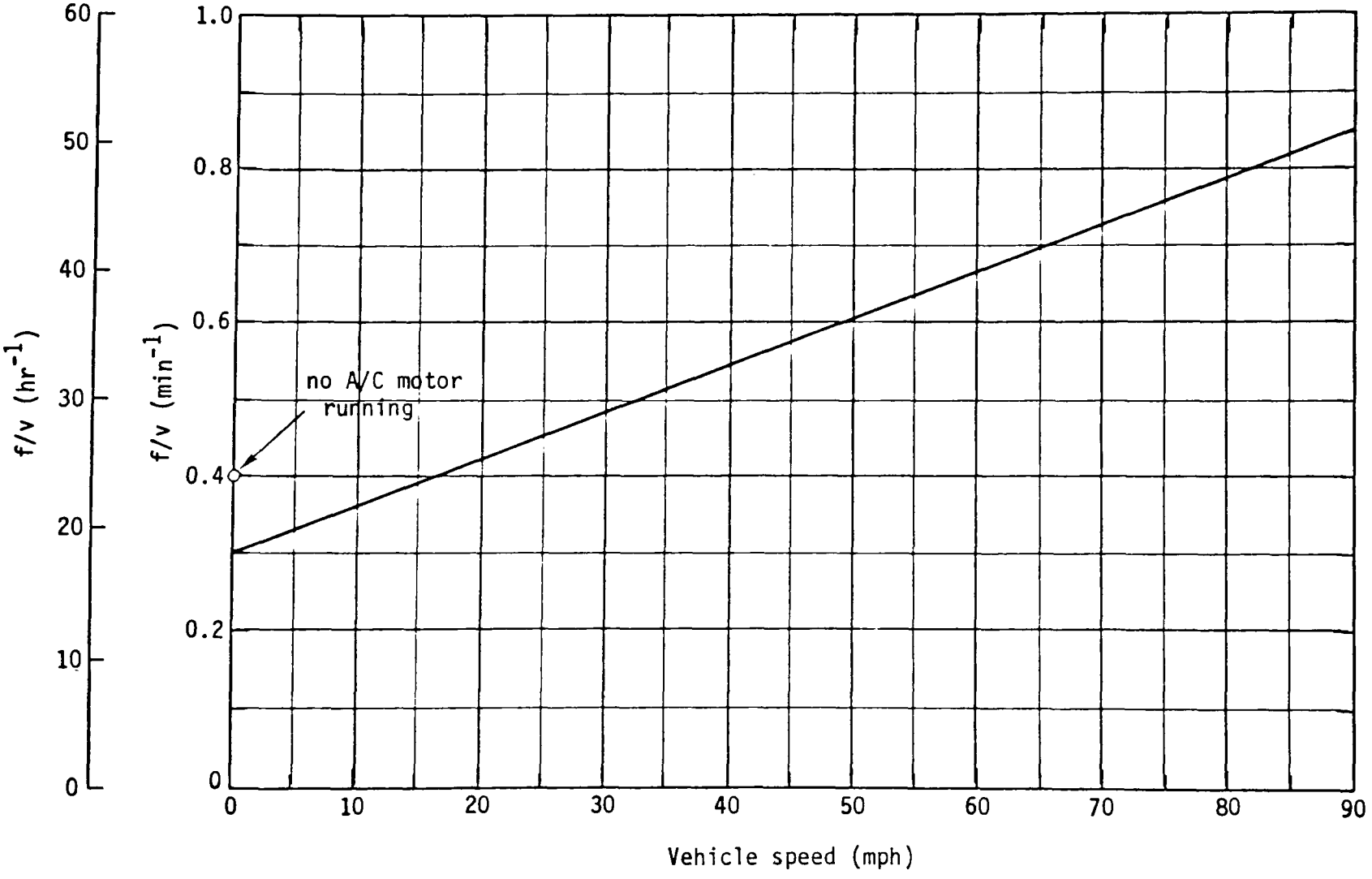


Fig. 2--Air exchange and infiltration rates in closed passenger compartment when air conditioning is set at a maximum

which corresponds to the upper limit of the estimates of Megaw [13] based on simple shelter-structure experiments.

DOSE REDUCTION FACTOR

Effectiveness estimates of evacuation are expressed in terms of the DRF. This value is the ratio of the dosages received during evacuation to that incurred in the open assuming no evacuation (i.e., a stationary unprotected receptor). DRF values are estimated for both WB and thyroid exposures. The DRF for WB gamma dose is given as

$$(DRF)_{\gamma} = \frac{EC + IC + FD}{EC_o + IC_o + FD_o} ,$$

where

EC = external gamma airborne-source dose (evacuation),

EC_o = external gamma airborne-source dose (no evacuation),

IC = inhalation airborne-source dose (evacuation),

IC_o = inhalation airborne-source dose (no evacuation),

FD = external gamma surface-source dose (evacuation),

FD_o = external gamma surface-source dose (no evacuation).

The DRF for thyroid dose is given as

$$(DRF)_{thyroid} = \frac{TC}{TC_o} ,$$

where

TC = thyroid inhalation dose (evacuation),

TC_o = thyroid inhalation dose (no evacuation).

The EC, IC, FD, and TC dose components (those components received with evacuation) may include doses incurred during delay times prior to evacuation--but after cloud arrival--and/or doses received in a vehicle during evacuation. The EC and FD components received in the vehicle

during evacuation would result from penetration of cloud and fallout gamma radiation, respectively. The inhalation dose (IC and TC) components received in the vehicle during evacuation would result from the inhalation of airborne radioiodine. The EC_o, IC_o, FD_o, and TC_o dose components are the reference values corresponding to the dosages incurred over the total time span considered for the EC, IC, FD, and TC components above. The dose components are developed by integrating the time-dependent source for evacuation and sheltering for a unit downwind dilution factor, as reviewed below.

Doses downwind from an accidental release of airborne gaseous fission products are dependent on the concentration of the airborne radioactive material, which can be expressed as follows for continuous source release conditions:

$$\chi(r,t) = (\chi(r)/\dot{Q})\ \dot{Q}(t) \qquad (Ci/m^3) \quad ,$$

where $\chi(r)/\dot{Q}$ (sec/m^3) is the ratio of the concentration $\chi(r)$ (Ci/m^3), at a distance r from the release to the source release rate $\dot{Q}$ (Ci/sec); and $\dot{Q}(t)$ (Ci/sec) is the time-dependent source-release rate function. In general, the dose at r is given by the integral of the concentration over the period of exposure, T_e:

$$D(r) = \int_0^{T_e} K_D\ \chi(r,t)\ dt \qquad rem \quad ,$$

where K_D is a dose conversion factor. For this study, calculations were performed assuming $\chi(r)/\dot{Q}$ unity (i.e., a unit dilution factor), since it is a common multiplier for all dose components and therefore does not affect DRF values. Accordingly, the dose component estimates described here are based on integrations of the time-dependent sources both inside and outside the evacuation vehicle. The release rate at the source is assumed to be constant with a correction for simple radioactive decay over a release period, T_s:

$$\dot{Q}(t) = \frac{f_r Q_o}{T_s}\ e^{-\lambda t} \qquad (Ci/sec) \quad ,$$

where Q_o is the initial radionuclide activity inventory in the reactor at the time of an accident (Table 1, p. 4), f_r is the radionuclide release fraction (DBA assumptions), and λ is the radioactive decay constant. For ease of illustration, the development of the following dose components does not use subscripts designating each radionuclide source, and it should be understood that summations over radionuclide sources are performed in making computations.

The following discussions in this section deal with the relationships used for calculations of the dose components. These calculations are obtained from differential rate equations and integration over the time-dependent sources. Derivations of the dose component relationships are detailed where necessary in Appendix B (p. 59 ff.).

DOSE COMPONENTS--NO EVACUATION

Whole-body cloud and thyroid dose components assuming no shelter protection are given as

$$\begin{bmatrix} EC_o \\ IC_o \\ TC_o \end{bmatrix} = \begin{bmatrix} K_1 \\ K_2 \cdot B \\ K_3 \cdot B \end{bmatrix} e^{-\lambda(T_R+T_a)} \int_0^{T_e} \dot{Q}(t)\, dt$$

$$= \begin{bmatrix} K_1 \\ K_2 \cdot B \\ K_3 \cdot B \end{bmatrix} \frac{f_r Q_o\, e^{-\lambda(T_R+T_a)}}{T_s \lambda} (1-e^{-\lambda T_e}) \qquad \text{rem} \quad ,$$

where K_1, K_2, and K_3 are the dose conversion factors given for WB cloud gamma, WB inhalation, and thyroid inhalation doses, respectively, and B is the breathing rate assumed to be 3.4×10^{-4} (m^3/sec). In the above formula, the source release duration, T_s, is assumed to be the downwind exposure time, T_e.

The local fallout deposition rate outside the shelter is assumed to be $V_g\chi(r,t)$ (Ci/sec-m^2); and the depletion rate, to be due to only radioactive decay. Expressing the airborne concentration as $\chi(r,t) = \chi_o\ e^{-\lambda t}$, where χ_o includes the $\exp[-\lambda(T_R+T_a)]$ term, the outside ground-fallout deposition, $F_g(t)$ (Ci/m^2), is obtained from the following equation:

$$\frac{dF_g(t)}{dt} = V_g\chi_o\ e^{-\lambda t} - \lambda F_g(t) \quad .$$

Integrating for $F_g(0) = 0$,

$$F(t)_g = V_g\chi_o t\ e^{-\lambda t} \qquad (\mathrm{Ci/m^2}) \quad .$$

The fallout dose component is given by integration of $F_g(t)$ over the time of cloud passage, T_e, plus the contribution from the fallout source after cloud passage integrated over the reference time, T_v:

$$FD_o = K_4\left[\int_0^{T_e} F_g(t) + F(T_e)\int_0^{T_v} e^{-\lambda t}\ dt\right]$$

$$= V_g\chi_o K_4\left\{\frac{1}{\lambda^2}\left[1-(\lambda T_e+1)\ e^{-\lambda T_e}\right] + \frac{T_e\ e^{-\lambda T_e}}{\lambda}\left(1 - e^{-\lambda T_v}\right)\right\} \quad \mathrm{rem} \quad ,$$

where K_4 is the ground-source, gamma-dose conversion factor. In the equation above, T_v is 0.25 hr, which enables evacuation and sheltering to be compared, on the same time basis. That is, 0.25 hr is assumed to be the time it takes for leaving a ground-fallout contaminated shelter area immediately after cloud passage (see Ref. 1).

DOSE COMPONENTS--EVACUATION

The dose components of the DRF-numerators of the equations on p. 13 are given in Table 2 for convenience in discussing the calculational procedure used in estimating the effectiveness of evacuation. The time considerations of the calculational model are designated by the case and subcase divisions corresponding directly to the time-frame illustration given in Fig. 1 (p. 7). For example, in case 1, all dose components are zero, since evacuation takes place prior to cloud arrival. The remainder of the cases correspond to various other time-combination considerations after cloud arrival, indicated by the relationships given under the heading "Operational Time Limits."

The calculational times given in Fig. 1 are the values used in the dose-component relationships for computing the evacuation dosages for each subcase. The manner in which the calculational times are used in the computing procedure is based on the assignment of their values to the dummy arguments T_1, T_2, and T_3 of the general dose-time functions, F or F'. In Table 2, the F- and F'-functions are also given under the column heading as "$F_{n\ell}$ and $F'_{n\ell}$," respectively, where the n-index designates the function type and the ℓ-index identifies the specific application for each subcase. The F and F' apply, respectively, to cloud- and fallout-source dose components. The F_1-function is used for computing dose components for the airborne cloud source outside an evacuation vehicle; the F_2 function, for the airborne source inside the vehicle. The F'_1- and F'_2-functions are both used for computing dose components for the ground-fallout source outside the vehicle. The F functions (developed in Appendix B) are essentially the integrated time functions of the dose components for a unit radionuclide source. Dose-component calculations are carried out for the total time considered, including a maximum time of 0.25 hr after cloud passage to allow for DRF comparisons of sheltering and evacuation on a common basis. That is, for sheltering effectiveness calculations in Ref. 1, shelter exit takes place after cloud passage followed by an assumed 0.25-hr period to leave the area of ground-fallout contamination in the vicinity of the shelter structure.

Table 2

EVACUATION DOSE COMPONENTS

Case	Operational Time Limits	Calculation Times	$F_{n\ell}$ or $F'_{n\ell}$	F Times T_1	T_2	T_3	Dose Components
1	$(T_D+T_T) < (T_R+T_a)$						
2 a	$(T_R+T_a) \leq (T_D+T_T) \leq (T_R+T_a+T_e)$ $T_D < (T_R+T_a)$	$T'_T - (T_D+T_T) \quad (T_R+T_a)$	F_{11} F_{21} F'_{11}	0 0 0	T'_T T'_T T'_T	 0 0	EC = $KE(A_vF_{11}+\epsilon G_vF_{21})$ IC = $KI \cdot F_{21} \cdot \epsilon$ TC $KT \cdot F_{21} \cdot \epsilon$ FD = $KF \cdot A'_v \cdot F'_{11}$
b	$T_D \geq (T_R+T_a)$	$T'_D \quad T_D \quad (T_R+T_a)$	F_{21} F_{11} F_{12} F'_{11} F'_{12}	T'_D T'_D 0 T'_D 0	T_T T_T T'_D T_T T'_D	0 0 0	EC $KE(\epsilon G_vF_{21}+A_vF_{11}+F_{12})$ IC $KI(F_{12}+\epsilon F_{21})$ TC $KT(F_{12}+\epsilon F_{21})$ FD $KF(A'_vF'_{11}+F'_{12})$
3 a	$(T_D+T_T) > (T_R+T_a+T_e)$ $T_D < (T_R+T_a)$	$T'_T - (T_D+T_T) - (T_R+T_a+T_e)$	F_{21} F_{11} F'_{11}	0 0 0	T_e T_e T_e	T'_T T'_T	EC $KE(\epsilon G_vF_{21}+A_vF_{12})$ IC $KI \cdot F_{21} \cdot \epsilon$ TC $KT \cdot F_{21} \quad \epsilon$ FD $KF \cdot A'_v \cdot F'_{11}$
b	$(T_R+T_a) \leq T_D < (T_R+T_a+T_e)$	$T'_D \quad T_D - (T_R+T_a)$ $T'_T \quad (T_R+T_a+T_e) \quad T_D$ $T''_T \quad (T_D+T_T) \quad (T_R+T_a+T_e)$	F_{21} F_{11} F_{12} F'_{11} F'_{12}	T'_D T'_D 0 T'_D 0	T'_T T'_T T'_D T'_T T'_D	T''_T T''_T 0	EC $KE(\epsilon G_vF_{21}+A_vF_{11}+F_{12})$ IC $KI(F_{12}+\epsilon F_{21})$ TC $KT(F_{12}+\epsilon F_{12})$ FD = $KF(A'_vF'_{11}+F'_{12})$
c	$T_D > (T_R+T_a+T_e)$	$T''_D \quad T_D \quad (T_R+T_a+T_e)$	F_{11} F'_{11} F'_{21}	0 0 T_e	T_e T_e T''_D	 T''_D T_T	EC $KE \cdot F_{11}$ IC $KI \cdot F_{11}$ TC $KT \cdot F_{11}$ FD $KF(A'_vF'_{21}+F'_{11})$

$$F_1(T_1,T_2) \quad \frac{1}{\lambda}(1-e^{-\lambda T_2})\, e^{-\lambda T_1}$$

$$F_2(T_1,T_2,T_3) \quad e^{-\lambda T_1}\left[\frac{1}{\lambda}(1-e^{-\lambda T_2}) - \frac{1}{K}(1-e^{-KT_2}) + (e^{-\lambda T_2}-e^{-KT_2})\,\frac{1}{K}(1-e^{-KT_3})\right]$$

$$F'_1(T_1,T_2,T_3) = \frac{1}{\lambda^2}\left[(\lambda T_1+1)\, e^{-\lambda T_1} \quad (\lambda T_1+\lambda T_2+1)\, e^{-\lambda(T_1+T_2)}\right] + \frac{(T_1+T_2)}{\lambda}\,(1-e^{-\lambda T_3})\, e^{-\lambda(T_1+T_2)}$$

$$F_2(T_1,T_2,T_3) = \frac{T_1}{\lambda}\,(1-e^{-\lambda T_3})\, e^{-\lambda(T_1+T_2)}$$

