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Enhanced evaporation of water droplets due to surface contamination

Robert Bernard Hughes

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ENHANCED EVAPORATION OF WATER DROPLETS
DUE TO SURFACE CONTAMINATION

By
ROBERT BERNARD HUGHES, 1945-

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Approved by
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ABSTRACT

Experimental evidence for enhanced evaporation of small (3-9 µ radius) water droplets are presented. Both "pure" droplets and droplets contaminated with surface active materials fell into air of known relative humidity (96-99 per cent) at an ambient temperature of 29.9°C and evaporated. The rates of evaporation were determined by photographing the evaporating drops, measuring the distance a drop fell during a fixed time interval, and applying Stokes law. The contaminated droplets exhibited a rate of evaporation $1.8 \mu^2 \text{sec}^{-1}$ faster than "pure" drops. This can be compared with rates for pure drops of 1.9 and 5.7 µ² sec⁻¹ at 0.1 and 0.3°C dew point depressions respectively. Finally, the increase in the rate appears to be independent of the relative humidity within the range studied.
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1. Background

**Evaporation of pure water drops.** The first reasonable explanation of the evaporation of pure water drops was proposed by Maxwell in 1877 (Fuchs, 1959). Maxwell assumed that the drops were spherical, at rest with respect to the gaseous media, curvature had no effect on the vapor pressure, the evaporation was a steady state equilibrium process, and the rate of evaporation was solely dependent on molecular diffusion through the gaseous media. The mass rate of evaporation was given as

$$\frac{dm}{dt} = 4\pi aD(\rho_\infty - \rho_s)$$  \hspace{1cm} (1)

where \(D\) is the diffusion coefficient of the vapor in air, \(a\) is the drop radius, \(\rho_\infty\) is the water vapor density in the air at an infinite distance from the drop, and \(\rho_s\) is the water vapor density at the surface of the drop. In terms of surface area the rate may also be written as

$$I_M = \frac{d(a^2)}{dt} = \frac{(2D/\rho_L)}{(P_0 - \rho_s)}$$  \hspace{1cm} (2)

where \(\rho_L\) is the density of the drop. It has been shown by Bradley, Evans, and Whitlaw-Gray (1946) that the mass rate of evaporation (1), when expressed in terms of evaporation per unit of surface area, approaches infinity as the radius approaches zero. To overcome these and other difficulties Fuchs (1934) derived the following rate expression

$$I_F = I_M \left[ \frac{D}{(a\alpha)} + \frac{a}{(a+\Delta)} \right]$$  \hspace{1cm} (3)

where \(\nu = (kT/2\pi m_2)^{1/2}\), \(k\) is the gas constant per molecule, \(\alpha\) is the condensation coefficient, \(m_2\) is the mass of the vapor molecule, and \(\Delta\) is the "jump distance" (on the order of a mean free path of the vapor molecules).

Similar rate expressions have been derived by other investigators. Monchick and Reiss (1954) using a nonequilibrium distribution function of the velocities derived the expression

$$I_{mr} = \frac{(\rho_\infty - \rho_s)}{[(a/D) + (1/\alpha\nu) - (1/2\nu)]}$$  \hspace{1cm} (4)

Wright (1960) has shown (4) to be equivalent to (3) if \(\Delta = D/2\nu\). Brock (1964),
and Okuyama and Zung (1967), while concerned with different aspects of evaporation and growth, arrived at similar expressions. Okuyama and Zung have compared the rates calculated from the equations of Maxwell, Monchick and Reiss, and Fuchs for drops at 0°C evaporating into a vacuum. They found that for drops of 1 cm, 10, and 1 μ, the Maxwellian rate is approximately 0.04, 36, and 450 per cent greater than Fuchs' rate. Recently Duguid (1969) has shown that experimental evaporation rates for "pure", freely falling, water drops, 3-8 in radius, are best predicated by Maxwell's theory rather than the more complex theories. However, these rates may have been partially influenced by impurities on the drop surface.

