# Aerosol behaviour traced by artificial and natural radioactivity

By PER B. STOREBØ, *Norwegian Defence Research Establishment, Kjeller, Norway*

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ABSTRACT

Simultaneous daily samples of nuclear bomb debris have been statistically analysed based on the assumption that day-to-day variations are due to compression or dilution of a basic population. Monthly normalized standard deviations are presented from October 1956 to December 1964. Sorting of results into dry and rainy weather collections suggests that the "quantums" of radioactivity of individual particles are greatest when the bomb debris is collected in rain, indicating that most of the collection in rain is due to the larger particles acting as condensation nuclei.

Natural aerosols have a similar size range. This suggests a variation of life-time with aerosol size. Some aspects are illustrated by computation of apparent life-time of gross aerosols, when two groups are in steady state with respect to radon daughters. Apparent life-time is shorter for the RaB/RaD than for the RaD/RaF ratio. Published measurements are discussed.

## 1. Introduction

It is always difficult to trace a phenomenon for which no natural tracer exists. Natural radioactivity has been used for investigating certain aspects of pollution in the air or aerosols. But it is certainly not a suitable tracer, because it distributes itself in a skew manner among aerosol particles.

Nuclear bomb debris may also to a certain degree be accepted as a tracer for aerosols, because many particle characteristics are similar. In this paper it is sought to bring to light some aspects of aerosol behaviour through conclusions based on measurements and computations regarding both natural and artificial radioactivity.

## 2. Nuclear bomb debris

Since the latter part of 1956 measurement of the deposition of nuclear bomb debris at Kjeller has been carried out on multiple daily samples. From October 1956 to June 1957 three daily samples were taken, after which period the number was reduced to two. Regardless of the weather the sampling pots have been washed and scraped each day, and the wet samples were dried and transferred to counting planchets. Total beta radiation was measured two days after end of the sampling.

The procedure offers some possibility for examining the sampling accuracy by statistical means, and thereby to bring out some information about the debris itself. A casual inspection of the records shows that although sample means vary widely from day to day, the individual samples generally follow the same trend. It is therefore considered unsatisfactory to assume that all samples within a certain period are drawn from one population. However, two or three daily samples are insufficient for reliable estimates of the accuracy involved, and measurements over an extended period, say 1 month, have to be pooled.

In order to carry through a calculation, the following working hypothesis was adopted:

> It was assumed that for the whole pooling period the same basic normal distribution existed in the atmosphere, a distribution where unit samples would give a mean $m$ with variance $\sigma^2$. For any particular day this basic distribution was assumed diluted or compressed, so that unit samples would give a mean $b \cdot m$ with a variance $b \cdot \sigma^2$.

In this hypothesis the basic distribution is an idealized feature and $m$ may be regarded as a normalization parameter. Two simultaneous daily samples are therefore just sufficient for an estimate of $\sigma^2$.

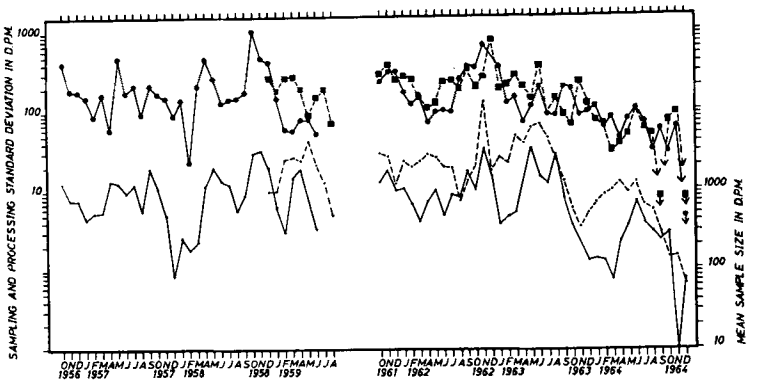


FIG. 1. Sampling and processing standard deviation. Monthly means for sampling and processing standard deviation for Norwegian nuclear debris samples, normalized to a sample size of 1000 dpm. Circles indicate deposition samples, squares air concentration samples. Symbols with arrow pointing downwards indicate computed zero standard deviations. The lower set of curves shows the mean size of the samples upon which the computation was based.

