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Meteorological aspects of air pollution pertinent to establishing urban air quality standards*

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ABSTRACT. This paper summarises the results of some of the diffusion studies carried at Trombay with argon-41 from CIRUS stack as tracer. The downwind concentrations as observed over time intervals varying from a few minutes to several weeks have been studied as a function of meteorological variables. The implications of these considerations in urban air pollution surveys and the importance of correctly estimating the short-term concentrations of effluent toxic gases from industries are then discussed.

1. Introduction

With the growing concern about atmospheric pollution, various organisations and agencies are now embarking on air pollution monitoring programmes. The measurements in course of these programmes are however not always made with the use of same averaging period so that it becomes at times, difficult to compare the results of various air pollution surveys. Similarly the effects of various air pollutants are also expressed in terms of a wide range of averaging times. A study of variation of concentration of pollutant with averaging time would permit a direct comparison of various air quality standards when they are transformed to equivalent concentrations for a common-time period. Once some relationships between actually observed long term concentrations and shorter term concentrations have been established at a site, some of the expensive and laborious short term measuring techniques can be replaced by less expensive long term methods, *e.g.*, lead peroxide candles for SO_2 and thermoluminescent dosimeter for radioactivity etc.

In this paper the effect of variation of concentration with sampling period has been studied in case of isolated point source utilising data collected during diffusion studies at Trombay, carried out with the use of argon-41 as tracer. Similar considerations have been extended to data analysed in case of multiple sources of conventional chemical pollutants by McGuire and Noll (1971) at 17 air quality monitoring stations in United States. The relationships between sampling periods and concentrations established during above two studies have been compared. The utility of these types of studies in areas of air quality criteria and standards development has been discussed.

2. Short-term diffusion at Trombay as studied with the use of argon-41 as tracer

In last few years an increasing volume of experimental results has been published with regard to the mean concentration or dosages that can be expected from effluent release from isolated point sources. But data concerning the time history of concentrations from such sources has only recently started appearing in literature. It is possible to study the concentrations as related to the averaging period only in cases where continuous time history is available. In nuclear installations where any of the operating reactors releases argon-41 produced by activation of natural argon present in the air during its passage through the reactor structure, the A^{41} can be used as a real time tracer for meteorological studies. A study of variation of concentration with sampling period is then possible with use of this tracer.

(a) *Experimental details*

The CIRUS reactor at Trombay releases through its 120 m stack, 640 Ci of A^{41} per day (Soman and Abraham 1965). Downwind measurements of concentrations of A^{41} have been made (Sachdev and Nadgir 1969) at Apsara meteorological station with a measuring system developed at Trombay (Sachdev *et al.* 1966). The Apsara meteorological station is at an elevation of about 38m m. s.l. on the western edge of a valley formed by bifurcation of the Trombay hill, the valley being open to the sea in the south. The location of this meteorological station along with the CIRUS stack is shown in Fig. 1. To the northeast of the station the elevation increases to about 183 m, the distance between this level and the station being about 1220 m. The wind instruments consisting

