LONG RANGE TRANSPORT AND DIFFUSION: AN APPROACH TO THE PROBLEM FROM THE HEALTH PROTECTION POINT OF VIEW

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Abstract

The problem of transport and diffusion of gaseous releases in the atmosphere after travel distances from some tens up to some hundreds of kilometers is analyzed, with the aim of deriving an expression for the cloud-dosage at ground level. Taking into account the experimental data available at present, a function is calculated which relates the coefficient of diffusion to the time of travel. With very conservative assumptions from the health protection point of view, the radially symmetrical equation of diffusion has been solved for an instantaneous release, and the integrated concentration along the travel direction calculated. The results show that, only after a travel of 100 km the values of cloud-dosage are about ten times lower than that obtained by extrapolation of Pasquill estimates, during category F of stability.

Introduction

The health-physicist is asked sometimes to assess the risk to which the population of a nearby country would be exposed in the event of a release of gaseous radioactive effluents from a source some hundreds of kilometers distant as a result of an accident at a nuclear plant sited in his own country. The present work attempts to provide an evaluation of the dilution of gaseous effluents in the atmosphere over such distances, based on the available experimental data, and taking into account the need to allow for the usual worst-event criteria but not going beyond the bounds of a realistic concept of the physical and meteorological phenomena governing such diffusion.

For the next development of this study it is necessary to recall here some results coming from the statistical theory of diffusion[1]: as well known this theory is concerned with following the trajectories of the various particles of air and evaluating their dispersion by means of statistical models. From the analytical point of view, this involves a Lagrangian-type mathematical approach; without going into the merits of the mathematical development of this theory, it is however worthwhile noting one result which may be helpful to us. Assuming that $\sqrt{\overline{Y^2(t)}}$ is the quadratic mean dispersion of the various trajectories after a time t has elapsed, it can be shown that the following relationship applies for long times[1]:

$$\overline{Y^2(t)} \approx 2Kt \qquad (1)$$

where K is a constant. This result will be utilized in the further development of the present study.

Physical phenomena which regulate atmospheric diffusion and their dependence on spatial scale

The moment at which a gaseous emission occurs in the atmosphere near the ground marks the beginning of a continuous sequence of events which results in time in the evolution of the cloud, such as we can observe externally. The increase in the size of the cloud implies the presence of two factors essential to diffusion: in the first place the part of the turbulence spectrum which becomes actively involved in the diffusion is that part whose wavelength is of the same order of magnitude as the cloud whereas, as well known, the turbulence component with a shorter wavelength tends only to mix cloud particles locally and the component with a much longer wavelength tends to move the cloud without changing its dimension; in the second place increasingly elevated atmospheric zones gradually become involved, in which both the turbulence spectrum and the thermal stability change. Within these continuously changing diffusion conditions it is nevertheless possible to distinguish an initial phase, for short periods, during which the part of the atmospheric boundary layer involved is that nearest the ground (surface boundary layer). In this case turbulence is essentially correlated to the aerodynamic characteristics of the terrain (i.e. is a function of the ground roughness parameter) and is substantially regulated by the conditions of ground surface heating and cooling. The large body of experimental data collected to date on this phase is adequate to permit reliable forecasting of diluition in air up to distances of some kilometers over terrain which is not excessively irregular: for this purpose the estimates made by Pasquill[2] provide a good summary of the data collected by several authors.

There is, however, a second phase of diffusion over distances of some kilometers up to some tens of kilometers during which increasingly high regions of the boundary layer gradually become involved in the diffusion. In general, diffusion in this second interval is calculated by extrapolating the data referring to the initial phase, using a technique which, though arbitrary, provides adequate safety margins especially with respect to the stable condition. These calculations are generally accepted as valid, even if no practical experimental data have been collected for such special situations.

Not seldom however, in risk evaluation relative to accidental release, the health physicist is used to assume the continuous presence of category F conditions over distances up to 100 km, and thus to base concentrations in air on the values extrapolated from Pasquill's estimates. Such an assumption seems to be not realistic; we know in effect that during the night when clear sky is present, the thermal stability near the ground increases with decreasing wind force, but the wind direction becomes more and more indeterminated, so that the product of the mean wind velocity and the time of travel cannot be regarded as a measure of the distance reached, although it does measure the path of travel. At last, taking into account that the category F is present only during the night (1-2 hours before sunset to 1-2 hours after dawn) it may be said that the continuous presence of highly stable conditions will seldom be verified over distance of more than some tens of km; so, in making calculations for the purposes of public health protection, it would be absurd to make such an assumption for distances of the order of hundreds of kilometers. Let us now analyze the physical and climatological phenomena which play a part in diffusion over such long distances and consider whether it is possible to derive any benefit from the limited amount of experimental data on this scale collected so far.

The transport and diffusion of gaseous effluents at mesoscale level

In covering distances from some to some tens of kilometres the diffusing cloud tends gradually to involve the entire boundary layer up to an altitude of about 1000 m (planetary boundary layer). At these altitudes the turbulence actively involved in diffusion is chiefly that induced by thermal effects, whereas the influence of the terrain with its aerodynamic and thermal characteristics tends gradually to decrease in importance.

