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CLOUD PHYSICS LABORATORY PROJECT SCIENCE AND  
APPLICATIONS WORKING GROUP

by

R. J. Hung

Final Technical Report

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the National Aeronautics and Space Administration  
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The manuscript was typed by Ms. Carol Holladay. Her patient and skillful typing was essential to bringing this report to its present form.

## SUMMARY

The cloud chamber in the Space Shuttle provides a facility to study droplet-vapor interactions which would resemble those in a natural cloud. A better understanding of the microphysical phenomena of cloud physics will greatly improve the accuracy of weather forecasts, in particular, a better control of precipitation, inhibition of fog formation, and dispersal of fog by modification.

In the zero-gravity experiment of the cloud formation, a successful study of microphysical processes depends upon the accurate measurement of some initial key parameters. For instance, the study of droplet growth relies heavily on knowing the water vapor-air mixing ratio; and the study of nucleation depends on knowing the relative humidity. The purpose of the present study is to numerically simulate the conditions of the expansion chamber under zero gravity environment and investigate the minimum accuracy of the initial dew point temperature required in the experiments. This study certifies low cost in the cloud chamber design and maintains high quality experiments in the Space Shuttle missions.

Dynamics of oscillation, rotation, collision and coalescence of water droplets in Skylab simulations are also investigated.

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## I. INTRODUCTION

The general objective of the Zero-Gravity Atmospheric Cloud Physics Laboratory Program is to improve the level of knowledge in atmospheric cloud physics research by placing at the disposal of the terrestrial-bound atmospheric cloud physicist a laboratory that can be operated in the environment of zero-gravity or near zero-gravity. This unique laboratory will allow studies to be performed without mechanical, aerodynamical, electrical, or other techniques to support the object under study. In the meanwhile, the uniform and homogeneous thermodynamic environment offered by the zero-gravity environment provides the best opportunity to study the basic phenomena of thermal diffusion which is particularly essential to understanding the micro-physical processes in atmospheric clouds.

By taking advantage of a zero-gravity environment to define many of the processes in clouds that are not yet fully understood is derived in the philosophy of the operation of the Shuttle-Spacelab Cloud Physics Laboratory. Of course, the final objective of the mission is to investigate how men can influence weather, by changing, for example, drop distributions and nuclei concentrations, or by adding pollutant compositions.

To support the development work and hardware design criteria on the Shuttle-Spacelab Cloud Physics Laboratory Payload, the following activities have been performed under the support of the present contract.

- (1) A group of scientists from the cloud physics scientific community were invited to serve as consultants and also to participate in the working group meetings. The purpose of the service was to provide the advice and the guidance of the definition of experiments and scientific input to the Atmospheric Cloud Physics Laboratory at the Shuttle Spacelab mission.
- (2) Two subcontracts were granted under the present contract to scientists in the cloud physics scientific community for the support of terrestrial simulation of cloud physics experiments in the Space Shuttle missions.
- (3) Inhouse study of numerical simulation of drop growth in a low gravity environment, and the analysis of Skylab fluid mechanics simulation are performed under the support of this contract.

The proposed cloud chambers in the Space Shuttle include three experimental chambers, i.e., expansion chamber, continuous flow diffusion chamber, and the diffusion chamber. The present inhouse study is limited to the discussion of numerical simulation of droplet growth studies in the expansion chamber which is designed to simulate the pseudo-adiabatic ascent of a parcel of air. During the adiabatic expansion of the cloud chamber, no heat is allowed to cross the boundary of the cloud chamber. The walls of the chamber are cooled by a cooling system at such a rate as to prevent heat transfer from the walls. The only source of heat in the entire experiment comes from the latent heat released or absorbed during condensation or evaporation within the chamber. The purpose of

the present inhouse study is to numerically simulate the conditions of the expansion chamber under zero gravity environment and investigate the minimum accuracy of the initial dew point temperature required in the experiments. This study will certify low cost in the cloud chamber design and maintain high quality experiments in the Space Shuttle mission.

The following three branches of fluid mechanics simulation under low gravity environment also have been accomplished in this report:

(1) oscillation of the water droplet which characterizes the nuclear oscillation in nuclear physics, bubble oscillation of two phase flow in chemical engineering, and water drop oscillation in meteorology; (2) rotation of the droplet which characterizes nuclear fission in nuclear physics, formation of binary stars and rotating stars in astrophysics, and breakup of the water droplet in meteorology; and (3) collision and coalescence of the water droplets which characterizes nuclear fusion in nuclear physics and processes of rain formation in meteorology.

This project also supported a graduate student while he accomplished his Master's of Science in Engineering degree here at The University of Alabama in Huntsville.

A detailed list of the scientists from the cloud physics scientific community invited to participate in the working group meetings is given in Appendix A. Two subcontracts supported by the contract are described in Appendix B.

## II. STUDY OF THE PROCESSES OF DROPLET GROWTH IN CLOUD CHAMBER AND DYNAMICS OF WATER DROPLETS IN SKYLAB SIMULATION

The processes of nucleation and growth of droplets are a particular interest in cloud physics. Our knowledge of these processes is still rudimentary because adequate observation of them under laboratory conditions required that gravitational effects be absent which is a difficult condition to be met in a terrestrial laboratory.

Techniques to support droplets artificially in the terrestrial laboratory are possible by employing levitation apparatuses by vertical wind tunnel, by applied electrostatic potential, by high frequency acoustic waves (or ultrasonic waves), and by laser beam. Any of the techniques mentioned above tend to mask some other types of phenomena such as change or distortion of the shape of droplets, create or dampen the oscillations of droplets, etc. The alternate approach is to obtain zero-gravity conditions for 20-30 minutes required for observations. Drop towers, aircraft flying parabolic trajectories, and sounding rockets can not provide zero-gravity conditions for more than a few minutes. The obvious solution to carry out these experiments is to utilize a satellite.

The Space Shuttle, in contrast to a one shot satellite can provide a long duration, low gravity environment at a reasonable cost. The anticipated time of observation of a cloud in the Space Shuttle chamber is "tens of minutes," and may be as long as 90 minutes. This time duration of the observation in the Space Shuttle chamber is comparable to a life-time of natural clouds in which discrete droplets or a group

of droplets last some 20-30 minutes. Thus, the droplets can float in the cloud chamber for the natural duration of processes. Droplet-vapor interactions would then resemble those in a natural cloud.

In the zero-gravity experiment of the cloud formation, a successful study of microphysical processes depends upon the accurate measurement of some initial key parameters. For instance, the study of droplet growth relies heavily on knowing the water vapor-air mixing ratio; and the study of nucleation depends on knowing the relative humidity. The former places stringent requirements on the accuracy of the initial absolute temperature of the saturator, while the latter depends on a very accurate knowledge of the relative temperature between the saturator and the expansion chamber.

In the present study, we numerically simulated the conditions of the expansion chamber under zero gravity environment and investigated the minimum accuracy of the initial dew point temperature required in the experiments. The results of the numerical simulations are included in the following pages.

The study of the dynamics of water droplets has also been carried out in this report. Skylab 4 crew members performed a series of demonstrations showing the oscillations, rotations, as well as collision coalescence of water droplets which simulate various physical models of fluids under low gravity environment. The results from the Skylab demonstrations provided much interesting information and illustrated the potential of an orbiting space-oriented research laboratory for the study of more sophisticated fluid mechanics experiments. The results of this study are also included in the following pages.

Mr. James E. Huckle, a graduate student in the Department of Mechanical Engineering at The University of Alabama in Huntsville, accomplished his Master's of Science in Engineering degree in the Fall of 1977/78, under the support of this contract. The topic of the thesis presented by Mr. Huckle is "The Growth of Water Droplet in a Low Gravity Environment."

In this report, two papers based on our inhouse study are included. The topics are

- (1) "Accuracy of Initial Dew Point Temperature and the Growth of Droplet in Expansion Chamber Under Low Gravity Environment."

This article has been accepted for publication and will appear in J. Rech. Atmos. 11, 1977.

- (2) "Skylab Fluid Mechanics Simulations: Oscillation, Rotation, Collision and Coalescence of Water Droplets Under Low Gravity Environment."

This paper was presented at the Eighth Conference on Space Simulation, and was also published in NASA SP-379, Space Simulation, pp. 563-574, Scientific and Technical Information Office, National Aeronautics and Space Administration, Washington, D. C., 1975.

ACCURACY OF INITIAL DEW POINT TEMPERATURE AND THE GROWTH  
OF DROPLET IN EXPANSION CHAMBER UNDER LOW GRAVITY ENVIRONMENT \*

ABSTRACT

The cloud chamber in the Space Shuttle provides a facility to study droplet-vapor interactions which would resemble those in a natural cloud. Droplet growth studies in the expansion chamber at the low gravity environment is designed to simulate the pseudo-adiabatic ascent of a parcel of air. A minimum accuracy of initial dew point temperature is questionable for the design of the expansion chamber. A computer simulation of drop growth in the expansion chamber under zero-gravity environment has been investigated. The simulation includes the time dependent study of saturation ratio, pressure and drop radius for initial water-vapor saturation temperatures, corresponding to dew point temperatures at 18, 17.998, 17.990, 17.900 and 17.000°C, under cooling rates of 6, 2, 1 and 0.3°C/min for each case. The results show that the best suggested accuracy of initial dew point temperature is 0.01°C for the expansion chamber experiment. However, the temperature accuracy at 0.1°C is also acceptable if the experiment is avoided during the beginning few minutes.

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\* This article was accepted for publication and will appear in J. Rech. Atmos., 11, 1977.

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## I. — Introduction

A better understanding of the microphysical phenomena of cloud physics will greatly improve the accuracy of weather forecasts, in particular, a better control of precipitation, inhibition of fog formation, and dispersal of fog by modification. It may also contribute to the moderation of severity of destructive phenomena such as hail and tornadoes.

The processes of nucleation and growth of droplets are of particular interest in cloud physics. Our knowledge of these processes is still rudimentary because adequate observation of them under laboratory conditions required that gravitational effects be absent which is a difficult condition to be met in a terrestrial laboratory.

In clouds, discrete parcels of moist air and entrained particles can last nearly a half hour, rising and falling for miles. During these movements, the constituents within the parcel are constantly interacting. The volume of the cloud can be several cubic miles.

A cloud chamber encloses only a minuscule fraction of a volume of a natural cloud. When droplets through condensation are produced inside a terrestrial cloud chamber, they soon drift to the bottom of the chamber, ending the experiment before any long duration process can be studied.

Techniques to support droplets artificially in the terrestrial laboratory are possible by employing levitation apparatuses which are by vertical wind tunnel, by applied electrostatic potential, by high frequency acoustic waves (or ultrasonic waves), and by laser beam (Hung et al., 1974 [1]). Any of the techniques mentioned above tend to mask some

other types of phenomena such as change or distortion of the shape of droplets, create or dampen the oscillations of droplets, etc. The alternate approach is to obtain zero-gravity conditions for 20-30 minutes required for observations. Drop towers, aircraft flying parabolic trajectories, and sounding rockets can not provide zero-gravity conditions for more than a few minutes. The obvious solution to carry out these experiments is to utilize a satellite (TRW, 1977 [2]; General Electric, 1977 [3]).

The Space Shuttle, in contrast to a one shot satellite can provide a long duration, low gravity environment at a reasonable cost. The anticipated time of observation of a cloud in the Space Shuttle chamber is "tens of minutes," and may be as long as 90 minutes (TRW, 1977 [2]; General Electric, 1977 [3]). This time duration of observation in the Space Shuttle chamber is comparable to a life-time of natural clouds in which discrete droplets or groups of droplets last some 20-30 minutes (Greco and Turner, 1975 [4]). Thus, the droplets can float in the cloud chamber for the natural duration of the processes. Droplet-vapor interactions would then resemble those in a natural cloud.

The proposed cloud chambers in the Space Shuttle include three experimental chambers, i.e., expansion chamber, continuous flow diffusion chamber and diffusion chamber (TRW, 1977 [2]; General Electric, 1977 [3]). The present paper is limited to the discussion of numerical simulation of droplet growth studies in the expansion chamber which is designed to simulate the pseudo-adiabatic ascent of a parcel of air. During the adiabatic expansion of the cloud chamber, no heat is allowed to cross the boundary of the cloud chamber. The walls of the chamber are cooled by a cooling system at such a rate as to prevent heat transfer from the

walls. The only source of heat in the whole experiment comes from the latent heat released or absorbed during condensation or evaporation within the chamber.

In the zero-gravity experiment of the cloud formation, a successful study of microphysical processes depends upon the accurate measurement of some initial key parameters. For instance, the study of droplet growth relies heavily on knowing the water vapor-air mixing ratio; and the study of nucleation depends on knowing the relative humidity. The former places stringent requirements on the accuracy of the initial absolute temperature of the saturator, while the latter depends on a very accurate knowledge of the relative temperature between the saturator and the expansion chamber (TRW, 1977 [2]; General Electric, 1977 [3]).

The purpose of the present study is to numerically simulate the conditions of the expansion chamber under zero gravity environment and investigate the minimum accuracy of the initial dew point temperature required in the experiments. It is of particular interest, therefore, to investigate the time-dependent evolution of saturation ratio, water vapor pressure, and drop growth under different initial humidities and different cooling rates. The variations of time-dependent saturation ratio, pressure and drop growth under a small change in the initial humidity, which corresponds to different temperature readings, have been numerically simulated. This study will certify low cost in the cloud chamber design and maintain high quality experiments in the Space Shuttle mission.

## II. — Theoretical Analysis

During an adiabatic expansion of the cloud chamber, no heat is allowed to cross the boundary of the chamber. The only source of heat comes from the latent heat released or absorbed during condensation or evaporation within the chamber. These adiabatic expansions of a mixture of dry air, water vapor and liquid water can be described by the first law of thermodynamics and equation of the growth of the droplets based on microphysical processes.

Pertinent assumptions in this study are no gravitational force, no heat exchange with the walls and a constant number of uniformly sized droplets. The thermodynamics for a closed system of the cloud chamber containing a mixture of dry air, water vapor, and liquid water can be described by the first law of thermodynamics, as follows:

$$\delta Q = dU + pdV \quad (1)$$

where  $\delta Q$  is the latent heat released or absorbed minus the heat required to raise the temperature of liquid water within the chamber, i.e.,

$$\delta Q = L dW_L - S_W W_L dT . \quad (2)$$

Here,  $dU$  denotes the change of the internal energy of the mixture of dry air and water vapor;  $p$ , the pressure of the mixture;  $dV$ , the change of the volume of the cloud chamber during expansion;  $L$ , the latent heat;  $S_W$ , the specific heat of liquid water;  $T$ , the temperature of the mixture; and  $W_L$ , the liquid water content which is defined

$$W_L = \frac{4}{3} \pi \rho_W \sum_1^n N_1 (r_1^3 - r_{10}^3) \quad (3)$$

where  $N_1$  is the total number of droplets with a radius of  $r_1$ ;  $r_{10}$ , the radius of the nucleus;  $\rho_W$ , the liquid water density; and  $n$ , the total number of classes of the size spectrum of droplets.