$KE = S\,K_1\,\Gamma \qquad S = f_r\,\frac{Q}{T_e}$

$KI = S\,B\,K_2\,\Gamma \qquad \Gamma \quad \exp\left[-\lambda(T_R+T_a)\right]$

$KT = S\,B\,K_3\,\Gamma \qquad K \quad L_v + \lambda$

$KF = S\,V_g\,K_4\,\Gamma \qquad \lambda = \frac{.693}{T_{1/2}}$

B = breathing rate, 3.4×10^{-4} (m^3/sec)

V_g deposition velocity, 0.005 (m/sec)

ϵ = ingress fraction ($\begin{cases} 0.8, & \text{radioiodine} \\ 1.0, & \text{rare gases} \end{cases}$

G_v finite-source correction factor, 0.003

A_v = gamma attenuation, 0.95

A'_v = 0.6

The dose-component relationships are given in the right-hand column of Table 2. The applicable F-functions are shown with a double index to identify the particular form used for each specific subcase, where the T_1, T_2, and T_3 argument variables are identified by the column values. For example, the external cloud-gamma dose component for case 2b is

$$EC = KE(\varepsilon G_v F_{21} + A_v F_{11} + F_{12}) \qquad \text{rem} \quad ,$$

where $\varepsilon G_v F_{21}$ (hr) is the dose-time function component for the airborne source in the vehicle for the interval T_T; $A_v F_{11}$ is the dose-time function component for the airborne source outside the vehicle for the interval T_T; and F_{12} is the dose-time component for the airborne source outside the vehicle for the interval of unprotected exposure T_D'. In the above relationships, ε is the radionuclide ingress fraction for the evacuation vehicle, A_v is the cloud-gamma radiation attenuation, and G_v is the finite airborne source-geometry correction factor. The constant, KE, for each radionuclide source is given by

$$KE = \left(\frac{\chi}{\dot{Q}}\right) K_D f_r \frac{Q}{T_e} \exp[-\lambda(T_R+T_a)] \qquad \text{rem/hr} \quad ,$$

where

$\chi/\dot{Q} = 1$ (sec/m^3),

K_D = dose conversion factor (rem-m^3/sec-Ci),

f_r = radionuclide release fraction,

Q = radionuclide source (Ci),

T_e = cloud exposure time (hr),

λ = radionuclide decay constant (hr^{-1}),

T_R = source release time (hr),

T_a = cloud arrival time (hr).

The inhalation dose components IC and TC for the WB and thyroid, respectively, use the F_1 and F_2 dose-time functions in the same fashion as indicated for EC above. The fallout dose component, FD, in subcase 2b, includes the F_1'- and F_2'-functions for ground-γ fallout source outside the vehicle. The F_1'-function applies to the time interval, T_D', where unprotected exposure is contracted prior to evacuation; the F_2' is multiplied by the vehicle attenuation of the gamma radiation, A_v', for exposure inside the evacuation vehicle during the transit interval, T_T.

Calculation of the dose components for the DRF estimates is performed by time-stepping the T_D and T_T values over the time subcases indicated in Fig. 2.

III. RESULTS

The results of this study are discussed in two subsections below. The first subsection presents dose reduction factor (DRF) plots for the WB and thyroid in terms of a comparison of evacuation and sheltering as protective action measures against the release of gaseous fission products. Four basic source release cases are considered:

Case	Time Delay to Start of Source Release T_R, Hr	Exposure Duration T_e, Hr	Cloud Travel Time From Facility T_a, Hr
A	1.5	0.5	1
B	2.0	1.0	1
C	2.5	3.0	1
D	2.5	6.0	1

The source release and duration times, T_R and T_e, respectively, for cases A, B, and C above correspond to release categories PWR 1, PWR 3, and PWR 4 in Ref. 2. Case D is like case C but has a larger assumed source-release duration time of 6 hr, adequate to demonstrate the comparative trends in evacuation and sheltering effectiveness. Also, sufficient data are given to allow extrapolation and cross-plotting.

The second subsection focuses on a procedure for using the results in making recommendations for protective actions based on pertinent input information associated with a release incident. Although use of the procedure is illustrated by example, note that it would be difficult--within the scope of this study--to anticipate all possible situations involving a release incident that may arise in terms of time, logistics, and other specific factors. The following information, however, provides guidance and insight for consideration of sheltering and evacuation.

DOSE REDUCTION FACTORS--SHELTERING AND EVACUATION

Figures 3 and 5 through 13 give DRF values for sheltering and evacuation for the above-mentioned release cases. Sheltering and evacuation DRF plots are given for both WB and thyroid. The abscissa is the delay

time, T_D, measured from the incident initiation time, elapsed before physical transit is in effect. The DRF, applicable to evacuation, is plotted in terms of the transit-time parameter, T_T, which is the time it takes to evacuate out of and away from the reference location, with some protection offered by the assumed evacuation vehicle. Based on the time-frame given in Fig. 1 (p. 4), the analysis model assumes that unprotected exposure can occur over all or some portions of periods T_D and T_T, after cloud arrival (see cases 2 and 3, Fig. 1).

The DRF applicable to sheltering is also plotted in terms of the transit-time parameter, T_T, which is the time it takes to actually gain shelter entrance. Accordingly, (T_D+T_T) is the total shelter-entrance delay time that may or may not exceed cloud arrival time. When (T_D+T_T) does not exceed cloud arrival time, maximum shelter benefit is available, indicated by the horizontal portions of the SS and LS curves in Figs. 3 and 5 through 13. When (T_D+T_T) exceeds the cloud arrival time, the analysis model assumes that doses are contracted for conditions of unprotected exposure prior to entering the shelter--indicated by the rising portions of the SS and LS curves in Figs. 3 and 5 through 13.

Figure 3 gives the case A (source release time, T_R = 1.5 hr; cloud arrival time, T_a = 1 hr; and cloud exposure time, T_e = 0.5 hr) for evacuation and sheltering. For the evacuation portion of Fig. 3, the DRF is given in terms of five different transit-time parameter values of T_T, ranging from 0.125 to 1 hr. As shown in Fig. 3, the DRF = 0 for delay-plus-transit periods (T_D+T_T), which are less than the time elapsed from event initiation until cloud source arrival (T_R+T_a). For example, for an assumed evacuation transit time, T_T = 1 hr, the DRF = 0, for delay periods, $T_D \leq 1.5$ hr, as indicated by (1) in Fig. 4. As T_D increases, evacuation takes place during cloud passage under vehicle protection conditions and the DRF increases to a plateau as indicated by (2) in Fig. 4. The DRF for evacuation in Fig. 3 (and Fig. 5) does not increase for increasing T_D between 2.0 and 2.5 hr as indicated in Fig. 4 between (2) and (3), since the assumed evacuation transit-time interval (T_T=1 hr) is greater than the cloud-source exposure interval

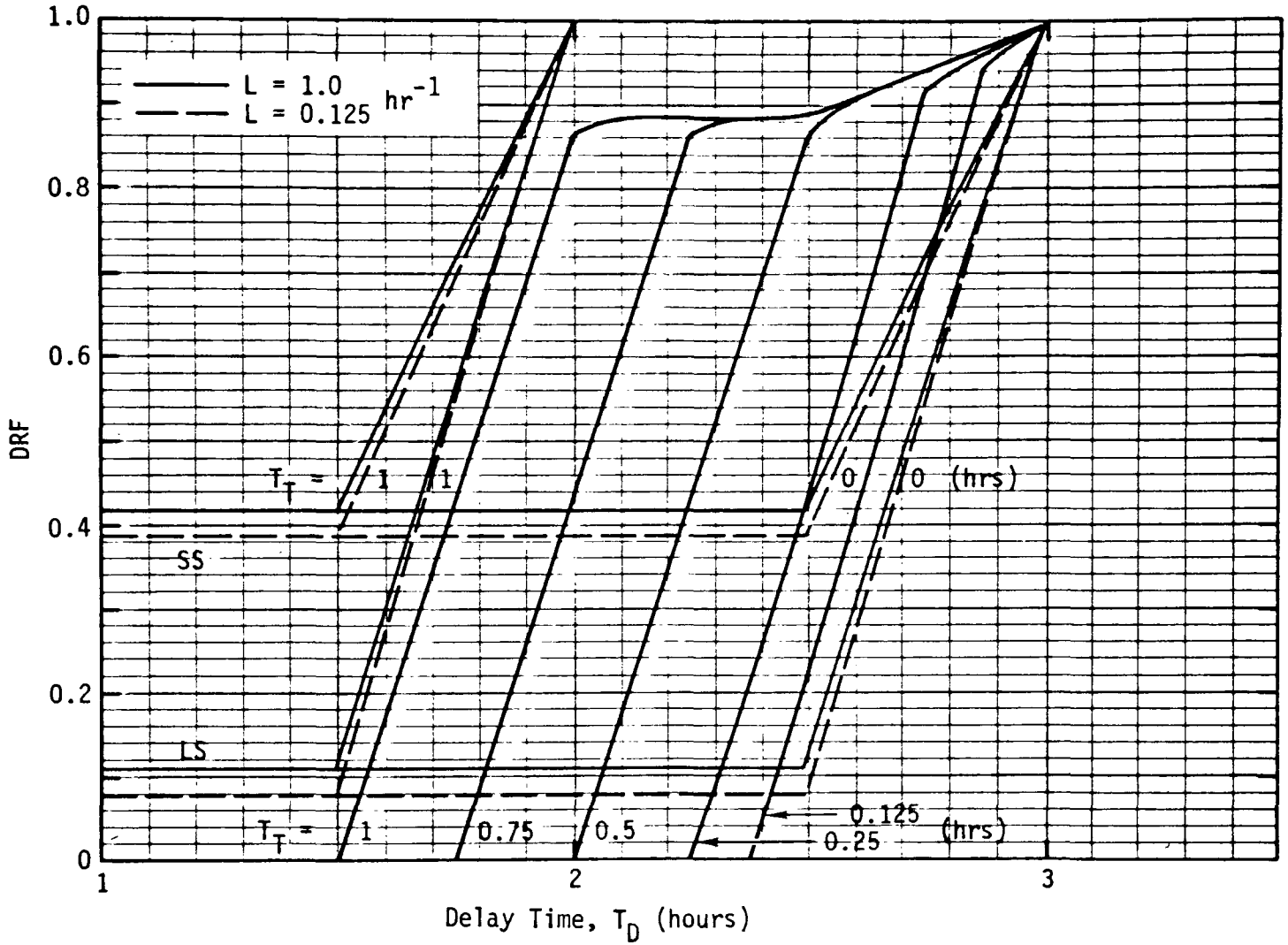


Fig. 3--Evacuation and sheltering WB DRF versus T_D, case A (T_R=1.5,T_a=1,T_e=0.5)

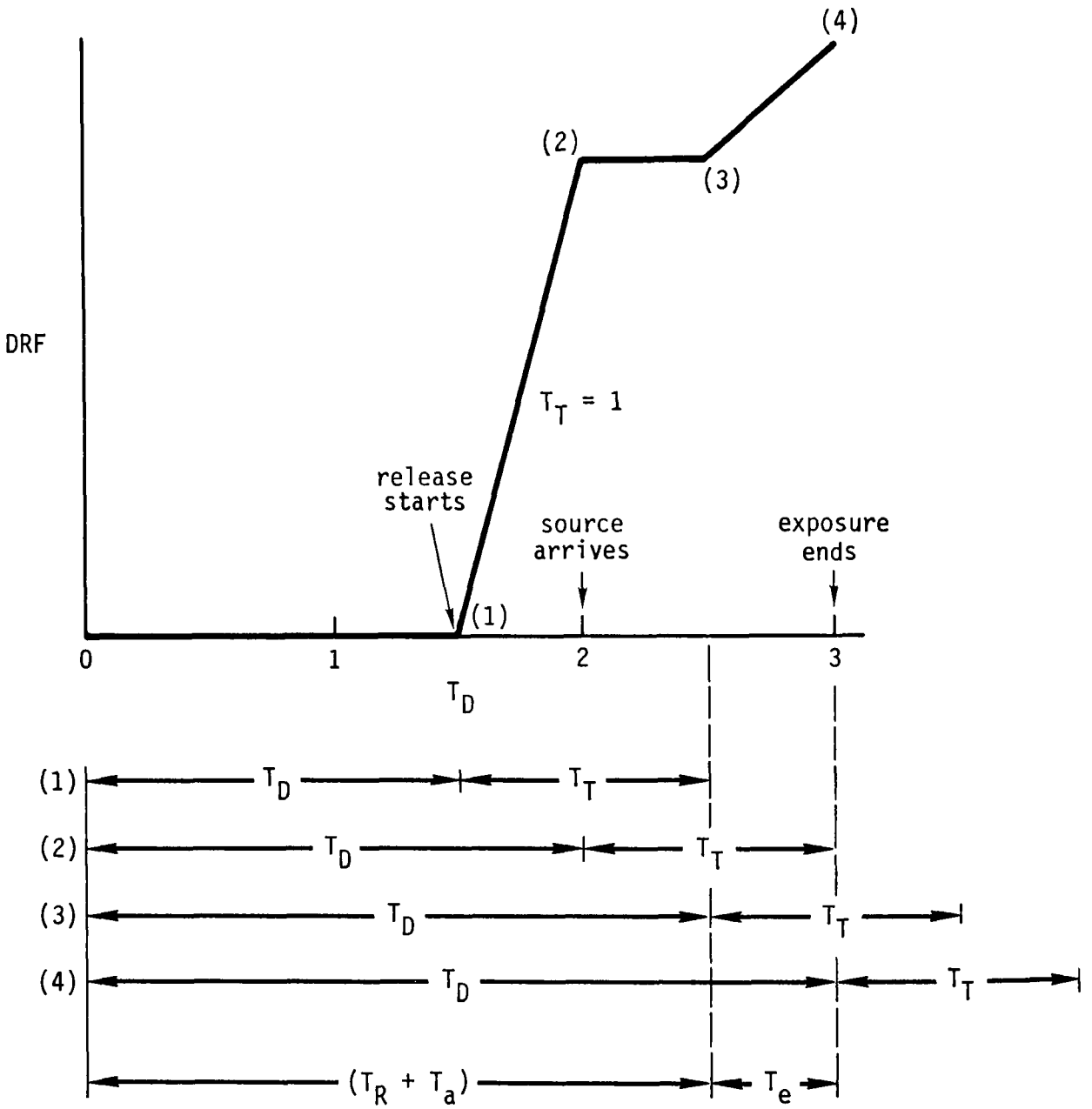


Fig. 4--Sheltering DRF for case A (T_R = 1.5, T_a = 1, T_T = 1)

(T_e=0.5 hr). Then, as T_D further increases, the DRF again increases as indicated in Fig. 4 between (3) and (4) as unprotected exposure is incurred, since evacuation is not assumed to commence until the cloud has passed.