It can be said that concentrations are controlled by wind trajectories between the point of emission and the receptor area and by the vertical mixing characteristics along the path of travel[3]: any long distance diffusion model must therefore incorporate parameters which make allowance for the influence of atmospheric stability profiles on the vertical dispersion of the released material. In fact the vertical dispersion of a cloud which has been moving for several hours may be lower than that predicted by the Gaussian model as a result, for example, of the confinement of vertical mixing below a well defined stable layer over long distances[3]. One of the most frequent cases, and therefore a case for which we have made allowance in the proposed model, is an inversion at altitude caused by the subsidence of air masses; the effect of this inversion is similar to that shown in a suggestive picture by R.W. Davies [4].

The model which we now propose in order to describe transport and diffusion at mesoscale level, i.e. up to several hundreds of km, does not claim to make any scientifically based allowance for the physical phenomena which determine dilution over such distances: actually such a study would be impossible, mainly because of the difficulty of producing experimental data which would serve this purpose. Since some data (albeit from varied sources) are available, however, it was decided to adopt the protectionist standpoint and to make allowance for them by selecting a model which would place an upper limit on all experimental concentration data. Fig.1 gives experimental horizontal dispersion data σ_y obtained by 19 authors[1] for time of travel up to more than 100 hours, collected by J.L.Heffter[5]: they come from a wide variety of experiments using both instantaneous and continuous sources. The same figure also gives values for K which can be deduced from the statistical theory for long time intervals (1). The figure also shows that the straight line C places a lower limit on all the data, with the only exception of the points marked by ✦ : in fact such data are inconsistent with our model because they refer to an instantaneous release of constant level balloons at an altitude of 30000 feet, together with a travel time of a few hours. The equation of the line C is a power function, i.e.:

$$\sigma_y \approx 0.2 \cdot t^{1.5} \quad (km) \qquad (2)$$

from which we obtain, taking (1) into consideration:

$$K = 2 \cdot 10^{-2} \cdot t^{2} \quad (km^2/h) \qquad (3)$$

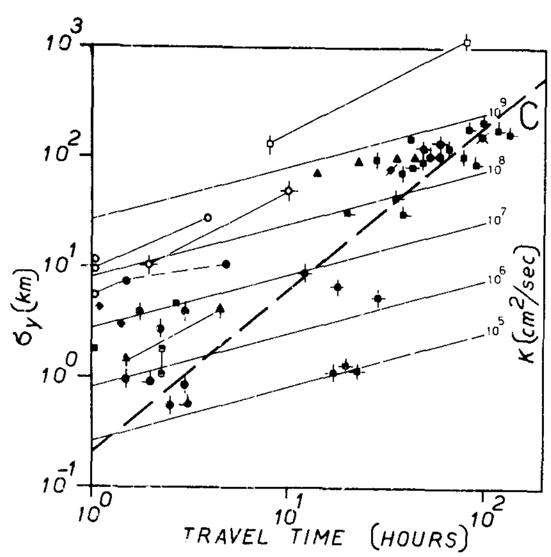

Fig. 1

If we now assume that vertical diffusion is limited by the presence of an inversion at altitude, we may suppose that vertical dispersion is homogeneous within the layer of height D above ground, where D is the height of the base of the inversion.*This assumption appears reasonable provided that distances reach 50–100 kilometers. In this case it is enough to resolve the equation of radially symmetrical diffusion in two dimension for an instantaneous emission: the hypothesis of radial symmetry can be accepted as a good approximation since the diffusion of the cloud along the direction of travel generally differs little from the transverse diffusion.

The basic equation is therefore as follows:

$$\frac{\partial C}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(K r \frac{\partial C}{\partial r}\right) \tag{4}$$

If we assume for the diffusion coefficient K a general espression of the type $K = a \cdot t^n$ and supposing an instantaneous, homogeneous, vertically linear emission (M: mass of pollutant per unit of height: Q/D) the solution of this equation is given by:

$$C(r,t) = \frac{M e^{-\frac{r^2}{(\beta t)^{n+1}}}}{\pi (\beta t)^{n+1}} \tag{5}$$

where $\beta = \left(\frac{4a}{n+1}\right)^{1/(n+1)}$; in our case putting $a = 2 \cdot 10^{-2}$ and $n = 2$ we obtain $\beta \approx 0{,}3$ ($km^{2/3}/h$).

In health protection calculations it is useful to know the "cloud dosage". This value can easily be determined by means of formula (5), provided that a given value $\bar{u}$ is fixed for the mean wind speed at the time at which the cloud passes over the site for which it is required to know the cloud dosage. Assuming the time of passage of the cloud over the site to be negligible in comparison with the time elapsed since emission, it can be assumed that t in (5) is constant; the cloud dosage will be given by the following expression:

$$C.D. = 2\int_0^{\infty} C(r,t)\frac{dr}{\bar{u}} = \frac{Q}{D\bar{u}\sqrt{\beta^3 t^3 \pi}} \qquad (Ci \cdot h \cdot km^{-3}) \tag{6}$$

It will be apparent that the concentration is expressed as a function of time of travel t. As already stated, it is only necessary to bear in mind that the proposed model starts to become valid for traveltimes exceeding the period of time needed for the cloud to disperse into the vertical layer of thicknees D. With excessively long times, however, diffusion on a synoptic scale becomes predominant. It is therefore reasonable to state that the proposed model is valid for an interval between a ten and one hundred hours, when low wind speeds are involved.