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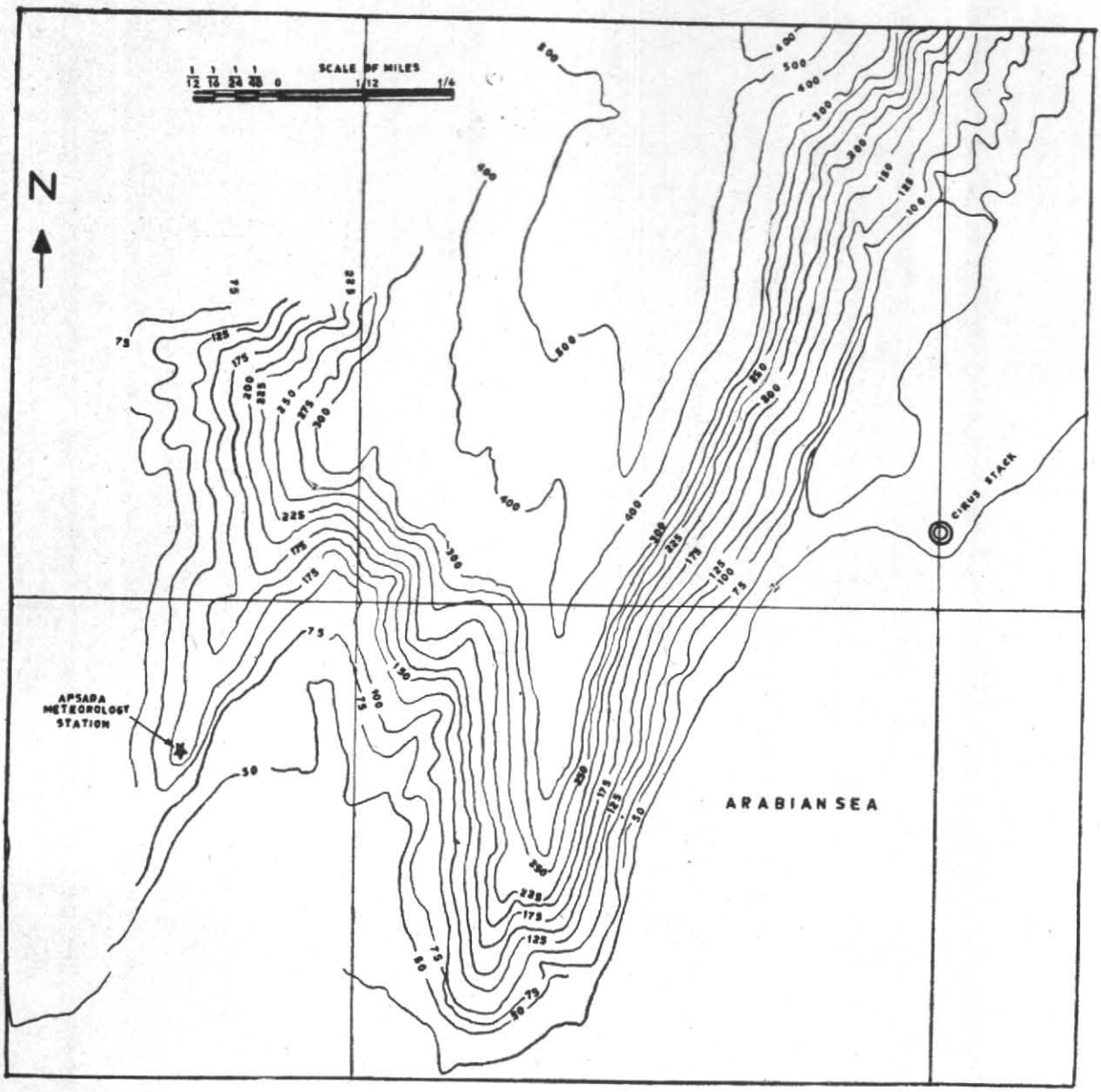

Fig. 1. Location of Apsara Meteorological Station and CIRUS stack at Trombay

of a standard deviation computer, a photoelectric anemometer and a potentiometric wind vane were mounted on a 2.4 m mast on the flat roof of the meteorological station.

(b) Correlation of observed concentration with meteorological predictors

Fig. 2 shows some of the typic races of the record of argon-41 concentrations o◦a ined at Apsara monitoring station during period of steady ENE winds. Since the Apsara meteorologicalstation is exactly downwind from the CIRUS stack for ENE winds only it was important that those periods of record of A^{41} concentration obtained at Apsara having steady ENE winds only without indication of meandering be selected for analysis.

From the results of various field experiments at Trombay and elsewhere it apears that the standard deviation of horizontal wind direction fluctuations $\sigma\theta$ can be very effectively used to construct a set of diagrams for summarising experimental diffusion data (Slade 1965, 1968; Sachdev and Nadgir 1969). Such diagrams are useful for estimating diffusion directly from meteorological measurements. In the above experiments $\sigma\theta$ was used as an index of disperison. A standard deviation computer (θ-N system) developed at Trombay (Sachdev and Rawlani 1968) was used for recording the $\sigma\theta$ values.