The shapes of the other DRF T_T-parameter cases can be explained in the same manner as above for the (T_T=1) example (see the time-frame model in Fig. 1). Figure 3 shows that for $T_T \leq T_e$ (i.e., $T_T \leq 0.5$), no plateau exists for the DRF curves--a situation corresponding to that where the T_T time span never exceeds T_e. The maximum value assumed for T_T is 1.0 hr; however, it would be a simple extrapolation to include values of $T_T > 1$. The minimum value assumed for T_T is 0.125 hr, since it is assumed that not much evacuation could take place during exposure to a radioactive cloud source over shorter periods. Note that the maximum value of $T_T = 1$ is chosen to illustrate extreme situations, especially for those in which the release duration is shorter than 1.0 hr (e.g., case A). That is, the question can be posed as to how evacuation transit time can exceed cloud exposure time, T_e, when it is assumed that cloud exposure takes place over the transit time, T_T. That situation, of course, would not normally be expected. Logistic conditions, however, could conceivably give rise to extended exposure-transit periods. For example, the only available evacuation route (or portions of it) may parallel the cloud trajectory, or changing wind direction and cloud trajectory may give rise to unfavorable cloud exposure conditions, not to mention other possible vehicle transport problems that could develop (e.g., stalling, traffic jams).

For comparison, Fig. 3 also plots the DRF values for sheltering: the SS and LS for low (L=0.125) and representative (L=1) ventilation rates for the same total time-frame conditions. The delay time, T_D, is given by

$$T_D = \Delta T + (T_R + T_a) - T_T \quad ,$$

where ΔT is the amount of time delay spent accessing a shelter *after* cloud arrival (in Ref. 1, Fig. 8, ΔT is given as T_1). For convenience,

only $T_T = 1$ and $T_T = 0$ (ideal shelter timing) are plotted. The horizontal portions of the curves parallel to the abscissa correspond to the best shelter protection that can be expected for the conditions given (i.e., ∿0.4 for SS and ∿0.1 for LS). The shelter DRF plots for $T_T = 0$ correspond to the situation in which shelter access is effected prior to cloud arrival (i.e., ideal shelter timing). For example, in Fig. 3 this access is accomplished for $T_D \leq 2.5$. The effectiveness of sheltering can be compared with that of evacuation in the space bounded by the SS curves for L = 0.125, $T_T = 0$ (right and bottom); and the ordinate connecting the LS (L=0.125, T_T=0) and SS (L=1,T_T=1) intercepts. Clearly, T_T and T_D tradeoffs can be made for DRF comparison between evacuation and sheltering. For example, Fig. 3 shows an almost equivalent protection advantage for SS sheltering (ideal timing), assuming representative ventilation conditions, as compared to a 15-min evacuation transit time--each action for a delay time of 2.5 hr after the onset of an incident involving a 1.5-hr release time, a 0.5-hr cloud exposure time, and a 1-hr cloud arrival time. The DRF values given in Fig. 3 as well as in Figs. 5 through 13 assume a T_a = 1-hr cloud arrival time. The DRF values for other cloud arrival times would correspond to a linear time shift of curves along the abscissa given by (T_D-1+T_a). For example, if instead of $T_a = 1$ (as in Figs. 3 and 5 through 13), $T_a = 0.5$, then,

$$\mathrm{DRF}\ (T_D-0.5)\Big|_{T_a = 0.5} \simeq \mathrm{DRF}\ (T_D)\Big|_{T_a = 1} .$$

Figure 5 gives plots for the case-A thyroid DRF. The evacuation DRF curves are similar in shape to the WB DRF curves in Fig. 3 (see discussion above). The plateau DRF value in Fig. 5 is somewhat less than in Fig. 3 because of the external dose components in the WB DRF values. For sheltering, both low (L=0.125) and representative (L=1) ventilation rates are given for ideal timing (T_T=0) and $T_T = 1$.

Figures 6 and 7 are the case-B DRF plots for the WB and thyroid, respectively. Additional T_T-parameter curves are given for the DRF to

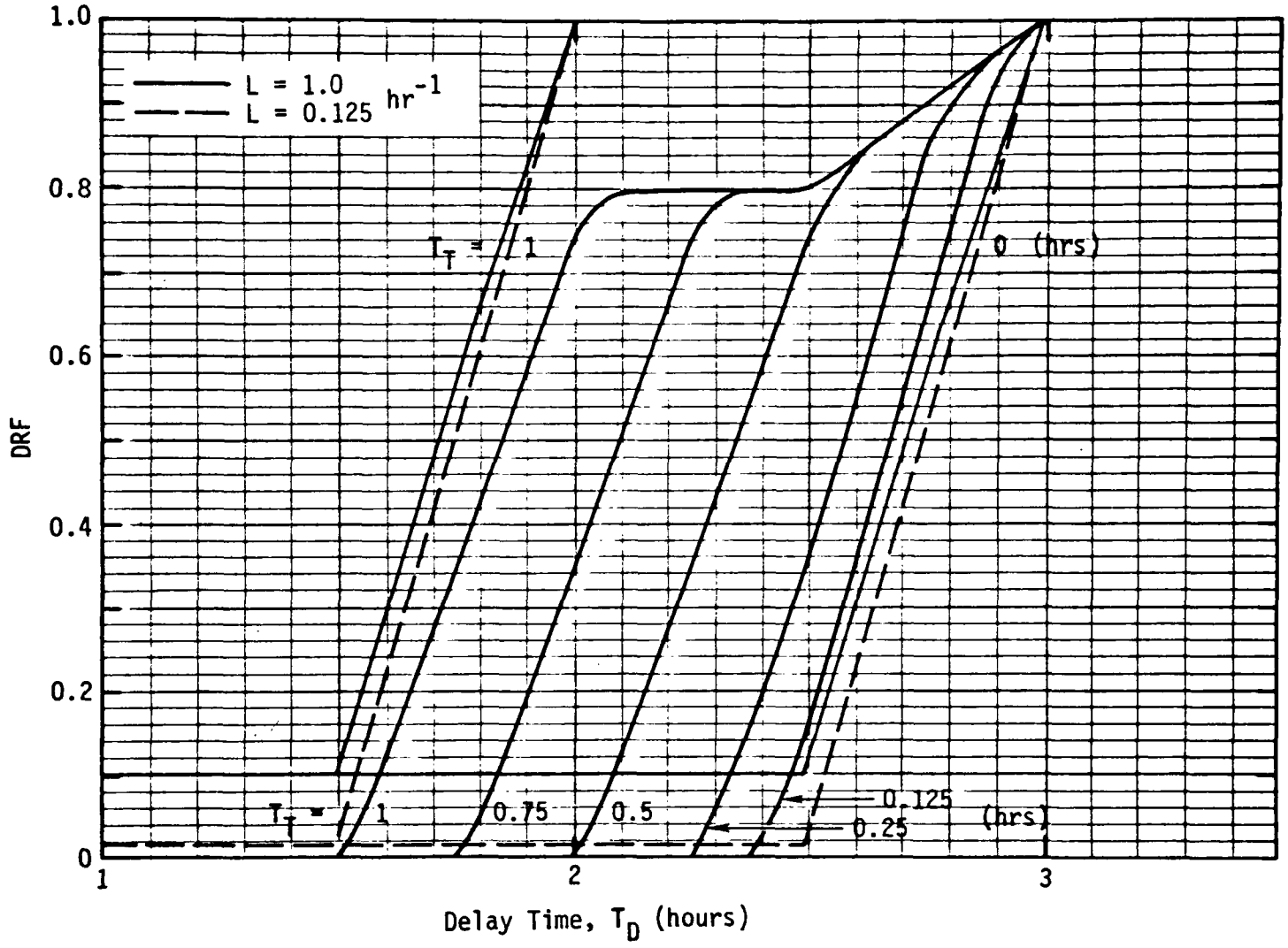


Fig. 5--Evacuation and sheltering thyroid DRF versus T_D, case A (T_R=1.5,T_a=1,T_e=0.5)

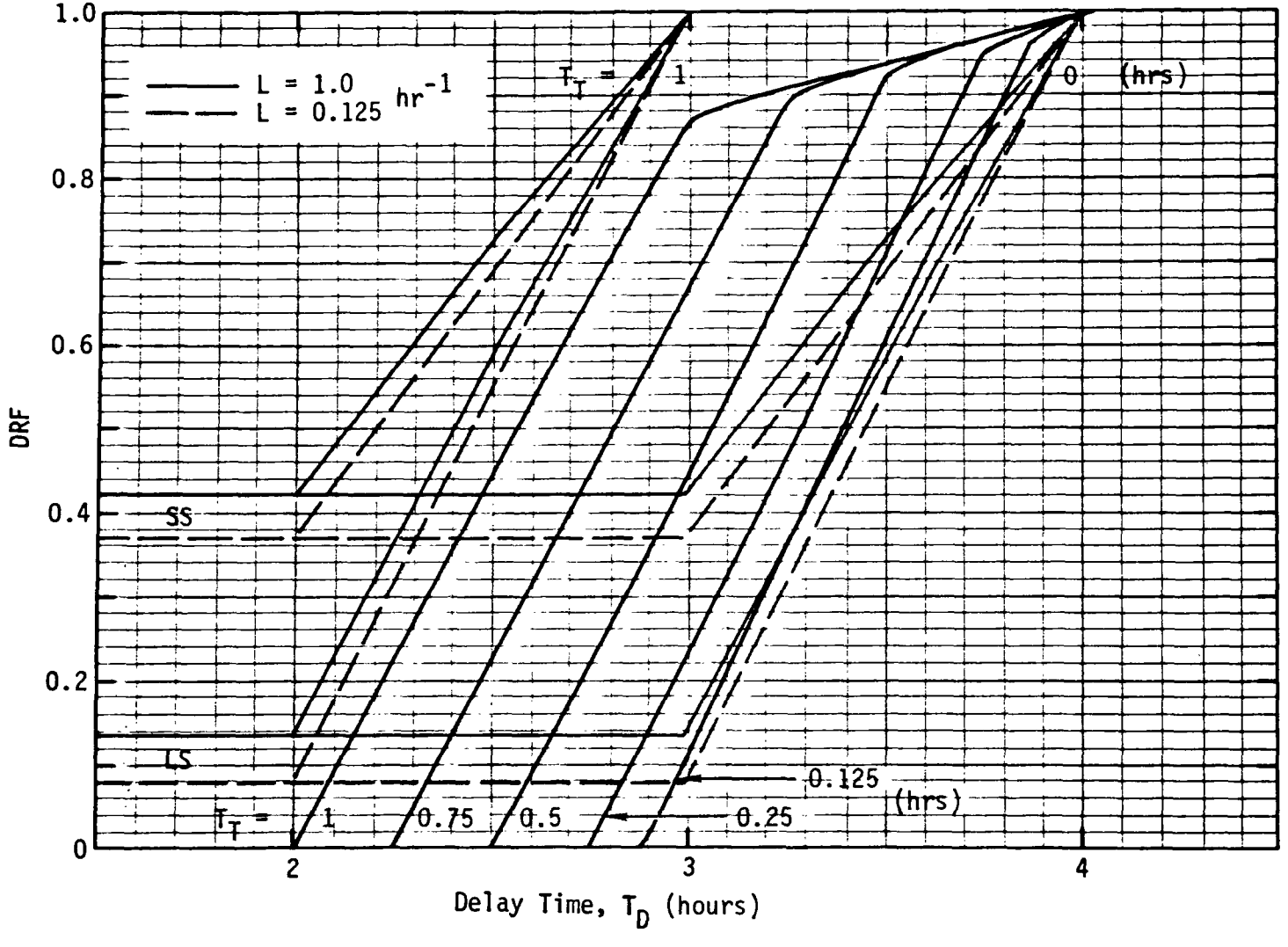


Fig. 6--Evacuation and sheltering WB DRF versus T_D, case B (T_R=2,T_a=1,T_e=1)

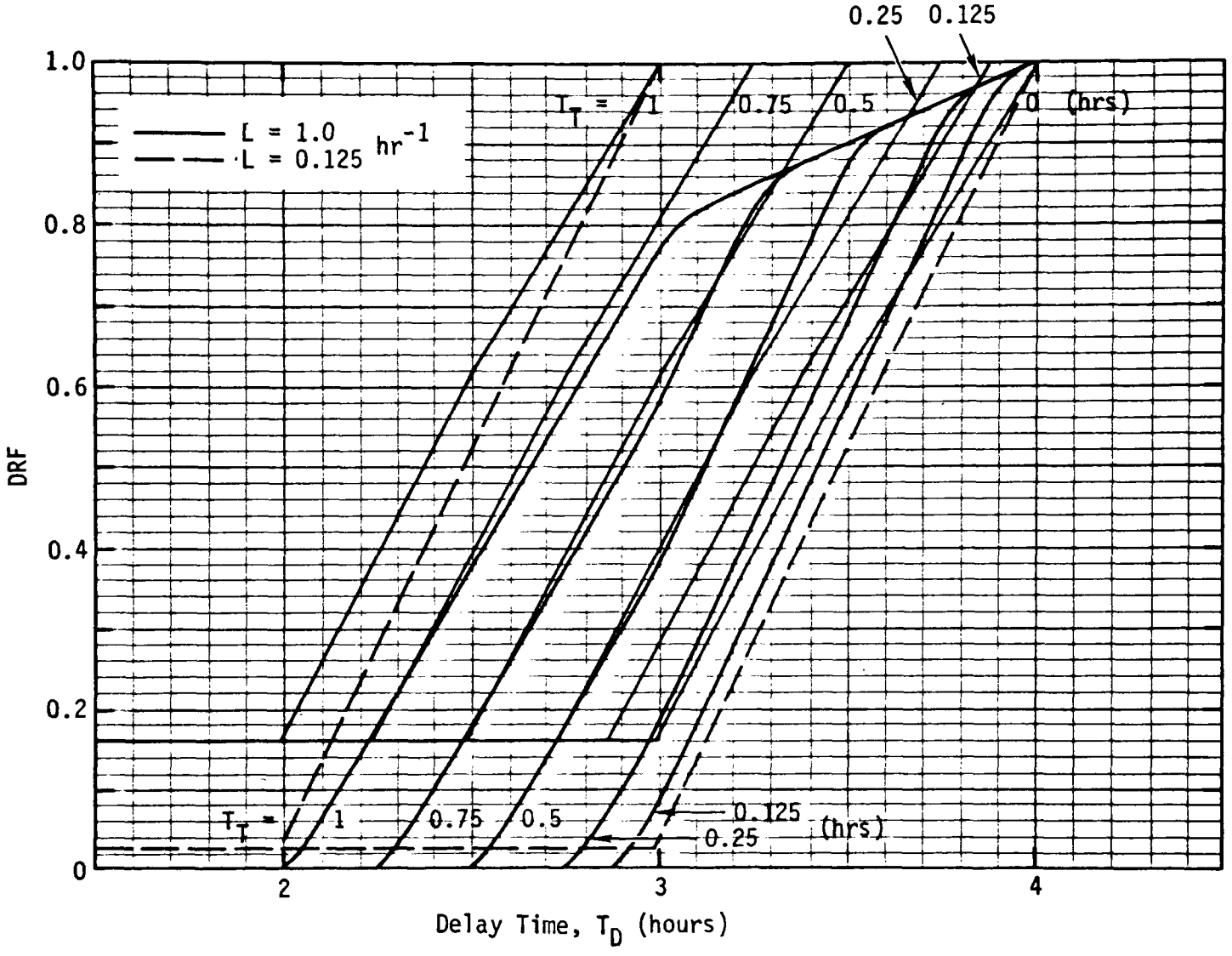


Fig. 7--Evacuation and sheltering thyroid DRF versus T_D, case B (T_R=2,T_a=1,T_e=1)

indicate their linear scaling positions along the abscissa. Including the additional scales makes it possible to perform graphical T_D and T_T tradeoff evaluations for evacuation and sheltering. The shapes of the evacuation curves are somewhat different from those given for case A in Figs. 3 and 5 in that the plateaus are absent. This difference is due to the transit-exposure time for evacuation being less than or equal to the cloud exposure time ($T_T \leq T_e$). Also, sheltering for the WB dose is somewhat less favorable in case B as compared with case A, especially for the SS shelter. For example, for L = 1, ideal sheltering is comparable for an evacuation transit time, T_T = 0.5; whereas in Fig. 3, the WB-dose protection for sheltering is somewhat comparable to evacuation for T_T = 0.25. Moreover, for case B, the evacuation DRF is significantly lower than the sheltering DRF for the T_T = 0.25-hr evacuation time.

