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THE GEOMETRY AND PHYSICAL PROPERTIES  
OF EXHAUST CLOUDS GENERATED  
DURING THE STATIC FIRING  
OF S-IC AND S-II ROCKET ENGINES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1972



0061165

## TECHNICAL REPORT STANDARD TITLE PAGE

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| 1. REPORT NO.<br>NASA CR-2049                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  | 2. GOVERNMENT ACCESSION NO.                      |                            | 3. RECIPIENT'S CATALOG NO.                                   |  |
| 4. TITLE AND SUBTITLE<br>THE GEOMETRY AND PHYSICAL PROPERTIES OF EXHAUST CLOUDS<br>GENERATED DURING THE STATIC FIRING OF<br>S-IC AND S-II ROCKET ENGINES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  |                                                  |                            | 5. REPORT DATE<br>June 1972                                  |  |
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| 7. AUTHOR(S)<br>Richard E. Forbes, Michael R. Smith, and Ralph R. Farrell                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |  |                                                  |                            | 8. PERFORMING ORGANIZATION REPORT #<br>IES-7-10-2            |  |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Institute of Environmental Sciences<br>Mississippi State University<br>State College, Mississippi                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |  |                                                  |                            | 10. WORK UNIT NO.                                            |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |  |                                                  |                            | 11. CONTRACT OR GRANT NO.<br>NGL 25-001-32                   |  |
| 12. SPONSORING AGENCY NAME AND ADDRESS<br><br>NASA<br>Washington, D. C. 20546                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  |                                                  |                            | 13. TYPE OF REPORT & PERIOD COVERED<br><br>CONTRACTOR REPORT |  |
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| 15. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |  |                                                  |                            |                                                              |  |
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| 17. KEY WORDS<br><br>Cloud growth<br>Mass-Energy conditions<br>Mass-Energy flux<br>Diffusion                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  |                                                  | 18. DISTRIBUTION STATEMENT |                                                              |  |
| 19. SECURITY CLASSIF. (of this report)<br><br>Unc1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  | 20. SECURITY CLASSIF. (of this page)<br><br>Unc1 |                            | 21. NO. OF PAGES<br><br>104                                  |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |  |                                                  |                            | 22. PRICE<br><br>\$3.00                                      |  |



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## INTRODUCTION

The prediction of the growth and diffusion characteristics of natural and man-made clouds and exhaust plumes has been the object of much research during the past fifty years. Most of this work has been of an empirical nature and involved the prediction of the trajectory of the cloud or plume axis under fairly uniform meteorological conditions and other associated restrictive assumptions. During the past two years a research team from Mississippi State University has been attempting to develop numerical simulation techniques which will permit the prediction of the growth and diffusion of exhaust clouds which are generated during the static firing of various size rockets under arbitrary meteorological conditions. The verification of the numerical simulation model required the acquisition of various experimental data to test the reliability and accuracy of the prediction scheme under various meteorological conditions.

The experimental program was conducted at the NASA Mississippi Test Facility at Bay Saint Louis, Mississippi during the static firing of the S-IC-13,-14 and -15 rocket engines and the S-II-13,-14, and -15 rocket engines. The data compiled during the experimental

program consisted of photographic recordings of the time-dependent growth and diffusion of the exhaust clouds, the collection of meteorological data in the ambient atmosphere, and the acquisition of data on the physical structure of the exhaust clouds which were obtained by flying instrumented aircraft through the clouds.

The results of this experimental program indicates that at the lower altitudes the rocket exhaust cloud or plume closely resembles a free-jet type of flow. At the upper altitudes, where the cloud is approaching an equilibrium condition, the structure is very similar to a natural cumulus cloud. The photographic records of the cloud growth have been normalized through the use of an image rectifier to give a true shape of the normalized cloud. The condensation of the water vapor at the upper altitudes gives indication of the general structure and shape of the exhaust cloud; however, it was noted, through the use of infrared color film, it was possible to differentiate between the exhaust product cloud and the water vapor cloud and that the water vapor cloud did not necessarily define the true extent of the exhaust products cloud. The distribution of dry bulb temperature and relative humidity throughout the exhaust clouds during the various stages of development and dissipation are shown graphically in text. In addition a mass-energy balance was established for the S-IC rocket

exhaust cloud and the results indicate that approximately 100% of the cooling water supplied to the exhaust gas deflector is vaporized and entrained in the exhaust jet.

#### DESCRIPTION OF EXPERIMENTAL PROGRAM

Photographic records of the time dependent growth and dissipation of the rocket exhaust cloud were made utilizing 16 mm movie film recording at 12 frames per second, and both color and infrared color film in a K-17B camera. The K-17B (9.5 inch film) was actuated with an intravelometer which was set to fire every five seconds. In addition, 35 mm and 4½ x 5 cameras were used to obtain photographs of the cloud from fixed wing aircraft. The ground-based cameras were mounted on top of the Central Control Building (Building 1200) which was located approximately 3700 meters (12,200 feet) from the S-IC test stand and approximately 3000 meters (10,000 feet) from the A-2 test stand. (Figure 1).

Meteorological data on the temperature structure of the atmosphere and the magnitude and direction of the upper winds was obtained from the U. S. Weather Bureau located at MTF. On the day of a static firing, meteorologists released radiosonde equipped balloons every three hours for approximately 12 hours prior to the scheduled static firing in order to assure that rapid changes in the upper atmosphere did not occur which would lead to undesirable acoustic

reflections. An additional sounding was made one hour prior to the scheduled firing. A radiosonde and balloon were released at engine ignition in order to map the structure of the atmosphere during the time the rocket engine was actually firing. In most cases only minor changes of the structure of the atmosphere occurred during the several hours preceding the static firing; therefore, the meteorological data taken during the static firing was actually used to compare with the data acquired by the aircraft.

A compact, lightweight airborne data acquisition system (ADAS) was constructed by the research team to be installed in a single engine aircraft to make probings through the exhaust cloud during its growth and dissipation. The system was installed in a Piper PA-24 aircraft and had the capability of recording all the airborne data on analog tape or of telemetering the data directly to the Data Handling Center at the Mississippi Test Facility. In all tests the data were recorded on-board and at the same time telemetered to the DHC for real-time processing. In this manner the data were available for immediate review.

The normal mode of data acquisition was to telemeter the data directly from the aircraft to the data handling center at NASA-MTF. An omni-directional antenna mounted on the roof of the Data Handling Center was utilized for data acquisition. At the test recording

station, the acquired data were simultaneously recorded on analog tape and also processed through an analog-digital converter. The digital information was run through a calibration routine to convert the digital index value to a true engineering unit (TEU). The TEU data was then stored in a digital format on magnetic tape and this provided the basis for all future data reduction processes. The data reduction system was so designed that oscillograph plots of all the variables could be presented simultaneously with data reduction.

Due to the large updrafts which occurred in the clouds, the aircraft gained several hundred feet during a typical pass through the cloud, such that the measurement of temperature had little significance if it was referenced to the temperature at the point of penetration. In order to correct for this deficiency the temperature in the cloud was referenced to the ambient temperature at the same altitude. A calibration curve for the atmospheric temperature was composed from the pre-test and post test calibration data. Thus at a given altitude, an undisturbed temperature could be obtained from the calibration curve. If the aircraft climbed during the test run it was possible to reference the temperature at any particular instance and time to the undisturbed temperature at the same altitude outside the cloud. In this manner, a temperature difference  $\Delta T$  was defined such that the temperature difference was zero outside

the cloud, and the shape of the temperature distribution curve was an indication of the temperature distribution at some mean altitude which occurred during the test run.

Pre-test and post-test calibrations were made on the airborne data system and these calibrations were checked against the meteorological data to ensure good correlation.

#### REDUCTION OF PHOTOGRAPHIC RECORDS

The 9½ inch film from the K-17B camera was utilized to obtain the time-dependent growth and dissipation histories of the rocket exhaust clouds. The film was installed in a Weston photographic image rectifier and the correct elevation and azimuth angles of the camera were set into the device so that a normalized view of the exhaust cloud was projected upon the recording plane. The edge of the exhaust jet and the condensation cloud were traced upon the drafting paper which was attached to the normalized plane. By repeating the tracings at various time intervals, a time sequence and history of the cloud growth was obtained. In order to check the accuracy of the normalized view of the cloud and assure that the proper elevation and azimuth angle were utilized, the height of the cloud at various time intervals was noted from the various aircraft that were used during the experiment. These heights and times were then used to cross reference the altitude of the cloud at the

identical times as it was shown in the normalized plane. In all instances the final projection in the normalized plane agreed within less than two and one half percent of that observed by the aircraft.

#### METEOROLOGICAL DATA

The meteorological data obtained from the radiosonde released at the time of engine ignition was utilized to define the temperature distributions and wind velocity field in the region immediately above and adjacent to the test stands. Complete tabulation of the meteorological data obtained during these tests is presented in Appendix I. Plots of the temperature distribution and the relative humidity distribution in the atmosphere are presented as functions of altitude for each test condition.

#### ACQUISITION OF AIRBORNE DATA

At the beginning of this project it was anticipated that the photographic records would yield good time-dependent history of the growth and dissipation of the water vapor cloud and that the exhaust products would be encompassed in this cloud. Analysis of photographic records from an S-IC static firing indicated that the boundary of the exhaust products cloud could possibly be quite different from that of the water vapor cloud due to the difference in density and molecular weight of the two gases. At this point

it was deemed desirable to equip an aircraft with adequate instrumentation to delineate the temperature and liquid water content distributions in the cloud, such that the predictions from the numerical simulation program could be correlated with the physical structure of the cloud. In addition, the properties of such an exhaust cloud have not previously been defined and it was anticipated that a cloud could possibly be utilized for weather modification research. Utilizing a surplus S-1B telemetry package and spare components located on the test facility, the research team assembled a compact, lightweight airborne data acquisition system which was installed in a single engine aircraft. The total self-contained package weighed approximately 250 pounds including approximately 100 pounds of NI-CAD batteries.

The temperature sensors for the airborne package were developed utilizing thermistors mounted in a cylindrical housing with one of the thermistors moistened continuously to provide a wet bulb temperature reading. The temperature head was calibrated using an improvised flow chamber which simulated the flow velocities that were being encountered during the test program. It was felt that the care utilized in the design of the flow chamber and in the calibration of the temperature sensors was such that the final data were extremely reliable. The airborne temperature data compared very favorably with that obtained from the radiosonde.

Prior to the acquisition of test data during a static firing, a pre-test calibration was run by flying the aircraft at various airspeeds at a mean altitude that was thought to be representative of that at which the predominance of test runs would be made. In addition, the aircraft was flown at some mean airspeed at three or four different altitudes in order to establish a good temperature versus altitude calibration. During the static firing, the pilot of the aircraft waited until the exhaust cloud approached its equilibrium altitude before penetrating the cloud. Extreme turbulence and updrafts were encountered in several of the firings; however, the aircraft was always operated to prevent over-stressing its structure. In most cases moderate to severe turbulence was encountered as the aircraft penetrated the condensation cloud; however, the core of the cloud appeared to be fairly laminar such that the pilot experienced almost no turbulence during the time he was passing through the center of the cloud. During each run the aircraft was flown on a more or less north to south path such that the aircraft data were obtained in the same plane as the photographic data. In this manner a cross correlation of cloud thicknesses could be obtained. Immediately following the static firing and after the exhaust cloud dissipated, the aircraft conducted a post-test calibration in order to determine the possibility of calibration drift during the test run. In most cases it was not necessary to



make corrections in the data due to the stable design of the amplifiers.

#### REDUCTION OF AIRBORNE DATA

Data obtained by the airborne data acquisition system included dry and wet bulb temperatures, aircraft airspeed, pressure altitude, and an event marker to indicate cloud penetration and exit. The event marker was manually activated by the pilot upon entry and exit of the cloud. Due to the importance of obtaining valid measurements with the dry and wet bulb thermistors, this system was duplicated in order that these variables could be recorded on two independent systems. Following a flight the raw data were transformed, using appropriate calibration factors, into true engineering units. Upon obtaining the true engineering units data, an analysis was undertaken to determine the best manner in which the data should be presented to give a physically realistic description of events in and surrounding the cloud.

Radiosonde data were available for each firing from a sounding beginning at the time of engine ignition. It was felt that, wherever possible, the data acquired by the aircraft should be compared with that obtained from the radiosonde sounding. Dry bulb temperatures obtained by the aircraft could be compared directly with

ambient temperature readings recorded by the radiosonde at a given altitude. In addition, conversion of the aircraft dry and wet bulb readings into relative humidity would allow a comparison of this variable with that obtained by the radiosonde at a given altitude. Measurements within the cloud would indicate the deviation of relative humidity and temperature from ambient at a given altitude. Since it was impossible to maintain aircraft altitude in the rapidly developing cumulus clouds, it was necessary that all measurements be referred to the undisturbed or ambient conditions at a given altitude. The instantaneous value of relative humidity within the cloud has direct meaning since it represents the moisture content in the cloud as compared to ambient conditions surrounding the cloud. However, when analyzing temperatures within the cloud one must account not only for the measured value compared to ambient but any changes induced by climbing or driving of the aircraft.

The following procedures were utilized in converting the dry and wet bulb temperatures into relative humidity and temperature deviations from ambient within the cloud (disturbed temperature).

The instantaneous aircraft altitude was indicated by a sensitive calibrated altimeter set to 1013.2 millibars (29.92 inches of mercury) prior to take off. It is assumed, in all calculations, that the altitude as measured by the altimeter is the correct value of

this variable.

In order to calculate relative humidity values from dry and wet bulb temperatures, one must account for the ambient pressure at which the readings were taken. The standard psychrometric chart is, in general, referenced to a sea level pressure of 1013.2 millibars and is not usable for our purpose. However, if one knows the altitude (and thus pressure) at which the aircraft is flying, psychrometric relations may be developed from basic thermodynamic considerations which will give the correct value of relative humidity at that altitude when the dry and wet bulb temperatures are known. Altitudes measured by the aircraft were converted to pressure using the I.C.A.N. (International Commission for Air Navigation) atmosphere:

$$P = 1013.2 \left[ \frac{1 - 0.0065Z}{288} \right]^{5.2568}$$

where P is in millibars and Z in meters. Since the altimeter was set to 1013.2 millibars prior to take off, it was felt that this procedure provided sufficient accuracy for purposes of calculating relative humidity at a given altitude. Pressures thus calculated were utilized along with dry and wet bulb temperatures to calculate the relative humidity at a given altitude. The psychrometric routine used to perform these calculations was developed from basic thermodynamic considerations and gave good results when compared to

the variable pressure psychrometric chart given by Berry, Bollay, and Beers (1). A documented copy of the psychrometric routine is on file with the Data Handling Center at NASA Mississippi Test Facility. Recorded relative humidity as calculated from this procedure should be nearly instantaneous, possessing only the time lags inherent in the thermistors and the altitude (of order one tenth second).

It is a recognized fact that the earth's atmosphere is not homogenous and that one may measure spatial variations of some property even when flying at a fixed altitude. This factor was readily apparent when attempts were made to indicate cloud temperatures in useable form. Temperatures indicated within the clouds were influenced by two factors; the variation due to the presence of the cloud and the changes produced by climbing and diving of the aircraft while in the cloud. Both factors must be accounted for in an analysis of temperature disturbances (relative to ambient) produced by the clouds.

The following procedure was utilized to provide the most meaningful indication of the temperature disturbances created by the clouds. Dry bulb temperatures, as measured outside the clouds, were used along with altitude to obtain a relationship between altitude and dry bulb temperature when these variables were not under the influence of a cloud. Standard least squares techniques

were used to obtain a relationship giving the best temperature (in the least squares sense) when the altitude was known. It was determined that a linear relationship of the form:

$$T_{\text{calc.}} = a + bZ$$

gave sufficient accuracy for our purposes since the altitude change of the aircraft was generally less than 500 meters for successive passes through the cloud on a given firing.  $T_{\text{calc.}}$  is the expected temperature at a given altitude  $Z$  if one is outside the influence of the cloud. Although this relationship was obtained by fitting data outside clouds, it could now be used to calculate the temperature one would expect to measure in the cloud at a given altitude if the cloud had no influence on the temperature. A comparison of  $T_{\text{calc.}}$  and the actual dry bulb temperature measured at a given altitude would indicate the disturbance in temperature produced by the cloud presence. This temperature difference, where

$$\Delta T = T_{\text{meas.}} - T_{\text{calc.}}$$

indicates heating in the cloud (relative to ambient) if  $\Delta T$  is greater than zero or cooling if  $\Delta T$  is less than zero. Calculations have been performed using the data from both dry bulb systems.

As was expected, there were slight differences in the absolute

magnitudes of relative humidity and disturbed temperature as measured by the two independent dry-wet systems on the aircraft. These differences were, in general, negligible and more importantly the trend as indicated by the two systems was similar in all cases. This will be discussed in more detail when considering the analysis of the data.

At this point, consideration will be directed to the analysis of data as obtained for particular firings. Meaningful data were recorded for the following four static firings:

|         |                   |
|---------|-------------------|
| S-IC-13 | 6. February 1970  |
| S-IC-15 | 30 September 1970 |
| S-II-14 | 31 July 1970      |
| S-II-15 | 30 October 1970   |

The S-IC stage is fueled by a LOX-RP1 system whereas the S-II is a LOX-Liquid Hydrogen system. The fuel flow, heat release, and firing duration of the two stages differ significantly and thus one would not expect the cloud geometry and composition to be similar for the two stages. In addition, meteorological parameters will significantly affect the growth and dissipation of the clouds. These factors will be considered in the following discussion.

## DATA FOR SIC ROCKET EXHAUST CLOUDS

S-IC-13

6 February 1970

The data to be discussed will be similar for each of the four firings. These will include a listing of the pertinent radiosonde meteorological parameters, typical photographs from which the rectified cloud images were traced, typical rectified cloud geometry, relative humidity profiles within the clouds, and disturbed temperature profiles in the clouds. Complete radiosonde soundings are presented in the appendices along with the entire set of rectified cloud images and typical tabulated data recorded in the clouds by the airborne data acquisition system.

For cloud S-IC-13, airborne data were recorded by a research aircraft from Pennsylvania State University in addition to the data recorded by the Mississippi State aircraft. The Penn. State aircraft operated independently of the MSU task, funding being provided by the MITRE Research Corporation of Bedford, Massachusetts. The duplication of effort on firing S-IC-13 was indeed fortunate since the magnetic tape containing the data from the MSU aircraft was misplaced or erased prior to the recording of a hard copy of the data. In general, the Penn. State aircraft penetrated the S-IC cloud in the vicinity of 4500 meters (15,000 feet) MSL while the penetrations made by the MSU aircraft were in the vicinity of 3000 meters (10,000 feet) MSL.

Radiosonde soundings of ambient temperature and relative humidity have been plotted versus altitude in meters in Figures 2 and 3. These figures are presented first in order that subsequent measurements and observations may be analyzed in light of the prevailing meteorological conditions. The temperature inversion in the vicinity of 1000-2000 meters in Figure 2 should be expected to affect the cloud geometry as will be shown later. The relative humidity profile may be used as a cross check on humidities recorded by the aircraft outside the clouds when aircraft altitude is known.

In general, several penetrations of each cloud were made by the aircraft for a particular static firing. In the following discussion, these penetrations will be referred to in chronological order as Pass 1, Pass 2, etc.

Rectified cloud geometry was determined from the 9.5 inch photographic plates by the method previously discussed. Prints of typical photographs for firing S-IC-13 are shown in Figures 4, 5, and 6 at 20, 60, and 160 seconds after engine ignition. The test stand and other physical characteristics of the Mississippi Test Facility are clearly evident in the photographs and were used in developing the appropriate length scales and angles necessary to produce the rectified images. The prints shown in Figures 4, 5, and 6 are necessarily shown in black and white, however, it should be emphasized that the original plates from which the rectified clouds were produced

were in color. The color film gave superior resolution of the cloud geometry against the background as compared to black and white photography and this characteristic cannot be adequately shown in the black and white prints.

Several interesting features of the cloud are evident in Figures 4, 5, and 6. The cloud is well defined against the background since the LOX-RP1 system produces a dark gray exhaust emission. Figure 4 indicates that the initial phase of cloud development is predominately a free jet type of flow since the cloud angle to the horizontal is approximately 30 degrees. The angle between the blast deflector axis and the horizontal is 30 degrees and this factor dominates the cloud geometry during the early stages of development. Figure 5 shows that free convection or buoyancy has become important in the growth process since the angle between the cloud axis and the ground is now approximately 45 degrees. Engine cut off for S-IC-13 was at approximately 125 seconds after ignition. Figure 6 indicates that the lower portion of the cloud had begun to detach from the test stand at 160 seconds with a small residual dark cloud in the vicinity of the test stand.

The color negative from which Figure 6 was printed showed that the cloud underwent a condensation process at a specific altitude. The white portion of the cloud in which condensation was occurring could be clearly delineated from the gray non-condensable exhaust

products in the cloud. The altitude at which condensation was first observed has been indicated on the rectified images which were traced from the color negatives.

The time dependent cloud geometry for cloud S-IC-13 is shown in Figures 7 and 8. The 300 meter length scale provides a reference from which cloud dimensions may be determined. The K-17 cameras provided only 205 seconds of coverage for this particular firing, however Figure 8 shows that the vertical development of the cloud had exceeded the field of view of the camera at this time. The cloud top is approximately 4500 meters above the ground at 160 seconds after engine ignition and moves out of the field of view prior to the next photograph (5 seconds between photographs).

The approximate vertical growth rate of the cloud may be determined by making measurements between successive traces on Figures 7 and 8. The maximum vertical growth rate for firing S-IC-13 occurred between 130 and 160 seconds where the height increased approximately 1200 meters in 30 seconds, giving an average growth rate of 40 meters per second. The maximum rate of climb as measured by the Penn. State aircraft while in the S-IC cloud was approximately 38 meters per second which compares favorably with the growth rates measured from the cloud geometry.

The dashed horizontal line on Figure 8 (approximately 1740 meters above the surface) indicates the altitude at which condensation was

first observed in the cloud photographs. The condensation process begins in the vicinity of the temperature inversion in the vicinity of 1000-1700 meters as indicated by the radiosonde data of Figure 2. The latent heat released in the condensation process provides the heat input to the cloud to continue the cumulus development to higher altitudes after engine cut off.

Three passes were made through cloud S-IC-13 by the Penn. State aircraft. Engine ignition was at 1546:41 Central Standard Time with entry into the cloud first made at 1555:33; or approximately nine minutes after engine ignition. Aircraft elevation at entry into the cloud was approximately 4250 meters for all three passes.

The relative humidity profiles of the cloud are shown in Figures 9, 10 and 11 where relative humidity has been plotted versus time. The dashed vertical lines indicate cloud penetration on the left and cloud exit on the right. Figures 9, 10, and 11 indicate good comparison between the aircraft data and radiosonde data for relative humidity when the aircraft is outside the cloud; the value being of order 80% at the penetration altitude. Figure 9 indicates that relative humidities of approximately 125% are encountered half way through the cloud, this value decreasing back to ambient conditions prior to exit from the cloud. The super-saturated conditions indicate the unstable nature of the cloud at this point in time. The relative humidity measurements were made through a reverse flow

psychrometer, thus there is no possibility of water droplet impact affecting the measurement. Maximum relative humidities encountered on pass 2 through the cloud were approximately 100% indicating a saturated condition near the center of the cloud.

A sharp decline in relative humidity was noted near the center of the cloud during pass 3 as shown in Figure 11. This decrease was caused by a decrease in aircraft altitude near the center of the cloud during pass 3. The aircraft entered the cloud at 4200 meters, descended to 3900 meters at the center of the cloud, and exited the cloud at 4100 meters. Reference to the radiosonde sounding (Figure 3) shows that one would expect the relative humidity to vary as shown in Figure 11 if, in the latter stages of cloud development, the ambient conditions were impressed on the cloud during the dissipation phase.

Cloud disturbed temperature has been plotted versus time in Figures 12, 13, and 14. Reference to these figures indicates that, statistically, the cloud has reached temperature equilibrium with the ambient atmosphere at the time of the first pass. Passes two and three indicate temperature equilibrium with the ambient atmosphere; local temperature deviations of order  $\frac{1}{2}$  degree centigrade being the maximum recorded in the cloud.

S-IC-15

30 September 1970

Figures 15 and 16 contain temperature and relative humidity histories of the ambient atmosphere recorded by radiosonde at ignition time for firing S-IC-15. The measured temperature lapse rate is significantly less than the adiabatic lapse rate in the vicinity of 1500 - 3000 meters. The average relative humidity is approximately 20 - 40% which is considerably less than that recorded for firing S-IC-13. Cloud photographs are shown in Figures 17 and 18 at 65 seconds and 200 seconds after ignition, respectively. The effect of wind on the cloud geometry is apparent in the preceeding figures, showing that the cloud has been displaced to directly above the test stand at 200 seconds after ignition. Complete wind profiles are shown in Appendix I.