The following relation is obtained after dividing Equation (1) by  $dt$ , with consideration of Equation (2) (Lin, 1976 [5]):

$$\frac{dT}{dt} = \frac{\gamma-1}{\gamma} \left[ \left( L + \frac{\gamma}{\gamma-1} R_V T \right) \frac{1}{JR} \frac{dW_L}{dt} + \frac{T}{p} \frac{dp}{dt} \right] \cdot \left( 1 + \frac{S_W W_L}{J C_p} \right)^{-1} \quad (4)$$

where  $\gamma$  denotes the specific heat ratio of the mixture;  $R_V$ , the gas constant of the water vapor;  $J$ , the number of moles of the mixture;  $R$ , the gas constant of dry air; and  $C_p$ , the constant pressure specific heat for one mole of the mixture.

The effect of Brownian movement is neglected in the present model. The droplet will grow to a size greater than one micron ( $\mu\text{M}$ ) in seconds in the expansion chamber. Brownian motion appears to be important for drop diameters less than one micron. This will justify our assumption.

The growth of droplets due to the condensation and evaporation is governed by the following equations (Carstens et al. 1974 [6])

$$\frac{dr}{dt} = \frac{\rho_{\text{sat}}^{(\infty)} D_{\text{eff}}}{\rho_W (r+l)} \left( S - 1 - \frac{a}{r} + \frac{c}{r^3} \right) \quad (5)$$

where

$$D_{\text{eff}}^{-1} = D^{-1} + \frac{bL}{K} \quad (6)$$

$$l = \left( \frac{l_\beta}{D} + \frac{l_\alpha bL}{K} \right) D_{\text{eff}} \quad (7)$$

$$l_{\alpha} = (1 - \frac{\alpha}{2}) \frac{K}{\alpha p} \frac{\gamma-1}{\gamma+1} (\frac{8\pi T}{R})^{1/2} \quad (8)$$

$$l_{\beta} = (1 - \frac{\beta}{2}) \frac{D}{\beta} (\frac{2\pi}{R_v T})^{1/2} \quad (9)$$

$$a = \frac{2\sigma}{R_v T \rho_w} \quad (10)$$

$$C = \frac{3 i M_w m_s}{4\pi M_s} \quad (11)$$

Here,  $\rho_{sat}(\infty)$  is the saturation vapor density at infinity;  $s$ , the saturation ratio of water vapor in air;  $r$ , the radius of the droplet;  $l$ , characteristic length which is the weighted average of  $l_{\alpha}$  and  $l_{\beta}$ ;  $b$ , the slope of a linearized  $\rho_{sat}(\infty)$  and  $T$  curve;  $D$ , the diffusion coefficient of water vapor in the air;  $K$ , the thermal conductivity of the mixture;  $\alpha$ , the accommodation coefficient which is 0.67 in our case;  $\beta$ , the sticking coefficient which is 0.03536 in our case;  $R$ , the gas constant of dry air;  $\sigma$ , the surface tension of water;  $i$ , factor of Van't Hoff;  $M_w$ , the molecular weight of water;  $m_s$ , the mass of hygroscopic material dissolved; and  $M_s$ , gram molecular weight of hygroscopic nucleus.

In the present study, the diffusivity,  $D$ , of water vapor in the air follows the model presented by Fuller et al., (1966 [7])

$$D = \frac{0.001 (M_a^{-1} + M_v^{-1})^{1/2} T^{1.75}}{p (V_a^{1/3} + V_v^{1/3})^2} = \frac{11.911 T^{1.75}}{p} \quad (12)$$

where  $M_a$  is the molecular weight of air;  $M_v$ , the molecular weight of vapor;  $V_a$ , the diffusion volume of air; and  $V_v$ , the diffusion volume of vapor. The other constants, employed in Equations (5) to (11) which

are temperature dependent can be simplified as follows (Paluch, 1971 [8]):

$$K = 0.1675 \times 10^{-6} (T - 273.16) + 0.5725 \times 10^{-4} \text{ (cal/cm}^{\circ}\text{K-sec)} \quad (13)$$

$$L = 737.44 - 0.52 T \text{ (cal/g)} \quad (14)$$

$$\sigma = 75.7 - 0.148 (T - 273.16) \text{ (dynes/cm)} \quad (15)$$

The semi-empirical expression is used for  $\rho_{\text{sat}}(\infty)$  and  $b$ , i.e.,

$$\rho_{\text{sat}}(\infty) = 4.847 \times 10^{-6} \left( \frac{273.16}{T} \right)^{5.737104} \cdot \exp \left[ 6718.235 \left( \frac{1}{273.16} - \frac{1}{T} \right) \right] \quad (16)$$

$$b = \rho_{\text{sat}}(\infty) \left( \frac{6718.235}{T} - 5.7373104 \right) \frac{1}{T} \quad (17)$$

In the Space Shuttle experiments, cooling rates are assumed to be constant, i.e.,

$$\frac{dT}{dt} = \text{constant.} \quad (18)$$

In our particular cases, constant cooling rates with 6, 2, 1 and 0.3 °C/min are of special interest.

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### III. — Computational Scheme

After substituting Equation (3) into (4), and Equation (6) to (17) into Equation (5), the fundamental equations are finally reduced to Equations (4), (5) and (18). These three simultaneous differential equations can be written in the following matrix form

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} \frac{dx(1)}{dt} \\ \frac{dx(2)}{dt} \\ \frac{dx(3)}{dt} \end{bmatrix} = \begin{bmatrix} A_{14} \\ A_{24} \\ A_{34} \end{bmatrix} \quad (19)$$

where  $x(1)$ ,  $x(2)$  and  $x(3)$  express pressure, radius of water droplet, and temperature, respectively. These equations can now be integrated by an existing computer program developed by Thompson (1975 [9]) with some modifications.

We have considered twenty cases in which five initial water vapor saturation temperatures, corresponding to dew point temperatures at 18.000, 17.998, 17.990, 17.900 and 17.000 °C, with cooling rates of 6, 2, 1 and 0.3 °C/min, have been taken into account. In these computations, the initial pressure is  $10^6$  dynes/cm<sup>2</sup>; and the initial drop radius or radius of the nucleus is  $5 \times 10^{-5}$  cm or 0.5  $\mu$ . Calculations were made for one mole of air and water vapor. The density and specific heat of water are

assumed to be unity. It is also assumed that NaCl with mass  $10^{-13}$  gram was dissolved in the droplets. With this amount of salt, the droplets are in equilibrium at  $20^{\circ}\text{C}$  air with dew point temperature at  $18^{\circ}\text{C}$ . The number density of nucleus is assumed to be 300 per  $\text{cm}^3$ .

The results of the computation in the time-dependent study of saturation ratio, pressure, and drop radius will be discussed in the following section.

#### IV. — Results and Discussions

Figures 1, 2, 3 and 4 show the time-dependent study of saturation ratio for cooling rates corresponding to 6, 2, 1 and 0.3°C/min, respectively. Each of the figures express five curves of time-dependent evolution of saturation ratios corresponding to air-vapor mixtures at the initial dew point temperatures 18, 17.998, 17.990 and 17 °C. It is clearly indicated that three curves are drawn coincidentally for the case of initial dew point temperatures at 18, 17.998, and 17.990 °C within a fraction of a division. In these figures, one vertical division represents a change of  $25 \times 10^{-4}$  in the saturation ratio. Slight deviations are shown for saturation ratios for the case of initial dew point temperatures between 18 °C and 17.990 °C. Peak saturation ratios of 1.029, 1.012, 1.007 and 1.0024 are obtained for cooling rates of 6, 2, 1 and 0.3 °C/min, respectively, at the initial dew point temperature 18 °C.

In order to have more insight of the characteristics of saturation ratio and its deviation for initial dew point temperatures between 18 °C and 17.990 °C, the maximum percentage of deviations have been computed. The expression is given by

$$\text{Max } \Delta S \left. \begin{array}{l} 17.900^{\circ}\text{C} \\ 18.000^{\circ}\text{C} \end{array} \right\} = \left| \frac{S_{17.900^{\circ}\text{C}} - S_{18.000^{\circ}\text{C}}}{S_{18.000^{\circ}\text{C}}} \right|_{\text{Max.}} \times 100 \quad (20)$$

where  $\text{Max } \Delta S \left. \begin{array}{l} 17.900^{\circ}\text{C} \\ 18.000^{\circ}\text{C} \end{array} \right\}$  denotes the maximum percentage deviation of

saturation ratio for dew point temperatures between 18.000°C and 17.900°C;

$S_{17.900^{\circ}\text{C}}$ , saturation ratio with initial dew point temperature at  $17.900^{\circ}\text{C}$ ; and  $| \Delta S |_{\text{Max}}$ , the maximum value. Table 1 shows the computed maximum deviation of the saturation ratios for different cooling rates. It is shown that the maximum deviation of saturation ratios between these two initial dew point temperatures are essentially less than 0.63% which occurred at operation time  $t = 0.0$  sec. for the cooling rates at 6, 2, 1 and  $0.3^{\circ}\text{C}/\text{min}$ . These results suggest that  $0.1^{\circ}\text{C}$  accuracy of initial dew point temperature in the expansion chamber at the Space Shuttle mission is proper at least based on the time-dependent study of saturation ratio.

Figures 5, 6, 7 and 8 show the time dependent evolution of pressure for cooling rates corresponding to 6, 2, 1 and  $0.3^{\circ}\text{C}/\text{min}$ , respectively. These figures also imply that the time-dependent evolution of pressures are practically no different for the cases corresponding to initial dew point temperatures at 18, 17.998, and  $17.990^{\circ}\text{C}$ . The computations of the maximum percentage deviation of pressure for the cases of initial dew point temperatures between  $18^{\circ}\text{C}$  and  $17.900^{\circ}\text{C}$  are also accomplished analogous to that of the saturation ratio shown in Equation (20). Table 1 indicates that the maximum deviation of pressure for the cases of initial dew point temperatures between  $18^{\circ}\text{C}$  and  $17.9^{\circ}\text{C}$  are essentially less than 0.24% for the various cooling rates. These results also support the similar conclusions obtained from the simulation of saturation ratios.

Figures 9, 10, 11 and 12 show the time dependent evolution of drop size for cooling rates corresponding to 6, 2, and 1 and  $0.3^{\circ}\text{C}/\text{min}$ , respectively. Similar to the results obtained for the simulations of saturation ratios and pressures, there are no differences for the time dependent growth of drop sizes for cases corresponding to initial dew point temperatures in the ranges

from 18 to 17.990°C. A deviation of time dependent growth of drop size is shown for the case of initial dew point temperatures between 18°C and 17.990°C for all the cooling rates assumed. Table 2 shows the maximum deviation of time dependent growth of drop size for this case. This table indicates that maximum deviation of the growth of drop size for the case of initial dew point temperatures between 18°C and 17.900°C can be as high as 21, 28, 34 and 43% for cooling rates corresponding to 6, 2, 1 and 0.3°C/min, respectively, which occurred in the experiments during the first few minutes. After the experimental operation time 0.85, 2.41, 4.66 and 15.3 minutes have passed for cooling rates corresponding to 6, 2, 1, and 0.3°C/min, respectively, the percentage deviation for the cases between these two initial dew point temperatures will be declined less than 2%. At these moments, the operating temperatures will be 14.9, 15.1, 15.3 and 15.4°C for cooling rates corresponding to 6, 2, 1 and 0.3°C/min, respectively, if the initial operating temperature is assumed to be 20°C. These results, based on the time dependent growth of droplets indicate that 0.01°C accuracy of the initial dew point temperature is perfectly satisfactory for the experiments in the expansion chamber. However, this temperature accuracy can also be dropped at 0.1°C if we would skip the experiments in the first few minutes for the case of the studies of drop growth.

Howell (1949, [10]) has calculated the time dependent evolution of the saturation ratios for the growth of uniform droplets under the condition of constant rate of ascent, whereas a constant rate of cooling is used in the present study. These differences made a direct comparison

between our results and Howell's to be difficult. However, there are similarities in which the peak of saturation ratios for both cases are the same magnitudes and also exhibit the same asymptotic approaches as the time increases.

In conclusion ,  $0.01^{\circ}\text{C}$  accuracy of the initial dew point temperature for the experiments in the expansion chamber is always the most acceptable condition for cases of time dependent study of saturation ratio, pressure and droplet growth under cooling rates 6, 2, 1 and  $0.3^{\circ}\text{C}/\text{min}$ . It is also recommended that  $0.1^{\circ}\text{C}$  accuracy of the initial dew point temperature is acceptable for experiments of the study of the saturation ratio and pressure; however, special care must be attempted for the case of drop growth studies in which the experiment shall be avoided to carry out in the beginning few minutes. These results may be evidence to justify the proposed  $0.1^{\circ}\text{C}$  temperature accuracy of the expansion chamber in the Space Shuttle mission subjected to the conditions outlined above.

#### ACKNOWLEDGMENT

The authors are indebted to R. E. Smith and J. B. Anderson of NASA/Marshall Space Flight Center for stimulating discussions. They also acknowledge the support of the present study through NASA/Marshall Space Flight Center under Contract No. NAS8-31321.

## REFERENCES

- [1] Hung, R. J., Vaughan, O. H., and Smith, R. E. (1974) — A zero-gravity demonstration of the collision and coalescence of water droplets, Progress in Astronautics and Aeronautics, Vol. 48, pp. 515-530.
- [2] TRW (1977) — Final definition and preliminary design study for the initial atmospheric cloud physics laboratory (A Space Mission Payload). NASA/Marshall Space Flight Center.
- [3] General Electric (1977) — Final definition and preliminary design study for the initial atmospheric cloud physics laboratory (A Space Mission Payload). NASA/Marshall Space Flight Center.
- [4] Greco, R. V., and Turner, R. E. (1975) — Cloud Physics Laboratory: A Step Toward Weather Control, Astronautics and Aeronautics 3, 44-48.
- [5] Lin, C. L. (1976) — Computational and Calculational Support for Terrestrial Simulation Chamber, Tech. Rep. Univ. Missouri-Rolla, Mo., pp. 141.
- [6] Carstens, J. C., Podzimek, J., and Saad, A. N. (1974) — On the analysis of the condensational growth of a stationary cloud droplet in the vicinity of activation, J. Atmos. Sci., 31, pp. 592-596.
- [7] Fuller, E. N., Schettler, P. D., and Giddings, J. C. (1966) — A New Method for Prediction of Binary Gas-Phase Diffusion Coefficients, Ind. Eng. Chem., 58, pp. 19-27.
- [8] Paluch, I. R. (1971) — A model for cloud droplet growth by condensation in an inhomogeneous medium, J. Atmos. Sci., 28, pp. 629-639.
- [9] Thompson, K. O. (1975) — First Order Ordinary Differential Equation Solver (FOODES), Univ. of Alabama in Huntsville Computer Services pp. 12.
- [10] Howell, W. E. (1949) — The growth of cloud drops in uniformly cooled air, J. Meteor., 6, pp. 134-149.