Figures 8 and 9 contain additional T_T-parameter curves for sheltering to illustrate the tradeoff possibilities involving delay and transit time, T_D and T_T, for the representative ventilation rate (i.e., L=1). For example, suppose that the delay time for sheltering were T_D = 3 and it took T_T = 0.25 hr to enter a LS shelter after notification (DRF=0.36, Fig. 9). Suppose also that the evacuation delay time were T_D = 3.2 and it took T_T = 0.5 to evacuate out of the contaminated area after notification (DRF=0.64). Then, from a WB-dose protection standpoint, sheltering in the LS would be recommended. If SS sheltering were considered for the same T_D and T_T conditions given above, sheltering might still be recommended but not quite as strongly as for the LS (DRF=0.57 and 0.64 for sheltering and evacuation, respectively, in Fig. 8). If thyroid-dose protection were the consideration for the same delay time, T_D, ranging from around 2.8 to 3.2 hr for both sheltering and evacuation for the same T_T values given above for sheltering and evacuation, it would almost be a "toss-up" as to what action would be recommended (DRF ranges between 0.22 and 0.58 for both sheltering and evacuation; see Fig. 7).

Figures 10 and 11 are the case-C DRF values for the WB and thyroid, respectively. Here, sheltering increasingly becomes less attractive than for the shorter cloud-exposure cases A and B. For example, for

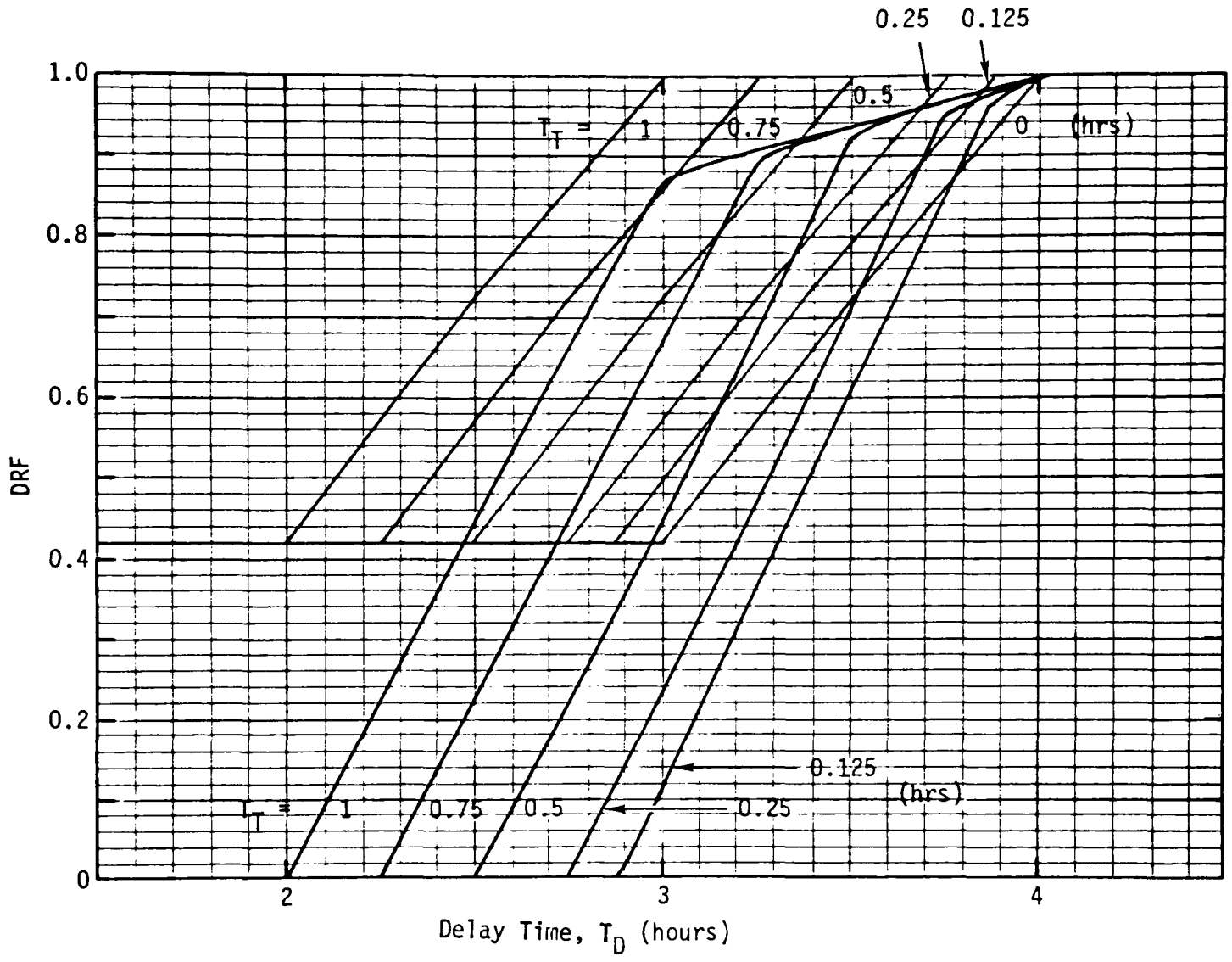


Fig. 8--Evacuation and SS sheltering WB DRF versus T_D, case B (T_R=2,T_a=1,T_e=1), L = 1 (sheltering)

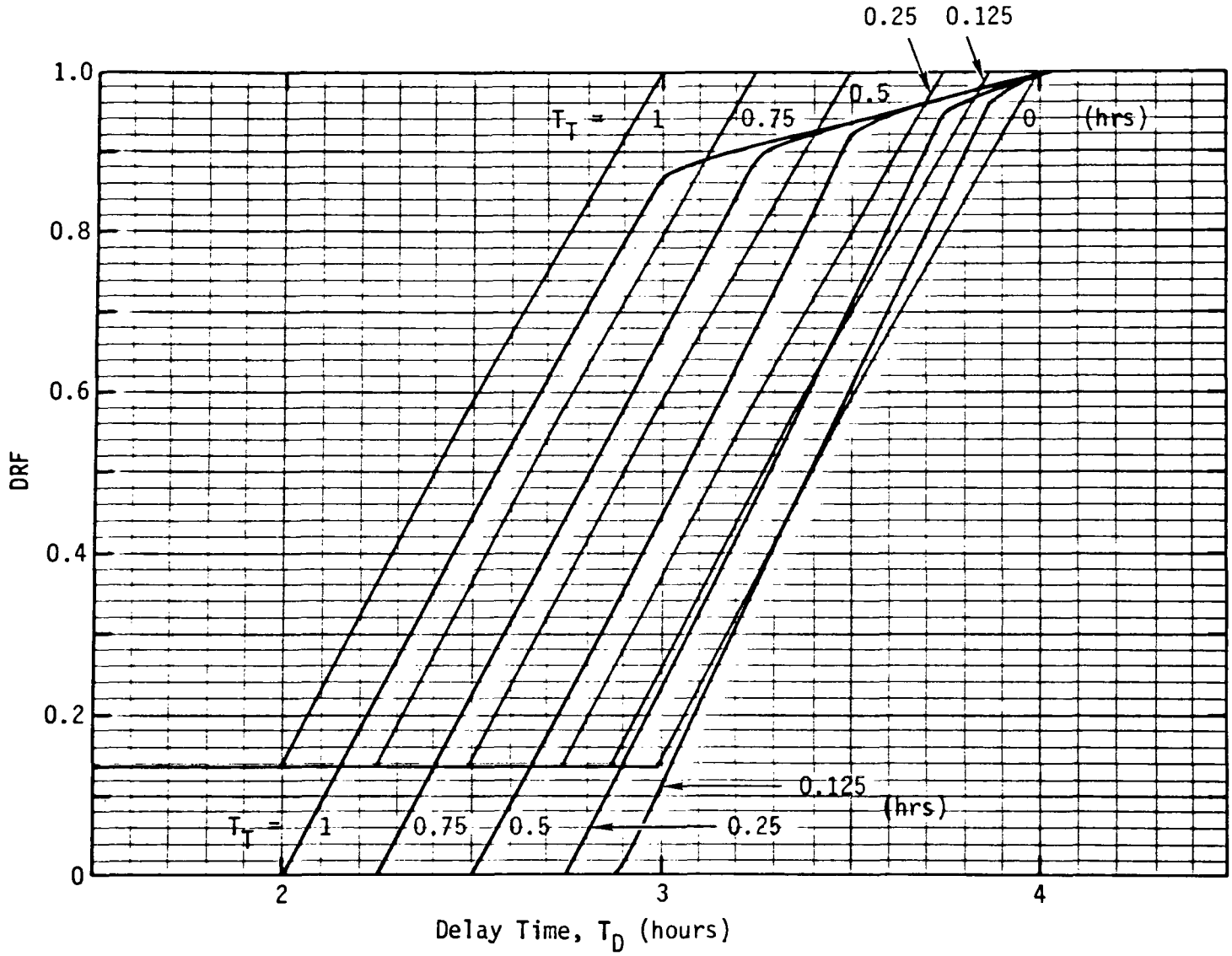


Fig. 9--Evacuation and LS sheltering WB DRF versus T_D, case B (T_R=2,T_a=1,T_e=1), L = 1 (sheltering)

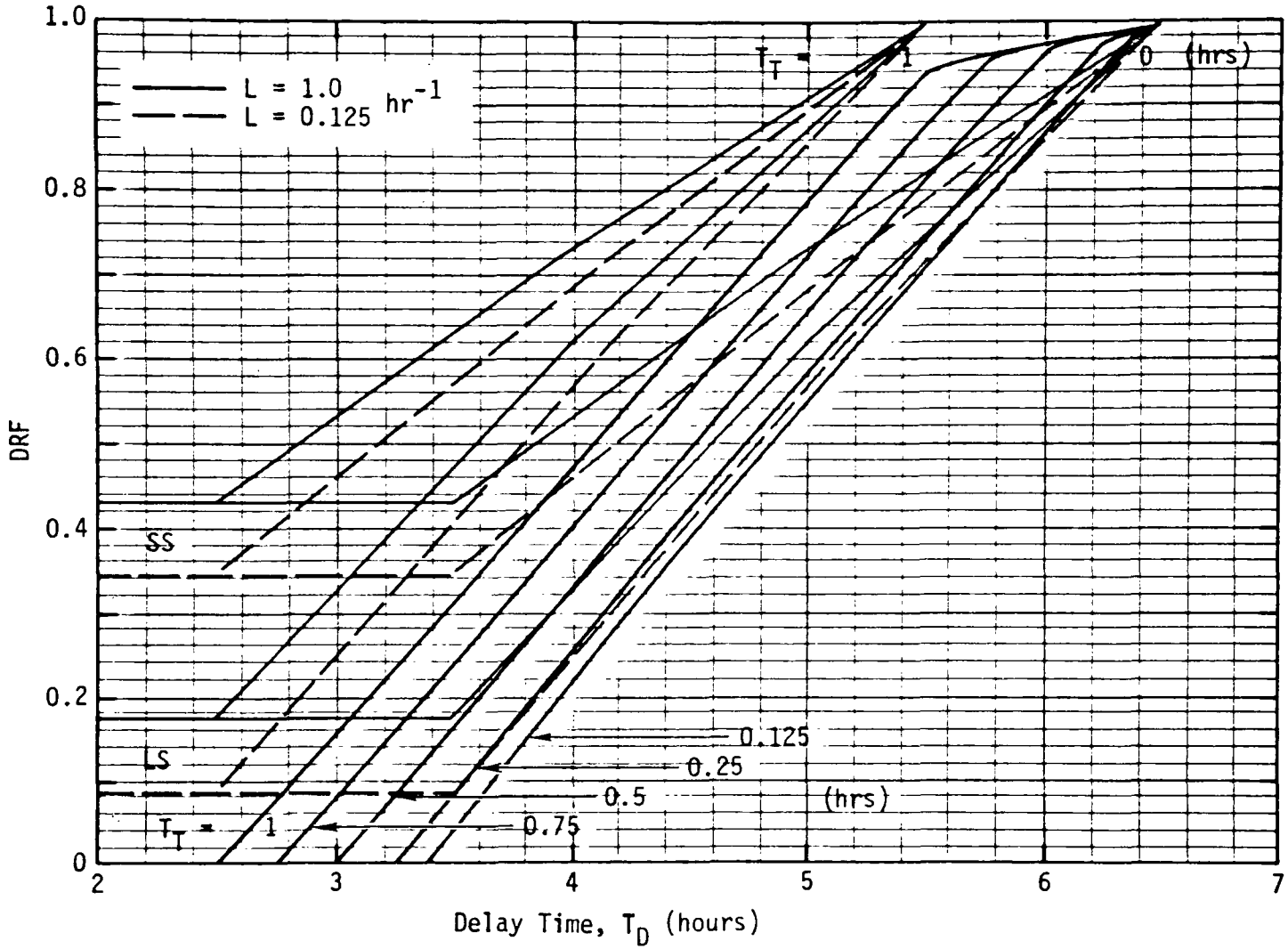


Fig. 10--Evacuation and sheltering WB DRF versus T_D, case C (T_R=2.5,T_a=1,T_e=3)

