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Japan Atomic Energy Research Institute

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CONVERSION FACTORS FOR ESTIMATING RELEASE RATE OF GASEOUS RADIOACTIVITY BY AN AERIAL SURVEY

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Conversion factors necessary for estimating release rate of gaseous radioactivity by an aerial survey are presented. The conversion factors were determined based on calculation assuming a Gaussian plume model as a function of atmospheric stability, down-wind distance and flight height. First, the conversion factors for plumes emitting mono-energy gamma rays were calculated, then, conversion factors were constructed through convolution for the radionuclides essential in an accident of a nuclear reactor, and for mixtures of these radionuclides considering elapsed time after shutdown. These conversion factors are shown in figures, and also polynomial expressions of the conversion factors as a function of height have been decided with the least-squares method. A user can easily obtain proper conversion factors from data shown here.

Keywords: Release Rate, Gaseous Radioactivity, Aerial Survey, Conversion Factors, Estimation, Reactor Accident

航空機サーベイを利用した気体状放射性廃棄物放出率の推定のための変換係数

日本原子力研究所東海研究所環境安全研究部
斎藤　公明・森内　茂

（1988年1月21日受理）

本レポートは，航空機サーベイを利用し気体状放射性廃棄物の放出率を推定する際に用いられる変換係数を表したものである。放出率推定方法およびこれの実サーベイデータへの応用例は別の論文にまとめている。変換係数は，廃棄物がガウスプレームモデルに従って拡散すると仮定したシミュレーション計算から，大気安定度，風下距離ならびに飛行高度の関数として求めた。まず，単色エネルギーガンマ線を放出するプルームを仮定して変換係数を計算した。次に，このデータに基づき，原子炉事故時に重要な核種毎の変換係数，さらに，これらの核種の混合比が事故後の経過時間に従い変化していく際の，総放出率を推定するための変換係数を計算した。計算した変換係数はすべて本レポートで図に表した。また，最小二乗法により飛行高度の関数のかたちで変換係数の多項式近似を行い，その係数を日本原子力研究所の大型コンピュータのファイルに収めた。これらから，航空機を用いて放出率を推定する際，図からの直読あるいは簡単な計算により，容易に必要な変換係数を得ることが可能となった。本研究は，原子炉事故時に重要な情報の一つであるソースタームを迅速に評価するために貢献することが予想される。

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1. INTRODUCTION

In case of a nuclear plant accident, information on the kind and amount of radionuclides released into the atmosphere (so called source term) is important to correctly assess the effect of the accident and to take appropriate countermeasures. The most effective way to know the release amount into the atmosphere is to measure with a stack gas monitor[1-6]. Nevertheless, the source term is so important that plural methods for obtaining these data should be prepared, because stack monitors may not function enough, for example, the radionuclides may escape from the plant through unexpected pathways.

Many attempts have been made to estimate the amount of gaseous radioactive effluents from monitoring data[7-10]. However, there have been seldom cases to estimate release rate directly from an aerial survey. In another paper[11], we are going to introduce two methods for estimating the release rates of gaseous radionuclides making use of a spatial exposure rate distribution measured by an aerial survey. These methods are effective because of their simplicity and rapidity.

In these methods, the maximum exposure rate or the integrated exposure rate are converted to release rates by multiplying conversion factors, which have been decided beforehand from simulation. The aim of this report is to provide the conversion factors available under various conditions.

The simulation was carried out with the Monte Carlo method on the assumption that the released radionuclides disperse in accordance with the Gaussian plume model with discrete atmospheric stability categories of A-F[12,13]. In this simulation following parameters were varied: 1)Energy of emitted gamma rays, 2)Atmospheric stability, 3)Down-wind distance, and 4)Height difference between a plume axis and a flight line of an aircraft.

Next, the conversion factors for radioactive nuclides essential in nuclear plant accidents were constructed through convolution from those for mono-energy gamma rays. Further, the conversion factors for a mixture of radionuclides were determined as a function of elapsed time after reactor shutdown for noble gases and for iodine. All of the conversion factors are expressed in polynomial terms as a function of height difference. The line graphs of the conversion factors are presented in this report, and coefficients of the polynomial expressions are stored in the computer file at JAERI. In case of an accident, one can easily read the needed conversion factors from the line graphs, also, obtain numerical data from simple calculation with the polynomial expressions.

2. ESTIMATION METHODS

Though the estimation methods are explained in another paper[11), here, we repeat the explanation in order to clarify the meaning of the conversion factors.

An aircraft is supposed to fly above a radioactive plume keeping a constant altitude in a direction at right angle to the plume axis and to measure the gamma exposure rates every constant time interval as shown in Fig.1. Fig.2 shows a typical distribution of spatial exposure rates measured by a flight in the way mentioned above. The distribution is used to estimate the release rates. Here, we consider two methods:

1) A method using the maximum exposure rate;

2) A method using the integrated exposure rate.

2)Atmospheric stability, 3)Down-wind distance, and 4)Height difference between a plume axis and a flight line of an aircraft.

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1) A method using the maximum exposure rate;

2) A method using the integrated exposure rate.

The spatial exposure rates are related to the radioactivity release rate with the following equations if the release rate and wind velocity are constant.

$$D_{max} = k_1 \cdot \frac{Q}{u}, \tag{1}$$

$$D_{int} = \int_{-R}^{+R} D(y) \cdot dy = k_2 \cdot \frac{Q}{u}, \tag{2}$$

where

D_{max} = maximum exposure rate,

D_{int} = integrated exposure rate,

y = cross-wind distance, where the intersection with a plume axis is 0,

D(y) = exposure rate at a cross-wind distance of y,

Q = release rate of radioactivity,

u = wind velocity,

R = integral range,

k_1, k_2 = conversion factors.

These equations are transformed as follows;

$$Q = \frac{u}{k_1} \cdot D_{max}, \tag{3}$$

and

$$Q = \frac{u}{k_2} \cdot D_{int} = \frac{u}{k_2} \cdot \int_{-R}^{+R} D(y) \cdot dy. \tag{4}$$

The maximum exposure rate and the integrated exposure rate are converted to the release rate by equations (3) and (4), respectively. Obviously method 1 is simpler than method 2. In method 2 a cross-wind distance y must be known, and so instruments for identifying the flight position are required, though it is possible to roughly estimate the cross-wind distance provided an aircraft flies in a nearly constant speed. While, method 1 has a disadvantage that the estimated release rate is directly affected by fluctuation of conditions such as meanders of a plume.

These methods were applied to survey data around nuclear reactors in Tokai-mura, and the estimated release rates agreed with values from stack monitors within a factor of 2-3[11]. Also, it was found that release rates estimated by method 2 fluctuate less than those by method 1 in respect to change of atmospheric stability assumed and of flight position.

3.CALCULATION OF CONVERSION FACTORS

The conversion factors for plumes emitting mono energy gamma rays were determined based on the simulation using the Monte Carlo calculation on the assumption that radionuclides disperse in accordance with the Gaussian plume model. The gamma-ray transport calculation code YURI[14] developed by JAERI was used for the calculation. Exposure rates calculated with this code have been proved to agree with reliable experimental data with accuracy better than 10% [14,15].

Base on the simulation data for mono-energy gamma rays, conversion factors were constructed for radioactive nuclides important in emergency, and for a group of these radionuclides. With the least-squares method, a polynomial expression of the 4-th order was fitted to logarithm of these conversion factors as a function of a height difference for every condition, so a conversion factor at any height difference is calculated from the next equation;

$$k(h) = \exp(a_0+a_1\cdot h+a_2\cdot h^2+a_3\cdot h^3+a_4\cdot h^4) \qquad (5)$$

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$$k(h) = \exp(a_0+a_1\cdot h+a_2\cdot h^2+a_3\cdot h^3+a_4\cdot h^4) \quad (5)$$

where,

h = height difference between a flight line and a plume axis in meter,

a_0, a_1, a_2, a_3, and a_4 = coefficients.

The units of this expression (originally expressed in μR/Ci and μR•m/Ci) are easily converted to other units by adding a constant to the 0-th order coefficient. For example, −4.97 and −46.4 must be added when μR/Ci(μR•m/Ci) is converted to aC/kg/Bq(aC•m/kg/Bq) and C/kg/Bq(C•m/kg/Bq), respectively. Also, −1.44 and −42.9 must be added when μR/Ci(μR•m/Ci) is converted to aGy/Bq(aGy•m/Bq) and Gy/Bq(Gy•m/Bq), respectively, where Gy stands for a unit of air kerma. All of the coefficients of the polynomial expressions calculated in this study are stored in a file of the host computer at JAERI.

3.1 Conversion factors for mono-energy gamma rays

In the simulation, it is assumed that the lateral and vertical concentration distributions due to the atmospheric turbulence are Gaussian, and that the standard deviations change as a function of down-wind distance. The standard deviations were calculated from the analytical formulae of Imai[13] originally based on the data of Pasquill[12], who classified the atmospheric stability condition into 6 categories. Constant wind speed of 1m/s and a release height of 100m were assumed. The change of release height does not affect the conversion factors significantly, unless it is extremely low. The height difference between a plume axis and a flight line is a main factor to determine vertical distribution of exposure rates. The radioactive nuclides in a Gaussian plume were assumed to emanate gamma rays with 14 mono-energies of 0.02MeV to 6MeV, and the gamma rays were detected at ten different heights of 100 through 1100m at down wind distances of 500, 1000 and 2000m.

Basic environmental conditions assumed in this calculations were as follows: 1) Transport media consist of air and soil adjoining each other with an infinite plane; 2) Air with a constant density of 0.00120g/cm consists of N_2 (75.7% weight fraction), O_2 (23.2%), and Ar (1.3%); and 3) Soil with a constant density of 1.33g/cm consists of SiO_2 (63% weight fraction), Al_2O_3 (18%), Fe_2O_3 (9%), and H_2O (10%).

The number of histories in one calculation was taken to be more than 1,000,000. The Monte Carlo calculation loses the statistical accuracy as a height difference increases because of decrease of photons. In this study, the calculated data having more than 40% statistical uncertainties were not used to derive the polynomial expressions. Over this height, the conversion factors are supposed to be calculated by simple extrapolation, which is not expected to have serious effect, because the bad statistical accuracy of the Monte Carlo calculation indicates the low radiation level.

To obtain conversion factors for method 2, the spatial exposure rates were integrated along the cross-wind distance from −800m to +800m, where the intersection with the plume axis is taken to be 0m. Under ideal conditions, the integration should be carried out over an infinite range. Nevertheless, in fact, it is impossible to measure exposure rates over an infinite range by an aerial survey. An exposure rate at a point far from the plume axis does not contribute much to the integrated value. Therefore, the integral range was determined as some finite range large enough to approximate infinity in most cases.

Fig.3 and 4 show the fitted curves of the conversion factors for mono energy gamma plumes for every combination of a down-wind distance and an atmospheric stability category. We did not show conversion factors for atmospheric stability A at a down-wind distance of 2000m, because the change of the conversion factors due to a down wind distance is so large that the release rates estimated at this position may include large error. Though dimensions of conversion factors in formulae (3) and (4) include the wind-velocity dimension, the units of the conversion factors shown in the figures do not include it positively for the sake of simplicity. A user must take wind velocity into account, when estimating release rates from formulae (3) and (4).

Differences of values among the conversion factors due to atmospheric stability were examined at height differences of 100, 300 and 500m, and the following features were made clear:

1) As a whole, conversion factors for stability category D-F are similar, on the other hand, the conversion factors for category A often differ much from the other conversion factors;

2) The difference decreases as the gamma energy increases. When the gamma energy is under 100keV the maximum difference of 2 order is observed, while, in energy range over 200 keV the conversion factors agree within 20 % if the atmospheric stability is neutral or stable(D-F). And over 1 MeV the conversion factors for all atmospheric stability except A agree within a factor 2;

3) The difference increases as a height difference increases;

4) The difference increases as a down-wind distance increases;

5) For gamma energy of more than 1MeV the difference in method 2 is smaller

than that in method 1, however, for smaller energy this tendency does not always hold.

3.2 Conversion factors for radionuclides

From the data calculated in the previous section, conversion factors were constructed through convolution for radionuclides anticipated to be released in nuclear plant accidents. Intensities and energies of gamma rays from these radionuclides shown in Fig.5 are from ENSDF[16]. A conversion factor for arbitrary energy was calculated by exponential interpolation from the conversion factors for 14 discrete mono-energies. By summing up a conversion factor multiplied by the intensity for each gamma energy, a conversion factor for a nuclide was determined as follows,

$$k(i,h,s) = \sum_j g_{ij} \cdot k(E_{ij},h,s), \quad (6)$$

where

i = denotation of a nuclide,

h = height difference(m),

s = atmospheric stability category(A–F),

g_{ij} = intensity of the j-th gamma ray of the i-th nuclide,

E_{ij} = energy of the j-th gamma ray of the i-th nuclide(MeV).

For every nuclide shown in Fig.5, the conversion factors were calculated. Furthermore, a polynomial expression was fitted to logarithm of conversion factors at 10 height differences. Fig.6 11 show conversion factors for radioactive krypton, xenon and iodine. Drastic difference of factors among the nuclides is observed. For the other nuclides, line graphs of the conversion factors are not shown in this report, however, the coefficients of the polynomial expressions are stored in the computer file.

Generally speaking, the intercept of a curve is high when the total energy emitted by a nuclide per disintegration is large, and the decline or shape of the curve is concerned with the energy spectrum of the emitted gamma rays (shown in Fig.5). The total gamma ray energy emitted per disintegration and the mean energy of the gamma rays are shown in Table 1 for krypton, xenon and iodine, which may help one to understand these tendency. For example, in case of krypton, the nuclides which emanate high energy gamma rays ($^{87-90}Kr$) are similar in the decline and absolute values. While, the other krypton nuclides (^{83m}Kr, ^{85}Kr and ^{85m}Kr) have their own characteristic curves. In particular, ^{85}Kr emanates only low energy gamma rays, so the conversion factors decrease rapidly as a height difference increases. Nuclides which emanate high energy gamma rays tend to decay faster than those with emanation of low energy gamma rays. Therefore, in an nuclear reactor accident, the nuclides whose conversion curves are shown in the lower parts of the figures mainly contribute to exposure in the middle or late stage of a nuclear accident.

If concentration ratios of radioactivity of released nuclides are known, one can construct conversion factors for estimating the total release rates of a mixture according to the following equation,

$$k(h,s) = \sum_i f_i \cdot k(i,h,s) \qquad (7)$$

here, f_i is relative concentration of radioactivity of the i th nuclide, where the total concentration is normalized to 1.0.

3.3 Conversion factors as a function of time after shutdown

In a reactor accident, various nuclides are possibly released into the atmosphere. Nuclide composition of released gaseous radioactivity depends on a reactor type, exposure history of fuel and accidental condition. Also, it changes as a function of elapsed time after reactor shutdown, and the spectral change of emitted gamma rays is so appreciable[17). However, on the assumption of some typical accidental conditions, time dependent conversion factors can be constructed for a mixture of radionuclides.

Here, dependency of the conversion factors on time after shutdown was investigated for a group of noble gases and for that of iodine in case of BWR accidents. The radioactivity concentration of nuclides released from a BWR is from the data library of SPEEDI (the System for Prediction of Environmental Emergency Dose Information)[18) developed by JAERI. The concentration ratios are not expected to differ significantly from that of a PWR. The time dependent conversion factors were calculated according to equation(7) for noble gases and for iodine separately. In an accident, one can construct appropriate conversion factors assuming the ratio of concentration of total noble gases to that of total iodine, though in most cases noble gases are considered to be dominant.

3.3.1 Noble gases

Three burn-up conditions of 5,000, 10,000 and 30,000 MWd/tU were assumed. Fig.12-a), b) and c) show the changes of concentration ratios of radioactive noble gases due to time after shutdown for burn-up of 5,000MWd/tU 10,000MWd/tU and 30,000MWd/tU, respectively. Main difference among these three burn-up conditions is the amount of ^{85}Kr having a long life time, which affects the constructed conversion factors in late stage of a reactor accident. Considering the change of these concentration ratios, conversion factors were calculated for 13 elapsed times of 1h through 1,000h. Polynomial expressions of the conversion factors were decided as usual. Fig.13–18 show of the fitted curves for three different burn-up conditions. Comparison of the conversion factors was made at height differences of less than 500m among different elapsed times, different burn-up and different atmospheric stability, and the following features were made clear:

a) Both absolute values and decline of the conversion factors change rapidly as a function of elapsed time after shutdown, especially, in the early stage of the accident. This tendency is very clear compared with iodine;

b) Burn-up condition affects little the conversion factors before 350h. However, the conversion factors at 600–1,000h vary evidently according to burn-up. The conversion factors for burn-up of 5,000MWd/tU and 30000MWd/tU differ from that for 10,000Mwd/tU by 50% at maximum;

c) Table 2 shows ranges of atmospheric stability where conversion factors agrees with that for stability category D within a factor 2 and within 20%. When the atmospheric condition is neutral or stable(categories D-F), almost all of the conversion factors agree with that for stability category F within 20%. At a down-wind distance of 500m, a conversion factor for stability category D can represent that for any stability category within ambiguity of factor 2. Tendency concerning height difference or down-wind difference is similar to that for mono-energy gamma rays.

3.3.2 Iodine

Three burn-up conditions of nuclear fuel just the same as those in noble gases were considered. Further, two cases were assumed: One is that ^{132}I is supplied from decay of ^{132}Te which transferred into fuel rod plenums (case A); The other is that there is no supply of ^{132}I (case B). In case A, the concentration ratio data of ^{132}I from the library of SPEEDI was modified by data of Minami[19].

Fig.19 shows the concentration ratios of radioactivity of released iodine as a function of time after shutdown. In this figure, a) and b) denote the case A and B, respectively. Conversion factors for a group of iodine and the polynomial expressions were constructed in the same way as for noble gases. The fitted curves are shown in Figs.20,21 and Figs.22,23 for case A and B, respectively. The following features on the conversion factors were made clear:

a) The burn-up condition hardly affects the conversion factors in case of iodine, because the burn-up condition mainly changes the amount of ^{129}I that does not contribute the spatial exposure rates because the concentration is much lower than those of the other nuclides.

b) The conversion factors at 1h and 1000h for case A are quite similar to those for case B. The supply of ^{132}I from decay of ^{132}Te delays the change of the conversion factors with time because of emission of high energy gamma rays. For case B, the conversion factor at 200h is almost same as that at 1000h. The maximum discrepancy between case A and B appears at 100 200h, and the conversion factor for case A is about 4 times as large as that for case B.

c) Table 3 shows ranges of atmospheric stability where conversion factors agree with that for stability category D within a factor 2 and within 20%. When the atmosphere is in neutral or stable condition(categories D-F), the conversion factors do not change much.

3.4 Another usage of conversion factors

Change of exposure rates on the ground per unit radioactivity release with time after shutdown can be inferred from data shown here, because the exposure rate distribution is considered to be almost symmetrical to the plume axis along z co-ordinates. The existence of the ground does not disturb the maximum exposure rate so much, for example, the disturbance is 20-30 % for 0.1 MeV gamma rays and less for gamma rays with higher energies[20].

4. CONCLUSION

The conversion factors, necessary for estimating release rate of gaseous radioactivity using an aerial survey, were calculated assuming a Gaussian plume model for mono-energy gamma rays, for critical radionuclides and for a mixture of these nuclides changing with time after shutdown. Also, with the least-squares method polynomial expressions of the conversion factors were determined as a function of height difference between a flight line and a plume axis. Line graphs of the conversion factors calculated in this study are shown, also, the coefficients of the polynomial expressions are stored in a file of the host computer at JAERI, so that a user can easily obtain a proper conversion factor. The estimation methods are quite effective if the composition of radionuclides in a plume is known, and this report is expected to rapidly provide appropriate data necessary for estimating source terms in an accident.

ACKNOWLEDGEMENT

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Table 1 Total energy and average energy of gamma rays emitted per disintegration of radioactive krypton, xenon and iodine.

NUCLIDE	TOTAL ENERGY (MeV)	AVERAGE ENERGY (MeV)
^{83m}Kr	2.58×10^{-3}	1.10×10^{-2}
^{85}Kr	2.24×10^{-3}	5.17×10^{-1}
^{85m}Kr	1.57×10^{-1}	1.65×10^{-1}
^{87}Kr	7.92×10^{-1}	9.55×10^{-1}
^{88}Kr	1.96×10^{0}	1.34×10^{0}
^{89}Kr	1.82×10^{0}	1.12×10^{0}
^{90}Kr	1.29×10^{0}	7.52×10^{-1}
^{131m}Xe	2.01×10^{-2}	3.12×10^{-2}
^{133}Xe	4.54×10^{-2}	5.03×10^{-2}
^{133m}Xe	4.16×10^{-2}	5.56×10^{-2}
^{135}Xe	2.49×10^{-1}	2.49×10^{-1}
^{135m}Xe	4.32×10^{-1}	4.48×10^{-1}
^{137}Xe	1.88×10^{-1}	5.42×10^{-1}
^{138}Xe	1.13×10^{0}	8.48×10^{-1}
^{139}Xe	8.84×10^{-1}	5.56×10^{-1}
^{129}I	2.47×10^{-2}	2.87×10^{-2}
^{131}I	3.81×10^{-1}	3.61×10^{-1}
^{132}I	2.28×10^{0}	7.62×10^{-1}
^{133}I	6.06×10^{-1}	5.85×10^{-1}
^{134}I	2.61×10^{0}	8.57×10^{-1}
^{135}I	1.57×10^{0}	1.18×10^{-0}
^{136}I	3.40×10^{-4}	1.90×10^{-4}

Table 2 Ranges of atmospheric stability where conversion factors agree with that for stability category F within a factor 2 and within 20%. a) for method 1, b) for method 2. Radioactive noble gases are assumed to be released from fuel with burn-up of 10,000 MWd/tU.

TIME AFTER SHUTDOWN (h)	RANGE OF ATMOSPHERIC STABILITY					
	DOWN-WIND DISTANCE 500 m		DOWN-WIND DISTANCE 1000 m		DOWN-WIND DISTANCE 2000 m	
	FACTOR 2	20%	FACTOR 2	20%	FACTOR 2	20%
1	A-F	B-F	B-F	C-F	C-F	D-F
2	A-F	B-F	B-F	C-F	C-F	D-F
3.5	A-F	B-F	B-F	C-F	C-F	D-F
6	A-F	B-F	B-F	C-F	C-F	D-F
10	B-F	B-F	B-F	C-F	C-F	D-F
20	B-F	B-F	C-F	C-F.	C-F	D-F
35	B-F	C-F	C-F	D-F	D-F	D-F
60	B-F	C-F	C-F	C-F	D-F	D-F
100	B-F	C-F	C-F	C-F	D-F	D-F
200	B-F	C-F	B-F	C-F	D-F	D-F
350	B-F	C-F	C-F	C-F	D-F	D-F
600	B-F	C-F	C-F	C-F	D-F	D-F
1000	B-F	B-F	C-F	C-F	D-F	D-F

TIME AFTER SHUTDOWN (h)	RANGE OF ATMOSPHERIC STABILITY					
	DOWN-WIND DISTANCE 500 m		DOWN-WIND DISTANCE 1000 m		DOWN-WIND DISTANCE 2000 m	
	FACTOR 2	20%	FACTOR 2	20%	FACTOR 2	20%
1	A-F	B-F	B-F	C-F	C-F	D-F
2	A-F	B-F	B-F	C-F	C-F	D-F
3.5	A-F	B-F	B-F	C-F	C-F	D-F
6	A-F	B-F	B-F	C-F	C-F	D-F
10	B-F	B-F	B-F	C-F	C-F	D-F
20	B-F	B-F	C-F	C-F.	C-F	D-F
35	B-F	C-F	C-F	D-F	D-F	D-F
60	B-F	C-F	C-F	D-F	D-F	D-E
100	B-F	C-F	C-F	D-F	D-F	D-E
200	B-F	C-F	C-F	D-F	D-F	D-E
350	B-F	C-F	C-F	D-F	D-F	D-E
600	B-F	C-F	C-F	D-F	D-F	D-E
1000	B-F	C-F	C-F	D-F	D-F	D-E

Table 3 Ranges of atmospheric stability where conversion factors agree with that for stability category F within a factor 2 and within 20%. a) for method 1, b) for method 2. Radioactive iodine is assumed to be released from fuel with burn-up of 10,000 MWd/tU.

TIME AFTER SHUTDOWN (h)	RANGE OF ATMOSPHERIC STABILITY					
	DOWN-WIND DISTANCE 500 m		DOWN-WIND DISTANCE 1000 m		DOWN-WIND DISTANCE 2000 m	
	FACTOR 2	20%	FACTOR 2	20%	FACTOR 2	20%
1	B-F	B-F	B-F	C-F	C-F	D-F
2	B-F	B-F	B-F	C-F	C-F	D-F
3.5	B-F	B-F	B-F	C-F	C-F	D-F
6	B-F	B-F	B-F	C-F	C-F	D-F
10	B-F	B-F	B-F	C-F	C-F	D-F
20	B-F	B-F	B-F	C-F	C-F	D-F
35	B-F	B-F	B-F	C-F	C-F	D-F
60	B-F	B-F	B-F	C-F	C-F	D-F
100	B-F	B-F	B-F	C-F	C-F	D-F
200	B-F	B-F	B-F	C-F	C-F	D-F
350	B-F	B-F	B-F	C-F	C-F	D-F
600	B-F	B-F	B-F	C-F	C-F	D-F
1000	B-F	B-F	B-F	C-F	C-F	D-F

TIME AFTER SHUTDOWN (h)	RANGE OF ATMOSPHERIC STABILITY					
	DOWN-WIND DISTANCE 500 m		DOWN-WIND DISTANCE 1000 m		DOWN-WIND DISTANCE 2000 m	
	FACTOR 2	20%	FACTOR 2	20%	FACTOR 2	20%
1	A-F	B-F	B-F	C-F	C-F	
2	A-F	B-F	B-F	C-F	C-F	
3.5	A-F	B-F	B-F	C-F	C-F	
6	A-F	B-F	B-F	C-F	C-F	
10	A-F	B-F	B-F	C-F	C-F	
20	A-F	B-F	B-F	C-F	C-F	
35	A-F	B-F	B-F	C-F	C-F	
60	B-F	B-F	B-F	C-F	C-F	
100	B-F	B-F	B-F	C-F	C-F	
200	B-F	B-F	B-F	C-F	C-F	
350	B-F	B-F	B-F	C-F	C-F	
600	B-F	B-F	B-F	C-F	C-F	
1000	B-F	B-F	B-F	C-F	C-F	

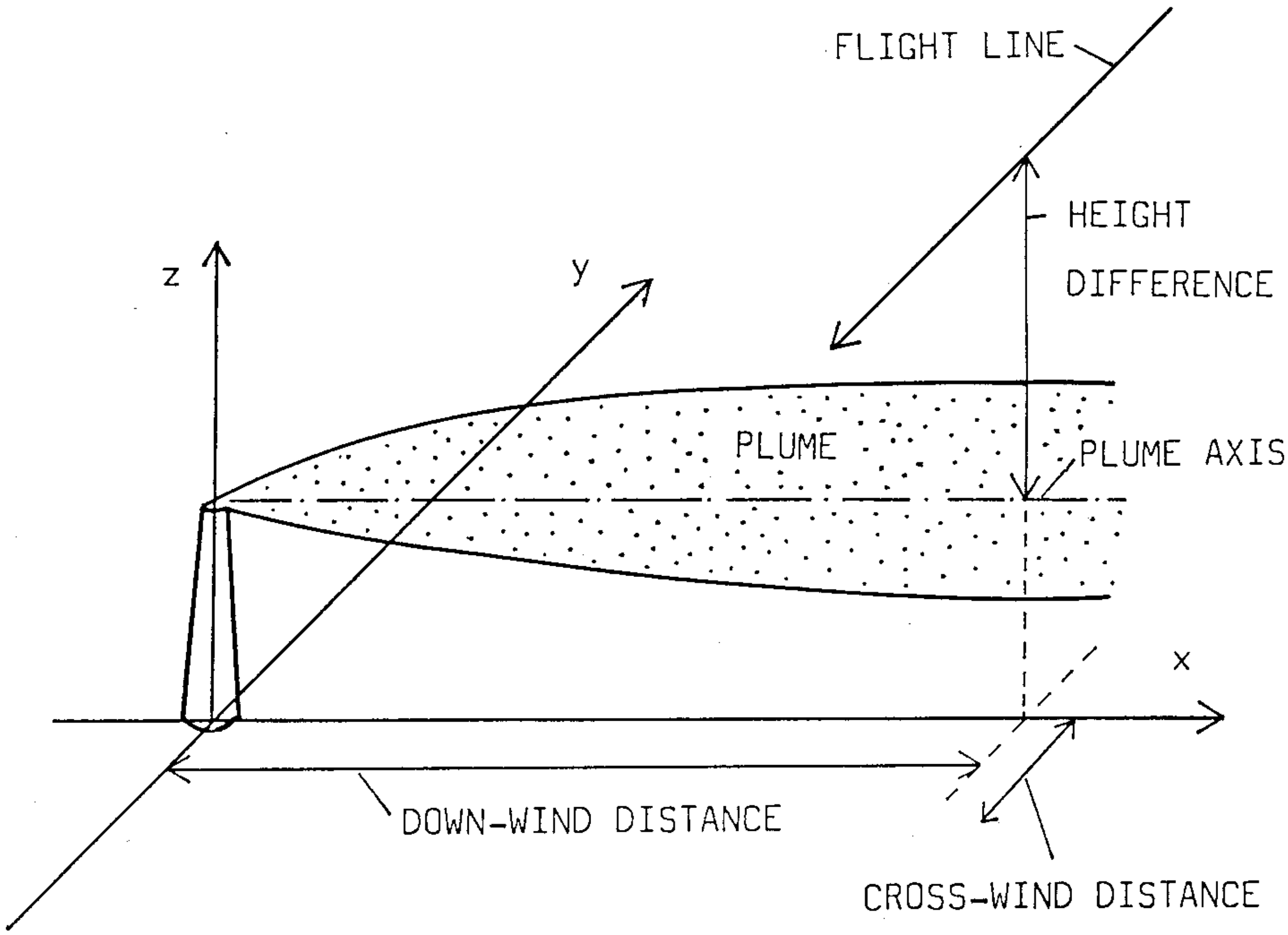

Fig.1 Flight method of a survey for estimating a release rate of gaseous radioactivity.

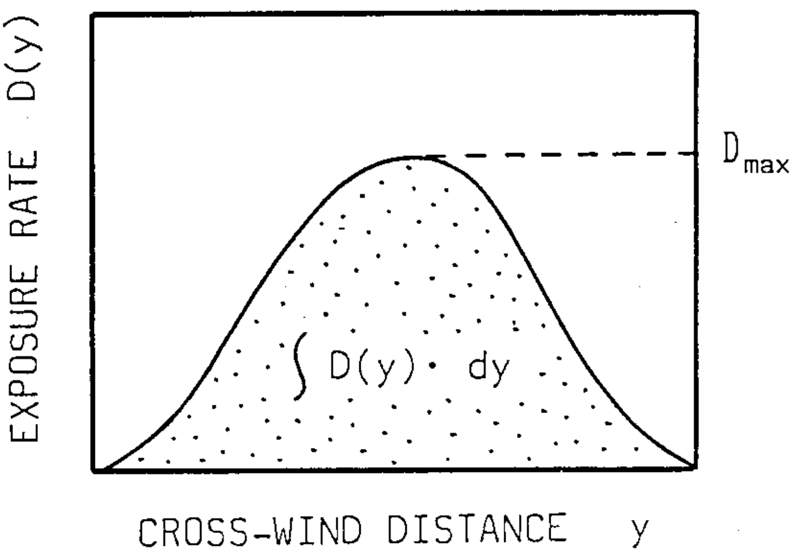

Fig.2 Typical distribution of exposure rates measured by an aerial survey for estimating a release rate of gaseous radioactivity.

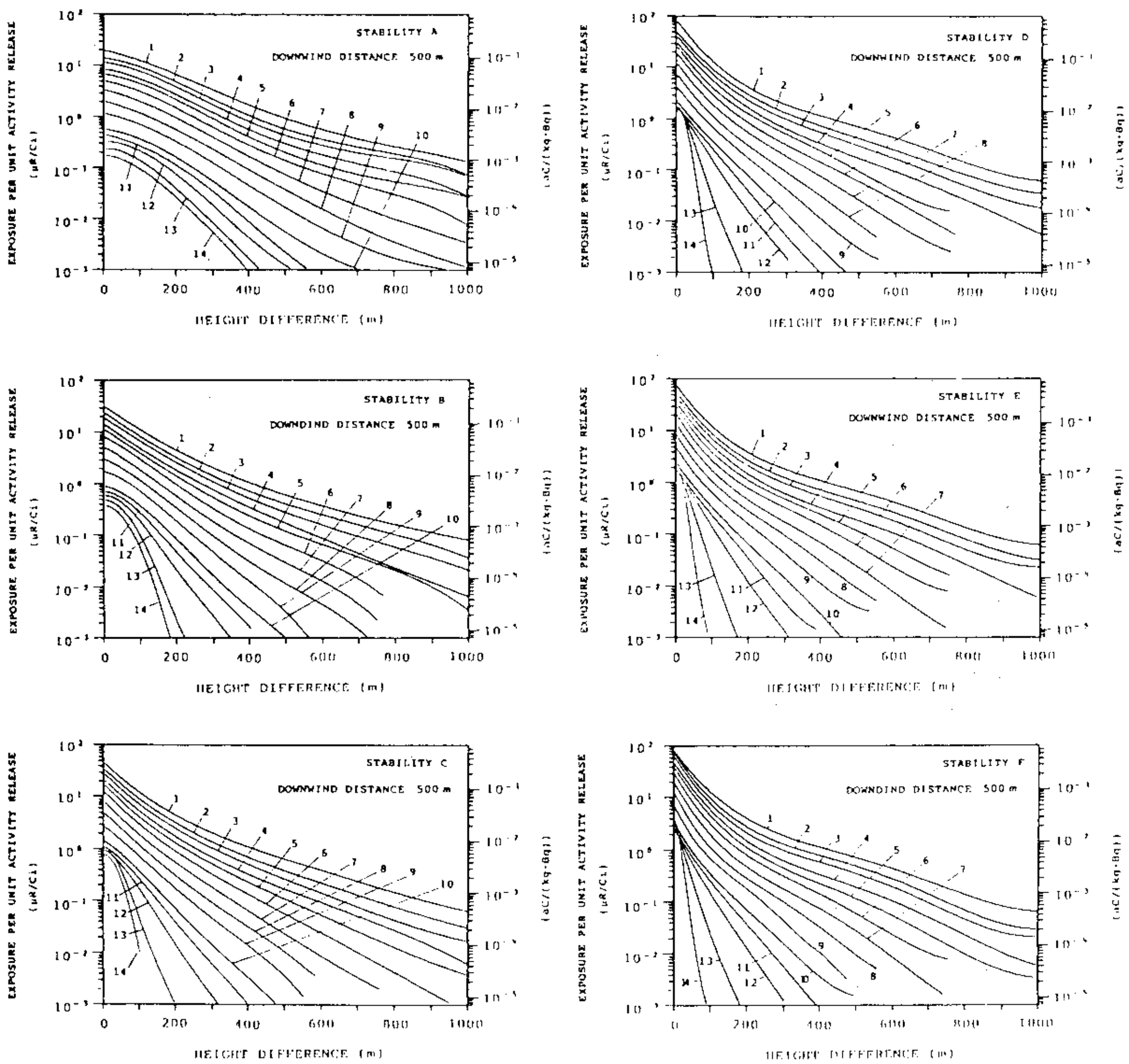

Fig.3-1 Conversion factors for method 1 at a down-wind distance of 500m for plumes emitting gamma rays with mono-energies. Energies denoted by numerals in the figures are as follows, 1=0.02, 2=0.03, 3=0.05, 4=0.07, 5=0.1, 6=0.2, 7=0.35, 8=0.6, 9=1.0, 10=1.5, 11=2.0, 12=3.0, 13=4.0 and 14=6.0MeV.