The idea leading to the hypothesis was that the source for all particles in the samples had to be previous explosions. If the debris was spread all over the northern hemisphere, more or less the same type of particles must be present everywhere. However, the amount of particles collected might be much determined by the physical conditions of the air mass passing over the area. Precipitation would carry down more particles than dry weather, and air which for a long time had been close to the surface and filtered through vegetation or purified by precipitation would have a low debris content, while air which had recently come from above would have a high debris content.

There are some obvious weaknesses in the hypothesis. The purification processes may be selective and depend on particle size or inertia, thereby changing the population. Further, fresh debris with an uneven hemispherical distribution may be present, causing a population change simultaneously with a concentration change. And radioactive decay will systematically shift the amount of radioactivity associated with a certain particle during the pooling period, thereby causing a systematic population change. These objections should be kept in mind when the results are discussed.

Based on the presented working hypothesis formulae for computation have been worked out (STOREBØ, 1965). They will not be presented here, but it should be mentioned that they incorporate standardization factors for the individual samples, counting efficiencies, counting variance and small-sample correction. It is, however, not possible to take into account the influence of sample processing, because it varies in the same way as the sampling itself. The final determination of $\sigma^2$ involves a subtraction of the counting variance from the total variance. It is thus possible to arrive at the absurd result of a negative number. When this happened as a result of the monthly pooling, the result was corrected to zero.

Computed results of the combined sampling and processing standard deviation normalized to a nominal sample size of 1000 dpm are shown in Fig. 1 on a monthly basis for the periods October 1956 to June 1959 and October 1961 to December 1964, together with mean sizes of the samples upon which the computations were based. If the processing variance could be considered negligible, the normalized sampling standard deviation $\sigma_{1000}$ should have the character of a parameter for the distribution from which the samples were taken, i.e. it should not be influenced by the way of sampling. Other samples from the same distribution with mean $M$ dpm should therefore have a sampling standard deviation $S$ determined by

$$S^2 = \sigma_{1000}^2 \cdot M/1000.$$

Together with Fig. 1 this formula may be used for estimating sampling confidence intervals for atmospheric bomb debris samples for which

these intervals have not been determined otherwise.

Simultaneous measurements of air concentration may be handled by the same formulae. No extensive duplex measurements of air concentration of nuclear bomb debris have been carried out in Norway. But from December 1958 comparable measurements were made at Gardermoen and Kjeller, two stations about 15 km apart. Filters at Kjeller have generally been changed 2.5 hours later than those at Gardermoen, and the mean concentration values are slightly different when measured three days after the end of the sampling period.

During the computation the Kjeller measurements were first "standardized" by bringing the monthly mean value to the same level as Gardermoen. This procedure may eliminate part of the climatological difference, but it must be clear that a higher standard variation is to be expected than for simultaneous sampling at the same place. On the other hand, compared to deposition measurements the processing variance should be less, because the filters themselves are measured without notable processing taking place.

The computed results of the normalized standard deviation for the air filters Kjeller/Gardermoen are also entered on Fig. 1, together with mean sizes of these measurements. It appears that the two sets of results are of the same magnitude, and this gives some credence to the validity of the working hypothesis. It is also reassuring that seasonal variations in deposition do not appear to influence the normalized sampling accuracy.

The mean trends in the time variation may best be studied by comparing with the change expected due to normal radioactive decay. In order to do this the concept of "radioactivity quantum index" will be introduced:

Assume for the moment that the air mass sampled contains a number $r$ of identical particles each associated with a radioactivity amount $q$, and that there is a probability $p$ for picking a given particle during the sampling period. Standard samples would then show a mean radioactivity $b \cdot m = q \cdot r \cdot p$ with a variance $b \cdot \sigma^2 = q^2 \cdot r \cdot p(1-p)$. In general $p$ will be small and $q$ is given as

$$q \approx \frac{\sigma^2}{m}.$$

Such a simple treatment is not sufficient when a range of different particles is present in the air. Nevertheless, it is plausible that the expression for $q$ may be used as a measure for the radioactivity associated with a "typical" particle, and it will be called "radioactivity quantum index".

Close to the date of the test producing the nuclear debris, radioactive decay will introduce a systematic error in the calculation of $q$. When the date is known, a correction can be made, which usually will affect only the 2–3 first pooling periods after the test.

The bomb-test calendar will usually not give univocal answers to the question about the production dates. However, 4 periods have been selected for which a date may be fixed after which one may be reasonably sure that no debris has been produced, and the corrected results based on ground deposition are presented in Fig. 2 together with background lines showing normal decay lines for the radioactivity.

