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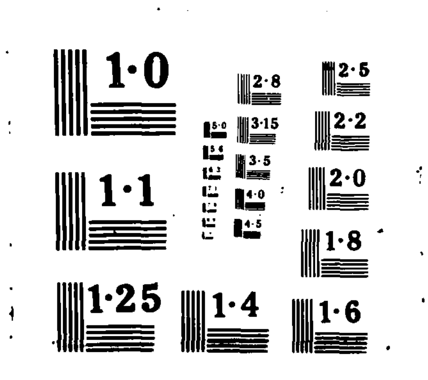
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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

A METHOD OF ESTIMATING THE LONG-TERM AVERAGE CONCENTRATION FROM THE POWER PLANT'S HIGH STACK

by

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FOREIGN TECHNOLOGY DIVISION

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Using Gaussian plume model, Considering affection of terrain, pollutant decay and precipitation scavenging, the formula for estimating the long-term average concentration from the power plant's high stack was proposed in this paper. Because the wind, stability and mixing depth are calculated from routing meteorological data, we can estimate the average concentration without any field observation. It is a significative method on economy and practical use for electing plant location and assessing air quality.

A METHOD OF ESTIMATING THE LONG-TERM AVERAGE CONCENTRATION FROM THE POWER PLANT'S HIGH STACK

Ma Fujian, Wang Yanchang, Pan Yunxian and Zhou Chaofu.

Using the Gaussian plume model, this paper considered the effects of terrain, pollutant decay and precipitation scavenging, and proposed the formula for estimating long-term average ground level concentration for the power plant's high stack. Since parameters such as wind, stability, mixing depth, etc. were calculated from routine meteorological data, the average concentration could be estimated without any field observation. This is a method with significance in practical use and economy for selecting a preconstruction plant site and assessing air quality.

The assessment of air quality and selection of a plant site for a fossil-fueled power plant both require estimating the long-term average concentration. Our country has set coal as the primary fuel for fossil-fueled power plants. Most of them are located near coal mine entrances or in hilly regions, and usually lack pollution meteorological observa-

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tion data. Therefore, how to use routine meteorological data from nearby weather stations to estimate the long-term average concentration distribution caused by emissions from fossil-fueled power plants is an urgent problem waiting for solutions.

Currently, the popular Gaussian plume model discribes the rules of point source diffusion quite successfully. It has a simple form and clear physical concept, and the model estimated values correspond fairly well with the observed values; therefore, it enjoys extensive application. When this model is used to estimate pollutant long-term average concentraiton distribution, meteorological parameters such as wind, stability and mixing depth are required in addition to data in plume rise and diffusion coefficient. Effects of terrain and precipitation scavenging should also be considered for the model. Through numerous experiments and theoretical research, many formulae and figures have been proposed which can be used for selecting proper atmospheric diffusion coefficients and plume rise [1]. Thus, how to use routine ground level meteorological observation data to estimate atmospheric stability and mixing depth has become the key to the application of the model.

This paper proposed a model and method that, with given diffusion coefficient and plume rise, uses the routine ground level meteorological data to estimate the ground level long-term average concentration caused by emissions from a fossil-fueled power plant's high stack, and an example was given. Said method is simple to use and is especially suitable for regions with only ground weather stations. It provides an effective method for the industry to conduct preconstruction site selection and air quality assessment.

I. Establishing The Model

The well-known Gaussian plume model is:

$$C(x, y, O; H) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \exp\left[-\frac{H^2}{2\sigma_z^2}\right] \qquad (1)$$

where σ_y and σ_x are horizontal and vertical diffusion coefficients respectively. H is the effective stack height.

In the atmospheric boundary layer, due to the thermal and dynamic action of its under side, a layer with violent turbulence movement is formed above the ground and is called the atmospheric mixing layer. The portion above the mixing layer is usually of stable structure and will suppress the pollutant's upward diffusion. The high stack of a fossile-fueled power plant can reach 200 meters making the effective stack height reaching hundreds of meters. Therefore, the model should take the suppression and reflection effects of the stable structure above the mixing layer into consideration. The following basic form of the Gaussian point source model is adopted:

$$C(x, y, O; H) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \cdot \sum_{n=-\infty}^{\infty} \exp\left[-\frac{(2nL - H)^2}{2\sigma_z^2}\right] \qquad (2)$$

where L is the mixing depth, n is the number of reflection - (generally select between 3 to 5).