Evaporation through monolayers.

Flat surfaces. There are many investigations concerned with the retardation of evaporation from flat surfaces starting, according to La Mer (1962), with Benjamin Franklin in 1765. Generally, the majority of these investigations have shown that surface active materials (SAM) either have no effect or reduce the rate of evaporation [see La Mer (1962) and Gaines (1965) for reviews of this subject].

There is, however, some evidence that changes in the surface may increase evaporation rates. Hedestrand (1924) suggested that it was logical to assume that a decrease in surface tension, the force between molecules in a surface, could cause an increase in evaporation. However, his experimental work showed no influence on the rate of evaporation due to the presence of a monolayer.

Evidence for increased evaporation is implied in an article by Jarvis (1962). He reported the results of a series of experiments in which air of various relative humidities was passed over the surface of the water at different flow rates. At a relative humidity of 55 per cent and an air flow of 6 liters per minute, measurement of the surface temperature of the water showed a decrease of as much as 0.4°C when the surface was covered with cetyl alcohol or oleic acid as compared to a clean surface. Jarvis attributed this effect to a decrease in the convective overturning of the
surface layer. Although the statement was made that under these conditions the rate of evaporation was reduced, no mention was made of experimental measurements of this reduced rate. Due to the latent heat required to vaporize the water, a lower temperature could be accounted for by increased evaporation. Jarvis also reported a private communication from Ewing who found that it was possible for SAM to decrease the surface temperature of water even when the materials were structurally incapable of reducing evaporation. Specifically, it was found that the surface temperature of a tank of sea water, with an unspecified film, could be reduced by 0.3°C. Ewing attributed this effect to the suppression of "surface streaming".

Kingdon (1963) showed, experimentally, that it was not only possible to increase the evaporation of water by the adsorption of foreign molecules on the surface but that these rates were faster than could be explained by simple diffusion. He explained his results in the light of the work of Knache and Stranski (1965) who showed that evaporation from a crystalline metal surface occurred preferentially from imperfect sites. At a site where a foreign molecule is present the binding energy between the atoms is smaller and the rate of evaporation was found to depend on the nature and concentration of these sites. Kingdon assumed that the evaporation of water molecules is controlled principally by the hydrogen bonds between the water molecules. He proposed that the presence of adsorbed foreign molecules weakened these bonds and thus increased the evaporation.

Droplets. A paper that is often cited in defense of the theory that a monolayer slows down the rate of droplet evaporation is the work of Eisner, Quince, and Slack (1960). A mist of water droplets with radii from 4 to 40 μ containing small quantities (0.025 to 0.4 per cent) of fatty alcohols was generated and allowed to fall into a vertical tube. Size distributions were determined by samples taken at the top and bottom of the tube. It was found that the dispersion droplets fell much further than the pure droplets. Thus it was inferred that droplet life was increased and this was explained by assuming that the condensation coefficient, α, was reduced. It was noted that concentrations as low as 0.05 per cent were as effective as 0.2 per cent
concentrations.

Derjaguin, Fedoseyev, and Rosenzweig (1966) studied the rate of evaporation of water drops after exposing them to an atmosphere saturated with cetyl alcohol vapor. Three hundred micron water drops were supported on glass filaments and placed in a controlled environment chamber for periods ranging from five minutes to twenty five hours. During these time periods, cetyl alcohol vapor was adsorbed on the surface of the drops. The drops were removed to another chamber where they evaporated and the changes in drop size followed with microscope. It was noted that the evaporation occurred in two steps. Initially the drop evaporated rapidly, as a pure drop, but then the rate abruptly decreased.

Another work which lends support to the concept that monolayers reduce evaporation is the work of Snead and Sung (1968). These workers studied the evaporation rate, in a Millikan oil drop apparatus, of droplets .5-2.5μ in radius. These droplets were produced by atomizing various dispersions of water- n decanol- petroleum ether. The amount of alcohol used ranged from 2.5 to 10 per cent by weight with an equal weight of the dispersing agent. It was observed that the emulsion droplets evaporated, by a factor of several hundred, slower than the rate estimated for pure water.