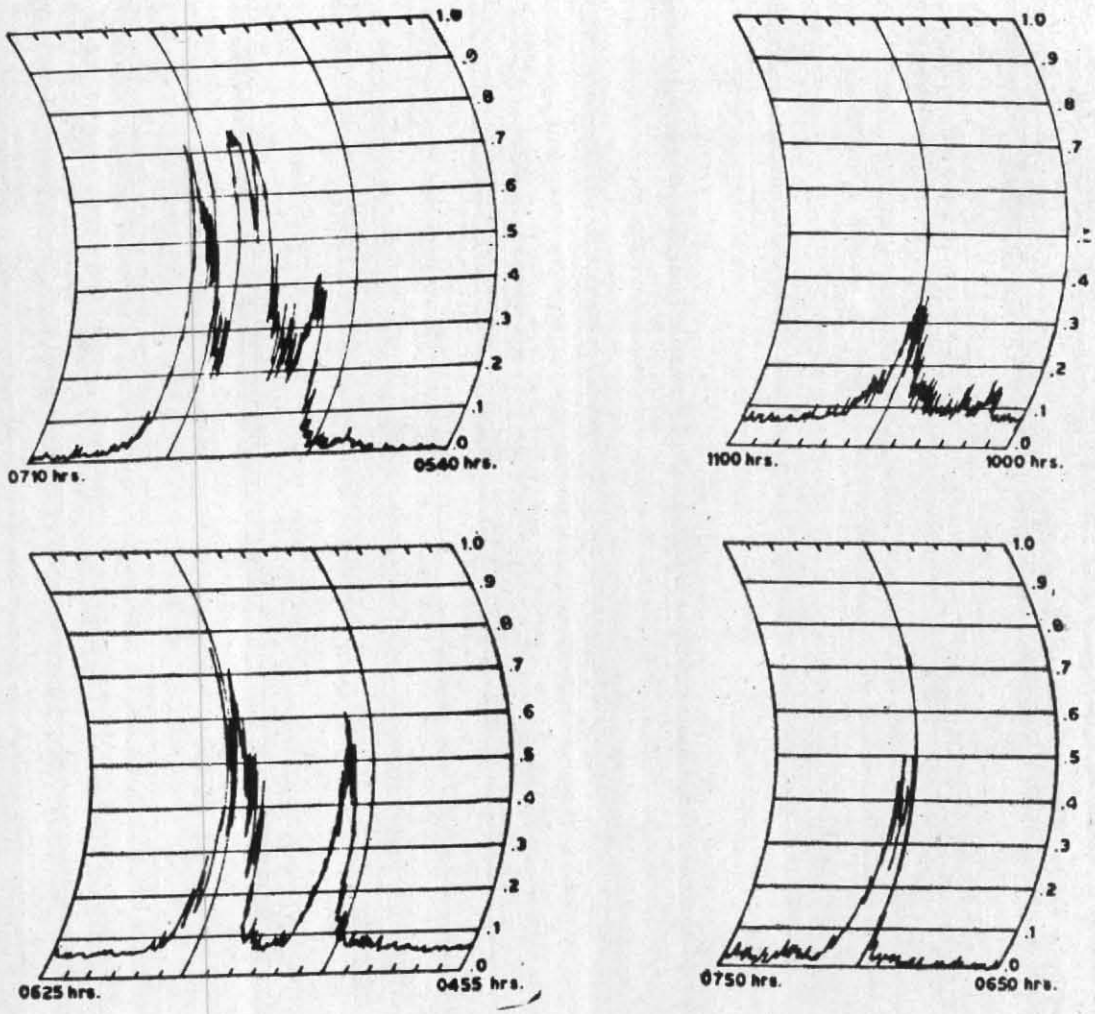

Fig. 2

Typical graphic records of the concentration of A^{41} from CIRUS stack, as recorded at Apsara Met. Station Chart speed : 3"per hr. Full scale vertical deflection : 600 counts per min.

