October 28, 1983

STATE OF ILLINOIS)
) SS.
COUNTY OF COOK)

UNITED STATES OF AMERICA

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

In the Matter of CONSUMERS POWER COMPANY (Midland Plant, Units 1 and 2)	Docket Nos. 50-329 OM 50-330 OM 50-329 OL 50-330 OL

AFFIDAVIT OF JOHN P. BRADLEY

My name is John P. Bradley. I have previously been a witness in this proceeding and my professional qualifications are in the record. I swear that the statements made in the attached Affidavit are true and correct to the best of my knowledge and belief.

John P. Bradley
John P. Bradley

Signed and sworn to
before me this 19th
day of October, 1983.

Dennis W. Trettel
NOTARY PUBLIC

October 28, 1983

AFFIDAVIT OF JOHN P. BRADLEY
ON STEAM FOG DEPLETION BY TREES

I. PURPOSE OF AFFIDAVIT

During the hearings held on March 9 and 10, 1983, the Atomic Safety and Licensing Board inquried of witnesses for both the Applicant and the NRC Staff whether it would be useful and cost effective for Applicant to plant a stand of trees in the near future along Gordonville Road to mitigate the effects of fog from the Midland plant cooling pond on the road. Tr. 12620, 12792. This affidavit considers the type, location and depth of trees that should be planted along Gordonville Road to be effective in fog depletion or as a fog barrier.

II. THE AVAILABLE LITERATURE

Very little has been written on the subject of fog depletion by trees. Of the several books available on fog,[1/] only one volume (Studies on Fogs In Relation to Fog-Preventing Forest, edited by Takeo Hori and published by

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[1/] In addition to the book discussed in the text, the following books may provide useful information:

Theory of Fog Condensation, by A.G. Amelin, published by the Israel Program for Scientific Translations, 1967;

Fog, by Alexander McAdie, published by MacMillan Company, 1934;

Studies on Ice Fog, Final Report, by Takeshi Ohtake, published by the National Center for Air Pollution Control, 1970;

Physics of Precipitation, edited by Helmut Weickmann, published by American Georgraphical Union, 1960.

Tanne Trading Co., Ltd., in 1953) proves to apply to the area of interest, and only two articles contained within that volume ("A Theoretical Study on the Changes of Liquid Water Contents of Intruding Stationary Sea Fogs Due to the Capturing Action of a Forest in the Coastal Region", by Takaharu Fukutomi; and "On the Capture of Fog Particles by a Forest", by Hirobumi Oura) actually provide information helpful in estimating the usefulness of planting trees between the Midland Plant cooling pond and nearby Gordonville Road as a way of reducing the effect of the fog produced by the cooling pond on the road.2/

III. APPLICATION OF THE LITERATURE TO THE MIDLAND SITE

In order to apply the Fukutomi data to the Midland plant, we must make the assumption that the fogs caused by the cooling pond would have characteristics similar to the sea fogs analyzed in the Fukutomi article. However, it is not clear that this assumption can be made.

One characteristic -- the ambient air-to-water temperature range -- is of particular significance in comparing the source of fogs. Another characteristic -- the degree to which the ambient air temperature drops below the freezing point of water -- is of particular significance in comparing the effectiveness of trees in removing fog.

2/ Copies of these articles are appended hereto as Attachments 1 and 2, respectively.

With respect to the first characteristic, the air-to-water temperature range, the Fukutomi article does not set forth the sea water or ambient air temperatures that occurred during the course of the field studies. However, there are certain climatological expectations for Hokkaido, Japan, the area in which the studies were conducted. The mean sea water temperature in this location varies from 70°F. to 40°F. from summer to winter. The mean air temperature varies from 70°F to 20°F from summer to winter.[3/] These figures differ from the anticipated Midland cooling pond surface temperature range of from 98.3°F to 70.9°F from summer to winter[4/] and from the anticipated Midland site ambient air temperature range of from 66.2°F to 23.0°F from summer to winter.[5/] It appears, therefore, that the air/water temperature contrasts experienced during the Hokkaido field studies were not as great as those expected at the Midland site. With a sufficiently low ambient air temperature, the

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3/ <u>See</u> Bernhard Haurwitz and James M. Austin, <u>Climatology</u>, <u>plates 1 and 2, (McGraw-Hill Book Company, Inc. 1944)</u>

4/ <u>See</u> the Final Environmental Statement related to the operation of Midland Plant, Units 1 and 2, Nureg-0537, Table 4.2, p. 4-25. The figures in the text are seasonal averages derived from the Table 4.2 monthly average cooling pond surface temperatures assuming that Unit 1 is back end limited and Unit 2 is operating with its "valves wide open" -- an operating mode yielding the greatest heat rejection to the pond.

5/ <u>See</u> Midland Plant, Units 1 and 2, Final Environmental Report, Table 2.3-7. The figures in the text are seasonal averages derived from the monthly averages given in Table 2.3-7.

larger air-to-water temperature contrast at Midland could produce fog in greater frequency and of greater duration than at Hokkaido. And, it is also possible that a "thicker" (more liquid water droplets per unit volume) fog might be produced at Midland because of the larger air-to-water temperature contrast.

A significant characteristic in comparing the effectiveness of trees in removing fog is the ambient air temperature in which the fog is formed. Generally, at air temperatures above the freezing point of water, fog water droplets can be captured by stands of needle-leaved trees (see the discussion of the Oura findings, below). However, as the air temperature drops below freezing, the fog water droplets, while remaining liquid, become supercooled, and tend to plate out as rime ice when contacting vertical objects having sharp edges (see Tr. 12567-12569 for a definition of rime ice and a description of its formation). All other things remaining equal, rime ice formation becomes more likely the further the air temperature drops below freezing.

The formation of rime ice could close up air spaces between the needles of the fog sweeping evergreens, thus reducing the effectiveness of the trees in removing additional fog droplets. Winter air temperatures at the Midland site drop below 0°F on occasion, whereas this extreme might not have occurred during the Hokkaido field studies. Therefore, it is possible that the Hokkaido data reflects a greater ability of needle-leaved trees to remove fog particles than would be likely at the Midland site.

To apply the Fukutomi data to the Midland site, we must assume that the theoretical capturing coefficient graph given in the Fukutomi article[6/] is applicable to the forests described in Oura's paper, and that the postulated Midland tree plantings would sweep the fog in a manner similar to the Oura forests. If these additional assumptions are entertained, we can interpolate values for the Midland site from the Fukutomi capturing coefficient graph, which plots the liquid water content of fog versus the downwind difference into the stand of trees. The liquid water content is expressed as the ratio of the downwind liquid water content to the upwind liquid water content. All other factors remaining equal, the liquid water content may be (roughly) correlated with visibility, since the latter is proportional to the number of water droplets per unit volume of fog.

Oura's article describes the most efficient type of tree stand for reducing liquid water content as a comparatively sparse (0.18 tree/m^2) forest of needle-leaved trees, where the trees are approximately 12 meters tall with no lower branches. The affidavit of Clemens R. Nefe, filed concurrently with this affidavit, describes a postulated planting of White Spruce, Norway Spruce, Austrian Pine and Red Pine that compares favorably with this "sparse" forest so long as the planting reaches and is maintained at the height and density described by Oura. Unfortunately, this

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6/ See p. 101 of the Fukutomi article, appended hereto as Attachment 1.

would not likely be the case. Until the planting matures, the low height and small diameter of the trees would render the planting almost useless as a fog depletion device; fog could easily pass between or over the immature trees with little or no liquid water content reduction. And, as is indicated in Mr. Nefe's affidavit, the trees would not reach the approximate 40 foot height with touching crowns discussed by Oura until the end of the Midland plant's operating life.

Moreover, to eventually achieve the comparatively sparse characteristic of the most effective Oura-described forest, thinning of the Midland planting would be necessary. Unfortunately, thinning would produce large gaps through which fog could pass undepleted. Conversely, a failure to thin would likely lead to a reduction of fog depletion efficiency as the stand grew more dense.[7]

Fukutomi concludes that the less dense the fog and the greater the depth of the forest, the more effective the capturing action of the forest. Thus, a lack of available space for tree plantings at the Midland site would perhaps

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[7] Oura indicates that a forest of properly spaced but comparatively sparse (0.18 tree/m^2) needle-leaved trees is more effective in capturing fog particles than a thickly wooded (0.71 tree/m^2) forest of similar trees. This appears to be because the sparse forest allows the fog droplets to fully circulate, making it more likely that the droplets will be swept out by the needles. A thicker forest provides more of an obstacle to the fog droplets, and presents less over-all surface area for the sweeping action because the fog cannot easily penetrate the stand.

be the most significant factor in determining the effectiveness of such plantings for fog depletion. If the proper tree types were planted at Midland, and if the Japanese data is in fact applicable to the site, a 50-foot deep planting of approximately 40 foot tall trees spaced 0.18 tree/m^2 spanning the entire southern portion of the cooling pond might yield a roughly 10 to 15 percent reduction in the liquid water content of the fog before it reached Gordonville Road.[8/] Unfortunately, the affidavit of David A. Sommers, filed concurrently with this affidavit, indicates that, because of a Midland County Road Commission right-of-way and easement, a Dow pipeline easement, drainage ditches, a security fence and the need to keep the slope of the cooling pond dike free from penetrating root systems, the available space for tree plantings at Midland is limited to an average minimum depth of 8 feet. Even assuming that the trees were of the proper height and spacing, a planting of this shallow depth could not approach the 10 to 15 percent fog depletion discussed above.

In the affidavit of David A. Sommers, a postulated maximum tree planting varying from 68 to 109 feet in depth is discussed. Based on an interpolation of the Fukutomi capturing coefficient graph, the relative effectiveness of this postulated planting would vary from 15 to 25 percent.

8/ This calculation is derived from an interpolation of the Fukutomi capturing coefficient graph yielding downwind to upwind liquid water content ratios of 0.85 to 0.90, respectively.

Again, these percentages assume approximately 40 foot tall trees spaced 0.18 tree/m^2. Shorter trees and/or different spacing would yield lower percentages.