While SAM are usually reported to retard evaporation there are a number of experimental and theoretical papers which suggest that SAM might enhance evaporation. In the formulations for droplet evaporation in which α appears [Rooth (1957); Fuchs (1959); Monchick and Reiss (1954); Snead and Zung (1968)], and increase in α due to a change in the surface characteristics would increase the rate. There is experimental evidence that α can be changed. Izmailova, Prokhorov, and Derjaguin (1957) treated both sodium chloride and SiO₂ condensation nuclei with various SAM and measured the water vapor density necessary for growth to occur. Their work showed that α could be increased or decreased depending upon the SAM used. One of the substances causing an increase was isoamyl alcohol. A recent article by Pueschel, Charlson, and Ahliquist (1969) showed that droplets grown from aerosols generated from sea water, which is known to contain SAM,
were smaller at a given relative humidity than droplets grown from either a pure NaCl or synthetic sea water solution. They attributed their results to a higher water vapor density over the droplets produced from the sea water aerosols.

Derjaguin, Bakanov, and Kurgin (1960, 1961) theoretically analysed droplet evaporation through monolayers using a "diffusion" model. The final expression derived for the quasistationary evaporation of a drop covered with a monolayer was

$$\frac{dm}{dt} = 4\pi a^2 \left( \rho_\infty - \rho_s \right)/ \left[ \left( \frac{C_o}{C_p} \right) \left( \frac{\delta}{D_1} \right) + \left( \frac{1}{\alpha v} \right) + \left( \frac{a^2}{D(a+\Delta)} \right) \right]$$  \hspace{1cm} (5)

where $C_p$ is the concentration of the evaporating liquid in the film, $C_o$ is the concentration of the water in the vapor, $D_1$ is the diffusion coefficient of the liquid molecules in the film, and $\delta$ the thickness of the film. A second model, involving adsorption equilibrium, was proposed by Derjaguin and Durgin (1964) in which the solution was

$$\frac{dm}{dt} = 4\pi a^2 m_2 (C_\infty - C_s)/ \left[ R + \left( \frac{1}{\alpha v} \right) + \left( \frac{1}{D} \right) \left( \frac{a^2}{a+\Delta} \right) \right]$$  \hspace{1cm} (6)

where $R$ is the resistance of the monolayer to evaporation; $C_\infty$ is the number of water molecules per cubic centimeter at an infinite distance from the surface of the drop; and $C_s$ is the number of water molecules per cubic centimeter, in the vapor at the drop surface. Further development of the equilibrium model was achieved by Zung (1969). He suggested that there were four processes to be considered in determining the net rate: the rate from the liquid phase into the monolayer, the rate from the monolayer back into the liquid, the rate into the gas phase, and the rate from the gas phase into the monolayer. The net rate of evaporation is then

$$\frac{dm}{dt} = 4\pi (a+\delta)^2 m_2 (C_\infty - C_s)/ \left[ R + \left( \frac{1}{\alpha v} \right) + \left( \frac{a+\delta}{D(a+\delta+\Delta)} \right) \right]$$  \hspace{1cm} (7)

Zung has attributed any increase in evaporation to an increase in the condensation coefficient and/or to the effect of curvature on the monolayer.

Tovbin and Savinova (1956) found that isoamyl alcohol, during the first 0.002 seconds, increased the rate of evaporation from a stream of water. At the time they attributed the increased rate to nonsteady-state conditions.
At longer periods of time evaporation was retarded. Derjaguin (1961) states that they also saw an increased rate with octyl alcohol.