The effects of different meteorological conditions on the model parameters must be considered when deriving the formula for long-term average concentration. The wind direction is divided into fifteen directions and wind velocity into 5 levels. The atmospheric stability is divided into 4 classes. Thus, the formula for long-term average concentration can be described as follows:

$$C(x, y, O:H) = \sum_{k=1}^{16} \sum_{m=1}^{4} \sum_{l=1}^{5} \varphi_{kml} C_{kml}(x, y, O:H) \qquad (3)$$

where

$$C_{kml}(x, y, O:H) = \frac{16}{2\pi}\left(1 - 2.546\frac{|y|}{x}\right) \cdot \frac{Q}{x} \hat{C}_{ml}(x) \left\{ \sum_{n=-\infty}^{\infty} \exp\left[- \frac{\left(2nL_m - H_{ml} + \frac{h_7}{2}\right)^2}{2\sigma_{zm}^2} \right] \right\}$$

$$\cdot \exp\left[-1.925 \times 10^{-4} \frac{x}{Iu} \right] \cdot R$$

and

$$\hat{C}_{ml}(x) = \frac{2}{\sqrt{2\pi u / \sigma_{zm}}}$$

In formula (3):

k: wind direction subscript, k=1 - 16

m: stability classification subscript, m=1 - 4

l: wind velocity level subscript, l=1 - 5

Φ_{kml}: relative frequency at wind velocity of l, stability classification of m and wind direction of k, and:

$$\sum_{k=1}^{16} \sum_{m=1}^{4} \sum_{l=1}^{5} \varphi_{kml} = 1$$

R: precipitation decay factor

$C_{kml}(x, y, O:H)$: ground level concentraiton with wind direction, stability and wind speed at k, m and l, respectively.

C(x, y, O:H): ground level long-term average concentration

In the above formula, if m=4 which indicates stable atmospheric condition, then in Equation (3) n=0.

The formula for long-term average concentration takes the effects of the mixing layer on high stack diffusion into consideration. It also considers effects of the discontinuous modification on the bordering lines between the 16 wind directions, terrain adjustment proposed by Egan for a situation where the plume's effective stack height is greater than the terrain height (h_T), pollutant decay and precipitation scavenging.

For a rough under side, the effects of terrain on the plume's diffusion can simply be included in the effects of terrain on the plume's effective stack height. Egan (1975)[2] proposed to replace H with TeH, where Tc is the terrain modification factor. When $H \geqslant h_T$, $Tc=1-h_T/2H$, thus $TeH=(H-\frac{h_T}{2})$.

L is the half-life of pollution decay (in hours). x/u (x is the downwind distance from the point source, u is average wind speed) is the time required (in seconds) for the pollutant to travel from the source to the receiving point. These express the effects of decay on concentration distribution during the pollutant's transport process [3]. The process of precipitation scavenging is more complicated, and its effects on long-term average concentration can be roughly estimated by adopting the average effects method.

If the effects of discontinuous modification, terrain modification, pollutant decay and precipitation scavenging are not considered, formula (3) can be transformed to the simplest form of long-term average concentration:

$$C(x,0,0:H) = \sum_{k=1}^{16} \sum_{m=1}^{4} \sum_{l=1}^{5} \varphi_{kml}(x,0,0:H) \qquad (4)$$

and

$$C_{kml}(x,0,0:H) = \frac{16}{2\pi} \cdot \frac{2Q}{\sqrt{2\pi}\, x u_l \sigma_{zm}} \sum_{n=-\infty}^{\infty} \exp\left[-\frac{(2nL_m - H_{ml})^2}{2\sigma_{zm}^2}\right]$$

II. Determination Of Parameters

Using formula (3) to estimate long-term average concentration requires values for the following parameters: σ_{xm}, H_{ml}, U_{kml}, L_m, Φ_{kml}, etc. If plume rise and diffusion coefficient are selected from existing research results, then other parameters can be estimated from routine ground meteorological observation data.

