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ELEVENTH SEMI-ANNUAL REPORT

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on

Oscillatory Combustion in Rockets

Prepared by	Supervisors
D. Juedes	Prof. G. L. Borman
C.W. Savery	Prof. P. S. Myers
R. Sowls	Prof. O. A. Uyehara

Department of Mechanical Engineering
University of Wisconsin
Madison, Wisconsin 53706

Introduction

This report gives a summary of progress during the reporting period on the investigation of droplet vaporization in the region of the critical point. The investigation consists of two projects. In the first project droplets are suspended on a thermocouple bead and exposed to a flowing stream of heated air at elevated pressures. In the second project droplets are caused to fall through a stagnant high temperature, high pressure gas environment.

During the reporting period a contractors report[1] summarizing the work on the theory of critical region vaporization was issued. The part of this work dealing with steady state vaporization was also published as a journal article.[2] A summary of the work on suspended Freon and heptane droplets was issued as a contractors report[3] and will also be presented as a paper.[4] The previously completed work on unsteady heat transfer also appeared as a journal article[5] during the reporting period.

With the conclusion of the suspended Freon droplet data taking at the start of the reporting period, a program was initiated to obtain vaporization histories for CO_2 and ethane in air. After the graduation of C. W. Savery in August the work has been continued by D. L. Juedes.

The falling drop experimental apparatus has been successfully operated and has produced data on CO_2 drops falling in helium. Apparatus for data reduction was fabricated and work on data analysis was begun.

Suspended Drop Experiment

A Contractor's Topical Report[3] was published August 1, 1969. The abstract is quoted in the following paragraph.

> Measured histories of vaporizing n-heptane and Freon-13 droplets suspended in a heated air stream are reported. The range of air conditions was $1.5 < P < 100$ atm and $100 < T_\infty < 300°$ F. Comparisons are made with film theory calculations corrected for the effects of total pressure on thermodynamic properties. Agreement was satisfactory for liquid steady-state temperatures and mass transfer rates except for Freon-13 where significant differences were found at air pressures above 1.25 P_c. Freon-13 droplet histories were found to be completely unsteady for pressures above 60 atm. The absence of steady-state conditions was found to correlate with the critical mixing point for the Freon-13-air system.

A paper summarizing the suspended drop investigation[4] is to be presented at the AIAA Aerospace Sciences Meeting, January 19-21, 1970 in New York.

In addition to the work reported in the topical report, ethane and carbon dioxide drop vaporization data were obtained at reduced pressures of 1.22 and 1.0. The range of conditions for the ethane data was:

ethane drops in air
pressure: 58.9 atm where P_c = 48.3 atm
air temperature range: 120° - 225° F
where T_c = 91° F

The carbon dioxide data covered the range:

carbon dioxide drops in air
pressure: 72.9 atm where P_c = 72.9 atm
air temperature range: 110° - 240° F
where T_c = 87.5° F

This brief program of ethane and carbon dioxide data acquisition was an attempt to give some breadth to the suspended drop data by comparing data for two additional compounds with the extensive Freon-13 results. Ethane is of interest because it is a paraffin fuel with a critical temperature almost identical to Freon-13 and because it has a critical pressure about 20% higher than Freon-13. Carbon dioxide has a critical temperature about the same as Freon-13 and ethane, but its critical pressure is about twice as great. A comparison of the properties of the two compounds tested with those of n-heptane and Freon-13 is given in Table I.

TABLE I
Properties of Test Liquids

	Freon-13	n-heptane	ethane	carbon dioxide
Family	fluorocarbon	paraffin	paraffin	oxide
Formula	$CClF_3$	C_7H_{16}	C_2H_6	CO_2
Mol. Wt.	105	100	30	44
Crit. Temp. (K)	302	540	305	304
Crit. Press. (atm)	38.2	27	48.2	72.9

An important part of the steady-state wet bulb temperature calculations is the determination of the droplet - film interface mole fraction. Since vapor-liquid equilibrium data for ethane-nitrogen are available [6], equilibrium constant method results can be compared with the data. This comparison is shown on Fig. 1.

The agreement between calculated and measured values is within 10%. A comparison between carbon dioxide-nitrogen equilibrium composition was previously given in Ref. 3. The agreement was very good at the critical pressure and 32° F.

A comparison between wet bulb temperatures determined by steady-state calculations and the experimentally determined wet bulb (plateau) temperatures is shown on Fig. 2 for the ethane drop vaporizing in air at a reduced pressure of 1.22. The agreement between the low pressure theory and the data is very good. The high pressure theory results vary from 10° F low at 100° F air temperature to 15° F low at an air temperature of 225° F.

Carbon dioxide measured wet bulb temperature data are compared with calculations on Fig. 3. The ambient pressure is 72.9 atm, the critical pressure of carbon dioxide. The wet bulb temperatures calculated by high pressure theory are about 10 - 15° F below the measured values. The temperatures calculated with low pressure assumptions give better agreement.

These recent results with ethane and carbon dioxide are encouraging when considered in the context of the more comprehensive program of Freon-13 vaporization reported in Ref. 3. On the basis of Freon-13 data only it was concluded that under conditions of moderate ambient gas temperature ($1 < T_\infty/T_c < 1.5$) and high pressure ($0.75 < P/P_c < 1.75$) predictions by film theory corrected and uncorrected for high pressure properties were consistently 10 - 15° F below the measured plateau (wet bulb) temperatures. Furthermore, it was concluded that low pressure theory gave slightly better temperature predictions

at reduced pressures below 1.25. These conclusions made on the basis of Freon-13 drops vaporizing in air are supported by the recently obtained ethane and carbon dioxide data reported for the first time here.

Because the amount of carbon dioxide and ethane data reported is small the program has been continued in order to collect additional carbon dioxide and ethane data.

Starting in September, attempts were made to gather additional data for carbon dioxide vaporizing in air at reduced pressures of 0.75 and 1.0. It was difficult to obtain good data because of a frequent "feeding" problem. As a suspended carbon dioxide drop was vaporizing in the heated air stream, carbon dioxide vapor would "feed" out of the probe tip and onto the base of the vaporizing droplet. Initially it was thought that some fluid residing in the small uncooled portion of the probe tip was being heated and vaporized by the air stream thus causing it to feed out of the probe tip. After several more attempts to collect data, the feeding phenomenon occurred even more frequently and for longer periods of time until almost continuous feeding was observed. At this point, it was deduced that the valve which is activated to allow carbon dioxide liquid to flow from the condenser into the probe was faulty. The valve was replaced and hopefully the feeding problem has been eliminated. No data has been collected since the valve was replaced.

Some good data (during which motion pictures showed no evidence of feeding) was collected for carbon dioxide vaporizing in air at a reduced pressure of 0.75 (54.7 atm). A comparison

between plateau temperatures determined by steady-state calculations and experimentally determined temperatures are shown in Fig. 4. The plateau temperatures calculated using high pressure theory are 25 - 30° F below the measured values, while the plateau temperatures calculated using low pressure assumptions are 10 - 15° F below the measured values. Here again the data supports the Freon-13 based conclusion that the low pressure theory gives better plateau temperature predictions than the high pressure theory at reduced pressures below 1.25. However, the agreement between the data and the theory is not as good as that for the Freon-13 data and the carbon dioxide data at a reduced pressure of 1.0.