For studies of the variation of concentration with sampling time countrates over successive $2\frac{1}{2}$ min. intervals during the period of record were read from the chart. These were combined in groups to give the mean counting rates over periods varying from 5 min. to entire duration of the 'run'. The ratios of concentrations over different sampling periods were then plotted as a function of the ratio of sampling periods. The duration of the 'runs' among the cases studied varied from 10-40 min. A straight line could be fitted to the points obtained by plotting the ratio of concentrations over different sampling periods *vs* the ratio of sampling periods in case of each individual 'run'. The straight lines obtained from all runs fall into three distinct categories according to observed range of σ_θ (as sampled over 10 min) during the course of the run. Fig. 3 shows the mean value of the ratio of mean/peak concentration in each category *vs* the ratio of sampling periods. The greatest variation in the ratio of concentrations being in the most unstable case ($\sigma_\theta = 9$–$15°$) where large portions of the plume can be brought down rapidly to the ground level; the least variation in ratio occurs in the case where fluctuations are smallest.

Singer *et al.* (1963) hypothesised a power law connecting variance of concentration with smoothing interval. Their paper also summarised the observations of several other workers on mean-to-peak concentration ratios. This data as well as from Cramer *et al.* (1964) appears to be adequately described by the equation:

$$\chi(T) = \chi(\tau)\,(\tau/T)^b \qquad (1)$$

where $\chi(T)$ is the average concentration over the sampling interval T, $\chi(\tau)$ some arbitrary reference value of average concentration over time τ (assumed to be 2.5 min. in this case), and b is some cons-

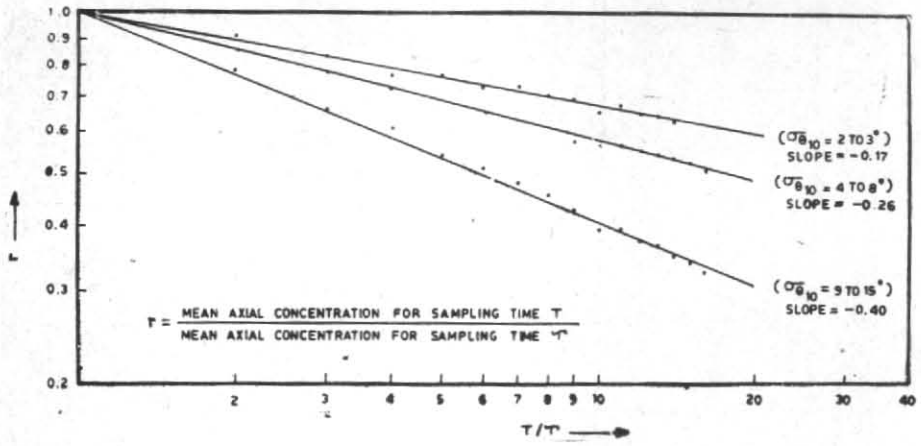

Fig. 3

Variation of mean to peak concentration with sampling time, as a function of standard deviation of horizontal wind direction fluctations

tant. This equation easily follows from the hypothesis of power law. Since the factor b is a function of the turbulent state of the atmosphere it could be expected to vary with surface roughness wind speed, stability and height above the ground. The variation in wind speed among the cases studied at Trombay has been small. With other variables ramaining unchanged the values of b depend on stability.

(c) *Utility of this type of studies in interpretation of urban air quality data*

Curves of Fig. 3 have immense applications in evaluating and interpreting short-term air quality data. These enable one to estimate concentrations over varying time-periods with the knowledge of concentration over a given averaging period. The validity of power relationship in Eq. (1) has been tested at Trombay upto a period of 40 min. as shown in Fig. 3. However, one requires to use such a relationship for periods extending upto a few days. Wippermann (1961) and Meade (1960) have confirmed the validity of Eq. (1) up to a period of 4 days and 1 day respectively. As emphasised by Ramsdell and Hinds (1971), the extension of Eq. (1) to time scales other than those over which the studies have been carried out should be made with caution because this implies assumption of similarity of turbulence over different time scales. Latest techniques of recording the real time history of tracer concentrations permit detailed studies of concentration fluctuations and relationship of the concentration over different time scales. These would help in ascertaining the validity of such extensions.

