Ministry of Economy, Trade and Industry
Low Rise Industrial Source Dispersion Model
METI-LIS Model Ver. 2.0

Technical Manual

METI-LIS
Version 2.02

(Ministry of Economy, Trade and Industry
- Low rise Industrial Source dispersion MODEL)

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Ministry of Economy, Trade and Industry (METI), Japan

Developed under the cooperation of
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Japan Environmental Management Association for Industry (JEMAI) was entrusted with the administration of the METI’s fund, and organized the METI-LIS development advisory committee*. Nagasaki Research Development Center, Mitsubishi Heavy Industries, Ltd. was entrusted with the wind tunnel experiments for the development of the METI-LIS original version. Suuri-Keikaku Co. Ltd. programmed and developed the software.

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Outline of the METI-LIS Model

A short history of the model

Measures have been taken for many years for environmental control of such air pollutants including sulfur
dioxide and nitrogen oxides mainly emitted from high stacks. In contrast, most HAPs (hazardous air pollutants)
are emitted from relatively low sources, and therefore their dispersion is affected in the first stage by nearby
buildings or other ground-based objects, tending to cause a downward motion called downdraft or downwash.

As a Gaussian dispersion model, which incorporates the downdraft effect, the ISC model authorized by
the US Environmental Protection Agency (EPA) has been widely used. The Ministry of Economy, Trade and
Industry (METI), Japan planned to develop an improved downdraft model based on the ISC model in 1996,
when HAPs were newly taken into the Air Pollution Prevention Act in Japan. A series of wind tunnel and field
experiments* were carried out for the modeling under the funding of the METI, and a pilot version of the model
came out in 2001 as the METI-LIS.

The Research Center for Chemical Risk Management (CRM), AIST contributed to the development of
the METI-LIS from the beginning, and took the initiative in developing the present improved version (Ver.2)
with more reasonable algorithm, additional functions and further user-friendly handling tools. The English
version was developed in parallel.

* Kouchi et al., 2004: Development of a low-rise industrial source dispersion model, Int. J. Environment
and Pollution, 21, 325-338.
Some results of the wind tunnel experiments and outdoor experiments are included in this document.
Further data obtained in a series of tracer dispersion experiments, including the METI-LIS validation
data, are provided from the same internet site where the METI-LIS software can be downloaded.

Characteristics of the model

The METI-LIS puts special importance to expressing the effect of downdraft when building data around
the sources are given, while it gives solutions of simple Gaussian plume and puff formula for elevated sources.

The model was intended for wide use, not only by researchers and educators, but by industries which
release pollutants to make responsible care plans, governmental bodies to guide or instruct industries, and
citizens to join risk communication. For this purpose, the model software was equipped with simple handling
tools and advanced graphic user interface, and was provided for free use.

Essential input data are emission rate and other emission conditions such as location, height, gas volume
and temperature, and meteorological factors at every hour during the averaging period. Users can select an
optional mode of average simulations for either short-term or long-term. For most locations in Japan, the
AMeDAS data supported by the Japan Meteorological Agency (provided in CD every year) are applicable to the
latter case. In the English version, long-term meteorological data file is imported as an external file prepared by
the users.
In addition to dispersion calculation for a gaseous or particulate matter from point sources, simple treatment of line sources of a gaseous matter is possible.

**Download and start up**

The METI-LIS software and its user’s manuals (Technical manual and Operation manual) can be freely downloaded from the internet site (http://www.riskcenter.jp/metilis/, or from the CRM homepage→ “Exposure Assessment Models”).
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1. Meteorological Data Requirements

1.1 Required Meteorological Data and Input Methods

The task of dispersion models is to calculate how pollutant concentrations are distributed as a result of dispersion. Dispersion conditions are governed by meteorological conditions. Therefore, meteorological data are essential input items for dispersion models as well as the volume of emitted pollutant.

In case that a temporal average of concentration distributions is required, the dispersion model makes calculations in steps of one hour or less. Therefore, as a minimum, meteorological data at each hour of the evaluation term are necessitated. If those data of shorter intervals are available, the more precise calculations become possible. For example, having six data for each hour (that is, for every 10 minutes), the dispersion calculation can be made in 10-minute intervals, and accuracy of the hourly average concentration will be improved since the average of six calculation results can be taken.

Among the meteorological conditions, wind direction, wind speed, and atmospheric stability have substantial effect on dispersion conditions. Data measured by anemometers can be used for the wind-direction and wind-speed inputs. Atmospheric stability, however, cannot be measured directly, but has to be determined from such data as solar radiation, in the daytime, and cloud-cover ratios, at night.

1.1.1 Wind Direction and Wind Speed

It should be noted when using hourly wind-direction and wind-speed data that the value notated for a given hour is the average value of the final 10 minutes of the preceding hour. Hourly records at meteorological observatories generally have this property, but we can use those values as the representative for each hour when more accurate data, such as those in 10-minute intervals, are not available.

Wind-direction and wind-speed data are needed in concentration calculation of the dispersion model, and also the wind-speed is used to determine the atmospheric stability beforehand. Typical wind data for the area or region are required for the determination of atmospheric stability. Nevertheless, those data used in the dispersion model must be local values. Their measurement station should be within the evaluation area. Even if you cannot obtain measurement data from within the evaluation area because the area is small, data should still be taken within a five-kilometer radius of the emission source, although it depends on the topography. Data from measurement stations more than 10 kilometers away should be interpreted as merely reference data. Data from measuring stations in mountainous areas, or separated by mountains from the emission source area, should be seriously considered to apply even if it is within a 10-kilometer radius.

The height of the measurement is also important. The measurement point should be
higher than surrounding buildings, trees, or hills to avoid any local effects these may produce on the measurements. A proposed guideline is, taking \( h \) as the height of the measurement above ground level, first to ensure that \( h \) satisfies at least \( h \geq 6 \) meters, second, there are no buildings or other obstacles as high as \( \frac{2}{3}h \) within a radius of \( h \) around the measurement point (unless the measurement point is taken at the top of a building). Furthermore, there should be no large buildings (higher than \( h \) and taking more than 10 degrees of the total viewing angle) within a radius of \( 10h \) of the measurement point.

The recommended format for wind-direction data are compass-point notation (north-north-east: 1; north: 16; calm: 0; missing measurements: 9999). Any other notation methods such as angles, measured clockwise from due north, (degrees; missing measurements: 9999), must be converted to the above format before input.

Wind-speed data should be expressed to 0.1m/s accuracy. The input data for long-term average simulations, however, the wind-speed data of 1m/s accuracy are acceptable.

1.1.2 Solar Radiation

The daytime Pasquill stability category is determined by entering solar radiation data measured with a pyrheliometer, accumulated or averaged for the time interval of serial meteorological data, most generally in the hour immediately prior to the notated hour, and combining it with the previously mentioned wind-speed data.

While solar radiation is affected by weather, or most directly by cloud cover, weather is not very local in nature and are often similar at all locations in the same plain. Therefore, the model can tolerate substitutions of solar radiation data measured as far away as 10–20 kilometers when the solar radiation cannot be measured in the evaluation area or its neighboring areas.

1.1.3 Alternate Data for Solar Radiation

In case of the internal lands of Japan, the AMeDAS, from the Japan Meteorological Agency, measures the sunlight ratio at one point in every about 20 kilometer grid. The sunlight ratio expresses the accumulated duration of sunlight, in excess of a fixed strength, received in the hour immediately prior to the notated hour. The ratio is expressed numerically between zero and 1 in 0.1 hour steps. A very precise solar radiation estimate can be obtained by including a calculation that evaluates the sun elevation at each hour along with the sunlight ratio. Section 1.2.3 gives the actual calculation method. The METI-LIS model software incorporates this estimation formula.

1.1.4 Atmospheric Stability Category

(1) Stability category table

Pasquill stability categories are determined with Table 1.1. Night stability types are discussed below.
Table 1.1: Stability category table

<table>
<thead>
<tr>
<th>Wind speed at ground level U (ms⁻¹)</th>
<th>Daytime Solar radiation Q (0.01 kWm⁻²)</th>
<th>Night (Solar elevation &lt; 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60 &lt; Q</td>
<td>30~59</td>
</tr>
<tr>
<td>U &lt; 2.0</td>
<td>A</td>
<td>A-B</td>
</tr>
<tr>
<td>2.0~2.9</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>3.0~3.9</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>4.0~5.9</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>6.0 &lt; U</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

(2) Classification of night stabilities

Originally Pasquill stability categories at night are determined from cloud-cover data. There are no examples today, however, of nightly cloud-cover measurements taken every hour, even at meteorological observatories. Some experts have suggested determining night stabilities based on measurements of net radiation to replace cloud-cover data. But unless measured on one’s own, obtaining net radiation data is difficult.

Others have considered, on first principles, night atmospheric stability to approach a neutral when wind speeds of a certain degree are present. Otherwise, they speculate, night atmospheric stability varies according to the relative strength of radiation cooling, which, in turn, corresponds to the degree of cloud cover, when wind speeds are slow. However, the idea of determining stability under light wind or calm conditions from cloud cover has a defect. As radiation cooling progress with time, stability changes between early evening and just before sunrise even under the same cloud conditions. Furthermore, the relative strength of cooling is dependent on the surrounding terrain, the region, and the season. As a rule, the night atmosphere is stable under light winds regardless of the cloud cover unlike the stability differences during the day between fair and cloudy conditions. Analytic results from turbulence data taken by numerous studies in the past show that changes in these turbulence intensities are mainly attributable to wind speed. Stability differences contributed by net radiation amounts are small in comparison.

From this conclusion, night stability has been modeled on the assumption it is solely dependent on wind speed. Therefore, the model uses only wind-direction and wind-speed data for night stability calculations; cloud cover or other input data are not needed.

In deference to Pasquill, the night stabilities in Table 1.1 were G, F, and E, in order from the slowest wind speed, in Version 1 of the METI-LIS model. These figures have been revised in this version after analyzing domestic data.

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1 The period from 1 hour before sunset to 1 hour after sunrise is regarded as nighttime. In addition, the stability class will be set to D within 1 hour before and after nighttime.
1.2 Internal Processing of Meteorological Data

Once you have either specially measured the meteorological conditions in the evaluation area or obtained them by searching existing data, the next step is to verify that the data is formatted so that they can be directly entered into and processed by the dispersion model. While the model software has some latitude in the data formats it can accept and process, data formats that do not conform to these limits will have to be preprocessed. Check the software operation manual (Reference Materials in Appendix) for the formats of input data.

The next sections describe how each type of meteorological data is used after entry.

1.2.1 Wind Speed

(1) Determining atmospheric stability
While wind-speed data is first used to determine atmospheric stability, the model assumes the wind speed has been measured at a height of 10 meters above ground level as a default value. If the measurement height of the input wind-speed data is significantly different, it should be scaled to a 10-meter equivalent wind speed. The adjustment uses the wind power law (Equation 1.1), described below. The difficulty is that the correction coefficient (the wind profile exponent) is a function of atmospheric stability and, thus, an iterative calculation should be made for higher accuracy. To do it, first, an intermediate stability is assumed and the corresponding correction coefficient is found. Using this coefficient, the observed wind speed is converted to its 10-meter equivalent and, with this wind speed, the stability is determined. The correction coefficient corresponding to this new stability is found and the 10-meter equivalent wind speed is recalculated again. The present model however neglects this iteration process, because it gives only slight effect on the results.

