Comparison of Nordic dose models

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Abstract

A comparison is made between the models used in the four Nordic countries, Finland, Norway, Sweden and Denmark, for calculation of concentrations and doses from releases of radioactive material to the atmosphere. The comparison is limited to the near-zone models, i.e. the models for calculation of concentrations and doses within 50 km from the release point, and it comprises the following types of calculations:

a. Concentrations of airborne material

b. External gamma doses from a plume

c. External gamma doses from radioactive material deposited on the ground.

All models are based on the gaussian dispersion model (the gaussian plume model).

Unit releases of specific isotopes under specific meteorological conditions are assumed. On the basis of the calculation results from the models, it is concluded that there are no essential differences. The difference between the calculation results only exceeds a factor of 3 in special cases. It thus lies within the known limits of uncertainty for the gaussian plume model.

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INTRODUCTION

The SNODAS group[1)] decided in 1976 to carry out a comparison of the models used in the four Nordic countries, Finland, Norway, Sweden and Denmark, for calculating doses from radioactive material released to the atmosphere. Such a comparison can partly be used for demonstrating any errors and deficiencies of the models and partly as a kind of reference material in comparing dose calculations made in the different Nordic countries.

The model comparison is at first limited to comprising the near-zone models, i.e. the models used within 50 km's distance from the release point.

Without knowledge of the "fundamental" properties of the models, any comparison of the results of more complex calculations, e.g. doses from accidental releases, are of limited value. In the first phase of the model comparison, which is here reported upon, it was therefore decided to omit subjects where it was known in advance that there were differences between the models. Such differences manifest themselves, for example, in calculating plume rise and in the dose conversion factors for inhalation doses (the relation between the inhaled activity of given isotopes and the radiation doses to given organs).

This investigation only considers unit releases of a few isotopes under well-defined atmospheric conditions. A later phase can include releases that are more complicated both regarding the isotopic composition and the atmospheric dispersion conditions.

There are no differences in principle between the individual models in the way they are used in this comparison. All models use, e.g., the same dispersion model (the Gaussian) and the same calculation principle for external gamma doses from a plume (finite plume size). In reality the model comparison, described here, is rather a comparison of different implementations (in

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1) SNODAS is an abbreviation of, "Samordning af Nordiske Dosisberegninger og Atmosfæriske Spredningsberegninger" (Co-ordination of Nordic dose calculations and atmospheric dispersion calculations) and is a working group set up in May 1975.

the form of computer programs) of the same theoretical model. The differences in calculation results do not, however, signify errors, as there can be differences in, for example, the attitude to calculation accuracy considering the area of application of the models.

2. ASSUMPTIONS FOR THE COMPARISON

2.1. General considerations

The starting point for the comparison is that all the models considered use the Gaussian dispersion model and can describe the Pasquill stability classes A to F (i.e. the models (computer programs) contain the dispersion parameters for these stability classes). A short-term release of radioactivity, where the material is released at a constant speed from a point source, is considered. The release is assumed to take place over a flat homogeneous terrain, and the meteorological conditions is assumed to be constant during the time of release. This applies to atmospheric stability as well as to wind speed and to mean wind direction. Similarly, the effective release height is assumed constant.

2.2. Meteorological conditions

Two situations are considered:

a. Atmospheric stability: Pasquill F
   Wind speed: 2 m/s
   Mixing height: 200 m

b. Atmospheric stability: Pasquill C
   Wind speed: 5 m/s
   Mixing height: 1000 m

2.3. Release height

For each of the meteorological situations mentioned under 2.2, two effective release heights of 20 meters and 100 meters are considered. Plume rise caused by decay heat (self-heating) and thermal heat is disregarded.

2.4. Deposition

For each of the four combinations of meteorological conditions and release height, the following deposition situations are considered.

a. No deposition

b. Dry deposition only with v_g = 1 cm/sec.

c. Wet deposition (wash-out) only with $\lambda_g = 10^{-4} sec^{-1}$

d. Combined dry and wet deposition where,

v_g = 1 cm/sec

$\lambda_g = 10^{-4}$ sec^{-1}

2.5. Isotopes released

The duration of the release is assumed to be 1800 seconds (= ½ hrs.) and the release-rate is assumed to be constant.

The isotopes are chosen so that isotope concentrations and doses show caracteristic features of the models.

The isotopes released are:

Mother product	Daughter product
Kr 89	Rb 89
Te 132	I 132
Xe 133	-
Cs 137	-

Calculation are made for doses/concentrations from a total release of 1 curie of each of the mother products in question. In addition calculations are made for doses/concentrations from the daughter products that are formed by decay of the mother product during transport downwind and during the decay of the mother product after deposition on the ground.

3. RESULTS OF THE COMPARISON

A description of the models of the individual countries is given in appendices 1 through 4.

To achieve as good a description as possible, these descriptions were made by the experts in the countries concerned.

A comparison of the parameters used in the models is given in a paper prepared by the Institute for Atomic Energy (IFA), Norway, which is attached as appendix 5.

The calculation results are shown in figs. 1 - 344. The curves that are shown in the figures are plotted on the basis of calculation results received from the individual countries. Evident errors in these results (e.g. decade errors) where corrected before plotting, while it was not possible in all cases to correct smaller (and thus less important) errors (e.g. digital errors) that are seen as small bends in the curves plotted.

A survey of the results of the model comparison is given in the following sections together with an analysis of the inlying models. No detailed analysis has been attempted as the aim was to point out characteristics that give, or could give rise to differences in the calculation results. Further reference should be made to the model descriptions, appendices 1 - 4.

3.1. Concentration of airborne material

As the differences in conversion factors from concentrations to inhalation doses are not evaluated in this investigation, it was decided just to compare the calculations of the integrated air concentration at ground level.

The calculation results from the four countries are shown in figs. 1 - 72.

The calculation of concentrations of airborne radioactive material on the basis of a Gaussian dispersion model is very simple, but it is included here as a kind of control material because differences in the calculated concentrations will be reflected both in the calculated external gamma doses from the plume and in the calculated external gamma doses from radioactive material deposited on the ground.

There is no large difference between the concentrations calculated with the four models. The difference is on an average 10 - 20% and can chiefly be ascribed to the fact that the dispersion parameters of the Pasquill stability categories are not calculated in the same way. The Danish model interpolates directly on the curves given by Turner in ref. 1, while the models of the other countries use different approximations of the Pasquill/Gifford curves (e.g. Martin-Tikvart). The difference

is of greatest significance at short distances (out to ca. 10 km) and is particularly apparent in the Finnish model where the concentrations at the distance 0.5 km can be 50 - 70% lower than those calculated with the models of the other countries (see, e.g., figs. 1 - 6).

In the calculations carried out here, only the Finnish and the Danish models take into account the fact that vertical dispersion in the atmosphere is limited by a mixing layer. This is only of perceptible importance in the case of stability C and a release height of 100 m (see, e.g., figs. 9 - 12).

Deposition is treated in principle in a similar fashion in the four models (explicit solution of the relevant differential equations). A comparison of the concentrations of given isotopes calculated under given release conditions (stability, wind speed and release height) with or without deposition, shows that the relative differences between the calculation results from the models are not affected by the presence or absence of deposition.

3.2. External gamma dose from a plume

The calculation results are shown on figs. 73 - 144.

The doses are calculated at points at the ground vertically under the axis of the plume for an exposure time of 1800 s (= the time that it takes for the plume to pass the point under consideration).

The differences between the dose values calculated with the four models are considerably larger than in the case of the concentration calculations. In most cases, the ratio between the largest and the smallest value calculated at a given point under given release conditions, is between a factor 2 and factor 3, but in a few cases it reaches a factor 10.

The differences between the calculation results of the models can mainly be ascribed to three circumstances:

a) Choice of integration method: In each of the four models a different method is used to integrate the dose contributions from the individual part-elements of the plume. Experience shows that the calculated doses are very sensitive to the choice of integration method, especially in the area close to the source (within a distance of c. 5 - 10 km).

b) Choice of build-up factor: In some american model comparisons (ref. 2) it has been ascertained that differences in build-up factors were the most significant reasons for differences between the calculated external gamma doses from the plume. Different build-upfactors are used in the four models under discussion (see appendix 5).

c) Choice of energy energy groups: The number of energy groups and the mean energy in the groups are different in the four models. (See appendix 5).

In the individual cases it is difficult to point out the exact reason for the differences between the calculated doses. However, in general, the differences are greatest for isotopes with low gamma energies (^{132}Te and especially ^{133}Xe) and in situations with relatively large atmospheric dispersion (Pasquill C, see, e.g. figs. 75, 77, 87 and 89). In these cases the mean free path of the photons is small in relation to the atmospheric dispersion parameters (σ_y and σ_z) which, experience shows, makes great demands on the accuracy of the method of numerical integration.

A comparison between figs. 73 - 96 and figs. 97 - 144 shows that the relative differences between the results are not affected by the presence or absence of deposition.

3.3. External gamma dose from radioactive material deposited on the ground

The calculation results are shown on figs. 145 - 344.

External gamma doses are calculated in air 1 meter above ground. The calculations are made for the following exposure times, reckoned from the time at which deposition started at the location in question:

1 sec, 1800 sec, 1 hour, 24 hours, 3 days and 7 days

Only points in the wind direction vertically under the axis of the plume are taken into consideration.

In cases of wet deposition alone only one release height (20 m) is considered. With only wet deposition present, the amount of material deposited is independent of the release height. In the calculations, all models except the Danish take into account the dose build-up in air. All other things being

equal, this means that the doses calculated with the Danish model are a factor 1.1 to 2 below the doses calculated with the models of the other countries. The difference is largest for Te 132 where it is a factor 2.

Only the Danish and the Finnish model take account of the mixing layer. Only in calculations relating to Pasquill C and a release height of 100 m, does the mixing layer imply a smaller increase of the doses.

In the following considerations of the differences between the calculated doses, "corrections" are made for the above differences in the calculation assumptions.

It should be noted that no calculations were made with the Norwegian model for (dose) integration times below three days, and calculations with the Swedish model were not made in all situations for the 1 s integration time.

It applies in general that the calculated doses are in best agreement for situations with simultaneous wet and dry deposition (figs. 265-344). (It is disregarded that the Finnish model uses dispersion parameters slightly different from those of the other models at the distance 0.5 km).

Poorest agreement is found between the calculation results for dry deposition alone - although there are no large differences (10 - 80% when a correction is made for the differences mentioned earlier). The small extra complication introduced into the models when calculating the amount of material that is dry-deposited, seems to be the main reason for the somewhat larger differences.

The Finnish and the Danish models are in best agreement regardless of the type of deposition situation.

The agreement between the Swedish model and the other models is good with the exception of doses for the two isotopes Rb 89 and Te 132:

Doses from Rb 89 for the integration time of 1 s are in all situations a factor ca. 2 lower than the doses calculated with the other models (see, e.g., figs. 145 and 265). For Te 132, the difference between the doses calculated with the Swedish model and the doses calculated with the other models increases from a factor of ca. 1.2 to a factor of ca. 2.4, when the integration time increases from 1 s to 1 day. When the integration time is increased to more than 1 day, the difference is not increased further (see, e.g., figs. 150 - 154 and 330 - 334).

4. CONCLUSION

On the basis of the present investigation of the calculation results from the dispersion and dose models of the four Nordic countries, it can be concluded that there are no essential differences between the doses and concentrations calculated from the models.

The differences seem to be largest for the external gamma doses from the plume, where there can be up to a factor 2 to 3 between the calculated doses. Considering the fact that use of a Gaussian dispersion model under idealized conditions (point source, flat homogeneous terrain, constant mean wind direction during the release, etc.,) cannot predict concentrations within less than a factor 2 to 3 up to 10 kilometers from the release point, differences of up to a factor of 3 must be acceptable.

Some of the minor differences in the calculation results indicates however, there might be a few smaller errors in some of the computer programs used for the calculations. These minor defects should be corrected before any comparison between more complicated dose calculations is made.

5. REFERENCES

1. D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates. National Air Pollution Control Association, Cincinatti, Ohio, (1969). (Public Health Service Publication No. 999-AP-26) 84 pp.

2. Carl V. Gogolak, Comparison of measured and calculated radiation exposure from a boiling water reactor plume, HASL-277, September 1973.

CALCULATION RESULTS

A. Concentrations of airborne material

Fig. 1 - 72

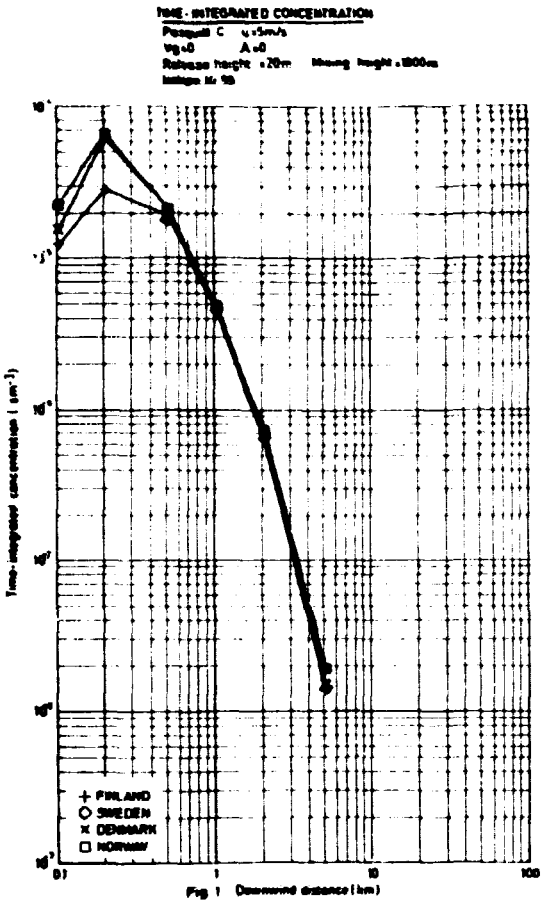


Fig 1 Downwind distance (km)

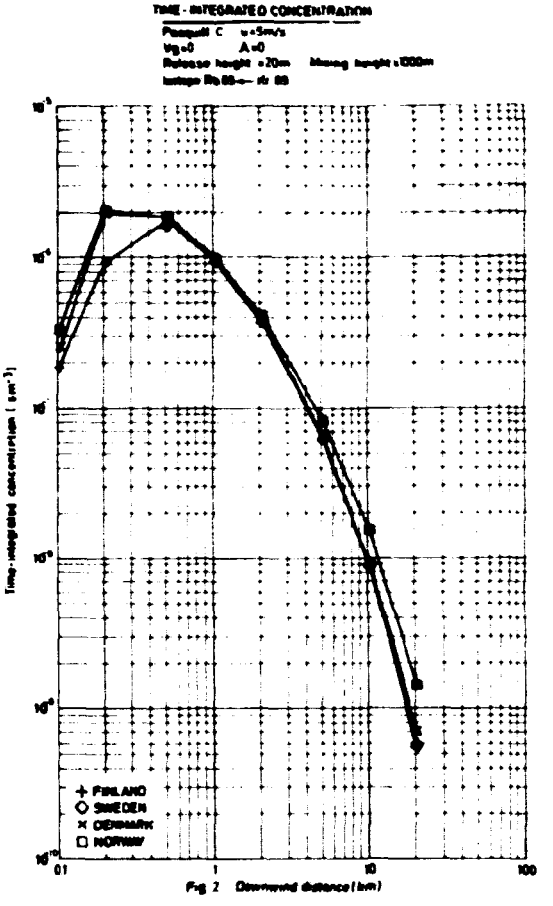


Fig 2 Downwind distance (km)

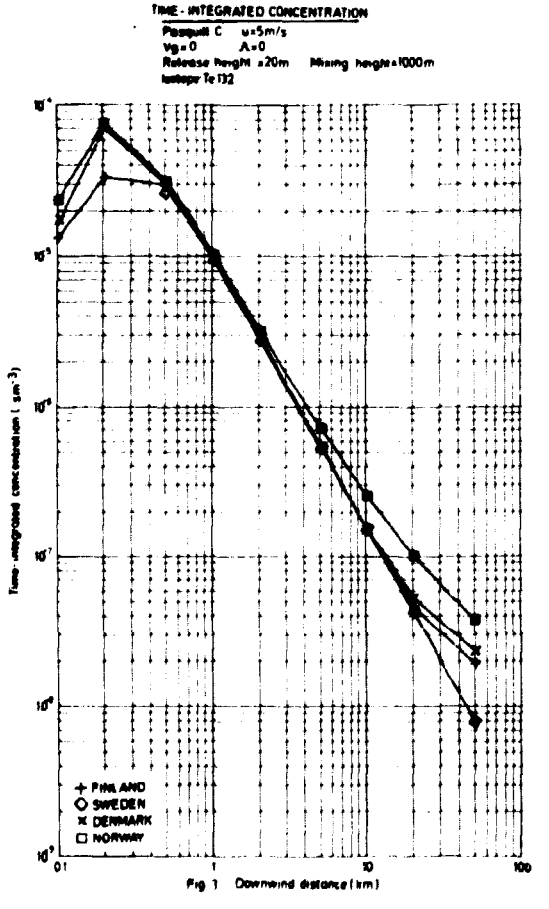


Fig 3 Downwind distance (km)

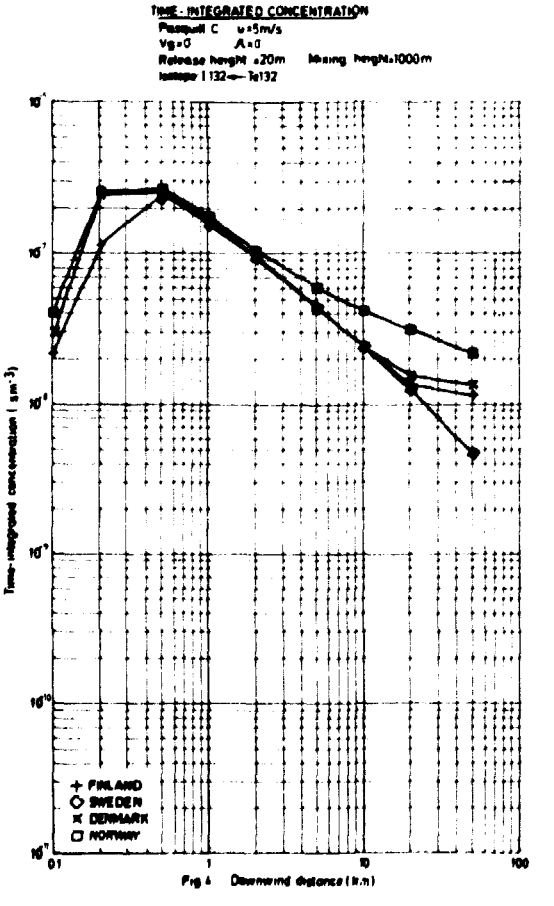


Fig 4 Downwind distance (km)

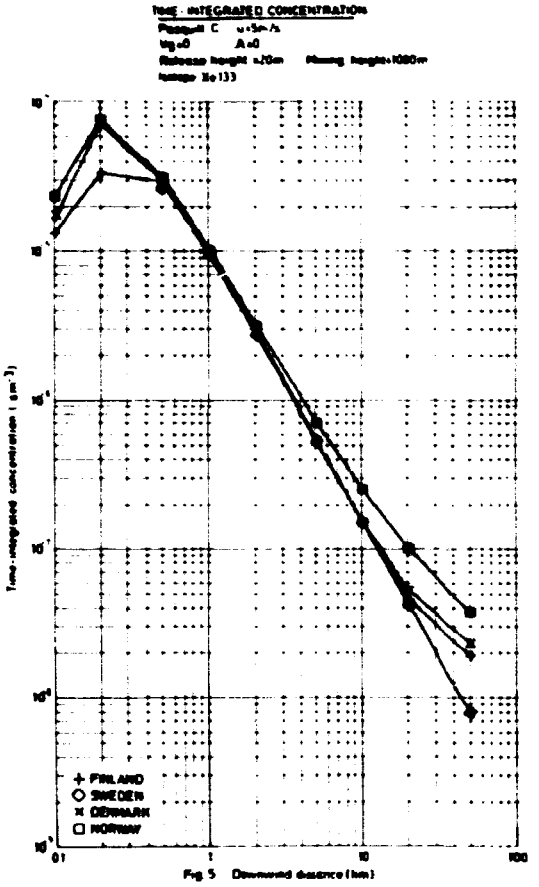


Fig 5 Downwind distance (km)

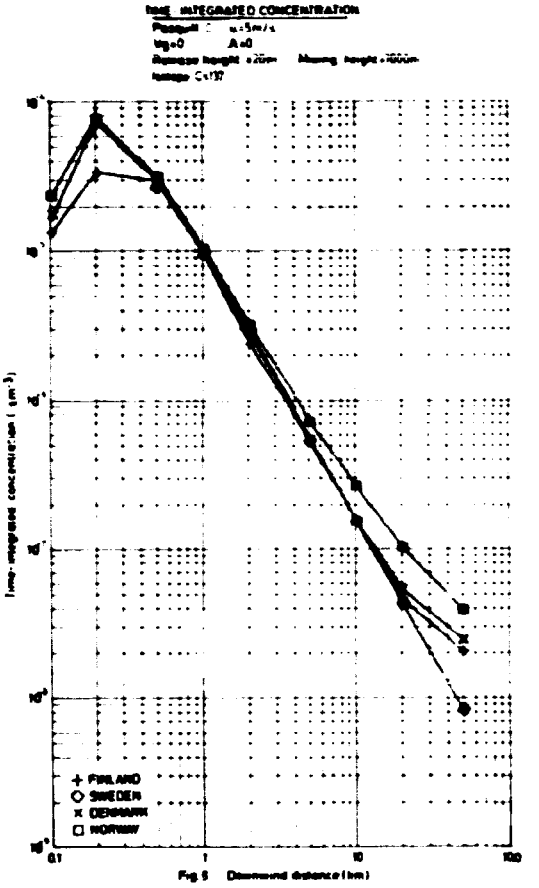


Fig 6 Downwind distance (km)

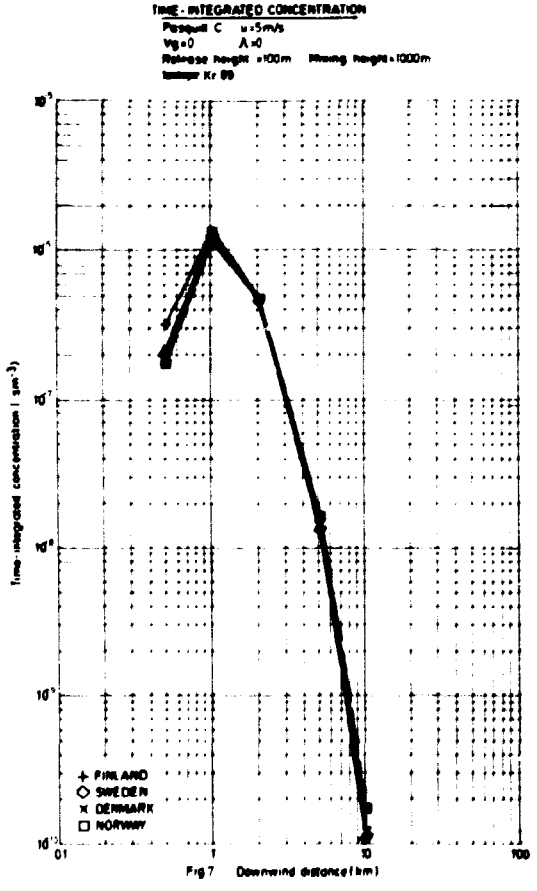


Fig 7 Downwind distance (km)

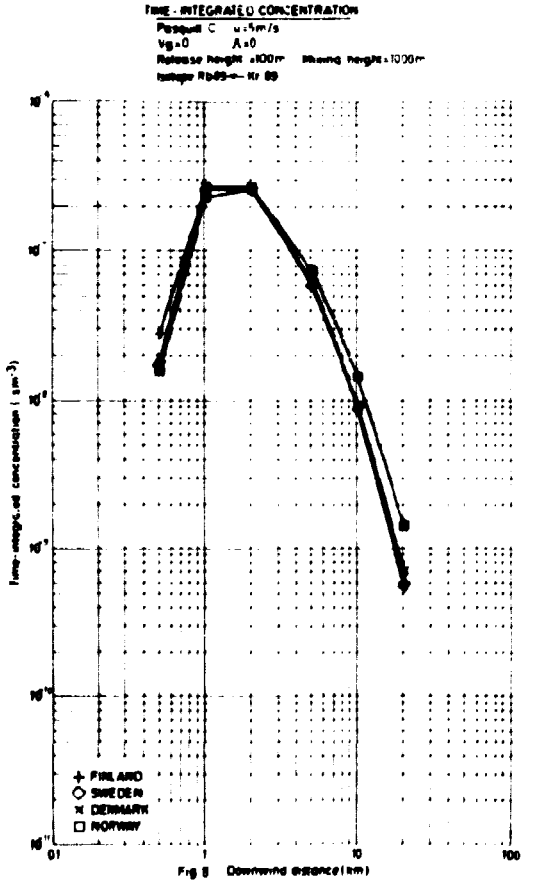


Fig 8 Downwind distance (km)

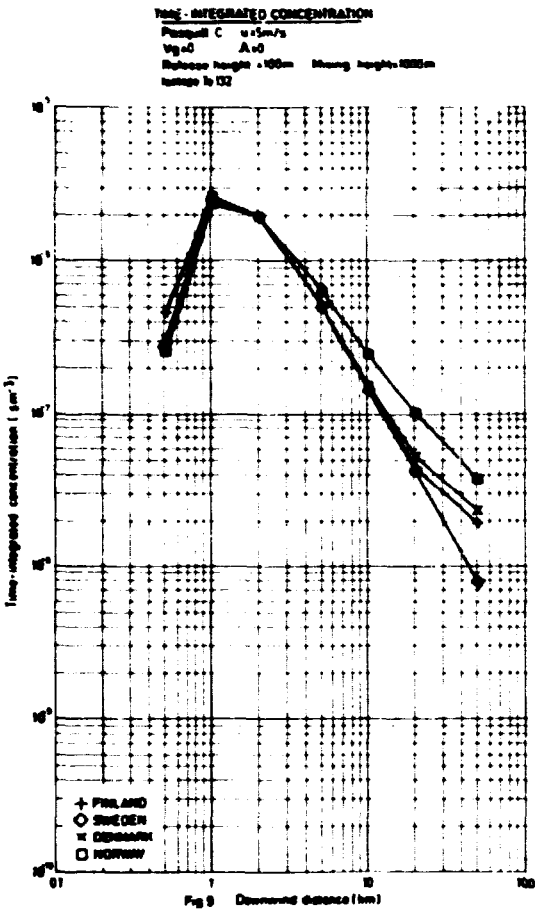
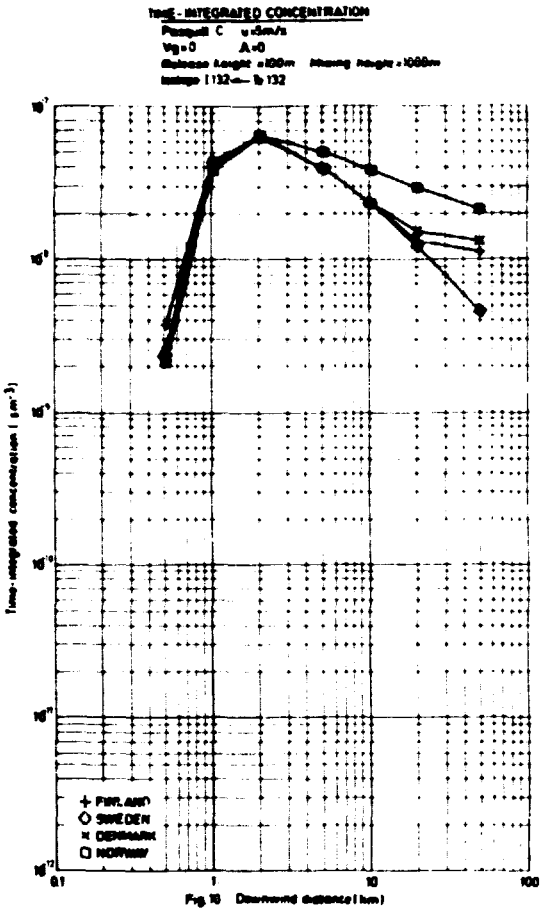


Fig 9 Downwind distance (km)



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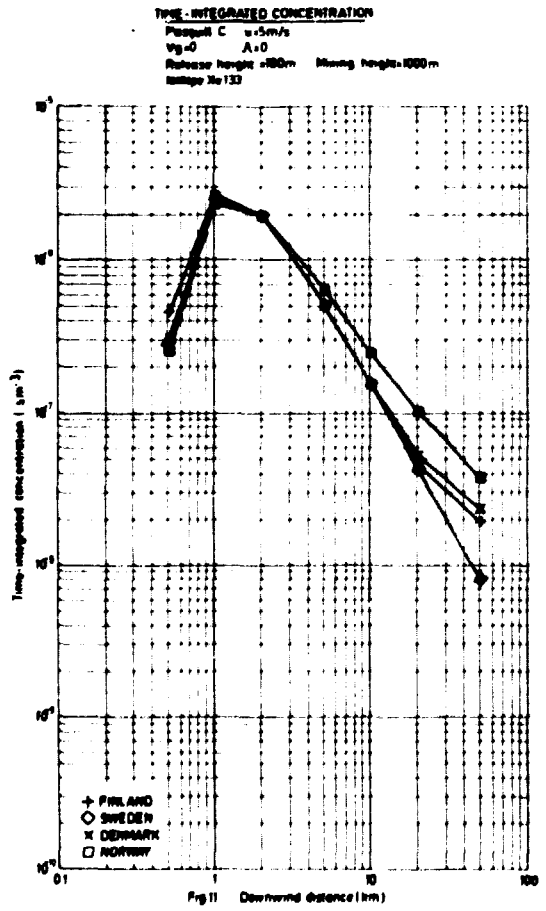


Fig 11 Downwind distance (km)

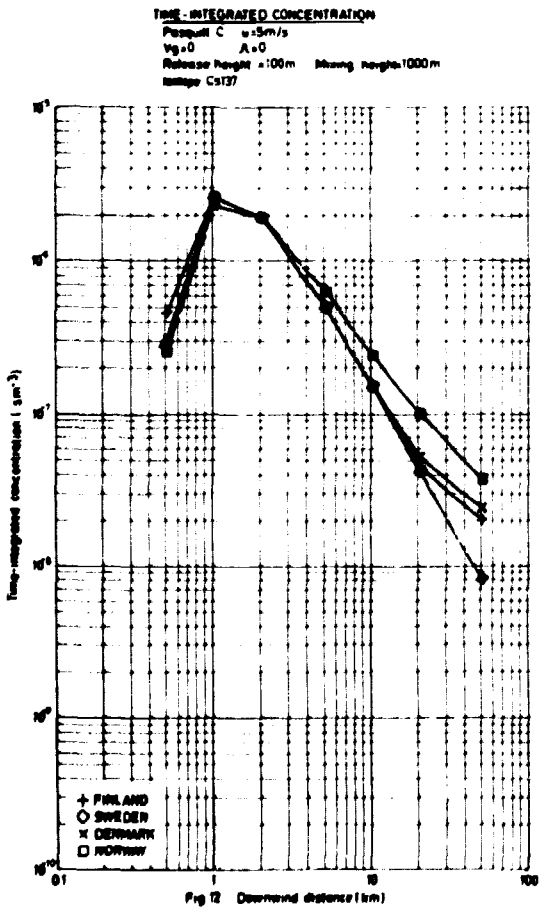


Fig 12 Downwind distance (km)

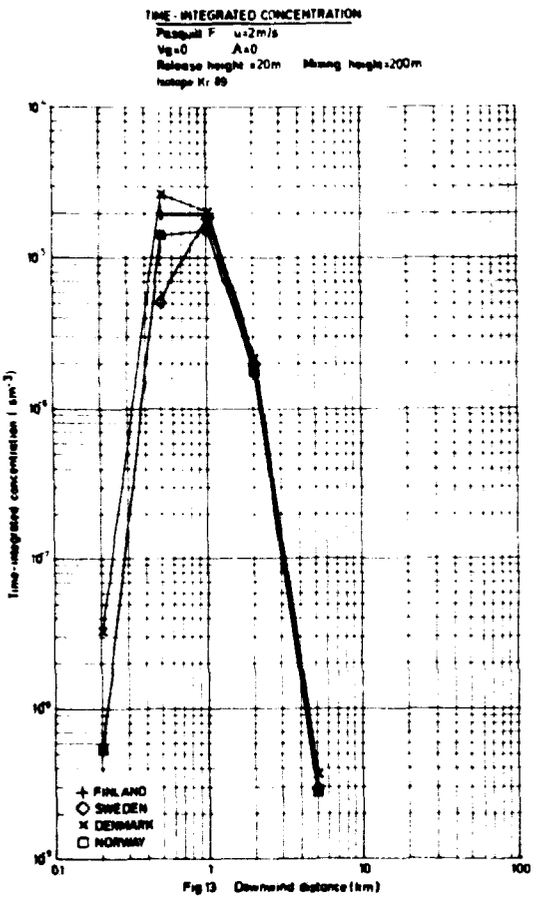
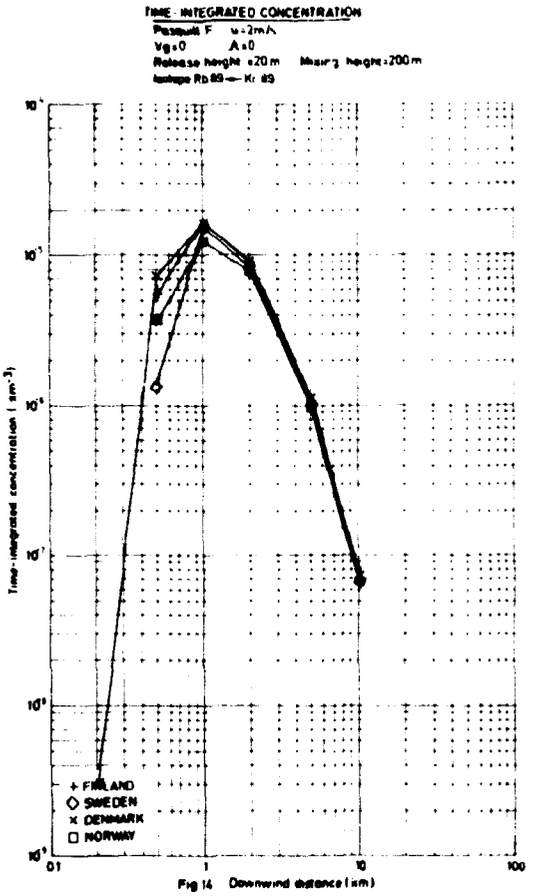


Fig 13



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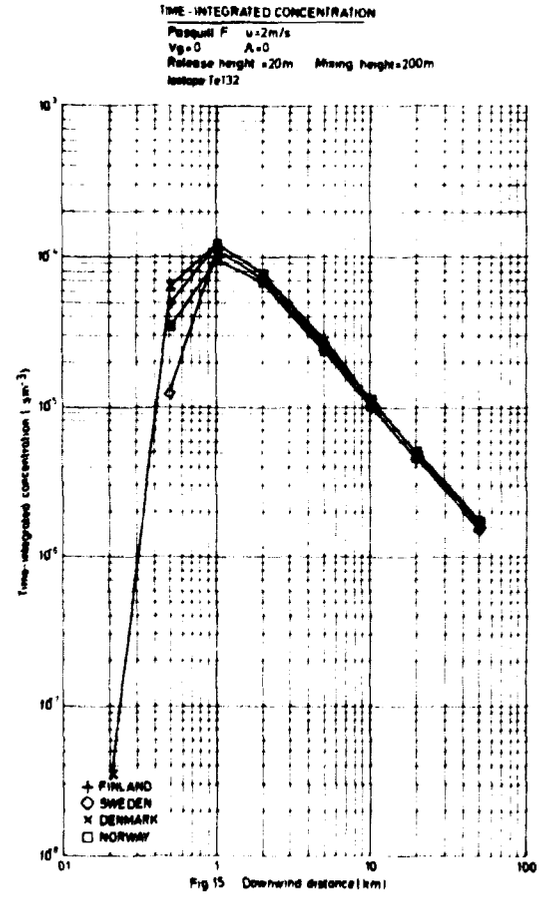


Fig 15

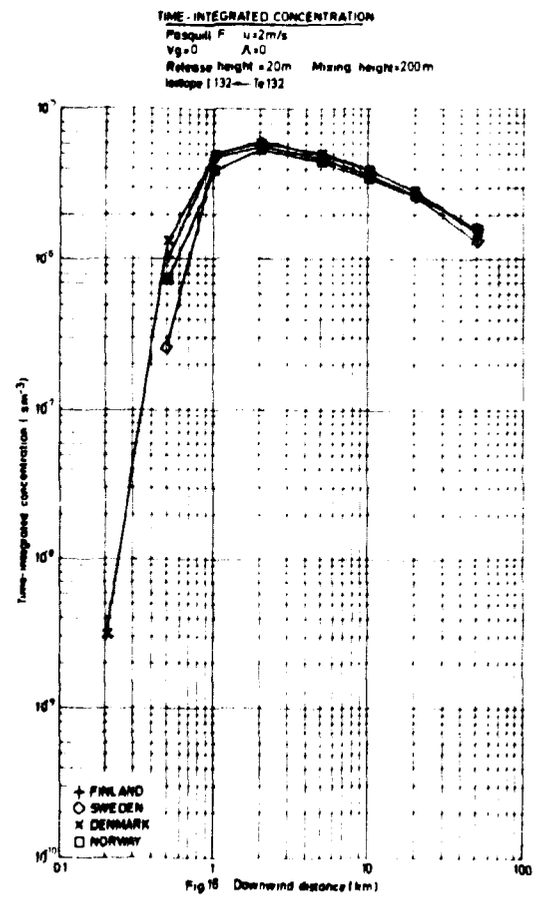


Fig 16

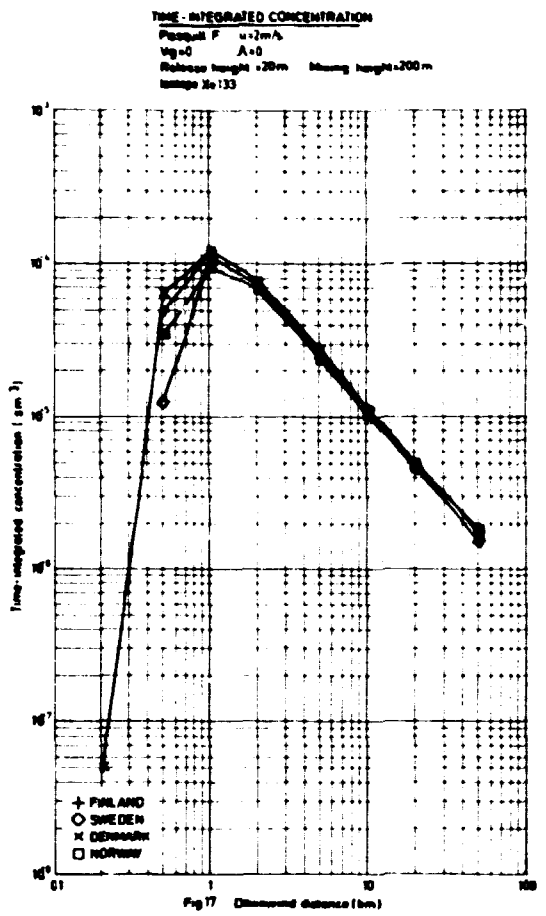
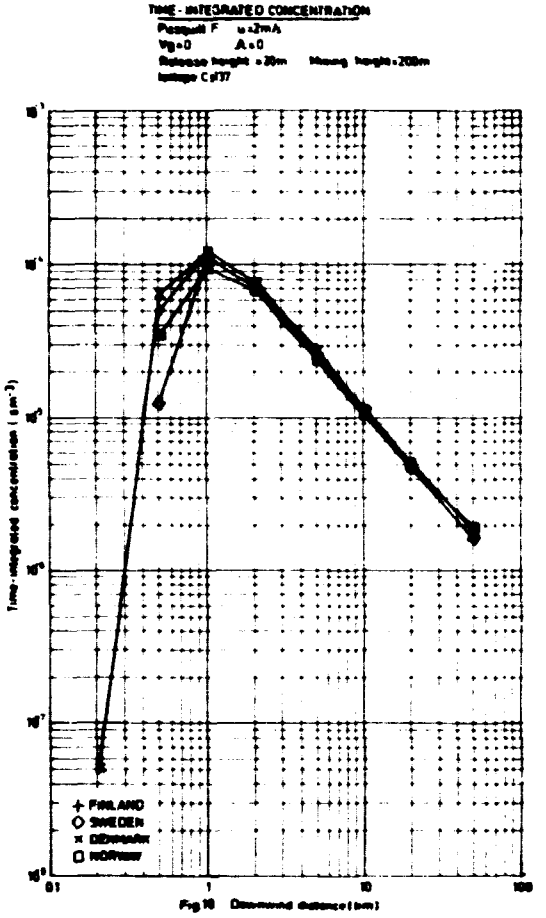


Fig 17



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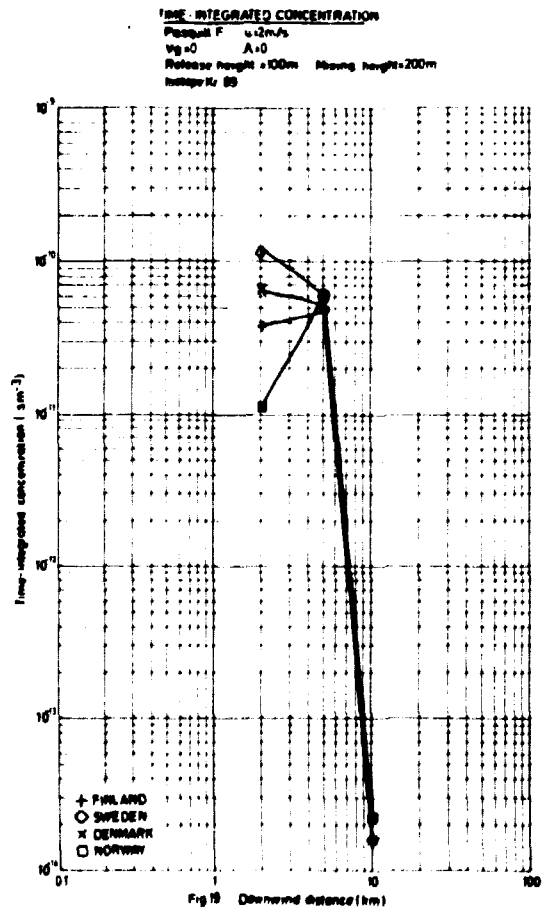

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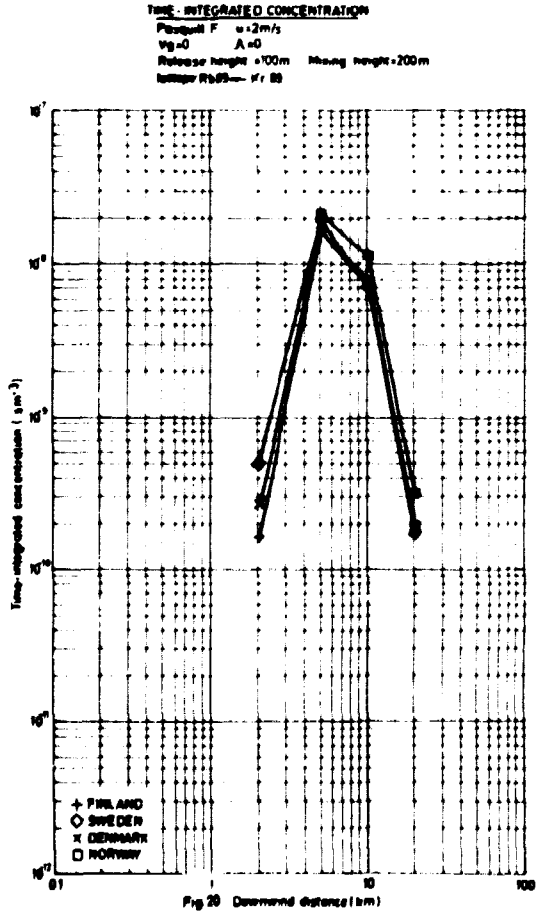

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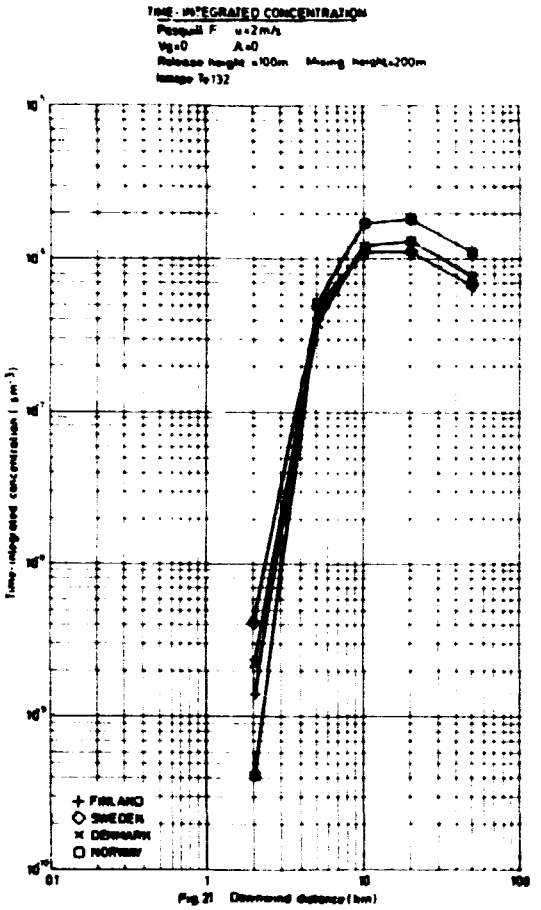

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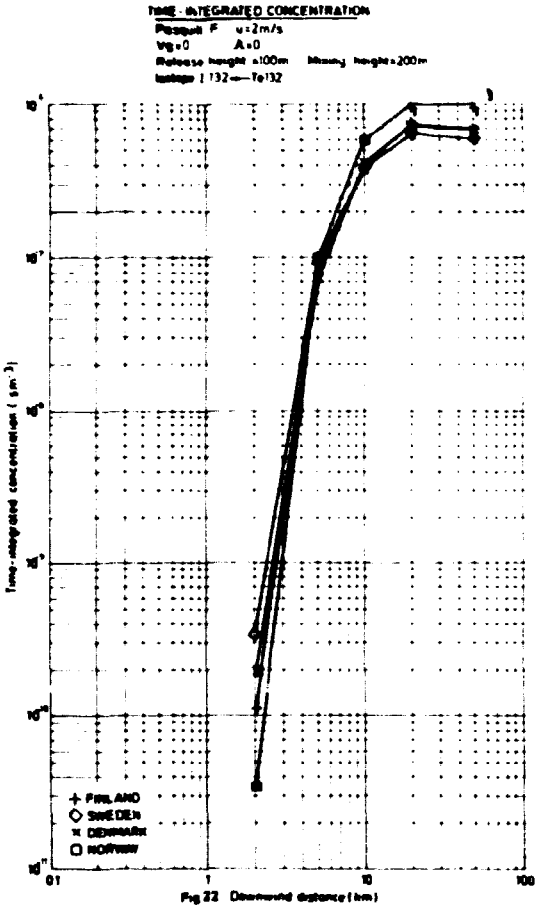

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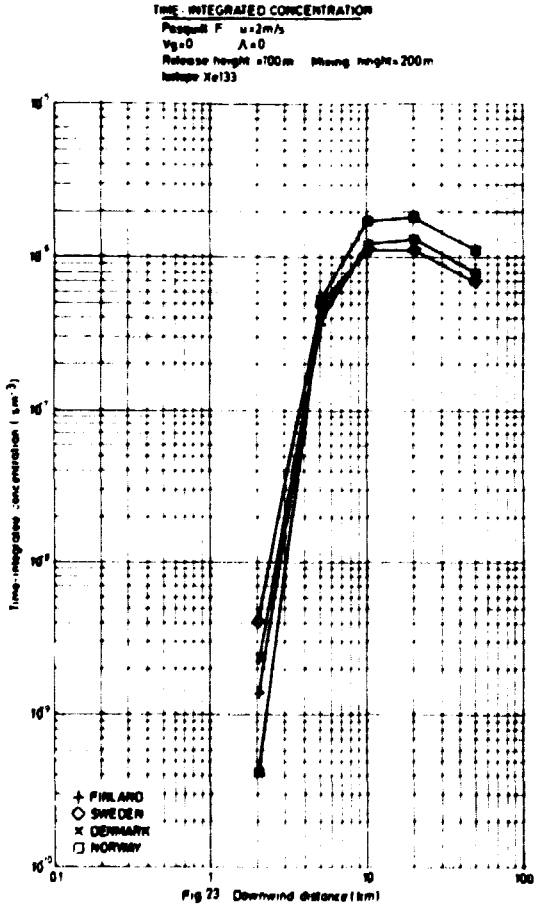


Fig 23

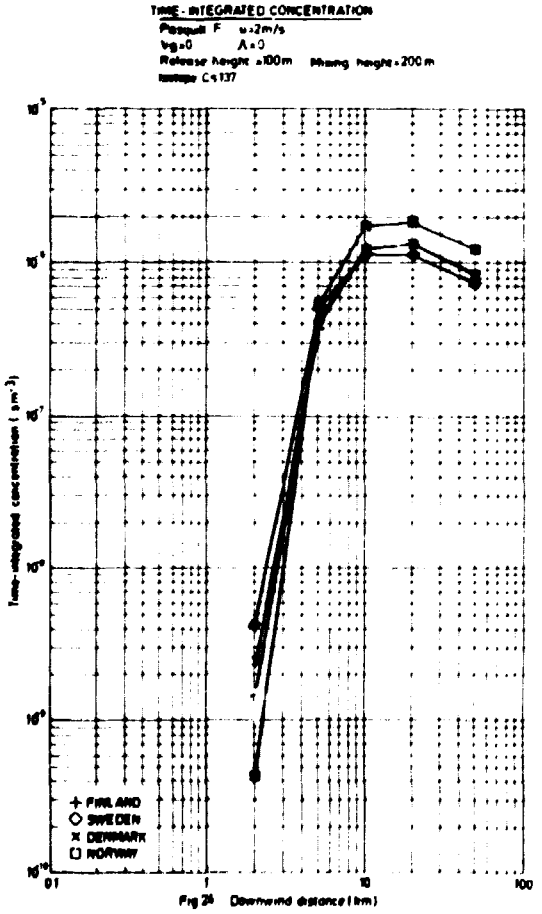


Fig 24

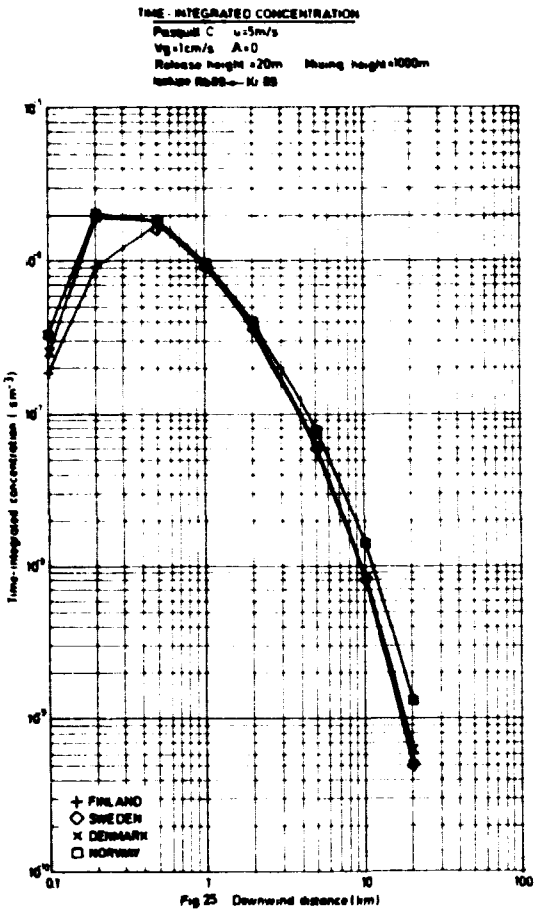


Fig 25 Downwind distance (km)

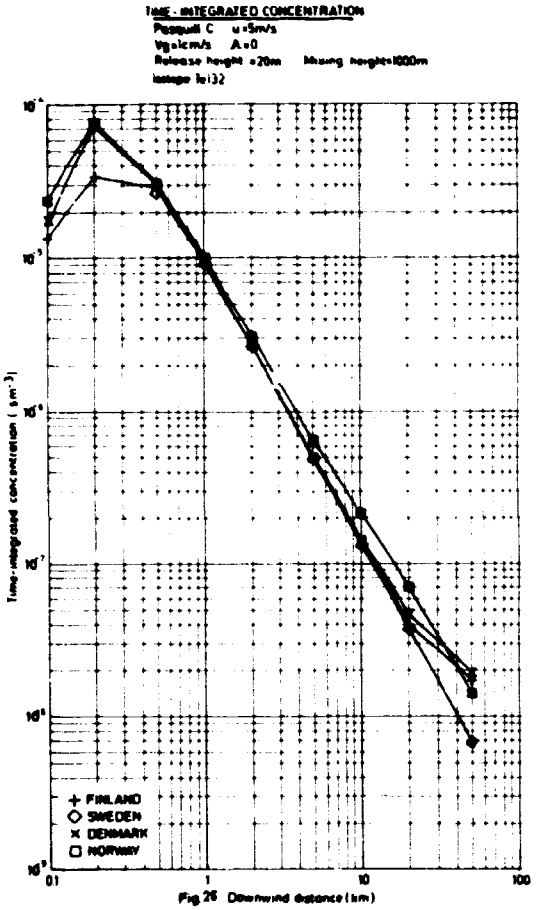
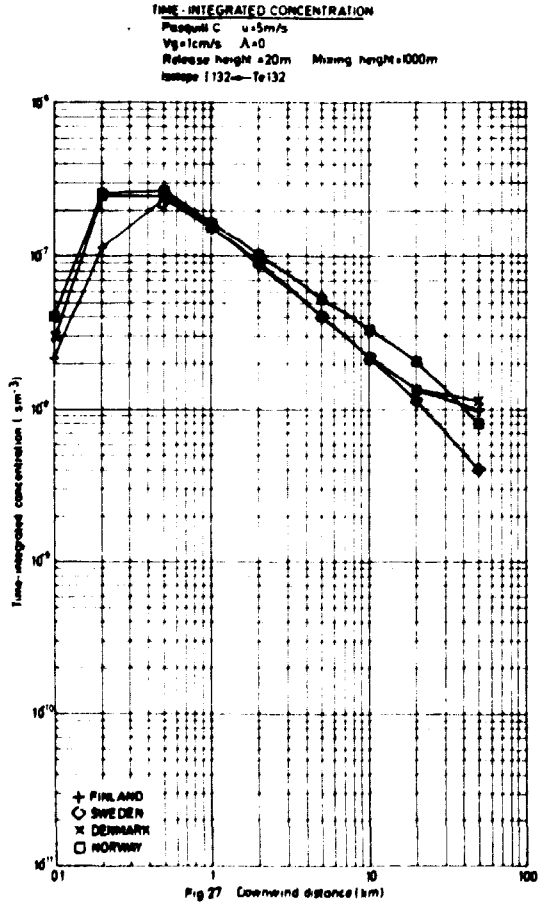


Fig 26 Downwind distance (km)



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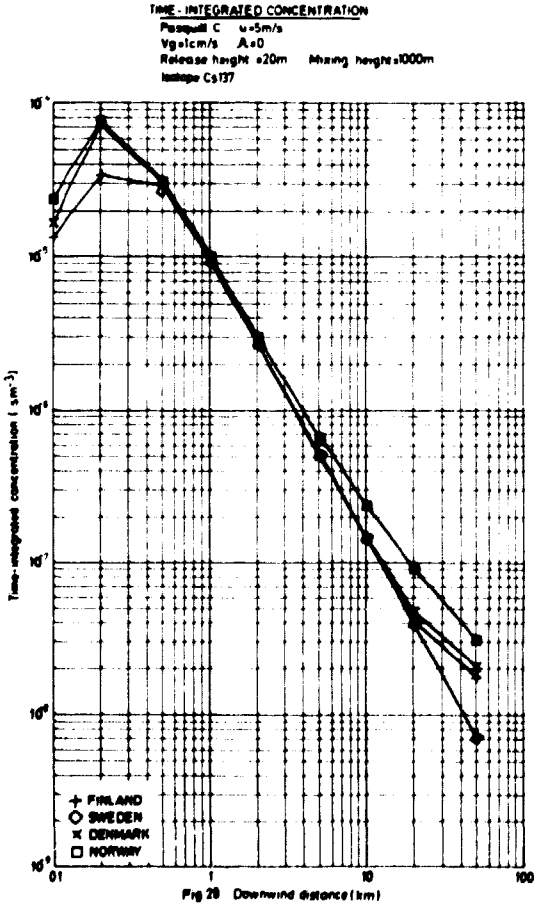
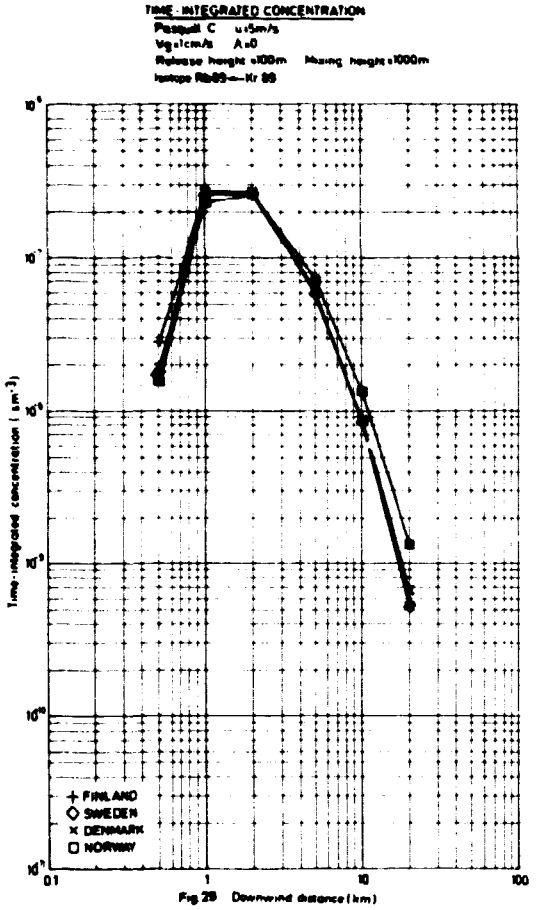


Fig 28 Downwind distance (km)



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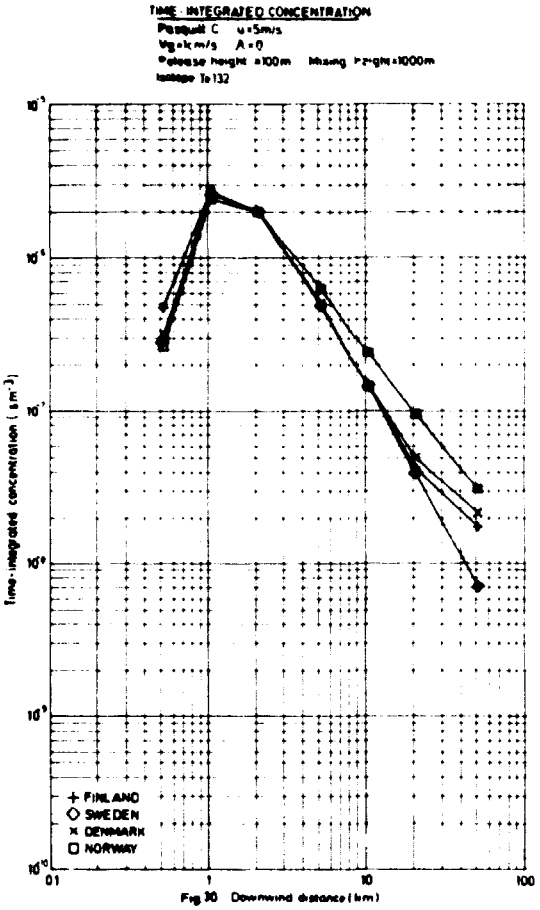


Fig 30 Downwind distance (km)

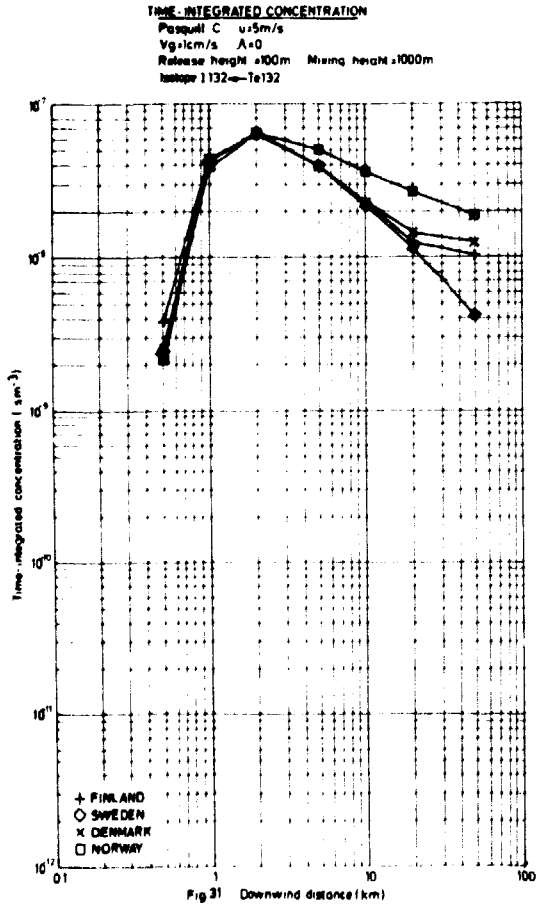


Fig 31 Downwind distance (km)

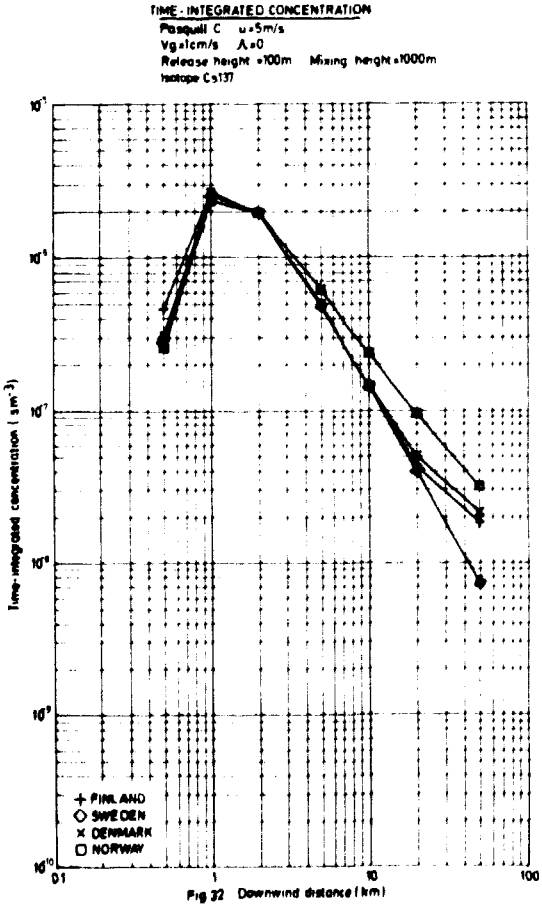


Fig 32 Downwind distance (km)

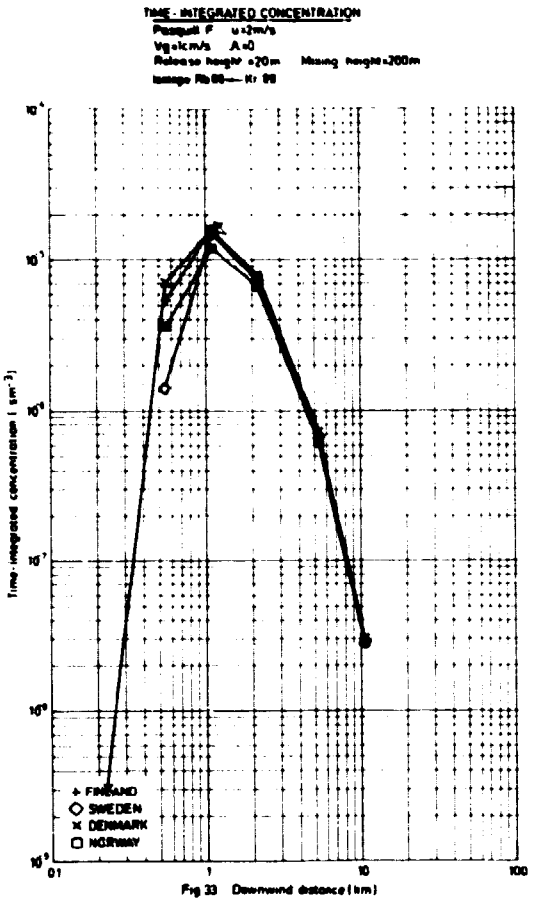


Fig 33 Downwind distance (km)

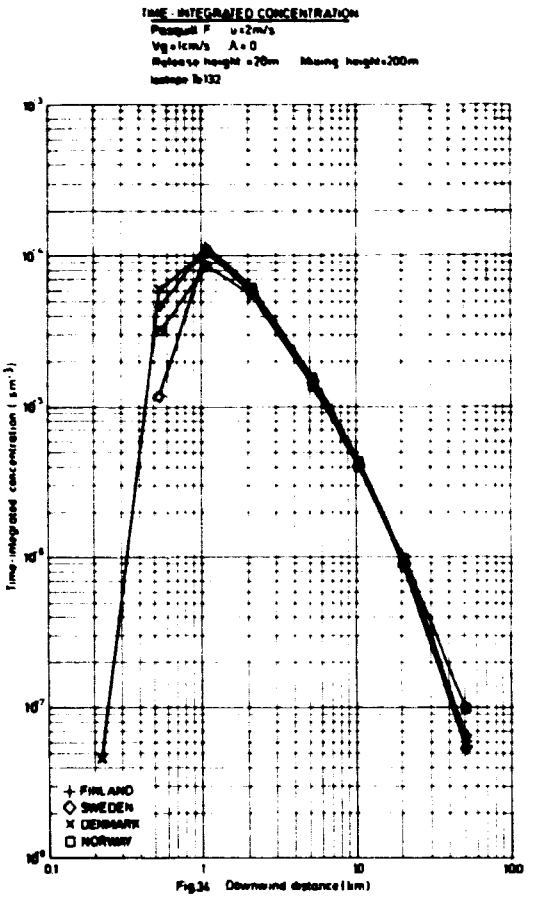


Fig.34 Downwind distance (km)

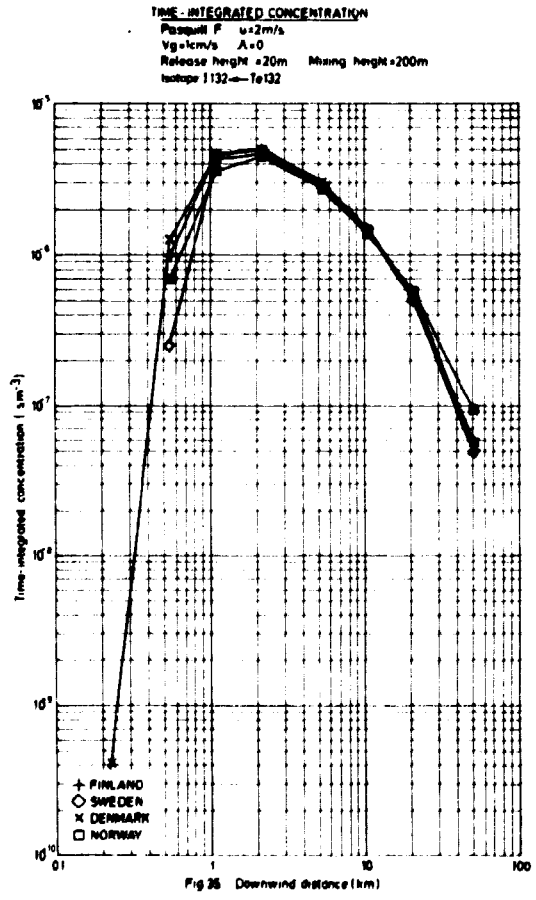


Fig 35 Downwind distance (km)

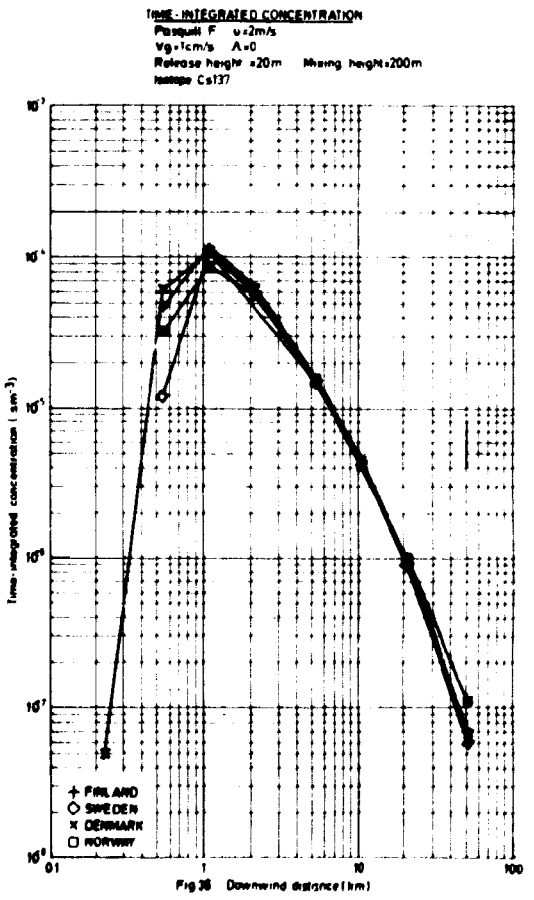
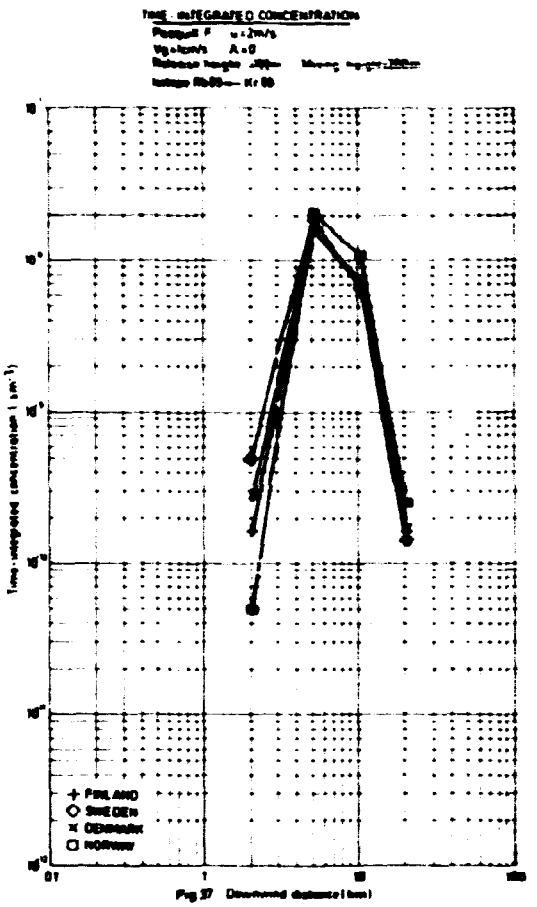
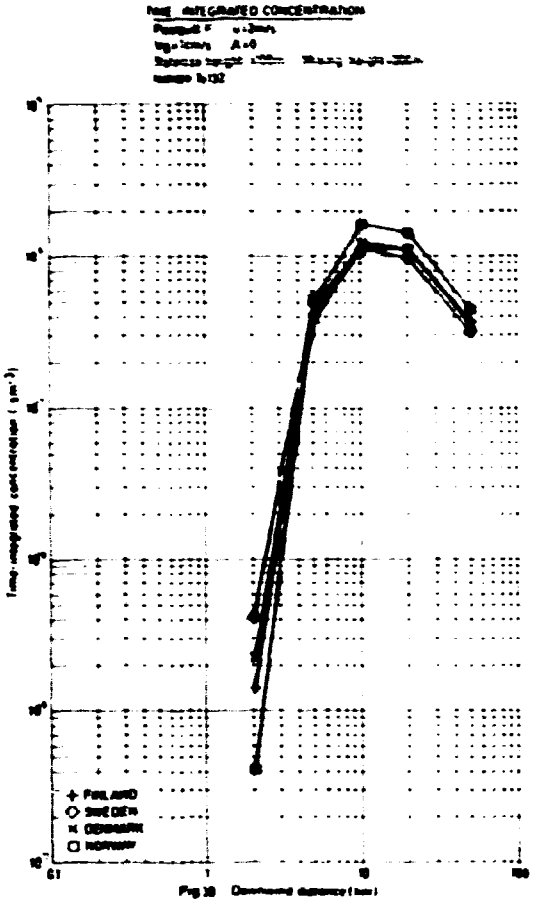


Fig 36 Downwind distance (km)


+ FINLAND
◇ SWEDEN
× DENMARK
□ NORWAY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◇ SWEDEN
× DENMARK
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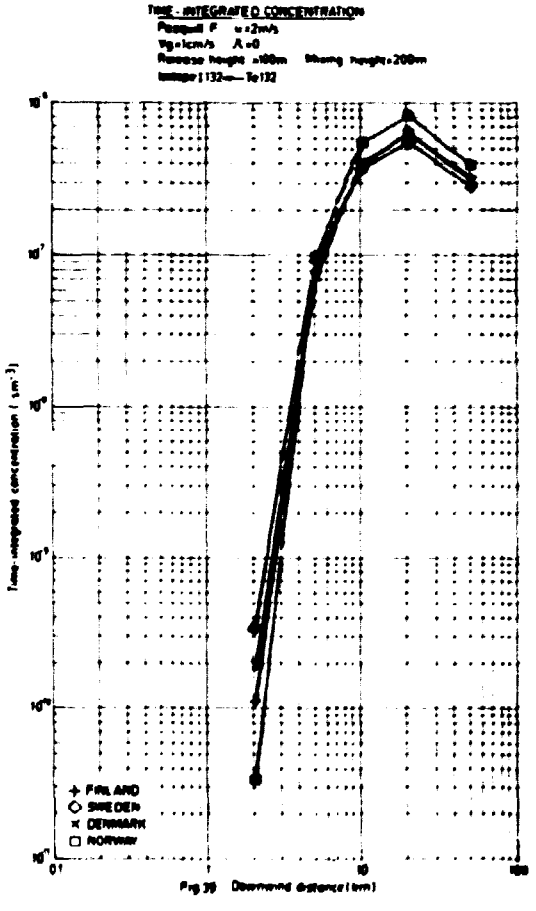
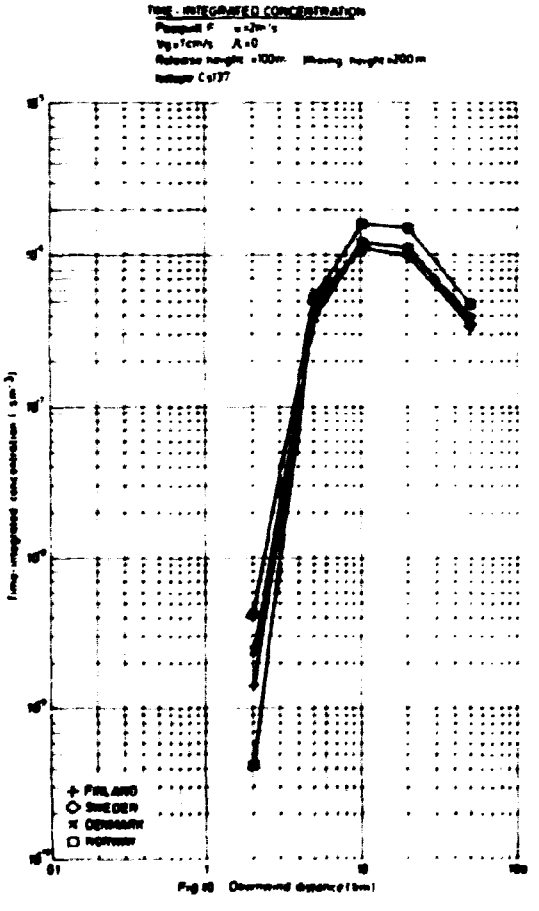

+ FINLAND
◇ SWEDEN
× DENMARK
□ NORWAY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× DENMARK
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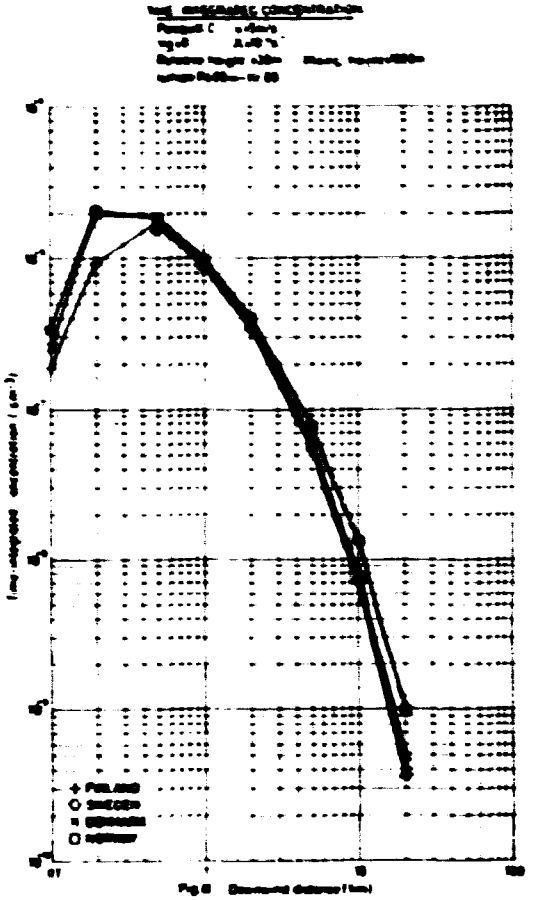
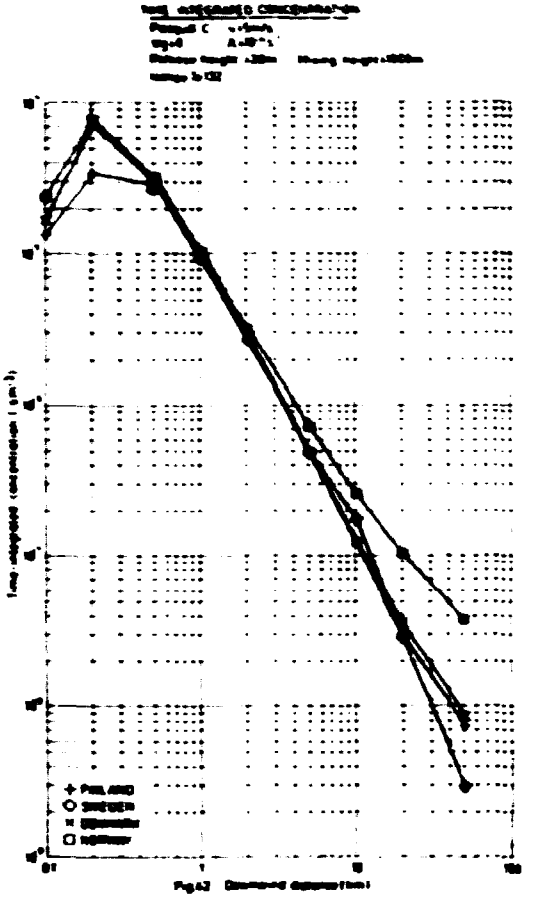
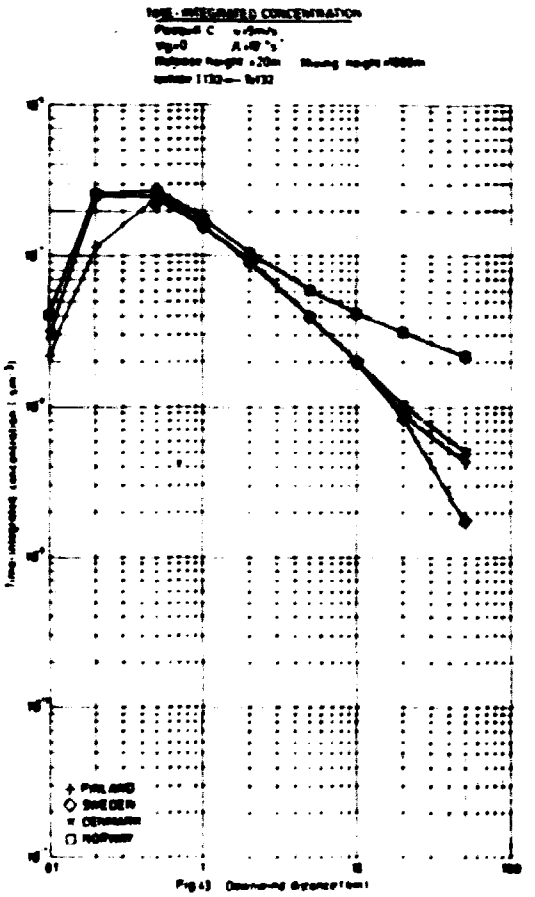
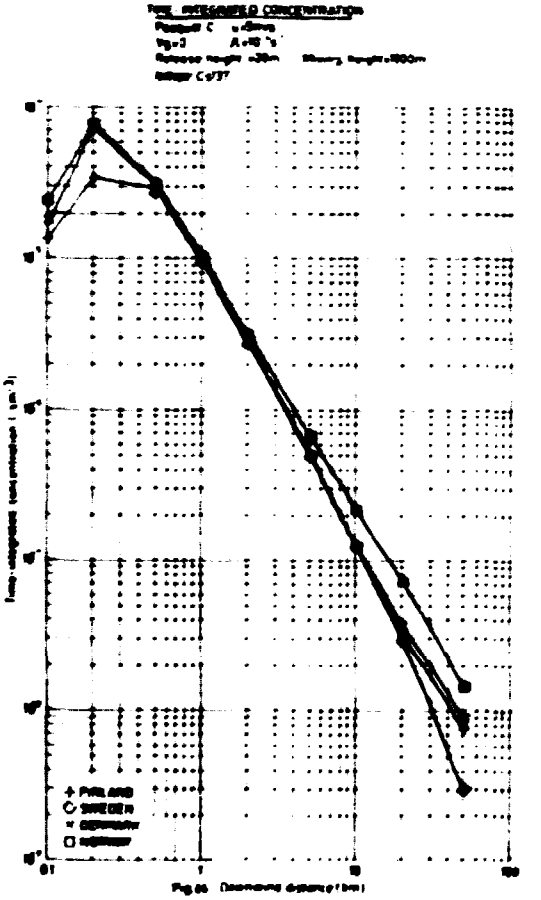








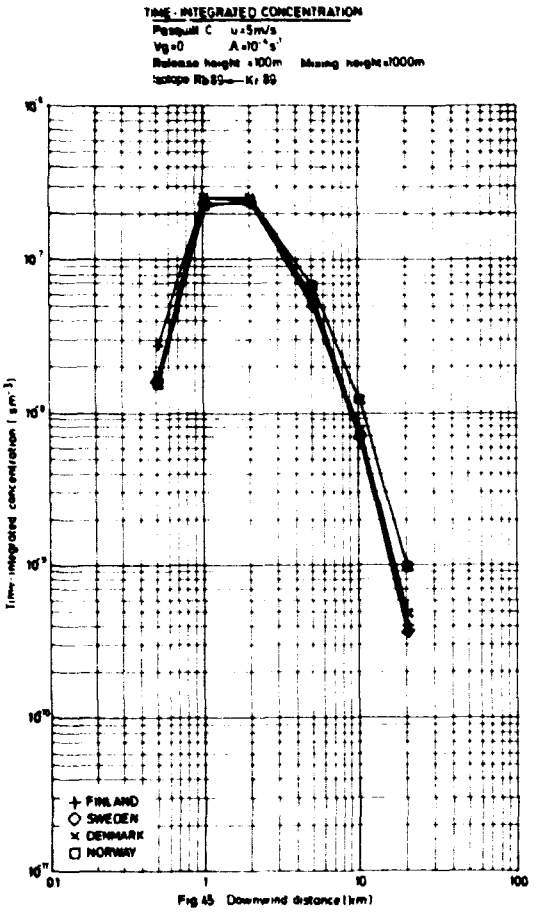


Fig 45 Downwind distance (km)