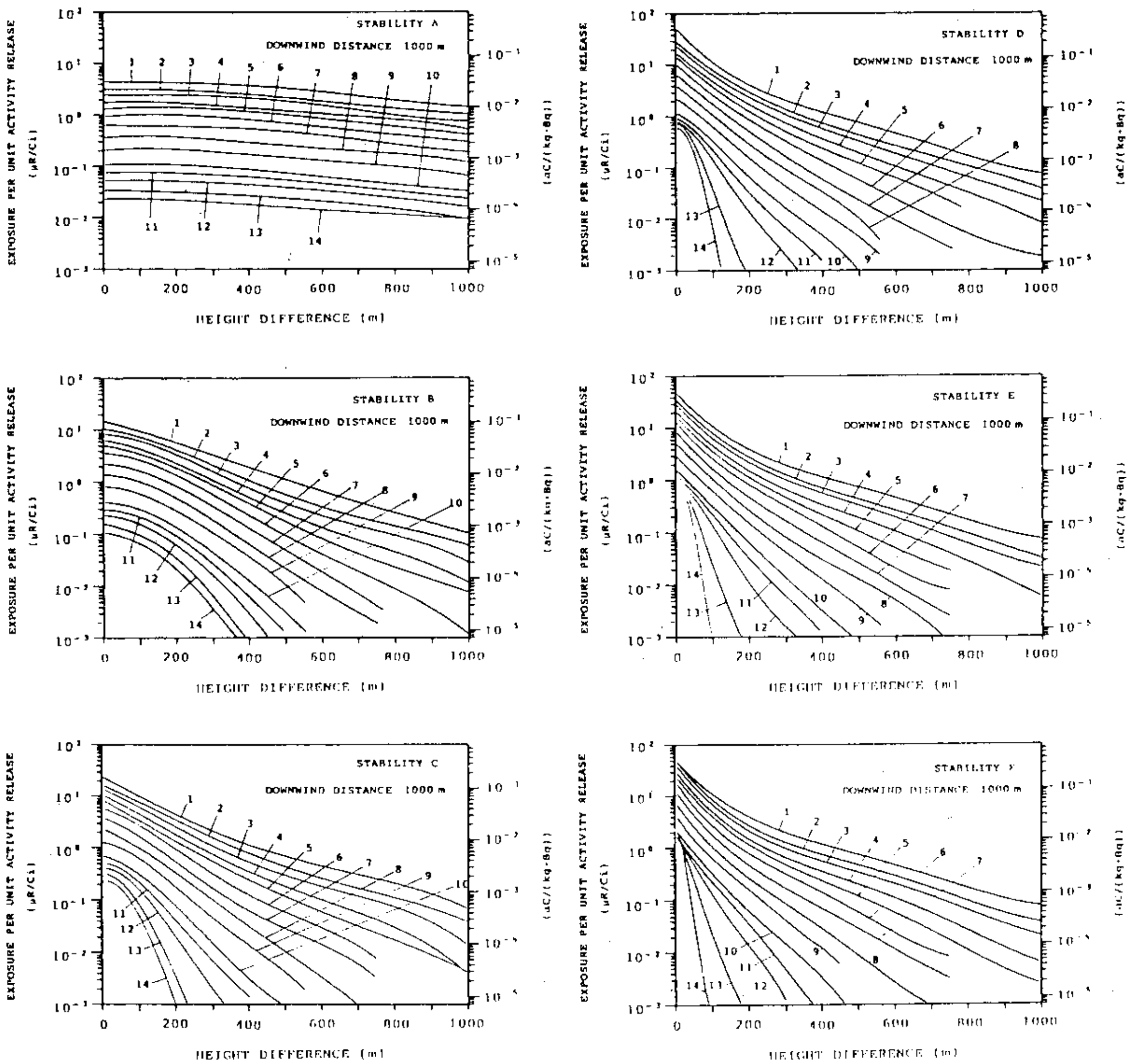

Fig.3-2 Conversion factors for method 1 at a down-wind distance of 1000m for plumes emitting gamma rays with mono-energies. Energies denoted by numerals in the figures are as follows, 1=0.02, 2=0.03, 3=0.05, 4=0.07, 5=0.1, 6=0.2, 7=0.35, 8=0.6, 9=1.0, 10=1.5, 11=2.0, 12=3.0, 13=4.0 and 14=6.0MeV.

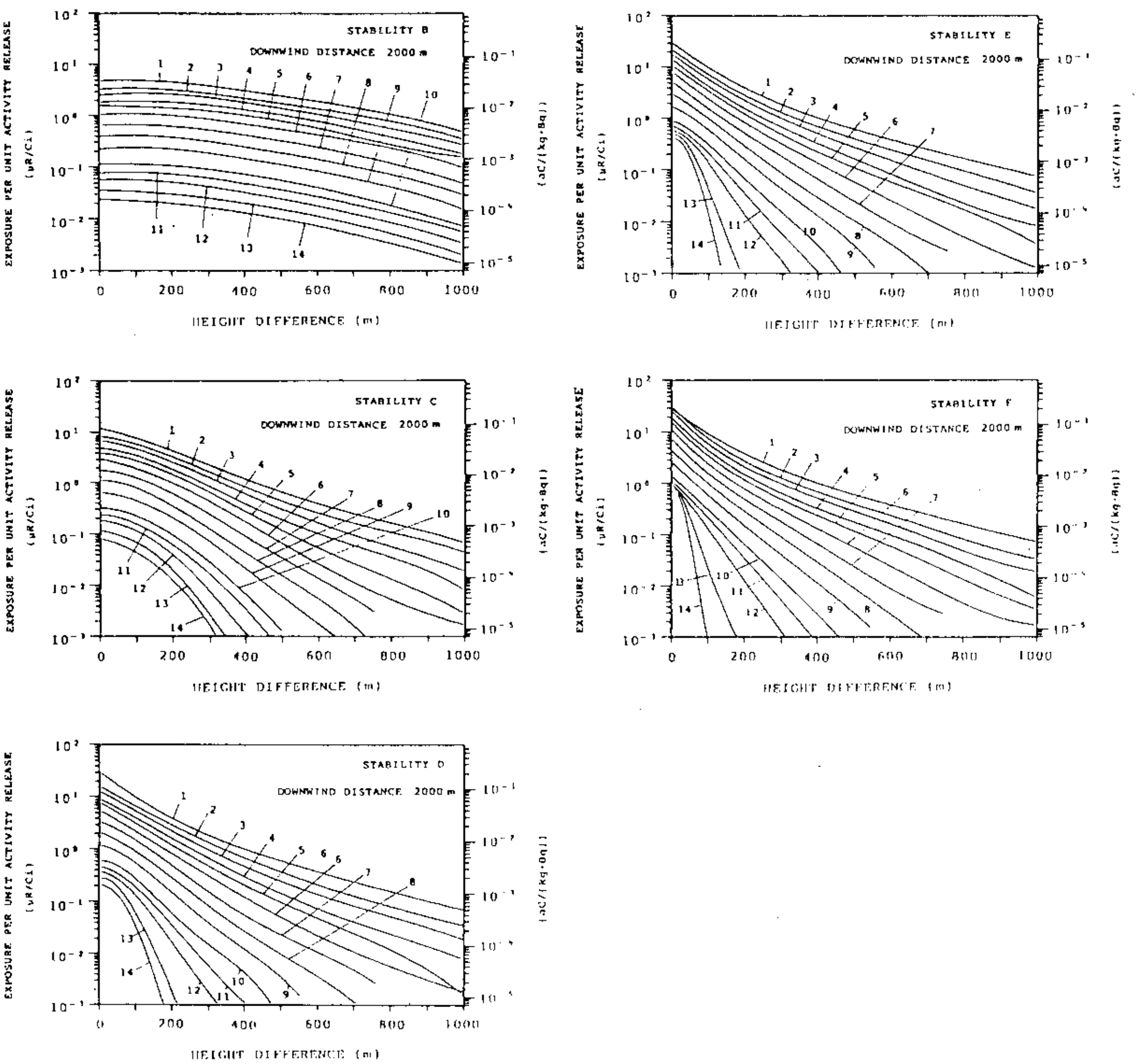

Fig.3-3 Conversion factors for method 1 at a down-wind distance of 2000m for plumes emitting gamma rays with mono-energies. Energies denoted by numerals in the figures are as follows, 1=0.02, 2=0.03, 3=0.05, 4=0.07, 5=0.1, 6=0.2, 7=0.35, 8=0.6, 9=1.0, 10=1.5, 11=2.0, 12=3.0, 13=4.0 and 14=6.0MeV.

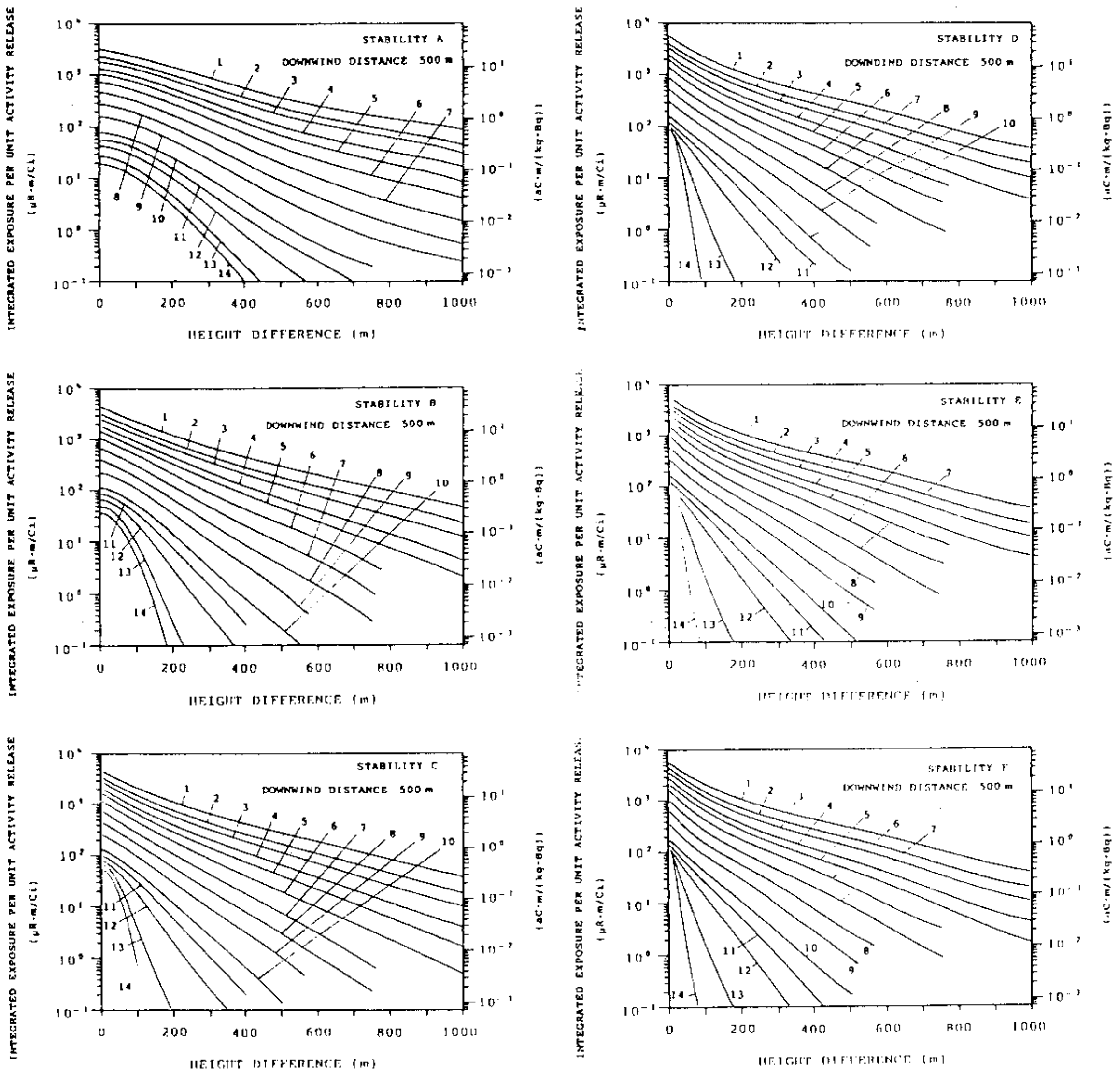

Fig.4-1 Conversion factors for method 2 at a down-wind distance of 500m for plumes emitting gamma rays with mono-energies. Energies denoted by numerals in the figures are as follows, 1=0.02, 2=0.03, 3=0.05, 4=0.07, 5=0.1, 6=0.2, 7=0.35, 8=0.6, 9=1.0, 10=1.5, 11=2.0, 12=3.0, 13=4.0 and 14=6.0MeV.

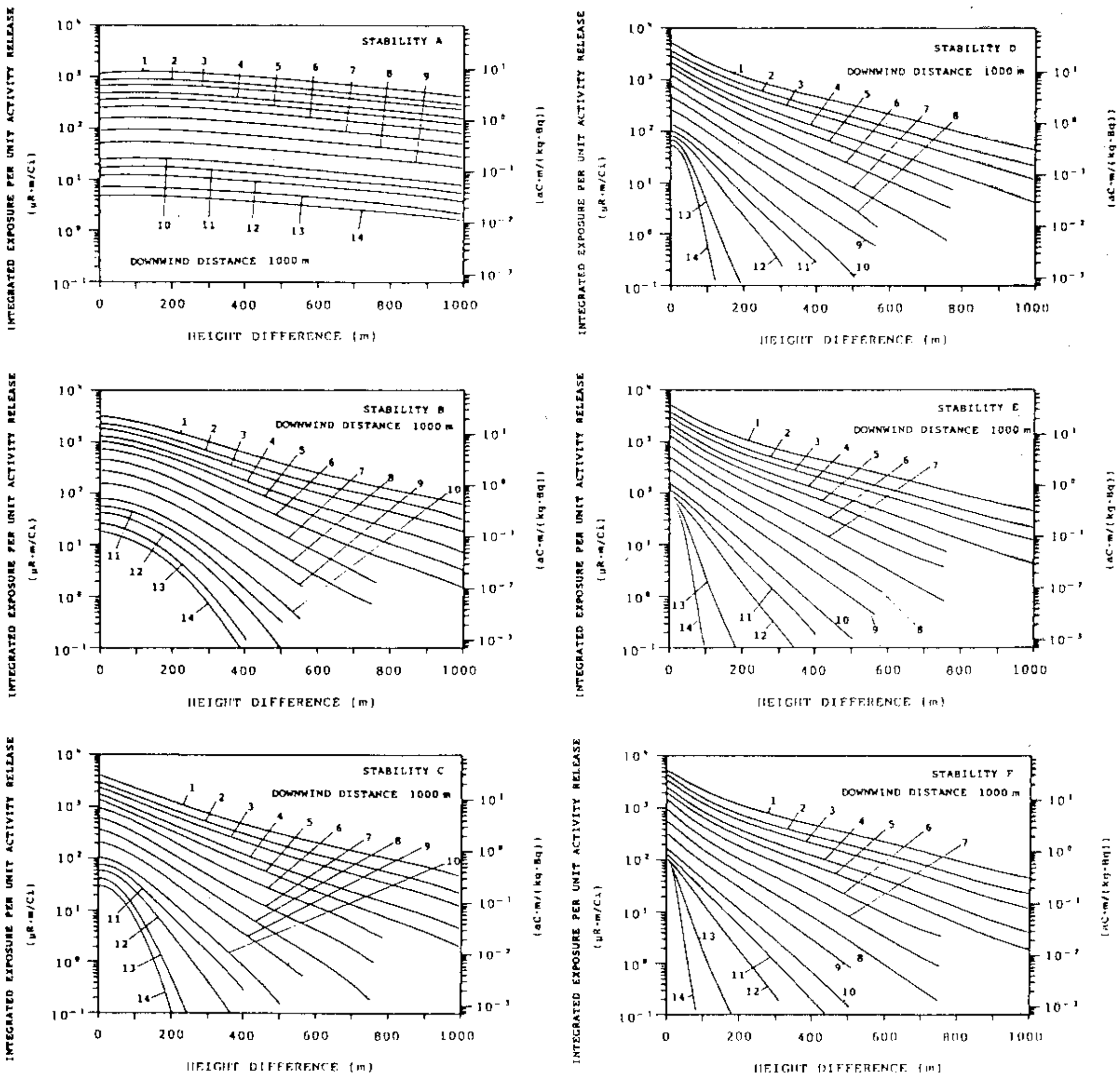

Fig.4-2 Conversion factors for method 2 at a down-wind distance of 1000m for plumes emitting gamma rays with mono-energies. Energies denoted by numerals in the figures are as follows, 1=0.02, 2=0.03, 3=0.05, 4=0.07, 5=0.1, 6=0.2, 7=0.35, 8=0.6, 9=1.0, 10=1.5, 11=2.0, 12=3.0, 13=4.0 and 14=6.0MeV.

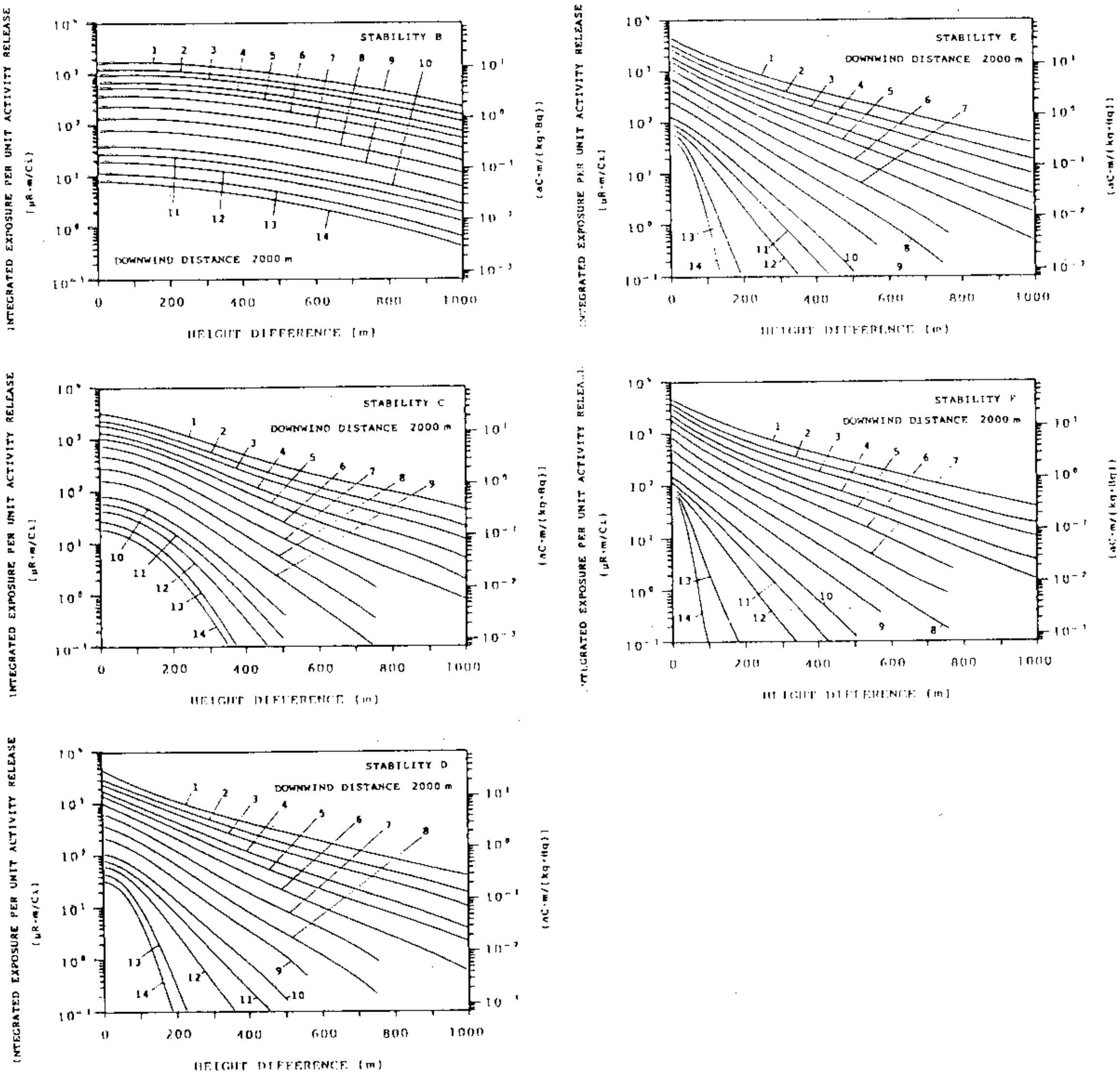

Fig.4-3 Conversion factors for method 2 at a down-wind distance of 2000m for plumes emitting gamma rays with mono-energies. Energies denoted by numerals in the figures are as follows, 1=0.02, 2=0.03, 3=0.05, 4=0.07, 5=0.1, 6=0.2, 7=0.35, 8=0.6, 9=1.0, 10=1.5, 11=2.0, 12=3.0, 13=4.0 and 14=6.0MeV.

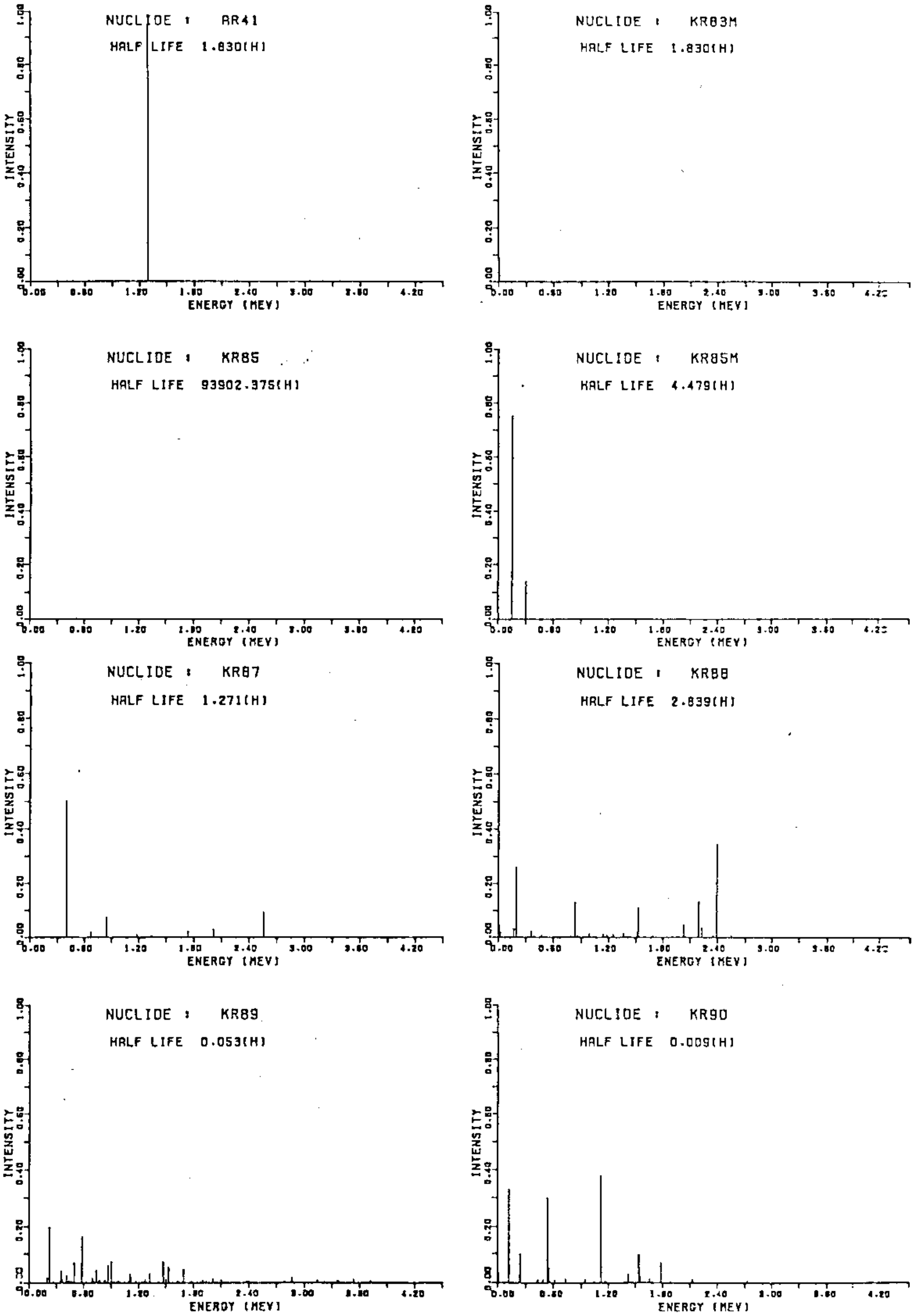

Fig. 5(1) Intensities and energies of gamma rays from radionuclides essential in a nuclear reactor accident according to ENSDF.

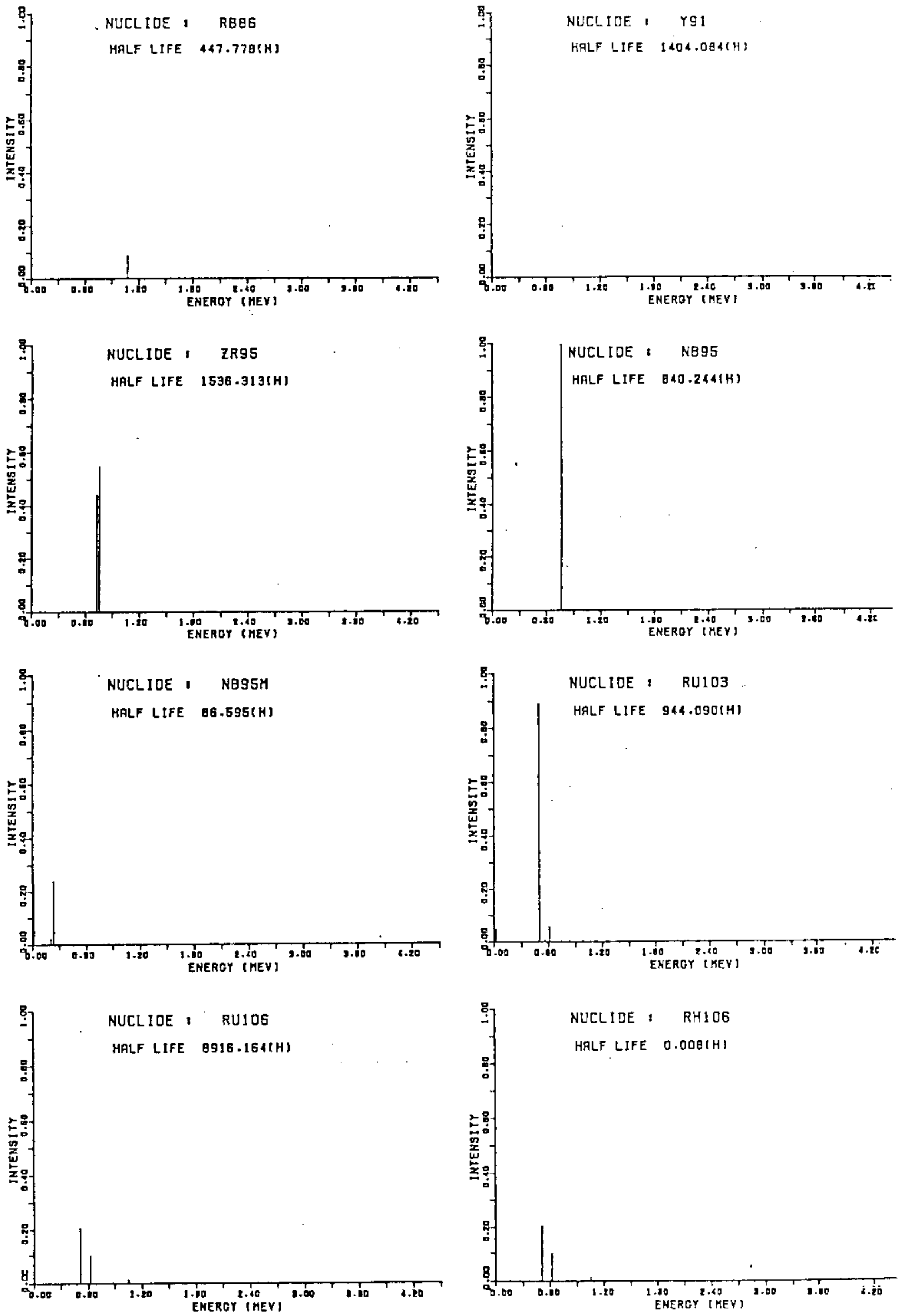
NUCLIDE : RB86
HALF LIFE 447.778(H)
INTENSITY
ENERGY (MEV)
NUCLIDE : Y91
HALF LIFE 1404.084(H)
INTENSITY
ENERGY (MEV)
NUCLIDE : ZR95
HALF LIFE 1536.313(H)
INTENSITY
ENERGY (MEV)
NUCLIDE : NB95
HALF LIFE 840.244(H)
INTENSITY
ENERGY (MEV)
NUCLIDE : NB95M
HALF LIFE 86.595(H)
INTENSITY
ENERGY (MEV)
NUCLIDE : RU103
HALF LIFE 944.090(H)
INTENSITY
ENERGY (MEV)
NUCLIDE : RU106
HALF LIFE 8916.164(H)
INTENSITY
ENERGY (MEV)
NUCLIDE : RH106
HALF LIFE 0.008(H)
INTENSITY
ENERGY (MEV)

Fig. 5 (2)

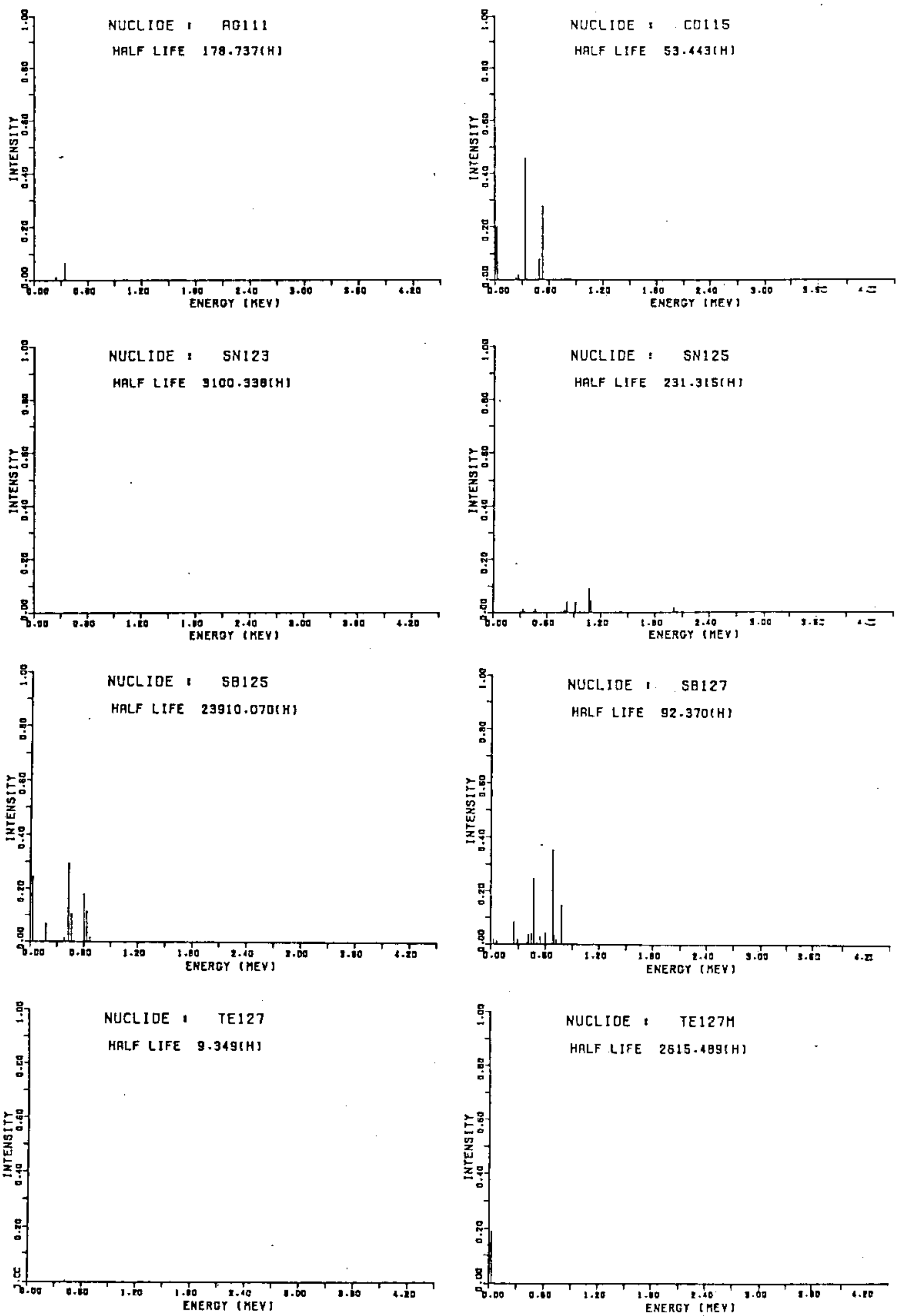
NUCLIDE : AG111
HALF LIFE 178.737(H)
NUCLIDE : CD115
HALF LIFE 53.443(H)
NUCLIDE : SN123
HALF LIFE 3100.338(H)
NUCLIDE : SN125
HALF LIFE 231.315(H)
NUCLIDE : SB125
HALF LIFE 23910.070(H)
NUCLIDE : SB127
HALF LIFE 92.370(H)
NUCLIDE : TE127
HALF LIFE 9.349(H)
NUCLIDE : TE127M
HALF LIFE 2615.489(H)
INTENSITY
ENERGY (MEV)

Fig. 5 (3)