Rectified cloud images in Figures 19, 20, and 21 show the cloud geometry from 50 to 325 seconds after ignition. The cloud detaches from the vicinity of the test stand between 125 and 155 seconds and continues the growth process while drifting to the south. Condensation was first observed at an altitude of approximately 1680 meters as shown on Figure 20. It will be recalled that this is in the vicinity of the region of constant temperature lapse rate.

Engine ignition for S-IC-15 was at 1817:05 Central Daylight Time. Four passes were made through the cloud by the MSU aircraft while the Penn. State aircraft made 3 passes. The entry and exit altitudes for each aircraft on each pass are shown in Table 1.

| Table 1. Cloud Entry and Exit Altitudes S-IC-15 |         |         |                    |         |         |
|-------------------------------------------------|---------|---------|--------------------|---------|---------|
| <u>MSU</u>                                      |         |         | <u>PENN. STATE</u> |         |         |
|                                                 | IN      | OUT     |                    | IN      | OUT     |
| Pass 1                                          | 3120 m. | 3480 m. | Pass 1             | 3635 m. | 3489 m. |
| Pass 2                                          | 3140 m. | 2930 m. | Pass 2             | 3518 m. | 3459 m. |
| Pass 3                                          | 2460 m. | 2490 m. | Pass 3             | 3424 m. | 3276 m. |
| Pass 4                                          | 2600 m. | 2600 m. |                    |         |         |

The Penn. State aircraft first entered the cloud approximately 6 minutes after engine ignition whereas the MSU aircraft made pass 1 approximately 3 minutes after ignition. To preserve the chronology of events the MSU cloud data will be discussed first, however one

should be aware that during the latter passes both aircraft may have been in the cloud at the same time. The times of entry and exit may be determined from the figures.

Relative humidity histories in the cloud as measured by System 1 on the MSU aircraft are shown in Figures 22, 23, 24, and 25. The data will only be shown for System 1 since it was determined that data recorded were essentially the same for both systems.

Figure 22 is perhaps the most interesting data recorded during this work. The relative humidity rises sharply to 100% on entry into the cloud, decreases near the center of the cloud and again rises to around 100% after passing the center of the cloud. The vortex nature of the cloud is evidenced in this data, the relative humidity at the center being lower than 100% because of entrainment of ambient air into the center of the vortex. The response of the system is seen to be good as indicated by the rapid return to ambient on cloud exit.

Subsequent figures indicate that the cloud relative humidity is only slightly disturbed from ambient for passes 2, 3, and 4. Pass 2 was begun approximately 7 minutes after ignition, indicating that the cloud rapidly reaches equilibrium with the surrounding atmosphere.

Disturbed temperature is given in Figures 26, 27, 28, and 29 for the four passes through the cloud.

The first pass through the cloud produced unexpected results in the disturbed temperature measurement as shown in Figure 26. The data (System 1) recorded on pass 1 are shown in Table 2.

Table 2: Recorded Data - MSU Aircraft

| TIME<br>(SEC.) | T <sub>D</sub><br>(°F) | T <sub>W</sub><br>(°F) | ALTITUDE<br>(FEET) | RELATIVE HUMIDITY<br>(%) |
|----------------|------------------------|------------------------|--------------------|--------------------------|
| 1820:12        | 49.2                   | 31.5                   | 10279              | 16                       |
| :13            | 47.4                   | 31.7                   | 10234              | 17                       |
| :14            | 44.1                   | 32.6                   | 10194              | 28                       |
| :15            | 39.6                   | 33.2                   | 10237              | 45                       |
| :16            | 36.4                   | 33.5                   | 10301              | 70                       |
| :17            | 35.5                   | 33.4                   | 10277              | 77                       |
| :18            | 34.5                   | 33.6                   | 10396              | 89                       |
| :19            | 36.1                   | 34.4                   | 10388              | 84                       |
| :20            | 36.6                   | 35.0                   | 10438              | 84                       |
| :21            | 35.7                   | 35.1                   | 10451              | 92                       |
| :22            | 34.2                   | 34.8                   | 10478              | 104                      |
| :23            | 35.0                   | 34.2                   | 10553              | 95                       |
| :24            | 35.0                   | 33.8                   | 10587              | 87                       |
| :25            | 35.8                   | 33.2                   | 10642              | 77                       |
| :26            | 36.8                   | 32.9                   | 10746              | 68                       |
| :27            | 38.9                   | 33.6                   | 10772              | 57                       |
| :28            | 39.8                   | 34.5                   | 10827              | 56                       |
| :29            | 39.3                   | 35.0                   | 10890              | 62                       |
| :30            | 39.0                   | 35.2                   | 10930              | 66                       |
| :31            | 38.6                   | 35.3                   | 10937              | 71                       |
| :32            | 38.4                   | 35.5                   | 10982              | 74                       |
| :33            | 38.4                   | 35.4                   | 11034              | 73                       |
| :34            | 38.5                   | 35.6                   | 11144              | 74                       |
| :35            | 37.8                   | 35.7                   | 11164              | 76                       |
| :36            | 36.8                   | 35.7                   | 11318              | 88                       |
| :37            | 36.5                   | 35.5                   | 11329              | 88                       |
| :38            | 36.1                   | 35.6                   | 11341              | 95                       |
| :39            | 36.0                   | 35.5                   | 11475              | 95                       |
| :40            | 35.9                   | 35.0                   | 11478              | 91                       |
| :41            | 36.1                   | 34.6                   | 11483              | 88                       |
| :42            | 37.7                   | 33.9                   | 11495              | 73                       |
| :43            | 40.0                   | 32.9                   | 11435              | 50                       |
| :44            | 41.4                   | 32.4                   | 11452              | 40                       |
| :45            | 42.1                   | 31.7                   | 11423              | 34                       |
| :46            | 42.7                   | 31.2                   | 11442              | 30                       |
| :47            | 43.2                   | 30.7                   | 11407              | 27                       |
| :48            | 43.7                   | 30.3                   | 11401              | 24                       |
| :49            | 44.0                   | 30.0                   | 11398              | 22                       |
| :50            | 44.2                   | 29.7                   | 11374              | 21                       |
| :51            | 44.3                   | 29.4                   | 11357              | 20                       |
| :52            | 44.5                   | 29.3                   | 11383              | 19                       |
| :53            | 44.7                   | 29.1                   | 11317              | 18                       |

Data presented are time (seconds), dry bulb temperature ( $^{\circ}\text{F}$ ), wet bulb temperature ( $^{\circ}\text{F}$ ), aircraft altitude (feet), and relative humidity (%). These data are typical, however the complete set would also contain the dry and wet bulb temperatures as recorded on System 2 and the second calculated relative humidity.

The relative humidity increased rapidly from 15 - 20% to approximately 100% as entry was made into the cloud. In the areas of high relative humidity the dry and wet bulb readings are essentially identical; for example at time 1820:21  $T_D = 35.7^{\circ}\text{F}$  and  $T_W = 35.1^{\circ}\text{F}$ . This indicates a significant cooling of the cloud relative to the ambient surroundings since the cloud temperature is indicated both by the wet bulb and dry bulb when the relative humidity is 100%. No liquid water content (rain) was observed by the pilot during the first pass, indicating that the dry bulb temperature suppression was not produced by "wet bulbing" on the dry thermometer.

The reduced temperature in the cloud can only be explained by adiabatic expansion of the cloud which produces the cooling effect. The momentum of the exhaust jet is sufficient to transport the cloud to altitude and the resulting expansion process, when assumed adiabatic, will produce significant reductions in the cloud temperature. This produces a highly unstable situation and the cloud must

be penetrated during the early stages of development to observe this phenomenon. For example, Figure 27 shows that approximately 4 minutes later the cloud has areas that are above as well as below ambient temperature. Pass 3 (in Figure 28) indicates that the temperature depression is completely absent and the cloud has attained a central temperature which is approximately  $4^{\circ}$  Centigrade above ambient. Figure 29 indicates that the cloud is tending to approach equilibrium with the surroundings, the central heated region being much smaller and the disturbed temperature around  $3^{\circ}\text{C.}$  above ambient.

The relative humidity and disturbed temperature traces recorded by the Penn. State aircraft in cloud S-IC-15 are shown in Figures 30 through 35. The first pass was made through the cloud approximately 4 minutes after engine ignition. Figure 30 indicates relative humidities of 30% above ambient for the first pass; a slight rise above ambient near the cloud center for pass 2 (Figure 31) and little or no change for pass 3 (Figure 32).

Figure 33 indicates that the Penn. State aircraft also experienced a cooling effect upon entering the cloud for the first pass. The temperature at the cloud center was measured at approximately  $5^{\circ}\text{C.}$  below ambient. Pass 2 (Figure 34) indicated that the cloud was still cooler than ambient, but only near the center of the cloud.

Pass 3 (Figure 35) indicated only slight deviations in the cloud temperature with slight cooling ( $1^{\circ}\text{C.}$ ) either side of the cloud center and near ambient conditions near the entrance, center, and exit.

## DATA FOR SII ROCKET EXHAUST CLOUDS

S-II-14

31 July 1970

Radiosonde soundings of relative humidity and temperature are shown for firing S-II-14 in Figures 36 and 37. The weather conditions were hot and humid at the time of firing with numerous small cumulus clouds in the area. The bases of the cumulus were generally around 1100 meters MSL with tops measured at 3000 meters MSL. Several light rain showers were observed in the area at the time of firing.

Engine ignition was at 1400:27 Central Daylight Time with the first penetration made approximately 17 minutes after engine ignition.

Figures 38 and 39 are photographs of the cloud at 50 seconds after ignition (Figure 38) and 110 seconds after ignition (Figure 39). The numerous natural cumulus clouds in the area at the time of firing can be seen in these photographs. The cloud produced by the second stage (S-II) firings is white in appearance and does not have the "smoky" appearance of the S-IC clouds. Thus the clouds produced a much sharper contrast on the color film making it very easy to distinguish the rocket cloud from any natural clouds which may appear in the photographs. Total firing duration for the second stage is approximately 6 minutes.

The time dependent cloud traces are shown in Figures 40 and 41. These traces depict the cloud geometry from 50 seconds after ignition to 450 seconds after ignition. The cloud height at 450 seconds is approximately 3400 meters. It can be seen that the cloud vertical growth rate is much smaller than for the S-IC clouds. This is to be expected since the mass, momentum and heat input rates to the cloud are much smaller for the second stage.

Relative humidity profiles of the cloud are given for the two passes in Figures 42 and 43. Pass 1 was made at an altitude of 4000 meters MSL while pass 2 was at an altitude of 2900 meters MSL. The average humidity is approximately 100% for all of pass 1 while this value exists only for a small portion of the cloud during pass 2.

Figures 44 and 45 present the disturbed temperature versus time. The statistical fit for  $T_{calc}$  presented a problem for this particular firing since it was impossible to remain entirely clear of natural cumulus during the calibration runs.

Figure 44 indicates a decrease in temperature of approximately  $2.5^{\circ}\text{C}$  shortly after entry into the cloud and the temperature remains at this value for the entire pass. The disturbed temperature does not return to zero upon exiting the cloud, however the data indicated the return to near undisturbed conditions approximately 20 seconds after cloud exit. At the time of the first pass the cloud had begun to merge with the natural cumulus clouds in the area making it

difficult to clearly determine the extent of the rocket cloud.

The disturbed temperature trace for the second pass is shown in Figure 45. The central temperature of the cloud is around  $5^{\circ}\text{C}$  below ambient with the disturbed temperature at entrance and exit being essentially zero.

S-II-15

30 October 1970

Relative humidity and temperature soundings as given by the radiosonde for firing S-II-15 are shown in Figures 46 and 47. The significant factor for this firing is the particularly low value of relative humidity at all altitudes above 1000 meters MSL (approximately 10%). There also exists a weak temperature inversion in the vicinity of 1000 meters MSL as shown in Figure 47.

Figure 48 presents the cloud photograph at 50 seconds after ignition and Figure 49 depicts the cloud 200 seconds after ignition. At 200 seconds after ignition the cloud has begun to separate into two distinct clouds at a point approximately 750 meters above the ground.

Cloud traces covering the period from 50 seconds after ignition to 550 seconds after ignition are shown in Figures 50, 51, and 52. A comparison of Figure 50 and Figure 40 indicates that the clouds for S-II-14 and S-II-15 have essentially the same height at 200 seconds. Meteorological factors however, play an important role in the final development of the cloud. This factor is particularly noticeable when one compares the cloud geometry for these two firings at 450 seconds. Cloud S-II-14 (Figure 41) attained a height of approximately

3360 meters in 450 seconds while S-II-15 only reached a height of 1200 meters in the same period (Figure 52). The geometry dependence of the cloud on the ambient relative humidity is thus graphically demonstrated in these two firings. These results also indicate the futility of attempting to produce reasonable results with empirically based cloud growth formulas when the pertinent meteorological parameters are not included.

Although firing S-II-15 produced a well defined cloud photographically, this was not evidenced on the three passes through the cloud. The relative humidity traces for the entire flight, including the three passes through the cloud, produced a constant value of relative humidity at approximately 20%. This value is perhaps more indicative of the actual atmospheric value of relative humidity than the 10% produced by the radiosonde, since the 10% is approximately the lower limit of measurement for the sonde.

A comprehensive study of the relative humidity and disturbed temperature data for the three passes, and for periods outside the cloud, indicated that the aircraft data system was operating properly. Dry bulb temperatures from the aircraft compare (within  $2^{\circ}\text{C}$ ) to those measured by the sonde at a given altitude and, as previously mentioned, the relative humidity values as measured by the sonde and the aircraft compare very favorably. Based on these arguments we must conclude that the relative humidity trace (Figure 53) and the disturbed temperature

trace (Figure 54) are correct for this firing. It can be seen that there is no significant change in relative humidity for the pass through the cloud and that, statistically, there is no deviation of the cloud temperature from ambient. These data are only shown for pass 1 since subsequent passes (2 and 3) produced essentially identical results. Ignition for S-II-15 occurred at 1515:43 Central Daylight Time with pass 1 being made through the cloud approximately 4 minutes after ignition. Evidently the atmosphere was so dry on this particular day that the firing produced no perturbations on the atmosphere even in the interior of the cloud.

## CONCLUSIONS

The time dependent geometry and physical cloud properties have been presented for four static rocket firings, including two S-I-C firings and two S-II firings. Pertinent meteorological parameters have been presented for each firing and the prevailing weather conditions were seen to have a strong influence on the growth of the clouds. Although the maximum aircraft penetration altitude in the S-I-C clouds was approximately 4200 meters, the pilots estimated that on several occasions the maximum cloud tops appeared to reach 7500 meters.

A new technique was developed to verify the previous measurements of evaporation and entrainment of blast deflector cooling water into the cloud. Small hollow glass spheres (approximately 10 microns in diameter) were injected into the cooling water at the pumping station. These particles were subsequently detected on all passes through the clouds by using an impact type sampler. The particles are clearly identifiable under a microscope and are also sufficiently small that they may be injected into natural clouds at the updrafts near the base of the clouds.

Perhaps the most interesting data recorded were the reduced temperatures during the first passes through the developing clouds.

This is evidently a result of the very rapid vertical development of the clouds. Data presented in this report will provide input to an analytical model which will attempt to predict, using known numerical techniques, the time dependent geometry and properties of the cloud.

## Appendix I

### Tabulated Radiosonde Data

## S-IC-13

| HEIGHT | TEMP C | VTEMP C | PRESSURE | REL HUM | W DIR | W SPD<br>M/SEC | DEW PT |
|--------|--------|---------|----------|---------|-------|----------------|--------|
| 0      | 147    | 156     | 10260    | 490     | 950   | 50             | 42     |
| 132    | 127    | 135     | 10100    | 486     | 1170  | 56             | 22     |
| 291    | 113    | 121     | 9910     | 582     | 1151  | 52             | 34     |
| 444    | 99     | 107     | 9730     | 647     | 1186  | 55             | 35     |
| 616    | 88     | 96      | 9530     | 658     | 1177  | 52             | 28     |
| 765    | 73     | 80      | 9360     | 657     | 1014  | 41             | 13     |
| 925    | 64     | 70      | 9180     | 540     | 920   | 50             | -21    |
| 1087   | 52     | 57      | 9000     | 497     | 926   | 59             | -43    |
| 1150   | 46     | 51      | 8930     | 522     | 932   | 60             | -42    |
| 1261   | 50     | 55      | 8810     | 468     | 943   | 62             | -53    |
| 1354   | 52     | 55      | 8710     | 265     | 921   | 50             | -124   |
| 1420   | 52     | 53      | 8640     | 100     | 898   | 41             | -238   |
| 1467   | 49     | 50      | 8590     | 100     | 865   | 31             | -240   |
| 1592   | 59     | 62      | 8460     | 265     | 421   | 8              | -117   |
| 1689   | 59     | 67      | 8360     | 612     | 3291  | 11             | -8     |
| 1778   | 53     | 59      | 8270     | 525     | 3068  | 20             | -35    |
| 1957   | 40     | 48      | 8090     | 730     | 3073  | 33             | -3     |
| 1988   | 37     | 45      | 8060     | 728     | 3090  | 30             | -6     |
| 2140   | 31     | 38      | 7910     | 643     | 3227  | 20             | -28    |
| 2316   | 23     | 27      | 7740     | 493     | 204   | 4              | -71    |
| 2495   | 8      | 12      | 7570     | 474     | 914   | 9              | -90    |
| 2677   | -2     | 2       | 7400     | 650     | 1656  | 13             | -60    |
| 2852   | -14    | -12     | 7240     | 196     | 1892  | 32             | -216   |
| 3029   | -24    | -22     | 7080     | 245     | 2065  | 29             | -199   |
| 3199   | -36    | -35     | 6930     | 100     | 2725  | 24             | -307   |

Radiosonde Data: S-IC-13

## S-IC-13

| HEIGHT | TEMP C | VTEMP C | PRESSURE | REL HUM | W DIR | W SPD<br>M/SEC | DEW PT |
|--------|--------|---------|----------|---------|-------|----------------|--------|
| 3371   | -47    | -47     | 6780     | 131     | 2956  | 36             | -288   |
| 3500   | -57    | -56     | 6670     | 146     | 2832  | 35             | -284   |
| 3535   | -57    | -56     | 6640     | 132     | 2798  | 36             | -295   |
| 3630   | -57    | -56     | 6560     | 132     | 2763  | 39             | -295   |
| 3714   | -64    | -63     | 6490     | 103     | 2737  | 43             | -326   |
| 3921   | -72    | -70     | 6320     | 384     | 2696  | 63             | -189   |
| 4108   | -93    | -90     | 6170     | 639     | 2701  | 81             | -148   |
| 4285   | -105   | -102    | 6030     | 715     | 2899  | 80             | -146   |
| 4400   | -112   | -108    | 5940     | 770     | 2971  | 69             | -144   |
| 4491   | -121   | -118    | 5870     | 637     | 3047  | 61             | -175   |
| 4676   | -134   | -131    | 5730     | 720     | 2914  | 67             | -173   |
| 4769   | -144   | -142    | 5660     | 749     | 2932  | 80             | -179   |
| 4877   | -144   | -142    | 5580     | 633     | 2948  | 95             | -198   |
| 4973   | -144   | -143    | 5510     | 493     | 2963  | 97             | -227   |
| 5069   | -152   | -150    | 5440     | 514     | 2977  | 99             | -229   |
| 5252   | -169   | -167    | 5310     | 536     | 2962  | 86             | -240   |
| 5452   | -181   | -179    | 5170     | 511     | 3035  | 73             | -257   |
| 5627   | -193   | -191    | 5050     | 516     | 3125  | 68             | -267   |
| 5821   | -205   | -203    | 4920     | 585     | 3152  | 71             | -264   |
| 6018   | -219   | -218    | 4790     | 577     | 3032  | 109            | -280   |
| 6064   | -221   | -219    | 4760     | 577     | 3012  | 117            | -281   |

Radiosonde Data: S-IC-13

## S-IC-15

| HEIGHT | TEMP C | VTEMP C | PRESSURE | REL HUM | W DIR | W SPD<br>M/SEC | DEW PT |
|--------|--------|---------|----------|---------|-------|----------------|--------|
| 0      | 267    | 284     | 10140    | 420     | 49    | 15             | 128    |
| 385    | 229    | 243     | 9703     | 430     | 247   | 60             | 96     |
| 488    | 218    | 231     | 9590     | 433     | 237   | 60             | 88     |
| 761    | 191    | 204     | 9288     | 480     | 209   | 60             | 79     |
| 1134   | 155    | 167     | 8892     | 553     | 182   | 65             | 66     |
| 1302   | 139    | 150     | 8720     | 591     | 218   | 71             | 60     |
| 1508   | 122    | 132     | 8508     | 524     | 254   | 79             | 28     |
| 1676   | 109    | 117     | 8340     | 472     | 316   | 87             | 1      |
| 1807   | 111    | 117     | 8210     | 323     | 357   | 94             | -47    |
| 1907   | 108    | 114     | 8112     | 320     | 384   | 100            | -51    |
| 2170   | 100    | 105     | 7860     | 311     | 446   | 98             | -62    |
| 2356   | 100    | 106     | 7685     | 302     | 490   | 98             | -65    |
| 2762   | 102    | 107     | 7320     | 283     | 440   | 78             | -72    |
| 2834   | 97     | 102     | 7256     | 279     | 428   | 75             | -78    |
| 2922   | 92     | 97      | 7180     | 275     | 383   | 70             | -85    |
| 3062   | 96     | 101     | 7060     | 253     | 298   | 63             | -92    |
| 3250   | 87     | 91      | 6900     | 246     | 158   | 57             | -103   |
| 3641   | 67     | 71      | 6581     | 232     | 3539  | 54             | -127   |
| 3693   | 65     | 68      | 6540     | 230     | 3532  | 55             | -130   |
| 4033   | 39     | 44      | 6271     | 326     | 3495  | 64             | -109   |
| 4380   | 13     | 19      | 6010     | 465     | 3468  | 68             | -88    |
| 4430   | 10     | 15      | 5972     | 449     | 3464  | 69             | -95    |
| 4860   | -17    | -14     | 5660     | 331     | 3387  | 81             | -158   |
| 4902   | -20    | -17     | 5630     | 321     | 3388  | 84             | -164   |
| 5059   | -25    | -22     | 5520     | 284     | 3390  | 92             | -182   |
| 5263   | -38    | -35     | 5378     | 301     | 3392  | 104            | -187   |
| 5671   | -64    | -61     | 5105     | 338     | 3363  | 133            | -196   |
| 6078   | -90    | -87     | 4846     | 382     | 3304  | 159            | -206   |

Radiosonde Data: S-IC-15

## S-II-14

| HEIGHT | TEMP C | VTEMP C | PRESSURE | REL HUM | W DIR | W SPD<br>M/SEC | DEW PT |
|--------|--------|---------|----------|---------|-------|----------------|--------|
| 0      | 331    | 361     | 10130    | 500     | 2800  | 10             | 213    |
| 143    | 303    | 330     | 9970     | 532     | 3222  | 9              | 197    |
| 233    | 297    | 325     | 9870     | 562     | 3447  | 11             | 200    |
| 315    | 287    | 314     | 9780     | 594     | 3342  | 12             | 200    |
| 407    | 279    | 306     | 9680     | 608     | 2861  | 8              | 196    |
| 508    | 271    | 298     | 9570     | 622     | 2726  | 12             | 192    |
| 601    | 261    | 287     | 9470     | 640     | 2817  | 11             | 188    |
| 705    | 252    | 277     | 9360     | 645     | 2755  | 10             | 180    |
| 818    | 242    | 266     | 9240     | 650     | 2888  | 8              | 172    |
| 933    | 229    | 252     | 9120     | 656     | 3495  | 9              | 161    |
| 1077   | 218    | 241     | 8970     | 673     | 180   | 12             | 155    |
| 1224   | 204    | 225     | 8820     | 684     | 283   | 6              | 144    |
| 1382   | 192    | 212     | 8660     | 682     | 3078  | 0              | 132    |
| 1542   | 182    | 200     | 8500     | 681     | 1678  | 3              | 122    |
| 1695   | 173    | 191     | 8350     | 678     | 1408  | 9              | 113    |
| 1829   | 162    | 178     | 8220     | 676     | 1333  | 14             | 102    |
| 1975   | 158    | 174     | 8080     | 647     | 1354  | 16             | 92     |
| 2124   | 155    | 170     | 7940     | 614     | 1258  | 17             | 81     |
| 2243   | 152    | 164     | 7830     | 488     | 1302  | 11             | 45     |
| 2362   | 148    | 159     | 7720     | 439     | 2334  | 2              | 27     |
| 2473   | 139    | 150     | 7620     | 472     | 169   | 3              | 28     |
| 2595   | 126    | 139     | 7510     | 593     | 622   | 7              | 49     |
| 2765   | 120    | 133     | 7360     | 618     | 850   | 6              | 49     |