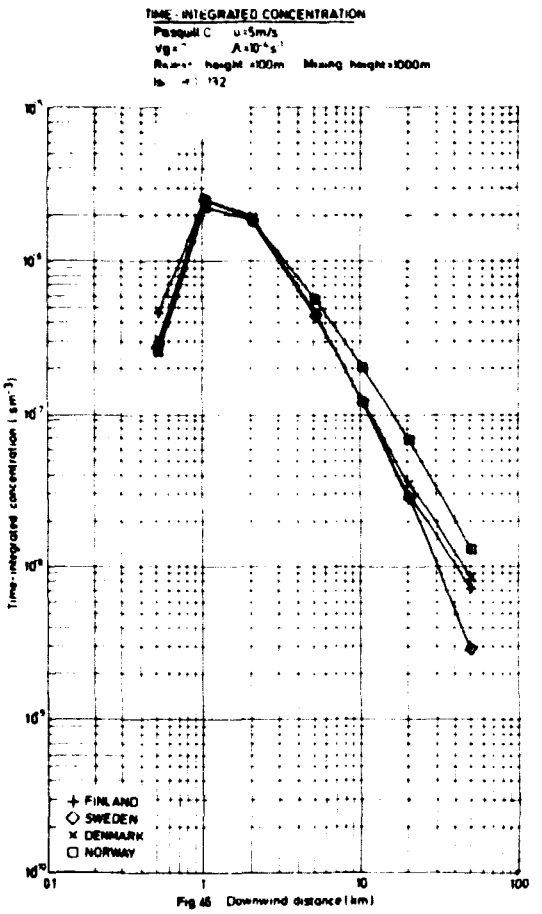


Fig 46 Downwind distance (km)

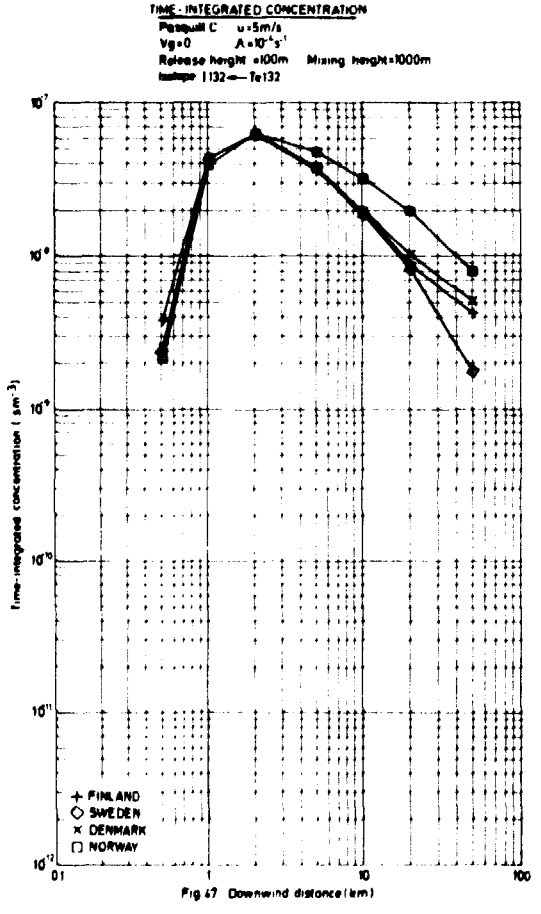


Fig 47 Downwind distance (km)

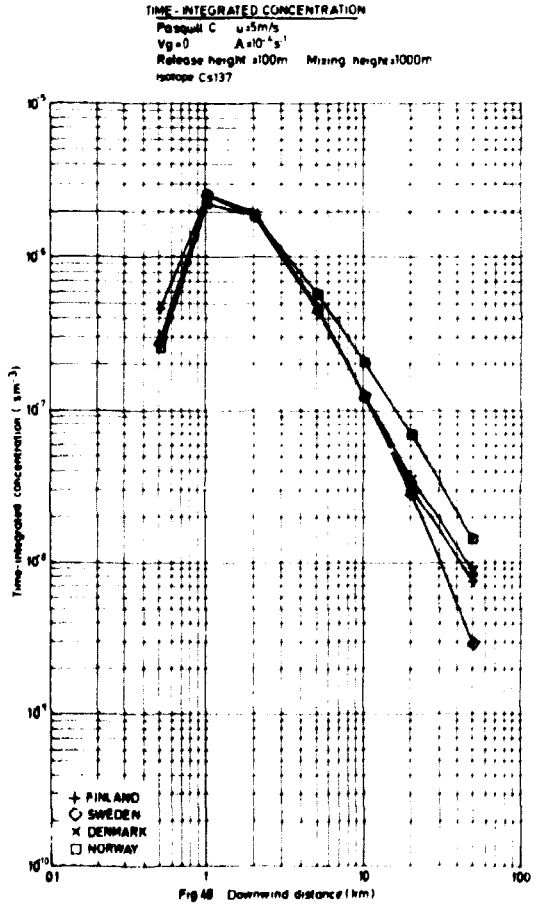


Fig 48 Downwind distance (km)

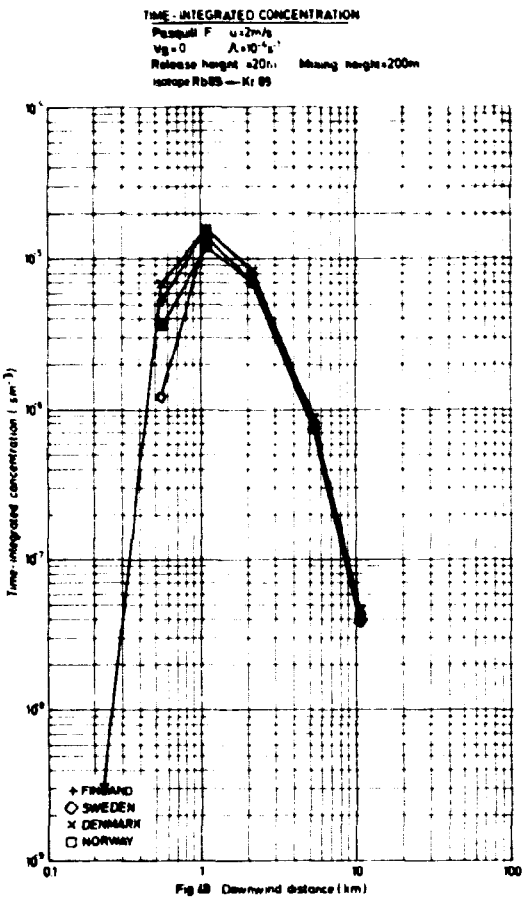


Fig 49 Downwind distance (km)

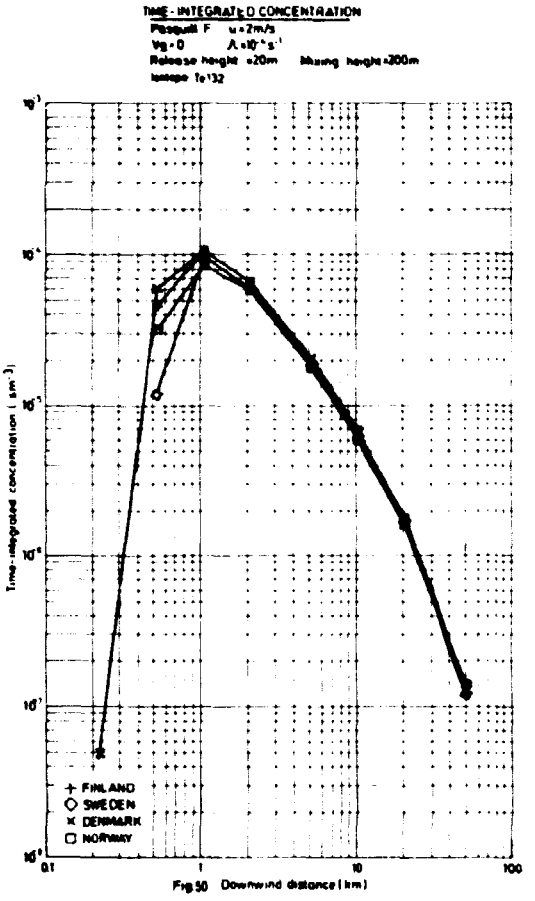


Fig 50 Downwind distance (km)

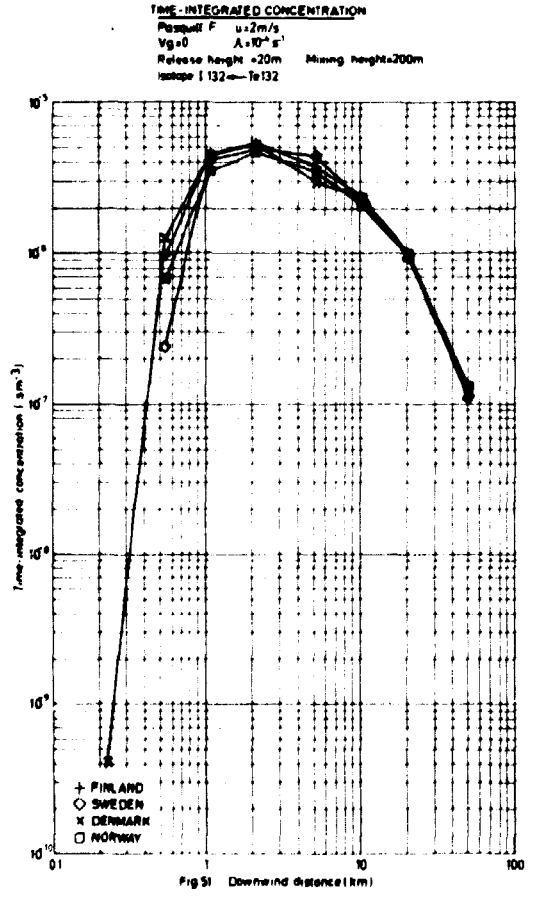


Fig 51 Downwind distance (km)

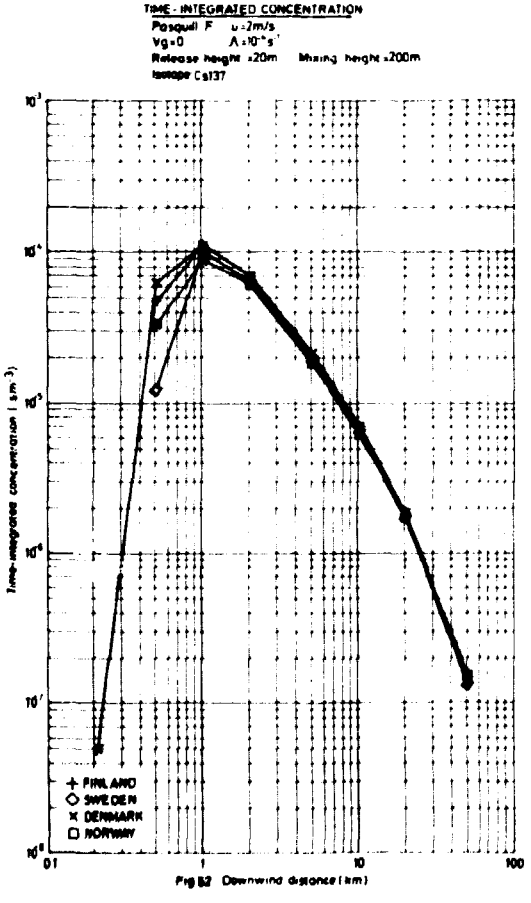


Fig 52 Downwind distance (km)

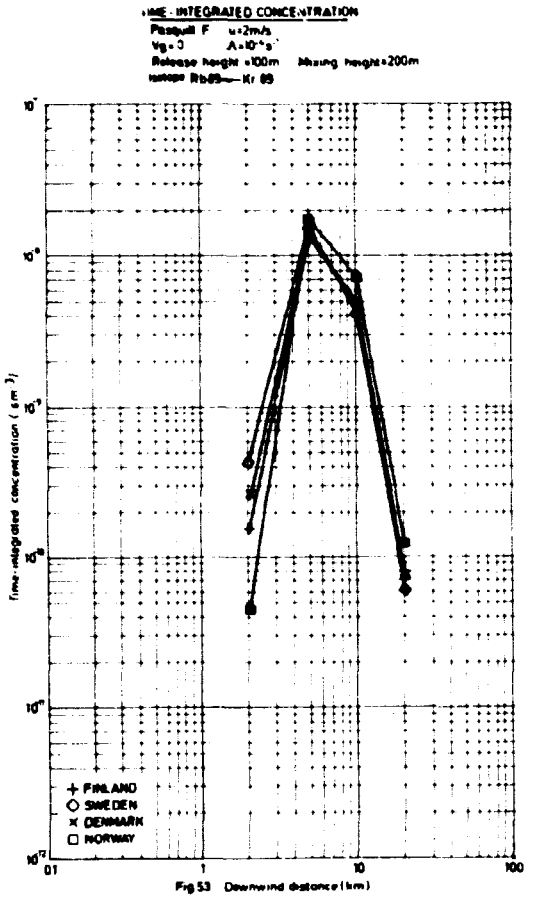


Fig 53 Downwind distance (km)

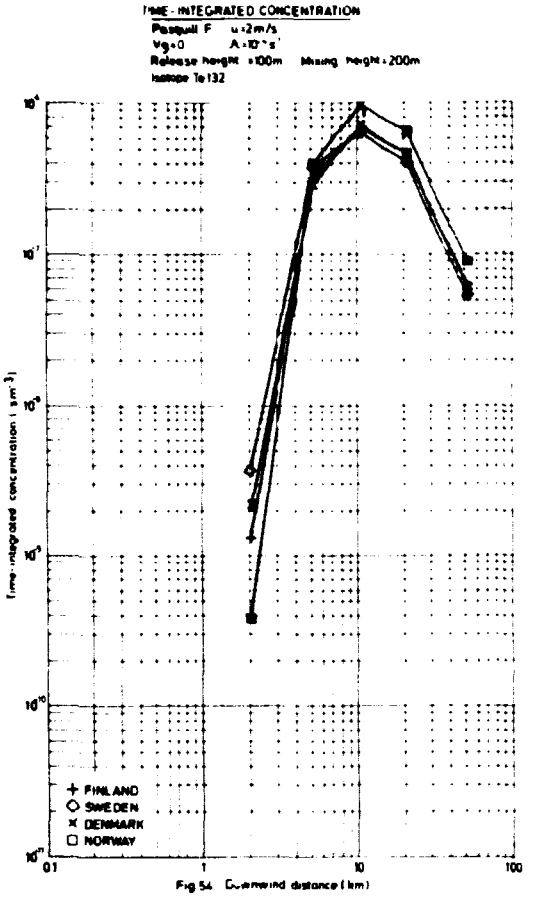


Fig 54 Downwind distance (km)

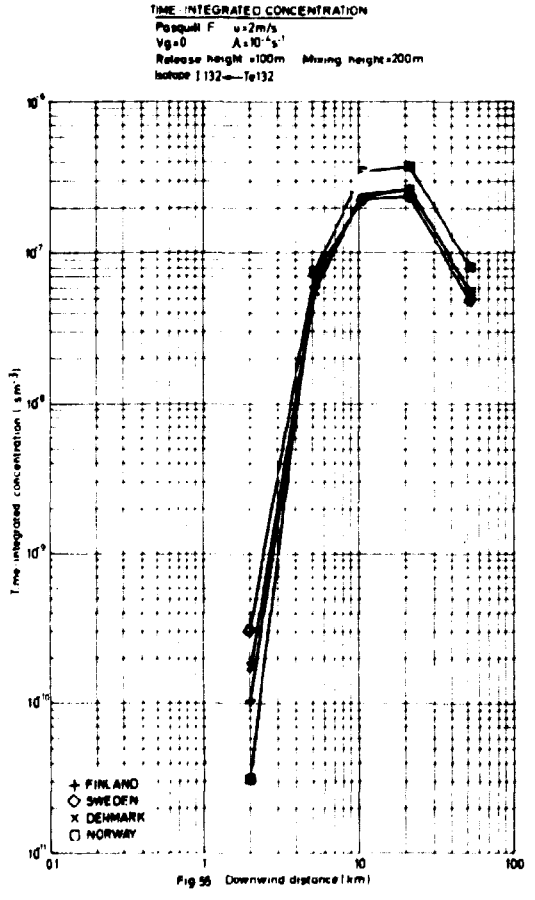


Fig 55 Downwind distance (km)

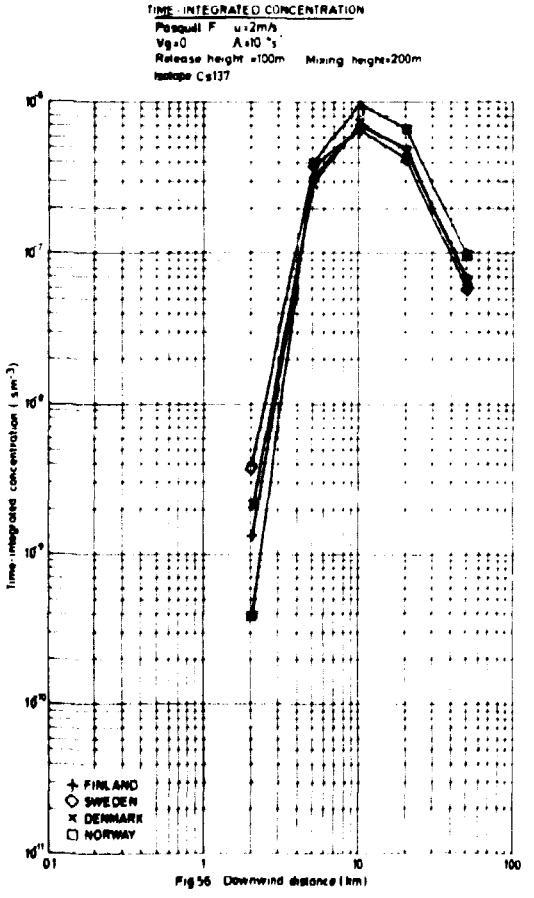


Fig 56 Downwind distance (km)

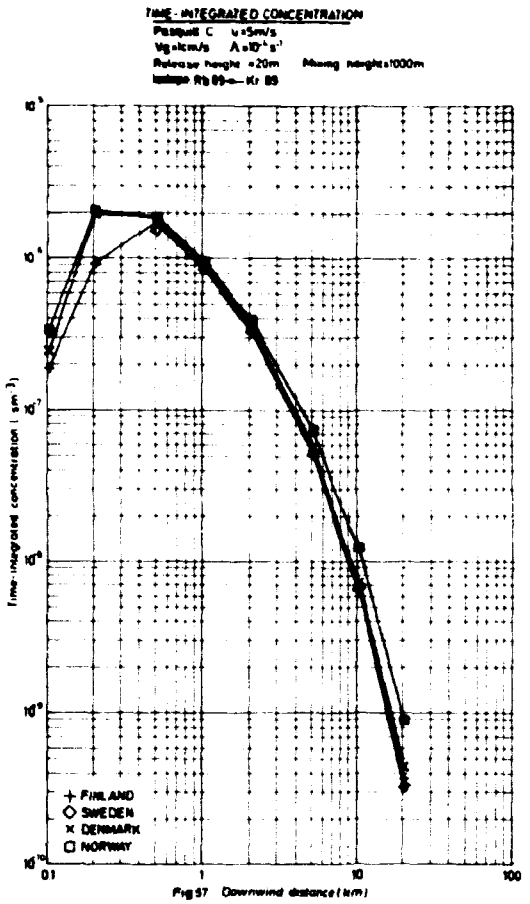


Fig 57 Downwind distance (km)

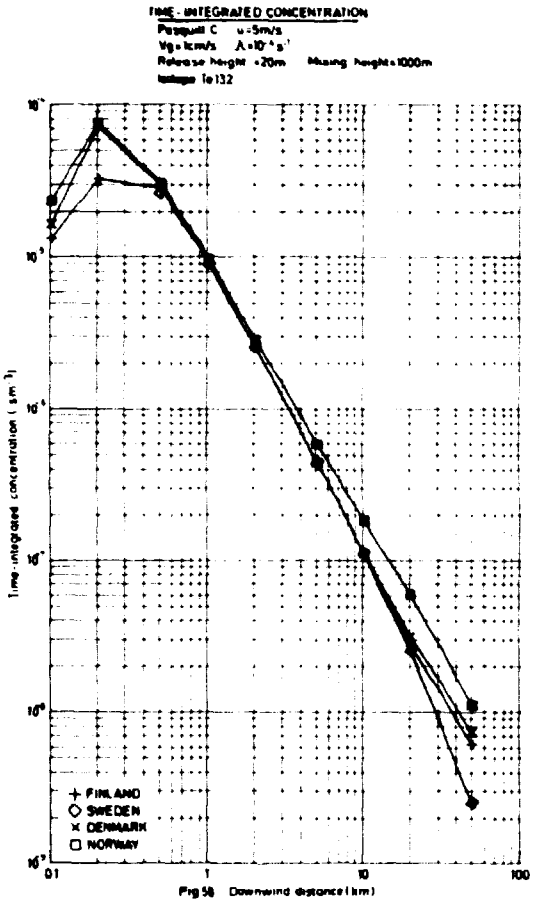


Fig 58 Downwind distance (km)

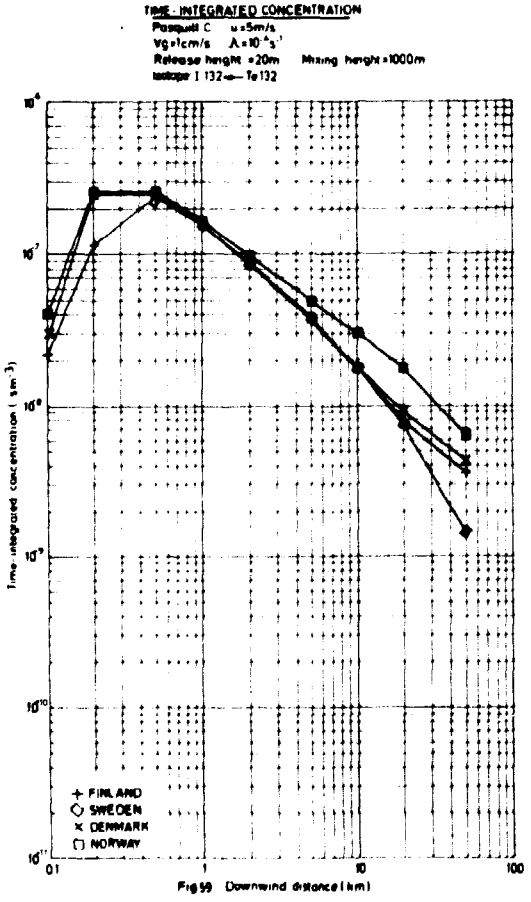


Fig 59 Downwind distance (km)

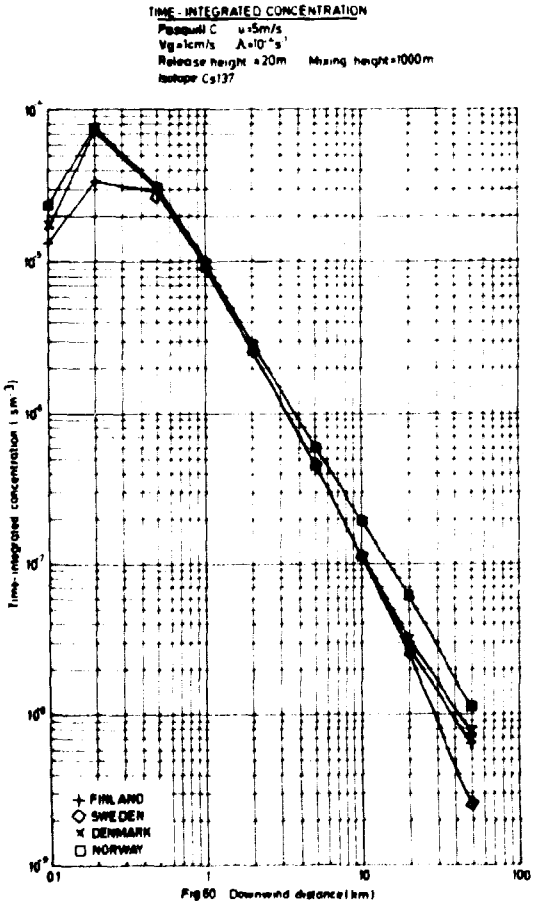


Fig 60 Downwind distance (km)

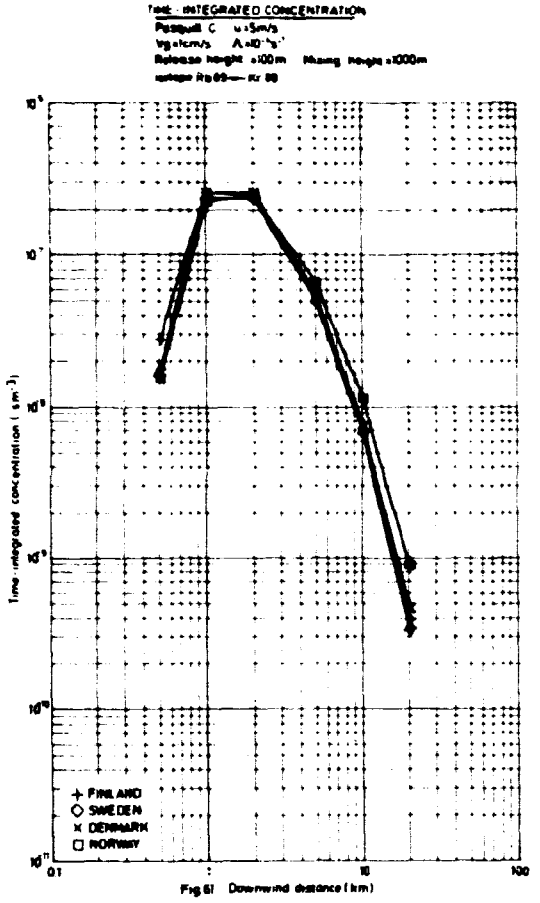


Fig 61 Downwind distance (km)

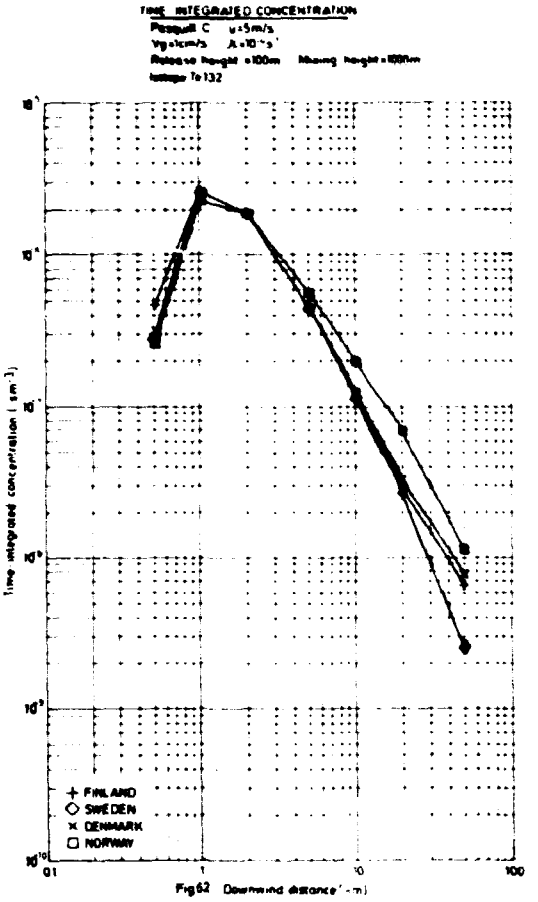


Fig 62 Downwind distance (km)

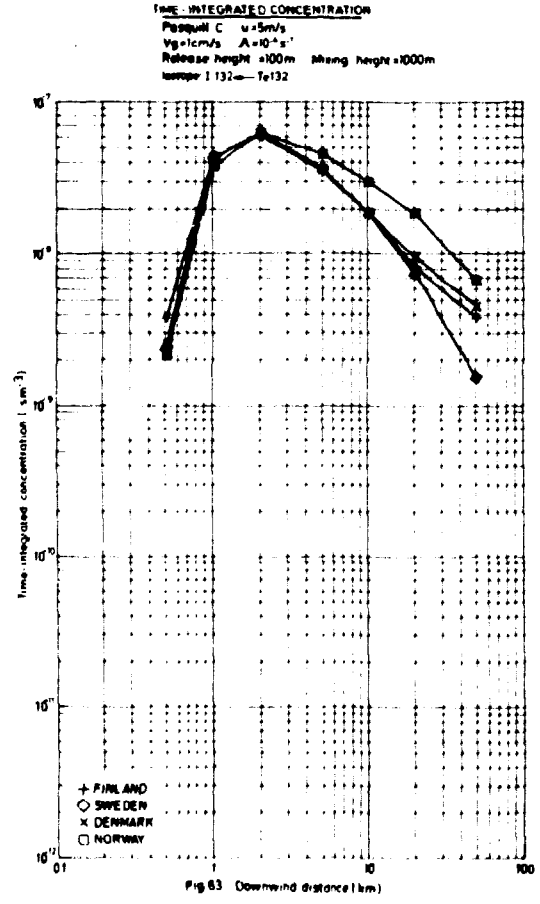


Fig 63 Downwind distance (km)

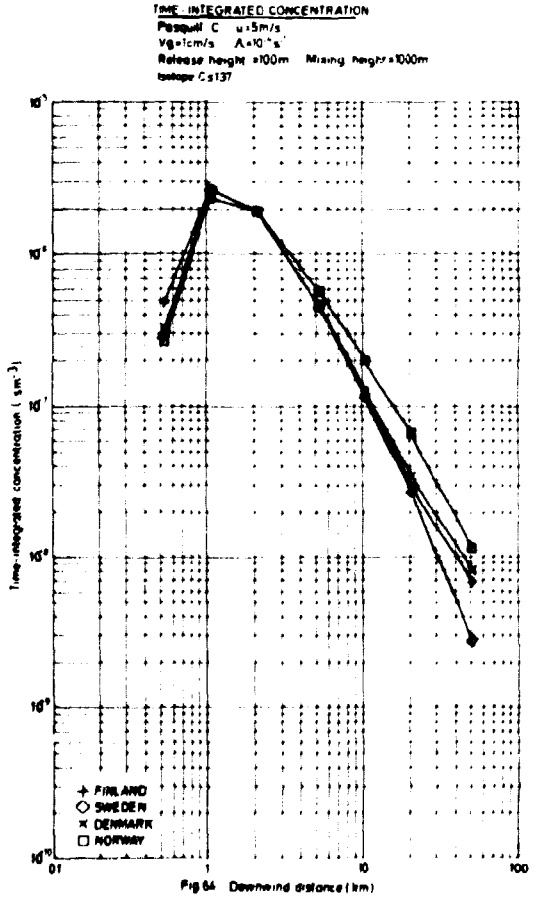


Fig 64 Downwind distance (km)

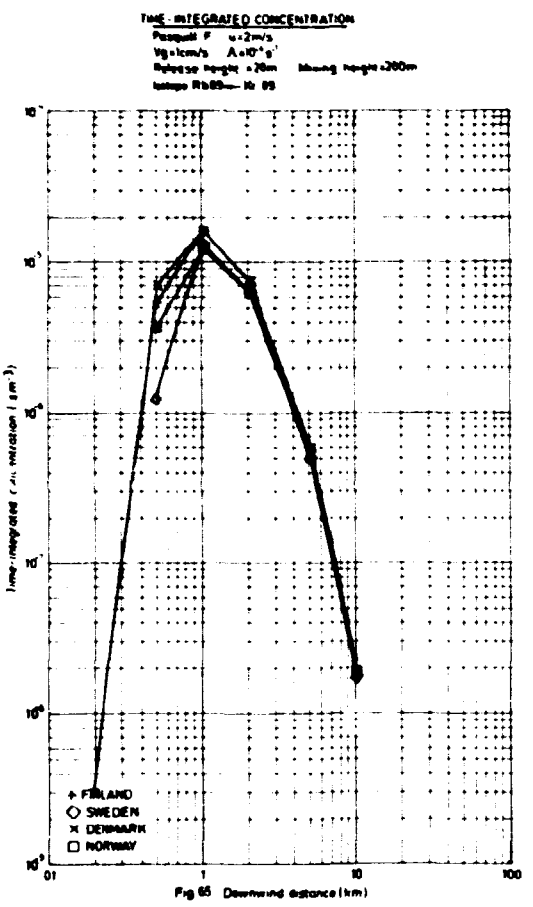


Fig 65

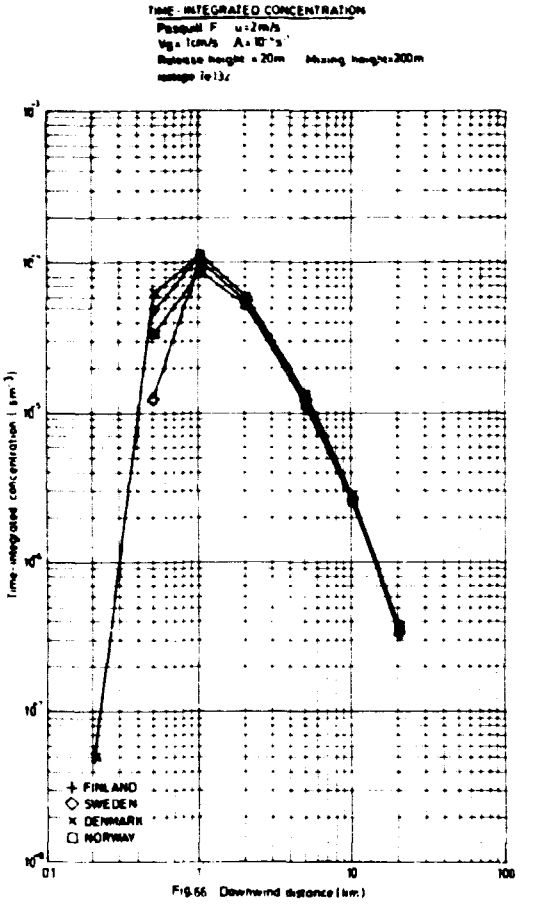


Fig 66

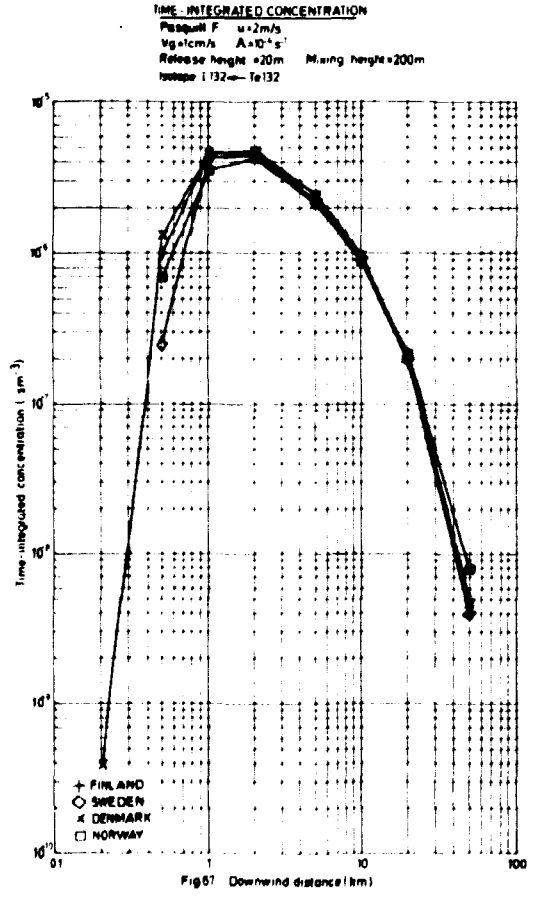


Fig 67

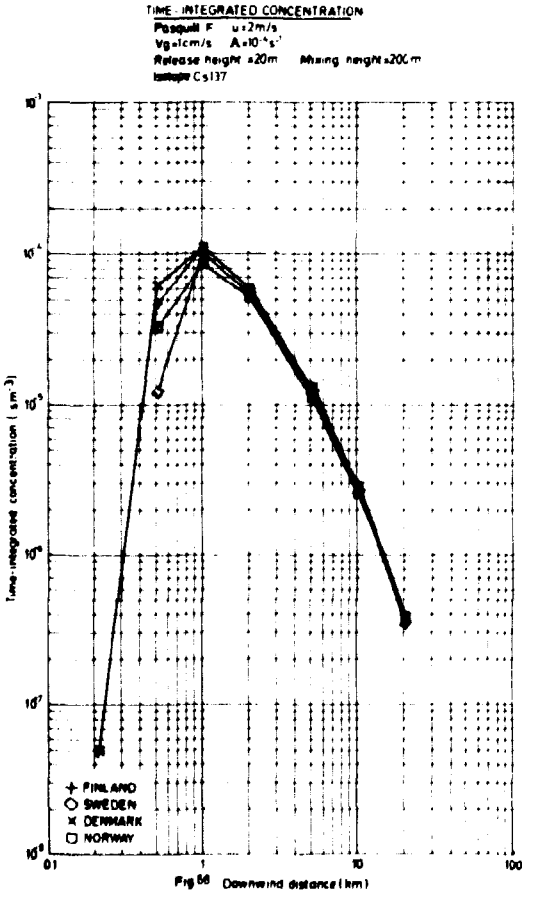


Fig 68

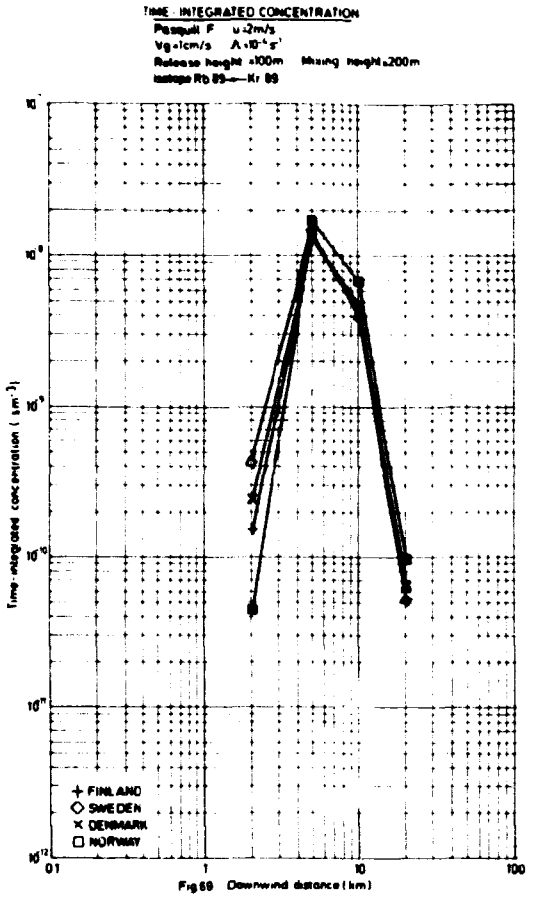


Fig 69

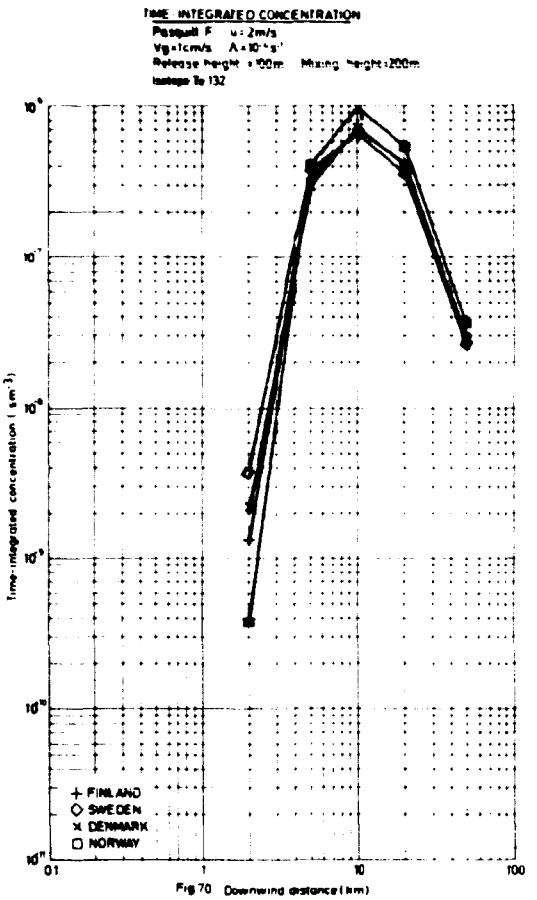


Fig 70

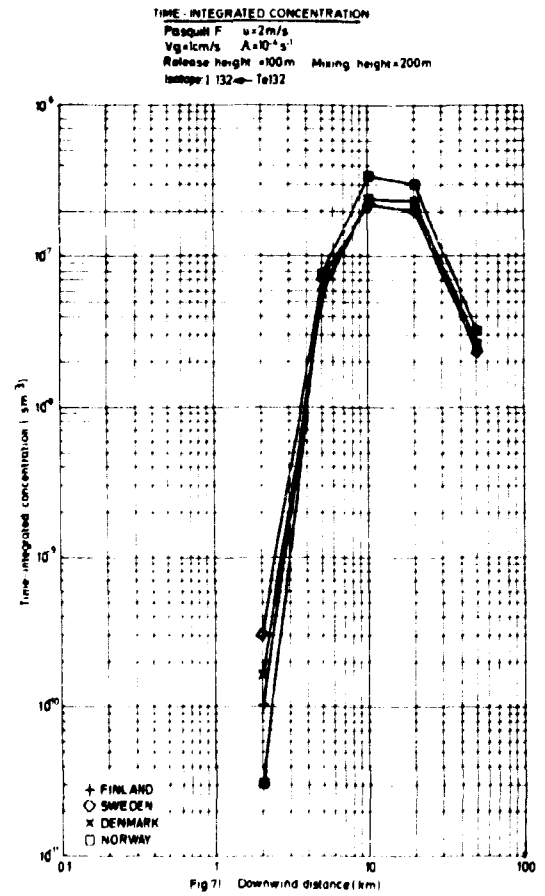


Fig 71

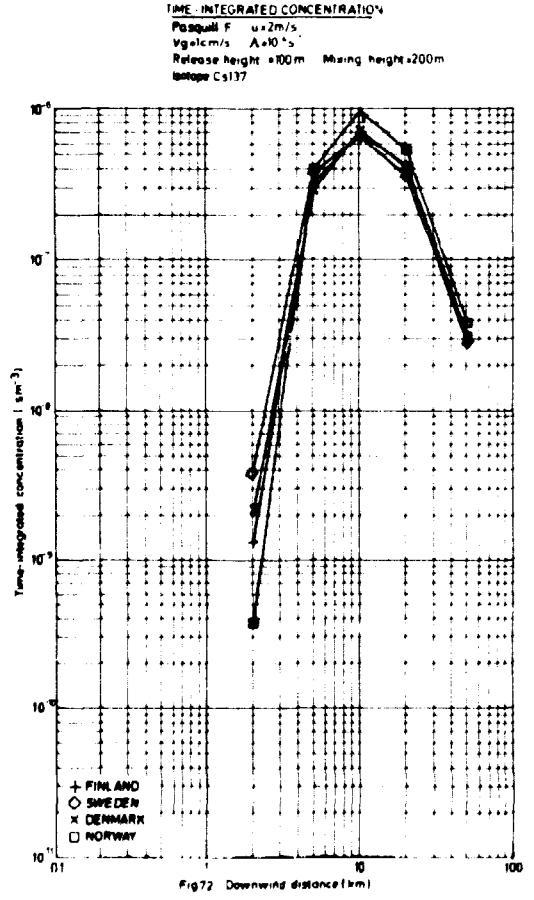


Fig 72

B. External gamma doses from a plume

Fig. 73 - 144

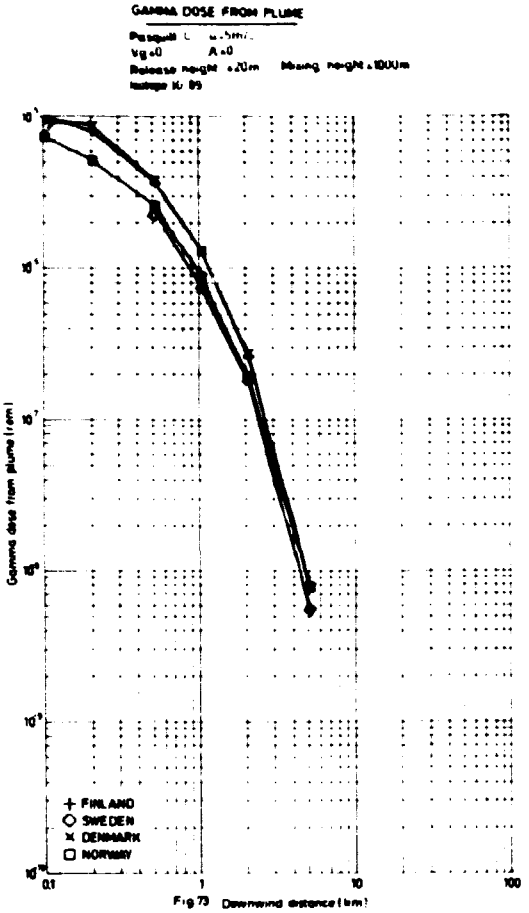


Fig 73 Downwind distance (km)

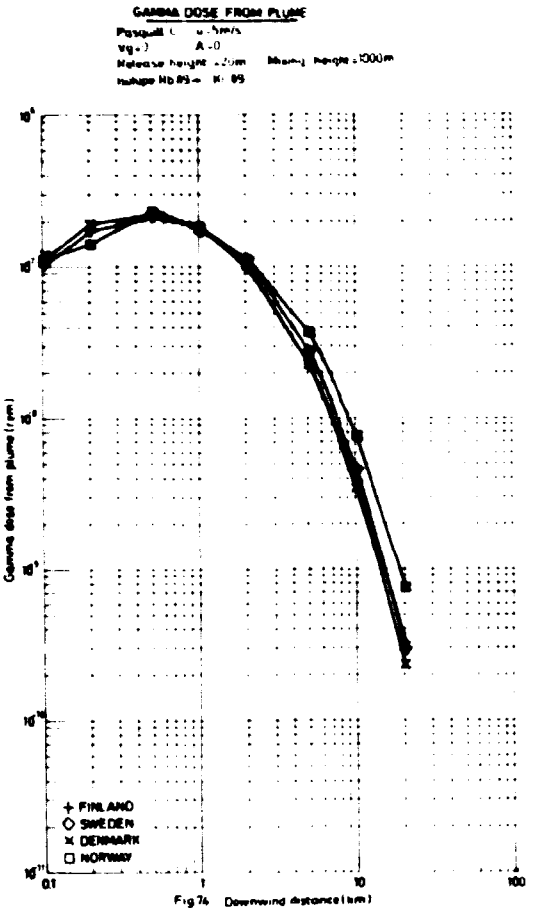


Fig 74 Downwind distance (km)

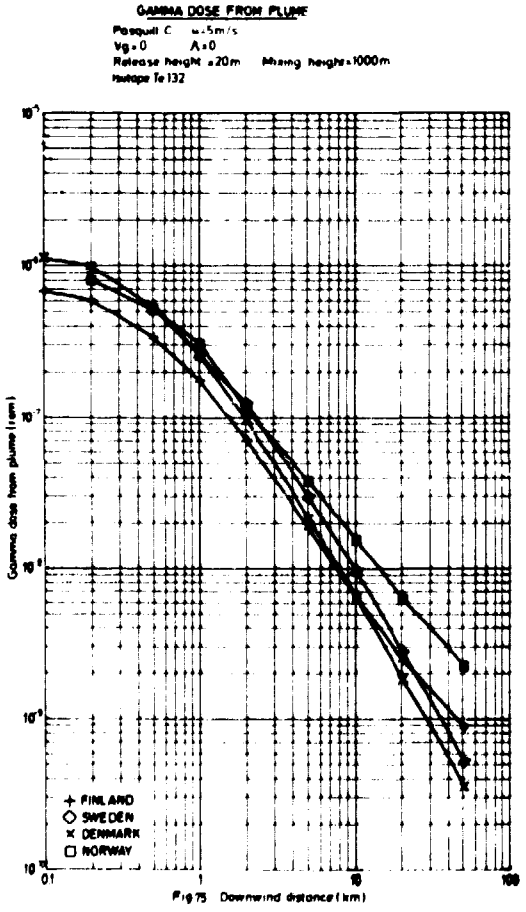


Fig 75 Downwind distance (km)

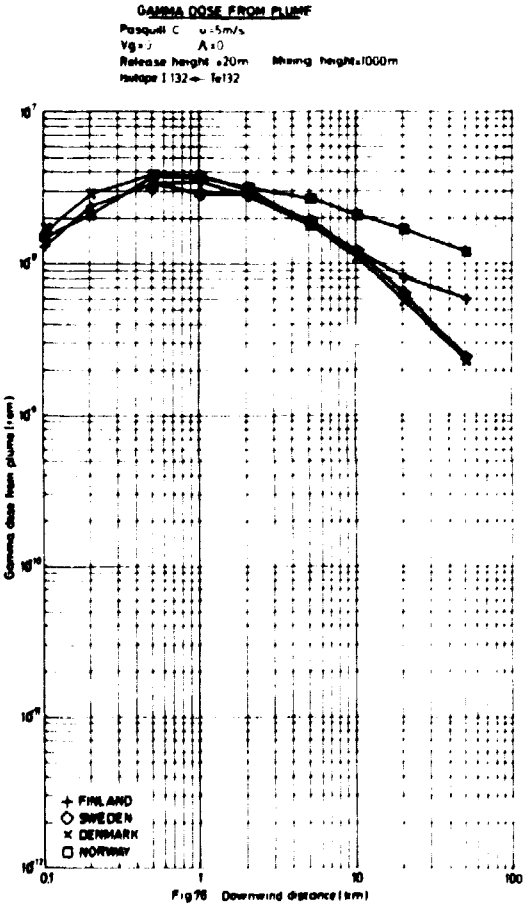


Fig 76 Downwind distance (km)

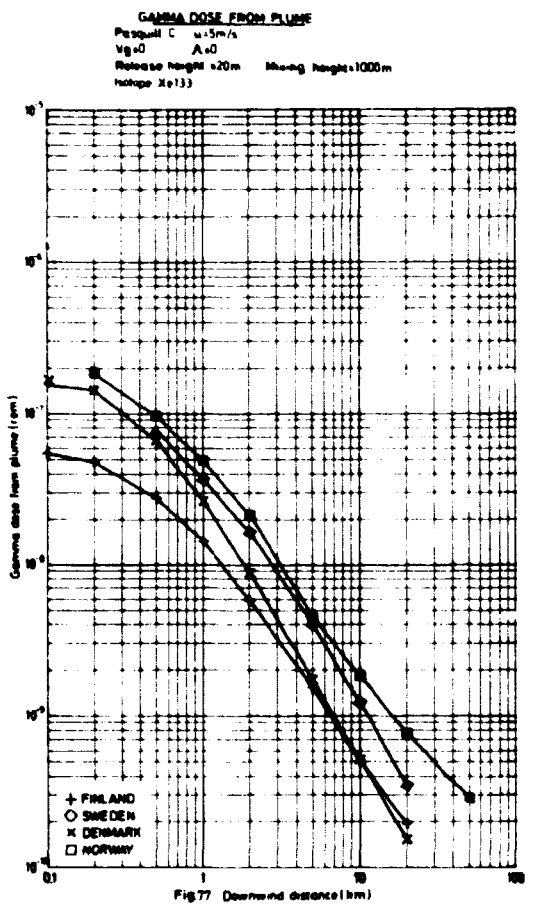


Fig 77 Downwind distance (km)

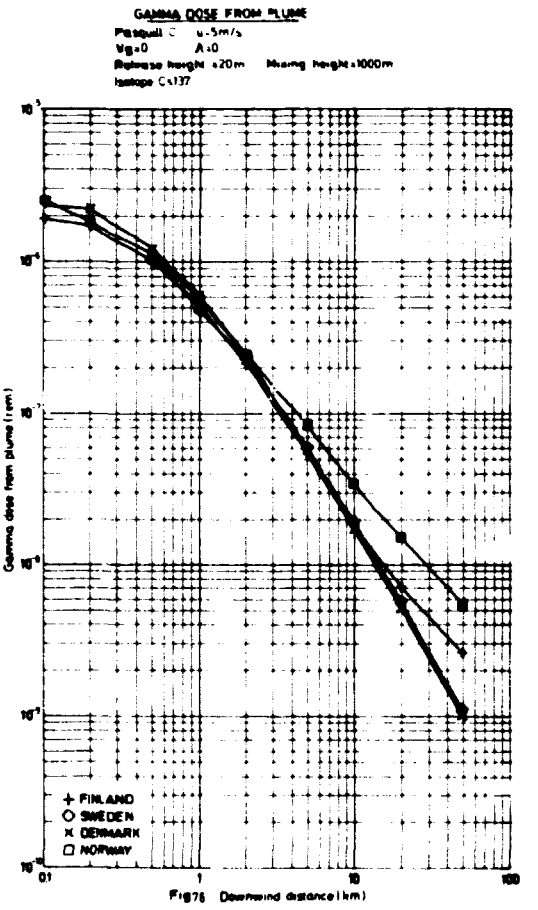


Fig 78 Downwind distance (km)

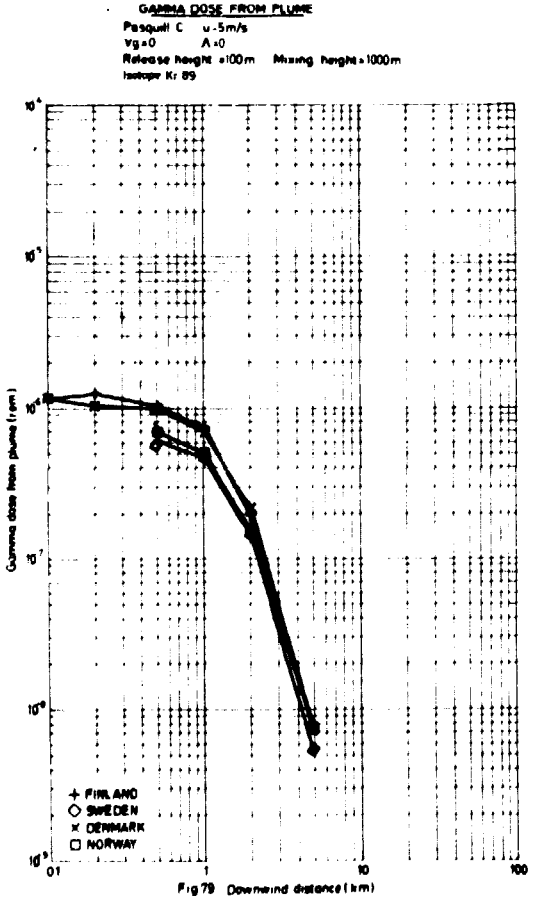


Fig 79 Downwind distance (km)

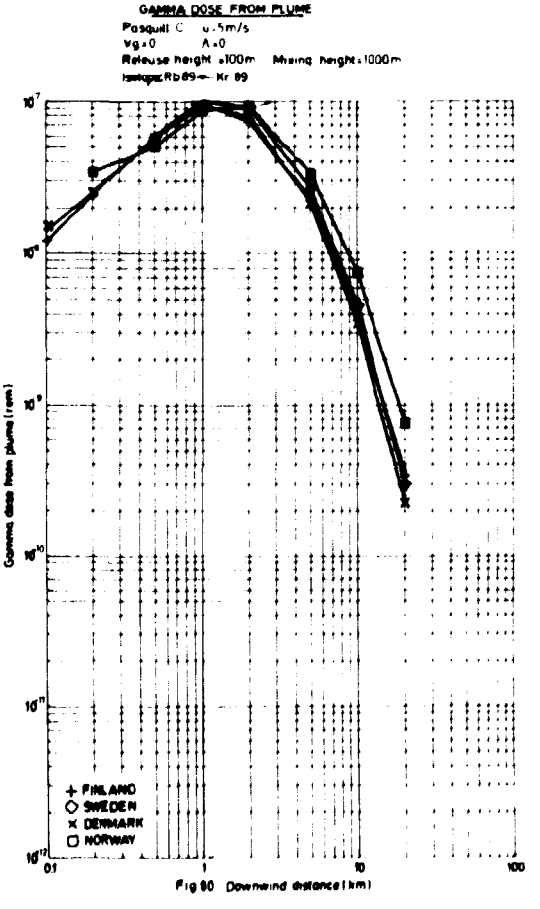


Fig 80 Downwind distance (km)

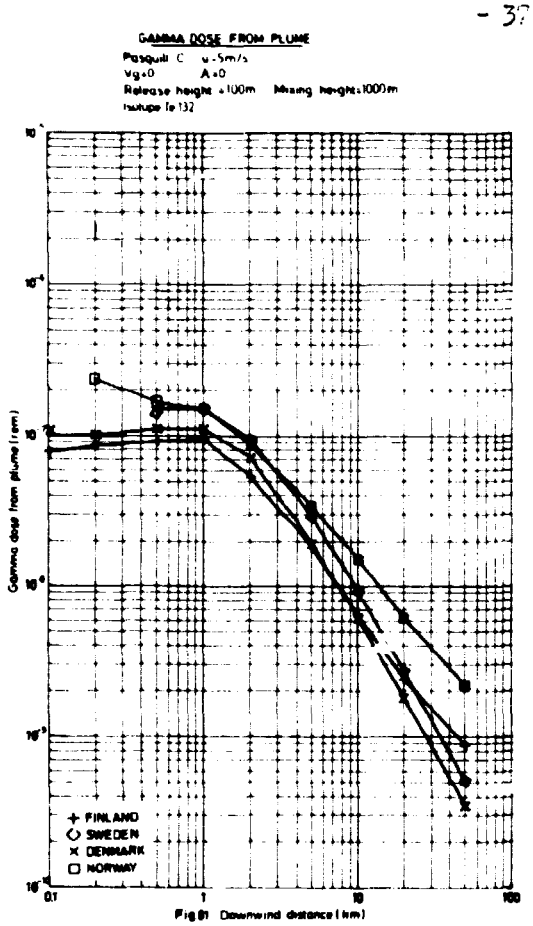


Fig 81 Downwind distance (km)

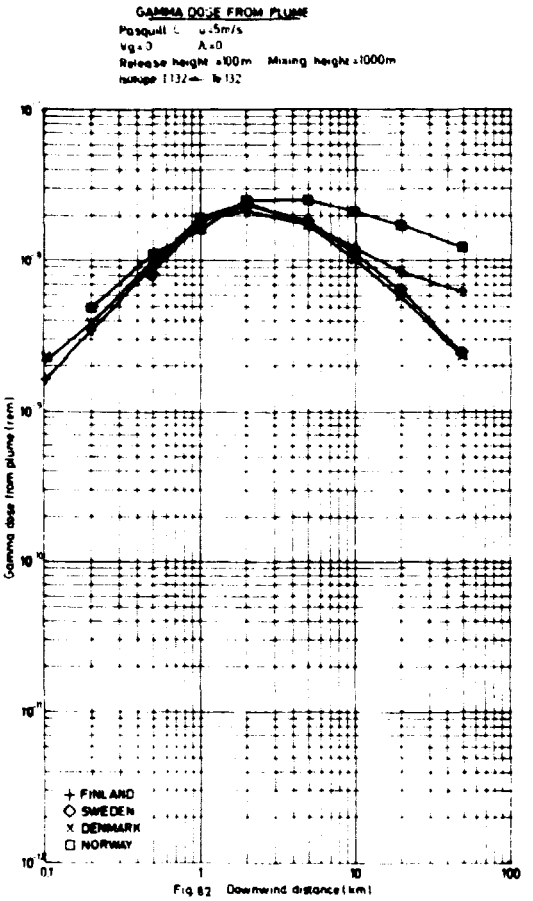


Fig 82 Downwind distance (km)

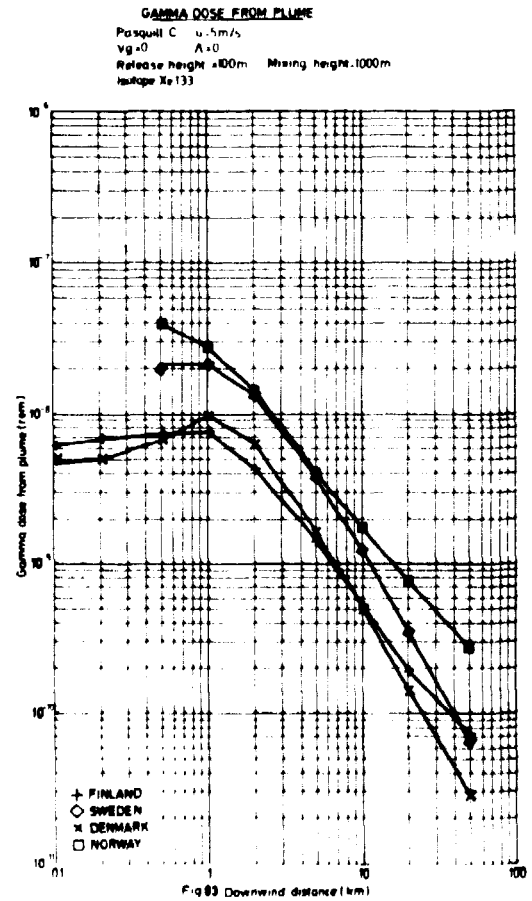


Fig 83 Downwind distance (km)

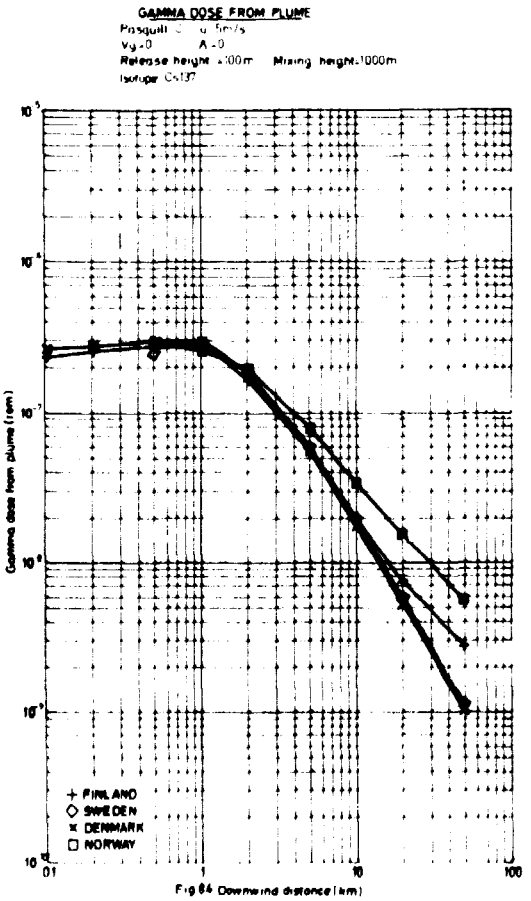


Fig 84 Downwind distance (km)

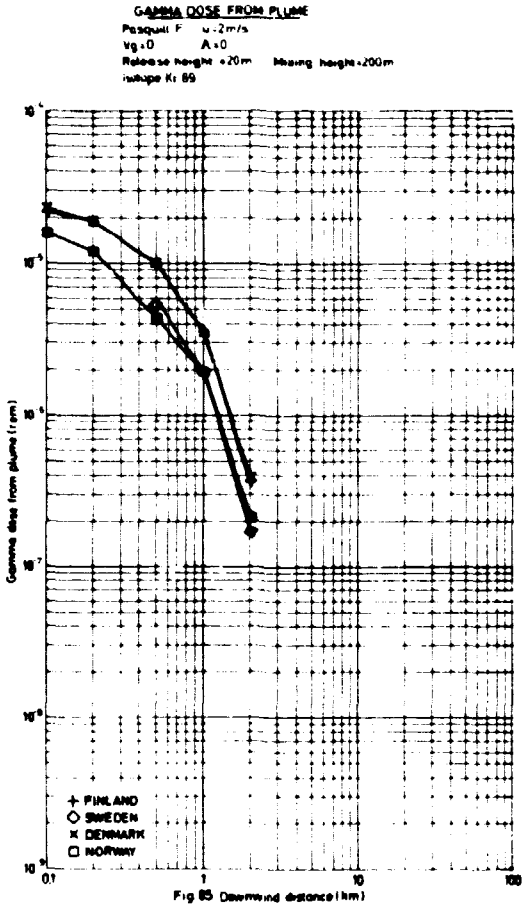


Fig 85 Downwind distance (km)

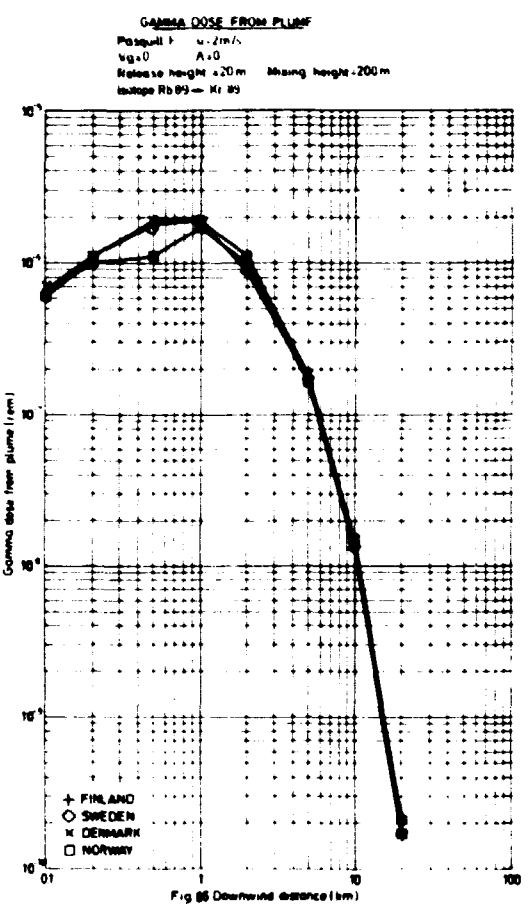


Fig 86 Downwind distance (km)

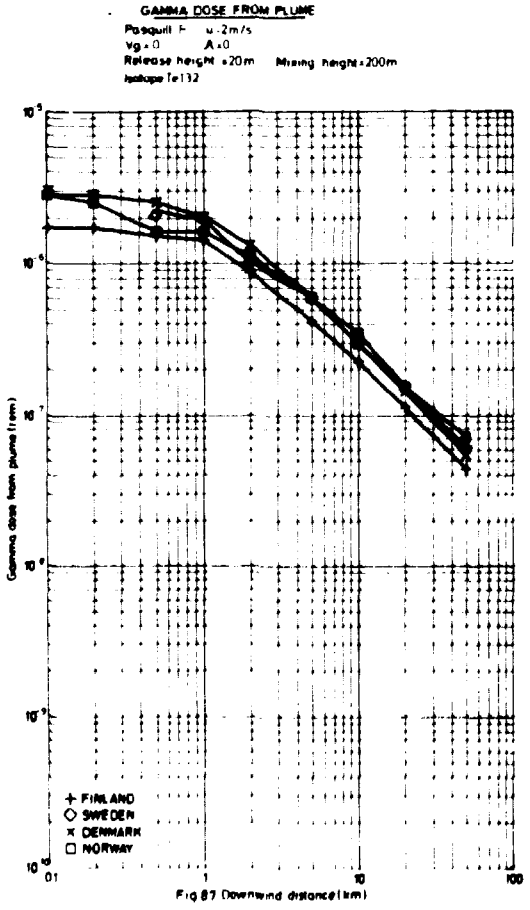


Fig 87 Downwind distance (km)

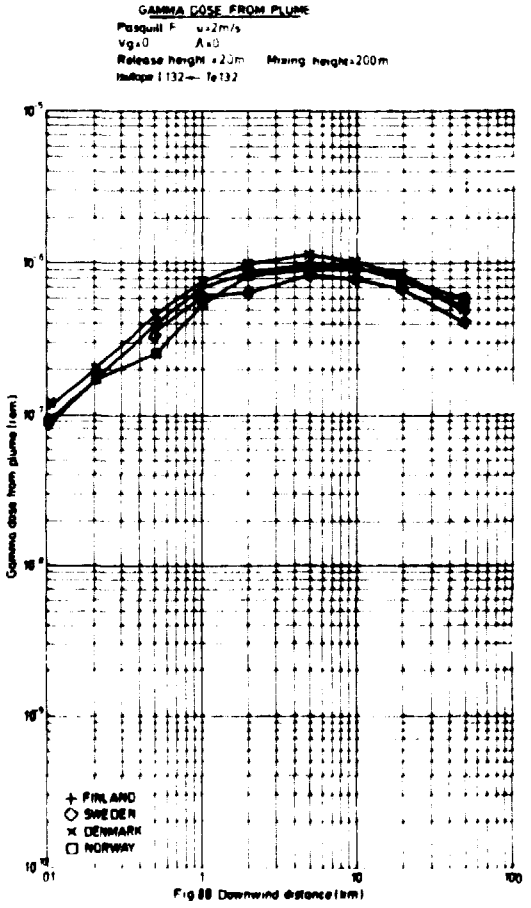
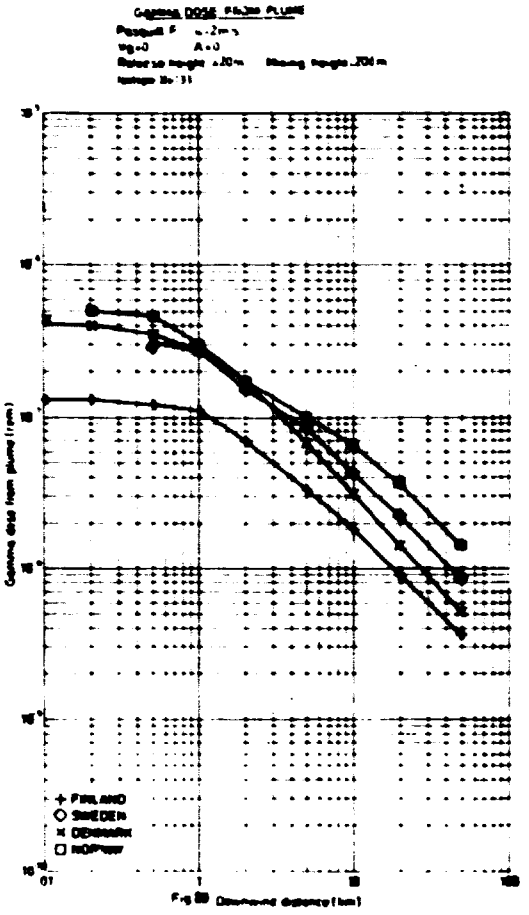
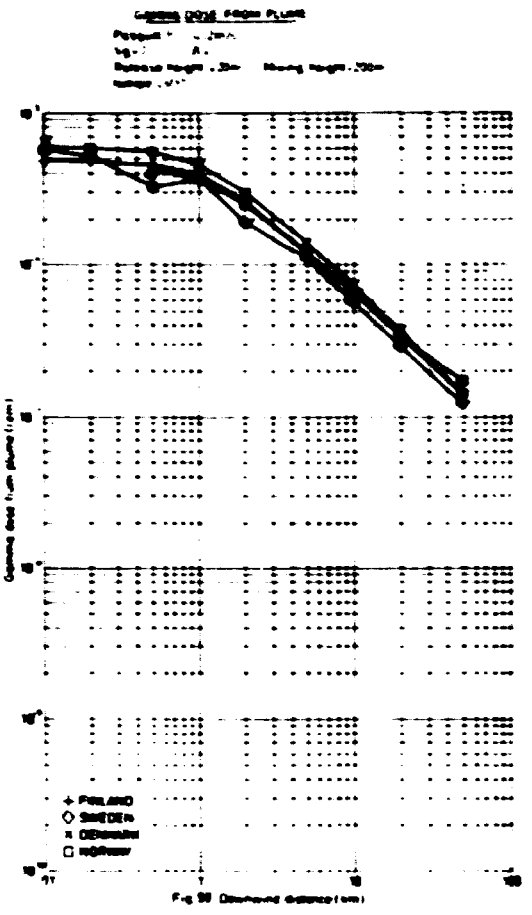


Fig 88 Downwind distance (km)


FINLAND
SWEDEN
DENMARK
NORWAY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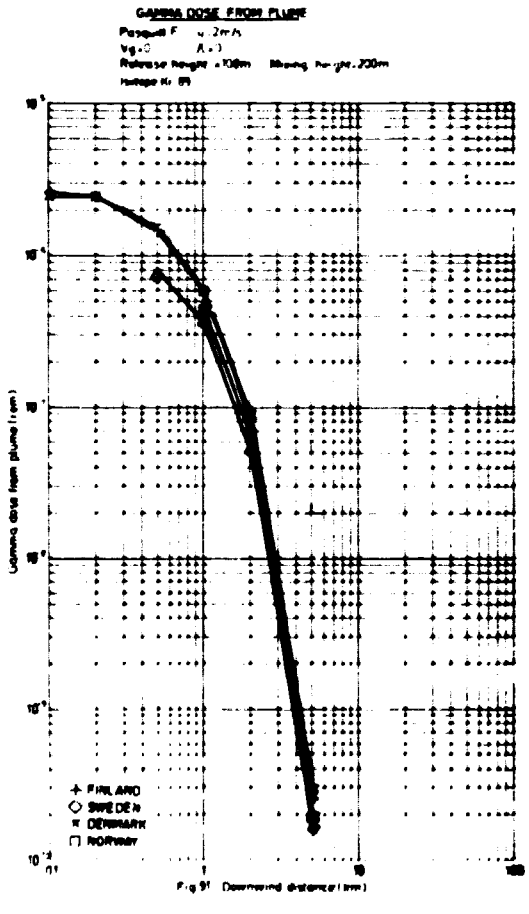
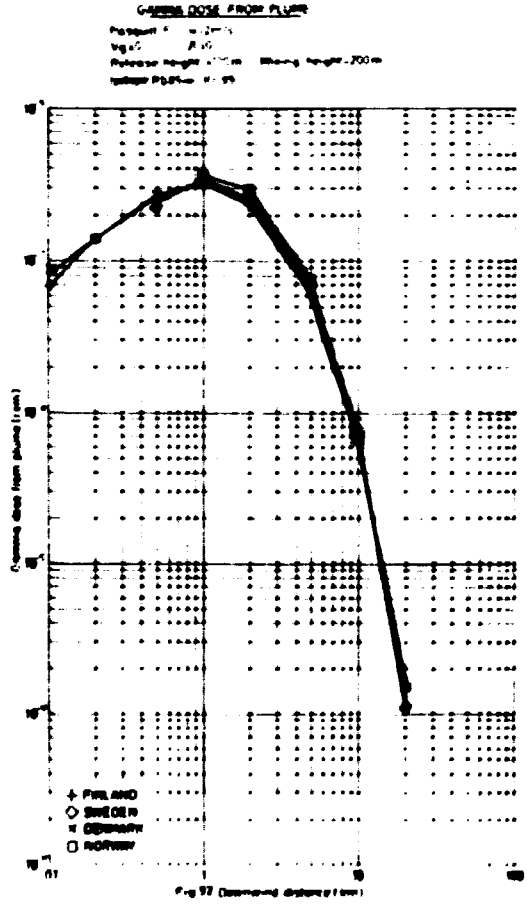
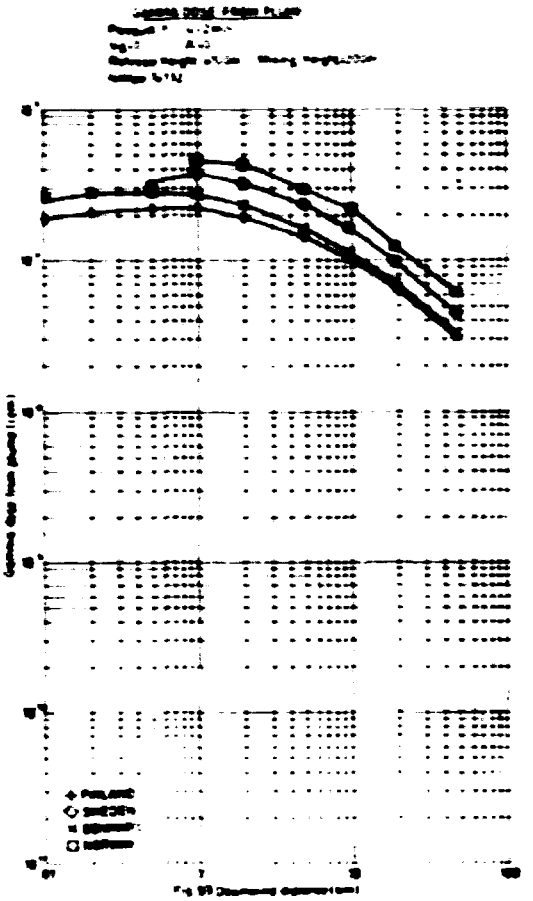
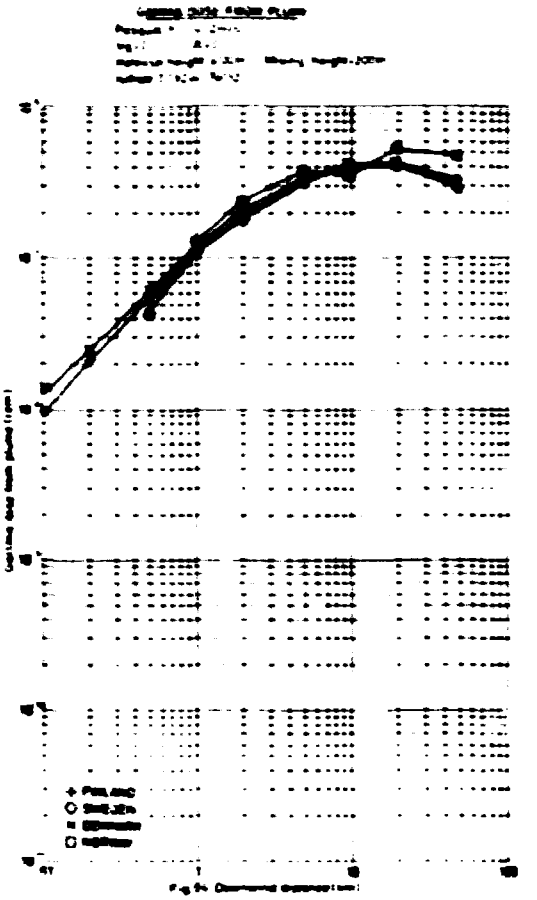
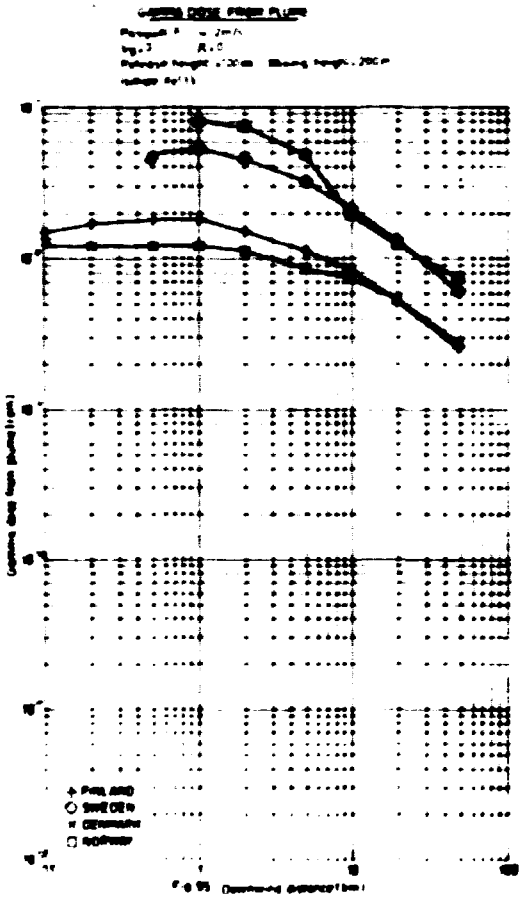
SWEDEN
DENMARK
NORWAY

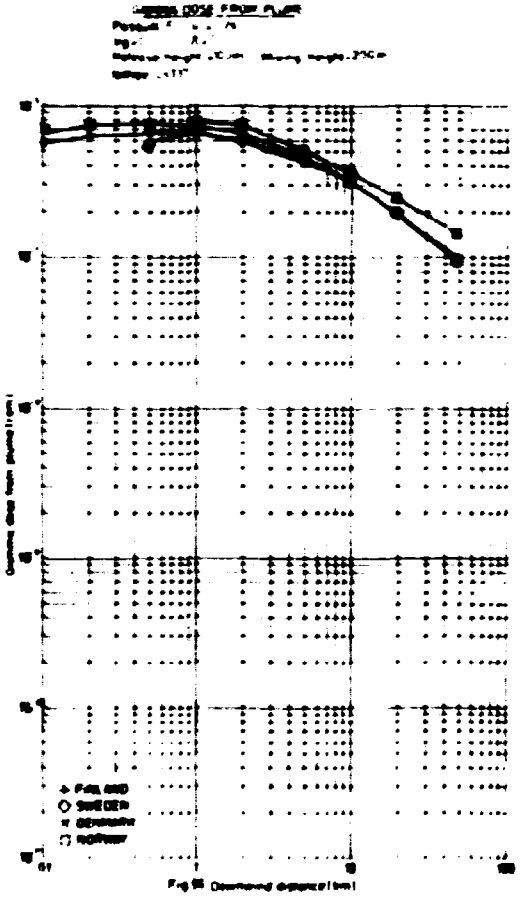

GAMMA DOSE FROM PLUME
FINLAND
SWEDEN
DENMARK
NORWAY


GAMMA DOSE FROM PLUME
FINLAND
SWEDEN
DENMARK
NORWAY









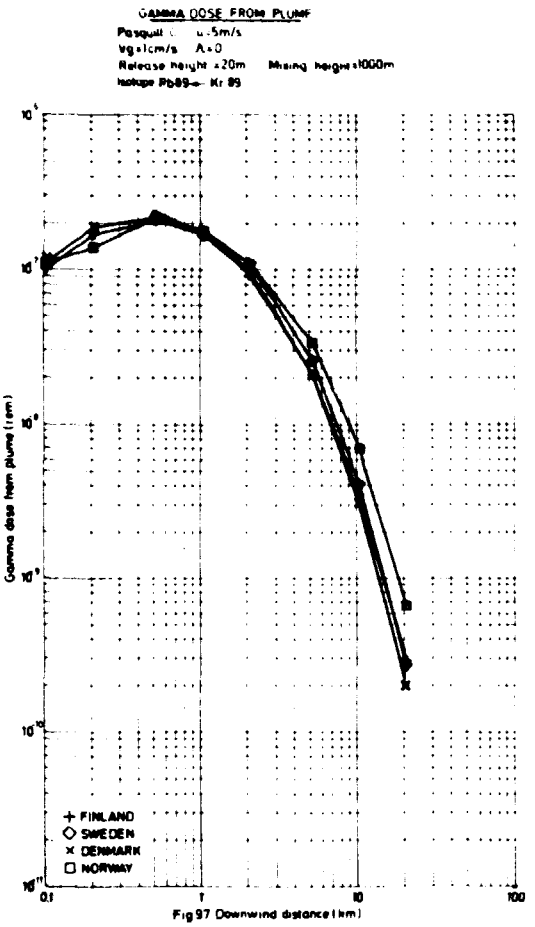


Fig 97 Downwind distance (km)

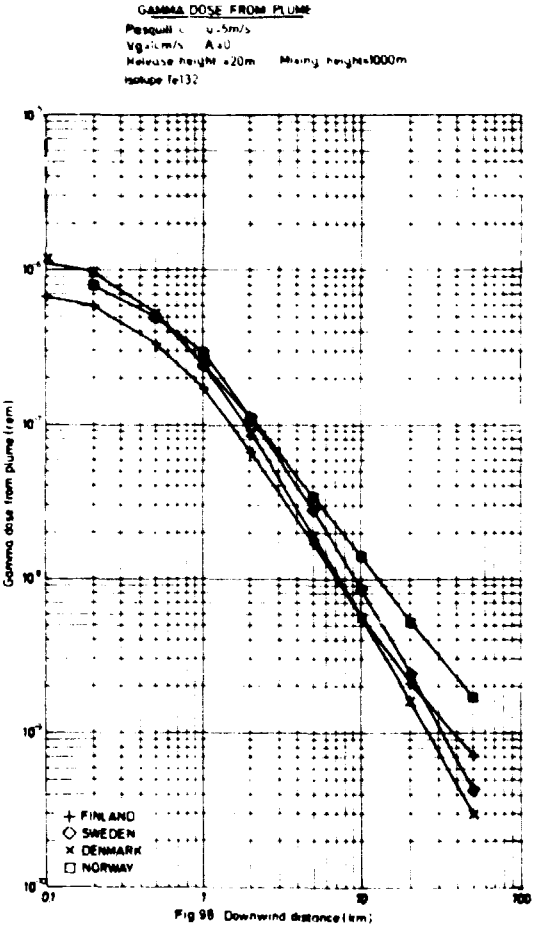


Fig 98 Downwind distance (km)