**Table 1. MAXIMUM PERCENTAGE DEVIATIONS OF SATURATION RATIO AND PRESSURE FOR THE CASE OF INITIAL DEW POINT TEMPERATURES BETWEEN 18°C AND 17.900°C.**

Cooling Rate (°C/min)	Saturation Ratio		Pressure	
	Max. Deviation (%)	Time (sec)	Max. Deviation (%)	Time (sec)
6	0.63	0.0	0.24	40
2	0.63	0.0	0.24	95
1	0.63	0.0	0.23	175
0.3	0.63	0.0	0.21	540

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TABLE 2. MAXIMUM PERCENTAGE DEVIATION OF THE GROWTH OF DROP SIZE FOR THE CASE CORRESPONDING TO INITIAL DEW POINT TEMPERATURE BETWEEN 18°C AND 17.900°C, AND MINIMUM OPERATION TIME AND HIGHEST TEMPERATURE FOR PERCENTAGE OF DEVIATION LESS THAN 2%.

Cooling Rate (°C/min)	Drop Size				
	Maximum Deviation		Minimum Operation Time for Deviation Less Than 2%		Highest Temperature* for Deviation Less Than 2% (°C)
	%	Time (sec)	Second	Minute	
6	21	27	51	0.85	14.9
2	28	80	145	2.41	15.1
1	34	155	280	4.66	15.3
0.3	43	504	918	15.3	15.4

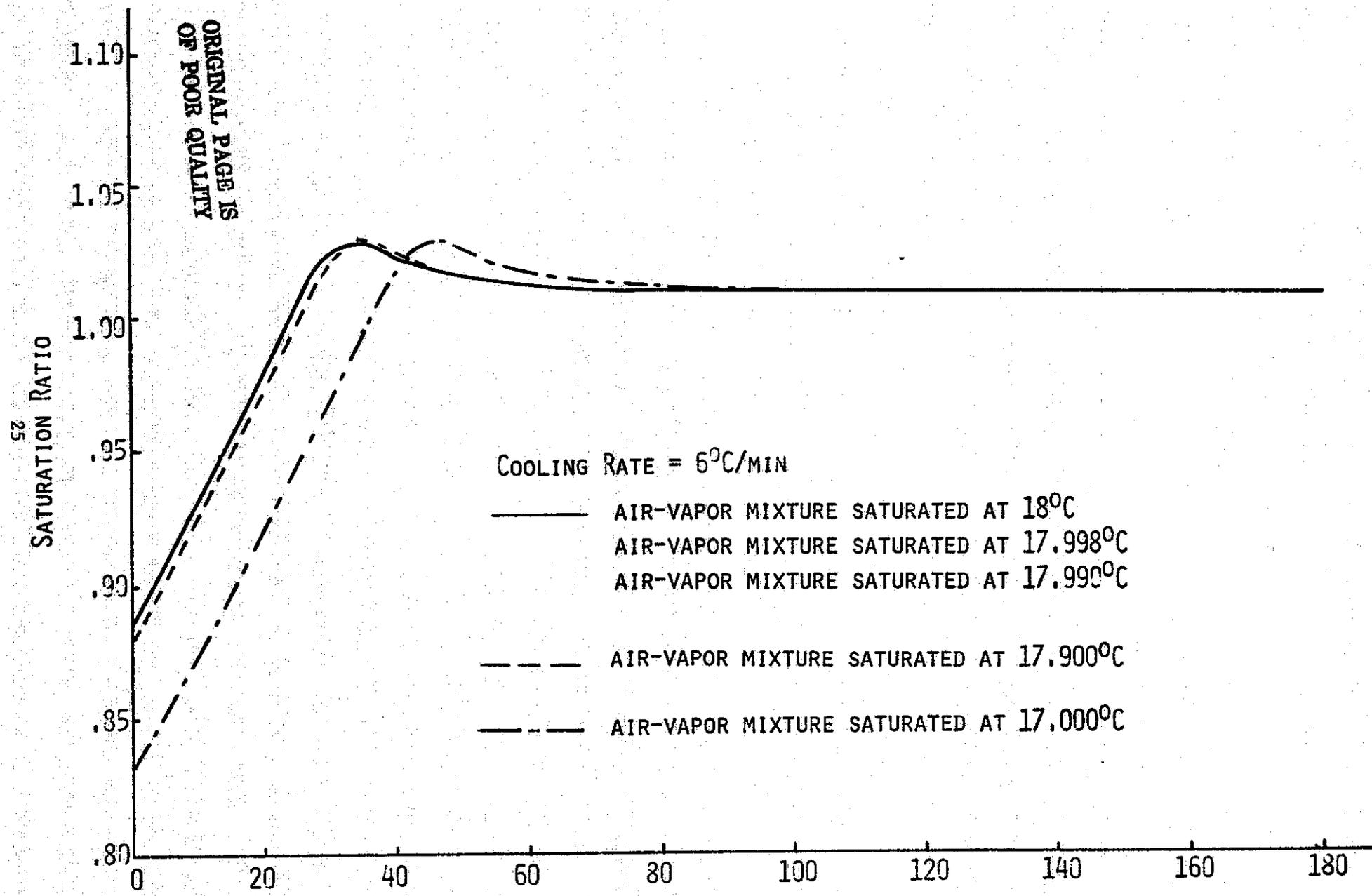
\* Initial temperature is assumed to be 20°C.

## FIGURE CAPTIONS

- Figure 1 — Time-dependent study of saturation ratios for cooling rate at  $6^{\circ}\text{C}/\text{min}$ .
- Figure 2 — Time-dependent study of saturation ratios for cooling rate at  $2^{\circ}\text{C}/\text{min}$ .
- Figure 3 — Time-dependent study of saturation ratios for cooling rate at  $1^{\circ}\text{C}/\text{min}$ .
- Figure 4 — Time-dependent study of saturation ratios for cooling rate at  $0.3^{\circ}\text{C}/\text{min}$ .
- Figure 5 — Time-dependent study of pressures for cooling rate at  $6^{\circ}\text{C}/\text{min}$ .
- Figure 6 — Time-dependent study of pressures for cooling rate at  $2^{\circ}\text{C}/\text{min}$ .
- Figure 7 — Time-dependent study of pressures for cooling rate at  $1^{\circ}\text{C}/\text{min}$ .
- Figure 8 — Time-dependent study of pressures for cooling rate at  $0.3^{\circ}\text{C}/\text{min}$ .
- Figure 9 — Time-dependent growth of drop radius for cooling rate at  $6^{\circ}\text{C}/\text{min}$ .
- Figure 10 — Time-dependent growth of drop radius for cooling rate at  $2^{\circ}\text{C}/\text{min}$ .
- Figure 11 — Time-dependent growth of drop radius for cooling rate at  $1^{\circ}\text{C}/\text{min}$ .
- Figure 12 — Time-dependent growth of drop radius for cooling rate at  $0.3^{\circ}\text{C}/\text{min}$ .

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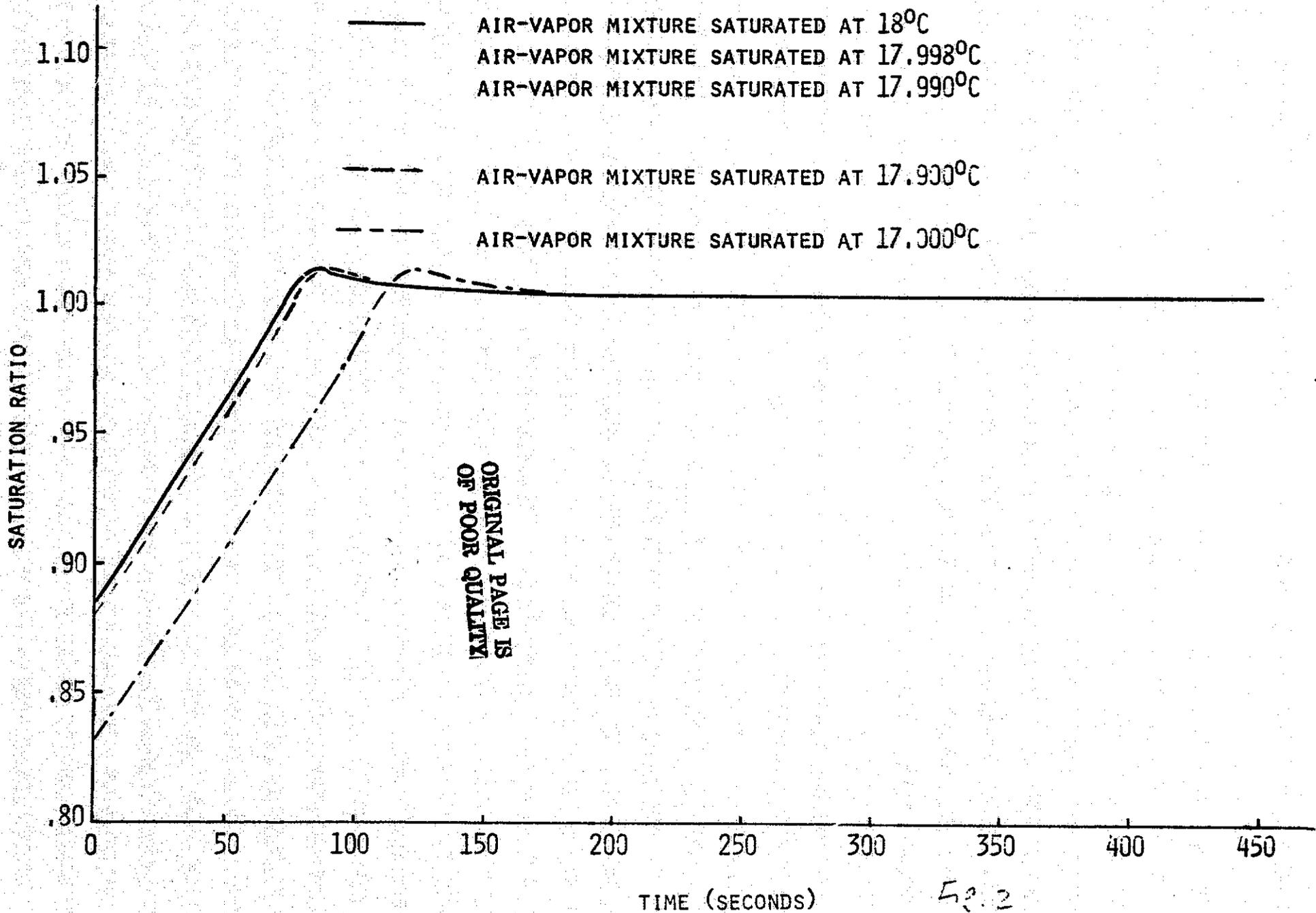
COOLING RATE = 6°C/MIN

- AIR-VAPOR MIXTURE SATURATED AT 18°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.998°C
- · - AIR-VAPOR MIXTURE SATURATED AT 17.990°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.900°C
- · - AIR-VAPOR MIXTURE SATURATED AT 17.000°C

TIME (SECONDS)

