NASA TECHNICAL MEMORANDUM

NASA TM X-3266

NASA TM X-3266

CONTROLLED GENERATION OF LARGE VOLUMES OF ATMOSPHERIC CLOUDS IN A GROUND-BASED ENVIRONMENTAL CHAMBER

Henry J. Hettel, Rosa G. de Pena, and Jorge A. Pena

Lewis Research Center

Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1975

1. Report No. NASA TM X-3266	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CONTROLLED GENERATION OF LARGE VOLUMES OF ATMOSPHERIC CLOUDS IN A GROUND-BASED ENVIRONMENTAL CHAMBER		5. Report Date August 1975 6. Performing Organization Code
7. Author(s) Henry J. Hettel, Rosa G. de Pena, and Jorge A. Pena		8. Performing Organization Report No. E-8292
9. Performing Organization Name and Address Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135		10. Work Unit No. 491-02 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Atmospheric clouds have been generated in a 23 000-cubic-meter environmental chamber as the first step in a two-part study on the effects of contaminants on cloud formation. The program was proposed by Pennsylvania State University's Department of Meteorology and was sponsored jointly by NSF and NASA. The generation procedure is modeled on the terrestrial generation mechanism so that naturally occurring microphysics mechanisms are operative in the cloud generation process. Temperature, altitude, liquid water content, and convective updraft velocity can be selected independently over the range of terrestrially realizable clouds. To provide cloud stability, a cotton muslin cylinder 29.3 meters in diameter and 24.2 meters high was erected within the chamber and continuously wetted with water at precisely the same temperature as the cloud. The improved instrumentation which permitted fast, precise, and continual measurements of cloud temperature and liquid water content is described.

17. Key Words (Suggested by Author(s))		18. Distribution Statement	
Clouds Cloud generation Cloud physics		Unclassified - unlimited STAR category 47 (rev.)	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 22	22. Price* $3.25

* For sale by the National Technical Information Service, Springfield, Virginia 22161

CONTROLLED GENERATION OF LARGE VOLUMES OF ATMOSPHERIC CLOUDS IN A GROUND-BASED ENVIRONMENTAL CHAMBER

by Henry J. Hettel, Rosa G. de Pena,* and Jorge A. Pena†

Lewis Research Center

SUMMARY

Atmospheric clouds have been generated in a 23 000-cubic-meter environmental chamber as the first step in a two-part study on the effects of contaminants on cloud formation. The program was proposed by Pennsylvania State University's Department of Meteorology and was sponsored jointly by NSF and NASA. The generation procedure is modeled on the terrestrial generation mechanism so that naturally occurring microphysics mechanisms are operative in the cloud generation process. Temperature, altitude, liquid water content, and convective updraft velocity can be selected independently over the range of terrestrially realizable clouds. To provide cloud stability, a cotton muslin cylinder 29.3 meters in diameter and 24.4 meters high was erected within the chamber and continuously wetted with water at precisely the same temperature as the cloud. The improved instrumentation which permitted fast, precise, and continual measurements of cloud temperature and liquid water content is described.

INTRODUCTION

Man's dependence on the weather is well known, and if it were possible to intentionally modify weather, even locally, the economic impact would be tremendous. Hail and severe weather cause millions of dollars worth of property damage annually. Drought, like the one that hit the Midwest during the summer of 1974, results in untold crop losses and the subsequent price increases. Fog and snow cause delays, danger, and death on highways and in airports.

---

*Associate Professor of Meteorology, Pennsylvania State University, University Park, Pennsylvania.

†Research Meteorologist, Pennsylvania State University, University Park, Pennsylvania.

Weather modification has already occurred accidentally as a result of man's contamination of the atmosphere: Our cities are shrouded in smog. It is time for us to fully understand the consequences of our actions in advance so that we can tailor our environment to our needs instead of destroying it.

One of the keys to understanding weather and weather modification is to understand the microphysics of clouds. How are clouds formed? What is the distribution of water droplets within the clouds? How can clouds be seeded or otherwise changed to cause precipitation? What is the influence of man-made contaminants on clouds? All of these questions and many others must be answered before we can attempt to fully understand or control weather.

Unfortunately, clouds in nature are difficult to study; they have limited lifetimes, they are delicate to the extent that a temperature change of only a few hundredths of a degree can destroy them, and they can only be reached by aircraft whose passage through them can modify their characteristics. Consequently, it is mandatory to study clouds in the laboratory where conditions can be carefully controlled and measured. The Space Power Facility (SPF) at the NASA Plum Brook Station is ideally suited to cloud physics research. The inherent capability of this 30.5-meter-diameter by 36.6-meter-high test chamber to accurately control pressure changes and the chemical composition of the test atmosphere suggested a unique capability to weather scientists. An experimental program sponsored jointly by NSF and NASA was initiated by Drs. Rosa and Jorge Pena of Pennsylvania State University's Department of Meteorology. The objective of this first program was to develop and demonstrate the experimental hardware and techniques required to create stable, long-lived clouds in the test chamber and to measure some characteristic properties.

APPARATUS

The overall configuration of the test facility may be seen in figures 1 and 2. Fundamentally, the facility consists of a tank within a tank. The outer tank has concrete walls and can be evacuated to 15 torr. The inner tank - the test chamber - is an aluminum vessel that can be evacuated to 10^{-7} torr. The annular space is, of course, the volume between the concrete enclosure and the test chamber. Thus, the concrete enclosure takes the major part of the atmospheric pressure load, with the aluminum vessel being subjected only to the differential pressure between the annular space and the test chamber. The maximum allowable limits on this pressure differential are 75 and 125 torr for the aluminum enclosure in crush and burst modes, respectively. The test chamber is 30.5 meters in diameter by 36.6 meters high and has a volume of 23 000 cubic meters; the annular volume is 22 000 cubic meters.

The chamber configuration and some of the cloud test instrumentation are shown in figure 3. The chamber walls are draped with cotton muslin hung from perforated 5.1-centimeter-diameter aluminum pipes. This cylinder of cloth (29.3 m diam by 24.4 m high) is hereinafter called the "water wall." Water is pumped from a reservoir into the perforated support header; from the header the water flows down the curtains into the reservoir again. This recirculating water system is wholly contained within the test chamber so that its operation is independent of the pressure levels and pressure changes in the chamber. Future wet wall installations will contain provisions to eliminate the gaps between the panels.

Two instruments are mounted on the stanchion supporting two quadrants of the facility's liquid nitrogen cold wall. The cold wall was not used in this study. The wet/dry bulb thermometer is at an elevation of 3.7 meters, and the hot wire anemometer is at an elevation of 12.2 meters. Also visible are the lower seven of the nine gelatin-slide droplet distribution sampler devices hung in mobile fashion. At the lower left, the bottom segment of the cloud density meter is partly visible. Also in partial view nearby is one of the three closed-circuit television cameras and a protective can housing a motion picture camera.