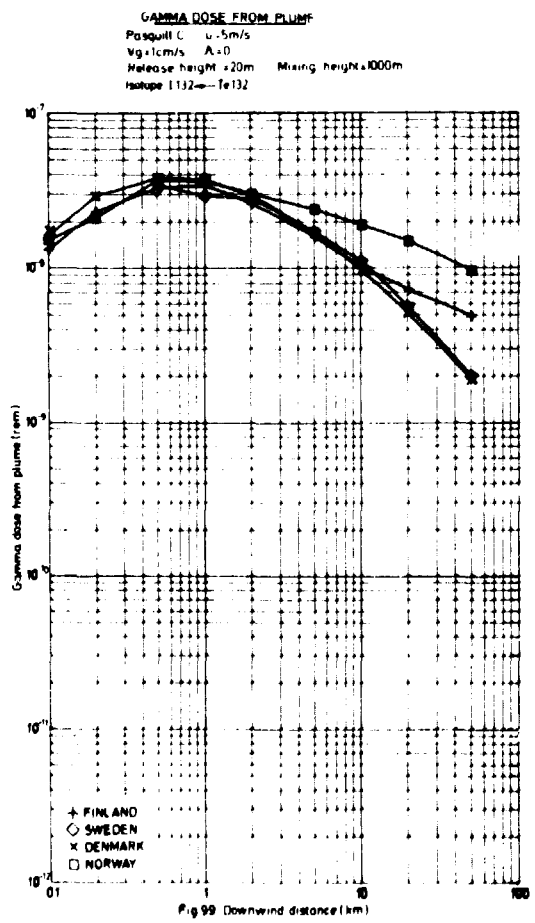


Fig 99 Downwind distance (km)

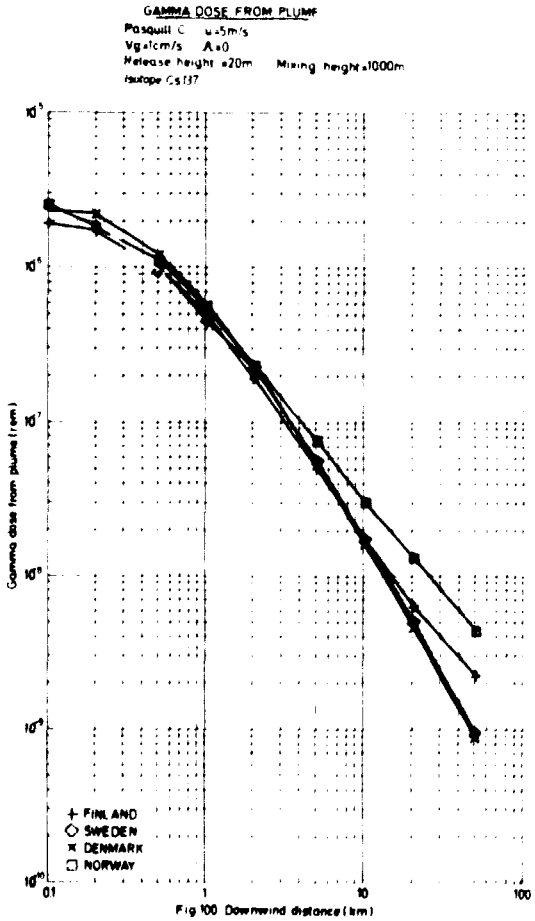


Fig 100 Downwind distance (km)

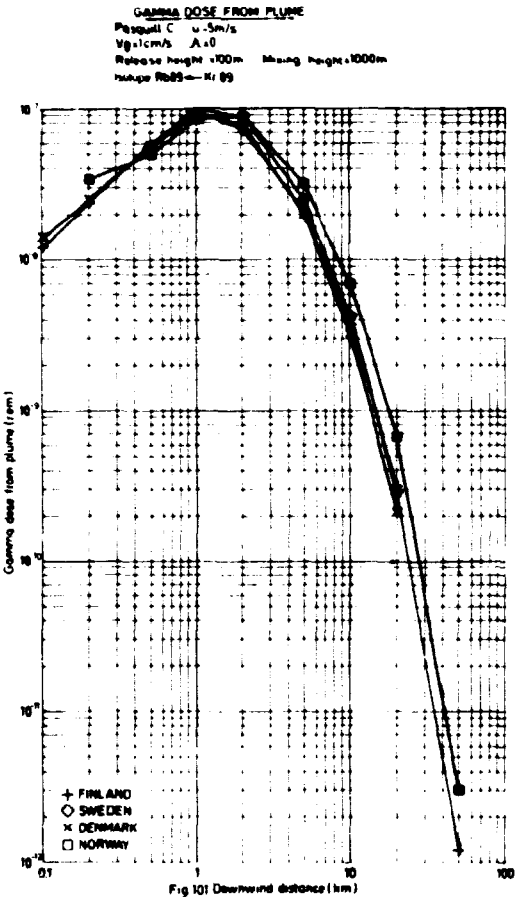


Fig 101

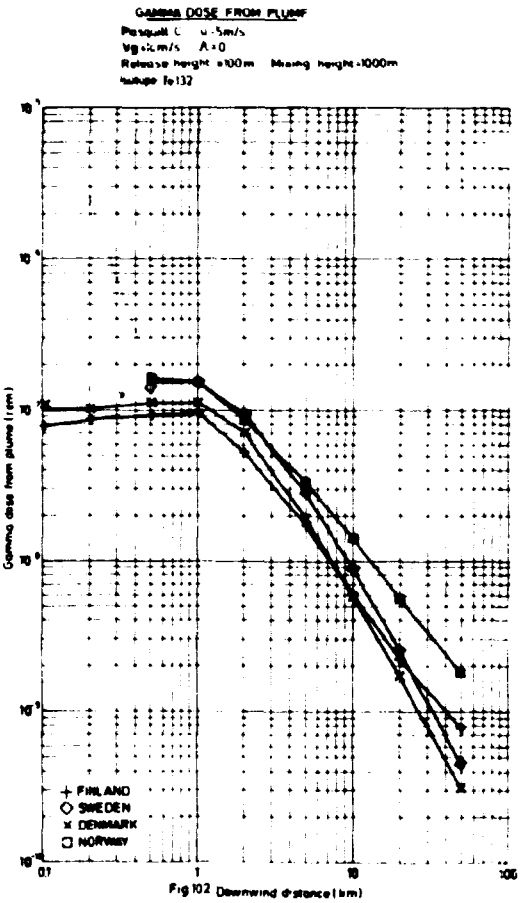


Fig 102

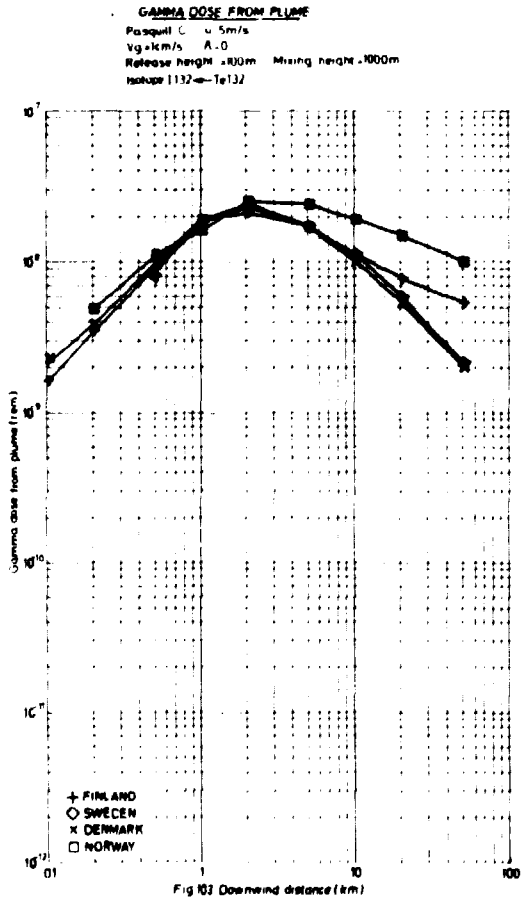


Fig 103

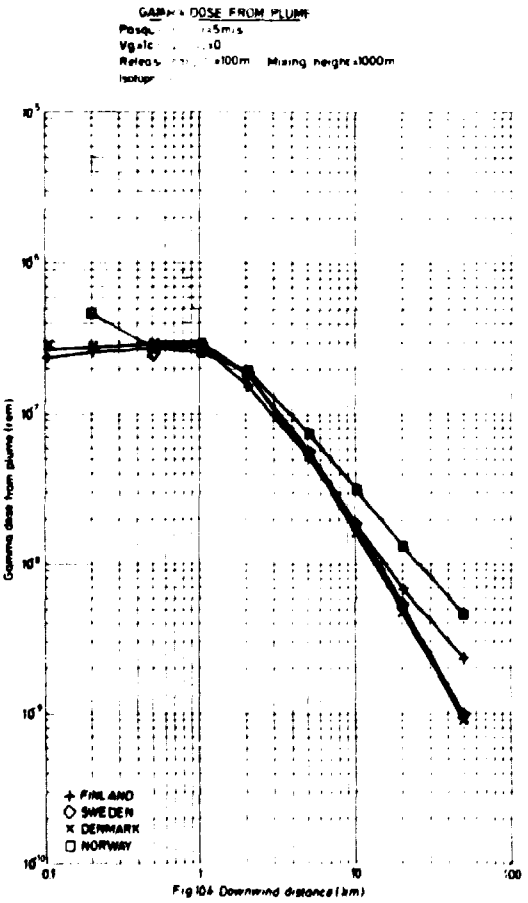


Fig 104

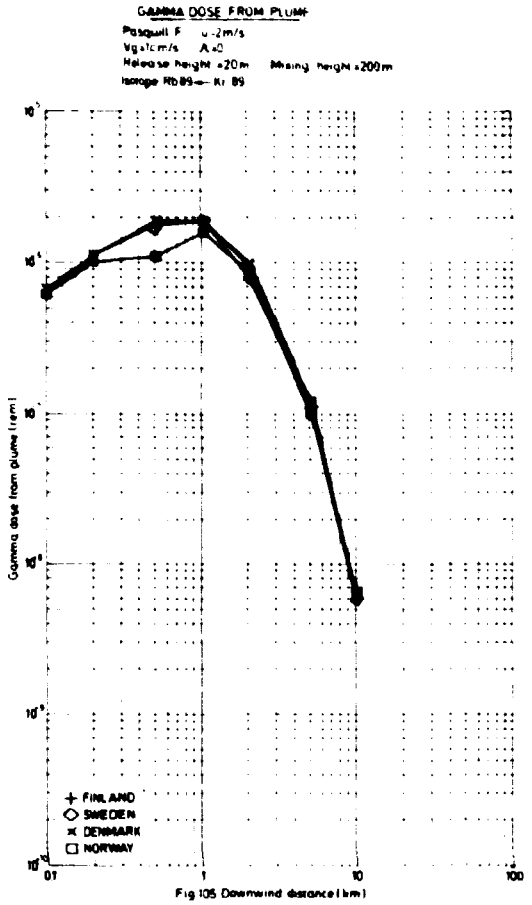


Fig 105 Downwind distance (km)

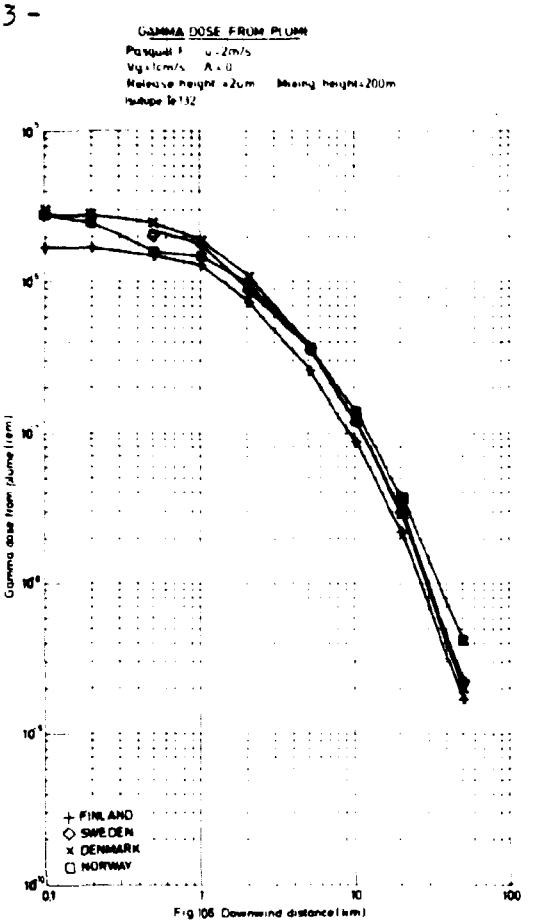


Fig 106 Downwind distance (km)

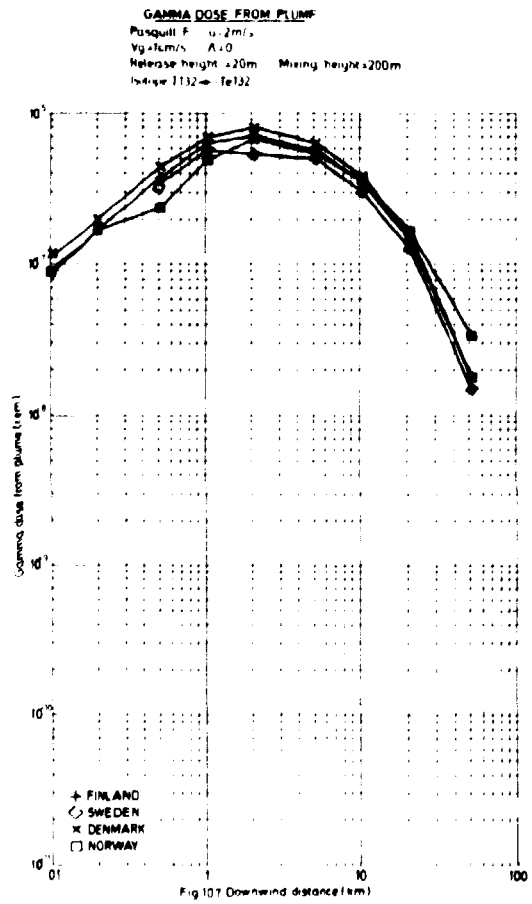


Fig 107 Downwind distance (km)

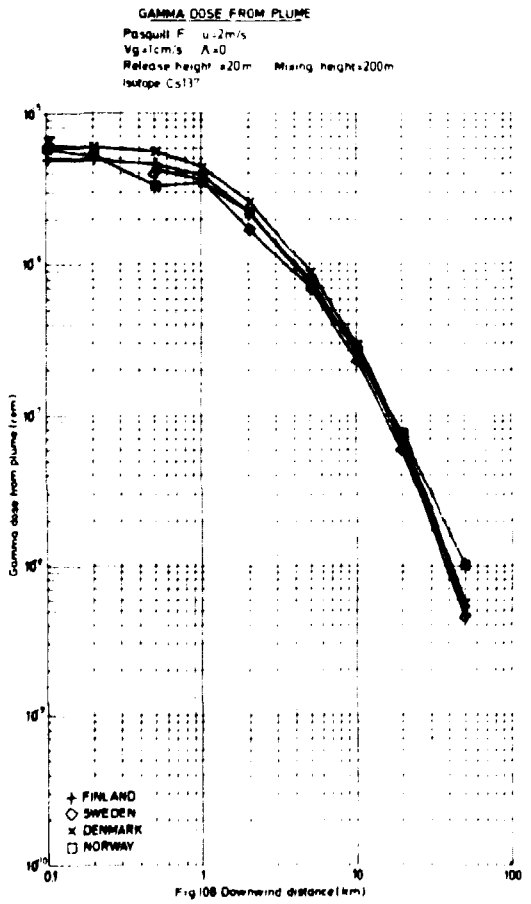


Fig 108 Downwind distance (km)

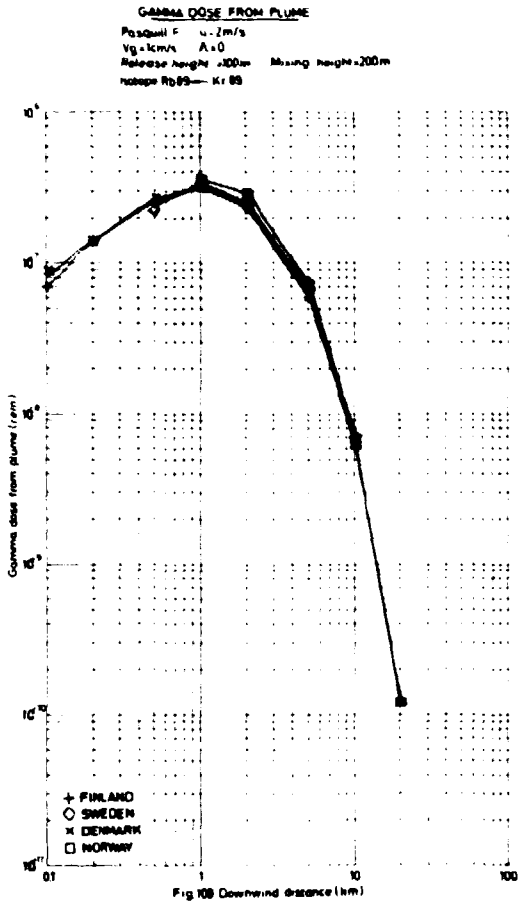


Fig 109 Downwind distance (km)

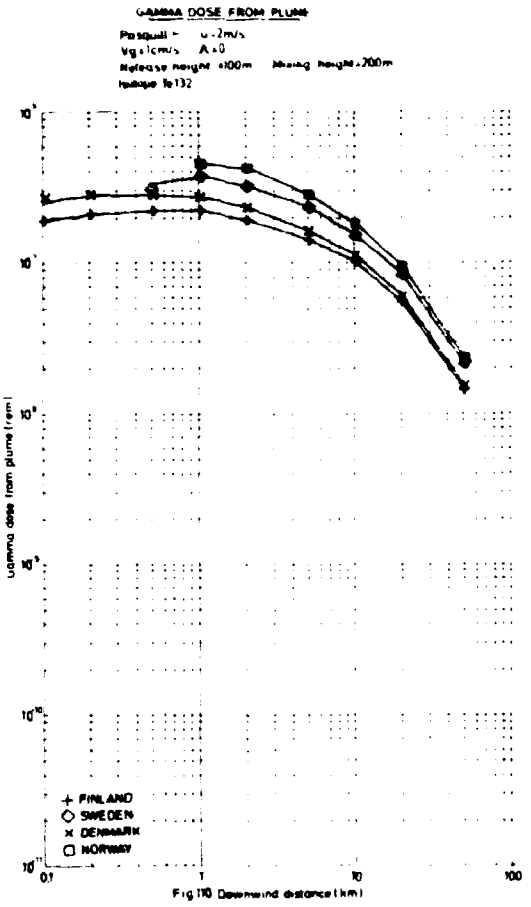


Fig 110 Downwind distance (km)

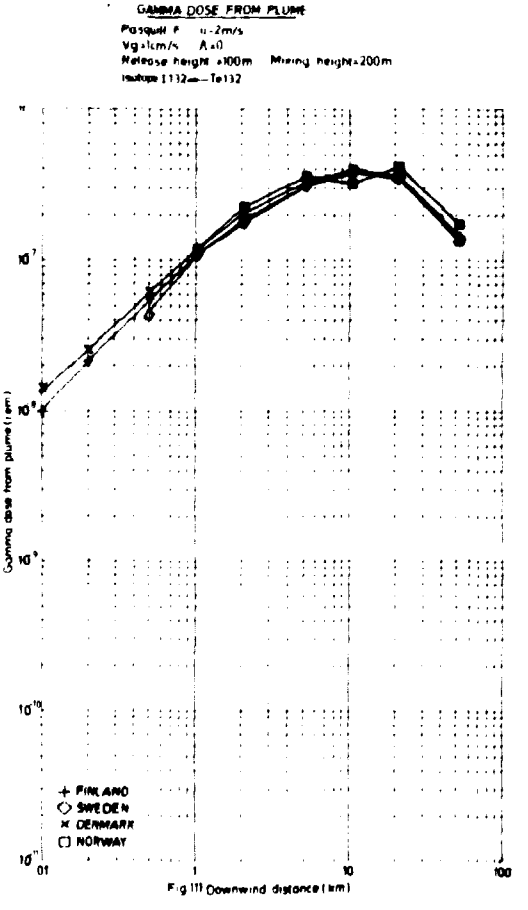


Fig 111 Downwind distance (km)

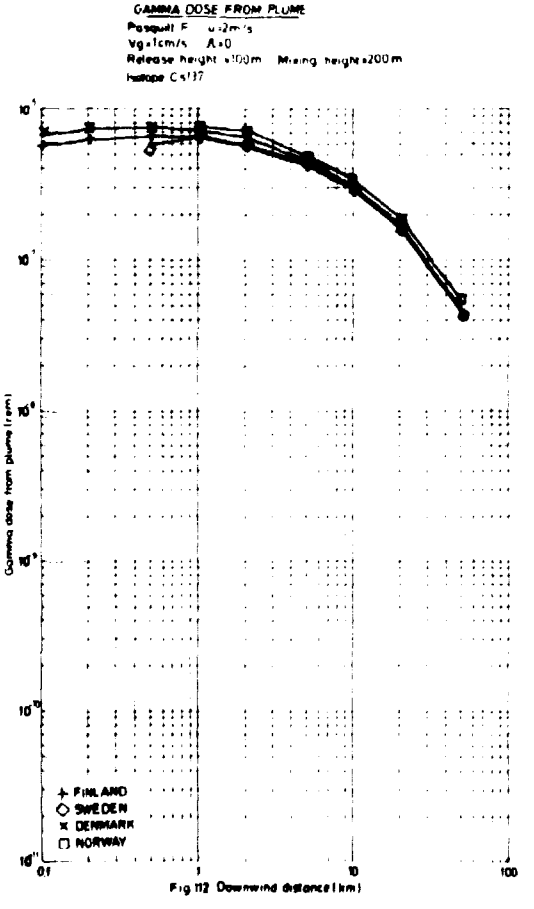


Fig 112 Downwind distance (km)

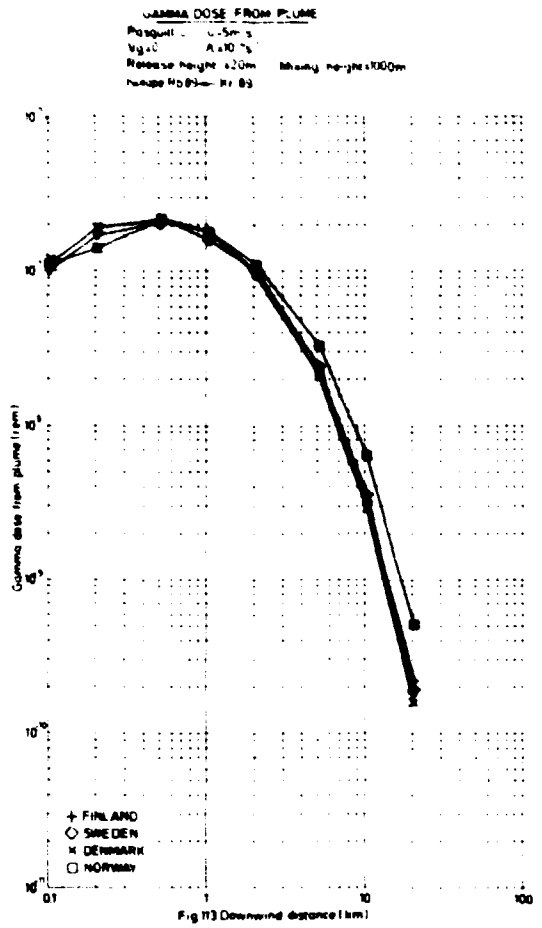


Fig 113 Downwind distance (km)

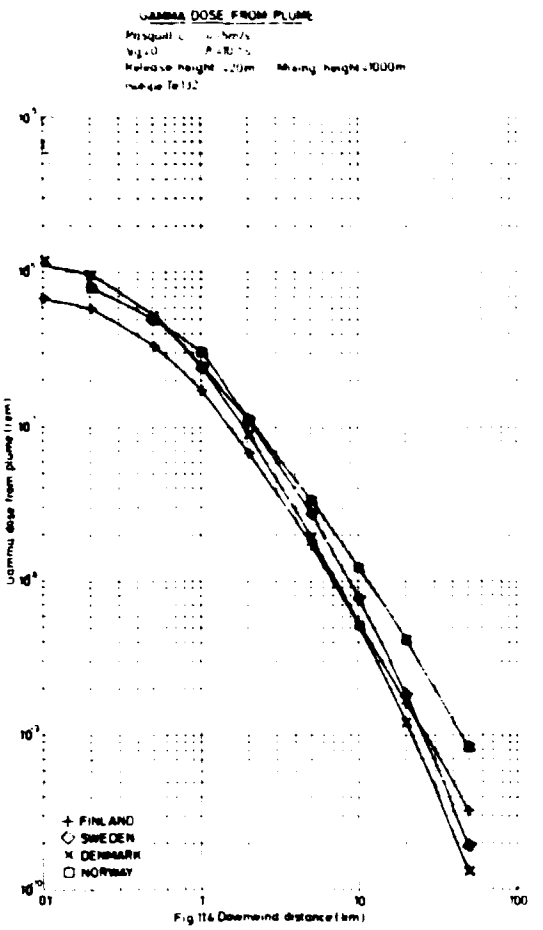


Fig 116 Downwind distance (km)

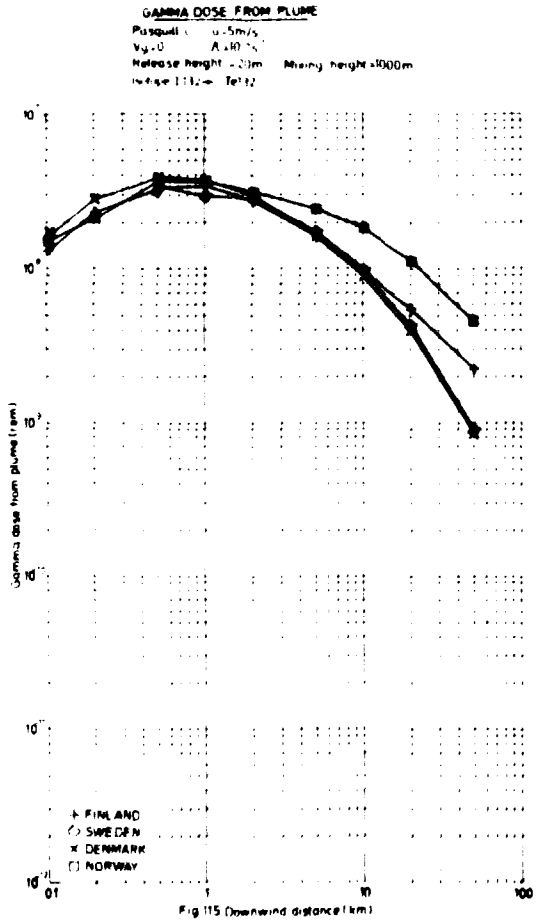


Fig 115 Downwind distance (km)

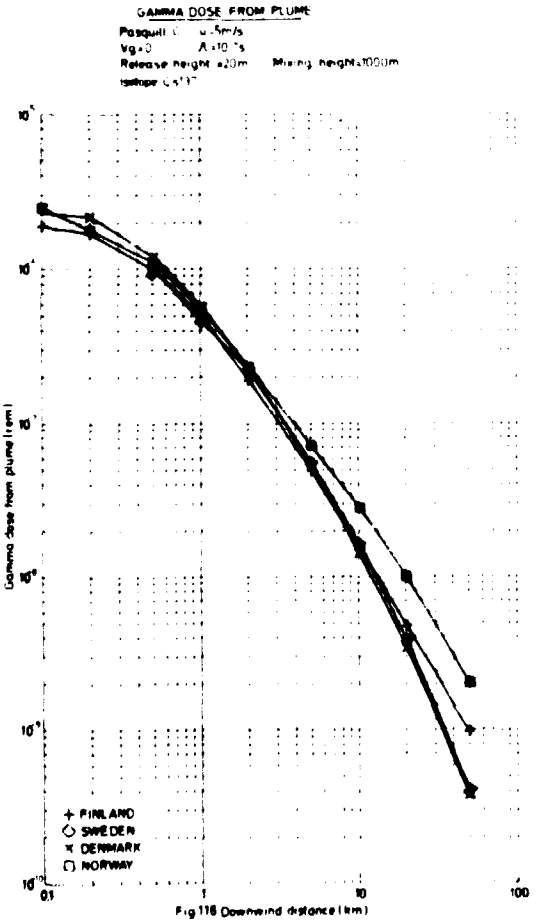


Fig 118 Downwind distance (km)

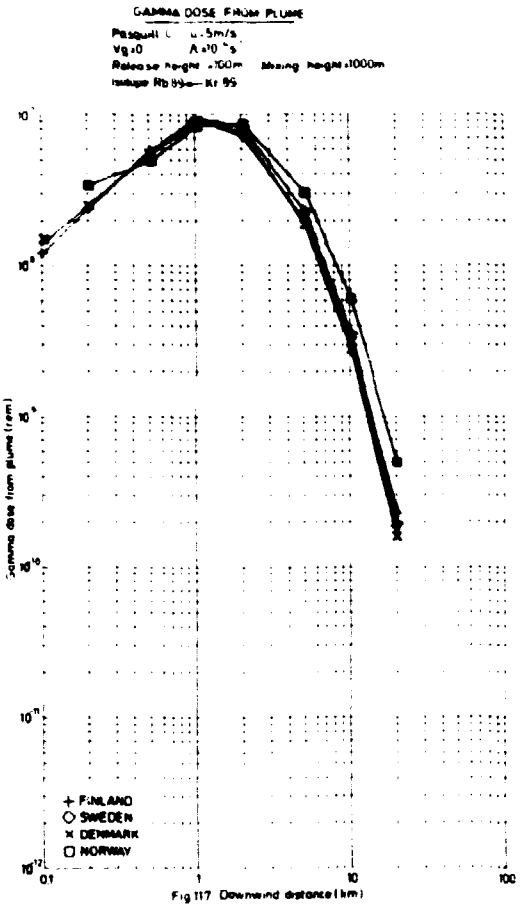


Fig 117 Downwind distance (km)

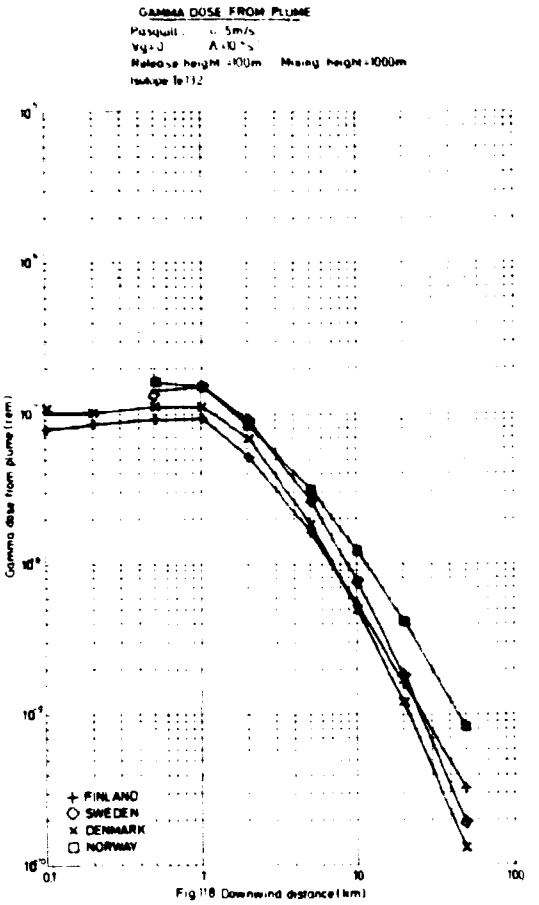


Fig 118 Downwind distance (km)

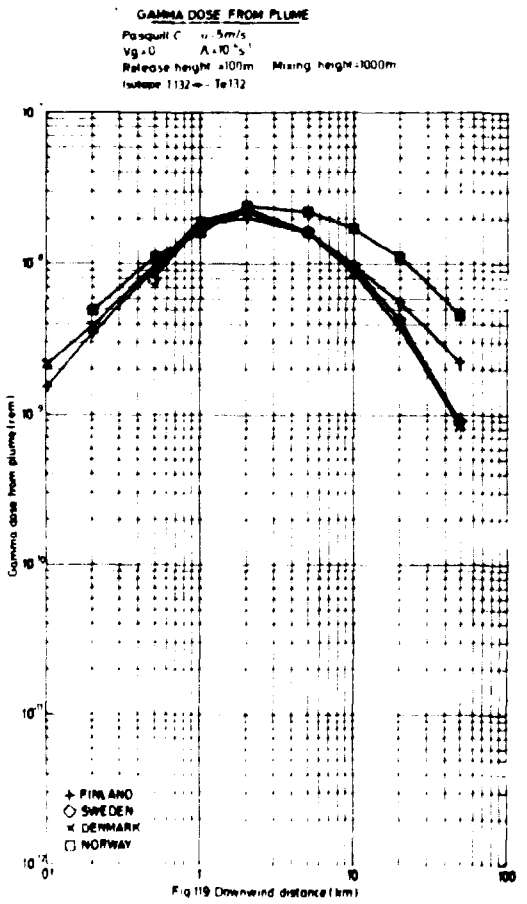


Fig 119 Downwind distance (km)

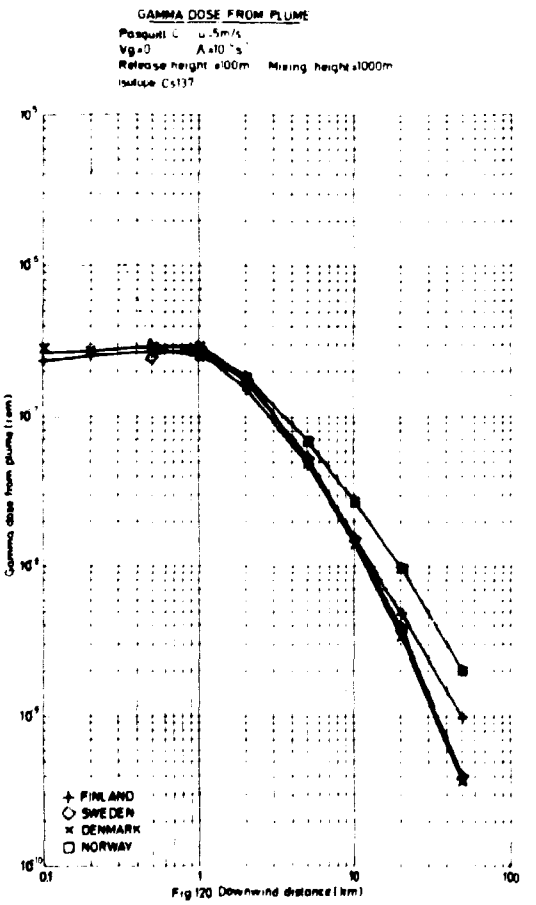


Fig 120 Downwind distance (km)

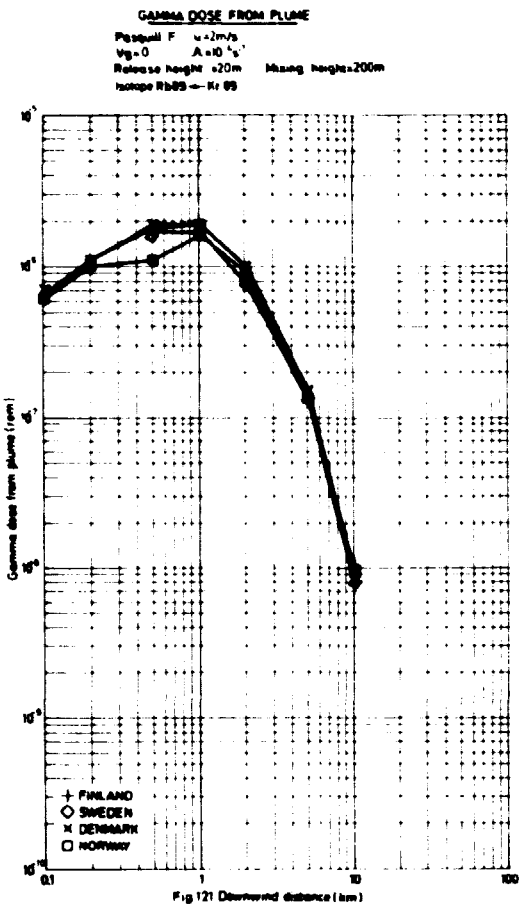


Fig 121 Downwind distance (km)

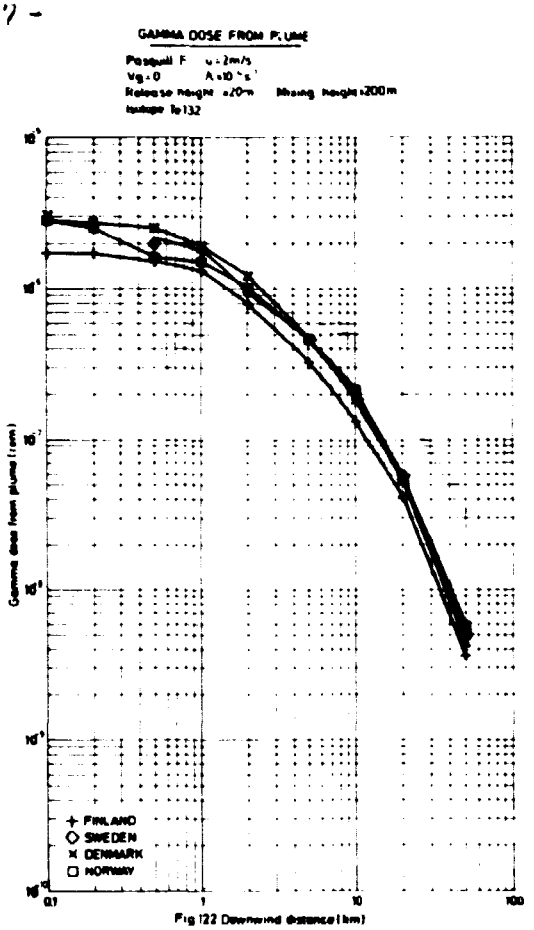


Fig 122 Downwind distance (km)

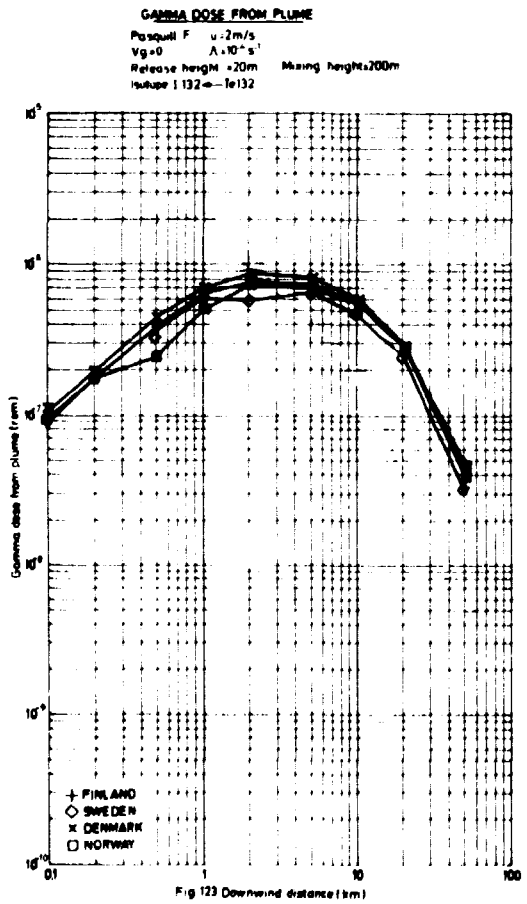


Fig 123 Downwind distance (km)

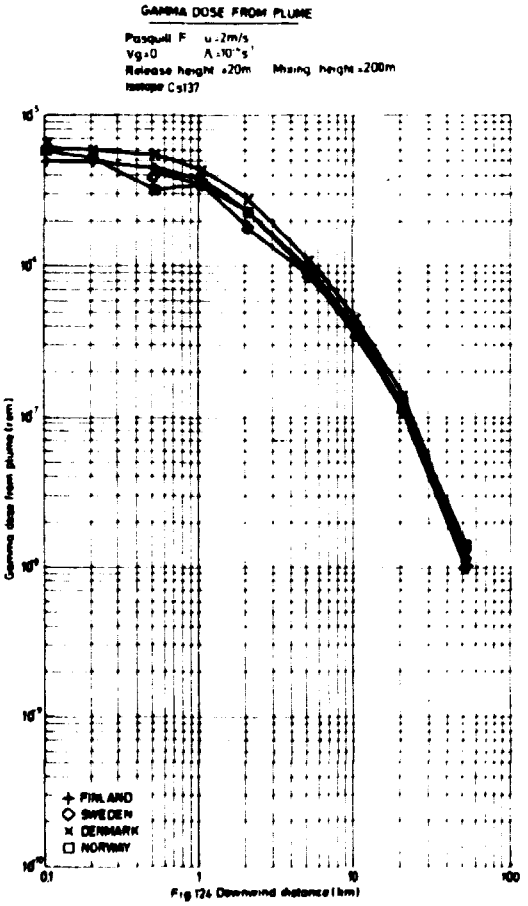


Fig 124 Downwind distance (km)

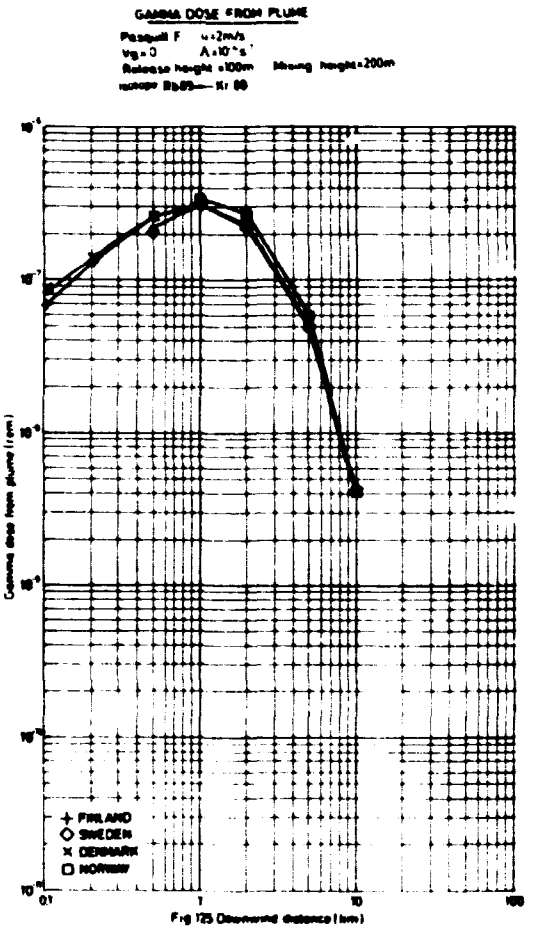


Fig 125 Downwind distance (km)

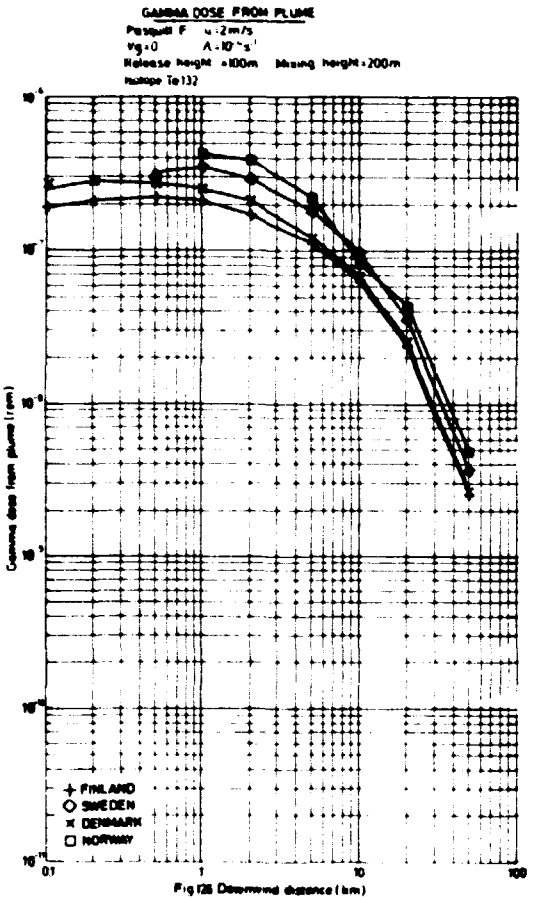


Fig 126 Downwind distance (km)

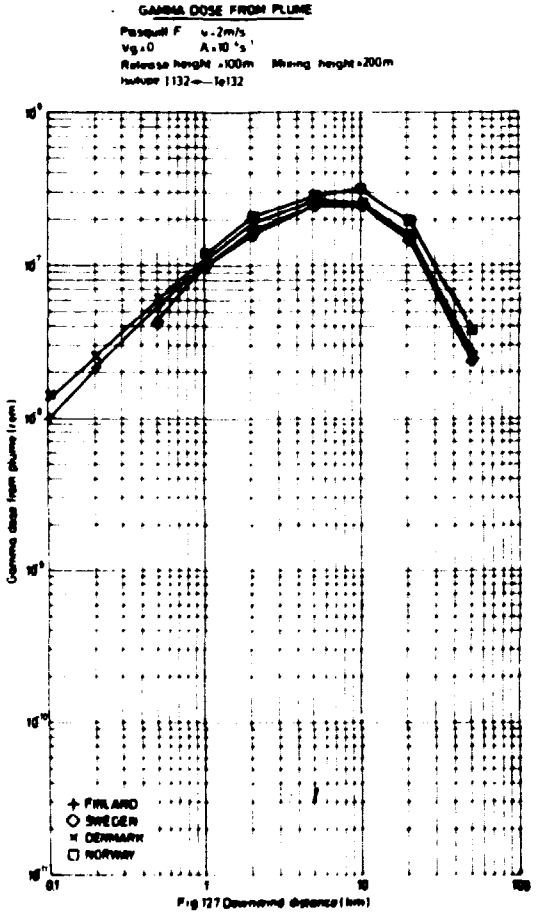


Fig 127 Downwind distance (km)

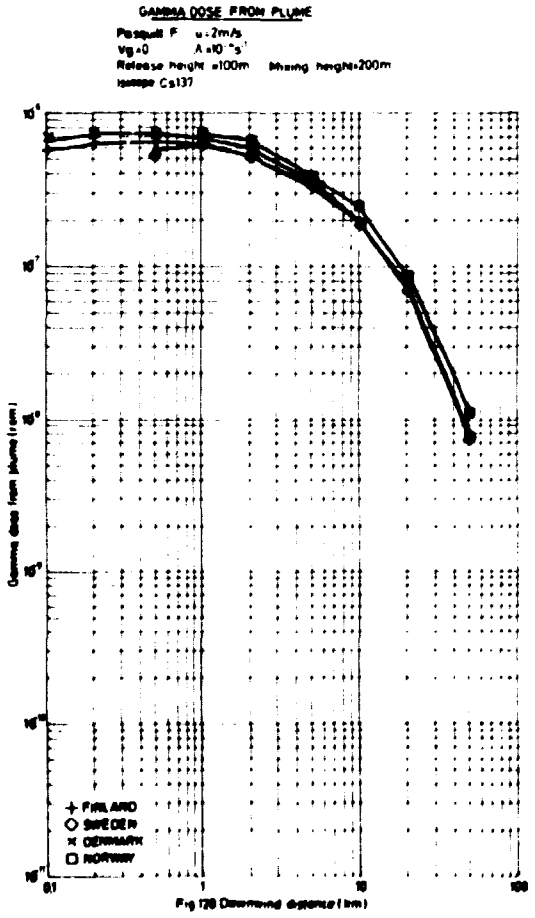


Fig 128 Downwind distance (km)

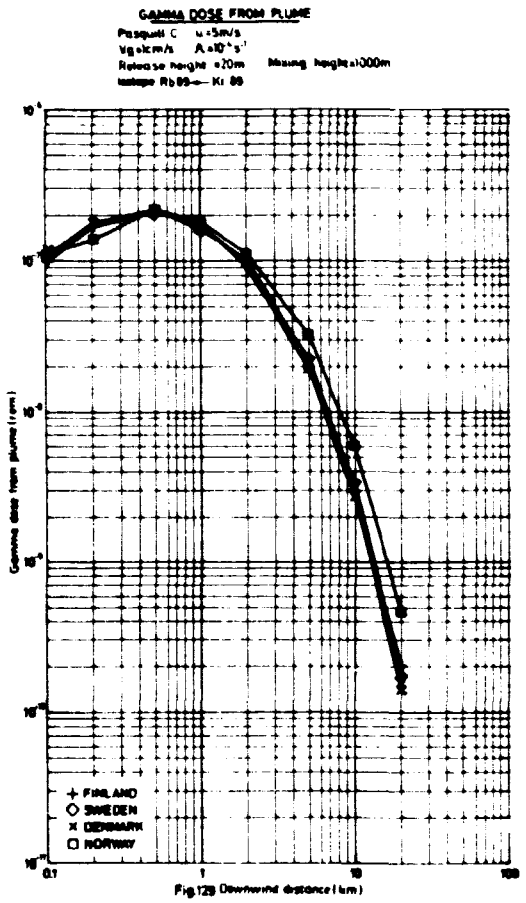


Fig.129

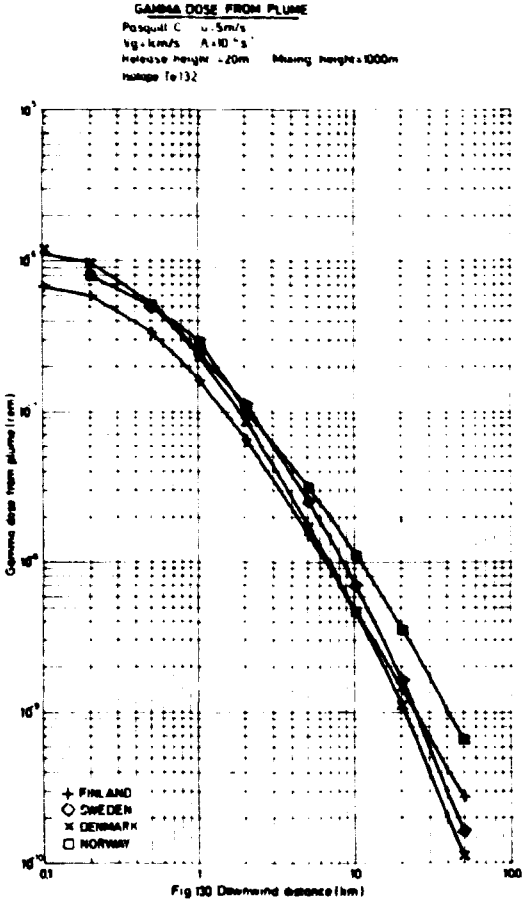


Fig 130

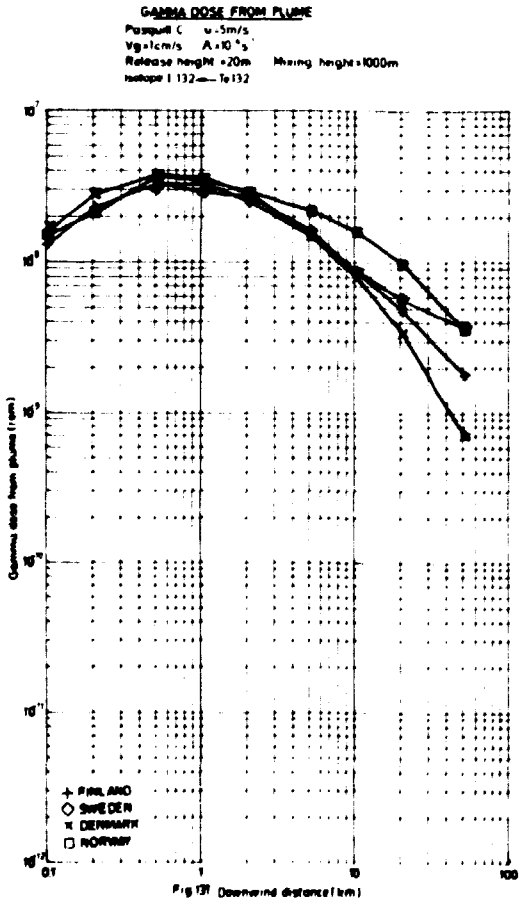


Fig 131

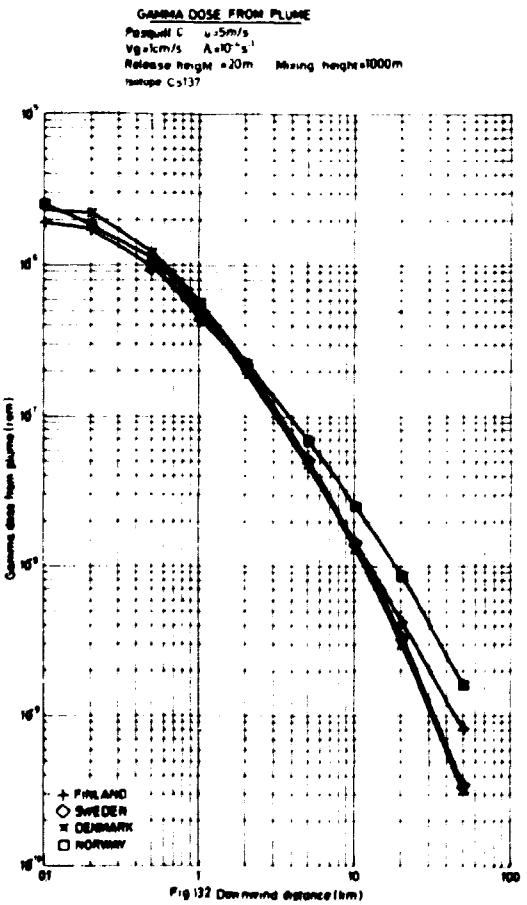


Fig 132

GAMMA DOSE FROM PLUME

Pasquill :5m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =100m Mixing height =1000m
Isotope Rb 89 — Kr 89

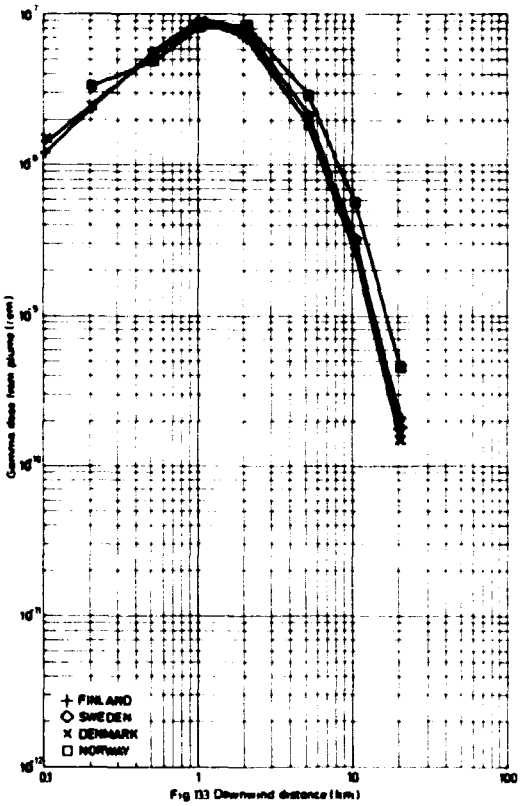


Fig 133 Downwind distance (km)

GAMMA DOSE FROM PLUME

Pasquill C u=5m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =100m Mixing height =1000m
Isotope Te 132

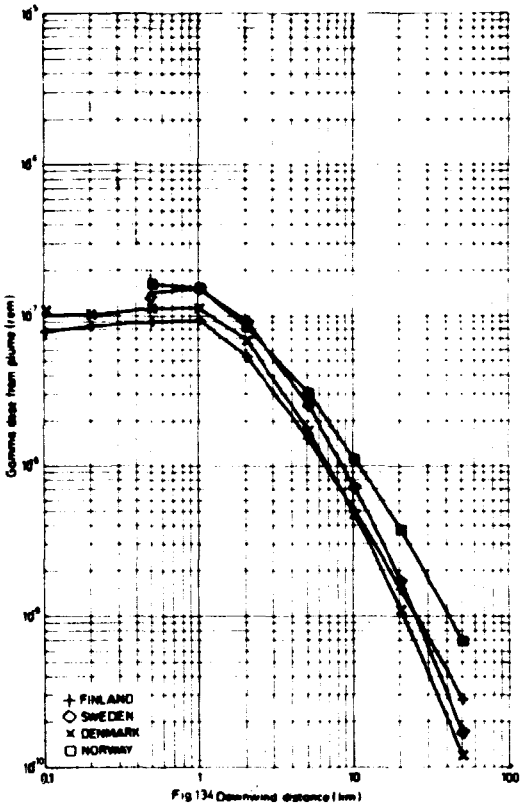


Fig 134 Downwind distance (km)

GAMMA DOSE FROM PLUME

Pasquill C u=5m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =100m Mixing height =1000m
Isotope I 132 — Te 132

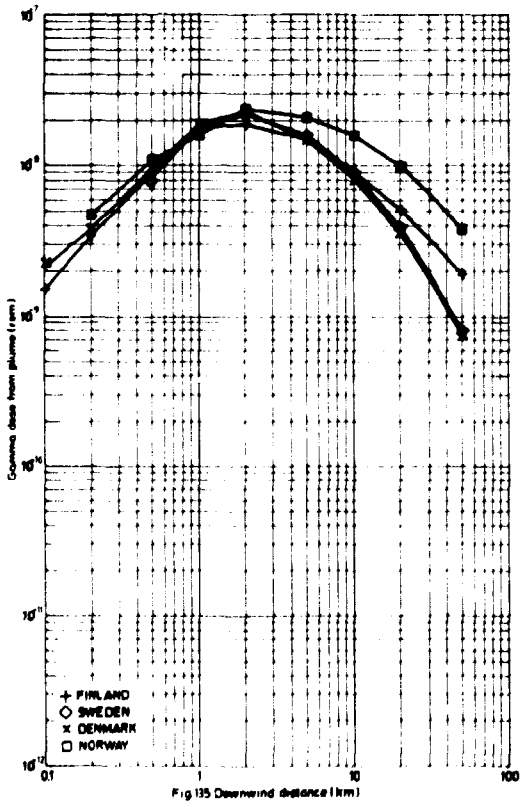


Fig 135 Downwind distance (km)

GAMMA DOSE FROM PLUME

Pasquill C u=5m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =100m Mixing height =1000m
Isotope Cs 137

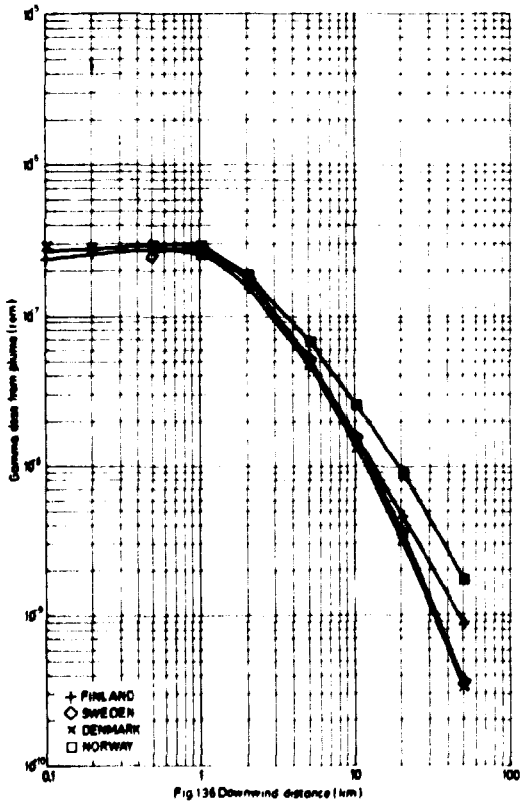
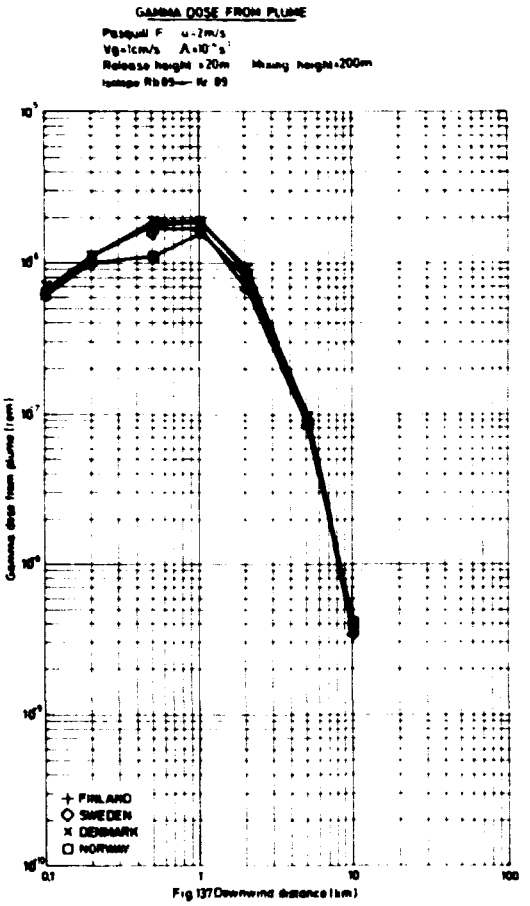
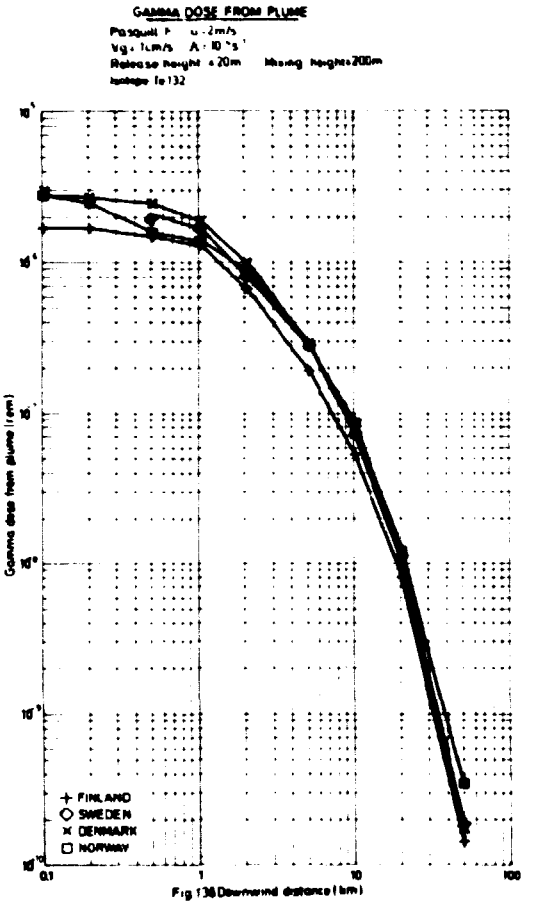
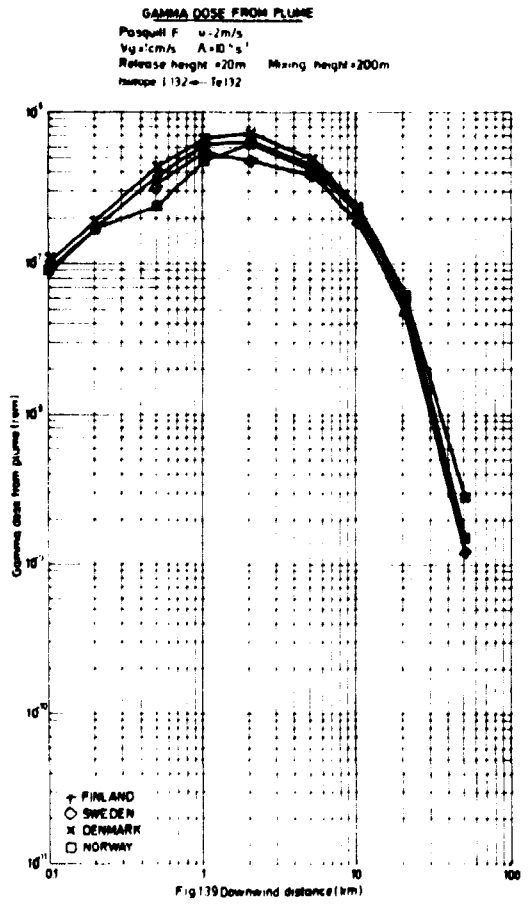
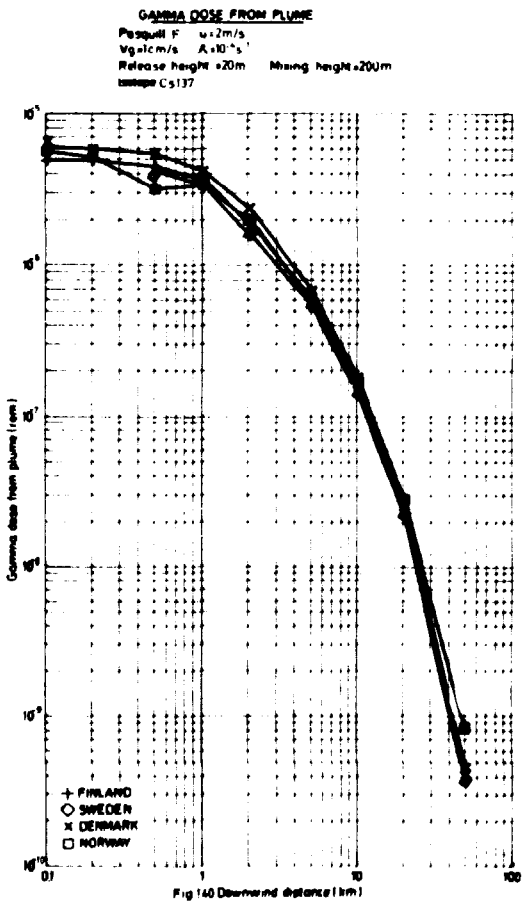


Fig 136 Downwind distance (km)


GAMMA DOSE FROM PLUME
Pasquill F u=2m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =20m Mixing height=200m
Isotope Rb89 — Kr 89
Gamma dose from plume (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 137 Downwind distance (km)


GAMMA DOSE FROM PLUME
Pasquill F u=2m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =20m Mixing height=200m
Isotope Te132
Gamma dose from plume (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 138 Downwind distance (km)


GAMMA DOSE FROM PLUME
Pasquill F u=2m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =20m Mixing height=200m
Isotope I 132 — Te132
Gamma dose from plume (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 139 Downwind distance (km)


GAMMA DOSE FROM PLUME
Pasquill F u=2m/s
Vg=1cm/s A=10⁻⁶s⁻¹
Release height =20m Mixing height=200m
Isotope Cs137
Gamma dose from plume (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 140 Downwind distance (km)

GAMMA DOSE FROM PLUME

Pasquill F u = 2m/s
Vg = 1cm/s A = 10⁻⁶ s⁻¹
Release height = 100m Mixing height = 200m
Isotope Rb 89 — Kr 89

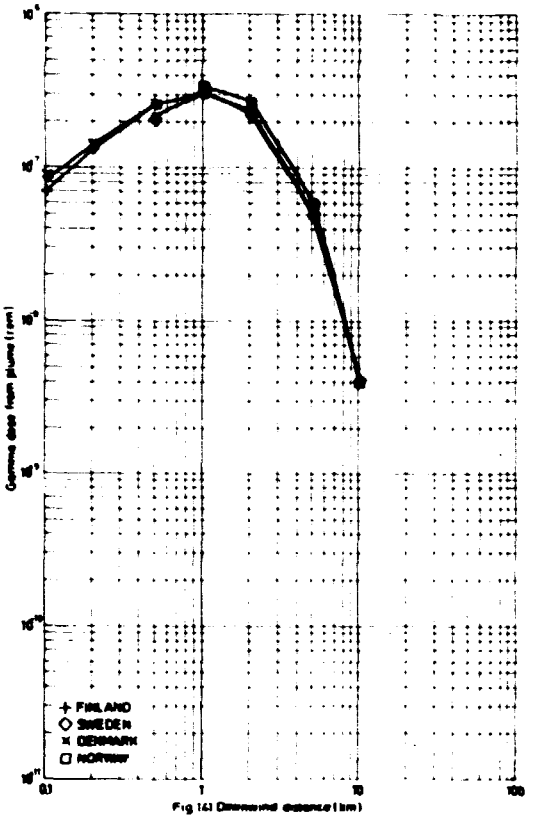


Fig 141 Downwind distance (km)

GAMMA DOSE FROM PLUME

Pasquill F u = 2m/s
Vg = 1cm/s A = 10⁻⁶ s⁻¹
Release height = 100m Mixing height = 200m
Isotope Te 132

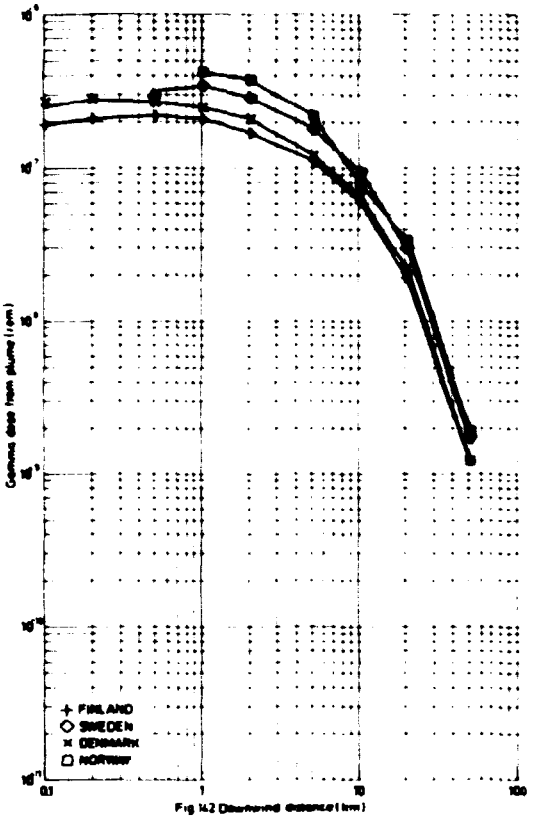


Fig 142 Downwind distance (km)

GAMMA DOSE FROM PLUME

Pasquill F u = 2m/s
Vg = 1cm/s A = 10⁻⁶ s⁻¹
Release height = 100m Mixing height = 200m
Isotope I 132 — Te 132

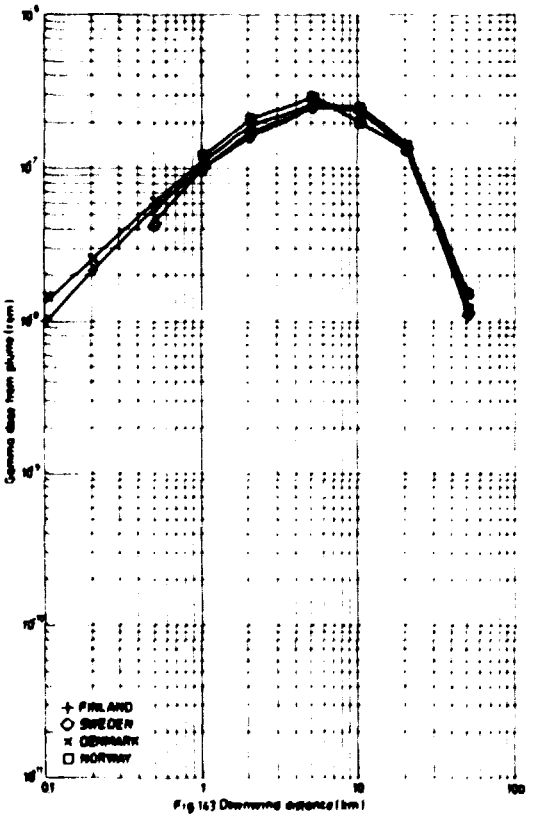


Fig 143 Downwind distance (km)

GAMMA DOSE FROM PLUME

Pasquill F u = 2m/s
Vg = 1cm/s A = 10⁻⁶ s⁻¹
Release height = 100m Mixing height = 200m
Isotope Cs 137

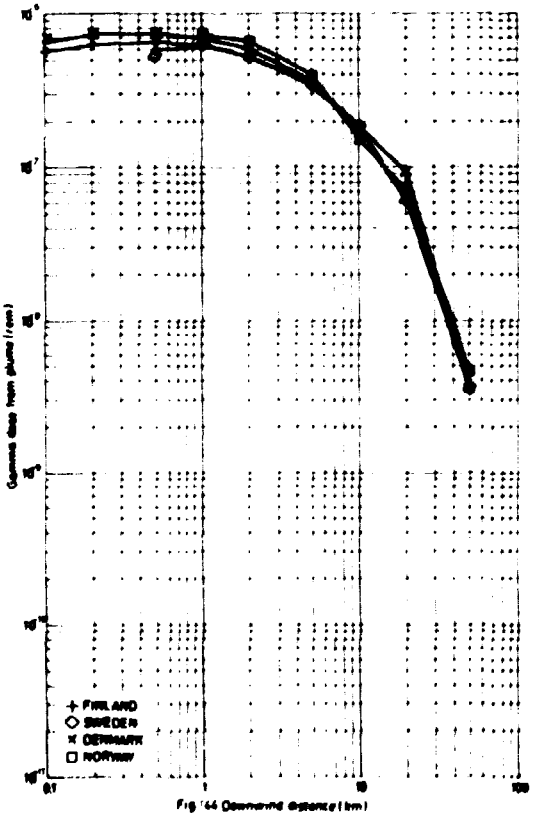
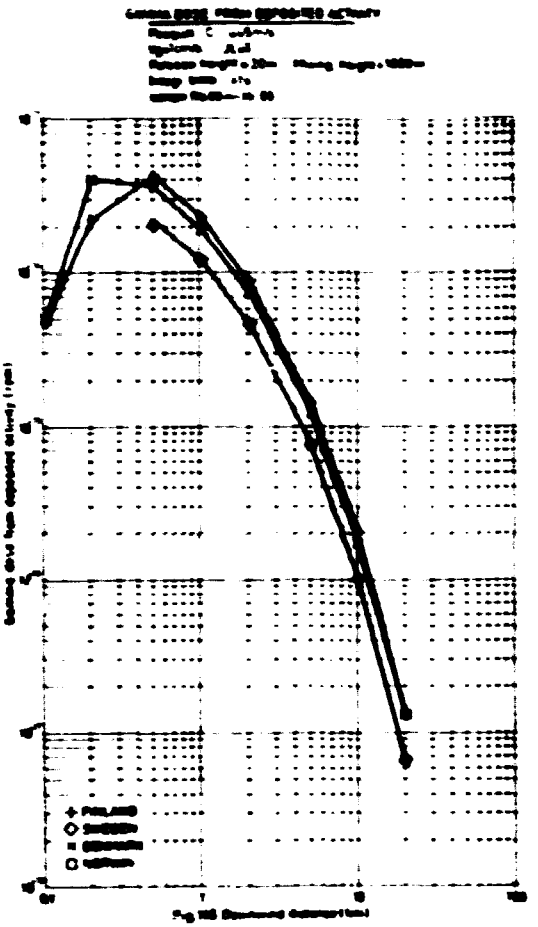
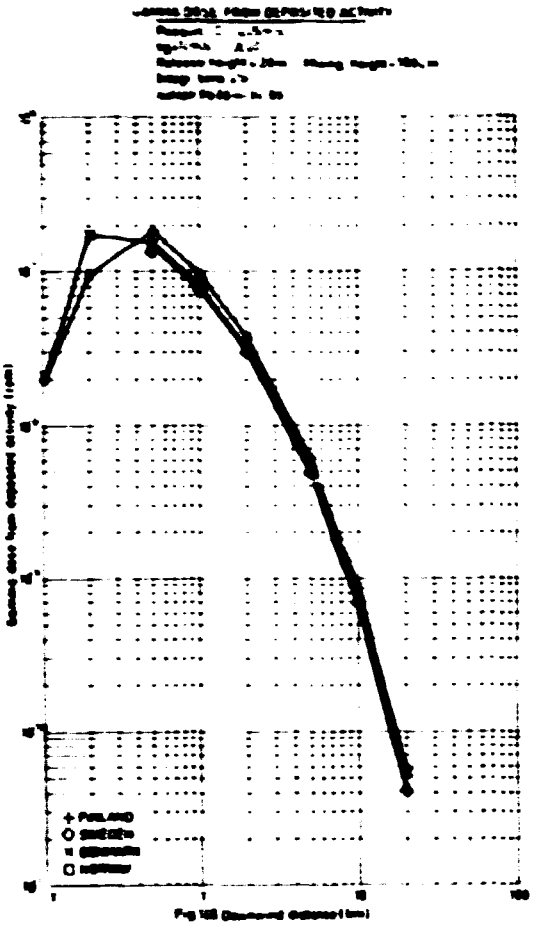


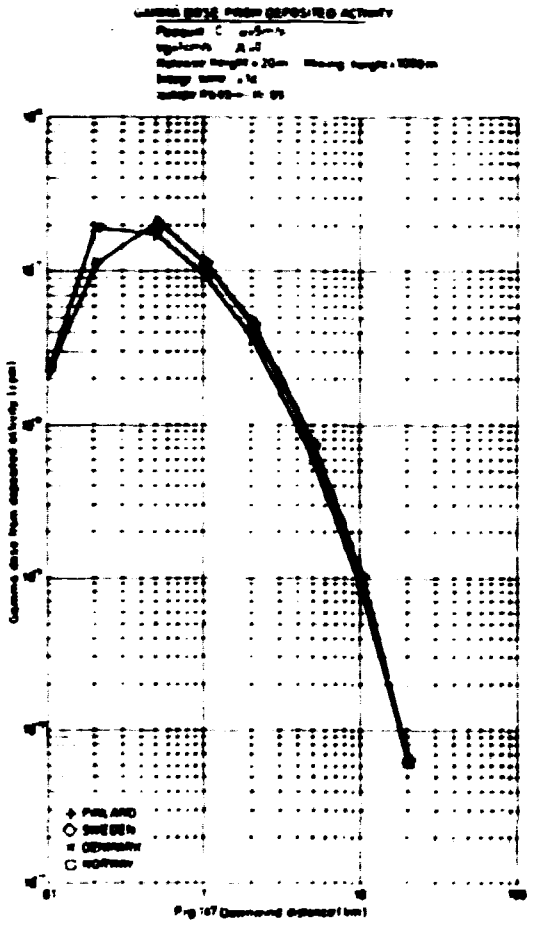
Fig 144 Downwind distance (km)

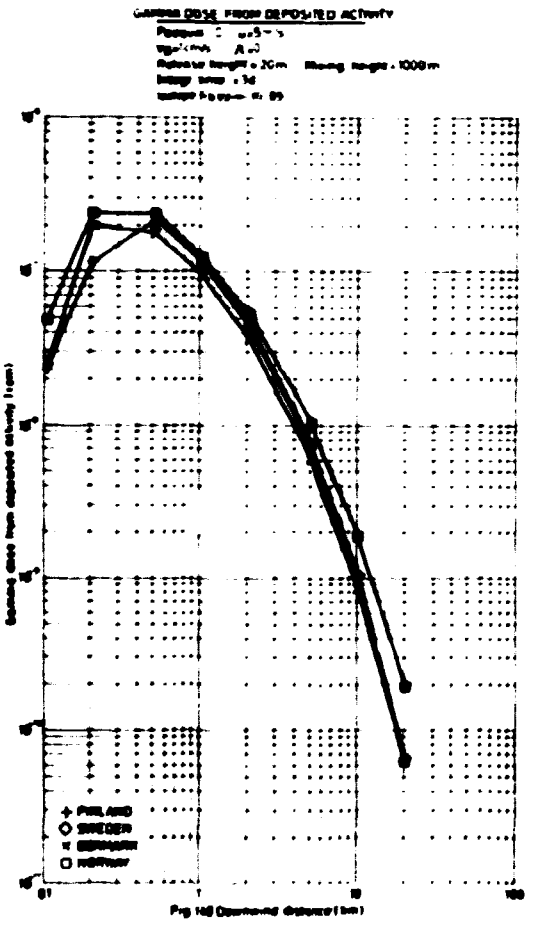
C. External gamma doses from radioactive material deposited on the ground

Fig. 145 - 344









GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =20m Mixing height=1000m
Integr time =7d
Isotope Rb89 — Kr 89

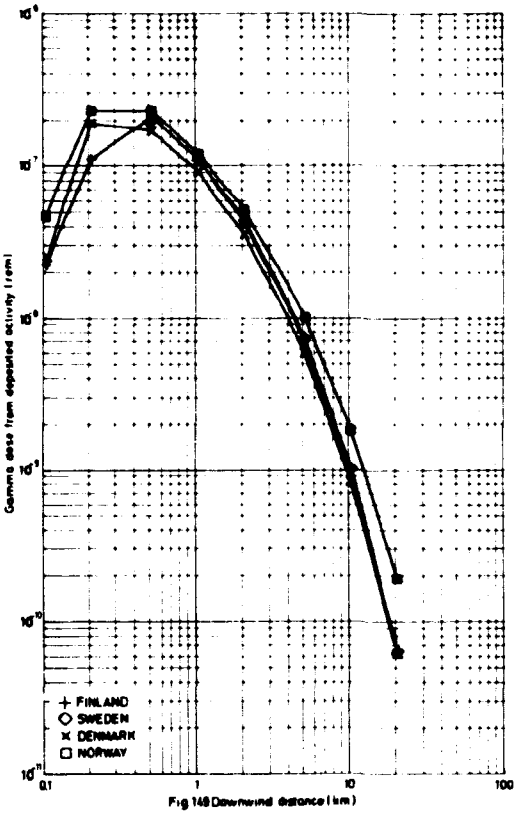


Fig 148

GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =20m Mixing height=1000m
Integr time =1s
Isotope Te132

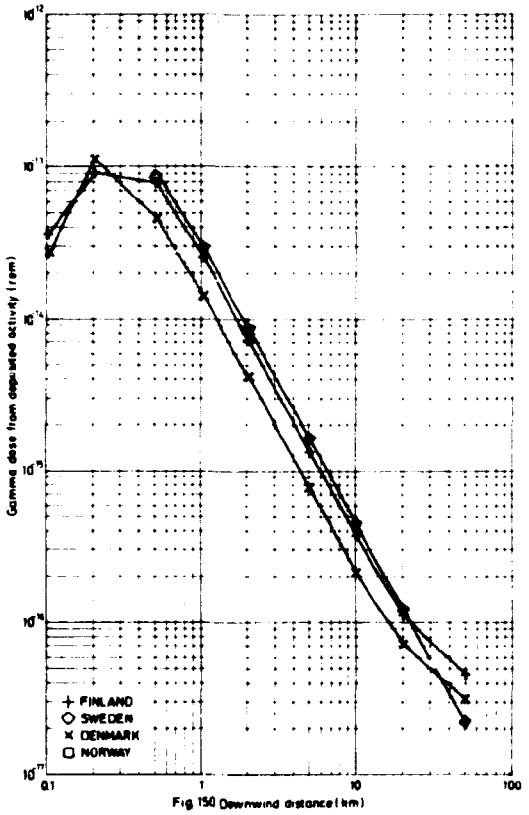


Fig 150

GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =20m Mixing height=1000m
Integr time =1h
Isotope Te132