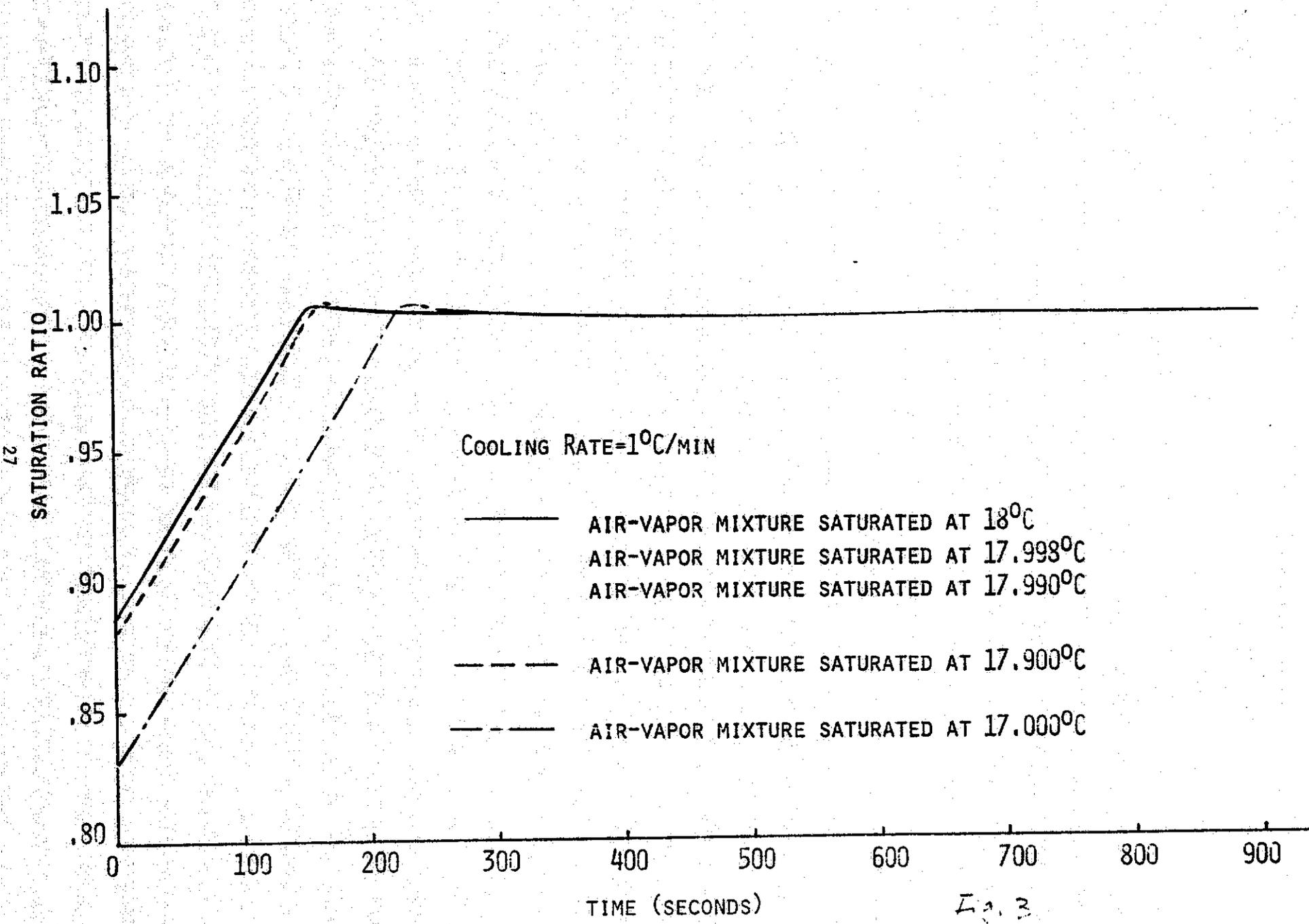
Fig. 1

COOLING RATE = 2°C/MIN

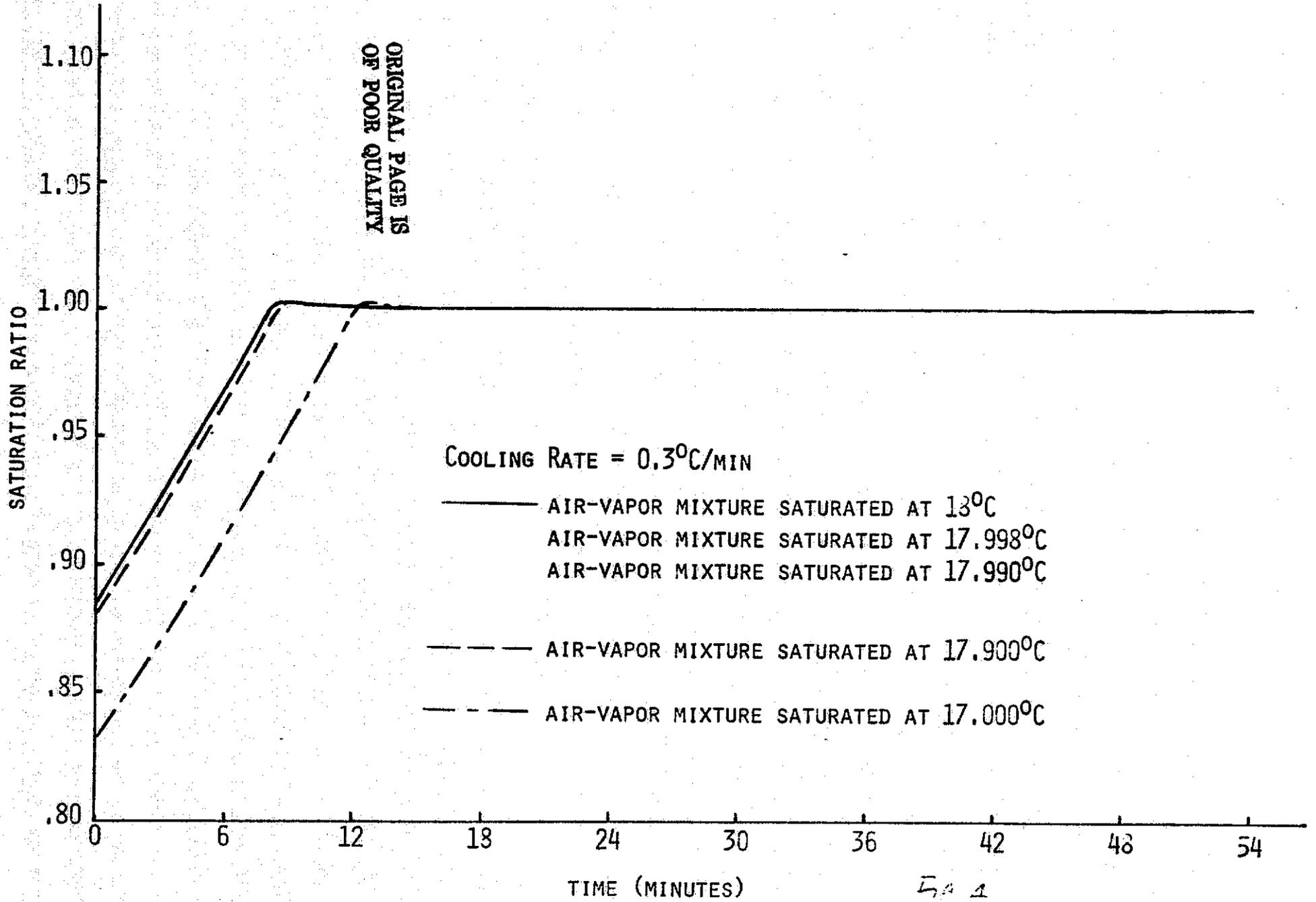


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Fig. 2



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COOLING RATE = 6°C/MIN

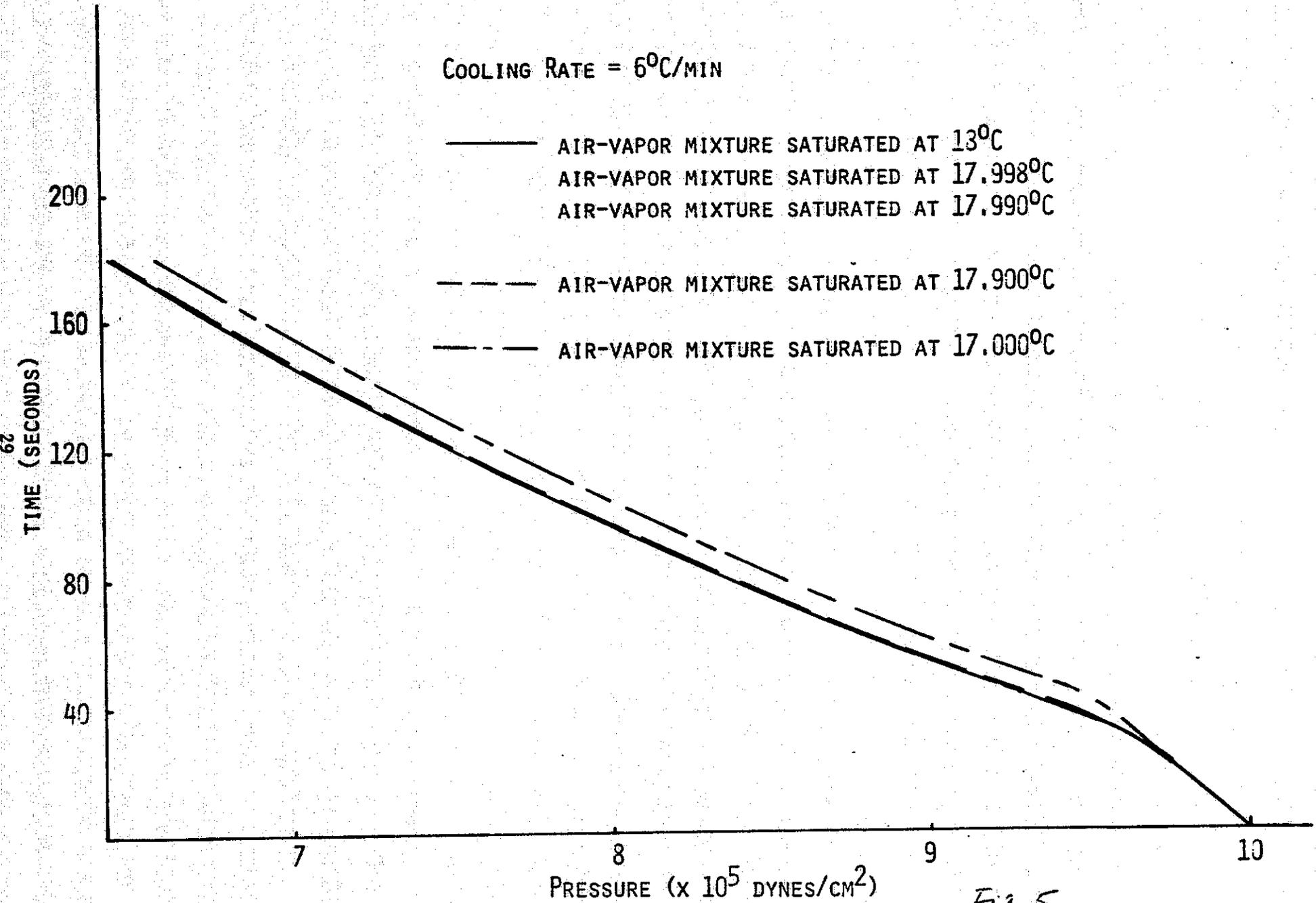
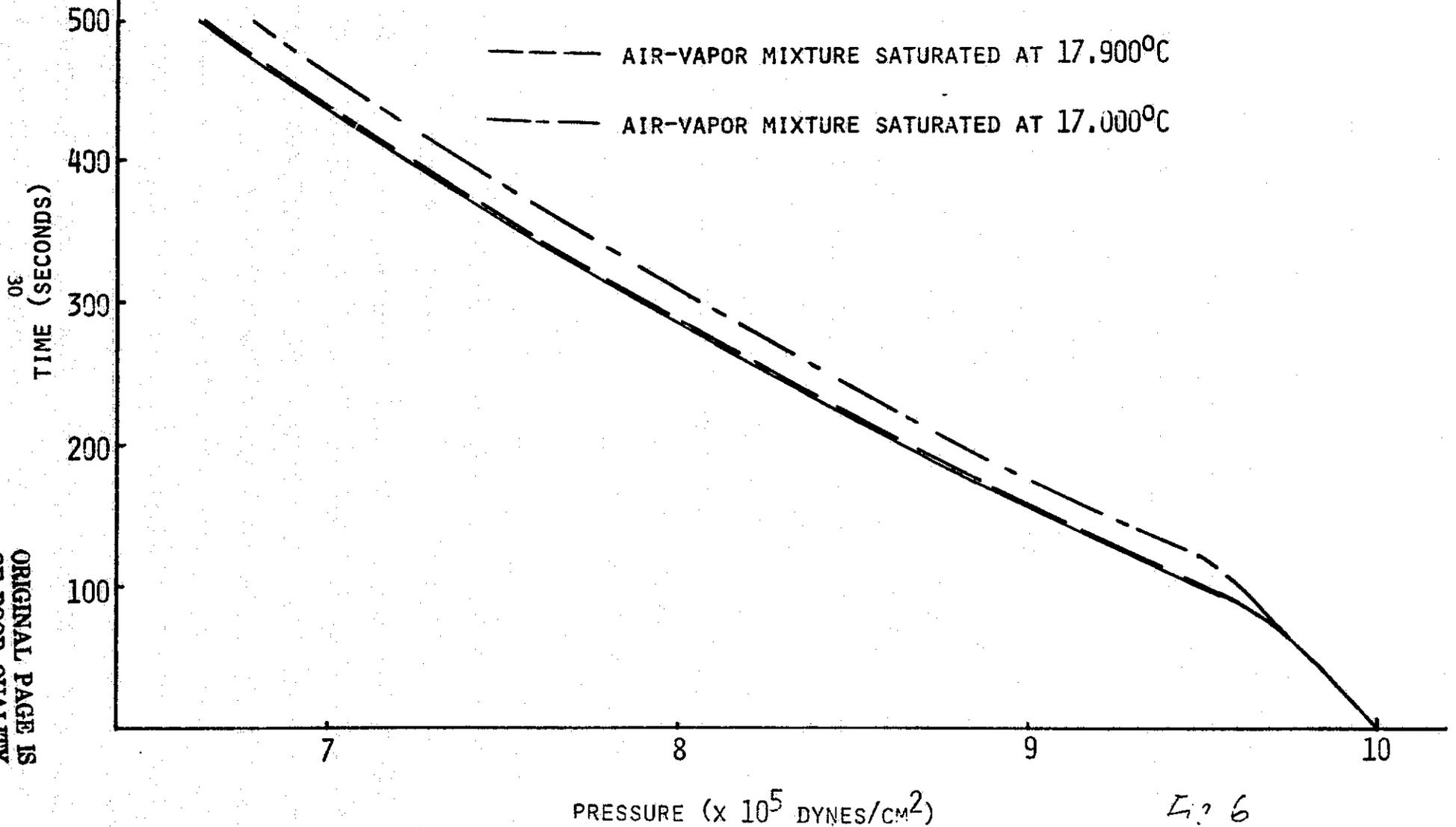


Fig. 5

COOLING RATE = 2°C/MIN

- AIR-VAPOR MIXTURE SATURATED AT 18°C
- AIR-VAPOR MIXTURE SATURATED AT 17.998°C
- AIR-VAPOR MIXTURE SATURATED AT 17.990°C
- AIR-VAPOR MIXTURE SATURATED AT 17.900°C
- AIR-VAPOR MIXTURE SATURATED AT 17.000°C

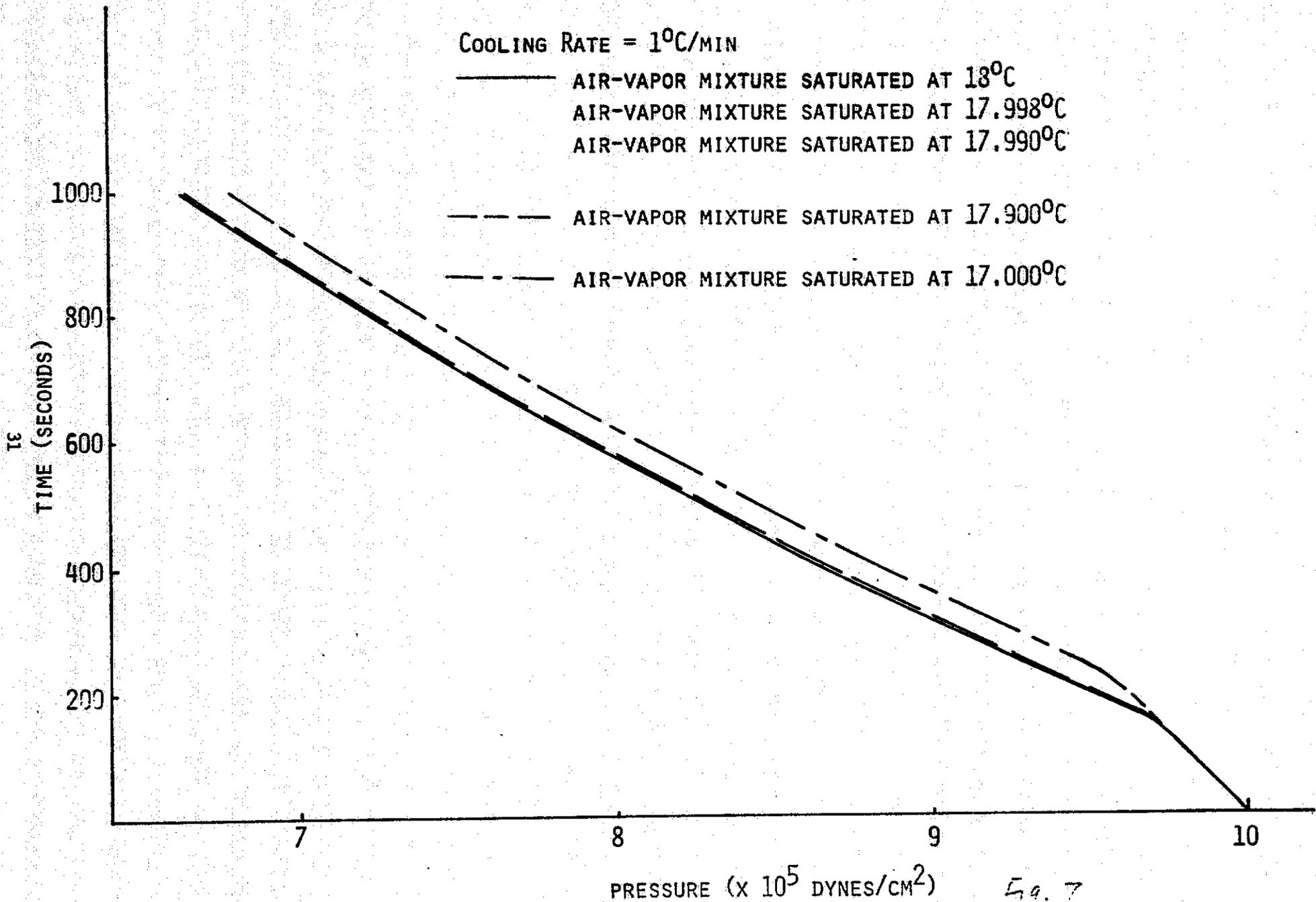


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Fig 6

COOLING RATE = 1°C/MIN

- AIR-VAPOR MIXTURE SATURATED AT 18°C
- AIR-VAPOR MIXTURE SATURATED AT 17.998°C
- AIR-VAPOR MIXTURE SATURATED AT 17.990°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.900°C
- · - AIR-VAPOR MIXTURE SATURATED AT 17.000°C