More recently, Leonov and Prokhorov (1967) presented direct evidence for increased evaporation. In their experiment, water drops of 3–4μ radius, aqueous solutions, or dispersions were produced by atomization and captured on a fine grid. The rate of evaporation of these drops were determined by measuring the size of the drops, at fixed time intervals, photographically. Increases in evaporation were found for solutions of three compounds at concentrations of 0.01 per cent. At higher concentrations these compounds inhibited evaporation. Decreased evaporation was found with all the dispersions of insoluble alcohols examined.

2. Apparatus

The majority of the apparatus and experimental procedures have already been described by Duguid (1969). In general, room air was injected into a thermal diffusion cloud chamber and the drops which formed were allowed to fall into a vertical drift tube. A constant temperature bath, maintained at 29.90 ± 0.1°C, surrounded the drift tube to insure that there were no convection currents. The vapor density in this tube was controlled by flushing, for at least one half hour before the start of the first run, with air of known humidity. Between each run the drift tube was rehumidified for at least 10 minutes. The drops were photographed at 0.50 second intervals and their sizes determined using Stokes law.

The only modification made in the apparatus of Duguid was the method of injecting the room air, containing the condensation nuclei, into the cloud chamber. In this work it was necessary to introduce SAM either by coating the condensation nuclei already present or to produce an aerosol of SAM. To accomplish this, room air was pumped over SAM contained in an anodized aluminum trough, see Fig. 1. The trough, which was covered with a glass plate, was 25 cm long by 2.5 cm wide and 2.5 cm deep with an inlet at one end and an outlet at the other. The temperatures of both the air stream and the liquid SAM were measured by copper constantan thermocouples. From the trough the air was passed into a glass chamber, 9 cm in diameter and 30 cm
long, which allowed the air to cool, gave more time for the condensation nuclei to adsorb SAM, and permitted small droplets of SAM to condense. In operation it was found that a mist formed and it was necessary to use an "absolute" (MSA type H) filter to reduce the number of nuclei and to remove the larger particles.

Briefly, the experimental procedure for the introduction of condensation nuclei was as follows. After the trough had been heated to the desired temperature, air was passed through the system to the tee fitting. This part of the system was purged for at least 2 minutes at a flow rate of 3 liters per minute. After this purging operation, the air stream was passed through the filter and cloud chamber for an additional 2 minutes. During this time, the drift tube was flushed with air of known vapor density. The SAM generating and humidifier systems were shut off, the cloud chamber sealed, and drops allowed to form. When a suitable number of drops had formed a sliding door on the floor of the cloud chamber was opened and the drops fell into the drift tube. The drops were photographed at 0.50 second intervals and their sizes determined using Stokes law.

In an attempt to learn the sizes of the particles which were introduced into the cloud chamber, the air stream which passed through the absolute filter was diverted into a Climet CI 201 particle analyzer. The results indicated that out of a total of 400 particles greater than .15\(\mu\) there would be fewer than 4 particles greater than .25\(\mu\) in the cloud chamber at any one time.

3. Results

In this investigation it was found convenient to relate the rate of evaporation of a drop, \(-d(a^2)/dt\), to the dew point depression, \(\Delta T\), of the air in the drift tube. The dew point depression is defined as the difference between the temperature of the ambient air \((T_\infty)\) and its dew point temperature \((T_{dp})\).

It is well known that a drop cools as it evaporates and that its temperature is lower than that of the ambient air. Thus, droplet evaporation
involves solving both the mass diffusion and heat flow problems simultaneously. For quasistationary evaporation, this requires that the heat used in evaporation be equal to the heat flux to the drop from the surrounding gas. As shown by Fuchs (1959) this results in the expression,

$$T_\infty - T_s = (1/\Gamma) (\rho_s - \rho_\infty)$$  \hspace{1cm} (8)

where $T_s$ is the temperature of the evaporating drop, $\Gamma = K/DL$, $K$ is the coefficient of thermal conductivity for the air, and $L$ is the latent heat of vaporization. For small temperature ranges a linear relation, $\rho = bT + C$, between the vapor density and the temperature of the liquid is a good approximation. Since the temperature range in this investigation was 0.4°C the approximation was made and substituted into (8) yielding

$$-T_s = (1/b + \Gamma) (-\rho_\infty - \Gamma T + C)$$  \hspace{1cm} (9)