It has been suggested that a stand of trees could be planted to act as a fog "barrier", deflecting rather than capturing fog particles and providing an effect similar to a fog screening fence.[9] Such a barrier might deflect steam fog generated by the cooling pond upward and away from Gordonville Road. However, to have such an effect, the planting would have to consist of a thick (both in depth and closeness together) stand of fully mature trees located as close as possible to the side of the road. In this location, the trees could pose a greater driving hazard than fog: ice accumulating on branches could fall on the road surface, and motorists running off the roadway would be in danger of hitting a tree. Moreover, because of the Midland County Road Commission right-of-way and easement and the Dow easement discussed in the affidavit of David A. Sommers, such a roadside planting is highly unlikely at Midland. Even if it could be properly positioned, the planting would not fully mature until near or after the end of the Midland plant's operating life, and thus would provide little -- if any -- effectiveness as a fog barrier for the greater part of the plant's lifetime.

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[9] For a discussion of the effectiveness of such a fence at Commonwealth Edison Company's Dresden Nuclear Power Station, see Murray and Trettel, Inc., "Report on Steam Fog Impact Engineering at Dresden Nuclear Power Station", Sections 4.6 and 7.2, May 26, 1978. Copies of this report were provided to the parties at the close of the hearing on February 18, 1983. Tr. 12362-12363.

IV. CONCLUSIONS

Certain types of trees have been found to be effective in removing liquid water droplets from air, and the removal efficiency is directly related to the distance through the trees that the water-bearing fog travels. If we could assume that the observations of Fukutomi and Oura are directly applicable to the Midland site, we could expect a best-case liquid water content reduction (and hence, visibility improvement) of approximately 10 to 15 percent for a 50-foot deep planting of approximately 40 foot tall trees spaced 0.18 tree/m^2. A 68 to 109 foot deep planting of trees the same height and spacing could yield approximately a 15 to 25 percent liquid water content reduction. Unfortunately, because it is not clear that the Japanese data is analogous to the Midland site, and because only a limited amount of space is probably available for the planting of trees that would, in any event, not fully mature until the end of the plant's operating life, fog depletion from a postulated planting at Midland would most likely be negligible for the better part of the plant's life expectancy. Moreover, a thick stand of trees would probably be equally ineffective as a fog barrier. It is highly unlikely that Consumers Power Company would be able to plant such trees close enough to the edge of Gordonville Road to be effective, and, in any event, the trees would simply not be tall enough for a large portion of the plant's operating life.

about 10 times as large as the former (cf. Ôura [2]*). Large value of n makes a large contribution to temperature rise Δf in favor of the evaporation of fog, but in such a way that, while it is rather small near the seashore, it grows rapidly in magnitude as the distance from the seashore increases (notice the functional form: $\sqrt{x^2 f_1(t)}$). That is to say, the temperature rise that might be caused by forests will become appreciable only when one goes inland a few kilometers from the seashore.

References

[1] *Yosida, Z.* (1952): Diurnal Chang of Air and Ground Temperature on a Foggy Day (in Japanese). Studies on Fog Preventing Forest 2, 143-160.
[2] *Ôura, H.*: On the Capture of Fog Particles by the Forest II; paper (16).
[3] *Kuroiwa, D.*: The Turbulent Diffusion of Fog Water near the Ground and the Fog-Preventing Effect of an Artificial Model Forest; paper (18).
[4] *Huzioka, T., Tabata, T., and Matsumura, N.*: The Distribution of Fog Water Contents around a Forest; paper (13).
[5] *Kozima, K., Ôno, T., and Yamaji, K.*: On the Size Distribution of Fog Particles in the Vicinity of a Fog-Preventing Forest; paper (20).

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* In this connection, reference is to be made to the papers by the following authors: *D. Kuroiwa* [3]; *T. Tabata, T. Huzioka, and N. Matsumura* [4]; *K. Kozima, T. Ôno, and K. Yamaji* [5].

Attachment 1

A Theoretical Study on the Changes of Liquid Water Contents of Intruding Stationary Sea Fogs Due to the Capturing Action of a Forest in the Coastal Region

By Takaharu FUKUTOMI

For the case where a stationary sea fog of finite thickness intrudes perpendicularly into the coastal forest zone, being carried by a horizontal wind, the changes of liquid water contents and air temperature, which are caused by the capturing action of the leaves and branches of woods, by the turbulent motion of air, and by the falling of fog particles due to gravity, are discussed theoretically on the following assumptions:

(1) The air is always saturated with water vapor;
(2) Two layers exist in the air space above the woods; in the lower layer the fog water contents and air temperature are kept constant in the vertical direction owing to the turbulent motion effected by the woods, while in the upper layer the air is less turbulent and has a constant eddy diffusivity equal to that of the intruding air mass;
(3) The wind velocity in each of these layers is constant;
(4) The fog particles are all of the same size and have the same eddy diffusivity as the air and water vapor.

As an application of the theory, a practical example is given in a special case, where the temperature around the forest in question is constant and the particle size is so small that the effect of free falling can b. neglected. The results are illustrated in Figs. 1~8.

§1. Introduction

In the investigations on fog-preventing forest, that were carried out from June to July in 1950 and 1951 at *Ochiishi* Seacoast in *Hokkaido* and in which the members of the Institute of Low Temperature Science and those of *Sapporo* Meteorological Observatory participated with joint efforts, we measured the fog water contents in the windward and the leeward as well as at the top of a forest consisting of conifer trees. From the results obtained, it was inferred that the fog water content was reduced in the leeward as compared with that in the windward. Since, however, the width of the forest ranged only from 100 m to 300 m and the measurement in the leeward was extended not farther than 300 m, we have had no other recourse but to make theoretical inquiries, in order to estimate the distribution of fog water contents for any width of the forest and for any extent in the leeward direction. For this purpose, we conceived of hypothetical models of a forest and of atmospheric layers resting on semi-empirical basis, and examined, through solving the fundamental differential equations, the diminution of fog water contents due to the capturing effect of the forest as well as due to the diffusion to the upper air.

§2. Preliminary Considerations

The problem concerning the prevention of advection fogs by forests and its influence over the inland has once been treated theoretically by *K. Takahashi* [1], which was based on the assumption that the advection fog has infinite thickness and the fog water content φ within the area of the forest is vanishingly small at the ground surface (the height of the forest being left out of account), while on the ground behind the forest no dissipation of fog takes place so that $\frac{d\varphi}{dz}=0$. He dealt mainly with the change of φ behind the forest due to the turbulent diffusion of the fog. His treatment is none the less of interest because it is primitive, since it is a pioneer work in this field.

Actually the condition $\varphi=0$ in the forest is not fulfilled, except at the rear part of a very wide and thick forest, as will be seen later in Fig. 3, in which the observed fog water content φ is plotted against the distance x from the windward edge of the forest with reference to the value of φ at the edge (φ_0).

On July 1, 1950, from 15^h to $17^h 30^m$, when the weather was fine and the wind velocity was 2~3 m/sec, the vertical distributions of temperature were measured by the use of *Assmann's* hygrometer just in front of, within, and just behind the forest, whose average height was about 8 m. Some of the results, which were confirmed by several repeated observations, are shown in Fig. 1. It will be seen from the figure that the temperature diminishes considerably from the ground surface up to the height of about 6m and takes approximately constant values from there up to 12m, then to decrease again with the increasing height. Thus it seems that in the forest zone there exist three more or less distinct atmospheric layers, of which the lowest one undergoes little turbulent disturbances owing to the resistance of thick shrubs and grasses; the intermediate layer (including the upper portion of trees and several meters above the tree crowns), where the uniform temperature prevails, is the seat of violent turbulence induced by branches or ups and downs of tree-tops; finally the uppermost layer keeps its original less turbulent condition, being unaffected by the existence of the forest.

The investigations on turbulence were carried out at the same time by other research members. According to their results, the vertical component of turbulence in the neighborhood of the forest was predominantly of the frequency 0.4~0.5 cycle, the wind velocity in front of the forest being 2,

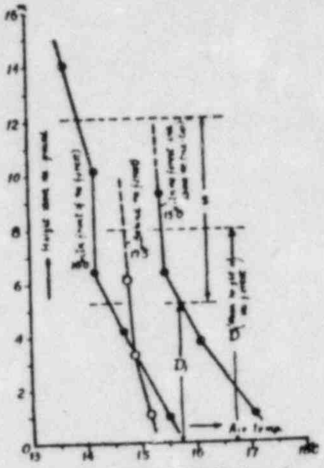

Fig. 1. Vertical distribution of temperature.

3, and 5 m/sec at the height of 1 m, 8 m, and 14 m, respectively, and further it was observed (i) that at the height of 1 m the intensity of turbulence was remarkably reduced in and behind the forest as compared with that in front of the forest, (ii) that at the height of 8 m the turbulence behind the forest was of the same order of magnitude as in the front, while within the forest it was markedly reduced, and (iii) that at the height of 14 m (higher than the trees) it was enhanced considerably in as well as behind the forest. Although the spots, where these observations were made, were different from those where the above-mentioned measurement of temperature was performed, the results obtained from two entirely different sorts of measurement seem to be in harmony with each other at least qualitatively.

In the intermediate layer, since the wind velocity is 3~5 m/sec, the size of turbulence of 0.4~0.5 cycle becomes 6~13 m, and, taking the result of the investigation by *Y. Takahashi* [2] for granted, the eddy diffusivity K comes out to be of the order 10^{4} cm^{2}/sec. *K. Takahashi* [3], on the other hand, obtained K of the order 10^{5}cm^{2}/sec for the wind with the velocity of about 10 m/sec from the observation of the diffusion of cloud at the height of 50 m above the ground. On the basis of these figures, we assumed in the following discussions, just for simplicity's sake, that the turbulence in the intermediate layer is considerably more intense than that in the upper layer, and consequently there prevails uniform vertical distribution of temperature and fog water content.