3. Long term diffusion pattern at Trombay

Over a period of time as the direction of mean wind shifts the effluents from isolated sources are carried away in different directions. The wind rose which gives the joint wind speed and direction frequency distribution is therefore a useful indicator of the characteristics features of the climate of a particular site. To obtain an estimate of average concentration over a period that is very long compared with that over which the mean wind is computed, the cross-wind integrated concentration is used. The long term concentration is obtained by multiplying the cross-wind integrated concentration by the frequency with which the wind flows towards a given sector and divide by the width of that sector at the distance of interest (Slade 1968). The cross-wind integrated concentration in turn is obtained by integrating the Gaussian form of diffusion equation for concentration at ground level from a continuous point source, *i.e.*,

$$\frac{\bar{\chi}}{Q} = \frac{1}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2}\right)\right] \quad (2)$$

where $\bar{\chi}$ is the average concentration from a continuous source of strength Q and height h, $\bar{u}$ the mean wind speed and σ_y, σ_z the standard deviations of plume concentration in y and z directions at distance x from the source. The cross-wind integrated concentration $\bar{\chi}_{CWI}$ from the continuous source equation is obtained by integrating Eq. (2) with respect to y from $-\infty$ to $+\infty$ and is given by

$$\bar{\chi}_{CWI} = \frac{2^{\frac{1}{2}} Q}{\pi^{\frac{1}{2}} \sigma_z \bar{u}} \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \quad (3)$$

The long term average (LTA) concentration can then be written as

$$\chi_{LTA} = \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \frac{0{\cdot}01 f Q}{\sigma_z \bar{u} (2\pi x/16)} \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \quad (4)$$

where the frequency f is expressed in per cent, $2\pi x/16$ is the sector width and Q, σ_z and u

are averages over the long term period. Fig. 4 shows the relative long term concentrations of argon-41 around CIRUS stack at Trombay at a distance of 1.2 km computed with a knowledge of turbulence pattern (Sachdev and Rajan 1971) and wind frequencies observed over the years 1960-63 at Apsara (Shirvaikar *et al.* 1969). The distribution pattern of the type shown in Fig. 5 is a very useful indicator of diffusion climate of any site. It will be seen that normalised concentrations vary very widely depending upon the direction from the source. The terrain modifies the distribution to such an extent that highest concentration occurs for southerly winds and in orders of magnitude is higher than the lowest concentration for SSW winds. For fixing the upper limit of emission rates for industrial effluents in cases of such a terrain it is to be seen that concentrations do not exceed the fixed air quality standards in worst affected sectors.

4. Variation of concentration with sampling time in case of multiple sources of pollution

In this country there is not much systematic data available on long term pollution levels from conventional multiple sources. But quite a few studies of this nature have been reported to be carried out in industrial locations abroad notably so in United States. One such study is by McGuire and Noll (1971). They have studied relationship between maximum concentrations and averaging time for five different air pollutants in 17 California cities. The maximum concentrations for averaging times of one hr, one day, one month and one year were shown to be approximately proportional to averaging time to an exponent. This relationship can be expressed as

$$C_{\max(t)} = C_{\max(h)} \cdot t^{b} \qquad (5)$$

where $C_{\max(h)}$ and $C_{\max(t)}$ are the maximum concentrations for one hour and t hours respectively and b in this case is an exponent which varies with the pollutant and the sampling location. This equation is based on a proposition by Larsen (1969) that for averaging times of one month or less the maximum concentrations are approximately proportional to averaging time to an exponent. This expression gives maximum concentration for various averaging times which differ from the observed maximum concentration by an average of 10 per cent. This equation plots as a straight line on log-log paper with log C_{max} plotted as a function of log t. The intercept at t equal to 1 hr is $C_{max(h)}$ and b is the slope of the line. Fig. 5 shows the maximum concentrations *versus* averaging time for oxidants downtown Los Angeles. The points shown are the maximum concentrations observed during the year for averaging times of one hour, one day and one month and the annual average concentration. The line shown is that best fits these points.