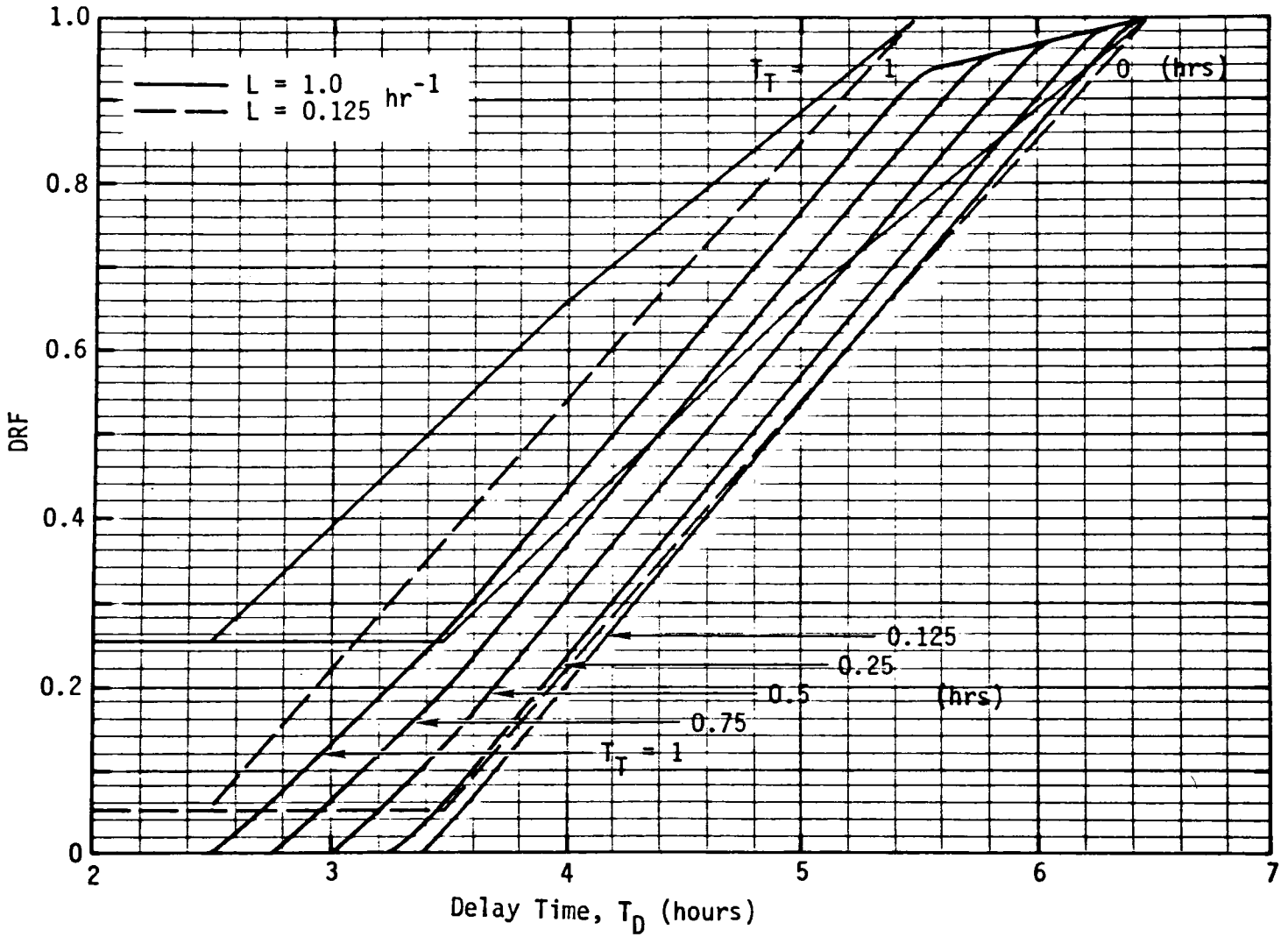


Fig. 11--Evacuation and sheltering thyroid DRF versus T_D, case C (T_R=2.5,T_a=1,T_e=3)

WB-dose protection (Fig. 10), the best sheltering protection (LS, L=0.125) corresponds to a T_T = 0.25 evacuation transit time; for a representative ventilation rate, (L=1) sheltering corresponds to a T_T = 0.5 evacuation transit time and evacuation is better than SS sheltering even for T_T = 1 evacuation time. For thyroid-dose protection, the situation is similar to that for the WB-dose protection for low ventilation rates, with a trend toward evacuation for representative ventilation rates (L=1).

Similarly, Figs. 12 and 13 (case D, T_e=6) show the increasing trend toward evacuation as the choice protective action. For example, for the low ventilation rate (L=0.125) in the LS shelter, it would be preferable to evacuate for delay times up to ∿3.5 hr for both WB and thyroid considerations--providing the evacuation transit time did not exceed 0.5 hr. For a representative ventilation rate (L=1), it would be preferable to evacuate, even though a T_T = 1-hr evacuation transit time is required for up to a 4.5 to 7 hr delay time (T_D) for the WB and thyroid, respectively.

Figures 3 and 5 through 13 clearly suggest the general trend toward evacuation as a preferable protective action when compared with sheltering. Of course, specific situations call for individual evaluation in arriving at a course of recommended action. The following subsection presents a procedure for using the DRF plots discussed above.

EVACUATE OR SHELTER?

This report analyzes the effectiveness of both evacuation and sheltering. (Reference 1 deals more specifically with sheltering effectiveness.) Up to this point, they have been discussed somewhat independently without specific regard for the combined use of the developed data. This subsection focuses on a procedure for providing guidance in making recommendations for the protection of individuals, either through evacuation or sheltering, from acute radiation exposure in the event of an emergency due to a nuclear incident. The overall time-frame embraces various actions that may be taken to protect the public for periods of 1 to 10 hr following the onset of an incident.

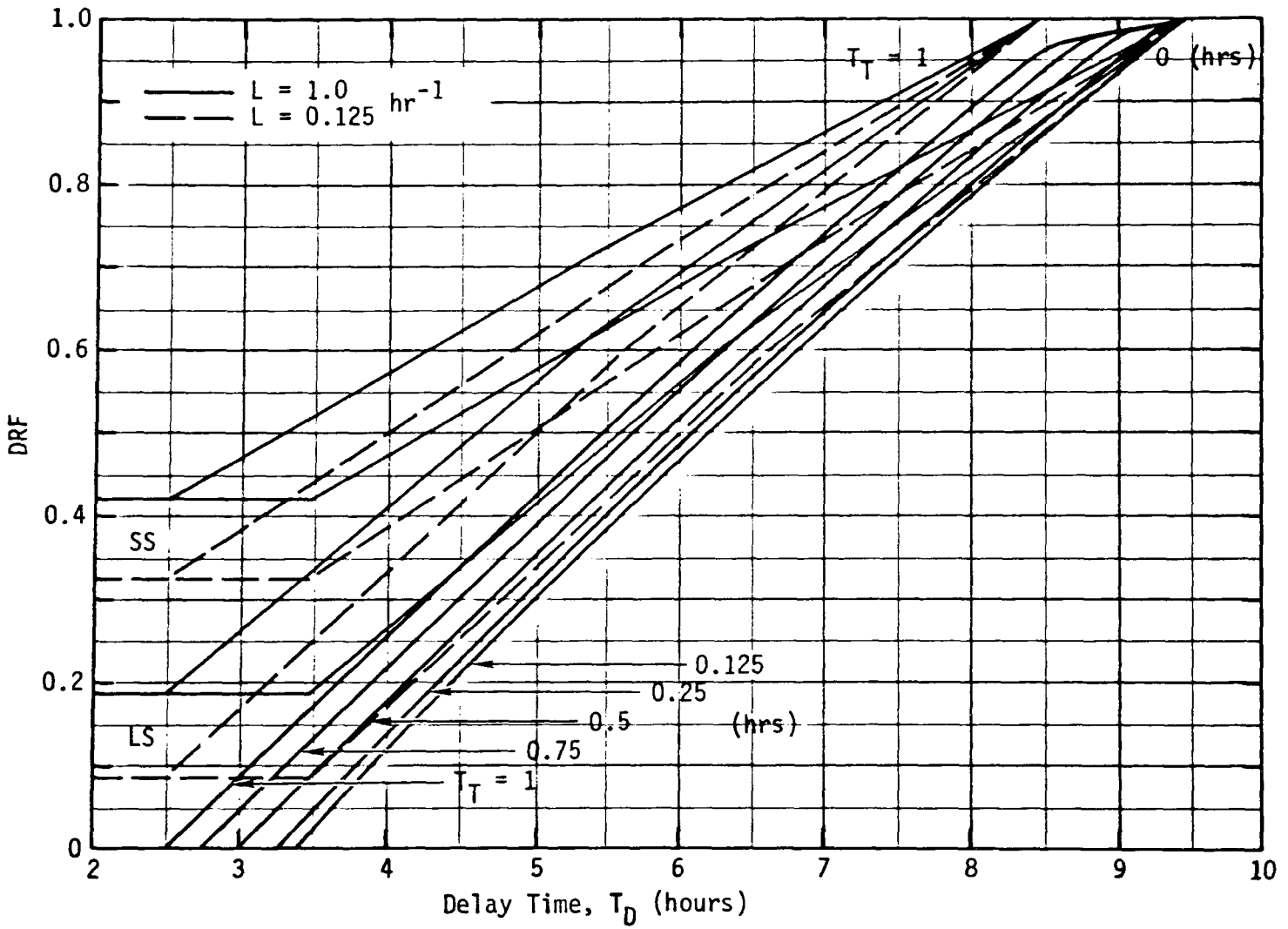


Fig. 12 --Evacuation and sheltering WB DRF versus T_D, case D (T_R=2.5,T_a=1,T_e=6)

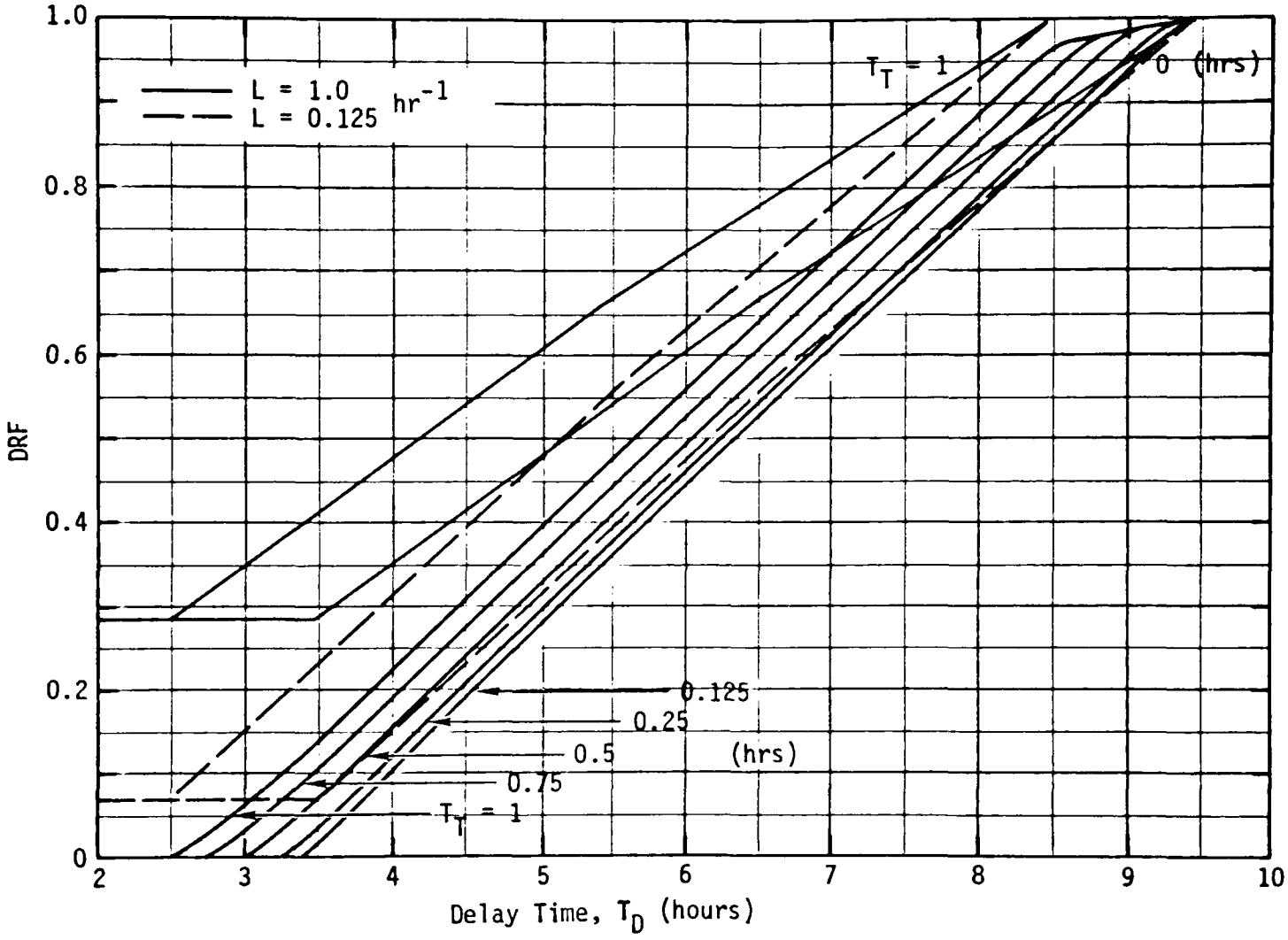


Fig. 13--Evacuation and sheltering thyroid DRF versus T_D, case D (T_R=2.5,T_a=1,T_e=6)

Figures 14a and 14b show the overall procedure for assessing and making recommendations. Though both figures are identical with regard to decision logic, Fig. 14a is expressed verbally and Fig. 14b more symbolically. Unfortunately, owing to the many possible values of the pertinent parameters, it is difficult to reduce such a decision process to a few blanket statements, although certainly that would be desirable. Figures 14a and 14b do, however, provide guidance for reducing the decision process to a usable level, while still preserving a reasonable amount of essential detail. In using Figs. 14a and 14b, the basic assumptions made in estimating DRF values (e.g., DBA release fractions, radioactive ingress fraction) should be kept in mind, especially from the standpoint of determining whether WB or thyroid dose would be more important.

The essential elements in Figs. 14a and 14b are keyed by circled numbers, which are used as reference in the following discussion. (Figure 14a does not have a (5), which lists formula approximations that can be used to make estimates of the DRF for evacuation and sheltering. The following discussion refers specifically to Fig. 14b, although it applies to Fig. 14a as well.)

(1) The significance of the projected doses for the WB and thyroid (D_{WB} and D_T, respectively) is determined by dividing by their respective protective action guides, $(PAG)_{WB}$ and $(PAG)_T$, respectively. Estimates of the projected dose correspond to a given location and cloud arrival time, assuming an estimated average wind speed and direction. If both ratios are less than one, no emergency protective action is recommended. However, recommendations for longer-term contamination control technologies may be made. If one or both of the ratios exceed unity, testing for cloud arrival time can be made in accordance with (2).