The most commonly used method to divide atmospheric stability is the P - T classfication method, yet the cloud height data required by said method are not measured by the ground weather stations of our country. Based on the characteristics of total and low cloud volumes measured by a ground weather station and using the P - T method as a base, the cloud indexes classifying radiation classes are substituted by total and low cloud volumes, and this is called the P - C method [4]. The classification results using this method correspond consistently with those using the P - T method. The P - C method classifications are listed in Table 1 and 2.

Table 1. Radiation Class Classification Table

(1) 云量 (4) 总云量/低云量	(2) 夜间	(3) 太阳高度 $h_\theta \le 15°$	$15° < h_\theta \le 35°$	$35° < h_\theta \le 65°$	$h_\theta < 65°$
≤ 4/< 4	-2	-1	+1	+2	+3
(4-7)/≤ 4	-1	0	+1	+2	+3
≥ 8/≤ 4 (5-7)/(5-7)	-1	0	0	+1	+1
≥ 8/(5-8)	0	0	0	0	+1
≥ 9/≥ 9	0	0	0	0	0

Key: (1) Cloud volume; (2) night; (3) Altitutde angle of the sun; (4) Total cloud volume/Low cloud volume.

Table 2. Atmospheric Stability Classes

(1) 10米高风速(米/秒)	(2) 太阳辐射等级 +3	+2	+1	0	-1	-2
< 2	A	A-B	B	D	E	F
2-2.9	A-B	B	C	D	E	F
3-4.9	B	B-C	C	D	D	E
5-6	C	C-D	D	D	D	D
> 6	C	D	D	D	D	D

Key: (1) wind Speed at a heigh of 10 meter m(m/sec); (2) Sun radiation classes.

Wind velocities U_{kml} and Φ_{kml} under different wind directions and stabilities can be obtained from weather station routine statistical data. Wind velocity at stack height can be derived using index rate.

The formula employing ground routine meteorological data proposed by Nozaki is adopted to estimate atmospheric mixing depth[5]. Nozaki's formula is as follows:

$$L = \frac{121}{6}(6 - P)(T - T_a) + \frac{0.169[U(Z) + 0.25]}{12 f \ln Z/Z_0}$$

where: T and T_a are ground temperature and dewing point, respectively, $U(Z)$ is the average wind velocity at height Z, Z_0 is ground roughness, f is the Clark coefficient and P is the Pasquill stability classification (from $P=1$ for unstable class A to $P=6$ for stable class F). Said formula includes contributions of thermal and dynamic turbulence. The average values of L for neutral to unstable structure are obtained separately to calculated L_m value.

III. Example

In order to evaluate possible pollution to the environment by sulfur dioxide emitted from the 180 meter stack at a power plant which is located downstream of the Yangtze River, the ground level long-term average concentration was estimated using the model. The terrain surrounding the plant is open and flat, and is slightly inclined from northwest to southeast. The one-year routine data from the local weather station are collected and statistics classifications of stability, wind velocity, wind direction and mixing depth are performed four times a day using the aforementioned method to obtain values of parameters U_{kml}, ϕ_{kml} and L_m which are required for the model estimation. Wind velocity is classified into five levels based on local meteorological features and they are listed in Table 3. Table 4 gives the statistical results of the annual ϕ_{kml} values under east wind. The average mixing depths under various stability conditions A, B, C, D are 1,400 meters, 1,200 meters, 900 meters and 650 meters, respectively.

Table 3. Wind Velocity Classification Table

(1) 风速等级	0	1	2	3	4
(2) 风速范围 (m/s)	1.0	1.0 - 2.4	2.5 - 4.4	4.5 - 6.0	6.0
(3) 平均风速 (m/s)	1.0	1.7	3.5	5.3	7.7

Key: (1) Wind velocity class; (2) Wind velocity range; (3) average sind speed.