Radiosonde Data: S-II-14



## S-II-14

| HEIGHT | TEMP C | VTEMP C | PRESSURE | REL HUM | W DIR | W SPD<br>M/SEC | DEW PT |
|--------|--------|---------|----------|---------|-------|----------------|--------|
| 2925   | 110    | 123     | 7220     | 621     | 465   | 5              | 41     |
| 3065   | 101    | 112     | 7100     | 584     | 614   | 13             | 23     |
| 3267   | 93     | 101     | 6930     | 434     | 769   | 15             | -24    |
| 3448   | 78     | 86      | 6780     | 493     | 834   | 18             | -20    |
| 3645   | 63     | 72      | 6620     | 542     | 748   | 30             | -21    |
| 3820   | 48     | 57      | 6480     | 639     | 539   | 22             | -13    |
| 3985   | 43     | 51      | 6350     | 600     | 379   | 9              | -27    |
| 4153   | 34     | 40      | 6220     | 501     | 296   | 7              | -59    |
| 4298   | 28     | 34      | 6110     | 492     | 117   | 4              | -67    |
| 4418   | 18     | 24      | 6020     | 495     | 2955  | 0              | -75    |
| 4553   | 6      | 12      | 5920     | 509     | 312   | 3              | -82    |
| 4662   | 2      | 7       | 5840     | 437     | 254   | 3              | -106   |
| 4801   | 0      | 3       | 5740     | 381     | 283   | 3              | -125   |
| 4899   | -13    | -9      | 5670     | 381     | 509   | 4              | -137   |
| 5040   | -23    | -19     | 5570     | 364     | 3017  | 2              | -151   |
| 5170   | -27    | -24     | 5480     | 298     | 2840  | 10             | -179   |
| 5286   | -32    | -30     | 5400     | 254     | 2692  | 13             | -202   |
| 5404   | -41    | -40     | 5320     | 138     | 2465  | 18             | -276   |
| 5508   | -46    | -45     | 5250     | 181     | 2425  | 22             | -252   |
| 5629   | -53    | -52     | 5170     | 232     | 2308  | 19             | -230   |
| 5736   | -60    | -59     | 5100     | 126     | 2090  | 22             | -302   |
| 5859   | -70    | -69     | 5020     | 214     | 2172  | 13             | -253   |
| 6016   | -80    | -78     | 4920     | 308     | 2557  | 11             | -221   |

Radiosonde Data: S-II-14

## S-II-15

| HEIGHT | TEMP C | VTEMP C | PRESSURE | REL HUM | W DIR | W SPD<br>M/SEC | DEW PT |
|--------|--------|---------|----------|---------|-------|----------------|--------|
| 0      | 226    | 235     | 10180    | 270     | 3300  | 31             | 27     |
| 85     | 213    | 218     | 10080    | 153     | 3404  | 32             | -60    |
| 171    | 202    | 207     | 9980     | 161     | 3498  | 34             | -62    |
| 318    | 186    | 191     | 9810     | 177     | 26    | 40             | -62    |
| 494    | 171    | 175     | 9610     | 185     | 29    | 46             | -69    |
| 664    | 154    | 158     | 9420     | 220     | 3599  | 63             | -61    |
| 863    | 134    | 139     | 9200     | 260     | 34    | 64             | -56    |
| 1010   | 121    | 124     | 9040     | 158     | 101   | 57             | -130   |
| 1048   | 129    | 131     | 9000     | 100     | 114   | 54             | -178   |
| 1198   | 134    | 136     | 8840     | 100     | 178   | 43             | -175   |
| 1246   | 136    | 138     | 8790     | 100     | 270   | 38             | -173   |
| 1361   | 129    | 131     | 8670     | 100     | 582   | 32             | -178   |
| 1547   | 118    | 120     | 8480     | 100     | 393   | 37             | -187   |
| 1736   | 110    | 112     | 8290     | 100     | 47    | 44             | -193   |
| 1786   | 108    | 110     | 8240     | 100     | 17    | 43             | -194   |
| 1908   | 108    | 110     | 8120     | 100     | 3538  | 40             | -194   |
| 2001   | 108    | 110     | 8030     | 100     | 3391  | 38             | -194   |
| 2084   | 102    | 104     | 7950     | 100     | 3252  | 38             | -199   |
| 2242   | 94     | 96      | 7800     | 100     | 2921  | 55             | -205   |
| 2403   | 79     | 81      | 7650     | 100     | 2815  | 76             | -217   |
| 2576   | 65     | 67      | 7490     | 100     | 2686  | 86             | -228   |
| 2742   | 59     | 61      | 7340     | 100     | 2537  | 89             | -232   |

Radiosonde Data: S-II-15

## S-II-15

| HEIGHT | TEMP C | VTEMP C | PRESSURE | REL HUM | W DIR | W SPD<br>M/SEC | DEW PT |
|--------|--------|---------|----------|---------|-------|----------------|--------|
| 2922   | 51     | 52      | 7180     | 100     | 2524  | 70             | -239   |
| 3105   | 43     | 44      | 7020     | 100     | 2771  | 58             | -245   |
| 3164   | 45     | 46      | 6970     | 100     | 2817  | 59             | -244   |
| 3269   | 37     | 38      | 6880     | 100     | 2895  | 60             | -249   |
| 3435   | 21     | 22      | 6740     | 100     | 2891  | 55             | -262   |
| 3605   | 11     | 12      | 6600     | 100     | 2854  | 63             | -270   |
| 3776   | -2     | -1      | 6460     | 100     | 2779  | 72             | -281   |
| 3951   | -14    | -13     | 6320     | 100     | 2672  | 80             | -290   |
| 4129   | -23    | -23     | 6180     | 100     | 2603  | 92             | -297   |
| 4285   | -33    | -32     | 6060     | 100     | 2606  | 101            | -305   |
| 4455   | -49    | -48     | 5930     | 100     | 2620  | 103            | -317   |
| 4629   | -65    | -65     | 5800     | 100     | 2570  | 95             | -330   |
| 4792   | -83    | -83     | 5680     | 100     | 2528  | 82             | -344   |
| 4943   | -98    | -98     | 5570     | 100     | 2581  | 84             | -356   |
| 5125   | -116   | -115    | 5440     | 100     | 2648  | 99             | -370   |
| 5295   | -130   | -130    | 5320     | 100     | 2672  | 96             | -381   |
| 5468   | -146   | -145    | 5200     | 100     | 2566  | 84             | -393   |
| 5615   | -156   | -156    | 5100     | 100     | 2483  | 104            | -401   |
| 5779   | -169   | -169    | 4990     | 100     | 2513  | 102            | -412   |
| 5915   | -182   | -182    | 4900     | 100     | 2557  | 96             | -422   |
| 6054   | -193   | -193    | 4810     | 100     | 2559  | 111            | -431   |

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Radiosonde Data: S-II-15

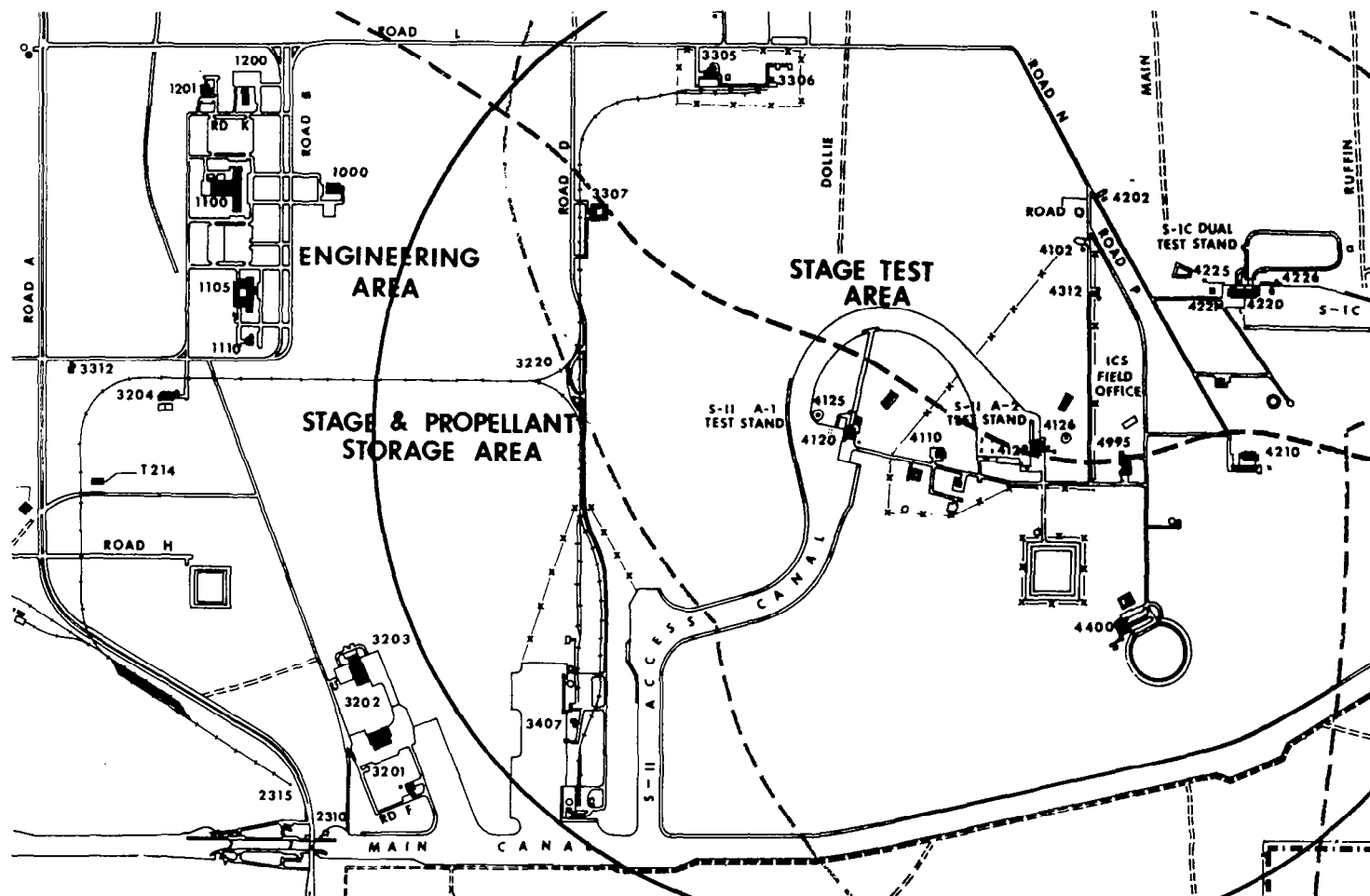


Figure 1. Map of Mississippi Test Facility.

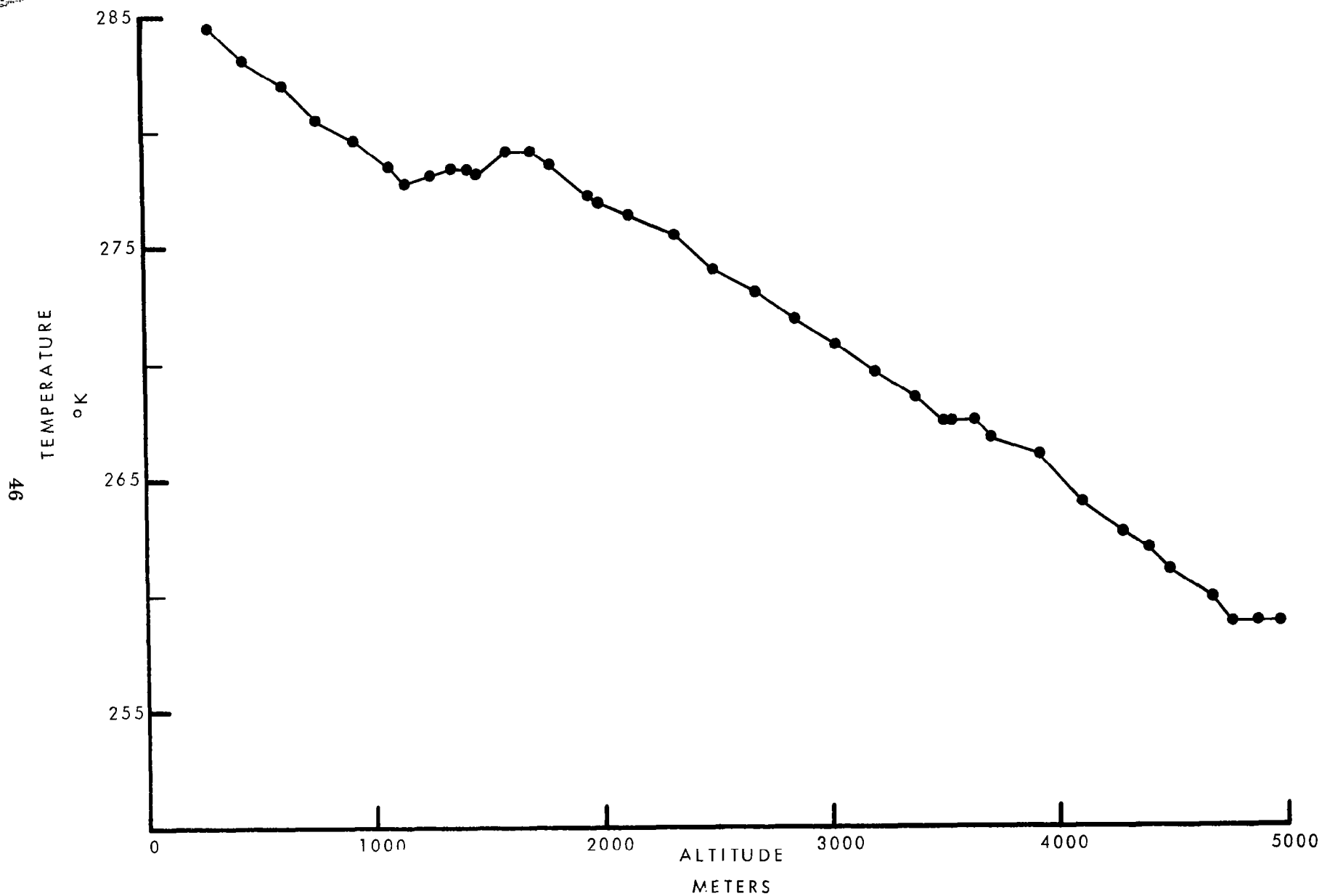


Figure 2. Radiosonde Temperature Sounding.  
Firing S-IC-13.

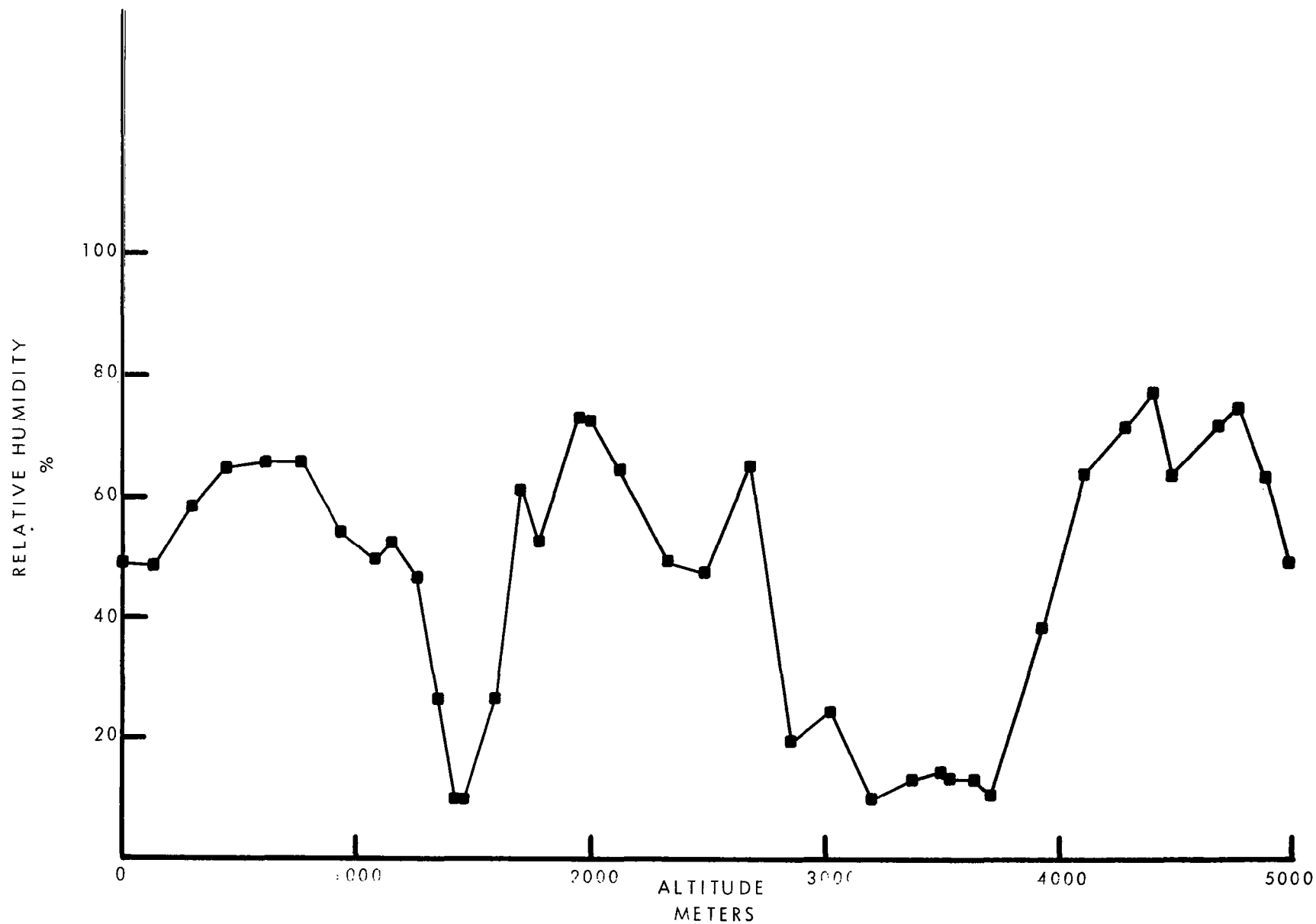


Figure 3. Radiosonde Relative Humidity Sounding.  
Firing S-1C-13.



Figure 4. Cloud Photograph 20 Seconds After Ignition. Firing S-IC-13.

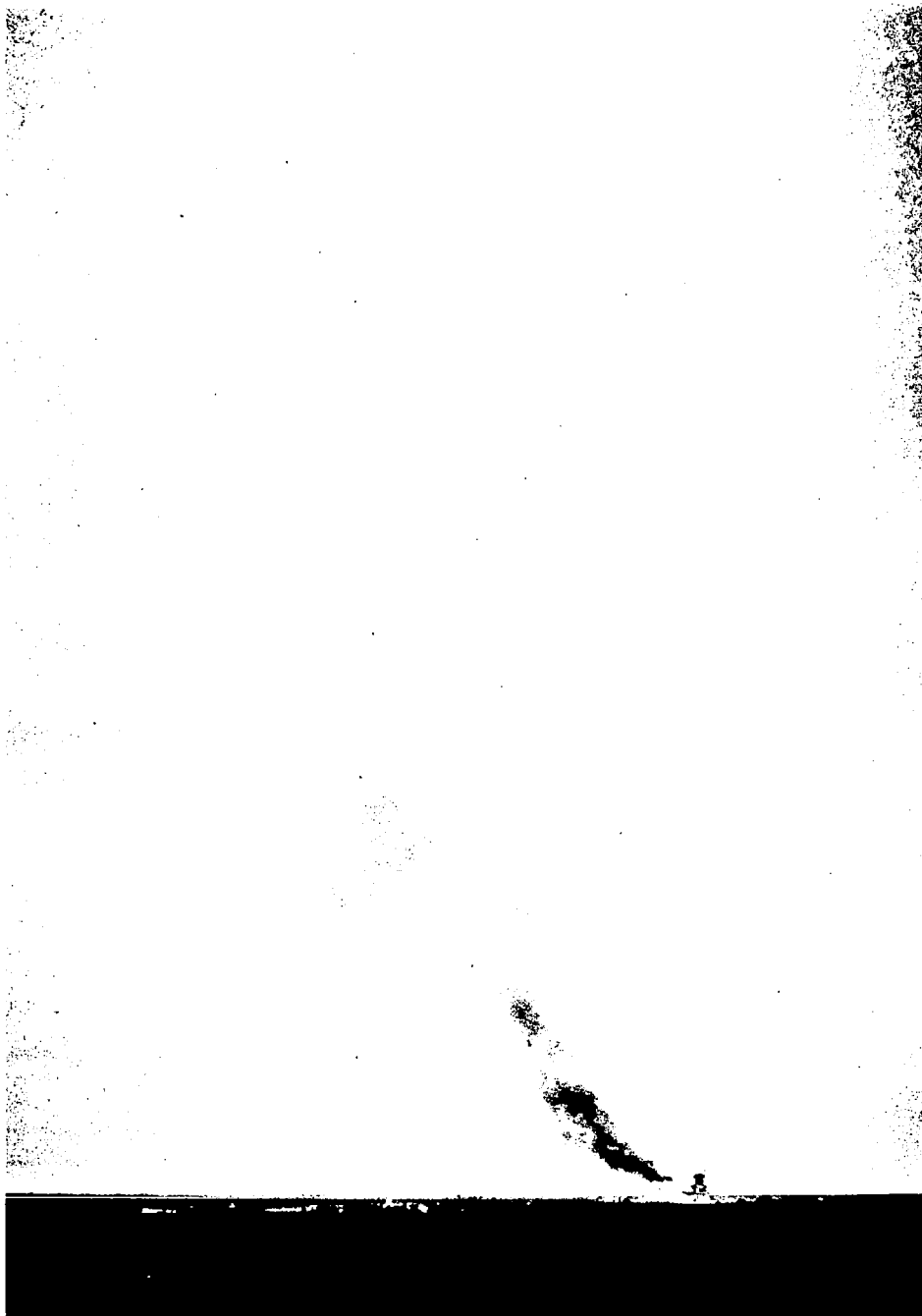


Figure 5. Cloud Photograph 60 Seconds After Ignition. Firing S-IC-13.



Figure 6. Cloud Photograph 160 Seconds After Ignition. Firing S-IC-13.

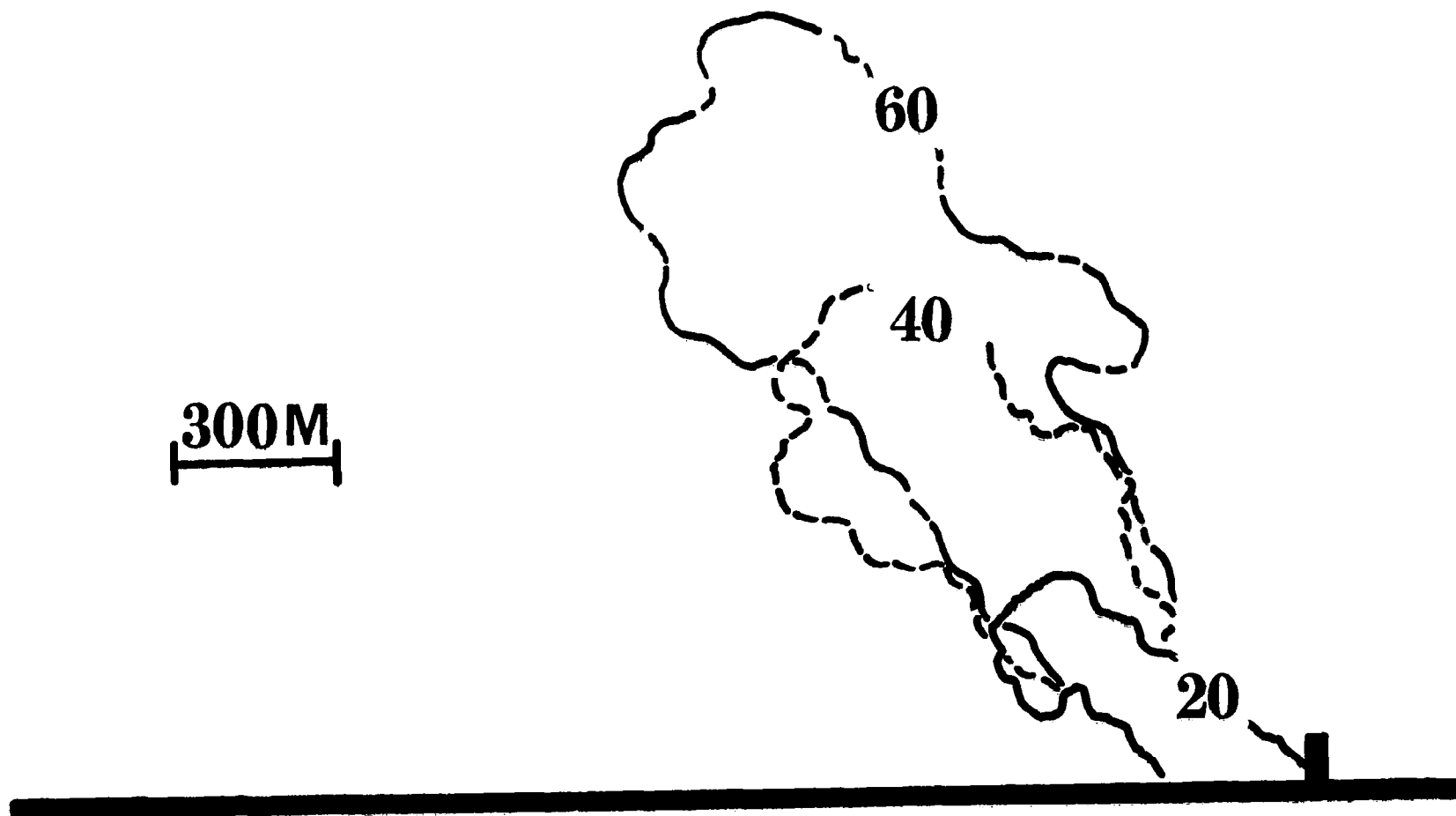


Figure 7. Rectified Cloud Geometry. Firing S-IC-13.