Substitution of Eq. (9) into (8) and the result into Eq. (2) produces

$$-d(a^2)/dt = (2D/\rho_L)(\Gamma/\Gamma + b)(\rho_{t\infty} + C - \rho_\infty)$$  \hspace{1cm} (10)

As $\rho_\infty$ is actually the equilibrium vapor density at the dew point temperature, $\rho_\infty = bT_{dp} + C$, where $b$ and $C$ are numerically the same as before. The rate of evaporation is then given by

$$-d(a^2)/dt = \left[2D/\rho_L\right] \left[\Gamma b/(\Gamma + b)\right] \left[T_\infty - T_{dp}\right] = \beta \Delta T$$  \hspace{1cm} (11)

where $\beta$ is a constant which is a function of the ambient temperature.

In order to determine the effect of SAM on evaporation, the rates for untreated drops were first determined. This was accomplished by passing air through the SAM generating system with the trough operating under three different conditions and determining the evaporation rates for the resulting drops. The three conditions were the clean trough at room temperature, the clean trough at 110°C, and the trough containing SAM at room temperature. In the latter case it was assumed that the vapor pressure of the SAM would be so low that there would be no effect on the evaporation rate. There appeared to be no differences in the rates under these three conditions. The results are shown in Fig. 2 in which the rate of evaporation, $-D(a^2)/dt$, is
plotted against the dew point depression, \( \Delta T \). A least squares fit of these data, obtained with the ambient air at a temperature of 29.9°C, gives the following first degree equation: 
\[
-d(a^2)/dt + (19.6 \pm 1.6) \Delta T + (0.1 \pm 0.4) \mu^2 \text{ sec}^{-1}.
\]

This compares favorably with Duguids (1969) results obtained with the drift tube at 30.00°C: 
\[
-d(a^2)/dt = (19.1 \pm 0.8) \Delta T + (0.2 \pm 0.2) \mu^2 \text{ sec}^{-1}.
\]

In both cases, the limits noted are at the 95 per cent confidence level. Although the drift tube temperatures differed by 0.1°C in the two cases, this causes a negligible change in the evaporation rate at a given dew point depression.

Once the rate of evaporation for pure water had been established two successive SAMs, dodecanol and hexadecanol, were placed in the trough and heated to temperatures of 85°C and 105°C respectively. A typical example of the raw data for dodecanol is shown in Table 1 while plots of the rates vs. dew point depressions are shown in Fig. 3 for dodecanol and Fig. 4 for hexadecanol. The least squares fit for these data are 
\[
-d(a^2)/dt = (17.8 \pm 1.6) \Delta T + (1.6 \pm 0.4) \mu^2 \text{ sec}^{-1} \quad \text{and} \quad -d(a^2)/dt = (18.0 \pm 2.3) \Delta T + (1.8 \pm 0.5) \mu^2 \text{ sec}^{-1},
\]

respectively. Since the increased evaporation is ascribed to the presence of the SAM, and both materials were alcohols differing only by 4 CH₂ groups in the carbon chain, it is not unlikely that they would affect the evaporation similarly. As the two sets of data appear almost identical they have been combined, Fig. 5, giving a rate expression 
\[
-d(a^2)/dt = (17.7 \pm 1.2) \Delta T + (1.7 \pm 0.3) \mu^2 \text{ sec}^{-1}.
\]

The line in Fig. 5 labeled "from Fig. 2" is the calculated line for the pure drops in Fig. 2.