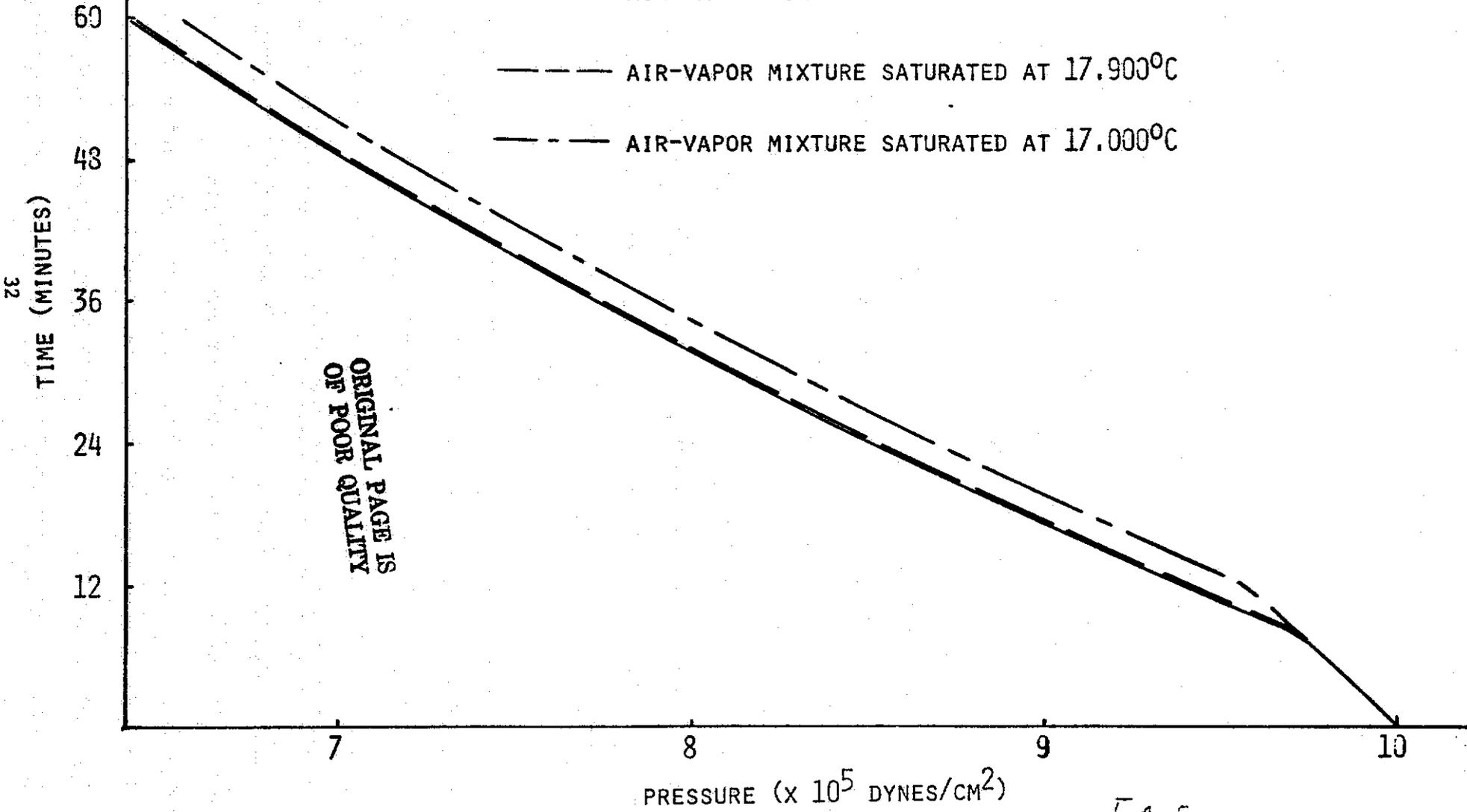


PRESSURE ( $\times 10^5$  DYNES/CM<sup>2</sup>)

Fig. 7

COOLING RATE = 0.3°C/MIN

- AIR-VAPOR MIXTURE SATURATED AT 18°C
- AIR-VAPOR MIXTURE SATURATED AT 17.998°C
- AIR-VAPOR MIXTURE SATURATED AT 17.990°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.900°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.000°C

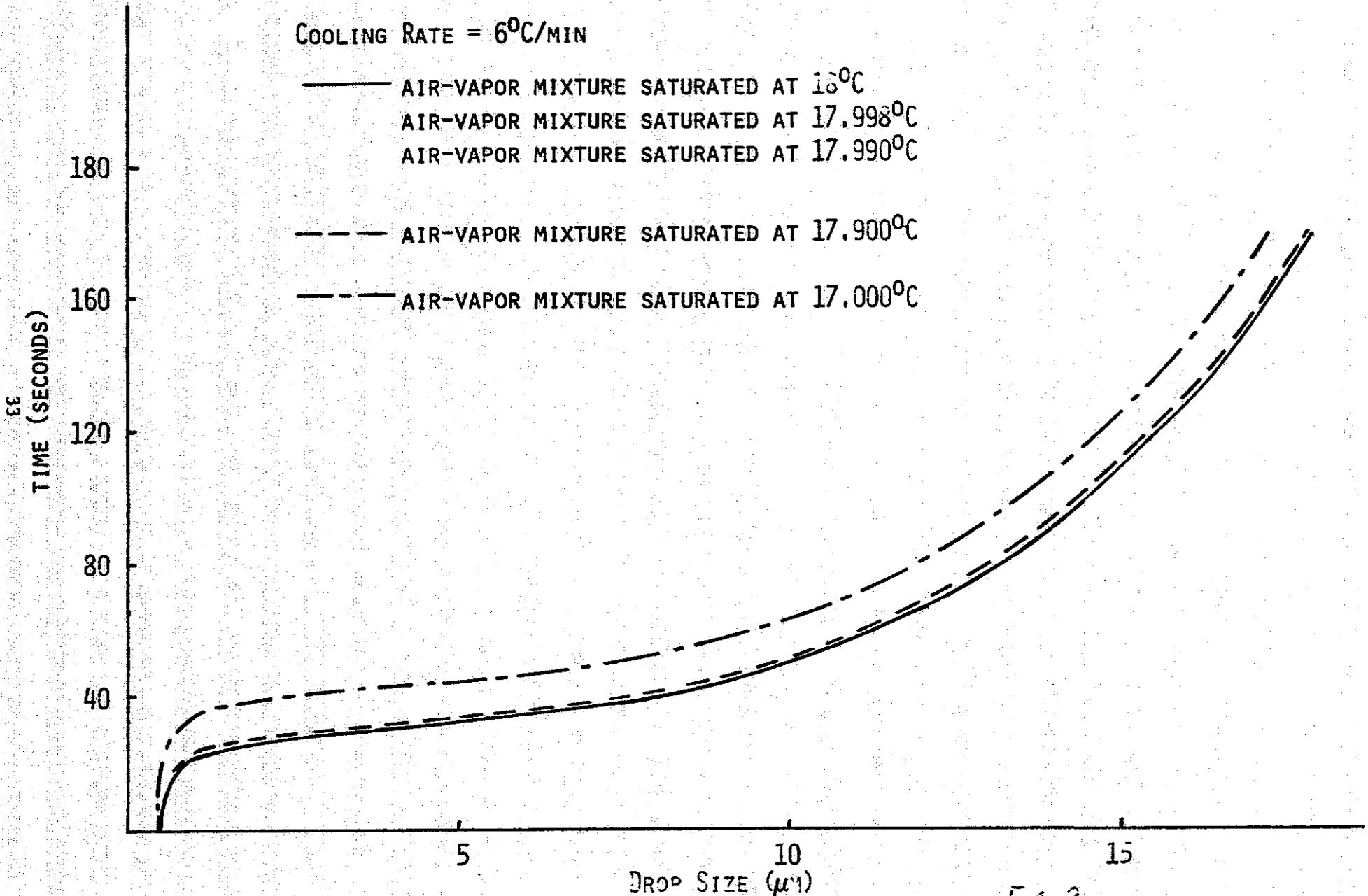


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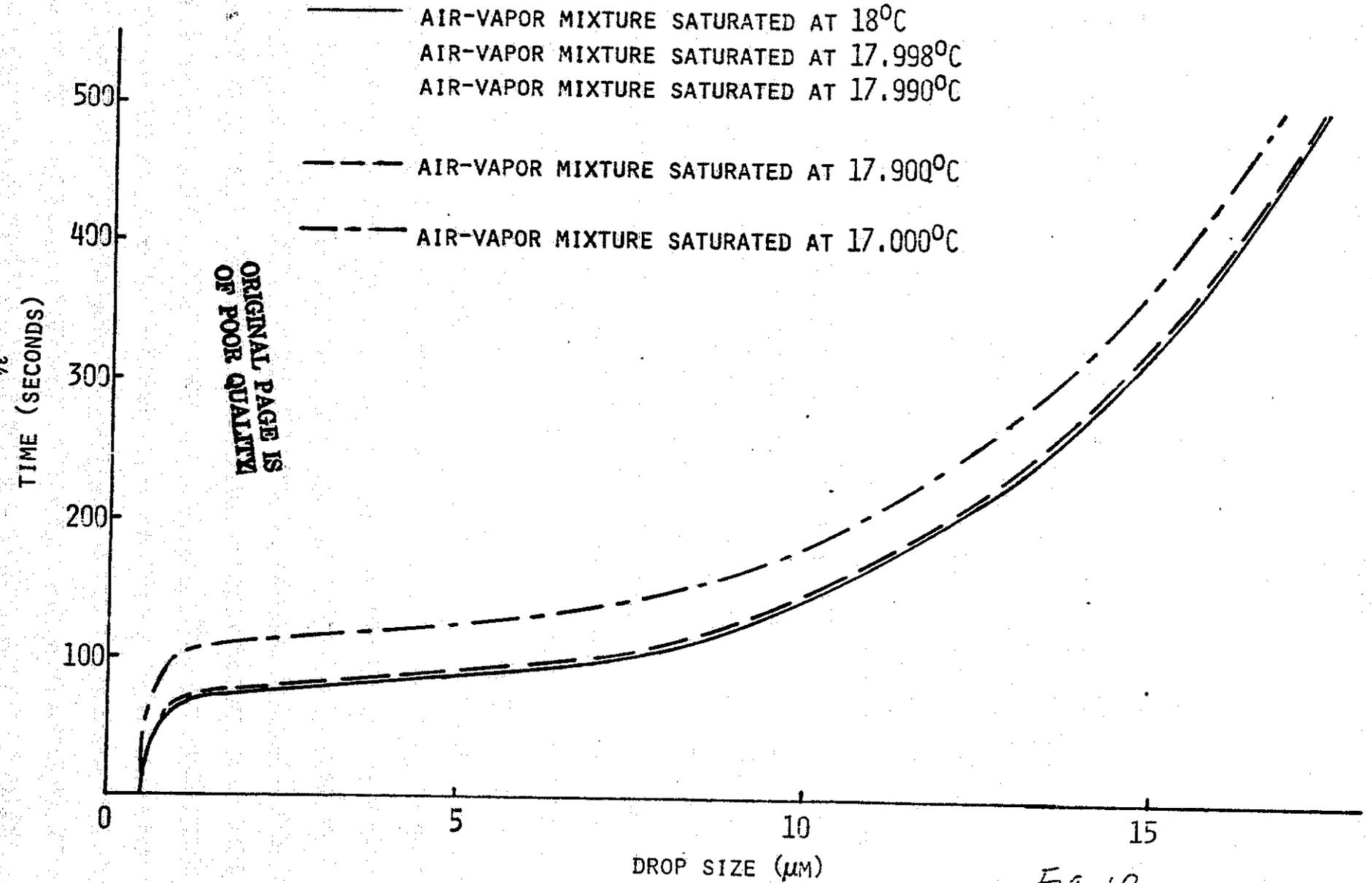
Eq. 5

COOLING RATE = 6°C/MIN

- AIR-VAPOR MIXTURE SATURATED AT 16°C
- AIR-VAPOR MIXTURE SATURATED AT 17.998°C
- AIR-VAPOR MIXTURE SATURATED AT 17.990°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.900°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.000°C



COOLING RATE = 2°C/MIN



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Fig 10

COOLING RATE = 1°C/MIN

- AIR-VAPOR MIXTURE SATURATED AT 18°C
- AIR-VAPOR MIXTURE SATURATED AT 17.998°C
- AIR-VAPOR MIXTURE SATURATED AT 17.990°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.900°C
- - - AIR-VAPOR MIXTURE SATURATED AT 17.000°C