The first period is the late spring and summer of 1957, using the last explosion of 16 April in the Soviet test series as the production date. The period is somewhat questionable, because British tests were performed just south of the equator in May and June, and smaller American tests in Nevada the whole summer.

The second period is winter and spring of 1958–59, during the test moratorium, where production date was set to the last big shot on 25 October 1958.

The third period is winter and spring of 1961–62 where production date was set to the last big shot in the test series on 4 November 1961. During this period Sovietic and American underground tests only took place.

The fourth period is 1963 and 1964, the beginning of the atmospheric test ban. Production date was set to 25 December 1962. However, the few big shots occurring at that time were well removed from the bulk of the big shots earlier in the test series. On the diagram is therefore also indicated the trend if production occurred two months earlier, at the end of the main insertion of debris into the atmosphere.

For this fourth period the radioactivity quantum indices based on the air concentration samples are plotted in the diagram. For the other periods the winters were dominated by cold and calm weather, so that air concentration

measurements were probably much influenced by local climate.

Fig. 2 indicates that the radioactivity quantum index decreases in about the same degree as would be the case for the radioactivity associated with one particular particle. There may be a tendency to be seen towards a more rapid decrease in the index than in the radioactive decay. A more realistic production date, for instance selected in the middle of the pertinent test series, would emphasize this tendency.

SISEFSKY (1961) has shown that there is a strong proportional relationship between particle mass and its associated radioactivity. It might therefore be permissible to interpret the radioactivity quantum index in terms of particle size. Fig. 2 would then indicate that the size of a "typical" particle is either constant or decreasing with time after the production. The implication of a decrease would be a more rapid deposition on the ground of the largest than of the smallest particles. This is a rather natural effect, and its appearance in the results supports the feeling of applicability of the working hypothesis to the problem at hand.

The deposition and air concentration data show some fine-structure when they are sorted according to precipitation conditions. During computation sorting into two groups took place. The first group contained those days when no precipitation occurred; for the air concentration measurements this condition had to be fulfilled both at Kjeller and at Gardermoen. The second group contained days with more than 1 mm precipitation, for air concentration at both stations. Each group was processed completely independently of other groups or of the unsorted material.

For the precipitation samples a problem of standardization arose: The normal size of the samples might be regarded as either proportional to the area of the sampling pot or proportional to the amount of precipitation collected. From theoretical considerations it is not easy to choose between these two possibilities, and the right solution is probably in between. During the computation all measurements with precipitation were standardized according to both hypotheses and the mean value used. However, the resulting difference was usually small, and any of the values might have been used.

In Fig. 3 is shown the normalized standard

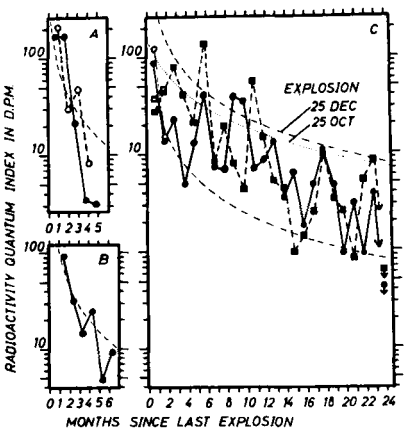


FIG. 2. The variation of radioactivity quantum indices after test series. In part A open circles show the deposition indices for the months May–August 1957 based on a production date 16 April 1957, while filled circles show the deposition indices for the months November 1958 to March 1959 based on a production date 25 October 1958. Part B shows the deposition indices for the months December 1961 to May 1962 based on a production date 4 November 1961. In part C filled circles show the deposition indices and filled squares show the air concentration indices for the months January 1963 to December 1964 based on a production date 25 December 1962, while open symbols for January and February 1963 indicate necessary corrections on the diagram if the production date was set to 25 October 1962. Broken and dotted curves indicate normal radioactive decay after production.

deviation for the two groups. The general trend is that the highest values for the deposition measurements are those associated with precipitation, and the difference is too large to be ascribed to the influence of sample processing. The most plausible explanation is that the radioactivity quanta, and therefore also the particles, collected in rain are larger than those collected in dry weather.