In Fig. 5, experimental temperature, mass, and size histories are given for a carbon dioxide drop vaporizing in air at $.75P_c$ and 152° F. For the first 0.4 second the drop is in the "heating up" or unsteady portion of its history. After 0.4 second the drop experiences steady-state vaporization at the wet-bulb or plateau temperature.

During the next reporting period, data will be collected for carbon dioxide vaporizing in air at reduced pressures of 0.75-1.25 and air temperatures from 100-300° F. Data will also be collected for ethane vaporizing in air at reduced pressures of 0.75-2.0 and air temperatures of 100-300° F.

At the present time the thermocouple which supports the drop and measures the plateau temperature has a teflon ring around the bead which helps support the drop. Initially data will be collected with the ring on the thermocouple bead at the

conditions mentioned above. Then the teflon ring will be removed and more data will be taken, again at the same conditions. Comparison of data taken with and without the teflon ring should determine what effect if any the ring has on the data.

Falling Drop Experiments

Since the last reporting period several improvements have been made in the apparatus, some photographic histories have been taken of CO_2 droplets evaporating into helium, the laboratory has been moved from T-25 into the new Engineering Research Building, and equipment has been developed to assist in obtaining numerical drop volume and motion histories from the photographic histories. What follows describes this work in more detail.

Early in the reporting period focusing jigs for the photography optics were made so that the pressurized apparatus could be disassembled and reassembled without going through a difficult and time consuming alignment and focusing procedure. The oven assembly was also modified so that disassembly and reassembly are simplified and so that its performance and reliability are improved. Although there is still room for improvement, the present oven assembly has been operated satisfactorily up to 1500° F.

The droplet forming mechanism is enclosed in a pressure vessel and consists of a reservoir connected to a blunted hypodermic needle through a very small solenoid valve. A droplet

is formed by allowing liquid to feed by gravity from the reservoir onto the needle tip until the droplet is heavy enough to break the surface tension force between the liquid and the needle tip. Hypodermic needles can be obtained from medical supply houses in sizes as small as 30 gauge and on special order as small as 37 gauge. Since 30 gauge needles form CO_2 droplets that are somewhat large for the purposes of this experiment, a variety of smaller sizes were obtained. Many of them came from the factory with their passages blocked. Even with the passages open fluid friction in the extermely fine bores made droplet forming difficult and unreliable. This problem was solved by modifying 30 gauge needles as shown in Fig. 6. The extension wire is crimped into the end of the needle and the opening in the side of the needle was made by carefully abrading it with a fine Arkansas stone. The size of the droplet is controlled by the fluid properties and by the difference in the circumferences of the hypodermic tubing and the extension wire. When a droplet is formed liquid accumulates at the junction of the tubing and the extension wire. The surface tension force of the extension wire downward on the liquid assists gravity in overcoming the surface tension force of the hypodermic tubing upward on the liquid. When enough liquid accumulates the droplet releases from the tubing and slides off the end of the extension wire. The extension wire must 1) be long enough to reach below the droplet as it releases from the tubing, and 2) be of a diameter smaller than required to support the droplet.

Use of an extension wire has made it possible to produce initial diameters of 0.6 to 0.7 mm, whereas the blunt needle gave droplets of 0.9 to 1.0 mm diameter.

Nitrogen was used as the gas in the initial attempts to photograph vaporizing CO_2 droplets. The droplets proved to be so unstable under these conditions that they would not fall straight enough to stay in the field of view of the camera. In order to overcome this difficulty without rebuilding the apparatus helium was tried as the gas. Seventy-five photographic histories of CO_2 droplets falling through helium have been taken. Gas phase pressures ranging from 600 psig to 1500 psig and temperatures ranging from 60° F to 1500° F were used. Both shadow and Schlerin photographs were taken at each condition. The framing rate was 400 per second, the magnification was 1:1, and the film was TRI X 120. A sample print enlarged 2X is shown in Fig. 7. At this point the laboratory was moved into the new Engineering Research Building. Since that time the effort has been on obtaining numerical data from the photographs.

In order to make droplet measurements with reasonable accuracy and effort, a large value of linear magnification and a means of positioning the film in the projector were required. Our projector was modified by fitting a 58 mm focal length lens in place of the original 308 mm focal length lens and making necessary modifications to the illumination system. In addition, a film carrier was constructed which permits scanning of the width as well as the length of the film to be controlled from the measuring station. The 35 foot length of our present labo-

ratory room permits linear magnifications up to 160 with this projector. Using this projector some of our data films were examined to determine droplet size histories.

The droplet histories were examined by projecting an image of each droplet on a piece of paper and tracing the apparent outline. Many of the droplets exhibit approximately elliptical profiles and appear to have an approximately vertical axis of symmetry. This suggests that reasonable values for the droplet volumes might be obtained by considering them to be ellipsoids of revolution with the horizontal axis being the major axis and the vertical axis being the minor axis and the axis of revolution. Figs. 8 and 9 give apparent volume vs. time data points calculated on this basis for several droplets. Some of the droplets data points fall in patterns that strongly suggest a rather large component of almost periodic variation. The amplitude of this suggested periodic component is usually larger than even generous estimates of the uncertainties of the individual data points. An effort is now being made to interpret the periodic component and to obtain information from the photographic histories with which to calculate a more reasonable volume history. An effort is also being made to reduce the uncertainty of the individual measurements.

Due to the difficult optical situation of the experiment, the indivudual droplet images on the film have edges of variable fuzziness. When tracing droplet outlines, as described in the preceding paragraph, this fuzziness leads to a fairly large uncertainty in the calculated volumes. It was felt that some

of this uncertainty could be removed if an elliptical outline were matched to the projected image of the droplet rather than to a tracing of the image that was made point by point. A device has just been finished which casts elliptical shadows on a droplet image allowing the entire outline to be fitted at once rather than traced a point at a time. Its operation is based on the fact that a projection of a circle on a plane not parallel to the plane of the circle is an ellipse.

The device consists of a transparent disk upon which equally spaced opaque concentric circles are drawn and which is held a short distance in front of the projection screen by a suitable positioner. The disk may be rotated about an axis in its own plane which passes through the center of its circles and which is constrained to lie in a plane parallel to the projection screen. This rotation permits the circles to cast shadows of easily varied eccentricity on the projection screen. The disk can also be rotated about an axis through its center and normal to the projection screen. This permits lining up the major axis of the elliptical shadow with the major axis of the droplet image. Horizontal and vertical motions of the center of the disk in a plane parallel to the projection screen are also possible. This permits centering the disks shadow over the droplet image. The two translations and two rotations permitted by the positioner were all made independent in order to simplify its use. The first test of this instrument was encouraging but a definite statement of its usefulness in reducing droplet volume uncertainty can not yet be made.

The immediate future will be devoted to reducing the available photographic data to numerical droplet size and position histories. This will require further development of technique as well as the actual work of making the measurements. When the results of this work are available, they will be used to guide the selection of conditions for taking additional CO_2-helium data.

In addition to more photographic CO_2-helium histories, CO_2- nitrogen, hydrocarbon-helium and hydrocarbon-nitrogen histories are desirable. It is felt that materials with critical temperatures between 280° K and 450° K and critical pressures up to about 75 atmospheres can be studied in the apparatus. Butane, ethane, pentane, propane and propylene are possibilities.