Schematically, the facility's pressure related components were valved for this test to provide the configuration of figure 4. Both the test volume and annular volume are pumped by independent roots blower trains at selectable pump rates of 1.0, 2.2, 4.7, 8.6, or 14.4 cubic meters per second. The atmosphere may be readmitted to the test chamber through a variable aperture 25.4-centimeter-inside-diameter valve. This latter process is historically termed "diving" since with aircraft simulators a pressure increase is analogous to a reduction of aircraft altitude.

Dry steam may be admitted to the test chamber in computer-controlled programmable quantities up to 500 grams per second. To accomplish rapid reduction of test chamber pressure, an 89-centimeter-diameter rapid action guillotine valve may be opened for programmable periods of time between the test and annular volumes. When the annulus pressure is below the test chamber pressure, gas blows from the chamber to the annulus. This mode of test chamber pressure reduction is termed "blowdown" as opposed to "pumpdown" wherein the pressure reduction is accomplished by means of the vacuum roughing train.

THEORY

To be a useful research tool, the facility must produce clouds in a natural way; thus, the following constraints are imposed on the cloud generation process:

(1) Precipitation of cloud droplets must be accomplished by adiabatic expansion to simulate the convective rise of warm air to higher altitudes.

(2) Minimal net flow of moisture or heat should cross the interface between the cloud and the chamber wall.

The cloud generation process devised to satisfy these constraints is depicted in figure 5. The segment AB is chamber pumpdown from atmospheric pressure. During this segment, the chamber gas temperature drops almost adiabatically to the point where, depending on the initial relative humidity, the atmosphere becomes saturated. Further pumpdown produces a cloud, which results in a smaller rate of temperature drop - the saturated adiabatic lapse rate.

The segment BC is a thermalization phase wherein heat flows from the chamber wall to the gas. As the gas temperature rises, the chamber pressure rises and the cloud water droplets evaporate. Eventually, state C is reached; the chamber atmosphere is now saturated with water vapor but contains no liquid water droplets. The criterion for selecting the pressure and temperature coordinates of state B is that state C will be reached at the preselected pressure chosen.

The segment CD is a heating and humidification procedure. Air from the external atmosphere is admitted to the chamber raising its pressure - the dive process. The gas is adiabatically heated in this process. To prevent the test atmosphere from becoming unsaturated, dry-steam is metered into the chamber at a precalculated rate sufficient to maintain the relative humidity at unity. The steam further serves as an additional heat source to the test atmosphere, thereby reducing the amount of adiabatic heating required, which in turn reduces the pressure change required.

The segment DE is a convection stabilization time. The air-steam mixture is introduced in a manner designed to emphasize convective stirring to ensure homogeneity. But it may be desirable to form the cloud under quiescent conditions; thus, a stabilization time is provided.

The segment EF is the adiabatic expansion - the blowdown segment - wherein cloud formation occurs. Two independent variables are preselectable - the total pressure change dP and the rate of pressure change dP/dt. The total pressure change controls with cloud liquid water content (CLWC) by means of its influence on the total temperature change. Thus, by preselecting the pressure drop it is possible to control the liquid water content of the resultant cloud. The second preselectable parameter dP/dt simulates the convection rise rate in the atmosphere, permitting clouds to be formed rapidly or slowly. Thus, the gamut of atmospheric conditions from highly turbulent to quiescent can be simulated at will.

The segment FG is the stabilized cloud segment wherein the chamber is isolated and static. The cloud exists in a system which is free from pressure and temperature effects - a condition unrealizable in the Earth's atmosphere - thus permitting extended non-perturbed observation times free from these atmospheric variables.

The sequence of events delineated previously can now be summarized. Segments A through E serve to produce a saturated fully gaseous homogeneous state in the test atmosphere, thereby minimizing any memory effect due to the prior operations. The cloud formation step reproduces the atmospheric mechanism of cloud production, so that naturally occurring microphysics mechanisms are operative in the cloud generation process.

OPERATIONAL CHARACTERISTICS OF THE CLOUD GENERATION PROCESS

Target cloud parameters include ambient pressure (altitude simulation), temperature, and liquid water content. Thus, the generation process must be so chosen that state F is characterized by these parameters, temperature being the most important. As previously mentioned, minimal influence of the chamber wall and water wall on the test cloud is achieved when the temperatures of the chamber wall, the water wall, and the test atmosphere are closely equal. Thus, the chamber and water walls must be cooled to the target temperature prior to pumpdown. Thereafter the pressure excursions must be precalculated to yield precisely the target parameters for state F. Thus, it is seen in figure 5 that the test atmosphere temperature at state F equals the chamber wall temperature TC.

Based on a thermodynamic analysis of the system behavior, a computer program was written to precalculate the requisite pressures and resultant temperatures of states B, C, and D. A typical program printout is presented in figure 6. The notation used is delineated in table I. The program input comprises the following: (1) The characteristics of the initial state, (2) the preselected characteristics of the final state, (3) the measured characteristics of the steam and ambient atmosphere, and (4) the preselected dynamics of the cloud formation process. This computer analysis, run immediately prior to beginning the cloud generation procedure each day, determines the proper path to get from the existing initial state to the desired final state by sequentially removing and adding constituent masses from and to the system. Thus, armed with the thermodynamic analysis of figure 6, the system shown in figure 4 is manipulated as follows. The test volume is pumped down to PCB and then sealed off while the annular volume is simultaneously pumped down to PAE. Following thermal equilibration, the dive valve is opened for TIMED seconds permitting measured chamber backfill from the atmosphere, while steam is simultaneously added according to the steamflow schedule generated in the dive calculation. At the end of the dive segment, the test atmosphere at PCD is permitted to stabilize convectively.

The blowdown segment is initiated by manually actuating a command signal to open the blowdown valve, and this is followed VALVE TIME seconds later by the command signal to initiate the blowdown valve's closing cycle. This large valve, weighing nearly 2000 kilograms (2 metric tons), is driven pneumatically. The time-dependent aperture functions for its opening and closing behaviors are factored into the computer program since the command CLOSE signal must be given 4.1 seconds prior to physical valve closure.

The cloud generation procedure is now operationally complete. The cloud is formed at PCF and TCF. The procedure may be augmented to interject steps to introduce atmospheric contaminants and/or selected condensation nuclei according to the needs of the experiment.

The dynamics of the cloud formation process are dictated by the mass flow rate of test atmosphere through the blowdown valve. Thus, the dynamics are dependent on the chamber to annulus differential pressure, the aperture of the blowdown valve VALVE TIME, and the final pressure desired. In this study, experimental blow rates up to 1 torr per second were attained at the 700-torr level. Higher blow rates can be achieved at lower pressure levels.

INSTRUMENTATION

Some properties of the test atmosphere were monitored continually: pressure, temperature, temperature distribution, humidity, cloud density, and convection currents. Signals from these sensors were read and recorded on magnetic tape 5 times per second by an on-line computer while at the same time being displayed for visual inspection on CRT's at the operators' consoles. In addition, samples of the aerosol were taken periodically on gelatin-coated slides to determine the droplet size distribution. The placement of the sensors within the test volume is shown in figures 7 to 9.

