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# Technical Memorandum

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SCTM 160-53-51

# THE EFFECT OF ICING ON THE FUZING SYSTEM OF THE MATADOR MOD-0 PILOTLESS AIRCRAFT

by

R. C. MAYDEW

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## ABSTRACT

A study has been made of the probability of accreting a thickness of ice at the baroports on the Matador Mod-0 fuselage sufficient to cause malfunctioning of the fuzing system.

The effect of icing due to freezing rain can be neglected. Icing due to supercooled clouds is more critical during the climb phase of the trajectory than during the dive phase. Only a negligible amount of the ice accreted during the climb phase would sublimate off during the cruise.

Probability analyses, which were based on conservative assumptions, indicate that the thickness of ice accretion at the baroports during the climb phase of the trajectory will be less than 1/32, 1/6 and 3/32 inch 96, 98.5 and 99.5 per cent of the time, respectively. The thickness of ice accreted during the dive phase will be less than 1/64 and 1/32 inch 98 and 99.7 per cent of the time, respectively.


Case No. 409.03 October 8, 1953

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## INTRODUCTION

The fuzing system of the Matador Mod-0 Pilotless Aircraft consists of a baro-port pressure system which turns on the radar fuzing system during the dive phase of the trajectory. The baro-port pressure system consists of two clusters of 1/32" diameter orifices located 90° apart at station 45 on the Matador fuselage. If icing conditions were encountered during the trajectory, it is conceivable that the ice formation would seal off the orifices with a resulting malfunction of the primary fuzing system.

The threefold purpose of this memorandum is to discuss the probability of encountering meteorological conditions conducive to icing; to determine the regions of the trajectory where icing could occur, and to determine the probability of accreting specified thicknesses of ice at station 45 during icing conditions.

NOMENCLATURE

| | |
|---|---|
| $A_c$ | Cross-sectional area of Matador at maximum diameter, square feet |
| $A_s$ | Surface area of Matador fuselage forward of maximum diameter, square feet |
| D | Droplet diameter, microns or feet |
| d | Diameter of body, feet |
| E | Collection efficiency, dimensionless |
| $R_u$ | Droplet Reynolds number, dimensionless |
| T | Ambient temperature, degrees Fahrenheit |
| t | Flight time, seconds |
| V | Aircraft velocity, feet per second |
| $W_i$ | Liquid water content, grams per cubic meter or pounds per cubic feet |
| $w_a$ | Specific weight of air, pounds per cubic feet |
| $w_d$ | Specific weight of supercooled water droplet, pounds per cubic feet |
| $w_i$ | Specific weight of ice, pounds per cubic feet |
| y | Ice thickness, inches |
| $\rho$ | Free stream density, slugs per cubic foot |
| $\mu$ | Viscosity, slugs per foot second |
| $\psi$ | Scale modulus, dimensionless |

## ICE FORMATION ON AIRCRAFT

The most common type of icing occurs when an aircraft flies through a supercooled cloud. Supercooled clouds are a suspension of tiny water droplets which remain unfrozen even though the temperature may be far below the melting point of ice. Water has been supercooled in the laboratory to -72°C [1] and windshield icing has been encountered over England on a Canberra at -50°C at an altitude of 45,000 feet.[2] However, it is generally believed that the frequency of occurrence of supercooled clouds at temperatures below -40°C is negligible.[3] This belief is borne out by the fact that the likelihood of the spontaneous nucleation freezing process (chance collisions of liquid molecules forming a critical size ice crystal) increases quite rapidly with decreasing temperature. Hence, it is implied that at temperatures below -40°C the cloud will be composed of ice crystals which merely bounce off an aircraft surface. An airplane, flying through a supercooled cloud, collides with the droplets and becomes wet with a continuous layer of supercooled water. Nuclei present on the surface initiate the transition from liquid to ice. Once a thin film of ice is deposited, succeeding water droplets freeze upon impact with the ice covered surface.

A less frequent type of icing is experienced when an aircraft encounters freezing rain. This occurs when an aircraft is flying through rain falling from clouds which are at above-freezing temperatures while the ambient temperature of the aircraft altitude is below freezing.

## PROBABILITY OF ENCOUNTERING ICING CONDITIONS

### Supercooled Clouds

Statistics on aircraft ice accretion over northwestern Europe have been compiled by the USAF Air Weather Service[4] based on 1340 weather reconnaissance missions made during the period 3 June 1944 to 3 May 1945. The flights were made at average altitudes of 5000 to 15,000 feet, but frequently measurements of thick cloud decks took pilots as high as 30,000 feet and down to a few hundred feet above the ground. Observational data from the pilots indicated that one or more instances of icing occurred on 307 of the 1340 flights for a percentage of 22.9%. In general, icing conditions were encountered more frequently during the winter and spring

seasons. The following table presents the frequency of icing with month of the year for most of the observations.

TABLE 1[4]

| Month: | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Missions: | 85 | 113 | 142 | 149 | 0 | 178 | 183 | 178 | 76 | 59 | 94 | 122 |
| Icing Reported: | 34 | 30 | 49 | 52 | 0 | 13 | 7 | 3 | 9 | 18 | 37 | 47 |
| Percentage: | 40 | 27 | 35 | 35 | 0 | 7 | 4 | 24 | 12 | 31 | 39 | 38 |

Statistics on aircraft ice accretion over the North Atlantic were accumulated by three C-54 weather reconnaissance aircraft on 40 round trips between North America and England during January to March 1944.[5] The percentage of the total flight time the aircraft was in clouds or icing at various altitudes is presented in Table 2.

TABLE 2

| Altitude (feet) | 5,000 | 8,000 | 10,000 | 12,000 | 15,000 |
|---|---|---|---|---|---|
| Time (per cent) In clouds | 60 | 33 | 24 | 17 | 12 |
| Time in icing | 42 | 27 | 19 | 13 | 4 |

A complete discussion of the frequency of occurrence of cloud types, the cloud types most conducive to icing, and other meteorology aspects of aircraft icing over Europe are presented by B. N. Charles in a Sandia Corporation Technical Memorandum.[6]

Freezing Rain

Freezing rain normally occurs in the late fall to early spring seasons of the year and, in general, is confined to the lowest 5000 feet of the

atmosphere. Icing data accumulated on scheduled air transport operations below 1000 feet altitude between Berlin and Kaliningrad (1414 flights) and Kaliningrad and Moscow (809 flights) between October and March 1929-1937 indicate that freezing rain was encountered about 4% of the time.[6] The frequency of occurrence of this condition should decrease with altitude.