It is possible that some hydrocarbon-helium data could be obtained without modification to the apparatus, and this will be tried. CO_2-nitrogen data as well as hydrocarbon-nitrogen data will require lowering the drop forming mechanism as much as possible. This is necessary so that the droplets do not reach speeds which make them so unstable that they leave the field of view of the camera. Some thought has been devoted to how this modification should be made, but no details have been decided as yet. It is thought that the modification should be made, however, as it can make the apparatus much more flexible. No other modifications to the pressurized apparatus are felt to be necessary at this time.

When the required information has been obtained from the photographic histories, it will be compared with existing droplet vaporization calculation techniques. Also, what is observed will be recorded in as logical and complete a manner as can be devised so that it may be incorporated into a theoretical model.

References

1. J. A. Manrique, "Theory of Droplet Vaporization in the Region of the Thermodynamic Critical Point," NASA CR-72558, June 2, 1969.

2. J. A. Manrique, G. L. Borman, "Calculations of Steady-State Droplet Vaporization at High Ambient Pressures," Int. J. Heat Mass Transfer, Vol. 12, pp. 1081-1095, (1969).

3. C. W. Savery, "Experimental Studies of the Vaporization of Droplets in Heated Air of High Pressures," NASA CR-72574, August 1, 1969.

4. C. W. Savery, G. L. Borman, "Experiments on Droplet Vaporization at Supercritical Pressures," AIAA 8th Aerospace Sciences Meeting, N.Y.C., January 19-21, 1970.

5. R. W. Goluba, G. L. Borman, "The Effect of Periodic Shock-fronted Pressure Waves on Instantaneous Heat Flux Rates," Int. J. Heat Mass Transfer, Vol. 12, pp. 1281-1293, (1969).

6. R. T. Ellington, et al., "Vapor-Liquid Phase Equilibrium in the Binary Systems of Methane, Ethane and Nitrogen," Proc. of Sym. on Thermophysical Properties, February 23-26, 1959, Purdue Univ., ASME, pp. 180-194.

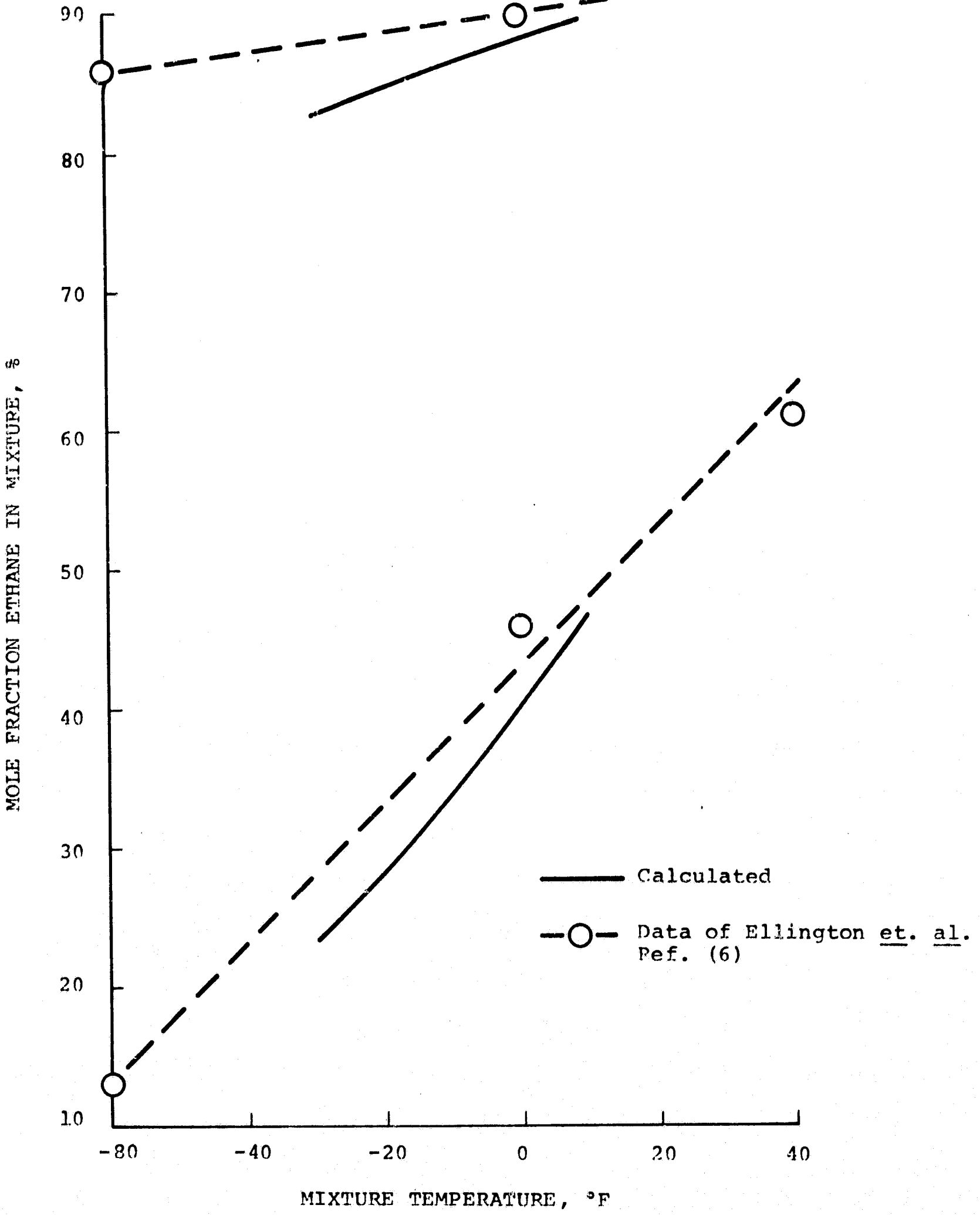


Fig. 1 Equilibrium Composition for Ethane-Nitrogen Mixture at 710 psia (48.3 atm, $P_c = 1$).