In an attempt to determine the vapor pressure of SAM required for increased evaporation to be evident, the trough with hexadecanol was operated at a number of different temperatures. The average evaporation rates, determined at various trough temperatures and normalized to a constant dew point depression, are shown in Table 2. It would appear that, with this particular experimental arrangement, a vapor pressure between 0.02 and 0.05 torr is necessary for the increased evaporation to be apparent. At lower vapor pressures no increase was observed in the rate. Although the average rate determined at the highest trough temperature, the maximum,
feasible temperature with this equipment, was slightly lower than that observed for pure drops, the amount of scatter in the results makes this rate questionable.

4. Discussion

After comparing the rates for "pure" droplet evaporation found by Duguid (1969) and that presented in this paper it appears that the method of nuclei injection has no direct influence upon the evaporation. While the results for the pure drops are consistent with Maxwell's evaporation theory, faster rates of evaporation were observed for droplets formed from condensation nuclei when either SAM, dodecanol or hexadecanol, was in the trough at an elevated temperature.

Since the noncontaminated nuclei, which were treated in the same manner as the contaminated nuclei, formed drops which showed no increase in the rate of evaporation it was assumed that the increased evaporation observed for doped drops was due to the SAM. Two possible means whereby the SAM might change the rate of evaporation without actually being incorporated on a drop were considered. Initially it was thought that some SAM may have gotten into the humidifier system and changed the relative humidity. In order to demonstrate that such was not the case, after a pure rate had been determined the SAM generating system was connected, SAM contaminated drops grown, and increased rates recorded. Then, pure drops were again generated and the lower rate was again in evidence. Secondly, if SAM had gotten into the drift tube the relatively humidity might have changed. In order to insure that this did not occur the pumps for the humidifier and SAM generating systems were shut off simultaneously and only after both systems were closed off was the sliding door sealing the cloud chamber from the drift tube opened.

From the data obtained with the particle analyzer, it was calculated that the cloud chamber would contain fewer than 4 particles with a radius greater than .25 μ while there were approximately 400 particles in the .15-.25μ range. To estimate the maximum possible coverage for a drop it was assumed that the condensation nucleus was a .25μ drop of pure SAM. Based on this,
a maximum surface coverage of 10 per cent was calculated for a 5μ drop. Since it is highly unlikely that all the drops would have the same surface coverage, the scatter in the data is not unexpected. Also, while not specifically shown in the figures, most of the drops which were 7μ and larger when first seen evaporated at an overall rate slower than those smaller than 7μ.

Although there appears to be a discrepancy between our data and others who have worked with SAM this is not the case. While other workers have reported decreased evaporation rates due to SAM they were dealing with drops with one or more layers of organic material while in our case only a small fraction of the surface was covered. Moreover, at low relative humidities the increase in the rate becomes negligible compared to the total rate and thus any increase would be masked.

Currently there is no theory for evaporation through a monolayer which allows a rate of evaporation to exceed the Maxwellian rate. The increased evaporation could possibly be explained by the doped drop being 0.07°C warmer than the pure drop. There is no reasonable means to account for the contaminated drop initially being warmer and, moreover, increased evaporation should cool the drop to a lower temperature and thus slow the evaporation. Another possibility is increased ventilation of the SAM treated drop. However, that the small amount of SAM present could change the surface characteristics enough to cause increased ventilation is improbable.

Kingdon (1963) proposed a mechanism which allowed evaporation to occur faster than the rate predicated by diffusion theory. The increased evaporation was ascribed to the formation of weak bonds between the surface water molecules and the contaminant at elevated temperatures which allowed water molecules to lease the surface more readily. Although, in the present case, the SAM appears to form strong bonds with the surface, a similar mechanism is still possible. The water molecules closest to the hydrophilic end of the SAM molecule could be more strongly bound to this molecule than they would normally be to another water molecule at that site. This increased attraction
could cause a weakening of the hydrogen bonding between other water molecules further away. Thus molecules at some finite distance from the SAM molecule would be less tightly held to the surface of the drop and would require less energy to escape. It is the evaporation of these, the weakly held, water molecules that could allow enhanced evaporation. This explanation would also explain why the two SAMs which were structurally very similar, particularly the hydrophilic end, would exhibit the same effect on the evaporation rate.