## ICING REGIONS OF MATADOR TRAJECTORY

### General

The climb and cruise phase of the Matador trajectory selected for this study correspond to the pre-set indicated dynamic pressure of 220 pounds per square foot.[7] The pushover and dive phase were selected from IBM trajectory calculations that correspond to the above-mentioned climb and cruise phase.

The ambient temperature is plotted versus flight time, altitude and velocity for the climb, cruise, and dive phases of the selected trajectory in figures 1a, 1b and 1c, respectively. The NACA standard atmosphere[8] was used throughout this study. In addition, the calculated boundary layer temperature and skin temperature for flight in clear air are shown in figures 1a, 1b and 1c. The effect of aerodynamic heating on the icing will be discussed later in the memo.

### Supercooled Clouds

Since supercooled clouds normally exist only in the temperature range of 32°F to -40°F, the potential icing regions of the trajectory can be determined. Figures 1a and 1c indicate that the time extent of the icing regions are 5.6 minutes and 0.35 minutes, respectively, for the climb and dive phases. It is apparent that the icing region during the climb will be more critical than the icing region during the dive.

### Freezing Rain

Since freezing rain is confined to the lower 5000 feet of the atmosphere, this type of icing could occur only during the first minute of the climb phase of the trajectory. During the dive phase it could

occur only for approximately 0.1 minute. However, the icing during the dive phase can be disregarded as the baro-system would have turned on the radars before this region is encountered. Hence, the icing due to freezing rain during the climb only need be further considered.

## RATE OF ICING IN SUPERCOOLED CLOUDS

### Distribution of Ice Over Matador Nose

A scaled sketch of the Matador fuselage forward of the maximum diameter is presented in figure 2. The location of the baro-ports is indicated in the sketch. Since the ports are located well forward of the maximum diameter, it is quite conceivable they are in the impingement region of the supercooled water droplets. As far as the author knows, studies of water droplet trajectories on bodies of revolution of this type have not been made to date. Water droplet trajectories have been determined on spheres, cylinders and flat plates by several investigators.[9 10] Tribus[9] recently determined droplet trajectories for a supersonic wedge. Bergrun[11] and Guibert[12] et al, calculated droplet trajectories about several airfoil sections with a differential analyzer. The equations of motion of the supercooled droplets can be sol ed numerically, on a differential analyzer, or by electronic simulation methods (as described by Tribus[13]). In order to accurately predict the area of impingement or the distribution of ice along the Matador nose, water droplet trajectory calculations would have to be made for this shape. The distribution of ice on any surface is primarily a function of droplet diameter, aircraft speed, and the surface size, shape and angle of attack.

It was felt that this study did not warrant the expense, time, etc. that would be involved in making water-droplet trajectory studies over the Matador for an accurate determination of ice distribution. Hence, the conservative assumption was made that the ice was evenly distributed along the nose to the maximum diameter of the fuselage. This is shown in figure 2 along with the probable distribution of the ice layer.

### Rate of Impingement

Using the assumption of constant ice thickness along the surface, the ice thickness accreted for any given flight period can be expressed as:

$$y = 12\ t\ E\ W_i\ V\ A_c/A_s\ w_i \qquad (1)$$

where $W_i$ (liquid water content) is in lbs/ft$^3$.

Collection Efficiency, E

The collection efficiency expresses the ratio of the amount of water which actually impinges on the surface to the total amount of free water in the volume swept by the surface (for the Matador, the amount swept by the cross-sectional area at the maximum diameter). The collection efficiency is a function of droplet size, air temperature and pressure, and four aircraft parameters, namely: velocity, size, shape and angle of attack. The collection efficiency cannot be accurately estimated unless droplet trajectory calculations, as mentioned previously for the ice distribution, are made. Hence, an assumption must be made for the collection efficiency of the Matador.

Table 3, which was extracted from Fraser,[14] indicates the variation of E with four parameters.

TABLE 3

Variation of E with Velocity, Scale, Shape and Droplet Size

| Body | Velocity (mph) | Value of E (percent) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Droplet Diameter (microns) | | | | | | |
| | | 5 | 10 | 15 | 20 | 30 | 40 | 50 |
| 1in. dia. | 200 | 10 | 75 | 93 | 100 | 100 | 100 | 100 |
| cylinder | 400 | 60 | 90 | 100 | 100 | 100 | 100 | 100 |
| Wing with | 200 | 0 | 0 | 0 | 1 | 10 | 17 | 25 |
| 20 ft. chord | 400 | 0 | 0 | 3 | 10 | 20 | 33 | 47 |

Examination of table 3 indicates E varies considerably with droplet diameter and to a lesser extent with velocity for the 20-foot chord

wing.

The variation of collection efficiency with droplet diameter for two airfoils is plotted in figure 3. The curve for the 20-foot wing was taken from table 3. The curves for the 15.8 foot chord wing were extracted from Hacker and Dorsch.[15] These curves are presented to point out (in the absence of collection efficiency data on slender bodies of revolution) the variation of E with droplet diameter on shapes the same order of magnitude in size and at approximately the same velocity as the Matador. The linear variation of E shown in figure 3 was used in calculations on the Matador.

Tribus[9] has determined the variation of collection efficiency for spheres in terms of the droplet Reynolds number and a scale modulus. The droplet Reynolds number is expressed as

$$R_u = \frac{\rho V D}{\mu} \tag{2}$$

The scale modulus is expressed as

$$\Psi = 9 \frac{w_a}{w_d} \frac{d}{D} \tag{3}$$

The collection efficiency has been plotted versus droplet Reynolds number with scale modulus as a parameter by Tribus.[9]

The variation of collection efficiency with droplet diameter was determined by this method for a sphere of the same diameter as the maximum Matador fuselage diameter using the four flight conditions of the Matador trajectory that represent the extremes of the icing regions shown in figures 1a and 1c. These four curves are presented in figure 4 along with the linear variation of E with D used in the Matador calculations. The collection efficiency for the Matador fuselage should be less than for a sphere of the same diameter as the decreased curvature of the flow streamlines around the Matador shape would allow more droplets to escape. Hence, the linear variation of collection efficiency used in this study should be quite conservative.

BAROPORT ICING

A reliable estimate of the minimum thickness of ice at station 45 necessary to seal off the ports or to clog the ports sufficiently to cause malfunction of the primary fuzing system is rather difficult to make. It seems reasonable that a sheet of ice the same thickness as the orifice diameter would probably clog the ports. Even partial closure of the ports would undoubtedly result in lag in the pressure system. Since a critical ice thickness could not be estimated, it was decided to determine the probability of accreting ice thicknesses on the same order of magnitude as the orifice diameter for the icing regions specified in figures 1a and 1c.