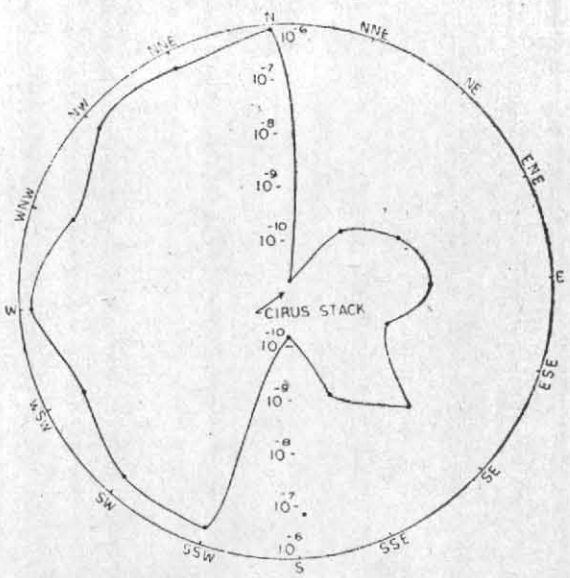

Fig. 4

Long term relative ground level concentrations of argon-41 at a distance of 1·2 km around CIRUS stack at Trombay

As an example of the utility of above types of studies Table 1 illustrates the conversion of typical criteria or standards from one averaging time to equivalent concentrations for differing averaging times. This table shows the effect which variations in b values have on predicted concentrations. Equivalent concentrations are shown for several averaging periods for the following two criteria or standards (1) 20 ppm for an 8-hr average carbon monoxide concentration and (2) 5. 0 pphm for an annual average sulphur dioxide concentration.

5. Discussion and Concluding remarks

It would thus appear that downwind concentration data collected with the use of argon-41 at Trombay and California air quality data both generally conform to the exponential relationship between concentrations and averaging times as given in Eq. (1) and (5) respectively. In most cases these relationships can be used to transform concentrations as averaged over periods upto about an hour and Eq. (5) is sufficiently accurate to predict maximum concentrations for averyging times up to one year.

The conversion mechanism the above two equations afford is particularly valuable in work relating to the establishment of air quality standards. Criteria pertaining to different effects of air pollutants which are expressed in terms of wide range of averaging times can be transformed to

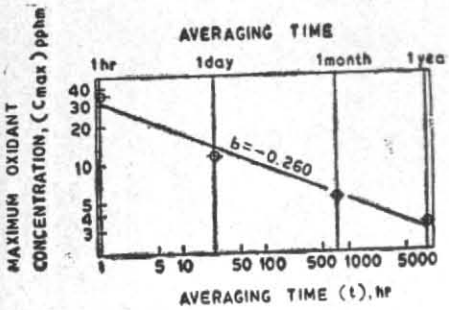

Fig. 5

Max. concentration *vs* averaging time for oxidant, downtown Los Angeles , 1967

(McGuire & Noll 1971)

equivalent concentrations for a common time period and thus permit a direct comparison.

The ability to transform data from one time period to another is very useful for planning and designing air quality monitoring programmes, because short-term concentrations might be predicted on the basis of longer period integrated samples, thus possibly eliminating the need for some continuous recording systems.

TABLE 1

Maximum concentrations expressed for various averaging periods for two pollutants for Basinwide Ranges and averages of *b* based on criteria shown in italics (McGuire and Noll)

	1 hr	8 hr	Day	Month	Year
	Carbon monoxide (ppm)				
—0·068 (Min.)	23·6	*20·0*	19·0	14·4	12·7
—0·139 (Av.)	26·7	*20·0*	17·2	10·7	7·6
—0·158 (Max.)	27·8	*20·0*	16·8	9·8	6·7
	Sulphur dioxide (pphm)				
—0·175 (Min.)	25		14	8	*5·0*
—0·265 (Av.)	56		24	10	*5·0*
—0·369 (Max.)	143		44	13	*5·0*

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