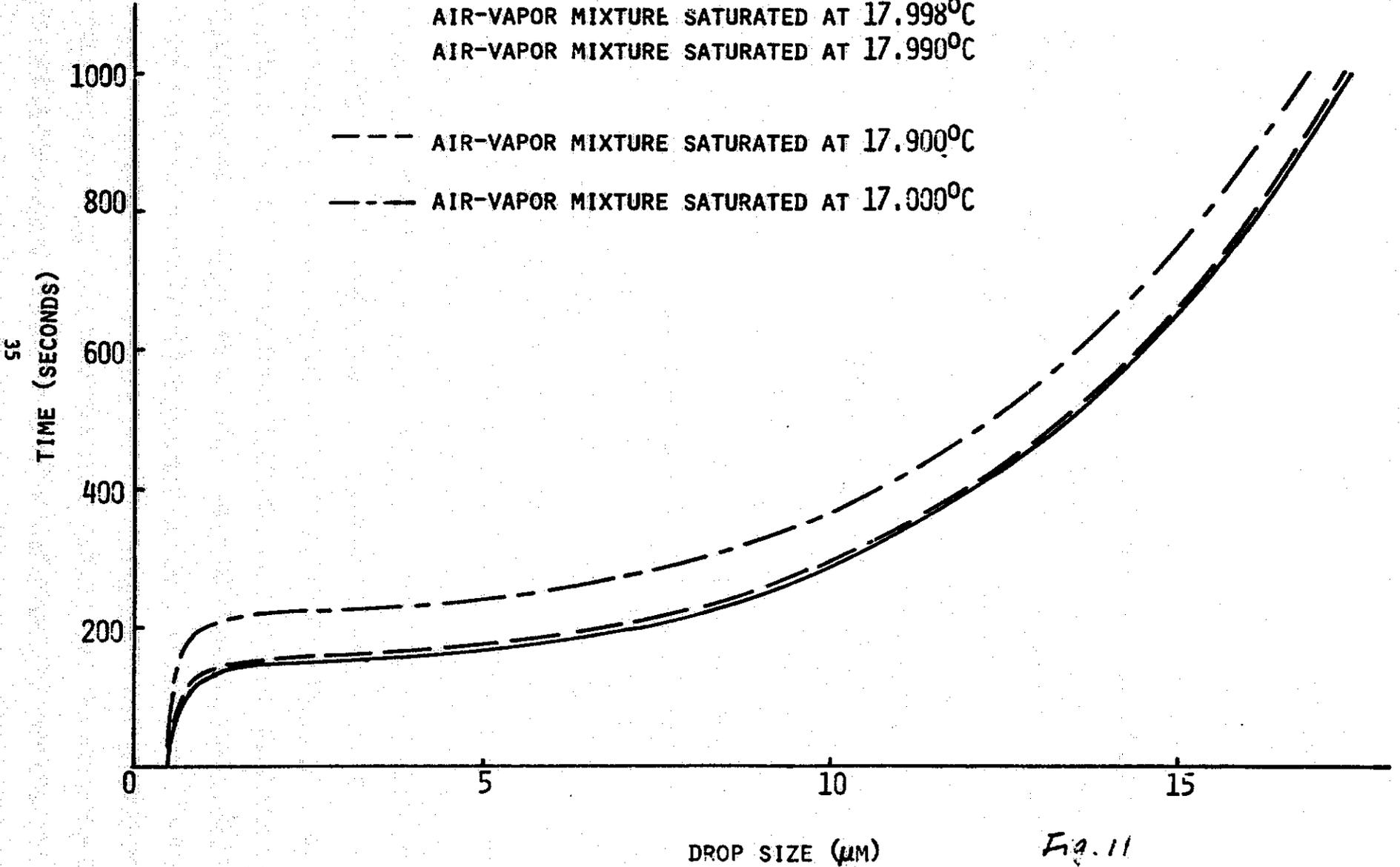


Fig. 11

COOLING RATE = 0.3°C/MIN

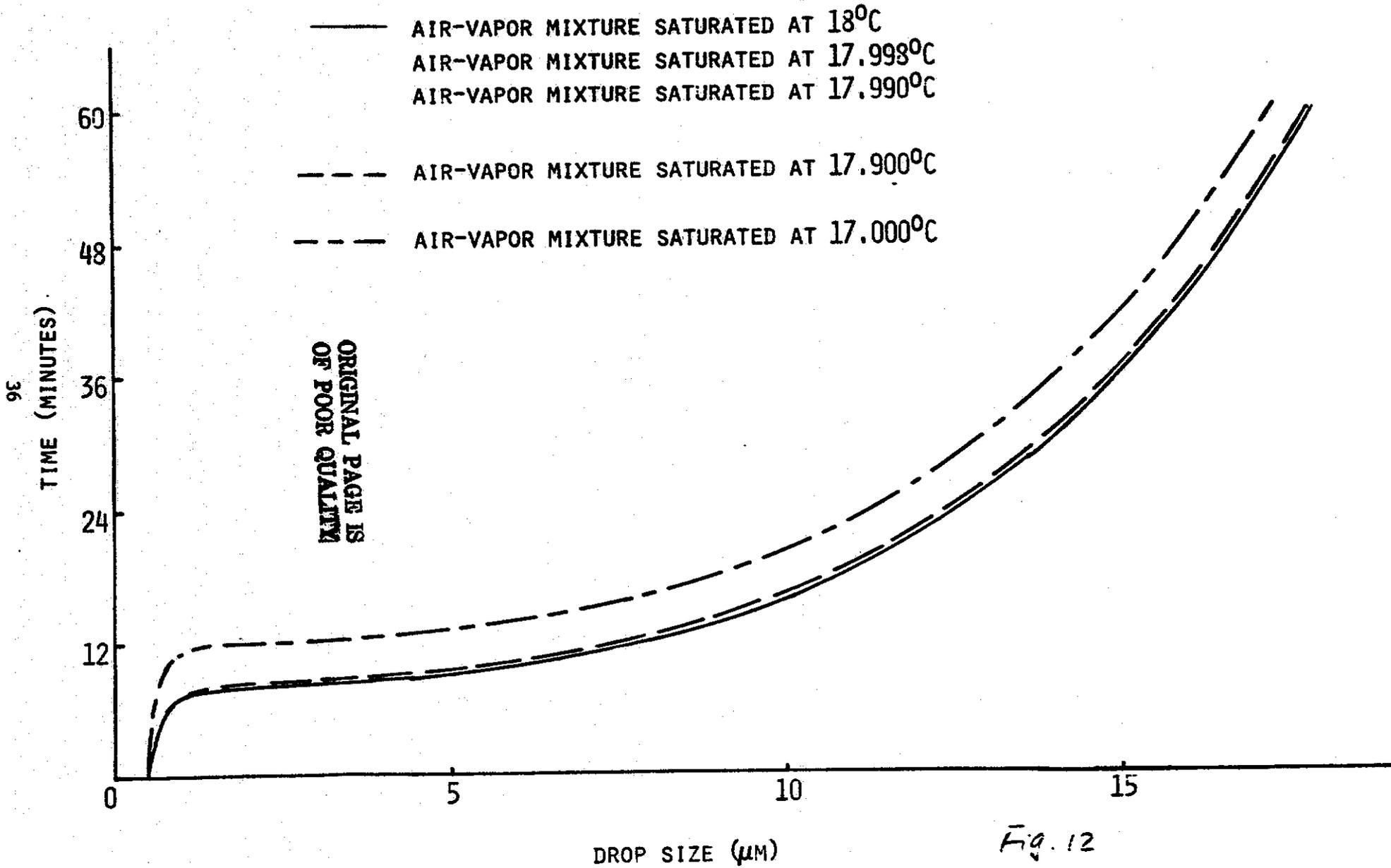


Fig. 12

## SKYLAB FLUID MECHANICS SIMULATIONS: OSCILLATION, ROTATION, COLLISION AND COALESCENCE OF WATER DROPLETS UNDER LOW-GRAVITY ENVIRONMENT\*

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### ABSTRACT

Studies of the dynamics of water droplets has been one of the most interesting areas in the fields of atmospheric microphysics, nuclear physics, astrophysics, fluid mechanics, mechanical engineering, and chemical engineering. Skylab 4 crew members performed a series of demonstrations showing the oscillations, rotations, as well as collision coalescence of water droplets which simulate various physical models of fluids under low gravity environment. The results from Skylab demonstrations show that these demonstrations have provided much interesting information and illustrate the potential of an orbiting space-oriented research laboratory for the study of more sophisticated fluid mechanic experiments.

### I. INTRODUCTION

Recently, the dynamics of oscillation, rotation, collision and coalescence of water droplets has triggered the imagination of researchers in various fields of physical sciences, such as meteorology, nuclear physics, astrophysics, fluid mechanics, mechanical engineering and chemical engineering. Lord Rayleigh (1879) first investigated mathematically the various modes of oscillation of fluids. Since then there have been many investigations concerning the dynamics of liquid drops, yet the mechanics of the oscillation (particularly nonlinear oscillation), rotation (particularly rotation breakup), and the coalescence processes still remain poorly understood.

To study and observe the dynamics of liquids in the terrestrial laboratory, artificial supports are required to eliminate the gravitational force and to provide for longer observational time. The levitation apparatuses which are available today are the vertical wind tunnel, electrostatic potential, high frequency acoustic waves (ultrasonic waves), and high energy level laser beams. Although these are useful techniques, their use tends to mask other types of minute forces and disturbs their effects which might confuse the experimental

\* This article was published in "Space Simulation," NASA SP-379, pp. 563-574, Scientific and Technical Information Office, National Aeronautics and Space Administration, Washington, D. C., 1975.

observations. Experiments performed in an orbiting spacecraft with its low gravity environment offer a technique to study fluids and observe their modes of oscillation without the side effects of artificial suspension techniques.

Prior to the Skylab program various studies had been performed in wind tunnels to observe the oscillations, rotations and coalescence of liquid drops (e.g., Beard and Pruppacher, 1971). However, many of the oscillation modes could not be detected or recorded because they were being masked by the aerodynamic forces. To understand how water droplets will oscillate, rotate and collide, and to see how fluids will behave under the low gravity environment, a series of simple science demonstrations were proposed for the Skylab mission. The demonstrations were designed to provide a data base for the design of a fluid mechanics and a cloud physics type laboratory to be flown as a part of the Spacelab Shuttle program. The Skylab 3 and 4 crews were requested to perform these science demonstrations so that the mechanics of collisions, coalescence, rotation, natural oscillations and techniques for manipulation and positioning of fluids in low gravity could be simulated and studied.

In the present paper, we have limited ourselves to a discussion of the following three branches of fluid mechanics simulation under low-gravity environment: (1) oscillation of droplet which characterizes the nuclear oscillation in nuclear physics, bubble oscillation of two phase flow in chemical engineering, and water drop oscillation in meteorology; (2) rotation of droplet which characterizes nuclear fission in nuclear physics, formation of binary stars and rotating stars in astrophysics, and breakup of water droplet in meteorology; and (3) collision and coalescence of droplets which characterize nuclear fusion in nuclear physics, and processes of rain formation in meteorology.

## II. EXPERIMENTAL ARRANGEMENTS

The hardware used in the Skylab fluid mechanics demonstrations consisted of on-board medical type syringes, pieces of tape attached to drinking straws, marker pen writing ink, grape drink, strawberry drink, pieces of thread, the teflon coated flat surface of the ED. 52 "web formation in zero gravity" spider cage, reflection mirror, etc., and the on-board color TV camera. The water used in the demonstration was colored, to enhance the photography, by adding a small amount of marker pen ink, grape drink mix, or strawberry drink mix to each drop. Movies of the dynamics of oscillations, rotations, collisions and coalescence of water droplets under low gravity environment were recorded on-board TV cameras. These series of color films are identified as Fluid Mechanics Demonstrations - TV 107.

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The films taken with the on-board TV cameras were later analyzed. Measurements of the characteristics of the drop oscillations, rotations, collisions and coalescence were made by using a Vanguard film analyzer. The amplitude and wavelength of the oscillations were determined directly from the film using appropriate scale factors. The frequency of oscillation and angular velocity of rotation were determined by counting the number of frames that were observed during the time interval and then dividing this count number by the TV camera framing rate.

In this paper, techniques and results of space simulation will be discussed. The theoretical analysis and comparison of the Skylab demonstration data with existing theory is out of the scope of the paper but it is published elsewhere (Vaughan, et al., 1974a; Vaughan, et al., 1974b; Hung, et al., 1974).

### III. SKYLAB FLUID MECHANICS SIMULATIONS

The Skylab science demonstration/simulation TV 107 (Fluid Mechanics Demonstration) has created much interest among the researchers in various fields, such as meteorology, nuclear physics, astrophysics, fluid mechanics, mechanical engineering and chemical engineering. In particular, fluid demonstration of oscillation, rotation, collision and coalescence of water droplets simulate some physical models of interests which may contribute toward the solutions of a great number of unsolved problems.

Some selected frames of oscillation, rotation, collision and coalescence of water droplets from TV 107 will be presented in this paper.

A. Oscillation of Water Droplet - Study of nuclear oscillations has been one of the major topics in nuclear physics in the last forty years. In particular, nuclear physicists are mostly interested in the investigation of nuclear deformation energy surfaces. To study these phenomena, a model of an incompressible liquid drop with charges uniformly distributed throughout the volume and a uniform surface tension is generally assumed (Cohen, et. al., 1974).

Atmospheric microphysics studies deals with droplet and droplet-droplet interactions. Particularly, oscillation of water droplet and oscillation breakup of droplet are closely correlated to the mechanism of rain formation (Mason, 1971).

Stability of bubble oscillation is very important for the study of two-phase flow in chemical engineering. Furthermore, chemical engineers are also very interested in the study of the dynamics of the contact line between the fluid and solid surface as the water droplet oscillated (West, 1911; Huh and Scriven, 1971).

These physical models of interests were very well simulated and are shown in the Skylab Fluid Mechanics Simulation. Figure 1 shows some selected frames of the various modes of water droplet oscillation. The numbers on the pictures in the figure show the

sequence of TV camera frames taken in the Skylab demonstration. Picture number 1 shows a water droplet with the diameter of 2.67 cm touched on opposite sides by two soda straws. Picture number 7 shows that two soda straws were plucked outward from the water droplet causing the water droplet to oscillate. We observe various modes of oscillation until the decay of oscillation occurs due to its internal damping. Picture number 9 shows the oscillation of a water droplet in longitudinal direction and picture 17 indicates the oscillation of a water droplet in transverse direction. Pictures number 22 and 24 show the transition of droplet oscillation from transverse direction to longitudinal direction. Pictures number 33 and 36 show the transition of droplet oscillation from longitudinal to transverse direction. Picture number 42 shows the recovery of the oscillation of a water droplet to its original shape due to damping effect.