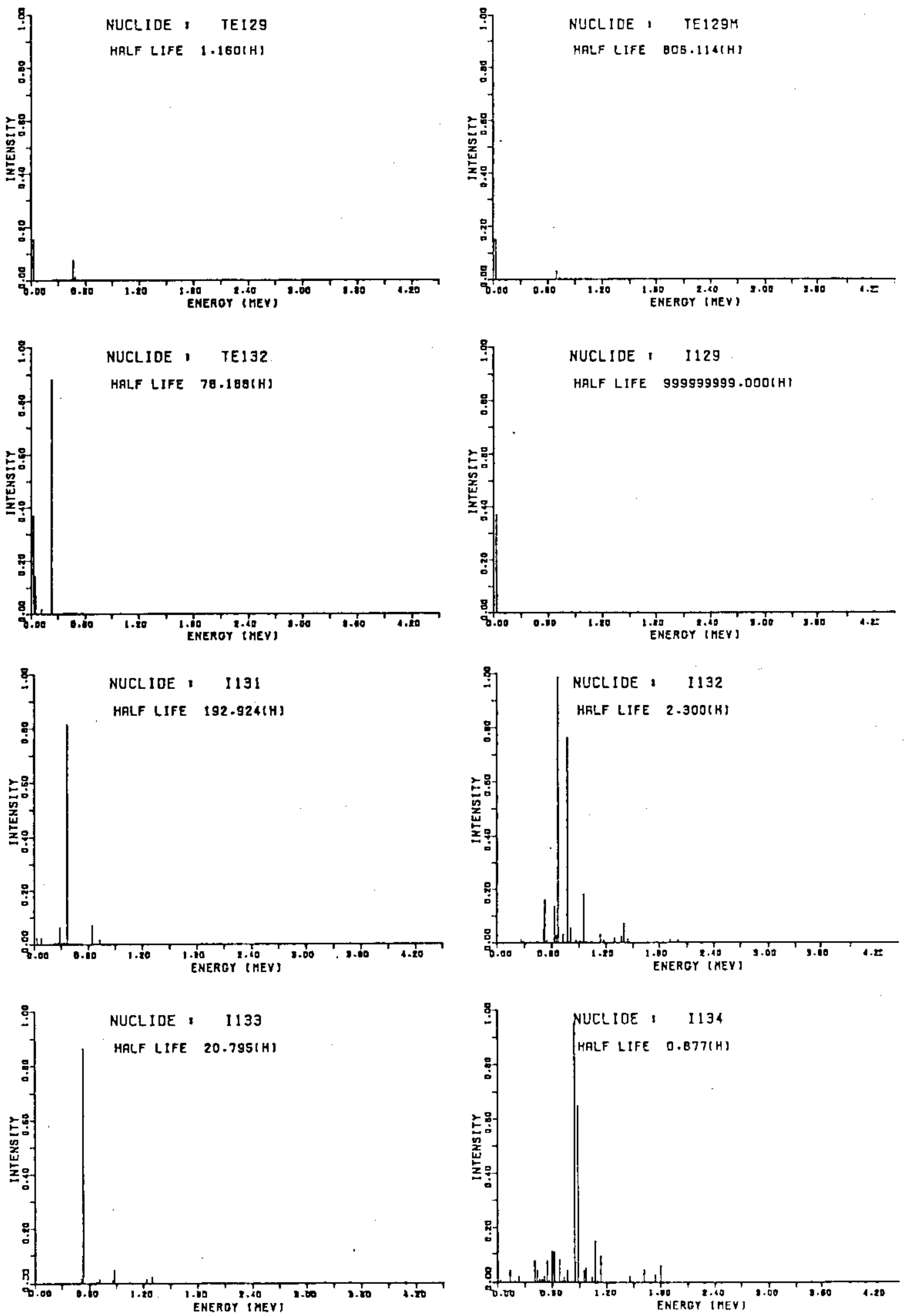
NUCLIDE : TE129
HALF LIFE 1.160(H)
NUCLIDE : TE129M
HALF LIFE 806.114(H)
NUCLIDE : TE132
HALF LIFE 78.188(H)
NUCLIDE : I129
HALF LIFE 999999999.000(H)
NUCLIDE : I131
HALF LIFE 192.924(H)
NUCLIDE : I132
HALF LIFE 2.300(H)
NUCLIDE : I133
HALF LIFE 20.795(H)
NUCLIDE : I134
HALF LIFE 0.877(H)
INTENSITY
ENERGY (MEV)
0.00
0.60
1.20
1.80
2.40
3.00
3.60
4.20
0.20
0.40
0.60
0.80
1.00

Fig. 5 (4)

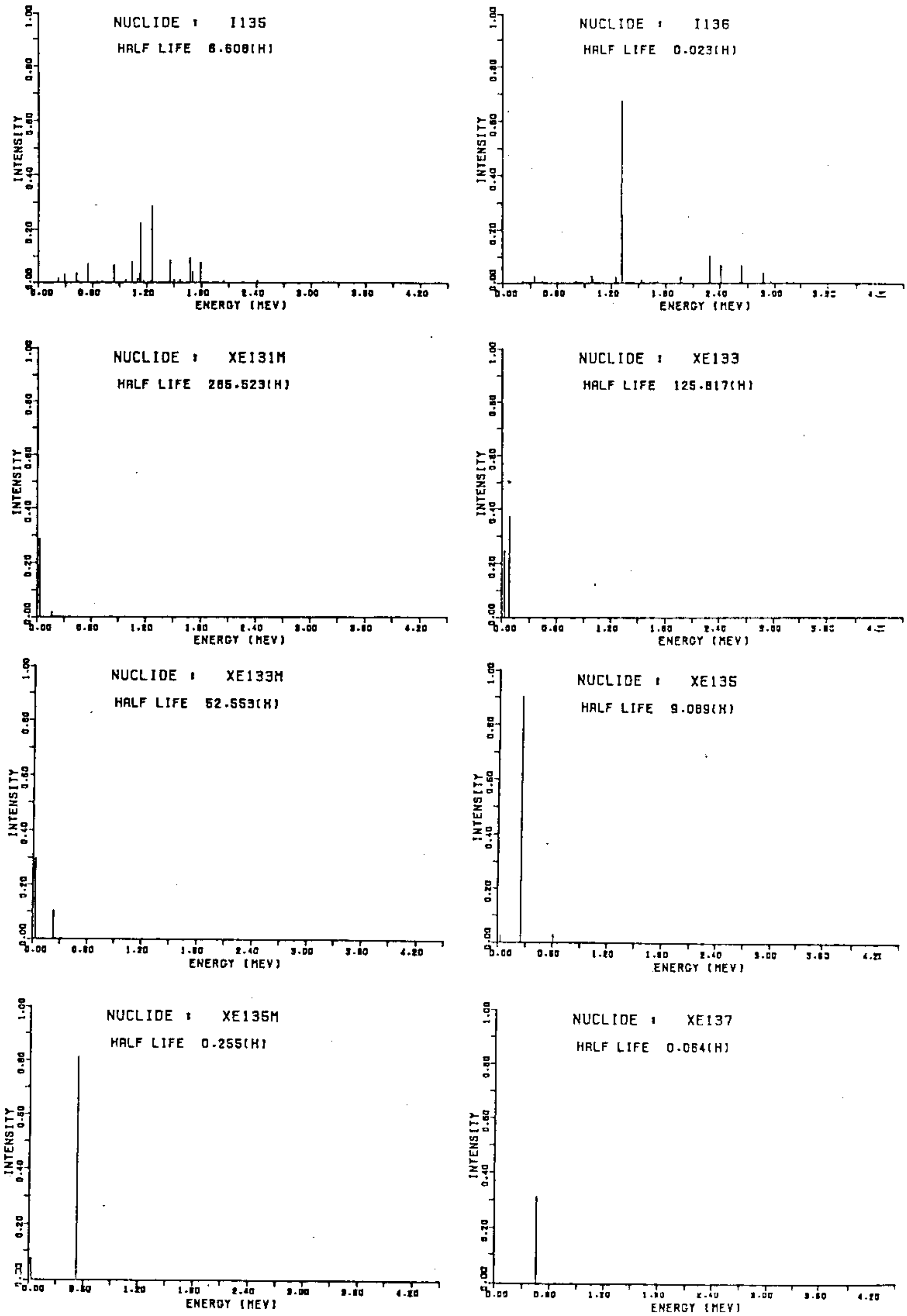
NUCLIDE : I135
HALF LIFE 6.608(H)
NUCLIDE : I136
HALF LIFE 0.023(H)
NUCLIDE : XE131M
HALF LIFE 285.523(H)
NUCLIDE : XE133
HALF LIFE 125.817(H)
NUCLIDE : XE133M
HALF LIFE 52.553(H)
NUCLIDE : XE135
HALF LIFE 9.089(H)
NUCLIDE : XE135M
HALF LIFE 0.255(H)
NUCLIDE : XE137
HALF LIFE 0.064(H)
INTENSITY
ENERGY (MEV)

Fig. 5 (5)

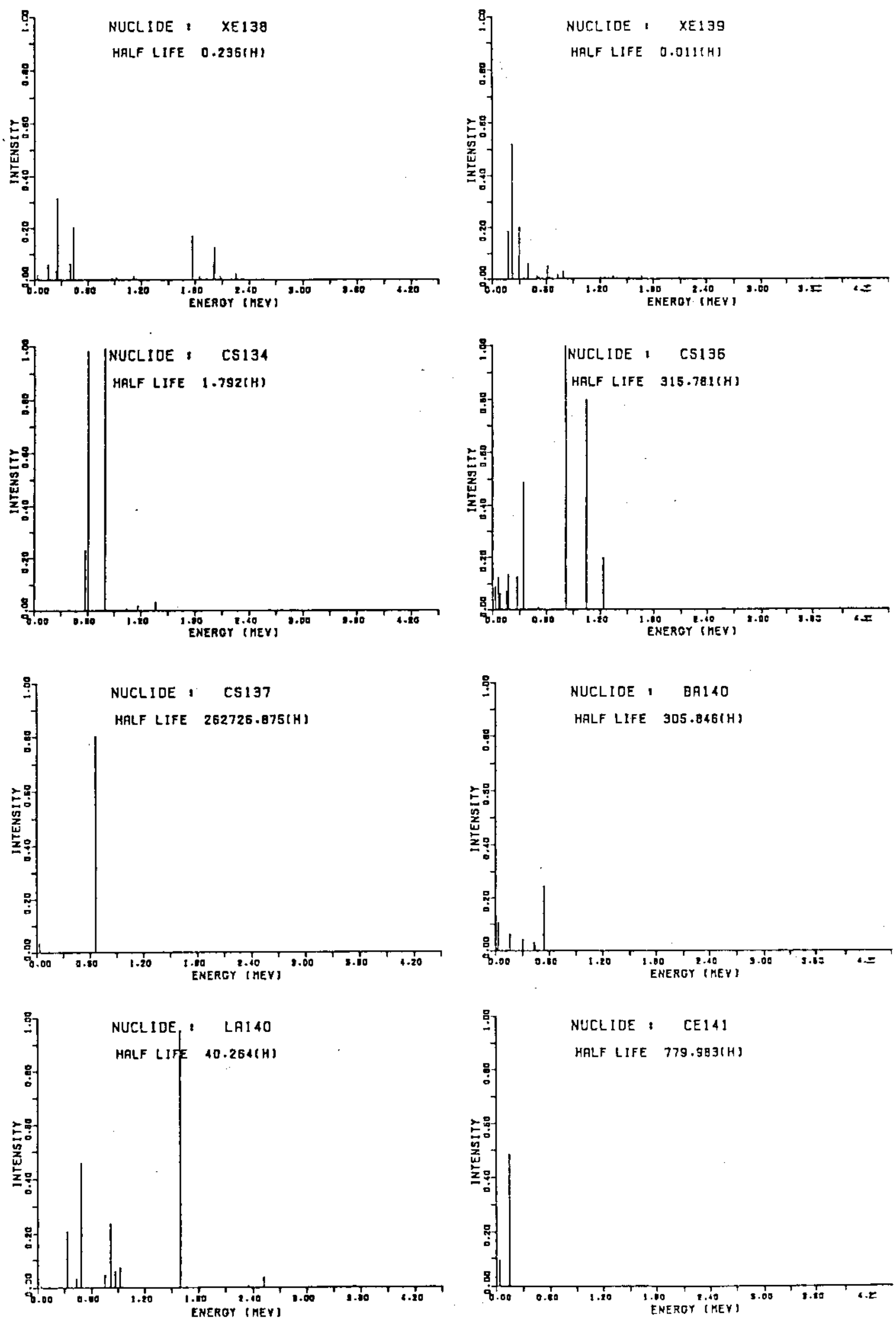
NUCLIDE : XE138
HALF LIFE 0.236(H)
NUCLIDE : XE139
HALF LIFE 0.011(H)
NUCLIDE : CS134
HALF LIFE 1.792(H)
NUCLIDE : CS136
HALF LIFE 315.781(H)
NUCLIDE : CS137
HALF LIFE 262726.875(H)
NUCLIDE : BA140
HALF LIFE 305.846(H)
NUCLIDE : LA140
HALF LIFE 40.264(H)
NUCLIDE : CE141
HALF LIFE 779.983(H)
INTENSITY
ENERGY (MEV)

Fig. 5 (6)

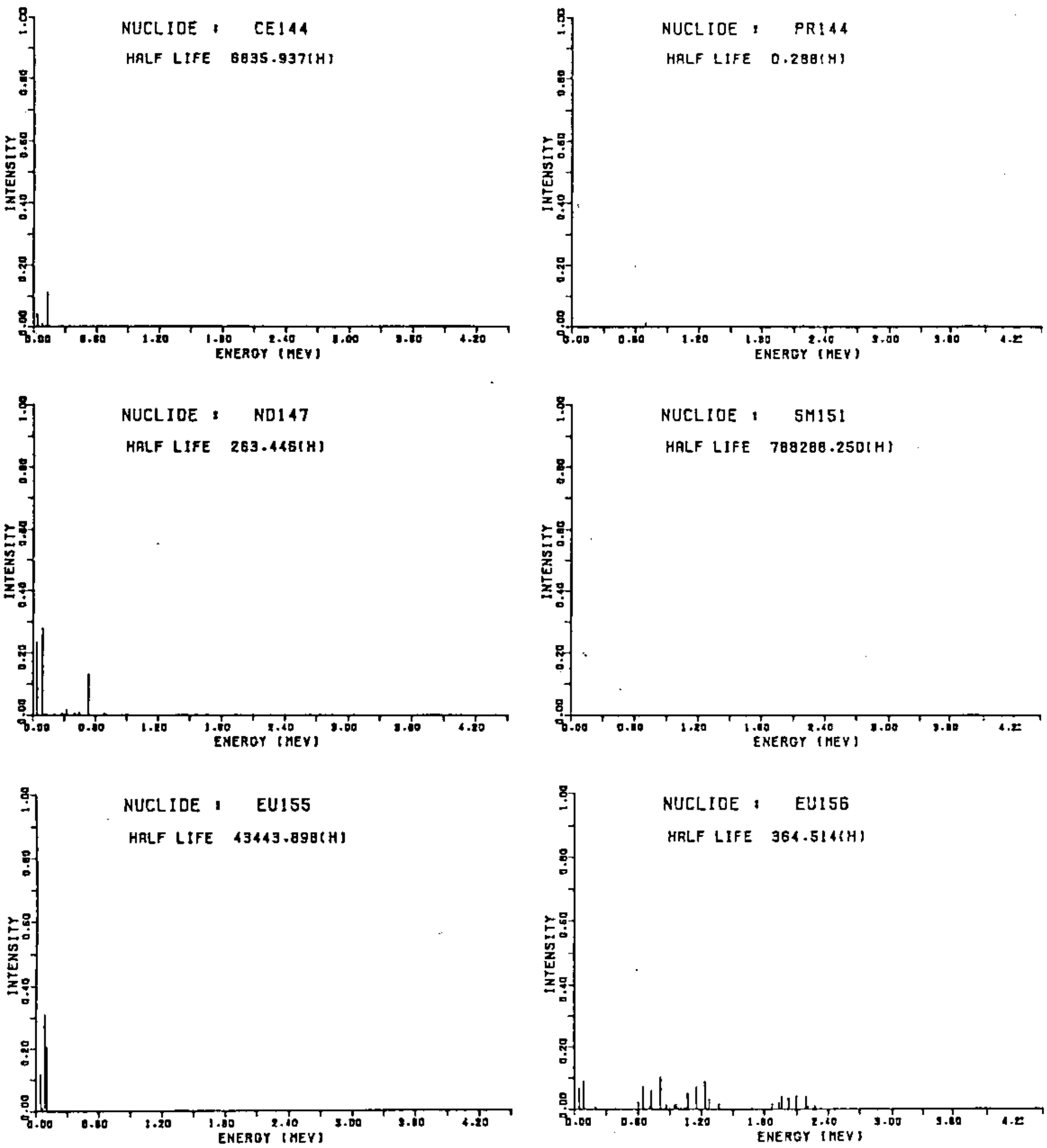
NUCLIDE : CE144
HALF LIFE 6835.937(H)
NUCLIDE : PR144
HALF LIFE 0.288(H)
NUCLIDE : ND147
HALF LIFE 263.446(H)
NUCLIDE : SM151
HALF LIFE 788288.250(H)
NUCLIDE : EU155
HALF LIFE 43443.898(H)
NUCLIDE : EU156
HALF LIFE 364.514(H)
INTENSITY
ENERGY (MEV)

Fig. 5 (7)

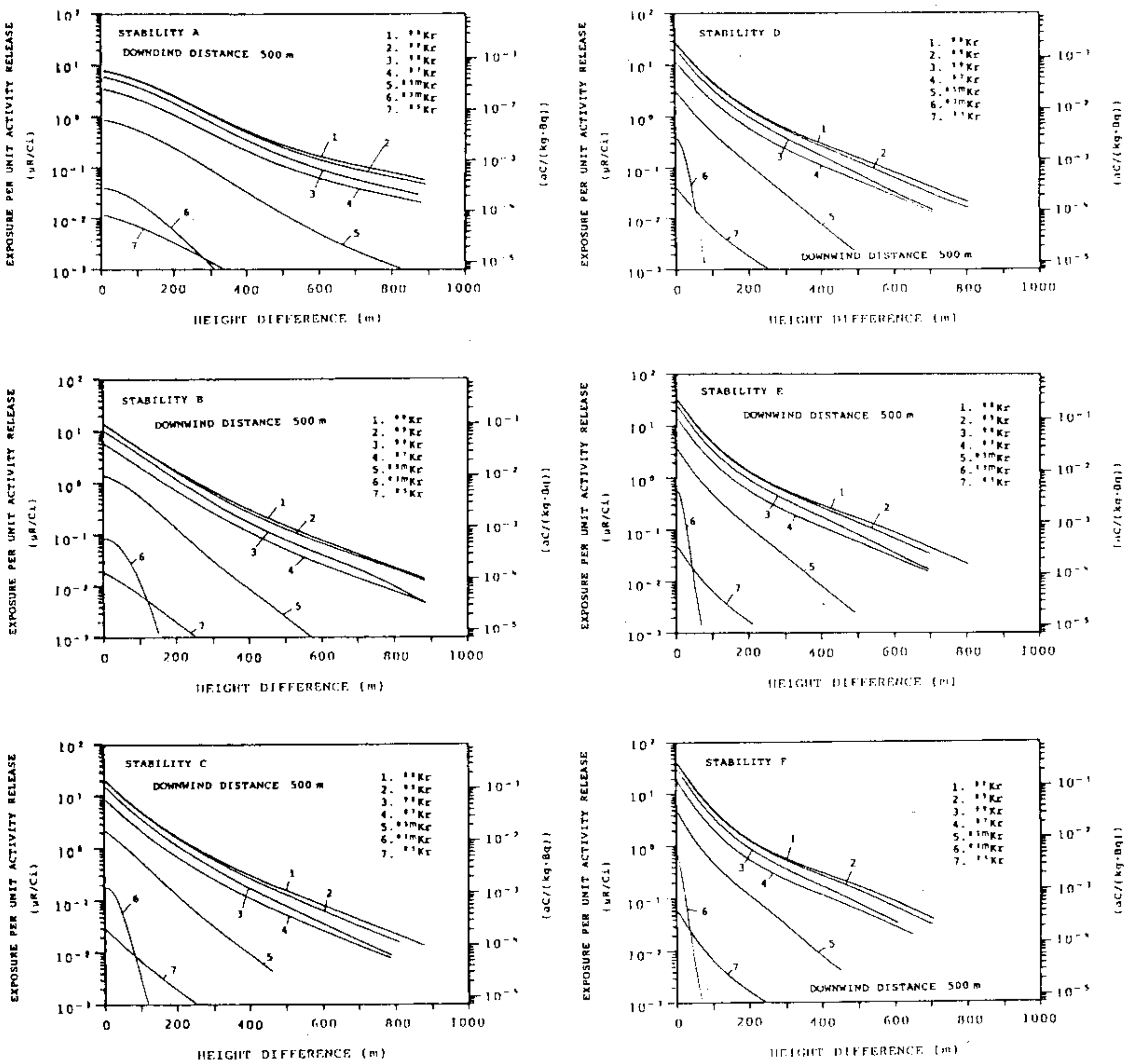

Fig.6-1 Conversion factors for method 1 at a down-wind distance of 500m for krypton.

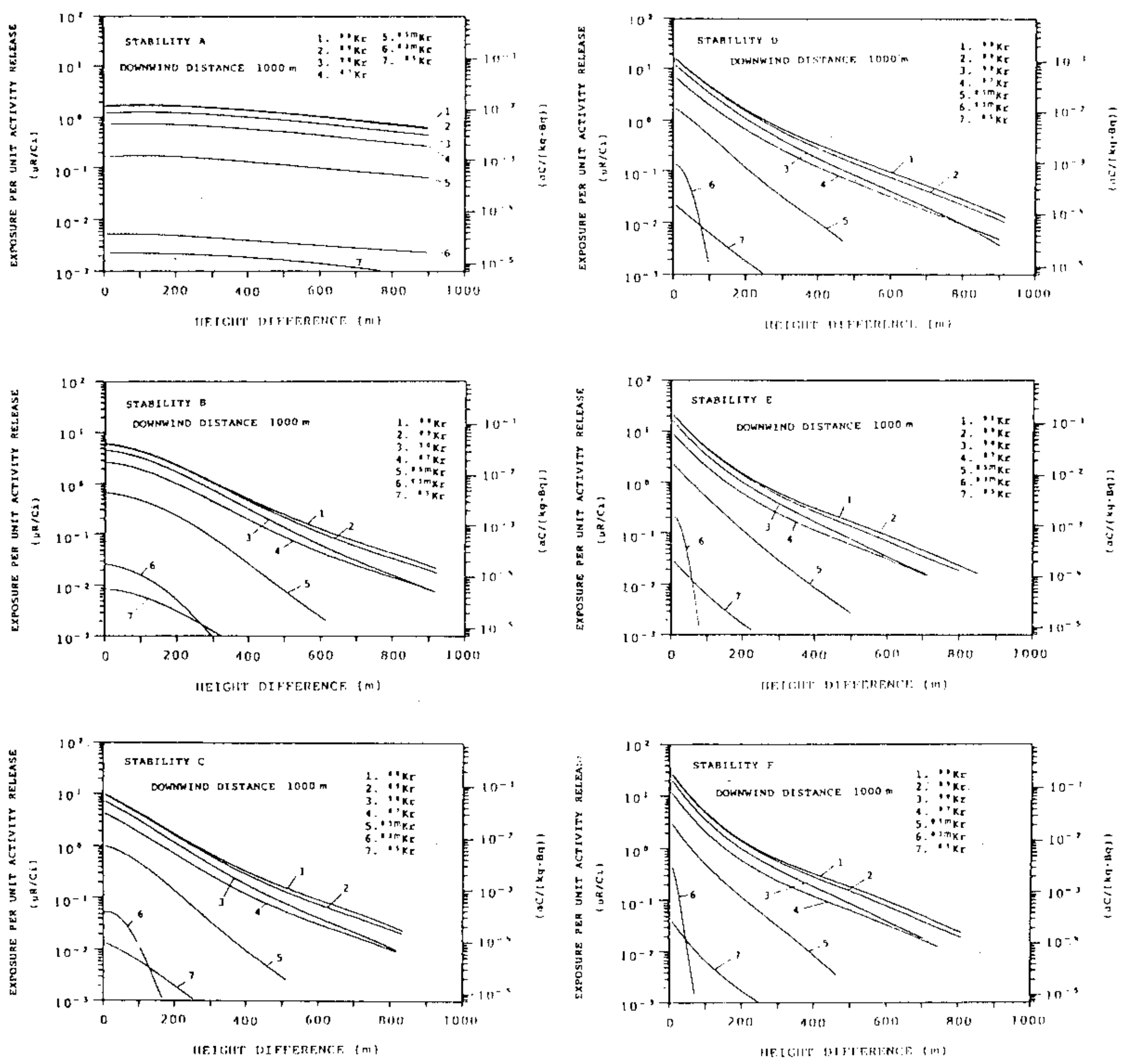

Fig.6-2 Conversion factors for method 1 at a down-wind distance of 1000m for krypton.

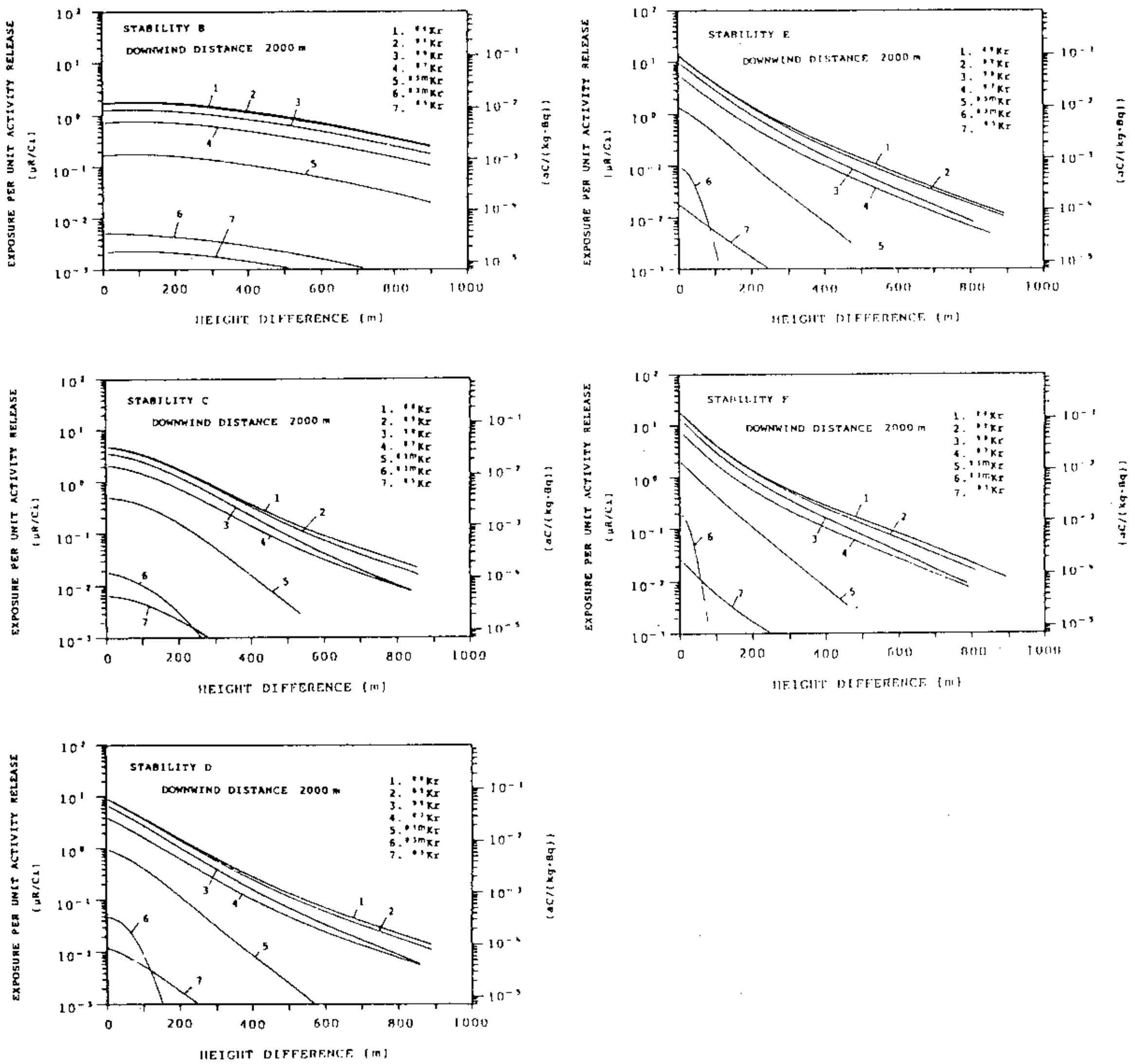

Fig.6-3 Conversion factors for method 1 at a down-wind distance of 2000m for krypton.

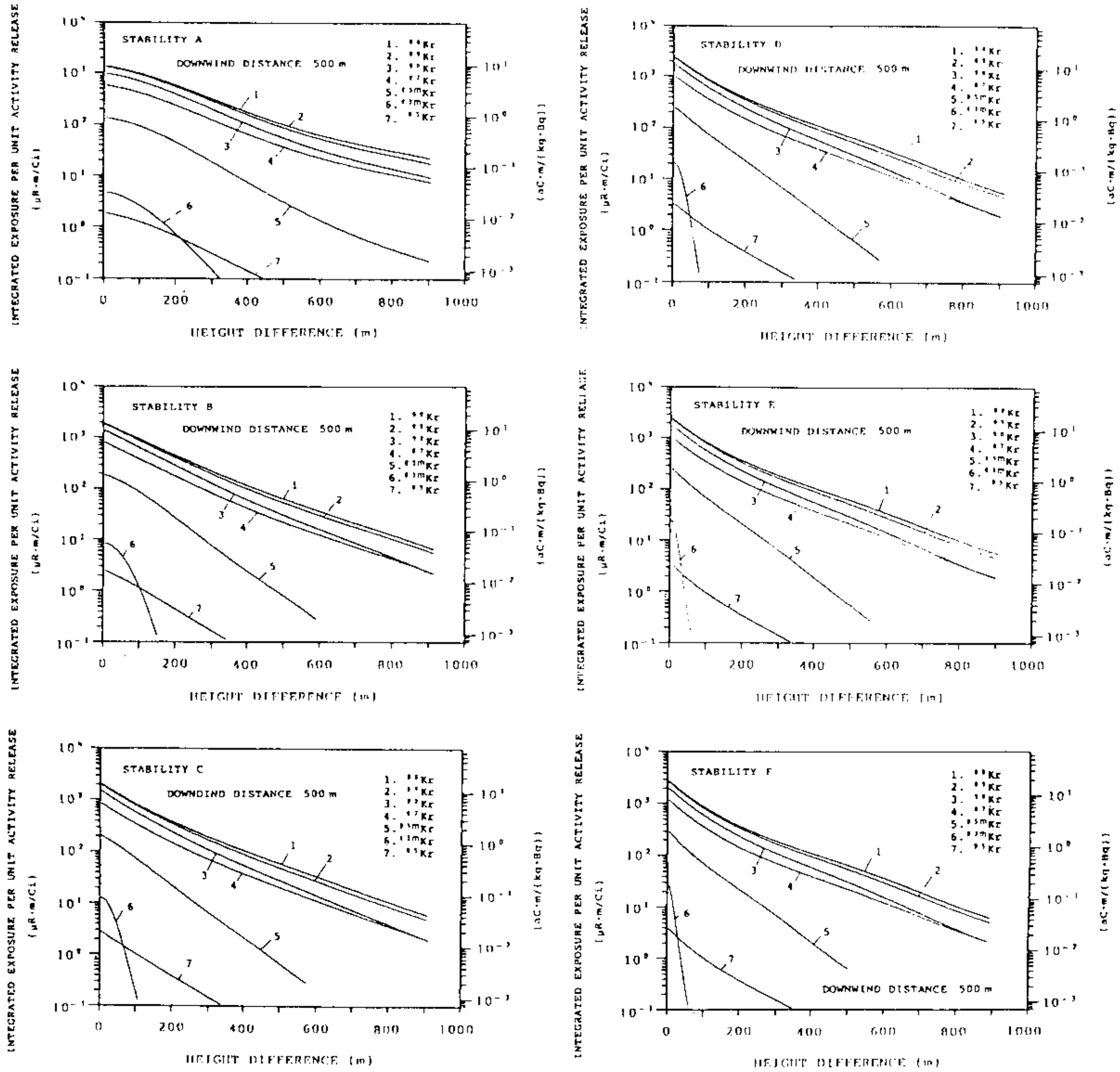

Fig.7-1 Conversion factors for method 2 at a down-wind distance of 500m for krypton.

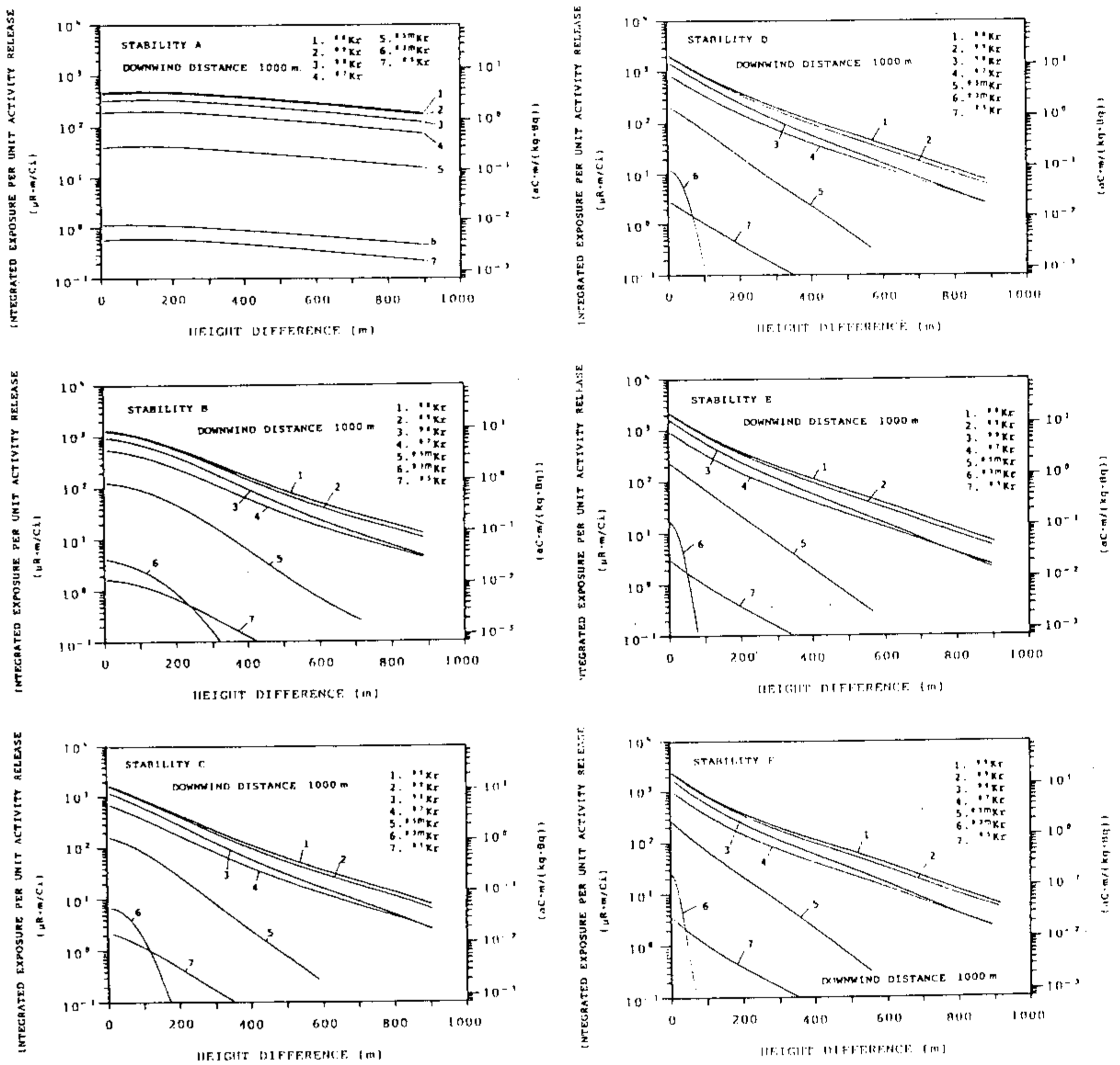

Fig.7-2 Conversion factors for method 2 at a down-wind distance of 1000m for krypton.