Some practical considerations for the application of the proposed model

As already noted, speed $\bar{u}$ (km/h) in formula (6) refers to the wind near ground level, whereas time of travel t is calculated on the basis of the mean speed within the layer of height D. In general it can be said that the mean wind

* From the analysis of vertical synoptic soundings it can be found that a minimum value for D, related to a frequence of the corresponding meteorological situations statically significant, is about 1 km.

speed value within 20-30 metres above ground is proportional to the mean wind[6] speed within the boundary layer (within D). If we assume as a working hypothesis that the proportional relationship between the two mean values is 1/2, formula (6) can be expressed as a function of scalar path x:

$$C.D. = \frac{2Q\sqrt{\bar{U}}}{D\sqrt{\pi\beta^3 x^3}} \qquad (Ci \cdot h \cdot km^{-3}) \tag{7}$$

in which $\bar{U} = 2\,\bar{u}$: the mean speed within layer D.

It should also be noted that, having selected the straight line C in the graph in Fig. 1, the situation at one hour after emission corresponds to stability category F with u = 2m/sec = 7 km/h. After a maximum of 10 to 15 hours in this situation there is a change to neutral or unstable conditions, if we suppose the same order of magnitude for the wind speed. Therefore, making $\bar{U}$ = 4m/sec in formula (7), the cloud dosage will be expressed by (with D = 1 km):

$$C.D. \approx \frac{26.3}{x^{1.5}} \cdot Q\,(Ci \cdot h \cdot km^{-3}) \tag{8}$$

The graph in Fig.2 gives two curves: curve A represents the pattern of cloud dosage according to Pasquill for a 1 Ci emission at ground level under category F conditions with a mean wind speed near ground level of 2 m/sec; above 10 km and up to 100 km this curve is drawn dashed, since in this interval the validity of Pasquill's model diminishes progressively. Curve B represents the pattern of cloud dosage according to the proposed model for an instantaneous release when the initial situation is characterized by category F with a mean wind speed near ground level of 2 m/sec; for a scalar path below 100 km the curve is dashed since, for the reasons given in the preceding paragraph, the proposed model, for such a low wind speed, is only applicable for times of travel greater than a ten of hours. Making allowance for the fact that, at low wind speeds, the vectorial path is shorter than the scalar path, the curve B will in fact be lower if the vectorial path is taken as variable x. Therefore, until a statistical study is made to evaluate the relationship between scalar and vectorial path under conditions characterized by mean wind speeds near ground level of 2 m/sec, curve B gives an overestimate of the cloud dosage values at mesoscale diffusion level if x is taken as the distance of travel

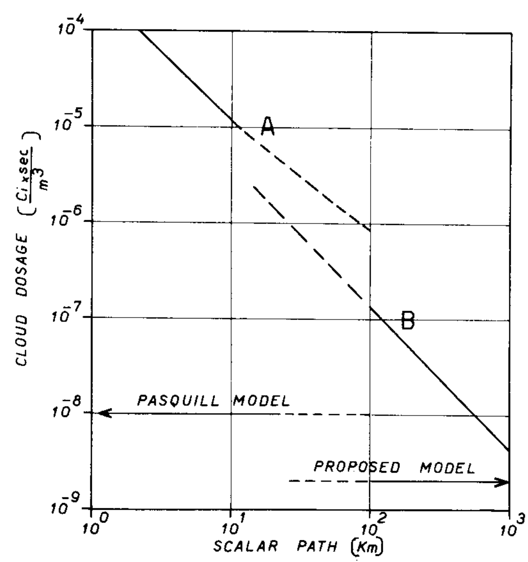

Fig. 2

Conclusion

In conclusion, taking as a working hypothesis that the vectorial path of the wind is equal to the scalar path, even for wind speeds at ground level of 2 m/sec, curve B of the graph in Fig. 2 can be used to provide a conservative estimate of concentrations at distance between some tens to some hundreds of km from the point of release.

The values deduced agree very closely with those proposed by Doury[7]. If one makes a comparison with the measurements taken at the time of the Windscale accident[8] in which the emission was prolonged (approximately 2 days) and not constant, one finds that the proposed curve gives values over distances between 100 and 500 km which are higher by factors ranging from 10 to 100 - this can partially be explained by the fact that the emission was prolonged and the wind field changed drastically.

It must finally be mentioned that, in addition to the pessimistic assumption that the distance reached is equal to the wind trajectory, other conservative hypothesis have been adopted, such as the absence of ground deposition during the travel-time of the cloud, the adoption of line C in Fig.1 for the relationship between σ_y and travel-time and, in calculating the cloud dosage, the hypothesis that time t remains constant during the passage over point x in question.

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