PROBABILITY OF ACCRETING A SPECIFIED THICKNESS OF ICE DURING FLIGHT IN A SUPERCOOLED CLOUD

Probability Analysis

Lewis and Bergrun[16] statistically analyzed flight icing data obtained in the United States and developed a method for determining the probability of exceeding any specified group of values of liquid-water content associated simultaneously with temperature and drop-diameter values lying within specified ranges. The data used included 252 icing encounters and 1038 observations of liquid-water content and drop diameter. They computed the probability $\Delta P_i$, that in any random icing encounter, the liquid water content would exceed a specified value $W_i$ while temperature and drop diameter are within specified ranges $\Delta T$ and $\Delta D$, respectively, for a specified horizontal cloud extent. This partial probability can be expressed as:

$$\Delta P_i = P_{\Delta D}\, P_{\Delta T}\, P_{W_i}\, (\Delta T) \qquad (4)$$

where

$P_{\Delta D}$ = the probability that the drop diameter will be within the interval $\Delta D$.

$P_{\Delta T}$ = the probability that the temperature will lie within the interval $\Delta T$.

$P_{W_i}(\Delta T)$ = the conditional probability that the liquid water content will be equal to or greater than $W_i$ under the condition that the temperature lies within the interval $\Delta T$.

Bergrun and Lewis analyzed the data by utilizing the temperature and drop diameter intervals presented below in Table 4.

Table 4

| Medium T, °F | ΔT, °F | Medium D, microns | ΔD, microns |
|---|---|---|---|
| 24 | 32 to 20.5 | 8 | 0 to 9.5 |
| 15.5 | 20.5 to 10.5 | 11 | 9.5 to 12.5 |
| 6.0 | 0.5 to 10.5 | 14 | 12.5 to 15.5 |
| -4.0 | -9.5 to 0.5 | 17 | 15.5 to 19.5 |
| -13.0 | -9.5 to-19.5 | 24 | 19.5 to 29.5 |
| -25 | -19.5 to -40 | 37 | 29.5 to 49.5 |
| | | 60 | over 49.5 |

All conceivable combinations of $\Delta D$ and $\Delta T$ in Table 4 provide 42 different values of $\Delta P_i$. Lewis and Bergrun state that the total probability of exceeding a given icing condition is the sum of the partial probabilities since the different possibilities are mutually exclusive. Specifically,

$$P = \sum_{i}^{n} \Delta P_i = \sum_{i}^{42} \Delta P_i \qquad (5)$$

Lewis and Bergrun prepared partial probability charts for two classes of clouds (cumulus and layer) and for three regions of the U. S. (Pacific Coast region, the plateau region and the eastern United States). The charts were prepared with $\Delta P_i$ plotted versus $W_i$ with $\Delta D$, $\Delta T$ and horizontal extent as parameters.

Probability of Exceeding a Specified Thickness of Ice During the Climb Phase of the Matador Trajectory

With the assumption of constant ice thickness along the surface, equation (1) can be used in conjunction with the partial probability charts to determine the probability of exceeding specific thicknesses of ice. Examination of figure 1a indicates the time extent of the potential icing region is 5.6 minutes and the average velocity is approximately 600 ft/sec. The ratio of the maximum cross-sectional area ($A_c$) to the surface area ($A_s$) is 0.159. Fraser[14] uses a value of 0.8 for the specific gravity of ice accreted on aircraft. Substituting the above values in equation (1), the thickness can be expressed as:

$$y = 0.477\ EW_i \qquad (6)$$

where

$y$ = ice thickness, inches

$E$ = collection efficiency, per cent

$W_i$ = liquid water content, grams/meter$^3$

The arbitrary variation of collection efficiency with drop diameter (presented in figure 3) when used in conjunction with equation (6) and the temperature intervals and drop diameter intervals tabulated in Table 4 can be used to determine the 42 partial probabilities (Lewis and Bergrun[16]) that ice thickness "y" will be exceeded in any random icing encounter. The summation of these partial probabilities will give the total probability of exceeding "y". These partial probabilities and the total probability were determined using charts prepared by Lewis and Bergrun for the Pacific Coast Cumulus cloud types. This cloud type represents the most severe icing conditions in the United States (i.e., the largest liquid water content). Hence, the implication is that this icing condition is at least representative of icing conditions that would be encountered by the Matador wherever used. The horizontal extent of the potential icing region during the climb is approximately 38 miles. To be conservative, a horizontal extent of 30 miles was used to determine partial probabilities from the charts. The partial probabilities were determined for ice thicknesses of 1/32, 1/16 and 3/32 of an inch and are presented in Tables I, II and III of Appendix I.

Examination of these tables indicates that the total probability of exceeding 1/32, 1/16 and 3/32 inch of ice at station 45 when the Matador has flown through a supercooled cloud during the climb is 17, 6 and 2 per cent, respectively. Another way of expressing the probability is that the ice thickness would be less than 1/32 inch 83 per cent of the time, between 1/32 and 1/16 inch 11 per cent of the time, between 1/16 inch and 3/32 inch 4 per cent of the time, and greater than 3/32 inch 2 per cent of the time the aircraft has flown through a supercooled cloud. As previously stated in this memo, the probability of encountering icing over Europe (yearly average) is less than 25 per cent of the time. Hence, the total probability of exceeding 1/32, 1/16 and 3/32 inch of ice for all flights is approximately 4, 1.5 and 0.5 per cent, respectively. It should be emphasized that because of the several conservative assumptions, the actual probabilities would be less than those calculated.

## Probability of Exceeding a Specified Thickness of Ice During the Dive Phase of the Matador Trajectory

The partial probabilities for the dive phase can be determined in the same manner as for the climb phase. Examination of figure 1c indicates the time extent of the potential icing region is 0.35 minutes and the average velocity is approximately 1075 ft/sec. The ice thickness can be expressed as

$$y = 0.055\ EW \qquad (7)$$

The partial probabilities for exceeding ice thicknesses of 1/64 and 1/32 of an inch during the dive are presented in Tables IV and V of Appendix I. A three mile horizontal extent was used for determining these probabilities.

These tabular results indicate that the probability of accreting more than 1/64 and 1/32 inch of ice during the dive phase of the trajectory in supercooled clouds is 9 and 1 per cent, respectively. As supercooled clouds are present only about 25 per cent of the time, the total probability of exceeding 1/64 and 1/32 inch for all flights is approximately 2 and 1/4 per cent, respectively. Hence, it can be concluded that possible icing in the climb phase of the trajectory is more critical than in the pushover and dive phase.