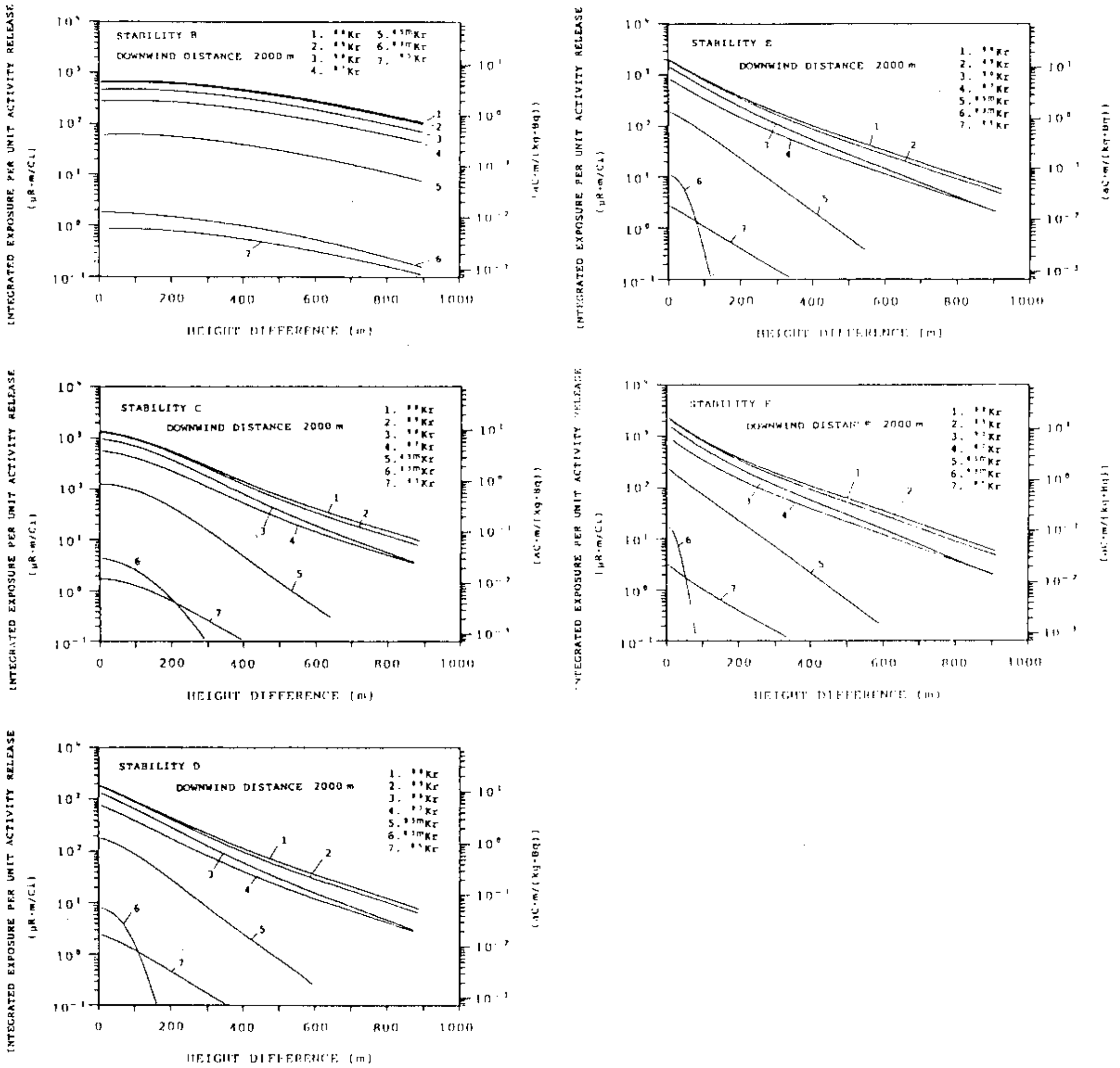

Fig.7-3 Conversion factors for method 2 at a down-wind distance of 2000m for krypton.

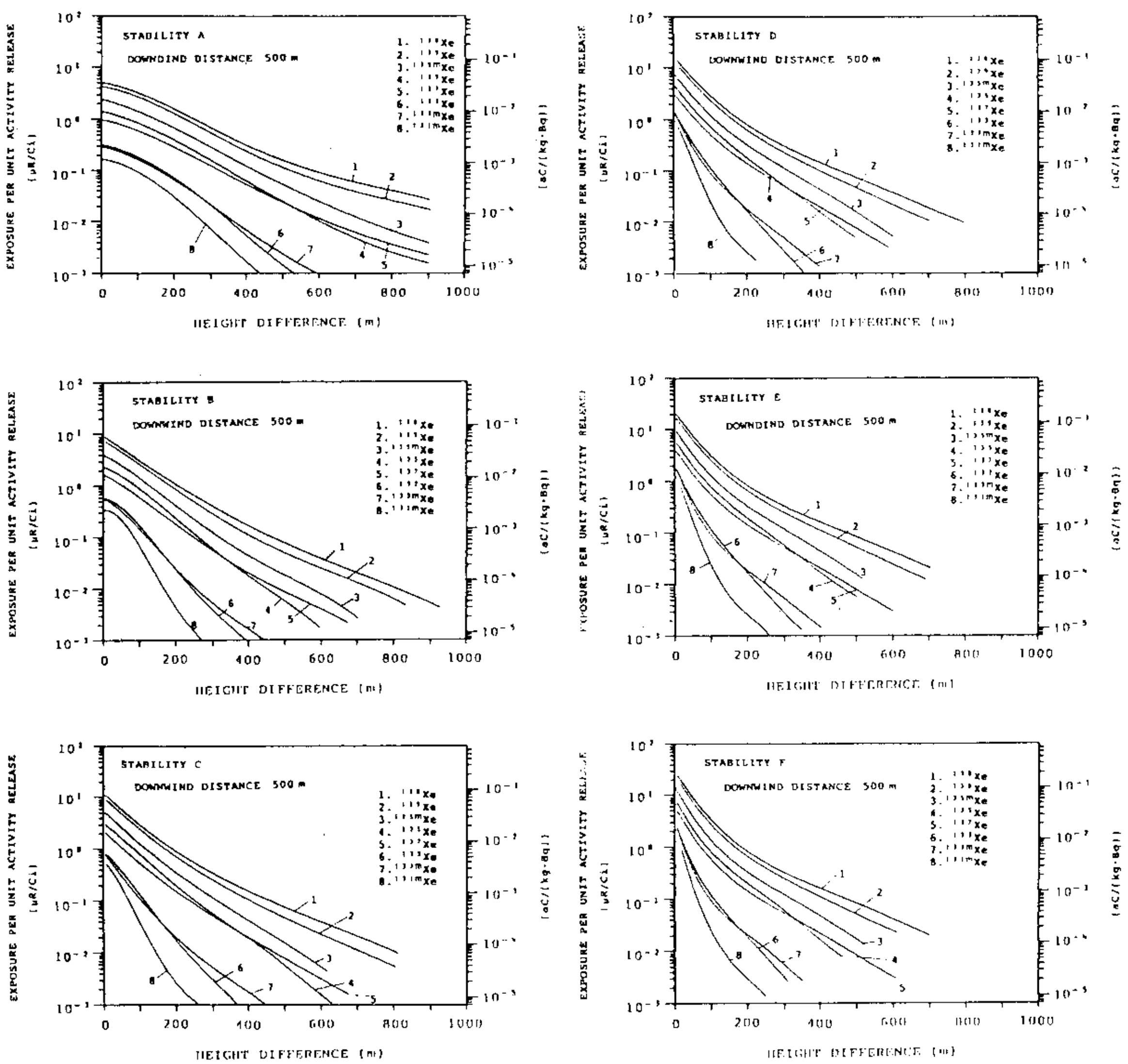

Fig.8-1 Conversion factors for method 1 at a down-wind distance of 500m for xenon.

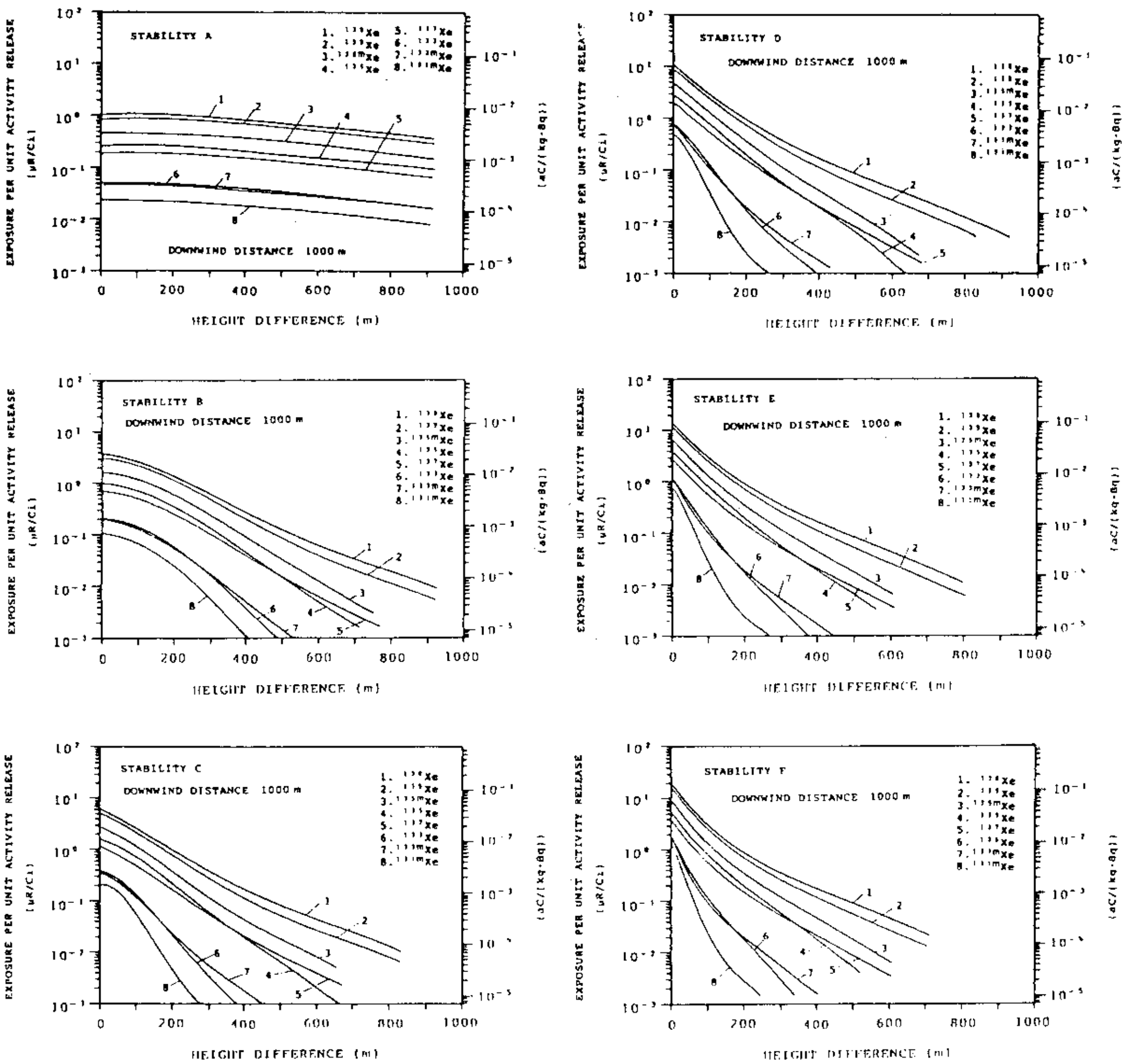

Fig.8-2 Conversion factors for method 1 at a down-wind distance of 1000m for xenon.

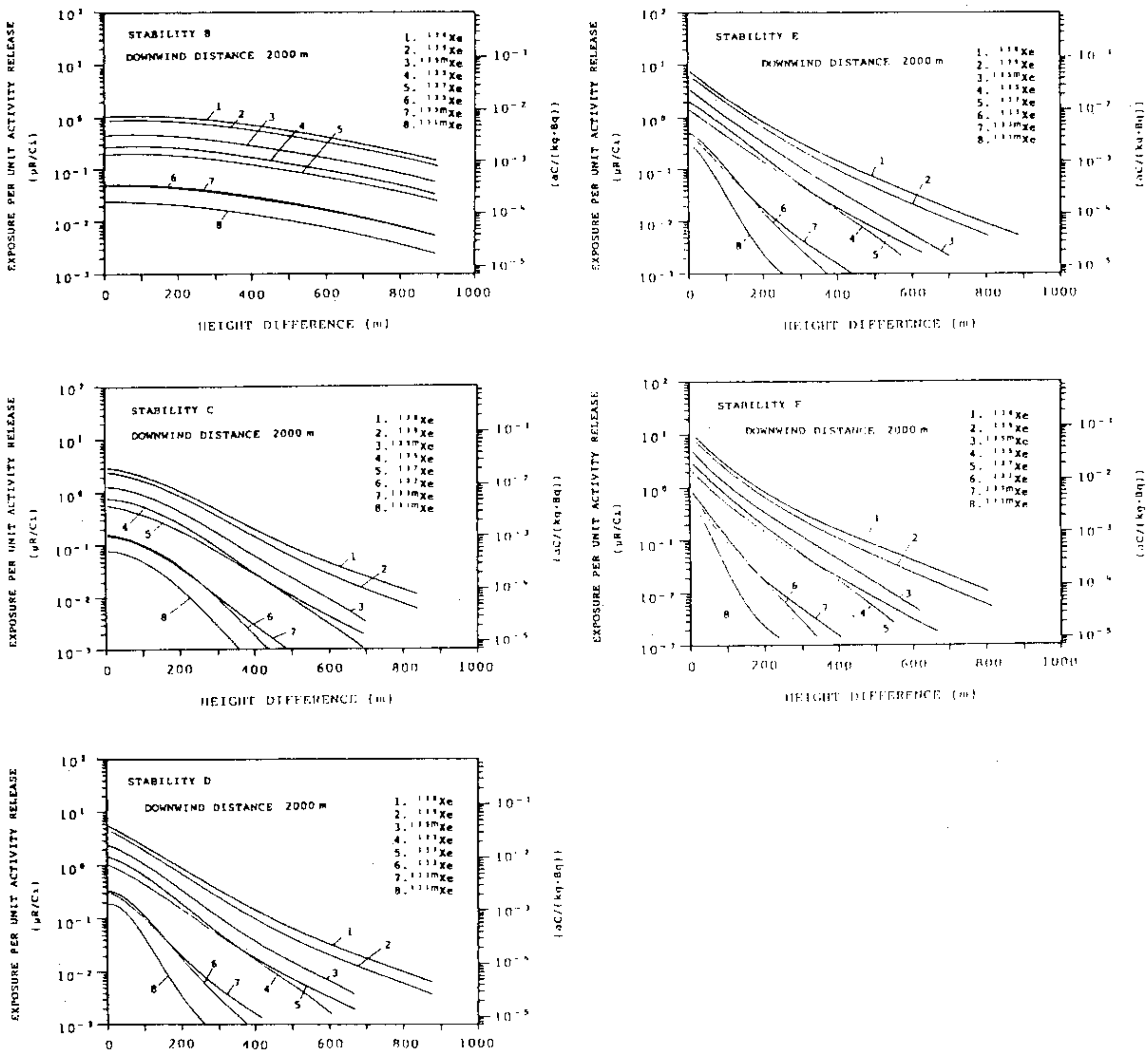

Fig.8-3 Conversion factors for method 1 at a down-wind distance of 2000m for xenon.

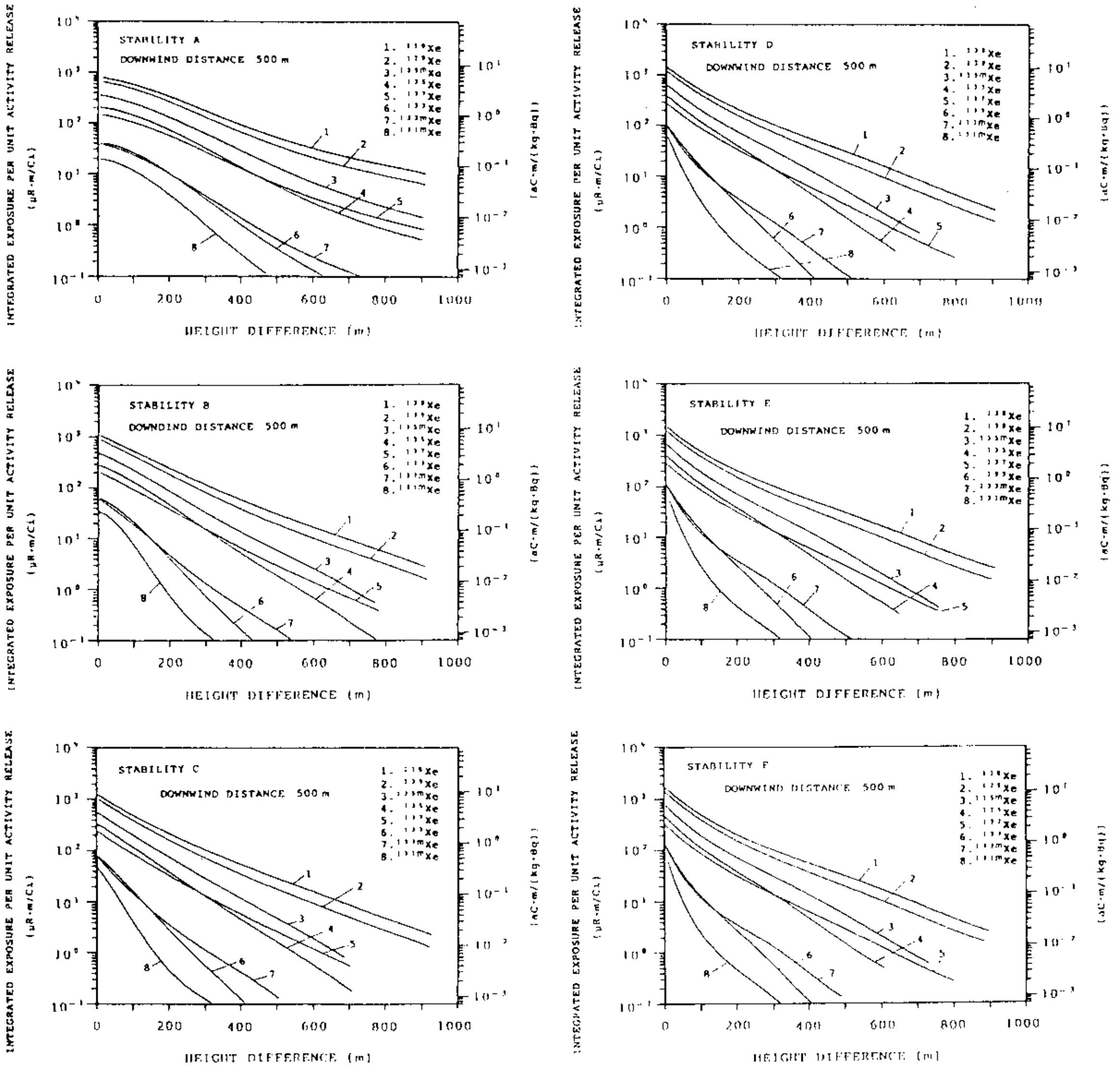

Fig.9-1 Conversion factors for method 2 at a down-wind distance of 500m for xenon.

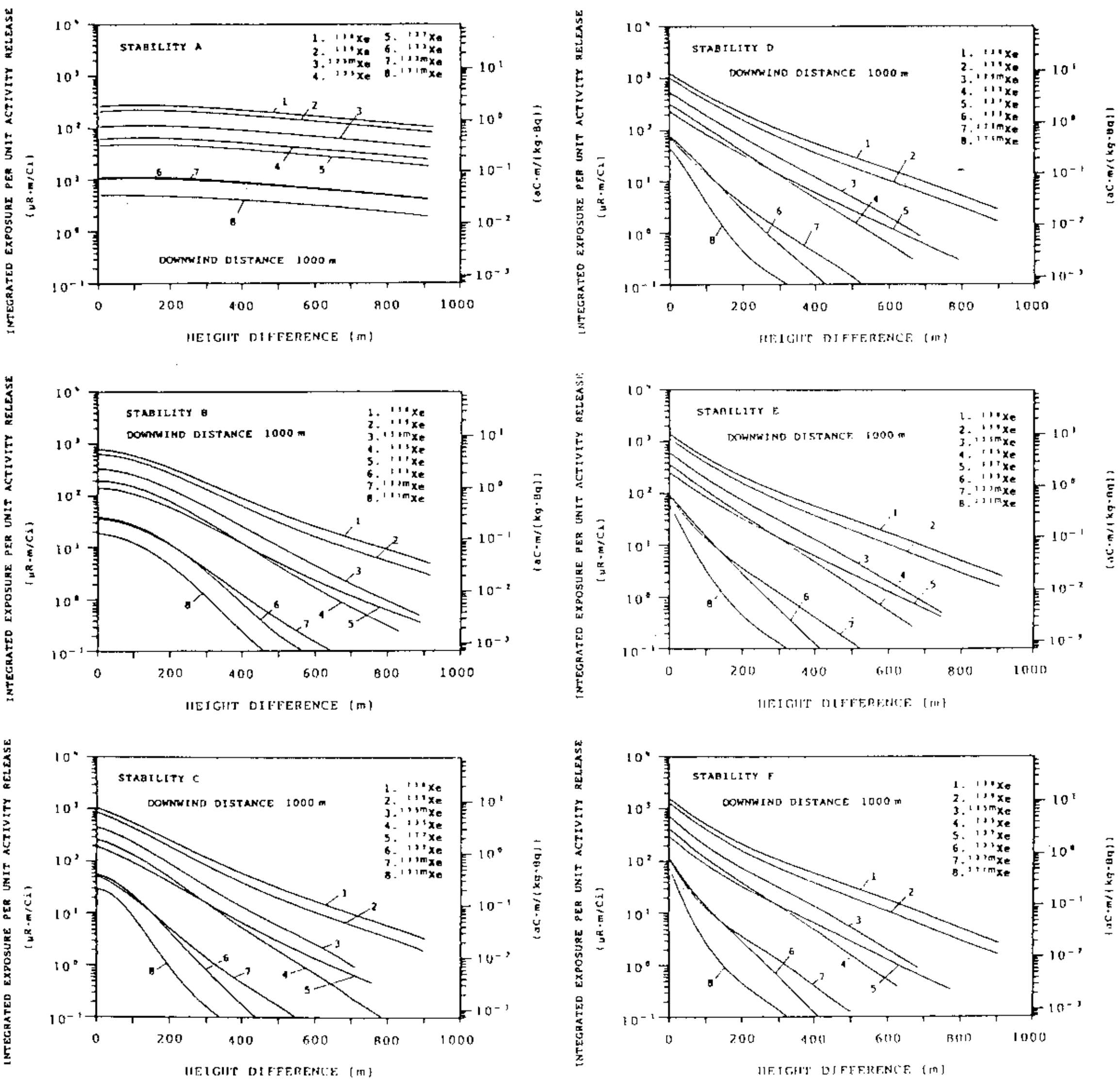

Fig.9-2 Conversion factors for method 2 at a down wind distance of 1000m for xenon.

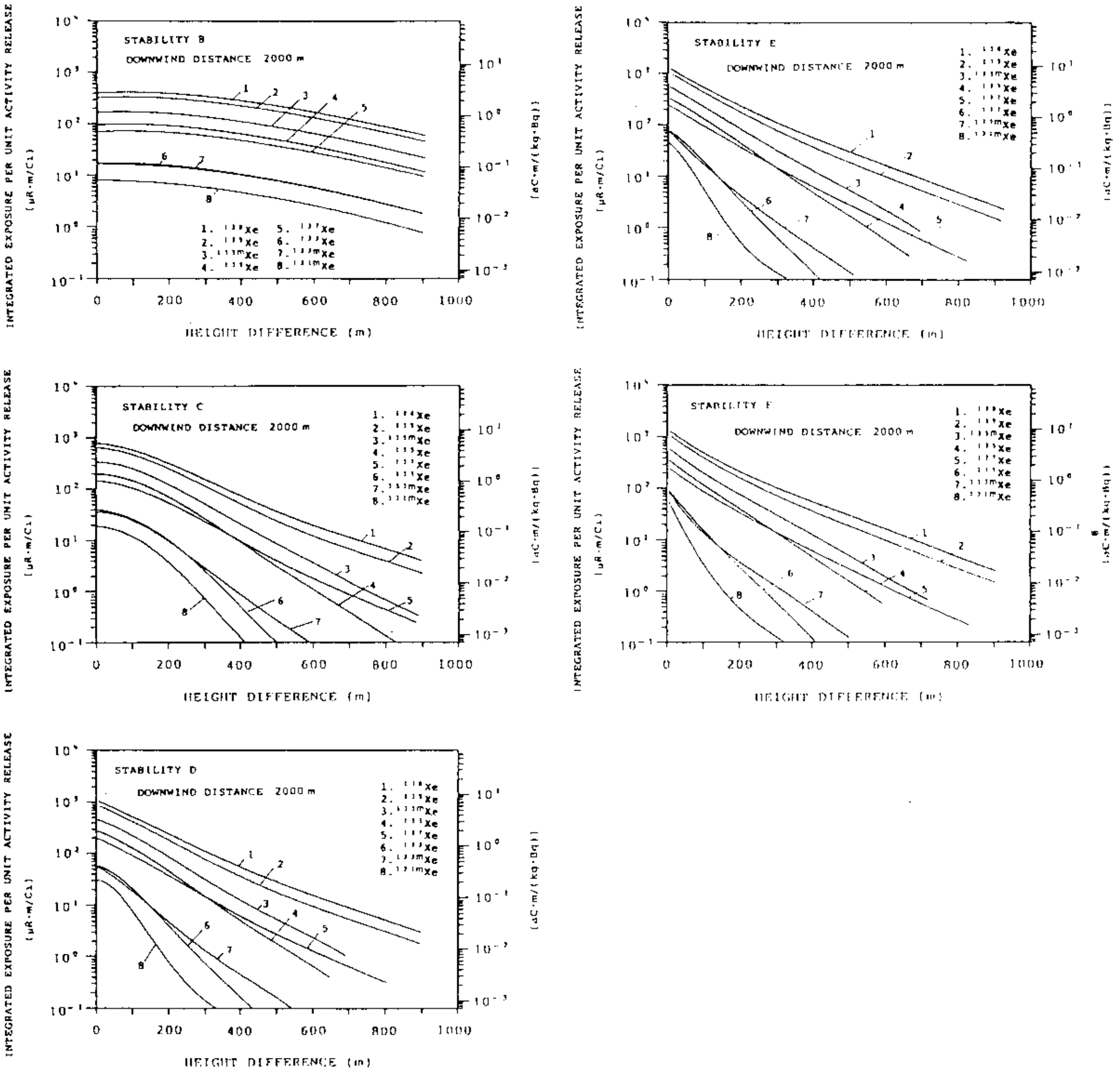

Fig.9-3 Conversion factors for method 2 at a down wind distance of 2000m for xenon.

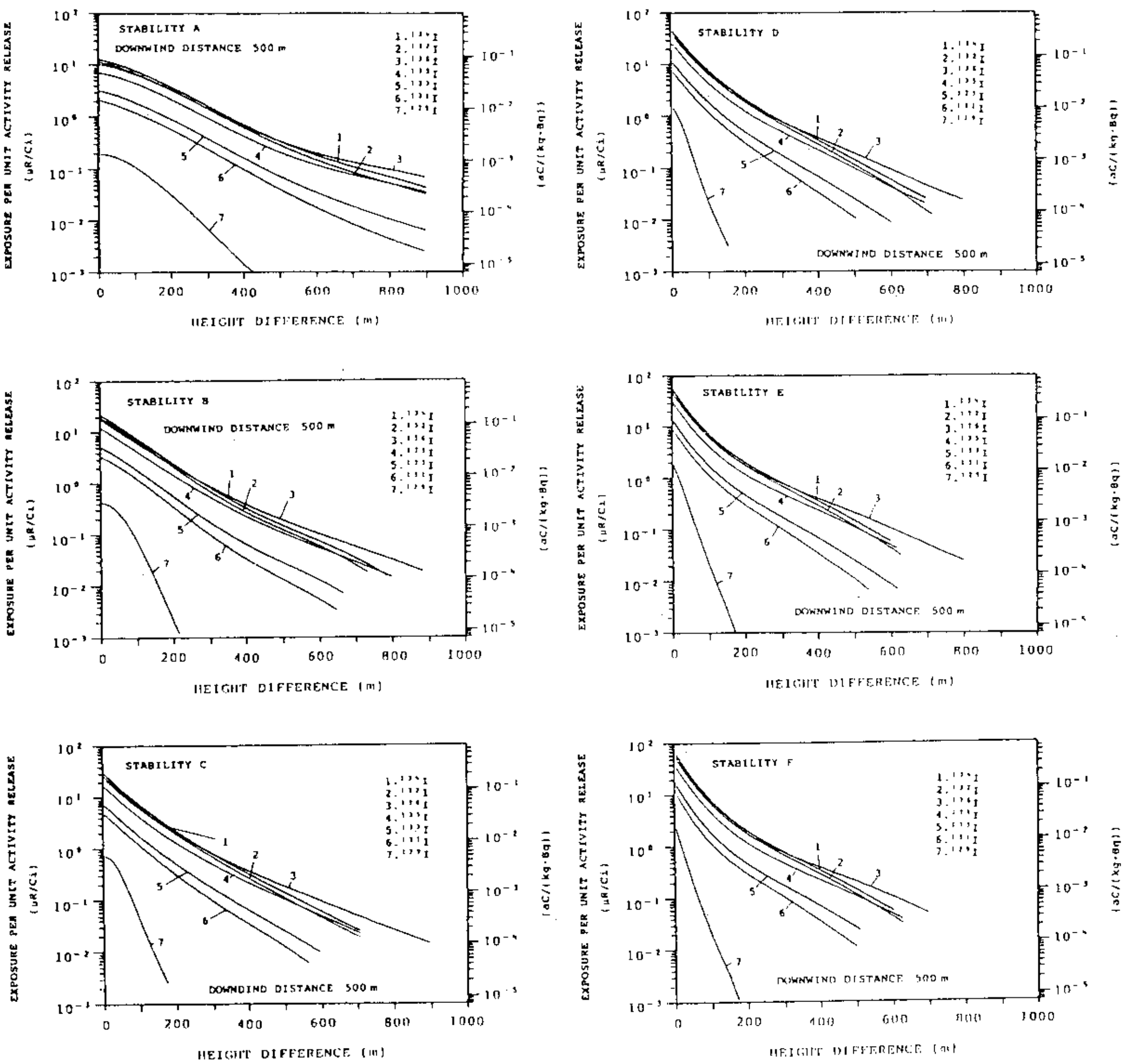

Fig.10-1 Conversion factors for method 1 at a down wind distance of 500m for iodine.

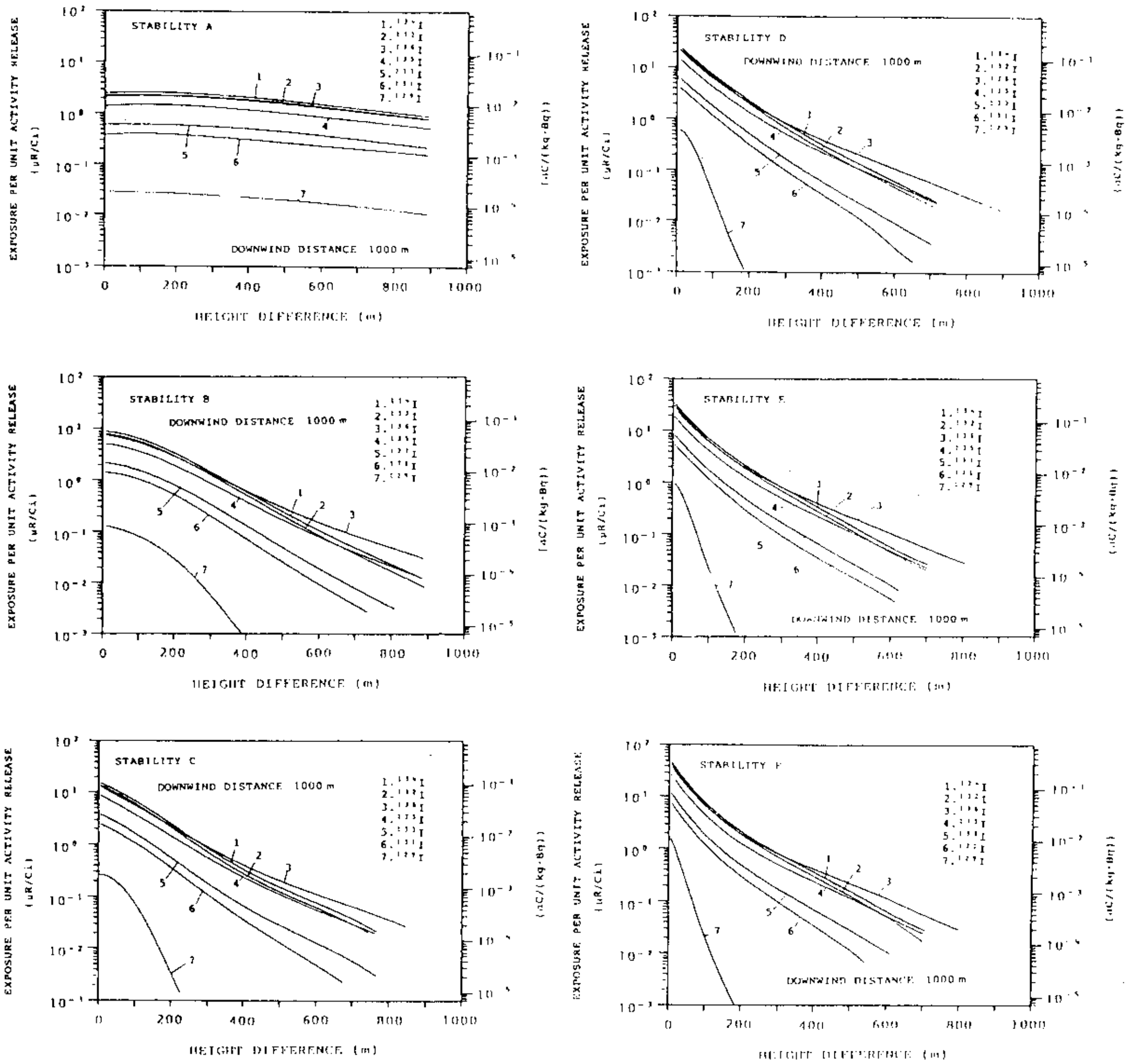

Fig. 10-2 Conversion factors for method 1 at a down-wind distance of 1000m for iodine.