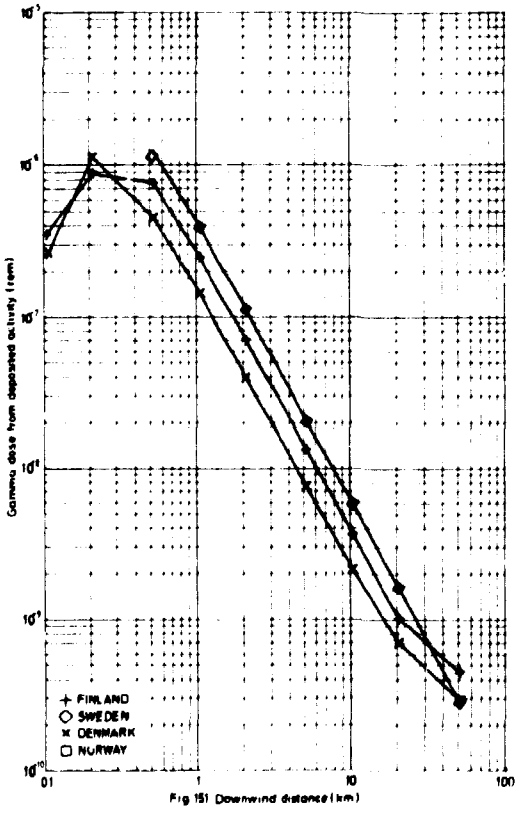


Fig 151

GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =20m Mixing height=1000m
Integr time =1d
Isotope Te132

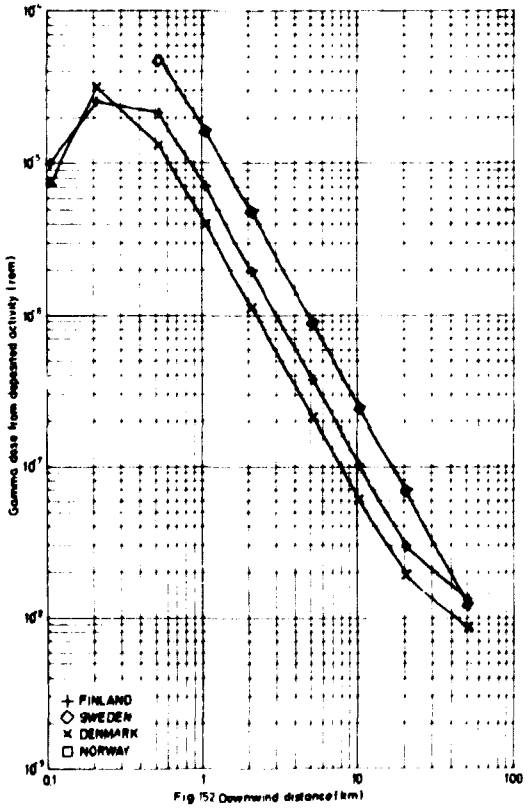


Fig 152

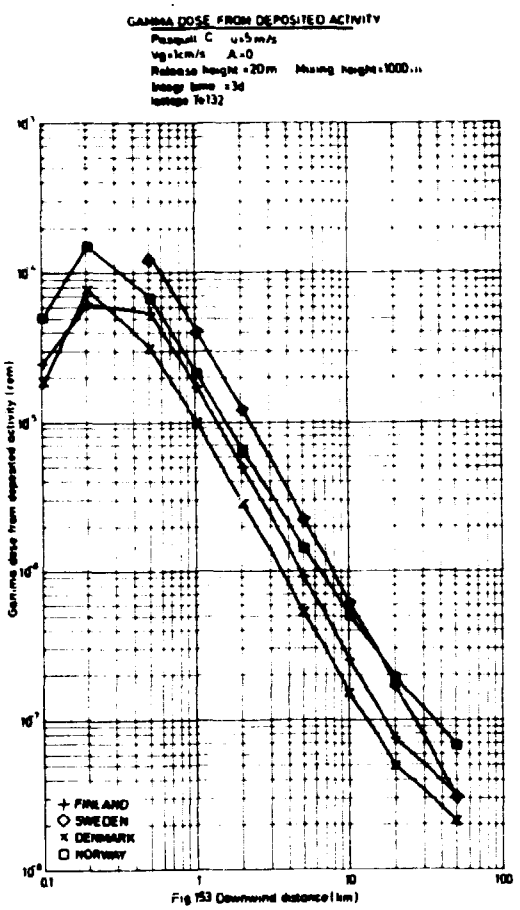


Fig 153 Downwind distance (km)

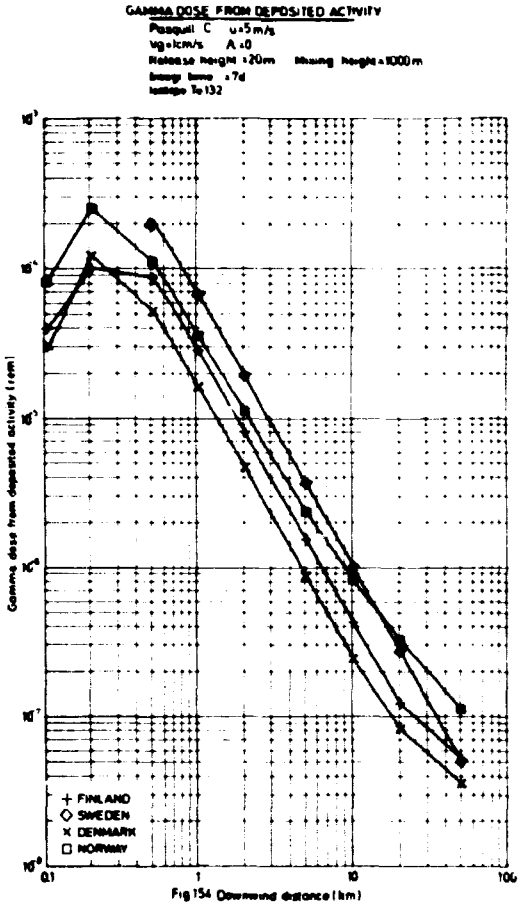


Fig 154 Downwind distance (km)

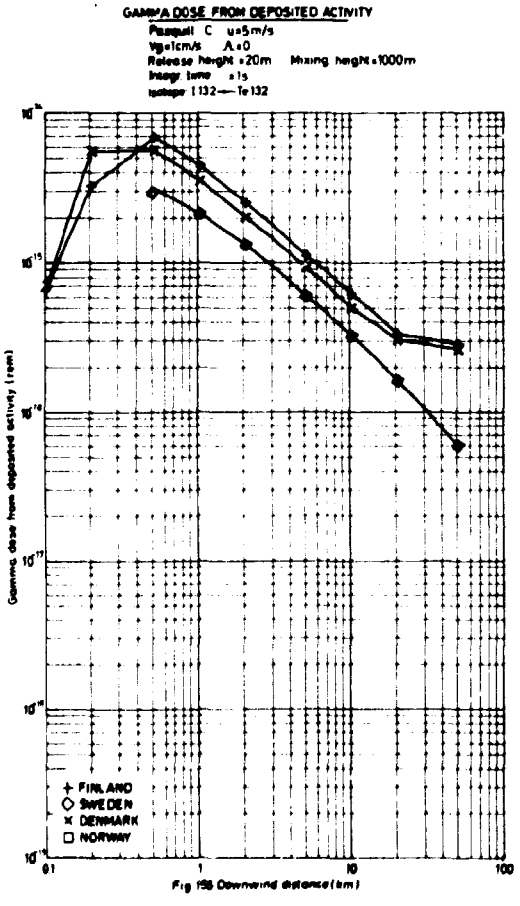


Fig 155 Downwind distance (km)

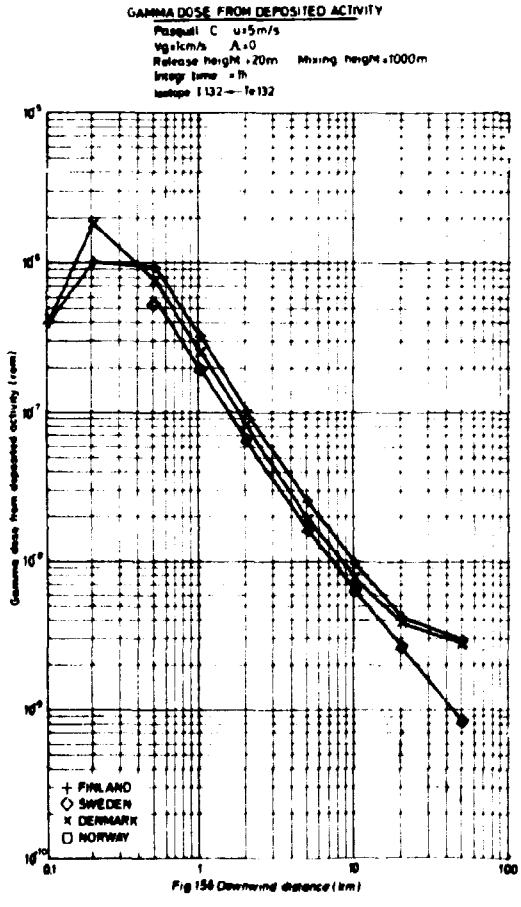


Fig 156 Downwind distance (km)

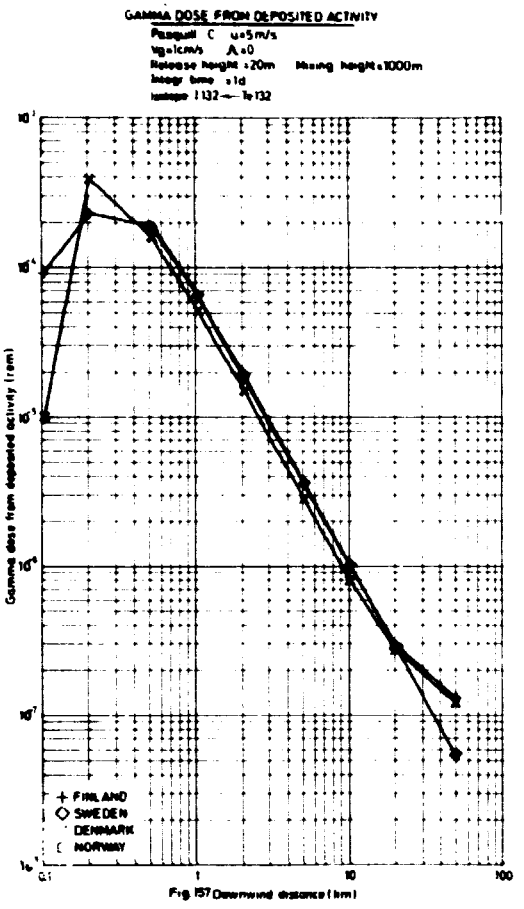


Fig 157 Downwind distance (km)

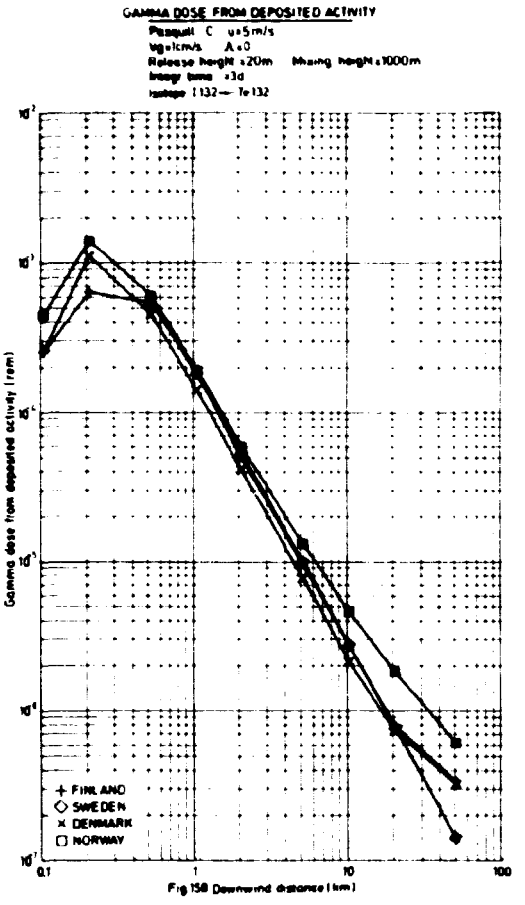


Fig 158 Downwind distance (km)

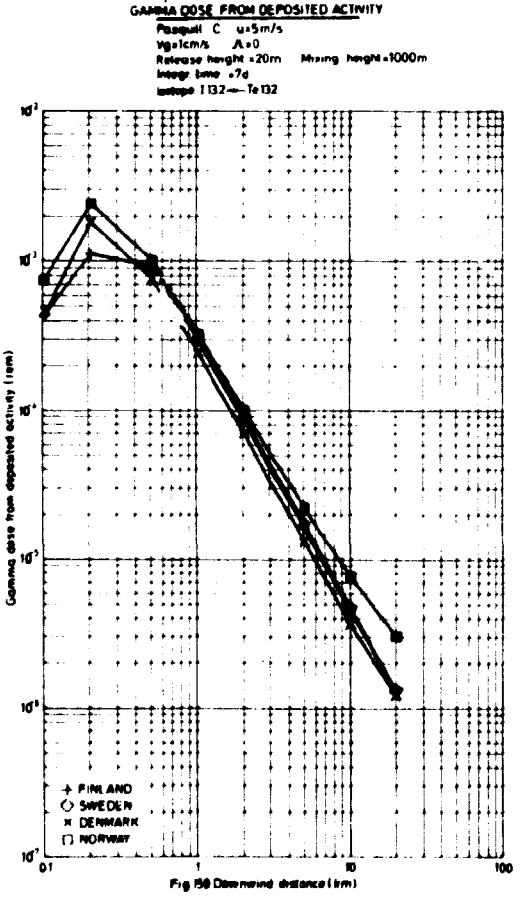


Fig 159 Downwind distance (km)

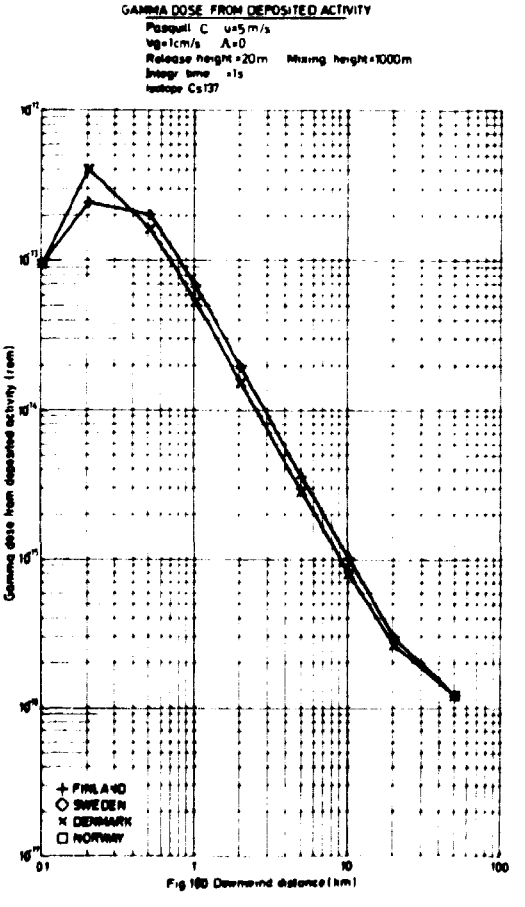


Fig 160 Downwind distance (km)

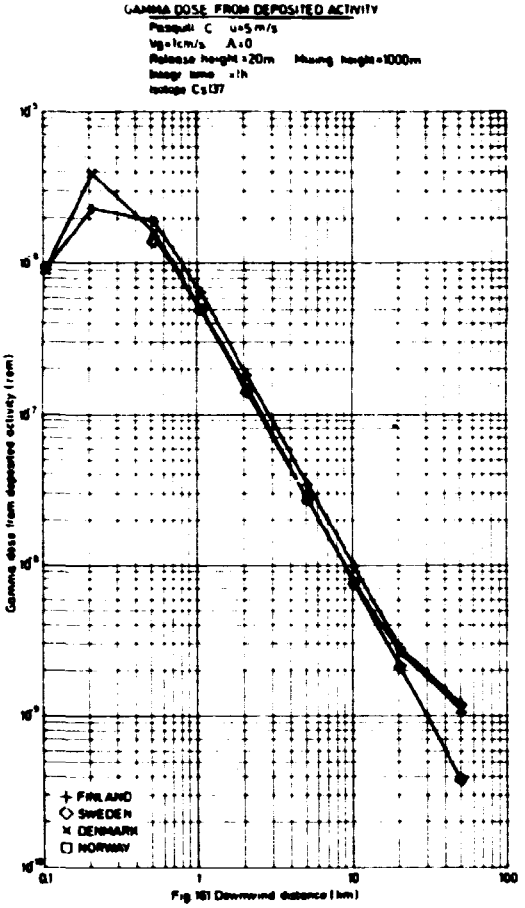


Fig 161

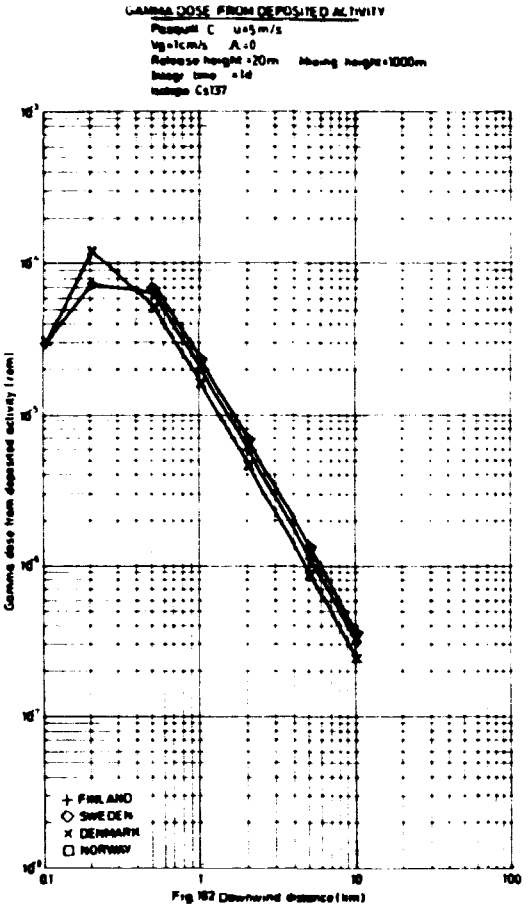


Fig 162

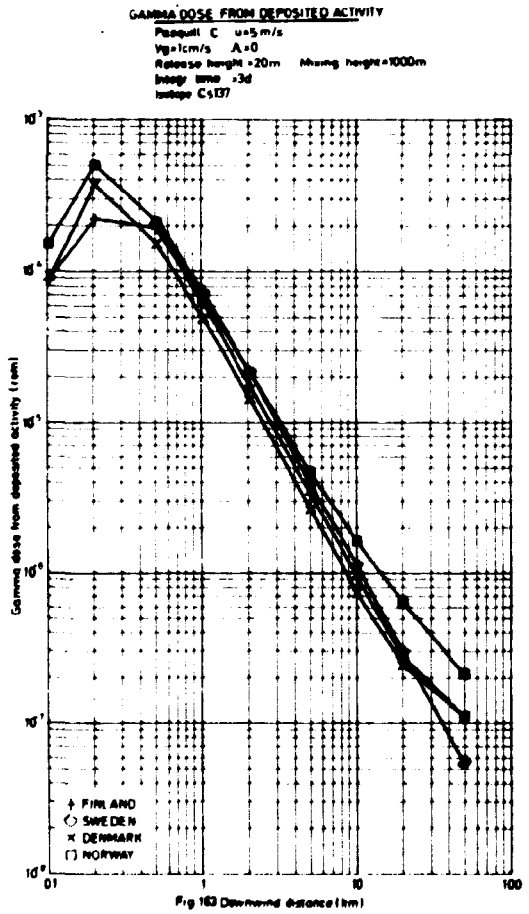


Fig 163

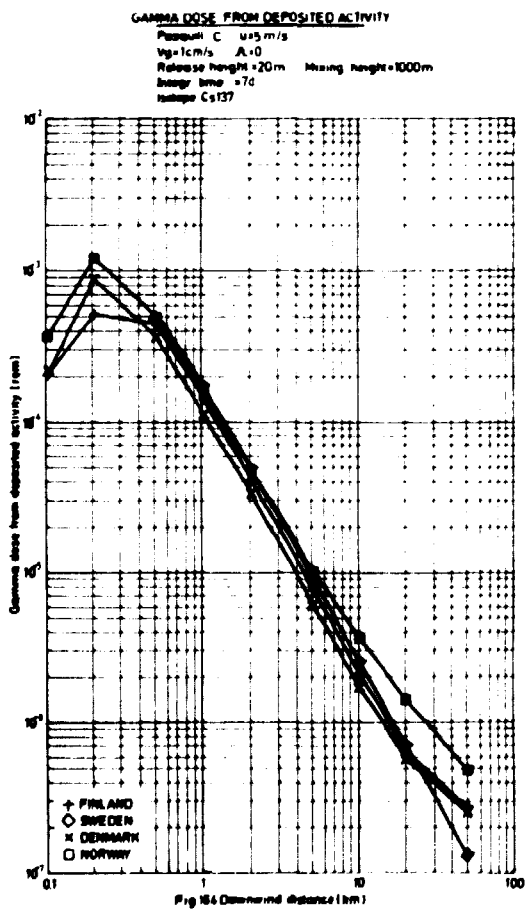
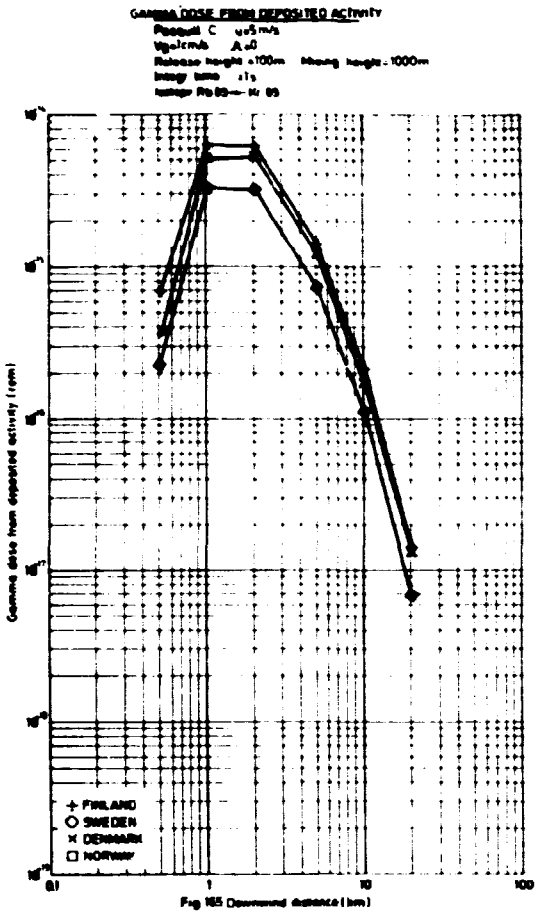
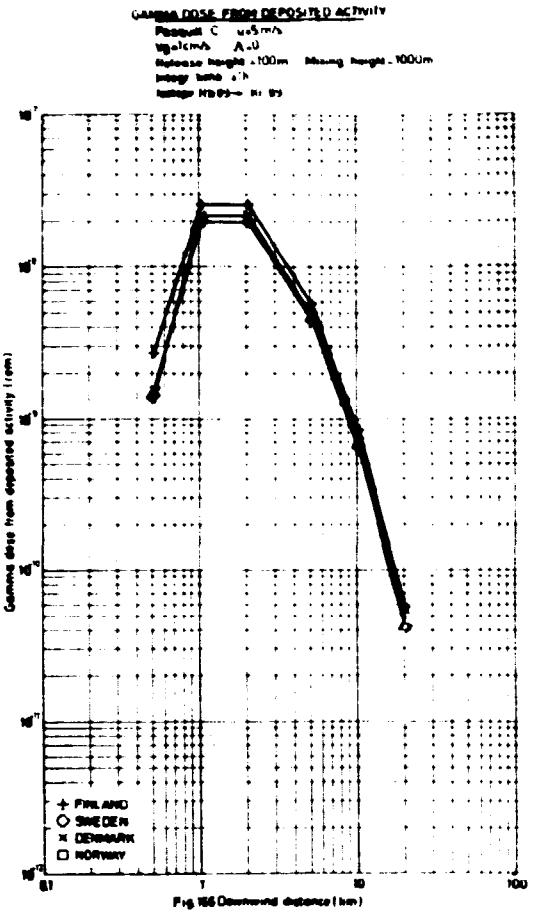
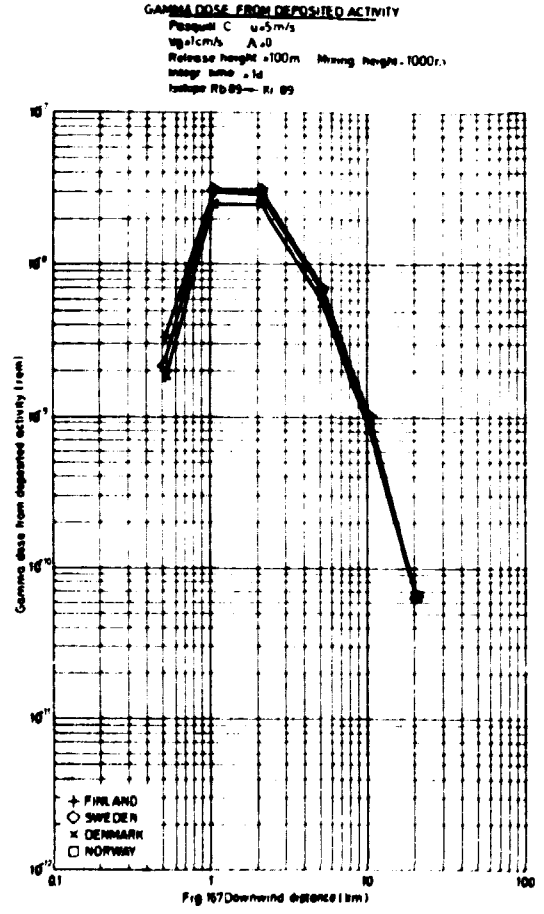
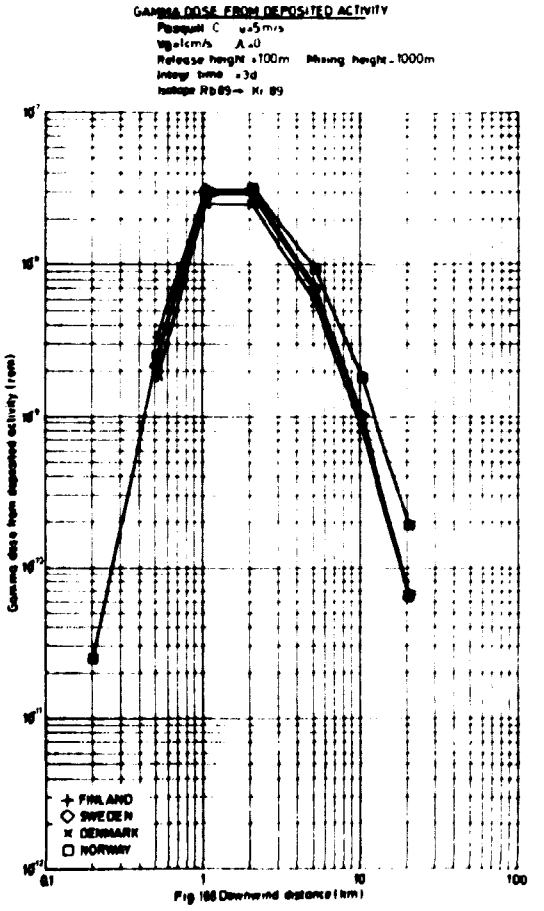


Fig 164


GAMMA DOSE FROM DEPOSITED ACTIVITY
Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =100m Mixing height = 1000m
Integr time =1s
Isotope Rb 89 → Kr 89
Gamma dose from deposited activity (rem)
+ FINLAND
○ SWEDEN
× DENMARK
□ NORWAY
0.1
1
10
100
Fig 165 Downwind distance (km)


GAMMA DOSE FROM DEPOSITED ACTIVITY
Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =100m Mixing height = 1000m
Integr time =1h
Isotope Rb 89 → Kr 89
Gamma dose from deposited activity (rem)
+ FINLAND
○ SWEDEN
× DENMARK
□ NORWAY
0.1
1
10
100
Fig 166 Downwind distance (km)


GAMMA DOSE FROM DEPOSITED ACTIVITY
Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =100m Mixing height = 1000m
Integr time =1d
Isotope Rb 89 → Kr 89
Gamma dose from deposited activity (rem)
+ FINLAND
○ SWEDEN
× DENMARK
□ NORWAY
0.1
1
10
100
Fig 167 Downwind distance (km)


GAMMA DOSE FROM DEPOSITED ACTIVITY
Pasquill C u=5m/s
Vg=1cm/s A=0
Release height =100m Mixing height = 1000m
Integr time =3d
Isotope Rb 89 → Kr 89
Gamma dose from deposited activity (rem)
+ FINLAND
○ SWEDEN
× DENMARK
□ NORWAY
0.1
1
10
100
Fig 168 Downwind distance (km)

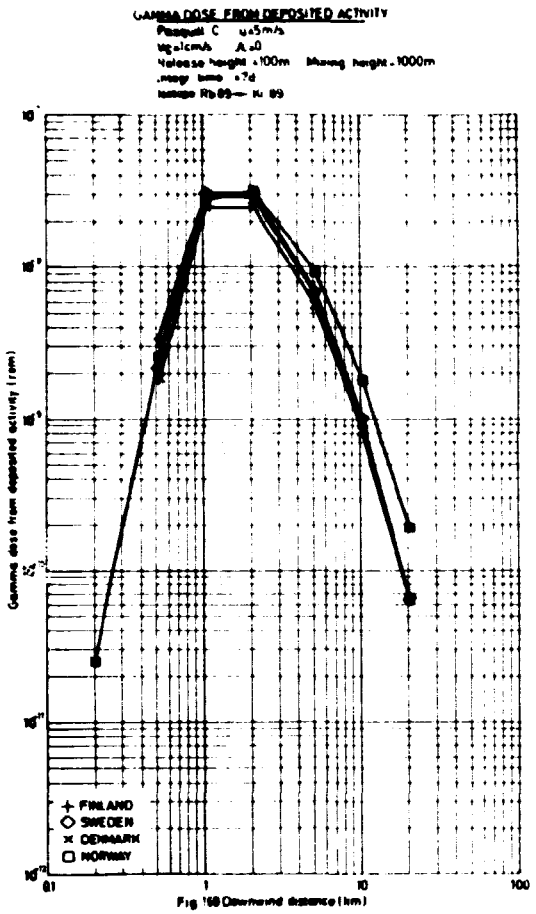


Fig 169

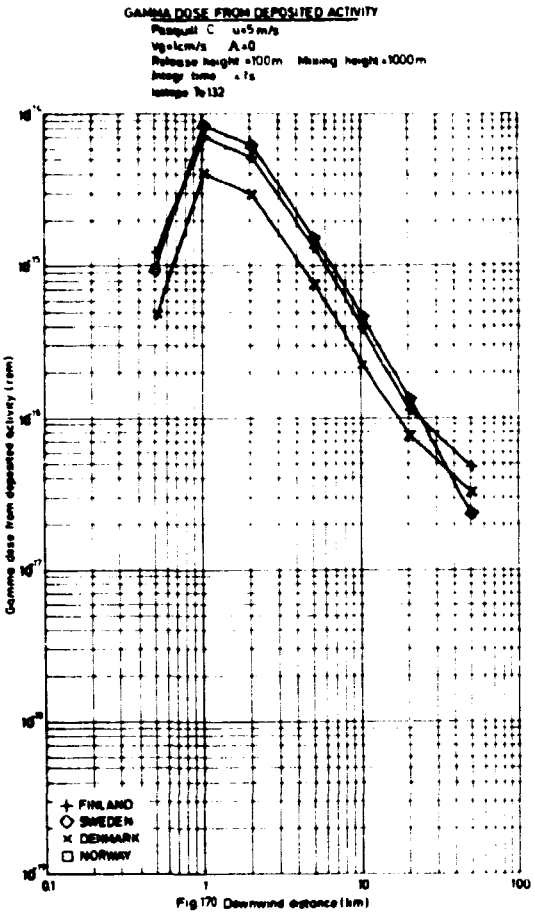


Fig 170

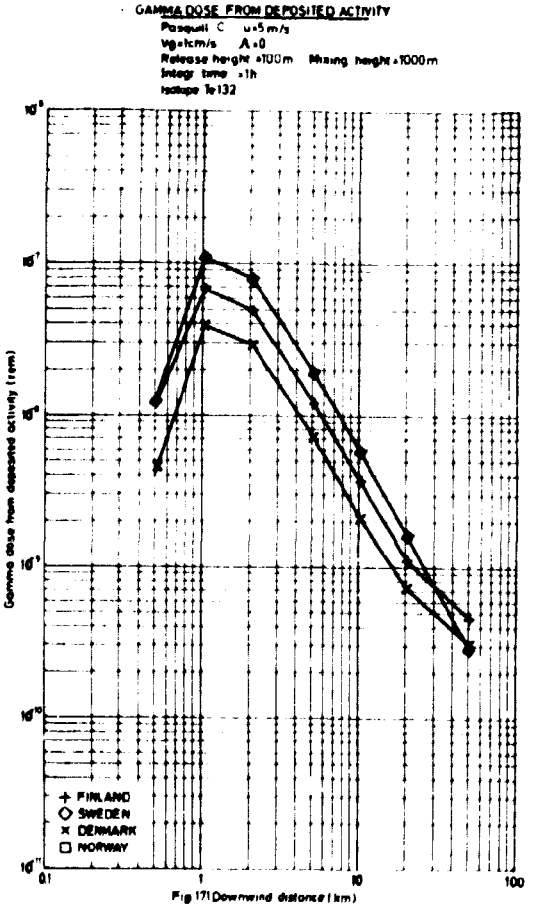


Fig 171

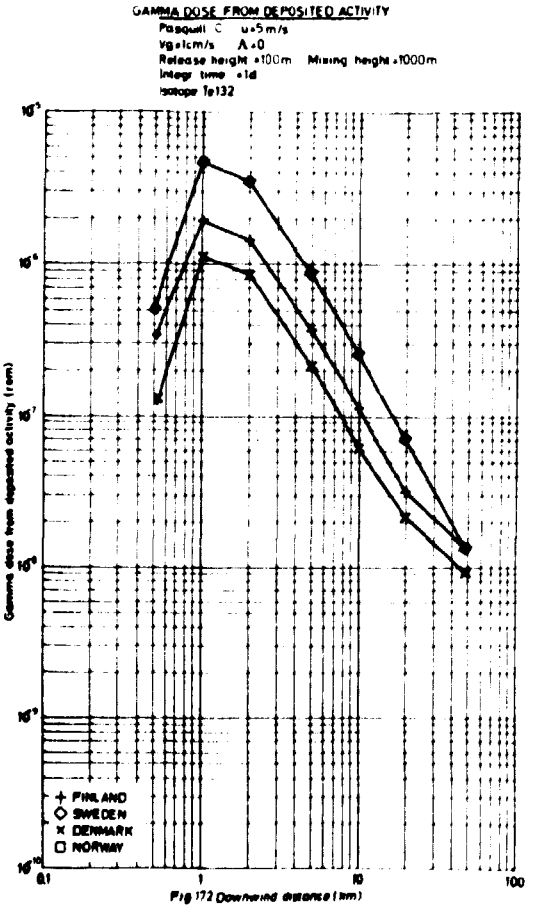


Fig 172

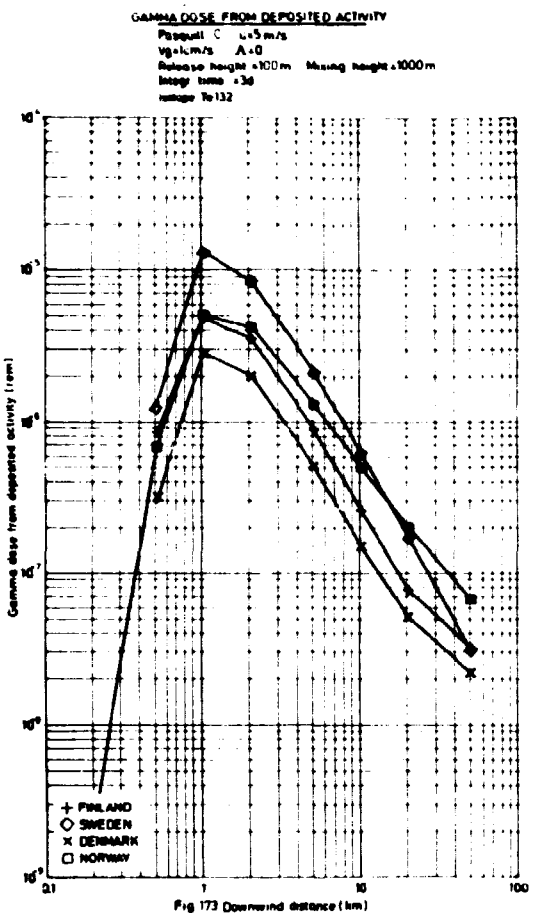


Fig 173 Downwind distance (km)

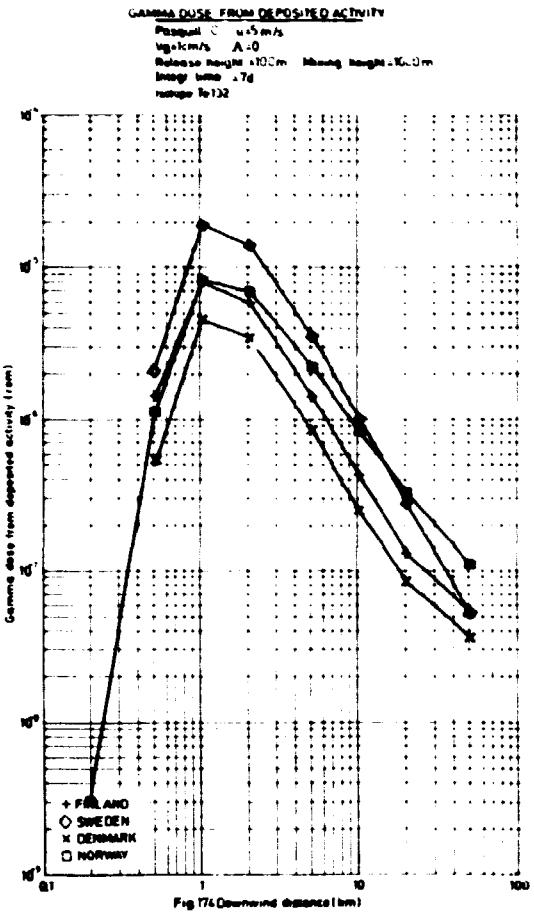


Fig 174 Downwind distance (km)

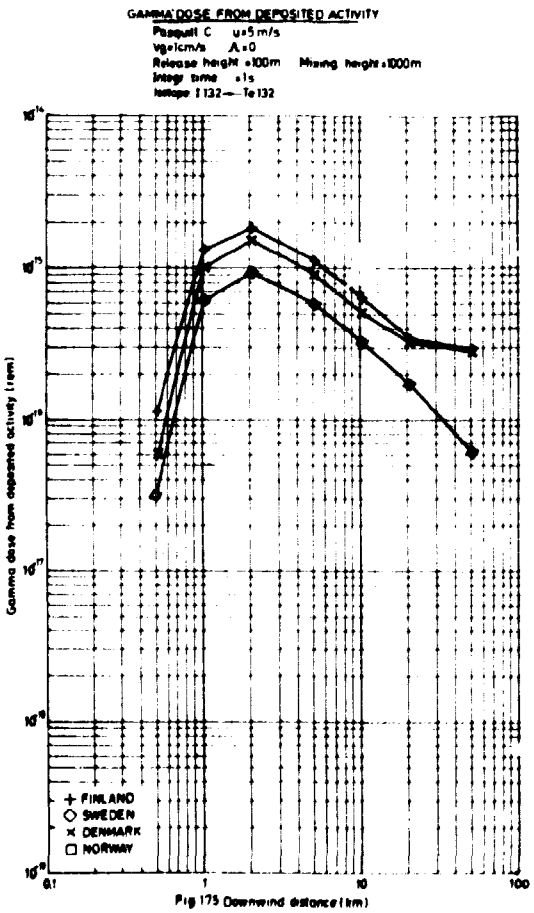


Fig 175 Downwind distance (km)

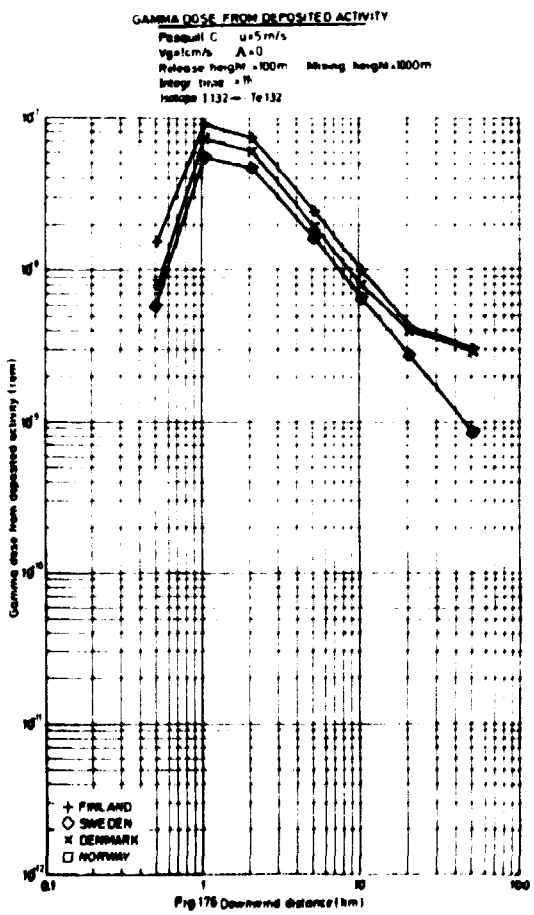
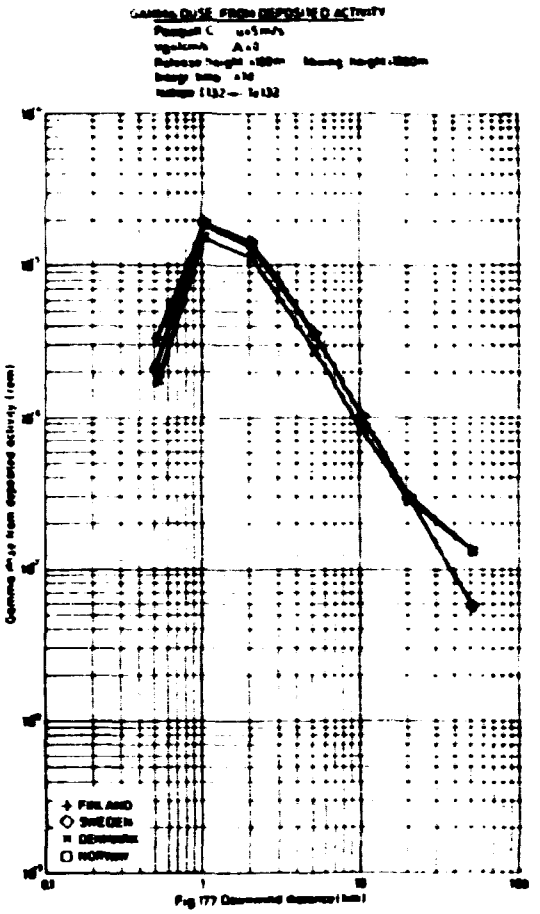
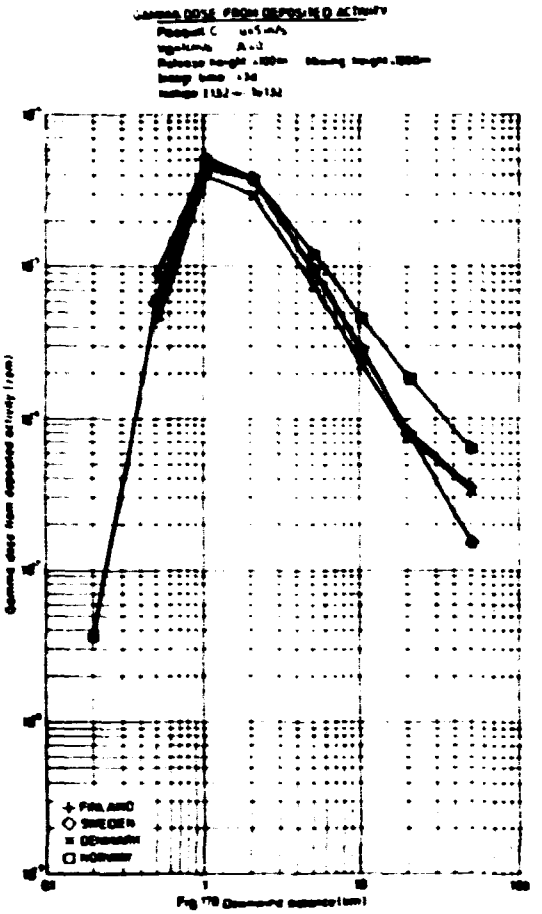
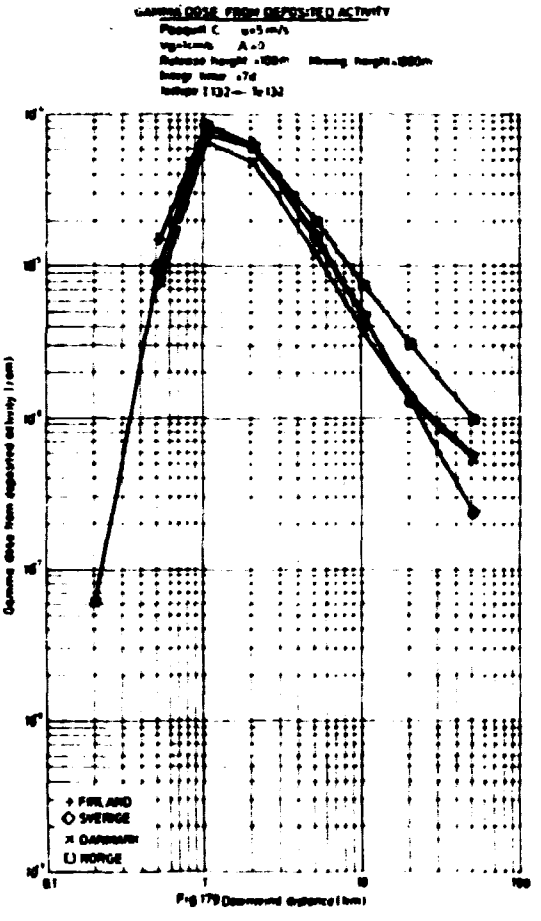
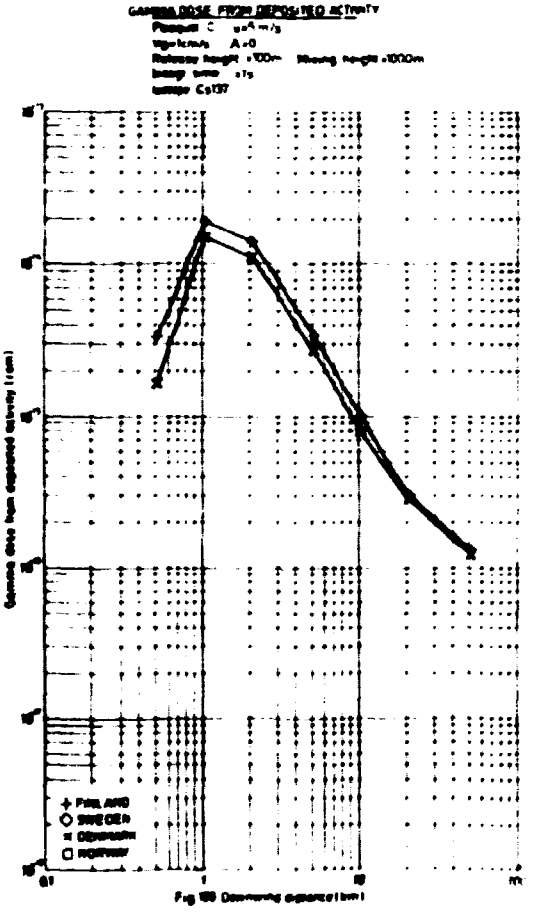


Fig 176 Downwind distance (km)


+ FINLAND
◇ SWEDEN
× DENMARK
□ NORWAY


+ FINLAND
◇ SWEDEN
× DENMARK
□ NORWAY


+ FINLAND
◇ SWEDEN
× DENMARK
□ NORWAY


+ FINLAND
◇ SWEDEN
× DENMARK
□ NORWAY

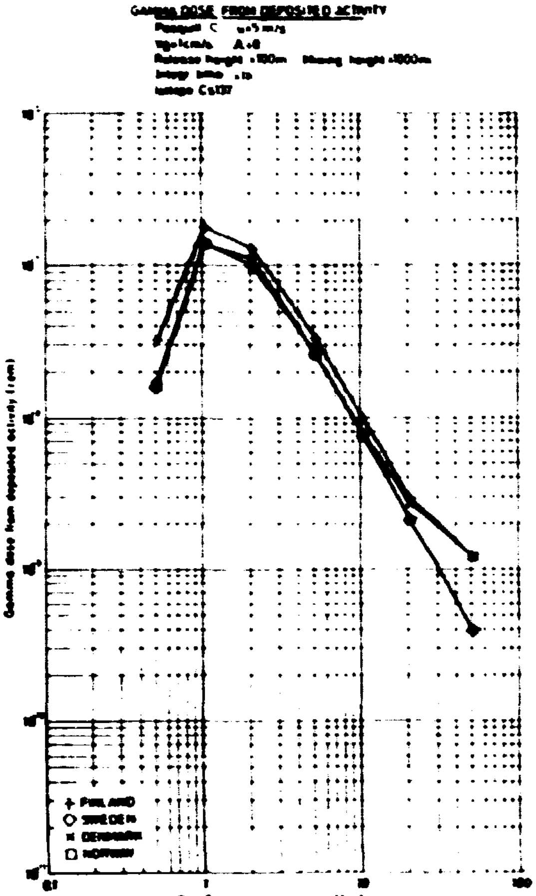


Fig 181 Downwind distance (km)

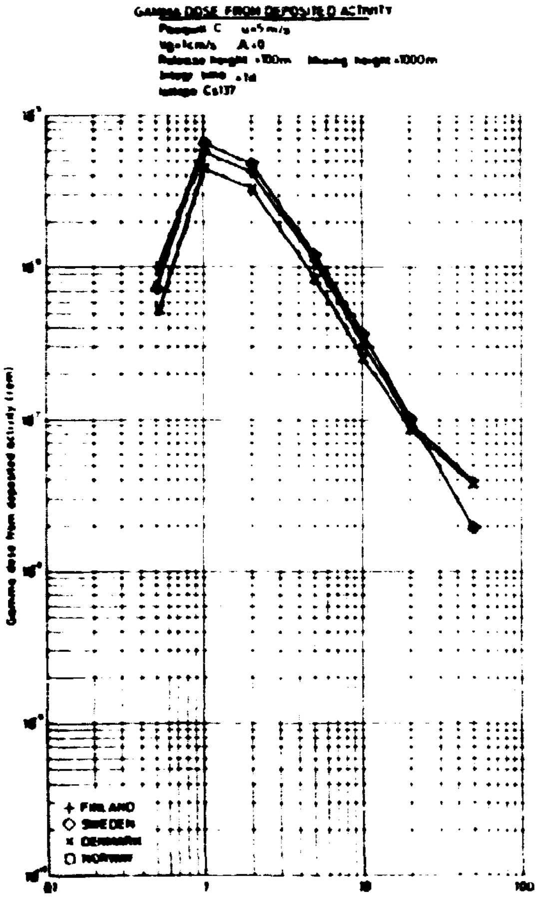


Fig 182 Downwind distance (km)

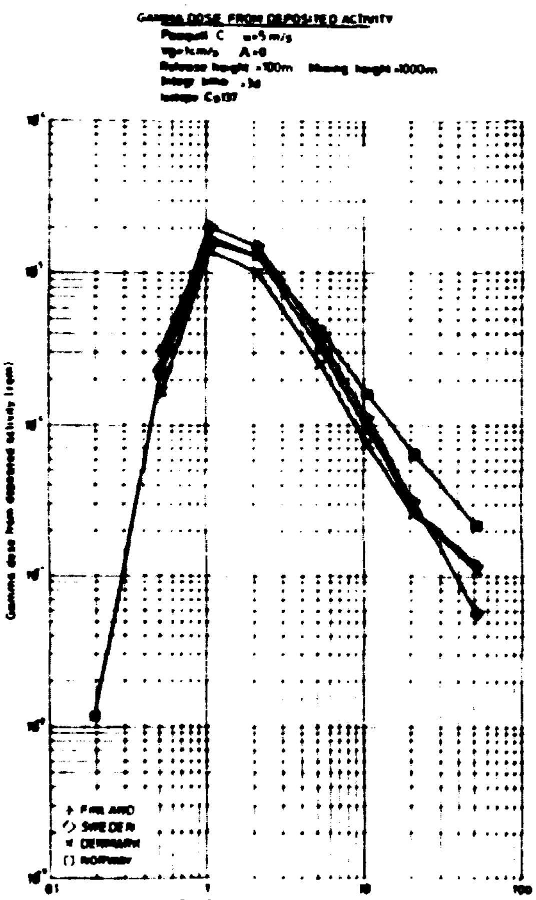


Fig 183 Downwind distance (km)

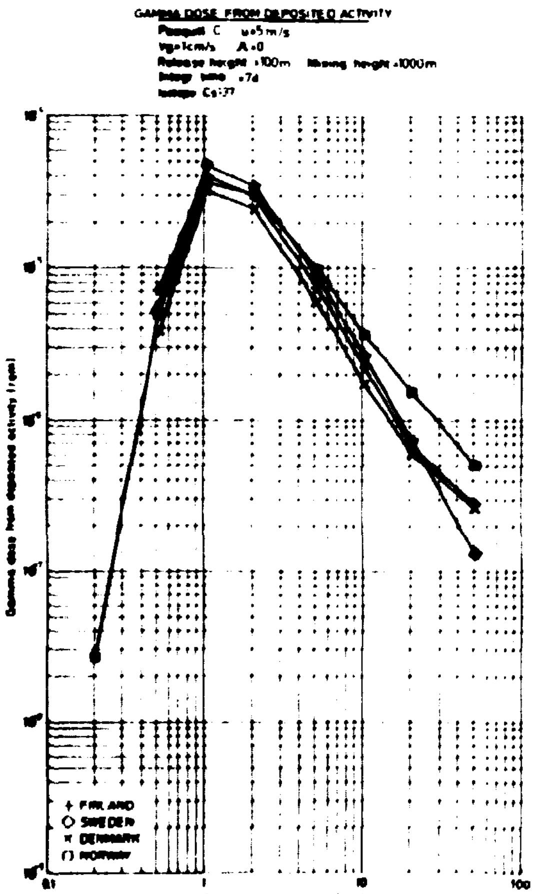


Fig 184 Downwind distance (km)

GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill F u = 2m/s
v_g = 1cm/s A = 0
Release height = 20 m Mixing height = 200 m
Integr. time = 1s
Isotope Rb 89 → Kr 89

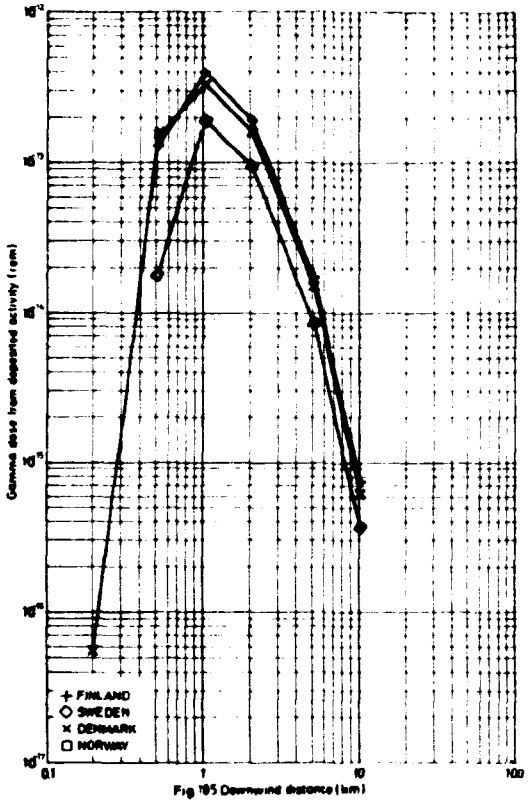


Fig 185

GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill F u = 2m/s
v_g = 1cm/s A = 0
Release height = 20 m Mixing height = 200 m
Integr. time = 1h
Isotope Rb 89 → Kr 89

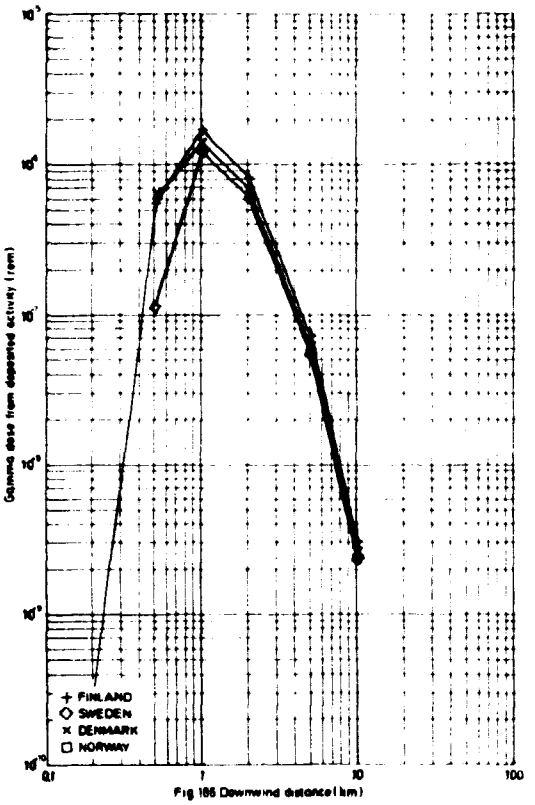


Fig 186

GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill F u = 2m/s
v_g = 1cm/s A = 0
Release height = 20 m Mixing height = 200 m
Integr. time = 1d
Isotope Rb 89 → Kr 89

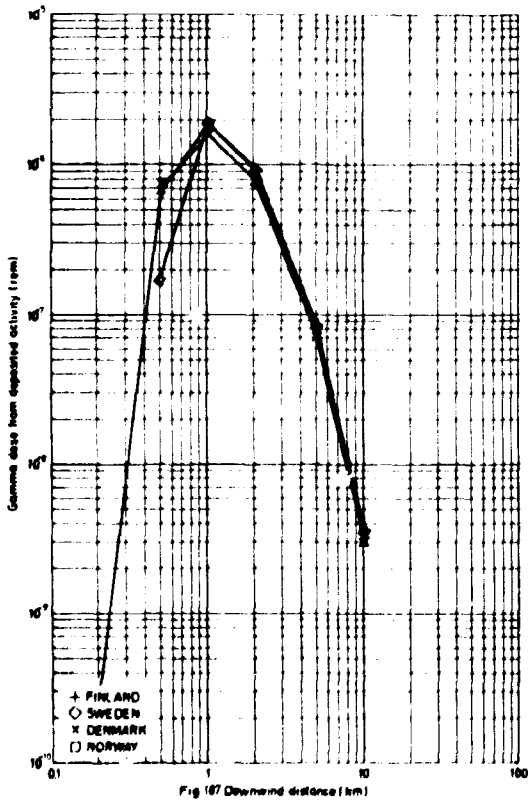


Fig 187

GAMMA DOSE FROM DEPOSITED ACTIVITY

Pasquill F u = 2m/s
v_g = 1cm/s A = 0
Release height = 20 m Mixing height = 200 m
Integr. time = 3d
Isotope Rb 89 → Kr 89

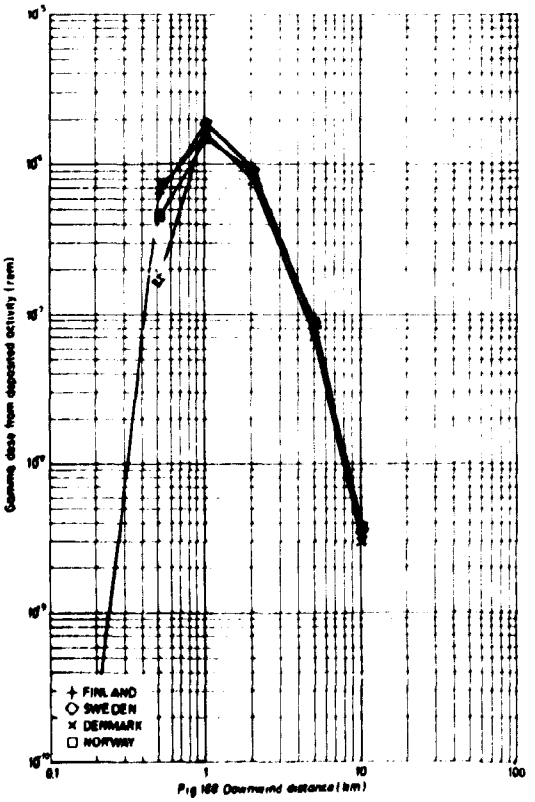


Fig 188

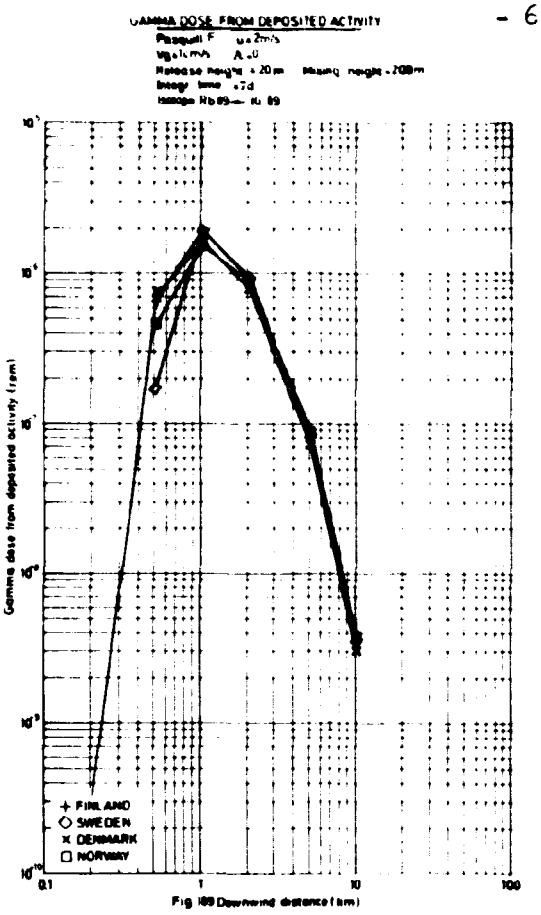
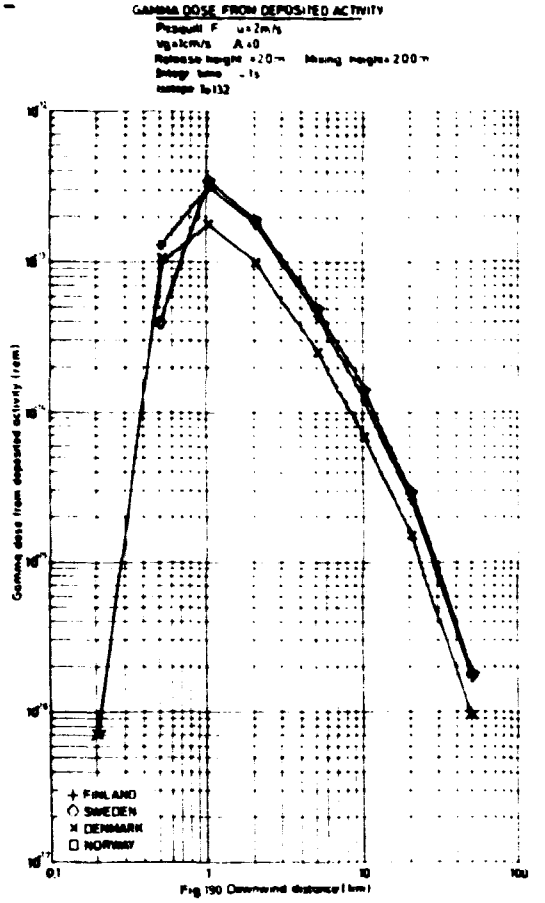


Fig 189 Downwind distance (km)



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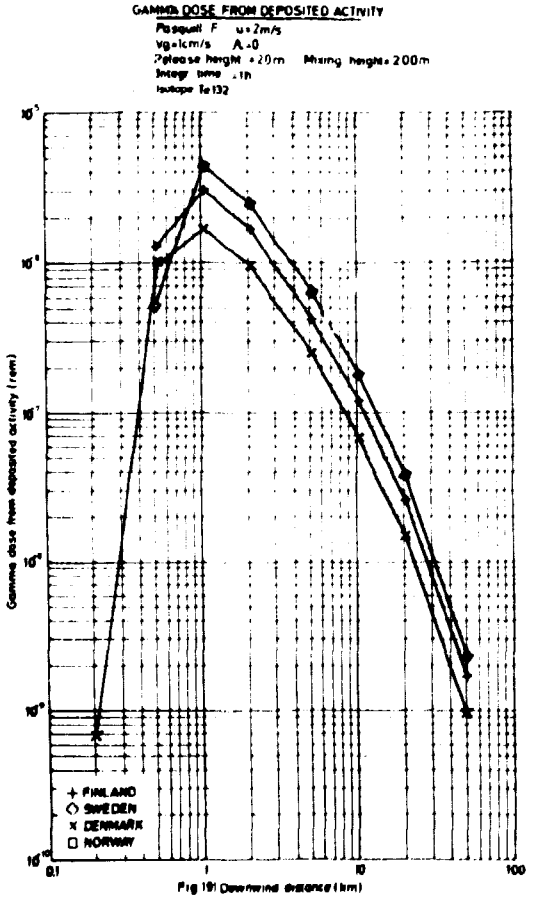

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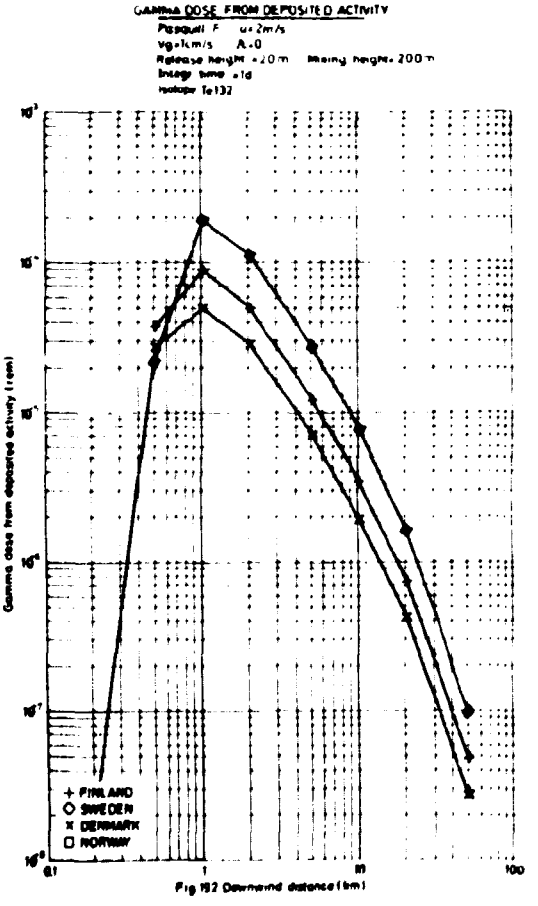

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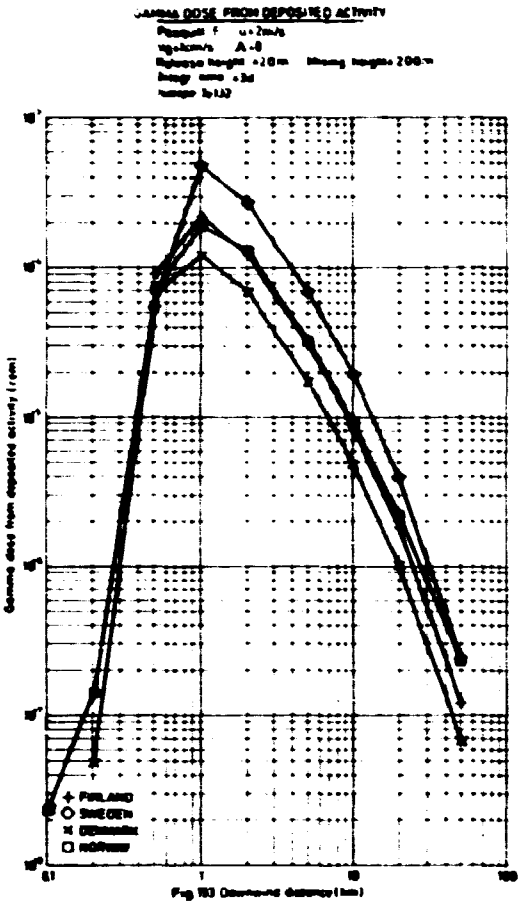
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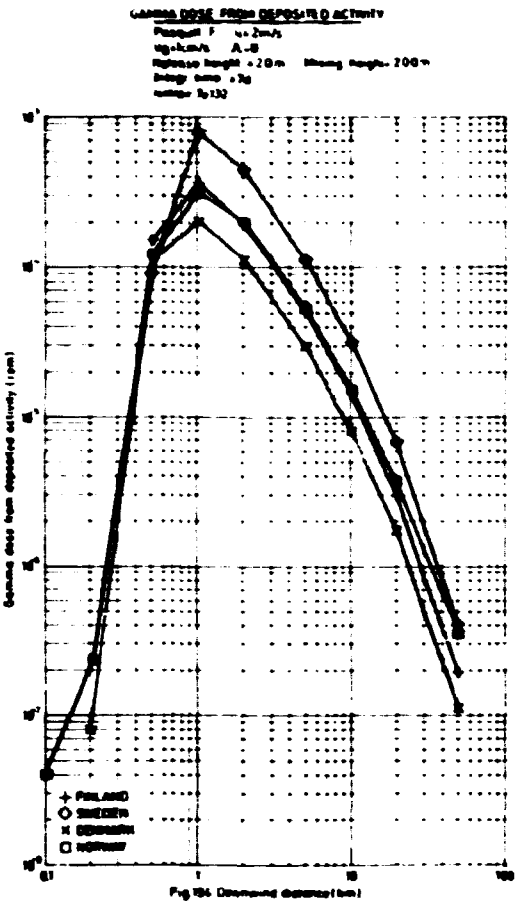
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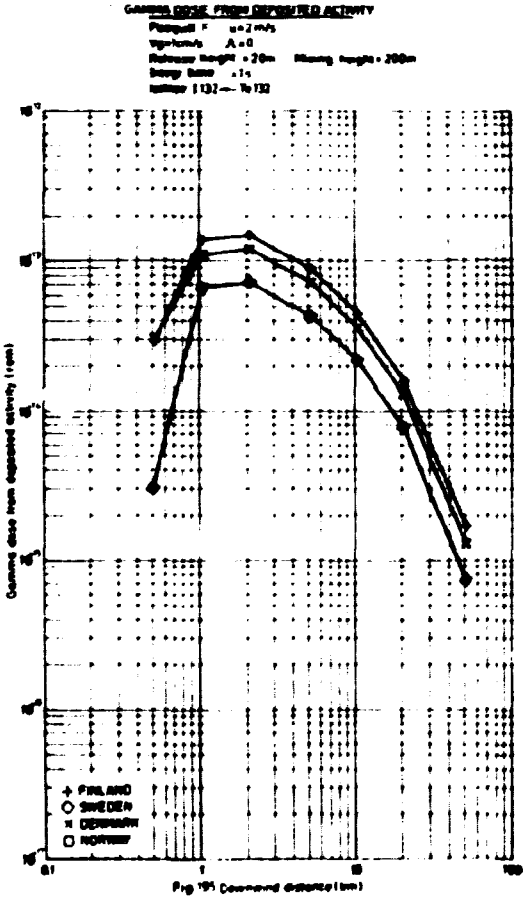
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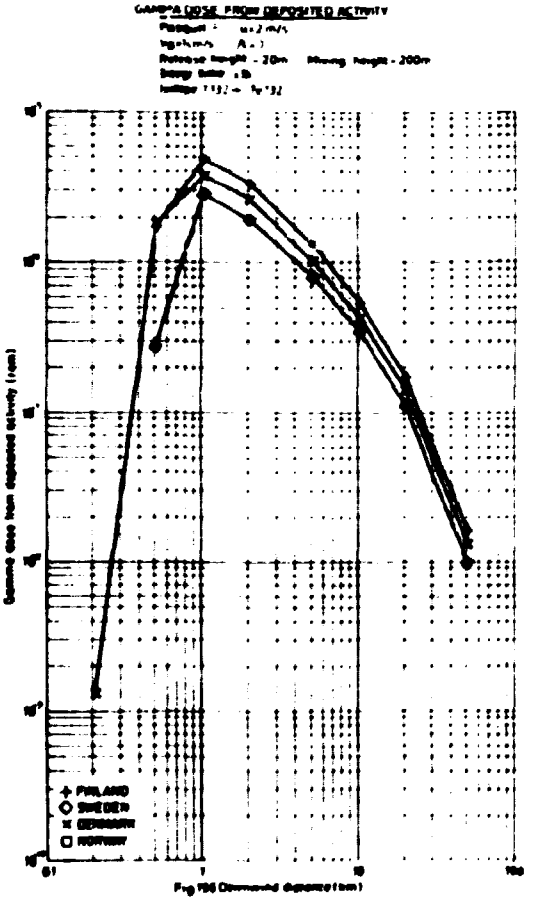
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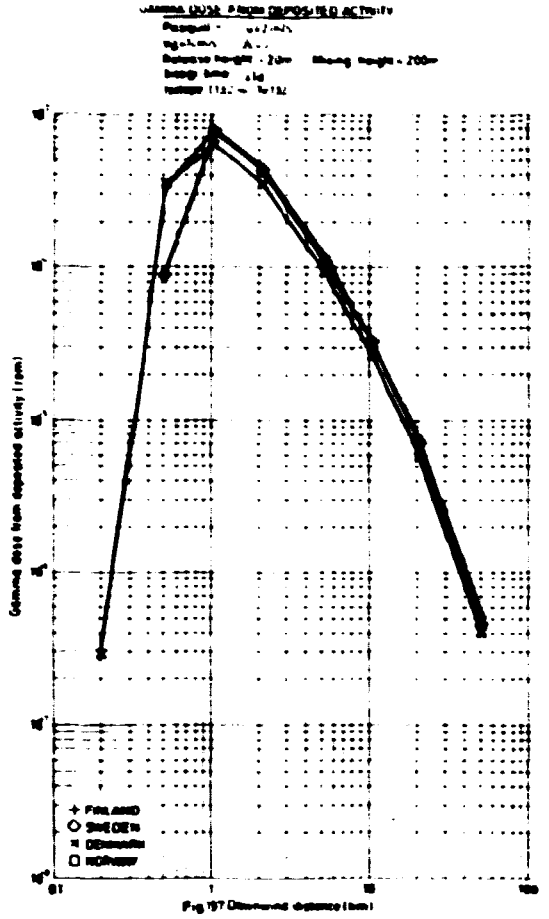
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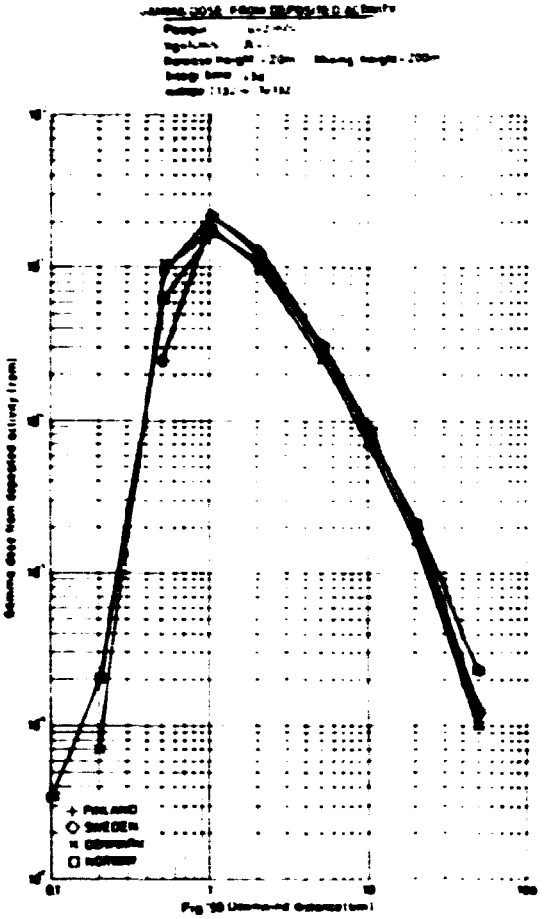
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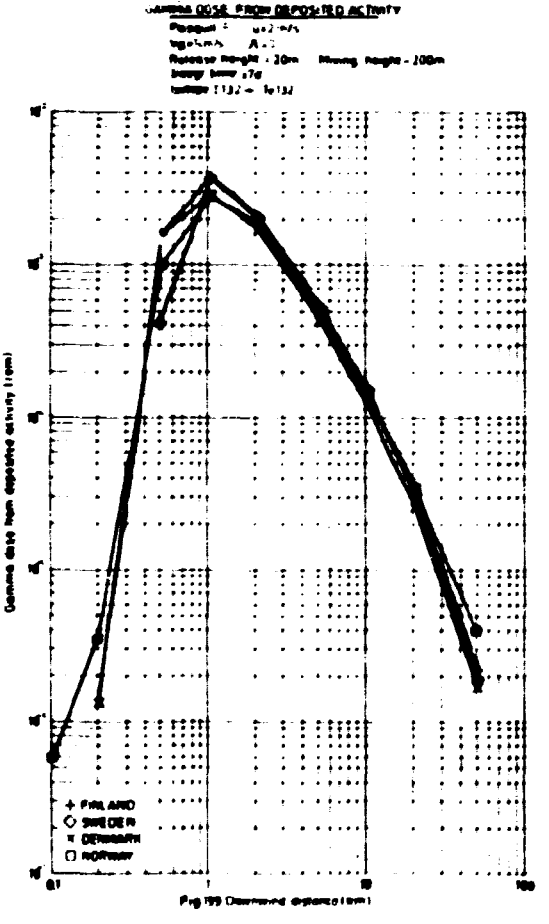
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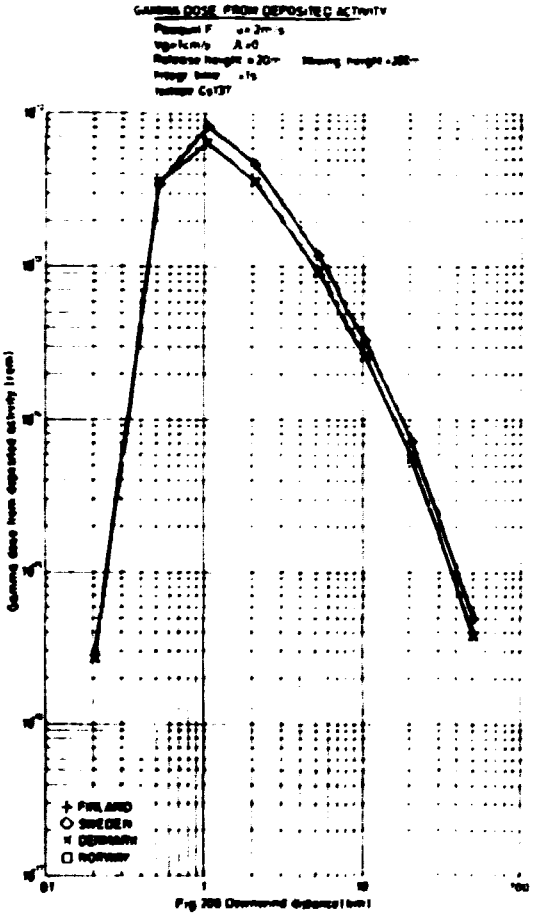
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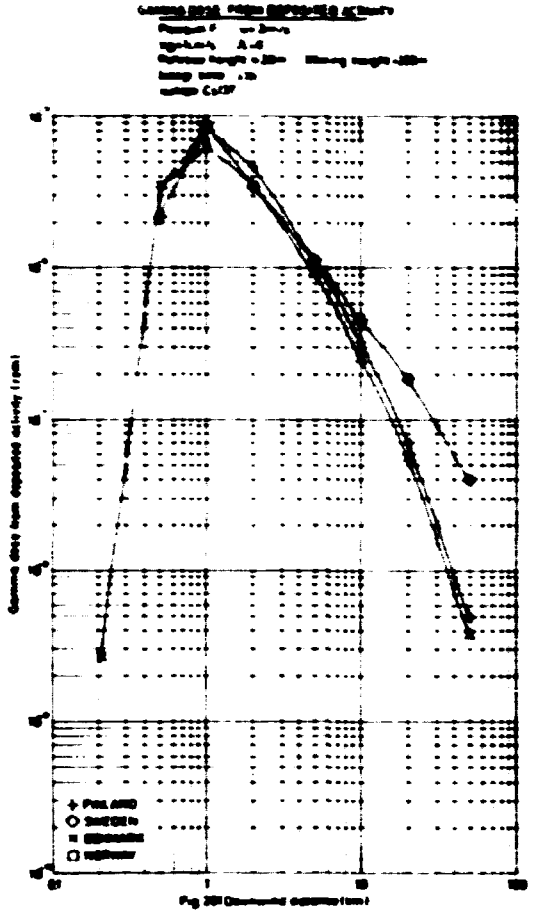
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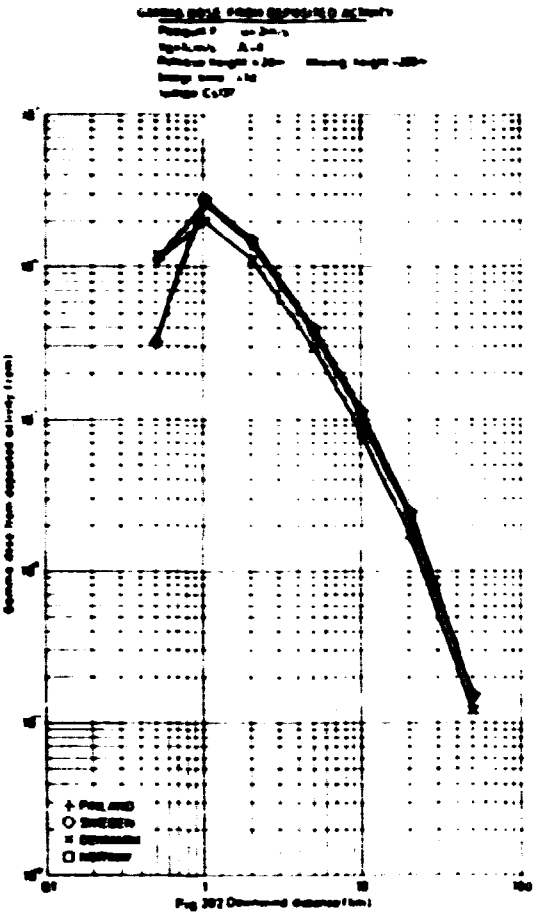
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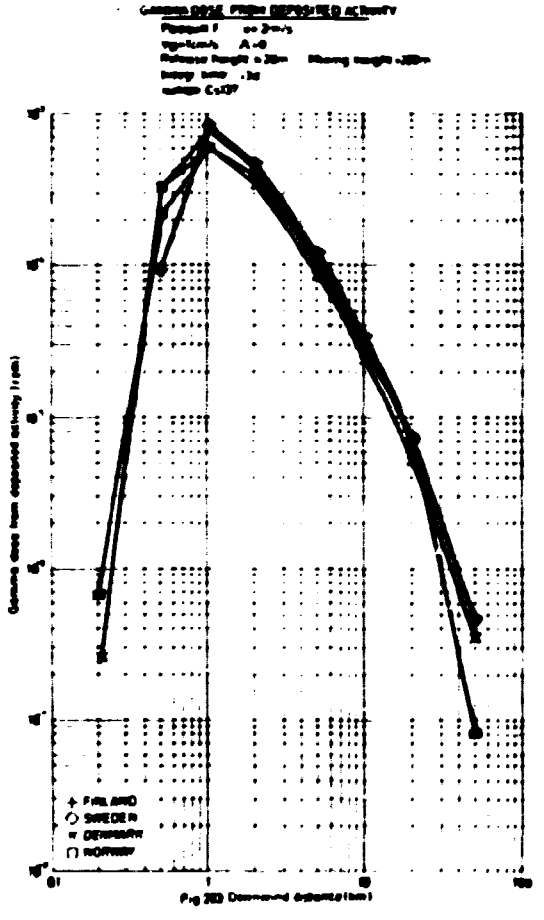
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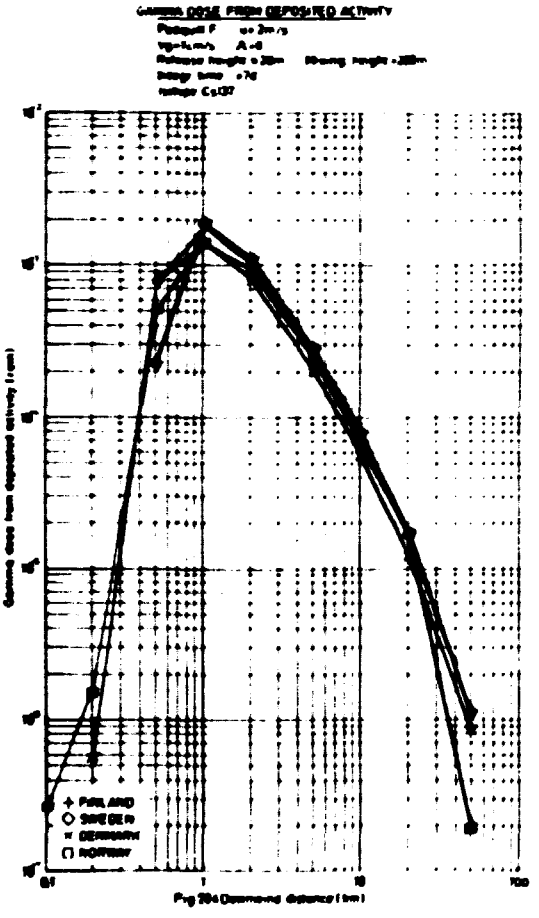
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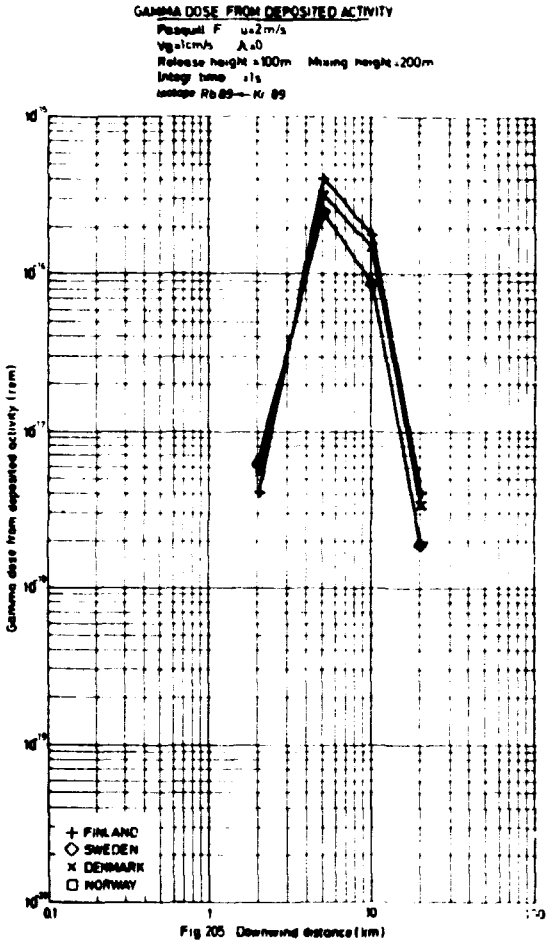
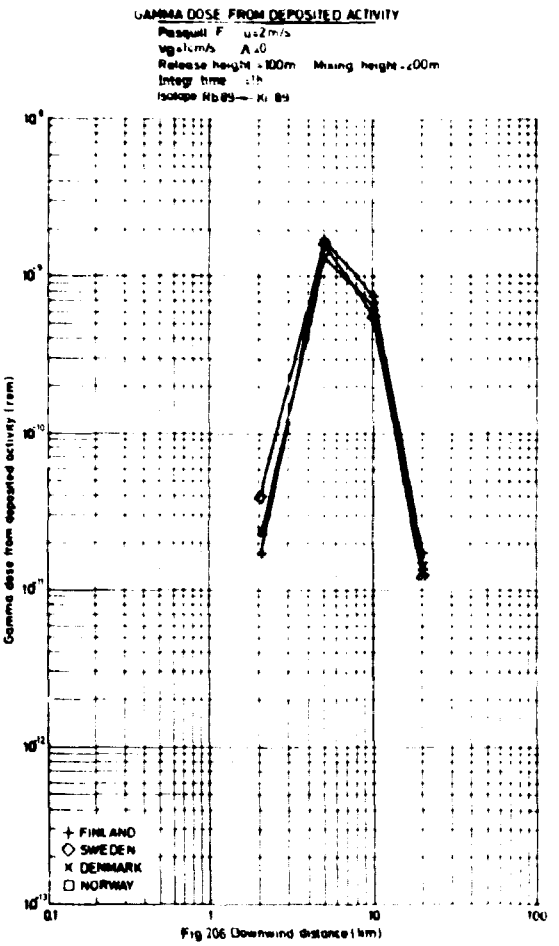