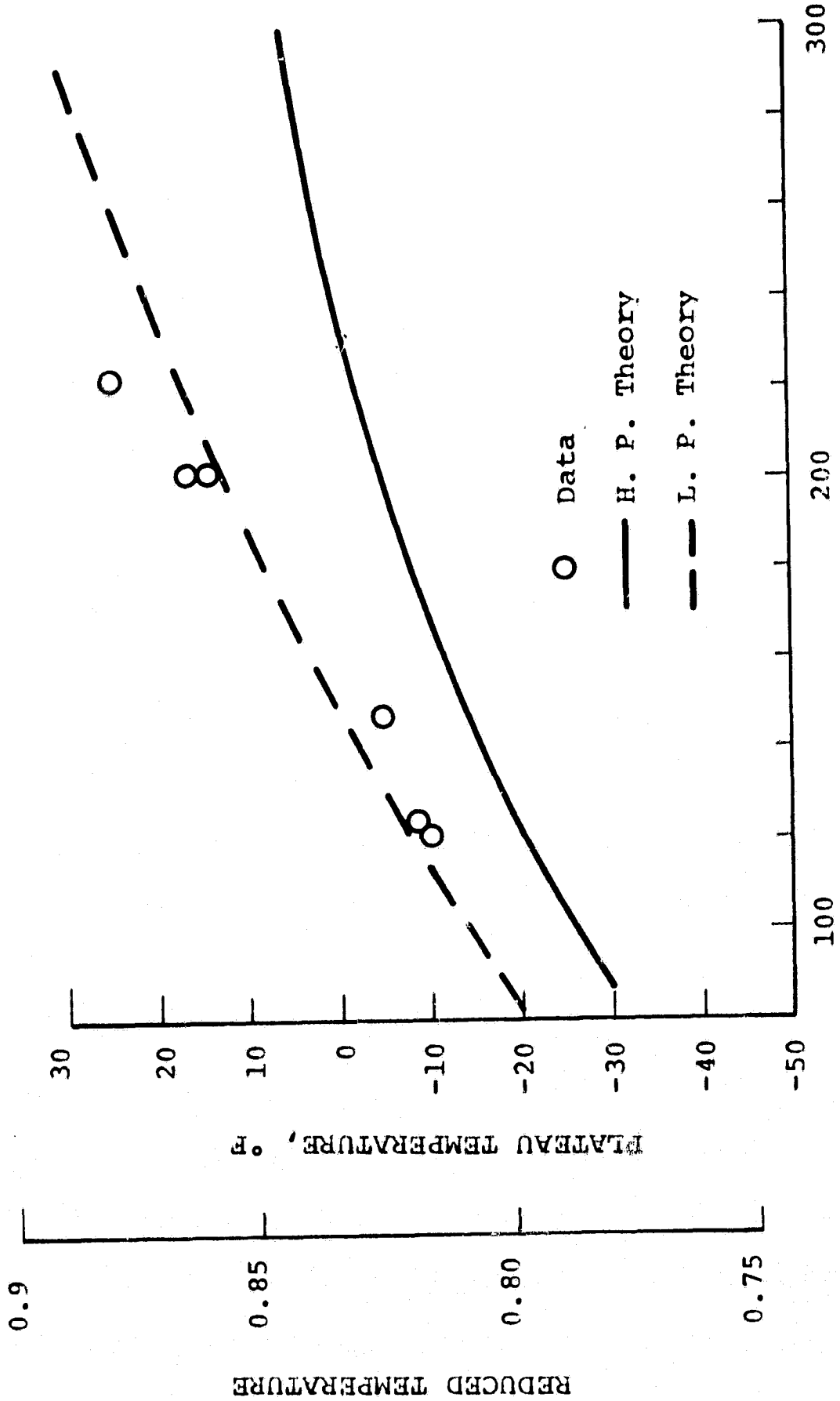


Fig. 2 Wet Bulb vs. Air Temperature for Ethane Drops Vaporizing in Air at 1.22 P_c.

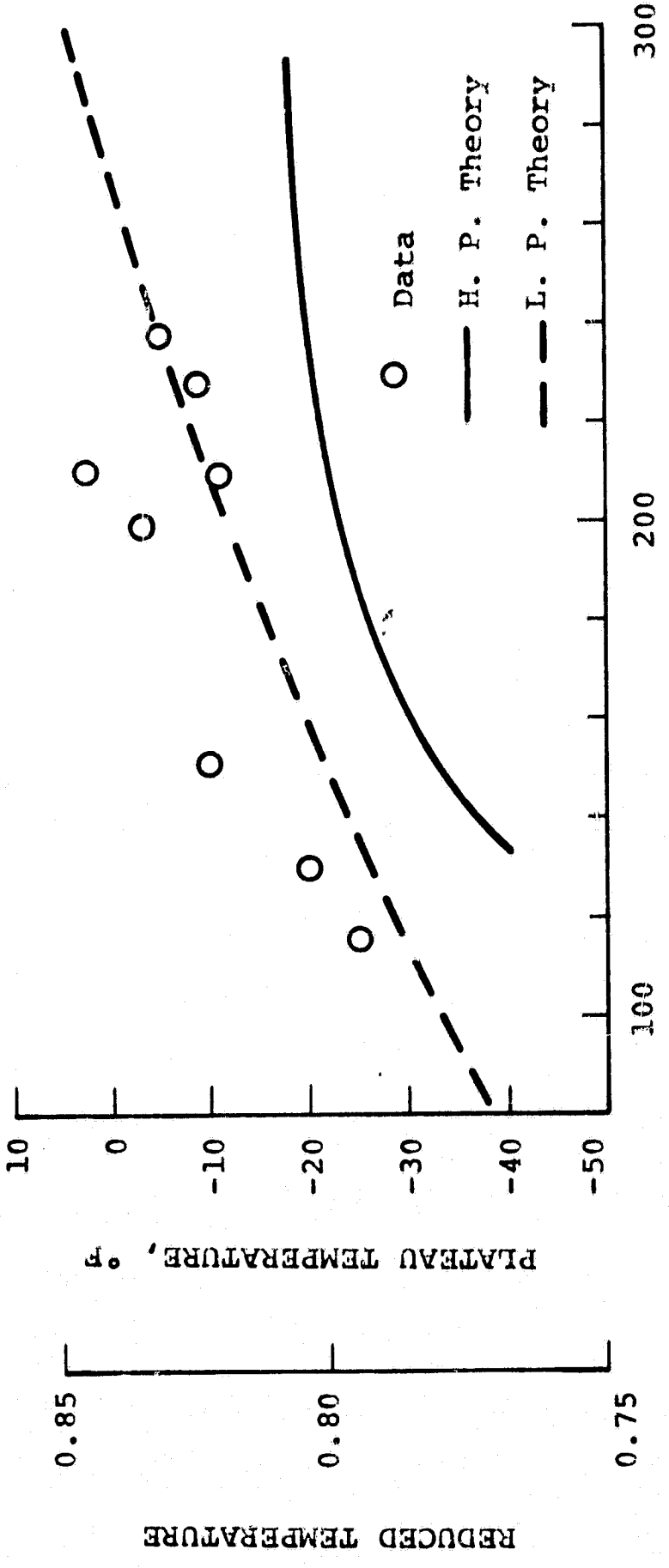


Fig. 3 Wet Bulb vs. Air Temperature for Carbon Dioxide Drop Vaporizing in Air at P_c.