It seems worth while to give here brief discussions about the question how the fog particles are carried by the air turbulence. Consider the air current simply as consisting of small air masses, each of which is conveyed with wind velocity while it makes in a vertical direction a sinusoidal vibration of the same amplitude with the same phase. The vertical velocity component is then given by

$$u = u_0 \sin pt \qquad (1)$$

where u_0 is the maximum value of u, t the [illegible], and $p = \frac{2\pi}{T}$ (T: period). If a fog particle of radius r, which is so small that the falling effect due to gravity can be ignored, is floating in the small air mass and moving in a vertical direction with such a velocity v that *Stokes'* law remains valid, then the equation of motion can be expressed as

$$\frac{dv}{dt} = \zeta (u - v), \qquad (2)$$

in which $\zeta = \frac{\eta}{m}$, $\eta = 6\pi\mu r$, $m = \frac{4}{3}\pi r^3(\rho - \sigma)$, μ = viscosity of air, ρ = density of water, and σ = density of air. Hence we get approximately the relation

$$\zeta = \frac{9\mu}{2r^2\rho} \cong \frac{0.778 \times 10^{-3}}{r^2}\ \mathrm{sec}^{-1}. \qquad (3)$$

From (1) and (2) the vertical velocity v and the vertical displacement y can be derived, thus

[illegible] $= \cos\delta \cdot \cos(pt - \delta), \qquad (4)$

$$y = \frac{u_0}{p} \cos\delta \cdot \sin(pt - \delta) + \mathrm{const}. \qquad (5)$$

We see therefore that, while the amplitude of air mass in vertical direction is $Y_0 = \frac{u_0}{p}$ (from (1)), the amplitude of the fog particle becomes $y_0 = \frac{u_0}{p}\cos\delta$, so that the ratio of these amplitudes is

$$\frac{y_0}{Y_0} = \cos\delta = \frac{1}{\sqrt{1 + \left(\frac{p}{\zeta}\right)^2}}, \qquad (6)$$

where

$$\frac{p}{\zeta} = \frac{4\pi\rho r^2}{9\mu T} = 8.08 \times 10^{3}\,\frac{r^2}{T}. \qquad (7)$$

Now, if we put the frequency of turbulence = 0.4 cycle, that is $T = 2.5$ sec. and $r = 10^{-3}$ cm (or 5×10^{-3} cm), we obtain $\frac{p}{\zeta} = 0.003$ (or 0.081), so that $\left(\frac{p}{\zeta}\right)^2$ can be neglected against unity, while if T becomes much smaller and takes, for instance, the value 0.25 sec, we get $\frac{p}{\zeta} = 0.030$ for $r = 10^{-3}$ cm and $\frac{p}{\zeta} = 0.81$ for $r = 5 \times 10^{-3}$ cm, that is to say, the fog particles of radius 10 μ, which appear predominantly in actual cases, can still follow the turbulent motion of air mass, whereas the particles of radius 50 μ cannot any more exactly move along with the turbulence ($y_r/Y_r = 0.78$).

In the following theoretical discussions on the changes of liquid water contents caused by the capturing effect of a forest, various factors such as distribution of air temperature, temperature of the ground, evaporation, free fall of fog particles due to gravity, and the like will be taken into consideration, so far as it goes, and what will be proved only insignificant shall be eliminated then and there from the discussions.

§ 3. Assumption Pertaining to the Forest and Atmospheric Layers; Introduction of Fundamental Equations

The assumed model of a forest and atmospheric layers is illustrated in Fig. 2. ab is the ground where a forest (height $= D$, width $= L$, length $= \infty$) exists, its front and rear space being an open area. Let z-axis be taken in the vertical direction upwards, and x-axis perpendicular to the length of forest zone and directed backwards. Supposing that the phenomena to be considered are independent of y, we now conceive an arbitrary number of vertical planes with spacing l perpendicular to x-axis, and direct our attention to the space intervening between two successive planes. (l may be taken equal to L, so long as the width of the forest is not too large; similarly, l may be put equal to the width of an open area if it is not very large.) We then conceive a horizontal plane cd in each space under consideration at the height of $s + D_1$ ($> D$) above the ground, dividing the atmosphere into upper and lower parts. Let the lower part of thickness s be called 'Layer I', the lowest layer adjacent to the ground of thickness D_1 where there exists no turbulence being excluded from consideration. (Obviously the thickness D_1 must be thicker within the forest than in the open area.) The upper part above cd-plane, which is considered to have thickness h, will be denoted by "Layer II".

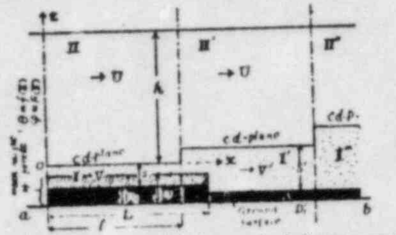

Fig. 2. Model of a forest and atmospheric layers assumed in the theory (vertical section perpendicular to the border line of the forest).

The foggy wind saturated with water vapor is assumed to be blowing in x-direction. In Layer II, let the temperature at (x, z) be T and let the fog water content in unit volume, the saturated vapor density, and the total water content, each at (x, z), be denoted by φ, w and q, respectively, so that $q = w + \varphi$, and further let both the wind velocity U and the eddy diffusivity K be regarded as constant. In Layer I, the mean wind velocity V is assumed constant within each space of width l separated by vertical planes and the temperature Θ, the fog water content ϕ, saturated vapor density W, and therefore the total water content $Q (= W + \phi)$ are considered as independent of z owing to the violent turbulence induced by the branches and leaves or by the ups and downs of the tree-tops of the forest.

As regards the influence of solar radiation, it plays the role of raising the temperature of the ground and so the temperature of the lower atmospheric layer. The direct effect upon air molecules, water vapor and fog particles will be left out of account, since the radiation will indeed largely be reflected back by the fog layer but will scarcely be thereby absorbed. Even if this inference were wrong, the present theory will safely be applied to the case of night fog.

Further, in order to simplify the problem, a value is assumed as the height h of the layer II such that up to this height the density ρ_a as well as the specific heat under constant pressure c_p may be regarded as independent of z and of the variation of temperature T. The error accompanying this simplified assumption is no more than about 6.5% even for $h=500$ m.

(1) Equations for Total Water Contents

As was stated in §2, the fog particles of radius not more than 10 μ can be considered to move constantly with the elementary portions of air and water vapor, unless the falling effect is taken into account. It is therefore simply assumed that the particles are all of the same size and have the same eddy diffusivity as the air mass, so that the falling effect may additively superposed on the diffusion effect. The time rate of change of the total water content in unit volume $q\ (=w+\varphi)$ in Layer II is then given by

$$\frac{\partial q}{\partial t}=K\frac{\partial^2 q}{\partial z^2}-U\frac{\partial q}{\partial x}+v\frac{\partial \varphi}{\partial z}. \tag{8}$$

where $K\dfrac{\partial^2 q}{\partial z^2}$ is the increase of q due to the eddy diffusion in z direction, $-U\dfrac{\partial q}{\partial x}$ that due to the transportation by the wind, and $v\dfrac{\partial \varphi}{\partial z}$ that brought about by the free fall of fog particles. The increase of water contents caused by the eddy diffusion in x-direction need not be taken into account, as $\dfrac{\partial^2 q}{\partial x^2}$ is exceedingly small compared to $\dfrac{\partial^2 q}{\partial z^2}$. The falling velocity of fog particle v is determined by *Stokes'* law:

$$v=\frac{2r^2 g}{9\mu}=1.26\times 10^6\cdot r^2\ \text{cm/sec}, \tag{9}$$

μ being the viscosity coefficient of air.

Next we consider the case of Layer I. The time rate of change of total water contained in the volume with unit basal area and height s (= thickness of Layer I) may be expressed by the equation

$$s\frac{\partial Q}{\partial t}=K\left(\frac{\partial q}{\partial z}\right)_{z=s}+v(\varphi)_{z=s}-Vs\frac{\partial Q}{\partial x}-Vsp\phi-v\phi \tag{10}$$

in which $K\left(\dfrac{\partial q}{\partial z}\right)_{z=s}+v(\varphi)_{z=s}$ means the quantity of water getting into Layer I from Layer II owing to diffusion and free fall, $-Vs\dfrac{\partial Q}{\partial x}$ the increase of water contents conveyed by the wind, and $Vsp\phi$ the quantity of water, of which the fog water carried by wind in unit time ($Vs\phi$) is deprived by the forest during its course of unit distance; p is namely the capturing coefficient per unit volume of space, which depends on the configuration of the forest, the mean wind velocity, the intensity of turbulence, and so forth. Even in the open area, since it is usually covered with shrubs and grasses, p is not to be considered vanishingly small, though much smaller than in the forest. The last term $v\phi$ in the above equation represents the amount of loss of fog water caused by the free fall to the lowest layer adjacent to the ground, where there exists no turbulence. Now that $(\varphi)_{z=s}=\phi$, Eq. (10) reduces to

$$\frac{\partial Q}{\partial t}=\frac{K}{s}\left(\frac{\partial q}{\partial z}\right)_{z=s}-V\frac{\partial Q}{\partial x}-Vp\phi. \tag{11}$$

(2) Equations for Temperature

The total heat content in unit volume of Layer II is evidently given by

$$E = \rho_a c_p T + q c_w T + w l\,, \qquad (12)$$

where ρ_a is the density of dry air, c_p its specific heat at constant pressure, c_w the specific heat of water, and l the latent heat of vaporization.