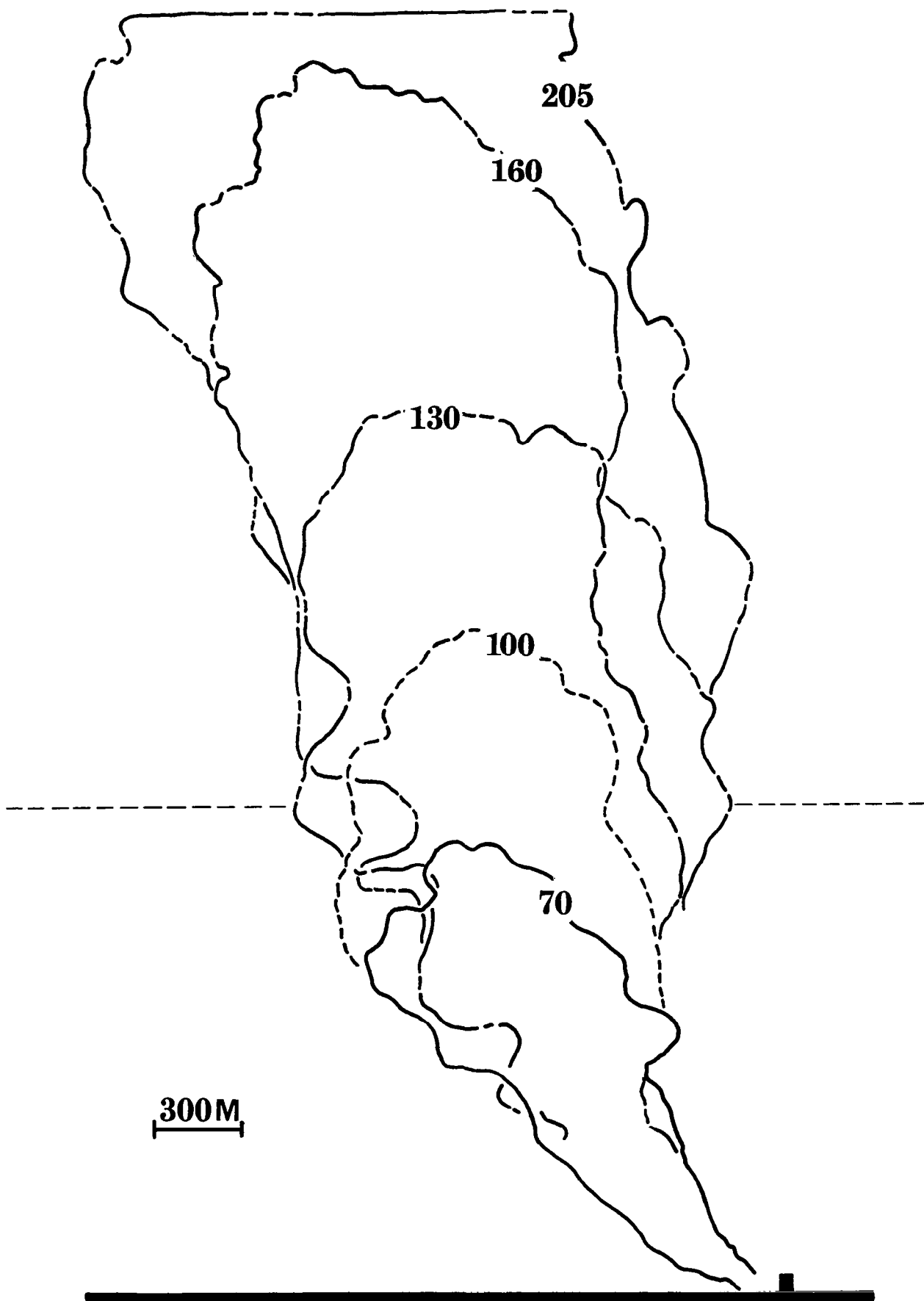


Figure 8. Rectified Cloud Geometry. Firing S-IC-13.

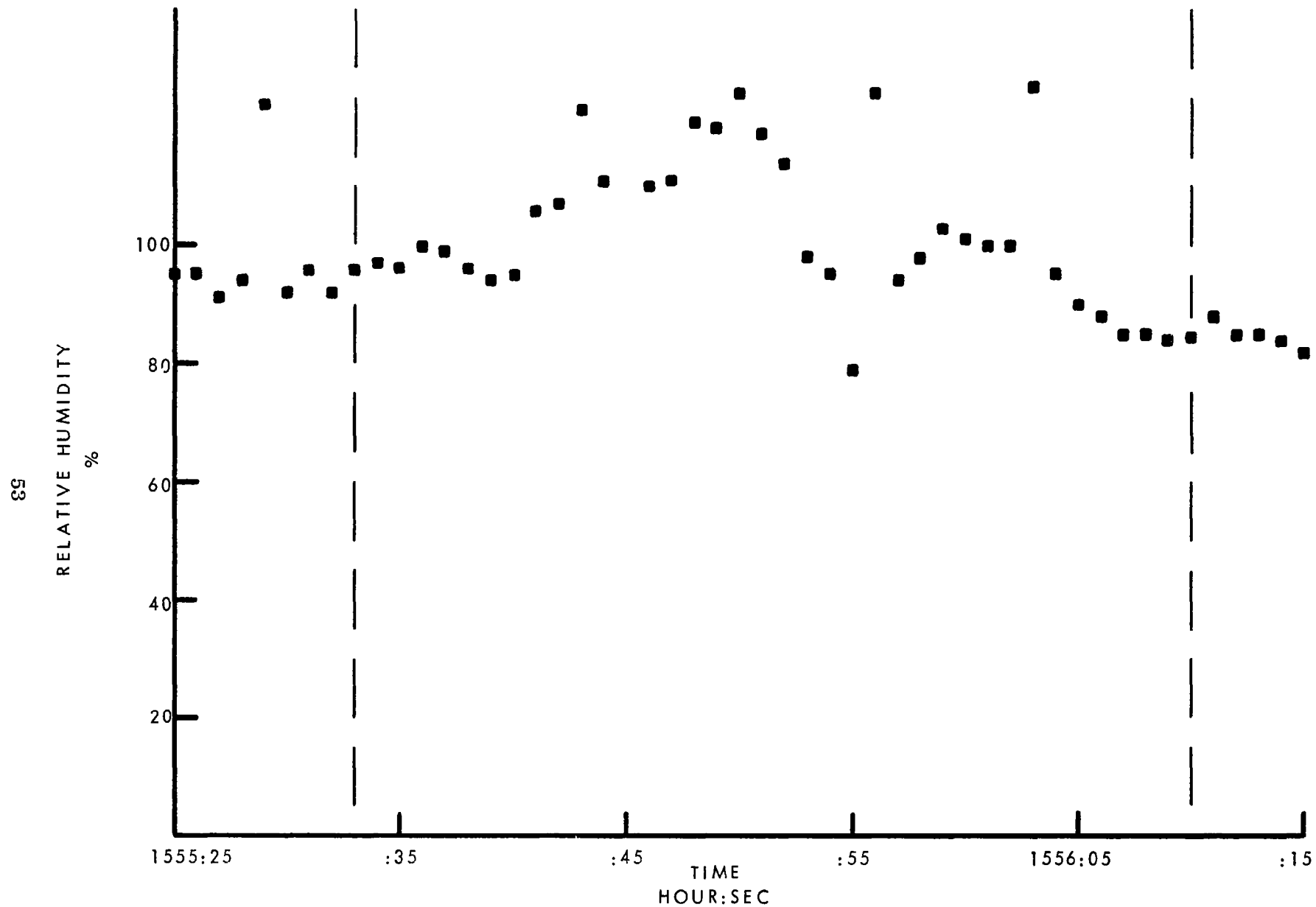


Figure 9. Relative Humidity In Cloud. Pass 1.  
Firing S-IC-13. Penn. State Aircraft.

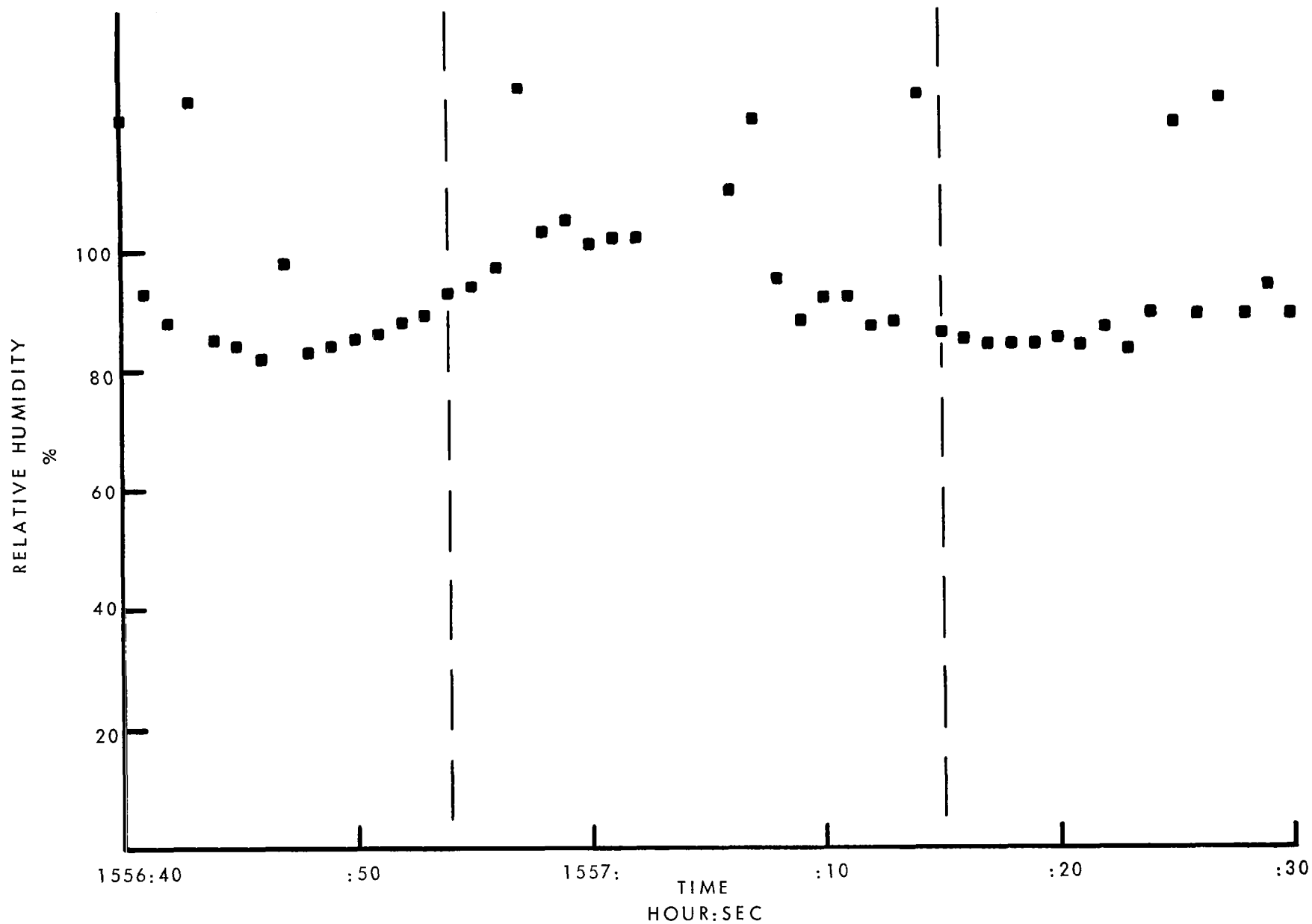


Figure 10. Relative Humidity In Cloud. Pass 2.  
Firing S-IC-13. Penn. State Aircraft.

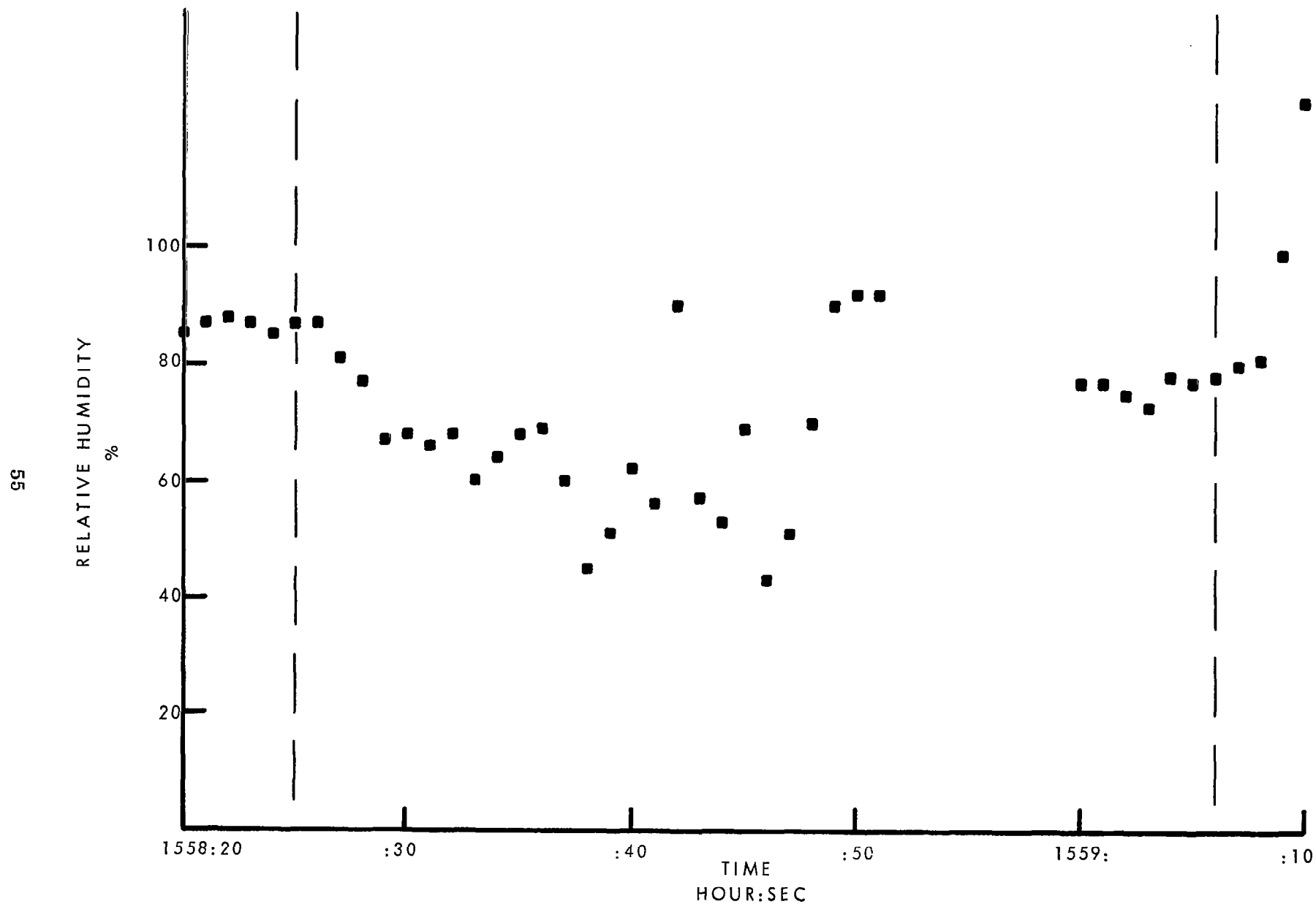


Figure 11. Relative Humidity In Cloud. Pass 3.  
Firing S-IC-13. Penn. State Aircraft.

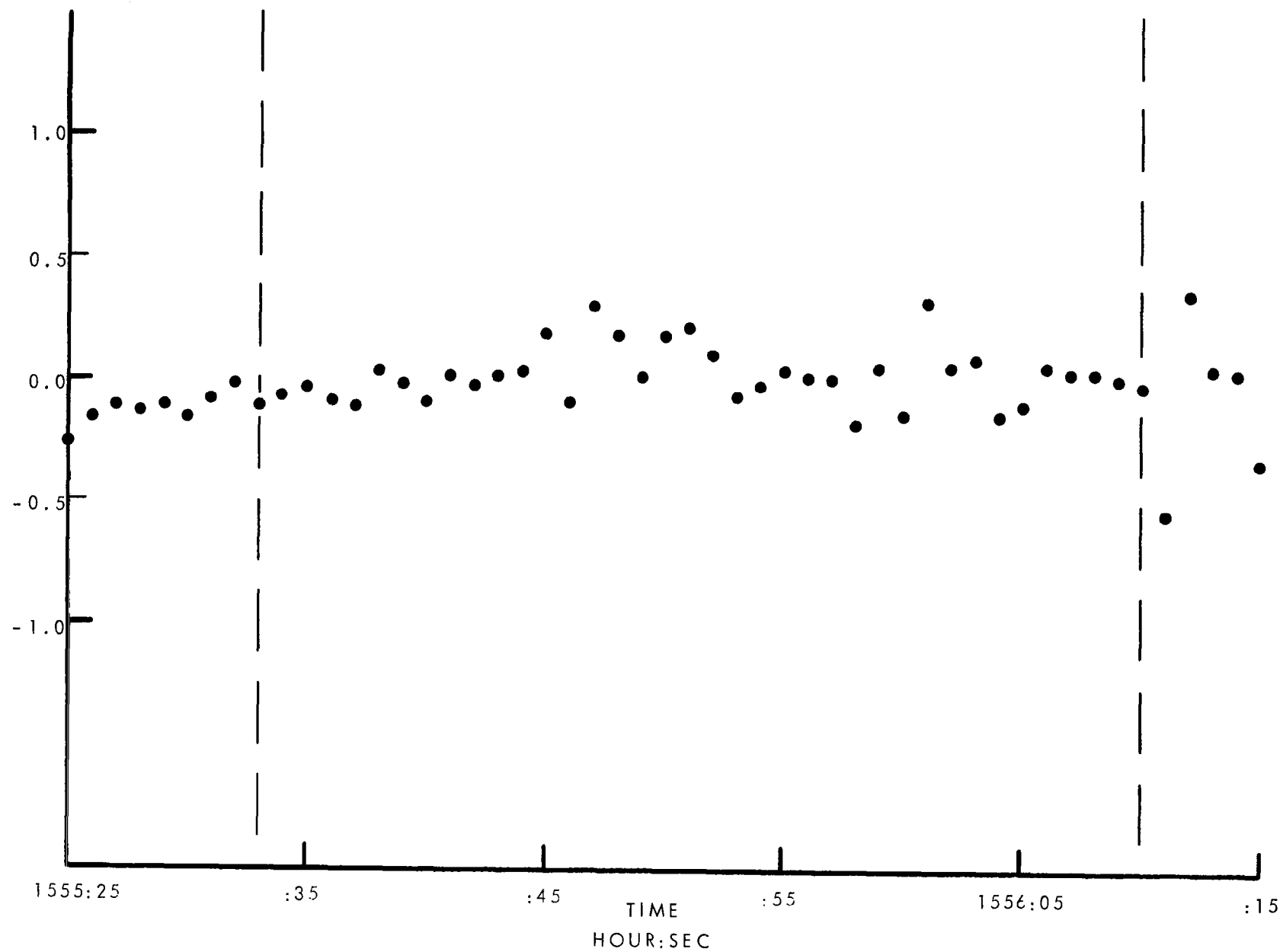


Figure 12. Disturbed Temperature In Cloud. Pass 1.  
Firing S-IC-13. Penn. State Aircraft.

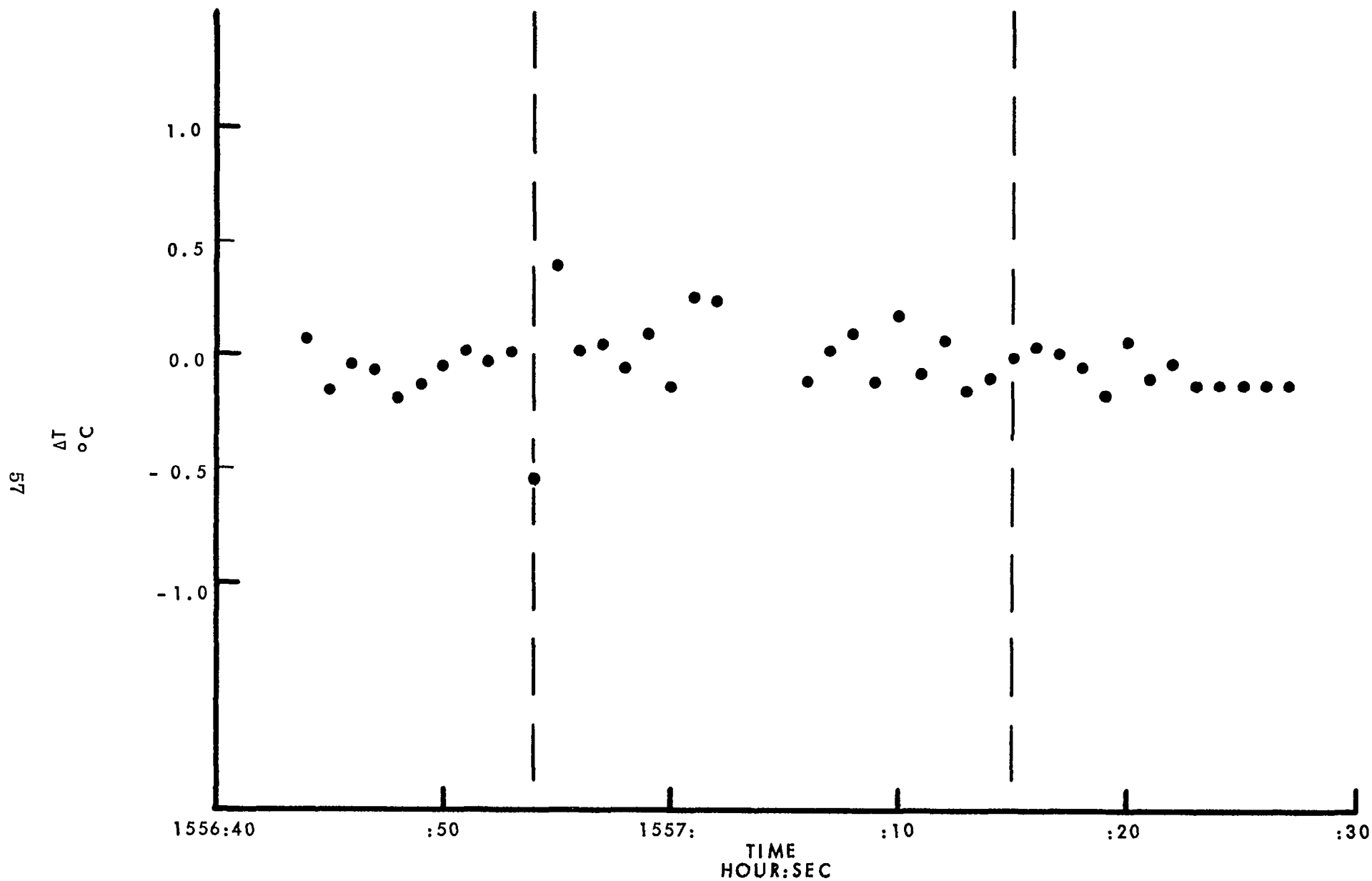


Figure 13. Disturbed Temperature In Cloud. Pass 2.  
Firing S-1C-13. Penn. State Aircraft.