(2) Local authorities can estimate T_D and T_T based on the geographical location; and estimates of T_R, T_e, T_a are obtained from the responsible power plant authorities. Based on this information, an estimate of cloud arrival time, (T_R+T_a), from the incident onset is made and compared with the time required for evacuation (T_D+T_T). If evacuation can be accomplished prior to the estimated cloud arrival time, then it

39a

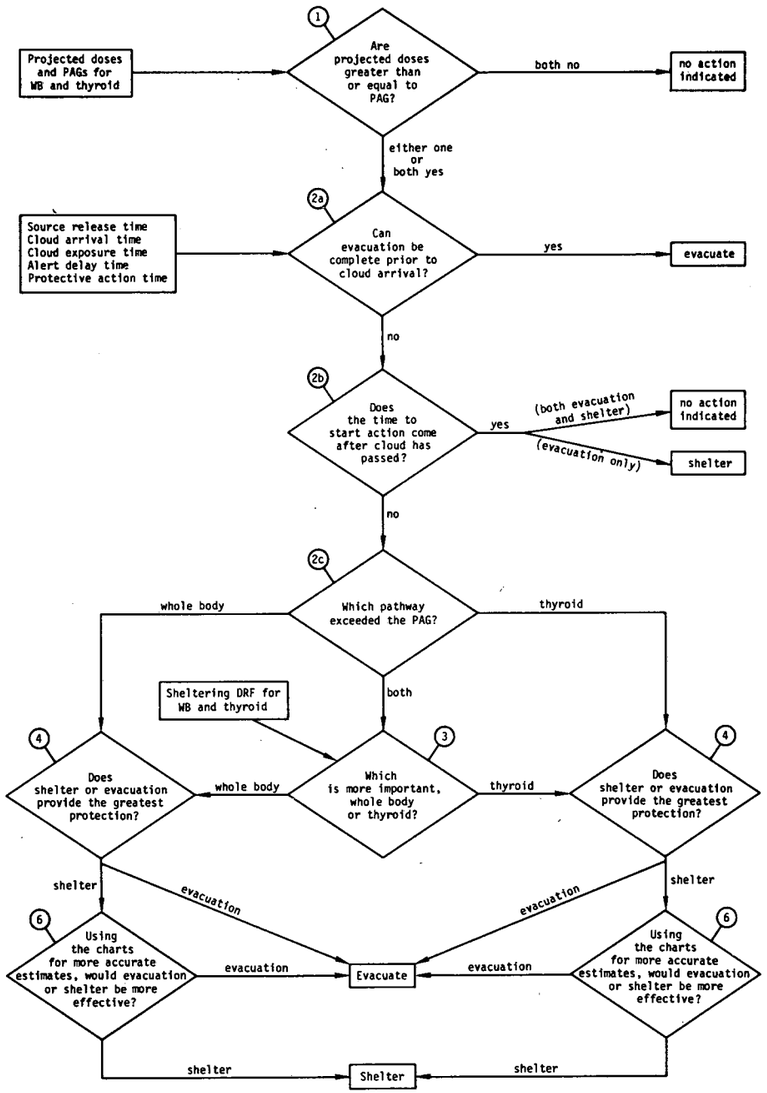
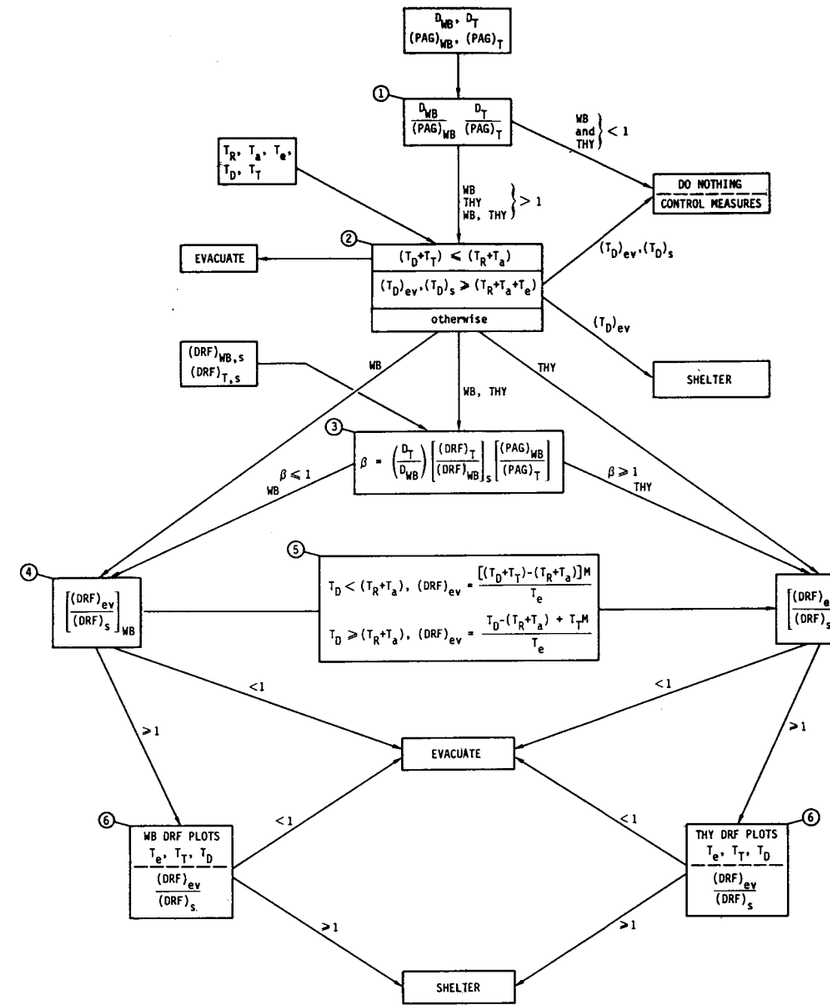


Fig. 14a--Evacuate or shelter?

39b



D - Projected dose
PAG - Protective action guide
T_R - Release time
T_a - Cloud arrival time from start of release to arrival of cloud
T_e - Cloud exposure time from initiation of event to evacuation
T_D - Delay time
T_T - Transport time
DRF - Dose reduction factor
WB - Whole body
T - Thyroid
S - Shelter
ev - Evacuation
v - Vehicle

Fig. 14b--Evacuate or shelter?

is recommended as the best means of protective action, since the DRF would be zero for evacuation. If, on the other hand, the estimated delay time, T_D, for evacuation, $(T_D)_{ev}$, and sheltering, $(T_D)_s$, exceeds the cloud passage, there would not be much that could be done from the standpoint of either of those particular emergency actions. If the estimated shelter delay time, $(T_D)_s$, does not exceed cloud passage (e.g., individuals may already be in a protective structure, $(T_D)_s = 0$), then sheltering would be recommended.

The remaining procedure deals with situations in which protective actions may be initiated after the estimated cloud arrival time. If in (1) the ratio exceeds unity for either the WB or thyroid (projected dose is greater than the PAG for either WB or thyroid), then (4) applies; if in (1) the ratio exceeds unity for both the WB and thyroid (projected doses exceed the PAGs), (3) applies.

(3) The β-test (see Fig. 14b) is made to determine whether the WB or thyroid dose is more important. That is, in selecting between evacuation and sheltering as the recommended course of action, if $\beta < 1$, the WB is more important; if $\beta > 1$, the thyroid. For $\beta = 1$, either the WB or thyroid could be selected for further evaluation of recommended protective actions. The DRF in (3) is for ideal sheltering conditions (T_1=0 and T_2=0, Ref. 1). Depending upon the value of β, either (4) for the WB (left side of Fig. 14b) or the thyroid (right side of Fig. 14b) applies. Note, however, that this evaluation of β is based on the DRFs for sheltering as indicated in Fig. 14b, where it is assumed that sheltering is preferred for reasons of expediency and cost. It is possible, however, that what may be the most important dose pathway for sheltering may not necessarily be the most important one for evacuation. Consequently, recommended evacuation based on, e.g., WB dose may not be particularly conservative for parallel thyroid dose reduction. The additional steps, however, that would be required to "tighten up" the logic in Fig. 14b is not warranted here since 1) the model is imperfect, 2) for most situations the decision will be conservative or adequate for reduction of the "less important" dose, and 3) much additional simplification in using Fig. 14b as a decision guideline procedure is awarded.

(4) The purpose of the indicated test is to compare ideal sheltering conditions with evacuation based on the ratio of the DRF values shown for either the WB or thyroid. Estimates of the evacuation $(DRF)_{ev}$ can be made according to the relationships given in (5) depending on the time parameters shown. Estimates of the WB $(DRF)_s$ for ideal-shelter timing conditions can be obtained from Fig. 15 or from the WB-dose shelter curves given in the applicable Figs. 3 and 5 through 13 discussed above. (WB $(DRF)_s$ values for ideal shelter timing can also be obtained from Ref. 1.) Figure 16 gives thryoid $(DRF)_s$ values for ideal sheltering conditions as a function of the air change rate, L, for the release cases considered. If the ratio given in (4) is less than unity, evacuation is recommended, as it would provide better protection than the best that could be provided by sheltering. When $\beta \geq 1$, (6) applies, in which case it may not be clear that evacuation is the better emergency protective action from the standpoint of reduced dosage and a further evaluation should be made with the aid of the graphical data.

(5) Approximations for the evacuation $(DRF)_{ev}$ values are given by the relationships in Fig. 14b. They are essentially linear relationships, which may be used in (4) (of course, the plots in Figs. 3 and 5 through 13 could also be used), and would certainly overestimate the $(DRF)_{ev}$ values for $T_D \geq (T_R+T_a+T_e) - T_T$. Figure 17 gives values of M for the linear relationships given in Fig. 14b, which can be used to approximate the DRFs for evacuation; these values are slope-adjustment factors that are functions of the exposure duration, T_e, determined from the calculated results for evacuation.

(6) As indicated in Fig. 14b, (6) allows for specific evaluations of a recommended protective action with the aid of the graphical data given in Figs. 3 and 5 through 13. Of course, it may be necessary to expand the graphical data given by interpolation or extrapolation; a sufficient amount of parametric data is given, however, to allow that.

The basic information required for (6) is T_e, T_D, and T_T, as indicated. At that point, either or both T_D and T_T may be different for evacuation and sheltering. For example, T_D may be somewhat different for evacuation and sheltering; T_T may be quite different. In (6) ,

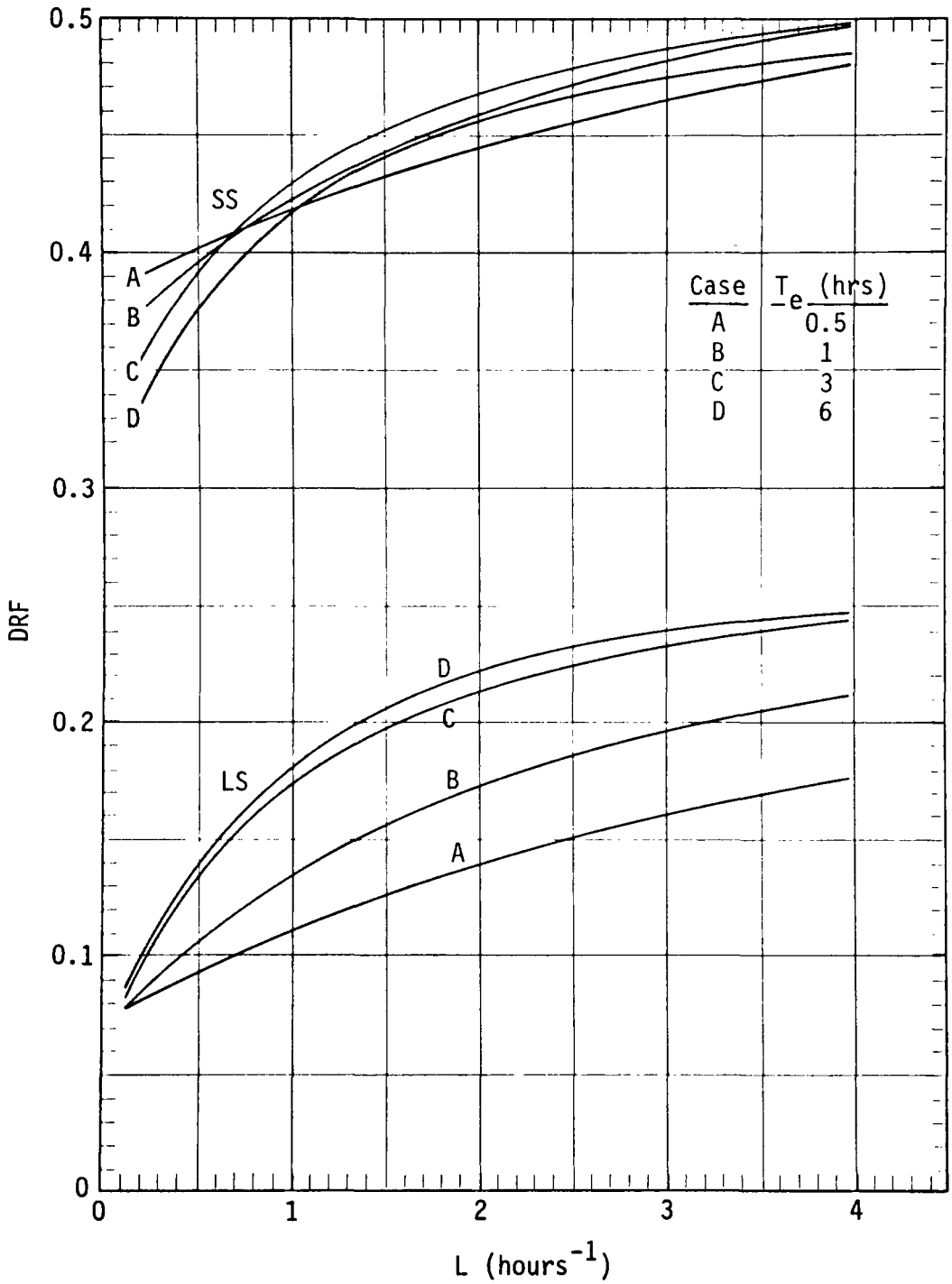


Fig. 15--WB DRF versus L, (ideal shelter timing)

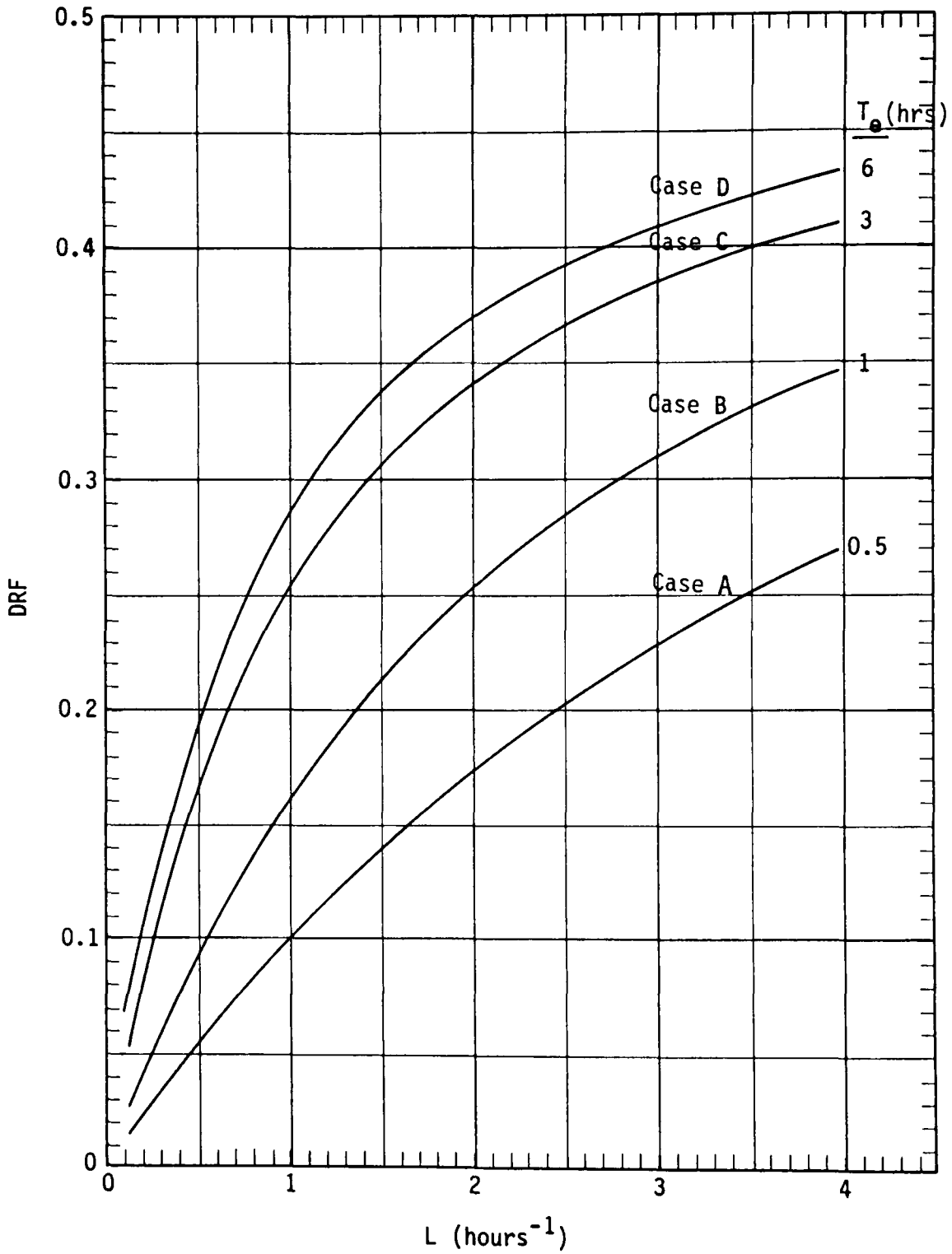


Fig. 16--Thyroid DRF versus L, (ideal shelter timing)