The atmospheric temperature on foggy days ranges from 6 to 14°C during the months June~Aug. in which the advection fogs most frequently appear at the south-eastern coast of *Hokkaido*. Within this range of temperature the relation

$$w = a + bT \text{ or } W = a + b\Theta \qquad (13)$$

with $a = 3.43$ g/m³ and $b = 0.601$ g/m³·deg holds with sufficient approximation between the saturated vapor density and the temperature. Substituting this in Eq. (12), we obtain

$$E = (\rho_a c_p + q c_w + bl)\, T + al. \qquad (14)$$

Of the three terms in the coefficient of T, which will be denoted by m in the following, the second term qc_w proves to be so small compared to the first or the third term that q may be replaced by its mean value $\bar{q}$. If we assume the mean temperature of 10°C and the mean fog water content of 0.5 g/m³, $\bar{q}$ becomes approximately 9.2 g/m³ (= 8.7 + 0.5). Thus, substituting the values

$$\begin{aligned} \rho_a c_p &= 1293\,(\mathrm{g/m^3}) \times 0.242 = 312 \text{ cal/deg}\,, \\ \bar{q} c_w &= 9.2 \times 1.0 = 9.2 \quad \text{''}\,, \\ bl &= 0.601 \times 587 = 353 \quad \text{''}\,, \end{aligned}$$

there results

$$m \simeq \rho_a c_p + \bar{q} c_w + bl \simeq 674 \text{ cal/deg}\,.$$

Since the temperature range that comes into question is 10 ± 5°C and the fog water content seldom surpasses the value 1 g/m³, the maximum percentage error of m to be induced by the replacement of q by $\bar{q}$ is

$$\frac{\Delta m}{m} = \frac{\Delta q \cdot c_w}{m} = \frac{(3.0 + 0.5) \times 1}{674} \simeq \frac{1}{200} \text{ or } 0.5\%,$$

the result which justifies the above-mentioned approximation.

Now, considering the time rate of change of the heat content in unit volume, we obtain the following differential equation for temperature in Layer II (cf. Eq. (8)):

$$m \frac{\partial T}{\partial t} = Km \frac{\partial^2 T}{\partial z^2} - Um \frac{\partial T}{\partial x} + v c_w \frac{\partial (T\varphi)}{\partial z}\,. \qquad (16)$$

In order to make further approximation, let us rewrite the first and third terms on the right-hand side of Eq. (16) as

$$Km \frac{\partial^2 T}{\partial z^2} + v c_w \frac{\partial (T\varphi)}{\partial z} = \frac{\partial}{\partial z} \left\{ Km \frac{\partial T}{\partial z} + v c_w T\varphi \right\}.$$

The ratio of the two terms in parentheses comes out to be about 1 : 1/22, when we adopt the values: $K = 2 \times 10^4$, $m = 674$, $\frac{\partial T}{\partial z} = 10^{-4}$, radius of the fog particle = 10 μ, $v = 1.26$ cm/sec, $c_w = 1$, $T = 10$°C, $\varphi = 0.5$ g/m³. It becomes still smaller in actual cases where $\varphi < 0.5$ g/m³. Thus the Eq. (16) reduces to

$$\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2} - U \frac{\partial T}{\partial x}\,. \qquad (17)$$

Similarly we obtain, for the time rate of change of the heat energy contained in the volume $s \times 1 \times 1$ in Layer I, the differential equation

$$sm \frac{\partial \Theta}{\partial t} = Km \left(\frac{\partial T}{\partial z} \right)_{z=s} + v c_w (T \cdot \varphi)_{z=s} - V s m \frac{\partial \Theta}{\partial x} - v c_w \Theta \cdot \phi + k(T_s - \Theta),$$

in which the first and second of the right-hand members represent the increase of heat content brought about by diffusion and by free fall of fog particles, respectively, the third member stands for the decrease of heat due to wind flow, the fourth the heat loss resulting from the free fall of fog particles to the undermost layer adjacent to the ground (characterized by the absence of turbulence), and the fifth corresponds to the heat gain from the undermost layer or from the trees (T_s: mean temperature of the ground and trees: k: coefficient of heat transfer). Since $(T \cdot \varphi)_{z=s} = \Theta \cdot \phi$, the above equation reduces to

$$\frac{\partial\theta}{\partial t}=\frac{K}{s}\left(\frac{\partial T}{\partial z}\right)_{z=0}-V\frac{\partial\theta}{\partial x}+\frac{k}{sm}(T_a-\theta). \tag{18}$$

(3) Summary of Equations

It follows from the above discussions that, within the error of 4—5%, the following equations are valid at least for the fog whose particles have the radii less than 10 μ:

$$\left.\begin{aligned}&q=\varphi+w=\varphi+a+bT,\\&\frac{\partial q}{\partial t}=K\frac{\partial^2 q}{\partial z^2}-U\frac{\partial q}{\partial x}+v\frac{\partial\varphi}{\partial z},\\&\frac{\partial T}{\partial t}=K\frac{\partial^2 T}{\partial z^2}-U\frac{\partial T}{\partial x},\end{aligned}\right\}\text{ for Layer II.} \tag{19}$$

$$\left.\begin{aligned}&Q=\phi+W=\phi+a+b\theta,\\&\frac{\partial Q}{\partial t}=\frac{K}{s}\left(\frac{\partial q}{\partial z}\right)_{z=0}-V\frac{\partial Q}{\partial x}-Vp\phi,\\&\frac{\partial\theta}{\partial t}=\frac{K}{s}\left(\frac{\partial T}{\partial z}\right)_{z=0}-V\frac{\partial\theta}{\partial x}+\frac{k}{sm}(T_a-\theta),\end{aligned}\right\}\text{ for Layer I.} \tag{20}$$

In the case of stationary state these equations become

$$\left.\begin{aligned}&q=\varphi+w=\varphi+a+bT,\\&\frac{\partial q}{\partial x}=\kappa^2\frac{\partial^2 q}{\partial z^2}+\varepsilon\frac{\partial\varphi}{\partial z},\\&\frac{\partial T}{\partial x}=\kappa^2\frac{\partial^2 T}{\partial z^2},\end{aligned}\right|\begin{aligned}&\left(\varepsilon=\frac{v}{U},\ \kappa^2=\frac{K}{U}\right)\\&\text{for Layer II.}\end{aligned} \tag{21}$$

$$\left.\begin{aligned}&Q=\phi+W=\phi+a+b\theta,\\&\frac{dQ}{dx}=\gamma\left(\frac{\partial q}{\partial z}\right)_{z=0}-p\phi,\\&\frac{d\theta}{dx}+\lambda\theta=\gamma\left(\frac{\partial T}{\partial z}\right)_{z=0}+\lambda T_a,\end{aligned}\right|\begin{aligned}&\left(\gamma=\frac{K}{sV},\ \lambda=\frac{k}{sVm}\right)\\&\text{for Layer I.}\end{aligned} \tag{22}$$

§ 4. Solutions for Stationary Case

Since the required quantities are not the total water contents but the fog water contents, we replace q and Q by φ

and ϕ by making use of (21) and (22), obtaining

$$\frac{\partial T}{\partial x}=\kappa^2\frac{\partial^2 T}{\partial z^2}, \tag{23}$$

$$\frac{d\theta}{dx}+\lambda\theta=\gamma\left(\frac{\partial T}{\partial z}\right)_{z=0}+\lambda T_a, \tag{24}$$

$$\frac{\partial\varphi}{\partial x}=\kappa^2\frac{\partial^2\varphi}{\partial z^2}+\varepsilon\frac{\partial\varphi}{\partial z}, \tag{25}$$

$$\frac{d\phi}{dx}+p\phi=\gamma\left(\frac{\partial\varphi}{\partial z}\right)_{z=0}-b\lambda(T_a-\theta). \tag{26}$$

For Layer II we give the boundary condition

$$\frac{\partial T}{\partial z}=0,\quad\frac{\partial\varphi}{\partial z}=0\quad\text{at}\quad z=h. \tag{27}$$

It is a well-known fact that the invasion of sea fog is always accompanied by the presence of temperature inversion up to the height of several hundred meters above the ground, and that in most cases the top of the fog lies a little below the top of the inversion layer. Moreover it is reasonable to consider that in the inversion layer the water vapor is in a saturated state when the fog is sufficiently dense.

Hence, if we take the top of the inversion layer as the upper boundary $z=h$, the condition (27) turns out to be a natural consequence. In practice however, as will be seen later, it matters little how to assume the condition at $z=h$, unless the thickness of fog is unduely small and so long as we take no account of the phenomena at considerable values of z or in uppermost regions of fog.

As the initial conditions at $x=0$ i.e. at the immediate front of the forest, we assume that the temperature and the fog water content of the invading air mass are

$$T_{x=0}=f(z),\quad\varphi_{x=0}=F(z). \tag{28}$$

Now the solution of Eq. (23) that satisfies the condition (27) is given by

$$T=\sum_{i=1}^{\infty}A_i(\tan\mu_i h\cdot\sin\mu_i z+\cos\mu_i z)\,e^{-\kappa^2\mu_i^2 x}+C_1, \qquad (29)$$

so that

$$T_{z=0}=\sum_{i=1}^{\infty}A_i e^{-\kappa^2\mu_i^2 x}+C_1, \qquad (30)$$

$$\left(\frac{\partial T}{\partial z}\right)_{z=0}=\sum_{i=1}^{\infty}A_i\mu_i\tan\mu_i h\cdot e^{-\kappa^2\mu_i^2 x}. \qquad (31)$$

Therefore we can solve Eq. (24) through substitution of (31), obtaining

$$\theta=\gamma\sum_{i=1}^{\infty}\frac{A_i\mu_i\tan\mu_i h}{\lambda-\kappa^2\mu_i^2}\cdot e^{-\kappa^2\mu_i^2 x}+T_0+C_2e^{-\lambda x}. \qquad (32)$$

Since Eq. (32) should coincide with Eq. (30), it is required that

$$C_1=T_0, \quad C_2=0,$$

and

$$\mu_i\tan\mu_i h+\frac{\kappa^2}{\gamma}\mu_i^2=\frac{\lambda}{\gamma}. \qquad (33)$$