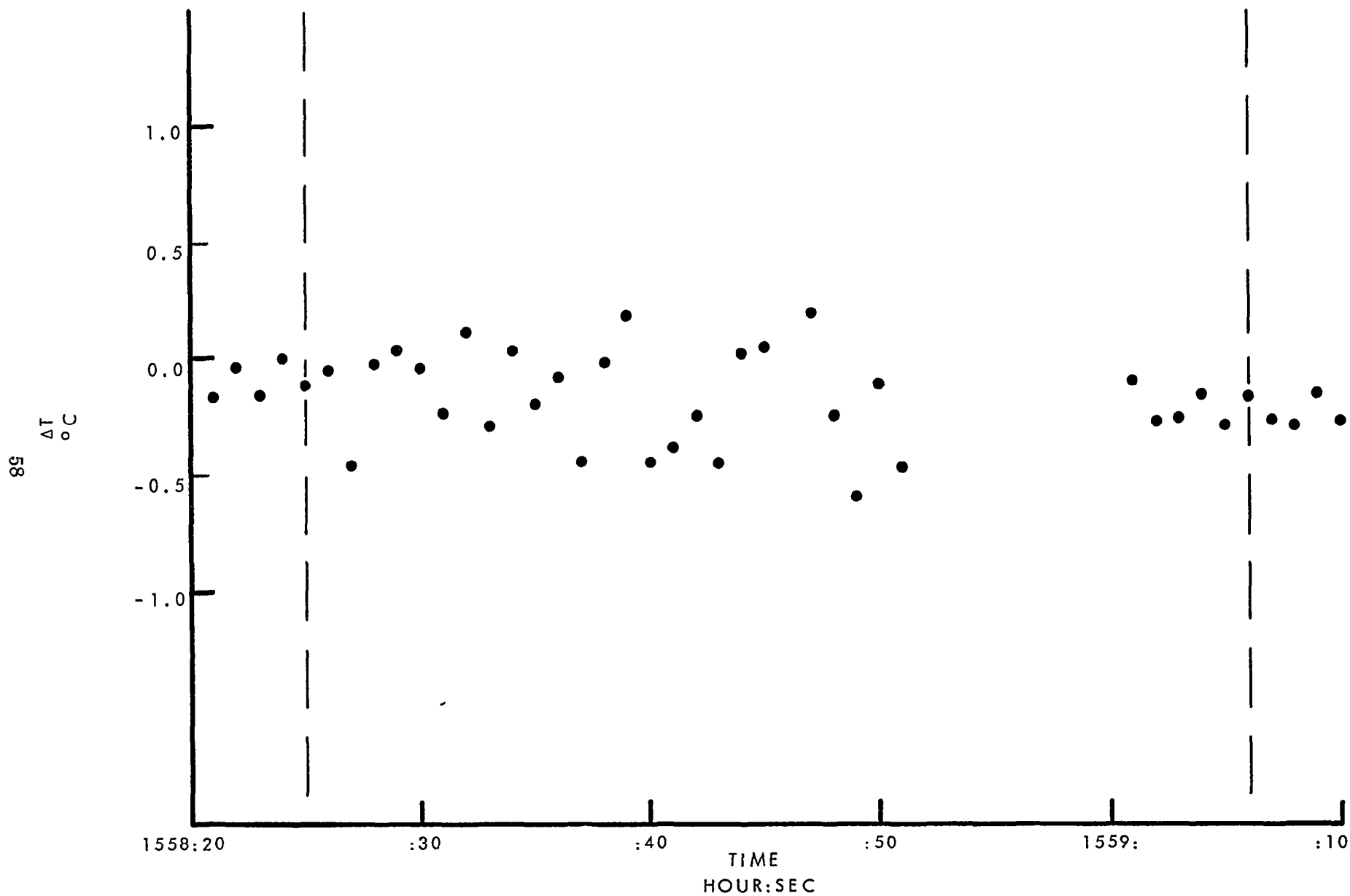


Figure 14. Disturbed Temperature In Cloud. Pass 3.  
Firing S-IC-13. Penn. State Aircraft.

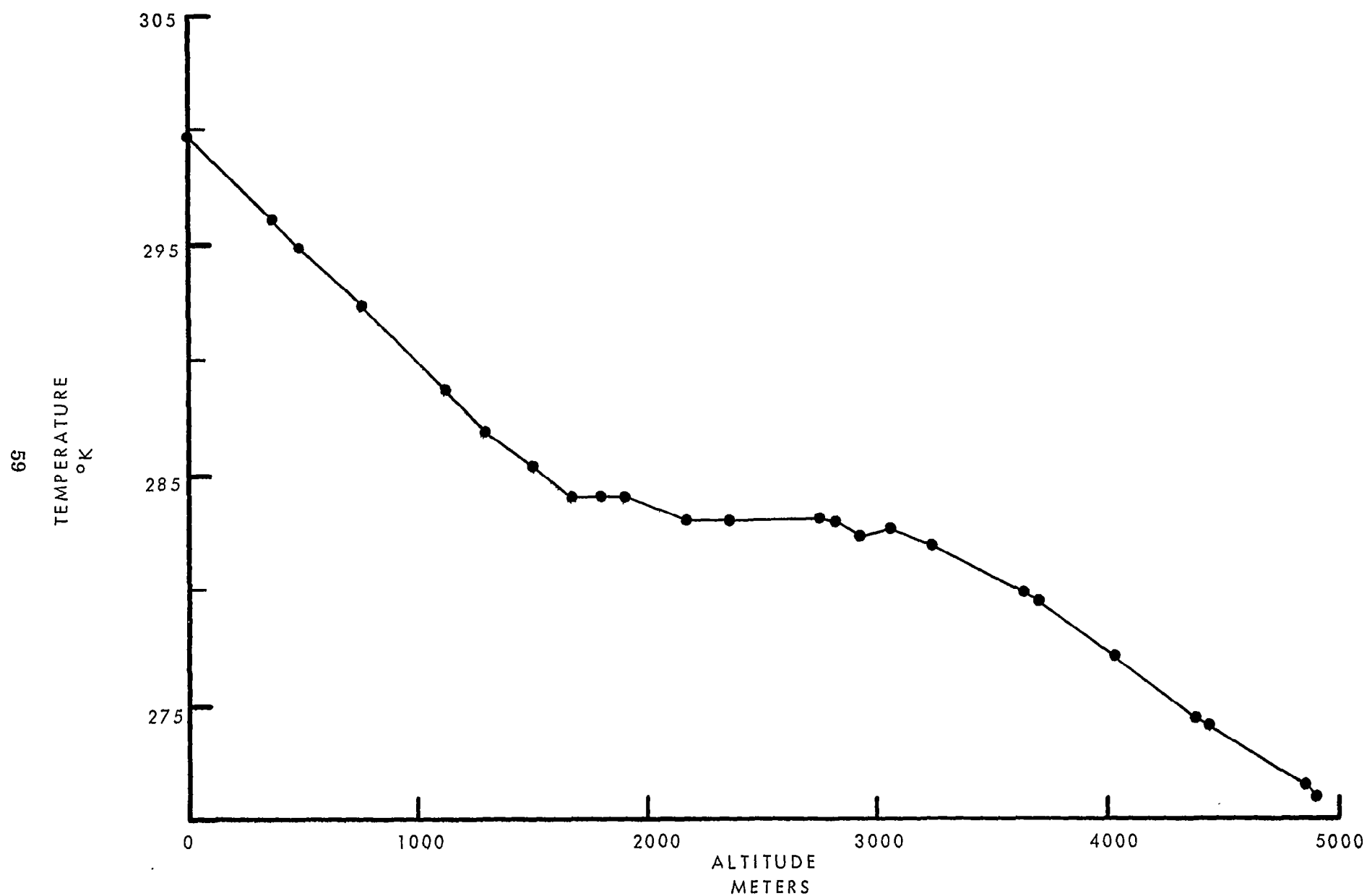


Figure 15. Radiosonde Temperature Sounding.  
Firing S-IC-15.

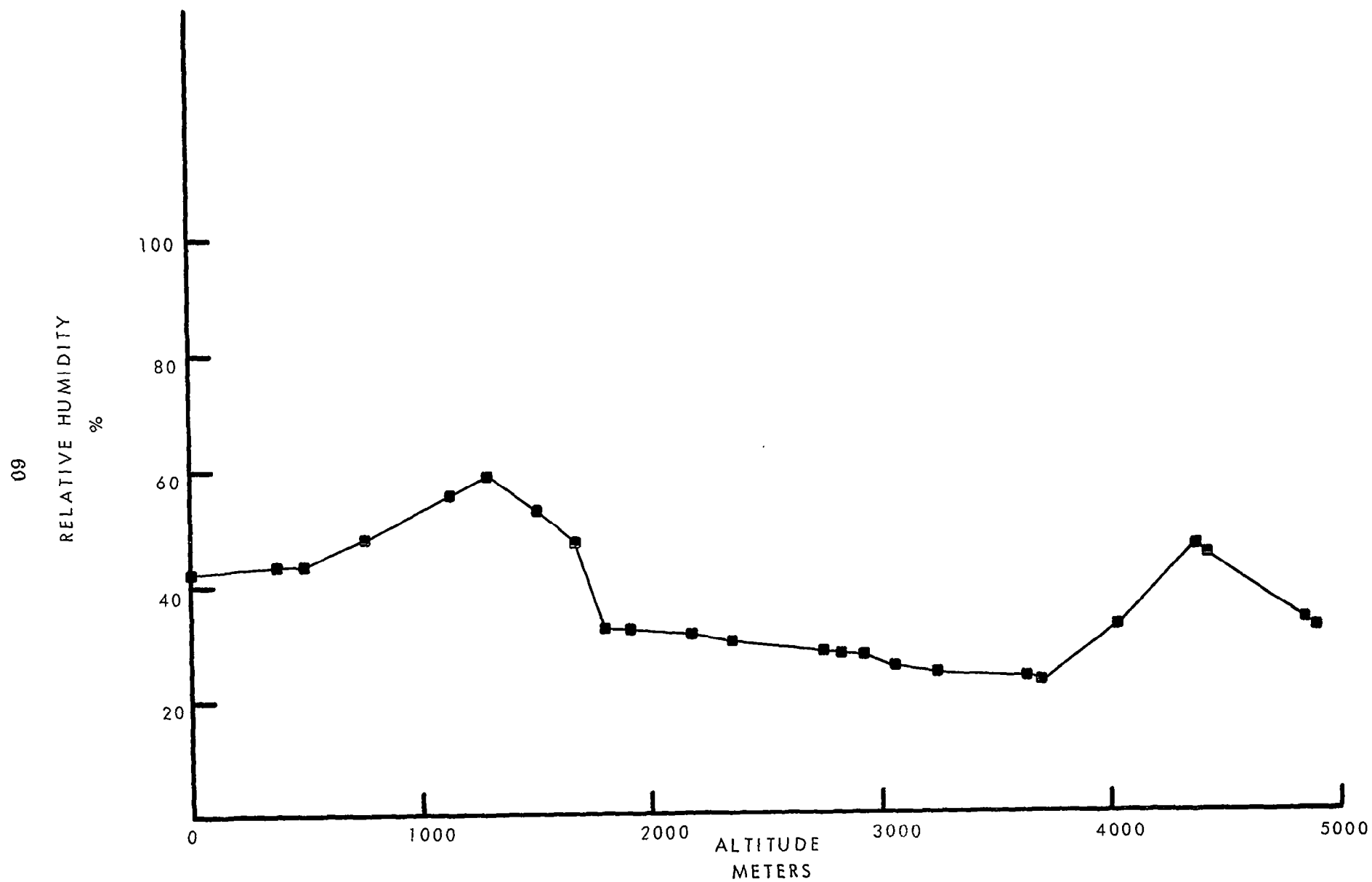


Figure 16. Radiosonde Relative Humidity Sounding.  
Firing S-1C-15.

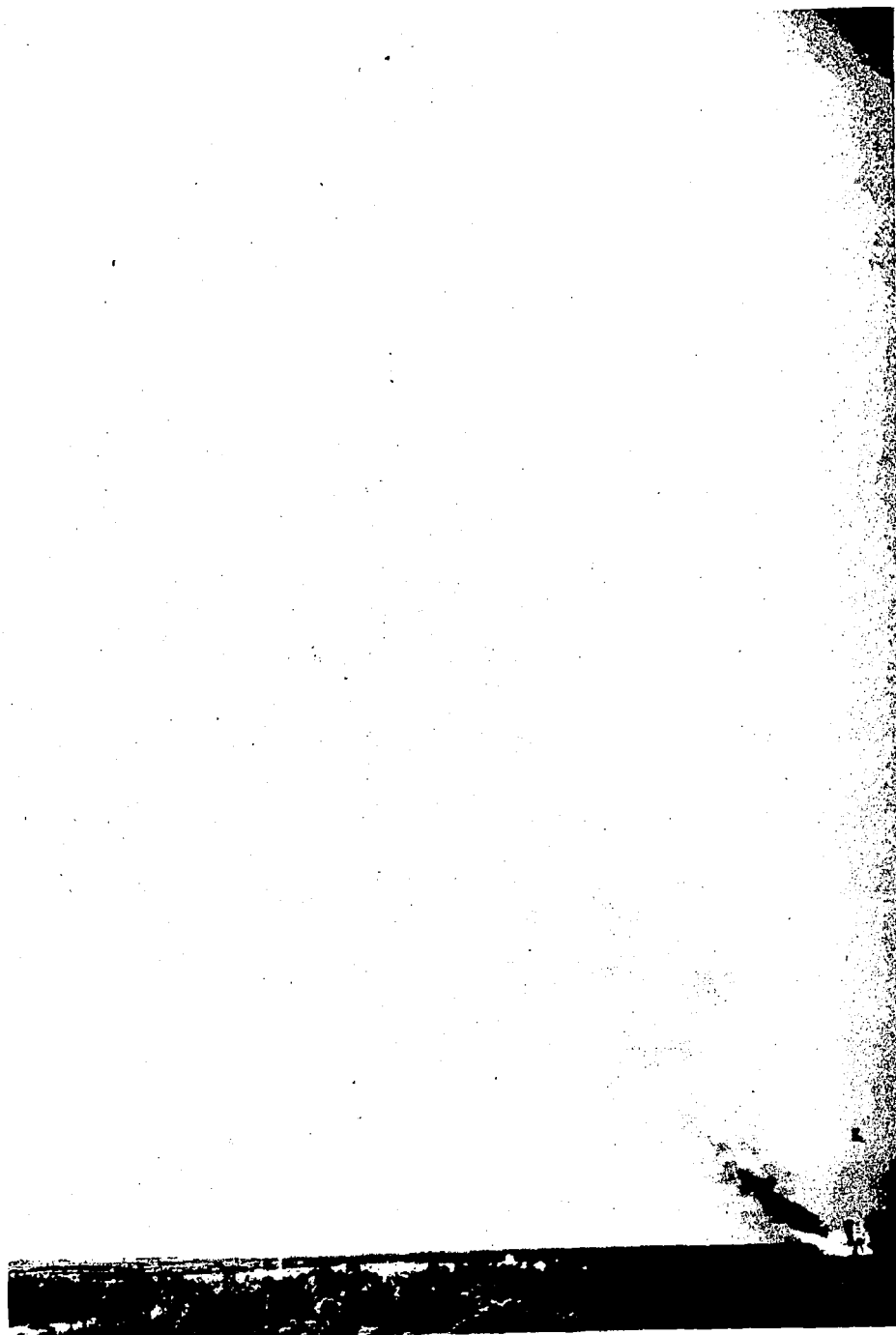


Figure 17. Cloud Photograph 65 Seconds After Ignition. Firing S-IC-15.

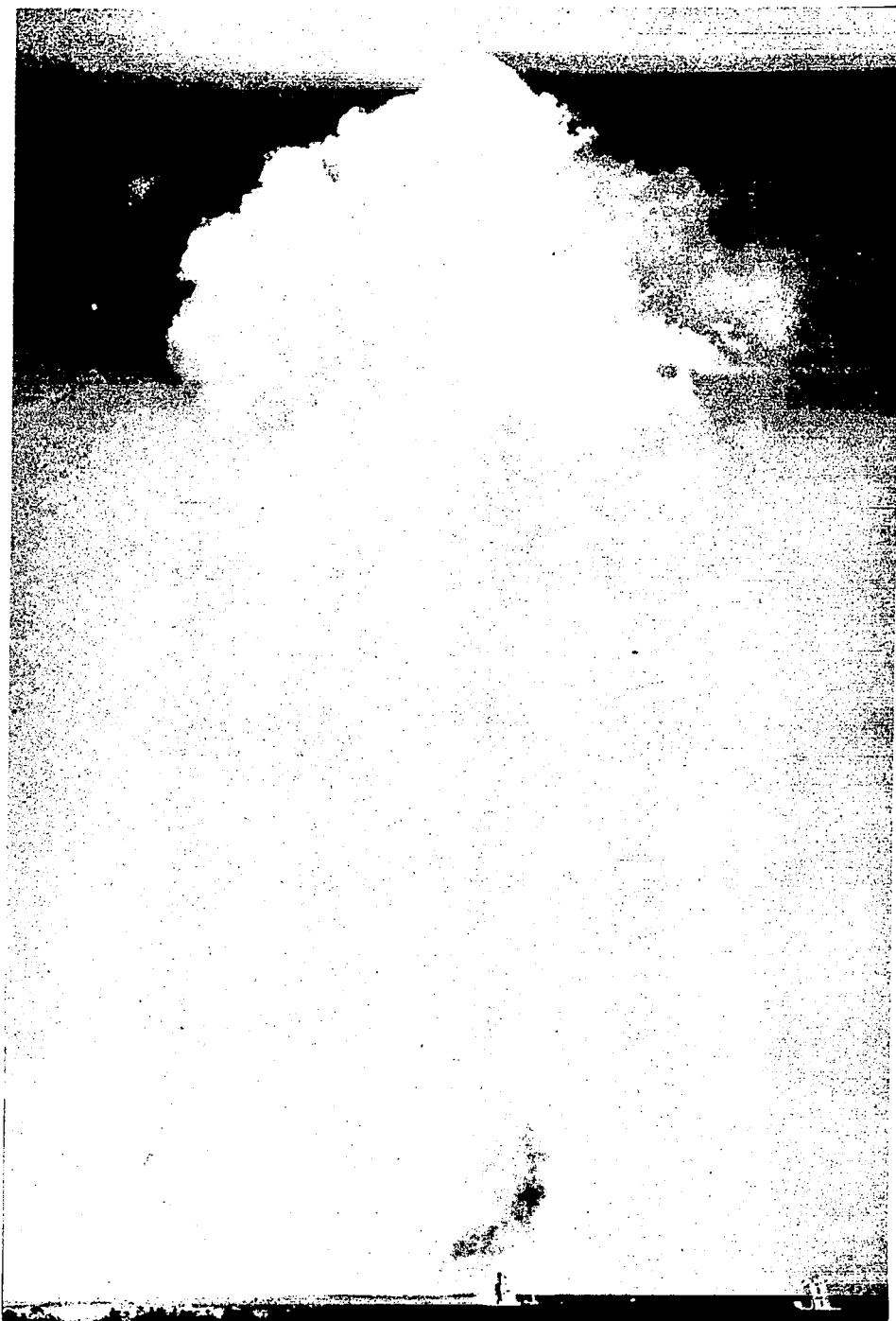


Figure 18. Cloud Photograph 200 Seconds After Ignition. Firing S-IC-15.

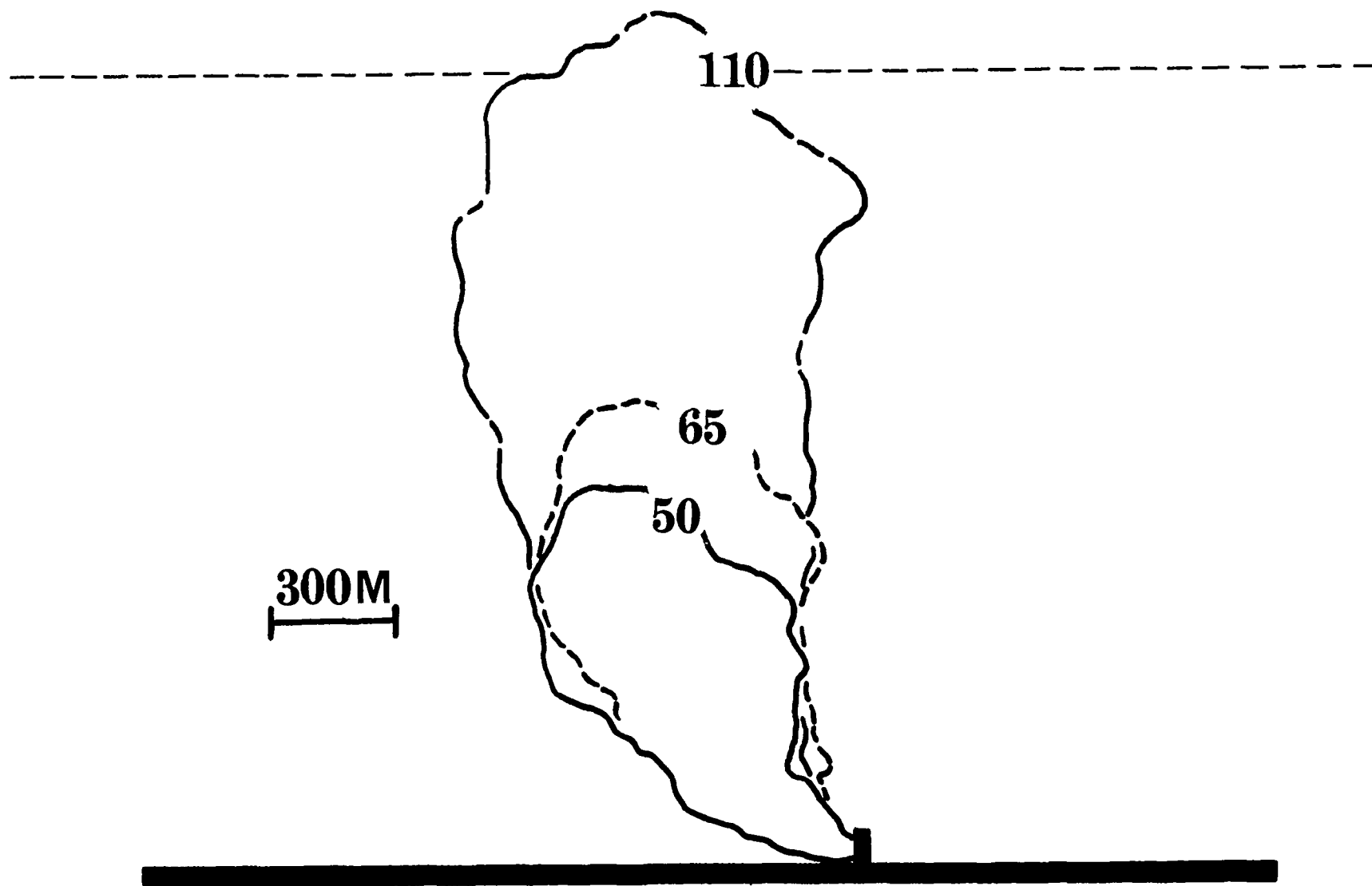


Figure 19. Rectified Cloud Geometry. Firing S-IC-15.

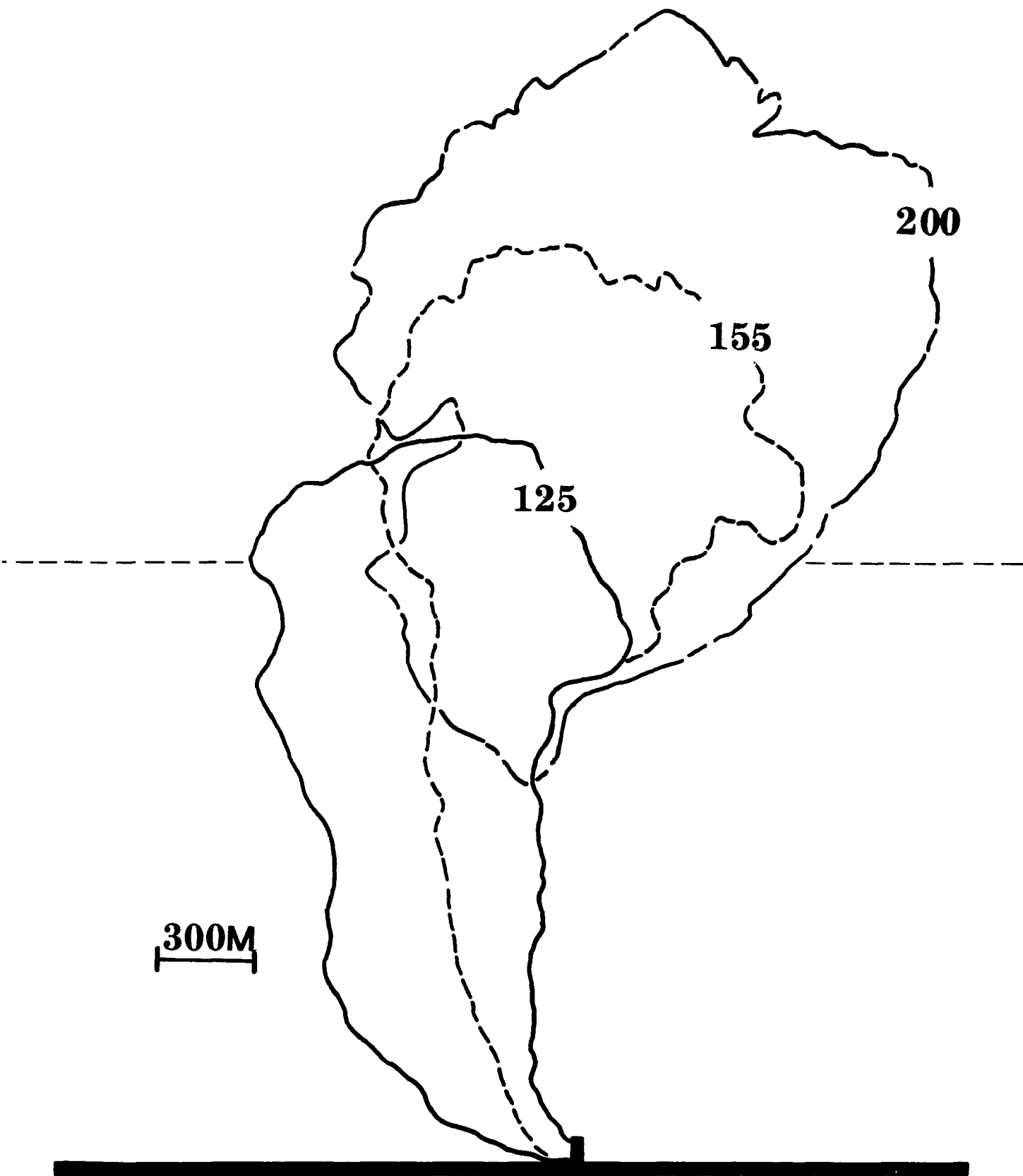


Figure 20. Rectified Cloud Geometry. Firing S-IC-15.