Pressure Measurement

Baratron gage heads were mounted in both the test and annular volumes and calibrated against a standard barometer placed adjacent to the gage heads. Deviations did not exceed 0.2 torr on successive days. The response time of the pressure transducer may be assessed from figure 10, which is a computer plot of recorded data on a 1-second time scale. The time slice selected spans the blowdown operation.

The computer time base is generated by a Hyperion clock accurate to within 1 millisecond. The blowdown valve's fractional aperture on this time base is also presented in figure 10, which shows that the valve started to open at 4981 seconds, was fully open from 4988.5 to 5036 seconds, and reseated closed at 5040 seconds. The steady-state pressure immediately prior to valve opening was 730±0.3 torr. The reading at 4983 seconds is significantly outside the noise envelope of the transducer; this indicates that the response time of the transducer to a pressure change is less than 2 seconds.

Temperature Measurements

Thermistors were used to measure the chamber wall and water wall temperatures, as well as the wet and dry bulb transducers for the computer-calculated humidity readout. The dry bulb temperature served also as the test gas temperature. The positions of these sensors are shown in figures 7 and 8. To obtain the water wall temperature, water dribbling from the bottom of one muslin panel was collected in a polystyrene trough canted off-horizontal so that the runoff cascaded over the water wall thermistor.

Temperature-sensitive solid-state diodes were used to determine the spatial temperature distribution in the test volume. As seen in figures 8 and 9, the six diodes were arranged in three sets of two each, yielding radial and vertical data on 6.1-meter centers.

The relative response of the two types of sensors is demonstrated in figure 10. Note that the temperature scale is 0.02 Centigrade degree per division. Considering first the test gas (dry bulb) thermistor, the steady-state measurement envelope of $20.67 \pm 0.01^{\circ}$ was exceeded within 4 seconds of valve opening; this indicated a response time of about 3 seconds to a temperature differential of only about 0.06°. The same performance is observed at valve closure, where the thermistor reaches equilibrium with the test gas within 4 seconds.

By comparison, the thermal response of the diode sensor is very slow. For example, at 5045 seconds,

$$\frac{\Delta T \text{ (diode)}}{\Delta T \text{ (thermistor)}} = 0.56$$

and 1 minute later has increased to only 0.78. Thus, for the time scale of events occurring in cloud microphysics, the response of the diode temperature sensor is too slow to give meaningful results.

Cloud Liquid Water Content

To monitor cloud stability, a simple absorption photometer was constructed to measure the radiation transmitted through a known path length of cloud. The radiation source was a 100-watt light bulb enclosed in a light-tight box from which radiation was permitted to escape through a 1.27-centimeter-diameter pipe 1 meter long. The interior of the pipe was blackened to minimize internal reflection. Thus, a slightly divergent pencil of radiation emerges from the light source.

An identical piece of hardware is positioned 21.3 meters distant so that the collimator tubes of the two elements are colinear. A photomultiplier tube in the latter measures the radiation transmitted through the intervening path. The orientation of this so-called cloud density meter (or nephelometer) is shown in figure 9. The detector is suspended from the light source by three fine wires attached to automatically self-alining mounting plates.

The calibration curve relating liquid water content to percent transmission is shown in figure 11. The transmitted intensity would be related to the cloud density by Beer's law were it not that water droplets are transparent. Thus, radiation losses probably result more from refraction effects than from absorption or scattering. This is presumed to be responsible for the deviation of the calibration curve from linearity at liquid water contents below 0.1 gram per cubic meter.

Between 0.1 and 1.0 gram per cubic meter Beer's law appears to be obeyed. Above 1.0 gram per cubic meter a shorter path length is needed for more precise measurements.

Over the percent transmission range from 100 to 10 percent the nephelometer is capable of measuring liquid water content with a precision of ±0.005 gram per cubic meter. Its response time is, in principle, the rise time of the photomultiplier - fractional microsecond - but in practice it is limited by the computer's data acquisition rate of 0.2 second between readings. Were the need to arise, meaningful nephelometer measurements could be taken on existing magnetic tape recorders as fast as 10 000 readings per second.

Convection Current Measurement

A Thermo-Systems Incorporated Model 1610 velocity transducer was used to continuously monitor the magnitude of the convection currents within the test volume. This instrument had just been factory calibrated and was operated with a full-scale sensitivity to dry air flow of 1 meter per second. Basically, the instrument is a hot wire anemometer. The probe tip is maintained at a constant temperature by a bridge circuit which varies the heating current required to offset the heat loss from the tip. Its response time to a tenfold step change in air flow is 0.8 second. Figure 12 presents two computer-drawn samples of measured convection currents, one taken midway through the convective stabilization segment DE and the other midway through the cloud study segment FG.

The turbulence observed was smaller than anticipated. The terrestrial atmosphere is considered quiescent when convection currents are of the order of 20 centimeters per second. The largest convection currents observed in the chamber study were 15 centimeters per second during the dive process. By terrestrial standards, therefore, the entire cloud generation process was accomplished under so-called quiescent conditions, with the generated cloud being available for study under turbulence conditions ten times smaller than available terrestrially.

Smaller turbulence values were observed after the chamber had been sealed and dormant for 18 hours. Turbulence peaks recorded over a 5-minute observation interval did not exceed 0.05 centimeter per second, which probably corresponds to the zero level noise range of the instrument.

CLOUD STABILITY

As was stated in the THEORY section, two constraints were imposed on the cloud generation process: (1) cloud formation by adiabatic expansion, and (2) minimal net flow of moisture or heat between the cloud and the chamber wall. The second of these constraints was not achieved. The temperature of the water wall was continually about 3 Centigrade degrees higher than the chamber metal temperature. What was overlooked was the heat added to the water by the pumps needed to drive the water to the top of the 25-meter-high water wall. Thus, the water wall acted as a heat source for the generated cloud during the cloud study segment. This heat source was sufficient to reduce the cloud's liquid water content at the rate of 3.9 percent of the amount present per minute. Consequently, the goal of achieving stable, long-lived clouds was not realized.

FEASIBILITY OF CONTROLLED CLOUD GENERATION

Five clouds were generated on consecutive days under a variety of preselected conditions of liquid water content and blowrate. Maximum values selected were 1.5 gram per cubic meter liquid water content and 1.0 torr per second blowrate. Target state temperature and pressure were not varied. During this sequence, the temperature of the terrestrial atmosphere varied between 5.6° and 12.6° C; the pressure varied between 746.3 and 761.7 torr; and the relative humidity varied between 43 and 81 percent.

The thermodynamic analysis used to find the experimental path required to go from initial state to target state correctly predicted the final state to within 0.2 torr, 0.9° C, and 0.15 gram per cubic meter. Better agreement between prediction and experiment should result after the water wall temperature discrepancy is corrected.

Unquestionably, controlled generation of large volumes of clouds with preselected properties is feasible. Figure 13 presents before and after views taken from a motion picture sequence of the formation of a 1.5-gram-per-cubic-meter cloud. The illuminated targets are 7.6, 15.2, and 22.9 meters (25, 50, and 75 ft), respectively, from the camera lens.