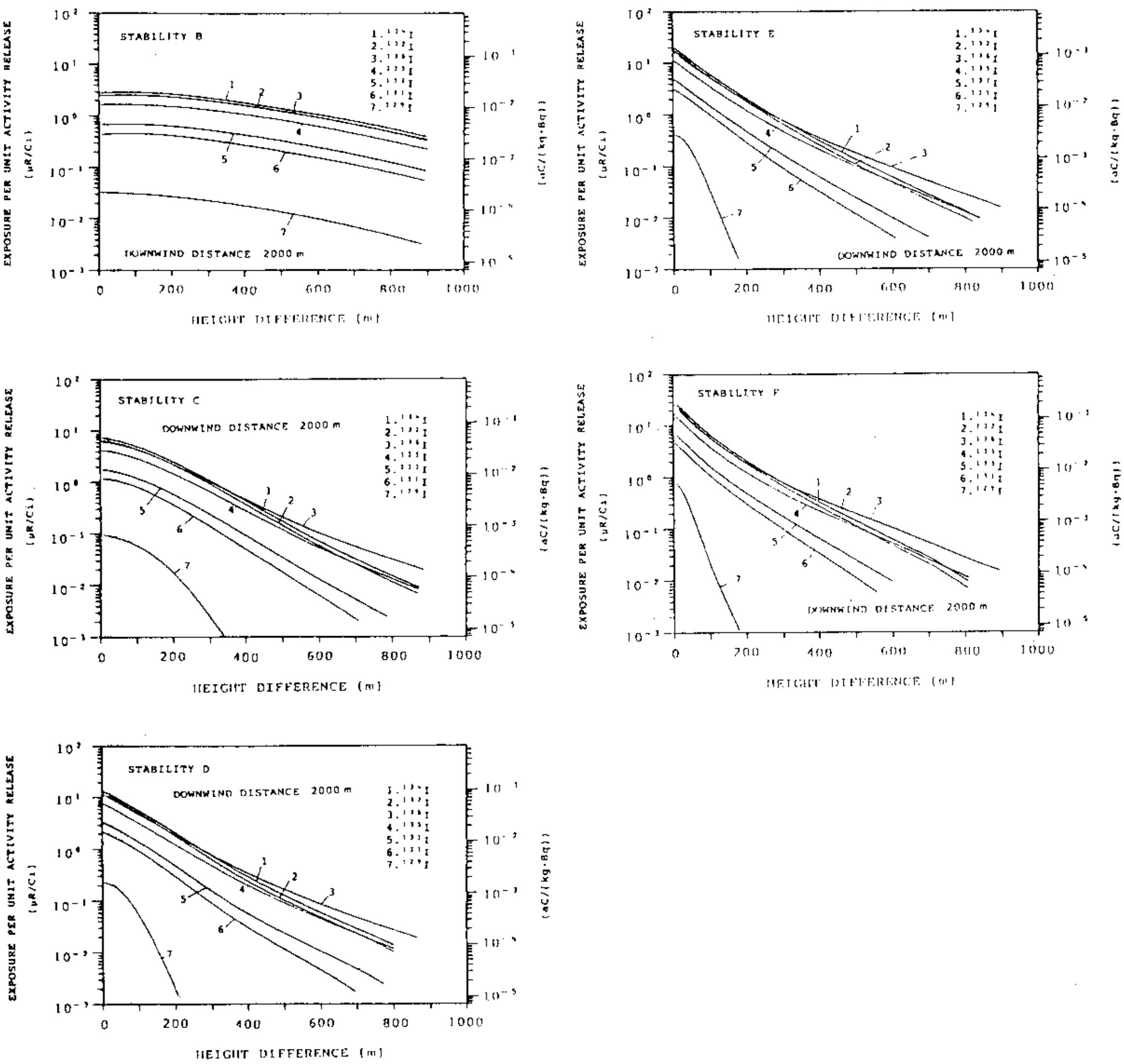

Fig.10-3 Conversion factors for method 1 at a down wind distance of 2000m for iodine.

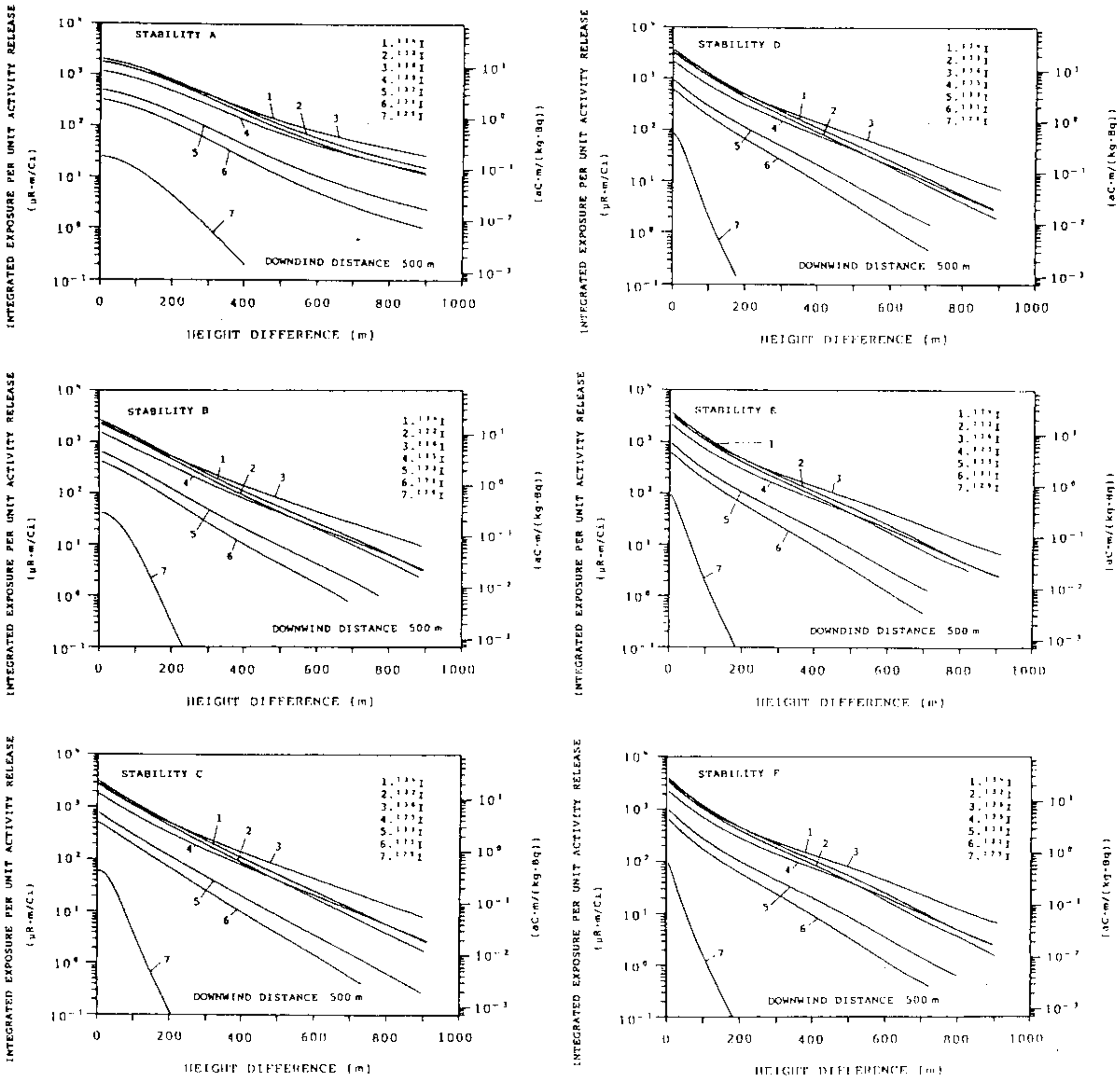

Fig.11-1 Conversion factors for method 2 at a down-wind distance of 500m for iodine.

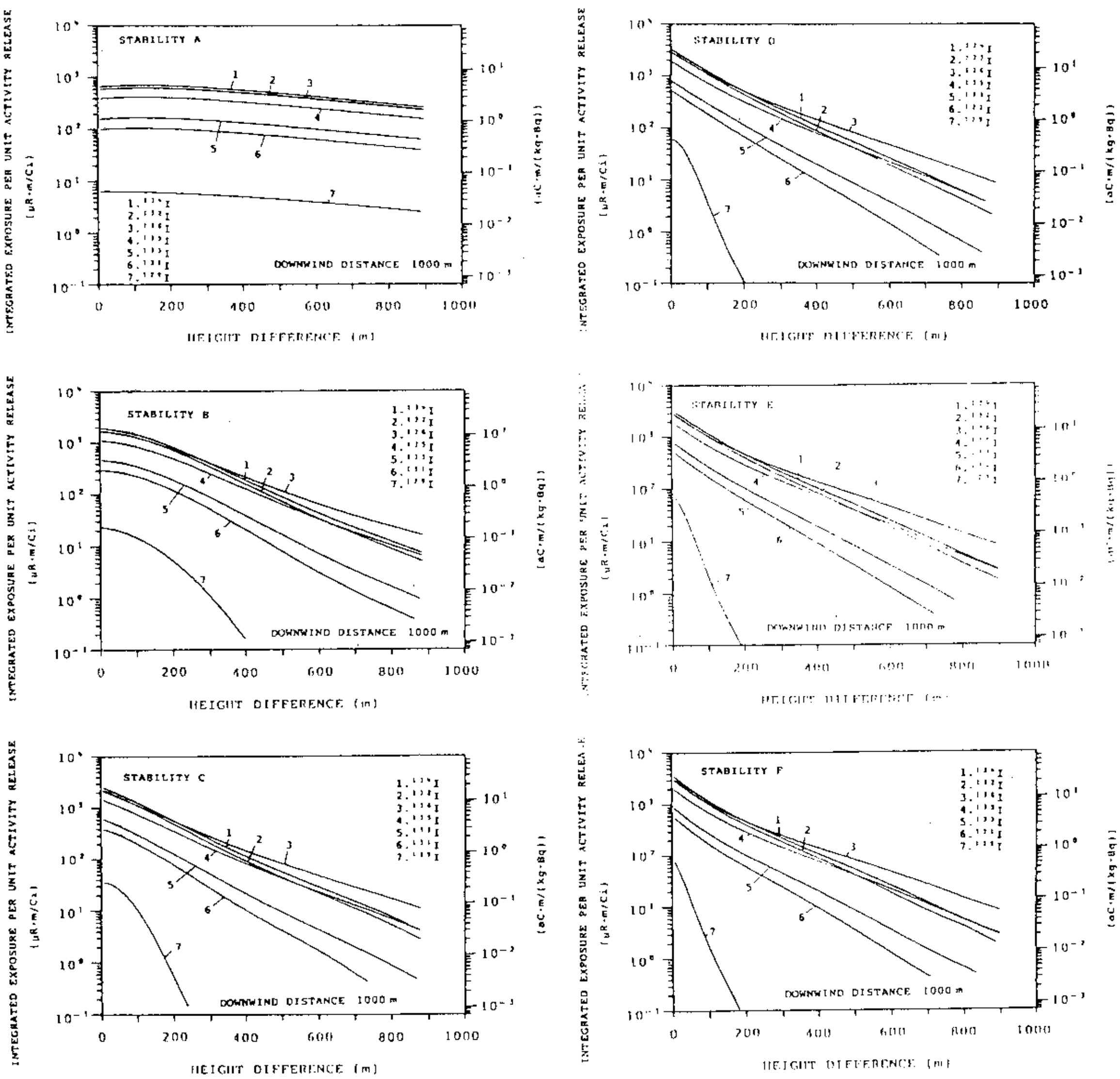

Fig.11-2 Conversion factors for method 2 at a down-wind distance of 1000m for iodine.

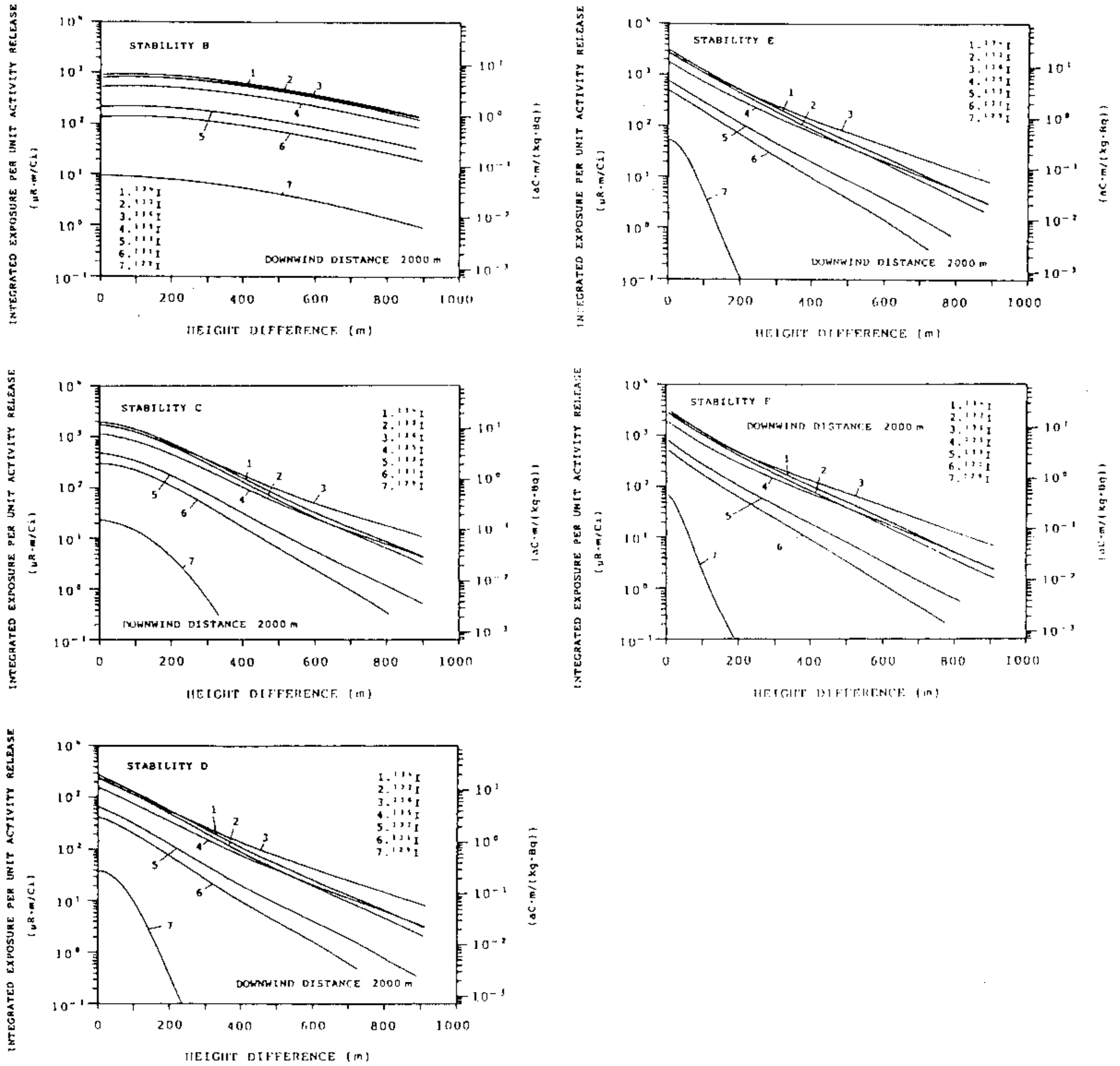

Fig.11-3 Conversion factors for method 2 at a down wind distance of 2000m for iodine.

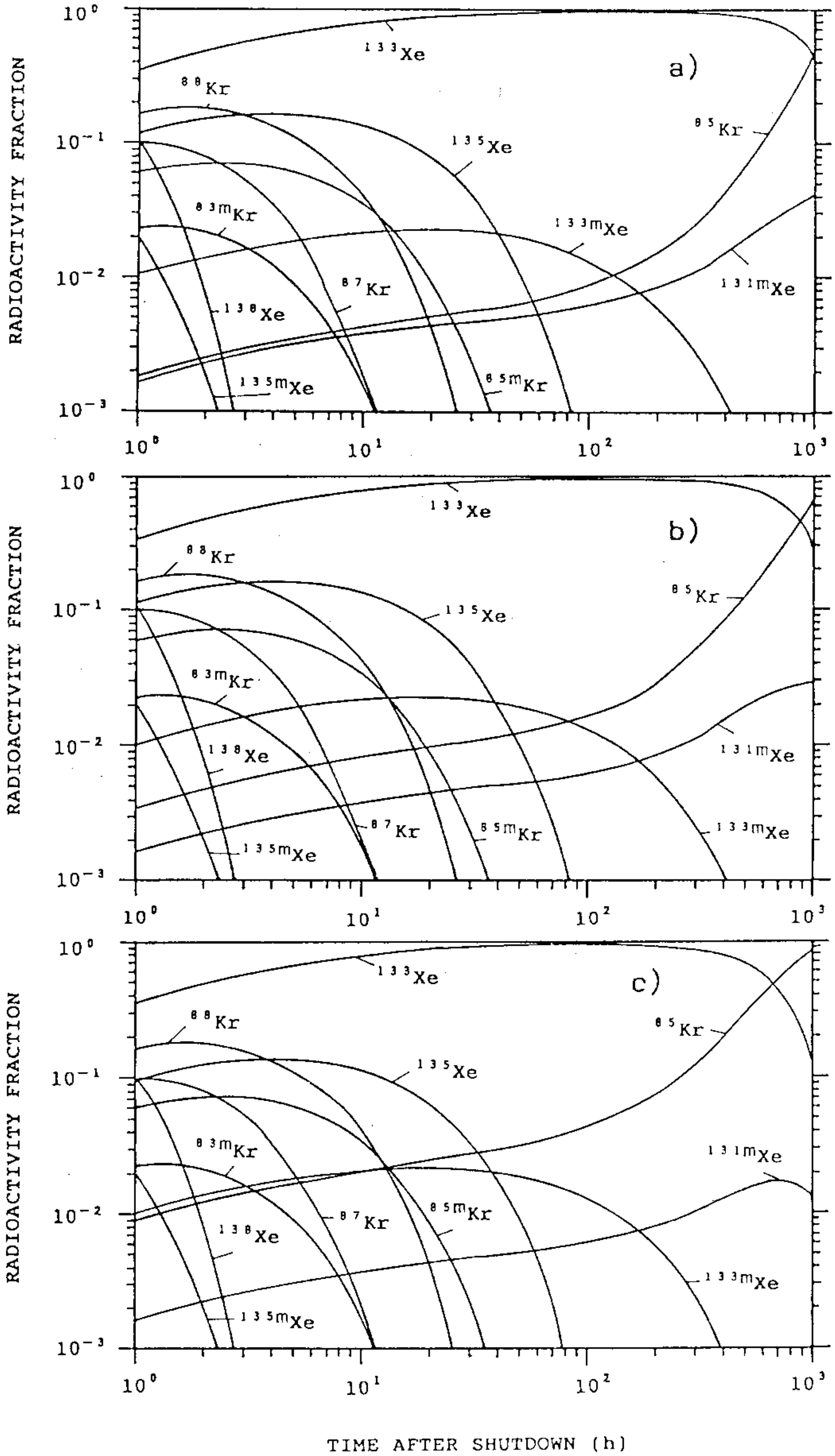

Fig.12 Concentration ratios of radioactivity of noble gases in a plume as a function of time after shutdown for fuels with burn-up of a) 5000Mwd/tU, b) 10000Mwd/tU and c) 30000Mwd/tU.

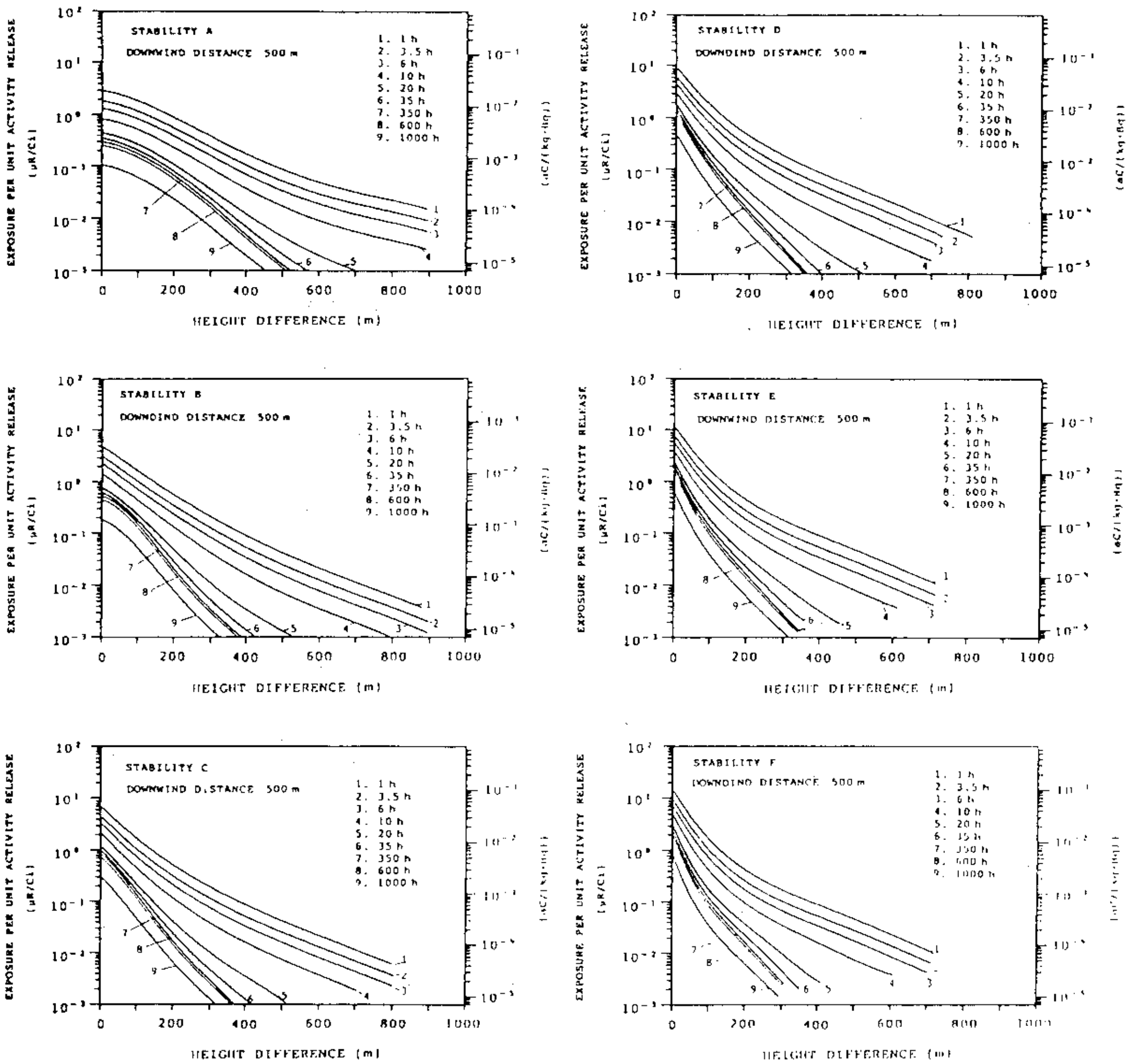

Fig.13-1 Conversion factors for method 1 at a down-wind distance of 500m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 5000Mwd/tU.

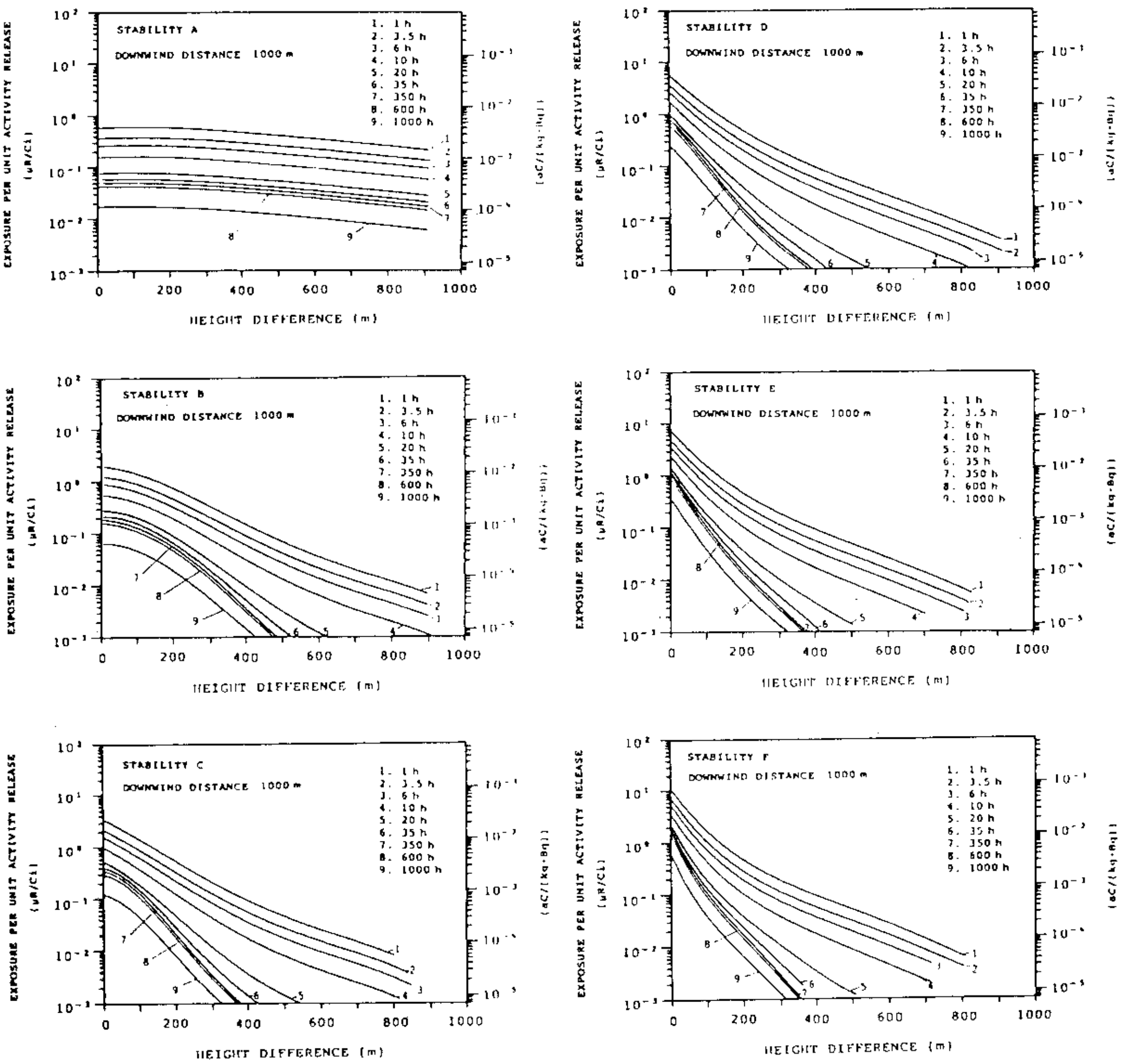

Fig.13-2 Conversion factors for method 1 at a down-wind distance of 1000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 5000Mwd/tU.

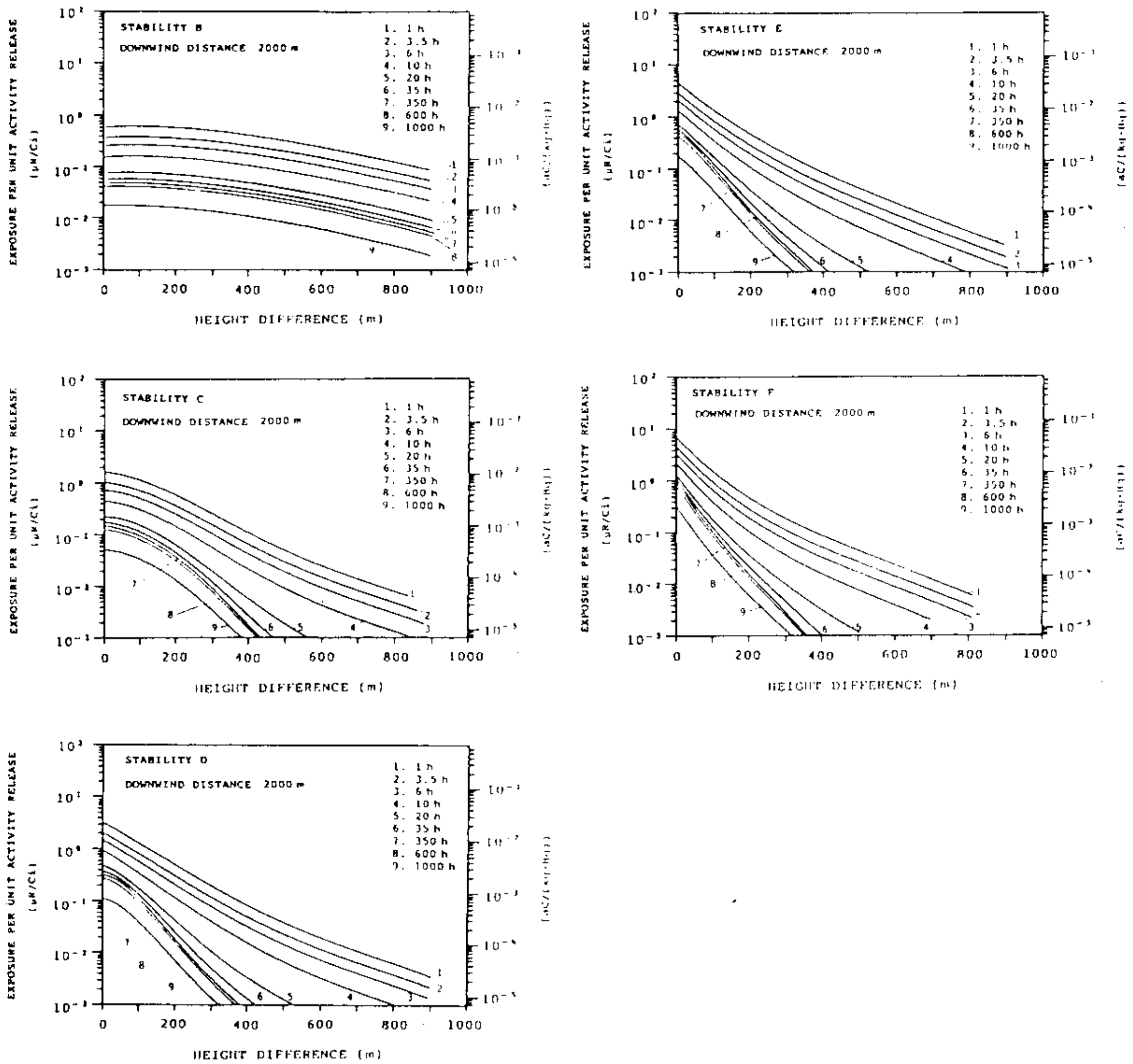

Fig.13-3 Conversion factors for method 1 at a down-wind distance of 2000m for a mixture of noble gases changing with time after shutdown. Burn up of fuel is 5000Mwd/tU.

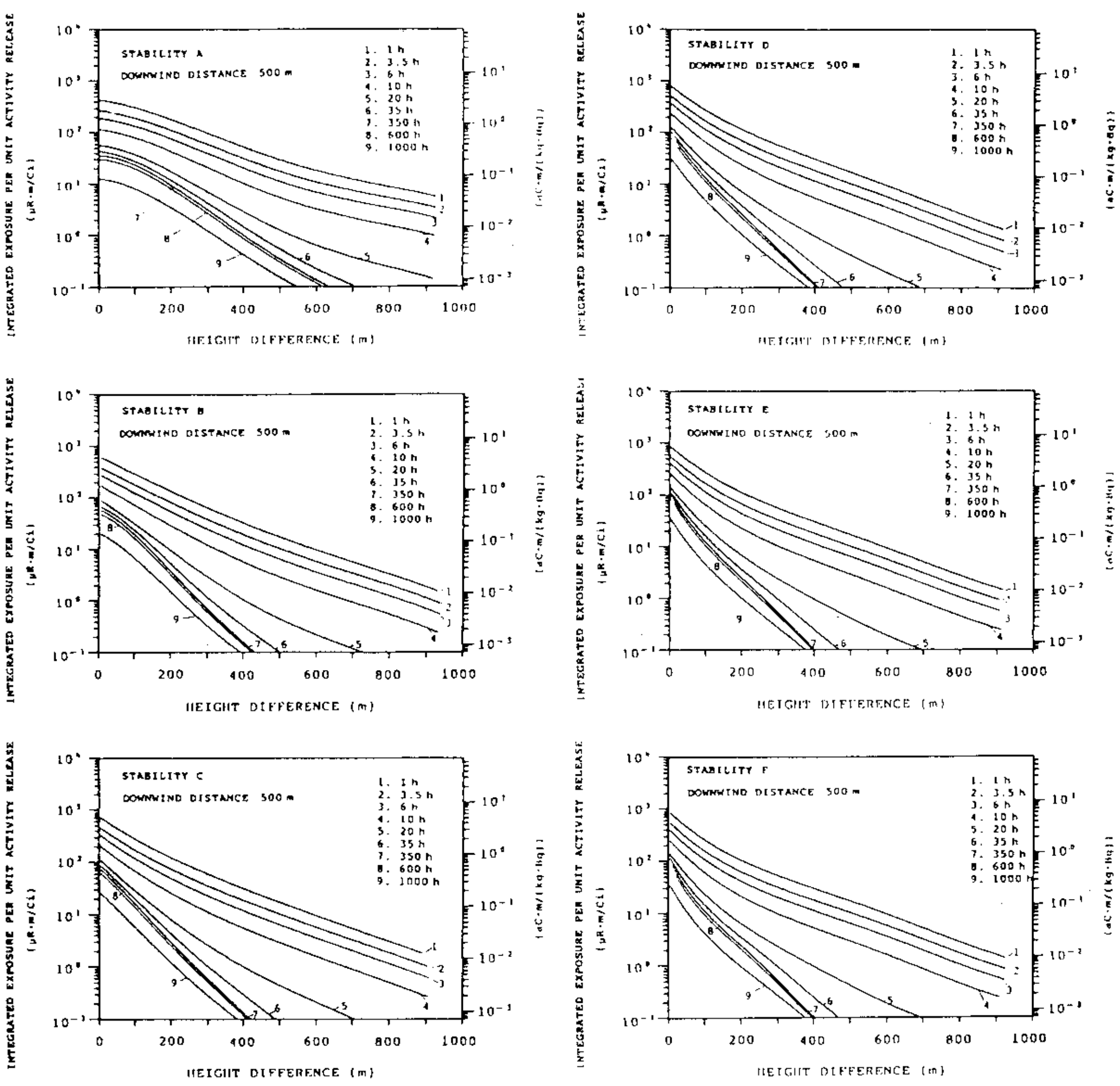

Fig.14-1 Conversion factors for method 2 at a down-wind distance of 500m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 5000Mwd/tU.