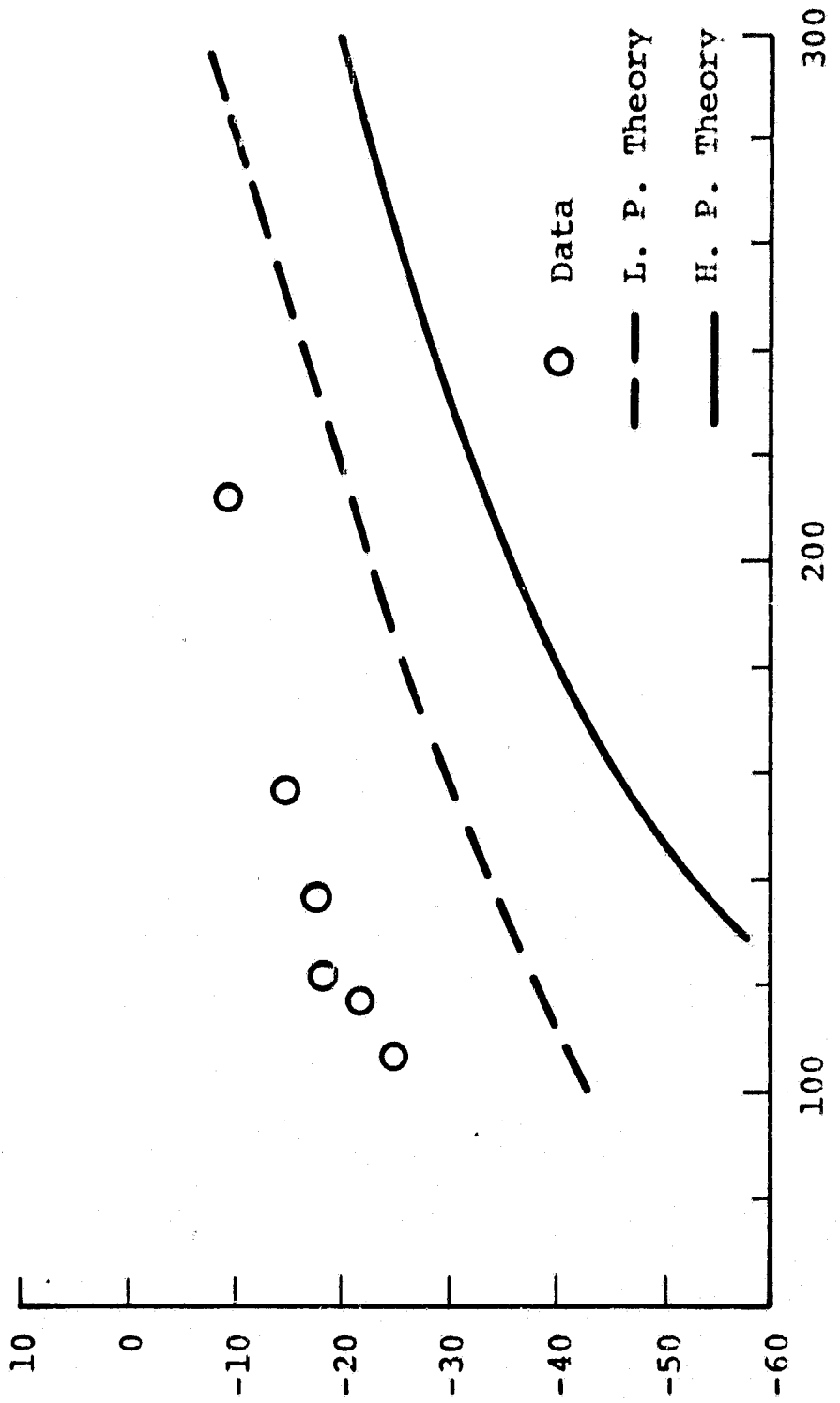
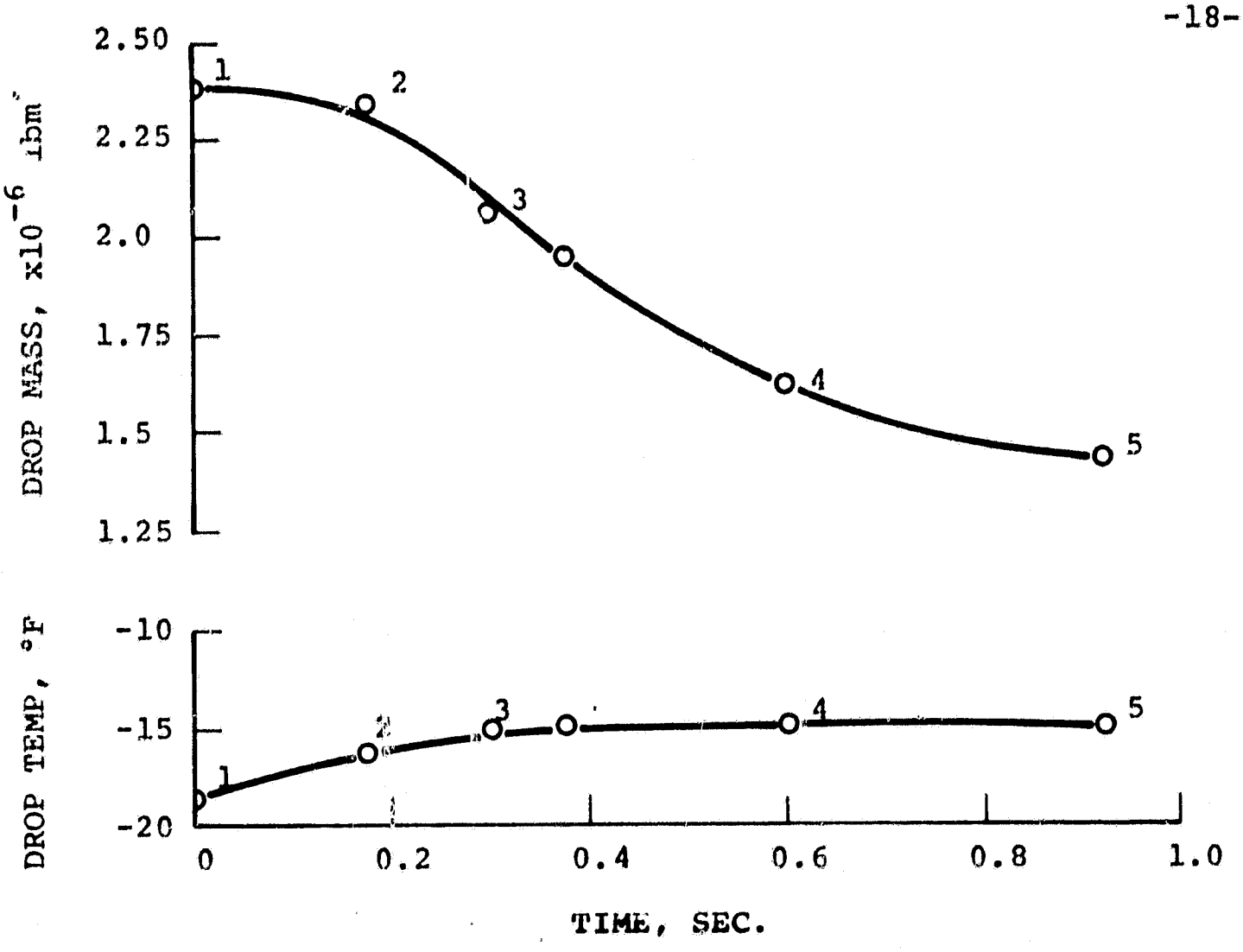


Fig. 4 Wet Bulb vs. Air Temperature for Carbon Dioxide Drop Vaporizing in Air at $.75P_c$.