OPERATION AT OFF-AMBIENT TEMPERATURES

One of the unique features of the Plum Brook space chamber is that it was designed to operate at temperatures between 50° and -190° C. Thus, the temperature range of meteorological interest is well within its capabilities. Refrigeration capacity totaling 1.6×10^{6} joules per second (450 tons) is available to provide temperatures down to 2° C. For lower temperatures, a liquid-nitrogen-augmented gas chiller system is available.

Thus, the Space Power Facility possesses both the temperature and pressure capabilities to do ice cloud studies. For such studies, all chamber surfaces must be coated so that ice forms nowhere on any surface.

CONCLUDING REMARKS

This feasibility study is the first part of a two-part program proposed by a meteorological research team at Pennsylvania State University sponsored by NSF and NASA. The second part, now in preparation, will study the effect on cloud properties of trace quantities of various contaminant gases. The production of five clouds was sufficient to proof-test the generation procedure and evaluate the capability of the instrumentation.

Installation of a heat exchanger in the water wall system will correct the temperature differential between the chamber and the water wall, thereby providing clouds with stable properties for considerably longer dwell times.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 7, 1975,
491-02.

TABLE I. - NOTATION IDENTIFICATION

	Identification
BLOWRATE	(PCE-PCF)/TIMEB, torr/sec
CLWC	Cloud liquid water content, g/m^3
PAE	Annulus pressure, state E (typical), torr
PCF	Chamber pressure, state F (typical), torr
PE	External atmosphere pressure, torr
RH	Fractional relative humidity, external atmosphere
STEAMFLOW	Steam mass flowrate at time in dive segment, g/sec
TAC	Annulus temperature, state C (typical), K
TC	Chamber wall temperature, K
TCD	Chamber temperature, state D (typical), K
TE	External atmosphere temperature, K
TIMEB	Elapsed time blowdown valve fully plus fractionally open, sec
TIMED	Time in dive segment, sec
TS	Steam temperature, downstream of nozzle, K
TW	Water wall temperature, K
VALVE TIME	Elapsed time from command signal to open blowdown valve to command signal to close, sec

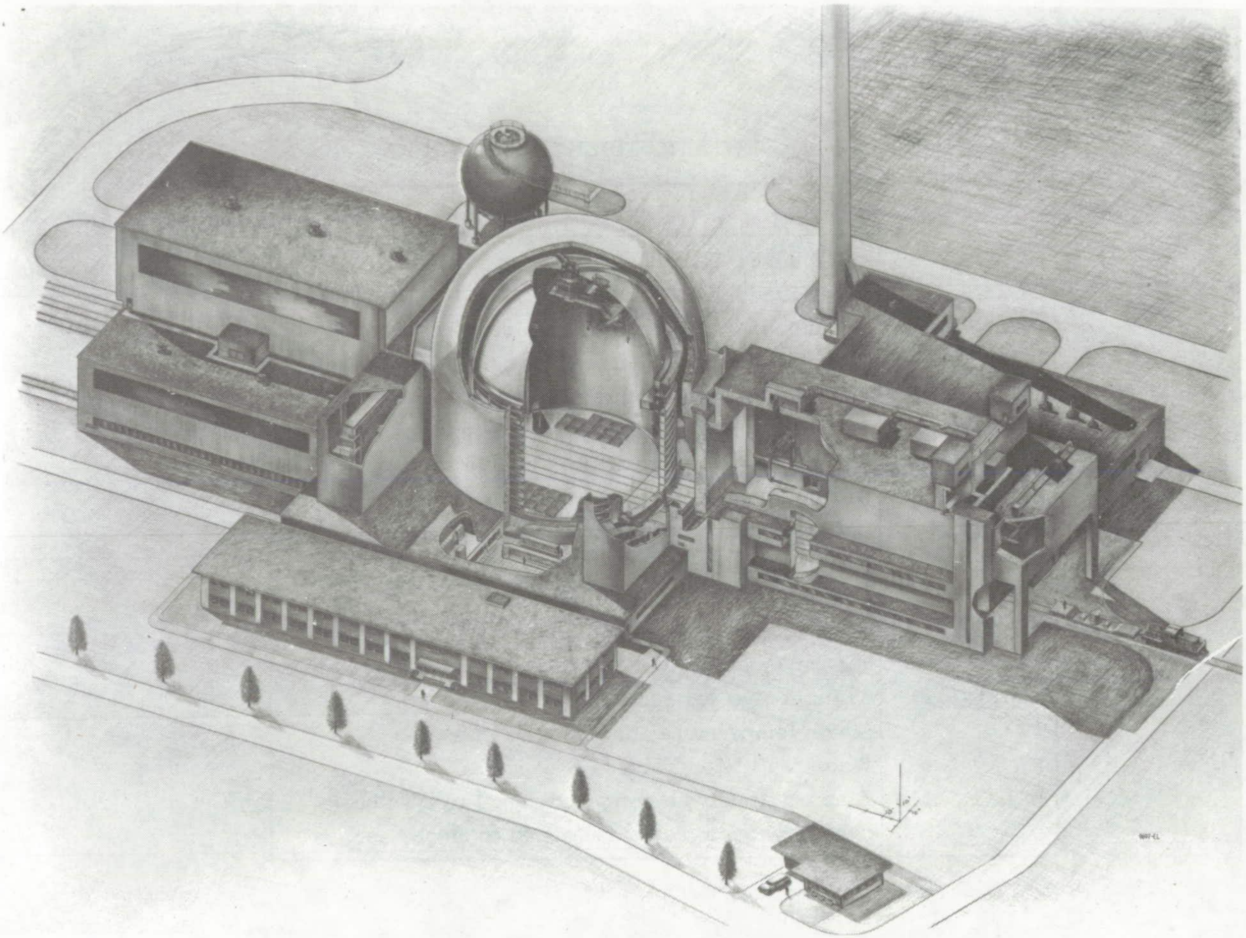


Figure 1. - Cutaway view of space power chamber.