Fig 205 Downwind distance (km)



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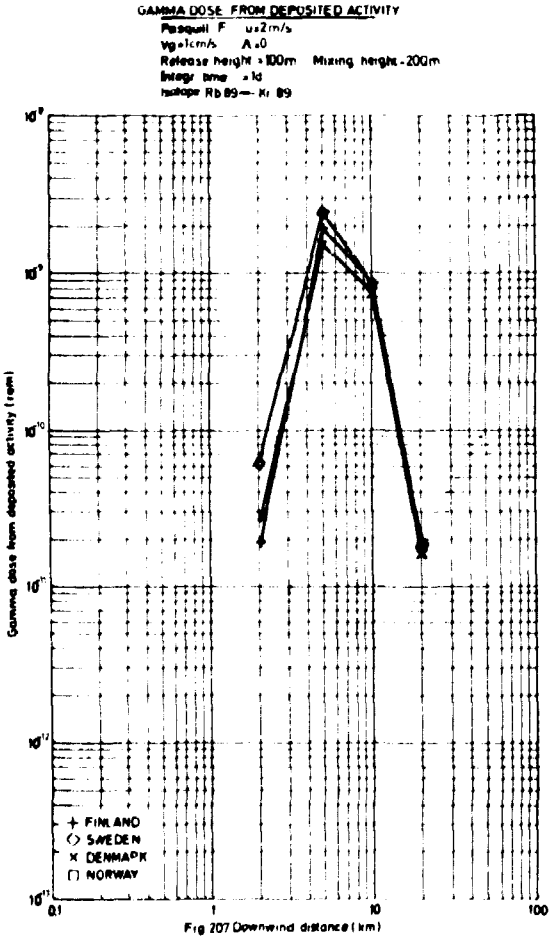

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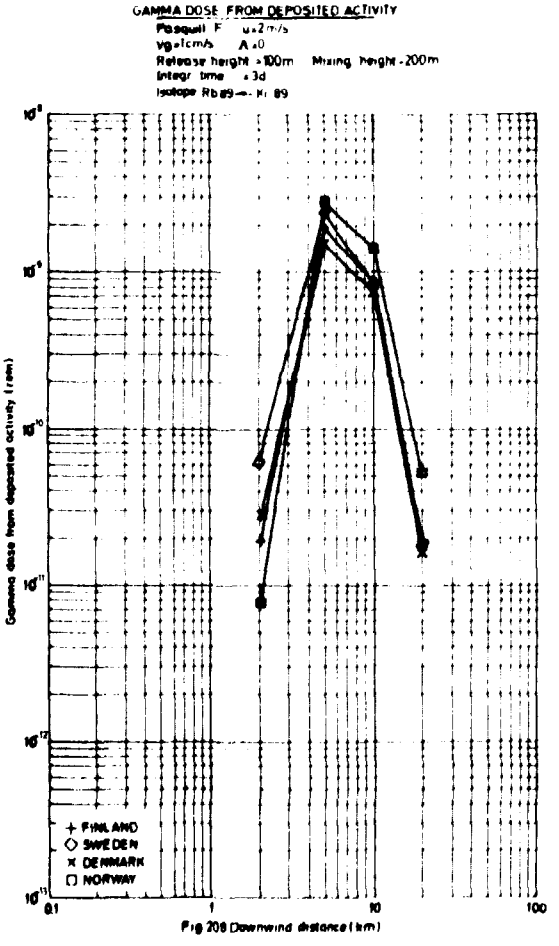

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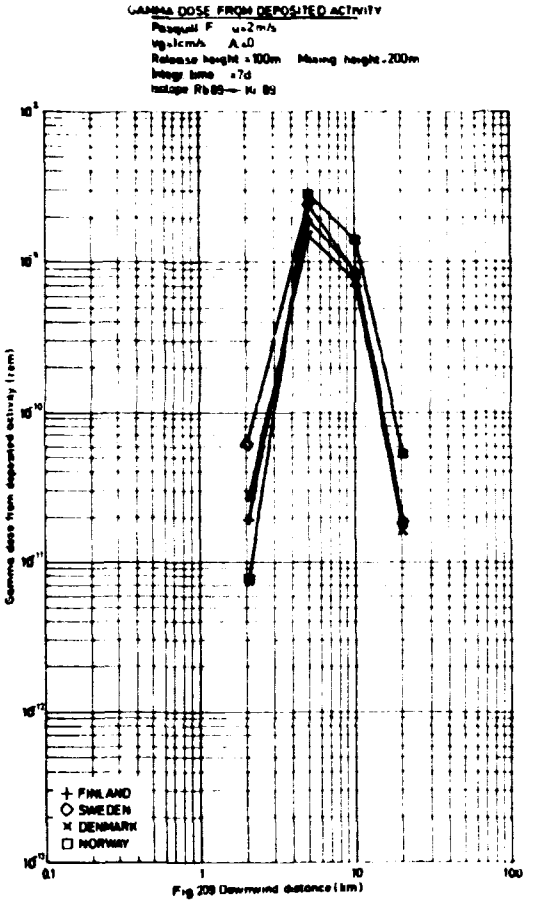
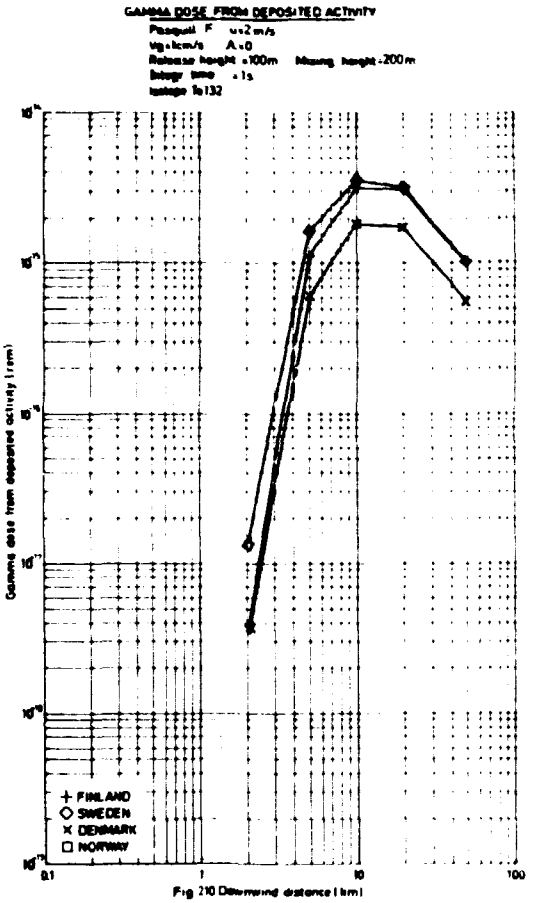


Fig 208



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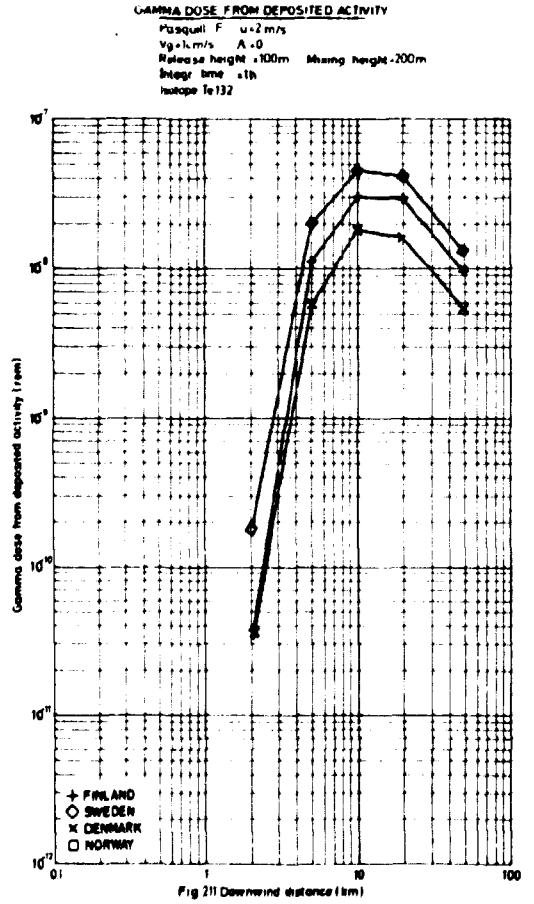

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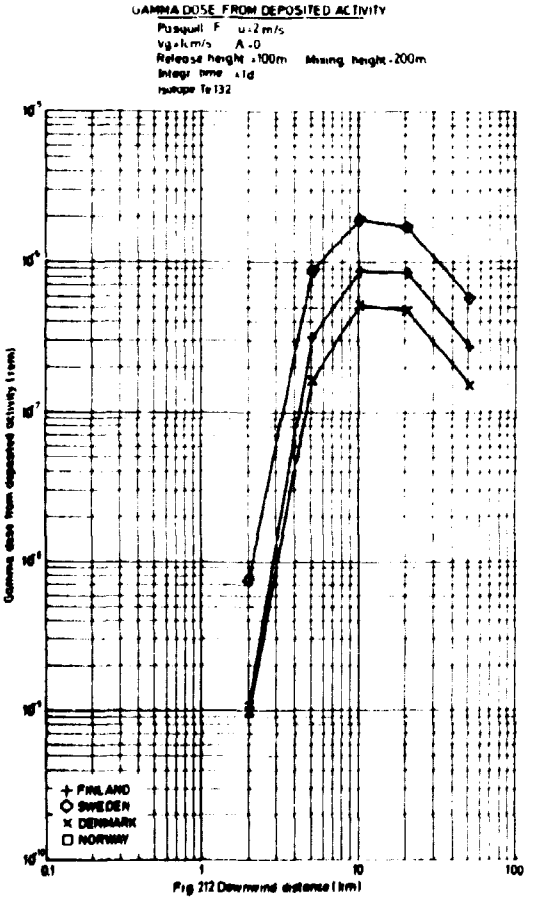

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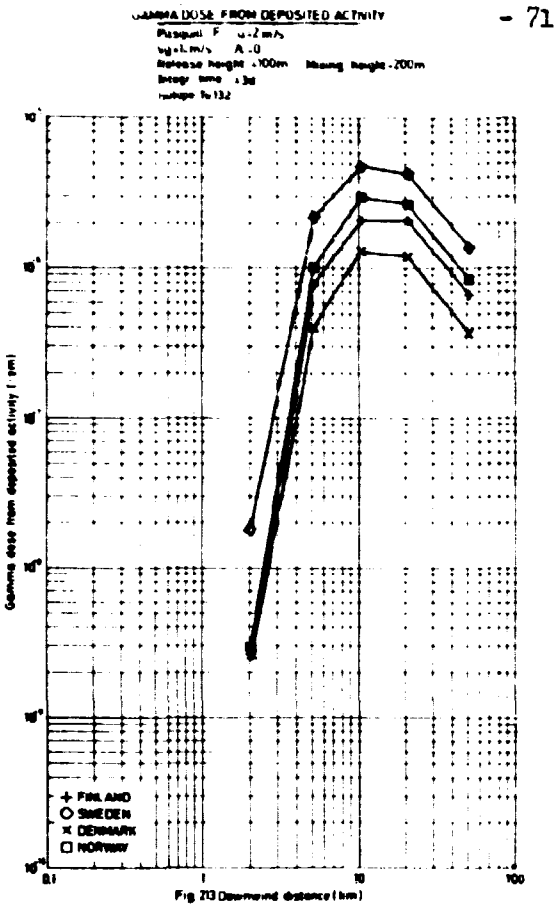

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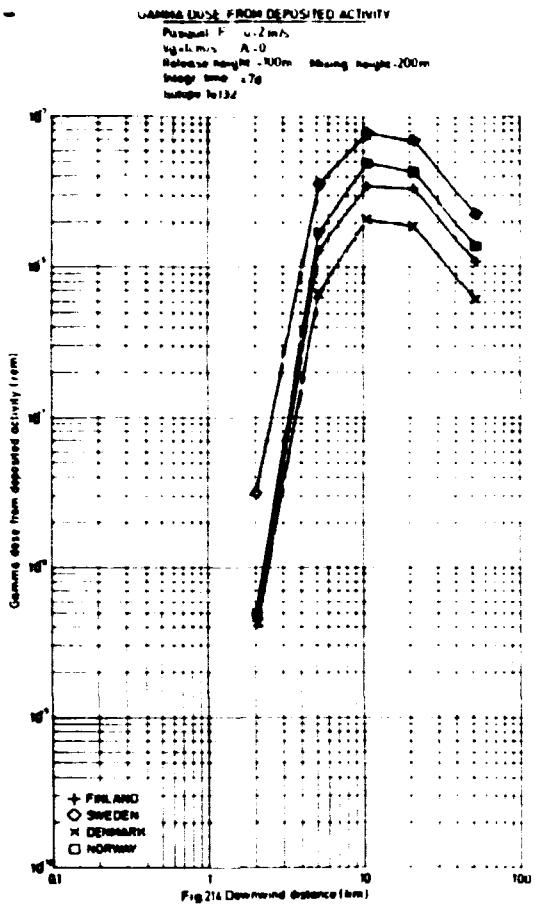

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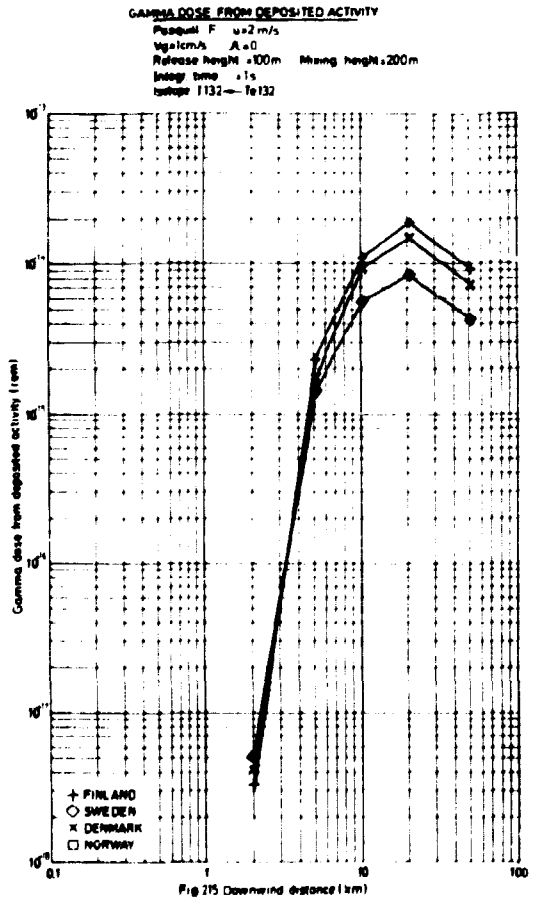

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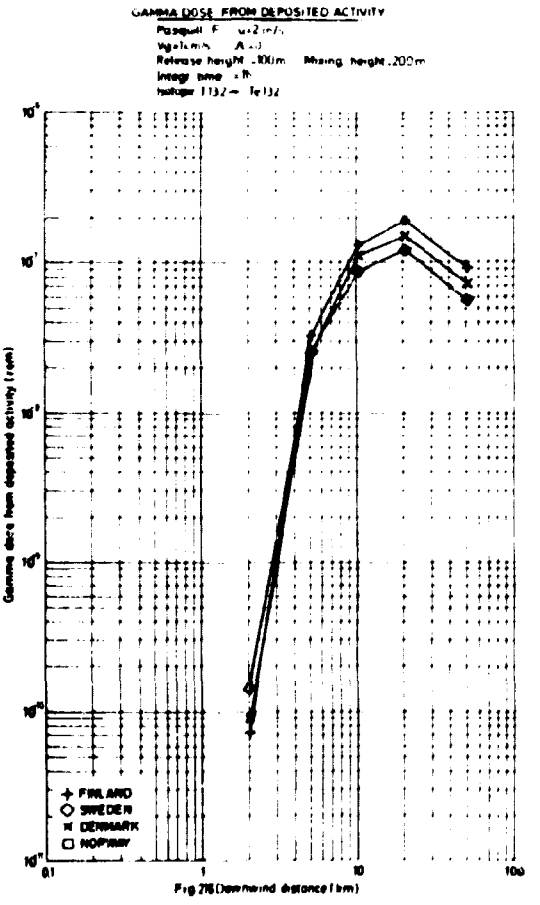

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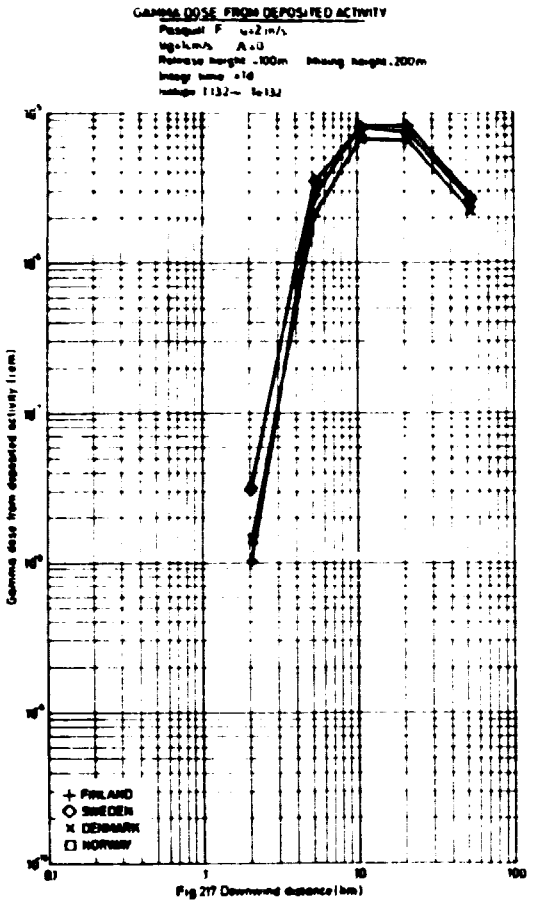

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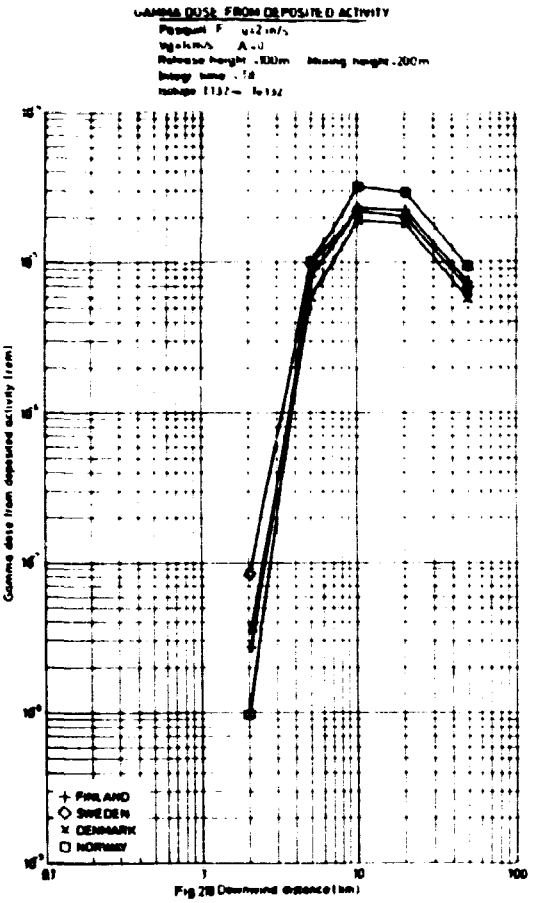

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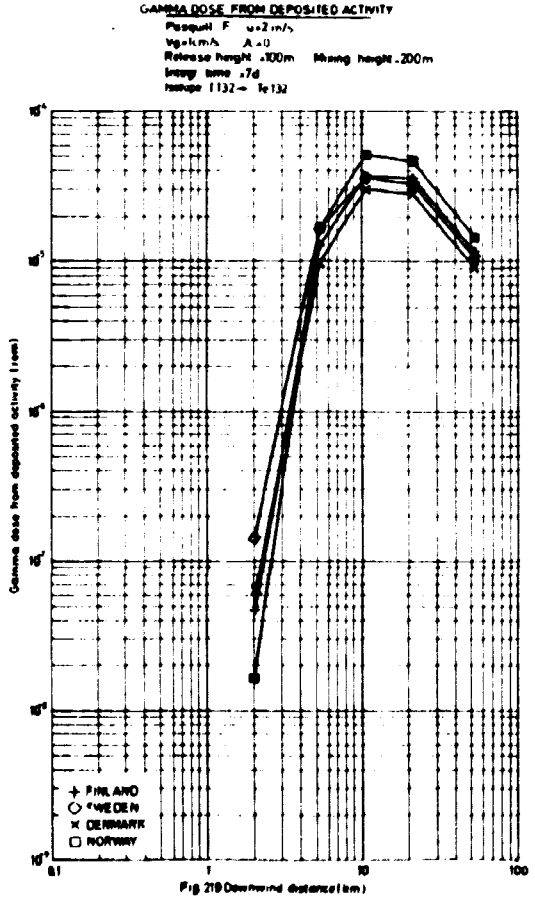

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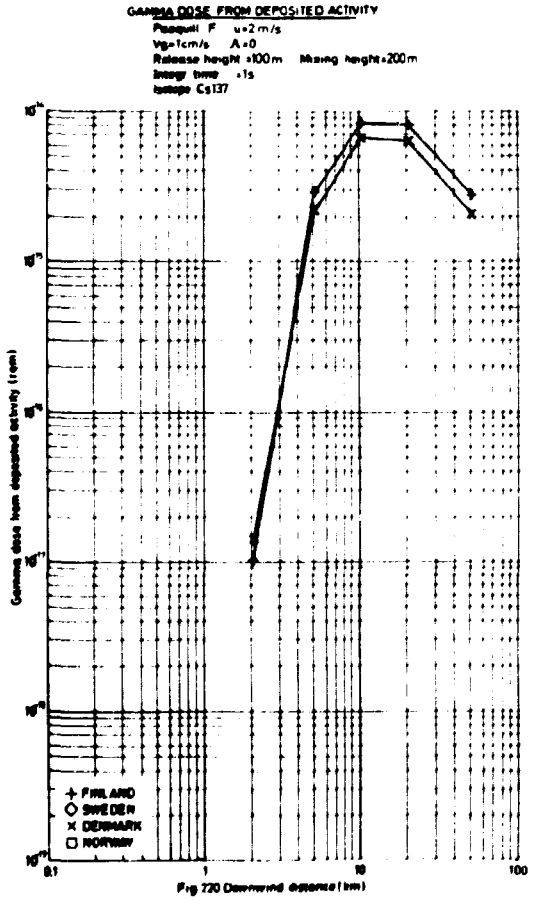

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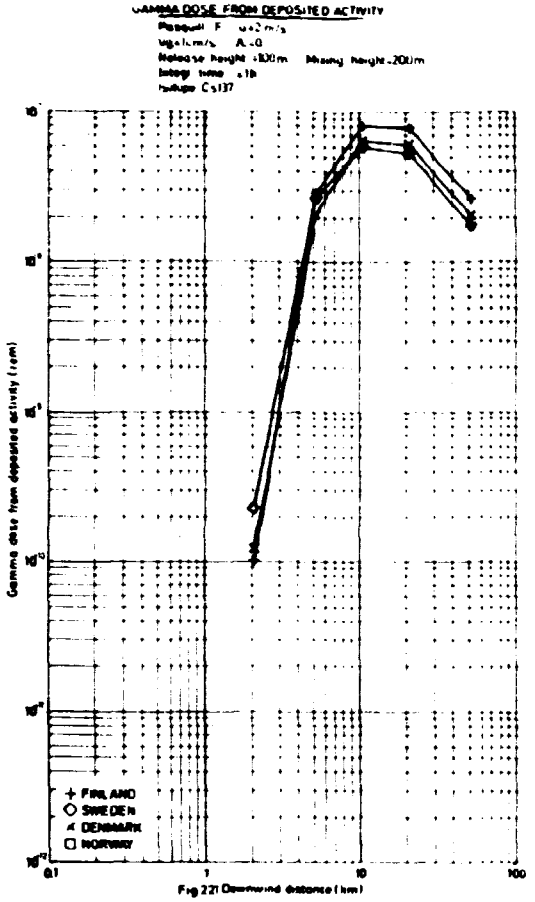

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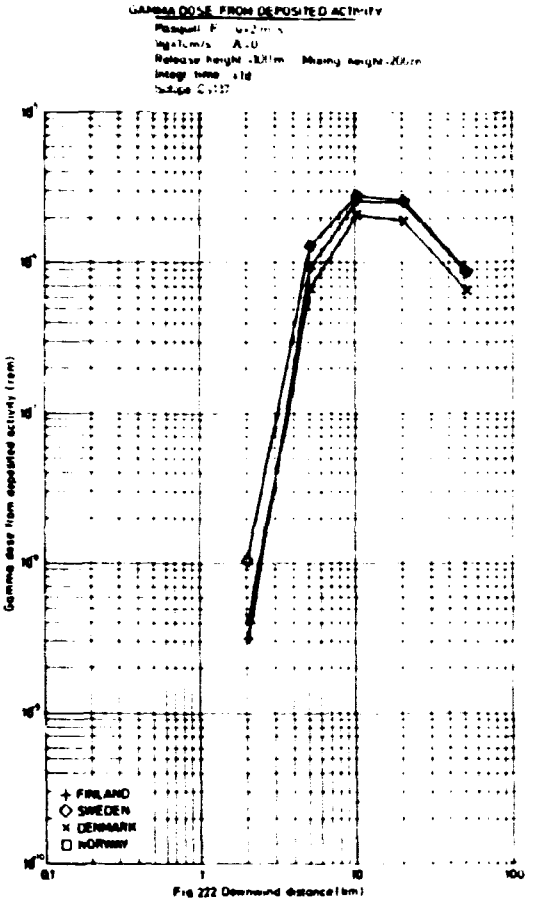

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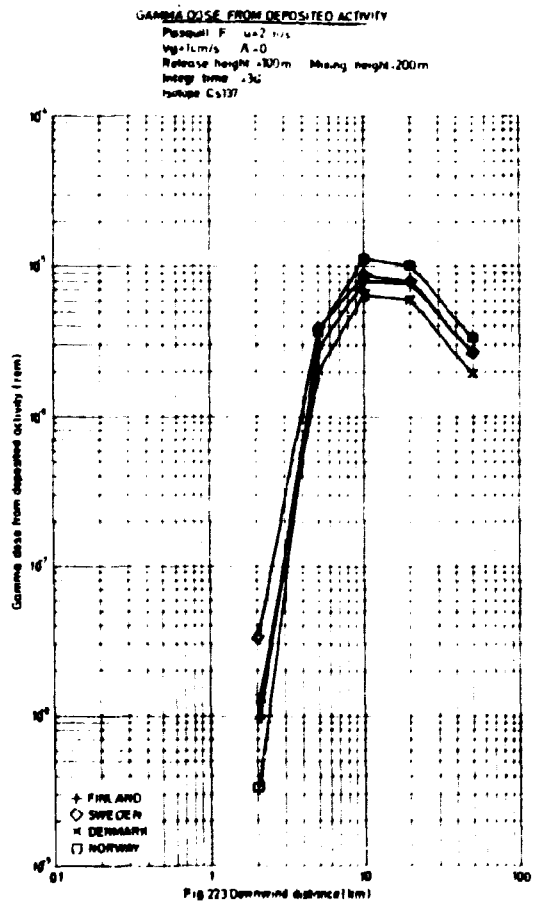

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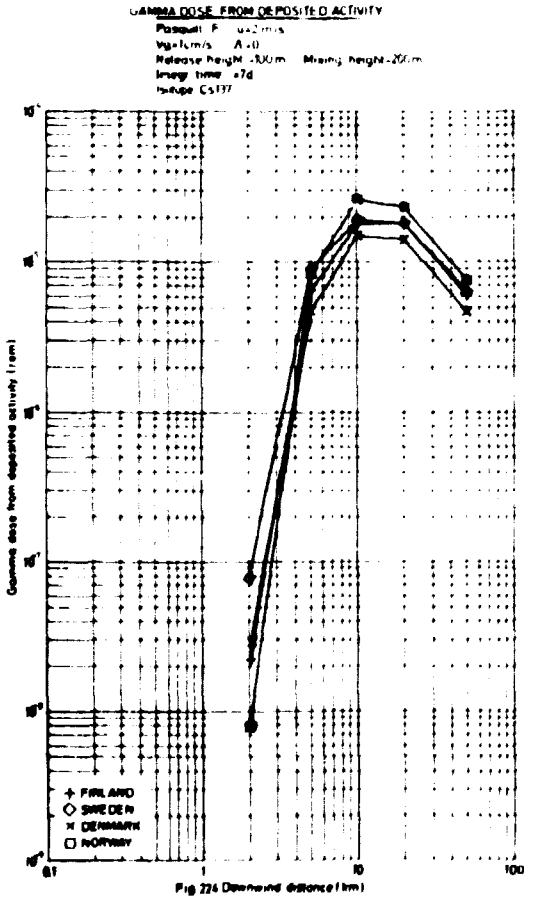

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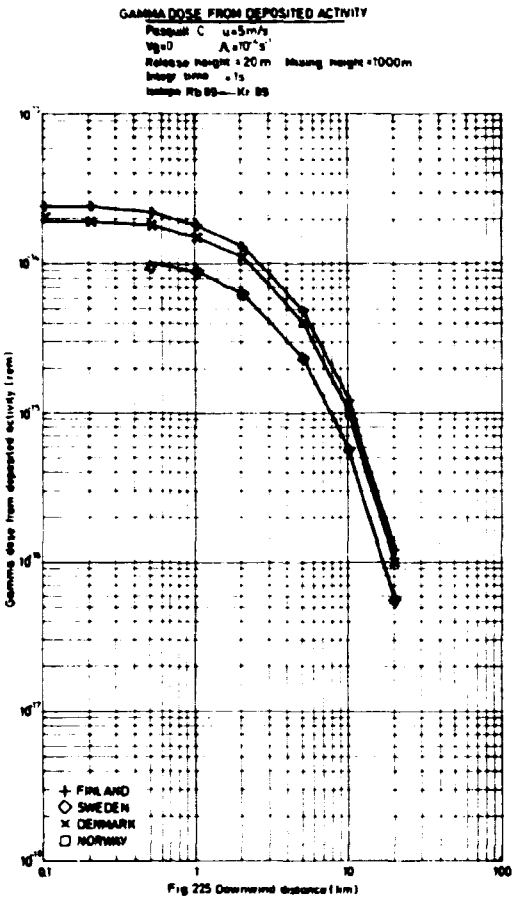

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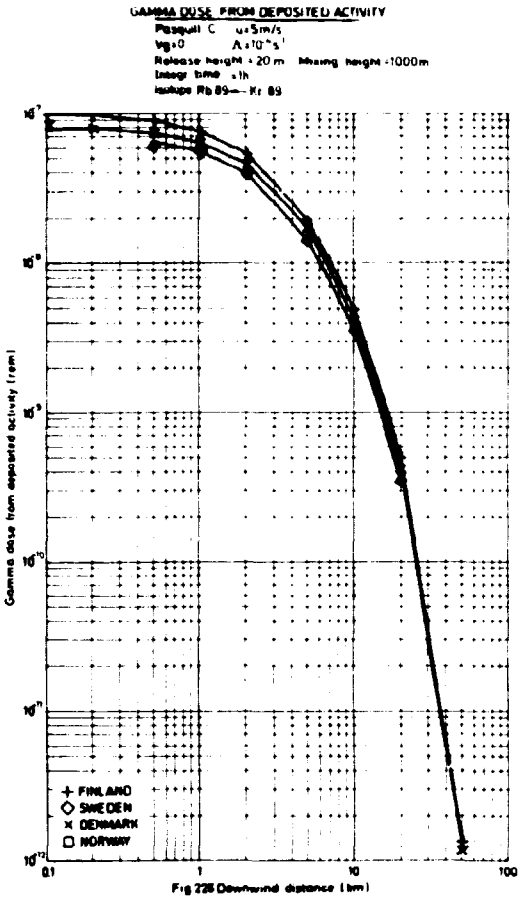

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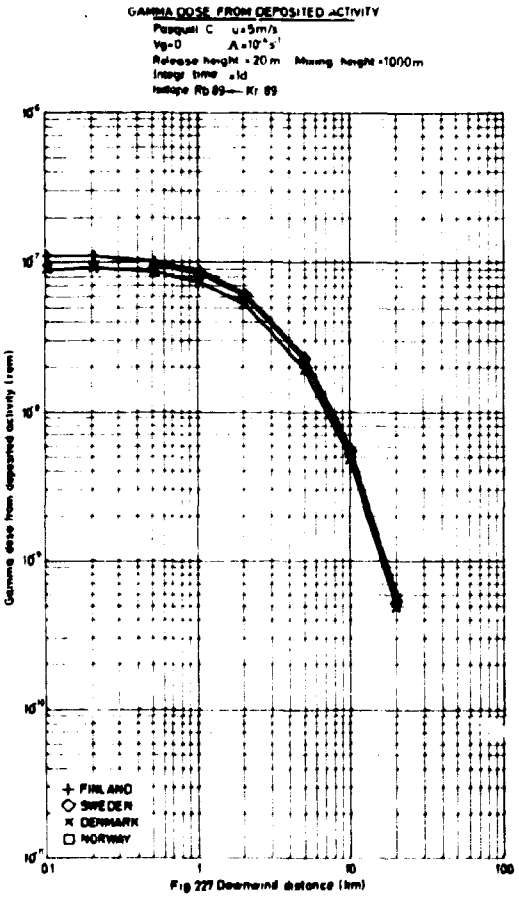

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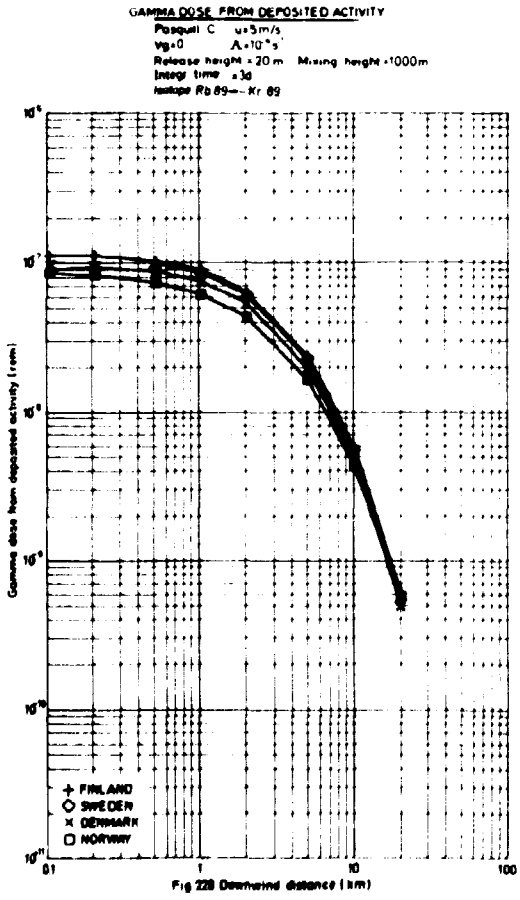

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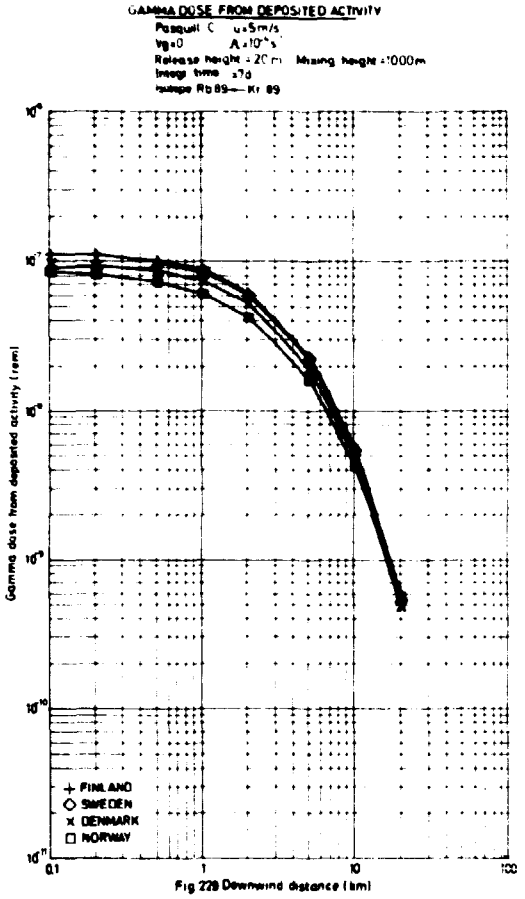

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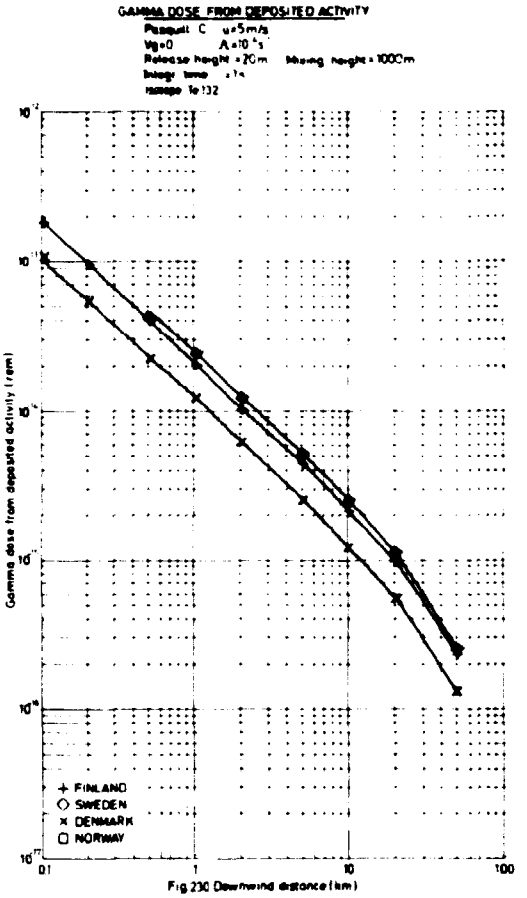

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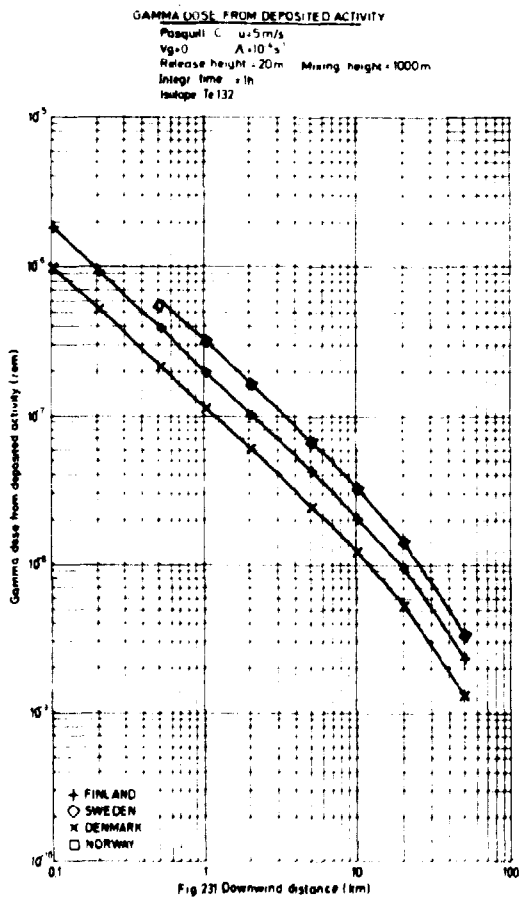

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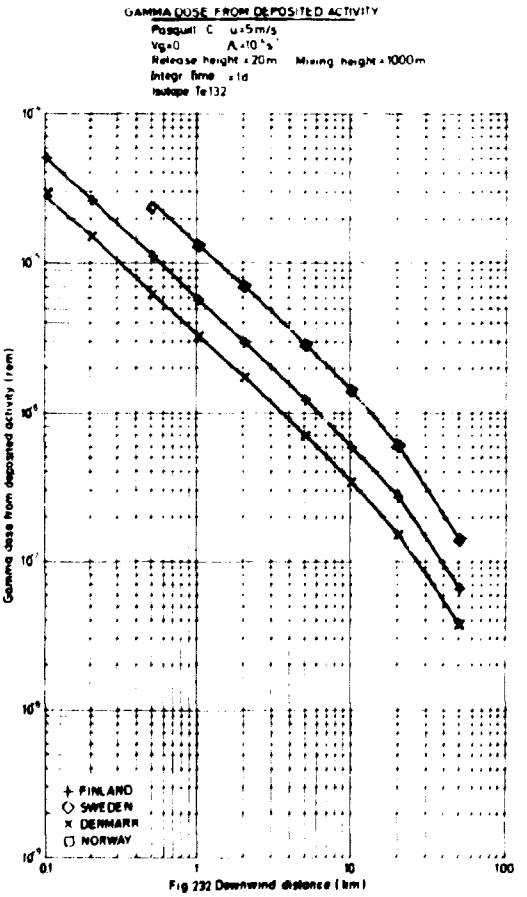

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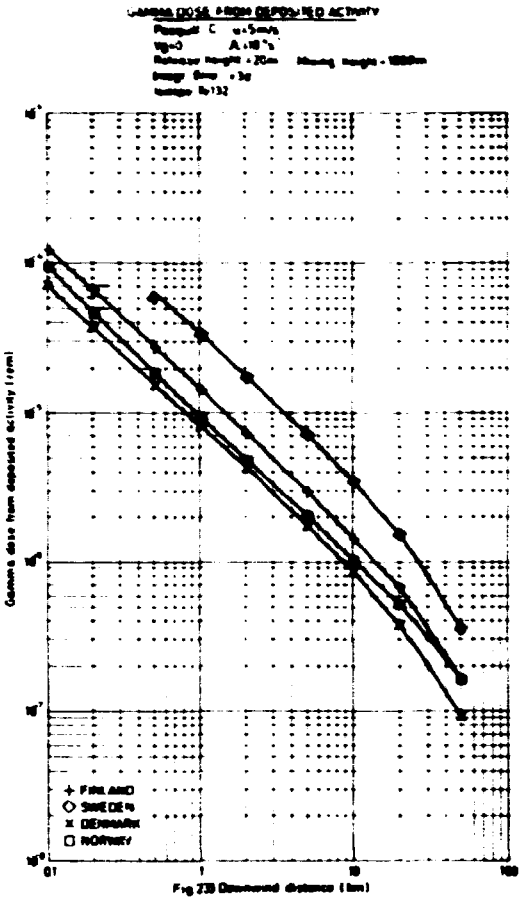

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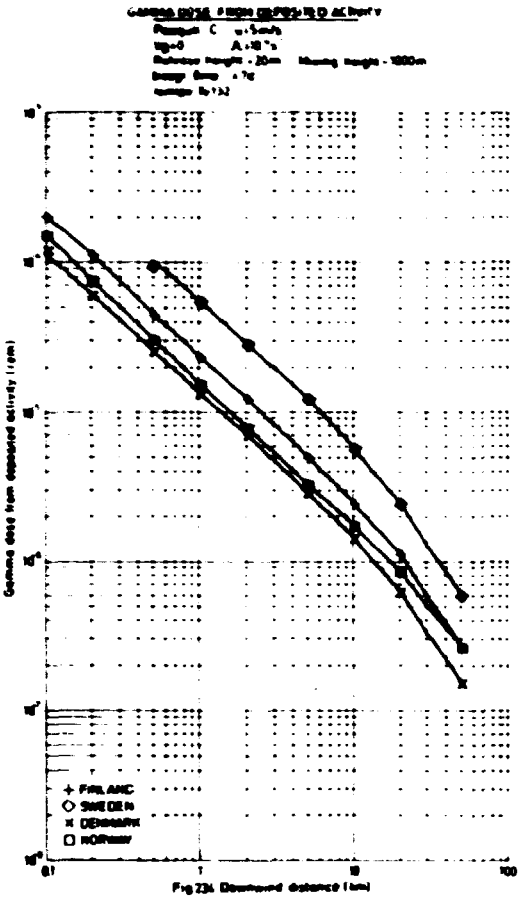

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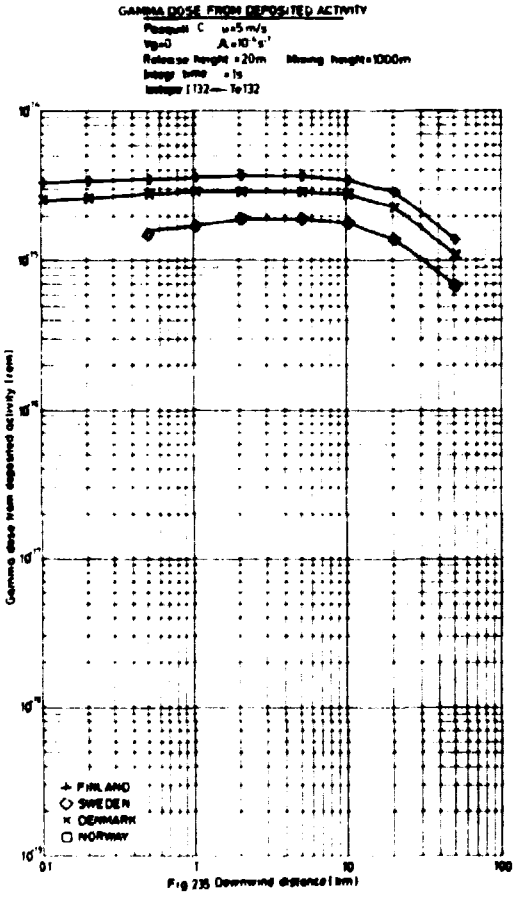

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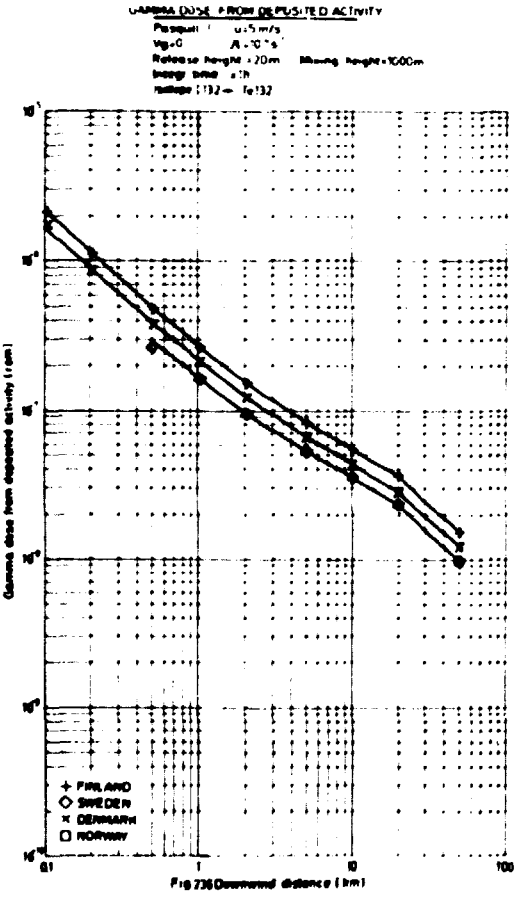


Fig 236

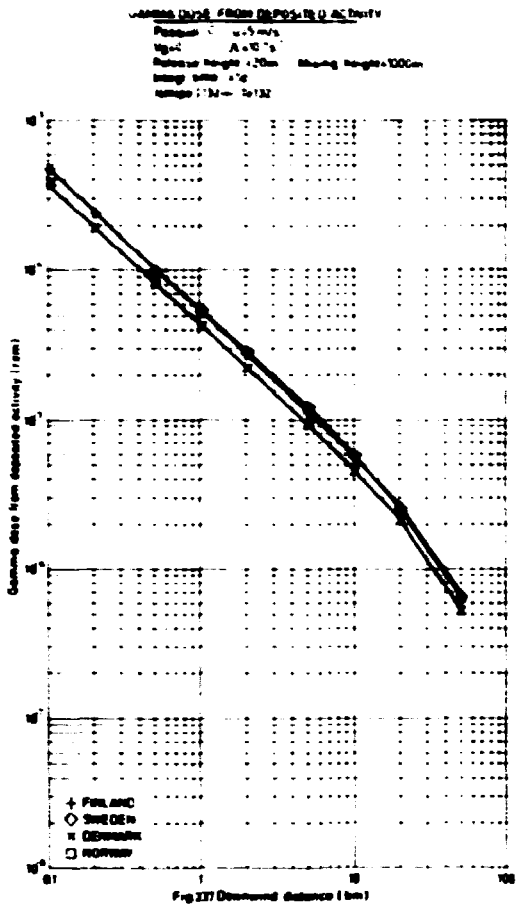


Fig 237 Downwind distance (km)

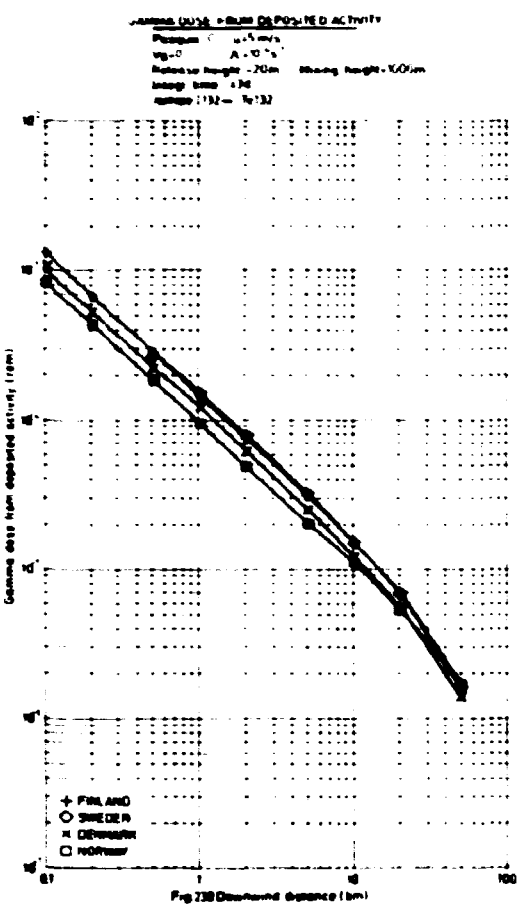
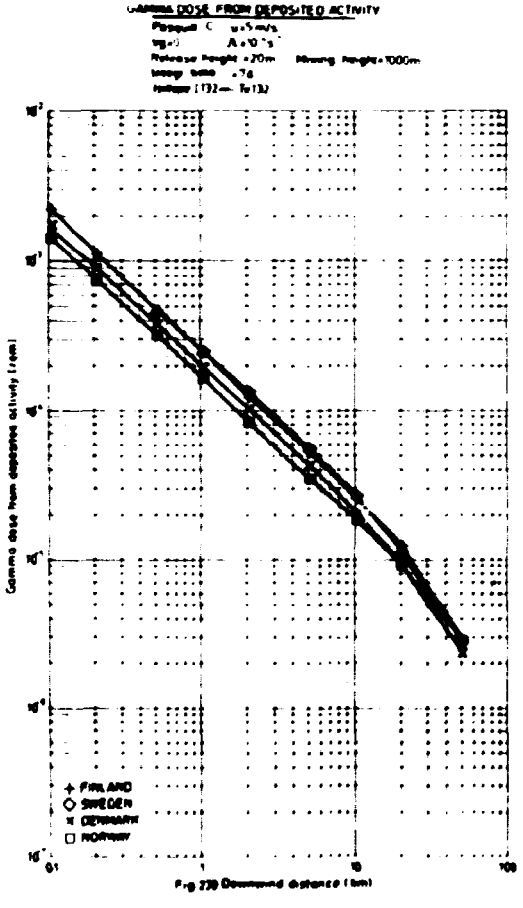


Fig 238 Downwind distance (km)



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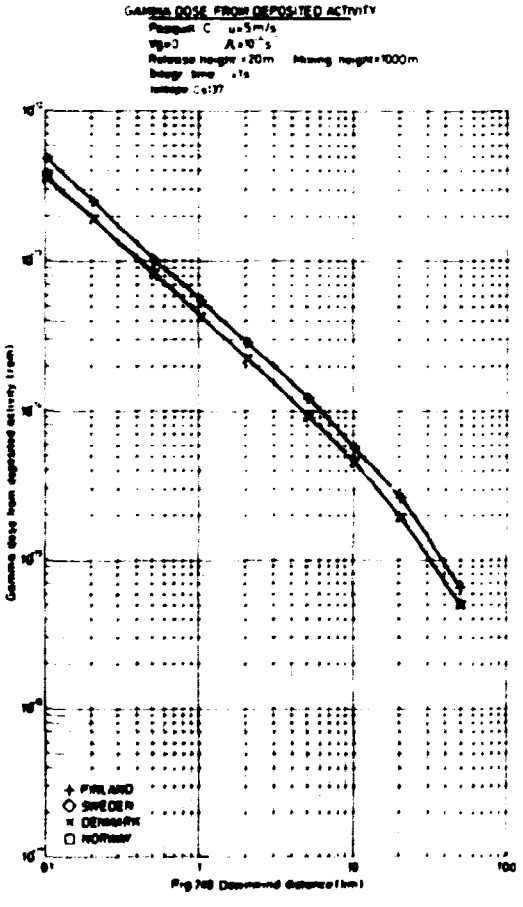

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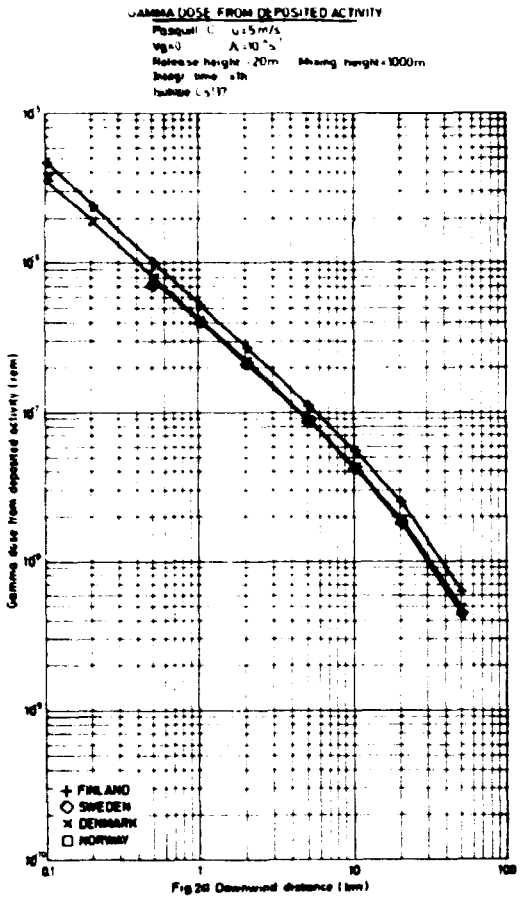


Fig 241 Downwind distance (km)

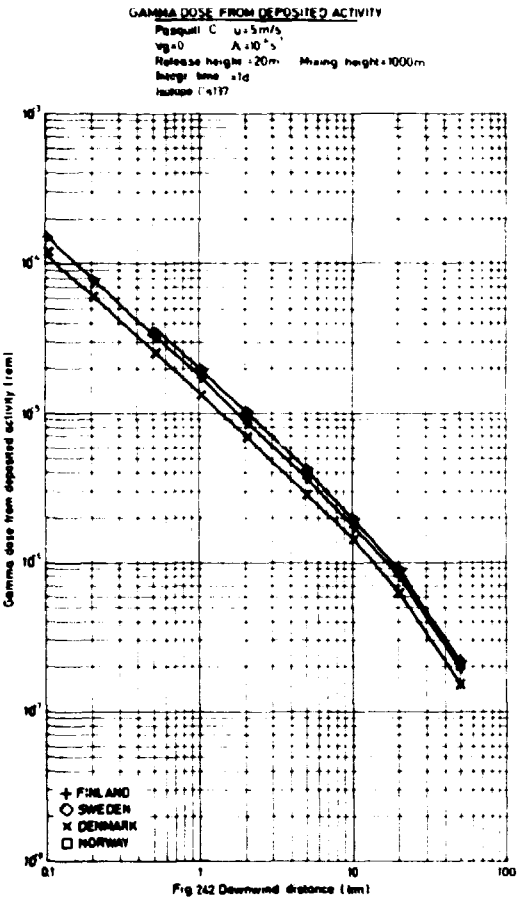


Fig 242 Downwind distance (km)

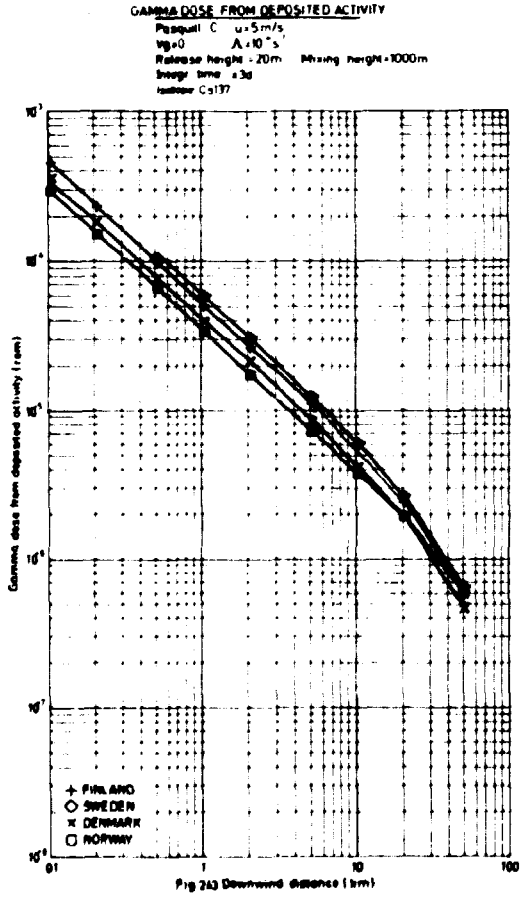


Fig 243 Downwind distance (km)

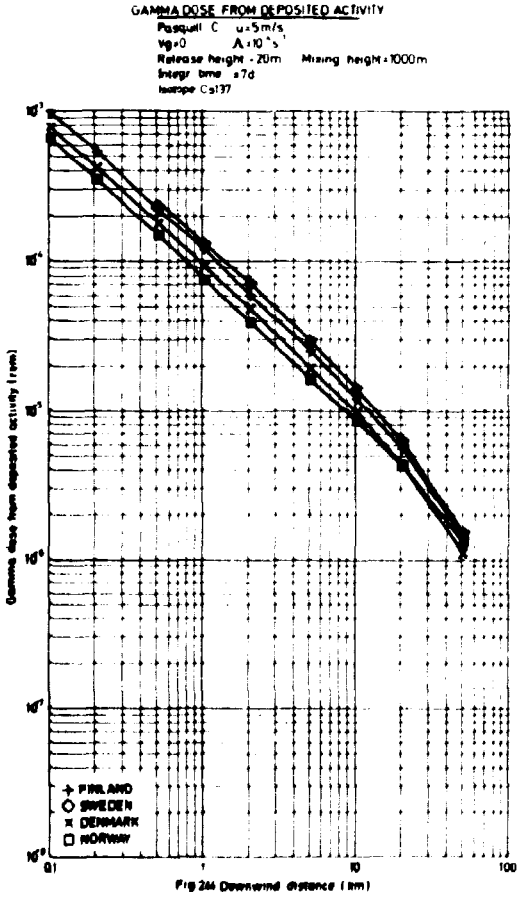


Fig 244 Downwind distance (km)

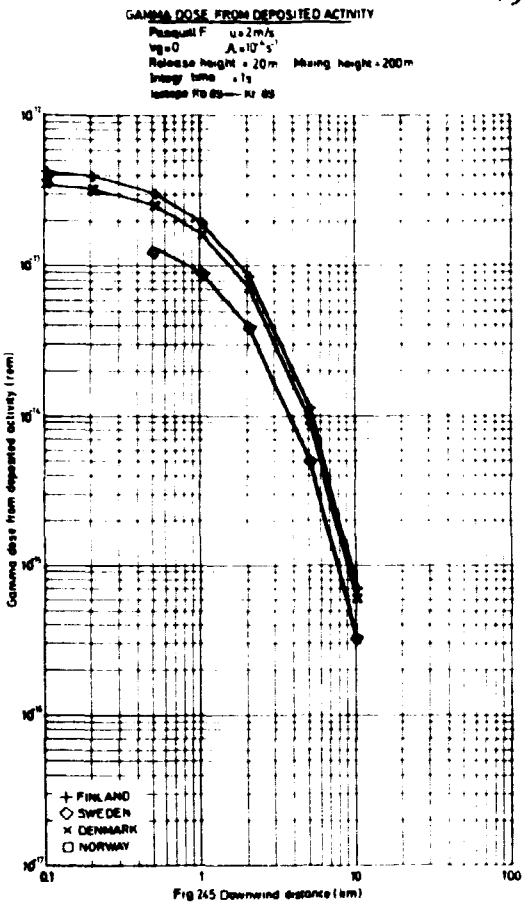


Fig 245 Downwind distance (km)

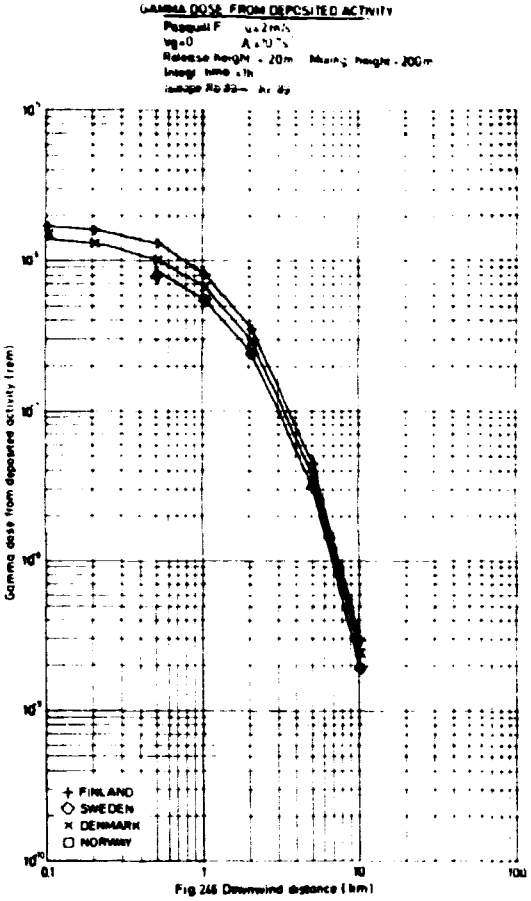
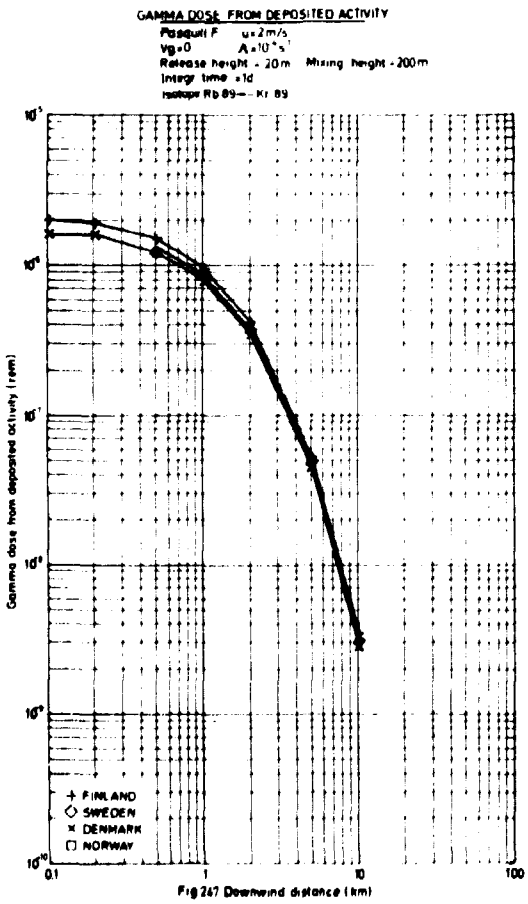


Fig 246 Downwind distance (km)



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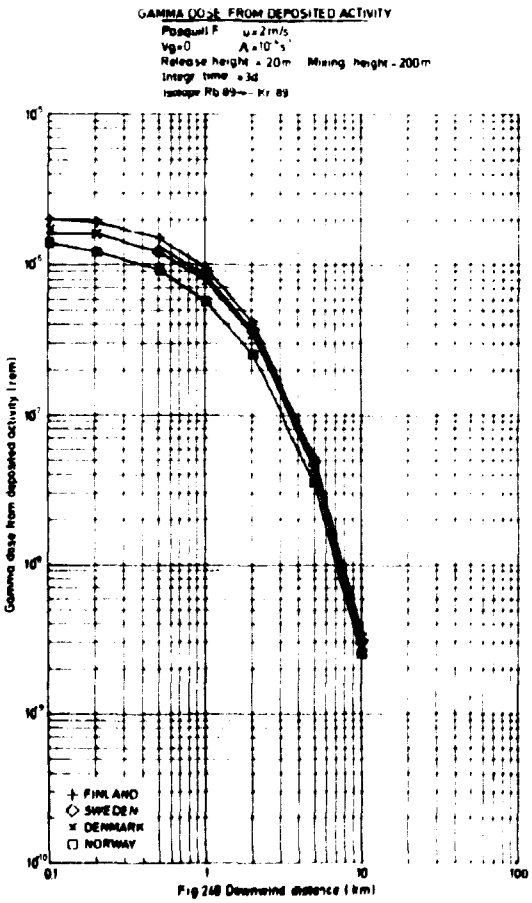
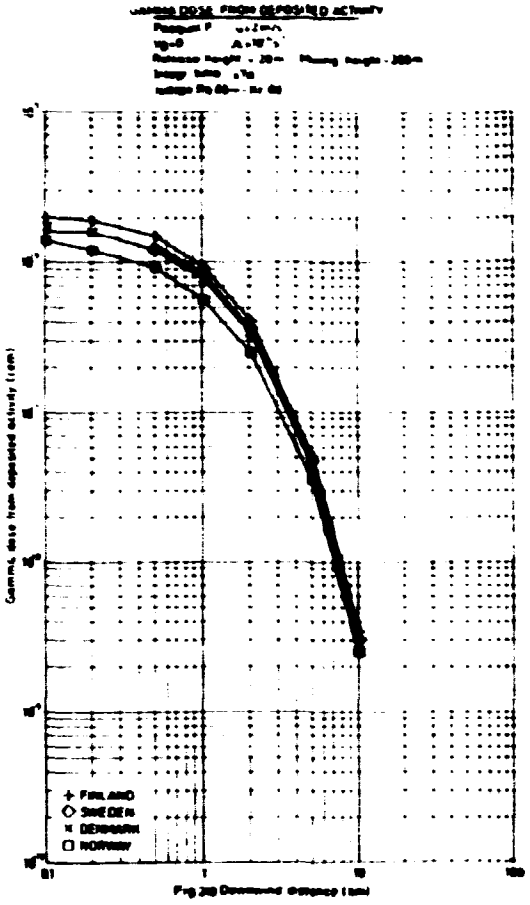


Fig 248 Downwind distance (km)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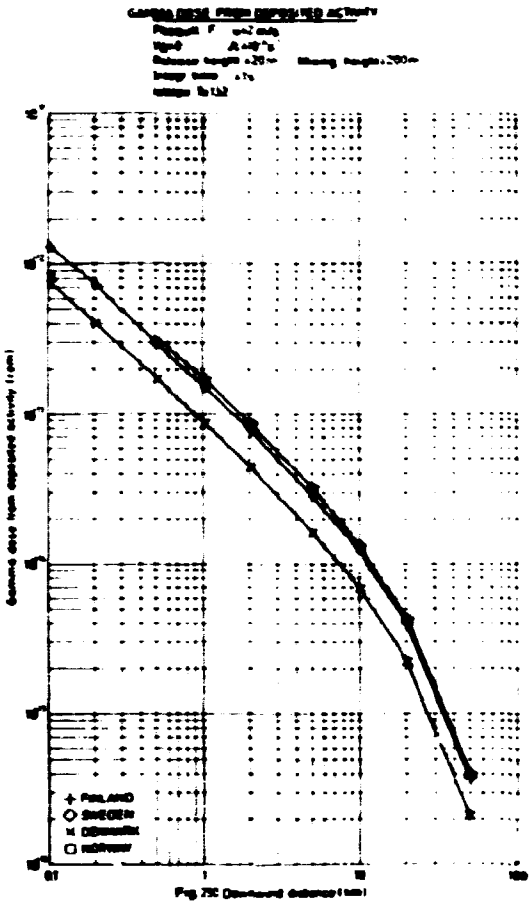
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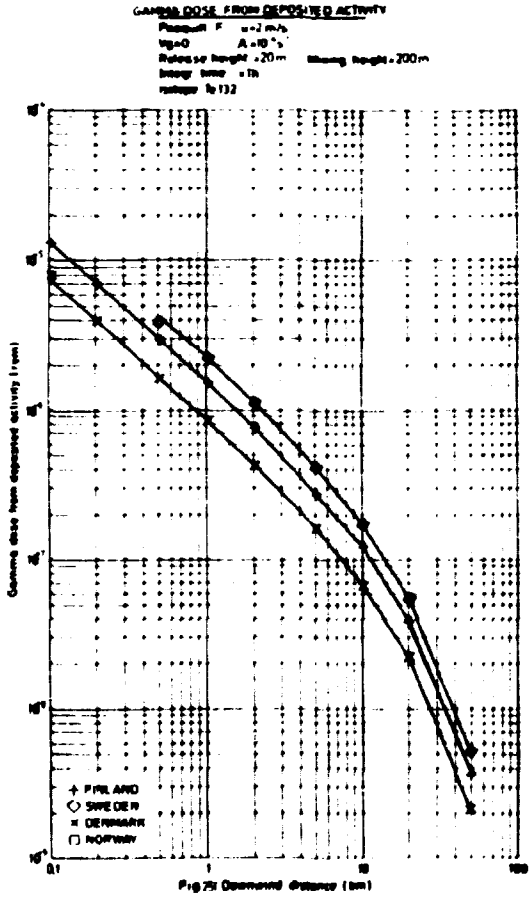
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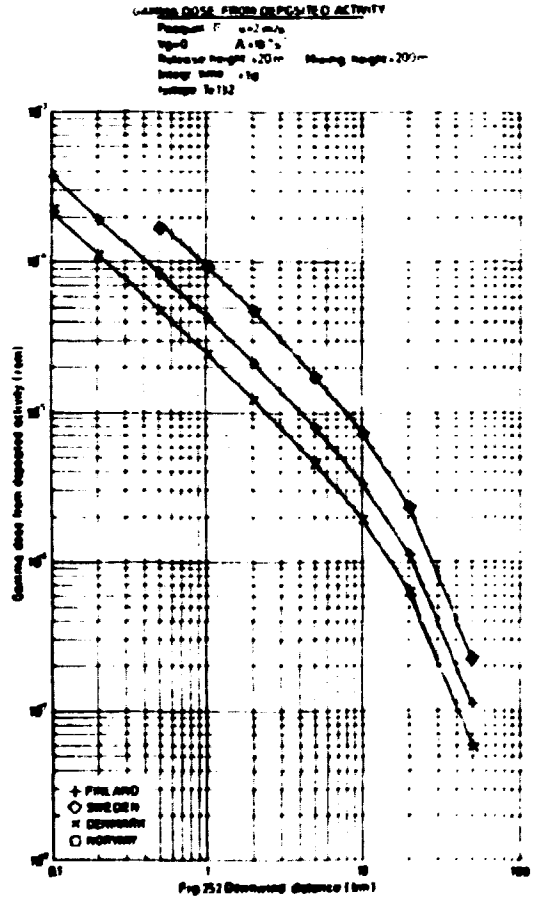
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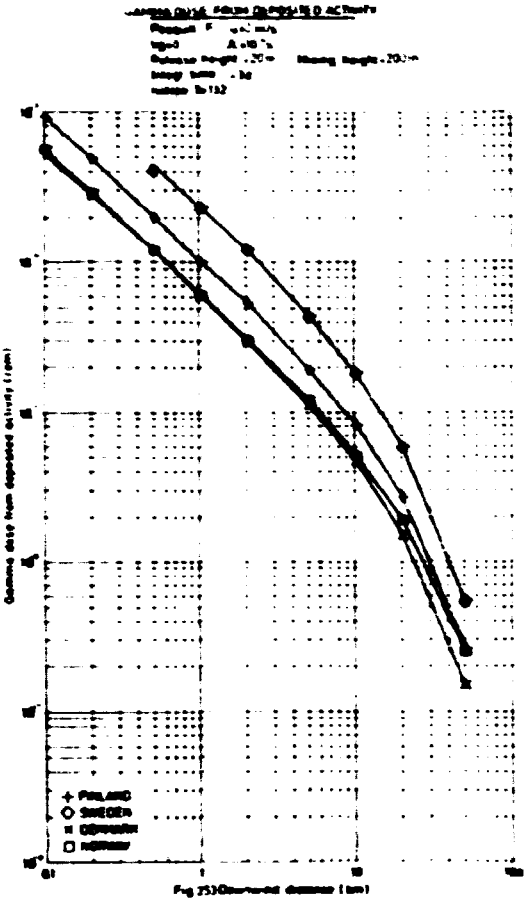
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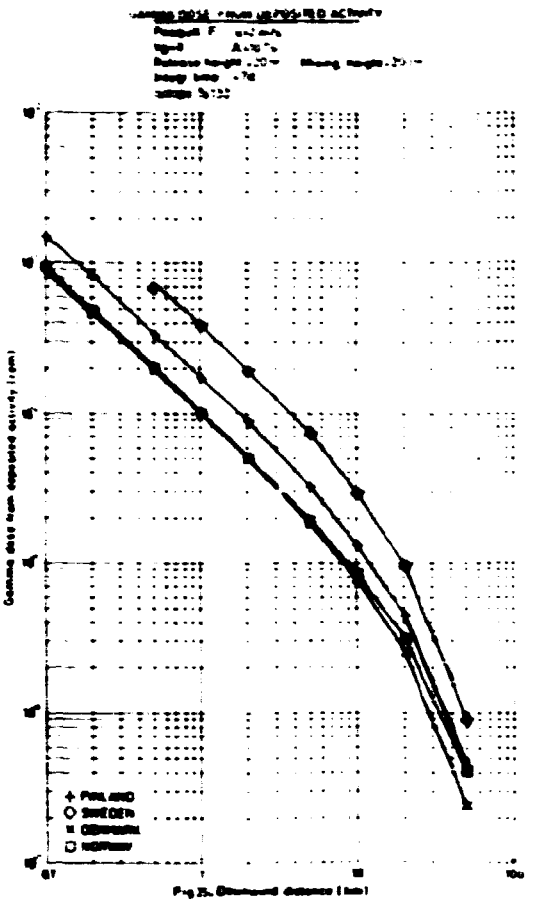
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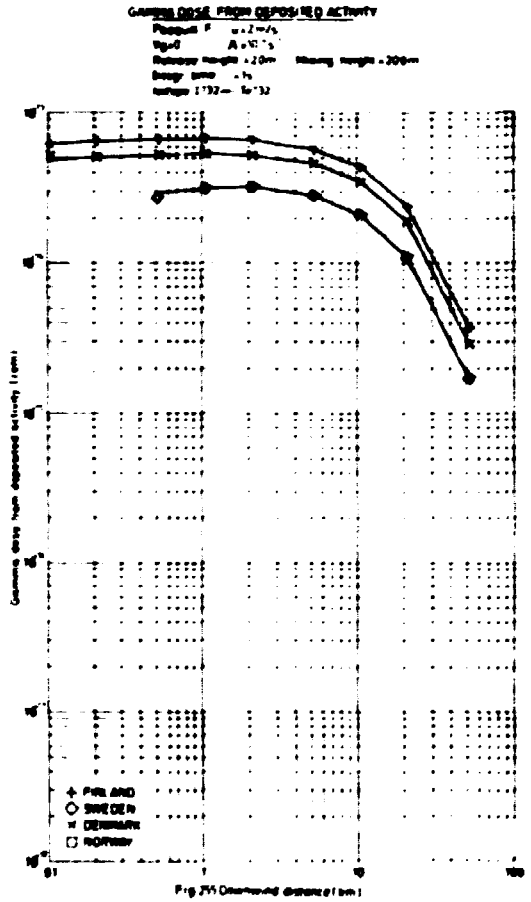
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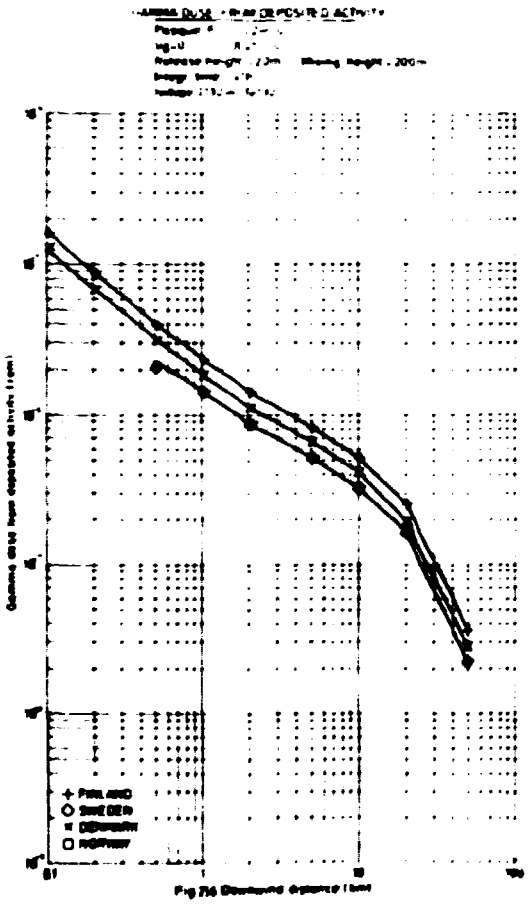
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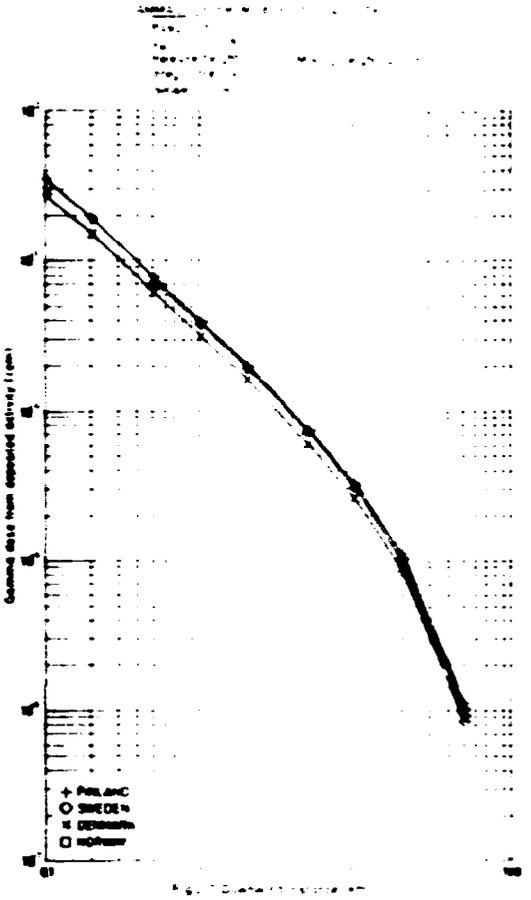
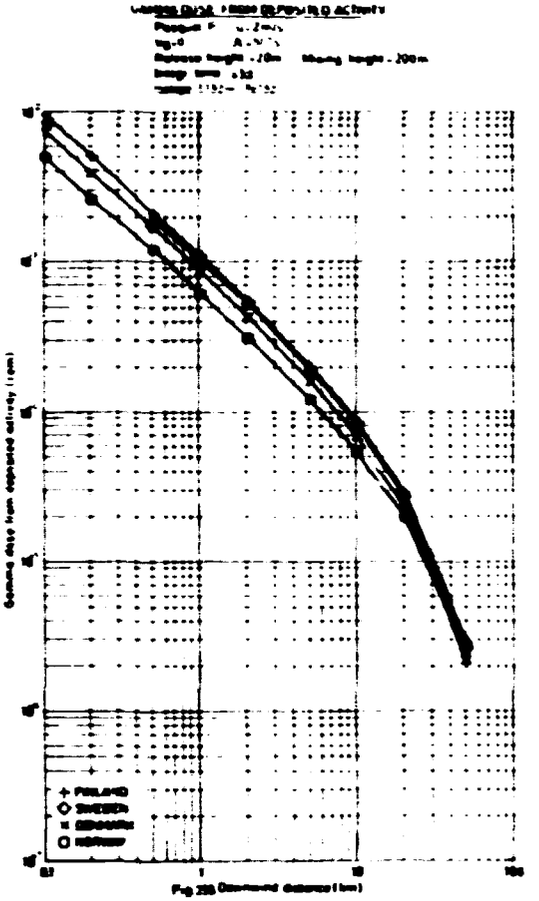
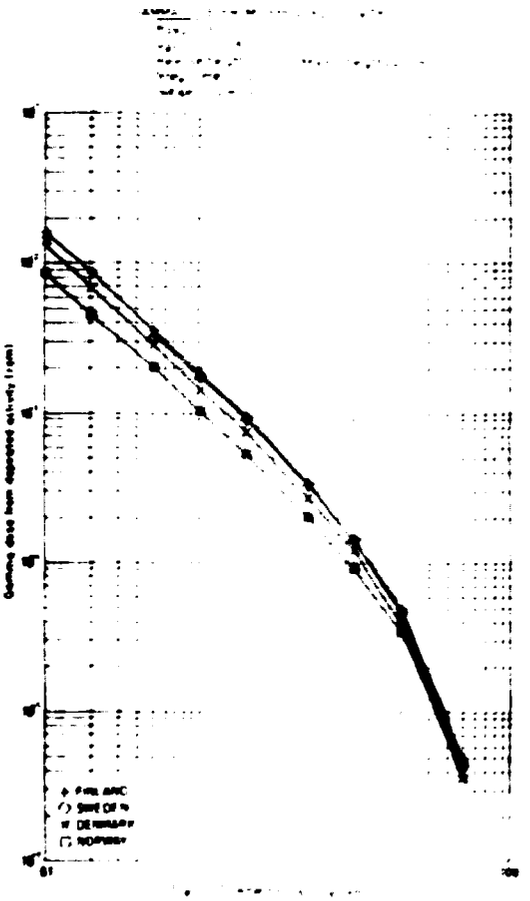
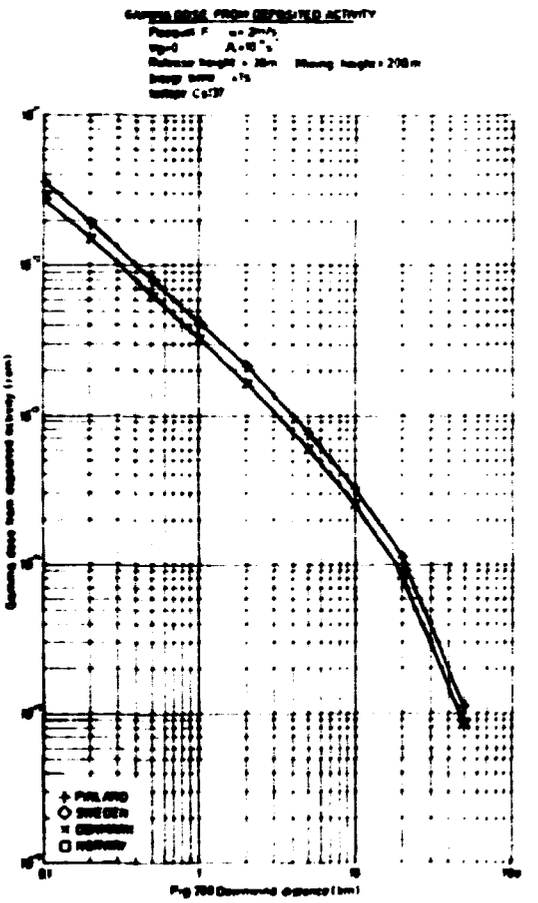