Table 4. Annual Φ_{mkl} Values (east wind)

(1) 稳定度 / (2) 风速 (m/s) φ_{kml}	A—B	C	D	E—F	Σ
1.0	0.0009	0	0.0011	0.0040	0.0060
1.7	0.0055	0.0034	0.0076	0.0172	0.0337
3.5	0.0048	0.0076	0.0172	0.0083	0.0379
5.3	0	0.0014	0.0103	0.0014	0.0131
7.7	0	0	0.0062	0	0.0062
Σ	0.0112	0.0124	0.0424	0.0309	0.0969

Key: (1) stability; (2) wind velocity.

The plume rise and dispersion parameter used in estimating this example are obtained from environmental wind tunnel and on-site equilibrium balloon tests[4]. The diffusion coefficient adopts an index form:

$$\sigma_z = C_x^d$$

Coefficients C and d are constants related to stability and are shown in Table 5[4]. Briggs formula series are still used to calculate plume rise. Under neutral and unstable conditions, " $\frac{2}{3}$ " power is used and the coefficient is 1.14; under stable conditions, " $\frac{1}{3}$ " power is used and the coefficient is 2.3. They are lower than the 1.6 and 2.9 given by Briggs[6][7].

Table 5. C, d Parameter Values

(1)稳定度 C、d值(2)	A—B	C	D	E—F
C	0.40	0.34	0.29	0.16
d	0.91	0.86	0.80	0.76

Key: (1) Stability; (2) C, d value.

The change in wind velocity with respect to altitutde follows the power rule. The on-site measured results using the bivane small balloon anemometer show that the powers from unstable class A to stable class E - F are 0.10, 0.13, 0.18, 0.25 and 0.35 in that order.

The assessment area is of a small scale due to the consideration of a flat terrain surrounding said plant. Ignoring the effects of terrain, decay and precipitation scavenging, the annual and seasonal average concentration distributions are estimated using formula (3) for said emission source. See Fig. 1. Said figures give the concentration distributions in an area within a radius of 15 kilometer with the emission source as the center. The low value regions of annual average concentration fall in the areas NE - NW and S - SE of the source, and the situations for spring and summer are similar to that of the annual. The low value regions for fall and winter, however, fall in the area NNW - NE of the source. The high concentration value regions are primarily distributed in areas west of the source: both spring and summer lean toward NW, and fall and winter lean toward SW. The annual average high value center is to the NW of the source with a weak high value center located to the east. The distance from the high value center to the source is shorter for spring and summer, about 2 - 3 kilometers; and it is farther for fall and winter, about 7 - 8 kilometers.

The characteristics of the concentration field are closely related to the flow field. Said area has larger annual average wind speeds in the SE and NW directions, and they are more evenly distributed in the rest of the directions. Wind direction is predominately from the east throughout the year with southeastern wind in spring and summer and northeastern wind in fall and winter. See Table 6 for details. Figure 2 gives the roses for annual wind direction, wind velocity and pollution coefficient. From this, it is obvious that the concentration high value center should be west of the source. The atmospheric unstable centers for both spring and summer are closer to the source, and they are the opposite for fall and winter.