This should lead to the opposite effect for the air concentration samples: when the largest particles are removed, the smallest ones are left. The air concentration measurements do indeed corroborate this conclusions, but the result can only be regarded as non-contradictory evidence. Dry weather is often associated with stable weather situations, favouring local influences on most parameters, and thus causing a high variability between the stations for this reason only; while precipitation usually is associated with more stormy weather, causing a well-mixed, unified atmosphere. When obser-

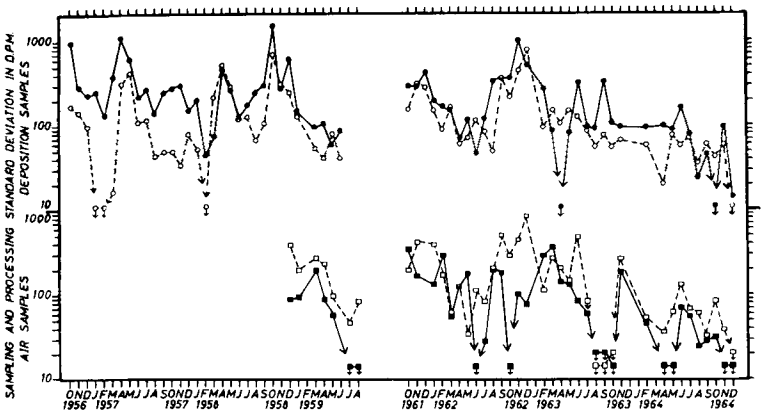


FIG. 3. Sampling and processing standard deviation sorted according to the weather during sampling. Circles refer to deposition samples, squares refer to air concentration samples. Filled symbols refer to at least 1 mm precipitation during sampling period, open symbols refer to no precipitation. Symbols with arrow pointing downwards indicate computed zero standard deviation.

vations from two stations are sorted according to precipitation conditions, the observed effect is apt to be produced due to the weather influence.

The reason for a selective collection of the bomb debris particles must be sought in the physics of the deposition process. In rain three classes of collection are possible, namely inertia governed collection, diffusion governed collection and collection of particles when they act as condensation nuclei. Collection by the first two processes has been studied by GREENFIELD (1957) for particles up to 10 $\mu$ diameter. The general result is of the type shown in Fig. 4. In the upper size range the collection efficiency drops off with decreasing particle size, determined by inertia collection. A broad minimum is found in the size range from about 1 $\mu$ radius down to about 0.05 $\mu$, and below this the efficiency increases with decreasing size due to diffusion collection. The latter collection mostly

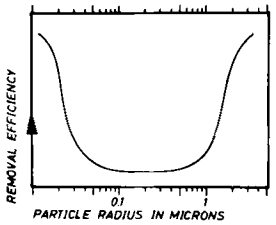


FIG. 4. Removal efficiency of particles in air by diffusional and inertial processes (in outline).

occurs on cloud droplets, and it is uncertain to what degree it will remove particles from the air, because many cloud droplets evaporate without taking part in precipitation.

Collection of particles due to their action as condensation nuclei for the water vapour should also be evaluated. This is an effect which would generally increase in efficiency with the particle size, at least with the amount of hygroscopic material associated with the particle, and the process is probably able to partly fill out the broad minimum produced by the other processes in the collection efficiency.

For dry deposition on the ground the collection occurs only by diffusional and inertial processes. The position of the efficiency line in Fig. 4 may be somewhat different from that of rain, because it depends on parameters determined by the collecting surface and the velocity and turbulence in the air current carrying the particles, the range of variability of which is much greater than in rain. However, the all-important parameter is still the particle size, and even with some shifts an efficiency minimum between some 0.05 and 0.5 $\mu$ radius should remain.

The natural place to search for an explanation for the difference between collections in rain and in dry weather will be in the condensation nuclei collection. The observed larger particles in precipitation samples must then indicate that a substantial part of the radio-

activity is found on particles in the size region for which dry collection efficiency is low, and further that the condensation nucleus process must be a very important collection process in precipitation.

The presented investigation does not give much detailed quantitative information about how the gross collection efficiency varies with particle size in nature. Dry deposition is a continuous process in nature, while deposition in precipitation is a discontinuous process. The mean collection efficiency over a longer period is determined by the integrated effect of all collection processes. A systematic study of the time variation of the nuclear bomb debris size distribution in ground level air after test series might have brought some answer to the problem. The value of the bomb debris would in such a study be due to it being a material for which the distribution parameters would undergo a steady and systematic change. The ground level air concentration of those particles for which the collection efficiency is low, would tend to show high values. Observed deviations from a time-smoothed variation might therefore be used for determining Nature's particle removal efficiencies.