## MATADOR ICING IN FREEZING RAIN

Previous discussion pointed out that freezing rain need be considered only for the climb phase of the trajectory. Lewis[17] indicates that the rate of precipitation of freezing rain corresponds to a liquid water content of 0.2 grams/meter$^3$ and the aircraft collection efficiency is usually 100% as the droplets are very large, between 500 and 1000 microns in diameter. Former discussion has indicated that freezing rain could occur during the first minute of flight or at any altitude below 5000 feet. However, the vertical extent of freezing rain must be small as the raindrops freeze and become sleet at temperatures only a few degrees above freezing. Hence, it was assumed that the maximum vertical extent of any freezing rain encounter would not exceed 1000 feet. A calculation of the ice thickness due to freezing rain from equation (1) for a thousand feet vertical extent indicates the layer would be approximately 0.003 inch thick. Also, since freezing rain probably would not occur over 4 per cent of the time, the probability of freezing rain causing a malfunction of the Matador fuzing system is negligible.

## EFFECT OF AERODYNAMIC HEATING

The boundary layer temperature and skin temperature at station 45 were calculated and are presented in figures 1a, 1b and 1c. The skin temperature was calculated for flight in clear air. The calculations were made based on a turbulent boundary layer existing at station 45. Heat flow due to radiation and heat flow to the inner body components were neglected in the heat balance. The convective heat flow through the boundary layer due to frictional heating was equated to the heat capacity of the skin and an iteration process was used to determine the trancient skin temperatures during the trajectory. The skin temperature lagged the boundary layer temperature considerably during the dive phase, but the temperatures were nearly equal during the other regions of the flight.

Messinger[18] has set up the energy balance for an unheated icing surface. He concludes that the surface temperature of an aircraft in icing conditions will be less than the surface temperature for the aircraft in clear air. Hence, the actual surface temperature in the icing regions shown in figures 1a and 1c would be less than the surface temperature plotted. Obviously, if the surface temperature were about 32°F, icing

would not occur. Hence, the effect of aerodynamic heating would be to decrease the extent of icing regions during the climb and dive phases.

## EFFECT OF SUBLIMATION

Messinger[18] has determined the rate of sublimation of an ice-covered surface in clear air. This sublimation rate (inches/hr.) was plotted by Messinger versus free stream velocity (knots) with altitude and boundary layer heat transfer coefficient (Btu/hr °F ft$^2$) as parameters. The application of this curve to the cruise trajectory of the Matador, using the flight data from figure 1b and the heat transfer coefficients calculated in the skin temperature determination, indicates that the sublimation rate would be negligible during the cruise. For an altitude of 30,000 feet, velocity of 400 knots, and a heat transfer coefficient of 24 Btu/hr ft$^2$ °F occurring at time 8.3 minutes during the climb, the rate of sublimation is 0.02 inches/hr. The sublimation rate decreases very rapidly with altitude. Hence, only a negligible amount of the ice accreted during the climb phase would sublime off during the remainder of the trajectory.

## CONCLUSIONS

The probability of ice formation at the baroport on the Matador nose causing a malfunction of the primary fuzing system has been studied. The results indicate that ice formation due to freezing rain is negligible; whereas, ice formation due to supercooled clouds is more critical.

Statistics on aircraft ice accretion over Europe indicate that supercooled clouds will be encountered approximately 25 per cent of the time on a yearly basis. During the winter months this percentage can be as high as 40 per cent.

Icing during the climb is more critical than icing during the dive phase of the Matador trajectory. A study of the sublimation rate during the cruise indicates that only a very small percentage of ice accreted during the climb would sublimate off during the cruise phase.

Based on the conservative assumptions of constant ice thickness along the Matador nose and a linear variation of collection efficiency with

droplet diameter, the probability analyses indicate that the ice accretion during the climb phase of the trajectory would be less than 1/32, 1/16 and 3/32 inch 96, 98.5 and 99.5 per cent of the time, respectively. With the same assumptions, the ice accretion during the dive phase will be less than 1/64 and 1/32 inch 98 and 99.7 per cent of the time, respectively. The actual probabilities of accreting the specified ice thicknesses should be less than indicated because of the conservative assumptions. These probabilities could be determined more accurately if water droplet trajectories were determined for the Matador body for the expected flight conditions. A more exact estimate of collection efficiency and area of impingement could be made from the water droplet trajectory calculations.

The thickness of ice necessary to cause malfunctioning of the baro-system is not known; however, it was assumed that an ice thickness the same order of magnitude as the orifice diameter would probably affect the normal operation of the baro-system.

## RECOMMENDATIONS

1. The diameter of the Matador baroports should be increased to 1/8 inch to reduce the probability of ice formation affecting the performance of the fuzing system.

2. An experimental investigation should be made to determine the effect of various ice-thicknesses on the functioning of the baro-system.

3. If the above-determined probabilities are considered too large, a study of water-droplet trajectories should be made so a more accurate determination of the probability of accreting a specified thickness of ice could be calculated.

R. C. MAYDEW - 5141

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APPENDIX I

TABLE I

Probability of Exceeding 1/32-Inch of Ice
During Climb (30-Mile Horizontal Extent)

| Medium temperature, T, °F | | | 24 | 15.5 | 6.0 | -4.0 | -13.0 | -25.0 |
|---|---|---|---|---|---|---|---|---|
| Temperature interval, ΔT, °F | | | 32 to 20.5 | 20.5 to 10.5 | 10.5 to 0.5 | 0.5 to -9.5 | -9.5 -19.5 | -19.5 -40 |
| Liquid Water Content $W_i$, grams/meter$^3$ | Medium drop dia, D, microns | Diameter Interval, ΔD, microns | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ |
| 0.82 | 8 | 0-9.5 | 0 | .00013 | .00040 | .00009 | 0 | 0 |
| 0.595 | 11 | 9.5-12.5 | .00002 | .00090 | .00190 | .00045 | 0 | 0 |
| 0.468 | 14 | 12.5-15.5 | .00012 | .00450 | .00750 | .00170 | 0 | 0 |
| 0.385 | 17 | 15.5-19.5 | .00040 | .01270 | .01800 | .00400 | 0 | 0 |
| 0.273 | 24 | 19.5-29.5 | .00270 | .01530 | .01570 | .01300 | .00034 | 0 |
| 0.177 | 37 | 29.5-49.5 | .00105 | .01600 | .01400 | .00340 | .00019 | 0 |
| 0.109 | 60 | >49.5 | .00160 | .01700 | .01400 | .00390 | .00050 | 0 |
| Totals | | | .00589 | .06653 | .07150 | .02654 | .00103 | 0 |