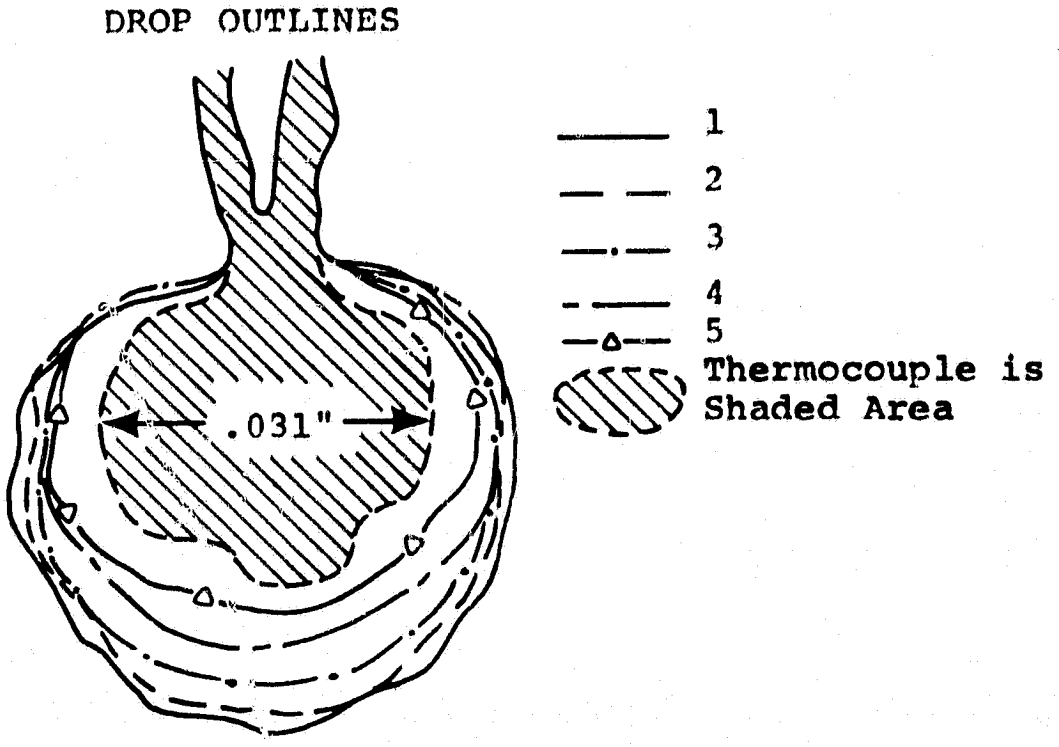


Fig. 5 History of Carbon Dioxide Drop Vaporizing at ambient conditions of $.75P_c$, 152°F, and 2.96 in/sec.

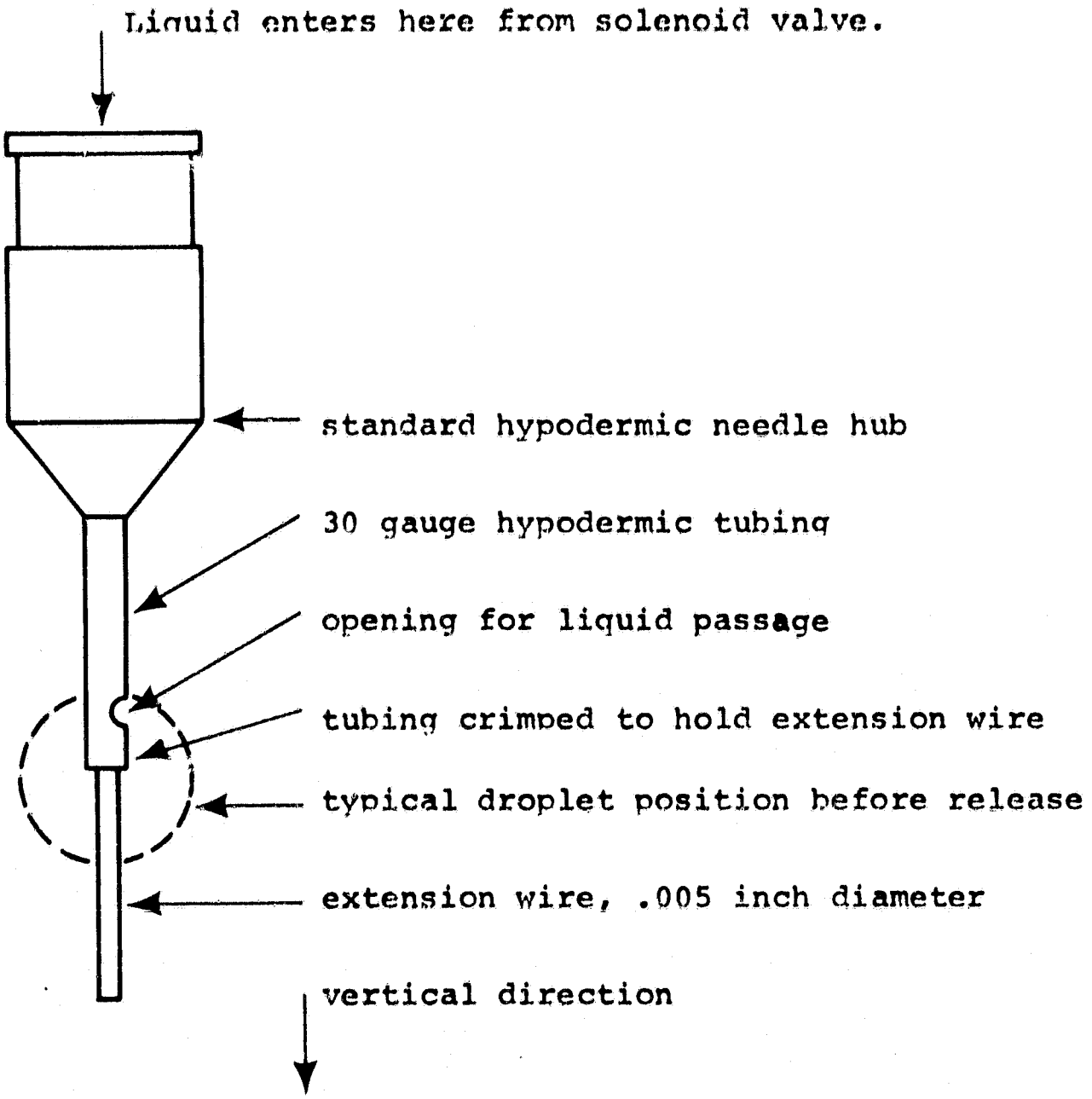


Fig. 6 Hypodermic needle modified to form smaller droplets. This figure is not drawn to scale.