(2) Input wind speeds for the dispersion equation
The wind speed used in the dispersion equation is the equivalent wind speed at the stack, or release, height. If the measurement height, \( h \), of the wind speed is lower than the stack height, the measurement height conditions mentioned in Section 1.1.1 may not be satisfied. Generally this does not concern us if \( h \) is higher than the stack height. The wind-speed height requires adjustment, however, if \( h \) and the stack height are two or more times different. The power law (Equation 1.1) is used in the correction equation.

\[
U_2 = U_1 \left( \frac{Z_2}{Z_1} \right)^P
\]

\( U_1 \): Wind speed at the measurement height (m/s)
\( U_2 \): Wind speed at the stack outlet height (m/s)
\( Z_1 \): Measurement height (m)
\( Z_2 \): Stack outlet height (m)

The wind profile exponent, \( P \), is not a universal value; the surrounding terrain and features
affect it. Nevertheless, values like those in Table 1.2 are used. The next chapter (2.2.2) touches on the treatment of the wind profile exponent in the METI-LIS model.

Table 1.2: Wind profile exponent, $P$ (values used in the EPA’s CDM)

<table>
<thead>
<tr>
<th>Stability</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>(2)</td>
<td>0.15</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.07</td>
<td>0.07</td>
<td>0.1</td>
<td>0.15</td>
<td>0.35</td>
<td>0.55</td>
</tr>
</tbody>
</table>

(1) From the Japan Environment Agency’s manual on regulations of nitrogen-oxide amounts
(2) Values from ISC3, CDM 2.0, and others (Upper value: urban use; Lower value: rural use)

1.2.2 Solar Radiation

Solar radiation is essential data for daytime stability classification. Solar radiation representations use several different units. Table 1.3 indicates the relationship of typical figures, shown in different units, associated with stability classifications.

Table 1.3: Solar radiation units and figures

<table>
<thead>
<tr>
<th></th>
<th>calcm$^{-2}$h$^{-1}$</th>
<th>Wm$^{-2}$</th>
<th>MJm$^{-2}$h$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>145</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>290</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>580</td>
<td>2.1</td>
<td></td>
</tr>
</tbody>
</table>

1.2.3 Alternate Data for Solar Radiation

The sunlight ratio, $ss$, (0–10) measured by the Japan Meteorological Agency’s Amedas platform can be converted to solar radiation, $rr$ (unit: 0.01 MJm$^{-2}$h$^{-1}$) with the following equation.

$$rr = (r_0 + 0.1ss(r_{10}-r_0)) \cos z$$  \hspace{1cm} (1.2)

The exception, when $ss = 0$, is:

$$rr = (77 + 15.2sm) \cos z$$  \hspace{1cm} (1.3)

Note that $r_0$, $r_{10}$, and the numerical values in equations 1.2 and 1.3 are statistically determined coefficients. (They take the same units as $rr$.) The coefficient $r_0$ is 144, but $r_{10}$ changes according to the hour, as shown in Table 1.4. The quantity $sm$ is the average of ten
separate ss readings taken on the day in question between 8 a.m. and 5 p.m. The quantity cosz (z is the zenith distance of the sun) is calculated with the following procedure.

\[
\cos(z) = \sin(\text{la}) \sin(\text{sl}) + \cos(\text{la}) \cos(\text{sl}) \cos(\text{ha})
\]

\(\text{la}\): Latitude of the target position
\(\text{n}\): Number of days from New Year’s Day to the target day
\(\text{ne}\): Number of days from New Year’s Day to the spring equinox (about 80)
\(\text{da}\): The phase of the target day in a one-year cycle \((2\pi(n-ne)/365)\)
\(\text{sl}\): Estimate of the sun’s declination \((23.5 \sin(da))\)
\(\text{ha}\): The sun’s hour angle at the target time – 30 minutes (0 at meridian time)

The value of \(\text{ha}\) at 12 o’clock, for instance, would use the sun’s hour angle at 11:30 as an average between 11 and 12 o’clock. Meridian time changes according to location (longitude) and season (equation of time). For example, the Chronological Scientific journal gives the meridian time in Tokyo on January 1 as 11:44 a.m. This means that the sun’s hour angle at 11:30 a.m., the value corresponding to noon, is 14 minutes before the meridian or, in angular representation, -3.5 degrees.

Table 1.4: Hourly values of \(r_{10}\), the solar radiation to a normal plane, equivalent to a sunlight ratio of 10 (units: 0.01 MJm\(^{-2}\)h\(^{-1}\))

<table>
<thead>
<tr>
<th>Hour</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r_{10})</td>
<td>270</td>
<td>320</td>
<td>340</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td>330</td>
<td>300</td>
<td>260</td>
</tr>
</tbody>
</table>

References:
2. The METI-LIS Model

The METI-LIS model is based on a Gaussian plume equation that assumes steady-state conditions. This equation is used to model emissions from a point source, such as a smokestack or exhaust outlet. This chapter deals with the base Gaussian equation, the plume-rise height of exhaust gas, methods of determining dispersion parameters, methods of modeling downwash effects caused by buildings neighboring the emission source, and the application conditions on the dispersion model.

The METI-LIS model adopted a downwash scheme based on that of the US Environmental Protection Agency’s (EPA) Industrial Source Complex (ISC) model, but the parameters in the dispersion widths describing the downwash effect were improved by incorporating the result of wind tunnel experiments. Another characteristic point of the METI-LIS different from the ISC is that the evaluation time which affects the dispersion width especially in the \( y \) (crosswind) direction can be adjusted for a simulation of short time dispersion observation.

Items not denoted in the ISC model, or notably different from the methods employed in Japanese studies, were determined in accordance with the 1985 Ministry of International Trade and Industry technology manual on forecasting air pollution concentrations in advance studies on industrial development (MITI manual).

2.1 Dispersion Equation

As a dispersion equation for point sources the steady-state Gaussian plume model is used. For each source and each hour, the origin of the calculation’s coordinate system is placed at the ground surface at the base of the stack. The \( x \) axis is positive in the downwind direction, the \( y \) axis is crosswind (normal) to the \( x \) axis, and the \( z \) axis extends vertically. The user-defined calculation points are converted to each source’s coordinate system for concentration calculation at each time period. The conversion method in the \( x \)-axis and \( y \)-axis directions is described below. The concentrations calculated for each source at each calculation point are summed to obtain the total concentration produced by the combined source emissions for that time period.

\[
C_{(x,y)} = \frac{QV}{2\pi u \sigma_y \sigma_z} \exp \left[ -0.5 \left( \frac{y}{\sigma_y} \right)^2 \right]
\]

(2.1)

\( C \): Concentration in the \( x, y, z \) directions \((\text{m}^3/\text{m}^3\text{ppb, ppm, or other units})\)

\( Q \): Pollutant emission rate \((\text{m}^3/\text{s})^2\)

\( m_N^3 \) is the volume of a gas under standard conditions (0°C, 1 atmosphere). \( N \) is the symbol for normal.
V: Vertical term (Equation 2.2)

\[ V = \exp \left[ -0.5 \left( \frac{z_r - h_e}{\sigma_z} \right)^2 \right] + \exp \left[ -0.5 \left( \frac{z_r + h_e}{\sigma_z} \right)^2 \right] \]

(2.2)

\( z_r \): Elevation of calculation point (m)
\( h_e \): Effective plume-rise height (m)

The vertical term, \( V \), represents the distribution of the Gaussian plume in the vertical direction. This term includes the calculation point elevation and the effects of the height caused by the emitted plume rise (the effective plume-rise height).

2.2 Coordinate Systems and Other Basic Settings

2.2.1 Setting Calculation Points

Users specify calculation points on a Cartesian (X-Y) coordinate system. Users can arbitrarily set the calculation area width in the east-west and north-south directions as well as the number of divisions (calculation points) the area contains. In the Cartesian coordinate system, the x axis is positive to the east of the user-specified origin of the calculation area and the y axis is positive to the north.

Taking the x and y coordinates of the source as \( x_s \) and \( y_s \) and the x and y coordinates of the calculation point as \( x_r \) and \( y_r \), the position of the calculation point in each time period is given by:

\[
x = -(x_s - x_r) \sin(WD) - (y_s - y_r) \cos(WD)
y = (x_s - x_r) \cos(WD) - (y_s - y_r) \sin(WD)
\]

(2.3)

In this equation, WD is the angle from which the wind is blowing. The downwind distance, \( x \), is used in calculating the building downwash and in calculating the dispersion parameters.

2.2.2 Wind-speed Elevation Correction

As described in Chapter 1, the calculation converts the observed wind speed to an equivalent wind speed at the actual height of the source. This adjustment uses the wind power law. The power law equation is of the form:

\[ u_s = u_{ref} \left( \frac{h_s}{z_{ref}} \right)^p \]

(2.4)

\( u_s \): Wind speed at the stack outlet height, \( h_s \) (m/s)
\( u_{ref} \): Wind speed at the wind-speed measurement height, \( z_{ref} \) (m/s)
hs: Stack outlet height (m)
z_{ref}: Wind-speed measurement height (m)

The wind profile exponent, \( p \), in this equation is set according to the stability. The values shown in Table 2.1 can be used as average values.

<table>
<thead>
<tr>
<th>Stability Category</th>
<th>Exponent p</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.07</td>
</tr>
<tr>
<td>B</td>
<td>0.07</td>
</tr>
<tr>
<td>C</td>
<td>0.10</td>
</tr>
<tr>
<td>D</td>
<td>0.15</td>
</tr>
<tr>
<td>E</td>
<td>0.35</td>
</tr>
<tr>
<td>F</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Note: The ISC model applies these values to rural areas.

2.3 Setting the Effective Stack Height

2.3.1 Stack-tip Downwash

When the source emitting air pollutants is a stack, the stack’s tower acts as a drag to the wind, producing a downwash known as stack-tip downwash. When the exit velocity of the exhaust gas from the source is less than 1.5 times the speed of the wind, a correction is applied to the stack height corresponding to stack-tip downwash.

The ISC model uses the stack-tip downwash method advocated by Briggs.\(^3\) We use this method unchanged here. This method adjusts the height of the physical stack as follows:

\[
h_s' = h_s + 2d_s \left( \frac{v_s}{u_s} - 1.5 \right) \quad v_s < 1.5u_s \quad (2.5)
\]

\[
h_s' = h_s \quad v_s \geq 1.5u_s \quad (2.6)
\]

\( h_s' \): Modified physical stack height (m)
\( d_s \): Stack diameter (m)
\( v_s \): Exhaust-gas exit velocity (m/s)

This modification is not applied when downwash effects due to building are calculated.

2.3.2 Sources Without Buoyancy-induced Plume Rise

If the gas emitted by the source is not significantly warmer than the ambient temperature

---

\(^3\) Briggs, 1973: Diffusion Estimation for Small Emissions, ATDL Contribution File No.79, Atmospheric Turbulence and Diffusion Laboratory.
and the wind speed is slow, buoyancy-induced plume rise can be disregarded. This treatment is allowed for the exhaust vents and ventilation towers that are mostly the case of the sources of hazardous chemical substances.

The building-downwash calculation is applied separately with the method described in Section 2.5.