$$P = \sum_{1}^{n} \Delta P_i = 0.17149$$

**TABLE II**

**Probability of Exceeding 1/16 - Inch of Ice During Climb**

30-Mile Horizontal Extent

| Medium temperature, T, °F | | | 24 | 15.5 | 6.0 | -4.0 | -13.0 | -25.0 |
|---|---|---|---|---|---|---|---|---|
| Temperature interval, ΔT, °F | | | 32 to 20.5 | 20.5 to 10.5 | 10.5 to 9.5 | 0.5 to -9.5 | -9.5 -19.5 | -19.5 -40 |
| Liquid Water Content, $W_i$, grams/meter$^3$ | Medium drop dia. D, microns | Diameter Interval ΔD microns | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ |
| 1.64 | 8 | 0-9.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.19 | 11 | 9.5-12.5 | 0 | 0 | .00005 | .00001 | 0 | 0 |
| 0.936 | 14 | 12.5-15.5 | 0 | .00018 | .00040 | .00010 | 0 | 0 |
| 0.770 | 17 | 15.5-19.5 | 0 | .00068 | .00190 | .00045 | 0 | 0 |
| 0.546 | 24 | 19.5-29.5 | .00014 | .00600 | .01240 | .00290 | 0 | 0 |
| 0.354 | 37 | 29.5-49.5 | .00020 | .00520 | .00700 | .00155 | .00002 | 0 |
| 0.218 | 60 | >49.5 | .00065 | .01000 | .01000 | .00230 | .00009 | 0 |
| Totals | | | .00099 | .02206 | .03175 | .00731 | .00011 | 0 |

$$P = \sum_{1}^{n} \Delta P_i = 0.06222$$

TABLE III

Probability of Exceeding 3/32 - Inch of Ice During Climb

30-Mile Horizontal Extent

| Medium temperature, T, °F | | | 24 | 15.5 | 6.0 | -4.0 | -13.0 | -25.0 |
|---|---|---|---|---|---|---|---|---|
| Temperature interval, ΔT, °F | | | 32 to 20.5 | 20.5 to 10.5 | 10.5 to 0.5 | 0.5 to -9.5 | -9.5 to -19.5 | -19.5 to -40 |
| Liquid Water Content, $W_i$, grams/meter³ | Medium drop dia, D, microns | Diameter Interval ΔD microns | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ |
| 2.46 | 8 | 0-9.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.785 | 11 | 9.5-12.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.405 | 14 | 12.5-15.5 | 0 | 0 | .00002 | 0 | 0 | 0 |
| 1.155 | 17 | 15.5-19.5 | 0 | .00003 | .00016 | .00005 | 0 | 0 |
| 0.82 | 24 | 19.5-29.5 | 0 | .00080 | .00250 | .00062 | 0 | 0 |
| 0.531 | 37 | 29.5-49.5 | .00003 | .00130 | .00250 | .00058 | 0 | 0 |
| 0.327 | 60 | >49.5 | .00020 | .00480 | .00580 | .00130 | .00002 | 0 |
| Totals | | | .00023 | .00693 | .01098 | .00255 | .00002 | 0 |

$$P = \sum_{1}^{n} \Delta P_i = 0.02071$$

TABLE IV

Probability of Exceeding 1/64 - Inch of Ice During Dive

3-Mile Horizontal Extent

| Medium temperature, T, °F | | | 24 | 15.5 | 6.0 | -4.0 | -13.0 | -25.0 |
|---|---|---|---|---|---|---|---|---|
| Temperature interval, ΔT, °F | | | 32 to 20.5 | 20.5 to 10.5 | 10.5 to 0.5 | 0.5 to -9.5 | -9.5 to -19.5 | -19.5 to -40 |
| Liquid Water Content, $W_i$, grams/meter$^3$ | Medium Drop dia., D microns | Diameter Interval ΔD microns | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ |
| 3.56 | 8 | 0-9.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.59 | 11 | 9.5-12.5 | 0 | 0 | .00001 | .00005 | 0 | 0 |
| 2.03 | 14 | 12.5-15.5 | 0 | .00018 | .00060 | .00015 | 0 | 0 |
| 1.67 | 17 | 15.5-19.5 | 0 | .00110 | .00280 | .00068 | 0 | 0 |
| 1.19 | 24 | 19.5-29.5 | .00030 | .01160 | .01900 | .00420 | 0 | 0 |
| 0.77 | 37 | 29.5-49.5 | .00043 | .00900 | .01000 | .00230 | .00005 | 0 |
| 0.475 | 60 | >49.5 | .00130 | .01400 | .01200 | .00300 | .00024 | 0 |
| Totals | | | .00203 | .03588 | .04441 | .01038 | .00029 | 0 |