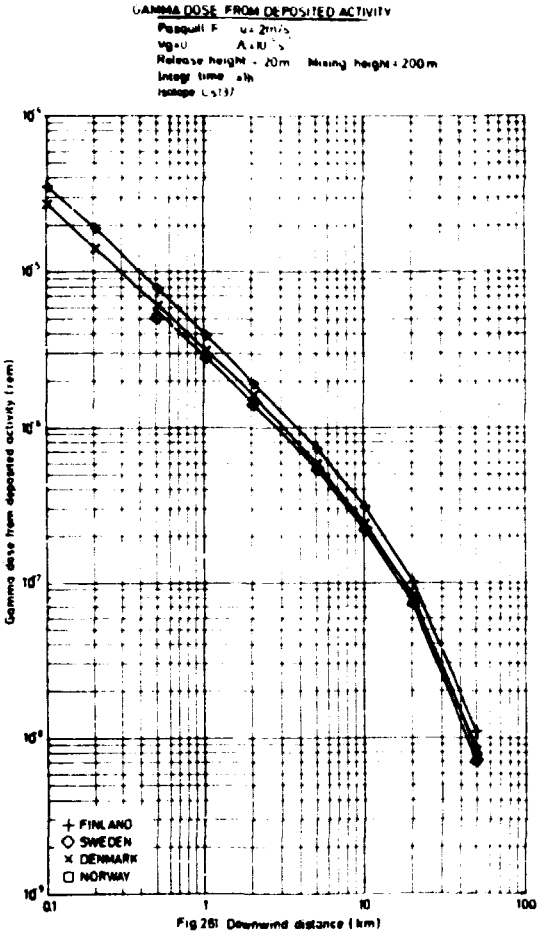


Fig 261 Downwind distance (km)

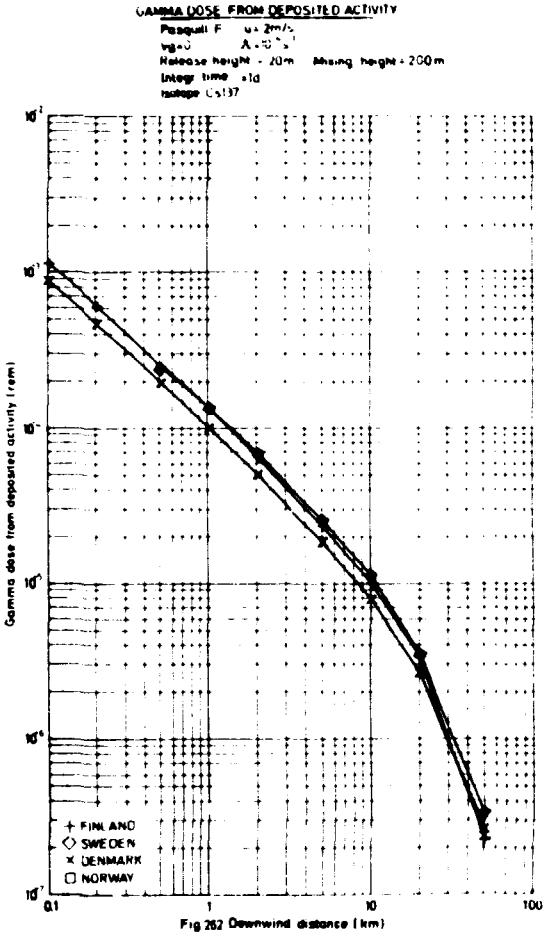
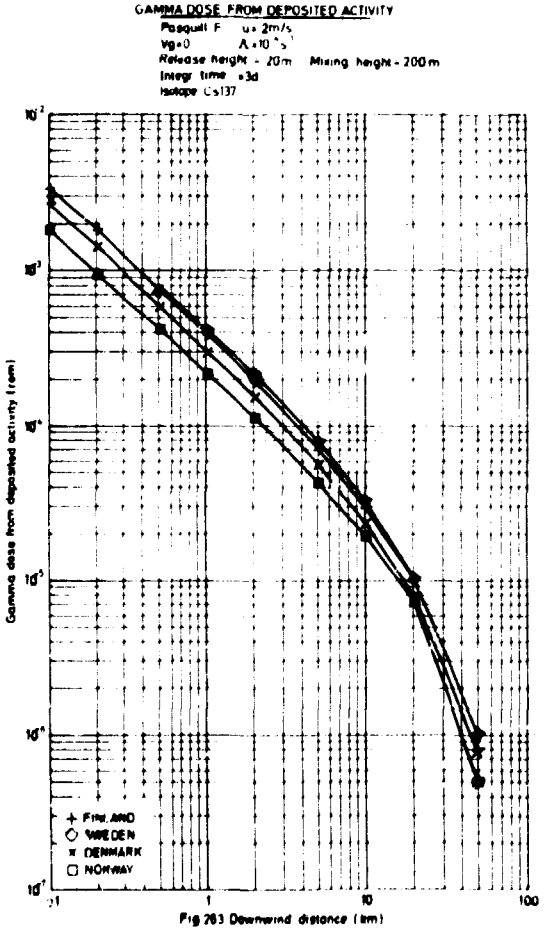


Fig 262 Downwind distance (km)



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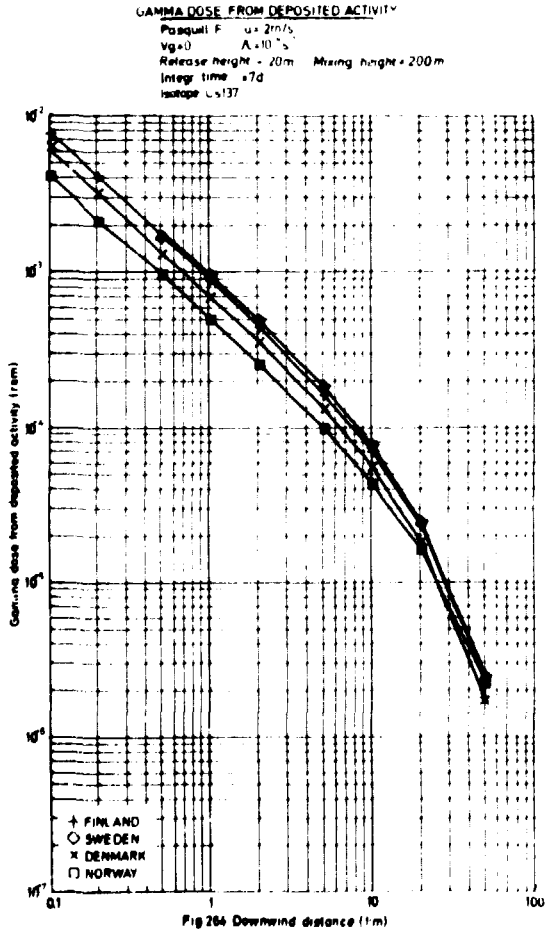

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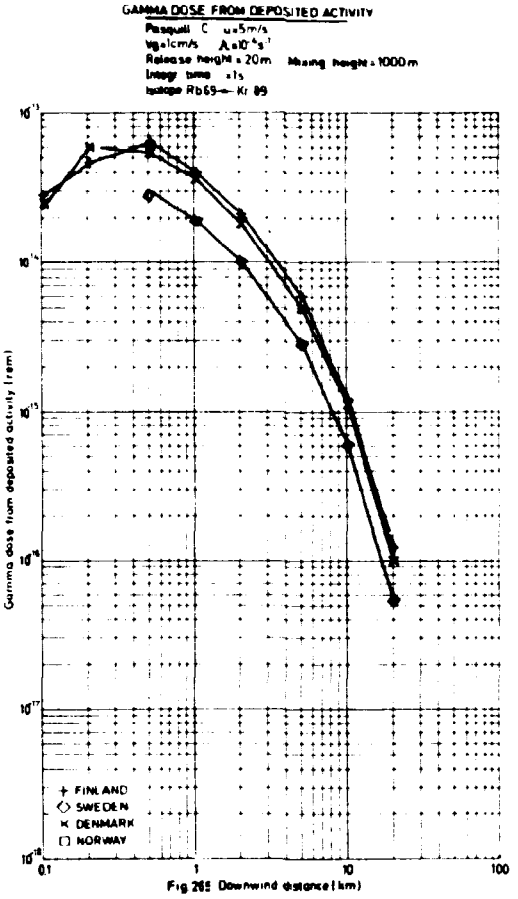

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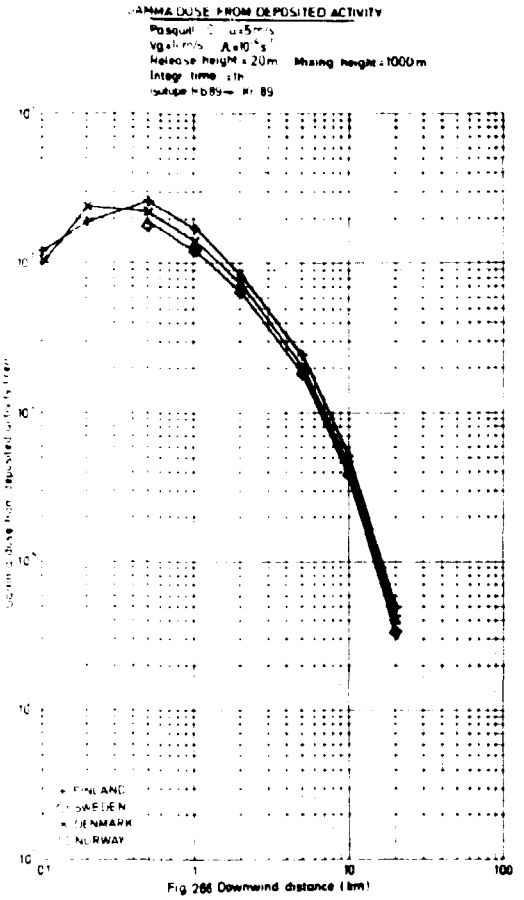

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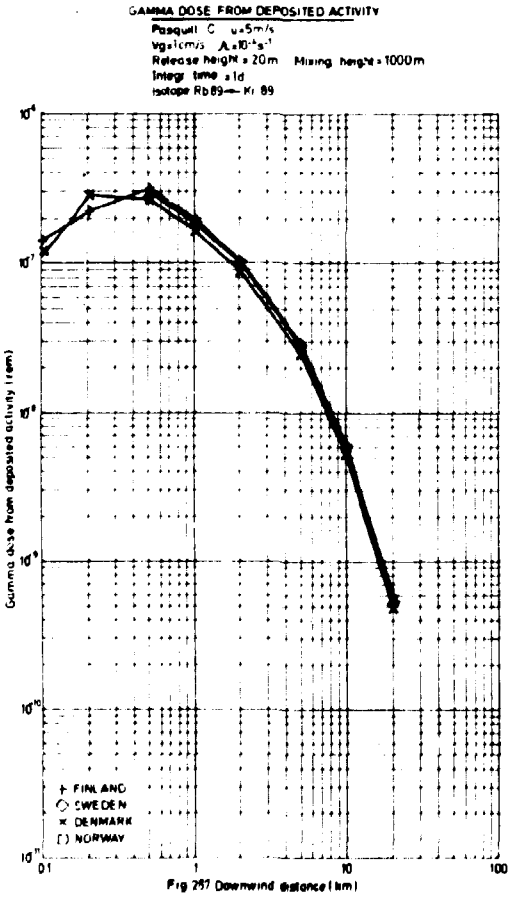

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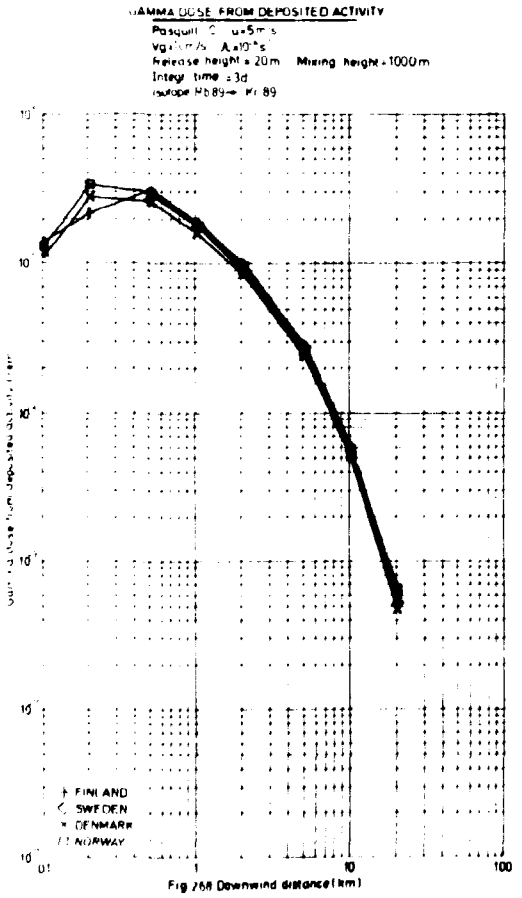
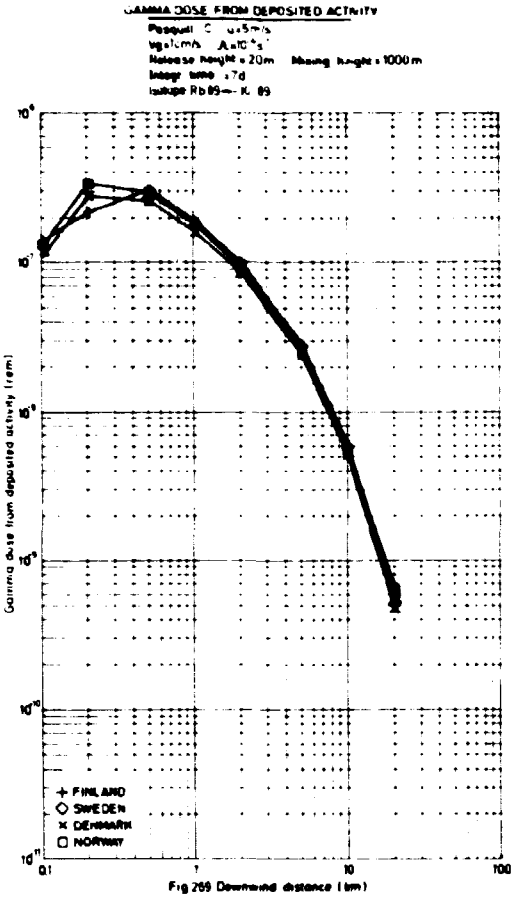


Fig 268 Downwind distance (km)



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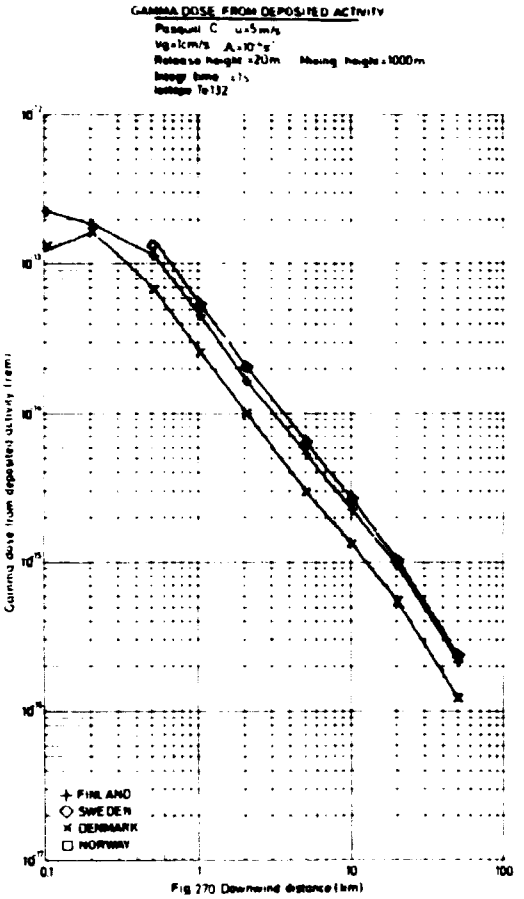


Fig 270 Downwind distance (km)

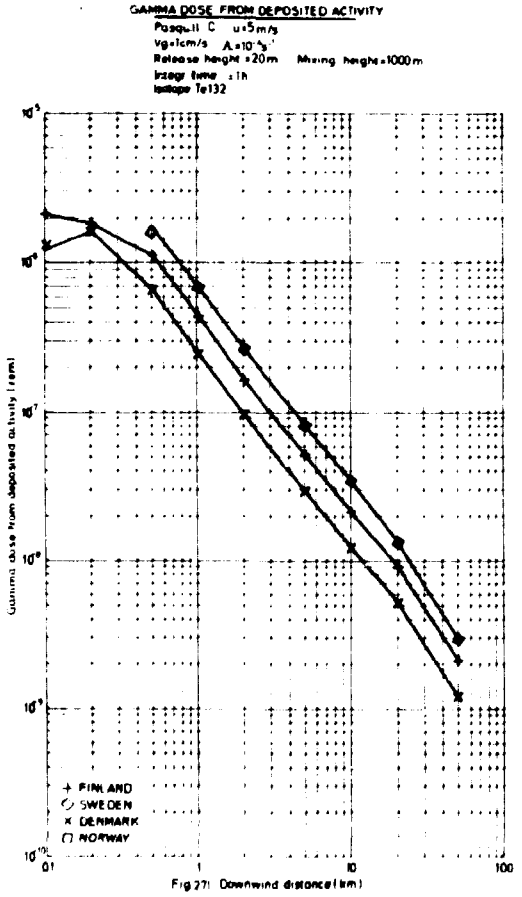


Fig 271 Downwind distance (km)

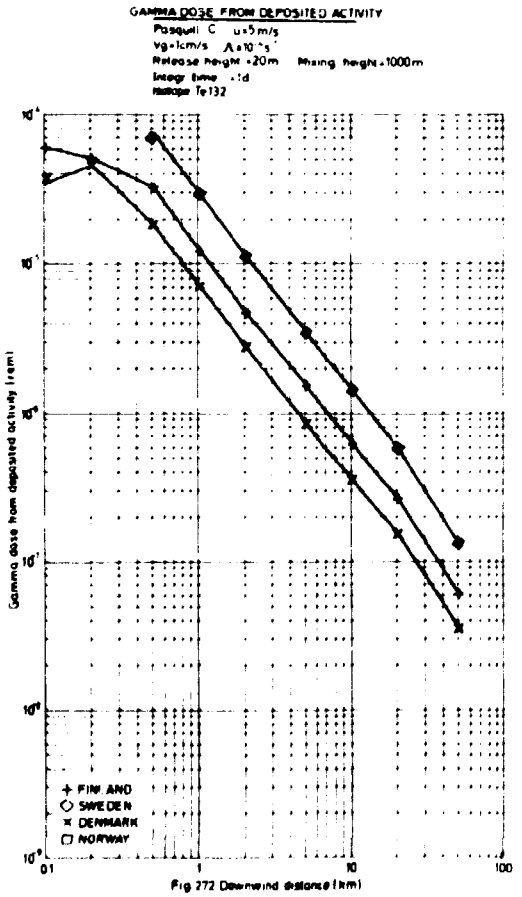
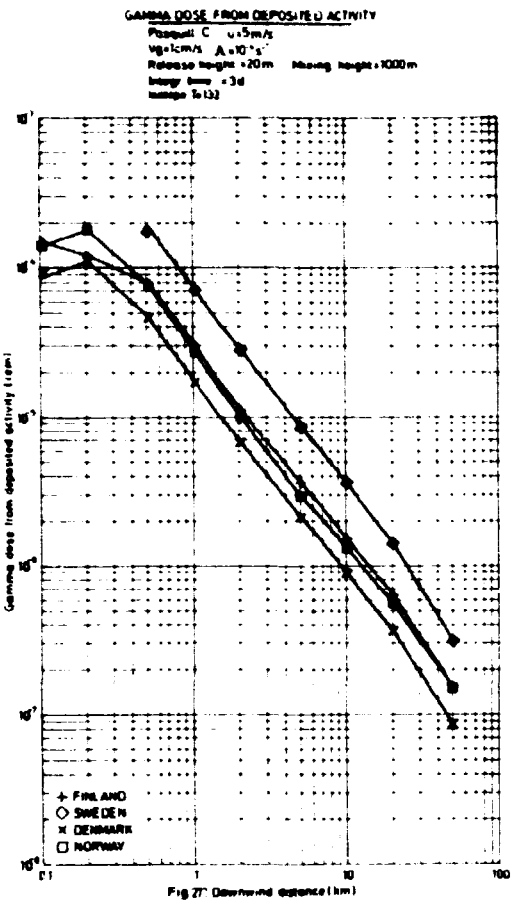


Fig 272 Downwind distance (km)



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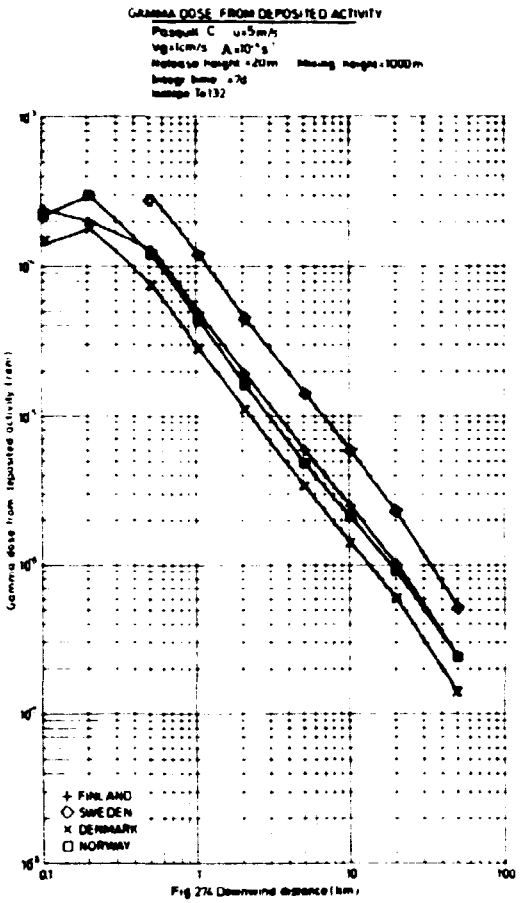


Fig 27a Downwind distance (km)

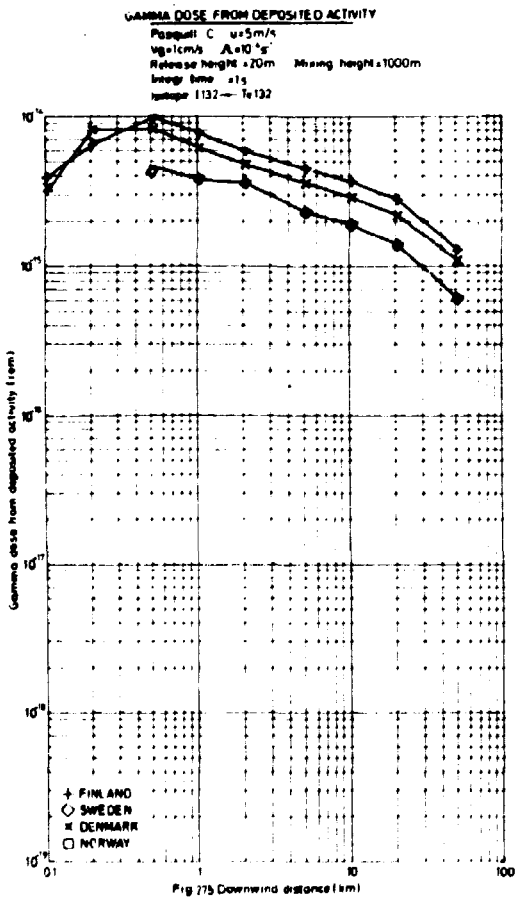


Fig 27b Downwind distance (km)

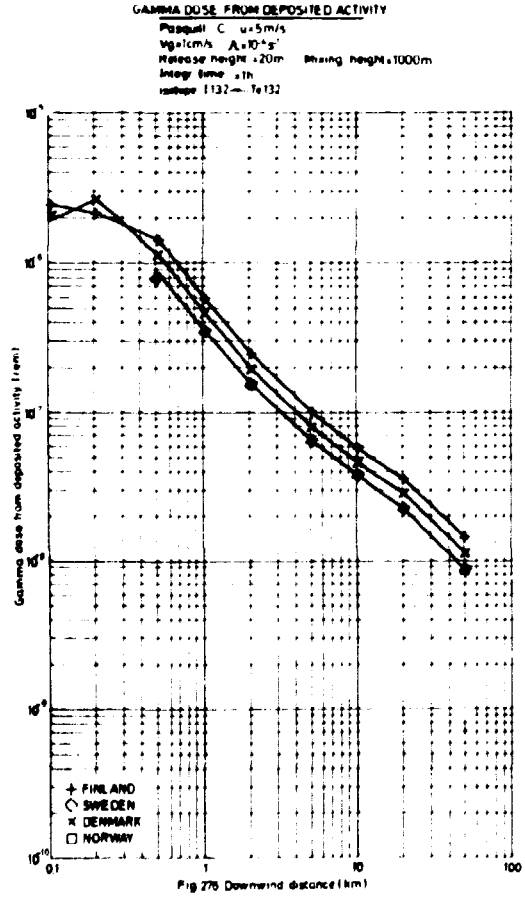


Fig 27c Downwind distance (km)

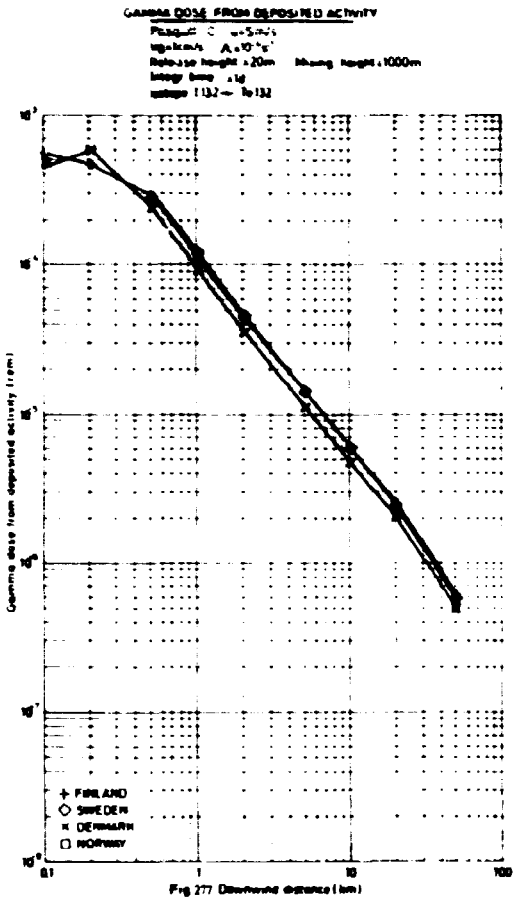
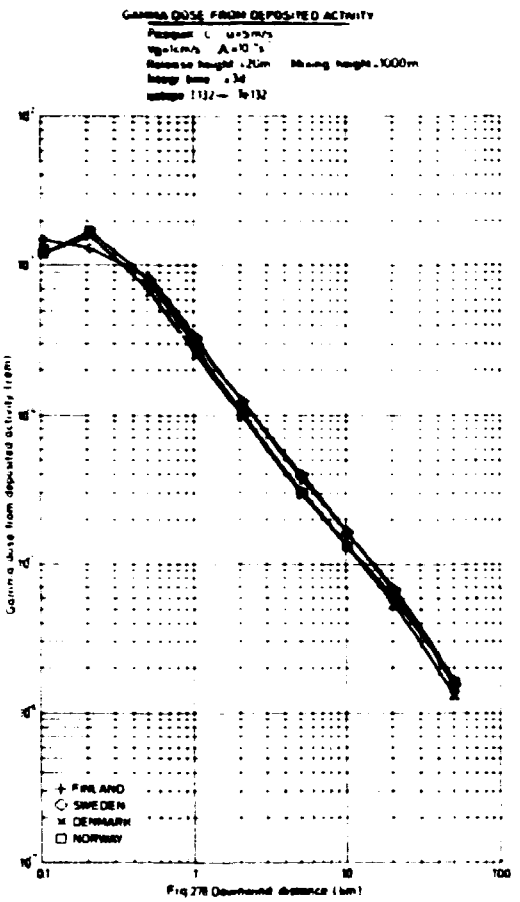


Fig 277 Downwind distance (km)



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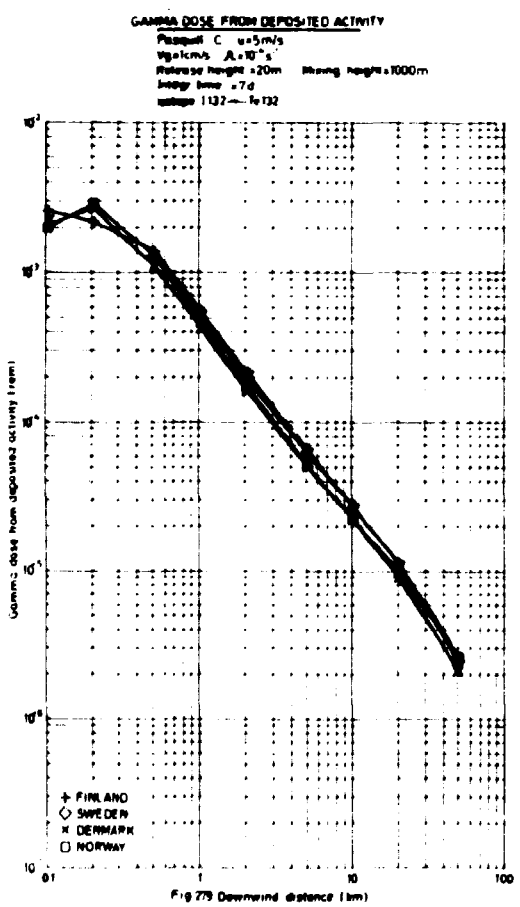
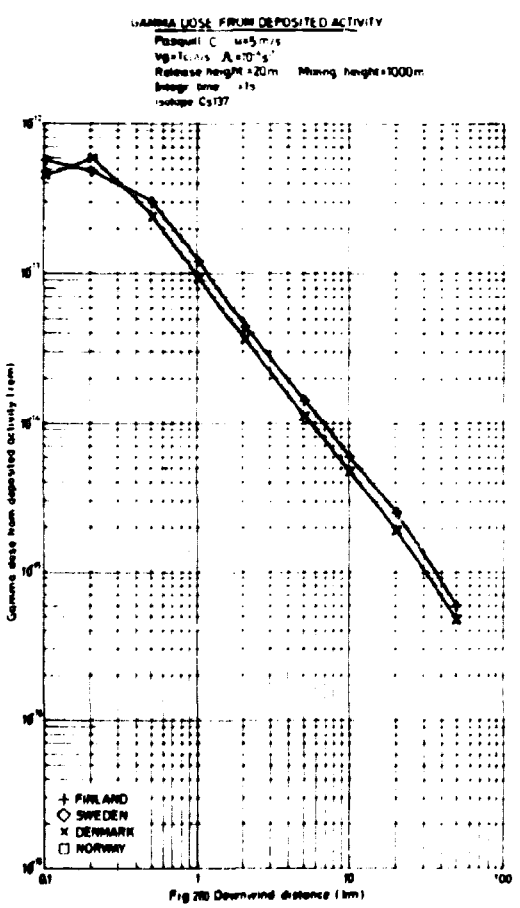


Fig 279 Downwind distance (km)



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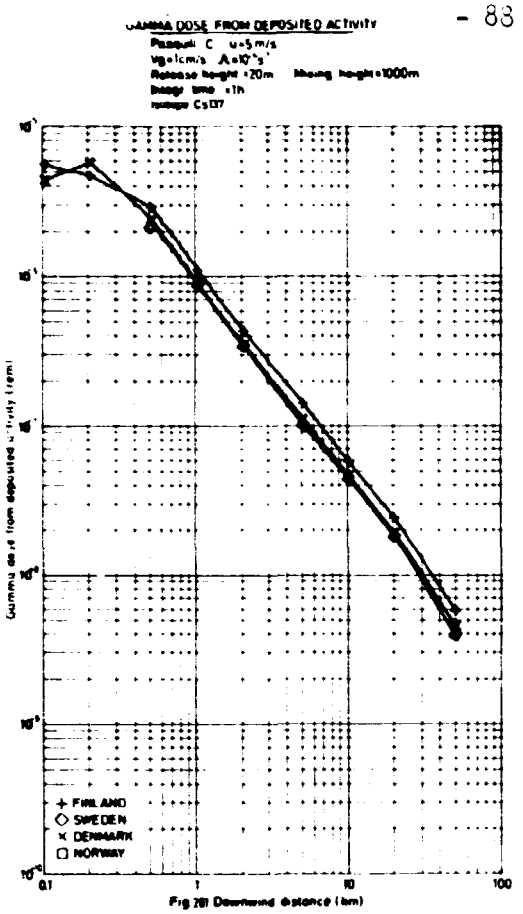
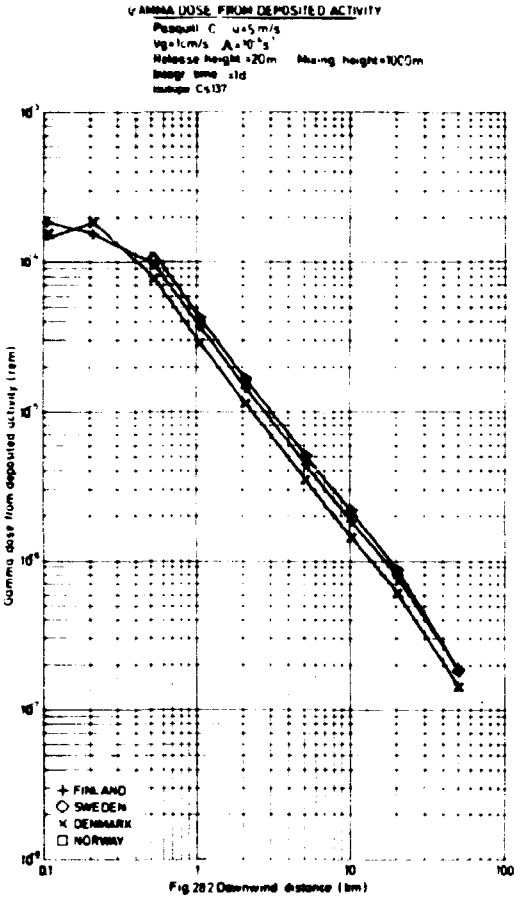


Fig 281 Downwind distance (km)



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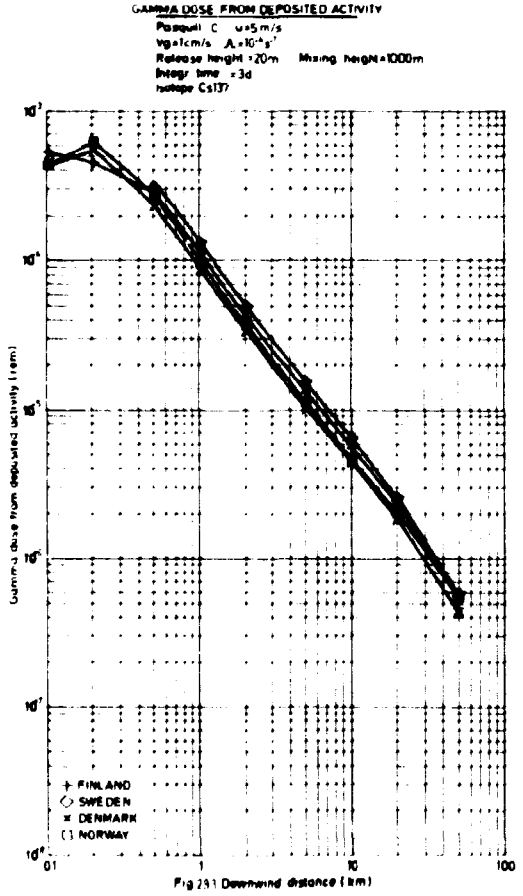
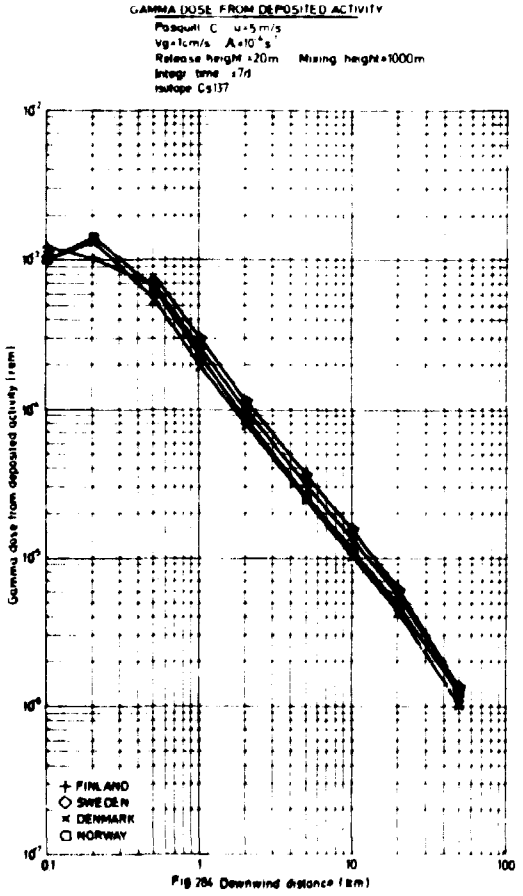


Fig 283 Downwind distance (km)



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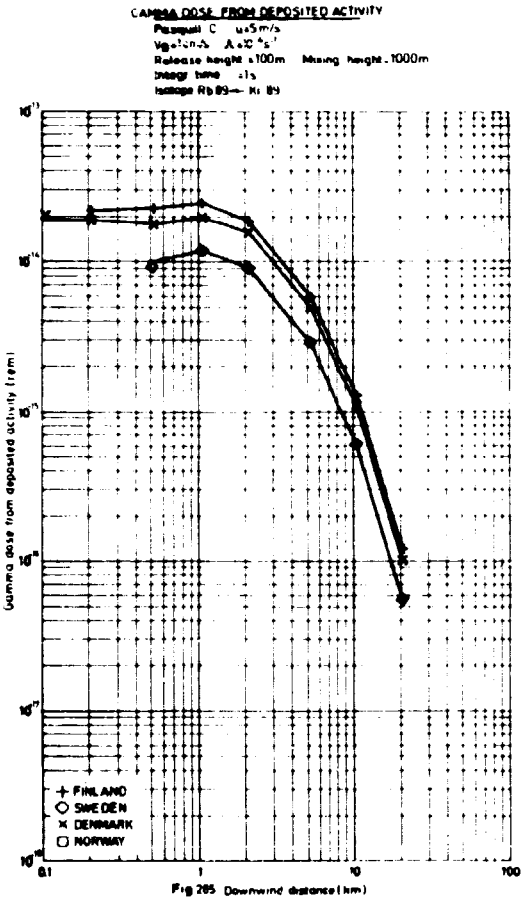
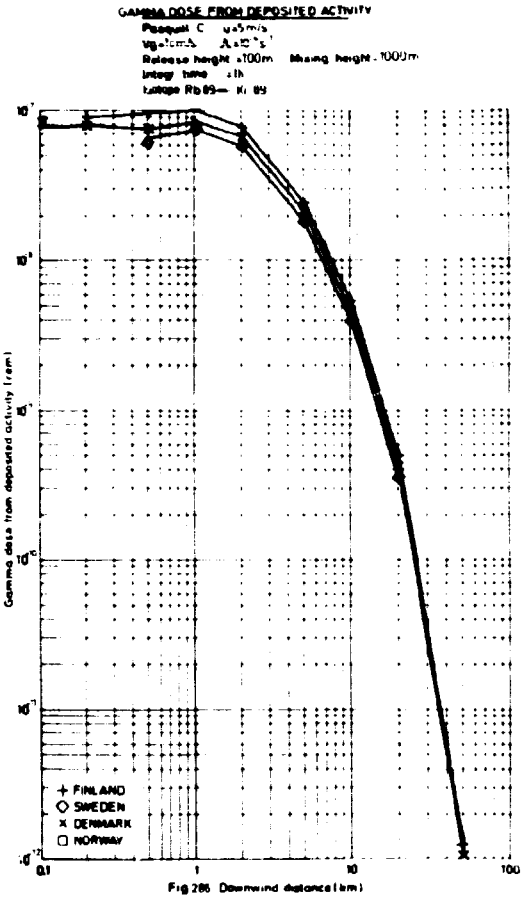


Fig 285 Downwind distance (km)



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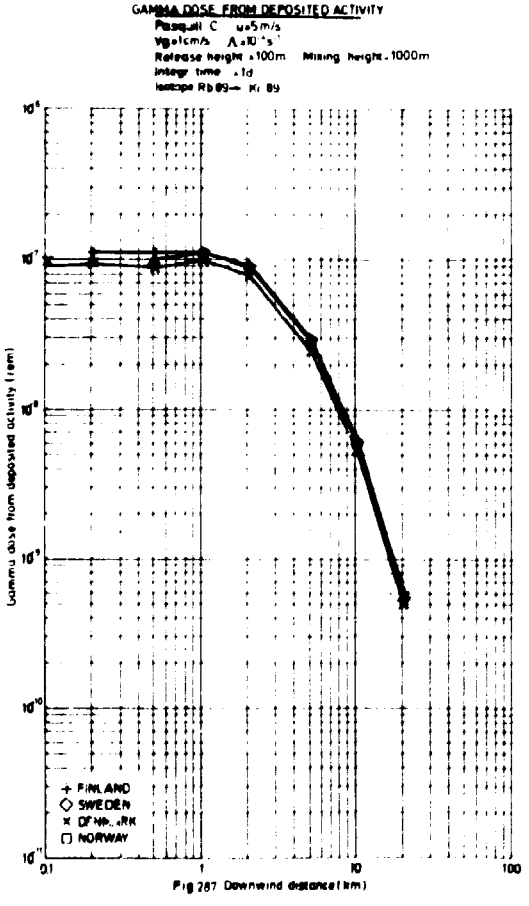

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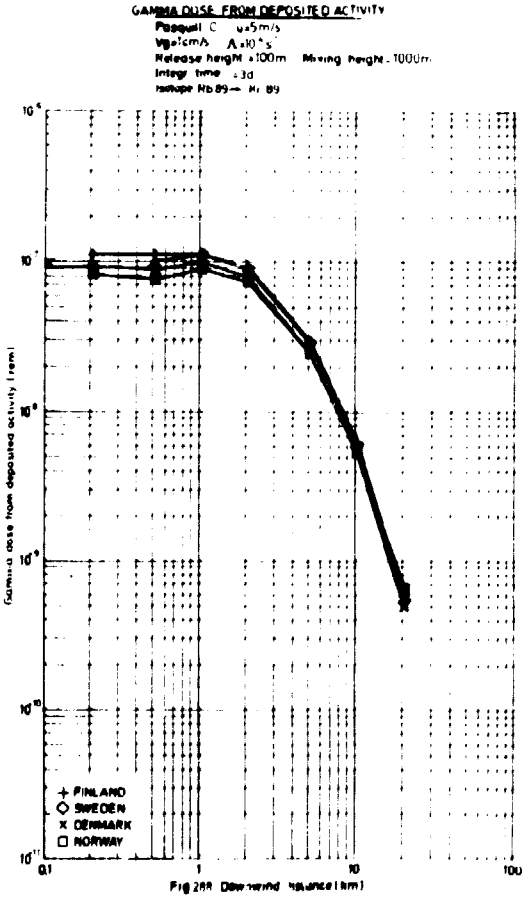


Fig 288 Downwind distance (km)

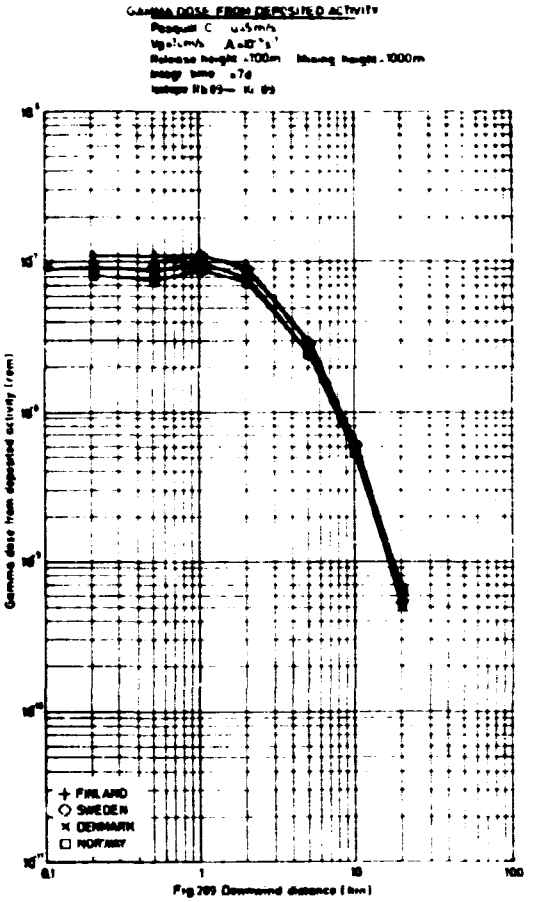


Fig 289 Downwind distance (km)

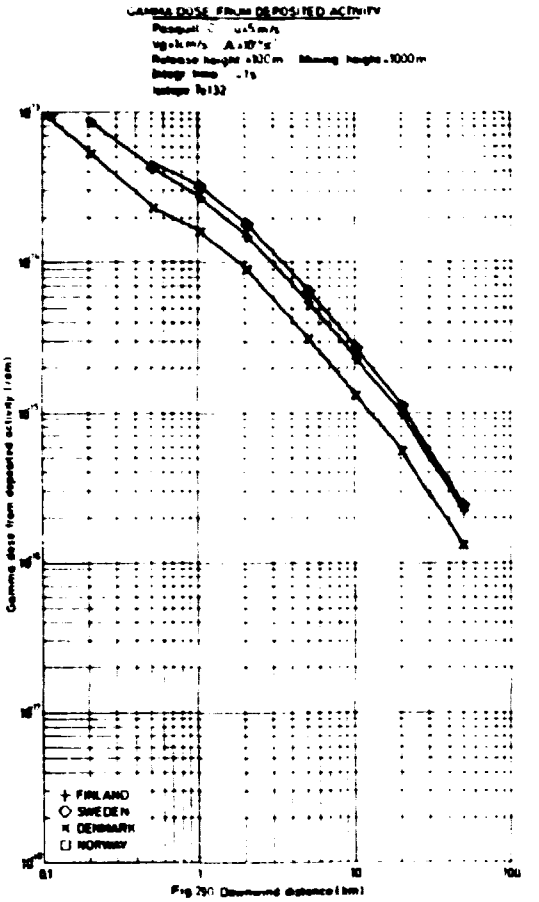


Fig 290 Downwind distance (km)

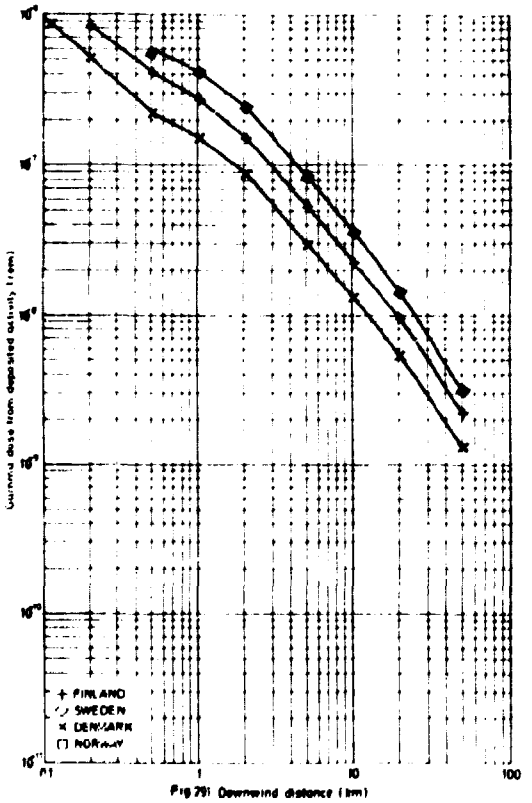


Fig 291 Downwind distance (km)

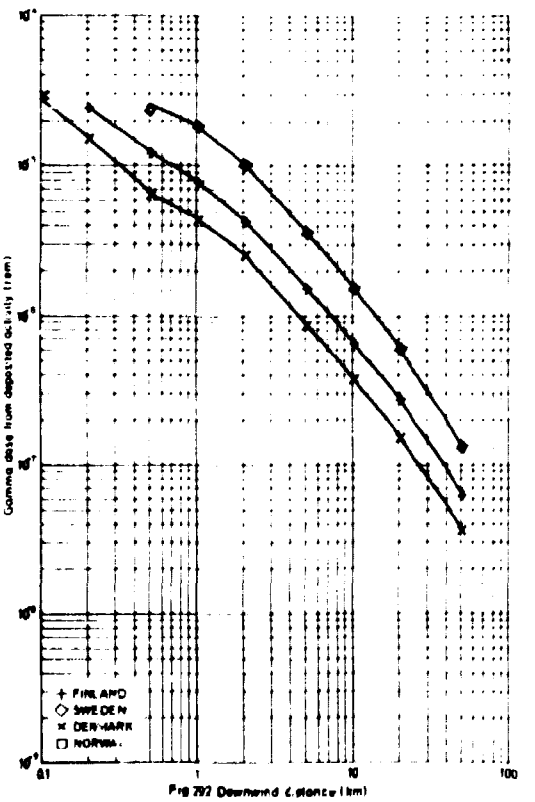


Fig 292 Downwind distance (km)

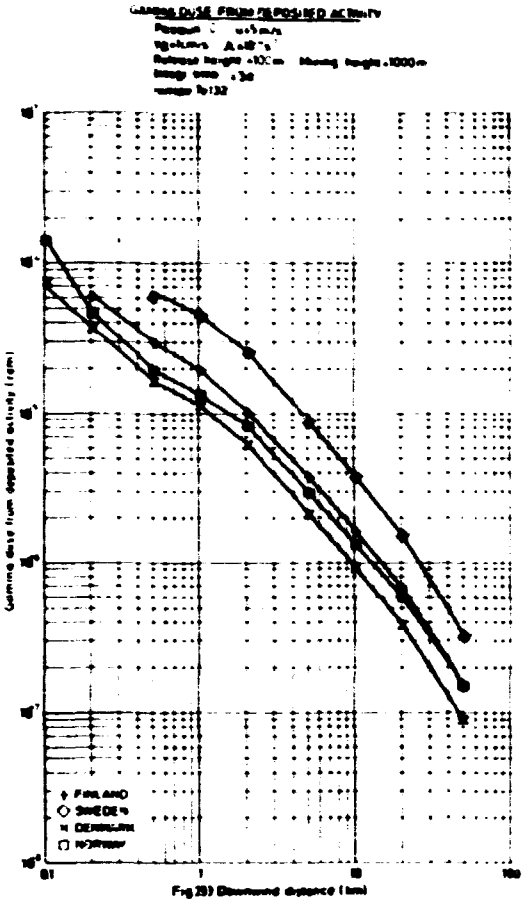


Fig 29j Downwind distance (km)

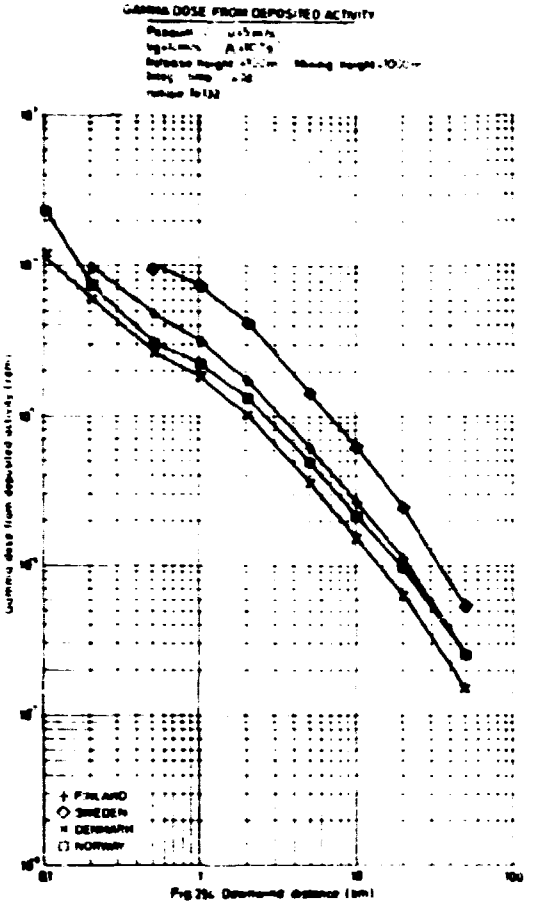


Fig 29k Downwind distance (km)

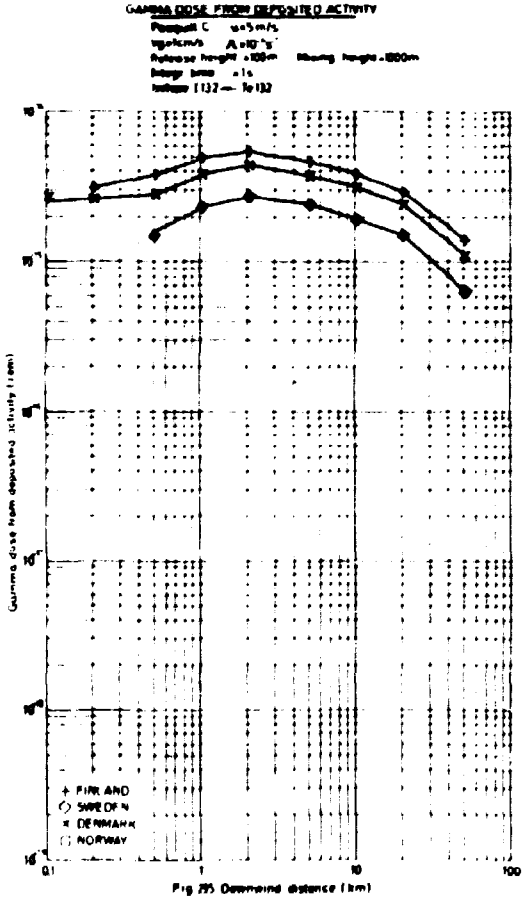


Fig 29l Downwind distance (km)

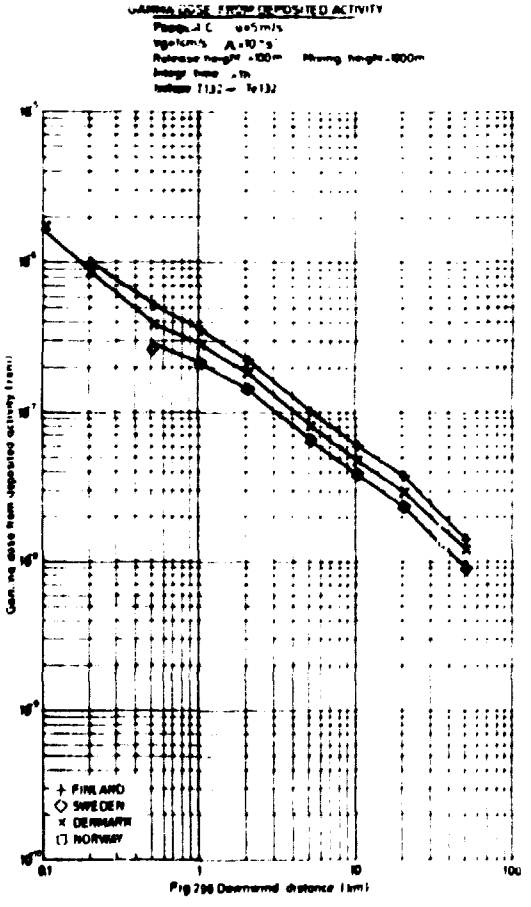
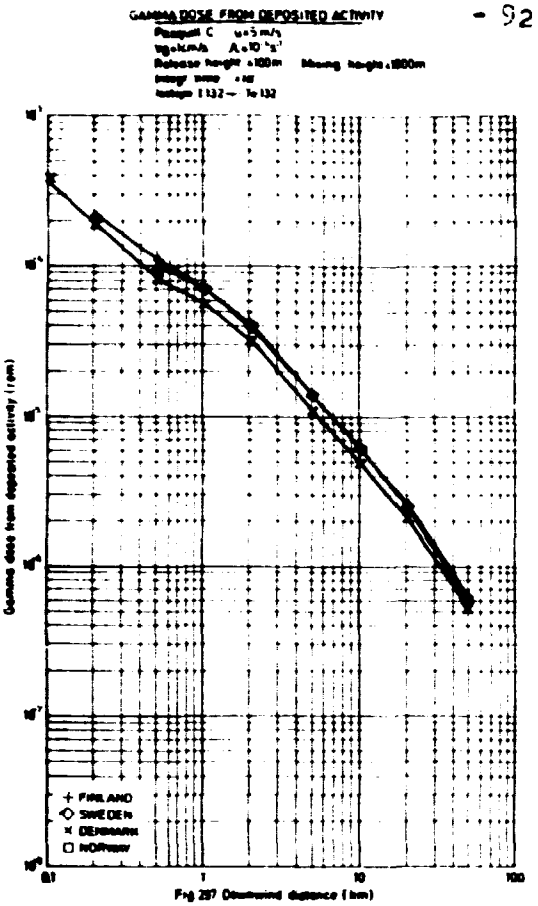
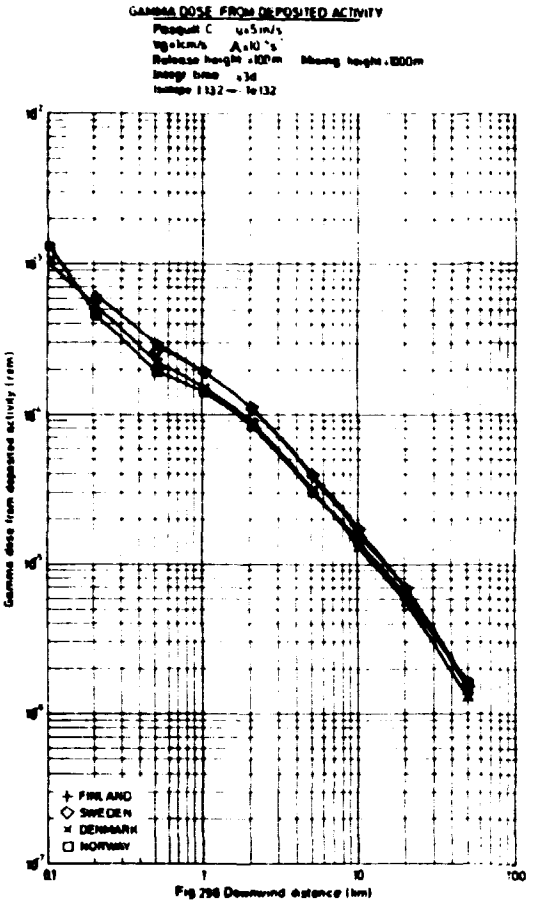
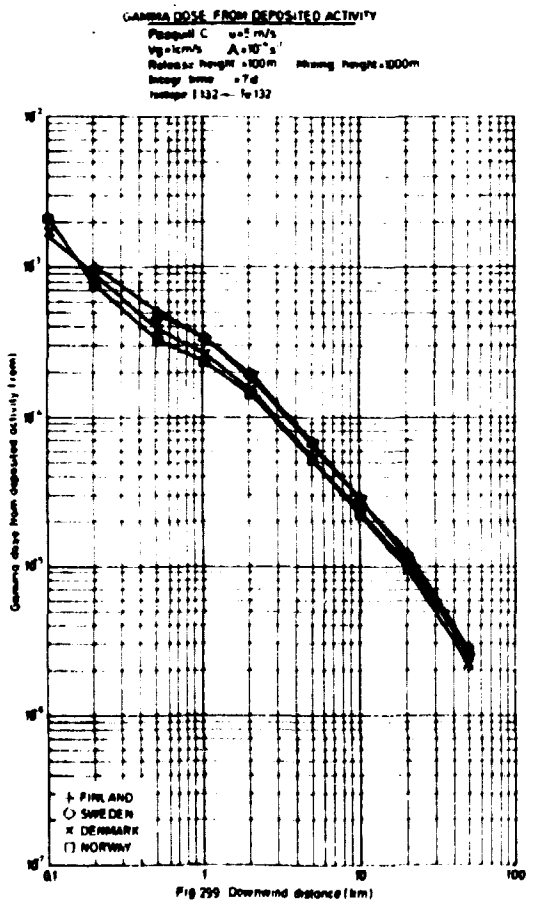


Fig 29m Downwind distance (km)


GAMMA DOSE FROM DEPOSITED ACTIVITY
Pasquill C u=5 m/s
Vg=1cm/s A=10⁻⁴s⁻¹
Release height =100m Mixing height =1000m
Integr time =4d
Isotope I 132 — Te 132
Gamma dose from deposited activity (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 297 Downwind distance (km)


GAMMA DOSE FROM DEPOSITED ACTIVITY
Pasquill C u=5 m/s
Vg=1cm/s A=10⁻⁴s⁻¹
Release height =100m Mixing height =1000m
Integr time =1d
Isotope I 132 — Te 132
Gamma dose from deposited activity (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 298 Downwind distance (km)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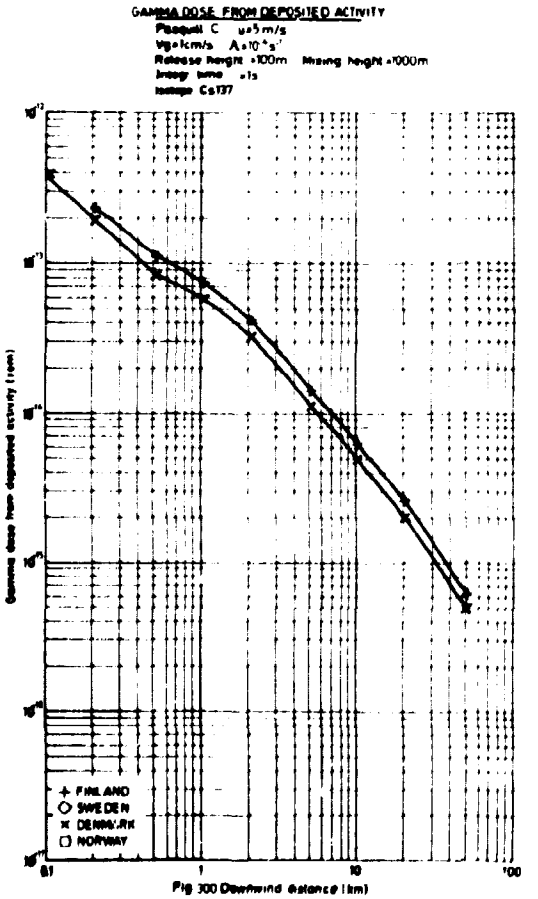
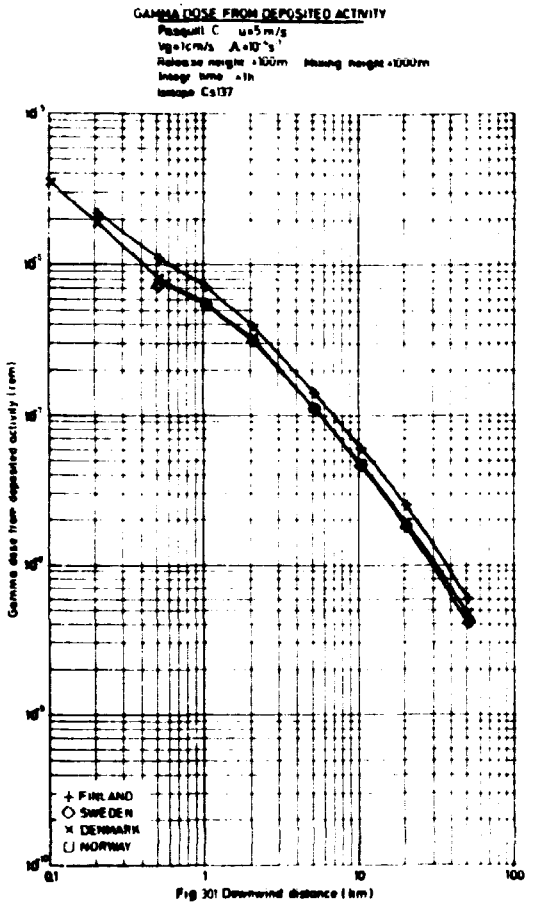
Pasquill C u=5 m/s
Vg=1cm/s A=10⁻⁴s⁻¹
Release height =100m Mixing height =1000m
Integr time =7d
Isotope I 132 — Te 132
Gamma dose from deposited activity (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 299 Downwind distance (km)


GAMMA DOSE FROM DEPOSITED ACTIVITY
Pasquill C u=5 m/s
Vg=1cm/s A=10⁻⁴s⁻¹
Release height =100m Mixing height =1000m
Integr time =1s
Isotope Cs137
Gamma dose from deposited activity (rem)
FINLAND
SWEDEN
DENMARK
NORWAY
0.1
1
10
100
Fig 300 Downwind distance (km)



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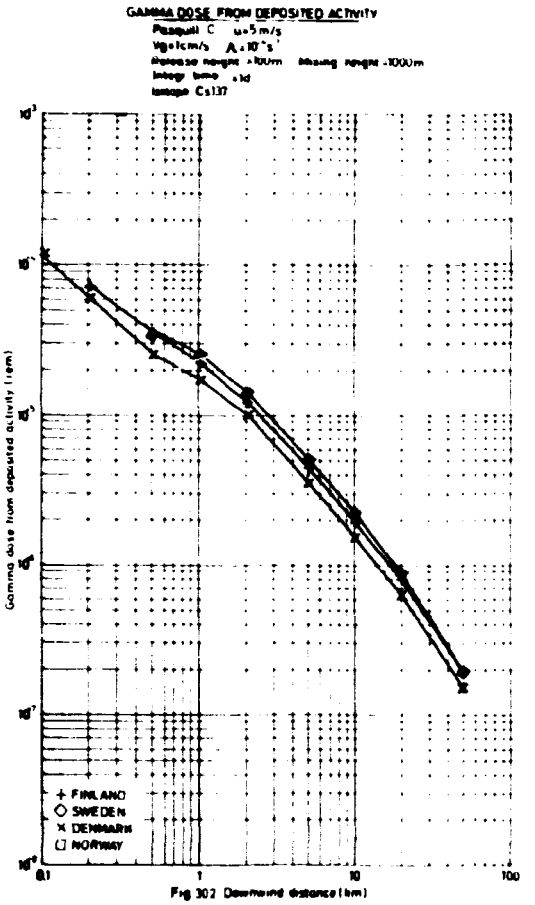

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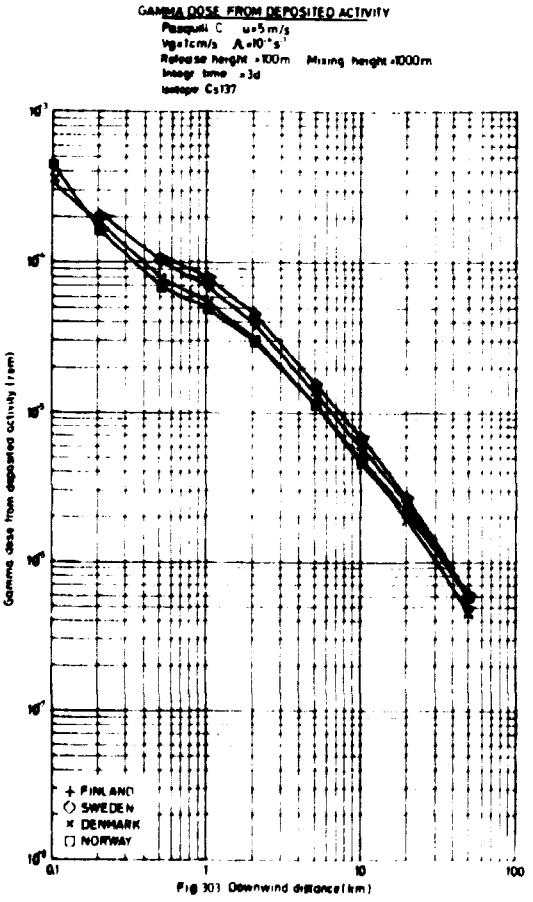

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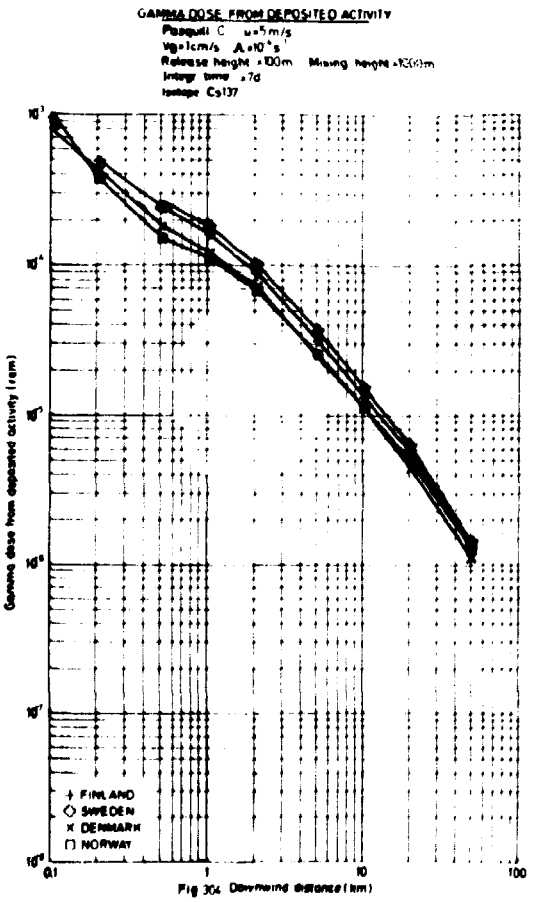

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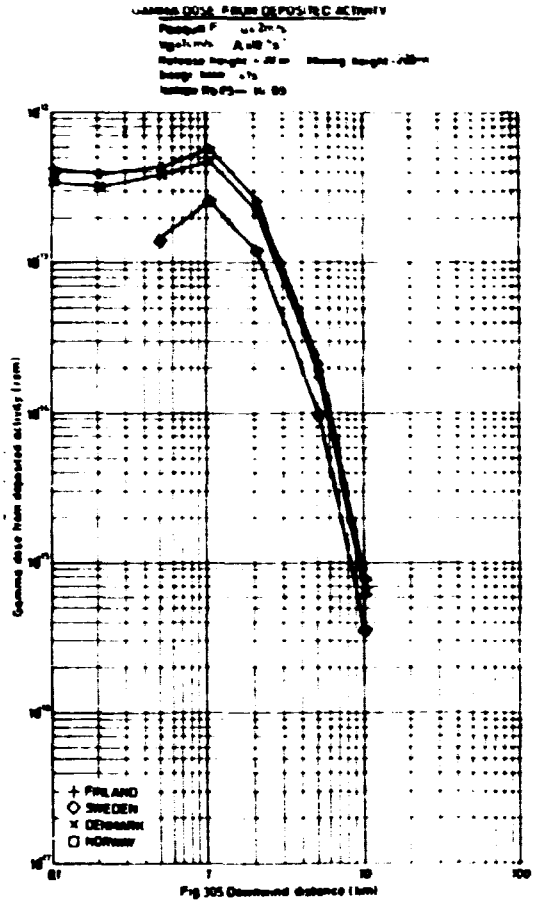

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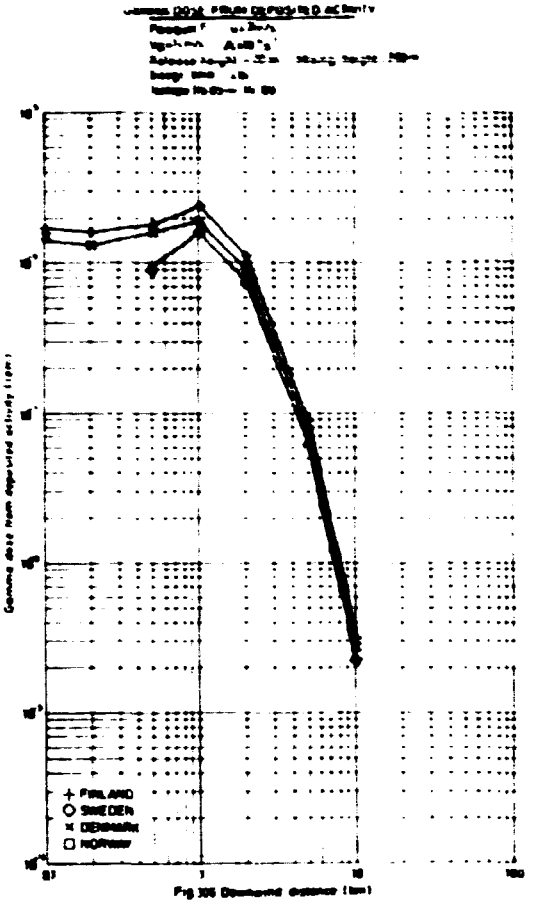

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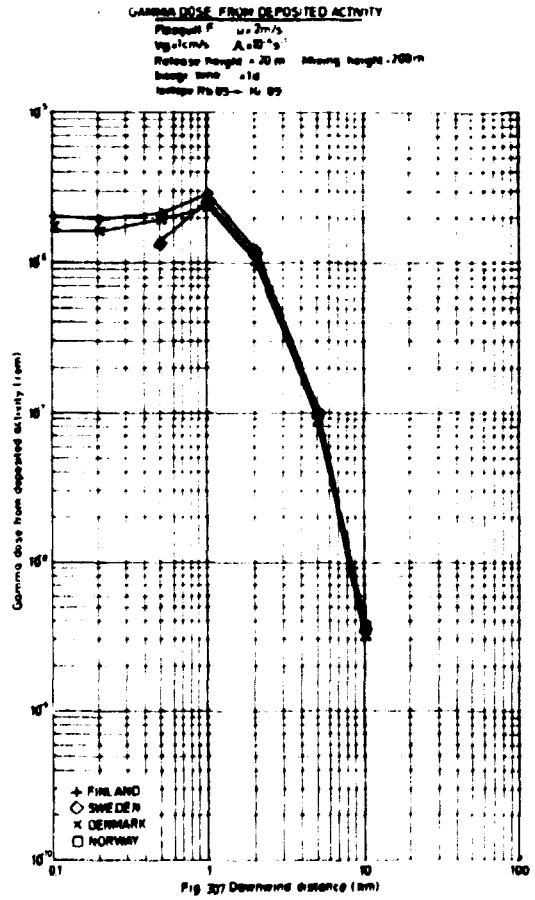

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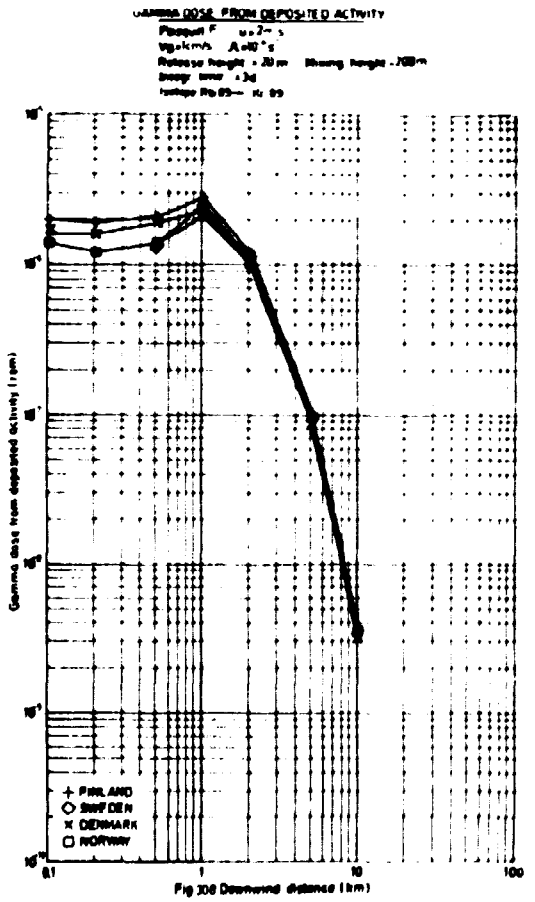