2.3.3 Sources With Buoyancy-induced Plume Rise

If the gas emitted by the source is comparatively warmer than the ambient temperature, the CONCAWE equation is employed, following the MITI manual.

\[
\begin{align*}
    h_e &= h_s + \Delta h \\
    \Delta h &= 0.175 \frac{Q_{th}}{u^{3/4}}
\end{align*}
\]

- \( h_e \): Effective plume-rise height (m)
- \( h_s \): Physical source height (m)
- \( \Delta h \): Buoyancy-induced plume rise (m)
- \( Q_{th} \): Emitted heat quantity (cal/s)

\[
Q_{th} = \rho C_p Q (T_s - T_A)
\]

- \( \rho \): Gas density at 0°C (1.293×10³ g/m³)
- \( C_p \): Isobaric specific heat (0.24 cal/K/g)
- \( Q \): Exhaust-gas volume per unit time (m³/s)
- \( T_s \): Exhaust-gas temperature (°C)
- \( T_A \): Ambient temperature (°C; default: 15°C)

2.4 Dispersion Parameters

Equations that fit the Pasquill-Gifford curves approximately are used to calculate the dispersion parameters. This model uses the approximation equations shown in tables 2.3 and 2.4. The same equations are also used in the ISC model. These approximation equations are functions of the downwind distance from the source and find the lateral dispersion width, \( \sigma_y \), and the vertical one, \( \sigma_z \), of Equation 2.1 respectively. These dispersion widths are contingent on atmospheric stability, which is determined by meteorological conditions. While 11 different categories can be accepted as atmospheric stability, those in the approximation equations are re-divided into only six categories (A to F). Table 2.2 shows the category mapping between the two. (See Section 1.1.4 for the data required to classify atmospheric stability.)
Table 2.2: Relationship between the observed atmospheric stability and the approximation equation index

<table>
<thead>
<tr>
<th>Atmospheric Stability</th>
<th>A</th>
<th>A-B</th>
<th>B</th>
<th>B-C</th>
<th>C</th>
<th>C-D</th>
<th>Dd</th>
<th>Dn</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximation Equation</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>Dn</td>
<td>Dd</td>
<td>C</td>
<td>B</td>
<td>A</td>
</tr>
</tbody>
</table>

Note: The atmospheric stabilities Dd and Dn are the D stabilities in the daytime and at night.

The equation for $\sigma_y$ is of the form:

$$\sigma_y = 465.11628(x)\tan(TH)$$  \hspace{1cm} (2.10)

$$TH = 0.017453293[c - d \ln(x)]$$  \hspace{1cm} (2.11)

The downwind distance, $x$, in equations 2.10 and 2.11 is in kilometers. The coefficients $c$ and $d$ are given in Table 2.3.

The equation for $\sigma_z$ is of the form:

$$\sigma_z = ax^b$$  \hspace{1cm} (2.12)

The downwind distance, $x$, is in kilometers, and $\sigma_z$ is in meters. The coefficients $a$ and $b$ are given in Table 2.4.

Table 2.3: Parameters Used to Calculate $\sigma_y$ from Pasquill-Gifford Curves

<table>
<thead>
<tr>
<th>Pasquill Stability Category</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24.1670</td>
<td>2.5334</td>
</tr>
<tr>
<td>B</td>
<td>18.3330</td>
<td>1.8096</td>
</tr>
<tr>
<td>C</td>
<td>12.5000</td>
<td>1.0857</td>
</tr>
<tr>
<td>D</td>
<td>8.3330</td>
<td>0.72382</td>
</tr>
<tr>
<td>E</td>
<td>6.2500</td>
<td>0.54287</td>
</tr>
<tr>
<td>F</td>
<td>4.1667</td>
<td>0.36191</td>
</tr>
</tbody>
</table>

$\sigma_y$ is in meters, $x$ in kilometers, and TH in radians.
Table 5.4: Parameters used to calculate $\sigma_z$ from Pasquill-Gifford curves

\[ \sigma_z (\text{m}) = ax^b \text{ (x is in kilometers)} \]

<table>
<thead>
<tr>
<th>Pasquill Stability Category</th>
<th>x (km)</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>A*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;.10</td>
<td>122.800</td>
<td>0.94470</td>
<td></td>
</tr>
<tr>
<td>0.10 – 0.15</td>
<td>158.080</td>
<td>1.05420</td>
<td></td>
</tr>
<tr>
<td>0.16 – 0.20</td>
<td>170.220</td>
<td>1.09320</td>
<td></td>
</tr>
<tr>
<td>0.21 – 0.25</td>
<td>179.520</td>
<td>1.12620</td>
<td></td>
</tr>
<tr>
<td>0.26 – 0.30</td>
<td>217.410</td>
<td>1.26440</td>
<td></td>
</tr>
<tr>
<td>0.31 – 0.40</td>
<td>258.890</td>
<td>1.40940</td>
<td></td>
</tr>
<tr>
<td>0.41 – 0.50</td>
<td>346.750</td>
<td>1.72830</td>
<td></td>
</tr>
<tr>
<td>0.51 – 3.11</td>
<td>453.850</td>
<td>2.11660</td>
<td></td>
</tr>
<tr>
<td>&gt;3.11</td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>B*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;.20</td>
<td>90.673</td>
<td>0.93198</td>
<td></td>
</tr>
<tr>
<td>0.21 – 0.40</td>
<td>98.483</td>
<td>0.98332</td>
<td></td>
</tr>
<tr>
<td>&gt;.40</td>
<td>109.300</td>
<td>1.09710</td>
<td></td>
</tr>
<tr>
<td>C*</td>
<td>all</td>
<td>61.141</td>
<td>0.91465</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;.30</td>
<td>34.459</td>
<td>0.86974</td>
<td></td>
</tr>
<tr>
<td>0.31 – 1.00</td>
<td>32.093</td>
<td>0.81066</td>
<td></td>
</tr>
<tr>
<td>1.01 – 3.00</td>
<td>32.093</td>
<td>0.64403</td>
<td></td>
</tr>
<tr>
<td>3.01 – 10.00</td>
<td>33.504</td>
<td>0.60486</td>
<td></td>
</tr>
<tr>
<td>10.01 – 30.00</td>
<td>36.650</td>
<td>0.56589</td>
<td></td>
</tr>
<tr>
<td>&gt;30.00</td>
<td>44.053</td>
<td>0.51179</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;.10</td>
<td>24.260</td>
<td>0.83660</td>
<td></td>
</tr>
<tr>
<td>0.10 – 0.30</td>
<td>23.331</td>
<td>0.81956</td>
<td></td>
</tr>
<tr>
<td>0.31 – 1.00</td>
<td>21.628</td>
<td>0.75660</td>
<td></td>
</tr>
<tr>
<td>1.01 – 2.00</td>
<td>21.628</td>
<td>0.63077</td>
<td></td>
</tr>
<tr>
<td>2.01 – 4.00</td>
<td>22.534</td>
<td>0.57154</td>
<td></td>
</tr>
<tr>
<td>4.01 – 10.00</td>
<td>24.703</td>
<td>0.50527</td>
<td></td>
</tr>
<tr>
<td>10.01 – 20.00</td>
<td>26.970</td>
<td>0.46713</td>
<td></td>
</tr>
<tr>
<td>20.01 – 40.00</td>
<td>35.420</td>
<td>0.37615</td>
<td></td>
</tr>
<tr>
<td>&gt;40.00</td>
<td>47.618</td>
<td>0.29592</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;.20</td>
<td>15.209</td>
<td>0.81558</td>
<td></td>
</tr>
<tr>
<td>0.21 – 0.70</td>
<td>14.457</td>
<td>0.78407</td>
<td></td>
</tr>
<tr>
<td>0.71 – 1.00</td>
<td>13.953</td>
<td>0.68465</td>
<td></td>
</tr>
<tr>
<td>1.01 – 2.00</td>
<td>13.953</td>
<td>0.63227</td>
<td></td>
</tr>
<tr>
<td>2.01 – 3.00</td>
<td>14.823</td>
<td>0.54503</td>
<td></td>
</tr>
<tr>
<td>3.01 – 7.00</td>
<td>16.187</td>
<td>0.46490</td>
<td></td>
</tr>
<tr>
<td>7.01 – 15.00</td>
<td>17.836</td>
<td>0.41507</td>
<td></td>
</tr>
<tr>
<td>15.01 – 30.00</td>
<td>22.651</td>
<td>0.32681</td>
<td></td>
</tr>
<tr>
<td>30.01 – 60.00</td>
<td>27.074</td>
<td>0.27436</td>
<td></td>
</tr>
<tr>
<td>&gt;60.00</td>
<td>34.219</td>
<td>0.21716</td>
<td></td>
</tr>
</tbody>
</table>

* If $\sigma_z$ exceeds 5,000 meters, 5,000 meters is used.

** $\sigma_z$ is 5,000 meters.
2.5 Building Downwash

2.5.1 Fundamental Concepts

The ISC model calculates downwash effects caused by buildings near the emission source based on the Huber-Snyder method. Huber and Snyder conducted various experiments under the neutral condition (Pasquill stability category C or D) using model buildings that were twice as tall as wide. From these experiments, they derived dispersion parameters that could be applied to downwash situations. In this study, we performed detailed wind-tunnel experiments on various alignments and sizes of buildings. We were able, from these results, to improve the reproducibility of ground concentration distributions over the ISC model.

(1) Range of downwash consideration

First, the range of downwash effects to be considered in the downwind direction is calculated. This method adheres to the ISC model. Taking the index L, the smaller of a building’s height or width, dispersion parameters that account for downwash are applied in the range 3L to 10L. Points closer to the source than 3L are out of the calculation’s scope. Dispersion parameters when farther downwind than 10L are calculated using stability-sensitive equations that approximate the Pasquill-Gifford curves. It must be ensured, however, the two methods do not create different dispersion parameter values at the border case of 10L. To resolve any discontinuities, taking $\sigma_z$ for example, we assumed that the values arrived at by Equation 2.13 and Equation 2.14 were equal at 10L. From this assumption, we derived Equation 2.15. This sets a virtual point source at an upwind distance of $x_z$ from $x=10L$.

Calculations made at downwind distances greater than 10L use dispersion parameters from this virtual point source instead of the actual point source.

(2) Calculating $\sigma_z$

The estimation method of $\sigma_z$ is as follows:

$$\sigma'_z = C_{z1} \cdot L + C_{z2} (x - 3L) \quad 3L \leq x < 10L \quad (2.13)$$

$$\sigma'_z = \sigma_z [x + x_z] \quad 10L \leq x \quad (2.14)$$

$\sigma'_z$: $\sigma_z$ after accounting for downwash (m)

$C_{z1}, C_{z2}$: Parameters (found through experimentation)

$L$: The smaller of the building’s height, $H_b$, or width, $W_b$ (m)

$\sigma_z [x + x_z]$: $\sigma_z$ from the virtual point source at the downwind distance $x + x_z$ (m)

---

4 The ISC model rounds off the value of $\sigma_z$ at 10L to 1.2L. This causes some discontinuity.
$x_z$: Downwind distance from the virtual point source (km)

$$x_z = \left( \frac{\sigma_z[10L]}{a} \right)^{1/b} - 0.01L \quad (2.15)$$

$\sigma_z[10L]$: $\sigma_z$ at 10L from Equation 5.13 (m)

a, b: Parameters from the equations approximating the Pasquill-Gifford curves

One improvement, brought about by the wind-tunnel experiments, over the ISC model is the correction of $C_{z1}$ and $C_{z2}$ in Equation 2.13 based on experiment values of $\sigma_z$. In practice, $C_{z1}$ and $C_{z2}$ are determined by calculating $\sigma_z$ for each unique experimental case with changing arrangement and size of building and fitting the value with the least square method.

**(3) Calculating $\sigma_y$**

The calculations for $\sigma_y$ are separated according to the building’s width-to-height ratio ($W_b/H_b$). Similar formulas as $\sigma_z$ are used for each category of $\sigma_y$. However, the width of the building that $\sigma_y$ is dependent on changes with the wind’s direction. Therefore, the width of the building in the plane projected in the direction perpendicular to the wind, $W_{b'}$, shown in Figure 2.1, is used.