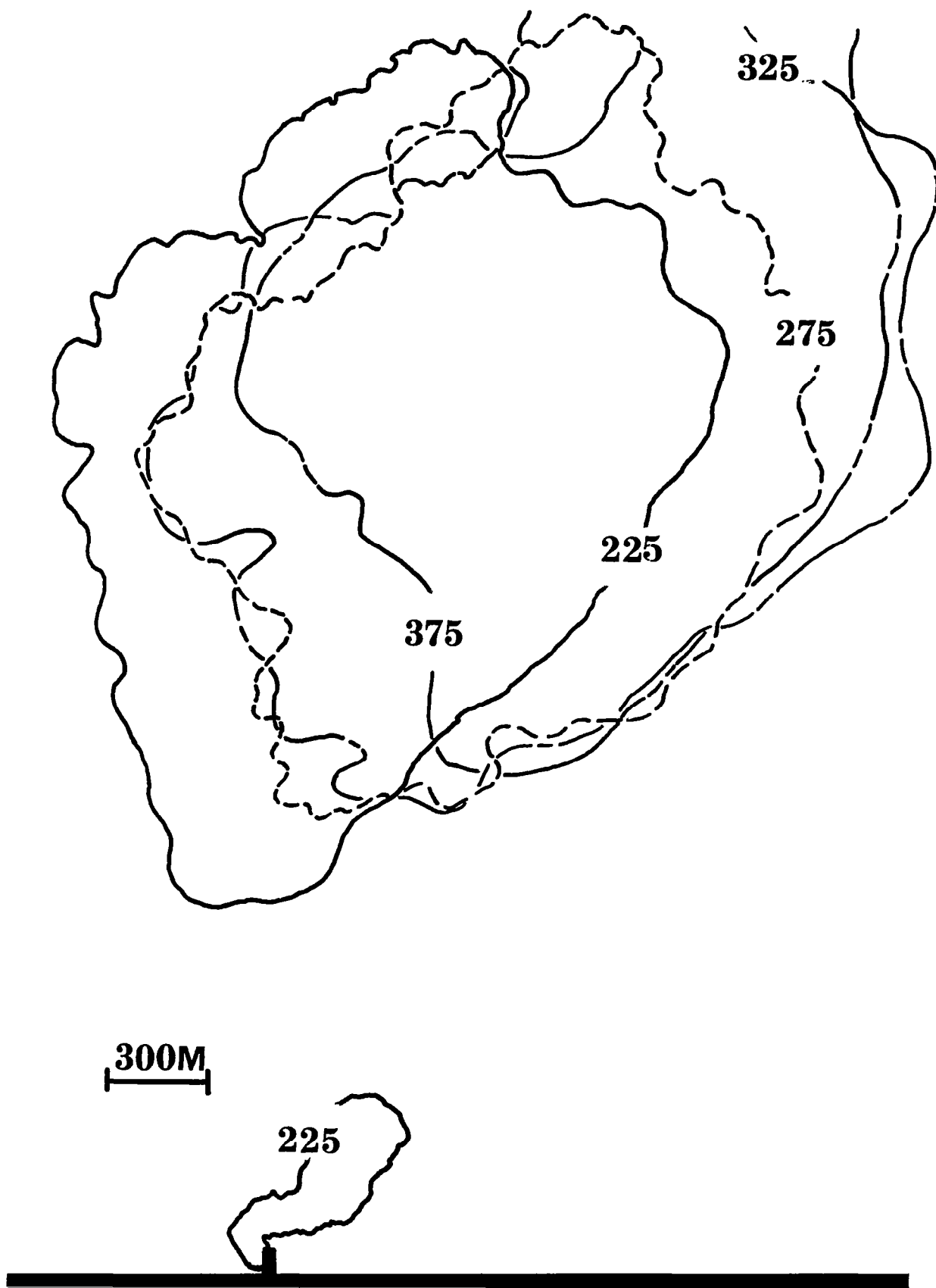


Figure 21. Rectified Cloud Geometry. Firing S-IC-15.

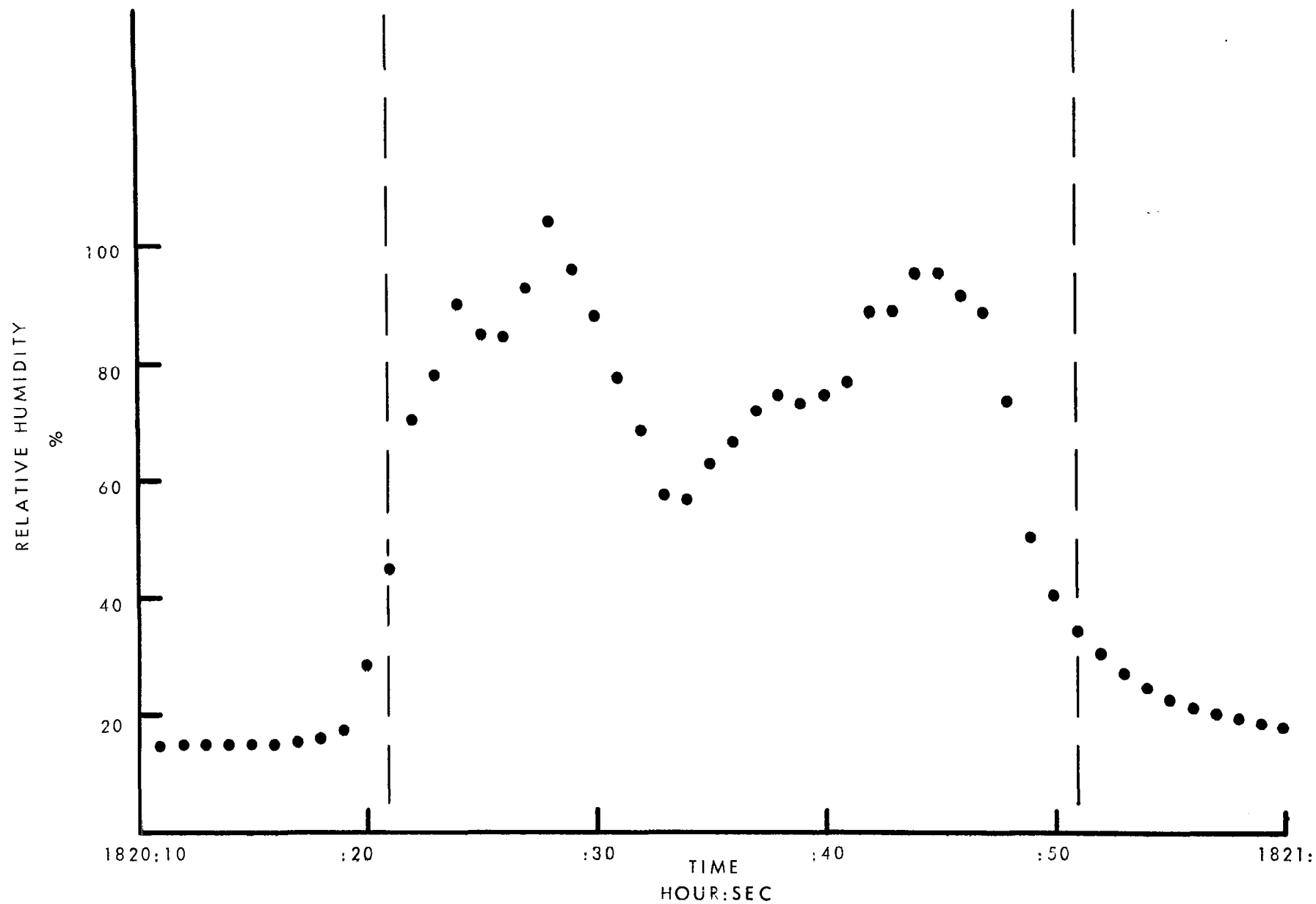


Figure 22. Relative Humidity In Cloud. Pass 1.  
Firing S-1C-15. MSU Aircraft.

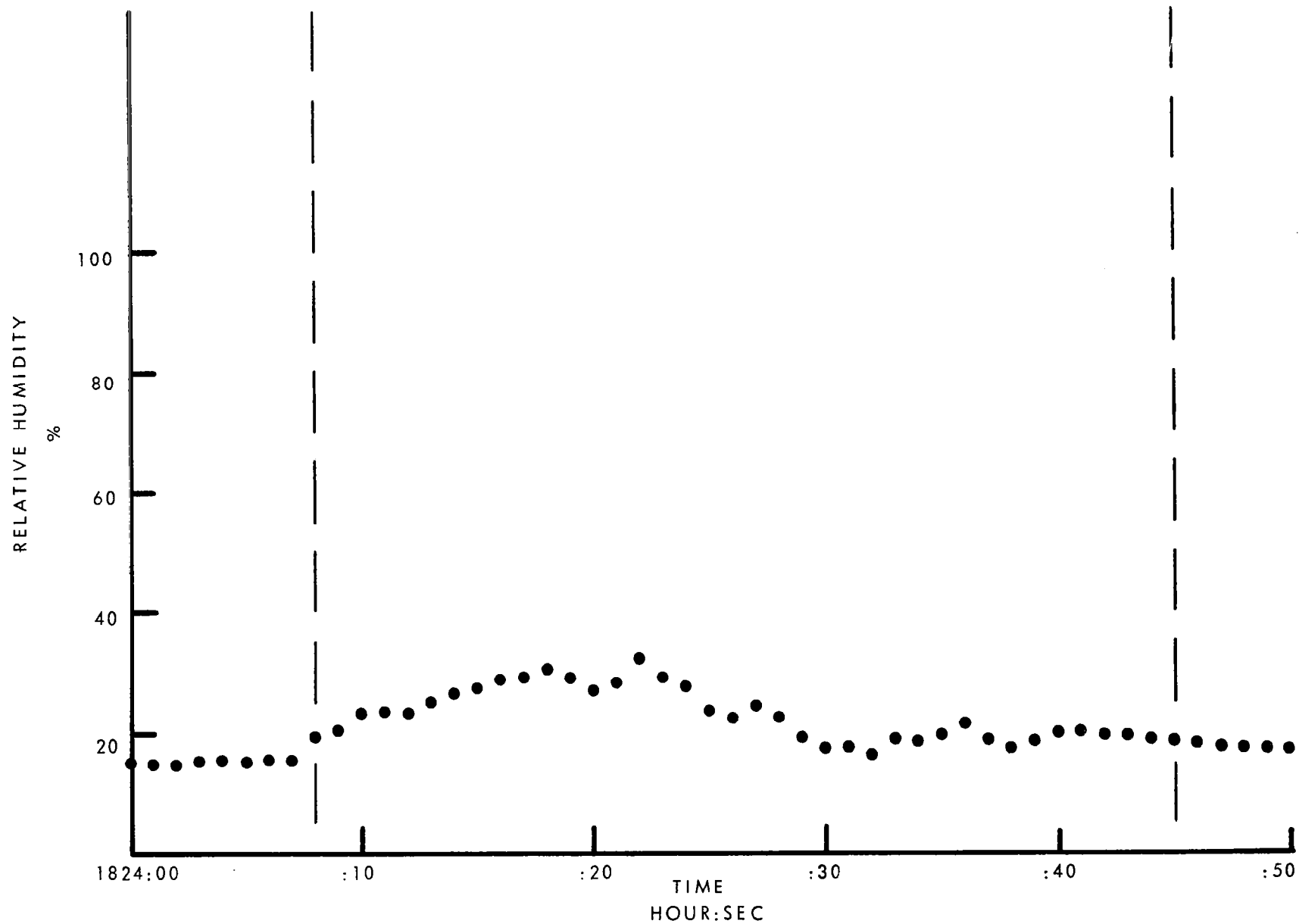


Figure 23. Relative Humidity In Cloud. Pass 2.  
Firing S-IC-15. MSU Aircraft.

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RELATIVE HUMIDITY

%

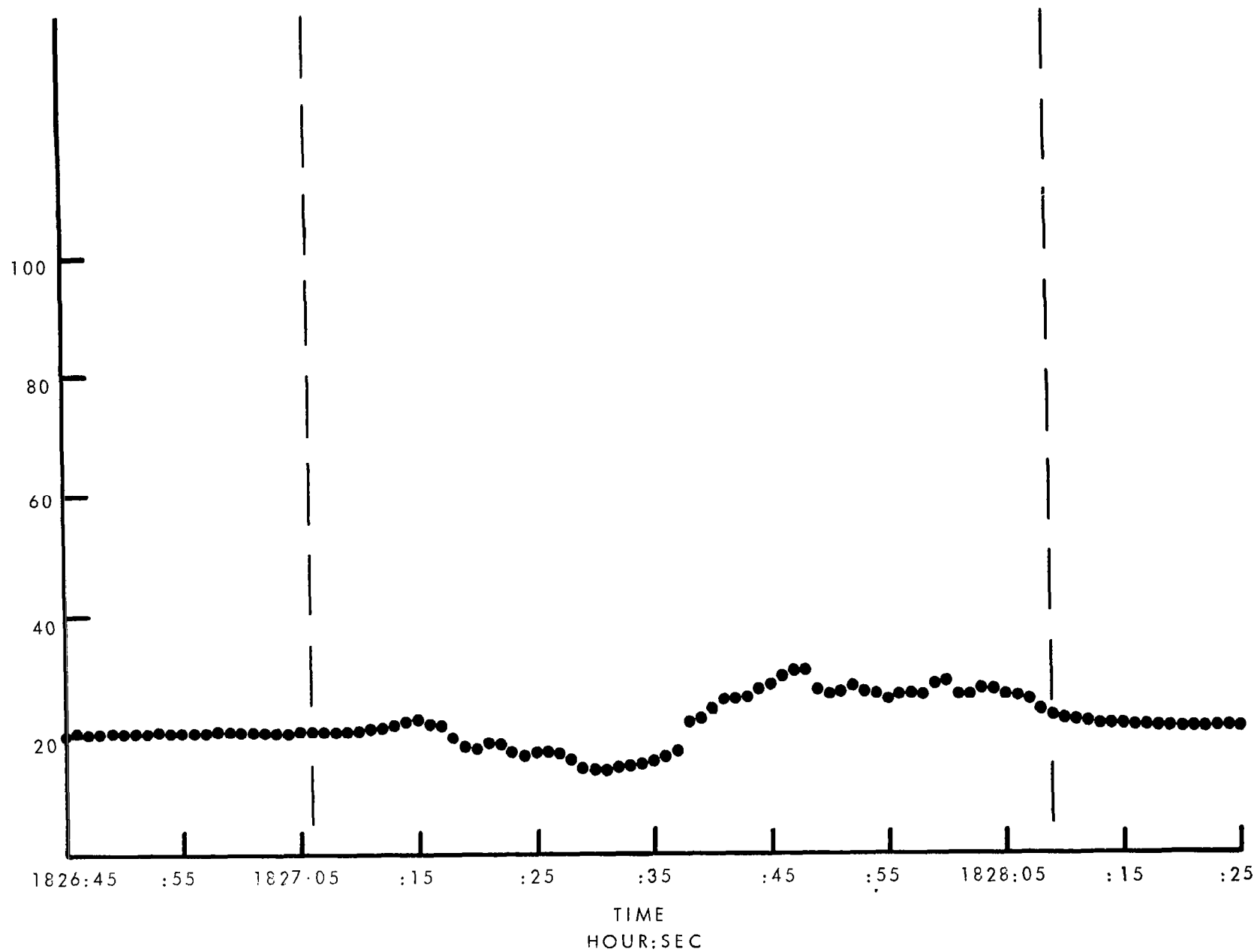


Figure 24. Relative Humidity In Cloud. Pass 3.  
Firing S-1C-15. MSU Aircraft.

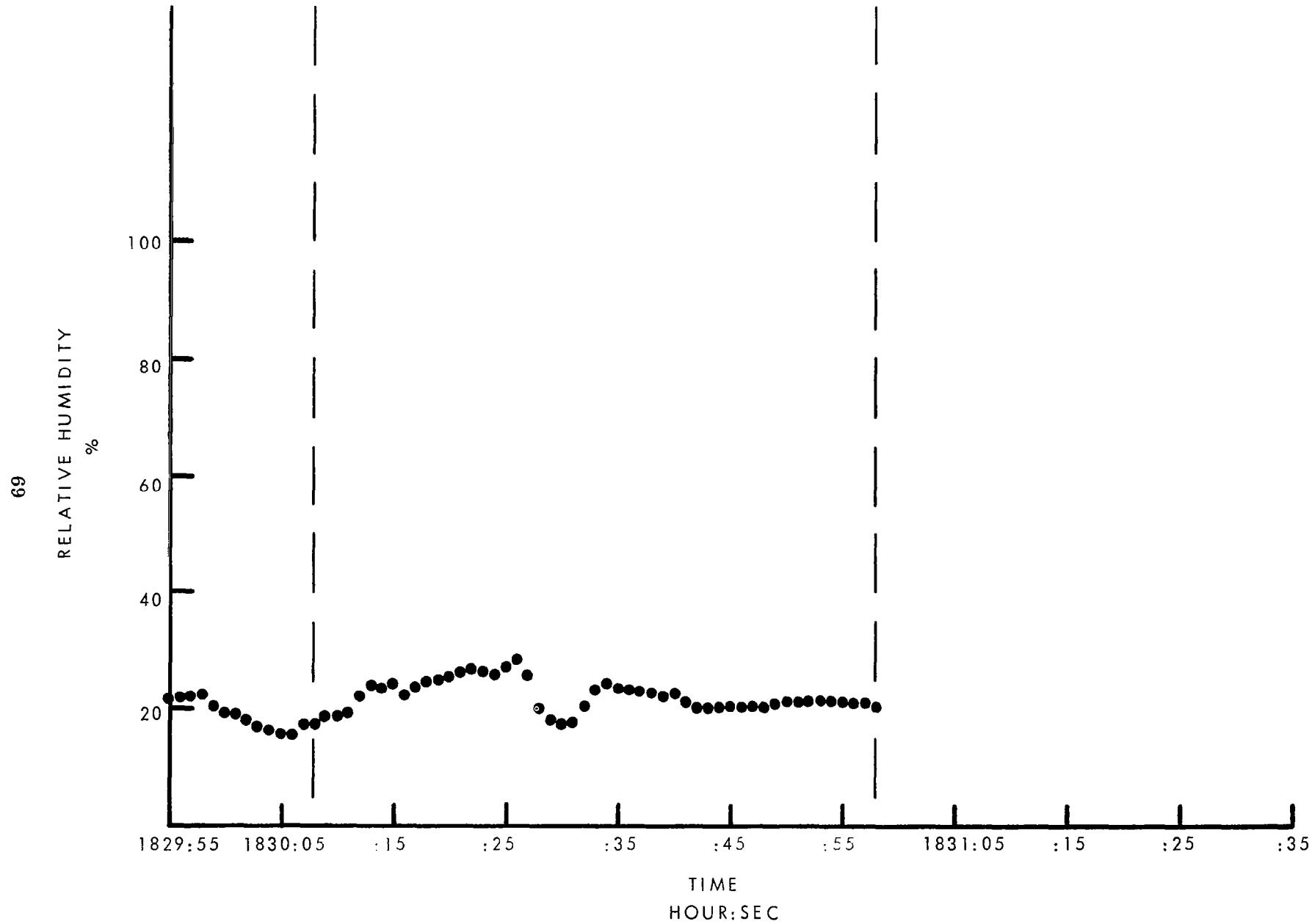


Figure 25. Relative Humidity In Cloud. Pass 4.  
Firing S-IC-15. MSU Aircraft.

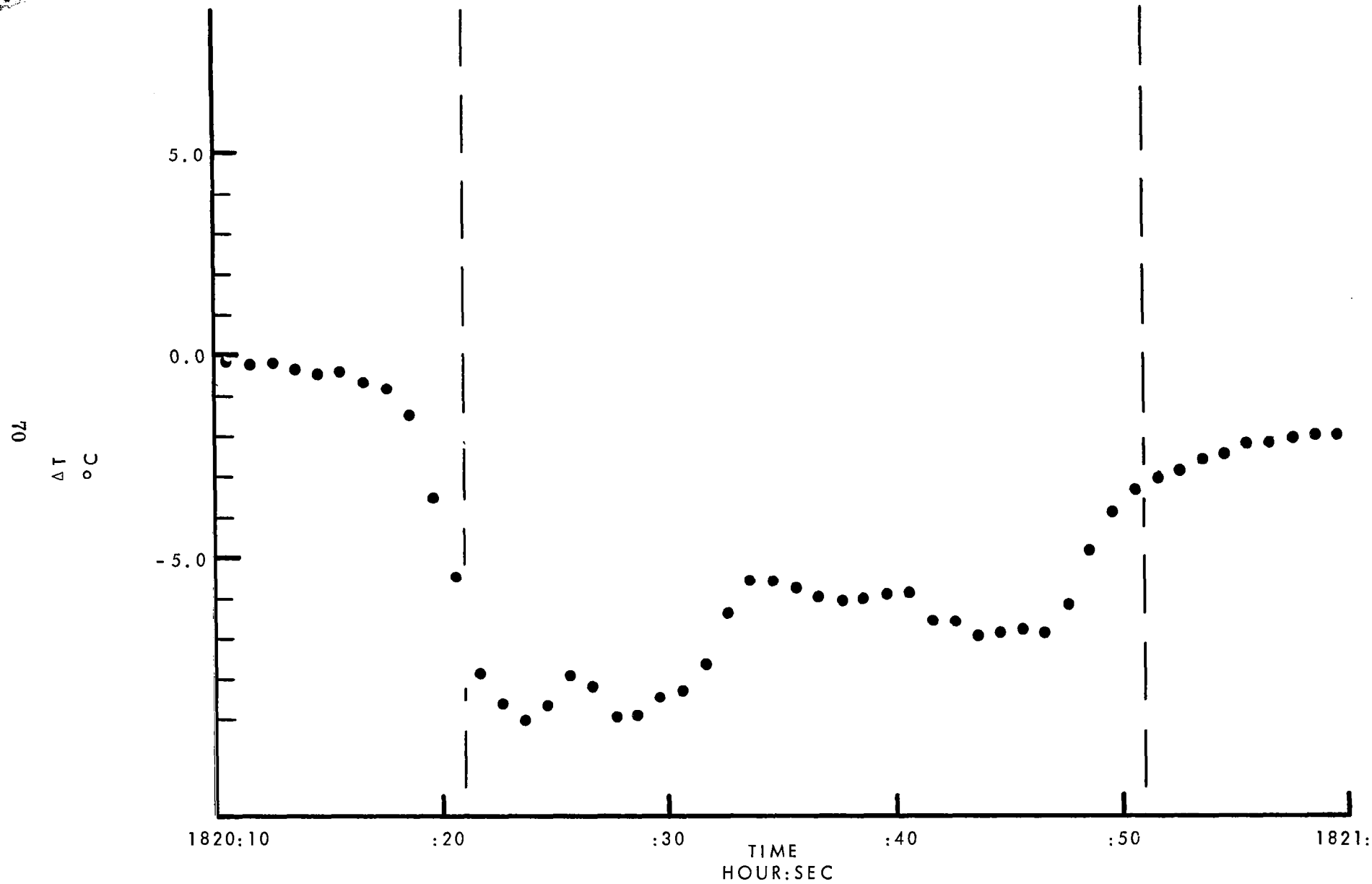


Figure 26. Disturbed Temperature In Cloud. Pass 1.  
Firing S-IC-15. MSU Aircraft.