Thus we get the distributions of temperature in Layer II and Layer I:

$$T=\sum_{i=1}^{\infty}A_i(\tan\mu_i h\cdot\sin\mu_i z+\cos\mu_i z)\,e^{-\kappa^2\mu_i^2 x}+T_0, \qquad (34)$$

$$\theta=\sum_{i=1}^{\infty}A_i e^{-\kappa^2\mu_i^2 x}+T_0, \qquad (35)$$

in which μ_i's are given by the infinite number of roots of Eq. (33), and the values of A_i can be obtained as follows: If we put

$$\chi_i(\mu_i,z)=\tan\mu_i h\cdot\sin\mu_i z+\cos\mu_i z, \qquad (36)$$

we get from (34) and (28)

$$f(z)-T_0=\sum_{i=1}^{\infty}A_i\chi_i(\mu_i,z), \qquad (37)$$

so that, multiplying both sides of this equation by $\chi_n(\mu_n,z)$ and integrating with respect to z from 0 to h, there results

$$\sum_{i=1}^{\infty}A_i\int_0^h\chi_i\chi_n dz=\int_0^h\{f(z)-T_0\}\,\chi_n(\mu_n,z)\,dz$$

which, by the use of the relations

$$\int_0^h\chi_i\chi_n dz=-\frac{\kappa^2}{\gamma} \qquad \text{for } i\neq n,$$

and

$$\int_0^h\chi_i\chi_n dz=\frac{1}{2}\left(h+h\tan^2\mu_n h+\frac{\tan\mu_n h}{\mu_n}\right) \quad \text{for } i=n,$$

can be transformed into

$$A_i=\frac{2\left[\dfrac{\kappa^2}{\gamma}\{f(0)-T_0\}+\displaystyle\int_0^h\{f(y)-T_0\}\,\chi_i(\mu_i,y)\,dy\right]}{2\dfrac{\kappa^2}{\gamma}+h+h\tan^2\mu_i h+\dfrac{\tan\mu_i h}{\mu_i}}. \qquad (38)$$

It is to be noticed that the values of A_i are negative, since $f(z)-T_0<0$.

The particular solution of (25) which satisfies the condition (27) is

$$q=\sum_{i=1}^{\infty}B_i\{\tan(\beta_i h+\alpha_i)\sin\beta_i z+\cos\beta_i z\}\,e^{-\sigma z}\cdot e^{-(\beta_i^2+\sigma^2)\kappa'^2 x}$$
$$+\sum_{i=1}^{\infty}D_i\{\tan(\delta_i h+\eta_i)\sin\delta_i z+\cos\delta_i z\}\,e^{-\sigma z}\cdot e^{-\mu_i^2\kappa^2 x}, \qquad (39)$$

where

$$\left.\begin{aligned}\sigma&=\frac{\varepsilon}{2\kappa'^2}, & \tan\alpha_i&=\frac{\sigma}{\beta_i},\\ \delta_i&=\sqrt{\mu_i^2-\sigma^2}, & \tan\eta_i&=\frac{\sigma}{\delta_i}.\end{aligned}\right\} \qquad (40)$$

Substituting $(\theta-T_0)$ given by Eq. (35) into Eq. (26), we get, on the other hand,

$$\frac{d\phi}{dx}+p\phi=\gamma\left(\frac{\partial q}{\partial z}\right)_{z=0}+b\lambda\sum_{i=1}^{\infty}A_i e^{-\kappa^2\mu_i^2 x}, \qquad (26)'$$

of which the first right-hand member can be obtained from (39), thus yielding

$$\frac{d\phi}{dx}+p\phi=\gamma\sum_{i=1}^{\infty}B_i\{\beta_i\tan(\beta_i h+\alpha_i)-\sigma\}e^{-(\beta_i^2+\sigma^2)\kappa^2x}$$
$$+\sum_{i=1}^{\infty}\Big[h\lambda A_i+\gamma D_i\{\lambda_i\tan(\lambda_i h+\eta_i)-\sigma\}\Big]e^{-\mu_i^2\kappa^2x}. \quad (41)$$

The particular solution of this equation is

$$\phi=\gamma\sum_{i=1}^{\infty}B_i\frac{\beta_i\tan(\beta_i h+\alpha_i)-\sigma}{p-\kappa^2(\beta_i^2+\sigma^2)}e^{-(\beta_i^2+\sigma^2)\kappa^2x}$$
$$+\sum_{i=1}^{\infty}\frac{h\lambda A_i+\gamma D_i\{\lambda_i\tan(\lambda_i h+\eta_i)-\sigma\}}{p-\kappa^2\mu_i^2}e^{-\mu_i^2\kappa^2x} \quad (42)$$

which is to be coincident with

$$(\varphi)_{z=h}=\sum_{i=1}^{\infty}B_ie^{-(\beta_i^2+\sigma^2)\kappa^2x}+\sum_{i=1}^{\infty}D_ie^{-\mu_i^2\kappa^2x}, \quad (43)$$

so that we have the relations

$$\beta_i\tan(\beta_i h+\alpha_i)=\frac{p}{\gamma}-\frac{\kappa^2}{\gamma}\sigma^2-\frac{\kappa^2}{\gamma}\beta_i^2+\sigma, \quad (44)$$

and

$$D_i=\frac{h\lambda A_i}{(p-\kappa^2\mu_i^2)-\gamma\{\lambda_i\tan(\lambda_i h+\eta_i)-\sigma\}}. \quad (45)$$

Substitution of (45) into (39) and (43) gives therefore

$$\varphi=\sum_{i=1}^{\infty}B_i\{\tan(\beta_i h+\alpha_i)\sin\beta_i z+\cos\beta_i z\}e^{-\sigma z}e^{-(\beta_i^2+\sigma^2)\kappa^2x}$$
$$+h\lambda\sum_{i=1}^{\infty}A_i\frac{\tan(\lambda_i h+\eta_i)\sin\lambda_i z+\cos\lambda_i z}{(p-\kappa^2\mu_i^2)-\gamma\{\lambda_i\tan(\lambda_i h+\eta_i)-\sigma\}}\cdot e^{-\sigma z}\cdot e^{-\mu_i^2\kappa^2x} \quad (46)$$

and

$$\phi=\sum_{i=1}^{\infty}B_ie^{-(\beta_i^2+\sigma^2)\kappa^2x}+h\lambda\sum_{i=1}^{\infty}\frac{A_ie^{-\mu_i^2\kappa^2x}}{(p-\kappa^2\mu_i^2)-\gamma\{\lambda_i\tan(\lambda_i h+\eta_i)-\sigma\}} \quad (47)$$

which represent the distributions of fog water contents in Layer II and Layer I, respectively. Here β_i's are obtained as the roots of Eq. (44) and B_i's can be calculated, just in the same way as in the case of A_i's, by the following procedure:

Put

$$M(z)=h\lambda\sum_{i=1}^{\infty}A_i\frac{\tan(\lambda_i h+\eta_i)\sin\lambda_i z+\cos\lambda_i z}{(p-\kappa^2\mu_i^2)-\gamma\{\lambda_i\tan(\lambda_i h+\eta_i)-\sigma\}}e^{-\sigma z} \quad (48)$$

and

$$Y_i(\beta_i,z)=\tan(\beta_i h+\alpha_i)\sin\beta_i z+\cos\beta_i z, \quad (49)$$

then, from the condition (28),

$$\sum_{i=1}^{\infty}B_iY_i(\beta_i,z)=\{F(z)-M(z)\}e^{\sigma z}. \quad (50)$$

Multiplying both sides of this equation by $Y_n(\beta_n,z)$ and integrating with respect to z from 0 to h, we get

$$\sum_{i=1}^{\infty}B_i\int_0^hY_iY_ndz=\int_0^h\{F(z)-M(z)\}e^{\sigma z}Y_n(\beta_n,z)dz.$$

But, since

$$\int_0^hY_iY_ndz=-\frac{\kappa^2}{\gamma} \qquad \text{for} \quad i\neq n,$$

and

$$\int_0^hY_iY_ndz=\frac{1}{2}\left\{h(1+u^2)+\frac{(u_i\beta_n-\sigma)(\beta_n-u\sigma)}{\beta_n(\beta_n^2+\sigma^2)}\right\} \quad \text{for} \quad i=n,$$
$$(u=\tan(\beta_i h+\alpha_i))$$

we find

$$B_i=\frac{2\left[\frac{\kappa^2}{\gamma}\{F(0)-M(0)\}+\int_0^h\{F(y)-M(y)\}e^{\sigma y}\cdot Y_i(\beta_i,y)dy\right]}{2\left(\frac{\kappa^2}{\gamma}\right)+h(1+u^2)+\frac{(u\beta_i-\sigma)(\beta_i-u\sigma)}{\beta_i(\beta_i^2+\sigma^2)}}. \quad (51)$$

Now let us investigate to what extent the capturing effect of the forest and the falling effect of fog particles contribute to the total diminution of fog water contents.

Since the amount of fog water n captured by the forest of width L in unit time is

$$n = Vsp\int_0^L \phi\,dx = \frac{Vsp}{\kappa^2}\left[\sum_{i=1}^{\infty}\frac{B_i}{\beta_i^2+\sigma^2}\left\{1-e^{-(\beta_i^2+\sigma^2)\kappa^2 L}\right\}\right.$$
$$\left.+\,b\lambda\sum_{i=1}^{\infty}\frac{A_i(1-e^{-\mu_i^2\kappa^2 L})}{\mu_i^2\{(p-\kappa^2\mu_i^2)-\gamma\{\delta_i\tan(\delta_i h+\eta_i)-\sigma\}\}}\right] \qquad (52)$$

while the total amount of fog water N intruding across the plane $x=0$ is

$$N = VsF(0) + U\int_0^h F(z)\,dz\,,$$

the decreasing ratio R at $x=L$ due to the capturing effect becomes

$$R = \frac{n}{N} =$$
$$\frac{p\left[\sum_{i=1}^{\infty}\frac{B_i}{\beta_i^2+\sigma^2}\left\{1-e^{-(\beta_i^2+\sigma^2)\kappa^2 L}\right\}+b\lambda\sum_{i=1}^{\infty}\frac{A_i(1-e^{-\mu_i^2\kappa^2 L})}{\mu_i^2\{(p-\kappa^2\mu_i^2)-\gamma\{\delta_i\tan(\delta_i h+\eta_i)-\sigma\}\}}\right]}{\kappa^2F(0)\left\{1+\frac{1}{F(0)}\cdot\frac{U}{V}\cdot\frac{1}{s}\int_0^h F(z)\,dz\right\}}.$$
$$(54)$$