When $1 \leq W_{b}/H_{b} \leq 5$

$$\sigma_y = C_{y1} \cdot W_{b} + C_{y2}(x - 3H_{b}) \quad 3H_{b} \leq x < 10H_{b} \quad (2.16)$$

$$\sigma_y = \sigma_y[x + x_y] \quad 10H_{b} \leq x \quad (2.17)$$

The relationship between equations 2.16 and 2.17 is the same as that between equations 2.13 and 2.14. If the building is extremely wide ($W_{b}/H_{b} > 5$), the $W_{b'}$ quantity multiplied by $C_{y1}$ in Equation 2.16 is replaced with $H_{b}$ before calculating. Conversely, if the building is extremely narrow but tall ($W_{b}/H_{b} < 1$), the $H_{b}$ quantity multiplied by $C_{y2}$ in Equation 2.16 is replaced with $W_{b'}$ before calculating.

When $W_{b}/H_{b} > 5$

$$\sigma_y = C_{y1} \cdot H_{b} + C_{y2}(x - 3H_{b}) \quad 3H_{b} \leq x < 10H_{b} \quad (2.18)$$

---

5 The ISC model assigns constants to $C_{z1}$ and $C_{z2}$ (0.7 and 0.067 respectively) in its version of Equation 5.13. Similarly, it uses 0.35 and 0.067 for $C_{y1}$ and $C_{y2}$ in Equation 5.16.

6 The ISC model uses the width in the projected cross-section for calculating $C_y$ as well. This model uses the normal width, $W_b$, since experimental results show $C_y$ has the same relationship with $W_b$ as $W_{b'}$. However, the model employs the width of the side closest to being perpendicular to the wind.
\[ \sigma_y' = \sigma_y [x + x_y] \hspace{1cm} 10H_b \leq x \]  \hspace{1cm} (2.19)

When \( W_b/H_b < 1 \)
\[ \sigma_y' = C_{y1} \cdot W_b + C_{y2} \left( x - 3W_b' \right) \hspace{1cm} 3W_b' \leq x < 10W_b' \] \hspace{1cm} (2.20)
\[ \sigma_y' = \sigma_y [x + x_y] \hspace{1cm} 10W_b' \leq x \] \hspace{1cm} (2.21)

Figure 2.1: Projected Width Found from the Angle Between the Wind and the Building

The aspect ratio of buildings for the wind-tunnel experiments was set as \( 1 \leq W_b/H_b \leq 5 \), considered to be the most common in landscape. Building-layout scenarios were classified into two groups in the determination of \( C_{y1} \) and \( C_{y2} \): building columns, when few buildings surround the source, and building clusters, when many do. Building columns and building clusters are defined here:

Building columns: One or a few buildings exist with facing the direction the wind is blowing from. This scenario would apply to a single-block building or a factory with few buildings constructed in a row.

Building clusters: Many buildings exist with several buildings in a line facing the direction the wind is blowing from. This scenario would apply to a factory with numerous buildings scattered around the emission source.

(4) Other considerations

Wind-tunnel experiments led to other model improvements in addition to \( \sigma_y \) and \( \sigma_z \). The METI-LIS model, unlike the ISC model, modeled the reduction in plume centerline height and changes in wind-speed caused by building wakes. It also uses a method (for locating virtual sources) that calculates the virtual lateral (crosswind) displacement of the source’s location when winds do not hit buildings perpendicularly.
2.5.2 Calculation Steps

The following are the calculation steps when accounting for building downwash effects.

1. Select buildings in the vicinity of the source and apply the processing in steps (2) and (3). If more than one building exists, apply the processing in steps (2) and (3) to all buildings.

2. After converting the buildings to their rectangular approximations, determine the height, $H_b$, and width, $W_b$, of each building (1 to i).

3. If any part of a building, as seen from the source, is within an area demarcated by $5L^*$ in the downwind and upwind directions and $L^*$ in each crosswind direction, it is treated as a downwash producer and step (4) is checked. In this case, $L^*$ is the smaller of $H_b$ and $W_b$ (see Figure 2.2).

4. Find the GEP stack height\(^7\) for buildings judged to produce downwash effects. Select the building with the largest GEP stack height as the representative building for the downwash calculation.

\[
\text{GEP Stack Height} = H_b + 1.5 \cdot \min(H_b, W_b) \tag{2.22}
\]

![Diagram showing the calculation of downwash effects](image)

5. Use Equation 2.23 to find the GEP stack height when the wind hits the building arrangement diagonally rather than at right angles (see Figure 2.1).

\[
\text{GEP Stack Height} = H_b + 1.5 \cdot \min(H_b, W'_b) \tag{2.23}
\]

$W'_b$: Projected building width with respect to the wind-direction axis

---

\(^7\) Good Engineering Practice (GEP) stack height: The necessary height to avoid downwash effects. The EPA regulates this for both new and existing facilities.
(2.24)

\[ W_e = W_b \cdot \cos \theta + L_b \cdot \sin \theta \]

(6) Compare the effective plume-rise height and the GEP stack height. If the effective plume-rise height is higher than the GEP stack height, downwash effects are not considered.

(7) Determine if the building group that contains the downwash-producing building in the calculation area is a building column (few buildings) or a building cluster (many buildings). Taking \( H_b \) as the height of the downwash-producing building, if the area of its building group is neither less than \( 5H_b \) in the downwind direction nor less than \( 3H_b \) in each crosswind direction, it is judged to be a building cluster. The source, however, may be on the downwind or upwind side of the building group (see Figure 2.3).

![Figure 2.3: Determining building columns and building clusters](image)

2.5.3 Downwash Method

Equations 2.13 and 2.16 (or its alternative, 2.18 or 2.20), representing dispersion width affected by downwash, have two parameters respectively. These parameters were determined by wind-tunnel experiment as follows.

(1) **Modeling \( C_{z1} \)**

Regardless if a building column or building cluster, \( C_{z1} \) is given as a linear equation with the non-dimensional physical stack height, \( H_s (h_s/H_b) \). The coefficients of this expression are found as functions of the building’s width-to-height ratio \( (W_b/H_b) \).

\[ C_{z1} = a \cdot H_s + b \quad (2.25) \]

\[
a = -0.00125 \left( \frac{W_b}{H_b} \right)^2 + 0.02 \left( \frac{W_b}{H_b} \right) - 0.329 \quad \text{if} \quad \frac{W_b}{H_b} \leq 5
\]
When \( \frac{W_b}{H_b} > 5 \),

\[
a = -0.26 \quad \frac{W_b}{H_b} > 5
\]

\[
b = -0.0045 \left( \frac{W_b}{H_b} \right)^2 + 0.051 \left( \frac{W_b}{H_b} \right) + 0.645 \quad \frac{W_b}{H_b} \leq 5
\]

\[
b = 0.788 \quad \frac{W_b}{H_b} > 5
\]

When the wind does not form a right angle with the building, the quantity \( C_{z1(\theta)} \) is found with one of the following equations using \( \theta \), the angle between the building and the wind-direction axis, (provided that \( 0^\circ < \theta \leq 45^\circ \) holds true) and the quantity \( C_{z1(0)} \), found with Equation 2.25.

**Figure 2.4: Concept when the wind does not form a right angle with the building**

When \( h_s > H_b \)

\[
C_{z1(\theta)} = C_{z1(0)} \quad (2.26)
\]

When \( h_s \leq H_b \)

\[
C_{z1(\theta)} = C_{z1(0)} (1 - 0.010 \theta) \quad \text{For building columns} \quad (2.27)
\]

\[
C_{z1(\theta)} = C_{z1(0)} (1 - 0.003 \theta) \quad \text{For building clusters}
\]

(2) **Modeling \( C_{z2} \)**

While the modeling concept is similar to \( C_{z1} \), \( C_{z2} \) responds differently in building columns and building clusters. Thus, it is calculated as follows according to the arrangement of the target buildings.
For building columns
\[ C_{z2} = 0.052 \]  \hspace{1cm} (2.28)

For building clusters
\[ C_{z2} = a \cdot H_s + b \]  \hspace{1cm} (2.29)

\[ a = 0.039 \]
\[ b = 0.0137 \left( \frac{W_k}{H_b} \right) - 0.0085 \hspace{1cm} 1 \leq \frac{W_b}{H_b} \leq 5 \]
\[ b = 0.0038 \hspace{1cm} \frac{W_b}{H_b} < 1 \]
\[ b = 0.059 \hspace{1cm} \frac{W_b}{H_b} > 5 \]

When the wind does not form a right angle with the building, \( C_{z2} \) is found as the quantity \( C_{z2(\theta)} \), similar to \( C_{z1} \). The quantity \( C_{z2(\theta)} \) is found with one of the following equations using \( \theta \), the angle between the building and the wind-direction axis, (provided that \( 0^\circ < \theta \leq 45^\circ \) holds true) and the quantity \( C_{z20} \), found with Equation 2.28 or Equation 2.29.

For building columns when \( h_s > H_b \)
\[ C_{z2(\theta)} = C_{z2(\theta = 0^\circ)} \left( 1 - 0.0136 \theta \right) \hspace{1cm} \frac{W_k}{H_b} > 1.0 \] \hspace{1cm} (2.30)
\[ C_{z2(\theta)} = C_{z2(\theta = 0^\circ)} \hspace{1cm} \frac{W_k}{H_b} \leq 1.0 \]

For building clusters when \( h_s > H_b \)
\[ C_{z2(\theta)} = C_{z2(\theta = 0^\circ)} \] \hspace{1cm} (2.31)

For building columns when \( h_s \leq H_b \)
\[ C_{z2(\theta)} = C_{z2(\theta = 0^\circ)} \left( 1 - 0.0072 \theta \right) \hspace{1cm} \frac{W_k}{H_b} > 1.0 \] \hspace{1cm} (2.32)
\[ C_{z2(\theta)} = C_{z2(\theta = 0^\circ)} \hspace{1cm} \frac{W_k}{H_b} \leq 1.0 \]

For building clusters when \( h_s \leq H_b \)
\[ C_{z2(\theta)} = C_{z2(\theta = 0^\circ)} \left( 1 - 0.0098 \theta \right) \] \hspace{1cm} (2.33)
(3) Modeling $C_{y1}$

The $C_{y1}$ model uses the projected width, $W_{b}'$, of the building, found with respect to the wind-direction axis with Equation 2.24, instead of the building’s width.

Like $C_{z1}$, $C_{y1}$ is given as a linear equation with the non-dimensional physical stack height, $H_s (h_s/H_b)$. The coefficients of this expression are found as functions of the building’s width-to-height ratio ($W_{b}/H_b$).

$$C_{y1} = c \cdot H_s + d$$  \hspace{1cm} (2.34)

$$c = -0.0170 \left( \frac{W_b}{H_b} \right)^2 + 0.173 \left( \frac{W_b}{H_b} \right) - 0.80 \hspace{1cm} \frac{W_b}{H_b} \leq 5$$

$$c = -0.36 \hspace{1cm} \frac{W_b}{H_b} > 5$$

$$d = 0.0464 \left( \frac{W_b}{H_b} \right)^2 - 0.461 \left( \frac{W_b}{H_b} \right) + 1.93 \hspace{1cm} \frac{W_b}{H_b} \leq 5$$

$$d = 0.791 \hspace{1cm} \frac{W_b}{H_b} > 5$$

When the wind does not form a right angle with the building, the quantity $C_{y1(\theta)}$ is found with one of the following equations using $\theta$, the angle between the building and the wind-direction axis, (provided that $0^\circ < \theta \leq 45^\circ$ holds true) and the quantity $C_{y1(0)}$, found with Equation 2.34.