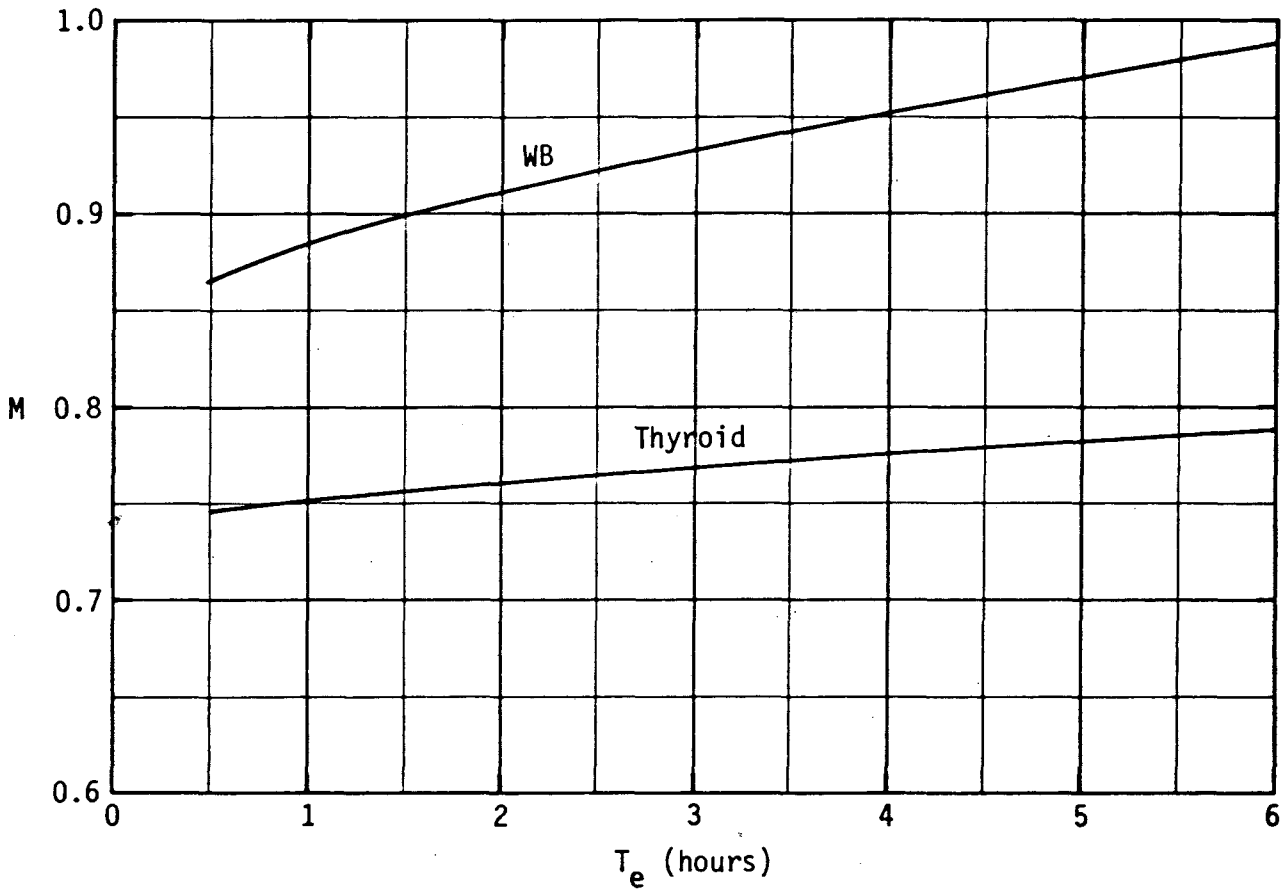


Fig. 17--M versus cloud exposure time

the ratio is determined from the graphical data, and a course of protective action can be recommended (as indicated in Fig. 14b), depending on the value of the ratio. When the ratio is unity (or near unity), other factors may affect the recommended course of action; in Fig. 14b, the sheltering option is indicated, since it is assumed to be preferred from the standpoint of cost for equivalent protection.

The remainder of this section focuses on use of Fig. 14b for protective-action decision planning. Figures 14a and 14b (p. 39) attempt to outline a procedural means for making protective action decisions in the event of an accidental release of gaseous airborne radioactive material from a nuclear power plant. In the event of an emergency, however, Figs. 14a and 14b might seem difficult to implement at first glance. Continuing familiarization with these figures, however, should make them useful guides for emergency decision-making on the state level. In that setting, modifications or simplifications of the procedural steps in Figs. 14a and 14b to better fit specific situations or locations may be necessary for ease of implementation. For example, the steps in Figs. 14a and 14b could be translated into some graphical (e.g., monograms) or tabular representation to compose a decision-making package together with the DRF plots.

Table 3 identifies the various parameters in Figs. 14a and 14b in terms of 1) the responsibility for their supply, 2) assumptions that can be made in the event that data are not available during an emergency situation (default), and 3) the basic decision relationship for each step in the process. The quantities marked with an asterisk are assumed available for ready usage and can be developed as part of the emergency planning programs. The other quantities would be indeterminate until the actual onset of an initiating event. Use of the decision-guideline methodology described above is illustrated below with numerical examples and assumptions from a hypothetical event.

Examples

Assume the following initial estimates obtained from a nuclear-power plant incident in which a gaseous fission-product release is predicted and the population area lies x = 5 mi downwind:

Table 3

EVACUATION/SHELTERING PARAMETERS

STEP	PARAMETERS	RESPONSIBILITY	DEFAULT ASSUMPTIONS	DECISION RELATIONSHIP	COMMENTS
1	D_{WB}, D_T $^*(PAG)_{WB}$, $^*(PAG)_T$	Facility EPA-State	—	$\frac{D}{PAG}$	—
2 — 2a†	T_R, $\bar{u}$ $^*T_D$, $^*T_T$, $T_a = \frac{^*x}{\bar{u}}$	Facility State	T_R 1 hr $\bar{u} = \bar{u}' + \gamma\bar{u}'$	$(T_D+T_T) \leq (T_R+T_a)$	T_D $^*T_N + {}^*T_M$ $T_T = \frac{^*w}{^*v_e}$, w plume width at x for stability B
2 — 2b†	T_e	Facility	T_e 1 hr	$\left.\begin{matrix}(T_D)_{ev} \\ (T_D)_s\end{matrix}\right\} \geq (T_R+T_a+T_e)$	Assumes $(T_D)_{ev} \geq (T_D)_s$
2 — 2c†	—	—	Assume decision relationship true	$\frac{D_{WB}}{(PAG)_{WB}} > \frac{D_T}{(PAG)_T}$	
3	$\left\lvert(DRF)_{WB}\right\rvert_s$ $\left\lvert(DRF)_T\right\rvert_s$	State	Assume WB controls	$\frac{D_T}{D_{WB}} \left[\frac{(DRF)_T}{(DRF)_{WB}}\right]_s \left[\frac{(PAG)_{WB}}{(PAG)_T}\right]$ >, D_T controls <, D_{WB} controls	For $\left\lvert(DRF)_{WB}\right\rvert_s$, see Fig. 15 For $\left\lvert(DRF)_T\right\rvert_s$, see Fig. 16
4	M, Fig. 17	State	—	$\left[\frac{(DRF)_{ev}}{(DRF)_s}\right]_{WB}$, $\left[\frac{(DRF)_{ev}}{(DRF)_s}\right]_T$	Calculate $(DRF)_{ev}$ See 3 above for $(DRF)_s$
6	$\left\lvert(DRF)_{WB}\right\rvert_s$ $\left\lvert(DRF)_{WB}\right\rvert_{ev}$ $\left\lvert(DRF)_T\right\rvert_s$ $\left\lvert(DRF)_T\right\rvert_{ev}$	State	—	$\frac{\left\lvert(DRF)_{ev}\right\rvert_{WB,\ T}}{\left\lvert(DRF)_s\right\rvert_{WB,\ T}}$	Estimate DRF's from Figs. 3 and 5 through 13

*Quantities developed during emergency planning

†Circled numbers in Fig. 14a.

x = downwind position
$\bar{u}$ = wind velocity, facility estimate
γ fraction for conservative windspeed estimate
$\bar{u}'$ wind velocity, local estimate
$^*v_e$ - evacuation transport velocity

T_N notification time
T_M = mobilization time
D dose
PAG - protective action guide
WB = whole body
T thyroid

Release time, T_R = 2 hr;

Windspeed, $\bar{u}$ = 5 mph;

Cloud exposure time, T_e = 1 hr;

Cloud arrival time, T_a = 1 hr;

Projected WB dose, D_{WB} = 10 rem;

Projected thyroid dose, D_T = 100 rem.

Assume also that the following protective action guides apply:

$(PAG)_{WB}$ = 5 rem;

$(PAG)_T$ = 25 rem.

Then in (1), both ratios for the WB and thyroid are greater than unity (i.e., 2 and 4, respectively) and therefore (2) applies.

Next, assume that an estimate of the evacuation delay time made by local authorities is T_D = 3 hr; that the atmospheric stability falls under class-D conditions; and that the cloud has a half-width, $W = 1.5\ \sigma_y$, i.e., 1.5 x 450 = 650 m at 5 mi (∿8050 m) downwind. Then, if evacuation could be effected laterally away from the cloud centerline axis (assuming x to be on the cloud centerline), at an assumed average speed of 2 mph (determined by the local authorities), an estimate of the transport time for evacuation would be

$$T_T = \frac{650(m)}{1610(m/mi)\ x\ 2(mi/hr)} \simeq 0.21\ hr \quad .$$

In the above example, it is assumed that T_T = 0.25 hr; and that from the reported windspeed above, the estimated cloud travel time from the facility to the population area is $T_a = x/\bar{u}$ = 1 hr.

For the above values, (T_R+T_a) = 3 hr, (T_D+T_T) = 3.25 hr, and $(T_R+T_a+T_e)$ = 4 hr; therefore, neither of the initial two time conditions are satisfied and neither the sheltering nor the evacuation ("do nothing") option is recommended at this point. If, for example, the estimated delay time for evacuation were $(T_D)_{ev}$ = 4.5 hr and that for sheltering were less than 4 hr, then sheltering would be recommended (for T_T = 0).

The next step is the β-test to decide which type of dose would be more important. With the assumed values, β is given as

$$\beta = \left(\frac{D_T}{D_{WB}}\right)\left[\frac{(DRF)_T}{(DRF)_{WB}}\right]\left[\frac{(PAG)_{WB}}{(PAG)_T}\right] = 2\,\frac{(DRF)_T}{(DRF)_{WB}} \quad .$$

The (DRF) values for ideal sheltering can be obtained as follows from Figs. 6 and 7 (pp. 28-29) for the WB and thyroid, respectively (DRF values for sheltering can also be obtained from Figs. 15 and 16, pp. 42-43):

L	DRF		
	WB		T
	SS	LS	
0.125	0.37	0.078	0.025
1.0	0.42	0.133	0.16

Evaluating the relationship above, the corresponding β-values can also be tabularized:

L	β	
	SS	LS
0.125	0.13	0.62
1.0	0.76	2.4

The values for β above indicate that the thyroid exposure would be more important for the LS shelter with a representative air change rate of L = 1 hr^{-1}; the WB exposures would be more important for the other sheltering conditions as indicated.

First, it is assumed in this example that the WB exposure is more important and (4) applies. Again, from Fig. 6, the average DRF values for the SS and LS are

	DRF	
SS	0.37 0.42	≃ 0.4
LS	0.078 0.133	≃ 0.1

Estimates of the evacuation $(DRF)_{ev}$ given by the second relationship in (5) (since $T_D=T_R+T_a$) are made and compared with the values given above. That is,

$$(DRF)_{ev} = \frac{T_D - (T_R+T_a) + T_T\ M}{1}$$

$$= 3 - (2+1) + 0.25 \times 0.87 \simeq 0.22 \quad .$$

Then, for the SS, the ratio given in (4) is 0.22/0.4 < 1; therefore, evacuation would be recommended instead of sheltering. Since 0.22/0.1 > 1 for LS sheltering, additional graphical evaluation as indicated by (6) applies only for low air-change rate conditions, since (as indicated above) the thyroid exposure would be more important for $L = 1\ hr^{-1}$.

Referring to Fig. 6 (p. 28), and assuming that $T_D = 3$ hr for both evacuation and sheltering in the LS, $T_T = 0.25$ hr for evacuation, and individuals are already in the LS ($T_1=0$), evacuation would not be recommended, since the ratio in (6) is 0.22/0.078 > 1.

As indicated above, the thyroid could be more important for the LS with a representative air change rate, $L = 1\ hr^{-1}$. Assuming the LS conditions, the DRF = 0.16 for sheltering (Fig. 16, p. 43). Again, estimates of the evacuation $(DRF)_{ev}$ indicated in (5) by the second relationship (since $T_D=(T_R+T_a)$) can be made and compared with the sheltering value; i.e.,

$$(DRF)_{ev} = 3 - (2+1) + 0.25 \times 0.75 = 0.19 \quad .$$

Since 0.19/0.16 > 1, additional graphical evaluation indicated in (6) applies for the LS for representative air-change rate conditions (L=1). If, for example, it were determined that LS sheltering access were to require T_T = 0.25 hr with the T_D = 3-hr delay time, then, referring to Fig. 7 (p. 29), evacuation would be recommended, since the ratio in (6) would be 0.19/0.38 < 1. On the other hand, if instead of T_T = 0.25 hr required for evacuation, it were estimated that T_T = 0.5 hr would be required, sheltering may be recommended, since the ratio in (6) would be close to unity and nothing would be gained from evacuation from the standpoint of dose reduction. The same conclusions would, for example, be reached for evacuation-time parameters, T_T = 0.25 hr and T_D = 3.2 hr.

Note that use of the procedure described in Fig. 14b (p. 39) is subject to some inaccuracy owing to plotting computed values as well as limitations of the model and the assumptions regarding numerical input parameters. The issue of accuracy is, of course, more important in making protective action recommendations when the margin of benefit is close one way or the other.

IV. CONCLUSIONS AND RECOMMENDATIONS

Evaluation of evacuation and sheltering effectiveness as emergency protective actions against a gaseous fission-product release is in this study based on calculational models that are necessarily idealized and assume the availability of the pertinent parameters and data for estimating benefits derived from protective actions. Use of the results, therefore, implies a certain amount of emergency preparation and planning irrespective of the idealized model assumptions. Accordingly, the results provide guidance by indicating how the pertinent fundamental parameters affect the benefits expected from evacuation and sheltering protective actions, and thus define their importance in the formulation of emergency planning. Note, however, that it will be difficult to deal with *all* parameters and unknowns for purposes of making timely decisions during the course of an emergency. For any potential incident, therefore, particular attention must be given beforehand to the identification, organization, and quantization of as many values as possible of an emergency plan.