Known measurements made in this field are not detailed enough. They are mostly limited to "typical sizes", and they have a tendency to lie within the interval for which the deposition efficiency is expected to be low.

## 3. Aerosols and natural radioactivity

Natural aerosols cover a size range which comprises the low-collection efficiency interval. However, they are in a sort of steady state with regard to production, transformation and removal. The particle size distribution therefore does not lend itself to a study of Nature's removal efficiency, and the study of normal life cycles or history of aerosols is hampered by this. However, by analogy a cautious transfer of conclusions from nuclear bomb debris to natural aerosols may be made. Due regard must of course be paid to the differences between the two materials, notably the much higher concentrations of natural aerosols and the opposite height gradients of the two particle classes.

From the presented investigation of nuclear bomb debris characteristics one might draw the following conclusions about the behaviour of natural aerosols:

(*a*) The deposition on the ground occurs both in dry weather and in rain, but to a certain degree different selections of the particles are deposited in different weather.

(*b*) The observed size distribution may be determined by production and coagulation, but is certainly also influenced by a removal efficiency varying with size.

(*c*) The average residence time or lifetime of aerosol particles in the atmosphere is dependent on the size.

In many cases it may therefore be a questionable simplification to deal with aerosols as if they were a homogeneous group. Such an assumption has for instance tacitly been made when natural radioactivity has been used for determining the life-time of aerosols.

A complicating factor for such studies is the tendency of the natural radioactivity atoms to associate themselves with the smallest aerosol particles, so that the distribution may be very skew in relation to the aerosol mass distribution. It is in principle the mean atmospheric age of the radioactivity atoms which is measured, and one should be very cautious in drawing the conclusion that this is the same as the age of the aerosol.

It is obvious that a better approximation might be sought with a number of homogeneous aerosol groups. Some fundamental differences between a one-group hypothesis and a multiple-group hypothesis may be illustrated by a model where only two groups are present, one rather short-lived aerosol component and one rather long-lived. Tentatively one may regard the short-lived component as the smallest and the largest particles, while the long-lived component should consist of the middle ones. Coagulation of particles may of course bring in some transfer of particles from one group to another.

Some computations have been made on a model of this kind. It was assumed that two aerosol groups existed in nature and that radon daughter products partitioned themselves between the groups in a fixed ratio. There was further a steady transfer of particles from the short-lived group to the long-lived group, and it was assumed that a steady state existed. The aim of the computation was then to see

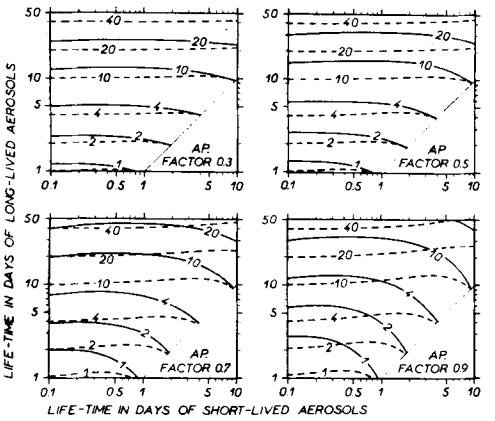


FIG. 5. Apparent age of gross aerosols. Solid curves give apparent age based on RaB/RaD ratio, broken curves based on RaD/RaF ratio. Two homogeneous groups are present, and the apportionment factor shows the fraction of RaA initially collected by the most short-lived group. Degree of transfer from short-lived to long-lived group is 0.2.

what the apparent age of the aerosols would be if interpretation of the resulting RaB/RaD ratio and RaD/RaF ratio were based on the hypothesis of homogeneous aerosols. Details are found in the appendix.

Some of the results are shown in Fig. 5. The degree of transfer from the short-lived to the long-lived group is here 0.2, i.e. 20 per cent of the particles in the short-lived group will end up in the long-lived group, while 80 per cent will be deposited on the ground as short-lived particles. Four apportionments of the radioactivity between the groups are shown: 90, 70, 50 and 30 per cent going directly to the short-lived aerosol group, while the rest is going directly to the long-lived aerosol group.