When $h_s > H_b$

$$C_{y1(\theta)} = C_{y1(0)}$$  \hspace{1cm} (2.35)

When $h_s \leq H_b$

$$C_{y1(\theta)} = C_{y1(0)} (1 - 0.015 \theta) \hspace{1cm} \text{For building columns}$$  \hspace{1cm} (2.36)

$$C_{y1(\theta)} = C_{y1(0)} (1 - 0.0069 \theta) \hspace{1cm} \text{For building clusters}$$

(4) Modeling $C_{y2}$

$C_{y2}$ is calculated by the following method because experimental results show that it is
contingent on the number of columns, \( N \), in a building column.\(^8\)

For building columns
\[
C_{y2} = 4.29 \times 10^{-4} \cdot N^2 - 7.86 \times 10^{-8} \cdot N + 0.073 \quad 1 \leq N \leq 7
\]
\[
C_{y2} = 0.039 \quad N \geq 8 \quad (2.37)
\]

For building clusters
\[
C_{y2} = 0.039 \quad (2.38)
\]

When the wind does not form a right angle with the building, \( C_{y2} \) is found as the quantity \( C_{y2(\theta)} \), similar to \( C_{z2} \). The quantity \( C_{y2(\theta)} \) is found with one of the following equations using \( \theta \), the angle between the building and the wind-direction axis, (provided that \( 0^\circ < \theta \leq 45^\circ \) holds true) and the quantity \( C_{y2(0^\circ)} \) found with Equation 2.37 or Equation 2.38.

When \( h_s > H_b \)
\[
C_{y2(\theta)} = C_{y2(0^\circ)} \quad \text{For building columns} \quad (2.39)
\]
\[
C_{y2(\theta)} = C_{y2(0^\circ)} \left(1 + 0.0149 \theta\right) \quad \text{For building clusters}
\]

When \( h_s \leq H_b \)
\[
C_{y2(\theta)} = C_{y2(0^\circ)} \quad \text{For building columns} \quad (2.40)
\]
\[
C_{y2(\theta)} = C_{y2(0^\circ)} \left(1 + 0.019 \theta\right) \quad \text{For building clusters}
\]

(5) Modeling wind-speed correction coefficients

Wind speeds change in the vicinity of buildings particularly in the areas behind buildings, although the severity of changes is somewhat dependent on the arrangement of buildings and conditions in the periphery. The concentration equation then uses a wind speed that factors in the wind-speed changes caused by buildings. We have found from experimental results that wind-speed changes are related to source height. Wind speed is particularly affected by building layouts when the source is lower than surrounding buildings. The wind speed is adjusted by multiplying a correction coefficient \( \alpha \) with the wind speed at the actual source height used in the calculation. Note that, like the ISC model, if the adjustment results

---

\(^8\) The distributed software programming uses \( C_{y2} = 0.039 \) in its calculations regardless of the building alignment (columns or clusters) and without accounting for the number of columns shown here.
in a wind speed of less than 1 m/s, a wind speed of 1 m/s will be substituted in the calculation.

\[ u'_s = \alpha u_s \]  \hspace{1cm} (2.41)

\[ u'_s \]: Wind speed influenced by buildings (m/s)

\[ \alpha \]: Correction coefficient

When \( h_s > H_b \)

\[ \alpha = 0.76 \quad \frac{W_b}{H_b} < 1 \]

\[ \alpha = 0.8 - 0.039 \left( \frac{W_b}{H_b} \right) \quad 1 \leq \frac{W_b}{H_b} \leq 5 \]  \hspace{1cm} (2.42)

\[ \alpha = 0.61 \quad \frac{W_b}{H_b} > 5 \]

When \( h_s \leq H_b \) (for building columns)

\[ \alpha_{(\theta = 0)} = 0.66 \quad \frac{W_b}{H_b} < 1 \]

\[ \alpha_{(\theta = 0)} = 0.72 - 0.056 \left( \frac{W_b}{H_b} \right) \quad 1 \leq \frac{W_b}{H_b} \leq 5 \]  \hspace{1cm} (2.43)

\[ \alpha_{(\theta = 0)} = 0.44 \quad \frac{W_b}{H_b} > 5 \]

\[ \alpha_{(\theta = N)} = \alpha_{(\theta = 0)} - 0.076(N - 1) \]

When \( h_s \leq H_b \) (for building clusters)

\[ \alpha = 0.72 \quad \frac{W_b}{H_b} < 1 \]

\[ \alpha = 0.913 - 0.194 \left( \frac{W_b}{H_b} \right) \quad 1 \leq \frac{W_b}{H_b} \leq 3 \]  \hspace{1cm} (2.44)

\[ \alpha = 0.33 \quad \frac{W_b}{H_b} > 3 \]

When the wind does not form a right angle with the building, \( \alpha \), from equations 2.42 to 2.44, is adjusted as follows using the angle \( \theta \) between the building and the wind-direction axis.

When \( h_s > H_b \)

\[ \alpha_{(\theta)} = \left[ 1 + 0.013 \, \theta - 2.2 \times 10^{-4} \theta^2 \right] \cdot \alpha_{(\theta = 0)} \quad W_b > H_b \]  \hspace{1cm} (2.45)
\[ \alpha_{(o)} = \alpha_{(o)} \quad \text{when } W_b \leq H_b \]

When \( h_s \leq H_b \) and \( W_b > H_b \)

\[ \alpha_{(o)} = \left[ 1 + 0.053 \theta - 8.3 \times 10^{-4} \theta^2 \right] \cdot \alpha_{(o)} \quad \text{for building columns} \quad (2.46) \]

\[ \alpha_{(o)} = \left[ 1 + 0.099 \theta - 1.98 \times 10^{-3} \theta^2 \right] \cdot \alpha_{(o)} \quad \text{for building clusters} \]

When \( h_s \leq H_b \) and \( W_b \leq H_b \)

\[ \alpha_{(o)} = \alpha_{(o)} \quad (2.47) \]

(6) **Modeling stack height correction**

When buildings exist near a source, the centerline height of the plume tends to be lowered by the wake effect of the buildings’ wake flow. The following adjustments are made in reference to the actual height of the source.

When \( h_s \leq 0.5H_b \)

\[ h_e = 0 \quad (2.48) \]

When \( 0.5H_b < h_s \leq H_b \)

\[ h_e = 0.5h_s \quad (2.49) \]

When \( H_b < h_s < 2.5H_b \), \( \frac{W_b}{H_b} \leq 1 \)

\[ h_e = 0.56h_s \quad \text{for building columns} \quad (2.50) \]

\[ h_e = 0.67h_s \quad \text{for building clusters} \]

When \( H_b < h_s < 2.5H_b \), \( \frac{W_b}{H_b} > 1 \)

\[ h_e = 0.44h_s \quad (2.51) \]

(7) **Modeling the virtual stack location**

When the wind strikes a building on a diagonal, the model transposes the plume centerline in the crosswind direction because the plume advances along the wall of the building. This result is incorporated by introducing a virtual source shifted by a displacement width, \( \Delta y_s \). This effect is presumed to be larger when the source is lower than the building; the higher the source, the smaller the effect.
Figure 2.5: Stack transposition for wind-direction changes

For building columns

When \( \frac{W_b}{H_b} \leq 1.0 \)

\[
\frac{\Delta y_s}{W'} = 2.0 \\
\frac{\Delta y_s}{W'} = -4.0 \left( \frac{h_s}{H_b} \right) + 6.0 \\
\frac{\Delta y_s}{W'} = 0.0
\]

When \( \frac{W_b}{H_b} > 1.0 \)

\[
\frac{\Delta y_s}{W'} = 2.0 \\
\frac{\Delta y_s}{W'} = -3.0 \left( \frac{h_s}{H_b} \right) + 5.0 \\
\frac{\Delta y_s}{W'} = 0.0
\]

For building clusters

\[
\frac{\Delta y_s}{W'} = 2.5 \\
\frac{\Delta y_s}{W'} = -3.0 \left( \frac{h_s}{H_b} \right) + 5.5
\]
\[
\frac{\Delta y_s}{W'} = 0.0 \quad \text{if } \frac{h_s}{H_s} > 1.83
\]
\[
W' = \left(\frac{1}{2} W_s\right) \cos \theta \quad (2.55)
\]

2.6 Other Precautions

2.6.1 Calculations for Calm Conditions

The ISC model does not make calculations for calm or weak-wind (under 1 m/s) conditions. These conditions, however, possibly occupy a considerably large part in calculating annual mean values, and therefore the METI-LIS model makes calculations for calm conditions using Turner-curve dispersion parameters and the puff equations given in the MITI manual. Weak-wind conditions are calculated with the plume equations. Downwash effects are ignored in calm conditions. Furthermore, the Briggs calm equation, Equation 2.56, is used when buoyancy-induced plume rise is assumed under calm conditions.

\[
\Delta h = 1.4 \left( \frac{Q}{H} \right)^{1/4} (d \theta / dz)^{-3/8} \quad (2.56)
\]

\(\Delta h\): Buoyancy-induced plume-rise effect on exhaust gas (m)

\(d \theta / dz\): Potential temperature gradient (°C/m)

Daytime: 0.003°C/m (atmospheric stabilities A–DD)

Night: 0.010°C/m (atmospheric stabilities DN–G)

See earlier notes for other symbols.

2.6.2 Evaluation Time of Dispersion Widths

This manual basically assumes that the calculations are performed on observed hourly meteorological conditions. The stack conditions input into the calculation are also adjusted to hourly values to match the meteorological conditions.

On the other hand, the evaluation time of the wind-tunnel experiments run in the study of dispersion models was three minutes. The evaluation time of the Pasquill-Gifford curves is also only a few minutes long. To evaluate the calculation results as values over an hour, some time correction is needed. The ISC model, however, adopts calculation values as is without commenting on time correction. At the present stage, we have no adequate correction method. Due caution, then, must be exercised when evaluating results.

A conventional time-correction method\(^9\) that has been frequently used is to increase the

\(^9\) Taking the calculated dispersion concentrations as three-minute values and the desired hourly values as 60-minute values, the conversion \(\sigma_y = \sigma_y \left( \frac{60}{3} \right)^{1/5} = 1.82 \sigma_y\) is used. Alternatives, such as one-fourth, have been suggested for the exponent.
value of $\sigma_y$ using a one-fifth power law. The validity of this method in downwash locations, however, has not been studied.

Another method that has been considered is such that the wind-direction axis for one wind direction is varied and multiple calculations made. The evaluation for long-term values is made after averaging (or, if necessary, weighting and then averaging) the results.

2.6.3 Annual Mean Value Calculations

Ambient air quality standards for chemical substances like benzene are given as annual mean values. In this manual, annual mean values are calculated by statistically processing the results of calculations run for every hour over a year period.

When finding concentration distribution plots for annual mean values, however, an eight-fingered distribution pattern forms. This is a result of the discontinuity at the borders between the 16 compass points used for wind direction records in the input meteorological conditions. To avoid this discontinuity in the long-term averaging mode, instead of using a fixed wind axis for each compass-point representation, a meteorological preprocessing program generates random numbers to even the wind-direction distribution within the same wind direction over the calculation period. This lessens the border discontinuities.

2.6.4 Differences from the ISC Model

As stated at the beginning of this chapter (2), the METI-LIS model was based primarily on the ISC model, apart from an improved means of handling downwash effects. We have, however, made some revisions to reflect the past course of modeling in Japan.

The differences from the ISC model are given here.

- Only point sources are handled. (A simple line source algorithm has been attached after Version 2, as shown in Chapter 3.)
  → The ISC model treats line, area, and volume sources differently. Integral calculations are used with line and area sources; a point-source approximation is used for volume sources.

- The land feature in the model domain is not specified.
  → The ISC model classifies regions as rural or urban. Specifically, dispersion parameters are separated into Pasquill-Gifford curves for rural regions and Briggs curves for urban regions.

- The CONCAWE equation is used for sources with buoyancy effects.
  → The ISC model uses a sequence of equations from Briggs according to stability and emission conditions (temperature and exit velocity).