$$P = \sum_{1}^{n} \Delta P_i = 0.09299$$

**TABLE V**

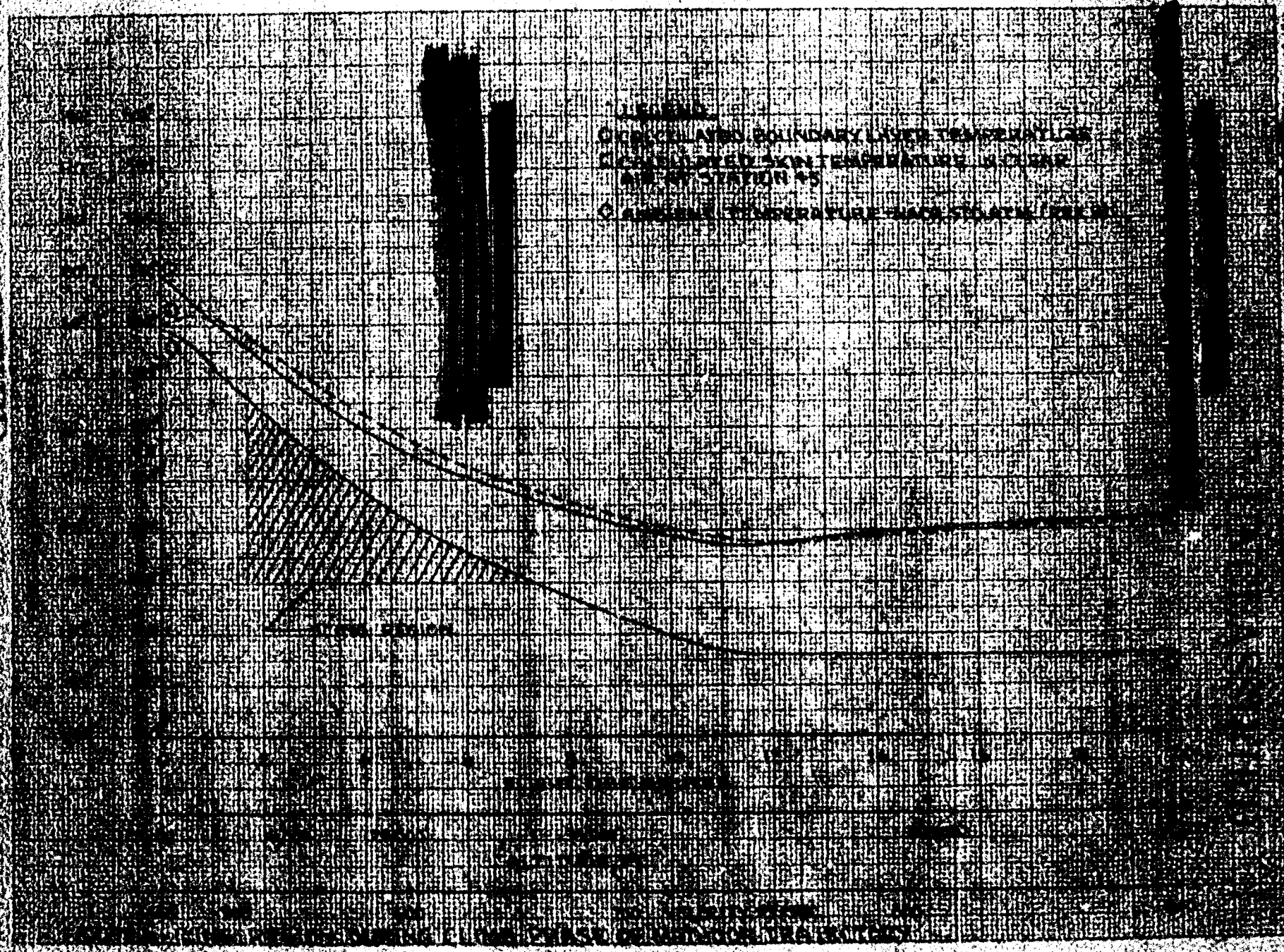
Probability of Exceeding 1/32 - Inch of Ice During Dive

3-Mile Horizontal Extent

| Medium temperature, T, °F | | | 24 | 15.5 | 6.0 | -4.0 | -13.0 | -25.0 |
|---|---|---|---|---|---|---|---|---|
| Temperature interval, ΔT, °F | | | 32 to 20.5 | 20.5 to 10.5 | 10.5 to 0.5 | 0.5 to -9.5 | -9.5 to -19.5 | -19.5 to -40 |
| Liquid Water Content, $W_i$, grams/meter$^3$ | Medium Drop dia., D microns | Diameter Interval ΔD microns | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ | $\Delta P_i$ |
| 7.13 | 8 | 0-9.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.59 | 11 | 9.5-12.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.03 | 14 | 12.5-15.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.67 | 17 | 15.5-19.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.19 | 24 | 19.5-29.5 | 0 | .00012 | .00058 | .00016 | 0 | 0 |
| 0.77 | 37 | 29.5-49.5 | 0 | .00057 | .00135 | .00030 | 0 | 0 |
| 0.475 | 60 | >49.5 | .00012 | .00350 | .00480 | .00105 | .00001 | 0 |
| Totals | | | .00012 | .00419 | .00673 | .00151 | .00001 | 0 |

$$P = \sum_{1}^{n} \Delta P_i = 0.01256$$

KEUFFEL & ESSER CO.
Millimeters, 3 mm, lines accented, cm. lines heavy.

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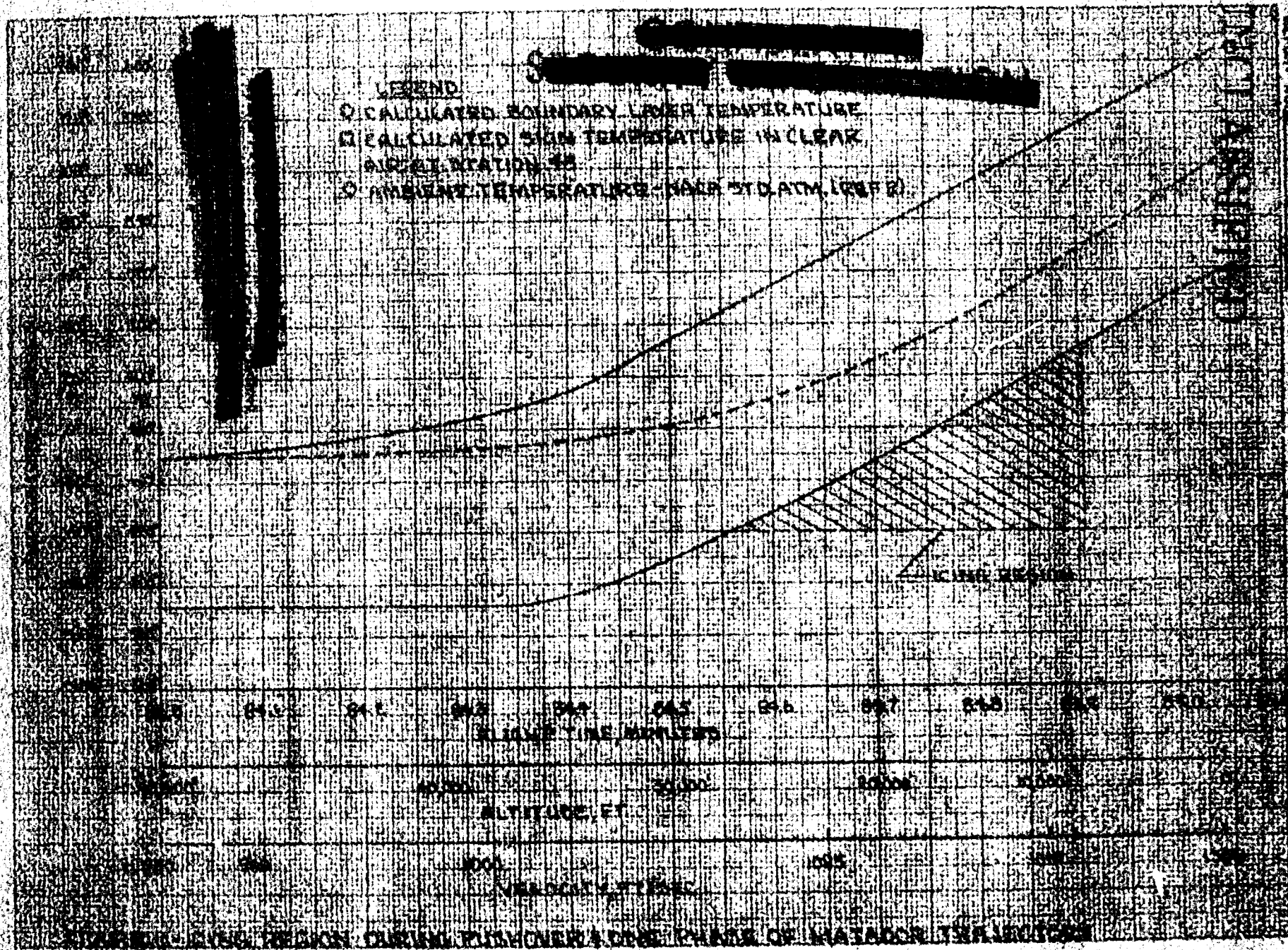