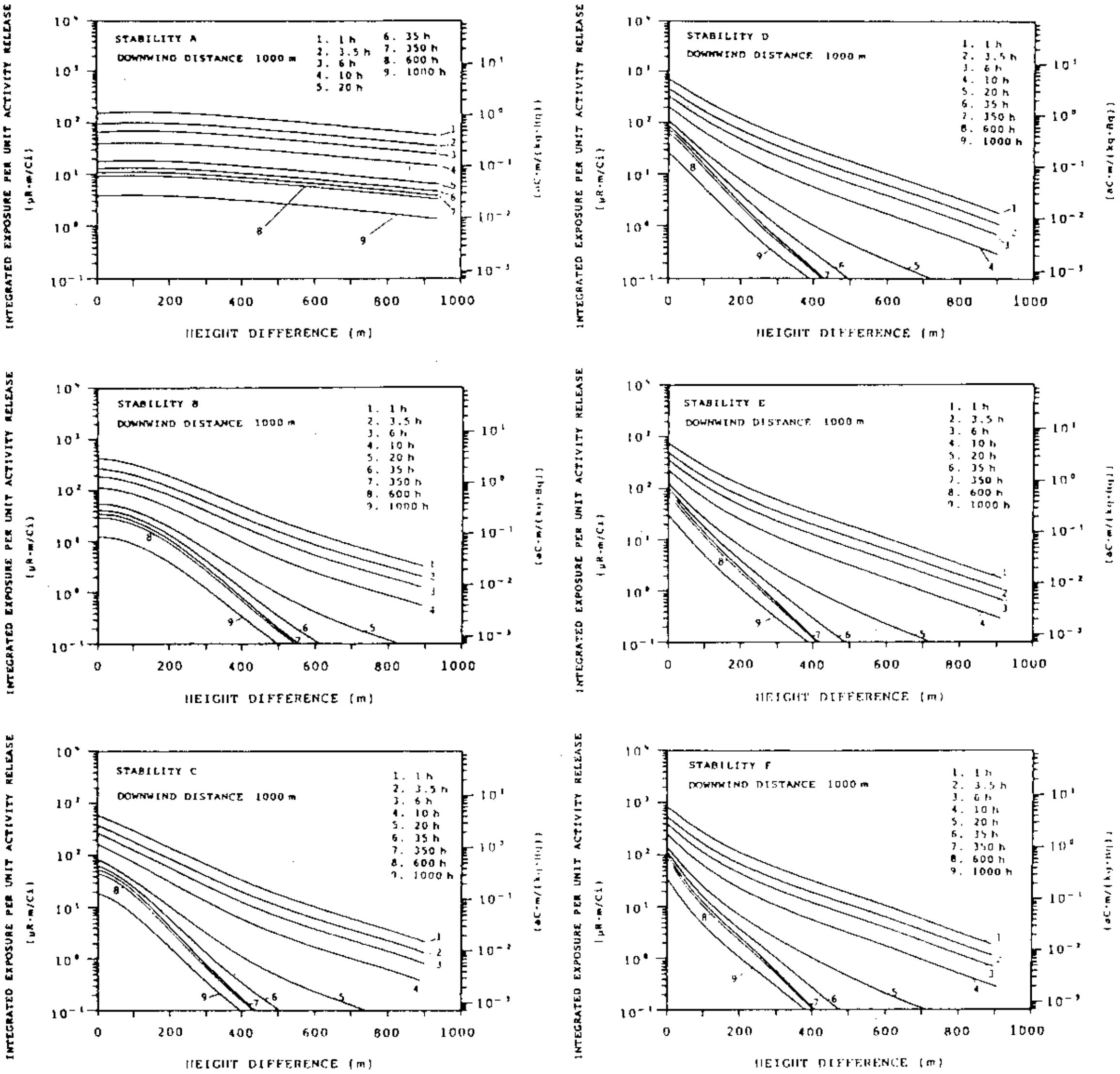

Fig.14-2 Conversion factors for method 2 at a down wind distance of 1000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 5000Mwd/tU.

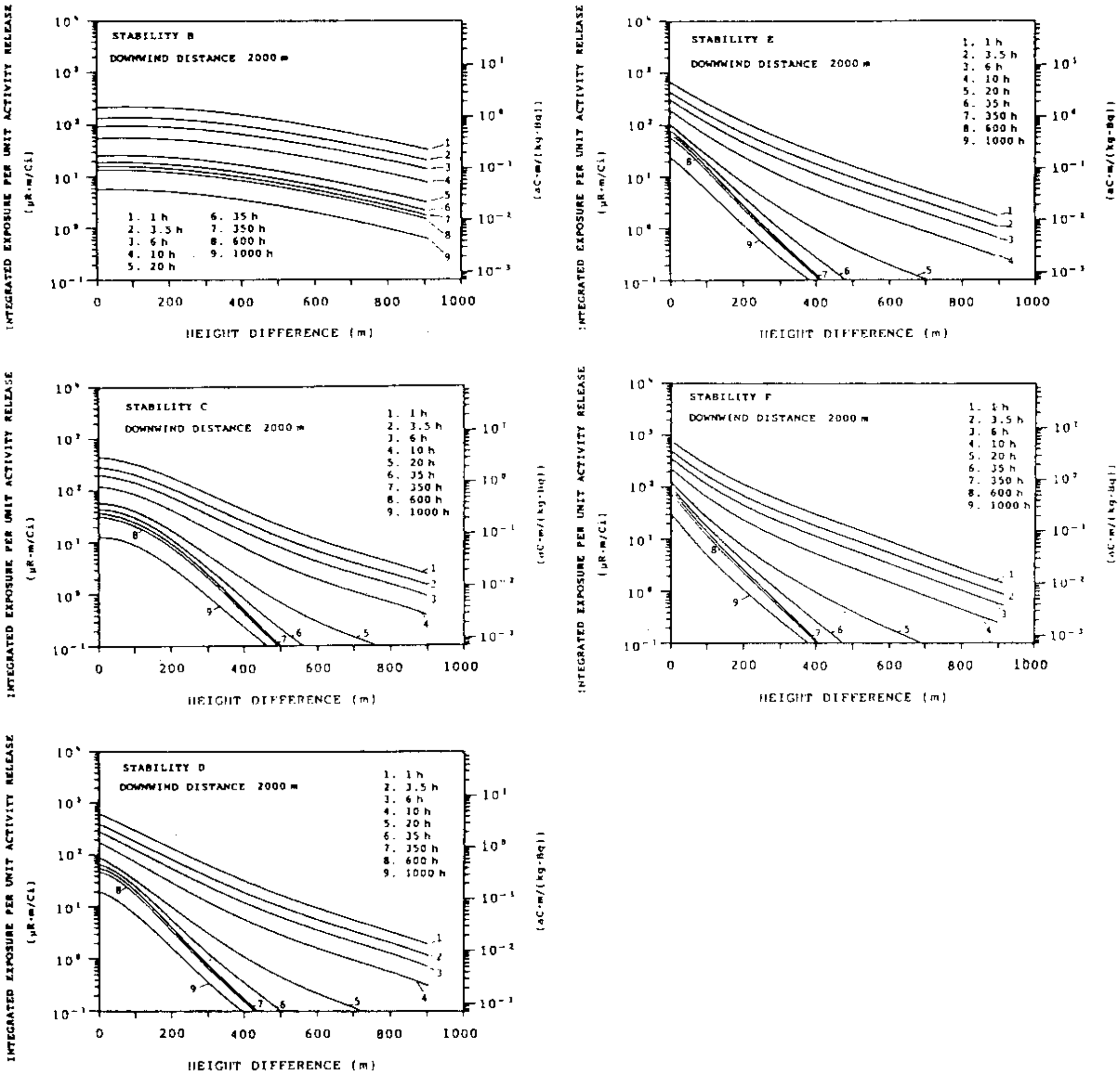

Fig.14-3 Conversion factors for method 2 at a down-wind distance of 2000m for a mixture of noble gases changing with time after shutdown. Burn up of fuel is 5000Mwd/tU.

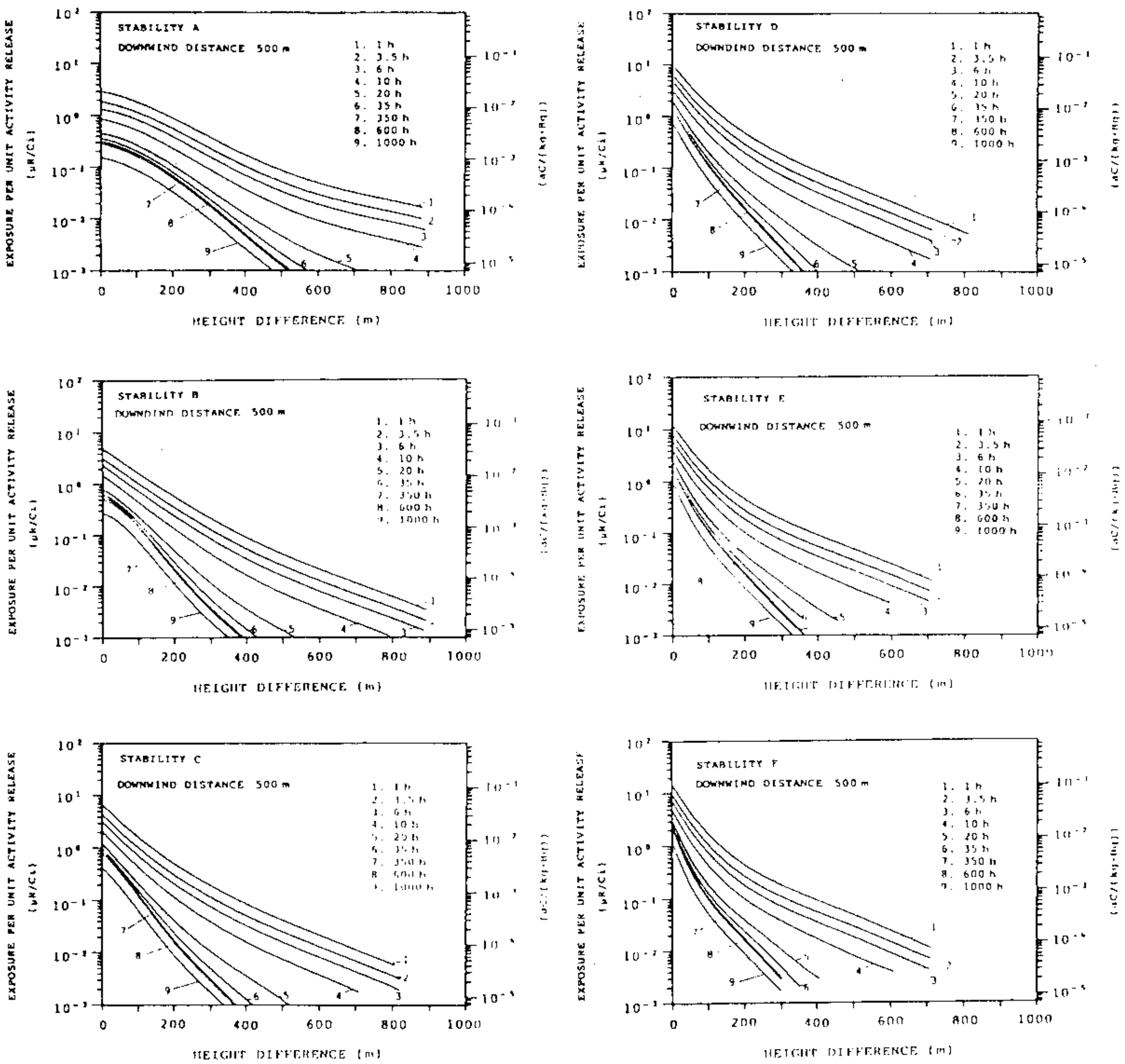

Fig.15-1 Conversion factors for method 1 at a down wind distance of 500m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 10000Mwd/tU.

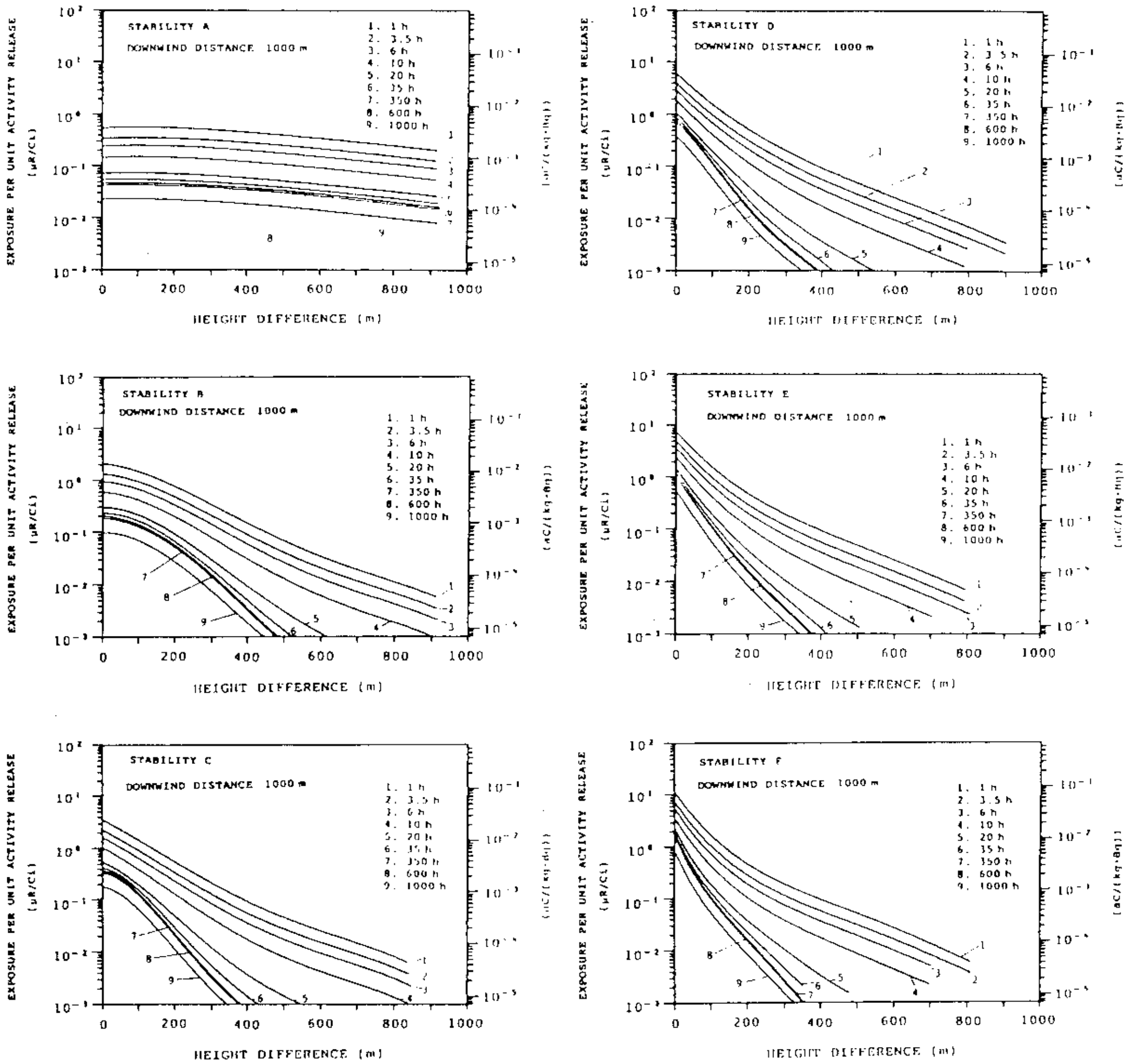

Fig.15-2 Conversion factors for method 1 at a down-wind distance of 1000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 10000Mwd/tU.

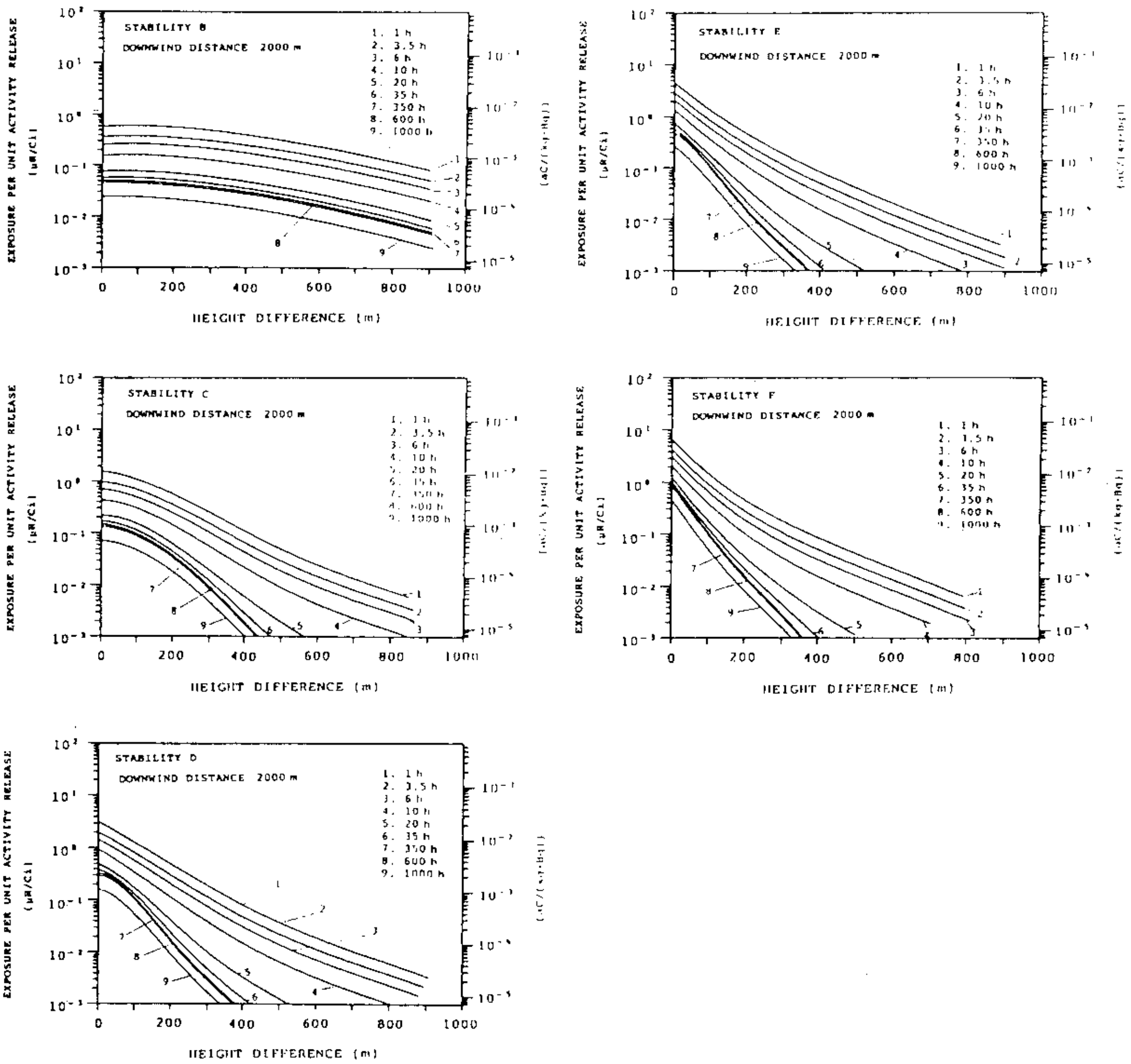

Fig.15-3 Conversion factors for method 1 at a down-wind distance of 2000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 10000Mwd/tU.

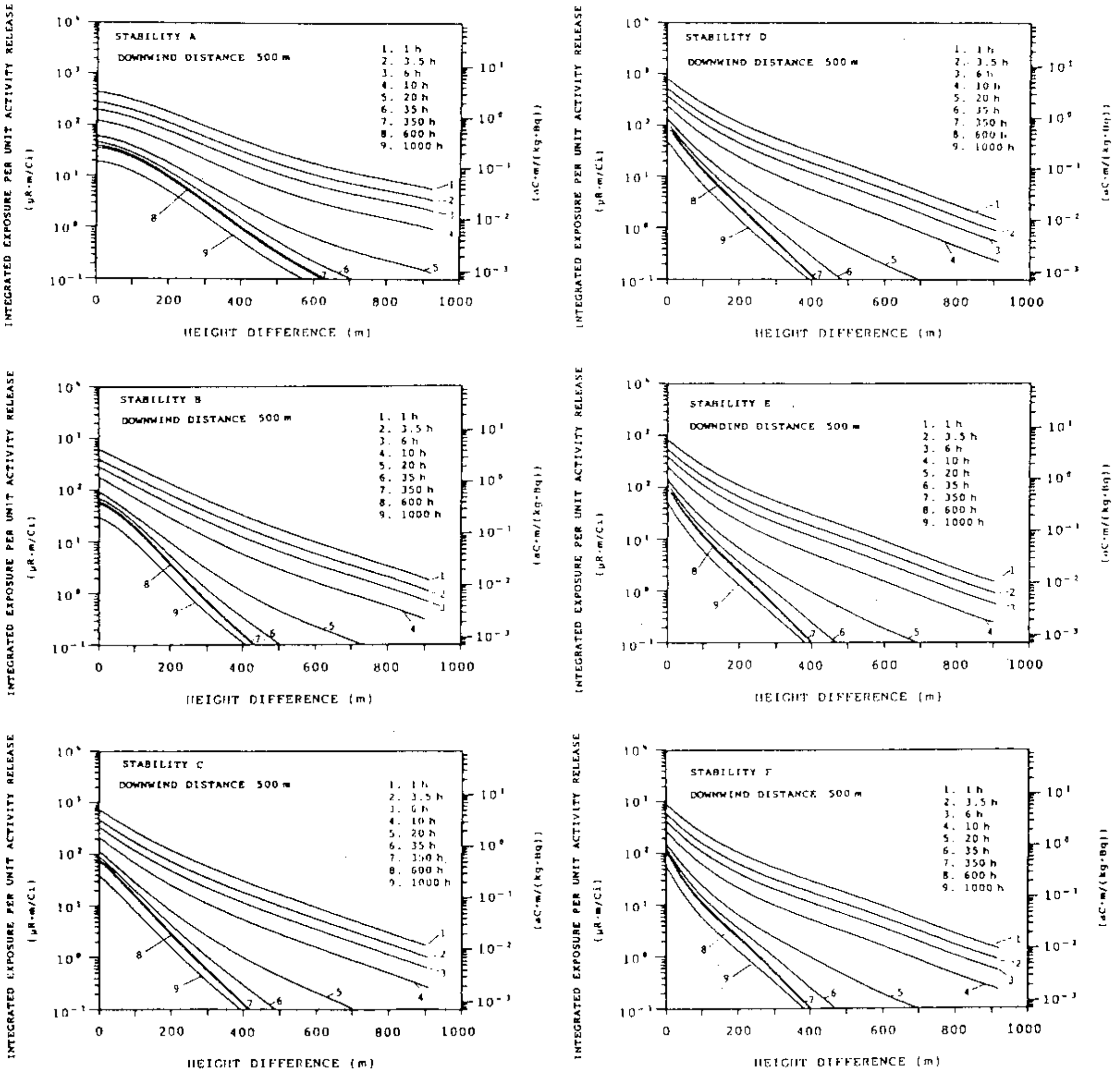

Fig.16-1 Conversion factors for method 2 at a down wind distance of 500m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 10000Mwd/tU.

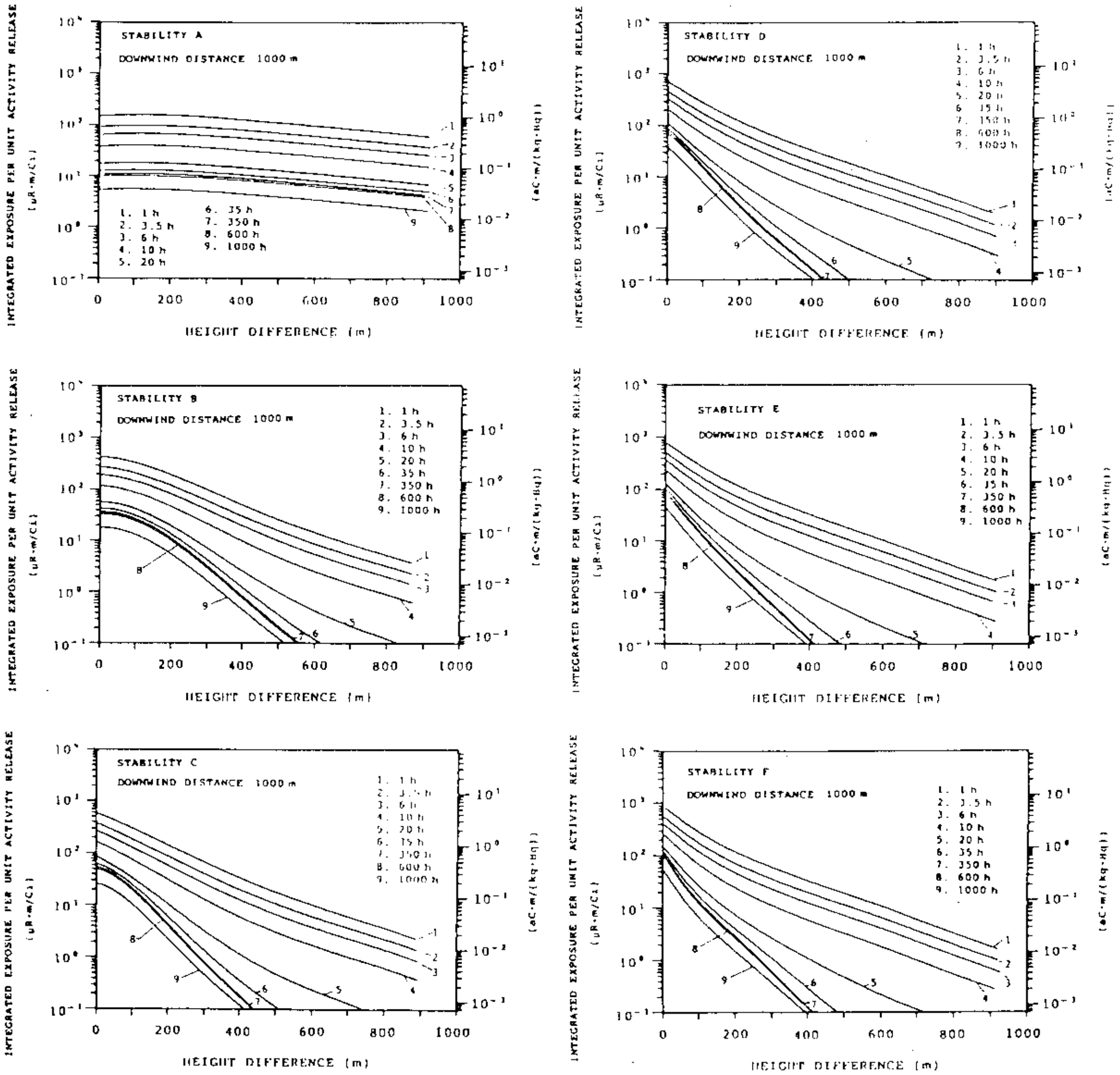

Fig.16-2 Conversion factors for method 2 at a down wind distance of 1000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 10000Mwd/tU.

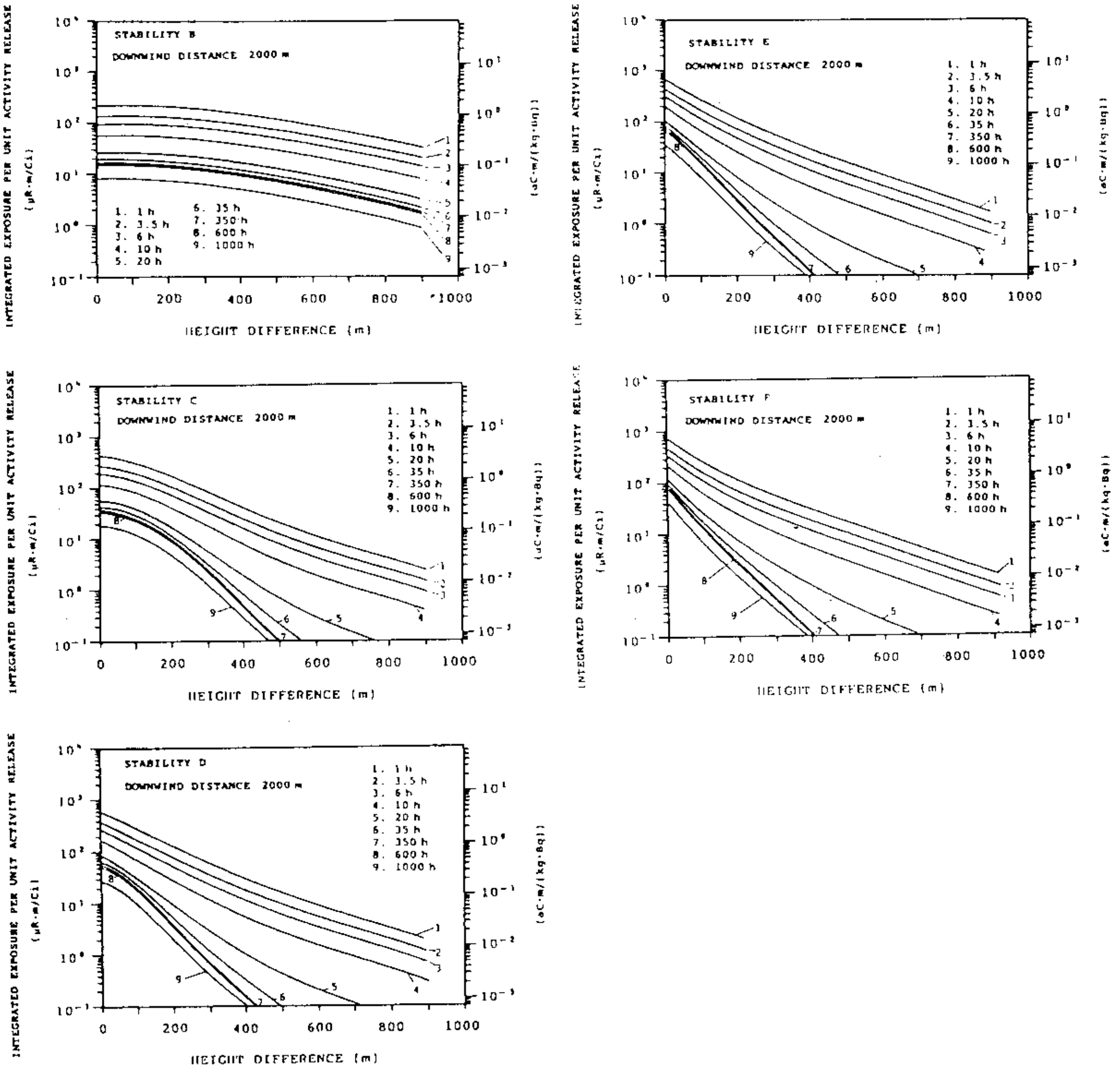

Fig.16-3 Conversion factors for method 2 at a down-wind distance of 2000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 10000Mwd/tU.

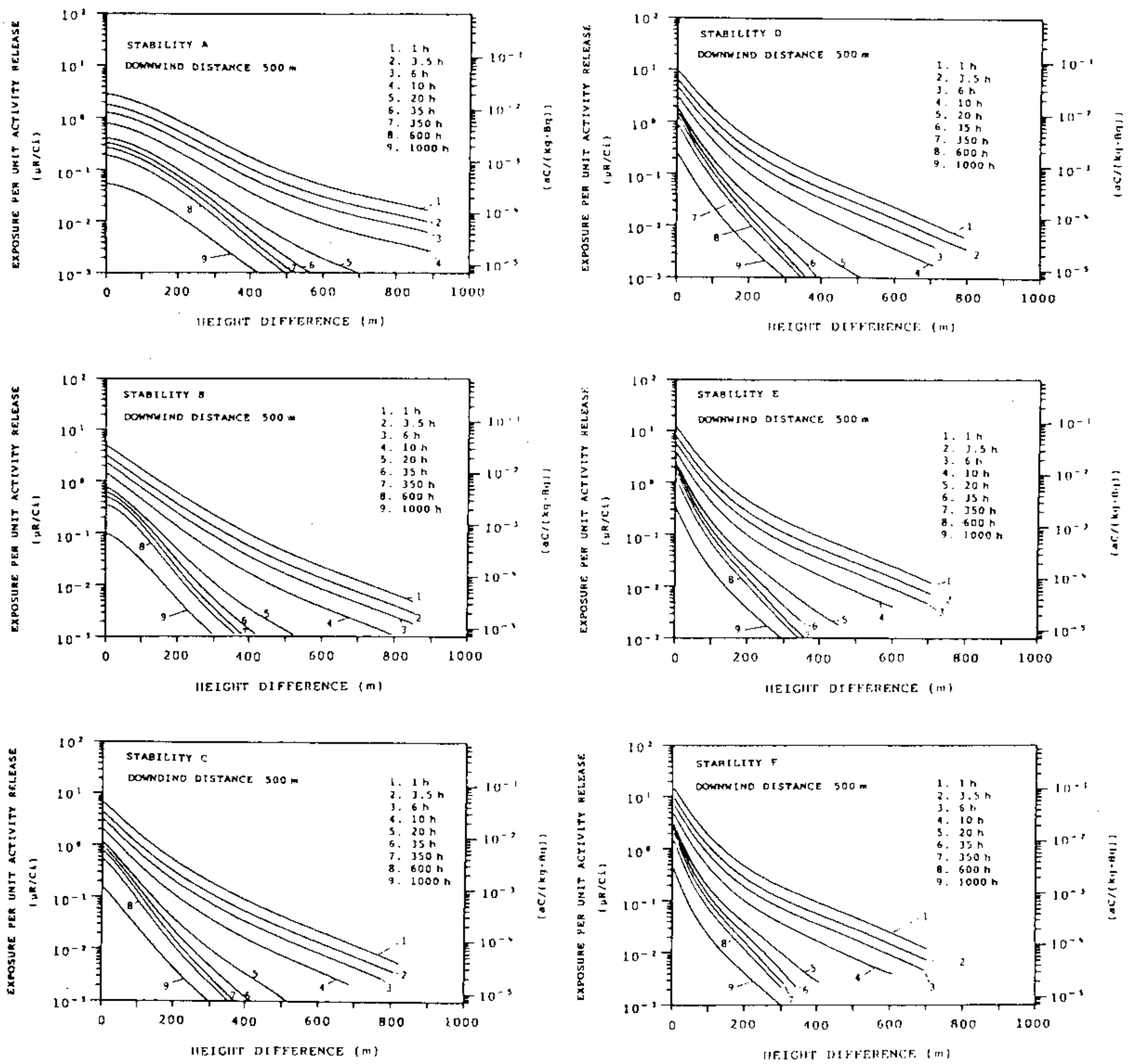

Fig.17-1 Conversion factors for method 1 at a down-wind distance of 500m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 30000Mwd/tU.