- Calculations are made including calm conditions.
  → The ISC model does not make calculations for winds under 1.0 m/s.
2.7 Application Conditions on the METI-LIS Model

2.7.1 Scope of the METI-LIS Model

The dispersion parameters obtained from wind-tunnel experiments were considered to correspond to the evaluation time of three minutes. The METI-LIS model has been modeled after these results. This means that due caution must be taken when applying the model. The scope of the model may be recognized by summarizing the configuration and conditions applied for the wind-tunnel experiment to construct this model.

(1) Calculation area

Figure 2.6 indicates the range of buildings and the range of concentration measurements used in the wind-tunnel experiments. The maximum range of concentration measurements was 30L. The quantity L here is the smaller of the building’s height or width.

(2) Stack height

When constructing the model, only wind-tunnel data in the $0.5 \leq \frac{Zs}{Hb} \leq 1.5$ range was used. The quantity Zs represents the stack height and Hb, the building height. The model was also constructed with values for the range $1.5 < \frac{Zs}{Hb} \leq 2.5$ that were extrapolated from experimental data in the $0.5 \leq \frac{Zs}{Hb} \leq 1.5$ range. For cases where $Zs/Hb > 2.5$, the model assumes there are no building downdraft effects, in keeping with the ISC model. The model’s handling of stack heights is summarized as follows:

- When $Zs/Hb > 2.5 \rightarrow$ ISC model (no correction for downdraft occurrences)
- When $Zs/Hb \leq 2.5 \rightarrow$ METI-LIS model
(3) Building width
When constructing the model, only wind-tunnel data in the $1.0 \leq \frac{Wb}{Hb} \leq 5.0$ range was used. The symbol $Wb$ represents the building width.

(4) Summarizing the model’s scope
Table 2.5 summarizes the scope of the METI-LIS model with respect to the data ranges of wind-tunnel experiments employed in the construction of the model.

Table 2.5: Scope of the METI-LIS model verified by wind-tunnel experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scope of the METI-LIS Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation area</td>
<td>$3L \leq X \leq 30L^{(*1)}$</td>
</tr>
<tr>
<td>Building cluster range</td>
<td>$X \leq 13L$</td>
</tr>
<tr>
<td>Stack height</td>
<td>$0 \leq \frac{Zs}{Hb} \leq 2.5^{(*2)}$</td>
</tr>
<tr>
<td>Building width</td>
<td>$1.0 \leq \frac{Wb}{Hb} \leq 5.0$</td>
</tr>
</tbody>
</table>

(*1) Maximum calculation area
The largest measured range in wind-tunnel experiments, 30L, is quoted here as the maximum calculation area. However, after a certain distance downwind from the stack, the dispersion width grows significantly larger than the building size and approaches a state in which the pollutant is dispersed with a general roughness. The effects of buildings located at a far distance, then, are anticipated to diminish. From this perspective, the model can in principle be applied to areas beyond 30L and to building clusters than exceed 13L in area.

Again, for the same reasons, the METI-LIS model can be applied when working with buildings such as apartment complexes that border an industrial site by treating the apartment complex and factory as building clusters. No other special preparation is required.

At this time, however, we have little research to verify exactly how far downwind the METI-LIS model can be applied or exactly how far building clusters can spread and still obtain valid results. This is a subject for future study.

(*2) As explained above, only wind-tunnel data in the range $0.5 \leq \frac{Zs}{Hb} \leq 1.5$ was used in the construction of the model. Parameters outside this range use extrapolated values. There is room for future study on the validity of applying the model outside of this verified range.
3. Dry Deposition Model and Line Source Model

Hazardous air pollutants like nickel compounds and dioxins (those attached to particles) exhibit a deposition phenomenon when they are in a particulate form larger than 10 μm. They must be evaluated with a dry deposition model, which works with particulate 10 μm or larger. Particles smaller than 10 μm can be treated similarly to gaseous matter and are evaluated with the normal METI-LIS model.

On the other hand, when forecasting the concentration of air pollutants at the border of an industrial complex, there may be a roadway running close to the complex’s border. The effects from the exhaust of automobiles cannot be ignored, as automobile exhaust also contains benzene and other pollutants. In this case, it is necessary to forecast the pollutants from moving sources as well. Unfortunately, moving sources create different dispersion patterns than the point sources covered in the METI-LIS model. When it is evident that the problem above is occurring, some additional information must be given to the model to make line source forecasts. Additionally, moving sources are assumed not to be affected by building downwash.

3.1 Dry Deposition Model

3.1.1 Basic Dispersion Equation

The basic dispersion equation uses the point-source plume equation in Equation 3.1.

\[ C(x, y, z) = \frac{Q}{2\pi \sigma_y \sigma_z u} \exp\left( -\frac{y^2}{2\sigma_y^2} \right) \left[ \exp\left( -\frac{(z-He)^2}{2\sigma_z^2} \right) + \exp\left( -\frac{(z+He)^2}{2\sigma_z^2} \right) \right] \]  

(3.1)

<table>
<thead>
<tr>
<th>Table 3.1: Dispersion equation symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
</tr>
<tr>
<td>( C )</td>
</tr>
<tr>
<td>( x, y, z )</td>
</tr>
<tr>
<td>( He )</td>
</tr>
<tr>
<td>( Q )</td>
</tr>
<tr>
<td>( u )</td>
</tr>
<tr>
<td>( \sigma_y )</td>
</tr>
<tr>
<td>( \sigma_z )</td>
</tr>
</tbody>
</table>

3.1.2 Gravitational Subsidence Equation

Gravitational subsidence uses Stokes equation (Equation 3.2).

This equation assumes that the particles are spherical. Non-spherical particles normally have slower gravitational subsidence velocities. Table 3.3 gives reference values for the
resistance correction coefficient, $\alpha^*$, which indicates a particle’s relative air resistance, for several particulate forms. Equation 3.2 is multiplied with the inverse of the resistance correction coefficient, for each particulate form, to arrive at the particulate’s subsidence velocity.

$$V_s = 2r^2 \frac{\rho_p g}{9 \mu \rho_a}$$  \hfill (3.2)

<table>
<thead>
<tr>
<th>Table 3.2: Gravitational subsidence equation (Stokes equation) symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>$V_s$</td>
</tr>
<tr>
<td>$r$</td>
</tr>
<tr>
<td>$\rho_p$</td>
</tr>
<tr>
<td>$\rho_a$</td>
</tr>
<tr>
<td>$\mu$</td>
</tr>
<tr>
<td>$g$</td>
</tr>
</tbody>
</table>

Table 3.3: Resistance correction coefficient, $\alpha^*$, for several particulate forms

<table>
<thead>
<tr>
<th>Form</th>
<th>Axis-to-Length Ratio</th>
<th>$\alpha^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical</td>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>Ellipsoidal</td>
<td>4</td>
<td>1.28</td>
</tr>
<tr>
<td>Cylindrical 1</td>
<td>1</td>
<td>1.06</td>
</tr>
<tr>
<td>Cylindrical 2</td>
<td>4</td>
<td>1.32</td>
</tr>
<tr>
<td>Triangular</td>
<td>–</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Figure 3.1 illustrates the relationship between the gravitational subsidence velocity and particle diameters between 0 and 80 $\mu$m.
3.1.3 Plume-Centerline-Height Reduction and Particulate Deposition Equation
Calculation results for gravitational subsidence are obtained with the next two equations.

(1) Plume-centerline-height reduction
The reduction in the plume centerline height due to gravitational subsidence is accounted for with the following equation.

\[ He \rightarrow He - \frac{V_s x}{u} \] (3.3)

Table 3.4: Particulate subsidence equation symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>Effective plume-rise height (the height evaluated with METI-LIS)</td>
</tr>
<tr>
<td>u</td>
<td>Mean wind speed</td>
</tr>
<tr>
<td>x</td>
<td>Downwind distance</td>
</tr>
<tr>
<td>(V_s)</td>
<td>Particulate subsidence velocity</td>
</tr>
</tbody>
</table>

(2) Particulate deposition equation
The amount of the substance in the atmosphere released in a given period declines over time because some of the settled particulate matter is absorbed by the surface. The deposition volumes and the atmospheric pollutant phenomena caused by deposition are accounted for here with the dry deposition correction equation given below, taken from the manual on
forecasting suspended particulate pollutants. This model introduces a correction coefficient \( \alpha \) and expresses the deposition effect through an additional term in the dispersion equation.

\[
C(x, y, z) = \frac{Q}{2 \pi \sigma_x \sigma_z u} \exp\left(-\frac{y^2}{2 \sigma_y^2}\right) \left[ \exp\left(-\frac{(He - V_x x / u - z)^2}{2 \sigma_z^2}\right) + \alpha(x) \exp\left(-\frac{(He - V_x x / u + z)^2}{2 \sigma_z^2}\right) \right]
\]

\((3.4)\)

\[
\alpha(x) = 1 - \frac{2V_d}{V_x + V_d + (uHe - V_x x) / \sigma_z \times (d \sigma_z / dx)}
\]

\((3.5)\)

\[
V_d = V_x + 0.006u
\]

\((3.6)\)

\[
FLUX = V_d C(x, y, z_{ref})
\]

\((3.7)\)

### Table 3.5: Particulate deposition equation symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q)</td>
<td>Volume of emitted particulate</td>
</tr>
<tr>
<td>(C)</td>
<td>Concentration</td>
</tr>
<tr>
<td>(x, y)</td>
<td>Coordinates ((x) represents the downwind axis)</td>
</tr>
<tr>
<td>(z_{ref})</td>
<td>Reference height</td>
</tr>
<tr>
<td>FLUX</td>
<td>Deposition volume of the pollutant</td>
</tr>
<tr>
<td>(u)</td>
<td>Mean wind speed</td>
</tr>
<tr>
<td>(V_d)</td>
<td>Dry deposition velocity</td>
</tr>
</tbody>
</table>

#### 3.2 Line Source Model

#### 3.2.1 Dispersion Equation

Sources with line-shaped characteristics are found by numerically integrating the point-source plume equation, Equation 3.8.

\[
C(x, y, z) = \frac{Q}{2 \pi \sigma_y \sigma_z u} \exp\left(-\frac{y^2}{2 \sigma_y^2}\right) \left[ \exp\left(-\frac{(z - He)^2}{2 \sigma_x^2}\right) + \exp\left(-\frac{(z + He)^2}{2 \sigma_x^2}\right) \right]
\]

\((3.8)\)
Table 3.6: Dispersion equation symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Concentration</td>
</tr>
<tr>
<td>x, y, z</td>
<td>Coordinates</td>
</tr>
<tr>
<td>He</td>
<td>Effective plume-rise height (= 0)(^{10})</td>
</tr>
<tr>
<td>Q</td>
<td>Volume of emission per unit distance and unit time (example: kg/km/hr)</td>
</tr>
<tr>
<td>u</td>
<td>Wind speed</td>
</tr>
<tr>
<td>(\sigma_y)</td>
<td>Horizontal dispersion width (P-G curve)</td>
</tr>
<tr>
<td>(\sigma_z)</td>
<td>Vertical dispersion width (P-G curve)</td>
</tr>
</tbody>
</table>

3.2.2 Setting the Initial Dispersion Width

Because there is very limited knowledge about the horizontal dispersion widths observed near roadways, this model sets the horizontal dispersion width to the target road width divided by 2.15, as given in the ISC3 line-source calculation schema released by the US Environmental Protection Agency.

The former Ministry of Construction conducted experiments on vertical dispersion widths and verified that there was little change due to meteorological conditions. Based on this conclusion, the model sets the initial vertical dispersion width to 3.5 meters.

3.2.3 Numerical Integration Method

There are several methods to integrate the point-source plume equation numerically. The most widely used method in practice is the Simpson formula of finding numerical integrals.