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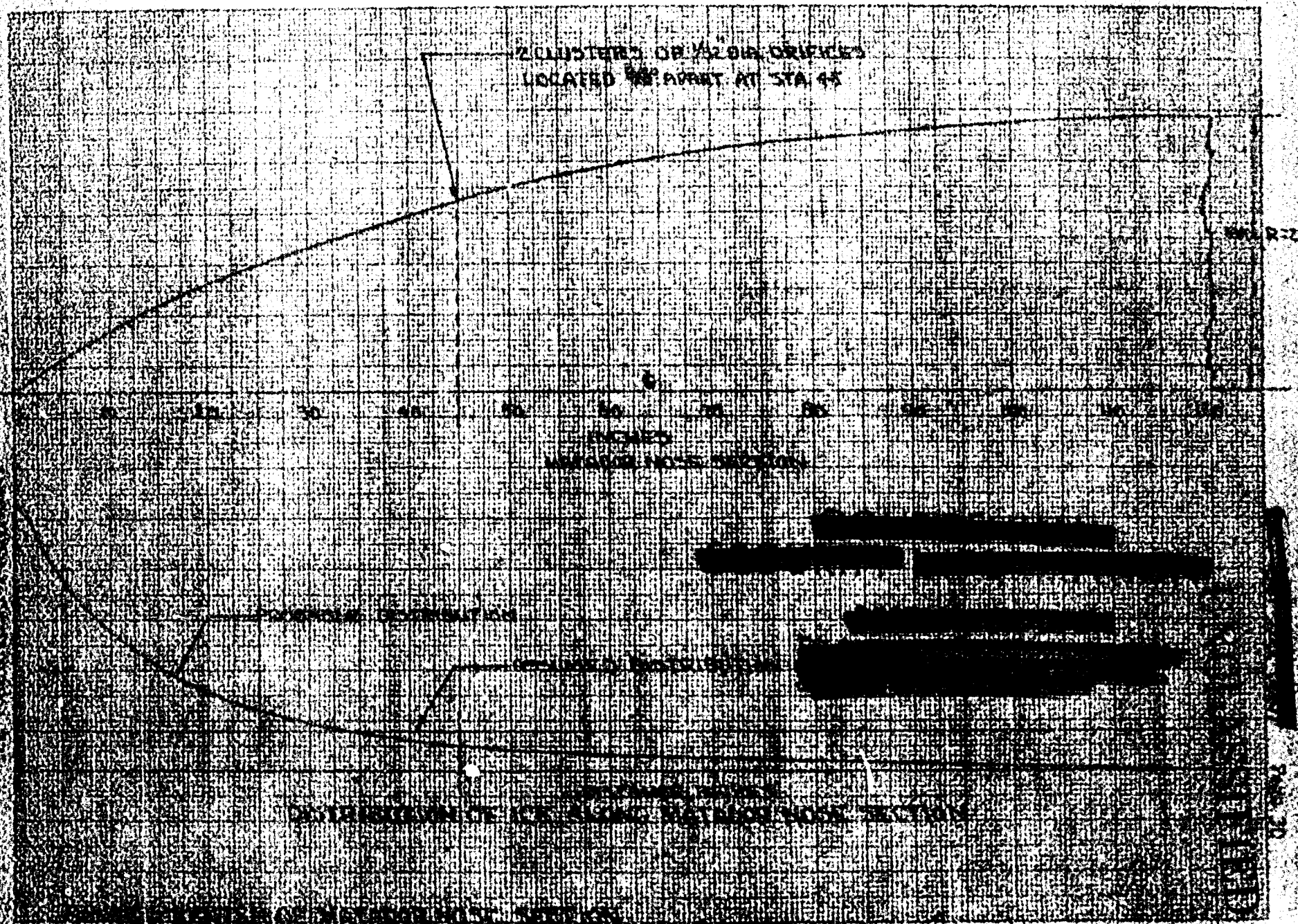