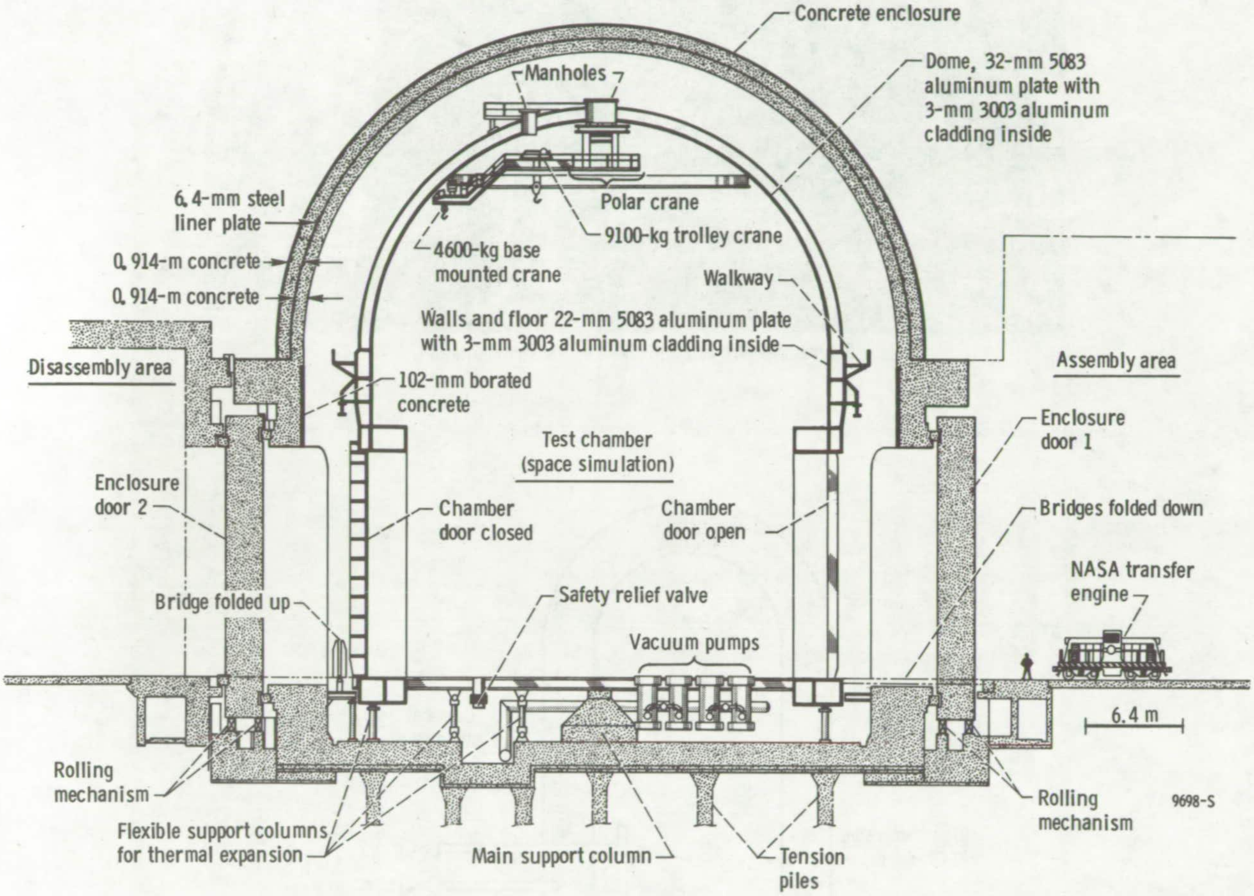


Figure 2. - Cross-sectional view of test chamber.

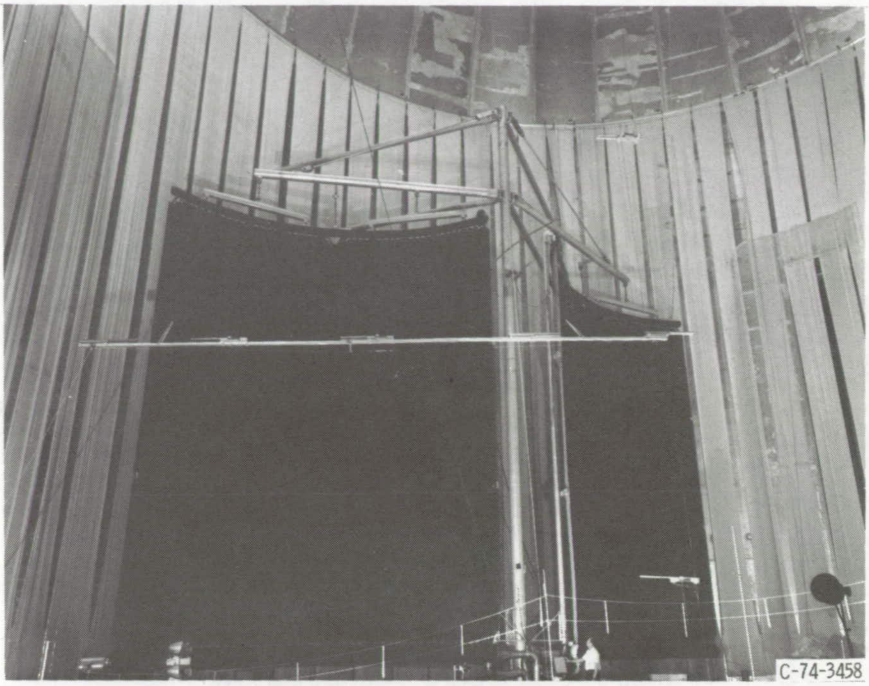


Figure 3. - Wet wall and cloud test instrumentation.

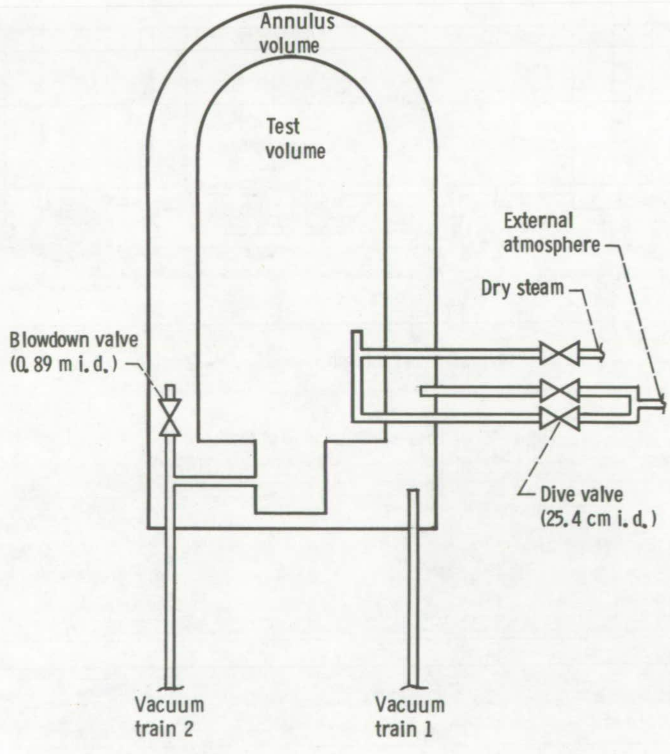


Figure 4. - Configuration of pressure-related facility components for cloud generation.