(1) \textit{Simpson formula}

The Simpson formula approximates a function piecewise with a second-order polynomial equation and integrates this approximation equation analytically. For example, after approximating the function \(f(x)\) defined for the segment \([x_1, x_2]\) with a second-order equation that passes through the segment’s endpoints and center point, the definite integral value found analytically is given by:

\[
\frac{x_2 - x_1}{6} \left( f(x_1) + 4f\left(\frac{x_1 + x_2}{2}\right) + f(x_2) \right)
\]

(2) \textit{Calculation technique}

By repetitively dividing segments and using the Simpson formula, a definite integral value can be found within the limits of the computer’s precision.\(^{11}\) Referring to “Numerical Recipes in C”.

\(^{10}\) The height of line sources and their effective height are both assumed to be 0.

\(^{11}\) The calculation precision of a 32-bit machine is limited by relative error to about 10\(^{-6}\) (from “Numerical Recipes in C”).
in C”, the calculation program finds the definite integral value \( \int_{a}^{b} f(x) \, dx \) for the function \( f(x) \) defined for the segment \([a, b]\) with the following formula:

\[
f_i = f \left( a + \frac{b-a}{N-1}(i-1) \right) i = 1, \ldots, N
\]

\[
S_N = \frac{b-a}{N} \left[ \frac{1}{2} f_1 + f_2 + f_3 + \cdots + f_{N-1} + \frac{1}{2} f_N \right]
\]

\[
\int_{a}^{b} f(x) \, dx \approx \frac{4}{3} S_{2N} - \frac{1}{3} S_N
\]

(3) Setting termination error tolerance

When the numerical integral value is nearly constant even as the integral points are increased, the calculation is considered to have converged. Numerically, the calculation is considered converged when the following inequality is satisfied.

\[
| \text{curr} - \text{prev} | < \text{TOL} \times \frac{| \text{curr} | + | \text{prev} |}{2}
\]

- \text{curr} : Current numerical integral value
- \text{prev} : Previous numerical integral value
- \text{TOL} : Preset termination error tolerance

In theory, the Simpson formula can find a real value to the limits of the computer’s precision. This program, however, recommends the termination error tolerance to 0.03 in the interest of saving calculation time.
Appendices

A. Validation using Wind Tunnel Experiment Data

1. Simple Model Building

The METI-LIS model was established through the improvement of the ISC model based on a series of wind tunnel dispersion experiments. These experiments were carried out with various configurations of unit cubes as model buildings. In this section, results of simplest configurations of buildings are compared with those calculated by the METI-LIS and the ISC models. The result is shown in Figure A1-1. Correlations between the observed and calculated concentrations are better for the METI-LIS, because newly introduced model parameters were determined on the basis of these experiments. Actually many other results with more complex building configurations were reflected in the model development, while they are not shown here.
Figure A1-1 Comparison of wind tunnel (x-axis) and simulated concentrations (y-axis) for simple cases. left: ISC, right: METI-LIS
2. A Factory Model

In the final stage of the METI-LIS model development, wind tunnel experiment using a realistic model of an existing factory was carried out to examine estimation accuracy of the METI-LIS model and adequacy of operation method. Here, the operation method means a total of such methods as to select a building which induces downdraft most largely, to extract building size parameters, to judge whether the configuration is building column or building cluster, and so on.

Model area was a part of K Plant of M Chemical Co., Ltd. (Figure A2-1(a)) located in the Kanto Plain. Model scale in the wind tunnel was 1/200. Major tanks and towers near source were modeled accurately, but other pipeline structures located further away were approximated to rectangular solid shape.

Wind condition of the experiment was set as NE +14deg (wind direction) 2.9m/s (wind speed). The roughness condition of windward side of wind tunnel observation point was set with similar condition of model experiment with simple building, which means air flow over flat land corresponding to dispersion width of C to D. Also, experiment with 2 different source heights (Zs) was carried out because many parameters of the METI-LIS model were given as a function of dimensionless stack height (Zs/HB), and such variation was thought to be necessary when evaluating the METI-LIS model. Zs was set at 7m and 21m, because surrounding buildings were 15 to 20m height. By this setting, Zs and HB is similar in height and therefore Zs/HB = approx 1.

Five main buildings near the source were selected to examine adequacy of operation method of the METI-LIS model. The selected buildings 1 to 5, shown in Figure A2-1(b), were approximated to rectangular solid shapes. Their sizes are shown in Table A2-1.

<table>
<thead>
<tr>
<th>Building</th>
<th>Building Width $W_b$ (m)</th>
<th>Building Height $H_b$ (m)</th>
<th>$W_b \times H_b$ (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
<td>16</td>
<td>512</td>
</tr>
<tr>
<td>2</td>
<td>46</td>
<td>20</td>
<td>920</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>20</td>
<td>660</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
<td>12</td>
<td>444</td>
</tr>
<tr>
<td>5</td>
<td>58</td>
<td>23</td>
<td>1,334</td>
</tr>
</tbody>
</table>
Each of buildings 1 to 5 were entered one by one into the METI-LIS model and the original ISC model. Calculation of the METI-LIS model followed the method of modeling as a large building cluster in each case. The calculated concentrations and experiment concentrations were compared to study the trend.

The result is shown in Figure A2-2 through A2-5. In either cases with stack height of 7m and 21m, the following can be seen.

(1) The METI-LIS model improved in estimation accuracy than the original ISC model, judging from coefficient of correlation and correlation diagram.

(2) Of buildings 1 to 5, selection of building 5 has the highest estimation accuracy, judging from coefficient of correlation and correlation diagram.

According to operation method\textsuperscript{12}, “the building that influence most on dispersion field” is selected as follows. First, every building is examined if it can have influence. Here, buildings 2 and 4 are eliminated. Next, GEP stack height is examined. The largest is building 5 and this result corresponds with the best fitting result of the METI-LIS simulation, as stated in (2).

From the comparison of the wind tunnel experiment and one-by-one simulation by the METI-LIS both applied to the plant layout, it is confirmed that the operation method adopted in the METI-LIS is adequate when only one building has to be selected.

\textsuperscript{12} See 2.5.2 Calculation Steps.

Figure A2-1(a) Structure configuration in K-plant.
Figure A2-1(b) Major five structures around the source in K-plant.
This area corresponds to the thick rectangular part in (a).
<table>
<thead>
<tr>
<th>Set buiding</th>
<th>ISC</th>
<th>METI-LIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>#2</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td>#3</td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>#4</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
</tr>
<tr>
<td>#5</td>
<td><img src="image9.png" alt="Graph" /></td>
<td><img src="image10.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

Figure A2-2 Comparison of wind tunnel (x-axis) and simulated concentrations (y-axis) for the source height of 7m. left: ISC, right: METI-LIS
<table>
<thead>
<tr>
<th>Set building</th>
<th>ISC</th>
<th>METI-LIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td><img src="image" alt="ISC comparison" /></td>
<td><img src="image" alt="METI-LIS comparison" /></td>
</tr>
<tr>
<td>#2</td>
<td><img src="image" alt="ISC comparison" /></td>
<td><img src="image" alt="METI-LIS comparison" /></td>
</tr>
<tr>
<td>#3</td>
<td><img src="image" alt="ISC comparison" /></td>
<td><img src="image" alt="METI-LIS comparison" /></td>
</tr>
<tr>
<td>#4</td>
<td><img src="image" alt="ISC comparison" /></td>
<td><img src="image" alt="METI-LIS comparison" /></td>
</tr>
<tr>
<td>#5</td>
<td><img src="image" alt="ISC comparison" /></td>
<td><img src="image" alt="METI-LIS comparison" /></td>
</tr>
</tbody>
</table>

Figure A2-3 Comparison (in logarithmic scale) of wind tunnel (x-axis) and simulated concentrations (y-axis) for the source height of 7m. left: ISC, right: METI-LIS
Figure A2-4 Comparison of wind tunnel (x-axis) and simulated concentrations (y-axis) for the source height of 21m. left: ISC, right: METI-LIS
Figure A2-5 Comparison (in logarithmic scale) of wind tunnel (x-axis) and simulated concentrations (y-axis) for the source height of 21m. left: ISC, right: METI-LIS
B. Validation using Available Results of Field Experiment

1. Millstone Experiment

Documents of air dispersion phenomena influenced by buildings are collected, and examined the field dispersion experiments and wind tunnel experiments in the past. Existing field observation data\(^1\) from overseas were applied to the METI-LIS model to examine the accuracy. By applying field data to the METI-LIS and ISC model, it was confirmed that the METI-LIS model has more accuracy than the ISC model. In this section, such results are described.

The field observation data used for examination were from survey at Millstone Nuclear Power Station in United States. The observed concentrations were in hourly average, whereas the METI-LIS and the ISC models use 3-10 minute average. The concentrations of the METI-LIS and the ISC models were corrected to hourly average by using the following simple correction method.

Set concentration distribution calculated with representative wind direction as \(C\). Shift the wind direction (right and left) by standard deviation of wind direction within 1 hour. Set calculated concentration with the shifted wind directions as \(C^+\) and \(C^-\). The wind frequency of \(C\), \(C^+\), and \(C^-\) were used to calculate the weighted average of concentration, which represent the hourly average.

Specifically, the equation below is used.

\[
C_{1hr} = \left( C + 0.61 x C^+ + 0.61 x C^- \right) / (1+0.61+0.61)
\]

Here, 0.61 is the frequency of shifted wind direction by amount of standard deviation; while frequency of representative wind direction is set as 1.

Gas tracer study (SF\(_6\)) was carried out in field observation of Millstone Nuclear Power Station to examine the downwash influence by buildings. Dispersion source is the vent (\(Vg^{14}/U\) is roughly 1) set at the roof of reactor building (UNIT2). Total of 36 cases were observed. As shown in figure B1-1, the samples were taken in 3 rows in arc shape from the source location (approximately 350m, 800m and 1,000m leeward of the source). From 36 cases, 8 cases were chosen that thought to have small fluctuations in wind direction and stability of neutral condition. In calculation, reactor building (UNIT2) was selected as the main building.

Compared result is shown in Figure B1-2 and Table B1-2. Meteorological condition is

\(^{14}\) \(Vg\) indicates exit gas velocity.
shown in Table B1-1.

The METI-LIS model has larger correlation coefficient than the ISC model. Cases that thought to have high estimation accuracy had actually high estimation accuracy. For cases that the ISC model did not have good agreement, the METI-LIS had greater accuracy than the ISC model.

However, numerical weighted average used in this study is a simple method, and it does not imitate the actual wind direction fluctuations. While inspecting accuracy, it is necessary to consider that such uncertainties and problems remain.