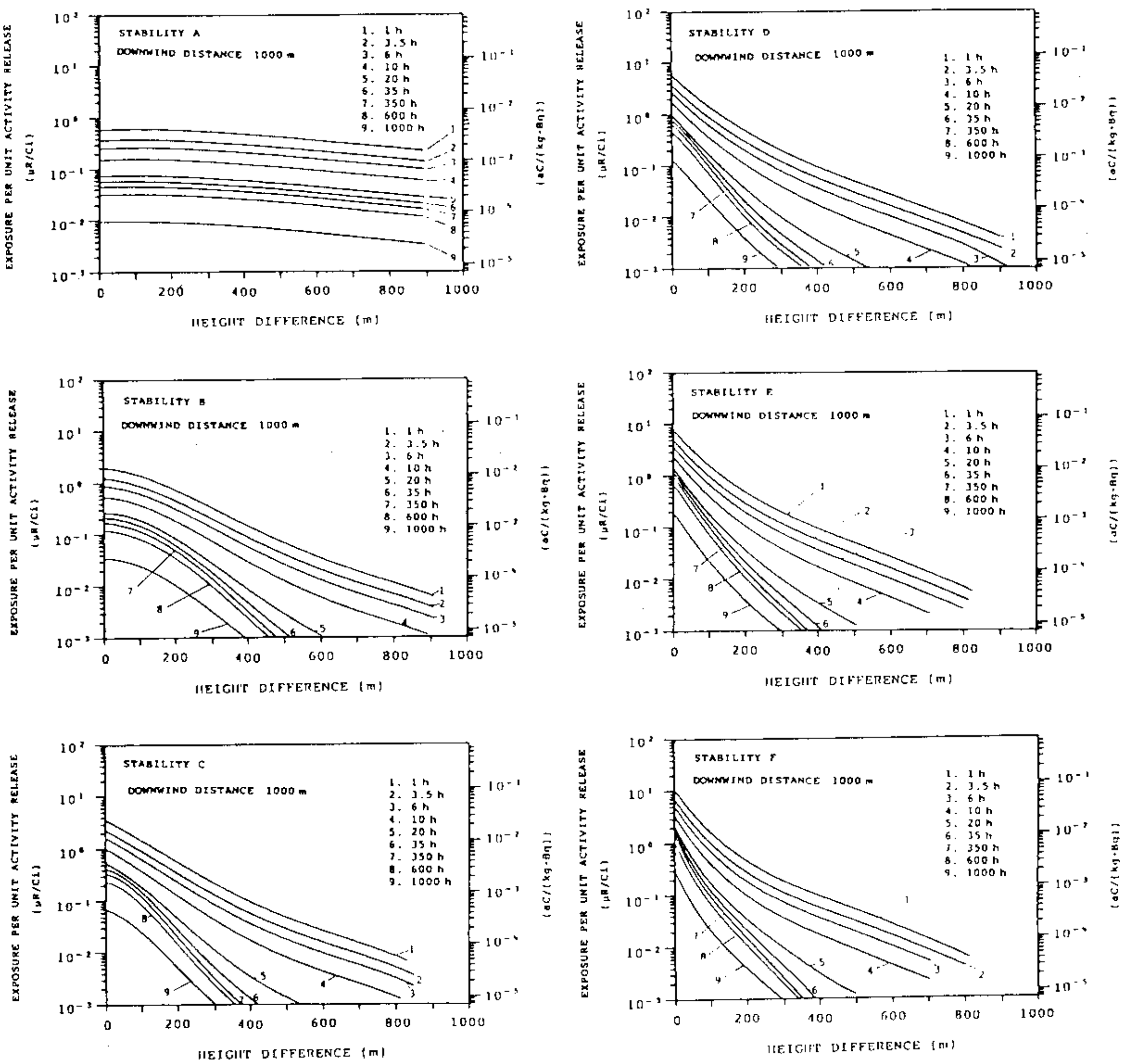

Fig.17-2 Conversion factors for method 1 at a down wind distance of 1000m for a mixture of noble gases changing with time after shutdown. Burn up of fuel is 30000Mwd/tU.

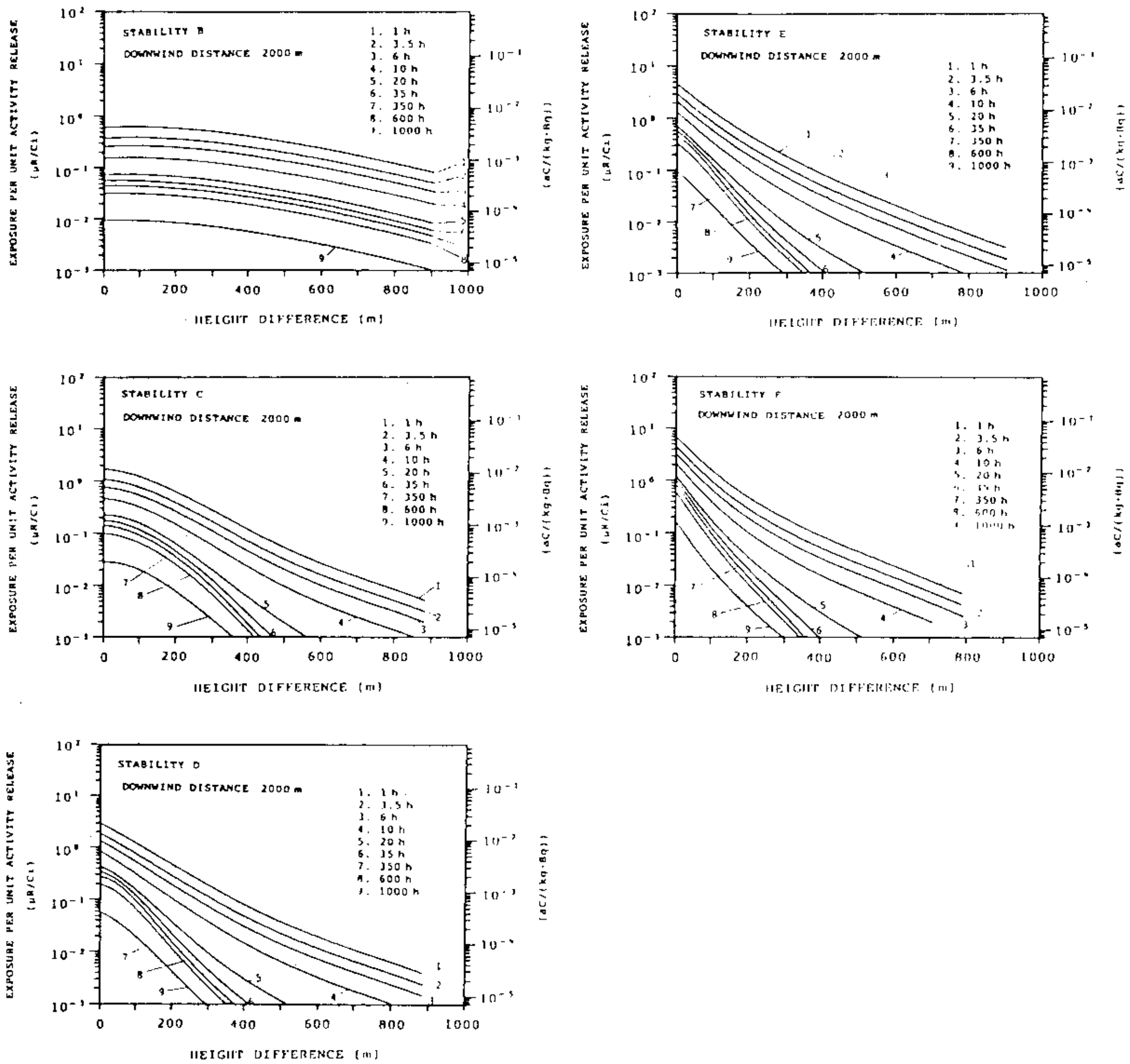

Fig.17-3 Conversion factors for method 1 at a down wind distance of 2000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 30000Mwd/tU.

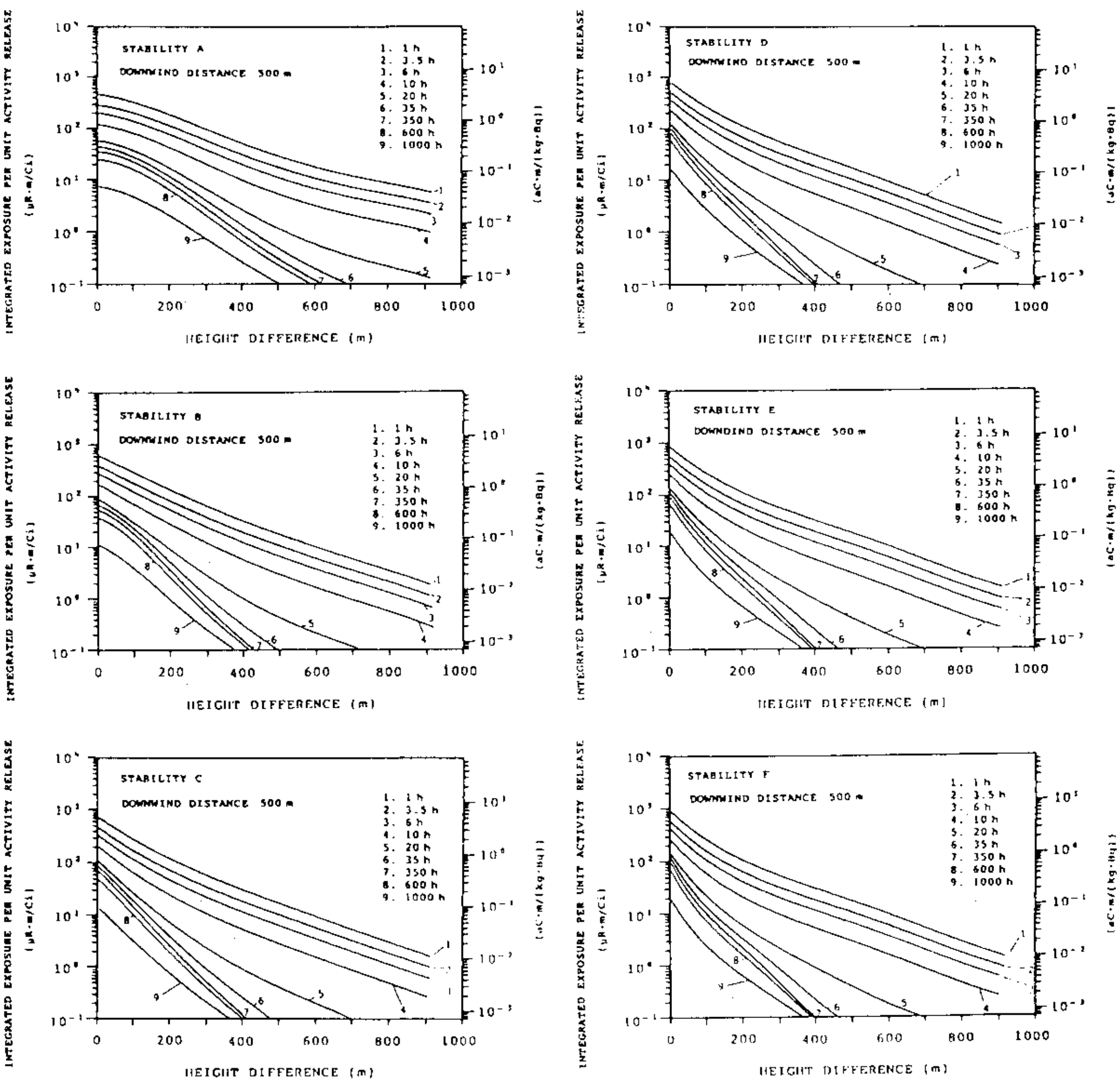

Fig.18-1 Conversion factors for method 2 at a down wind distance of 500m for a mixture of noble gases changing with time after shutdown. Burn up of fuel is 30000Mwd/tU.

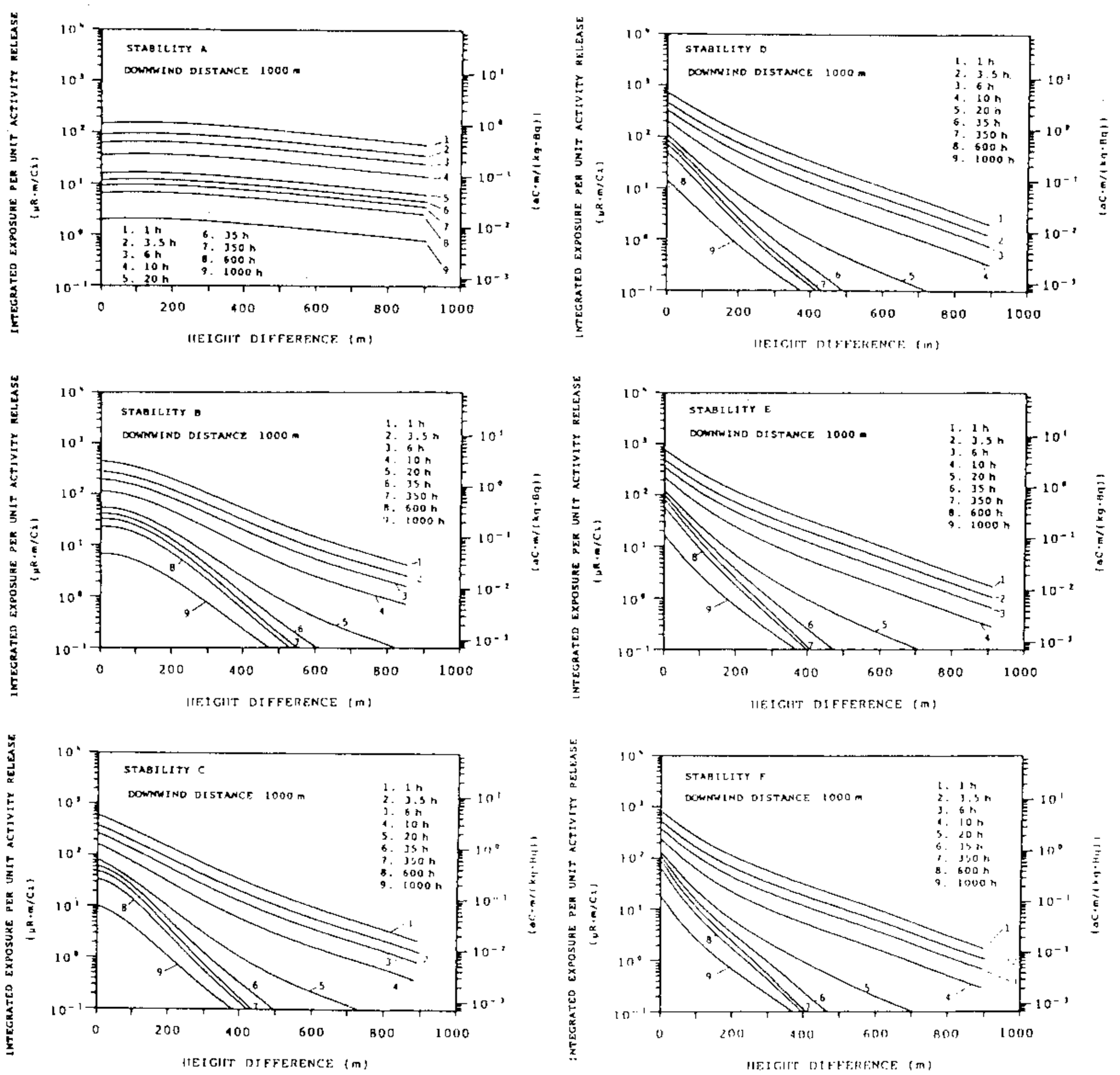

Fig.18-2 Conversion factors for method 2 at a down-wind distance of 1000m for a mixture of noble gases changing with time after shutdown. Burn-up of fuel is 30000Mwd/tU.

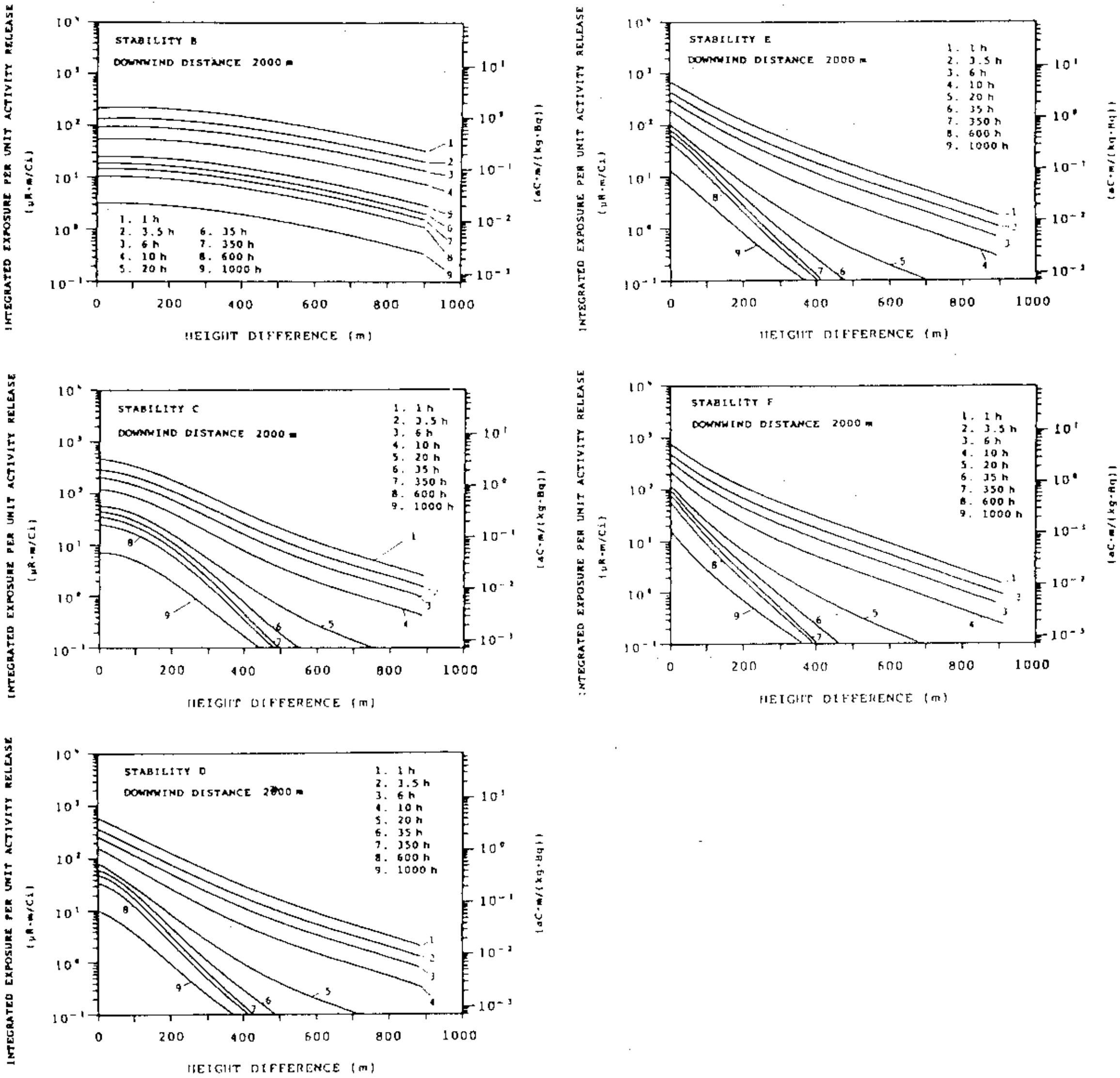

Fig.18-3 Conversion factors for method 2 at a down-wind distance of 2000m for a mixture of noble gases changing with time after shutdown. Burn up of fuel is 30000Mwd/tU.

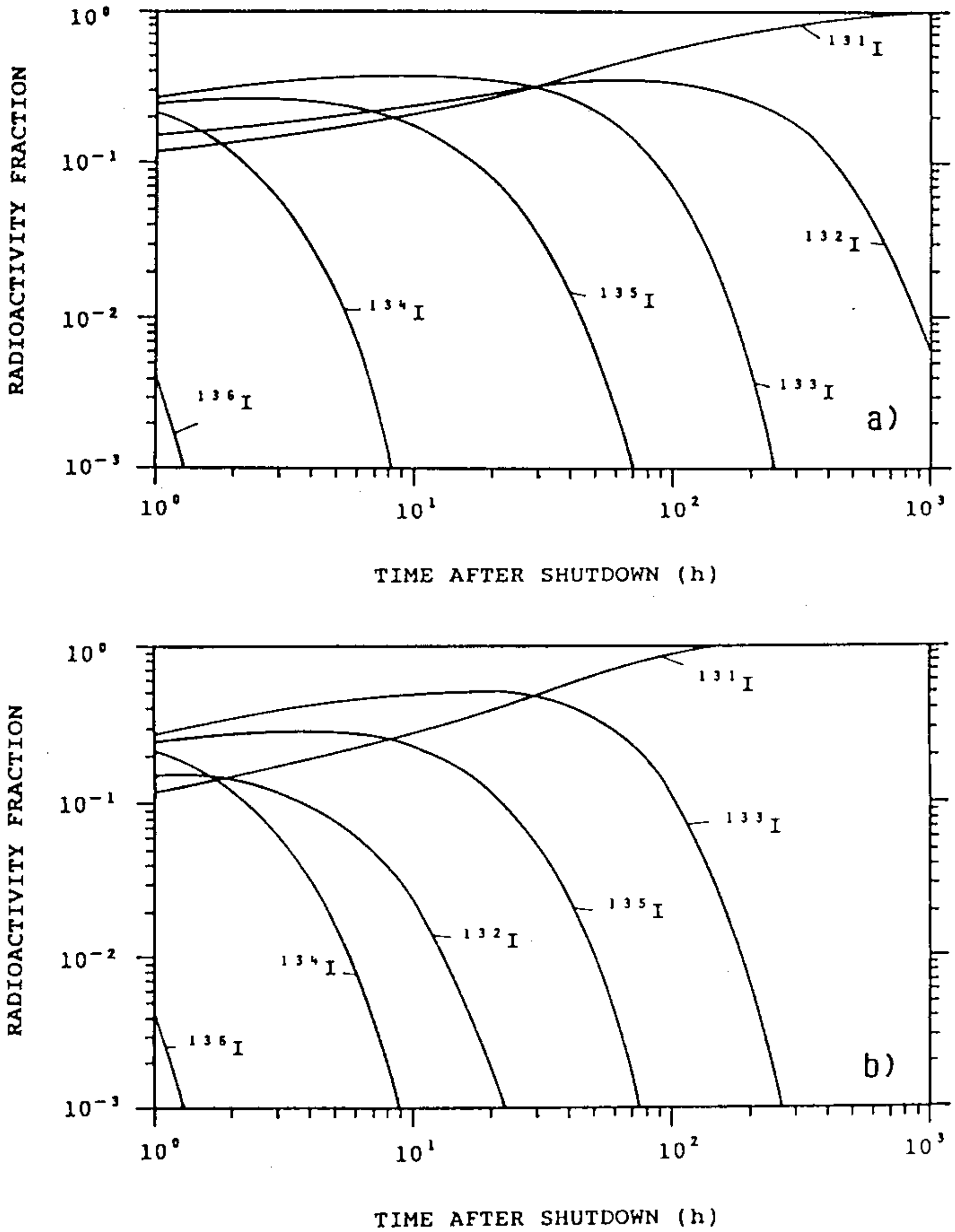

Fig.19 Concentration ratios of radioactivity of iodine in a plume a) where ^{132}I is supplied from the decay of ^{132}Te, b) where ^{132}I is not supplied from the decay of ^{132}Te.

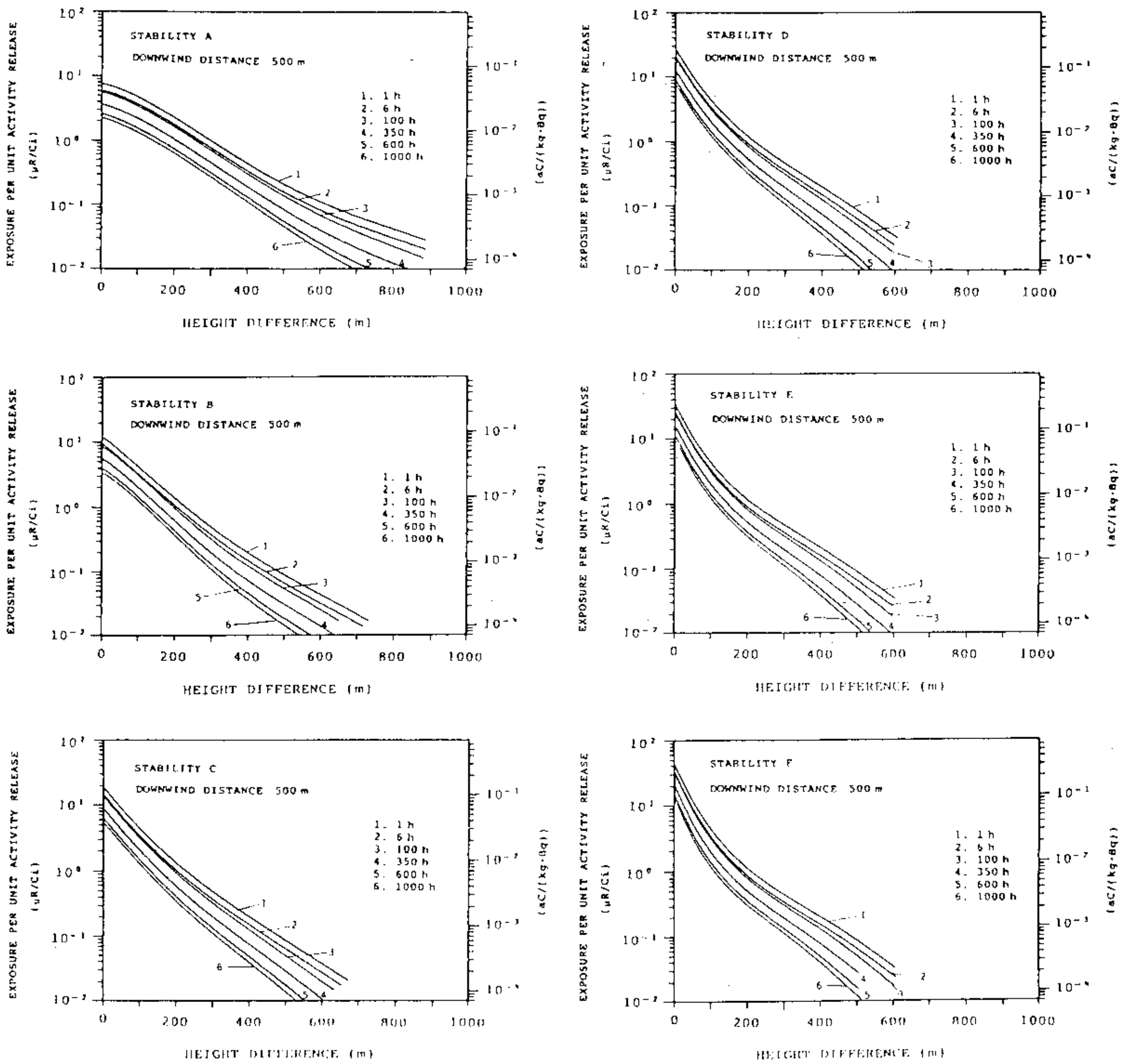

Fig.20-1 Conversion factors for method 1 at a down-wind distance of 500m as a function of time after shutdown for a mixture of iodine isotopes where ^{132}I is supplied from the decay of ^{132}Te.

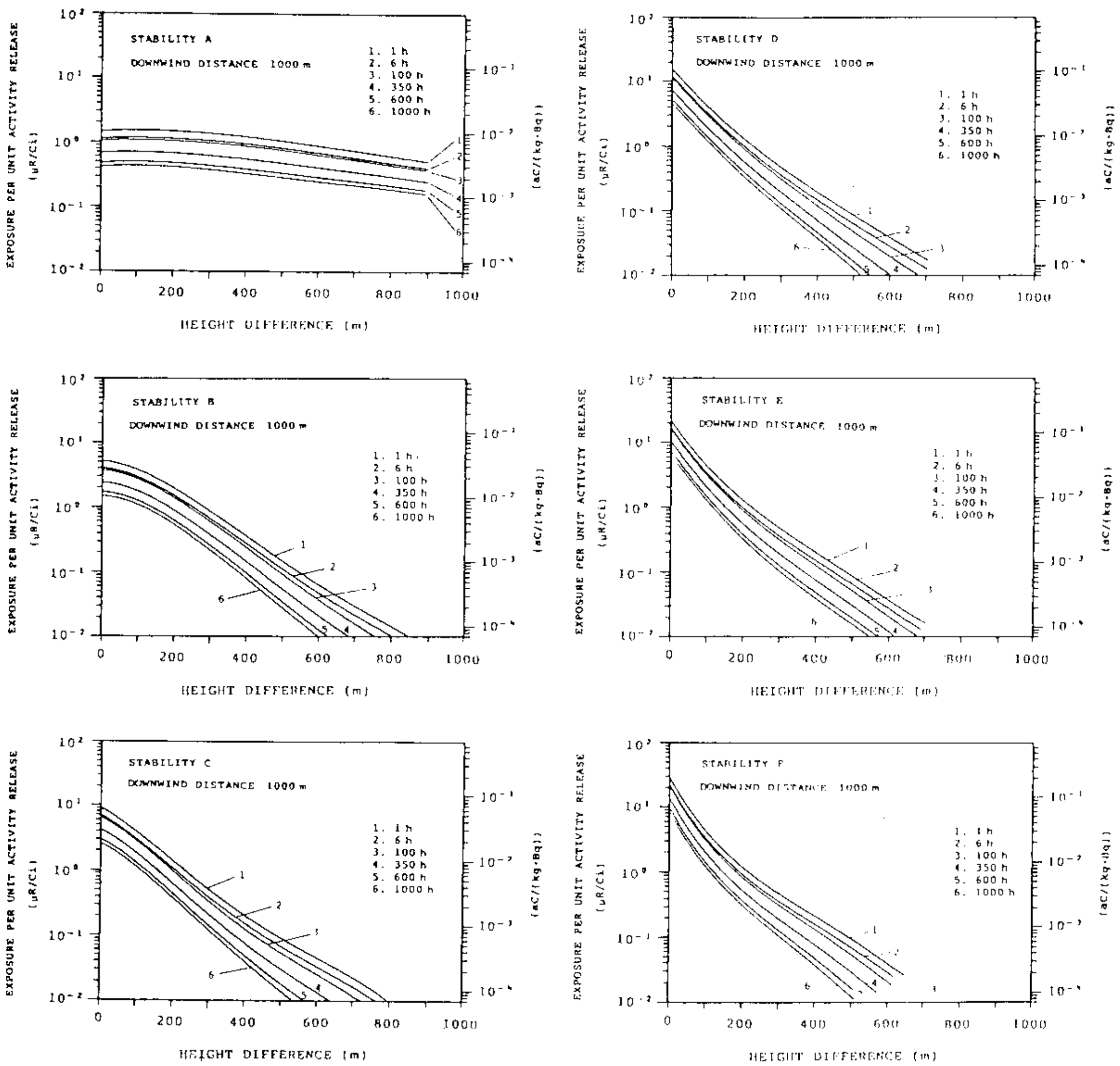

Fig.20-2 Conversion factors for method 1 at a down-wind distance of 1000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is supplied from the decay of ^{132}Te.

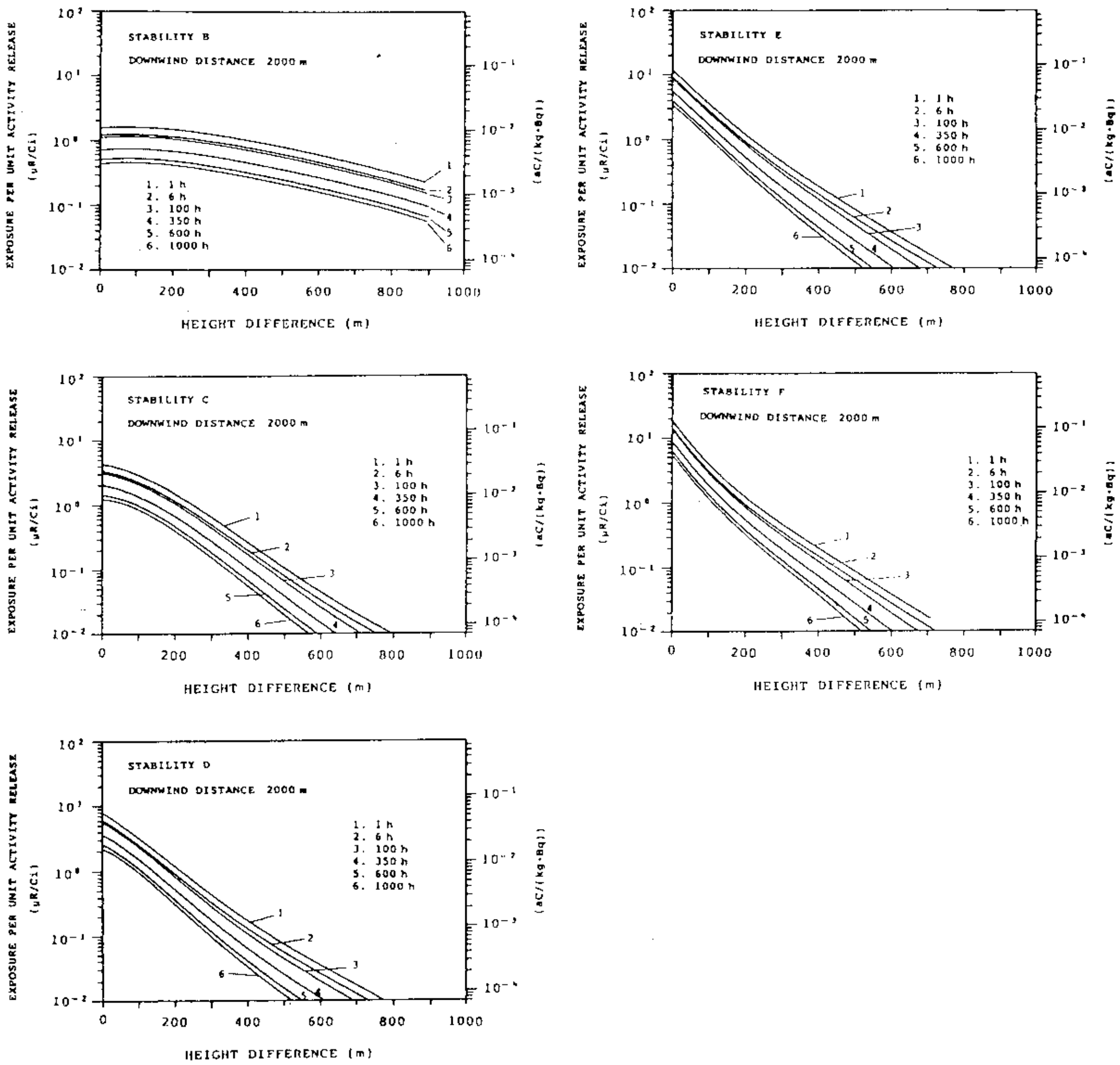

Fig.20-3 Conversion factors for method 1 at a down wind distance of 2000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is supplied from the decay of ^{132}Te.