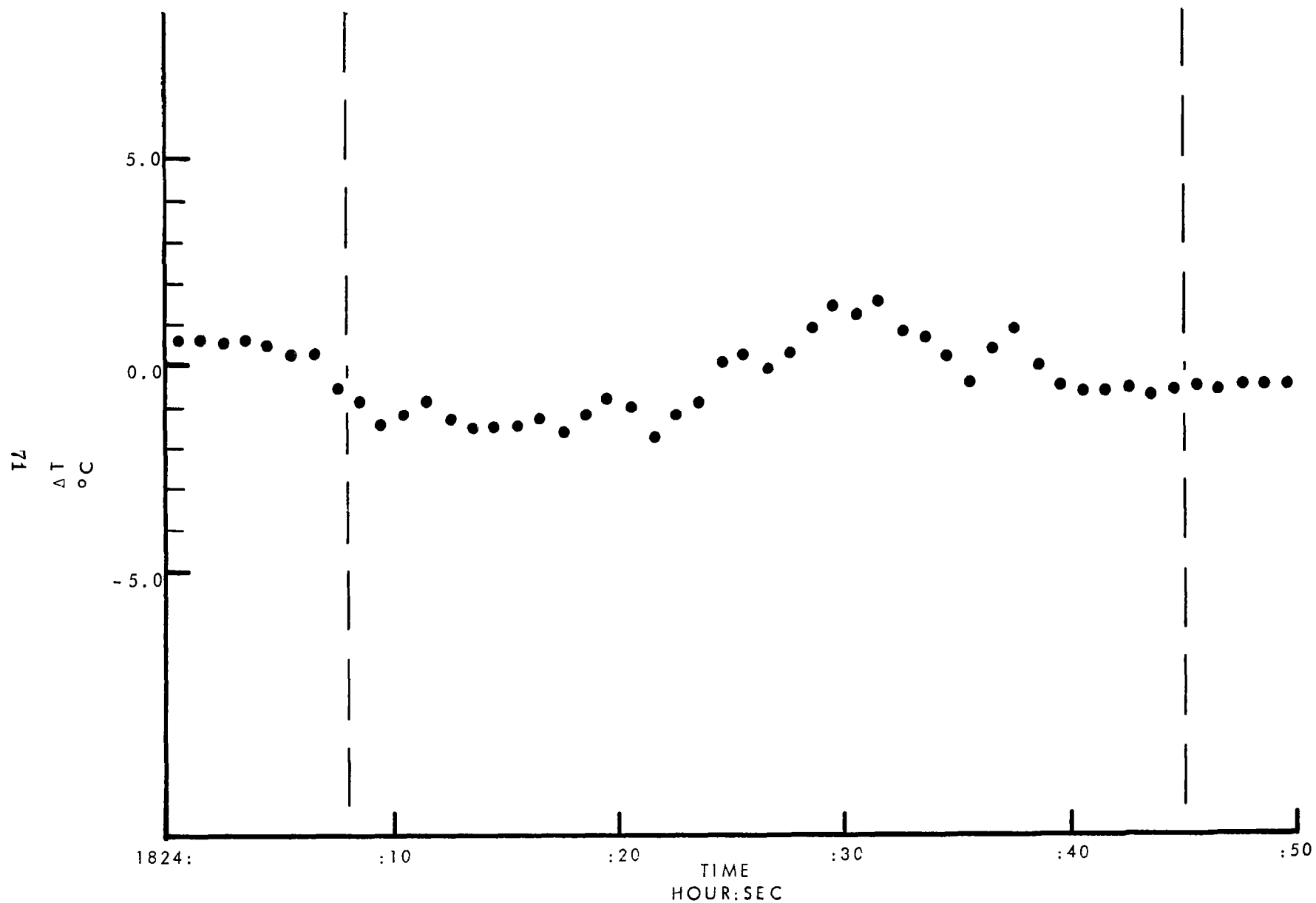


Figure 27. Disturbed Temperature In Cloud. Pass 2.  
Firing S-IC-15. MSU Aircraft.



72  
Δ °C

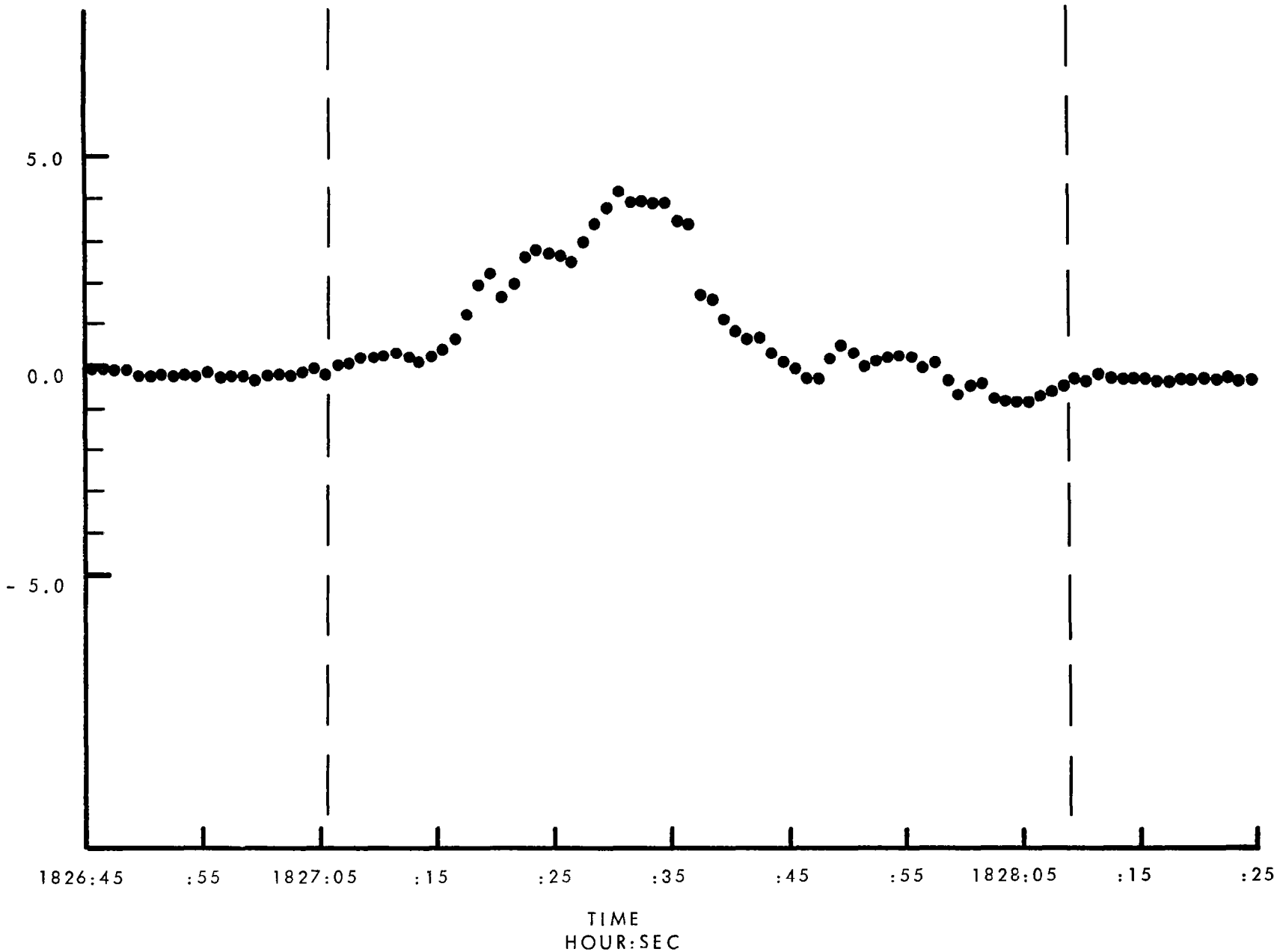


Figure 28. Disturbed Temperature In Cloud. Pass 3.  
Firing S-IC-15. MSU Aircraft.

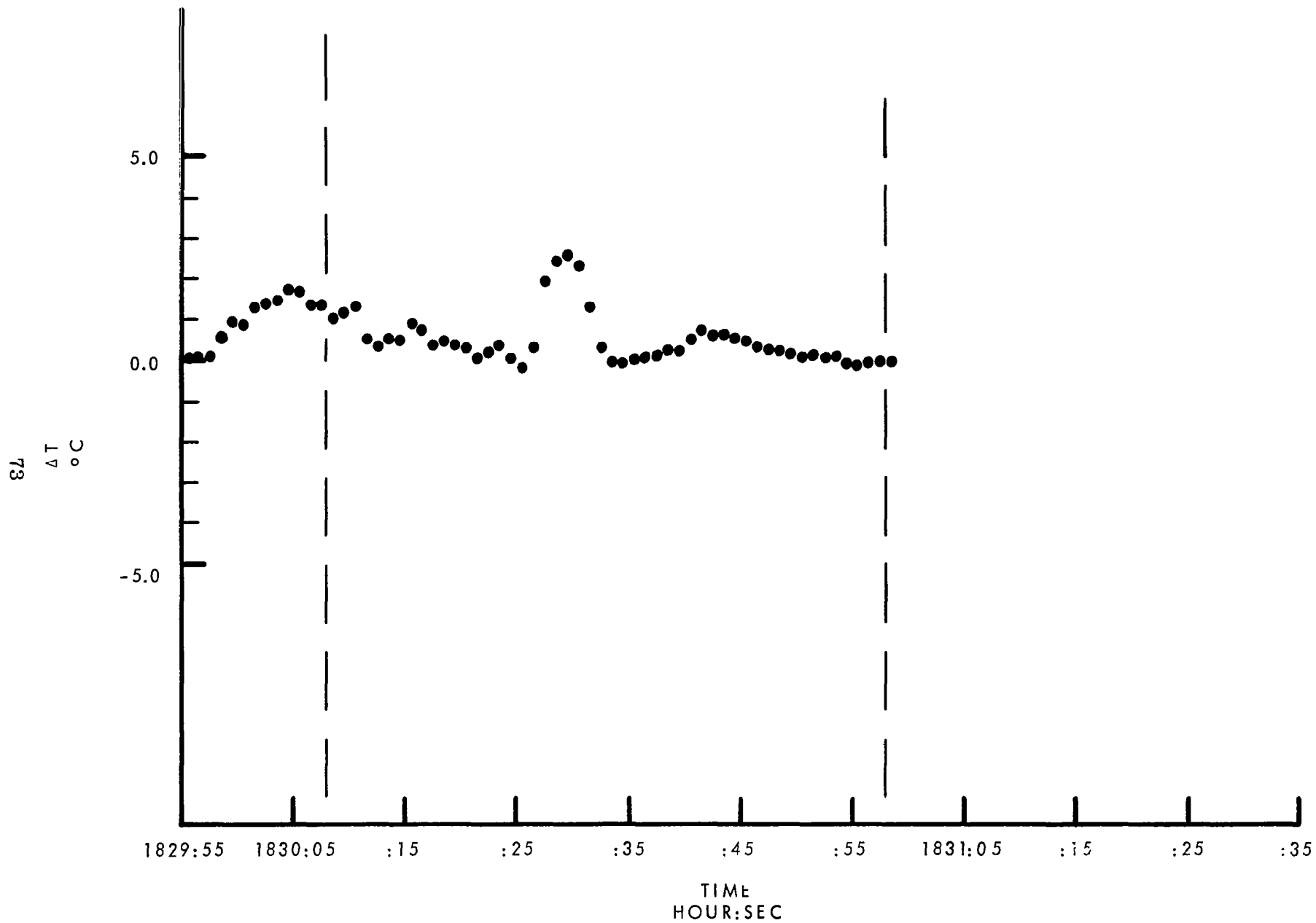


Figure 29. Disturbed Temperature In Cloud. Pass 4.  
Firing S-IC-15. MSU Aircraft.

RELATIVE HUMIDITY %

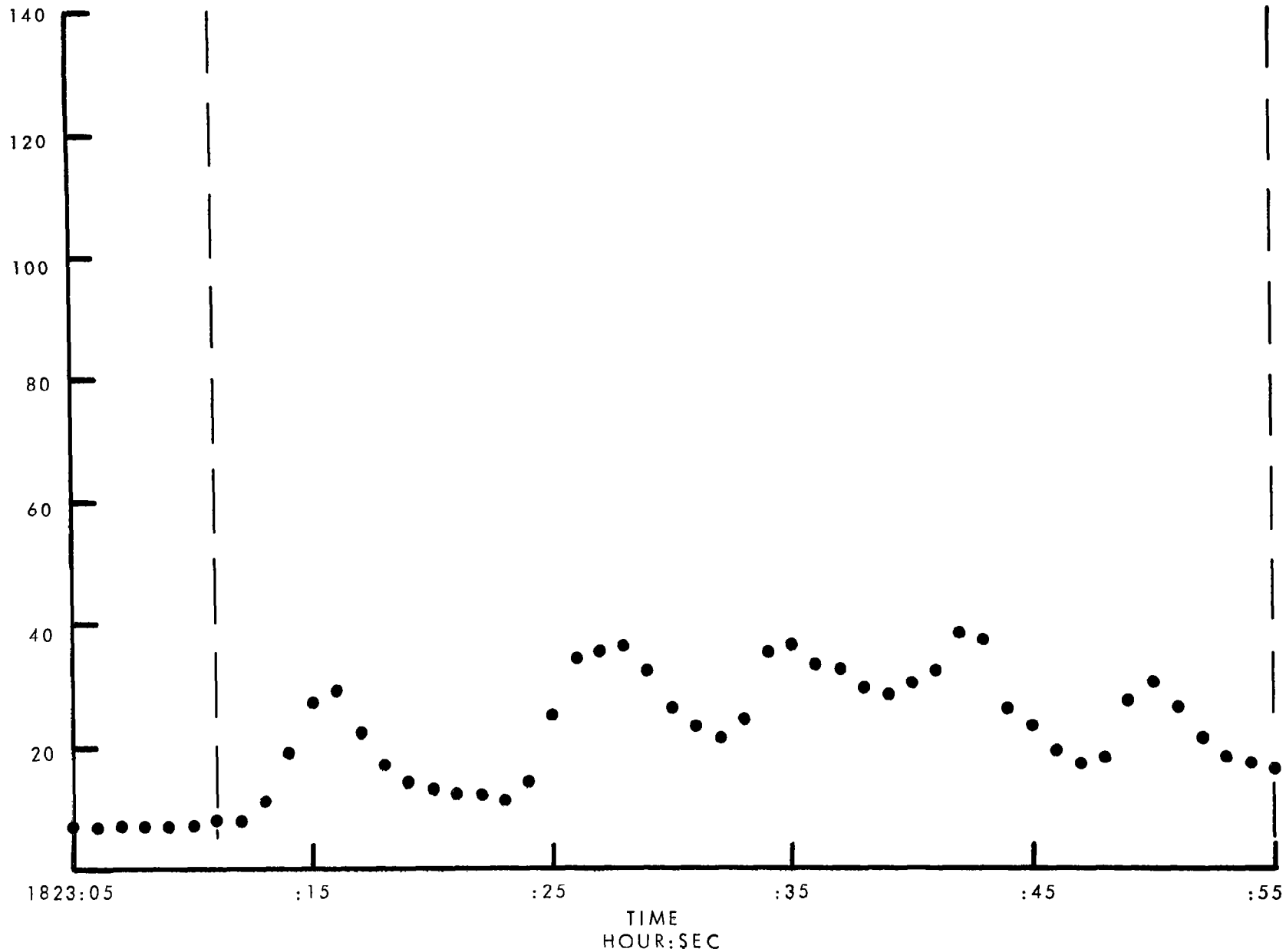


Figure 30. Relative Humidity In Cloud. Pass 1.  
Firing S-IC-15. Penn. State Aircraft.

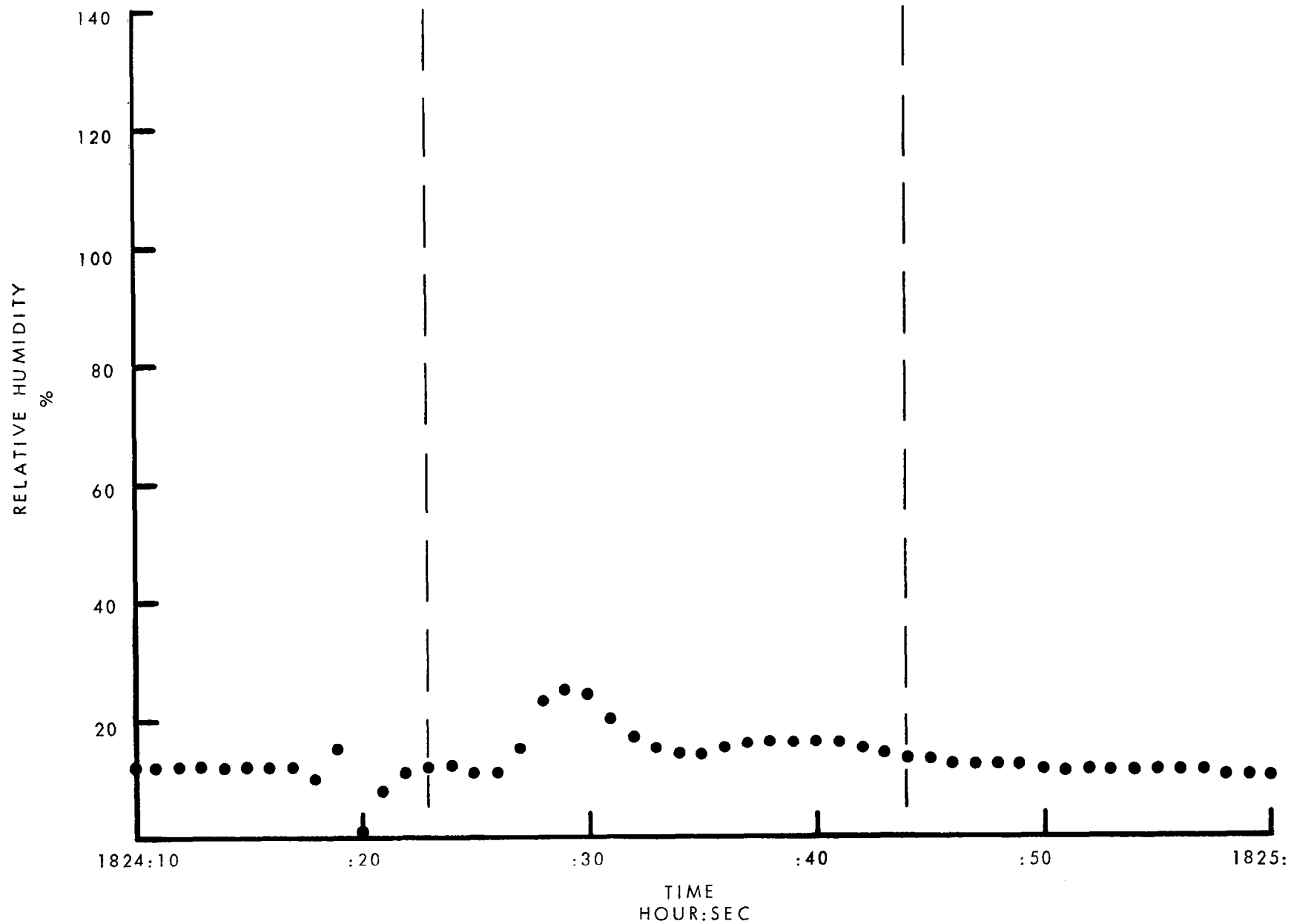


Figure 31. Relative Humidity In Cloud. Pass 2.  
Firing S-IC-15. Penn. State Aircraft.

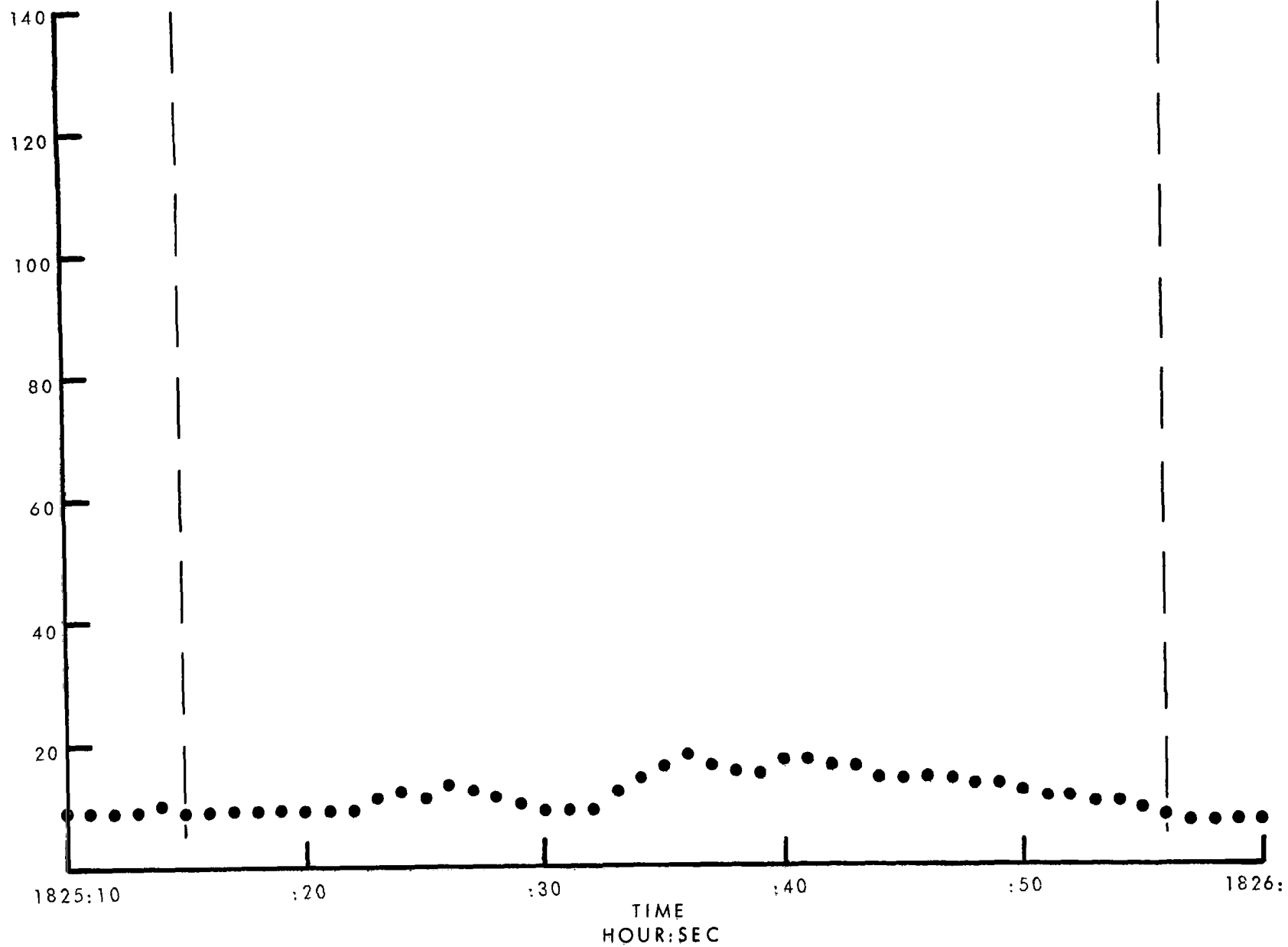
RELATIVE HUMIDITY  
%

Figure 32. Relative Humidity In Cloud. Pass 3.  
Firing S-IC-15. Penn. State Aircraft.