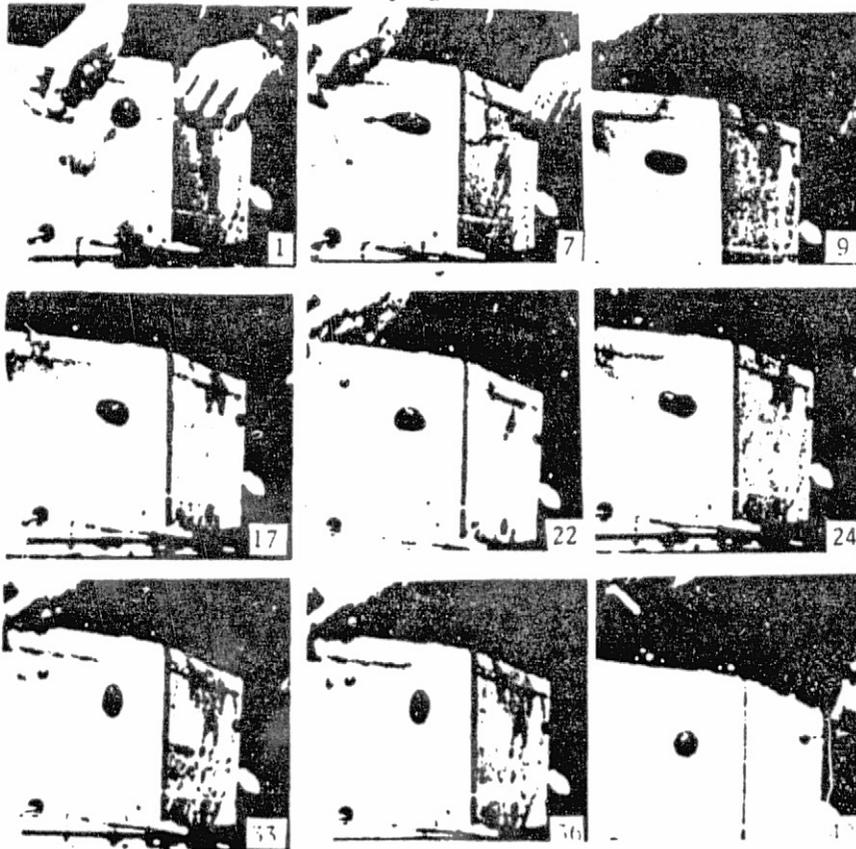


Figure 1. Skylab Fluid Mechanics Demonstration - Free Oscillation of Water Droplet.

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Figure 2 shows selected frames of the various modes of the oscillating water droplet attached to the flat surface. This is very useful for the study of droplet oscillations and the dynamics of contact line between the fluid and solid surface as the water droplet oscillated. Picture number 1 shows a drinking straw being inserted into the center of a water droplet attached to the flat surface. Pictures number 3 and 10 show the soda straw being pulled out of the water drop. Picture number 17 shows the oscillation of water droplet as it reaches its maximum amplitude right after the soda straw left the surface of the droplet. Pictures number 22 and 26 shows the water droplet decreasing its amplitude, and picture number 29 shows the oscillation of a water droplet descending to its minimum amplitude. Picture number 31 shows the increasing amplitude of a water droplet, and picture number 39 shows the proximate moment when the water droplet just completed one cycle of oscillation and returned to its maximum amplitude.

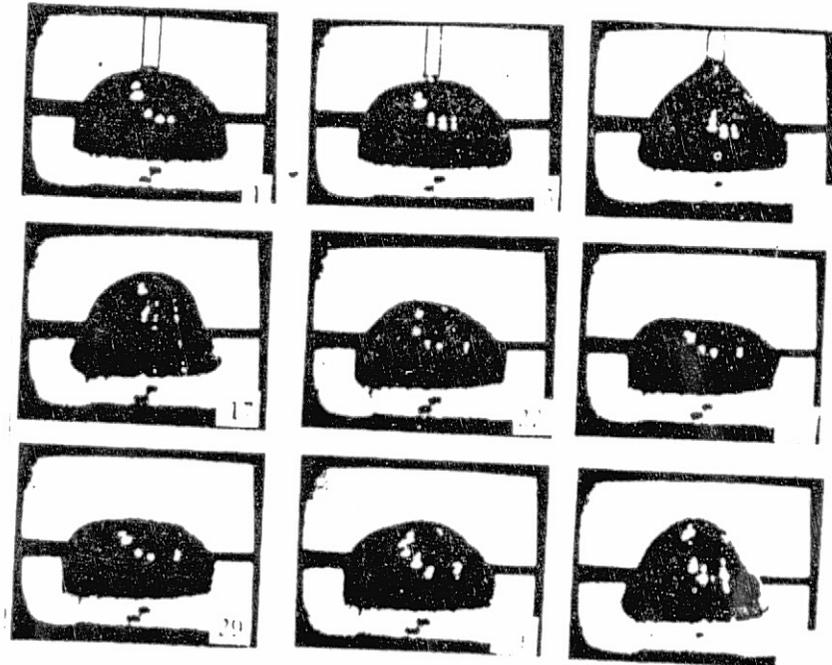


Figure 2. Skylab Fluid Mechanics Demonstration - Oscillation of Water Droplet Attached to the Flat Surface.

The dynamics of the droplet oscillation is governed by the boundary condition given by the Young-Laplace relation (Landau and Lifshitz, 1959). Solution of Young-Laplace relation leads to the relation of droplet oscillation (Rayleigh, 1879)

$$\omega^2 = \frac{\alpha l (l-1) (l+2)}{\rho R^3} \quad (1)$$

where  $\alpha$  denotes surface tension;  $\rho$ , the density of fluid;  $R$ , the radius of unperturbed liquid droplet;  $\omega$ , the circular frequency of oscillation; and  $\ell = 0, 1, 2, \dots$ , the integer numbers. Equation (1) shows that  $\ell = 0$  and 1 correspond only to rigid body oscillations, and the fundamental mode corresponds to  $\ell = 2$ . In general, the oscillation for each mode  $\ell$ , there are  $2\ell + 1$  oscillations along different directions. These oscillations with the same mode  $\ell$  have the same frequency. If we consider only the characteristics of the mode and not the type of oscillations in the various directions, the shape of the drop is (Hung, et al., 1974)

$$r = R + \sum_{\ell} a_{\ell} P_{\ell}(\cos \theta) \quad (2)$$

where  $P_{\ell}$  is the  $\ell$ th order Legendre polynomial;  $(r, \theta, \phi)$ , the axes of spherical coordinates; and the coefficients  $a_{\ell}$  are functions of time  $t$ :

$$a_{\ell} = R_{\ell} [b_{\ell} e^{-i\omega t}] \quad (3)$$

where  $\omega$  is given by Equation (1), and  $b_{\ell}$  is some amplitude of the oscillations.

Skylab Fluid Mechanics Demonstration provides us a good opportunity to study how well the theory stands.

B. Rotation of Water Droplet - About half the stars in the sky are binary stars. The fission theory, proposed by Poincaré in 1885, attempted to explain the occurrence of binary stars by a natural process of evolution of a single star. Unfortunately, recent investigation showed that the results were adverse to Poincaré's picture. A newer fission theory of rotating liquid drops has been proposed to study these problems (Chandrasekhar, 1969). Experimentally, the dynamics of rotating liquid drops simulate the characteristics of binary stars and rotating stars.

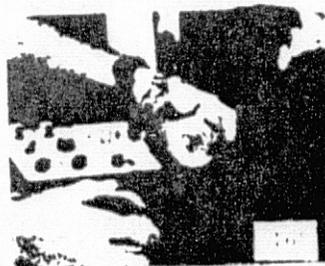
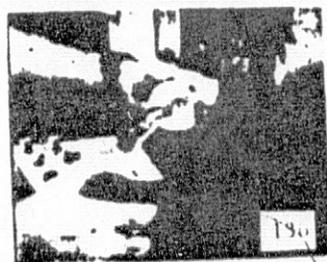
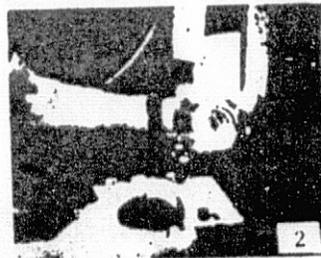
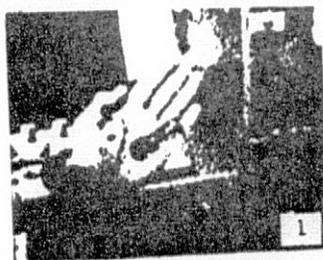
In nuclear physics, mechanics of fission process is the area which draws a great attention among the researchers. A model of an incompressible rotating liquid drop simulates the dynamic evolution of the stability of the mechanics of nuclear fission process (Cohen, et al., 1974).

In meteorology, dynamic of the breakup of water droplet is closely related to the warm cloud processes. The Skylab demonstration of rotating droplet is also of particular interest in large precipitation drop breakup.

Figure 3 shows some selected frames of the sequences of rotating drops exhibiting "dog bone" or "dumb bell" shape. To get the drop of water to rotate in the "dog bone" or "dumb bell" shape the astronaut conceived a simple technique which he used to produce initially a prolate spheroid by asymmetric excitation of the outer surface of the drop of water. After a few applications of this asymmetric excitation force the drop is caused to rotate at a higher rotational speed which produced an unstable oscillation

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mode and the drop then tears into two separate drops. Picture number 1 shows the drop of water rotating in the "dog bone" shape. Picture number 2 shows a drop being initially touched with the rotation tool. The astronaut touches the drop and later he causes it to begin to rotate. Each time the astronaut touched the drop at its outer surface with a rotating motion he caused it to rotate at a slightly higher rotational rate. After a number of encounters with the drop, it was then allowed to rotate until it began to breakup by itself. Picture number 136 shows the drop still in contact with the tool and being excited - note the start of the prolate sphere shape now occurring. Picture number 165 shows the drop now free of the tool but in a rotating/oscillating mode. Pictures number 747 thru number 752 show how the drop began to reach the unstable mode as it begins to rotate faster until it begins to neck down and breakup into two distinct drops. In future space flights, a demonstration should be performed in the low gravity environment to illustrate the case of the oblate spheroid rotating at increasing angular velocity until a ring of fluid similar to a "donut" is produced.



(Figure 3 to be Continued)

(Figure 3 Continued)

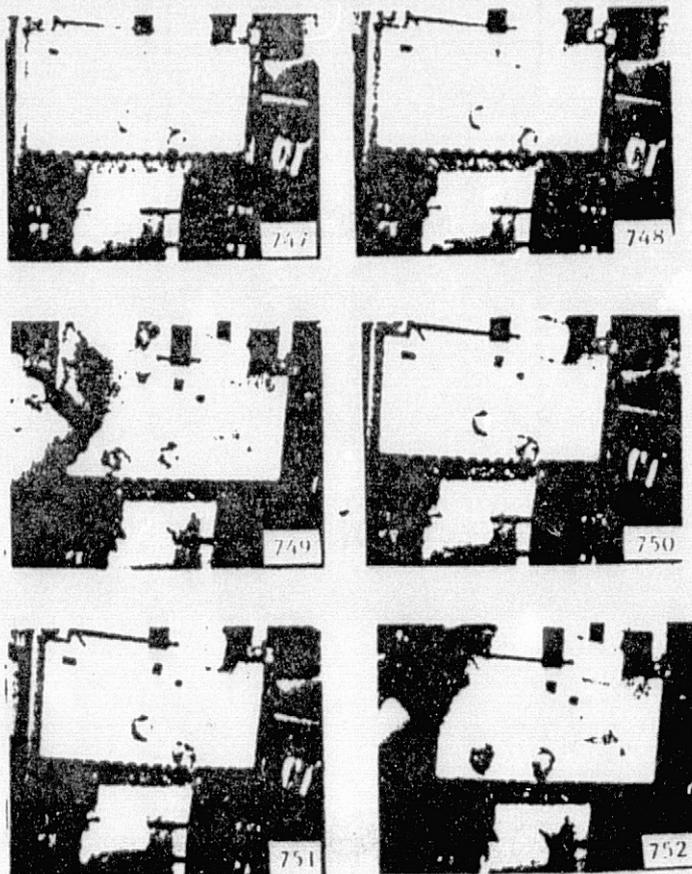


Figure 3. Skylab Fluid Mechanics Demonstration - Rotation of Water Droplet.

Based on the original work by Plateau (1866), Chandrasekhar (1965) extends the work and investigated various modes of oscillation on the stability of rotating drops. For an axisymmetrical form and uniform density, the figure of equilibrium depends on the value of the non-dimensional parameter  $\xi$  (Chandrasekhar, 1965)

$$\xi = \frac{1}{8\alpha} \rho \Omega^2 a^3 \quad (4)$$

where  $\Omega$  denotes the angular velocity of rotation;  $a$ , the equatorial radius of the distorted drop;  $\rho$ , density of drop; and  $\alpha$ ,

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the surface tension. As  $\xi$  decreases the figure tends to the oblate spheroid, and degenerates into a sphere as  $\xi = 0$ . However, as  $\xi$  increases, the figure rapidly departs from the spheroidal form. The polar regions are flat as  $\xi = 1$ ; as  $\xi$  increases beyond 1, the drop develops a dimple; and finally the breakup occurs.

The theory of time dependent evolution of rotating stability of liquid droplets has been a very active research field for many years. It is because of a conspicuous lack of experimental evidence to backup the boundary conditions assumed in numerical computation which makes the computer simulation still not completely explored. In this respect, the Skylab demonstration of a rotating droplet has enhanced the understanding of rotational stability of liquids.

C. Collision and Coalescence of Water Droplets - Recently studies of the dynamics of the collision and coalescence of water droplets has been widely used in simulating the mechanism of nuclear collision and nuclear fusion. These dynamic studies are considered to be a significant step in understanding fusion process of nuclear physics (Cohen, et al., 1974).

In cloud physics, the precipitation process is solely dependent on growth of droplets and ice crystals which is governed by the following three stages: (1) growth by nucleation process, this process includes condensation, ice deposition, and freezing of water droplets and ice crystals on the surface of foreign substances or of the same substances as nuclei; (2) growth by diffusion process, after a droplet or ice crystal has been nucleated and has surpassed the free energy barrier or critical radius, it enters a stage of growth by diffusion; and (3) growth by collision and coalescence process, the growth by diffusion process is negligible compared with that by coalescence process as the size of droplets is greater than 40 microns ( $\mu$ ) radius (Byers, 1965). This implies that the collision and coalescence process is one of the key processes of rain formation.

Figure 4 shows some selected frames of the collision and coalescence of two water drops. Picture number 1 shows the dark colored droplet moving toward the stationary pink colored droplet. The volumes of the two droplets are the same,  $30 \text{ cm}^3$ , or a sphere with a 3.85 cm diameter. Picture number 5 is at the moment when the two colliding droplets reached the critical separation distance, and suddenly the distance between two colliding droplets was bridged and coalescence then proceeded rapidly. Pictures number 7, 14, 19 and 20 show how two of the coalescence droplets fused into one, and how the nonlinear wave-wave interaction oscillated in the longitudinal direction. Pictures number 26 and 31 show how the nonlinear wave-wave interaction oscillated in the transverse direction. Pictures number 39, 51, 59 and 72 show the continuous nonlinear oscillations and how the nonlinear damping effect overcomes the nonlinear growth rate. Pictures number 93, 132 and 151 show the typical small amplitude oscillations of a water droplet.