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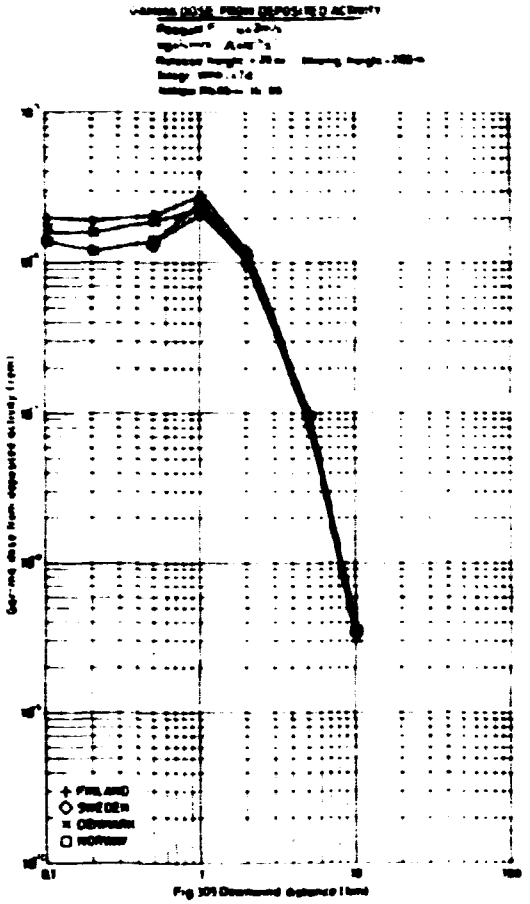
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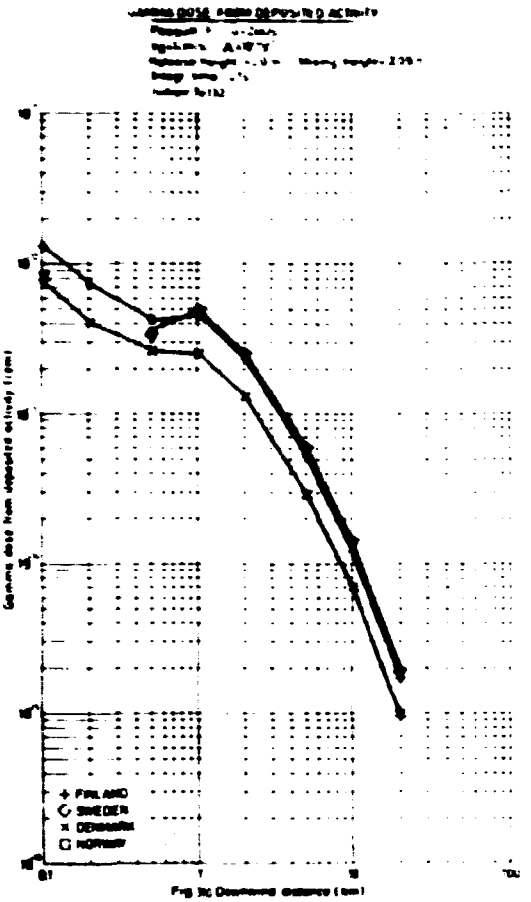
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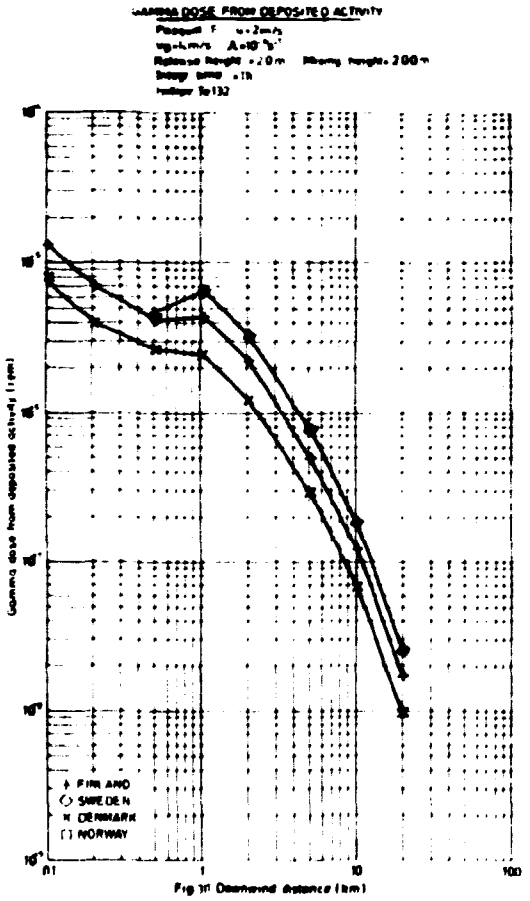
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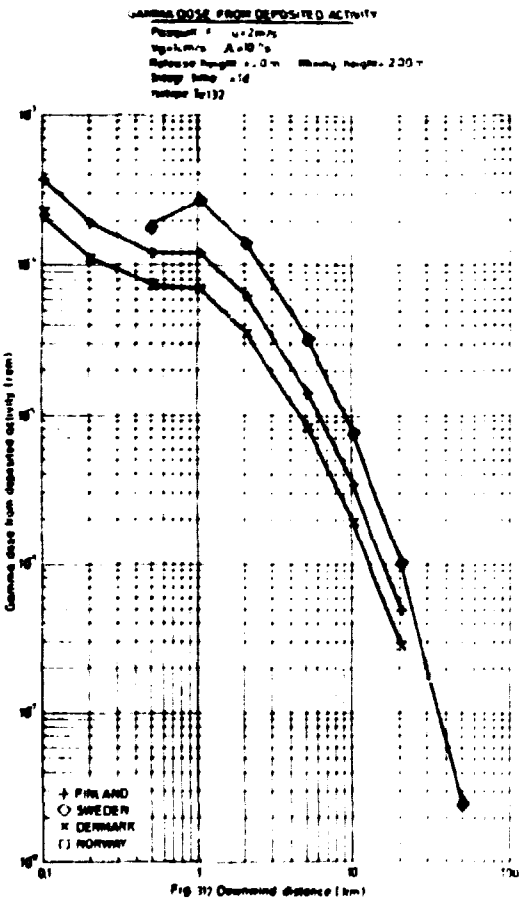
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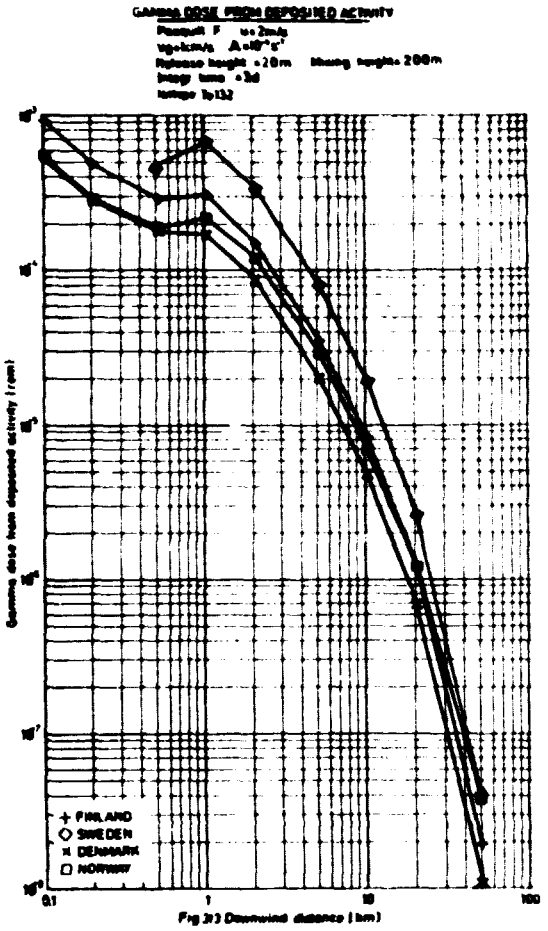

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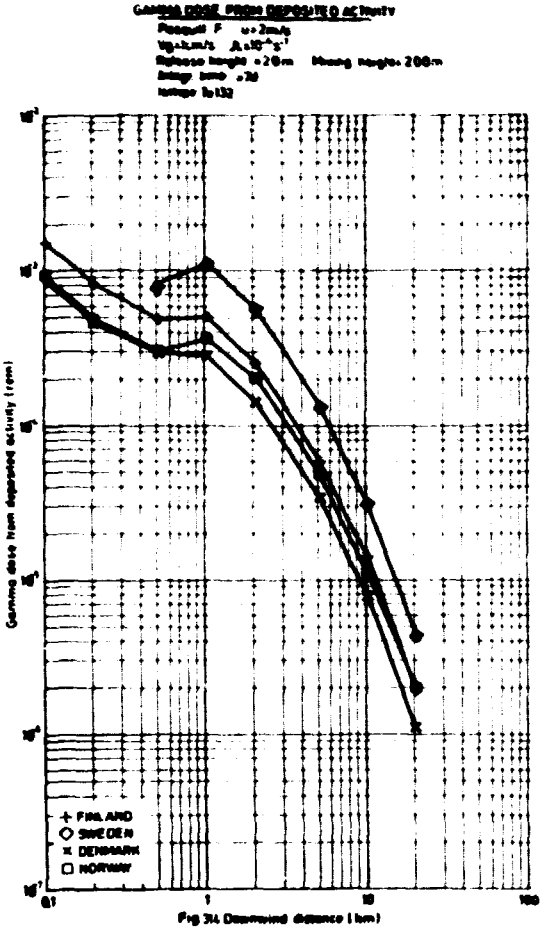

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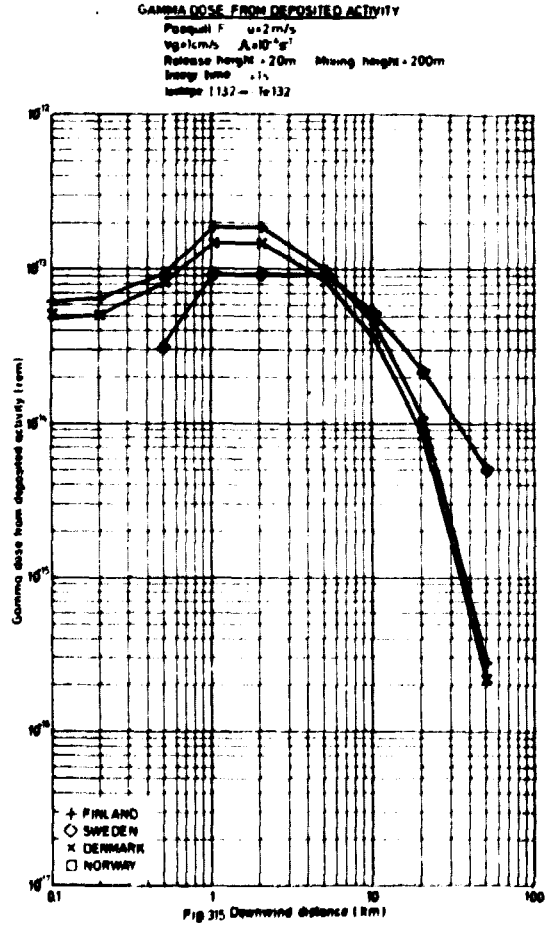

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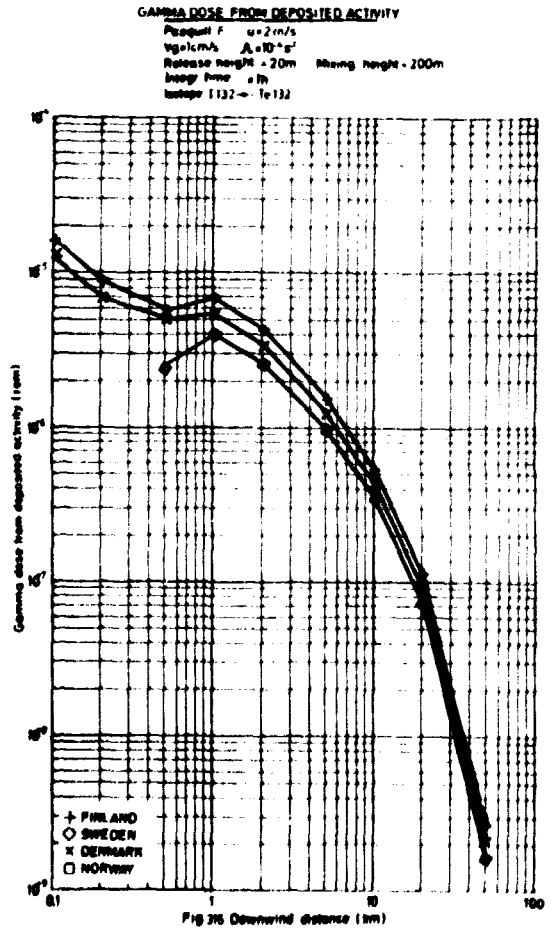

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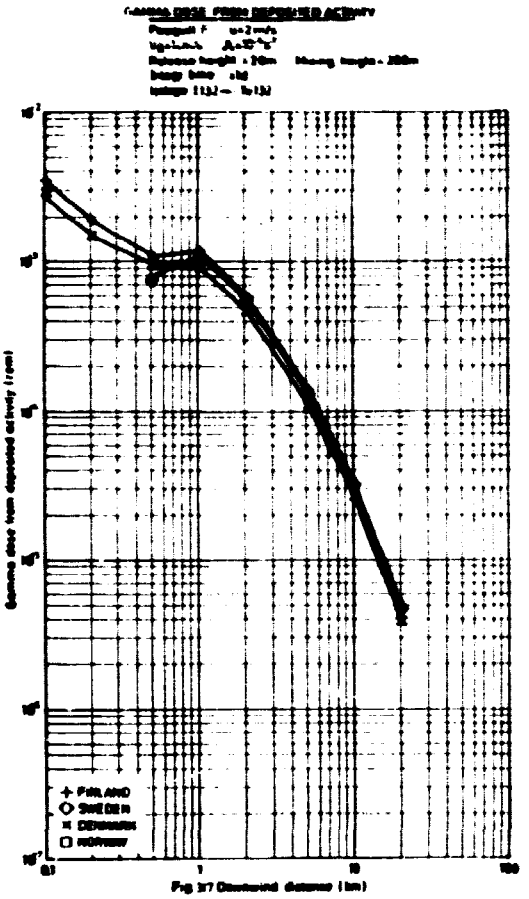

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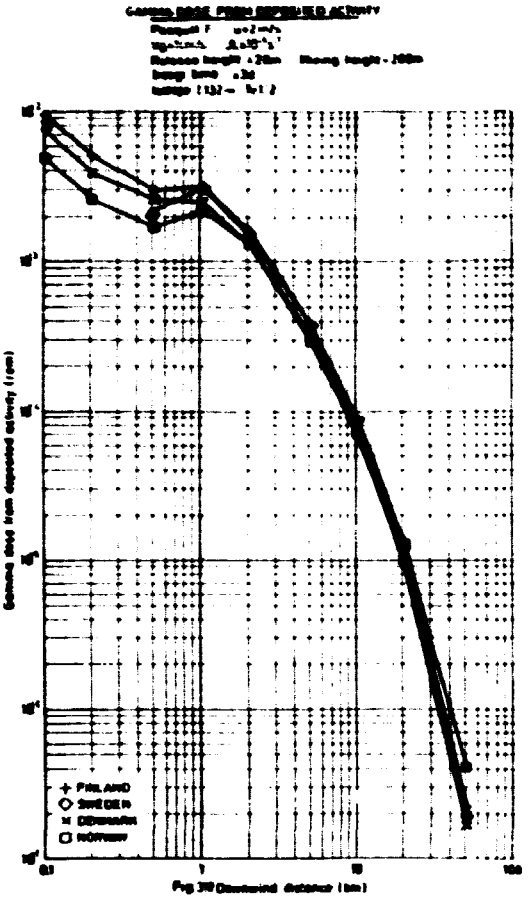

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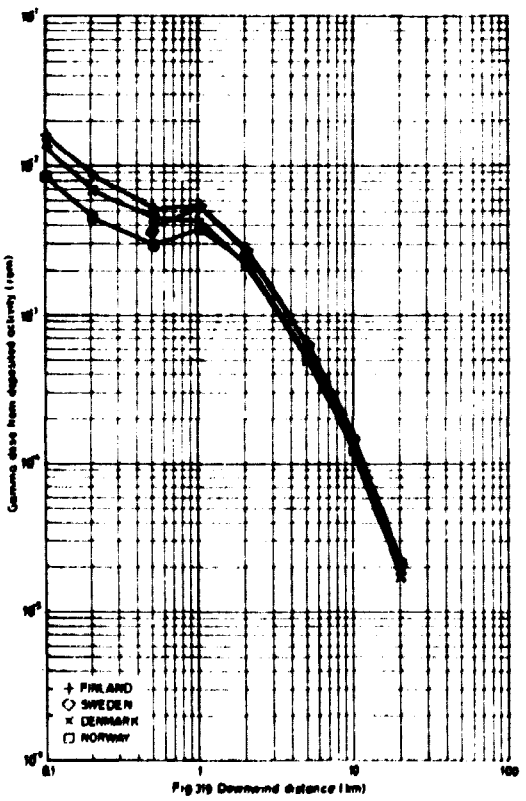

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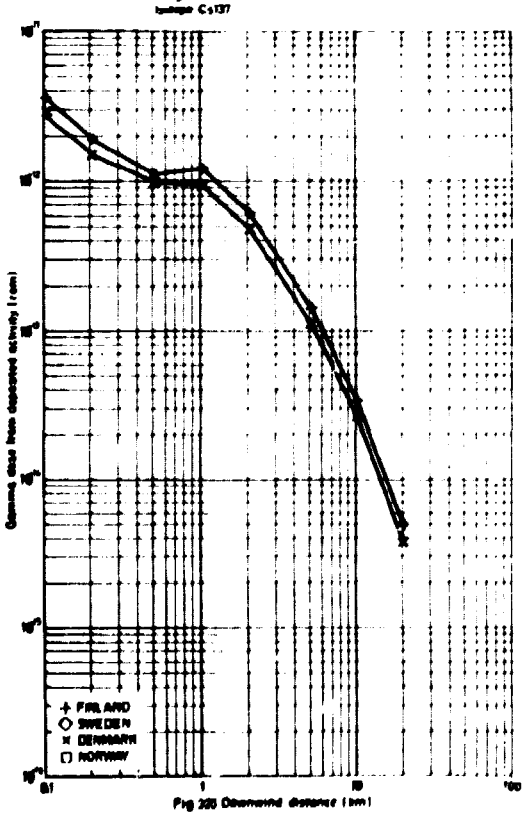

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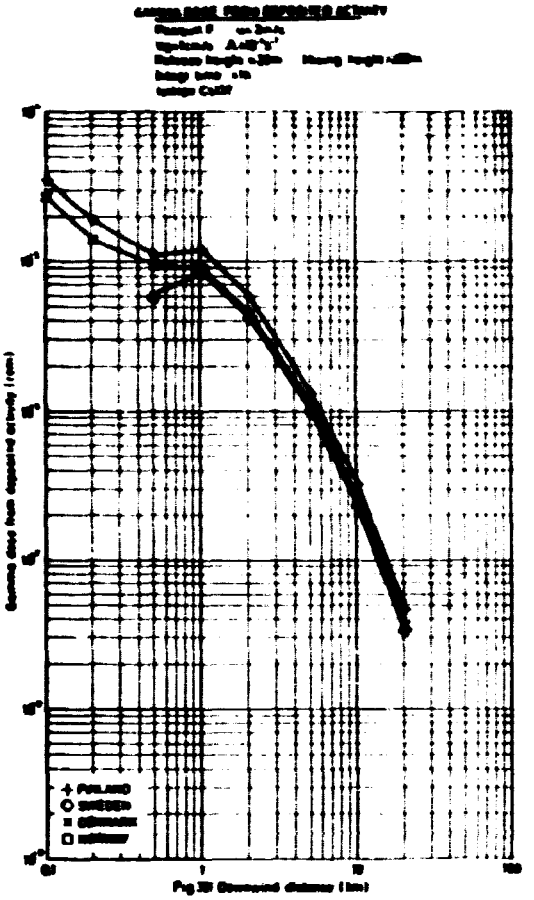
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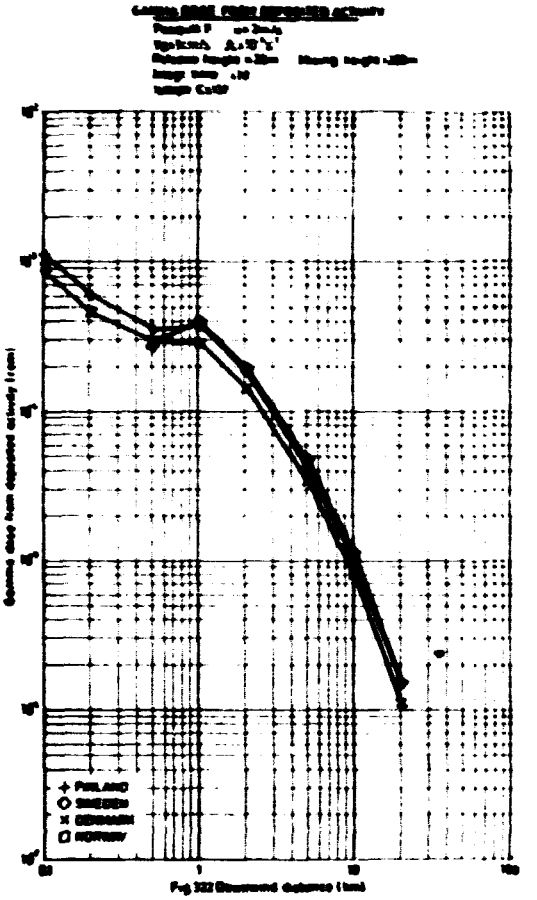
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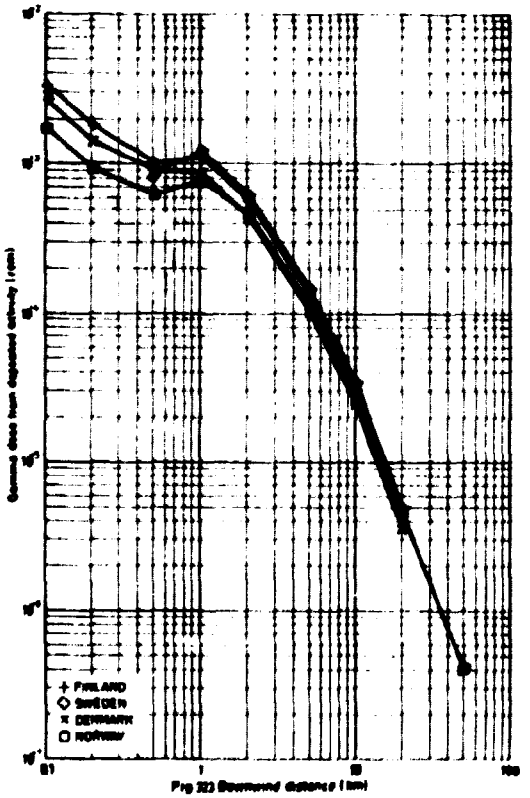
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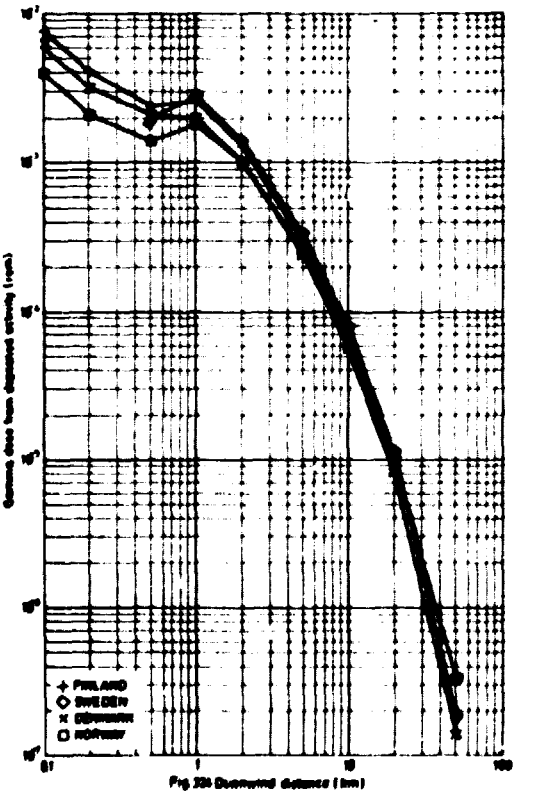
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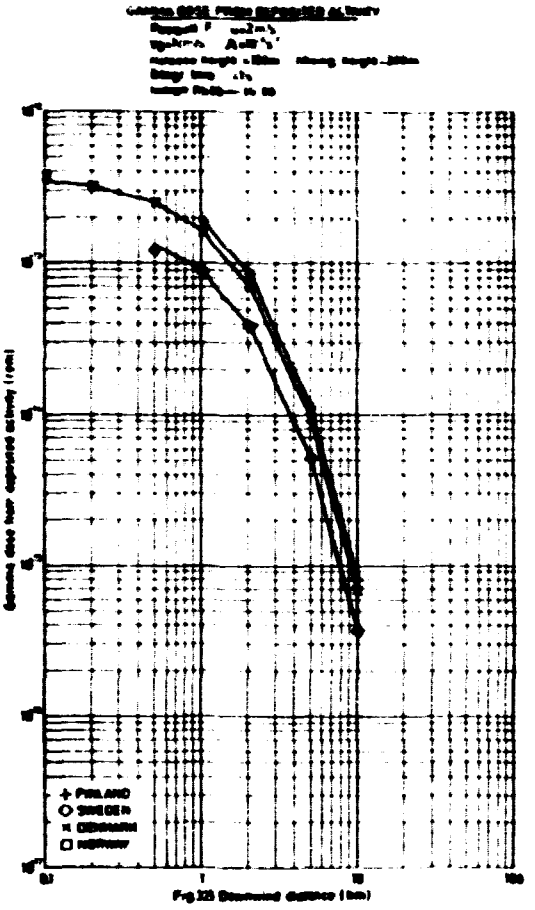

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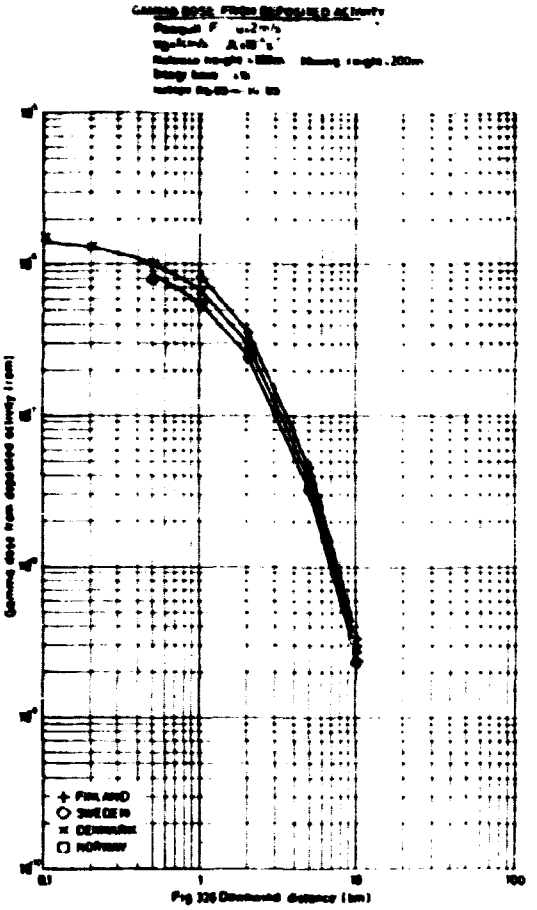

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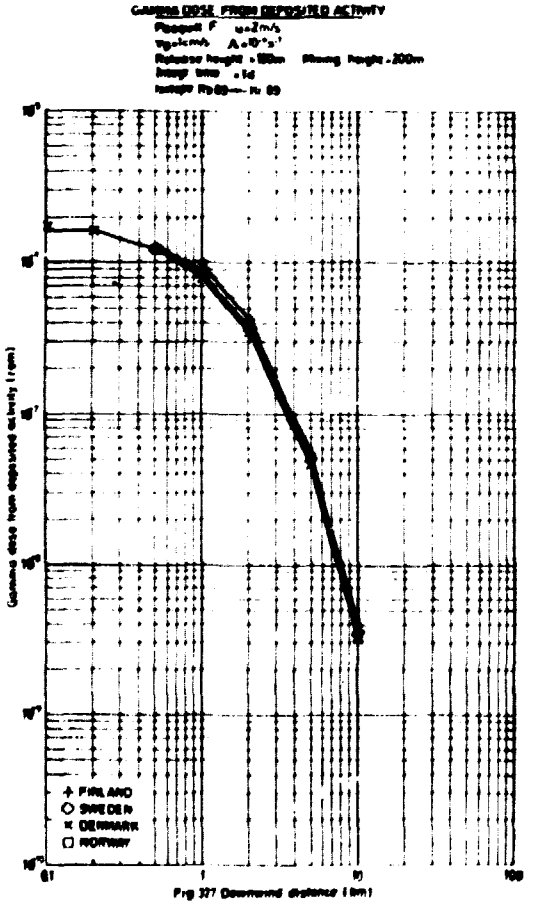

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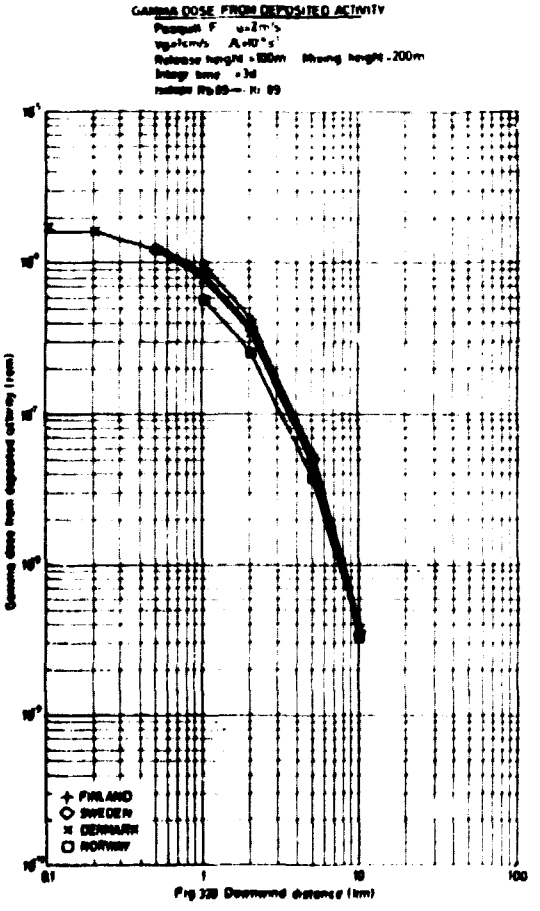

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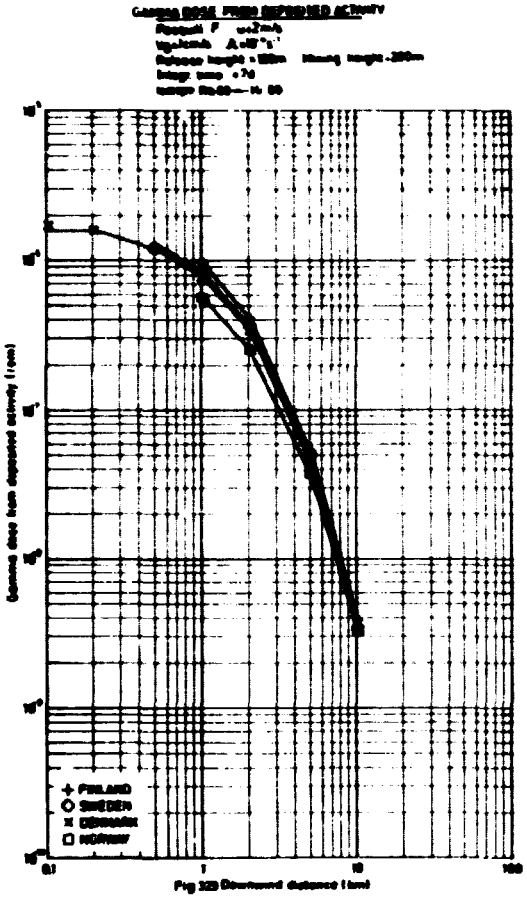
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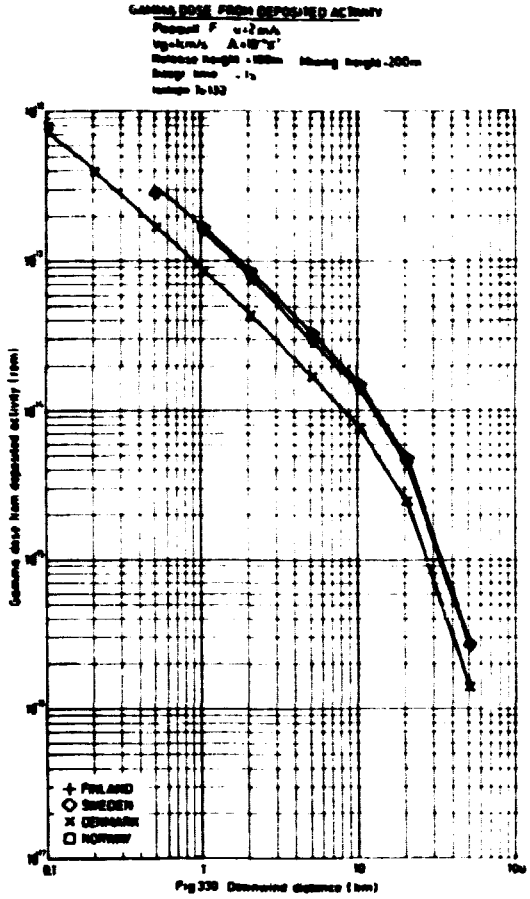
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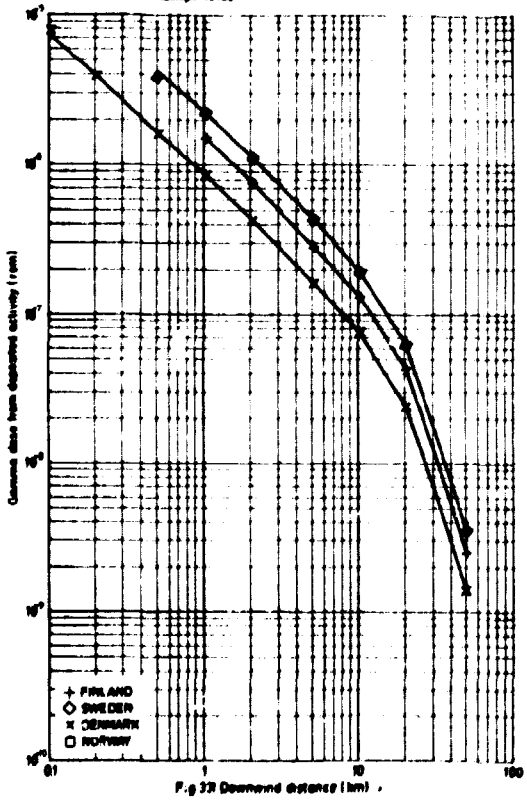
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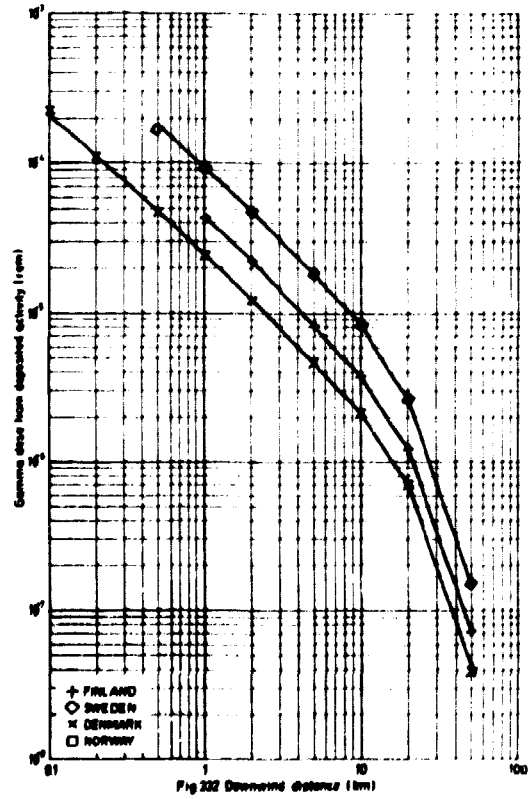
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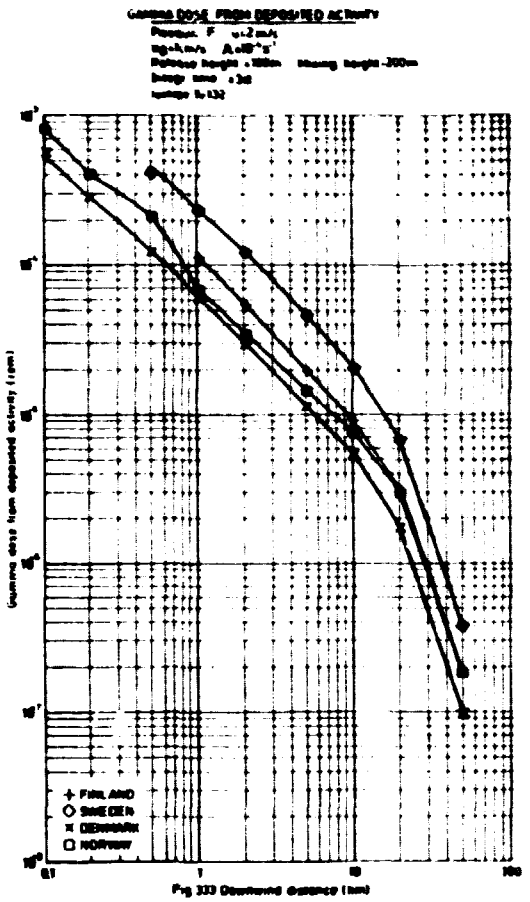
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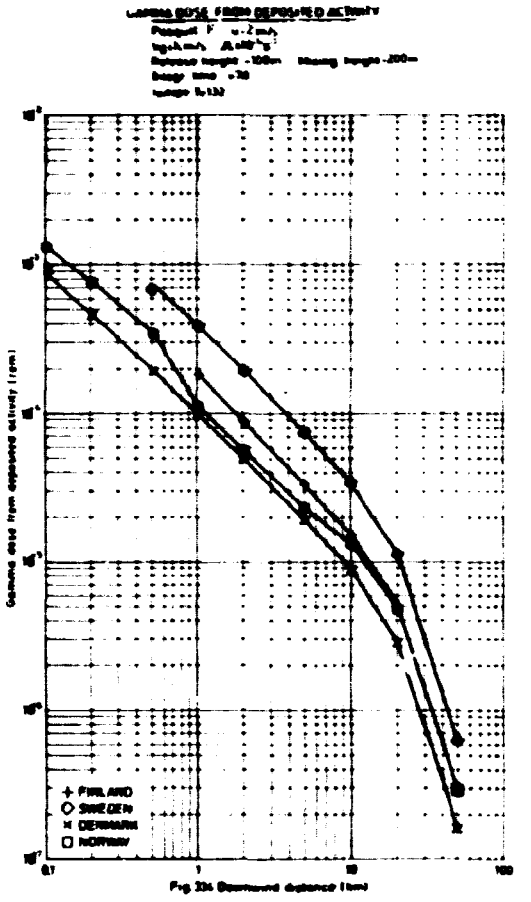
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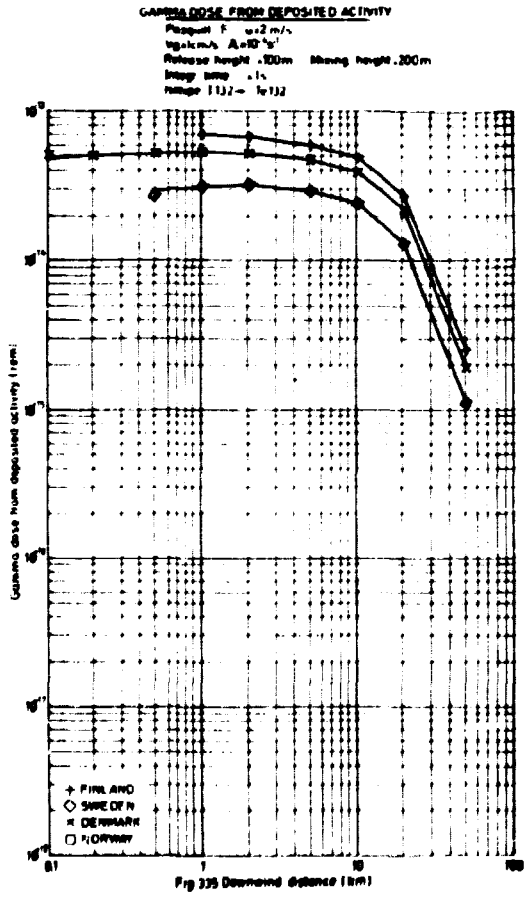
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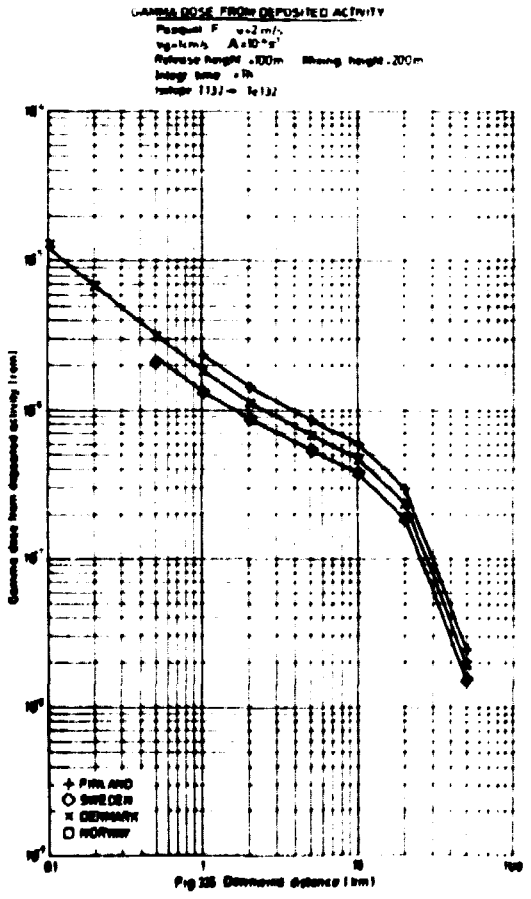
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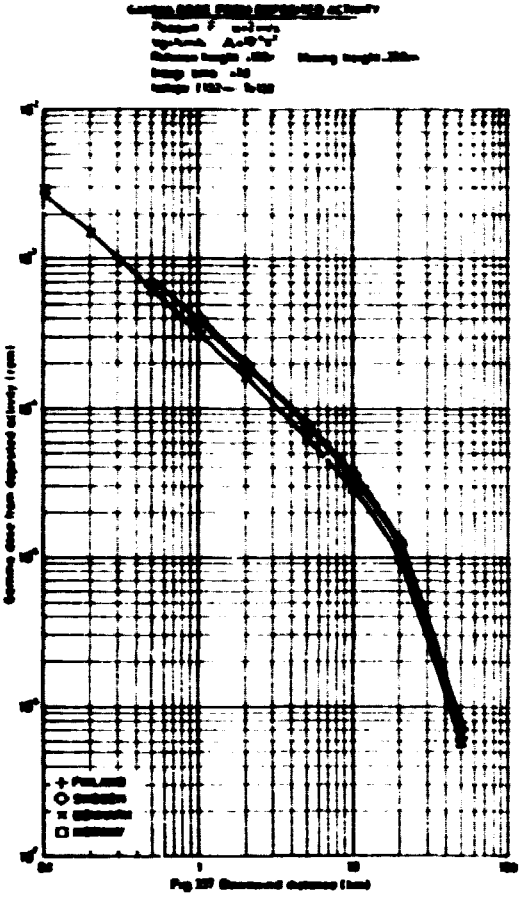
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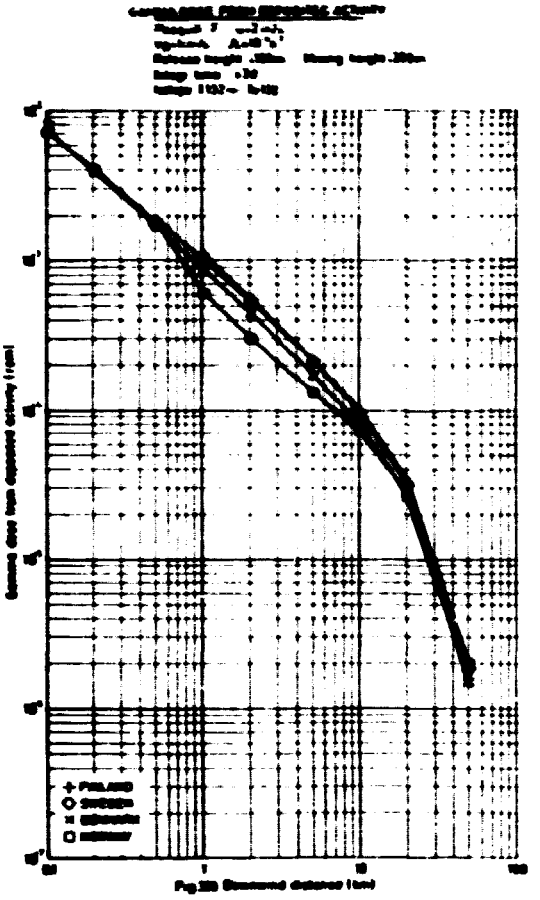
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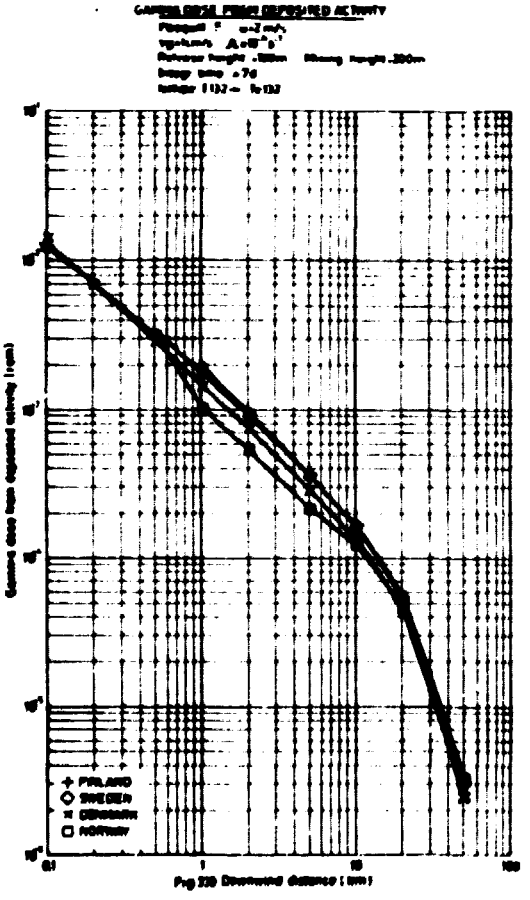
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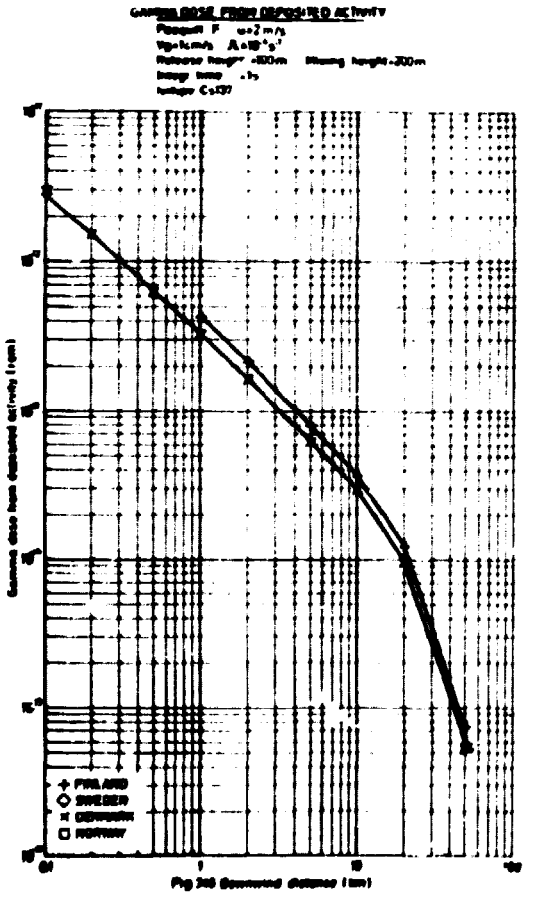
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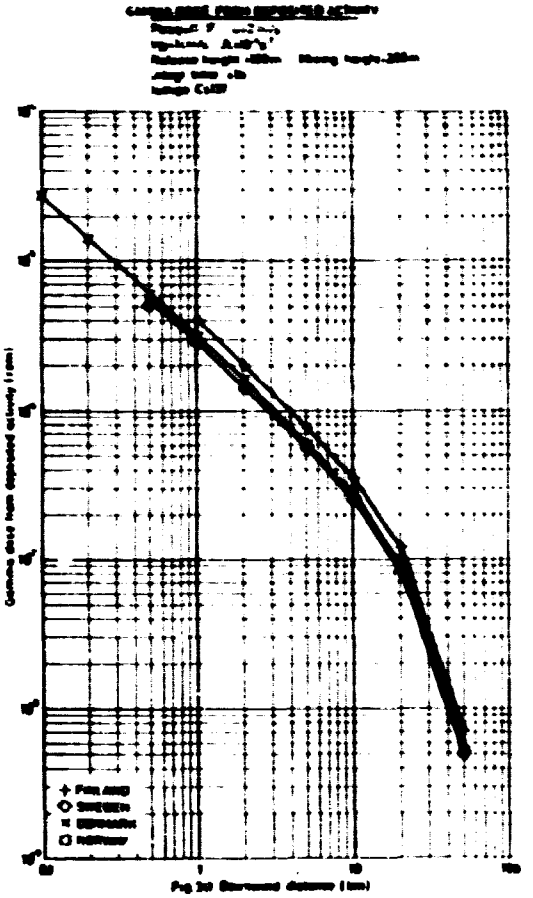
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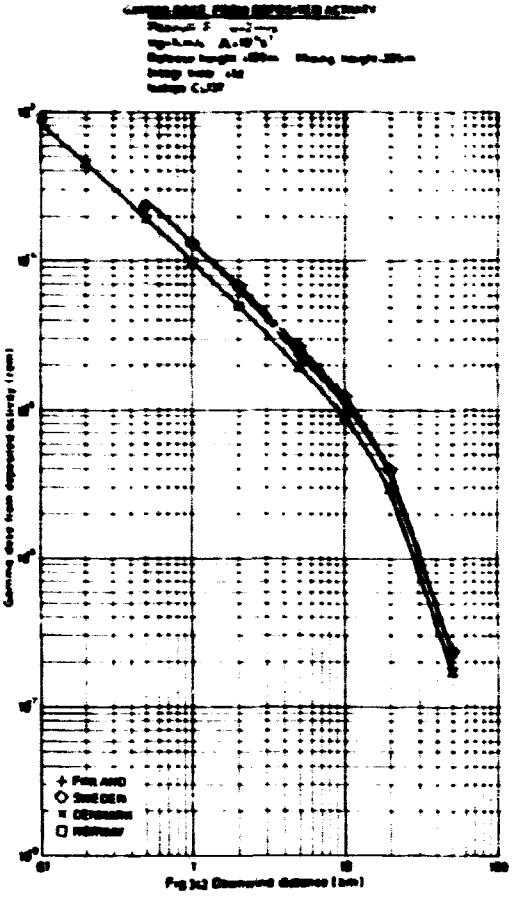
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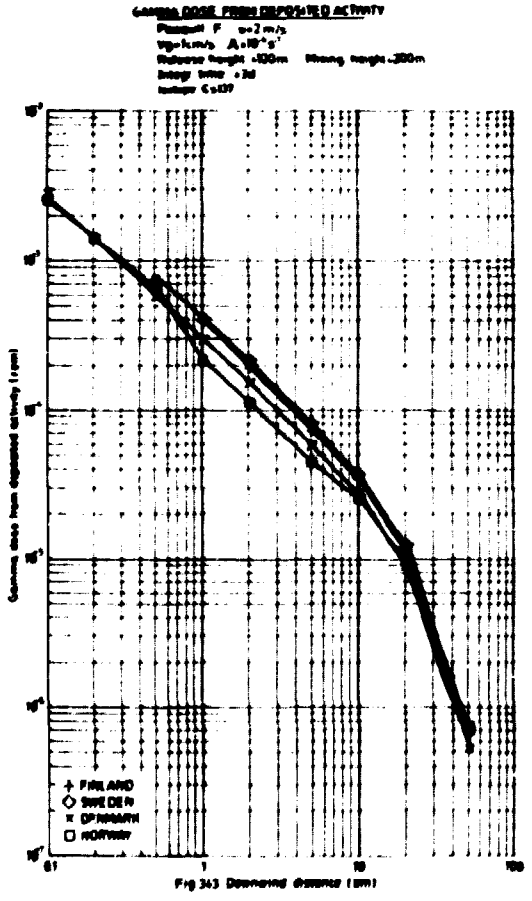
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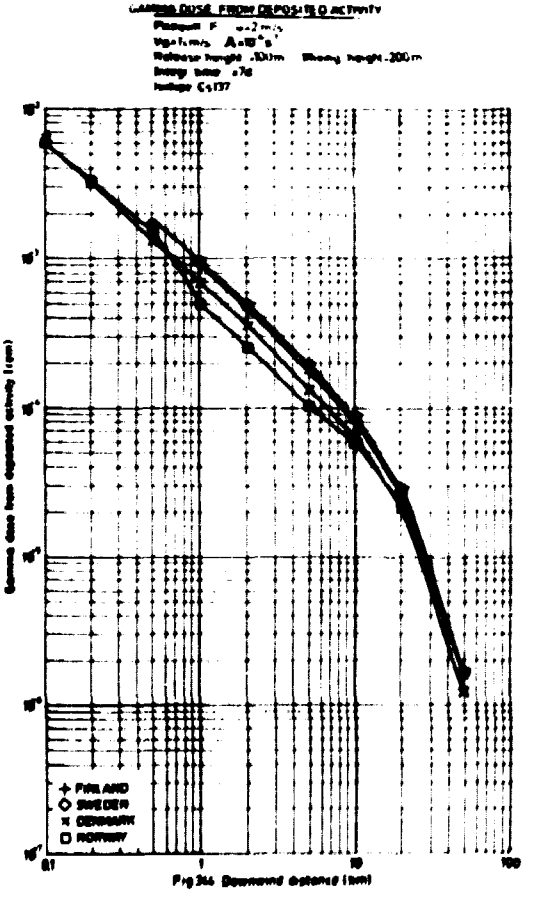
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APPENDIX 1

Description of the Finnish Model for Calculating Doses from Radioactive Material Released to the Atmosphere

by

Seppo Vuori

VALTION TEKNILLINEN TUTKIMUSKESKUS
STATENS TEKNISKA FORSKNINGSCENTRAL
TECHNICAL RESEARCH CENTRE OF FINLAND
Nuclear Engineering Laboratory

Seppo Vuori

Helsinki 1977-06-15

SNODAS

Dose models and parameters used in VTT's programs

1. Dose models

1.1. External gamma dose from cloud

The dose rate in tissue is calculated from

$$\dot{D}(xd,yd,zd) = K \cdot \sigma_{en} \cdot E \cdot Q \int_{x=0}^{\infty} \int_{y=-\infty}^{\infty} \int_{z=0}^{\infty} \frac{B(\mu r)}{4\pi r^2} e^{-\mu r} \cdot \chi(x,y,z)dxdydz \; \frac{rad}{s} \qquad (1)$$

where

$$K = 0.05928 \; \frac{rad/s}{(Ci/m^3)(MeV/disintegr.)m(cm^2/g)}$$

σ_{en} = energy absorption coefficient in tissue $\approx 0.03 \; \frac{cm^2}{g}$

[E] = MeV/dis ; [χ] = s/m^3 [Q] = Ci/s

$$B(\mu r) = \begin{cases} 1 + \mu r + \dfrac{(\mu r)^2}{7E^{2.4}} & 0.5<\text{MeV}<E\ 2\ \text{MeV} \\ 1 + 1.1\ \mu r + (\mu r)^2 & E<0.5\ \text{MeV} \end{cases} \qquad (2)$$

Because the integral in equation (1) is not very sensitive to gamma energy, we have only calculated with one energy (E = 1 MeV) and formed a normalized cloud gamma dose data-file

$$D_0(x_i,\phi_j,H_k) = \frac{\dot{D} \cdot u_{ref}}{Q\ E\ \sigma_{en}} \; , \qquad (3)$$

where E_γ = 1 MeV

μ = 8.15 x 10^{-3} m^{-1}

u_{ref} = 5 m/s

The D_0-values are calculated for different weather categories and four release heights in mesh points (x_i,ϕ_j). We have

used six-point Newton-Cotes formulas in the 3-dimensional integrations. We have utilized subprogram PLUME of code RACER and corrected the observed errors and made the necessary modifications. The cloud dose for nuclide n at the wind speed u is obtained from

$$D_{sub}^{(n)}(x_i, \phi_j, H_k) = g_{sub}^{(n)} \cdot \frac{1}{u} \cdot D_0(x_i, \phi_j, H_k) \cdot Q^{(n)} \qquad (4)$$

where

$$g_{sub}^{(n)} = \sigma_{en}^{(n)}(\text{tissue 1 MeV}) \cdot \sum_{\nu} f_{\nu}^{(n)} E_{\nu}^{(n)}(5\text{ cm}) \qquad (5)$$

$E_{\nu}^{(n)}$ = gamma energy of photon ν of nuclide n

$f_{\nu}^{(n)}$ = absolute intensity of photon ν per one disintegration

$E_{\nu}^{(n)}(5\text{ cm}) = 0.86\, E_{\nu}^{(n)}$ = effective gamma energy at 5 cm depth in tissue

The model for external dose calculation will be supplemented in the future by increasing the number of energy groups. In that case the normalized dose data file contains values for each energy group. The external dose for nuclide n is given by

$$D_{sub}^{(n)}(x_i, \phi_j, H_k) = \sum_{l=1}^{L} g_{sub}^{(n)}(E_l) \cdot \frac{1}{u} D_0(x_i, \phi_j, H_k, E_l) \cdot Q^{(n)} \qquad (6)$$

$$g_{sub}^{(n)}(E_l) = \sum_{\nu} f_{\nu}^{(n)}(E_{\nu}^{(n)} \in E_l) E_{\nu}^{(n)}(5\text{ cm})\, \sigma_{en}(E_l, \text{tissue}), \qquad (7)$$

where

$f_{\nu}^{(n)}(E_{\nu}^{(n)} \in E_l)$ = absolute intensity of photon ν per one disintegration if $E_{\nu}^{(n)}$ belongs to energy group l, otherwise zero.

1.2. External gamma dose from deposited activity

The dose rate from deposited activity on the ground is calculated simply by the following expression

$$\dot{D}^{(n)}_{fall}(x_i,\phi_j,t) = g^{(n)}_{fall} \times C_A(x_i,\phi_j,t) \qquad (9)$$

$[g_{fall}]$ = rem/s/(Ci/m²)

$[C_A]$ = Ci/m²

The dose factors g_{fall} are calculated with the formula:

$$g_{fall} = 0.02964 \sum_\nu f^{(n)}_\nu E^{(n)}_\nu (5\,cm)\, \sigma_{en}(E^{(n)}_\nu, tissue) \cdot \qquad (9)$$

$$[E_1(\mu(E^{(n)}_\nu)\cdot h) \cdot C(E^{(n)}_\nu)], \text{ where}$$

$$C(E^{(n)}_\nu) = \begin{cases} 1 + \dfrac{(E^{(n)}_\nu)\cdot h \cdot 1}{7(E^{(n)}_\nu)^{2.4}} & 0.5 < E^{(n)}_\nu < 2 \text{ MeV} \\ 2.1 \cdot \mu(E^{(n)}_\nu)\cdot h & E^{(n)}_\nu < 0.5 \text{ MeV} \end{cases} \qquad (10)$$

h = height of exposure point

The factor $C(E^{(n)}_\nu)$ takes into account the scattering in the air and the same expressions for build-up factor are used as for external cloud dose.

1.3. Internal dose from inhaled activity

$$\dot{D}^{(n)}_{inh} = g^{(n)}_{inh} \cdot Q \cdot \chi(x,y,z) \qquad (11)$$

$$[g^{(n)}_{inh}] = \frac{rem}{Ci\ s/m^3}$$

1.4. Necessary input and input options

In our program it is possible to calculate an arbitrary situation = stability category, wind speed, dry and/or wet

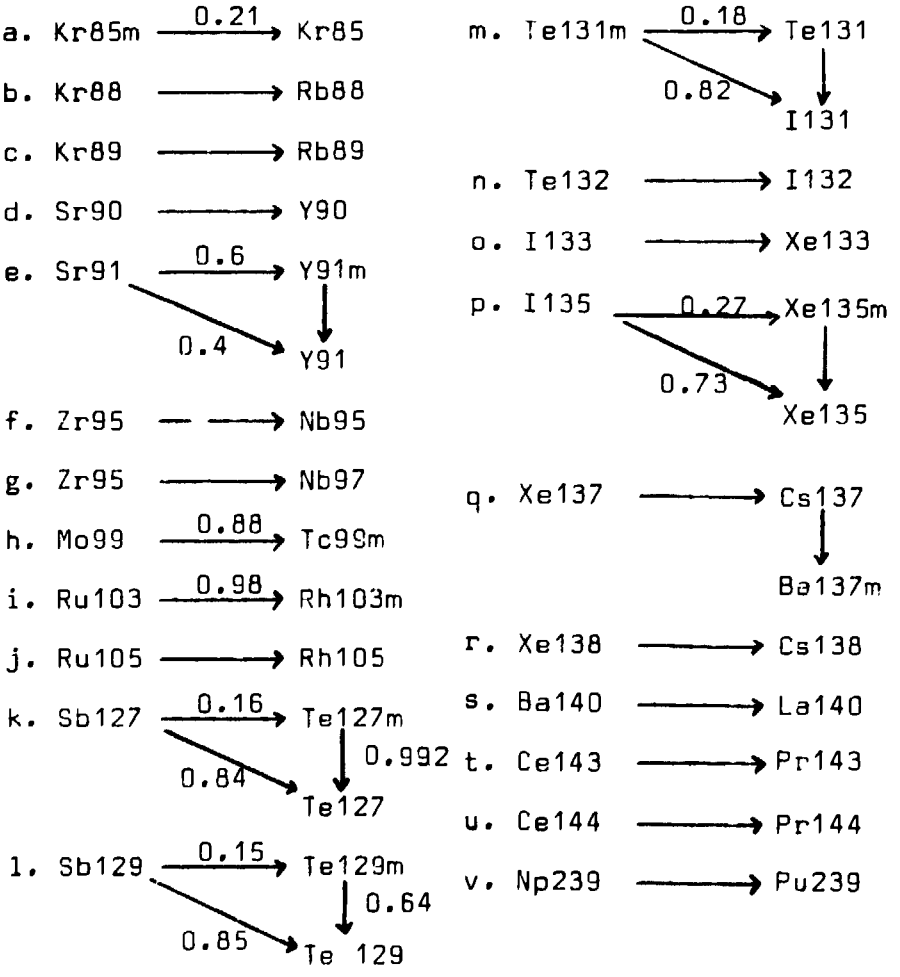
deposition, release height, mixing height, building wake, certain organ-dose, all available nuclides or a special group of them. Further it is possible to change the standard assumptions for the values of following parameters:

- nuclide inventory
- release fractions
- deposition velocities
- wash-out coefficients

In addition it is possible to calculate a probability distribution for different effects using a specified accident distribution and a distribution of meteorological conditions at the site concerned.

2. Daughter products

At present the following chains are used in the model:



The time dependences of the activity sources for mother and daughter nuclides are calculated using solutions to the corresponding set of differential equations before release, during dispersion and after deposition. The nuclides in a single decay chain can have different release fractions and different deposition velocities or wash-out coefficients. More accurate description of the methods is given in reference 1.

3. Inversion layer

Firstly the inversion layer is taken into consideration in the vertical dispersion parameter as a restriction to further vertical dispersion at large distances. Secondly the inversion layer is assumed to restrict the plume rise (see point 13). The values used for inversion layer heights are those given by Klug.

stability class	A	B	C	D	E	F
inversion height (m)	1500	1500	1000	500	200	200

4. Diffusion at long distances

In the case of some economic consequences it is necessary to estimate the concentrations at distances larger than 100 km and then the following procedure is used:

$$\sigma_z(x) = \sigma_z(100\ \text{km}) = \text{constant}$$
$$\sigma_y(x) = (x/100\ \text{km})^{1/2}\sigma_y(100\ \text{km}) \qquad (12)$$

5. Dispersion parameters and wind speed groups

The values for the dispersion parameters presented in references /2/ and /3/ are used. In the case of dispersion over terrain with greater roughness than assumed in the original data of these refs. the dispersion parameters have been corrected using the method proposed in the ref. /4/. For

every stability category three roughness classes can be used, one of which corresponds to smooth terrain and the original dispersion parameters.

The wind speed groups used in our study are:

Group	wind speed range	average speed
1	1... 2 knots	0.8 m/s
2	3... 5 "	2.1 "
3	6...10 "	4.1 "
4	11...15 "	6.7 "
5	16...20 "	9.3 "
6	21...25 "	11.8 "
7	>26 "	14.9 "

6. Deposition velocities

The deposition velocities used in the model are 10^{-2} m/s for iodines and particles and 0 for noble gases. These values can easily be changed via input.

7. Wash-out coefficients

The wash-out coefficients used in the model are 10^{-4} 1/s for iodines and particles and 0 for noble gases. These values can easily be changed via input.

8. Dose conversion factors

The dose conversion factors for cloud gamma and deposition gamma doses are listed in the enclosed table. The inhalation dose factors are based on WASH-1400. The deposition gamma dose factors are derived from the integrated doses presented in WASH-1400, but will be changed to values given by the formula in section 1.2.

9. Self-shielding of body

The self-shielding of body is taken into consideration by calculating the external dose at 5 cm depth in tissue (see point 1.1.). The attenuation in tissue is rather independent of gamma energy in the range (0.1...2 MeV).

10. Shielding and reduction factors

In the consequence calculation we take into consideration the shielding effect of buildings and other obstacles but not the effect of ventilation rate indoors. In reference /5/ we have used two population groups in the consequence calculation, namely

Group	fraction of population	shielding factor	breathing rate
1	35%	0.8	3.5×10^{-4} m³/s
2	65%	0.35	2.3×10^{-4} m³/s

The shielding factors for external dose from the cloud and from the deposited activity can be different and up to 3 shielding groups could be used.

11. Gamma energy groups

Until now we have used only one energy group (E = 1 MeV). The dependence on energy is rather near linear (according to Imai & Iijama, Health Physics, Vol 18, p. 214), if the release height and distance from central axis are not too large and the photon energy is not very low.

The normalized dose data library already contains the dose values for photon energies 0.04, 0.2 and 2.5 MeV as well, but the main program has not yet been changed as capable of handling more than one group.

For photons in the lowest energy group we have found that near the source the one-group model gives somewhat too low dose values at low release heights and clearly too large values in the case of elevated releases. At larger distances the division into energy groups instead of one energy has no significant effect on the dose values obtained.

12. Dose build-up factor

We have used an analytical approximation (eq.(2)). The same function has been used for instance in code RSAC and in the report JÜl-637-ST(Vogt). For gamma energy 1 MeV this expression gives the following values

μr	0.1	0.5	1.0	2.0	4.0	8.0
$B(\mu r)$	1.11	1.54	2.14	3.57	7.29	18.14

13. Plume-rise model

The solution of the differential equation given by Gifford with initial (t=0) values

$$z = z_0 = R_0/\varepsilon = \frac{(A_0/\pi)^{1/2}}{\varepsilon}$$

$$\mu r_0^2 \frac{dz}{dt} = F_m$$

is $$z^3 = z_0^3 + (z_B^3 - z_0^3)(1 - \cos(\sqrt{\beta}t)) + z_M^3 \sin(\sqrt{\beta}t) + z_R^3 (\sqrt{\beta}t - \sin(\sqrt{\beta}t)) \qquad (13)$$

where

$$z_M^3 = \frac{3F_m}{\sqrt{\beta}\varepsilon u} \qquad \text{(momentum)}$$

$$z_B^3 = \frac{3F}{\beta\varepsilon^2 u} \qquad \text{(buoyancy)}$$

$$z_R^3 = \frac{3F^*}{\beta^{3/2}\varepsilon^2 u} \qquad \text{(radioactivity)}$$

We apply equation (13) conservatively only until $t^* = \frac{\pi}{2}\frac{1}{\sqrt{\beta}}$ and set $z_M = z_R = 0$ and then the plume rise is given by

$$\Delta H = z_B - z_0 = \left(\frac{3F}{\beta\varepsilon^2 u}\right)^{1/3} - \frac{R_0(u)}{\varepsilon} \qquad (14)$$

The initial radius of the plume is assumed to be related with the building wake effect as follows:

$$R_0 = \begin{cases} 0 & \text{accidents like steam explosion} \\ 30\ \text{m}\ (1 - \exp(-u(\text{m/s})/2)) & \text{otherwise} \end{cases}$$

Using parameters corresponding air temperature $10^{\circ}C$ and $\varepsilon = 0.45$ we arrive at the following formula

$$\Delta H = 5.1\left(\frac{Q(MW)}{\rho u}\right)^{1/3} - \frac{R_0}{0.45} \qquad (15)$$

Finally the inversion layer is taken into consideration by the following way

$$H = \min\{H_0 + \max(\Delta H, 0),\ 0.8 * H_{inv}\} \qquad (16)$$

The values used for stability parameters are:

stability	A-D	E	F
β	1×10^{-4}	7×10^{-4}	2×10^{-3}

The wind speed variation with height is not taken into account in the plume rise formulas, but the average speeds of the different groups are used.

The plume rise is not assumed to be correlated with dry deposition.

14. Building wake

This effect has been taken into account by moving the plume backwards (x_{tr}) until the following condition is satisfied $4\pi\ \sigma_y(x_{tr})\sigma_z(x_{tr}) = \pi(30(1-\exp(-u/2)))^2$. In the case of steam explosion no building wake is assumed to occur.

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Table I Dose conversion factors for external doses from the cloud and from the deposited activity

N:o	Nuclide	g_{sub} (MeV/dis)·(cm^2/g)	g_{fall} (rem/s)/(Ci/m^2)	N:o	Nuclide	g_{sub} (MeV/dis)·(cm^2/g)	g_{fall} (rem/s)/(Ci/m^2)
1	H3	-	-	22	Sr90	-	-
2	C14	-	-	23	Sr91	1.68E-2	4.55E-3
3	N13	2.63E-2	-	24	Y90	1.16E-4	-
4	Ar39	1.11E-5	-	25	Y91m	1.43E-2	3.45E-4
5	Ar41	3.31E-2	-	26	Y91	9.29E-5	1.05E-5
6	Cr51	8.13E-4	1.22E-4	27	Zr95	1.91E-2	3.30E-3
7	Mn54	2.37E-2	3.22E-3	28	Zr97	2.27E-2	5.43E-3
8	Fe59	3.39E-2	4.44E-3	29	Nb95	2.01E-2	3.19E-3
9	Co58	2.77E-2	4.28E-3	30	Nb97	1.74E-2	1.96E-3
10	Co60	6.75E-2	1.03E-2	31	Mo99	4.95E-3	9.00E-4
11	Zn65	1.66E-2	1.11E-3	32	Tc99m	3.69E-3	9.27E-4
12	Kr83m	1.08E-3	-	33	Ru103	1.40E-2	2.50E-3
13	Kr85m	4.80E-3	-	34	Ru105	1.81E-2	3.90E-3
14	Kr85	-	-	35	Ru106	5.13E-3	9.23E-4
15	Kr87	1.99E-2	-	36	Rh103m	1.01E-3	-
16	Kr88	5.17E-2	-	37	Rh105	6.27E-4	4.80E-4
17	Kr89	5.66E-2	-	38	Ag110m	7.70E-2	5.00E-3
18	Rb86	2.70E-3	3.80E-4	39	Sb124	4.89E-2	3.61E-3
19	Rb88	2.30E-2	-	40	Sb127	2.26E-2	3.25E-3
20	Rb89	6.19E-2	-	41	Sb129	-	-
21	Sr89	-	-	42	Te127m	4.20E-6	1.36E-4

N:o	Nuclide	g_{sub} (MeV/dis)·(cm^2/g)	g_{fall} (rem/s)/(Ci/m^2)	N:o	Nuclide	g_{sub} (MeV/dis)·(cm^2/g)	g_{fall} (rem/s)/(Ci/m^2)
43	Te127	4.20E-5	2.08E-5	64	Cs136	6.42E-2	9.28E-3
44	Te129m	2.49E-3	3.10E-4	65	Cs137	-	-
45	Te129	2.17E-3	4.10E-4	66	Cs138	5.55E-2	-
46	Te131m	3.74E-2	6.00E-3	67	Ba137m	1.71E-2	2.83E-3
47	Te131	1.68E-2	2.70E-3	68	Ba140	4.49E-3	1.20E-3
48	Te132	7.17E-3	7.00E-4	69	La140	5.96E-2	9.72E-3
49	I131	1.01E-2	1.92E-3	70	Ce141	1.84E-3	5.77E-4
50	MI131	1.01E-2	-	71	Ce143	8.80E-3	1.84E-3
51	I132	5.91E-2	1.10E-2	72	Ce144	7.48E-4	1.47E-4
52	I133	1.64E-2	3.20E-3	73	Pr143	-	-
53	I134	7.01E-2	1.01E-2	74	Pr144	8.26E-4	1.33E-4
54	I135	3.76E-2	7.05E-3	75	Nd147	4.23E-3	8.70E-4
55	MI135	3.76E-2	-	76	Np239	3.62E-3	-
56	Xe131m	7.74E-5	-	77	Pu238	-	-
57	Xe133m	7.74E-4	-	78	Pu239	-	-
58	Xe133	7.73E-4	4.85E-4	79	Pu240	-	7.57E-6
59	Xe135m	1.36E-2	2.54E-3	80	Pu241	-	-
60	Xe135	6.94E-3	1.36E-3	81	Am241	6.00E-4	-
61	Xe137	3.66E-3	-	82	Cm242	5.40E-6	-
62	Xe138	5.63E-2	-	83	Cm244	4.20E-6	-
63	Cs134	4.03E-2	7.08E-3				

APPENDIX 2

Description of the Norwegian Model for Calculating Doses from Radioactive Material Released to the Atmosphere

by

Ulf Tveten et al.

The computer code used by IFA in the model comparison

We have used the program TIRION2 developed by the Safety and Reliability Directorate, UKAEA. The mathematical and physical models are thoroughly described in ref. (1), while more practical directions for its use are described in ref. (2).

We have made some modifications to TIRION2. Plume depletion by washout not incorporated in the original model, is included by us.

The following model descriptions are extracts from (1) and (2). Discussions and further details may be found in those references.

C O N T E N T S

1. DOSE MODELS

1.1 External gamma dose from cloud

As the cloud of fission products passes by it emits γ-rays which can be absorbed by people standing nearby. The total whole body dose received if there is one nuclide of integrated activity density $\chi(x,y,z)$ Ci-sec/m^3 emitting a γ-ray of energy $\bar{E}$ MeV is (3)

$$D_\gamma(x,y,\bar{E}) = 0.0404\ \mu_a(\bar{E}) \cdot \int_{x=0}^{\infty}\int_{y=-\infty}^{\infty}\int_{z=0}^{\infty} \frac{dx'dy'dz'}{r^2} \cdot B(\mu(\bar{E})r)\ e^{-\mu(\bar{E})r}\ \bar{E}\chi(x',y',z') \qquad (1$$

where $r^2 = (x - x')^2 + (y - y')^2 + z'^2$

$\mu_a(\bar{E})$ is the absorption factor (metre^{-1}) for γ-rays of energy $\bar{E}$ in air.

$\mu(\bar{E})$ is the corresponding attenuation factor in air (metre^{-1}) and

$B(\mu(\bar{E})r)$ is the exposure build-up factor.

We have parametrized $B(\mu(\bar{E})r)$ as follows. Let $\mu_r = \mu(\bar{E})r$

$$B(\mu(\bar{E})r) = [1 + a_1(\bar{E})\mu_r + a_2(\bar{E})\mu_r^2\ ]\exp\ (\ -\ a_0(\bar{E})\mu_r) \qquad (2)$$

using a least squares fit to data in (4). The parametrization used in Equation (2) tends to unity as $r \to 0$, as desired, and is only valid over the range of values of μ_r for which the fit was made, that is $\mu_r \leq 20$.

In practice, it is convenient to choose a number of energy bands $E_1 < \bar{E} < E_2$, $E_2 < \bar{E} < E_3$ etc. TIRION 2 uses eight of them, the various parameters a_0, a_1, a_2, μ, μ_a being calculated for a representative energy within each energy band. The values used are shown in Table 1.

TABLE 1.

Energy Band	Range of Energies (MeV)	a_0	a_1	a_2	μ_a (cm^2/g)	μ (cm^2/g)
1	0 - 0.1	0.055	1.762	1.443	0.023	0.151
2	0.1 - 0.3	0.058	1.070	0.962	0.030	0.106
3	0.3 - 0.6	0.008	0.985	0.443	0.029	0.080
4	0.6 - 0.8	0.001	0.978	0.366	0.028	0.071
5	0.8 - 1.0	- 0.010	0.965	0.266	0.027	0.064
6	1.0 - 1.5	- 0.017	0.944	0.203	0.026	0.052
7	1.5 - 2.0	- 0.025	0.882	0.117	0.024	0.044
8	2.0 - 3.0	- 0.027	0.812	0.073	0.021	0.036

As part of the input to TIRION 2 it is necessary to supply the following quantities, briefly described as energy factors.

$$\bar{E}_n^{(i)} = \sum_{j \in k} P_n^{(i)} (E_{n,j}^{(i)}) \, E_{n,j}^{(i)} \text{ MeV}$$

where $P_n^{(i)}(E_{n,j}^{(i)})$ is the probability that, when the i^{th} member of the n^{th} decay chain decays, it will emit a gamma ray of energy $E_{n,j}^{(i)}$ MeV. The summation is over all those values of j for which the emitted gamma ray is in energy band k.

In Equation (1) the following substitution is made when there are many nuclides

$$\mu_a(\bar{E})\, B(\mu(\bar{E})r)\, e^{-\mu(\bar{E})r}\, \bar{E}\, \chi(x', y', z') =$$

$$B(\mu(\bar{E}_k)r)\, e^{-\mu(\bar{E}_k)r}\, \mu_a(\bar{E}_k) \sum_n \sum_i \bar{E}^{(i)}_{n,k}\, \chi^{(i)}_n(x', y', z')$$

where $\bar{E}_k$ is the energy chosen as representative of energy bank k.

The triple integral is then evaluated using a nested Simpson's routine.

1.2 Background dose due to γ-radiation from deposited fission products

The deposited activity of the i^{th} nuclide of the n^{th} chain of fission products is

$$\chi^{(i)}_{Dn}(x,y) = v^{(i)}_{g\,n}\, \chi^{(i)}_n(x,y,z=0) \text{ Ci/metre}^2$$

At a time t after the accident this quantity will have changed due to the action of two mechanisms.

(i) Radioactive decay

When radioactive decay occurs together with plume depletion an approximate solution is found, see section 1.2.2. The resultant ground level concentration is $\chi^{(i)}_{Dn}(x,y,t)$.

(ii) Weathering

The gamma-dose observed above a contaminated surface is reduced by the weathering of nuclides, a broad term including among other mechanisms the removal of dust by the wind, the carrying away of material dissolved in water, the penetration of nuclides into the soil and uptake by vegetation. Therefore the concentration of each nuclide should be modified by a weathering factor $f^{(i)}_n(t)$ so that

$$\chi^{(i)}_{Dn}(x,y,t) \rightarrow \chi^{(i)}_{Dn}(x,y,t)\, f^{(i)}_n(t) \text{ Ci/metre}^2.$$

In principle $f_n^{(i)}(t)$ should be different for each nuclide. In practice, the only nuclide for which much information is available is ^{137}Cs (5). For that it has been shown experimentally that, if the dose rate above land contaminated by ^{137}Cs is $D(t = 0)$ immediately after the contamination has occurred, the dose rate t_y years later is

$$D_g(t_y) = D_g(t = 0) \exp(-0.023\, t_y)[0.63 \exp(-1.13\, t_y) + 0.37 \exp(0.0075\, t_y)].$$

The single exponential $\exp(-0.023\, t_y)$ gives the rate of radioactive decay of ^{137}Cs. The term in square brackets is the weathering factor for ^{137}Cs.

A discussion of the weathering of other nuclides is given in Ref. (6). It is concluded that so little is known about this subject that it is as well to assume that all nuclides behave as does Ceasium.

$$f_n^{(i)}(t) = 0.63 \exp(-1.13\, t_y) + 0.37 \exp(-0.0075\, t_y)$$

$$= f(t)$$

for all n and i. It follows that the dose rate to a person at position (x,y) t seconds after the accident is

$$D_g(x,y,t) = f(t)\ 0.0404 \int\int \frac{dx'dy'}{r^2} \sum_{k=1}^{8} B(\mu(\bar{E}_k)r)\, e^{-\mu(\bar{E}_k)r}\, \mu_a(\bar{E}_k) \sum_n \sum_i E_{n,k}^{(i)}\, \chi_{Dn}^{(i)}(x',y',t) \text{ rad/sec.} \quad (3$$

where $$r^2 = (x - x')^2 + y - y')^2 + 1$$

that is the dose rate is calculated at a height of one metre above the ground. The integral extends over the ground on which the activity has been deposited. The total dose received by a person who stays at the point (x,y) for a total of t seconds after the accident is simply given by

$$D_g(x,y) = \int_0^t dt' \, D_g(x,y,t') + D_\gamma(x,y) \qquad (4)$$

TIRION 2 performs the double integral of Equation (3) by using a Simpson's routine. It performs the integration of Equation (4) as explained in Appendix A of ref. (1). As with the dose from the passing cloud, no infinite plane approximations are used. Suitable approximations are being developed for use.

1.3 An approximate method for dealing with deposition, washout and decay.

The first step is to set up a grid between which the concentrations of the various nuclides can be interpolated quadratically. In practice we have found it convenient to establish the grid so that it is spaced equally in ln x. Therefore the grid points x_n are given by

$$x_n = \exp(\ (n-1)\ i_g\ ) \text{ metres} \qquad (5)$$

for $1 \leq n \leq N$, i_g being the interval in question. N can be chosen at the discretion of the user of TIRION 2; in general, sufficient accuracy is gained by taking $N \sim 40$ if $x_n \sim 100$ Km, that is, $i_g \sim 0.3$.

We begin at $x_1 = 1$ metre taking the total emitted activities $Q_n^{(i)}$ of each of the nuclides in each of the decay chains, where n identifies the decay chain and i the daughter. The time taken to travel between the points x_1 and x_2 is

$$t = (x_2 - x_1)/u \qquad (6)$$

We take as our starting point $Q_n^{(i)}(x_1)$ = released activity and use the equations for radioactive decay to find out how the concentration of each nuclide varies during that time interval, ignoring deposition, giving $Q_n^{(i)}(x_2 : ND)$ where ND stands for no deposition.

We see that, in the interval X_1 to x_2 the cloud should be depleted by a fraction

$$F_n^{(i)}(x_1,x_2) = \exp\left[-\sqrt{\frac{2}{\pi}}\,\frac{v_{gn}^{(i)}}{\bar{u}}\int_{x_1}^{x_2} dx'\,\exp(-h^2/2\sigma_z^2(x'))/\sigma_z(x')\right] \quad (7)$$

which we approximate by

$$F_n^{(i)}(x_1,x_2) = \exp\left[-\sqrt{\frac{2}{\pi}}\,\frac{v_{gn}^{(i)}}{\bar{u}}\cdot\frac{(x_2-x_1)}{2}\cdot\left\{\exp(-h^2/2\sigma_z^2(x_1))/\sigma_z(x_1) + \exp(-h^2/2\sigma_z^2(x_2))/\sigma_z(x_2)\right\}\right] \quad (8)$$

where $v_{gn}^{(i)}$ is the deposition velocity of the i^{th} member of the n^{th} chain. It follows that the total remaining activity of the i^{th} member of the n^{th} decay chain at a distance x_2 downwind is

$$Q_n^{(i)}(x_2) = Q_n^{(i)}(x_2;ND)\cdot F_n^{(i)}(x_1,x_2) \quad (9)$$

The corresponding concentration at a point (x_2, y, z), $\chi_n^{(i)}(x_2, y, z)$, is given by inserting $Q_n^{(i)}(x_2)$ into Equation (11) or Equation (17) in place of Q. In order to calculate concentrations at the next grid point x_3 the above method is reported beginning at x_2 with the activities $Q_n^{(i)}(x_2)$.

The amount of activity deposited per unit area from dry deposition and washout is

$$\begin{aligned} w(x,y) &= Vg\,\chi(x,y,o) + lg\int_o^\infty \chi(x,y,z)\,dz \\ &= Vg\,\frac{Q(x)}{2\pi u\sigma_y\sigma_z}\,e^{-\frac{y^2}{2\sigma_y^2}}\left[e^{-\frac{(-H)^2}{2\sigma_z^2}} + e^{-\frac{(H)^2}{2\sigma_z^2}}\right] \\ &\quad + lg\,\frac{Q(x)}{2\pi u\sigma_y\sigma_z}\,e^{-\frac{y^2}{2\sigma_y^2}}\cdot\sigma_z\sqrt{2\pi} \\ &= \left[Vg + lg\sqrt{\frac{\pi}{2}}\,\sigma_z e^{\frac{H^2}{2\sigma_z^2}}\right]\frac{Q(x)}{\pi u\sigma_y\sigma_z}\,e^{-\frac{y^2}{2\sigma_y^2}}\cdot e^{-\frac{H^2}{2\sigma_z^2}} \\ &= \left[Vg + lg\sqrt{\frac{\pi}{2}}\,\sigma_z\,e^{\frac{H^2}{2\sigma_z^2}}\right]\chi(x,y,o) \quad , \end{aligned}$$

where

Vg = dry deposition velocity (m/s).

lg = washout rate (1/s)

From this it is seen that the ground contamination is calculated if the dry deposition velocity is substituted with

$$Vg + lg \sqrt{\frac{\pi}{2}}\, \sigma_z\, e^{\frac{H^2}{2\sigma_z^2}}$$

1.4 Doses due to inhalation

In the earlier sections we have shown how to calculate the time integrated concentration $\chi_n^{(i)}(x,y,z)$ of the i^{th} member of the n^{th} chain of fission products. The total inhaled activity of this nuclide is $I_n^{(i)}(x,y)$ given by

$$I_n^{(i)}(x,y) = b_r\, \chi_n^{(i)}(x,y,z = 0) \text{ Ci}$$

where b_r is the breathing rate. b_r depends on the age of the person involved and on whether he is engaged in vigorous activity or not. In TIRION 2

$$b_r = 2.2 \times 10^{-4} \text{ metres}^3/\text{sec.} \qquad (10)$$

unless otherwise requested. Equation (10) is the breathing rate commonly assumed for adults. (6).