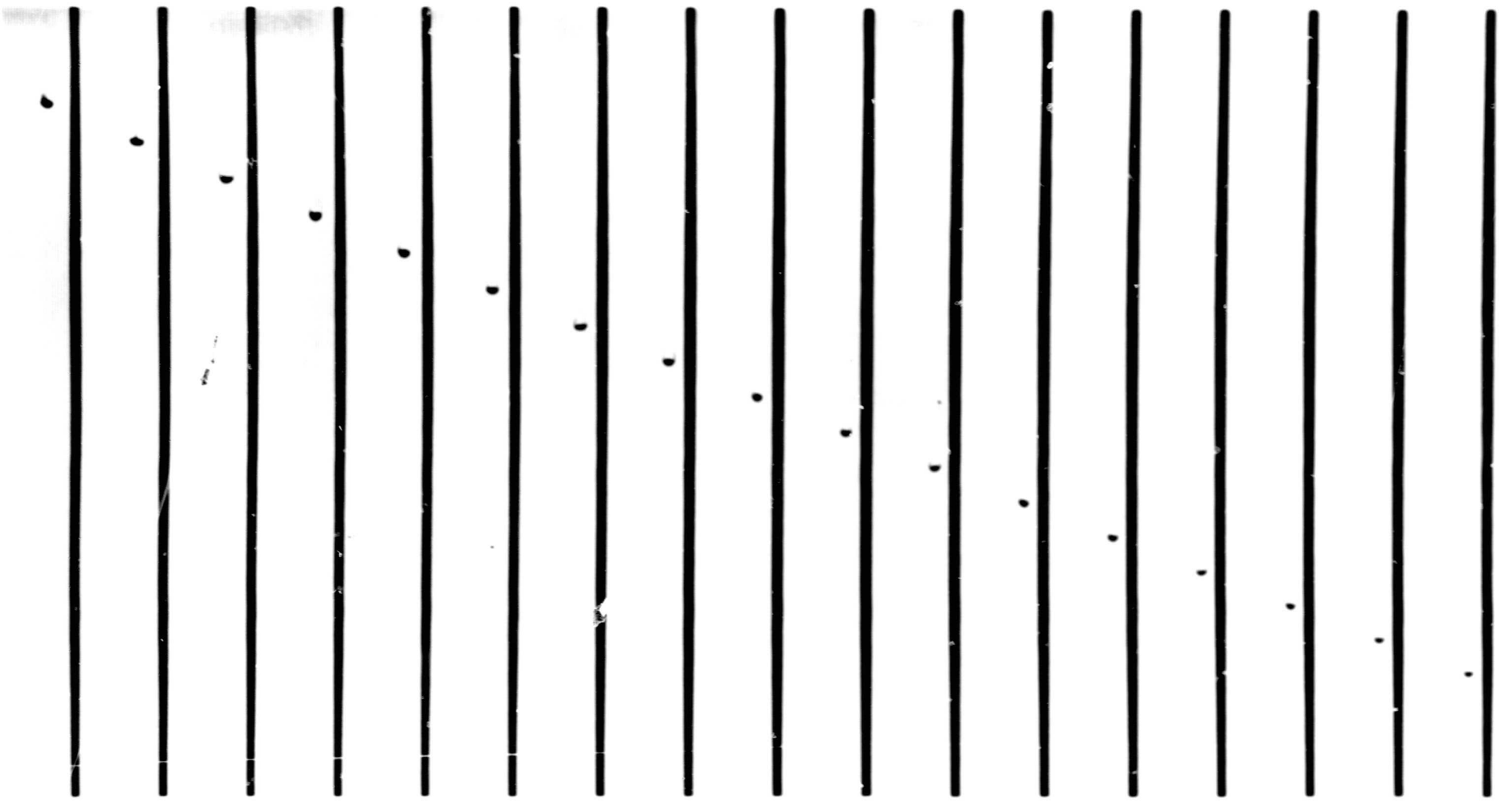


Fig. 7a Shadow photograph at 2X magnification of a CO_2 droplet falling through helium at 1500 psig and 1250 ^{o}F. The apparent volume history of this droplet is shown in Fig. 9.

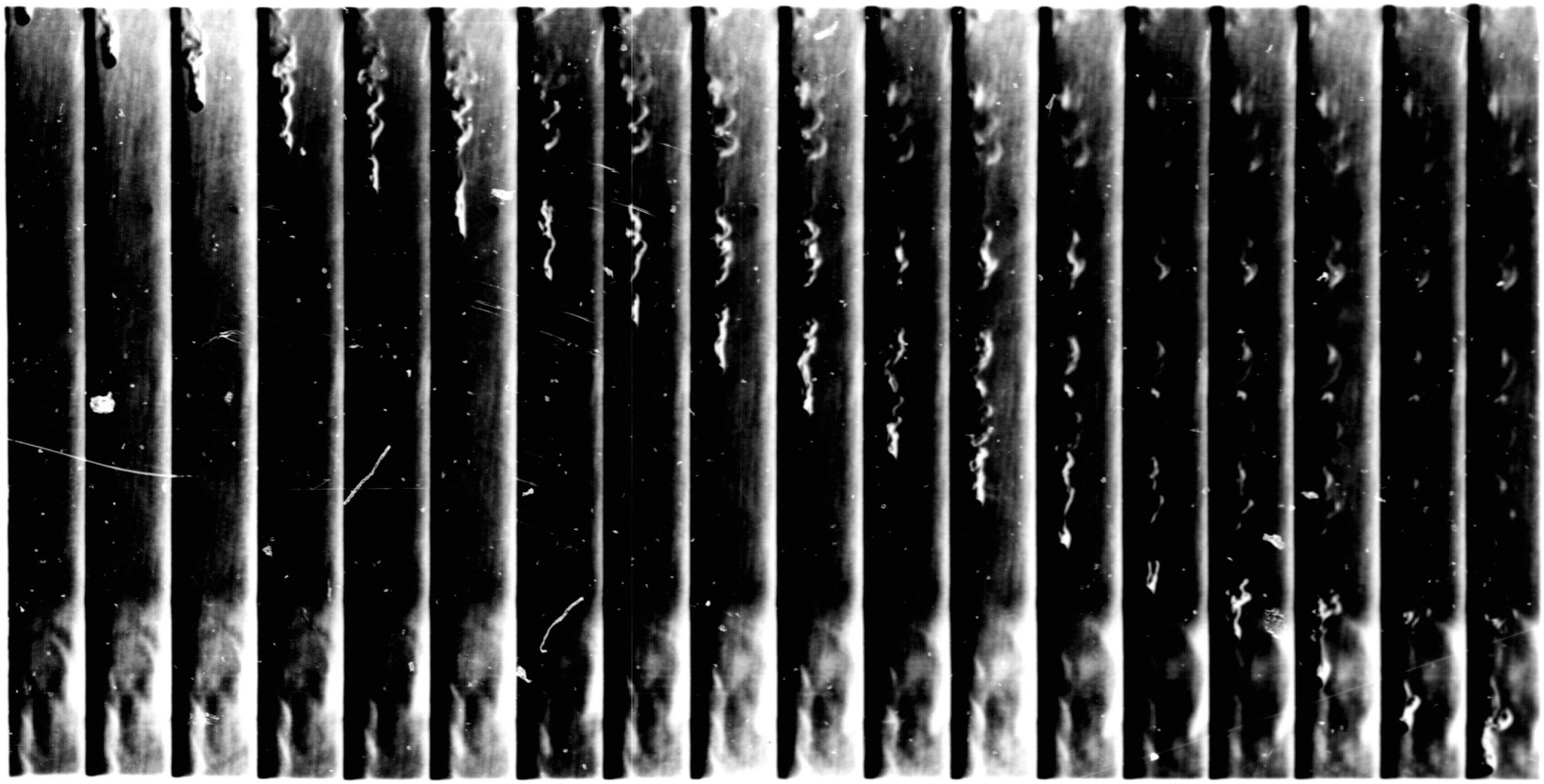


Fig. 7b Schlieren photograph at 2X magnification of a CO_2 droplet falling through helium at 1200 psig and 196 ^{o}F. The apparent volume history of this droplet is shown in Fig. 8.