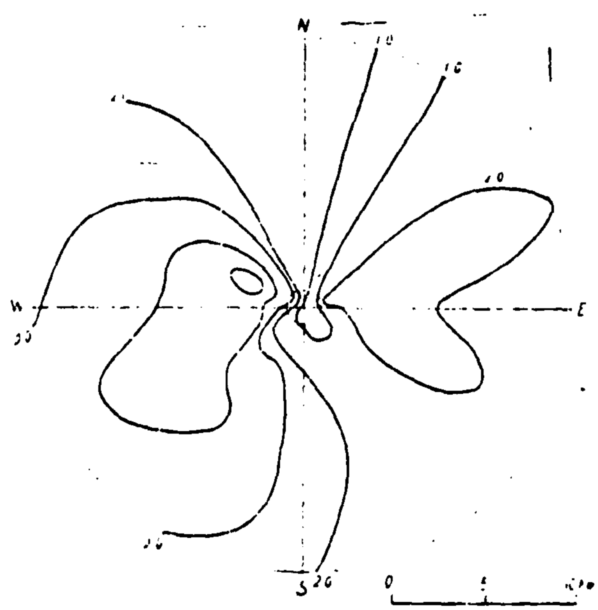


Fig. 1a. Annual average concentration distribution

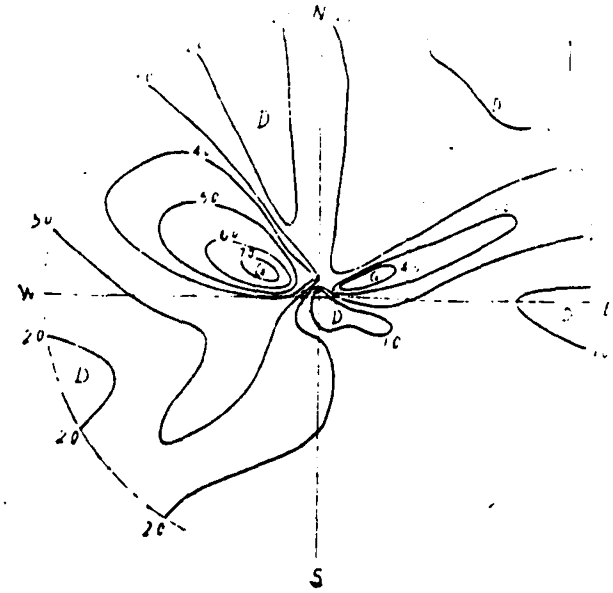


Fig. 1b. Spring average concentration distribution

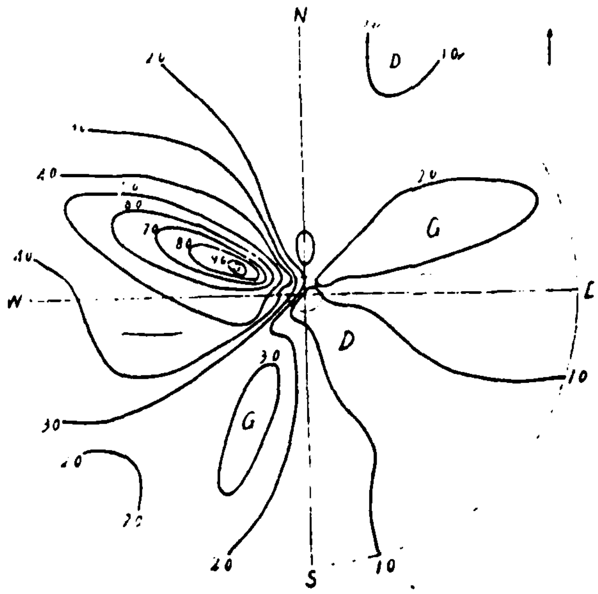


Fig. 1c. Summer average concentration distribution

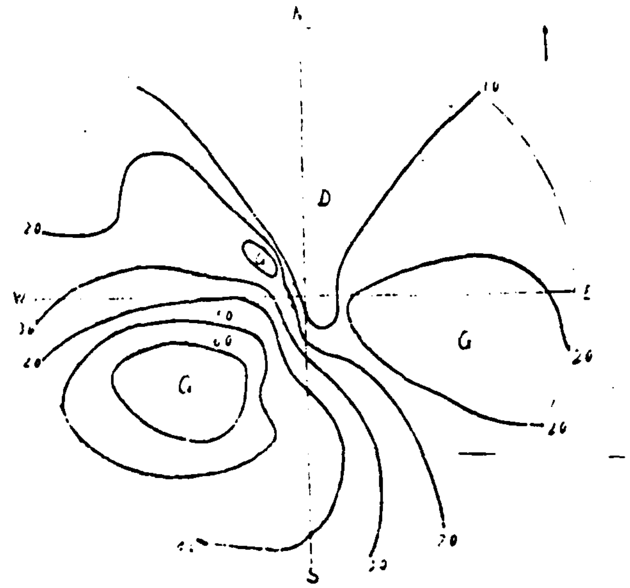


Fig. 1d. Fall average concentration distribution

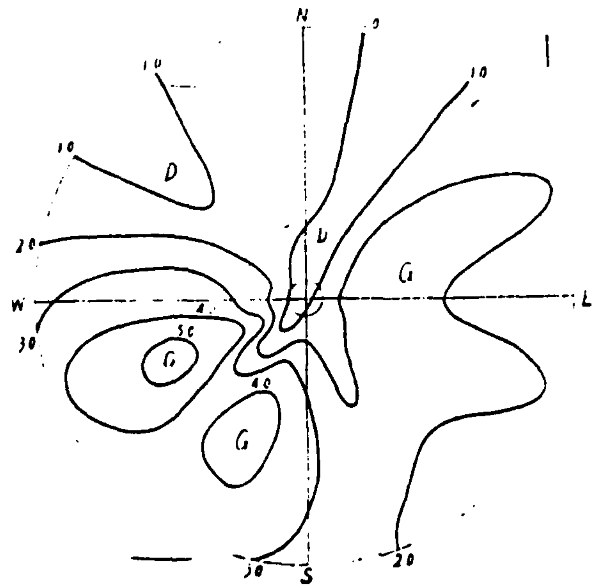
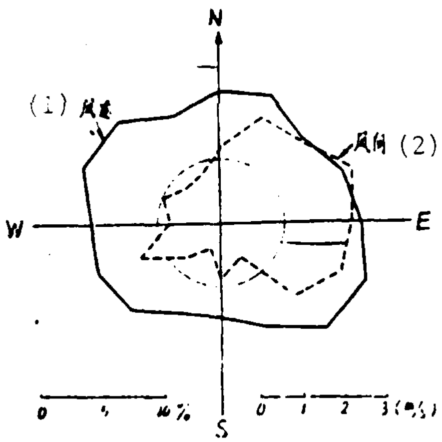


Fig. 1e. Winter average concentration distribution

Table 6. Average Wind Speed and Wind Direction

(1) 季节 / 风向、风速 (7)		春 (2)	夏 (3)	秋 (4)	冬 (5)	年 (6)
(8) 平均风速(米/秒)		3.3	3.1	2.5	3.2	3.0
NE—SE	(9) 所占	49	58	47	39	48
NE—E	百分	24	29	36	31	30
E—SE	频数	33	42	20	18	28

Key: (1) Season; (2) Spring; (3) Summer; (4) Fall; (5) Winter; (6) annual; (7) Wind direction, Wind velocity; (8) average wind velocity (m/sec); (9) percentage of occurrence frequency.



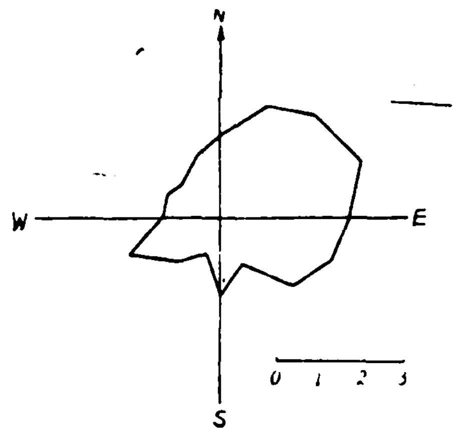


Fig. 2. a. Annual average wind velocity wind direction roses

b. Annual pollution coefficient rose

Key: (1) Wind speed; (2) Wind direction.

Although the relative location of the plant and residential areas can be qualitatively determined from the wind direction and pollution coefficient roses, the distance from the source and distribution range of the residential areas cannot quantitatively be obtained. The model estimation considers the combined effects of pollution meteorological conditions and dispersion parameters, and therefore, is able to give quantitatively the concentration distributions of areas under assessment.

IV. Conclusions

The method of estimating the ground level long-term average concentration from the power plant's high stack emission source proposed by this paper has the following advantages:

1. The physical concepts of the Gaussian plume model are clean. The calculation workload is not heavy so that the capabilities of a microcomputer can be fully exploited Pc—1500

2. It only requires routine meteorological data from ground weather stations to estimate the required pollution meteorological parameters such as wind, stability, mixing depth, etc. thereby conserving the time, man power and material required for field observation.

3. It takes full advantages of the existing research results of diffusion coefficients and plume rise rules. It does not require on-site field experiments of dispersion and plume rise in areas where the terrain conditions are not too complicated.

The analytical results of the example indicate that the annual and seasonal long-term average concentration distributions can be estimated rather conveniently by the model. Based on this, it will be very easy to conduct the plant site selection and determination of reasonable distribution of various facilities.

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