We have presented evidence that both dodecanol and hexadecanol, at low surface coverage, can increase the rate of droplet evaporation. Our results and method have been presented not to demonstrate any new or easy way of determining evaporation rates, for the method is none of these. Rather, we believe we have shown a new role that SAM may play in droplet evaporation.

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REFERENCES


FIGURE LEGENDS

Fig. 1  Diagram of SAM generating apparatus.

Fig. 2  Experimental evaporation rates of untreated drops.

Fig. 3  Experimental evaporation rates of drops contaminated with dodecanol.

Fig. 4  Experimental evaporation rates of drops contaminated with hexadecanol.

Fig. 5  Experimental evaporation rates of all drops with surface contamination.
Fig. 1
THESE DATA \( \frac{d\alpha}{dt} = 19.6\Delta T + 0.1 \)

Fig. 2
THESE DATA \( \frac{d\alpha^2}{dt} = 17.8\Delta T + 1.6 \)
THESE DATA \( \frac{d(a^t)}{dt} = 18.0\Delta T + 1.8 \).
THESE DATA \( \frac{d(a^2)}{dt} = 17.7 \Delta T + 1.7 \)

Fig. 5
### Table 1

DATA OBTAINED FOR AN EVAPORATING DROPLET CONTAMINATED WITH DODECANOL. DEW POINT DEPRESSION 0.10°C.

<table>
<thead>
<tr>
<th>Time (sec)</th>
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<th>Distance drop fell (mm) in .50 sec.</th>
<th>Droplet radius (microns)</th>
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<td>.70</td>
<td>3.46</td>
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<td>43.25</td>
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Table 2

RATES DETERMINED AT 0.15°C DEW POINT DEPRESSION WITH HEXADECANOL AS THE SAM IN THE TROUGH. VAPOR PRESSURE DATA FROM SPIZZICHINO (1956).

<table>
<thead>
<tr>
<th>Trough Temp. C</th>
<th>Ave. Rate $\mu^2 \text{sec}^{-1}$</th>
<th>Standard deviation</th>
<th>V.P. of SAM (mm)</th>
<th>Number of drops</th>
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<td>.0001</td>
<td>10</td>
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<tr>
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<td>3.1</td>
<td>.4</td>
<td>.006</td>
<td>8</td>
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<tr>
<td>140</td>
<td>2.9</td>
<td>.7</td>
<td>1.0</td>
<td>13</td>
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APPENDIX A

Apparatus

The experimental apparatus consisted of four distinct but integrated systems: the humidifier system, the SAM generating system, the photographic system, and a temperature monitoring system. Each system was vital and the breakdown of any one part made the collection of data worthless.

The humidifier system was composed of a pump, "absolute" filter, preconditioner, humidifier, vertical drift tube, and a hygrometer. Room air was introduced into the system by the pump (at a rate of one liter of air per minute), passed through the filter, and passed through a 500 ml Florence flask. The flask contained water heated to 40°C and served as a preconditioner by raising the relative humidity of the air. After the air had left the preconditioner it was passed via quarter inch tubing to a copper coil that was immersed in a constant temperature bath that was never warmer than 29.8°C. This coil, connected on the other end to the humidifier, served to bring the air to the temperature of the constant temperature bath. The humidifier, which was submerged in the same bath, was a lucite box 30 cm by 30 cm by 5 cm high with rows of baffles 1 cm apart. Contact between the air and water took place over a path approximately 7.5 meter long and 1 cm wide. It was felt that this distance was more than sufficient to insure that the air leaving the humidifier was saturated. From the humidifier the exiting vapor was transported through quarter inch copper tubing electrically heated to an elevated temperature so that no moisture would condense on the walls. The moist air next passed into another copper coil which was immersed in a constant temperature bath maintained at 29.9°C. This coil provided a means of conveying the conditioned air into the drift tube and heating it to 29.9°C at the same time. After passing through the drift tube the air was again transported through heated copper tubing to a Cambridge model 992-T1 and 992-C1 dew point sensing unit and then passed back into the room.