It appears from Fig. 5 that the apparent age of the aerosols based on the RaB/RaD ratio (i.e. on the ratio between short-lived and long-lived radioactivity) is usually less than the age based on the RaD/RaF ratio. Observations indicate this to be generally true. Published estimates (BLIFFORD *et al.*, 1952; HAXEL & SCHUMANN, 1955; LEHMANN & SITTKUS, 1959) range from 0.8 to 15 days for the RaB/RaD ratio and from 8 to 36 days for the RaD/RaF ratio.

In Fig. 6 is shown how the picture changes with the degree of transfer of particles from the short-lived to the long-lived group. The apportionment factor is here fixed at 70 per cent, and the degree of transfer varies from 0.05 (i.e. 5 per cent only of short-lived particles is transferred) to 1 (i.e. all short-lived particles are transferred). It is seen that even if the magnitude of the effect varies, the general trend is usually recognizable.

The two-group model should not be considered as anything more than a first approximation. It should further be noticed that Figs. 5 and 6 are based on steady state conditions and this will certainly not be the case for long-lived

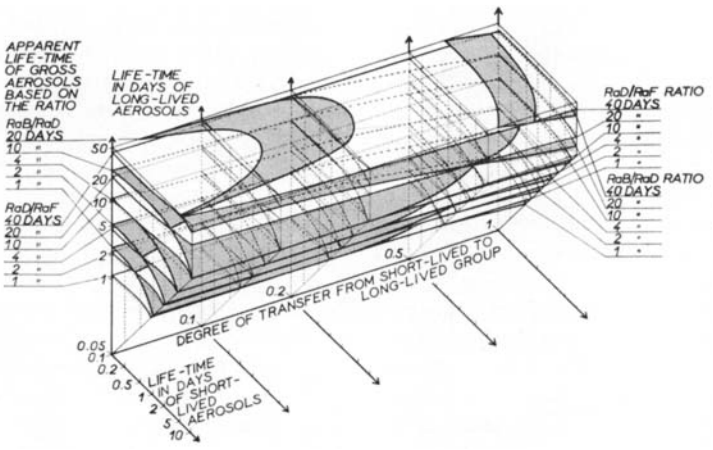


FIG. 6. Apparent age of gross aerosols. Surfaces delineated by solid curves give the apparent age based on RaB/RaD ratio, those delineated by dotted curves give the apparent age based on RaD/RaF ratio. Two homogeneous groups are present, and the short-lived group initially collects 0.7 of the RaA atoms. The degree of transfer from short-lived to long-lived group is varied.

aerosol components in an air mass crossing oceans and land areas, passing through heavily polluted big-city areas or the cleaner rural districts. It is to be expected that many parameters describing the aerosol composition vary from one place to another, and that a build-up phase or a fall-away phase is what is usually measured. It is only for certain characteristic changes that a clear apprehension of the effect can be obtained.

The aerosol content over the oceans is very much less than over the continent, and so is also the radon production. Where air from the oceans enters continents, one would expect a build-up phase, and short-lived aerosol components would be closer to a steady state condition than long-lived ones. Measurements might therefore tend to indicate a relatively low age of the aerosols. Such conditions may be found at Kodiak, Alaska, where BLIFFORD *et al.* (1952) measured 2.3 days based on the Ra(B + C)/RaD ratio, and in Germany, where 1.5 days was measured in Freiburg (LEHMANN & SITTKUS, 1959) and less than 6 days in Heidelberg (HAXEL & SCHUMANN, 1955).

Where air leaves large continents or has been staying over the continents for a long time, the longer-lived aerosol components also might be closer to a steady state condition, and a higher aerosol age might be indicated by measurements. Such conditions might be found at Washington, D.C., where Blifford *et al.* measured 15 days, and in French Morocco, where they measured 10.5 days.

The highest aerosol ages are expected to be found on ships or very small islands in the ocean, where only negligible local production of aerosols occurs. The measurements known to the author are too few, however, to constitute a real test of the hypothesis of different aerosol groups. It would certainly be interesting if an investigation of the geographical variability could be undertaken.

Aerosol samples made by filtering air will usually be representative for the aerosol composition in the air. Aerosol samples extracted from rain water may be more selective, because a variation in collection efficiency with size is at work during the collection. It will be in conciliation with the multiple group hypothesis that rain is a principal removal agent for long-lived aerosols, so that rain samples should be enriched in long-lived components of aerosols. And it is interesting to note that rain samples usually indicate a higher age than the air samples. LEHMANN & SITTKUS (1959) obtained a mean age of 14 days based on the RaD/RaF ratio for air filter samples, while an age of 33 days was found for precipitation samples.