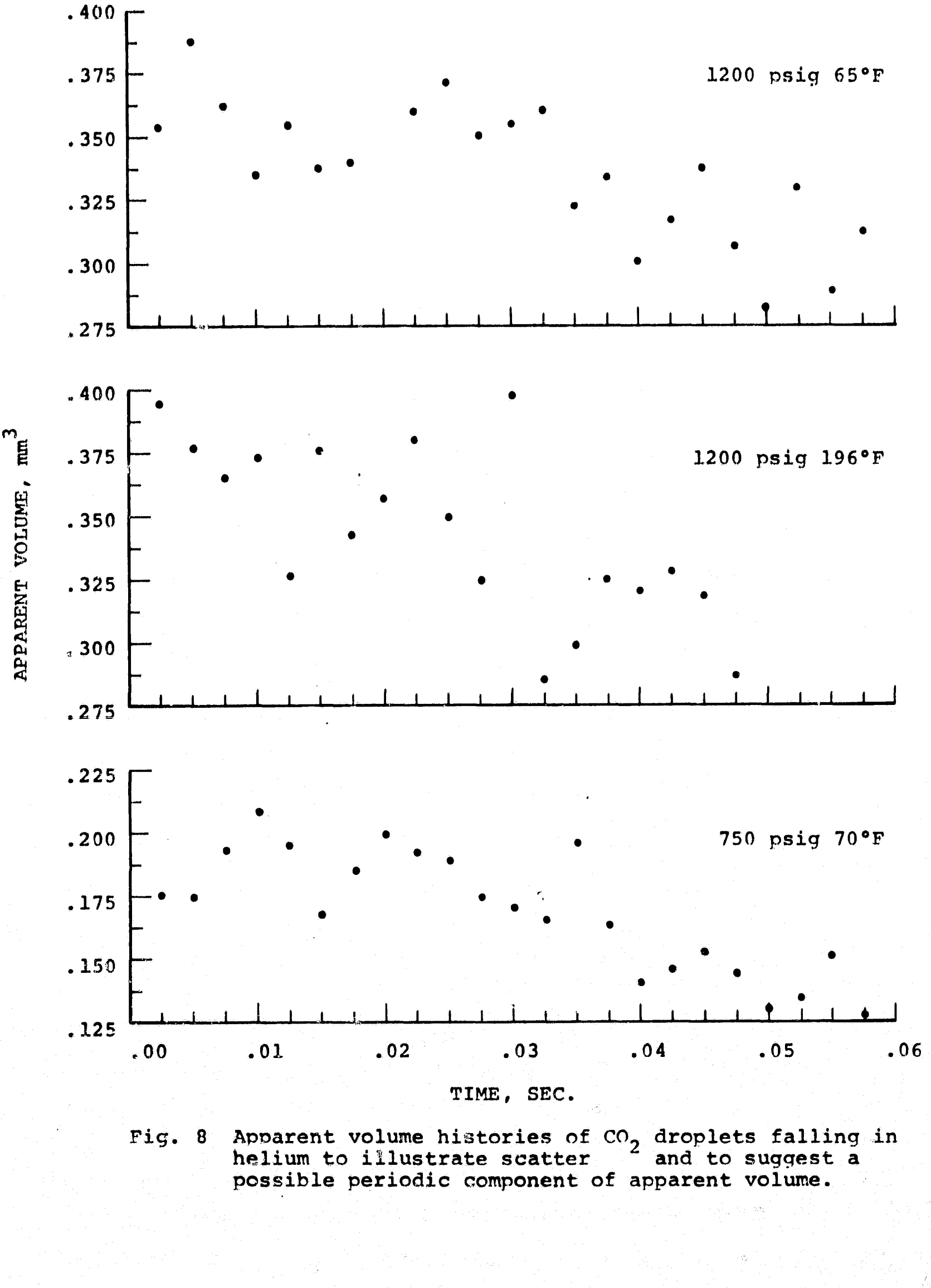


Fig. 8 Apparent volume histories of CO_2 droplets falling in helium to illustrate scatter and to suggest a possible periodic component of apparent volume.

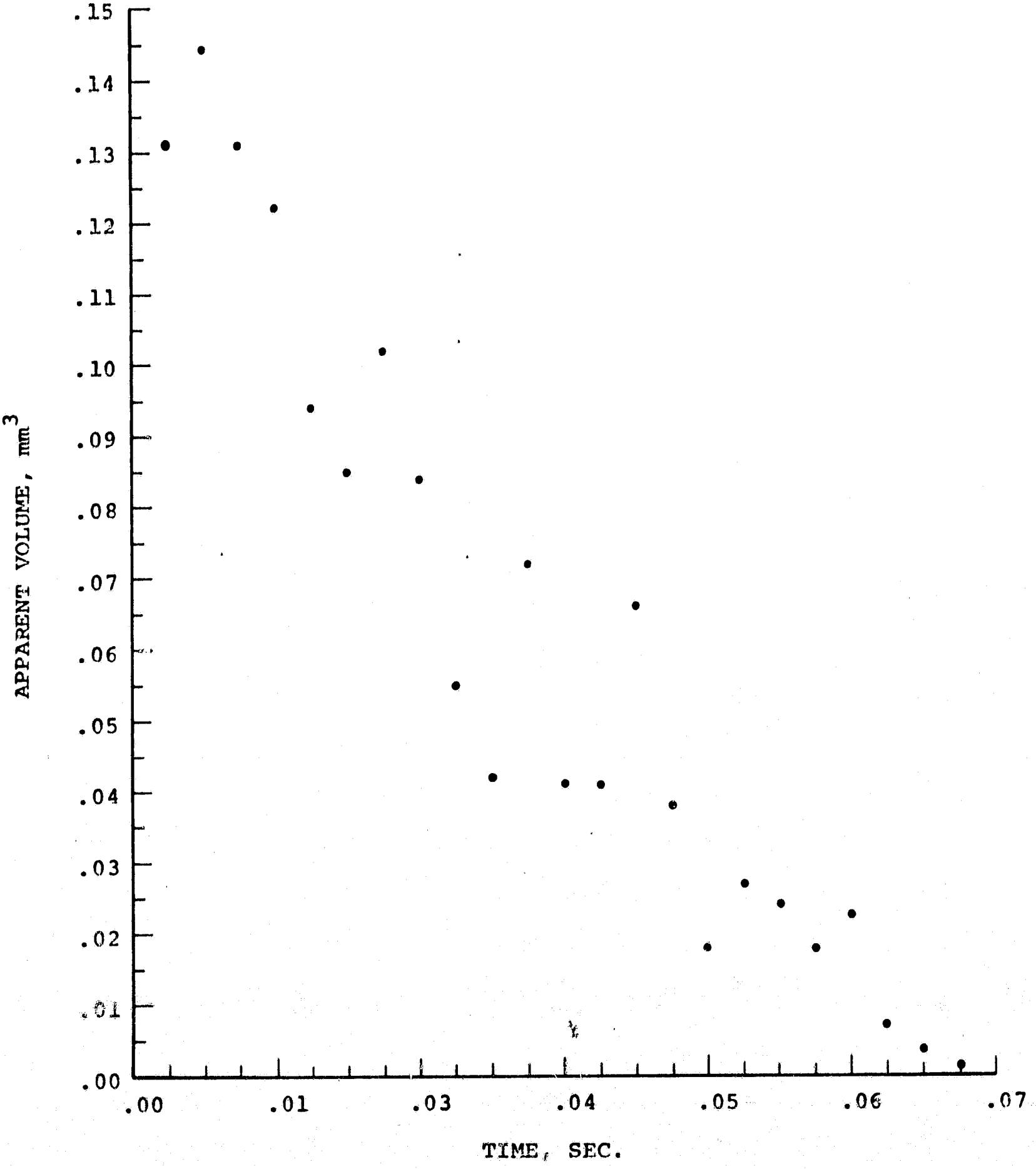


Fig. 9 Apparent volume history of a CO_2 droplet vaporizing in helium at 1500 psig and 1250°F.