The loss of fog water in the forest zone caused by the falling effect in unit time is, on the other hand,

$$j = v\int_0^L \phi\,dx = \frac{vn}{Vsp} \qquad (55)$$

and accordingly the decreasing ratio J at $x=L$ due to the falling effect is given by

$$J = \frac{j}{N} = \frac{v}{Vsp}R\,. \qquad (56)$$

If we assume the values $v=1.26$ cm/sec (corresponding to $r=10\mu$), $V=4.2$ m/sec, and $p=0.005$ (see the next section), the ratio J/R comes out to be 0.080; in other words, the capturing effect plays a much greater part in reducing the amount of fog water than the falling effect (more than ten times as great). The resultant diminishing ratio is evidently given by

$$G = R + J = \left(1+\frac{v}{Vsp}\right)R\,. \qquad (57)$$

§5. Application of the Formulas to a Special Case

If the size of fog particles be assumed sufficiently small, the falling effect becomes negligibly small, so that ε and therefore σ may be put equal to zero in the formulas obtained in the preceding section. Suppose further that the temperature is constant throughout the foggy atmosphere, a supposition which is not far from the truth in the case where it is windy beyond a certain measure and where the observational data to be dealt with are those obtained within the limited region of several hundred meters including a forest two or three hundred meters in width. Now that we can put $A_i=0$ besides $\sigma=0$, the formulas simplify to

$$\varphi = \sum_{i=1}^{\infty} B_i(\tan\beta_i h\cdot\sin\beta_i z+\cos\beta_i z)\,e^{-\beta_i^2\kappa^2 x}\,, \qquad (58)$$

$$\phi = \sum_{i=1}^{\infty} B_i e^{-\beta_i^2\kappa^2 x}\,, \qquad (59)$$

where

$$B_i = \frac{2\left\{\left(\frac{\kappa^2}{\gamma}\right)F(0)+\int_0^h F(z)\chi_i(x_i,z)\,dz\right\}}{2\left(\frac{\kappa^2}{\gamma}\right)+h(1+\tan^2\beta_i h)+\frac{\tan\beta_i h}{\beta_i}}\,, \qquad (60)$$

and

$$\beta_i\tan\beta_i h + \frac{\kappa^2}{\gamma}\beta_i^2 = \frac{p}{\gamma}\,. \qquad (61)$$

The amount of fog water captured by the forest as a whole in unit time becomes

$$n = \frac{Vsp}{\kappa^2}\sum_{i=1}^{\infty}\frac{B_i}{\beta_i^2}\left(1-e^{-\kappa^2\beta_i^2 L}\right), \qquad (62)$$

and the decreasing ratio of fog water at $x=L$ due to the capturing effect is given by

$$R = \frac{p}{\kappa^2}\,\frac{\sum_{i=1}^{\infty}\frac{B_i}{\beta_i^2}\left(1-e^{-\kappa^2\beta_i^2 L}\right)}{F(0)\left\{1+\frac{1}{F(0)}\,\frac{U}{V}\,\frac{1}{s}\int_0^h F(z)\,dz\right\}} \qquad (63)$$

It is to be noted that if, in addition, the condition $F(z)=\varphi_0=$ constant can be taken for granted, the expression (60) reduces to

$$B_i=\left(\frac{2ap}{\kappa^2\beta_i^2}\right)\Big/\left\{h+a+\frac{ap}{\kappa^2\beta_i^2}+ha^2\left(\frac{p}{\kappa^2\beta_i}-\beta_i\right)^2\right\}\cdot\left(a-\frac{\kappa^2}{\gamma}-\frac{V}{U}s\right). \tag{64}$$

§6. Examples

Since the application of the general formulas derived in §4 to the actual cases is impossible owing to the lack of exact knowledge as to several quantities such as the diffusion constants or the vertical distribution of fog water contents in the upper atmosphere, we must at the present stage content ourselves with considering the case of rough approximation stated in the preceding section. The general feature of the phenomenon might, however, be inferred from such simplified calculations.

The adopted numerical values of the constents are as follows: $s=7.5$ m, $V=4.2$ m/sec in the forest area; $s=12.1$ m, $V=2.6$ m/sec behind the forest: $K=2.2\times10^3\,\text{cm}^2/\text{sec}$ (not quite sure but provisionally assumed), $U=4.0$ m/s, $\kappa^2=K/U=0.055$ m, $a=Vs/U=7.87$ m; $h=100$ m; $F(z)=\varphi_0=1$ (the absolute value of fog water content is not needed).

(1) Estimation of fog-capturing coefficient of the forest.

First, in order to estimate the order of magnitude of the mean capturing coefficient per unit volume in Layer I, we solved Eq. (26) without taking account of the fog water coming from Layer II by dint of diffusion, obtaining

$$\phi=\varphi_0 e^{-p'x}, \tag{65}$$

where p' simply indicates a roughly estimated value of p. By reference to the observed relative fog water contents shown in Fig. 3, it was then noted that the value of p' ranged roughly from 0.002 to 0.009. Now, taking the diffusion from Layer II into consideration, the value of p was adjusted so as to fit in with the observational results and was found to be 0.005. Converting p into the capturing coefficient p_0 per unit effective volume of the forest, we finally get

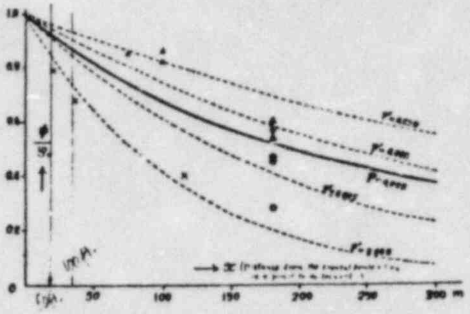

Fig. 3. Relation between the ratio of fog water content in the rear to that in front of the forest and its breadth.

$$p_0=\frac{s}{D-D_1}\,p=0.011/\text{m}^3.$$

(2) Variation of fog water contents in Layer I in the forest zone.

The above-obtained value of p (0.005) being inserted in (61) and (64), the calculation of the summation (59) was carried out, of which the first twenty terms were taken into account. The result is shown in Fig. 3 by the solid curve, and also in Fig. 4 where the width of the forest is taken equal to 1,000 m.

(3) Variation of fog water contents in Layer II in the forest zone.

The results obtained by the use of the formula (58) are illustrated in Fig. 5, in which the equi-fog-water-content curves for the values 0.95, 0.75, 0.50 and 0.25 are given, the fog water content of the intruding fog being taken as unity. If we

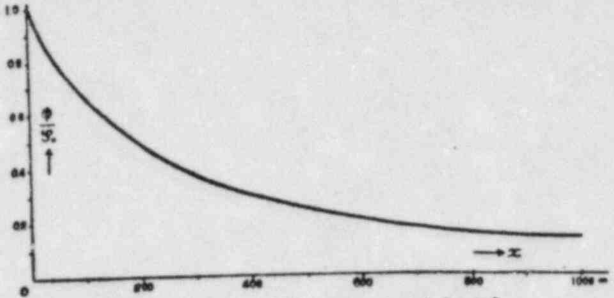

Fig. 4. Variation of fog water content in Layer I.

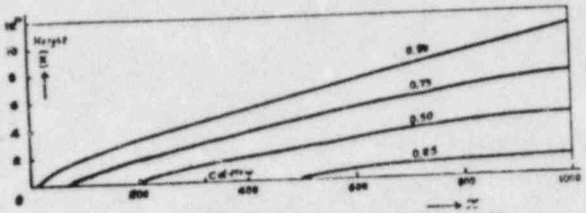

Fig. 5. Distribution of fog water content in Layer II.

regard the portion underlying and bordered by 0.95-curve as the region affected by the influence of the capturing action of the forest, it will be seen that the thickness of the affected region is only about 3 m above the top plane of Layer I at $x = 200$ m and not more than 10 or 11 m even at $x = 1{,}000$ m.

(4) Variation of fog water contents in Layer I′ and Layer II″ behind the forest.

Here it was assumed that the width of the forest is 200 m and the capturing efficiency p is zero in the open area behind the forest, and further that the vertical distribution of fog

water contents just at the back of the forest is given by ϕ and $\varphi(z)$ obtained in the preceding paragraph for $x = 200$ m. The results are shown in Figs. 6 and 7. It is a natural consequence that the ϕ-values increase gradually with increasing x behind the forest, since by virtue of turbulent diffusion fog intrudes from the upper layer into the open space where $p = 0$ to make up for the loss caused by the forest. The black spots in Fig. 6 indicate the actual values of relative fog water contents at 1~3 m above the ground observed during the field investigation in 1950. Although the number of observations

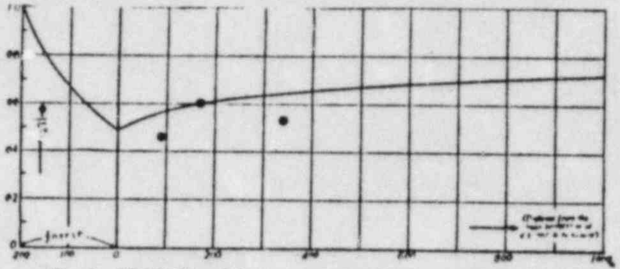

Fig. 6. Distribution of fog water content in the rear of the forest (Layer I′). (An example for the forest 200 m in breadth.)

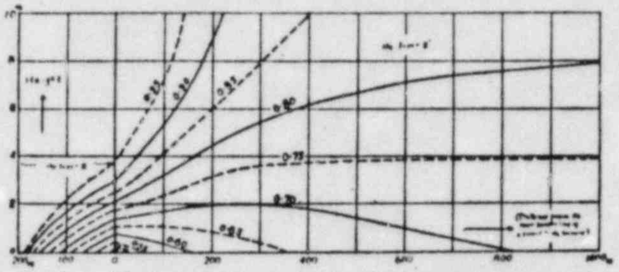

Fig. 7. Distribution of fog water content in the rear of the forest (Layer II′). (An example for the forest 200 m in breadth.)

is too few to draw any definite conclusion, it is very probable that better results would have been obtained if finite, though small, value of p were assumed for the open area behind the forest, which is actually covered with shrubs and grasses all over. The distribution of fog water contents in Layer II′ shown in Fig. 7 seems to indicate that here the influence of the forest is much more wide-spread than over the forest, but actually, when viewed in large relations, the region under noticeable influence is restricted to the undermost narrow space in Layer II′.