## 4. Conclusion

Aerosol behaviour is a complex field, and the application of one or two tracers will throw light over only limited parts. Studies of artificial and natural radioactivity tend to show that apprehension of the aerosol population as a mixture of several homogeneous groups, each with a characteristic life history, might serve as a useful approximation for some problems. Most measurements of natural radioactivity seem to fit into a coherent picture of this kind.

It is the opinion of the author that much more information could be obtained from systematic measurements of ratios of natural radioactive isotopes. Such measurements could be either of a mean or climatic type or of a short-period or "synoptic" type; both of these fields are at present short of observations.

## APPENDIX

It is assumed that the gross aerosols are composed of one short-lived group with mean life-time $1/\lambda_S$ and one long-lived group with mean life-time $1/\lambda_L$. If the rate of production of RaA-atoms is $R$ and the fraction of these atoms associating themselves with the short-lived aerosol group is $K$ (apportionment factor), the equations describing the radioactivity conditions of the short-lived group under steady state conditions will be

$$R \cdot K = (\lambda_A + \lambda_S) N_A, \tag{1}$$

$$\lambda_i \cdot N_i = (\lambda_{i+1} + \lambda_S) N_{i+1}. \tag{2}$$

$\lambda_A$ and $N_A$ are here radioactive decay constant and number of atoms present of RaA, while $\lambda_i$ and $N_i$ are corresponding quantities for the $i$th daughter element.

It is now further assumed that part of the short-lived aerosol group may be transferred to the long-lived group. In the formulae this can be achieved by setting

$$\lambda_S = \lambda_Q + \lambda_T, \tag{3}$$

where $\lambda_Q$ is a constant fixing the removal of aerosols from the atmosphere, and $\lambda_T$ is a constant fixing the transfer of particles to the long-lived aerosol group. The degree of transfer is expressed through the ratio $\lambda_T/\lambda_S$.

The equations describing the radioactivity conditions of the long-lived aerosol group under steady state conditions will now be

$$R(1-K)+\lambda_T \cdot N_A = (\lambda_A+\lambda_L)M_A, \quad (4)$$

$$\lambda_i \cdot M_i + \lambda_T \cdot N_{i+1} = (\lambda_{i+1}+\lambda_L)M_{i+1}, \quad (5)$$

where $M_A$ and $M_i$ are number of atoms present of RaA and of the $i$th daughter element respectively.

For computation of the apparant age of gross aerosols $1/\lambda$ based on the RaB/RaD ratio, it is assumed that radioactive equilibrium exists among the short-lived products and that $\lambda_D < \lambda$, so that apparant age can be determined by

$$\lambda_B(N_B+M_B) = \lambda(N_D+M_D). \quad (6)$$

For computations based on the RaD/RaF ratio the same assumption cannot be applied, and double application of an equation similar to (2) leads to

$$\lambda_E \cdot \lambda_D(N_D+M_D) = (\lambda_F+\lambda)(\lambda_E+\lambda)(N_F+M_F) \quad (7)$$

as the equation from which apparant age may be found.

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## ПОВЕДЕНИЕ АЭРОЗОЛЕЙ, ПРОСЛЕЖИВАЕМОЕ С ПОМОЩЬЮ ИСКУССТВЕННОЙ И ЕСТЕСТВЕННОЙ РАДИОАКТИВНОСТИ


Проведен статистический анализ одновременных проб радиоактивных остатков ядерных бомб в предположении, что ежедневные вариации обусловлены сжатием и расширением основной массы остатков. Представлены месячные нормированные стандартные отклонения с октября 1956 года по декабрь 1964 года. Сравнение результатов, соответствующих сухой и дождливой погоде, наводит на мысль, что «кванты» радиоактивности индивидуальных частиц наибольшие для радиоактивных остатков взрыва при дождливой погоде, указывая тем самым, что при этом большие частицы действуют как центры конденсации. Естественные аэрозоли имеют аналогичные размеры. Это предполагает связь между временем жизни аэрозоля и его размером. Некоторые аспекты иллюстрированы вычислением кажущегося времени жизни крупных аэрозолей, когда две группы находятся в установившемся состоянии по отношению к продуктам распада радона. Кажущееся время жизни короче для RaB/RaD, чем для RaD/RaF. Обсуждаются опубликованные измерения.