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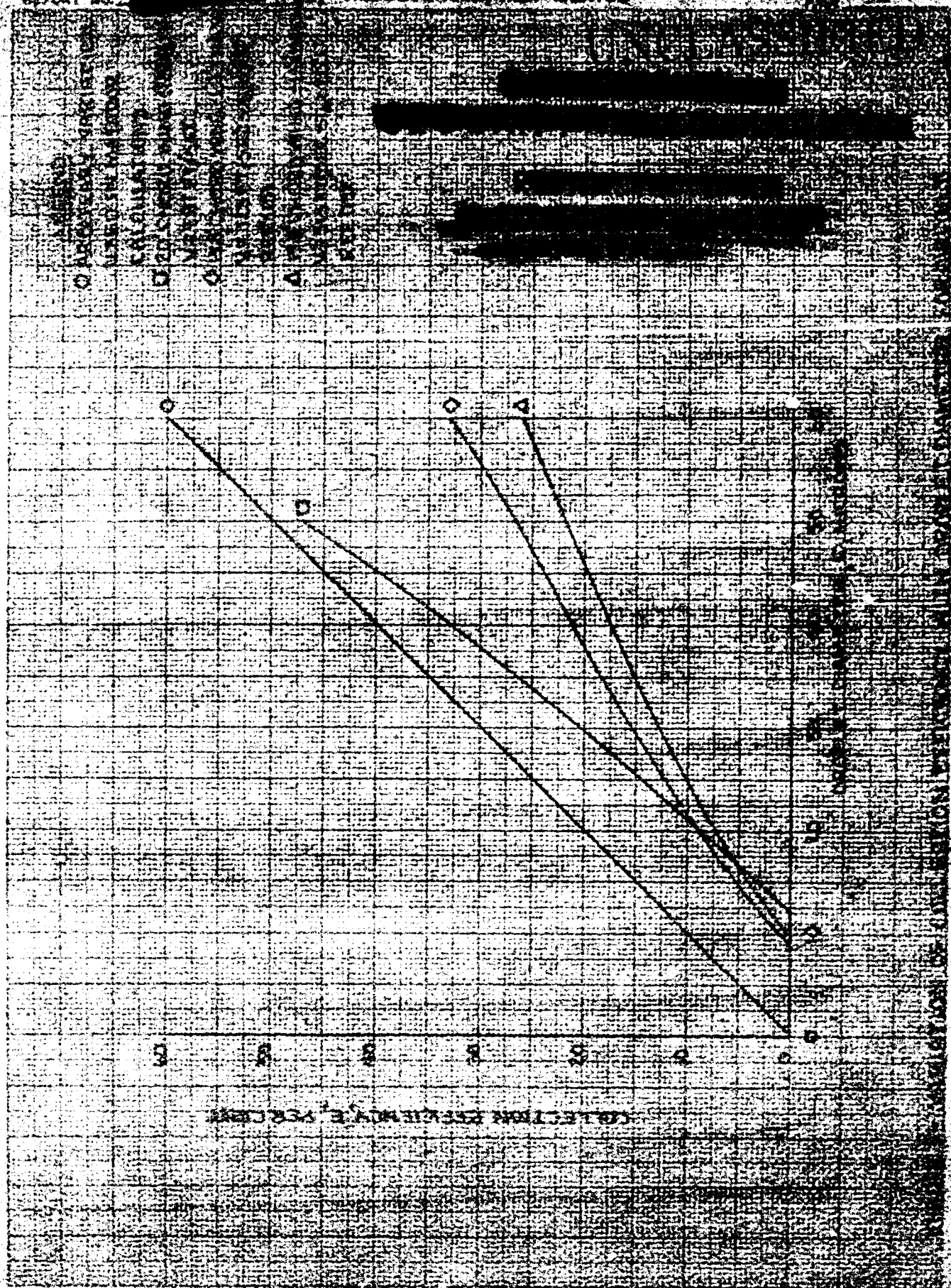

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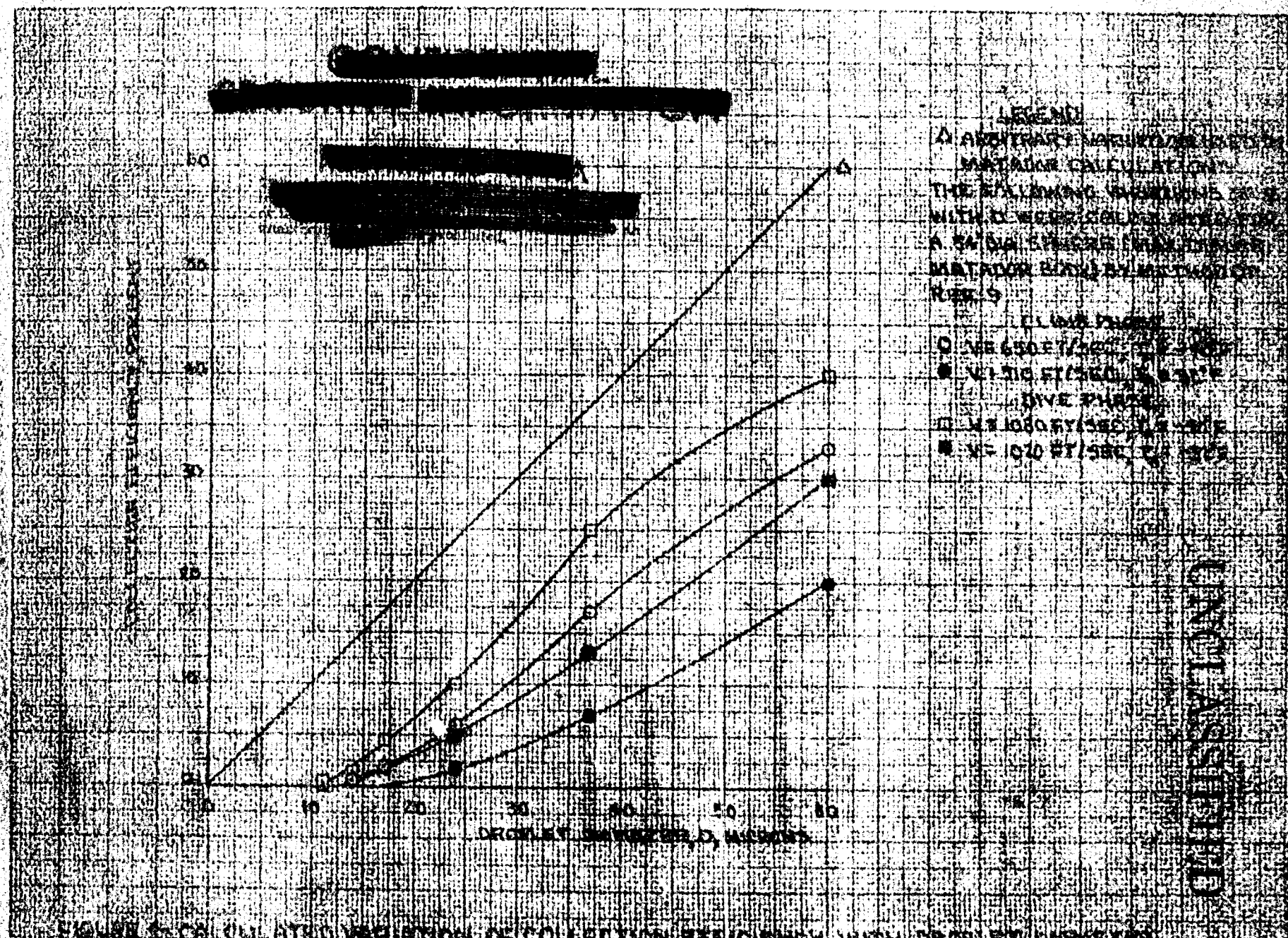


FIGURE 6. CALCULATED VARIATIONS OF COLLECTION EFFICIENCY WITH DROPLET DIAMETER

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