The SAM coating system was composed of a pump, flow valve, trough, condensation chamber, tee, and filter. Room air was pumped through the
trough which contained the SAM at an elevated temperature, at a rate of 3 liters per minute. The trough was made of anodized aluminum and was 10 inches long by 1 inch wide with quarter inch diameter copper tubing at each end for entrance and exit of the air. Visibility into the trough was provided by a glass top 10 inches long which was sealed into the trough by means of a rubber gasket. The exiting vapors then entered a glass condensing chamber. This chamber was a glass tube 3.5 inches in diameter and 12 inches long. The chamber served three purposes: allowed the air to cool, gave more time for the condensation nuclei to adsorb SAM, and permitted small droplets of SAM to condense. After leaving the condensing chamber the air stream passed through a filter (MSA type H) and then into the cloud chamber. After at least two minutes of passing this air through the cloud chamber both the SAM generating and humidifying systems were shut off. Condensation occurred on the nuclei in the chamber. After a few seconds a sliding door on the floor of the chamber was opened and the drops allowed to fall through a quarter inch diameter copper tube, two inches long, into the humidified drift tube where evaporation occurred.

The drift tube was illuminated by a GE quartz Q1000T3/C1 220 volt 1000 watt lamp. As soon as a drop fell into the drift tube the camera was activated and allowed to run for twenty to forty seconds. The maximum time of 40 seconds was due to the length of film that could be easily processed and concern that a longer time would allow the humidity in the drift tube to change. The optimum condition was the evaporation of a single drop and for about half the runs this was obtained. In the rest of the runs not more than four drops were present. When more than four drops appeared the film strip was not used because of the possibility of drop interaction and the difficulty in identifying individual drops from one frame to the next. Following the end of a run the humidifier system was reconnected and allowed to run for at least 10 minutes before the start of the next run. It was during this time interval that the temperature measurements were made.

The temperature monitoring system was composed of 4 pairs of copper-
constantan thermocouples and a Leeds and Northrup K-5 potentiometer with auxiliary null detector and constant voltage source. One pair of thermocouples measured the difference in temperature between the two constant temperature baths while the second pair measured any differences in temperature between the humidifier and its constant temperature bath. Using these two sets of readings a dew point depression was calculated. A third thermocouple pair measured the difference in temperature between the constant temperature bath set at 29.9°C and the heated SAM liquid. The fourth and last pair measured any difference in the temperature of the air stream over the SAM and the SAM.

In actual operation, the drift tube was purged with humidified air for at least 30 minutes before the start of the first run and reflushed for at least 10 minutes between runs. A SAM was placed in the trough which was heated to the desired temperature. Air was passed through the SAM generating system and injected into the cloud chamber. Both the humidifier and SAM systems were shut off and the drops allowed to grow in the thermal diffusion chamber. These droplets, 3-9 μ in radius, fell into the drift tube containing air of known vapor density. The tube was illuminated and pictures were taken of the evaporating droplets. The developed film was projected on a previously calibrated screen and the rate of fall of the droplets was determined employing Stokes equation and the rates of evaporation calculated.
Robert Bernard Hughes was born on September 3, 1945 to Helen F. and R. Evans Hughes in Philadelphia, Pennsylvania. He attended a private grade school, Martin Luther Day School, in Pennsauken, New Jersey, and received his high school diploma June 1964 from Cherry Hill High School, New Jersey. His college education was obtained at Rutgers University, Camden, New Jersey. He received an A.B. in chemistry from Rutgers University, June 1968. He has been enrolled, as a candidate for a Masters Degree in Chemistry, at the University of Missouri since September 1968 and has had a graduate teaching assistantship from the chemistry department and has had a summer National Science Foundation research assistantship during that time.