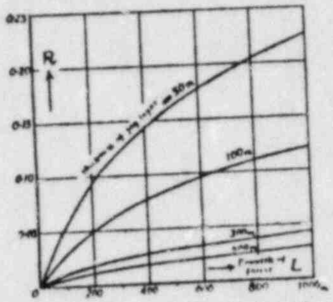

Fig. 8. Relation between the decreasing ratio of fog water content due to the capturing action of the forest and the breadth of the forest for various fog layers of different thicknesses.

(5) Total diminution of fog water due to the capturing effect.

Fig. 8 shows the total relative decrease of fog water contents R, calculated from Eq. (63) as a function of the width of the forest L. It is seen from the figure that the smaller the thickness of the fog and the larger the width of the forest, the more effective becomes the capturing action of the forest.

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A Theoretical Study on the Distribution of Fog Density in a Forest

By Zyungo YOSIDA

On the assumption that the vertical motion of a fog particle caused by turbulence of air in the forest is the same as the so-called one-dimensional "random walk", the vertical distribution of fog particles in the forest is deduced theoretically, with the result that fog density diminishes exponentially downwards.

1. When fog is flowing over a forest carried by wind, some of the fog particles leave the prevailing wind and enter the forest at its top. They are transported downwards by the turbulent motions of air into the forest and on their ways some of them are caught by the leaves of trees. In this way there appears a distribution of fog density in the forest such that the density diminishes gradually in the downward direction. The purpose of this paper is to deduce theoretically the density distribution in an idealized forest—infinitely wide and uniform—when the wind is supposed to continue flowing with an invariable velocity, fog carried by it being kept at a constant density.

2. We replace the forest by a layer of imaginary porous substance which fills uniformly the whole space between the ground surface and a horizontal plane lying at the same height as that of the forest. The porous substance imagined here is represented by an assemblage of leaves distributed in space with the same density as the mean density of leaves in the actual forest.

Fig. 1 represents a vertical section of the forest cut parallel to the direction of wind blowing from left to right. Our problem is to determine the fog density at a point in the forest like the one indicated by P in Fig. 1. Let the vertical

It might be worth noticing that, if there were no fluctuation in the effective mean radius of fog particles (r), a single measurement either with A or with B would be sufficient for the determination of fog water contents. As will be seen from the following considerations, however, the fluctuation of r cannot be ignored in actual cases, so that neither A nor B can be dispensed with.

On the assumption that r has a constant value ($r_m = 8.6\mu$, which is the mean of the r-values given in Table 2) for different fogs, the values φ_A and φ_B are calculated provisionally by substitution of f_1 and f_2 in (3) and (4), respectively. The results are indicated in Table 3, in which the corresponding values of r and φ that were obtained in our actual experiment are also given for comparison. It can be seen from the Table that the deviation of φ_A and φ_B from φ is considerable, and the larger the difference between r and r_m, the larger is the deviation. We thus arrive at the conclusion that in the present type of fog meter it is inevitable to use two fog collectors having different capturing coefficients, which involves the simultaneous measurement of the effective radius of fog particles. (The mean capturing coefficients of A and B are found to be 0.28 and 0.80, respectively, from the data given in Table 2 and the formulas (1) and (2).)

TABLE 3. *φ_A and φ_B Calculated on the Assumption that $r = 8.6\mu$, Compared with φ*

No. in TABLE 2	1	2	3	4	5	6	7	8	9
r (μ)	5.6	15.9	8.7	6.7	6.2	6.8	8.6	15.7	3.5
φ (mg/m^3)	138	201	93	184	184	162	268	330	190
r (μ)	8.6								
φ_A (mg/m^3)	76	487	116	160	163	133	268	823	46
φ_B (mg/m^3)	119	249	147	186	239	164	259	402	126

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On the Capture of Fog Particles by a Forest (I)

By Hirobumi ÔURA

The amounts of fog water entering and leaving the forest in a horizontal direction were measured by the use of vertical wire screens set in front of and in the rear of the forest, respectively, while that carried into the forest in a downward direction was determined by making use of a horizontal screen set above the tree crowns which was fitted with a mosquito curtain hung from its frame.

Three kinds of forests were compared with one another in respect of the capability of capturing fog particles. The most effective forest was found to be the one grown comparatively sparsely with needle-leaved trees having no lower branches. The forest next to this was thickly grown with needle-leaved trees with dense lower branches, and the last one was that which consisted of needle-leaved trees mixed with broad-leaved and whose density was intermediate between those of the other two.

It was further ascertained that the front surface of the forest was about three times as effective as the top surface.

§1. Introduction

The capture of fog particles by the forest near the coast performs an important function in protecting the land against the invasion of sea fogs.

It has been pointed out by many observers that the amount of fog water caught by the forest is not at all negligible. *Marloth* [1] noted that the forest on the summit of *Table Mountain* near *Cape Town* grew luxuriantly without any rain but solely with fog, and using his instrument "Nebelfänger" (a rain gauge with a bundle of grasses which was enclosed with metal gauze and so arranged that the fog deposited on it would run into the gauge) he ascertained that the forest arrested a number of fog particles even when none was collected on the ground. *Linke* [2] called attention to the fact that a rain gauge put for one year in the forest of *Picea* at *Frankfurt on Main* indicated the amount of water about twice as much as in the

Attachment 2

open, and used after *Suring* the term "horizontaler Niederschlag" for the precipitation caused by the presence of the forest. Similarly he observed, from four years' records at 2,500 ft elevation in the *Taunus* Mountains, where there are some 200 foggy days each year, that the rain gauge caught near the edge of the forest the amount of water averaging 157% of that in the open, and toward the interior 123%. The maxima were 300 and 260%, respectively. More recently, *Dieckmann* [3] also emphasized, through his experience at Mt *Brocken*, the importance of the precipitation of fog within the forest as the source of water in the district. (As to the work by *Kubner* [4], see "General Survey" written by *Yanda*.)

Now, in order to inquire into the fog preventing function of a forest in the case of sea fogs, in which we are interested, we have tried to determine the amount of fog water captured by the forest by measuring the amount of fog entering the forest, on the one hand, and that leaving it, on the other hand, at the same time to see how the capturing function depends on the structure of the forest. It is to be assumed that at the windward margin of the forest there exist only fogs that enter the forest, since the windward component of turbulent motion of air does not exceed the mean wind velocity. At the leeward margin there exist, for the same reason, only fogs that escape from the forest. As regards the upper surface of the forest, we have to take into account both the inflow and outflow of fogs, because there comes the vertical component of turbulent motion into question.

Aside from the direct measurement, in which we were engaged and which we shall describe in detail below, the amounts of inflow and outflow at the margins can be determined, if the wind velocity and the fog water content in unit volume are known, while those at the upper surface can be calculated with the help of the expression

$$K\frac{\partial \varphi}{\partial z} + \sum w_r f(r),$$

where

K: eddy diffusivity;
φ: liquid water content of fog in unit volume of air;
z: vertical coordinate directing upward;
w_r: falling velocity of a particle with radius r;
$f(r)$: number of fog particles with radius r in unit volume of air.

The first term represents the turbulent diffusion and the second term the falling effect of fog particles. Accordingly, if we can obtain the amounts of K, φ, w_r and $f(r)$ experimentally, we shall be able to calculate the net amount of inflow through the upper surface of the forest. *Tabata* and others [5] carried out the measurement along this line, and their results were compared with those obtained from our direct measurement, a tolerable agreement having been found.

From our experiments it was also observed that the amount of captured fog was largely affected by the conditions of the forest such as thickness or kind of trees.

§2. Experimental Method

Principle of measurement: Suppose that the forest is completely enclosed with an imaginary surface as shown by broken lines in Fig. 1. The turbulent air carries fog particles in or out through this surface. Thus the difference between the amount of fog water carried in (M) and that carried out (N) can be regarded as the amount caught by the forest. In front of the forest, where $N = 0$, a rectangular wire screen (Fig. 2d) was set vertically and the fog particles caught by it were collected into a self recording rain gauge. The amount of collected water is given by the product (wind velocity) × (liquid water content of fog) × (area

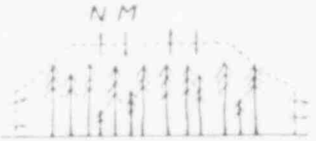

Fig. 1.

of the screen) × (collecting efficiency of the screen). In order to estimate the effective height of the forest, the stream lines of wind were traced by the use of smoke or a small balloon with no buoyancy carried freely by the wind. The same sort of measurement was also made on the leeward side of the forest.

The values of M and $M+N$, from which the amount $M-N$ entering the forest from above can be computed, were obtained in the following way. A pair of wire screens was placed horizontally above the forest, one for $M+N$ and the other for M. The one for $M+N$ was a single screen, which had no preference between upward and downward motions of turbulent air. The one for M was of such a construction that it kept the fog particles moving upwards from arriving at the screen; namely, it was fitted with a small ordinary mosquito curtain hung down from the frame holding the wire screen (Fig. 2c). The fog water collected by each of the screens was led separately to the self recording gauges placed on the ground.

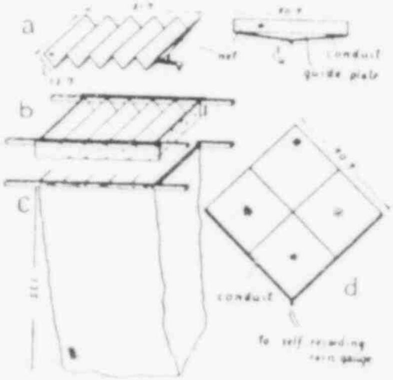

Fig. 2. Horizontal and vertical wire screens.