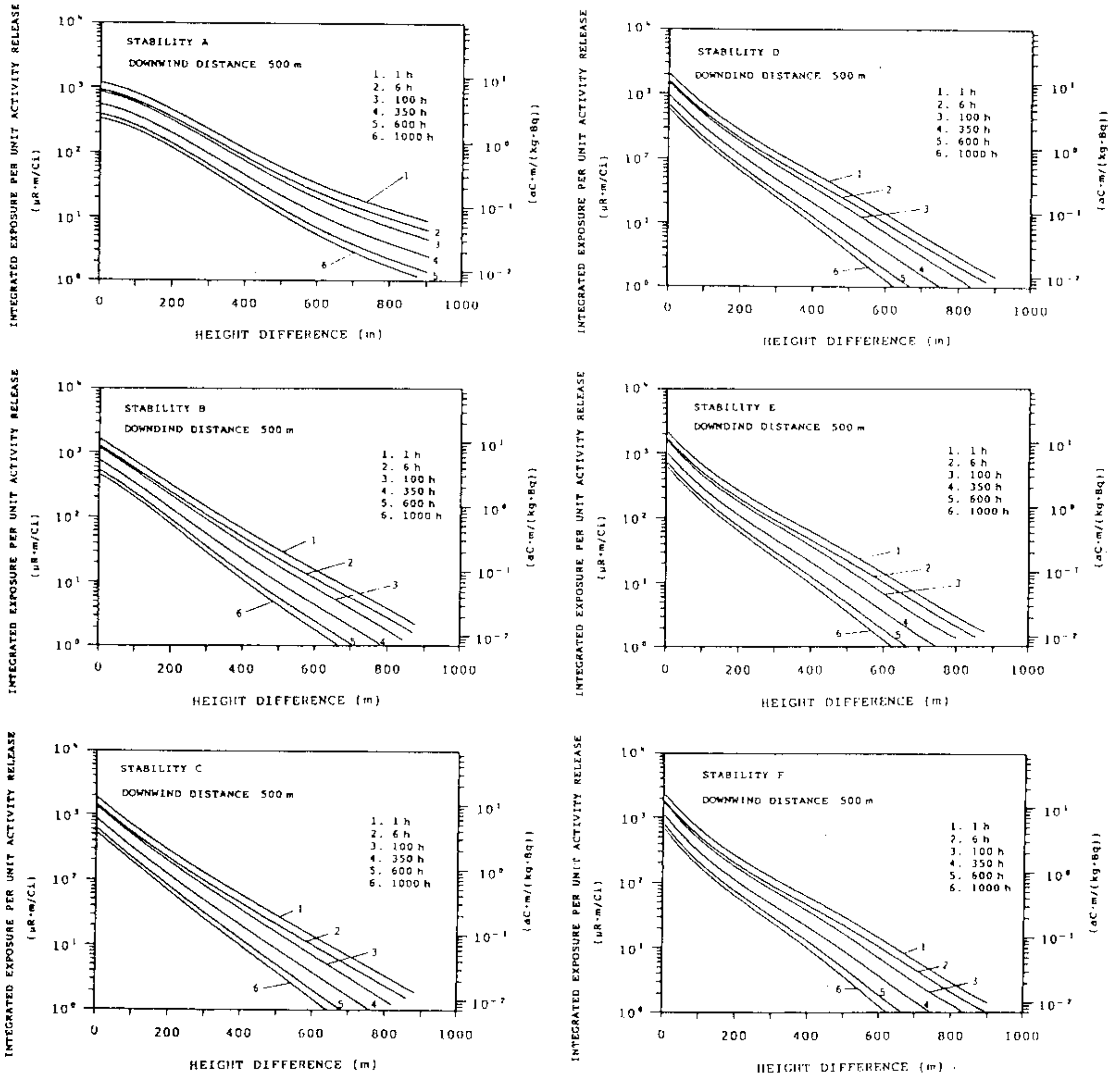

Fig.21-1 Conversion factors for method 2 at a down-wind distance of 500m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is supplied from the decay of ^{132}Te.

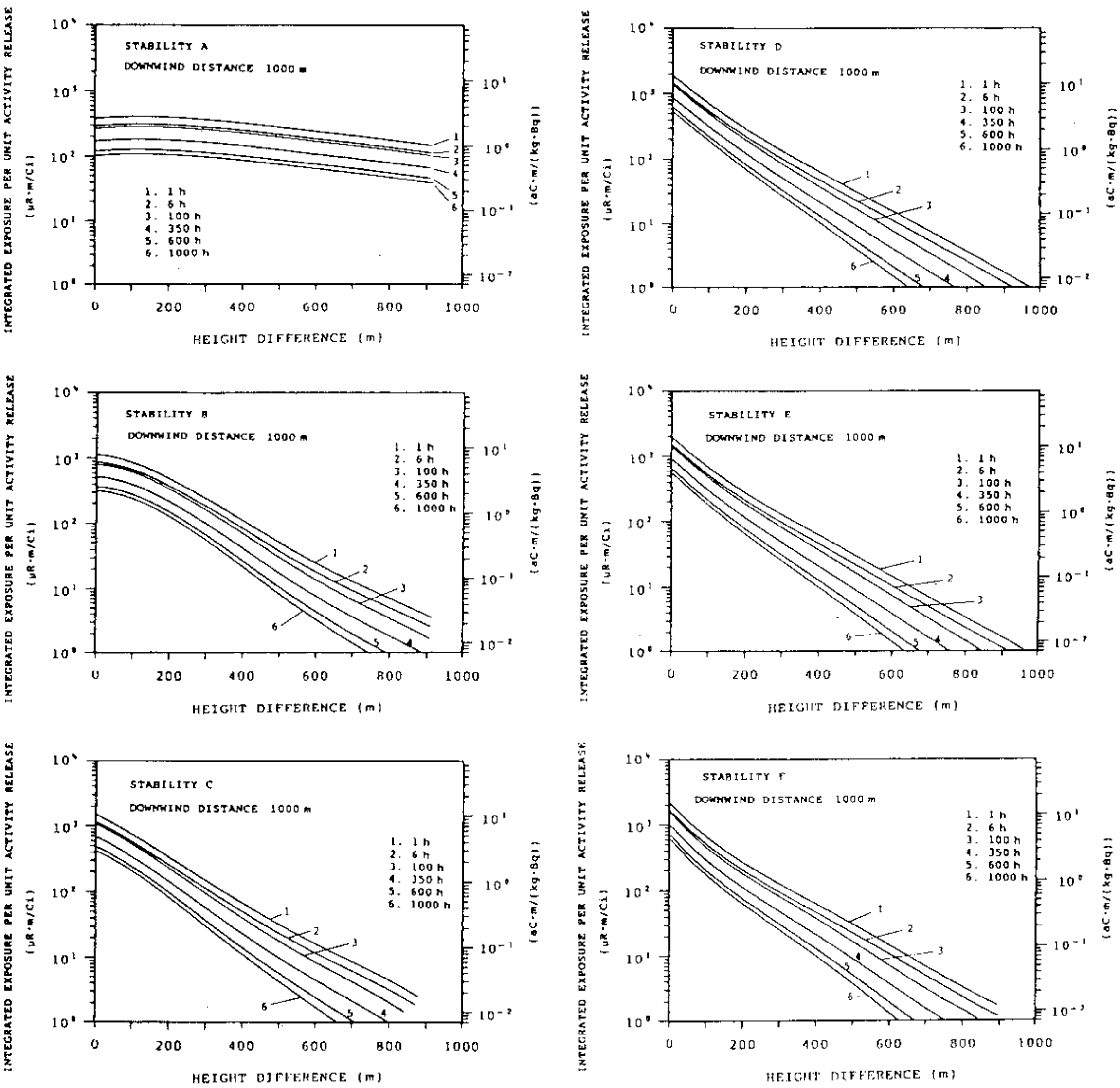

Fig.21-2 Conversion factors for method 2 at a down-wind distance of 1000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is supplied from the decay of ^{132}Te.

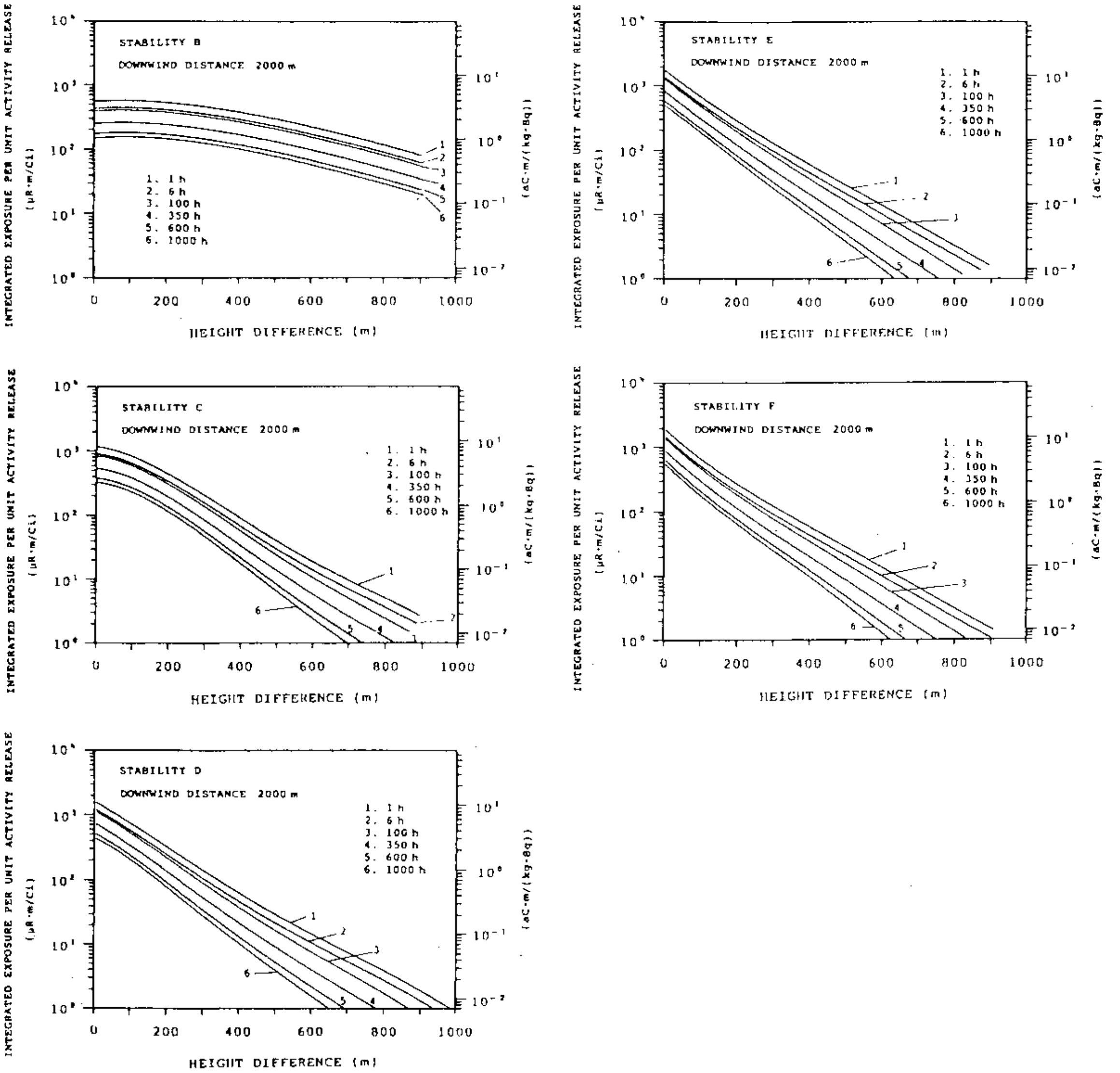

Fig.21-3 Conversion factors for method 2 at a down wind distance of 2000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is supplied from the decay of ^{132}Te.

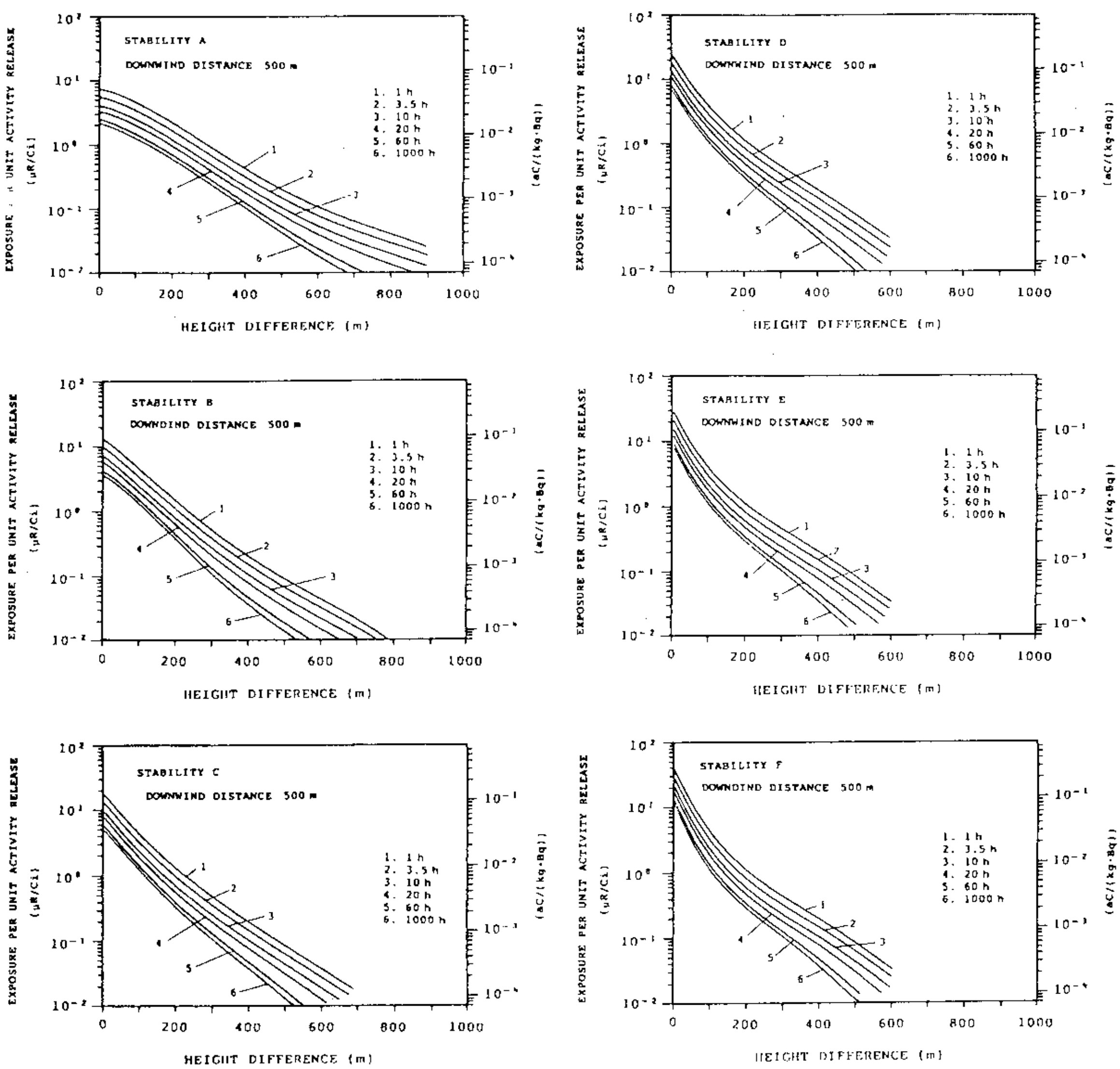

Fig. 22-1 Conversion factors for method 1 at a down-wind distance of 500m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is not supplied from the decay of ^{132}Te.

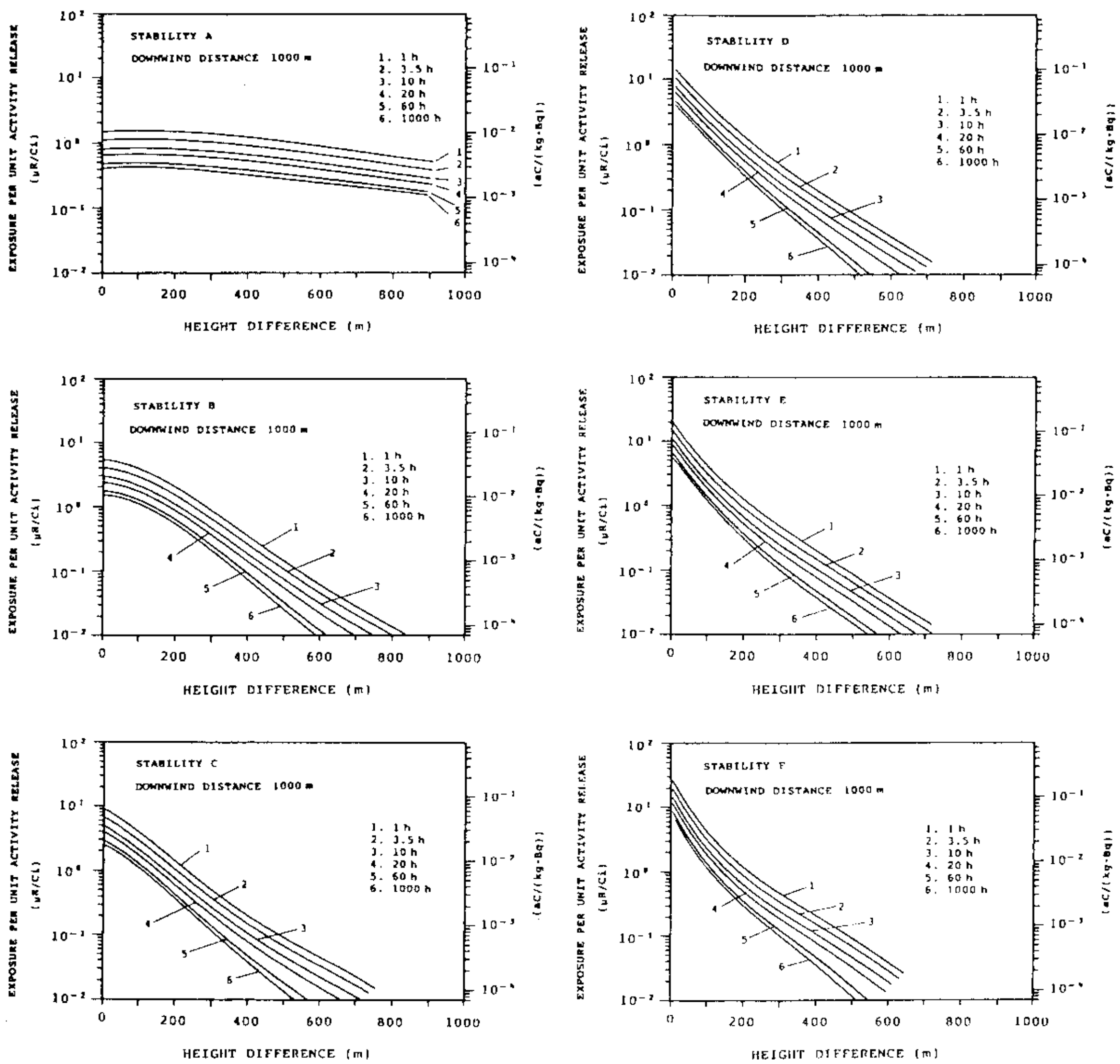

Fig.22-2 Conversion factors for method 1 at a down-wind distance of 1000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is not supplied from the decay of ^{132}Te.

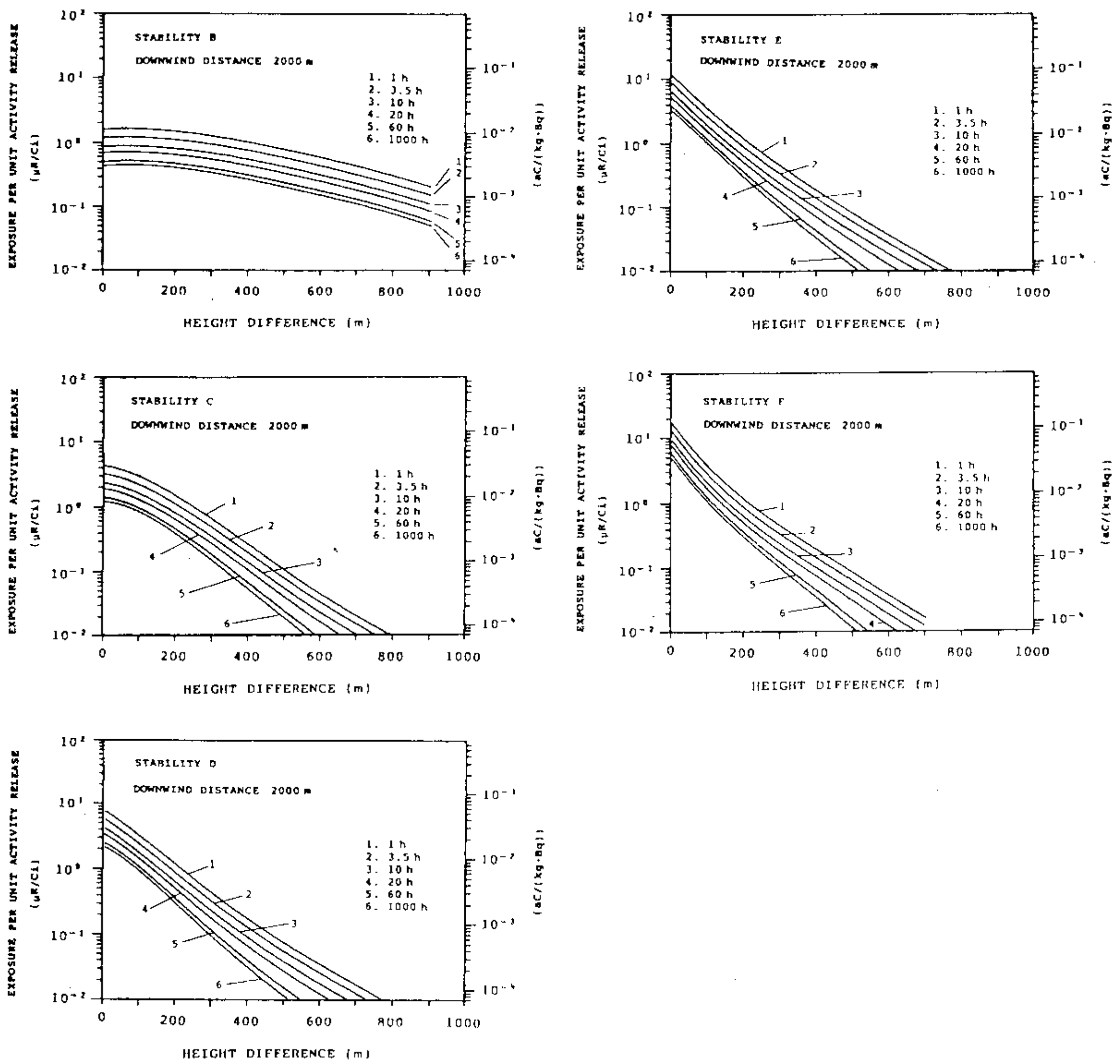

Fig.22-3 Conversion factors for method 1 at a down-wind distance of 2000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is not supplied from the decay of ^{132}Te.

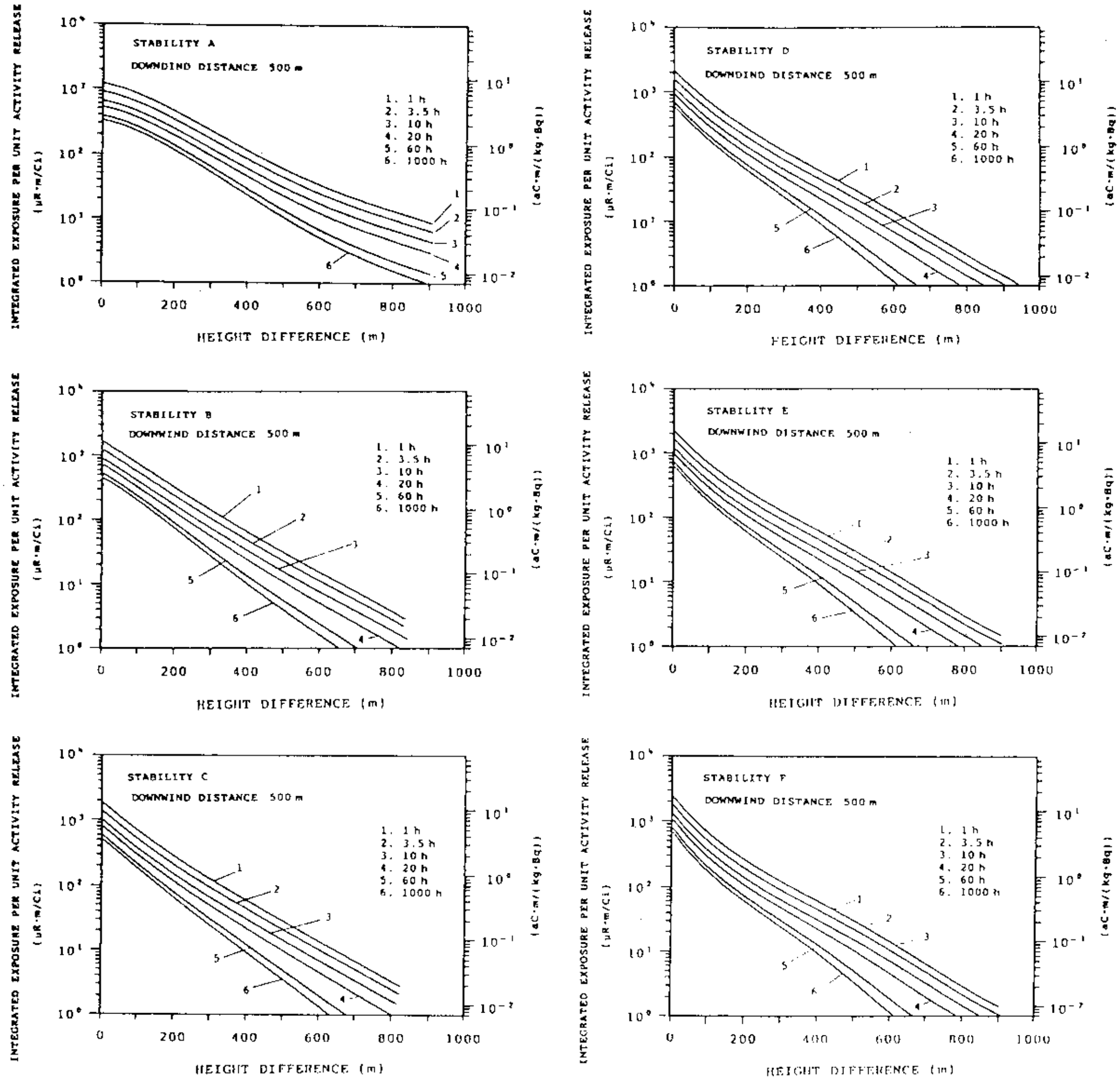

Fig.23-1 Conversion factors for method 2 at a down wind distance of 500m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is not supplied from the decay of ^{132}Te.

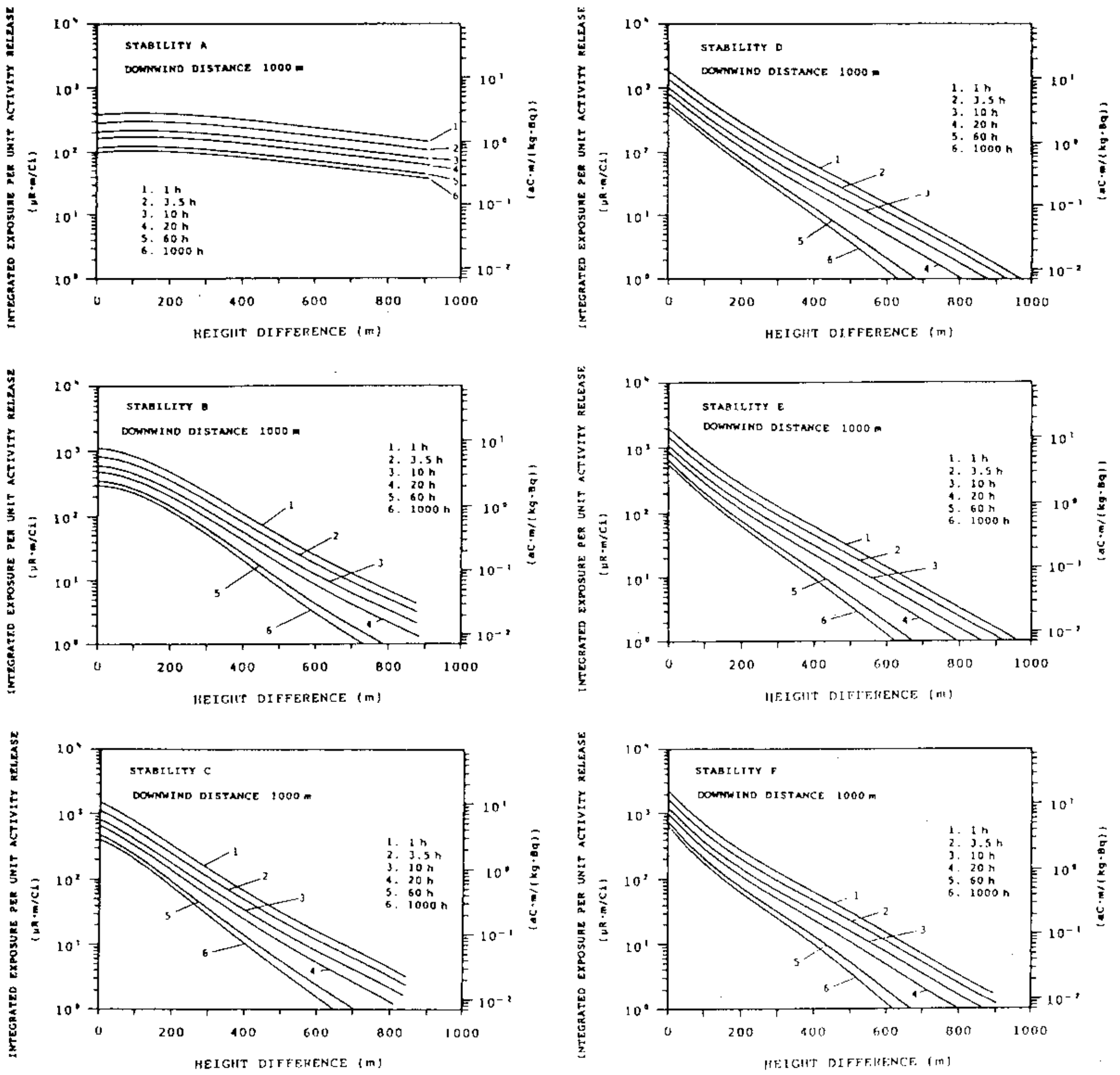

Fig.23-2 Conversion factors for method 2 at a down-wind distance of 1000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is not supplied from the decay of ^{132}Te.

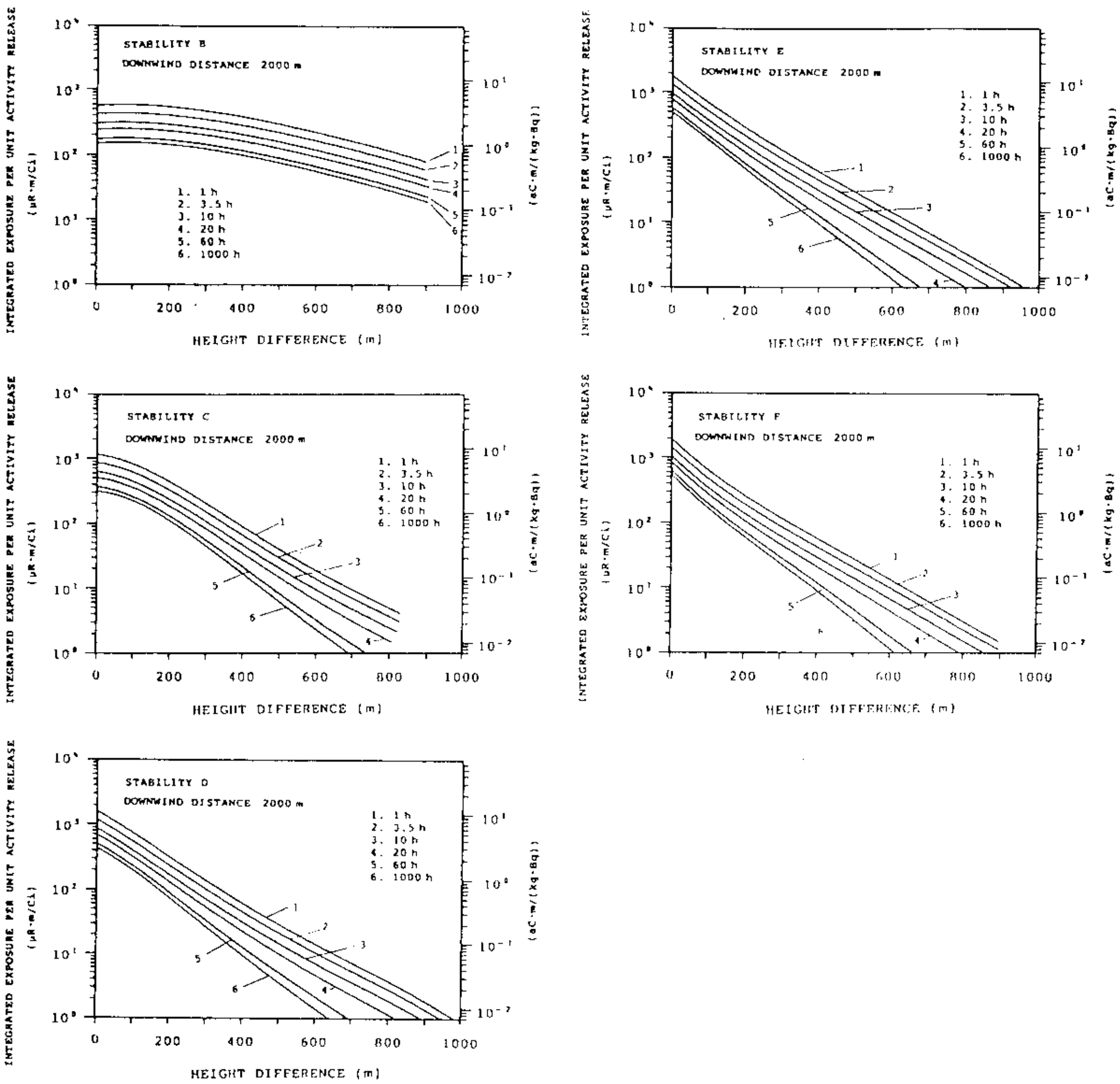

Fig.23-3 Conversion factors for method 2 at a down wind distance of 2000m changing with time after shutdown for a mixture of iodine isotopes where ^{132}I is not supplied from the decay of ^{132}Te.