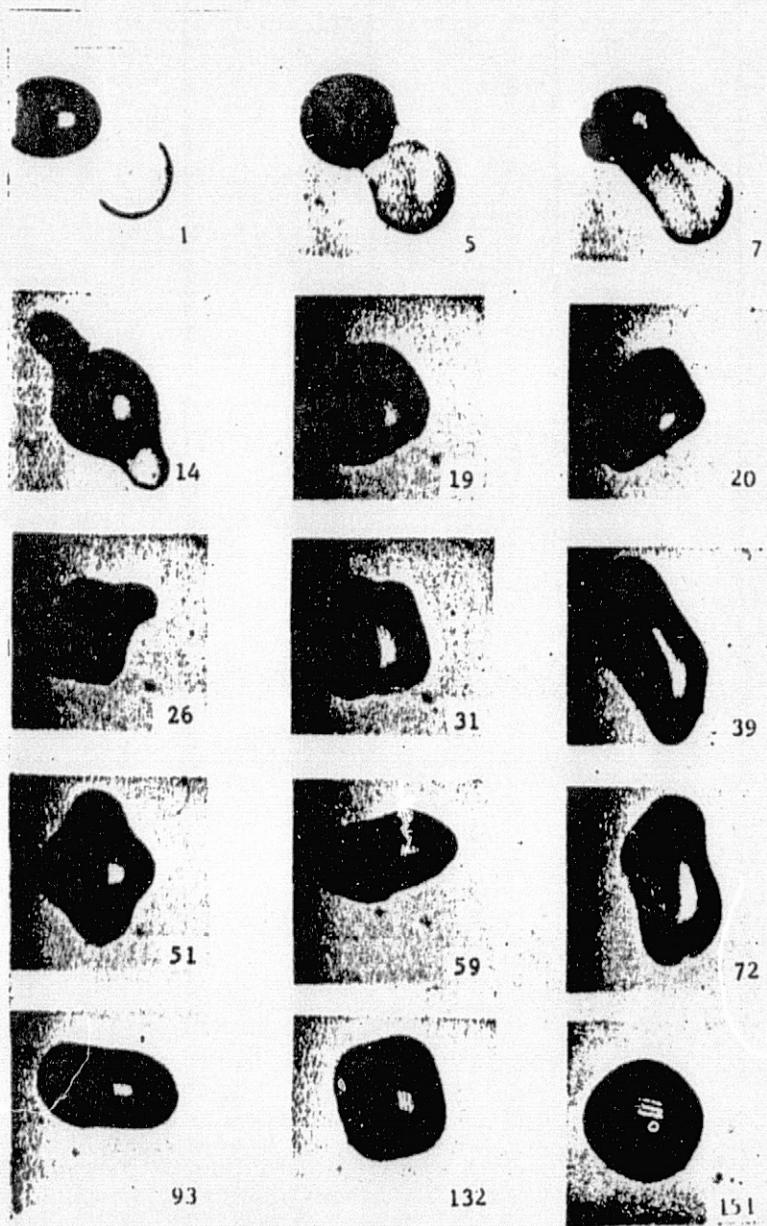


Figure 4. Skylab Fluid Mechanics Demonstration - Collision and Coalescence of Water Droplets.

The basic numerical techniques for studying collision and coalescence of an incompressible viscous fluid are those of the Marker-and-Cell (MAC) method which were developed by the Los

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Alamos group (Harlow and Welch, 1965). The MAC method solves the finite difference form of Navier-Stokes equations with the velocity components and pressure defined over a staggered Eulerian mesh. The surface tension effects given by Young-Laplace relation serves as the boundary condition for the free surface. To apply boundary conditions at the edges of the collision (contact point of droplets), further experimental evidence must be obtained to justify either the condition of zero tangential stress or free-slip condition and/or other conditions to confirm the validity of numerical computations. In this sense, Skylab demonstrations of the collision and coalescence of water droplets has helped in our understanding of this phenomena.

#### IV DISCUSSIONS AND CONCLUSIONS

The study of droplet dynamics has been, for many years, one of the most interesting topics in the fields of atmospheric micro-physics, nuclear physics, astrophysics, fluid mechanics, mechanical engineering, and chemical engineering. The Fluid Mechanics Demonstrations (TV 107 Series) performed during the Skylab missions produced excellent photographic data showing the oscillation, rotation, collision and coalescence of water droplets which simulate various physical models of interests under low gravity environment. Also, these TV 107 series of films provide interesting observations and illustrate the potential beneficial use of the low gravity environment for various branches of research. Particularly, scientific and technical evaluations have been provided by Skylab demonstrations to support the Zero-Gravity Atmospheric Cloud Physics Laboratory project in the future missions of Spacelab/Space Shuttle.

During the Skylab missions, special equipment was not available and video recording was used for data collection. These video tapes were subsequently transferred to 16 mm movie film which was then supplied to the researchers for analysis. In this respect, because of the restriction of speed of video recording, a laboratory type controlled experiment was not performed in the Skylab missions. However, qualitative in nature, these films have provided much interesting information and illustrate the potential of an orbiting research laboratory to provide data beneficial to terrestrial research problems.

#### ACKNOWLEDGEMENT

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## REFERENCES

- Beard, K.V. and H. R. Pruppacher, J. Atmos. Sci. **28**, 1445, 1971.
- Byers, H. R., Elements of Cloud Physics, Univ. of Chicago Press, Chicago, Ill., 1965.
- Chandrasekhar, S., Proc. Roy. Soc. (London) A **286**, 1, 1965.
- Chandrasekhar, S., Ellipsoidal Figures of Equilibrium, Yale University Press, New Haven, Conn., 1969.
- Cohen, S., F. Plasil, and W. J. Swiatecki, Ann. Phys. **82**, 557, 1974.
- Harlow, F. H. and J. E. Welch, Phys. Fluids **8**, 2182, 1965.
- Huh, C. and L. E. Scriven, J. Coll. and Interf. Sci. **35**, 85, 1971.
- Hung, R. J., O. H. Vaughan, Jr., and R. E. Smith, AIAA Paper No. 74-1256, 1974.
- Landau, L. D. and E. M. Lifshitz, Fluid Mechanics, Pergamon Press, London, 1965.
- Mason, B. J., The Physics of Clouds, Clarendon Press, London, 1971.
- Plateau, J., The Annual Report of the Board of Regents of the Smithsonian Institution, pp. 255, Government Printing Office, Washington, D.C., 1866.
- Rayleigh, L., Proc. Roy. Soc. (London) **29**, 71, 1879.
- Vaughan, O. H., R. E. Smith, and R. J. Hung, Proc. Conf. on Cloud Phys., pp. 408, Am. Meteor. Soc., 1974a.
- Vaughan, O. H., R. E. Smith, R. J. Hung and S. T. Wu, Proc. International Colloq. on Drops and Bubbles, Jet Propulsion Lab., 1974b.
- West, G. D., Proc. Roy. Soc. A **86**, 28, 1911.

## APPENDICES

## APPENDIX A

### CONSULTANTS FROM THE CLOUD PHYSICS SCIENTIFIC COMMUNITY AND PARTICIPATION OF WORKING GROUP MEETINGS

A group of scientists from the cloud physics scientific community were asked to serve as consultants for the present contract. Some of the scientists were also invited to participate in working group meetings. The purposes of the service and working group meetings were to provide the advice and the guidance of the definition of experiments and scientific input to the cloud physics laboratory project which was necessary to assure successful experiments on the Shuttle-Spacelab Cloud Physics Laboratory. Financial and limited administrative support for the scientists and engineers participating in the working group meetings was also provided from this contract. In general, the support for the personnel to attend the working group meetings consisted primarily of financial support for their travel to, from, and during the meetings, in addition to limited research activities at their home locations on specific items that were identified during the working group meetings. The support of meeting expenses, for example the working group meeting at the Plaza Inn, Denver, Colorado (September 16-18, 1975), was also provided by the present contract. The list of scientists who served as consultants and/or participated in working group meetings, requested by the present contract, are as follows:

(1) Dr. Larry Berbigler

University of Missouri - Rolla, Rolla, Missouri

(2) Dr. John C. Carstens

University of Missouri - Rolla, Rolla, Missouri

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- (3) Dr. Donald E. Coles  
California Institute of Technology, Pasadena, California
- (4) Dr. Kenneth Dunipace  
University of Missouri-Rolla, Rolla, Missouri
- (5) Dr. Harry Edwards  
Colorado State University, Fort Collins, Colorado
- (6) Dr. Dennis M. Garvey  
Colorado State University, Fort Collins, Colorado
- (7) Dr. Donald Hagen  
University of Missouri-Rolla, Rolla, Missouri
- (8) Dr. Peter Hobbs  
University of Washington, Seattle, Washington
- (9) Dr. Thomas E. Hoffer  
University of Nevada System-Reno, Reno, Nevada
- (10) Dr. Charles Hosler  
Pennsylvania State University, University Park, Pennsylvania
- (11) Dr. James Hudson  
University of Nevada System-Reno, Reno, Nevada
- (12) Mr. Jim Hughes  
Naval Research Laboratory - Arlington, Virginia
- (13) Dr. Jim Jiusto  
State University of New York, Albany, New York
- (14) Dr. James L. Kassner  
University of Missouri-Rolla, Rolla, Missouri
- (15) Mr. Warren Kocmond  
University of Nevada System-Reno, Reno, Nevada

- (16) Dr. Garland Lala  
State University of New York, Albany, New York
- (17) Dr. C. L. Lin  
University of Missouri-Rolla, Rolla, Missouri
- (18) Dr. Henry Loos  
Laguna Research Laboratory, Laguna Beach, California
- (19) Dr. Fred Rogers  
University of Nevada System-Reno, Reno, Nevada
- (20) Mr. Bob Ruskin  
Naval Research Laboratory, Arlington, Virginia
- (21) Dr. Bob Sax  
Experimental Meteorology Laboratory, Coral Gables, Florida
- (22) Dr. Pat Squires  
University of Nevada System-Reno, Reno, Nevada
- (23) Dr. Gabor Vali  
University of Wyoming, Laramie, Wyoming
- (24) Dr. James W. Telford  
University of Nevada System-Reno, Reno, Nevada
- (25) Dr. Helmut Weickmann  
NOAA, Boulder, Colorado
- (26) Dr. Dan White  
University of Missouri-Rolla, Rolla, Missouri.

## APPENDIX B

### SUBCONTRACTS FOR THE SUPPORT OF TERRESTRIAL SIMULATION OF SPACE SHUTTLE EXPERIMENTS

The cloud physics research under zero or low gravity conditions offers an opportunity to answer many problems that can not otherwise be solved on earth-bounded laboratories. By taking advantage of zero gravity to define many of the processes in clouds that are not yet fully understood, man can influence weather by changing, for example, drop distributions and nuclei concentrations, or by adding pollutant composition.

To support the development work and hardware design criteria on the Shuttle-Spacelab Cloud Physics Laboratory Payload, the terrestrial simulation was urgently necessary. Two subcontracts were granted from the present contract.

Two reports accomplished by the subcontractors were transmitted to NASA coordinator immediately after we received the reports. A summary of the reports are as follows:

- (1) "Computational and Calculational Support for Terrestrial Simulation Chamber," by J. C. Carstens and C. L. Lin of Cloud Physics Research Center, University of Missouri-Rolla, Rolla, Missouri.

The general nature of the problems related to heat and mass transfer in connection with humidity systems, cloud chamber wall, heat sink, flow analysis through the chamber, aerosol decay, and drop growth and/or evaporation for the simulated cloud chamber is investigated.

Computations on the humidifier system are undertaken to provide guidelines for the optimum humidifier design required by specified operating conditions. A general expression is derived to give any desired relative humidity for a wet channel with constant temperature of plates.

The thermal analysis of the terrestrial UMR cloud chamber shows that the maximum temperature drops of the inner wall in one minute are  $17.27^{\circ}\text{C}$  and  $12.94^{\circ}\text{C}$  when the initial wall temperatures are  $25^{\circ}\text{C}$  and  $-15^{\circ}\text{C}$ , respectively, provided that the maximum temperature difference between the thermoelectric unit is limited to  $10^{\circ}\text{C}$ . The temperature fluctuation along the inner wall for the case of the initial temperature at  $25^{\circ}\text{C}$  is only about  $0.026^{\circ}\text{C}$ . It seems therefore that the thermal analysis could be further simplified by using one-dimensional approach to the whole chamber wall.

The back-propagated effect of the sinusoidal temperature fluctuation created by the heat transfer through the cooling pipes inside the heat sink is also considered. It is found that the temperature fluctuation is damped out very rapidly and that the heat wave induced by the cooling pipes therefore will not be back-propagated seriously to the thermoelectric unit.

The effect of the flow pattern by the camera mounted in the zero-g cloud chamber is analyzed by assuming axisymmetric fluid flow approximated as a potential flow pattern. The solution of the flow pattern can be used to determine the

number of holes to be drilled or locations and directions of holes to be drilled along both of the end plates inside the zero-g chamber.

The drop growth and/or evaporation in the zero and the terrestrial chambers are numerically simulated by using Adam-Moulton predictor-corrector method. Good agreements are obtained with Saad et al.,'s results (1976). This method is then extended to include the gravitational effect by dividing the chamber into 5 layers. The profiles of temperature, supersaturation, liquid water content, vapor content, and drop growth with time are obtained along the height of the chamber. It is found that the maximum temperature and maximum supersaturation difference between layers 1 and 5 are around  $0.12^{\circ}\text{C}$  and 0.01, respectively for the characteristic length,  $l \approx 2\mu\text{m}$ . For  $l \approx 200\mu\text{m}$ , the maximum temperature difference between layers 1 and 5 is about  $0.08^{\circ}\text{C}$  and the drop growth is much slower than that of  $l \approx 2\mu\text{m}$ . In other words, the sedimentation of droplets plays an important role in limiting the expansion rate. In the present calculations, the collision and coalescence effect, the ventilation effect, the deposition on the wall, the mass diffusion, and the heat transfer are neglected. However, the latter two factors will be added to the program in the future.

The coolant flow analysis of zero-g simulated cloud chamber is also included in this report. We conclude that

some kind of heat-resistance material whose magnitude is a linear function along the flow direction, must be inserted between the channel and its upper wall in order to limit the temperature fluctuation inside the chamber wall. The difference between the solid wall temperature at the inlet and the inlet fluid temperature is also an important factor in limiting the temperature fluctuation and the cooling rate. Several cases of calculations which are based on different boundary conditions are conducted.

- (2) "Critical Review of Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development," by E. A. Carter, Consulting Meteorologist of Huntsville, Alabama.

This is a review of terrestrial environment data which can be applied to the Space Shuttle and other programs.

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