Posts of observations: Vertical screens were placed in front (A_1 point*) and in the rear (B_1 point) of the forest at the heights of 3 m and 6 m (Figs. 3 and 4), and three pairs of horizontal screens were set at points X_1, X and X, above the tree crowns (Fig. 5). Another pair set at A_1 in the open at the height of 2.5m (Fig. 6) was intended for measuring the amount of fog particles captured by the ground surface.

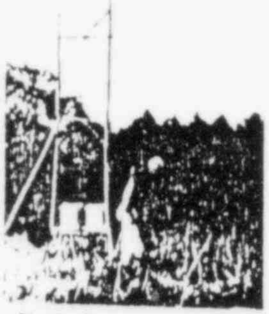

Fig. 3. Experiment by the use of balloon, A_1 point.

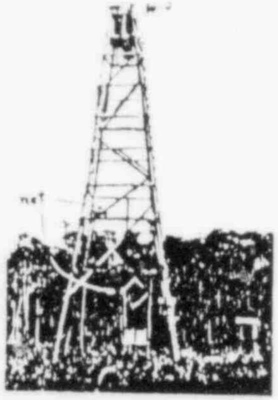

Fig. 4. B_1 point.

Nearly all the forest area was occupied by needle-leaved trees (*Picea Glehni*) except in the neighborhood of X point, where there were some broad-leaved trees (*Sorbus commixta* and *Betula Ermani*) mixed with the needle-leaved (*Abies sachalinensis*).

The forest around X_1 point was very thick (56 trees within a circle of radius 5m, that is, 0.71 tree per 1m²) and the trees from 5 to 9 m in height had many lower branches. The level at which the screens were placed was 8.6m above the ground.

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* As to the designations (A_1, B_1, ...) of the posts of observation, see "General Survey" written by Yosida.

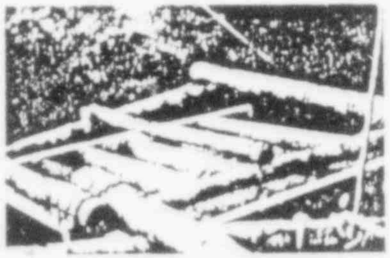

Fig. 5. The screens at X

Fig. 6. X point

The vicinity of X was sparsely wooded (58 trees within a circle of radius 10 m, or 0.18 tree per 1m²), and the trees had no lower branches, their height being about 12 m. The screens were set at the height of 12.4 m. Around the point Y there were within a circle of 10 m radius seventy needle-leaved and fifteen broad-leaved trees (0.27 tree per 1m²), and the height was 9–10 m. There were only few lower branches but the broad-leaved trees spread their branches extensively at their crowns. The height of the screens was 9.[illegible] m.

An idea of the features of the forest at each post of observation may be gained from Figs. 7, 8 and 9 (photo. by Muton (6)).

Fig. 7. X point

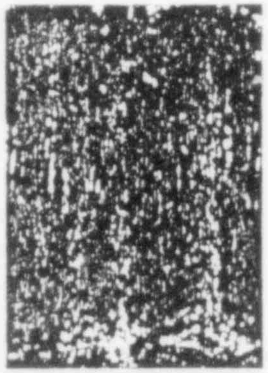

Fig. 8. X point

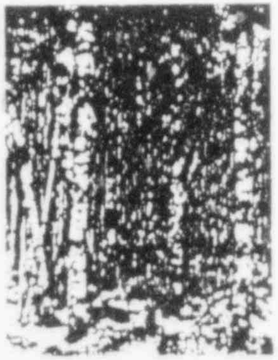

Fig. 9. X-point

Apparatus. [illegible] amount of the fog water [illegible] the forest.

As the screens were [illegible] water [illegible]

[illegible]

[illegible] of the screen was [illegible]

Since the [illegible] distance of water [illegible] the water drops grew to such an extent that [illegible]

[illegible] sec. This largely depends on the conditions of foggy wind. Naturally, the thinner the fog, the larger is the time constant, the time required for the fog to saturate the screen. In the actual observation the time constant was sometimes found to be as long as several hours.

The capturing coefficient of the screen, defined as the ratio of the amount of fog water caught by the screen to that passing across the area covered by the screen, was determined experimentally by blowing known amount of artificial fogs against the screen completely wetted beforehand. It came out 0.40 for the wind velocity v = 1.5 m/sec, 0.45 for v = 2–3 m/sec and [illegible] for v = 4–6 m/sec. Since in most cases of our observation v was about 3 m/sec, we assumed as the capturing coefficient the value 0.4, apart from the corrections to be mentioned below. There it is also assumed that the capturing coefficient is approximately independent of the direction of wind.

In the estimation of capturing coefficient, we must further take account of the fact that the stream lines of wind gradually spread out as they get near the screen, or, in other words, the flux of wind across unit effective area of the screen become smaller. We placed in the wind flow a square screen (with or without mosquito curtain), whose linear dimension was 1/4 that of the screen actually used in the field observation, and made the wind velocity twice as large as that most frequently observed in the field, namely 6 m/sec (according to Reynolds law of similarity). The plane of the screen was made inclined to the wind direction at various angles (from 20° to [illegible]). The stream lines were visualized by floating streamers of fine silk threads properly arrayed in the current of air. In this way we found that the flux of wind across unit effective area was reduced, owing to the presence of the screen with or without curtain, to 0.67 or 0.73,* which is to be regarded as the correction factor for obtaining the true capturing coef-

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* The decreasing rate of the flux of wind was found to be approximately independent of the inclination.

[illegible] the [illegible]tion
[illegible] for vertical screen,
[illegible] droplets with [illegible] wind
[illegible] the horizontal screen [illegible]

[illegible] we [illegible] the value [illegible] as the catching coefficient for [illegible] of the screen.*

[illegible] to be remarked that [illegible] of the size of [illegible] the screen and [illegible] about [illegible] of the evaporation of water [illegible] retained [illegible] the screen [illegible] was made of nothing [illegible] that the [illegible] air was saturated with water vapour.

[illegible] Experimental Results

We [illegible] that the [illegible] when the wind was strong, [illegible] that the amount of fog water M entering the forest [illegible] than the amount N leaving the forest. [illegible] the structure of [illegible] the [illegible] fog particles when [illegible] was absent. [illegible] of the fact that [illegible] the amount [illegible] and [illegible] was [illegible] the data [illegible] assumed that the fog [illegible] from above the forest was completely [illegible] by the forest.

[illegible] of the data [illegible] was [illegible] of great importance to distinguish fog from rain. As the [illegible] of the boundary between rain and fog, we take the value of water

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* [illegible]

droplet [illegible] of the falling velocity [illegible] which corresponds [illegible]. Let the velocity of wind be denoted by [illegible], then the ratio of the amount of water droplets passing through unit vertical area V to that passing through unit horizontal area H is equal to [illegible], provided the droplet size is considered uniform. We thus discriminate, as a rough approximation, between rain and fog according to the relations

V/H < [illegible] : rain,
V/H [illegible] : drizzle,
V/H > [illegible] : fog.

Fig. 10.

Putting together all the data obtained from a long series of measurements, we get the diagrammatic representation in Fig. 10. Here the amounts of fog water entering the forest from above the crowns at X_1, X_2 and X_3, and that passing through the horizontal screen at A downwards are plotted against V/H, the values at X_1 being taken as unity throughout. The data are so widely spread that it seems impossible to draw any significant conclusion. But on careful inspection it will be found that there is a general tendency that the amount of fog caught downwards relative to the amount at X_1 decreases with increasing V/H, and that the rate of decrease [illegible] of the [illegible] of the Forest [illegible]

[illegible] of the Forest [illegible]

The bleached [illegible] Figure 1. [illegible] according [illegible]

[illegible]

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible] the Forest [illegible]

Supposing that the fog water content increases linearly with height and using the data obtained with the vertical screen set in front of the forest, we came to the finding that for the fog whose V/H was about 30 the effect of the frontal surface of the forest was equivalent to that of the upper surface of the forest with about 3 times as much depth as its height.

The same sort of consideration yielded the result that the amount of fog water escaping from the forest at its back surface was about one twentieth of that entering at the front.

The author wishes to express his gratitude to Prof. *K. Aoki*, Mr. *J. Shimazaki* and Mr. *I. Terumoto* for valuable advices, encouragement and kind cooperation. He is also indebted to Prof. *Z. Yosida* for many helpful discussions and suggestions.

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On the Capture of Fog Particles by a Forest (II)

By Hirobumi OURA

In the summer of 1952 investigations were performed at *Akkeshi*, where the forest was grown with only broad-leaved trees and, as compared with that at *Ochiishi*, the trees were much taller while their density was smaller. The fog-capturing efficiency of the forest proved to be of the same order as that of the forest at *Ochiishi*. It was further found that the amount of fog water caught by the forest was as much as from six to ten times that caught by the open field.

§1. Main Object of the Research and Description of the Forest

In the investigation at *Akkeshi* in 1952, special attention was devoted to the fog-capturing function of a grassy field, in order that we may be able to compare it with that of the upper surface of the forest. It was further intended to make some "microscopic" study of the forest as to the capturing efficiency, since it was well anticipated that the motion of fog particles might largely depend on the local character of the forest, so that the measured amount of fog water might show wide variation according to the locality of the measuring apparatus.

The wire screen for collecting fog water was somewhat improved in its construction and was reduced in size to one third of that formerly used. We prepared three pairs of wire screens (each pair consisting of screens with and without mosquito curtain) and one pair was set above the tree crowns at Y (Fig. 1), while the other two were set at Y (Fig. 2) (cf. the chart given in the "General Survey" [1]). In addition to these, two umbrellas were put upside down on the forest ground at F and Y, in order to collect the fog water deposited on and dripping from the foliage of trees. In the open near the observatory house, a screen without curtain was set on the bare ground (Fig. 3) and another screen with curtain was