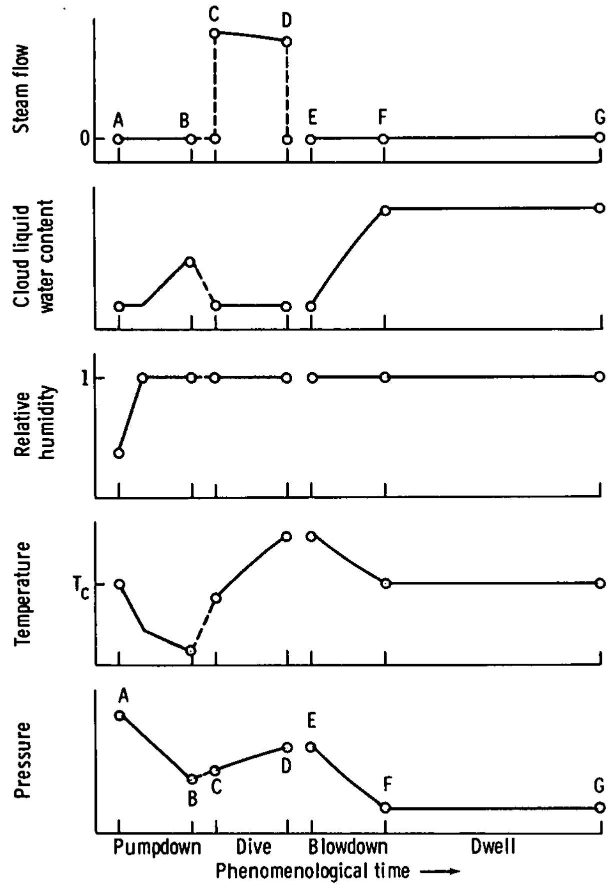


Figure 5. - Historigram of pertinent process parameters.

```
                CLOUD GENERATION PRECALC PROGRAM  <CG1.PA>

INPUT DATA:     PCF=      700.0000 TORR          CLWC=       1.0000 GRAMS/CU.METER
                TCW=      293.7200 KELVIN   BLOWRATE=        .5500 TORR/SECOND
                PCA=      749.5000                TCA=     293.7200
                 PE=      754.2000                 RH=        .8000
                 TE=      285.3000                 TS=     370.5000

CLOUD LIQUID WATER CONTENT CALCULATION
                PCF=      700.0000                PCE=     732.2183
                TCF=      293.7200                TCE=     295.2991

BLOWRATE-DEPENDENT BLOWDOWN CALCULATION

    PCF ITER        PAF ITER        PAE ITER         TIME          TEST1
  7.0012E+02      6.9975E+02      6.6778E+02      5.8583E+01      2.2599E-03
  7.0001E+02      6.9962E+02      6.6756E+02      5.8583E+01     -9.2814E-04
  7.0006E+02      6.9967E+02      6.6765E+02      5.8583E+01      3.6487E-04
  7.0004E+02      6.9965E+02      6.6761E+02      5.8583E+01     -1.5279E-04
  7.0005E+02      6.9966E+02      6.6763E+02      5.8583E+01      6.3852E-05
  7.0005E+02      6.9966E+02      6.6763E+02      5.8583E+01      6.3852E-05
                PAF=      699.6625                PAE=     667.6273
                TAF=      295.2969                TAE=     293.7200
           BLOWRATE=         .5500         VALVE TIME=      45.5787 SECONDS

DIVE CALCULATION
          TIME              PCHAM            TCHAM            STEAMFLOW
          <SEC>             <TORR>           <KELVIN>          <G/SEC>
       228.17203         732.21826        295.29907
       207.40021         731.17102        295.16895        152.63870
       187.06732         730.12537        295.03882        154.45856
       167.14383         729.08069        294.90869        156.21024
       147.60376         728.03711        294.77856        160.33917
       126.95749         726.91492        294.63843        163.15399
       108.13646         725.87366        294.50830        163.46631
        86.81339         724.67419        294.35815        167.43954
        67.26273         723.55566        294.21802        166.20581
        48.04510         722.43848        294.07788        167.50153
        27.79398         721.24304        293.92773        168.59503
         7.87494         720.04932        293.77759        169.73074
         0.00000         719.57227        293.71753        172.74084
                PCD=     732.2183                 PCC=     719.5723
                TCD=     295.2991                 TCC=     293.7175

PUMPDOWN CALCULATION
                PCB=     715.4950                 PCA=     749.5000
                TCB=     292.0533                 TCA=     293.7200

CALCULATION FINISHED
PROGRAM TERMINATED
```

Figure 6. - Thermodynamic route from initial to target state.

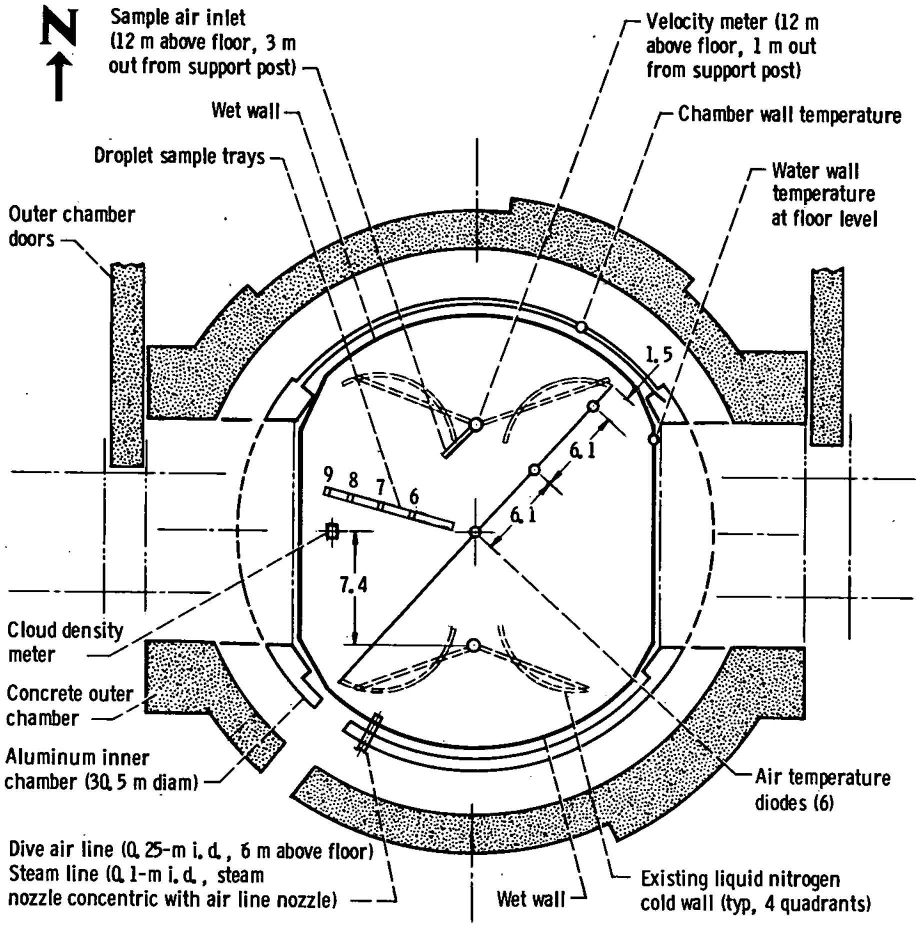


Figure 7. - Plan view of instrument placement in space power facility. All dimensions are in meters.