Table B1-1 Field observation conditions in Millstone Nuclear Power Station

<table>
<thead>
<tr>
<th>RUN No.</th>
<th>Date</th>
<th>Time</th>
<th>Wind Direction (deg)</th>
<th>Sigma_{\theta_b} (deg)</th>
<th>Wind Speed at Stack height</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1974/10/25</td>
<td>12:00</td>
<td>204.0</td>
<td>2.4</td>
<td>11.7</td>
<td>D</td>
</tr>
<tr>
<td>16</td>
<td>1974/10/25</td>
<td>13:00</td>
<td>198.0</td>
<td>3.0</td>
<td>11.4</td>
<td>D</td>
</tr>
<tr>
<td>17</td>
<td>1974/10/25</td>
<td>14:00</td>
<td>203.0</td>
<td>3.0</td>
<td>11.7</td>
<td>D</td>
</tr>
<tr>
<td>18</td>
<td>1974/10/25</td>
<td>15:00</td>
<td>208.0</td>
<td>2.8</td>
<td>11.4</td>
<td>D</td>
</tr>
<tr>
<td>51</td>
<td>1974/11/14</td>
<td>9:00</td>
<td>190.0</td>
<td>3.8</td>
<td>11.3</td>
<td>D</td>
</tr>
<tr>
<td>52</td>
<td>1974/11/14</td>
<td>10:00</td>
<td>187.0</td>
<td>2.7</td>
<td>12.5</td>
<td>D</td>
</tr>
<tr>
<td>53</td>
<td>1974/11/14</td>
<td>11:00</td>
<td>185.0</td>
<td>2.3</td>
<td>12.4</td>
<td>D</td>
</tr>
<tr>
<td>54</td>
<td>1974/11/14</td>
<td>12:00</td>
<td>184.0</td>
<td>2.2</td>
<td>12.4</td>
<td>D</td>
</tr>
</tbody>
</table>

Table B1-2 Comparison of the METI-LIS model and the ISC model
(Location: Millstone) (Hourly values)

<table>
<thead>
<tr>
<th>RUN No.</th>
<th>ISC Model</th>
<th>METI-LIS Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correlation Coefficient</td>
<td>Regression Equation</td>
</tr>
<tr>
<td>15</td>
<td>0.848</td>
<td>y=0.2531x+2.0898</td>
</tr>
<tr>
<td>16</td>
<td>0.925</td>
<td>y=0.2178x+1.5595</td>
</tr>
<tr>
<td>17</td>
<td>0.849</td>
<td>y=0.2121x+1.9996</td>
</tr>
<tr>
<td>18</td>
<td>0.697</td>
<td>y=0.2296x+2.8369</td>
</tr>
<tr>
<td>51</td>
<td>0.722</td>
<td>y=0.1804x+2.8499</td>
</tr>
<tr>
<td>52</td>
<td>0.713</td>
<td>y=0.1724x+2.8450</td>
</tr>
<tr>
<td>53</td>
<td>0.700</td>
<td>y=0.1639x+3.0306</td>
</tr>
<tr>
<td>54</td>
<td>0.658</td>
<td>y=0.1333x+3.6546</td>
</tr>
</tbody>
</table>

(*) Fluctuation coefficient: Smaller the fluctuation coefficient = Higher accuracy.
Figure B1-1(1) Layout of field observation at Millstone Nuclear Power Station
Figure B1-1(2) Layout of buildings of field observation at Millstone Nuclear Power Station
Figure B1-2(1) Comparison of field observation at Millstone Nuclear Power Station (x-axis) and simulated concentrations (y-axis). Left: ISC, right: METI-LIS.
Figure B1-2(2) Comparison of field observation at Millstone Nuclear Power Station (x-axis) and simulated concentrations (y-axis). Left: ISC, right: METI-LIS

<table>
<thead>
<tr>
<th>Millstone</th>
<th>ISC</th>
<th>METI-LIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run51</td>
<td><img src="image1" alt="ISC Graph" /></td>
<td><img src="image2" alt="METI-LIS Graph" /></td>
</tr>
<tr>
<td>Run52</td>
<td><img src="image3" alt="ISC Graph" /></td>
<td><img src="image4" alt="METI-LIS Graph" /></td>
</tr>
<tr>
<td>Run53</td>
<td><img src="image5" alt="ISC Graph" /></td>
<td><img src="image6" alt="METI-LIS Graph" /></td>
</tr>
<tr>
<td>Run54</td>
<td><img src="image7" alt="ISC Graph" /></td>
<td><img src="image8" alt="METI-LIS Graph" /></td>
</tr>
</tbody>
</table>
2. Tsurumi Experiment

Evaluation of accuracy of the METI-LIS model was carried out by using outdoor observed data of Tsurumi, located in Kanagawa prefecture in Japan\textsuperscript{15}. However, concentration in the METI-LIS model and the ISC model is average of time span 3 to 10 minutes, whereas field observations are approximately 1 hour. To solve such problem, calculations of the METI-LIS model and the ISC model were carried out using 6 data of 10 minute average of meteorology data. Average of 6 calculated data represents hourly average of the models. This hourly averages of the models are compared with field observation data.

In field observation in Tsurumi, gas tracer experiment is applied to examine the influence of downwash from buildings. Temporary building (height 4.9m, width 9.8m, length 2.4m) was set at plane field and gas tracer SF\textsubscript{6} is released from point source set at upper-middle edge of leeward plane of the building. Concentrations are collected at points from 6 circular arc (leeward: approximately 10m, 20m, 30m, 45m, 100m) as shown in Figure B2-1.

Total of 8 observation cases were carried out. From the 8 cases, case RUN8, with nearly neutral stability, and wind blowing directly toward the building (angle of the wind and building plane is 90 degrees), was chosen to examine the estimation accuracy. Results of comparisons are shown in Figure B2-2. Also, meteorology data of field observation is shown in Table B2-1.

From the results, Coefficient of Correlation of the METI-LIS model was larger than the ISC model. Improvement of the estimation accuracy was confirmed (Table B2-2).

\textsuperscript{15} Industrial Pollution Control Association of Japan: Research report for development of NOx dispersion simulation in urban area. -Gas Tracer Dispersion Study, 1991
Table B2-1 Gas tracer observed at Tsurumi used for dispersion experiment condition

<table>
<thead>
<tr>
<th>RUN No.</th>
<th>DATE</th>
<th>TIME</th>
<th>Wind Direction (deg)</th>
<th>Wind Speed (10m above ground)</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN8</td>
<td>1991/7/6</td>
<td>14:30~14:40</td>
<td>143</td>
<td>3.7</td>
<td>Neutral(C-D)</td>
</tr>
<tr>
<td></td>
<td>1991/7/6</td>
<td>14:40~14:50</td>
<td>136</td>
<td>4.0</td>
<td>Neutral(C-D)</td>
</tr>
<tr>
<td></td>
<td>1991/7/6</td>
<td>14:50~15:00</td>
<td>134</td>
<td>4.3</td>
<td>Neutral(C-D)</td>
</tr>
<tr>
<td></td>
<td>1991/7/6</td>
<td>15:00~15:10</td>
<td>140</td>
<td>3.8</td>
<td>Neutral(C-D)</td>
</tr>
<tr>
<td></td>
<td>1991/7/6</td>
<td>15:10~15:20</td>
<td>141</td>
<td>3.4</td>
<td>Neutral(C-D)</td>
</tr>
<tr>
<td></td>
<td>1991/7/6</td>
<td>15:20~15:30</td>
<td>149</td>
<td>3.6</td>
<td>Neutral(C-D)</td>
</tr>
</tbody>
</table>

Stability was set as D for calculation.

Table B2-2 Comparison of the METI-LIS model and the ISC model
(Location: Tsurumi, hourly data)

<table>
<thead>
<tr>
<th>RUN No.</th>
<th>ISC Model</th>
<th>METI-LIS Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC Regression</td>
<td>CV</td>
</tr>
<tr>
<td>Run8</td>
<td>0.684 y=0.2536x+308</td>
<td>0.929</td>
</tr>
</tbody>
</table>

CC: Coefficient of Correlation
CV: Coefficient of Variance
Figure B2-1 Outdoor Experiment Configuration in Tsurumi
<table>
<thead>
<tr>
<th>Location: Tsurum</th>
<th>ISC Model</th>
<th>METI-LIS Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN8 (Logarithmic Scale)</td>
<td><img src="image1" alt="ISC Model Graph" /></td>
<td><img src="image2" alt="METI-LIS Model Graph" /></td>
</tr>
<tr>
<td>RUN8 (Linear Scale)</td>
<td><img src="image3" alt="ISC Model Graph" /></td>
<td><img src="image4" alt="METI-LIS Model Graph" /></td>
</tr>
</tbody>
</table>

Figure B2-2 Comparison of observed data of Tsurumi and the METI-LIS Model: (Hourly data)
C. Outdoor Dispersion Experiment for Validation

The METI-LIS Version 2 (in Japanese) was publicized in December 2003 as a result of improvement of the original version. Accompanying the modification project, we enforced tracer dispersion experiments in four periods, two as a project organized by the New Energy and Industrial Technology Development Organization (NEDO), and the others by the Ministry of Economy, Trade and Industry (METI).

Dispersion observation summary is shown in Table below. Details of observation and validation of the METI-LIS model were organized in database format and it is open to public from the same internet site where the METI-LIS software can be downloaded.

### Outline of field observation by AIST-CRM

<table>
<thead>
<tr>
<th>Experiment Code</th>
<th>Location</th>
<th>Period</th>
<th>Emission Height (m)</th>
<th>Observation Height (m)</th>
<th>Tracer</th>
<th>Number of Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICH-0202-S1</td>
<td>Ichihara-A</td>
<td>Year 2002</td>
<td>6.9</td>
<td>12.0</td>
<td>PMCH(^\text{17})</td>
<td>14</td>
</tr>
<tr>
<td>ICH-0202-S2</td>
<td>Ichihara-A</td>
<td>Feb 26 to 28.</td>
<td>9.0</td>
<td></td>
<td>PMCP(^\text{18})</td>
<td>14</td>
</tr>
<tr>
<td>ICH-0301-S1</td>
<td>Ichihara-B</td>
<td>Year 2003</td>
<td>11.0</td>
<td>15.0</td>
<td>PMCH</td>
<td>13</td>
</tr>
<tr>
<td>ICH-0301-S2</td>
<td>Ichihara-B</td>
<td>Jan 21 to 24</td>
<td>15.0</td>
<td></td>
<td>PMCP</td>
<td>13</td>
</tr>
<tr>
<td>TOY-0302-S1</td>
<td>Toyohashi</td>
<td>Year 2003</td>
<td>15.0</td>
<td>24.5</td>
<td>PDCH(^\text{19})</td>
<td>15</td>
</tr>
<tr>
<td>TOY-0302-S2</td>
<td>Toyohashi</td>
<td>Feb 18 to 20</td>
<td>11.7</td>
<td></td>
<td>PMCP</td>
<td>15</td>
</tr>
<tr>
<td>TOY-0309-S1</td>
<td>Toyohashi</td>
<td>Year 2003</td>
<td>15.0</td>
<td>24.5</td>
<td>PMCH</td>
<td>17</td>
</tr>
<tr>
<td>TOY-0309-S2</td>
<td>Toyohashi</td>
<td>Sep 9 to 11</td>
<td>11.7</td>
<td></td>
<td>PMCP</td>
<td>17</td>
</tr>
</tbody>
</table>

\(^{16}\) 1 experiment is counted as 1 hourly data.
\(^{17}\) PMCH(perfluoromethylcyclohexane) C\(_{7}\)F\(_{14}\)=350.053
\(^{18}\) PMCP(perfluoromethylcyclopentane) C\(_{6}\)F\(_{12}\)=300.045
\(^{19}\) PDCH(perfluoro- dimethylcyclohexane) C\(_{8}\)F\(_{16}\)=400.060
Calculation result of the METI-LIS were satisfying for consistency with respect to horizontal dispersion width but had tendency to over estimate in the experiment series TOY-0302-S2, TOY-0309-S1, and TOY-0309-S2. The over estimation seems to be due to inconsistency of the correction of effective stack height and/or evaluated dispersion width in vertical direction. For remaining experiment cases, rather good results were obtained.

When using outdoor dispersion experiment database, it is proved statistically that the METI-LIS and the ISCST3 models have similar accuracy. In the METI-LIS, the result from wind tunnel experiment considering low rise emission source and downdraft effect of building(s) are incorporated. By this reinforcement, downdraft correspondence process of ISC model is strengthened in the METI-LIS model. From observation result, predominance of the METI-LIS over the ISC model was not clearly shown, but similar accuracy of the 2 models are proven. Since innumerable variations can exist in actual configuration of surrounding buildings near emission source, further use and evaluation of the METI-LIS are expected.

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20 ppq = 10^{-12}