Evacuation and sheltering are two emergency actions that can be implemented that would provide varying margins of protection depending on release characteristics, operational time constraints, and physical protection characteristics. Both actions should be considered when projected doses (for either WB, thyroid, or both) exceed a target protective action guide (PAG) level.

If evacuation can be effected prior to the predicted time of cloud arrival, it should in general be the preferred protective action, since exposure would then be avoided. Such a recommendation should not, however, be made without regard for the magnitude of the projected dose. For example, if the projected doses are large and can be avoided by evacuation, evacuation would be the preferred--if not, in some instances, the mandatory--course of action. If, on the other hand, the projected doses are small (but still exceed the PAG levels), sheltering may suffice, even though evacuation would be 100-percent effective as far as dose reduction is concerned.

If evacuation or sheltering cannot be effected until after the cloud has passed, individuals in the open would have contracted most of their dose (assuming they do not linger in the open ground-contaminated area more than a few hours after cloud passage) and any additional actions would be dictated by the urgency of avoiding additional exposure from ground fallout or ingestion; e.g., control measures that may very well include subsequent evacuation. However, the actual delay time, T_D, may be less for sheltering than for evacuation, in which case sheltering could provide some degree of protection depending on the access time required during exposure to an airborne cloud and fallout source. As defined in this study, the delay time for evacuation, T_D, is consistent with that defined by EPA, which includes the mobilization time estimated to be from 0.2 to 2 hr for evacuation [8]. For sheltering, the mobilization time and, hence, the corresponding delay time could be significantly less, resulting in a smaller time delay for shelter access. Summarizing, emergency planning guidance when evacuating can either be 100-percent effective (accomplished prior to cloud arrival) or virtually ineffective (could not be effected until after cloud passage):

1. If the projected dose exceeds the PAG by more than a few-fold, and
   a. timely evacuation is feasible, then evacuation is recommended; or
   b. timely evacuation is not feasible (i.e., the time available before cloud arrival is short compared with the required mobilization, warning, and transit time for evacuation), then sheltering is recommended.
2. If the projected dose does not exceed the PAG by more than a few-fold, then sheltering will probably be adequate and economically preferable.

Insofar as sheltering doses limit the degree of protection that can be offered by structures normally available to the public, but still can offer significant protection advantages, a condition--dictated by the time and logistic considerations--exists for which it is necessary to examine both evacuation and sheltering tradeoff options. For this condition, no all-encompassing statements of rule can be made if the optimum

protective action is to be recommended, even for the idealized model results developed in this study. This situation is where protective action either may not actually get under way or be completed prior to the predicted arrival time of the airborne cloud. The principal considerations in making tradeoff evaluations for recommending the appropriate protective action are WB and thyroid projected doses and PAG values; source release, duration, and cloud arrival times; estimated delay and implementation times for protective actions; and the nature of available sheltering structures and modes of evacuation.

For gaseous fission-product releases, both the WB and thyroid projected doses must be considered because one will be more important in the selection of the appropriate protective action depending on dose-to-PAG-level ratios and on modes of available sheltering. For example, in instances of substantial iodine release, where the thyroid dose is controlling, the efficiency of sheltering becomes largely dependent on ventilation control, particularly for increasing exposure durations; as a corollary, if the projected external WB dose is not relatively important, sheltering may be the most effective means of reducing doses.

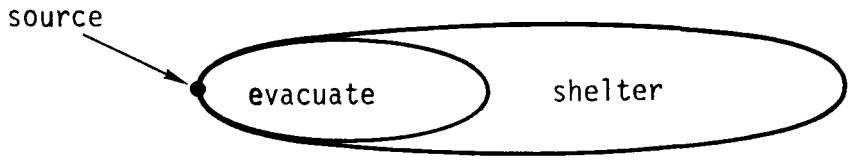
Sheltering becomes less attractive compared with evacuation for increasing durations of airborne exposure for WB and thyroid dose considerations--particularly, SS sheltering. For example, for exposure durations of around 3 hr or more, evacuation would be largely recommended in lieu of SS sheltering. LS sheltering, however, may still be somewhat competitive with evacuation as an emergency protective action for cloud exposure periods between 3 and 6 hr. Even at 6 hr, however, the LS shelter with a low ventilation rate may be only marginally competitive for certain situations of predicted long evacuation transit times away from the radioactive source region.

When analyzing sheltering and evacuation protective actions, the significance of air change rate in shelters is greater for thyroid than for WB doses, increases with cloud exposure duration, and is greater for LS shelters than SS shelters. Accordingly, substantial advantages for sheltering can be effected by deliberately controlling air change rates primarily for LS or for reducing projected inhalation doses.

Expedient filtration can be employed to improve the effectiveness of the shelter structure in reducing WB dose by stuffing cracks and openings with cloth or paper materials, which would reduce radioactive material ingress and/or the natural ventilation rate. Similarly, another means of respiratory protection is to cover the nose and mouth area with such common items as towels, handkerchiefs, or toilet paper: e.g., a crumpled handkerchief (or one with eight or more folded layers), a towel of three or more folded layers, or toilet paper of three or more folded layers can reduce inhaled radioactive material (particulate iodine in this study) by a factor of about 10 [14]. The reduction of the WB dose in a SS, however, is not appreciable--about 2.5 percent for low ventilation rates and about 15 percent for representative ventilation rates. The reduction in WB dose in a LS would be more appreciable--about 13 percent for low ventilation rates and about 70 percent for representative ventilation rates. For thyroid dose, however, the use of such expedient-filtration means could reduce doses by a factor of about 10 [14].

Conditions exist under which the optimal course of protective action consists of some split between sheltering and evacuation. For example, situations are examined in Ref. 1 for a combination of sheltering followed by evacuation as a protective action for the case where 1) the cloud is projected to arrive too soon to permit effective evacuation and 2) there are longer-than-expected periods of exposure. Conditions of shelter-exit time and subsequent evacuation-transit time can be identified for given exposure periods where sheltering followed by evacuation is advantageous as compared with sheltering alone.

Another evacuation/sheltering protective action combination may be effective for cases where it is desirable to evacuate people in a high-dose area, but shelter those in areas where the sheltering DRF will reduce the dose to within the PAG, and thus reduce the possibility of overloading the evacuation routes (see sketch below):



Note, however, that for the above consideration the high-dose area would normally be closest to the origin of release for ground-release assumptions. Accordingly, time constraints could limit the number of individuals who could be evacuated effectively.

Finally, there will be cases where LS sheltering gives adequate protection and is cheaper and quicker than evacuation, but where it is desirable to evacuate individuals for whom only SS shelter is available. This sort of shelter-availability split may be appropriate because timely evacuation may be more difficult in areas where LS are more prevalent than SS.

In summary, for emergency planning purposes, evacuation potentially provides the greatest margin of protection and should be the primary means of protective emergency action in the event of a gaseous fission-product release. On the other hand, sheltering may be the recommended protective action for two reasons: 1) because it is probably less expensive and less disruptive of normal activity than evacuation, sheltering may be appropriate under conditions of marginal danger; 2) it may be more expedient than evacuation. Since the majority of people are already inside some sort of shelter most of the time, mobilization time would be shorter, and the information that must be transmitted to them may be simpler than a set of evacuation instructions. Sheltering, therefore, may be appropriate if the time before cloud arrival is short, even though subsequent evacuation may be desirable.

Additional work is needed to develop complete guideline information for evacuation and sheltering recommendation procedures. For sheltering, both experimental and analytical areas are identified that would lead to the more accurate assessment of protection provided by available

structures [1]. For evacuation, there is a need for 1) model improvement to simulate more accurately the protection expected, and 2) obtaining and using more realistic data.

Model improvement could be made for the radioactive source components by including parent-daughter decay along with specific attenuation and consideration of finite source geometries for each radionuclide. The means of simulating evacuation during periods of exposure to radioactive sources should be expanded to deal more accurately with finite source geometries and evacuation routes and modes. Additional attention should also be given to expanding the evacuation model to address source releases that include radioactive particulate material. For useful planning, a guideline procedure for selecting the appropriate emergency protective action must be able to accommodate realistic data so as to focus on critical logistic areas. Accordingly, it would be useful to obtain some specific information--e.g., estimated evacuation delay and transport times, cloud arrival time, and projected doses (from current computer predictions)--to apply to the guideline selection procedure and also to point out where additional model improvement ought to be made.

Appendix A

LIST OF TERMS

SS = small structure

LS = large structure

T_R = time from incident to start of release from containment

T_a = time required for cloud to travel to point of consideration

T_e = cloud passage time (equal to or less than the duration of release)

T_D = delay time from initiating event to beginning of protective action

T_T = time spent in evacuating from contaminated area

T_S = time from beginning to end of source release (T_S equals T_e unless a wind shift shortens T_e)

F_g = outside ground fallout deposition

K_1 = WB-dose conversion factor for external cloud gamma exposure

K_2 = WB-dose conversion factor for exposure

K_3 = thyroid-dose conversion factor for inhalation exposure

K_4 = WB-dose conversion factor for external ground-fallout gamma exposure

T_r = time required to leave a shelter area after cloud passage to avoid dose from fallout

F = cloud-source dose component

F' = fallout-source dose component

F_1 = dose component for airborne cloud outside vehicle

F_2 = dose component for airborne source inside vehicle

F_1' and F_2' = dose components for ground fallout source outside the vehicle

T_1, T_2, and T_3 = dummy time variables for the F-functions

ε = ingress fraction

B = breathing rate

G_v = finite cloud-gamma source-correction factor for vehicle enclosure

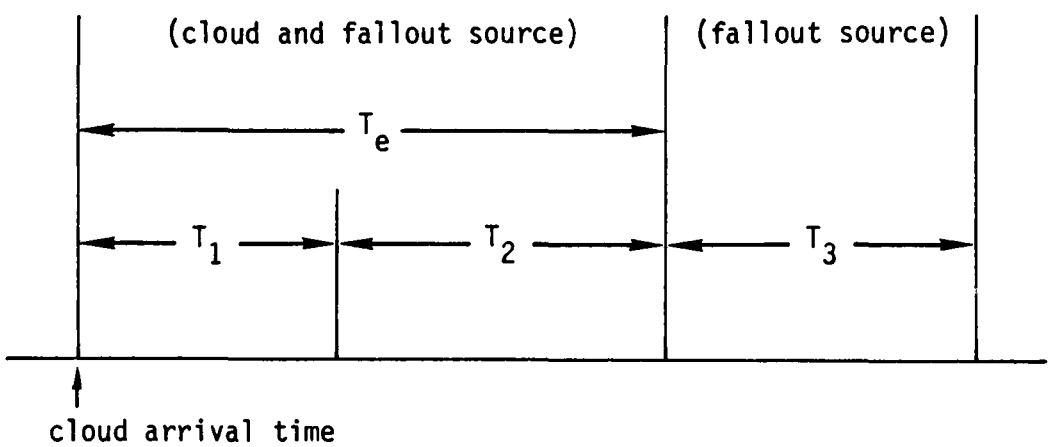
A_v = gamma attenuation factor

L = ventilation rate

Appendix B

DOSE REDUCTION FACTOR F-FUNCTIONS

The F-functions for cloud dose components (F) and fallout dose components (F') are developed below. The F-functions, with the exception of the F_1'-function (as noted below), are developed in terms of general time arguments T_1, T_2, and T_3, which correspond to the times shown in the sketch:



F-FUNCTIONS

The F_1-function is the dose-time function for cloud source exposures commencing after an interval, T_1, after cloud arrival and extending over a period, T_2. Accordingly, for a unit outside concentration ($\chi_o = 1$), F_1 is given as

$$F_1(T_1,T_2) = \int_{T_1}^{T_1+T_2} e^{-\lambda t}\, dt = \frac{e^{-\lambda T_1}}{\lambda}\left(1-e^{-\lambda T_2}\right) .$$

The F_2-function for cloud exposure is based on the concentration of airborne radioactive material inside the evacuation vehicle. The rate of change of the concentration in the vehicle for a unit outside concentration ($\chi_o = 1$) is

$$\frac{dC(t)}{dt} = L\, e^{-\lambda t} - K\, C(t) \ .$$

Choosing e^{Kt} as the integrating factor and rewriting as the total differential,

$$\frac{d}{dt}\left[e^{Kt} C(t)\right] = L\, e^{(K-\lambda)t} \quad ,$$

where $K = L + \lambda$. Integrating the above, for $C(0) = 0$,

$$e^{Kt} C(t) = (e^{Lt} - 1) \ ,$$

which yields the concentration in the vehicle given as

$$C(t) = (e^{-\lambda t} - e^{-Kt}) \ .$$

Assuming the vehicle starts to move after a period T_1 after cloud arrival and terminating after a period T_3 after cloud passage, the dose-time function, F_2, is given as

$$F(T_1,T_2,T_3) = e^{-\lambda T_1}\left[\int_o^{T_2} C(t)\, dt + C(T_2) \int_o^{T_3} e^{-Kt}\, dt\right]$$

$$= e^{-\lambda T_1}\left\{\frac{1}{\lambda}\left(1-e^{-\lambda T_2}\right) - \frac{1}{K}\left(1-e^{-KT_2}\right) + \left(e^{-\lambda T_2} - e^{-KT_2}\right)\frac{1}{K}\left(1-e^{-KT_3}\right)\right\}.$$

F'-FUNCTIONS

The F_1'-function is the dose-time function for fallout source exposures in an evacuation vehicle. The rate of change of the ground fallout deposition for a unit outside concentration and deposition velocity ($\chi_o V_g = 1$) is

$$\frac{dF_g(t)}{dt} = e^{-\lambda t} - \lambda F_g(t) \ .$$

Choosing $e^{\lambda t}$ as the integrating factor and rewriting as the total differential,

$$\frac{d}{dt}\left[e^{\lambda t} F_g(t)\right] = 1 \ .$$

Then, integrating for $F_g(0) = 0$,

$$e^{\lambda t} F_g(t) = t$$

and

$$F_g(t) = t\, e^{-\lambda t} \ .$$

Assuming the vehicle starts to move after a period T_1 after cloud arrival and terminating after a period T_3 after cloud passage, the dose-time function, F_1', is given as

$$F_1'(T_1,T_2,T_3) = \int_{T_1}^{T_1+T_2} F_g(t)\,dt + F_g(T_1+T_2)\int_o^{T_3} e^{-\lambda t}\,dt$$

$$= \frac{1}{\lambda^2}\left[(\lambda T_1+1)\,e^{-\lambda T_1} - (\lambda T_1+\lambda T_2)\,e^{-\lambda(T_1+T_2)}\right]$$

$$+ \frac{(T_1+T_2)}{\lambda}\left(1-e^{-\lambda T_3}\right)e^{-\lambda(T_1+T_2)} \quad .$$

F_2' is the dose-time function applicable to fallout source exposures in the evacuation vehicle for periods that commence and end after cloud passage. The time-argument arrangement given in the sketch above (p. 59) does not apply specifically to the formulation of F_2' here. Accordingly, the F_2'-function is given as

$$F_2'(T_1,T_2,T_3) = F_g(T_1)\,e^{-\lambda T_2}\int_o^{T_3} e^{-\lambda t}\,dt$$

$$= T_1\,e^{-\lambda T_1}\cdot e^{-\lambda T_2}\,\frac{1}{\lambda}\left(1-e^{-\lambda T_3}\right)$$

$$= \frac{T_1}{\lambda}\left(1-e^{-\lambda T_3}\right)e^{-\lambda(T_1+T_2)} \quad .$$

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