The subsequent dose received by any particular body organ depends on a number of factors among which are:

(a) the chemical form of the nuclides;

(b) the properties of the aerosol in which the nuclides occur;

(c) the aerodynamic properties of the aerosol particles as they are inhaled and deposited in various parts of the

respiratory system;

d) the transport of particles within the respiratory system and out of it into the gastro-intestinal tract and the lymphatic system;

(e) the absorption of the nuclides into the bloodstream;

(f) the distribution of the nuclides among organs and tissues and

(g) excretion from the body.

How the doses can be calculated is extensively reviewed in the Rasmussen Report (6). The model used is the ICRP lung model, with a separate treatment for gaseous fission products. This allows the calculation of a quantity $F_{n,k}^{(i)}(t)$; this is the dose in rems to organ k and time t following the inhalation of 1 Ci of the i^{th} nuclide of the n^{th} chain at t = 0. Thus the total dose to organ k integrated to time t is

$$D_k(x,y,t) = \sum_n \sum_i F_{n,k}^{(i)}(t) \cdot I_n^{(i)}(x,y)$$

The quantities $F_{n,k}^{(i)}(t)$ are known as inhalation factors. TIRION 2 requires them as input.

2. METEOROLOGICAL MODELLING OF TIRION 2

In common with many other codes TIRION 2 uses the conventional Gaussian formula for the time integrated concentrations at the point (x,y,z) namely,

$$\chi(x,y,z) = \frac{Q \exp\left(-y^2/2\sigma_y^2(x)\right)}{2\pi\sigma_z(x)\sigma_y(x)\ \bar{u}} \left\{ \exp\left[-(z+h)^2/2\sigma_z^2(x)\right] + \exp\left[-(z-h)^2/2\sigma_z^2(x)\right] \right\} \text{ Ci-sec/metre}^3. \qquad (11)$$

The meaning of those symbols not already defined is as follows:

(i) Q is the total amount of effluent emitted (Ci);

(ii) $\bar{u}$ is the mean wind-speed. As has already been seen, the wind-speed varies with height. It is therefore not possible to define $\bar{u}$ unambiguously. In many experiments $\bar{u}$ is the velocity of the wind at the height of the source or at the height of a nearby tower. Smith and Singer (7) show that a reasonable estimate of $\bar{u}$ is obtained by calculating the wind-speed at a height $0.62\ \sigma_z(x)$. This conclusion, however, is model dependent. Unless otherwise stated we assume that $\bar{u} = u(10)$;

(iii) h is the height of the source (metres);

(iv) $\sigma_z(x)$ and $\sigma_y(x)$ (metres) are the vertical and horizontal standard deviations respectively, to be determined empirically as is explained later;

(v) the pair of exponentials summed within the curley brackets in e.g., (11) expresses the fact that total reflection at the ground has been assumed.

2.1 Parametrizations of σ_z and σ_y

The actual parametrizations that we use for $\sigma_z(x)$ and $\sigma_y(x)$ are based on an enlargement of Pasquill's original scheme due to F.B. Smith (8). Beyond about 20 Km downwind there are few data on the behaviour of these parameters. Smith therefore obtained numerical solutions of the diffusion equation for downwind distances up to 100 Km using wind-speed and diffusivity values based on actual experience over a range of stability conditions. Ref. (8) presents nomograms that enable us to calculate $\sigma_z(x)$ given the time of day, cloud cover, wind-speed and meteorological roughness length z_o. Hosker (9) has produced parametrizations that are convenient for use on a computer.

$$\sigma_z(x) = g(x)\, F(z_o, x) \tag{12}$$

where
$$g(x) = a_1 x^{b_1}/(1 + a_2 x^{b_2}) \tag{13}$$

and
$$F(z_o, x) = \ln(c_1 x^{d_1})(1 + (c_2 x^{d_2})^{-1}) \text{ if } z_o > 10 \text{ cm} \tag{14}$$

or
$$F(z_o, x) = \ln(c_1 x^{d_1})/(1 + c_2 x^{d_2}) \text{ if } z_o < 10 \text{ cm} \tag{15}$$

The parameters (a_1, b_1, and a_2, and b_2) depend on the atmospheric stability category as shown in Table (2). The parameters (c_1, d_1, c_2 and d_2) depend on the meteorological roughness length as is shown in Table (3).

The lateral standard deviation $\sigma_y(x)$ is not yet available as part of Smith's scheme; indeed the parametrization of $\sigma_y(x)$ presents one of the greatest uncertainties in the implementation of a Pasquill type scheme. It is thought that $\sigma_y(x)$ is independent of z_o and Hosker uses the parametrization.

$$\sigma_y(x) = c_3\, x/(1 + 0.0001\, x)^{\frac{1}{2}} \tag{16}$$

where c_3 depends on the weather category as is shown in Table (4).

There remains the problem that $\sigma_y(x)$ is a function of averaging time or the duration of the release. (10, 11).

In TIRION 2, this effect can only be handled by applying one of the two following categories of release:

A. A 'short' release for which Equations (11) - (16) are appropriate. The periods usually recommended in the literature for the use of these Equations vary from ten minutes to about an hour.

B. A 'prolonged' release of a few hours or a day or so. We assume th that the effluent spreads uniformly into a sector of θ_s^o, so that

$$\chi(x,y,z) = \sqrt{\frac{2}{\pi}} \frac{Q}{4 x \tan(\theta_s/2)\sigma_z(x)\,\bar{u}} \cdot \left\{ \exp\left[- (z + h)^2/2\sigma_z^2(x) + \exp - (z + h)^2/2\sigma_z^2(x) \right] \right\} \quad (17)$$

In the UKAEA it is conventional to take $\theta_s = 30^o$. (12). The user of TIRION 2 must decide for himself which model is appropriate for the case being run.

TABLE 2

The parameters to be used in Equation (13)

Stability category	a_1	b_1	a_2	b_2
A	0·112	1·060	$5·38 \times 10^{-4}$	0·815
B	0·130	0·950	$6·52 \times 10^{-4}$	0·750
C	0·112	0·920	$9·05 \times 10^{-4}$	0·718
D	0·098	0·889	$1·35 \times 10^{-3}$	0·688
E	0·0609	0·895	$1·96 \times 10^{-3}$	0·684
F	0·0638	0·783	$1·36 \times 10^{-3}$	0·672

TABLE 3

The parameters to be used in Equations (14) and (15)

Roughness length	c_1	d_1	c_2	d_2
1 cm	1·56	0·048	$6·25 \times 10^{-4}$	0·45
4 cm	2·02	0·027	$7·76 \times 10^{-4}$	0·37
10 cm	e	0	0	0
40 cm	5·16	- 0·098	18·6	- 0·225
100 cm	7·37	- 0·0957	$4·29 \times 10^{3}$	- 0·60
400 cm	11·7	- 0·128	$4·59 \times 10^{4}$	- 0·78

TABLE 4

The parameter to be used in Equation (16)

Stability category	A	B	C	D	E	F
c_3	0·22	0·16	0·11	0·08	0·06	0·04

2.2 Inversion lids

As was explained at the beginning of this section, the atmospheric boundary layer has a 'lid' on it, that is a boundary above which the rate of turbulent diffusion is greatly reduced. Once a cloud of fission products has been spread sufficiently to 'collide' with this lid it rapidly mixes uniformly throughout the layer.

In TIRION 2 the user can choose to set an upper limit to the magnitude of $\sigma_z(x)$. As is done in the Rasmussen Report (6) the default values for the inversion lids are taken to be 1500 metres for A, B and C stability conditions and 1000 metres for D, E and F stability conditions.

2.3 Time varying meteorology

TIRION 2 does not allow the possibility that the weather conditions may change during a run. For example, the increasing insolation during the morning causes the height of the mixing layer to change and the weather category to tend to greater instability (8). Another example is the case of a low level overhead inversion at night. Effluent from a stack may well be emitted above this level. It may travel many miles downwind with relatively little diffusion (13). When the sun rises, however, the inversion may be broken down from the ground upward and relatively concentrated pollutant brought to the ground at surprisingly large distances downwind. TIRION 2 is not applicable in such a case. In the Rasmussen Report (6) the weather conditions are allowed to change every hour.

2.4 Distance to which model is valid

The schemes for classifying turbulent diffusion discussed by Gifford (14) are valid up to a distance of 10 Km or, at most, a few tens of kilometres because there is a paucity of experimental evidence for downwind distances beyond a few kilometres. As previously discussed, the scheme developed by F.B. Smith (8) and Hosker's parametrizations (9) are based on solutions to the diffusion equations for downwind distances up to 100 Km, the experimental content being known values of wind speed and diffusivity. The model is therefore valid to 100 Km and no further.

2.5 The range of velocity of the wind

Table (5) below is reproduced from Hosker's paper and shows the range of velocities measured a few metres above the ground covered by each stability class (9).

TABLE 5

Typical wind-speed ranges for the various stability categories

Stability category	Wind speed range (metres/sec)
A	1 - 2.5
B	1.5 - 5
C	2 - 6+
D	2 - 10+
E	2 - 5
F	2 3

The numbers are uncertain because, as has already been discussed, wind speed varies with the height above the ground. If the wind-speed exceeds 10 metres/sec category D applies (8). On the other hand, if the wind-speed is much below that given as the lower limit for the particular category in question, the model is not applicable (14).

3. PLUME RISE

The models programmed into TIRION 2 are those of Briggs (15) and Gifford (16). Plume rise can occur for a variety of reasons. Those relevant to nuclear safety calculations are as follows:

A. Momentum:- effluent emerging from a stack or through an orifice in a broken containment may have appreciable upward momentum. It is convenient to define a momentum parameter

$$F_m = \left(\frac{T}{T_s}\right) w_o^2 r_o^2$$

where T is the ambient temperature,
T_s is the temperature of the emerging effluent,
w_o is its upward velocity and
r_o is the stack radius.

B. Buoyancy:- a plume emerging from an environment in which there is, to take one example, a molten core, could be very hot. As a result there will be substantial upward forces acting upon it. We define a buoyancy parameter

$$F = g Q_H/(\pi \rho C_p T)$$

where g is the acceleration due to gravity,
Q_H is the rate of emission of heat,
ρ is the density of air and
C_p is the specific heat of air at constant pressure.

C. Radioactive decay:- as a cloud of fission products moves downwind it is continually being heated by γ-, α- and β-rays. We define a radioactive buoyancy parameter

$$F'' = g Q''/(\pi C_p \rho T)$$

where Q'' is the rate of heat emission to the plume from fission product activity.

The solution to the plume rise differential equations given by Gifford is (for Pasquill stability categories A-D)

$$s = z^3 = \frac{1}{\epsilon^2 \bar{u}} \cdot \left| \frac{F t^3}{3!} + \frac{F_m t^2}{2!} + F_m \right| + z_a^3 \qquad (18)$$

where ϵ is the entrainment constant, the radius of the plume being ϵz and z_a is the quantity r_o/ϵ, an effective initial height.

The height of plume rise is given by $z - z_a$.

For categories E and F the solution programmed into TIRION 2 is

$$s = \frac{3}{6\epsilon^2 \bar{u}} \left[F t \left(1 - \sin \frac{(\beta^{\frac{1}{2}} t)}{\beta^{\frac{1}{2}} t}\right) + F \left(1 - \cos(\beta^{\frac{1}{2}} t)\right) \right]$$

$$+ \frac{3F_m}{\beta^{\frac{1}{2}} \epsilon^2 \bar{u}} \sin(\beta^{\frac{1}{2}} t) + z_a^3 \cos(\beta^{\frac{1}{2}} t). \qquad (19)$$

β is the potential temperature gradient $d\theta/dz$ multiplied by (g/T). For Pasquill Class E conditions it is taken to be 0.5×10^{-3} while for Class F conditions it is 1.2×10^{-3} sec^{-2} (6).

In practice, the three buoyancy parameters are calculated at each grid point and Equation (18) or Equation (19) is used to calculate the height of rise from that point to the next. The height of emission is then replaced by $h_m(x)$, the total height of the plume at the point in question.

Plume rise is terminated at whichever is the lowest of the heights given by the following:

(a) if the upper edge of the plume touches the inversion lid;
(b) if the buoyancy parameter decays to zero;
(c) in the case of a momentum dominated plume, if the upward velocity falls to zero.

These are all regarded as temporary expedients to be replaced in a forthcoming revised version of TIRION 2.

4. INPUT AND OUTPUT OPTIONS

TIRION 2 is primarily designed to be a risk assessment computer code, but it has the input and output provisions to calculate doses and health consequences of an arbitrary weather situation. Some parameters are given default values. The user has, however, always the possibility to entre his own data.

4.1 Isotope data

TIRION 2 contains no data library. All isotope data (amounts, branching ratios, halflife, beta- and gamma data and deposition velocities) must be given as input. Radioactive decay is accounted for during a holdup time prior to release, and during a prolonged release as well as in all subsequent time intervals.

4.2 Roughness length and wind-speed groups

The dispersion parameter σ_z may be calculated for 6 roughness lengths: 1, 4, 10, 40, 100 and 400 cm. 10 cm is the default value.

It is up to the user of TIRION 2 to select the number of wind-speed groups for each weather category and also to determine the wind-speed representative for each group.

4.3 Gamma energy groups

TIRION 2 use 8 energy groups. The ranges are given in table 1. The present version of TIRION 2 uses the upper limit of the energy band as the representative energy for each band.

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APPENDIX 3

Description of the Swedish Model for Calculating Doses from Radioactive Material Released to the Atmosphere

by

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TEKNISK PM
D6200
1977-08-01

TPM-SM-61

DOSE MODEL DESCRIPTION - PARAMETER LIST

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1977-08-01

SUMMARY

To be able to compare results obtained by our models for computation of atmospheric dispersion and dose with data obtained by other models, details are specified in this paper concerning the present state of the models and set of data used in the computations:

1 Dose models
2 Daughter products
3 Inversion layer
4 Diffusion in the distance interval 30 - 100 km
5 Dispersion parameters
6 Dry deposition
7 Wash-out coefficients
8 Dose conversion factors
9 Shielding effect - body
10 Shielding effects - buildings
11 Gamma energy groups
12 Dose build-up factor
13 Plume rise model

1 Dose models

External gamma dose from cloud is calculated with numerical integration of the activity distribution in the air. Effects of build-up and attenuation are included here.

$$D_j' = K_o \int_o^\infty \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{B(\mu_j r)\, \exp(-\mu_j r)\, \chi'\, dx\, dy\, dz}{4\pi r^2} \left[\frac{rad \cdot m^2}{s \cdot MeV \cdot Ci}\right]$$

for energy j, where

$B(\mu_j r)$ = build-up factor

μ_j = attenuation coefficient $[m^{-1}]$

K_o = $4.91\ 10^{-1}$ $[(rad/s)/(MeV \cdot Ci/m^3)]$

χ' = $\frac{1}{2\pi\, \sigma_y\, \sigma_z} \exp\left[-0.5\ (y^2/\sigma_y^{\,2} + z^2/\sigma_z^{\,2})\right]$ $[m^{-2}]$

These calculations are initially made for totally 14400 combinations of parameters listed below.

24 weather types (9 stable and neutral,
14 unstable,
1 with inversion layer)
3 heights
10 downwind distances
5 cross wind distances
4 energys.

An alternative dose table calculation is made for six Pasquill-classes, where the concentration is calculated with different formulas of σ_z and σ_y (see section for dispersion parameter).

The actual dose is then calculated by interpolation in these tables with actual height, distance, energy and wind speed. The effect of activity decrease due to transport time in the air, deposition on ground plume rise and other effects are accounted for in this part of calculation.

$$D = \sum_i \sum_j Q_i\, \mu_j^{en}\, E_{ij}\, \frac{1}{u(h)} \exp\left(-\frac{\lambda x}{u(h)}\right) \cdot g(x) \cdot D_j' \ [rad/s]$$

Q_i = release of nuclide i [Ci/s]

μ_j^{en} = energy absorbtion coefficient for energy j $[m^{-1}]$

E_{ij} = energy per disintegration of energy j [MeV/dis]

$u(h)$ = wind speed at height h [m/s]

$$g(x) = \exp\left[-\frac{v_d}{u}\sqrt{\frac{2}{\pi}} \int_o^x \frac{\exp\left(-0.5\left(\frac{h(x)}{\sigma_z(x)}\right)^2\right) dx}{\sigma_z(x)} - \ell_g \frac{x}{u}\right]$$

$g(x)$ = correction for dry deposition and rain-out

$h(x)$ = height at distance x [m]

v_d = deposition coefficient [m/s]

ℓ_g = rain-out coefficient [s^{-1}]

The above formulas are not to be considered as complete or logical stringent, they just show the principal of calculation.

At this part the program also calculates doses due to inhalation of activity and doses from activity deposed on ground which are added to the external dose.

External gamma-dose from activity on ground is calculated in the following way

$$D = \sum_i \sum_j E_{ij} \cdot I_j \cdot \int_{t_1}^{t_2} W_i(x,y,t)\, dt \qquad [rad]$$

where

$$I_j = \frac{K_o}{2} \cdot \mu_j^{en} \int_1^{\infty} \frac{B(\mu_j r) \cdot \exp(-\mu_j r)}{r}\, dr$$

W_i = concentration of nuclide i at time t [Ci/m^2]

t_1, t_2 = start and stop time for integration [s]

When calculating W_i, contributions from both dry and wet deposition are considered.

Internal dose is calculated as

$$D = \sum_i \chi_i \cdot g(x) \cdot C_i \qquad [rad/s]$$

where

C_i = dose conversion factor [rad m^3/Ci s]

χ_i = concentration of nuclide i [Ci/m^3]

Some input options

- **Possibilities to calculate dose in single point or in a polar point grid (population dose summation)**
- **Plume rise or no plume rise**
- Dry deposition or not; rain-out or not
- **Different dose types**
- **Statistical calculations of doses.**

Main input data

- Weather data, stability, wind speed profile, existing of inversion layer (100 m), season variations
- Height of release
- Isotopes and corresponding activity release (Isotope propertys are in a program library)
- Daughter nuclides
- Release time and time in reactor (activity decay)
- Geometrical data concerning grid etc.
- Plume rise properties (initial heating).

2 Daughter products

Daughter products for the nuclides used in our computations are listed below.

Mother	Daugther
Te 132	I 132
Kr 85m	Kr 85
I 133	Xe 133
Xe 135m	Xe 135
Kr 88	Rb 88
Kr 89	Rb 89
Xe 138	Cs 138
Sr 91	Y 91
Zr 95	Nb 95
Mo 99	Tc 99m
Ru 105	Rh 105
Ba 140	La 140
Ce 143	Pr 143
Nd 147	Pm 147
Np 239	Pu 239

The build-up of daughter-products during transport in air is taken into account. In the case of ground-dose, contributions from daughter-products generated in the air and generated on the ground are included.

3 Inversion layer

The temperature gradient between 90 m and 30 m above the ground is used to determine if there is inversion or not. The actual height to the inversion is not calculated. Hence there is no grouping of height of inversion in relation to stability groups.

Fumigation formula is used when the temperature has a minimum on 90 m, and the mixing height is then always set to 100 m. Total mixing is assumed to occur at different distances from the release point according to height of release.

4 Diffusion in the distance interval 30 - 100 km

Diffusion in the close-in zone, 0.5 - 20 km, is computed by a statistical model based on Gaussian distribution. Concentration or dose is determined by extrapolation out to 50 alternatively 100 km.

5 Dispersion parameters

$$\sigma_y(x,s) = K_1 \cdot F_x \cdot Y_F \sqrt{\exp(-ax) + ax - 1}$$

$$a = 0.008$$

$$K_1 = \left(\frac{\dot{V}}{u}\right) \frac{\sqrt{2}}{a} = 130.815$$

$$F_x = \begin{cases} 1 & < 2400 \\ (x/2400)^{0.37} & x > 2400 \end{cases}$$

$$Y_F = \begin{cases} 1/(1 + 0.02\sqrt{s}) & s \geq 0 \\ 1.35 & s < 0 \end{cases}$$

$$\sigma_z(x,M,H,S) = (1-M) \cdot S_1 + M \cdot S_2$$

$$M = \begin{cases} 0 & s > 0 \quad \text{or} \quad s < 0 \text{ and Jan or Dec.} \\ 0.25\ (\text{month}-1) & s < 0, \quad \text{Feb-Nov.} \end{cases}$$

(Month 6 is classified as month 5, month 13-i is classified as month i, i = 1, 6)

$$S_1 = K_1 \cdot Z_F \sqrt{\exp(-Ax) + Ax - 1}$$

$$K_1 = \left(\frac{\bar{w}}{u}\right) \frac{\sqrt{2}}{A}$$

$$Z_F = \begin{cases} 1/(1 + S \cdot A_Z) & S \geq 0 \\ 1 & S < 0 \end{cases}$$

$$S_2 = \frac{D}{E} \sqrt{2(\exp^{(-Ex)} + Ex - 1)}$$

$$E = A \cdot (u/16)^{0.8}$$

$$D = \begin{cases} G & H \leq 50 \\ G + \left(\frac{1}{50} - \frac{1}{H}\right)\frac{5}{3} \cdot \left\{11\left(1 - \frac{u}{16}\right)\right\} & H > 50 \end{cases}$$

$$G = \left(\frac{\bar{w}}{u}\right) + 0.03\ \left(1 - \frac{u}{16}\right)$$

Thus σ_y and σ_z are continous function of S, u, x, M and H.

When using Pasquill classes we have used the formula given by Martin and Tikvart (1968).

6 Dry deposition - deposition velocities

Data, used:

I_2, Ru	$1 \cdot 10^{-2}$ m s^{-1}	Beattie and Bryants AHSP(S)R 135 AE experiments, I_2
Particulate, I, Ru, Cs, Sr etc	$3 \cdot 10^{-3}$ m s^{-1}	AHSP(S)R 135
Methyliodine	$1 \cdot 10^{-5}$ m s^{-1}	AHSP(S)R 135 AE experiments

These deposition velocities are applied to conditions at a distance of 1 km or more from release point.

No differentiation is made for partical size, or type of area.

Deposition over snow	$3 \cdot 10^{-3}$ m s^{-1}	Dickerson and Crawford: TID-4500, UC-35

7 Wet deposition - washout coefficients

Frontal rainfall	$3 \cdot 10^{-5}$ s^{-1}
Shower "	$1 \cdot 10^{-4}$ s^{-1}
Snow	$1 \cdot 10^{-4}$ s^{-1}
Value used in trajectory model for frontal precipitation	$3 \cdot 10^{-5}$ s^{-1}

8 Dose conversion factors

Different conversion factors for inhaled activity has been used, most freguently factors from WASH-1400.

9 Shielding effect - body

Screening factor	0.75	
Conversion factor tissue/air	1.1	
Shielding effect of body in external gamma dose calculations is accounted for by the factor		0.8

(UNSCEAR, vol 1, Levels)

10 Shielding effects - buildings

Outdoors		0.8
Indoors, wood	0.5	
concrete, bricks	0.1	
average value		0.2
Shielding factor, average population: indoors 17 hours outdoors 7 hours		0.35
Value used for the Urban Site Study		0.3

11 Gamma energy groups

NR	Energy [MeV]
10	0.09
3	0.17
7	0.21
11	0.26
12	0.32
5	0.42
4	0.52
6	0.96
2	1.08
8	1.27
13	1.85
1	2.35
9	2.98

Of these energies only No 10, 7, 2 and 9 are used in the present version of the table-program.

The second program, which summates the nuclides, does not use fixed gamma energy groups. The nuclides are divided into individual groups where the mid-point energy and the total energy within the group are given. The dose values for the mid-point energy is then obtained by interpolation.

Data is collected from ERDTMANN, G and SOYKA, W
Die γ-linien der radionuklid. Band 1.

Mid-point energys and energys in group (MeV)

Nuclide	γ-energy Top	Total γ-energy	Total β-energy
I 125	0.0287	0.0217	-
I 131	0.364	0.381	0.188
I 132	0.523	0.145	0.465
	0.668	0.866	
	0.773	0.751	
	0.955	0.578	
I 133	0.530	0.610	0.45
I 134	0.595	0.374	0.68
	0.847	1.532	
	1.073	0.425	
	1.807	0.254	
I 135	0.547	0.605	0.34
	1.132	0.590	
	1.45	1.150	
Kr 83m	0.01	0.00076	0.0418
Kr 85m	0.170	0.1571	0.243
Kr 85	0.514	0.0022	0.246
Kr 87	0.460	0.312	1.35
	2.555	0.463	
Kr 88	0.200	0.103	0.39
	0.835	0.179	
	1.530	0.230	
	2.300	1.533	
Kr 89	0.265	0.109	1.39
	0.580	0.315	
	0.966	0.272	
	1.554	0.617	
	2.770	0.794	
Xe 131m	0.034	0.023	0.16
Xe 133m	0.0304	0.0189	0.1963
	0.2332	0.0326	
Xe 133	0.0538	0.0447	0.153
Xe 135m	0.4506	0.4258	0.104
Xe 135	0.2496	0.2493	0.306
Xe 137	0.4550	0.1502	1.66
Xe 138	0.3185	0.3001	0.
	1.863	0.9000	
Rb 86	1.0788	0.0949	0.67
Rb 88	0.9195	0.1426	1.956
	2.0114	0.5164	
Rb 89	1.0941	1.6390	0.6
	2.4965	0.7964	
Cs 134	0.6971	1.5989	0.162
Cs 136	0.0940	0.0381	0.128
	0.2972	0.2121	
	0.9496	1.9106	
Cs 137	0.0329	0.0023	0.195
	0.6616	0.5599	
Cs 138	0.4467	0.2110	1.09
	0.9924	0.3380	
	1.4350	1.1141	
	2.3746	0.6124	

Nuclide	γ-energy Top	Total γ-energy	Total β-energy
Te 127m	0.0286	0.0106	0.0903
Te 127	0.3859	0.0049	0.224
Te 129m	0.0286	0.0081	0.27
	0.7105	0.0298	
	1.0933	0.0120	
Te 129	0.0278	0.0046	0.52
	0.4390	0.0441	
	1.0187	0.0114	
Te 131m	0.1060	0.0788	0.229
	0.3427	0.1247	
	0.8101	0.9014	
	1.2717	0.4965	
Te 131	0.1284	0.1069	0.73
	0.4560	0.1154	
	0.6377	0.0483	
	1.0701	0.1610	
Te 132	0.0323	0.0300	0.116
	0.2234	0.1982	
	0.6678	0.0401	
Sr 89	0.9091	0.000082	0.42
Sr 90	1.0	0.0	0.197
Sr91	0.5349	0.3583	0.63
	0.7417	0.2860	
	1.0546	0.3805	
Y 90m	0.1881	0.1967	0.054
	0.4897	0.4425	
Y 90	1.7607	0.00035	0.942
Y 91m	0.5402	0.5305	0.028
Y 91	1.2049	0.0036	0.604
Mo 99	0.0209	0.0027	0.407
	0.2141	0.0156	
	0.7505	0.1355	
Tc 99m	0.1315	0.1207	0.0164
Zr 95	0.7415	0.7246	0.12
Zr 97	0.1821	0.0058	0.72
	0.4854	0.0498	
	0.7435	0.7178	
	1.3002	0.1162	
Nb 95	0.7649	0.7582	0.0434
Ru 103	0.4986	0.4878	0.061
Ru 105	0.0516	0.0104	0.42
	0.1549	0.0091	
	0.2978	0.0560	
	0.4570	0.1394	
	0.7329	0.5109	
Ru 106	1.0	0.0	0.0119
Rh 105	0.3122	0.0807	0.173

Nuclide	γ-energy Top	Total γ-energy	Total β-energy
Sb 127	0.2548	0.03485	0.40
	0.4835	0.2020	
	0.6917	0.2805	
	0.8017	0.1505	
Sb 129	0.2342	0.0151	0.42
	0.5256	0.1650	
	0.8392	0.7740	
	1.0318	0.1479	
	1.3079	0.0848	
	1.7675	0.1861	
La 140	0.3146	0.0887	0.607
	0.4872	0.2248	
	0.8231	0.2979	
	1.5876	1.7178	
Ba 140	0.0290	0.0048	0.294
	0.1621	0.0108	
	0.3720	0.0365	
	0.5419	0.1423	
Ce 141	0.0368	0.0061	0.175
	0.1455	0.0717	
Ce 143	0.0396	0.0322	0.43
	0.2942	0.1526	
	0.6753	0.0928	
Ce 144	0.0465	0.0057	0.098
	0.1335	0.0144	
Pr 143	1.0	0.0	0.313
Nd 147	0.0396	0.0171	0.278
	0.0887	0.0264	
	0.4841	0.1008	
Pm 147	0.1212	0.000005	0.062
Pm 148	0.0404	0.0044	0.16
	0.3290	0.1589	
	0.5506	0.5837	
	0.6535	0.8169	
	0.9651	0.3812	
Pm 148	0.5502	0.1541	0.706
	0.9120	0.1368	
	1.4651	0.3223	
Pm 149	0.2868	0.9088	0.366
	0.5870	0.0726	
	0.8498	0.1683	
Pu 238	0.0210	0.00273	5.5
	0.1141	0.000012	
Pu 239	0.2007	0.0000023	5.157
	0.3887	0.0000236	
	0.0158	0.000126	
	0.0517	0.000012	
	0.1006	0.000024	
	0.1331	0.000008	
Pu 240	0.0782	0.000016	5.168
Pu 241	0.1019	0.000005	0.0053
Np 239	0.1060	0.0622	0.304
	0.2592	0.0742	

Nuclide	γ-energy Top	Total γ-energy	Total β-energy
Cm 242	0.0591	0.000027	6.11
Cm 244	0.1167	0.000013	5.81
U 235	0.0985	0.00671	4.410
	0.1805	0.1374	
U 238	0.0480	0.000036	4.195
U 239	0.0736	0.0484	0.424
	0.6408	0.0030	
	0.7455	0.0017	
	0.8363	0.0053	
	0.9733	0.0023	
Am 241	0.0588	0.0224	5.510
	0.1250	0.000013	
	0.2088	0.0000053	
	0.3449	0.0000101	
	0.6482	0.0000141	
Ar 41	1.2938	1.2841	
Zn 65	0.0082	0.0029	
	1.0801	0.5714	
Co 58m	0.0070	0.1547	
Co 58	0.5110	0.1533	
	0.8155	0.8209	
Co 60m	0.0617	0.0617	
Co 60	1.1732	1.1719	
	1.3325	1.3325	

12 Dose build-up factor B(μr)

Energy No	B(0)	B(1)	B(2)	B(3)	B(4)	B(5)	B(6)	B(7)	B(8)	B(9)	B(10)	B(11)	B(12)	B(13)	B(14)
1	1.00	1.76	2.65	3.61	4.57	5.63	6.70	7.76	8.91	10.10	11.2	12.4	13.7	14.9	16.2
2	1.00	2.06	3.53	5.44	7.35	9.87	12.40	14.90	18.10	21.30	24.4	28.3	32.3	36.2	40.2
3	1.00	3.54	8.61	19.00	29.30	51.90	74.50	97.20	141.30	185.40	229.6	318.3	407.0	495.6	584.3
4	1.00	2.42	4.75	8.48	12.20	18.20	24.20	30.20	39.20	48.10	57.1	70.5	83.9	97.3	111.0
5	1.00	2.56	5.25	9.80	14.50	22.40	30.50	38.50	51.40	64.20	77.1	97.7	118.3	138.9	159.5
6	1.00	2.10	3.67	5.75	7.84	10.70	13.50	16.30	19.90	23.50	27.2	31.8	36.4	41.0	45.6
7	1.00	3.23	7.58	16.20	24.90	43.60	62.30	80.90	116.60	152.30	188.0	258.0	328.0	398.0	468.0
8	1.00	1.99	3.32	4.99	6.65	8.77	10.88	13.00	15.60	18.20	20.8	23.9	27.0	30.2	33.3
9	1.00	1.69	2.45	3.25	4.04	4.88	5.72	6.56	7.44	8.32	9.2	10.1	11.0	12.0	12.9
10	1.00	4.64	11.70	25.10	38.40	65.40	92.40	120.00	169.00	219.00	269.0	363.0	458.0	553.0	648.0
11	1.00	3.02	6.82	14.10	21.40	36.30	51.20	66.20	93.50	121.00	148.0	199.0	249.0	300.0	351.0
12	1.00	2.80	6.05	12.00	17.90	29.10	40.30	51.60	70.80	90.00	109.0	142.0	175.0	207.0	240.0
13	1.00	1.84	2.87	4.03	5.20	6.53	7.86	9.20	10.70	12.20	13.7	15.4	17.1	18.7	20.4

Of these groups only No 10, 7, 2 and 9 are used in the present version of program. Build-up factors for μr > 14 are not shown here. Data are collected from JAEGER, R G et al, Engineering compendium on radiation shielding, Volume 1.

13 Plume rise model

The computation method is based on models by Briggs and Gifford, modified for use in neutral and unstable conditions. Effects by heat release - direct to the atmosphere or by activity decay in the plume - can be taken into consideration.

The wind variation with height is incorporated in the plume rise calculations.

The following limitations are used:

Plume rise by nuclear effects:	t_{max} = 3 600 s
Plume rise by thermal effects, in neutral and unstable conditions	t_{max} = 500/u s

Plume rise effects are not correlated to dry deposition; the program operates with both processes in an independent way. The formulae below have been used for plume rise calculations.

$\beta < 0$

$$h(x) = h_o + \left(\frac{3}{\varepsilon^2 \, u(h)}\right)^{\frac{1}{3}} \left[F^* \left[\sinh \left(\sqrt{|\beta|} \cdot t\right) - \sqrt{|\beta|} \cdot t\right] + F \cdot \sqrt{|\beta|} \cdot \left[\cosh \left(\sqrt{|\beta|} \cdot t\right) - 1\right]\right]^{\frac{1}{3}} \cdot \frac{1}{\sqrt{|\beta|}} \quad [m]$$

$\beta = 0$

$$h(x) = h_o + \left(\frac{3}{\varepsilon^2 \, u(h)}\right)^{\frac{1}{3}} \left[\frac{F^* \cdot t^3}{6} + \frac{F \cdot t^2}{2}\right]^{\frac{1}{3}} \quad [m]$$

$\beta > 0$

$$h(x) = h_o + \left(\frac{3}{\varepsilon^2 \, u(h)}\right)^{\frac{1}{3}} \left[F^* \left[\sqrt{\beta} \cdot t - \sin \left(\sqrt{\beta} \cdot t\right)\right] + F \cdot \sqrt{\beta} \left[1 - \cos \left(\sqrt{\beta} \cdot t\right)\right]\right]^{\frac{1}{3}} \cdot \frac{1}{\sqrt{\beta}} \quad [m]$$

where

$h(x)$	= height of plume center	[m]
h_o	= release height	
β	$= \frac{g}{T}\frac{\partial\theta}{dz}$ = stability parameter	$[s^{-2}]$
$\frac{\partial\theta}{\partial z}$	$= \left(\frac{\partial T}{\partial z} + 1\right)/100$ = potential temp grad	$[C^o/m]$
g	= 9.81 = gravity const	$[m/s^2]$
T	= absolute temperature	$[K^o]$
ε	= 0.53 = entrainment constant	[-]
$u(h)$	= wind speed at height h	[m/s]
t	$= x/u(h_o)$ = transport time	[s]
F	$= \frac{g\,Q}{\pi\,\rho\,C_p\,T}$	$[m^4\ s^{-3}]$
F^*	$= \frac{g\,Q^*}{\pi\,\rho\,C_p\,T}$	$[m^4\ s^{-4}]$

where

ρ	= 1.293 = density of air	$[kg \cdot m^{-3}]$
C_p	$= 1.0\ 10^{-3}$ = heat constant for air	$[J/kg \cdot K^o]$
Q	= initial heat	[W]
Q^*	$= C_1 \cdot C_2 \sum_i \sum_j Q\left(\frac{1}{2} E_{\gamma ij} + E_{\beta ij}\right)$	[W/s]

where

C_1	$= 3.7 \cdot 10^{10}$	$[\frac{dis}{s}/Ci]$
C_2	$= 1.602 \cdot 10^{-13}$	[Ws/MeV]
i	= index for nuclides	
j	= index for energy	

As seen from the above definitions, only half of the gammaenergy is assumed to be absorbed within the plume.

The non-linear implicit ($u = f(h)$) equations are solved by Newton-Raphson's method for actual weather and release conditions.

The cosine-term in the equation for $\beta > 0$ is set equal to zero for $\sqrt{\beta}\ t > \frac{\pi}{2}$.

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APPENDIX 4

Description of the Danish Model for Calculating Doses from Radioactive Material Released to the Atmosphere

by

Søren Thykier-Nielsen

1. DISPERSION MODEL

1.1. General description

The Gaussian model is used as basis [1, 2 and 4]. According to this model, a Gaussian distribution is assumed for the material concentration in the plane perpendicular to the wind direction. If it is further assumed that the ground surface has total reflection, the diffusion formula will be in a rectangular co-ordinate system with the origin in the source point (point of release) and the x-axis in the wind direction:

$$X(x,y,z,s,u) = Q(x,t) \cdot Sg(x,y,z,s,u) \qquad (1)$$

where

$$Sg(x,y,z,s,u) = \frac{1}{2 \cdot \pi \cdot u \cdot \sigma_y(x,s) \cdot \sigma_z(x,s)} \cdot e^{-\frac{y^2}{2 \cdot \sigma_y(x,s)^2}} \cdot \left[e^{-\frac{z^2}{2 \cdot \sigma_z(x,s)^2}} + e^{-\frac{(z+2 \cdot H)^2}{2 \cdot \sigma_z(x,s)^2}} \right] \qquad (2)$$

where

$X(x,y,z,s,u)$	= concentration [Ci/m^3]
$Sg(x,y,z,s,u)$	= relative concentration [s/m^3]
(x,y,z)	= co-ordinates of the detector point [m]
s	= atmospheric stability category
u	= wind speed [m/s]
$\sigma_y(x,s)$	= horizontal dispersion parameter [m]
$\sigma_z(x,s)$	= vertical dispersion parameter [m]
$Q(x,t)$	= effective source term [Ci/s] at time t
H	= effective stack height [m]

In eq. 2 it is assumed that the diffusion in the x-direction can be ignored. This assumption applies when the release takes place over a period of time that is equal to or greater than the transport time ($\frac{x}{u}$) from the source to the detector point in question [2 and 4].

Equation 2 cannot be used in cases where dispersion conditions are peceptibly influenced by a mixing layer that sets an upper limit to the atmospheric layer in which the released material is dispersed and in which there occurs turbulent diffusion. The existence of such a mixing layer will imply that the vertical distribution of material will change from a Gaussian to a homogeneous distribution with increasing distance from the source. As the mixing layer is supposed to be totally reflecting, the relative concentration distribution can be calculated, according to Turner [6], as follows:

The distribution of material below the mixing layer is influenced first from the distance x_L, where the concentration at the lower limit of the mixing layer is equal to one-tenth of the concentration in the plume centreline. From the distance x_L there is a gradual transition between a Gaussian and a homogeneous distribution in the vertical plane. The material distribution can, for $x_L < x$, be calculated by "folding" the actual source, both in relation to the ground surface and to lower limit of the mixing layer. In other words, there is a superposition of a number of imaginary sources (in principle infinitely many) that are identical to the actual source but lying at different distances under the ground surface, or above the lower limit of the mixing layer, respectively.

From a certain distance x_C ($x_L < x_C$), the vertical material distribution may be considered as homogeneous with good approximation.

x_L is calculated from

$$\sigma_z(x_L) = \frac{L-H}{\sqrt{2 \cdot \ln(10)}} = 0.466 \cdot (L-H) \qquad [\text{meter}]$$

where

L = the mixing height (the height of the atmospheric layer in which the released material is dispersed) [meter]

H = effective stack height [meter]

x_C is calculated from

$$\sigma_z(x_C) = \sigma_{zL} = \sqrt{\frac{2}{\pi}} \cdot L = 0.798 \cdot L$$

Thus there are the following expressions for the relative concentration:

a. $0 < x < x_L$

$$(2)\quad Sg(x,y,z,s,u) = \frac{\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)}{2\cdot\pi\cdot\sigma_y(x,s)\cdot\sigma_z(x,s)\cdot u}\cdot$$

$$\left[\exp-\left(\frac{z^2}{2\cdot\sigma_z(x,s)^2}\right)+\exp\left(-\frac{(z+2\cdot H)^2}{2\cdot\sigma_z(x,s)^2}\right)\right]$$

b. $x_L \leq x \leq x_C$

$$(3)\quad Sg_{B1}(x,y,z,s,u) = \frac{\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)}{2\cdot\pi\cdot\sigma_y(x,s)\cdot\sigma_z(x,s)\cdot u}\cdot$$

$$\left\{\exp\left(-\frac{z^2}{2\cdot\sigma_z(x,s)^2}\right)+\exp\left(-\frac{(z+2\cdot H)^2}{2\cdot\sigma_z(x,s)^2}\right)+\right.$$

$$\sum_{i=1}^{4}\left[\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L-2\cdot H-z}{\sigma_z(x,s)}\right)^2\right)+\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L-z}{\sigma_z(x,s)}\right)^2\right)\right.$$

$$\left.\left.+\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L+z}{\sigma_z(x,s)}\right)^2\right)+\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L+2\cdot H+z}{\sigma_z(x,s)}\right)^2\right)\right]\right\}$$

c. $x_C \leq x$

$$(4)\quad Sg_{B2}(x,y,z,s,u) = \frac{\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)}{\pi\cdot\sigma_y(x,s)\cdot\sigma_{zL}\cdot u}$$

The equations under b and c only apply to $-H \leq z < H$.

1.2. Mean concentrations

The mean concentration, $Sgm(x,z,s,u,\alpha)$, for a (narrow) sector is at a given distance, x, from the release point [4]:

$$(5)\quad Sgm(x,z,s,u,\alpha) = \sqrt{\frac{\pi}{2}} \cdot \frac{\sigma_y(x,s)}{2\cdot x\cdot tg(\alpha)} \cdot$$

$$\left[erf\left(\frac{x\cdot tg(\alpha)}{\sqrt{2}\cdot\sigma_y(x,s)}\right) - erf\left(-\frac{x\cdot tg(\alpha)}{\sqrt{2}\cdot\sigma_y(x,s)}\right)\right]\cdot Sg(x,o,z,s,u)$$

where

$erf(t) = \int_o^t \frac{2}{\sqrt{\pi}} \cdot e^{-v^2}\, dv$, the error function

α = the half sector angle for the sector in question

$2\cdot x\cdot tg\alpha$ = the sector width.

With good approximation, eq. (5) can be used for sectors with an angle of 30^o or less.

Another, and from a meteorological point of view principally different way of calculating the mean concentration in a given sector is to use the crosswind-integrated concentration:

$$Sg_t(x,z,s,u) = \int_{-\infty}^{+\infty} Sg(x,y,z,s,u)\, dy$$

$$= \sqrt{2\pi}\cdot\sigma_y(x,s)\cdot Sg(x,o,z,s,u)$$

The mean concentration, $Sgm_t(x,z,s,u,\alpha)$ at a given distance, x, will then be for a sector of width $2\cdot\alpha$ degrees:

$$(6)\quad Sgm_t(x,z,s,u,\alpha) = \frac{\sqrt{2\cdot\pi}\cdot\sigma_y(x,s)}{\frac{\alpha}{180}\cdot 2\cdot\pi\cdot x}\cdot Sg(x,o,z,s,u)$$

$$= \sqrt{\frac{2}{\pi}}\cdot\frac{90\cdot\sigma_y(x,s)}{\alpha\cdot x}\cdot Sg(x,o,z,s,u)$$

It can be shown that

$Sgm(x,z,s,u,\alpha) < Sgm_t(x,z,s,u,\alpha)$ for all $\alpha > 0$.

For given x-values, the difference between Sgm and Sgm_t will be less the smaller σ_y is in relation to the half sector-width,

i.e.,

$$\frac{\sigma_y(x,s)}{x \cdot tg\alpha} \to 0 \Rightarrow \frac{Sgm(x,z,s,u,\alpha)}{Sgm_t(x,z,s,u,\alpha)} \to 1$$

1.3. Effective stack height

When the release point is in the open country, the height at which the dispersion of the released material starts is generally greater than the actual height of the release point above ground. The difference is mainly due to turbulence around the point from which the material is released and to the speed at which the material travels upwards. Further, the temperature of the released material is of significance, because the plume (or cloud) will rise to a height that depends partly on the relationship between the emission of heat and the heat received from the surrounding air, and partly on atmospheric stability and wind speed. If the plume (or cloud) contains radioactive material, then heat will be continuously produced in the plume (cloud). This "self-heating" can in certain cases become so large that the plume continues to rise for a very long period of time, with the result that the effective stack height increases at the same time as the plume (cloud) moves in the direction of the wind. In the dispersion equations mentioned here, the effective stack height H (a constant) must be replaced by the function H(x), which is a function of the distance in the wind direction, x. The problem is dealt with in greater detail in [12] and [3].

1.4. The effective source term

The effective source term, Q(x,t), is equal to the release rate corrected for changes taking place in the distance between source point and detector point (as a result of fallout, radioactive decay, etc).

If a radioactive isotope is released with a constant speed ε [Ci/s], then the effective source term will be:

$$(7)\quad Q(x,t) = \varepsilon \cdot e^{-\lambda \cdot \frac{x}{u}} \text{ [Ci/sek] for } tf_1 + \frac{x}{u} \leq t \leq tf_2 + \frac{x}{u}$$

$$= 0 \quad \text{for } t < tf_1 + \frac{x}{u} \vee tf_2 + \frac{x}{u} < t$$

where

tf_1 = the time at which the release started
tf_2 = the time at which the release stopped
λ = the decay constant

The decay of the released isotopes during transport in the wind direction away from the place of release includes the creation of daughter products. Considering a mother isotope, the mother product, and its radioactive daughter product are both released from the source with the constant speeds ϵ_p [Ci/s], respectively, ϵ_d [Ci/s], the effective source terms will then be:

for the mother product:

$$Q_p(x,t) = \epsilon_p \cdot e^{-\lambda_p \frac{x}{u}} \text{ [Ci/sek]}$$

for the daughter product

$$Q_d(x,t) = \epsilon_d \cdot e^{-\lambda_d \frac{x}{u}} + \frac{\epsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p} \cdot \left(e^{-\lambda_p \frac{x}{u}} - e^{-\lambda_d \frac{x}{u}} \right) \text{ Ci/sek]}$$

where

λ_p = the decay constant for the mother product [s^{-1}]
λ_d = the decay constant for the daughter product [s^{-1}]

Note that ϵ_d may perhaps be equal to 0 (i.e. no separate release of the daughter product).

In calculating doses, the concept <u>time-integrated source term</u> is used:

$$I(x,te_1,te_2) = \int_{te_1}^{te_2} Q(x,\tau)\, d\tau$$

For a release with constant speed, such as described above, one finds:

$$(8)\quad I(x,te_1,te_2) =$$

$$(\min(te_1, tf_2 + \tfrac{x}{u}) - \max(te_1, tf_1 + \tfrac{x}{u}))\cdot Q(x,t)$$

$$\text{for } te_1 \leq tf_2 + \tfrac{x}{u} \wedge tf_1 + \tfrac{x}{u} \leq te_2, \text{ og}$$

$$= 0 \text{ for } tf_2 + \tfrac{x}{u} < te_1 \vee te_2 < tf_1 + \tfrac{x}{u}$$

1.5. Deposition

1.5.1. Deposition in general

Some of the material in the plume may deposit on the ground during transport in the wind direction. The mechanism of deposition is rather complicated, and here are only given the methods for calculating dry deposition and washout that are connected with the Gaussian model. Reference should otherwise be made to [6, 7 and 1].

When considering <u>dry deposition</u>, the so-called velocity of deposition, v_g, is used. This is defined as:

$$v_g = \frac{\text{deposited material per unit area of ground}}{\text{time integrated plume concentration at ground level}}$$

The amount of material that per time unit is deposited per area unit of the ground surface, is calculated as:

$$(9)\quad w_D(x,y,s,u) = v_g \cdot \chi'(x,y,-H,s,u) \quad [Ci/m^2/s]$$

where

v_g = velocity of deposition [m/s]

$\chi'(x,y,-H,s,u) = Q_D(x,t,s) \cdot Sg(x,y,-H,s,u)$
material concentration at ground level [Ci/m^3] corrected for deposition

Q_D (x,t,s) = effective source term corrected for deposition [Ci/s].

Assuming that deposition takes place along the whole distance from source point to detector point, $Q_D(x,t,s)$ is calculated as

$$(10)\quad Q_D(x,t,s) = Q_o \cdot \exp\left(-\lambda \cdot \frac{x}{u} - \int_o^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp\left[-\frac{1}{2}\cdot\left(\frac{H}{\sigma_z}\right)^2\right]}{\sigma_z(x,s)}\, dx\right)$$

where Q_o is the effective source term at the point of release. Wash-out is described by the so-called wash-out coefficient, l_g, defined as:

$$l_g = \frac{\text{fraction of total amount of activity washed out}}{\text{duration of precipitation}}$$

= the relative change of the amount of activity per time unit.

The amount of material that is deposited per area unit of the ground surface per time unit is calculated as

$$(11)\quad W_N(x,y,s,u) = \frac{Q_N(x,t,s)\cdot l_g}{\sqrt{2\cdot\pi}\cdot u\cdot\sigma_y(x,s)} \cdot \exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right) [Ci/m^2/sek]$$

where

l_g = the wash-out coefficient [s^{-1}]

$Q_N(x,t,s) = Q_o(t) \cdot e^{-(l_g + \lambda)\cdot\frac{x}{u}}$ [Ci/s]

= effective source term corrected for wash-out

$Q_o(t)$ = effective source term [Ci/s] at the point of release.

When dealing with mean concentrations at given distances (see section 1.2), the factor

$$\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right), \quad \text{in formula 11}$$

is replaced either by

$$\sqrt{\frac{\pi}{2}} \cdot \frac{\sigma_y(x,s)}{2 \cdot x \cdot tg(\alpha)} \cdot \left[erf\left(\frac{x \cdot tg(\alpha)}{\sqrt{2} \cdot \sigma_y(x,s)} \right) - erf\left(- \frac{x \cdot tg(\alpha)}{\sqrt{2} \cdot \sigma_y(x,s)} \right) \right]$$

or by

$$\sqrt{\frac{\pi}{2}} \cdot \frac{90 \cdot \sigma_y(x,s)}{\alpha \cdot x}$$

The material concentration in the plume, corrected for wash-out will be:

$$\chi_N(x,y,z,s,u) = Q_N(x,t,s) \cdot Sg(x,y,z,s,u)$$

During precipitation, dry and wet deposition (wash-out) can occur simultaneously. Assuming that the two deposition mechanisms influence the material in the cloud (or plume) independently of each other, the source term $Q_{DN}(x,t,s)$ corrected for deposition can be calculated as:

$$(12)\quad Q_{DN}(x,t,s) = Q_o(t) \cdot \exp\left(-(\lambda + 1_g) \cdot \frac{x}{u} \int_o^x \frac{v_g}{u} \sqrt{\frac{2}{\pi}} \frac{\exp(-\frac{1}{2} \cdot (\frac{H}{\sigma_z})^2)}{\sigma_z(x,s)} dx \right)$$

The amount of material that per time unit is deposited per area unit of the ground surface will be:

$$(13)\quad W_{DN}(s,y,s,u) = v_g \cdot Q_{DN}(x,t,s) \cdot Sg(x,y,-H,s,u) + \frac{Q_{DN}(x,t,s) \cdot 1_g}{\sqrt{2} \cdot \pi \cdot u \cdot \sigma_y(x,s)} \cdot \exp\left(-\frac{y^2}{2 \cdot \sigma_y(x,s)^2} \right) \quad [Ci/m^2/sek]$$

Both for dry deposition and for wash-out it applies that, provided the deposited amount of material is not removed from the location where it is deposited in any other way than by

radioactive decay, the total deposited amount at a given time, t, will be:

$$(14)\quad W(x,y,s,u,t,td_1,td_2) = \int_{td_1}^{t} w(x,y,s,u)\,dt$$

$$= 0 \quad \text{for } t \leq td_1$$

$$= w(x,y,s,u) \cdot \frac{1}{\lambda} \cdot \left[1-e^{-\lambda\cdot(t-td_1)}\right] \quad \text{for } td_1 < t \leq td_2$$

$$= w(x,y,s,u) \cdot \frac{1}{\lambda} \cdot \left[1-e^{-\lambda\cdot(td_2-td_1)}\right]\cdot e^{-\lambda\cdot(t-td_2)} \quad \text{for } td_2 < t$$

where

td_1 = time at which deposition started
td_2 = time at which deposition stopped.

It is assumed that the dispersion conditions and deposition parameters (v_g and l_g) do not change in the period of time in question.

Should there be a mixing layer above the release area, this will influence the dispersion conditions and thus possibly also the deposition. Formulas (9) to (14) will thus not necessarily apply in such a case.

1.5.2. Deposition of daughter products

Consider the situation mentioned in section 1.4, where an isotope - the mother product - and its radioactive daughter product are both released from the source with the constant rates ε_p [Ci/s] and ε_d [Ci/s], respectively. When calculating the source term for the daughter product corrected for deposition, as well as the amount of the daughter product deposited on the ground, one must take into account whether the mother product is deposited on the ground or not.

The source term of the daughter product corrected for deposition will be:

a. Without deposition of the mother product:

$$(15)\quad Q_d^*(x,s) = \varepsilon_d \cdot \exp(-\lambda_d \cdot \frac{x}{u}) \cdot g(x,s) + \frac{\varepsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p + \ell} \cdot (\exp(-\lambda_p \frac{x}{u}) - \exp(-\lambda_d \cdot \frac{x}{u}) \cdot g(x,s))$$

b. With deposition of the mother product

$$(16)\quad Q_d^*(x,s) = (\varepsilon_d \cdot \exp(-\lambda_d \cdot \frac{x}{u}) + \frac{\varepsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p} (\exp(-\lambda_p \cdot \frac{x}{u}) - \exp(-\lambda_d \cdot \frac{x}{u}))) \cdot g(x,s)$$

where

$$\ell = l_t = \left(+ \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} \cdot (\frac{H}{\sigma_z(x,s)})^2)}{\sigma_z(x,s)} dx \right) \cdot \frac{u}{x}$$ for dry deposition

$$= l_g$$ for wet deposition

$$= l_g + \frac{u}{x} \cdot \int_0^x \frac{v_g}{u} \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} (\frac{H}{\sigma_z(x,s)})^2)}{\sigma_z(x,s)} dx$$ for simultaneous dry and wet deposition

$$g(x,s) = \exp\left(- \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} (\frac{H}{\sigma_z(x,s)})^2}{\sigma_z(x,s)} dx \right)$$ for dry deposition

$$= \exp(-l_g \cdot \frac{x}{u})$$ for wet deposition

$$= \exp\left(- \left(l_g \cdot \frac{x}{u} + \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} (\frac{H}{\sigma_z(x,s)})^2}{\sigma_z(x,s)} dx \right) \right)$$ for simultaneous dry and wet deposition

The other symbols as given earlier.

It is assumed that the same deposition parameters can be used for both the mother product and the daughter product.

To facilitate the solution of the differential equations used in deriving the expression for the source term of the daughter product in <u>dry deposition</u>, the function $g(x,s)$ is approximated by the expression $\exp(-l_t \cdot \frac{x}{u})$. This approximation, which is <u>only</u> used in calculating the amount of the daughter product created by the decay of the mother product during transport from the source to the point in question, results in

a small over-estimation of both the source term $Q_d^*(x,s)$ and the amount of daughter product deposited on the ground.

The amount of material deposited per area unit of the ground per time unit is found by replacing Q_D, Q_N or Q_{DN} in formulas (9), (11) and (13) by the relevant expression for Q_d^*.

The total amount deposited of the daughter product at a given location is, at a given time, t:

$$(17)\quad W_d(x,y,s,u,t) = \int_{td_1}^{t} w_d(x,y,s,u)\,dt$$

If the mother product is not deposited, the expressions for W_d will be like those for W, i.e. the expressions given under formula (14). The following expressions therefore only apply to those cases where both mother and daughter product are deposited:

$$(18)\quad W_d(x,y,s,u,t,td_1,td_2) = 0 \quad \text{for } t \leq td_1$$

$$= w_d(x,y,s,u)\cdot\frac{1}{\lambda_d}(1-\exp(-\lambda_d\cdot(t-td_1))$$

$$+ w_p(x,y,s,u)\cdot\left(\frac{1}{\lambda_p} + \frac{1}{\lambda_d-\lambda_p}\cdot(\exp(-\lambda_d\cdot(t-td_1))\right.$$

$$\left. - \frac{\lambda_d}{\lambda_p}\cdot\exp(-\lambda_p\cdot(t-td_1))\right) \qquad \text{for } td_1 < t \leq td_2$$

$$= w_d(x,y,s,u)\cdot\frac{1}{\lambda_d}\,(1-\exp(-\lambda_d\cdot(td_2-td_1))\cdot\exp(-\lambda_d\cdot(t-td_2))$$

$$+ w_p(x,y,s,u)\cdot\frac{1}{\lambda_d-\lambda_p}\cdot\left(\frac{\lambda_d}{\lambda_p}\cdot(1-\exp(-\lambda_p\cdot(td_2-td_1)))\cdot\exp(-\lambda_p\cdot(t-td_2))\right.$$

$$\left. -(1-\exp(-\lambda_d\cdot(td_2-td_1)))\cdot\exp(-\lambda_d\cdot(t-td_2))\right) \qquad \text{for } td_2 < t$$

The index d indicates the daughter product and index p the mother product.

2. CALCULATION OF DOSES

2.1. Inhalation doses

A person located at a given time at a given point, P(x,y,z), will inhale radioactive material at a rate that is equal to the product of the breathing rate and the concentration of the radioactive material at this point.

The resulting dose (in rem) to a given organ (lungs, thyroid gland, etc.) is calculated as:

$$(19)\quad D_I(x,y,z,s,u) = \beta \cdot S(x,y,z,s,u) \cdot \sum_{i=1}^{n_{iso}} \delta_{k,i}(d) \cdot I_i(x,te_1,te_2)$$

where

β	= breathing rate [m^3/s]
$S(s,y,z,s,u)$	= relative concentration [s/m^3]
s	= stability category
u	= wind speed [m/s]
$\delta_{k,i}(d)$	= dose to organ k per inhaled unit of radioactivity of isotope no. i, integrated from the time at which the plume passed point P until d days after this time [rem/Ci]
$I_i(x,te_1,te_2)$	= integrated source term [Ci]
te_1	= time when exposure started [s]
te_2	= time when exposure ceased [s]
n_{iso}	= total number of isotopes in the plume.

2.2. External gamma doses

The external gamma doses to a person at a given point $P(x_d,y_d,z_d)$ is obtained by integrating the radiation contributions from the individual elements of the plume. If the plume contains n_{iso} isotopes, whose photon energies are distributed over n_e energy groups, the gamma dose (in rem) at point P is found to be:

$$(20)\quad D_G(x_d,y_d,z_d,s,u) = \frac{K}{4\pi} \cdot \eta \cdot \sum_{k=1}^{n_e} E_k^{\gamma} \cdot \sigma_k^{\gamma} \cdot \sum_{i=1}^{n_{iso}} f_{k,i} \cdot$$

$$\int_{\max(o,u\cdot(te_1-tf_2))}^{u\cdot(te_2-tf_1)} \frac{I_i(x,te_1,te_2)}{2\cdot\pi\cdot\sigma_y(x,s)\cdot\sigma_z(x,s)\cdot u}\cdot$$

$$\left(\int_{-H}^{\infty}\left(\exp\left(-\frac{z^2}{2\cdot\sigma_z(x,s)^2}\right)+\exp\left(-\frac{(z+2\cdot H)^2}{2\cdot\sigma_z(x,s)^2}\right)\right)\cdot\right.$$

$$\left.\left(\int_{-\infty}^{+\infty}\frac{B(\mu_k\cdot r)\cdot e^{-\mu_k\cdot r}}{r^2}\cdot\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)dy\right)dz\right)dx$$

where

r^2 = $(x-x_d)^2+(y-y_d)^2+(z-z_d)^2$ [m^2]

s = stability category

tf_1 = time for start of release [s]

tf_2 = time for end of release [s]

te_1 = time for start of exposure [s]

te_2 = time for end of exposure [s]

K = conversion factor, dose rate/(absorbed energy per gram per Ci) [(rem/s)/(MeV/g/Ci].

n_e = number of energy groups

E_k^γ = mean photon energy in k'th energy group [MeV]

$\sigma_k^\gamma=\sigma_k^\gamma(E_k^\gamma)$ = energy absorption coefficient for air in k'th energy group [m^2/g]

$f_{k,i}$ = photon yield of isotope no. i in the k'th energy group

$\mu_k = \mu(E_k)$ = linear attenuation coefficient for air, in the k'th energy group [m^{-1}]

$B(\mu_k\cdot r)$ = $1 + K_E(E_k)\cdot\mu_k\cdot r$, the build-up factor for the k'th energy group

$I_i(x,te_1,te_2)$ = integrated source term for isotope no. i [Ci]

η = shielding factor for buildings etc.

The creation of daughter products (see sec. 1.4) and the deposition (see sec. 1.5) may be accounted for in the integrated source term.

The model for external gamma doses from a plume does not take any possible mixing layer into consideration.
The integration over 3 dimensions is performed using Grauss-Christoffel quadrature with weight points calculated by a method described by Walter Gautichi.

2.3. External gamma doses from deposited radioactive material

The external gamma dose from radioactive material deposited on the ground to a person located at a given point is found by integrating the dose contributions from the individual part-elements of the ground. In the calculation it is assumed that the ground can be considered as an infinite, plane source, where the radioactive material is deposited with a constant density corresponding to the density on the ground immediately under the point in question. The dose is calculated in points that lie 1 m above the ground.

The dose will be:

$$(21)\quad D_S(x,y,s,u) = 0.2304 \cdot \eta \cdot \eta_g \cdot B \sum_{k=1}^{n_e} E_k^\gamma \cdot Ex(\mu(E_k^\gamma)\cdot 1)\cdot \mu_{en}(E_k^\gamma)\cdot \sum_{i=1}^{n_{iso}} f_{k,i} \cdot \int_{te_1}^{te_2} W_i(x,y,s,u,t,td_1,td_2)dt$$

where

$D_S(s,y,s,u)$	= the external gamma dose 1 m above the ground from the radioactive material deposited on the ground [rem]
$\mu_{en}(E_k^\gamma)$	= the linear energy absorption coefficient for air for the photon energy E_k^γ [m^{-1}]
$\mu(E_k^\gamma)$	= the linear attenuation coefficient for air for the photon energy E_k^γ [m^{-1}]
k	= energy group number ($1 \leq k \leq 8$)
i	= isotope number
n_{iso}	= number of isotopes

n_e = number of energy groups

E_k^γ = mean photon energy for energy group no. K

$f_{k,i}$ = photon yield for isotope no. i in the k'th energy group

$$Ex(\tau) \equiv \int_\tau^\infty \frac{e^{-\rho}}{\rho} d\rho$$

$W(x,y,s,u,t,td_1td_2)$ = the concentration of isotope no. i (Ci/m^2) on the ground vertically under the detector point at the time t, when the deposition takes place in the period of time from td_1 to td_2 (see otherwise sec. 1.5).

te_1 = start of exposure [s]

te_2 = termination of exposure [s]

td_1 = start of deposition [s]

td_2 = termination of deposition [s]

η = shielding factor for buildings etc.

η_g = shielding factor for ground roughness

B = correction factor for backscatter

3. DATA

This section gives a brief survey of some of the data included in the computer program set up on the basis of the model.

3.1. Dispersion parameters

The atmospheric stability is classified by the six Pasquill classes A - F [5,2]. For these stability classes, use is made of Turner's [2] ten-minute mean values for the dispersion parameters ($\sigma_y(x,s)$ and $\sigma_z(x,s)$).

3.2. Effective stack height

The effective stack height, H, is assumed to be constant and thus independent of the distance from the point of release. Thermal lift of the released activity is calculated on the basis of Briggs' formula. The calculation of the lift does not take decay heat and the latent heat of the accompanying steam into account.

In cases of unstable or neutral atmosphere, H is determined by

$$H = h + (36 \cdot P)^{1/3} \cdot u^{-1} \cdot x^{2/3} \qquad (22)$$

where

h = the physical stack height [m]
P = the release rate of the heat content of the plume (less the latent heat) [MW]

The plume rise is assumed to cease at a distance from the release point that is numerically equal to $177 \cdot P^{2/5}$. If this value is inserted into (22), the final height of the plume is found to be

$$H = h + 104 \cdot P^{3/5} \cdot u^{-1} \qquad (23)$$

In cases of stable atmosphere, H is determined by

$$H = h + \left(\frac{215 \cdot P}{u \cdot \rho}\right)^{1/3} \qquad (24)$$

where the stability parameter ρ is given by

$$\rho = \frac{g}{T} \cdot \frac{\partial\theta}{\partial z} \qquad [1/s^2]$$

$\partial\theta/\partial z$ is here the potential temperature gradient for the atmosphere, g is the gravity acceleration, and T the temperature of the atmosphere [^{o}K].

3.3. Daughter products

In calculating the external gamma doses both from airborne and from deposited radioactive material, use is made of the following, simplified decay chains:

	Mother product		Daughter product
a.	Kr 85 m	→	Kr 85
b.	Kr 88	→	Rb 88
c.	Kr 89	→	Rb 89
d.	Sr 90	→	Y 90
e.	Sr 91	→	Y 91
f.	Zr 95	→	Nb 95
g.	Zr 97	→	Nb 97
h.	Mo 99	→	Tc 99 m
i.	Ru 105	→	Rh 105
j.	Ru 106	→	Rh 106
k.	Te 129 m	→	Te 129
l.	Te 131 m	→	Te 131
m.	Te 132	→	I 132
n.	Sb 127	→	Te 129 m
o.	I 131	→	Xe 131 m
p.	I 133	→	Xe 133
q.	I 135	→	Xe 135

(continued)

	Mother product		Daughter product
r.	Xe 133 m	→	Xe 133
s.	Xe 135 m	→	Xe 135
t.	Xe 137	→	Cs 137
u.	Xe 138	→	Cs 138
v.	Ba 140	→	La 140
w.	Ce 143	→	Pr 143
x.	Ce 144	→	Pr 144
y.	Nd 147	→	Pm 147
z.	Np 239	→	Pu 239

3.2. Depositability

Argon-41 and all the krypton and xenon isotopes are reckoned not to be depositable. The other isotopes in question are reckoned to be depositable.

3.3. Data for calculating external gamma doses

3.3.1. Gamma energy groups

The division of energy groups shown in table 1 is found appropriate when calculating the external gamma doses (11).

Table 1

Photon energy groups

Group number	Energy limits (MeV)	Mean energies (MeV)
1	0-0.080	0.04
2	0.081-0.150	0.12
3	0.151-0.250	0.20
4	0.251-0.510	0.38
5	0.511-0.850	0.68
6	0.851-1.330	1.09
7	1.331-2.030	1.68
8	2.031-3.000	2.53

3.3.2. The distribution of the photon yields of the isotopes over the energy groups

Table 2

The photon yield of the isotopes in energy groups

Isotope	Energy group number							
	1	2	3	4	5	6	7	8
Ar 41						1.00		
Kr 83 m	0.09							
Kr 85 m		0.74		0.13				

(continued)

Isotope	Energy group number							
	1	2	3	4	5	6	7	8
Kr 87				0.84	0.16			0.35
Kr 88			0.42	0.05	0.23		0.14	0.53
Kr 89			0.31	0.99		0.55	0.70	0.42
Rb 88						0.13	0.21	0.02
Rb 89					0.17	1.29		0.27
Sr 91					0.42	0.33	0.05	
Zr 95					0.98			
Zr 97					0.92			
Nb 95					1.00			
Nb 97					1.00			
Mo 99	0.02		0.07	0.01	0.16			
Tc 99m		0.90						
Ru 103				0.88	0.06			
Ru 105				0.43	0.64			
Rh 105				0.24				
Rh 106				0.21	0.11	0.03		
Te 129m					0.06			
Te 129	0.19			0.17	0.01	0.02		
Te 131m	0.02	0.05	0.16	0.09	0.91	0.24	0.06	
Te 131		0.68		0.21	0.04	0.13		
Te 132	0.17		0.90					
I 131	0.03			0.87	0.09			
I 132			0.01		2.53	0.35	0.17	
I 133					0.90			
I 134		0.03		0.08	1.21	0.76	0.14	
I 135				0.07		0.91	0.42	
Xe 131m			0.02					
Xe 133m			0.14					
Xe 133	0.37							
Xe 135m					0.80			
Xe 135			0.91		0.03			
Xe 137				0.33				
Xe 138				1.32			0.65	
Cs 134					2.20	0.03	0.03	
Cs 136	0.11	0.06	0.36	0.71	1.00	1.02		

(continued)

Isotope	Energy group number							
	1	2	3	4	5	6	7	8
Cs 137					0.85			
Cs 138				0.23	0.08	0.25	0.73	0.27
Ba 140	0.11		0.06	0.11	0.34			
La 140				0.60	0.19	0.10	0.96	0.03
Ce 141		0.48						
Ce 143	0.11			0.48	0.15	0.02		
Ce 144	0.02	0.11						
Pr 144					0.02			
Nd 147		0.28		0.20				
Pm 149				0.02				
Pu 238								
Pu 239								
Pu 240								
Pu 241								
Ru 86						0.088		
Te 127m								
Te 127								
Sb 127				0.45	0.66	0.012		
Sb 129			0.029	0.084	0.75	0.44	0.093	
Np 239		0.23	0.16	0.14				
Am 241	0.36							
Cm 242								
Cm 244								

Source: references 8, 9 and 11

Note: Photon yields below 1% (0.01) are not included in the table or in the calculations of external gamma radiation doses.

3.3.3. Dose build-up factor, energy absorption coefficient and linear attenuation coefficient for air for energy groups

Table 3

Data for energy groups

Energy group no.	Energy absorption coefficient, $(\frac{\mu_{en}}{\rho})$ $(cm^2\ g^{-1})$	Linear attenuation coefficient $\mu(m^{-1})$	Dose build-up factor coefficient K_E
1	6.57 E-2	3.15 E-2	2.70
2	2.40 E-2	1.89 E-2	5.10
3	2.71 E-2	1.60 E-2	3.57
4	2.94 E-2	1.28 E-2	2.37
5	2.93 E-2	9.99 E-3	1.64
6	2.73 E-2	7.90 E-3	1.24
7	2.47 E-2	6.30 E-3	0.97
8	2.17 E-2	5.00 E-3	0.79

Source: references 10 and 11.

Note: The build-up factor is defined as $B_E(r) = 1+K_E \cdot \mu \cdot r$,

where $$K_E \equiv \frac{\mu-\mu_{en}}{\mu_{en}}$$

3.4. Dose-conversion factors for inhaled isotopes

Dose-conversion factors giving the relation between the amount of a given isotope which is inhaled and the resulting dose to the organ in question, integrated from the time of the passage of the plume and until a given number of days after this time, are taken from WASH-1400 [3, table D-2].

Use is made of the following integration periods in the models:

Bone marrow	30 days
Lungs	365 days (1 yr)
GI tract	7 days
Thyroid gland	30 days

The dose-conversion factors for the bone marrow are calculated as the dose-conversion factor for the period 7 days plus 0.5 times the dose-conversion factor for the period from 8 to 30 days after exposure. The dose-conversion factors thus calculated can hence be used for calculations of early and continuing somatic effects [3, sec. 9.2.2.1].

The breathing rate for adults is assumed to be $3.5 \cdot 10^{-4}$ m^3/s.

3.5. Shielding factors

In most cases the following shielding factors are used:

a. External gammadose from plume:
   Shielding from buildings etc.: $\eta = 0.6$.

b. External gammadose from radioactive material deposited on the ground:
   Shielding from buildings etc.: $\eta = 0.2$
   Shielding from ground roughness: $\eta_g = 0.7$.

In the comparison of models made by SNODAS (october 1977) all shielding factors are set equal to 1 and no correction factor for backscatter is used.

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APPENDIX 5

Comparison of Parameters used in Dose Models by the SNODAS Participants

by

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COMPARISON OF PARAMETERS USED IN DOSE MODELS BY THE SNODAS PARTICIPANTS

This report compares the answers given by the four SNODAS members to questions in a dose model parametre list questionaire. The tableformat has been frequently used in the comparison in order to get a result easy to overview. This format is also more convenient for the reader when he wants to draw his own conclusions. The four participants are idenitfied by the first letter in the name of the country.

The comparison of the answers from each question is contained within a section of the report, titled with the question.

Q1: **A description of dose models etc.**

These answers are too extensive to lend themselves to easy comparison, but the similarities and differences in approach are to a large extent found in the answers to the other questions.

Q2: Describe in which way daughter products are accounted for.

	Which models account for decay chains?	No. of parent isotope	Comment
D	All models	27	
F	All models use library of decay chains	22	
N	All models		No datalibrary is included in TIRION2. The allocated computer storage limits number of isotopes to 70, number of decay chains to 40 and number of isotopes in one chain to 7.
S	All models use library of decay chains	15	

NI = information not given in answer

Table 2.1

Q3: In which way is inversion layer accounted for?

		Seasonal variation ?	Comments
D	General approach as described by Turner (1) (Gaussian range, intermediate range, homogeneous range). Average inversion layer height (m) Pasq A B C D E F 1500 1500 1000 500 200 200	No	
F	Inversion heights restrict vertical diffusion and plume rise. Same inversion layer heights as D above	No	Inversion heights given by Klug
N	Default inversion heights (may be changed by user) Pasq A-C D-F 1500 1000	No	Growth of σ_z is limited by inversion height
S	The actual height to the inversion is not calculated. Fumigation formula with 100 m mixing height is used when the temperature has a minimum a 90 m.		

Table 3.1

(1) Turner D. Bruce: Workbook of Atmospheric Dispersion Estimates, US Dep. of Health, Education, and Welfare, PB-191 482, 1970.

Q4: How do you calculate diffusion at long distances?

	Dispersion model	Distance		Comments
D	Gaussian distribution	0- 50 km	)	Short release
	Crosswind integrated con-	50-100 km	)	0.5 to 2-3 hrs
	concentration (30^{o} sector)		)	
	Crosswind integrated concen.	0-100 km		Long term releases
F	Gaussian distribution	0-100 km		
	(The increase of σ_z-values is restricted by inversion layers)			
	$\sigma_z = \sigma_z$ (100 km)	> 100 km		
	$\sigma_y = (x/100\ km)^{1/2}\sigma_y(100\ km)$			
N	Gaussian distribution	0-100 km		Short releases
	σ_y and σ_z based on solution of the diffusion equation.	10-100 km		
	Crosswind integrated concentration in sector selected by user			Long releases
S	A statistical model based on Gaussian distribution for distances. ...	0.5 - 20 km		
	This model is extrapolated out to ...	50 or 100 km		

Table 4.1

Q5: Define your atmospheric stability groups.

	Classification	Value of dispersion parameters	No. of wind speed grps	Range of windspeed groups (m/s)
D	Pasquill	Pasquill/Gifford curves .	4	(1,3) ✱ (3,6) (6,10) (10, →)
F	Pasquill	Pasquill/Gifford+ curves	7	Average speeds: 0.8, 2.1, 4.1, 6.7, 9.3, 11.8, 14.9
N	Pasquill	Hosker's parametrization and σ_y and σ_z		no. of windspeed groups and average windspeeds in each group must be determined by the user
S	Calculate single weather cases. Risk assessment based on a meteorological data base collected over long observation periods.			

✱Mean windspeed in groups are adjusted according to release height.

+The original values are used for roughness z_o = 1 cm. For larger roughness values the dispersion parameters are corrected with a method proposed by F.B. Smith.

Table 5.1

Q6: List values of deposition velocities.

Isotope(s)	D	F	N	S
Noble gases	0	0	0	0
Iodine and others	10^{-2}-10^{-3}	10^{-2}	10^{-2}	
I_2, Ru				10^{-2}
Particulate, I, Ru, Cs, Sr, etc.				$3 \cdot 10^{-3}$
Methyliodine				10^{-5}
?				Deposition over snow: $3 \cdot 10^{-3}$

(units:m/s)

Table 6.1

None of the models described applies different deposition velocities for different types of areas, or particle sizes.

Q7: **List values of wash-out coefficients used.....**

	Wash out coefficient (s^{-1})
D	Noble gases: 0 Others : 10^{-5} - 10^{-4}
F	Noble gases: 0 Others : 10^{-4}
N	Noble gases: 0 Others : 10^{-4}
S	Frontal rainfall: $3 \cdot 10^{-5}$ Shower rainfall : $1 \cdot 10^{-4}$ Snow : $1 \cdot 10^{-4}$

Table 7.1

Q8 List dose conversion factors for isotopes....

D Uses data from table VI D-2 in WASH-1400

F Main part of inhalation dose factors from WASH-1400, Table VI D-2

N Will use WASH-1400 as a main reference in the future.

S Not specified where from data are obtained.

Table 8.1 compares the data given by S with the data in table VI D-2 in WASH-1400. The table shows the nuclides and their critical organs. The WASH-1400 data are converted from table VI D-2 using a breathing rate of $2.3 \cdot 10^{-4}$ m^3/s . There are no information on the breathing rate assumption made by S. The data are valid for an adult.

In the case of WASH-1400 the dose commitment is calculated as the integral of the dose rate over 50 years (GI-tract: 60 days). The general impression from the comparison is that the WASH-1400 data will give lower doses than the data from S.

The data for some nuclides differ more than others. None of the references give data for $Tc\text{-}99^m$ within the same order of magnitude. For Ru-106 the data from WASH-1400 is a factor 3-4 larger than the data from S.

Table 8.1

Nuclide	Critical organ	Conversion factor to obtain dose commitment to critical organ (rem m^3/Cis)	
	S	S	WASH-1400
H-3	Whole body	$8.72 \cdot 10^{-2}$	-
C-14	Fat	0.35	-
P-18	GI	0.28	-
Na-24	GI	1.40	-
Cr-51	GI	0.14	-
Mn	Liver	3.5	-
Fe	Spleen	1.56	-
Fe	Spleen	14	-
Co-58	GI	1.75	1.7
Co-60	GI	4.67	4.4
Zn-65	Whole body	4.63	-
Sr-89	Skeleton	92.6	6.9
Sr-90	Skeleton	$2.78 \cdot 10^3$	$6.4 \cdot 10^2$
Zr-95	Whole body	4.63	-
Nb-95	GI	2.33	1.6
Tc-99m	GI	$3.5 \cdot 10^2$	$2.5 \cdot 10^{-3}$
Ru-103	Lung	17.4	12.4
Ru-105	GI	2.0	0.28
Ru-106	Lung	$2.31 \cdot 10^2$	897
Te-132	GI	7.0	1.4
I-131	Thyroid	300	253
I-132	Thyroid	4.2	15
I-133	Thyroid	70	41
I-134	Thyroid	1.2	0.25
I-135	Thyroid	16	10
Cs-134	Whole body	11.6	-
Cs,137	Whole body	7.72	-
Ba-140	Skeleton	27.8	1.2

Q9 & Q10: **How is self shielding effect of body in external gamma dose calculation treated?**

	Shielding effect from body[x)]	Shielding factor due to buildings	
		avg. indoors	avg. popul.
D	0.8	ground: 0.14 plume: 0.6	ground: 0.33 plume: 0.75
F	0.86[+)]	0.35	0.5
S	0.8	0.2	0.35 (Lärforlägningsutr. 0.3)
N	-	-	ground: 0.33 plume : 0.75

x) Ratio of whole body dose to tissue dose.

+) Ratio of skin dose to whole body dose (dose at 5 cm depth) from external γ-radiation.

Table 9.1

All SNODAS participants disregard reduction of inhalation doses for the population group indoors.

Q11 List gamma energy groups eventually used in the external gamma dose model

D: 8 energy groups with average energy ranging from 0.04 MeV to 2.53 MeV.

F: 1 energy group (E = 1 MeV) and applies the results of ref. (1) which states that the energy dependence of the dose integral is rather linear. The model will be supplemented with energy groups 0.04, 0.2, and 0.5 MeV in the future.

N: 8 energy groups with upper group limit as representative energy for the group. The representative energies are: 0.1, 0.3, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0 MeV.

S: 4 energy groups represented by the energies 0.09 MeV, 0.21 MeV, 1.08 MeV and 2.98 MeV.

(1) Imai, K. and Iijima, T.: Assessment of Gamma-Exposure Due to a Radioactive Cloud Released from a Point Source, Health Physics, Vol. 18, p. 214.

Q12 List values of dose build up factor parameters for air.

A comparison of the buildup as function of attenuation ($\mu_r = \mu \cdot r$) for near 1 MeV γ's is made in the table below.

	Energy MeV	μ_r 1	2	3	5	8	
D	1.09	2.24	3.48	4.72	7.20	10.9	$1+k\mu_r$
F	1.0	2.14	3.57	5.28	9.57	18.1	$1+\mu_r+\frac{(\mu_r)^2}{7E^{2.4}}$ 0.5MeV<E<2MeV $1+1.1\ \mu_r+(\mu_r)^2$ E<0.5MeV
S	1.08	2.06	3.53	5.44	9.87	18.1	not known
N	1.0	2.25	4.07	6.48	13.1	27.9	$(1+0.965\ \mu_r+0.266\mu_r^2)e^{0.01\mu_r}$

Table 12.1

The data in line D is calculated from the tabulated value of k (= 1.24) for γ-radiation of energy 1.09 MeV.

This table shows that the data from F and S are consistent while the data from D is below the others for μ_r greater or equal to 3, and the data from N is well above the data from F and S.

Other energies are not examined.

Q13: **Describe your plume rise model**

Plume rise equations used by D, F and N are shown in Table 13.1.

Plume rise formulas

	Briggs formula from WASH-1400:
D	$z = z_o + 104Q^{0.6}\, u^{-1}$ for $\beta < 0$
	$z = z_o + \left(\frac{2150\, Q}{u\beta^2}\right)^{1/3}$ for $\beta > 0$
F	$\Delta H = 5.1 \left(\frac{Q}{\beta u}\right)^{1/3} - z_o \; ; \; x > \frac{\pi}{2} \sqrt{\frac{u}{\beta}}, \; z_o = \frac{R_o}{0.45}$ where $R_o = \begin{cases} 0 & \text{for steam explosion accident} \\ 30\,(1 - \exp(-/2)) & \end{cases}$
N	From Gifford: $z = 5.1 \left(\frac{1}{\beta u}\right)^{1/3} \left\| Q^{M} t \frac{1 - \sin(\beta^{1/2} t)}{\beta^{1/2}} + Q(1 - \cos(\beta^{1/2} t)) \right\|$ $+ z_a \cos(\beta^{1/2} t) \quad , \quad \beta > 0$ Plume levels off when maximum height is reached, that is when $\frac{dx}{dt} = 0$.
S	Plume rise calculation based on models by Briggs and Gifford Plume rise limited to: 1) rise by nuclear effects $t_{max} = 3600$ s 2) rise by thermal effects in neutral and unstable conditions $t_{max} = \frac{500}{u\beta}$

$[Q]$ = MW, $[Q^M]$ = MW/s, z_a - initial height

Table 13.1

D uses a two formula model, one formula describes the plume rise for neutral weather conditions ($\beta = 0$) and the other describes the plume rise for the stable weather classes. F and N applies formula which is valid for stable weather only. Weather classes A-D are treated conservatively (?) with the same formua with $\beta = 1.0 \cdot 10^{-4} s^{-2}$.

The atability parameter $\beta = \frac{g}{T} \frac{\partial \theta}{\partial z}$ influences the plume rise significantly. How different SMODAS participants have chosen the numerical values of β in their plume rise model is compared in table 13.2 below.

Pasgill class	D	F	N	S
A-D	0.0	$1.0 \quad 10^{-4}$		not given
E	$1.61 \cdot 10^{-4}$ to $8.3 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	
F	$8.3 \cdot 10^{-4}$ to $1.67 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	
G	$> 1.67 \cdot 10^{-3}$			

(unit: s^{-2})

Table 13.2

A direct comparison between the plume rise models is made and shown in Table 13.3 for the following test example:

$Q = 5$ MW, $Q^* = 0$ MW/s

$u = 2$ m/s

$\beta = 7 \cdot 10^{-4} s^{-2}$

$z_0 = 0$ (plume starts at ground level)

	Plume height 500 m downwind (m)
D	92
F	78[x)]
N	78
S	-

[x)] For steam explosion type of accident.

Table 13.3