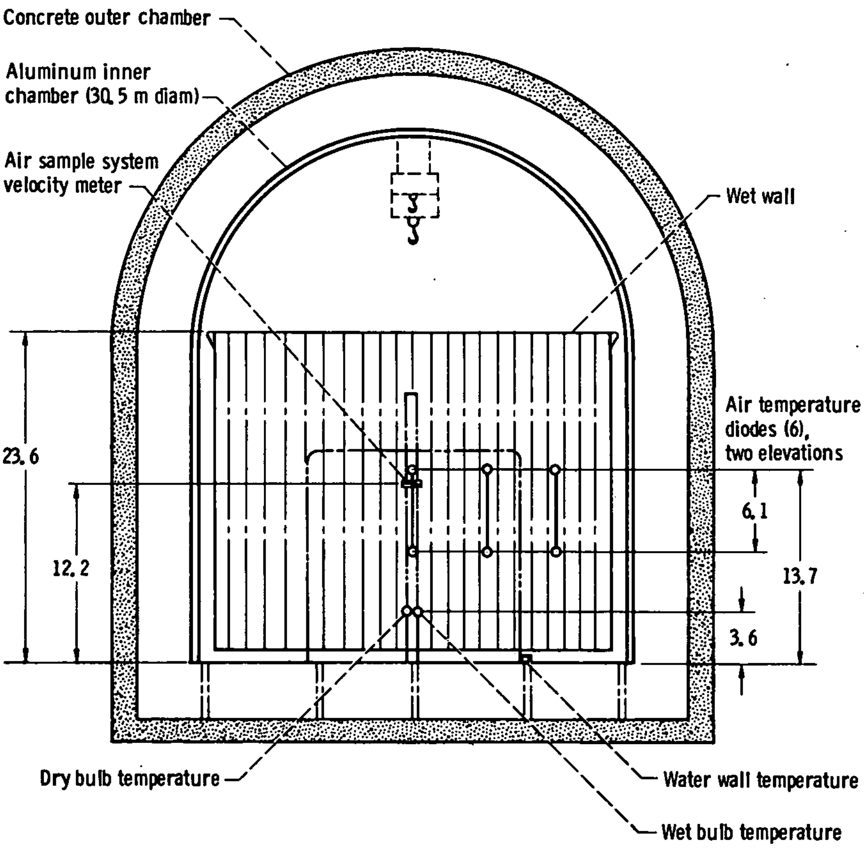


Figure 8. - Elevation view showing placement of part of instrumentation in space power facility. All dimensions are in meters.

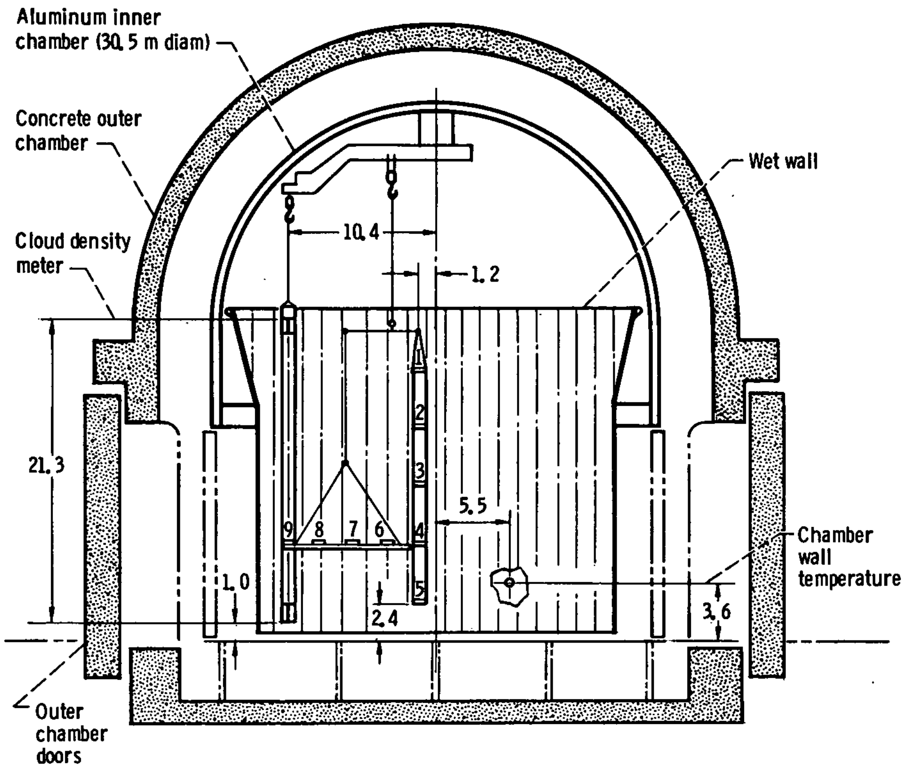


Figure 9. - Elevation view showing placement of remainder of instrumentation in space power facility. All dimensions are in meters.

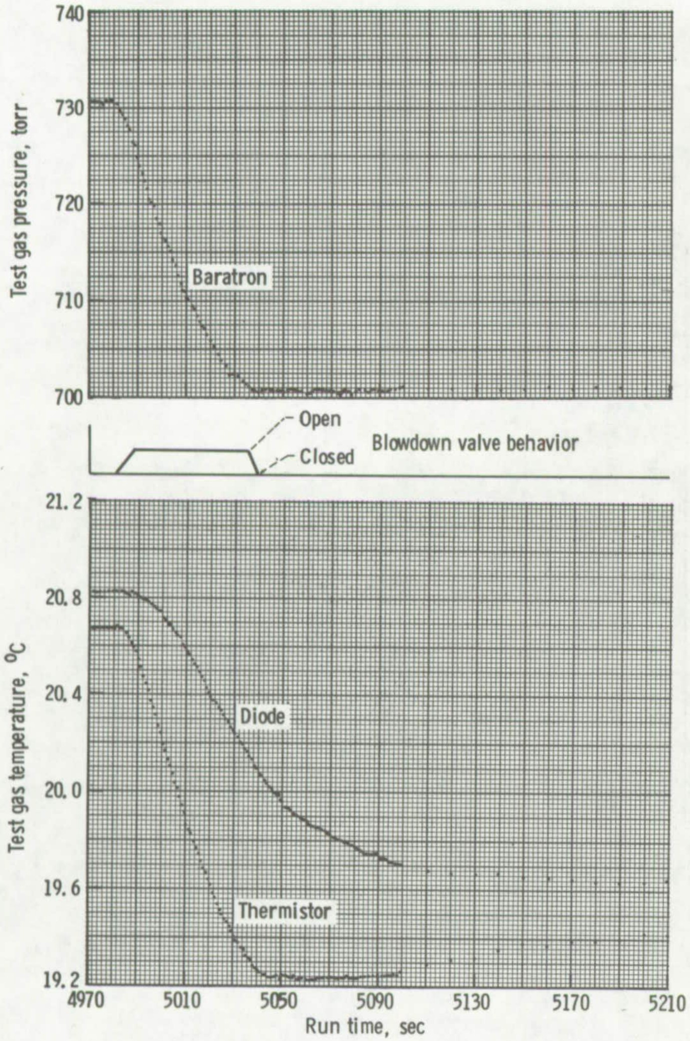


Figure 10. - Instrument performance evaluation.

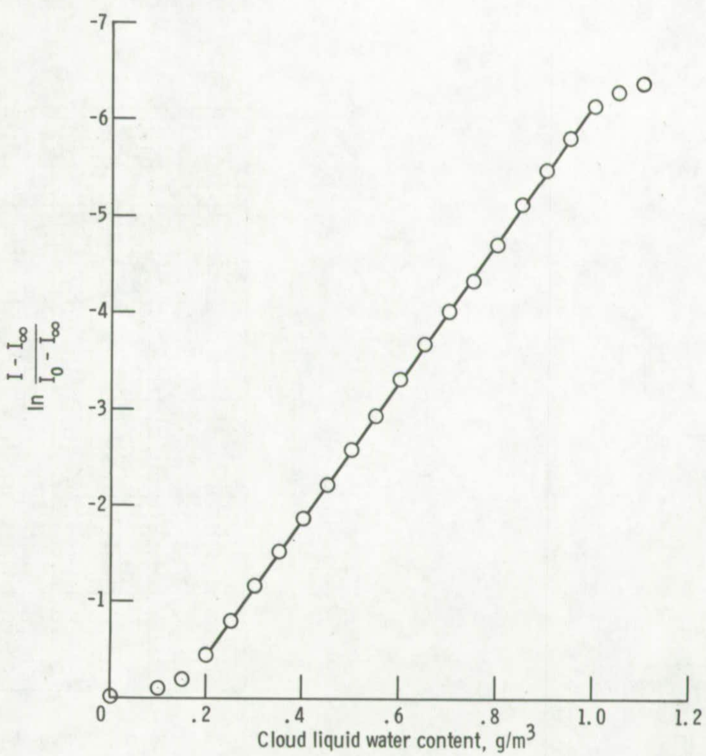


Figure 11. - Nephelometer calibration for 21-meter path length.

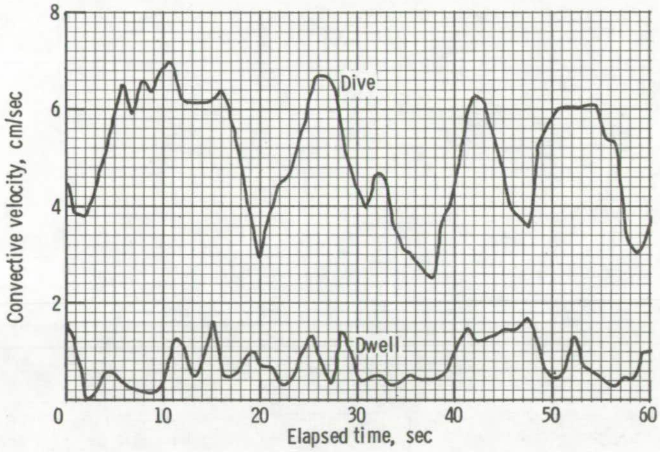
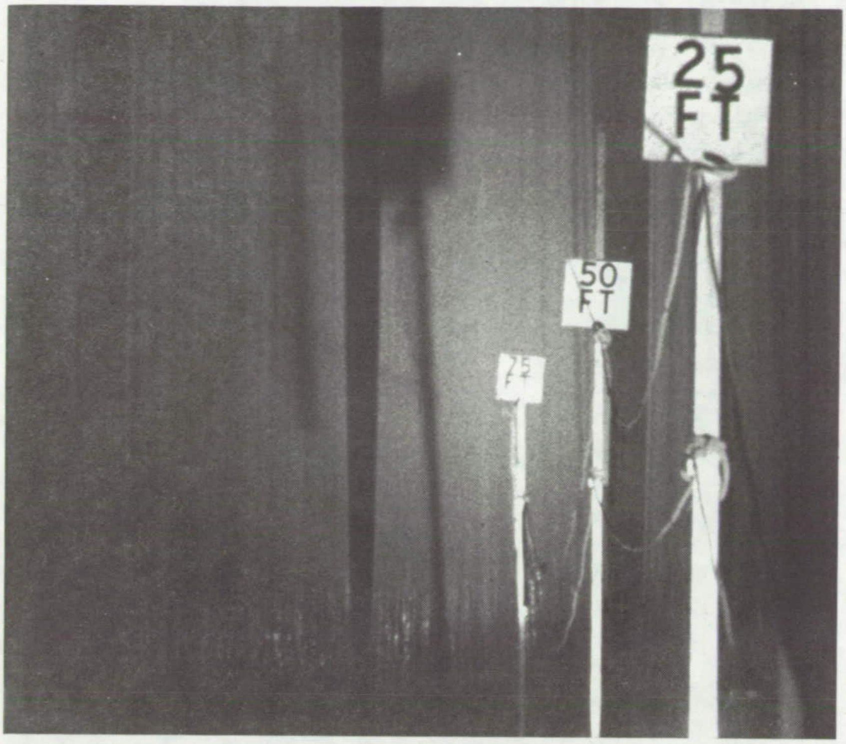
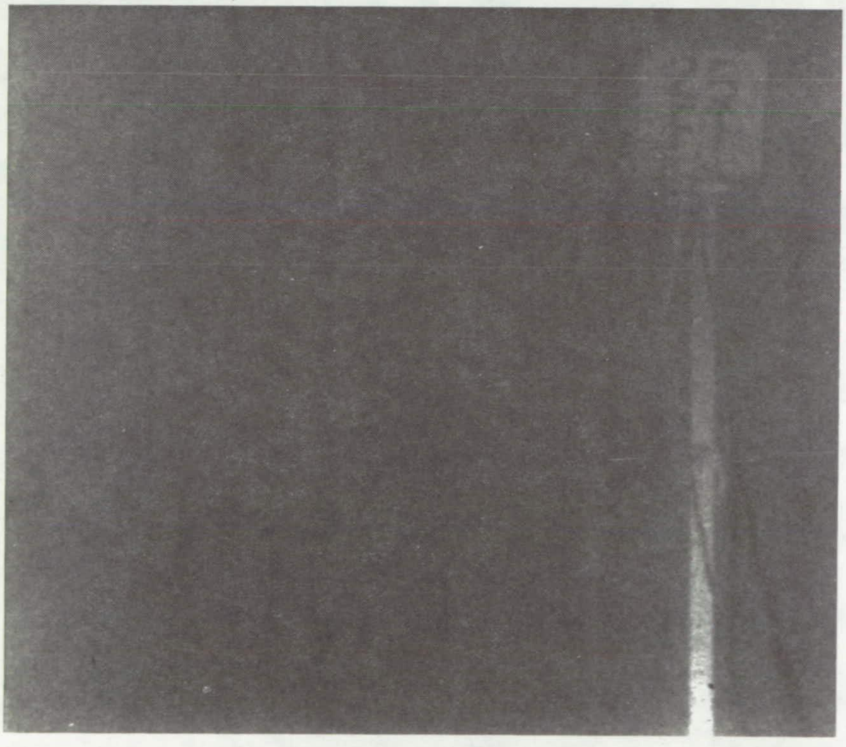


Figure 12. - Typical turbulence levels measured during dive and dwell segments of cloud formation process.



(a) Before cloud formation.



(b) After cloud formation.

Figure 13. - Frames from cineograph of cloud formation process.