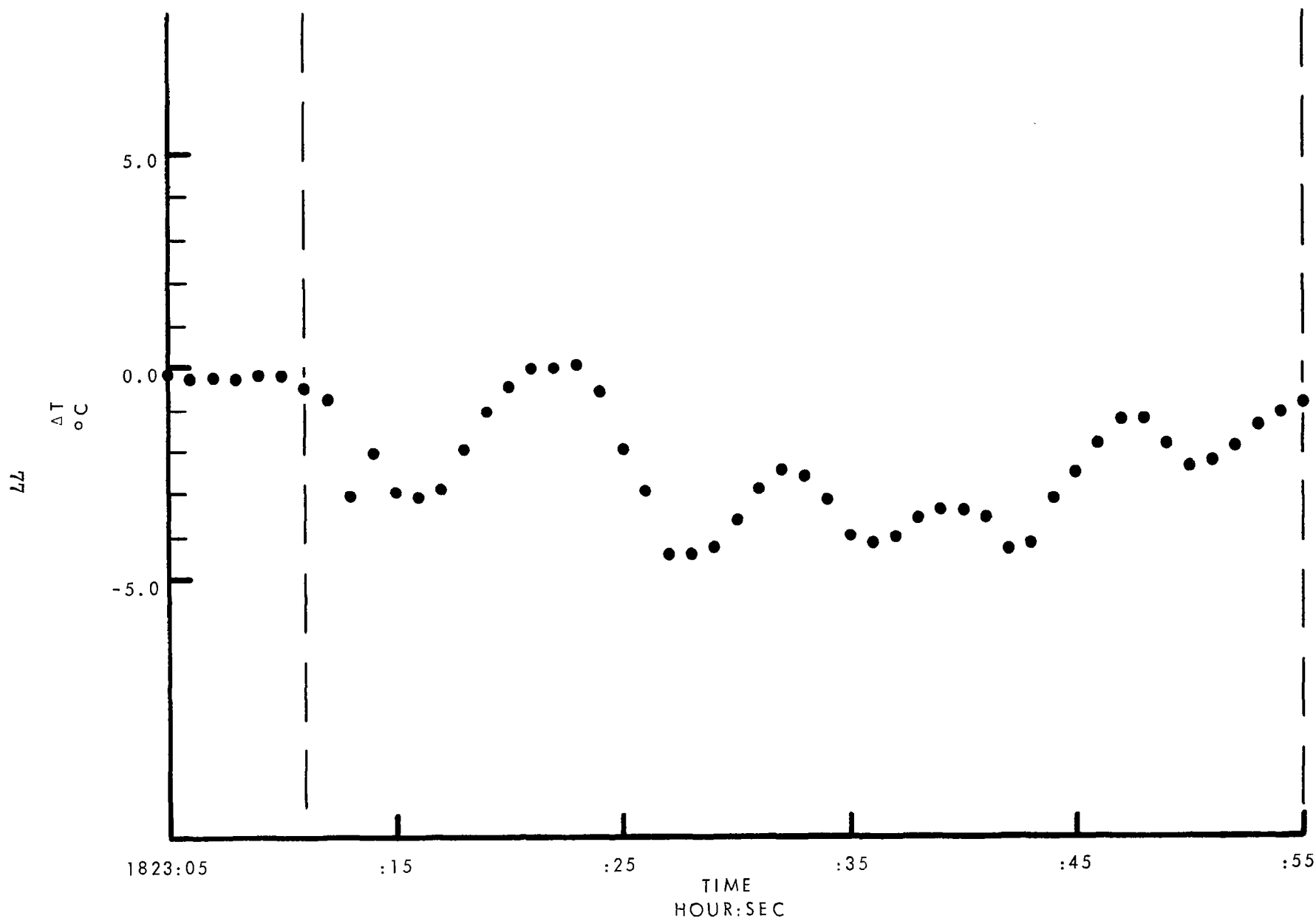


Figure 33. Disturbed Temperature In Cloud. Pass 1.  
Firing S-IC-15. Penn. State Aircraft.

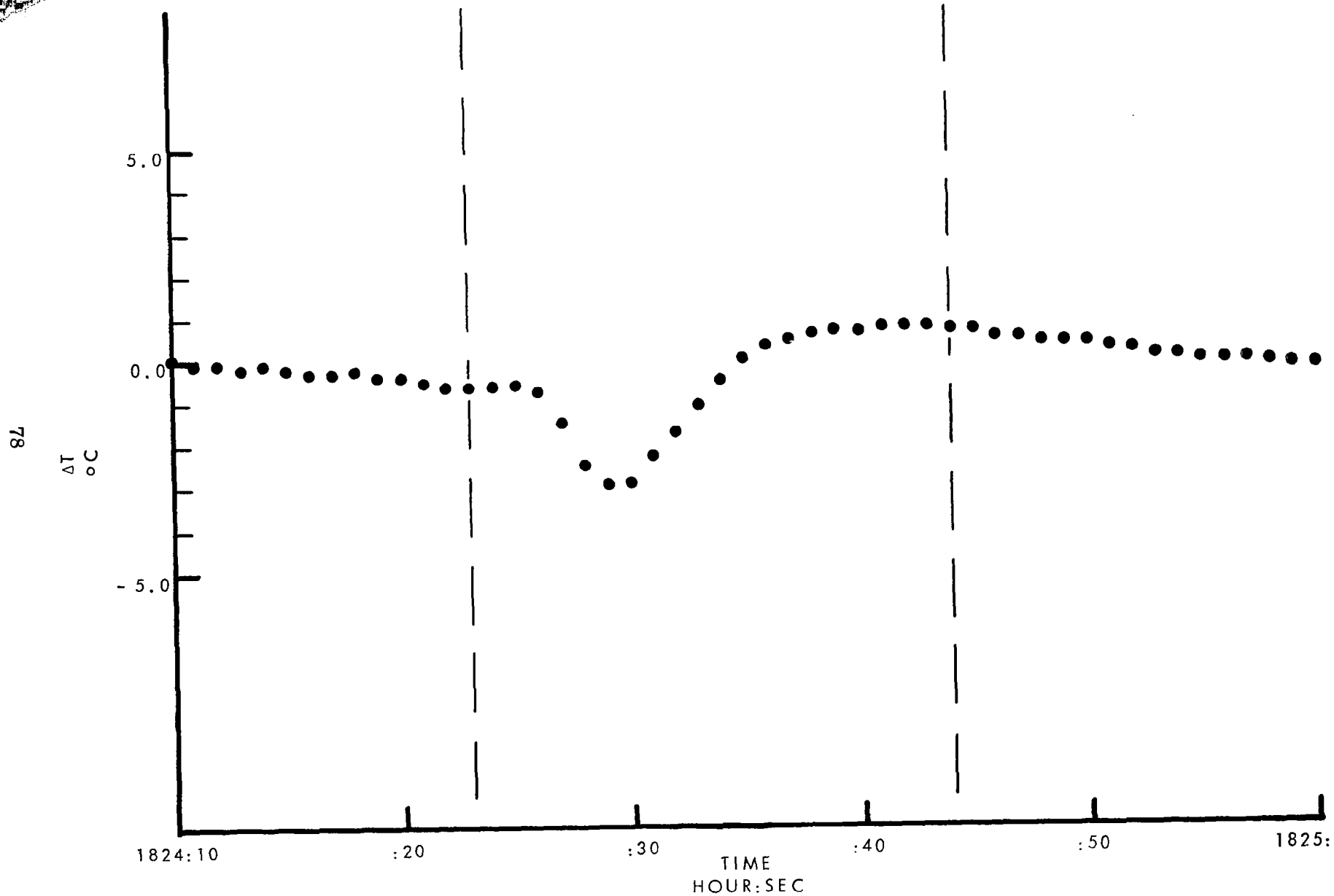


Figure 34. Disturbed Temperature In Cloud. Pass 2.  
Firing S-1C-15. Penn. State Aircraft.

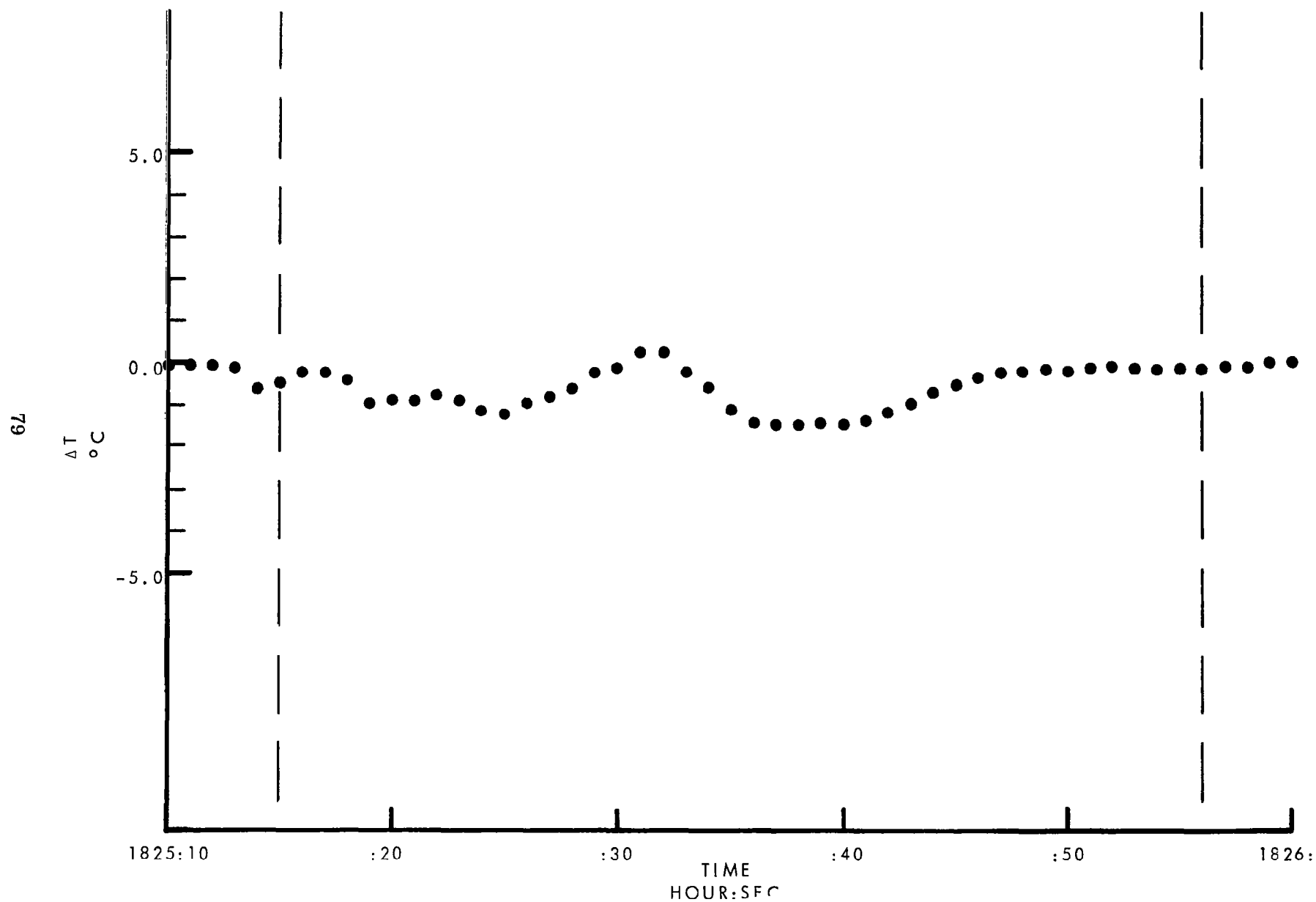


Figure 35. Disturbed Temperature In Cloud. Pass 3.  
Firing S-1C-15. Penn. State Aircraft.

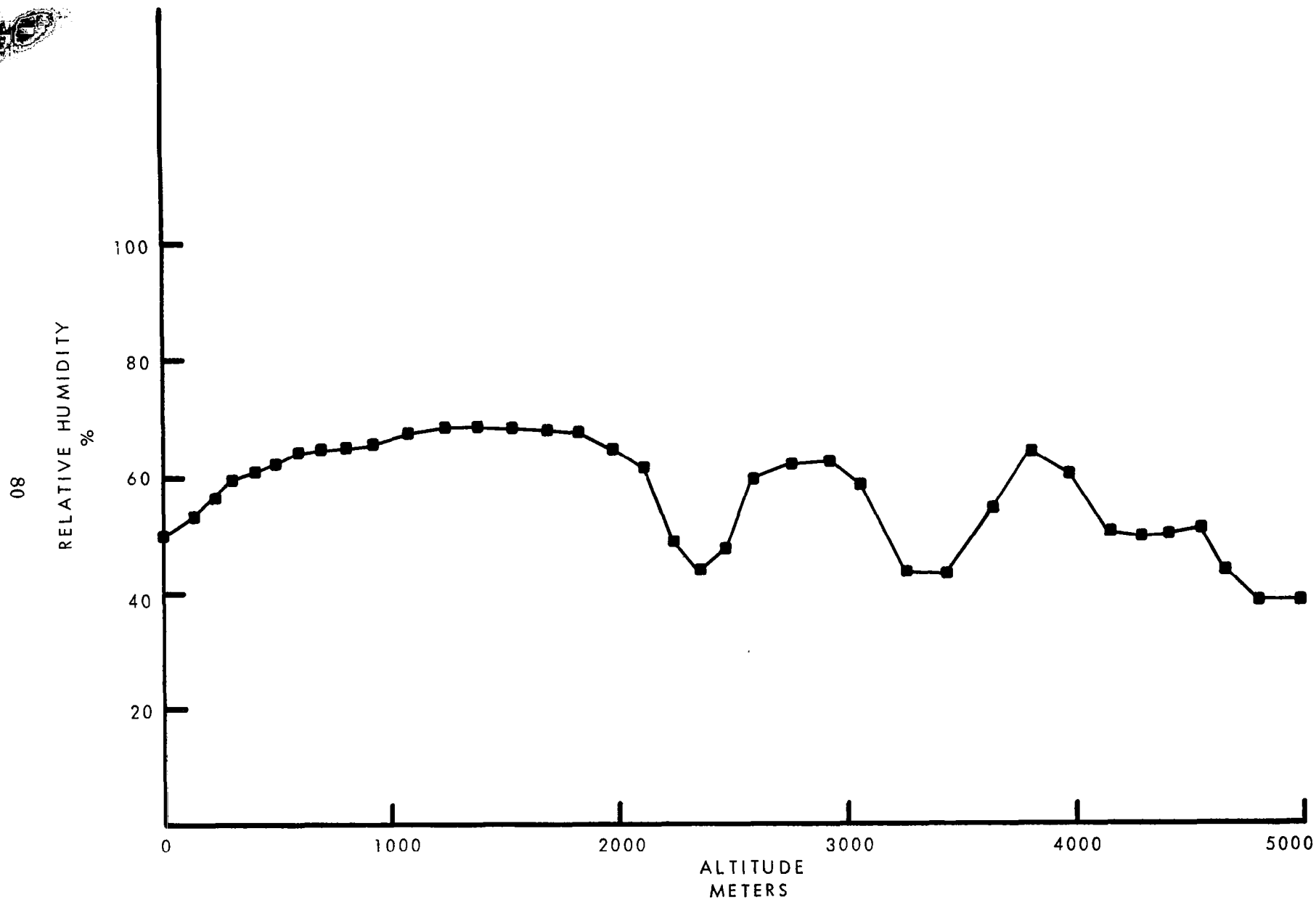


Figure 36. Rediosonde Relative Humidity Sounding.  
Firing S-11-14.

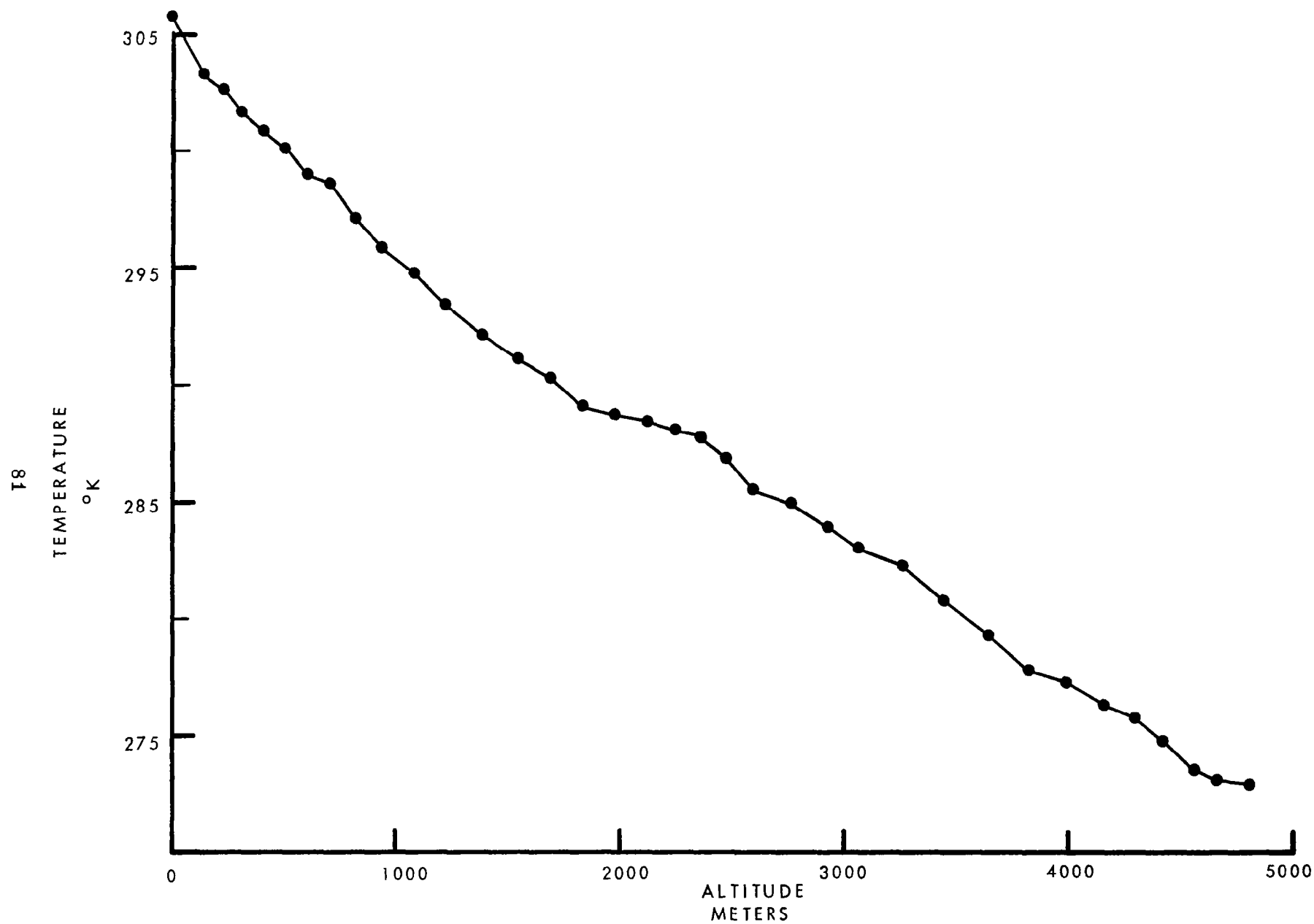


Figure 37. Radiosonde Temperature Sounding.  
Firing S-11-14.

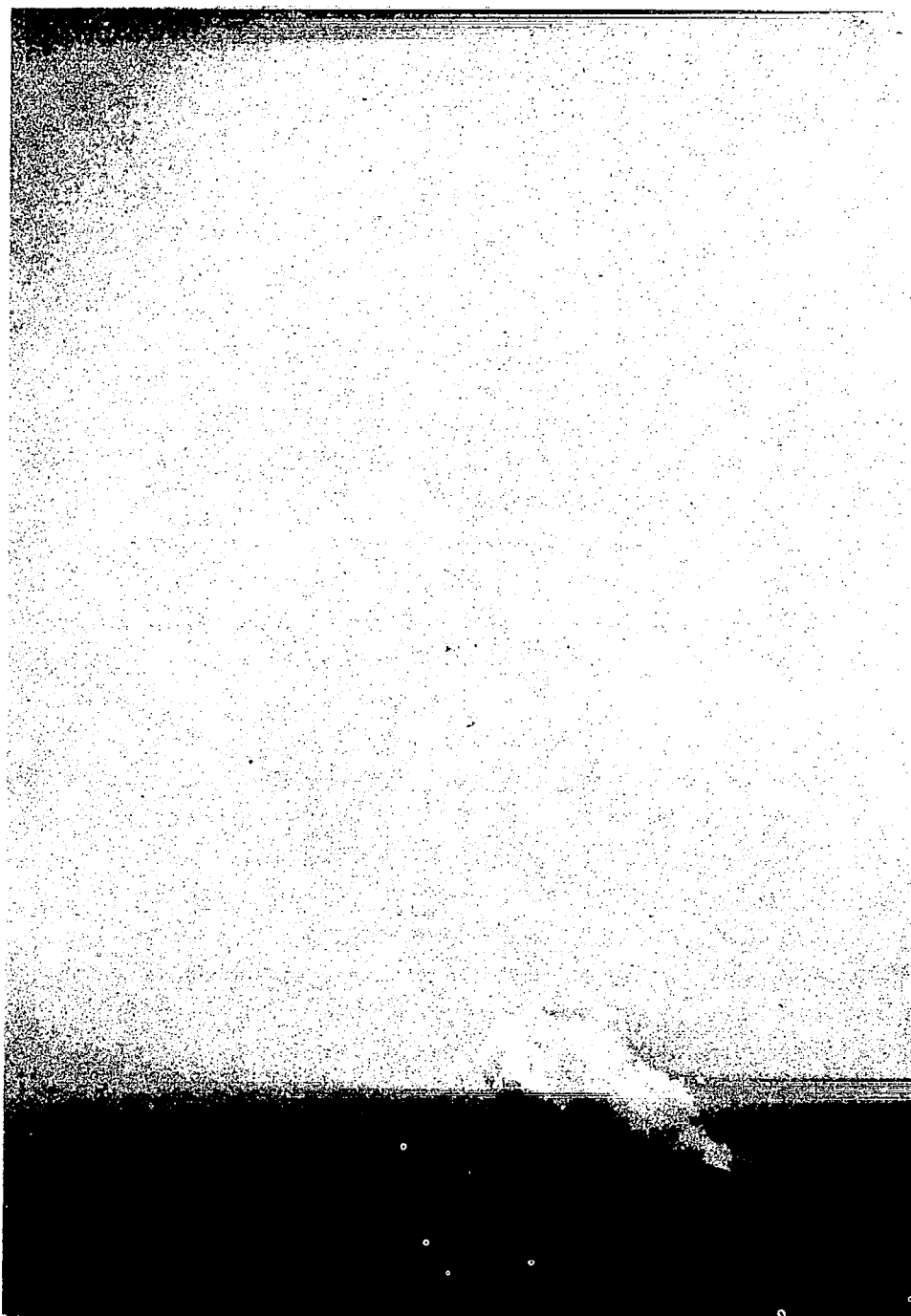


Figure 38. Cloud Photograph 50 Seconds After Ignition. Firing S-11-14.



Figure 39. Cloud Photograph 110 Seconds After Ignition. Firing S-II-14.

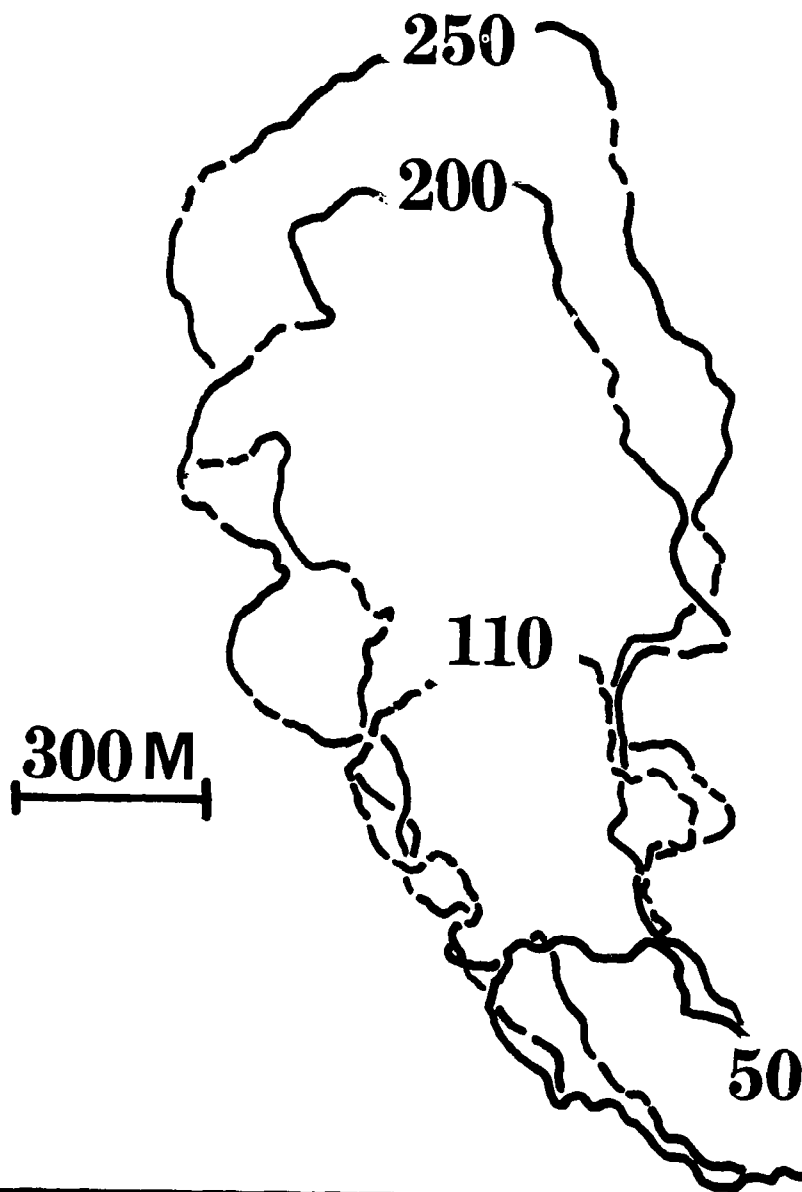


Figure 40. Rectified Cloud Geometry. Firing S-II-14.

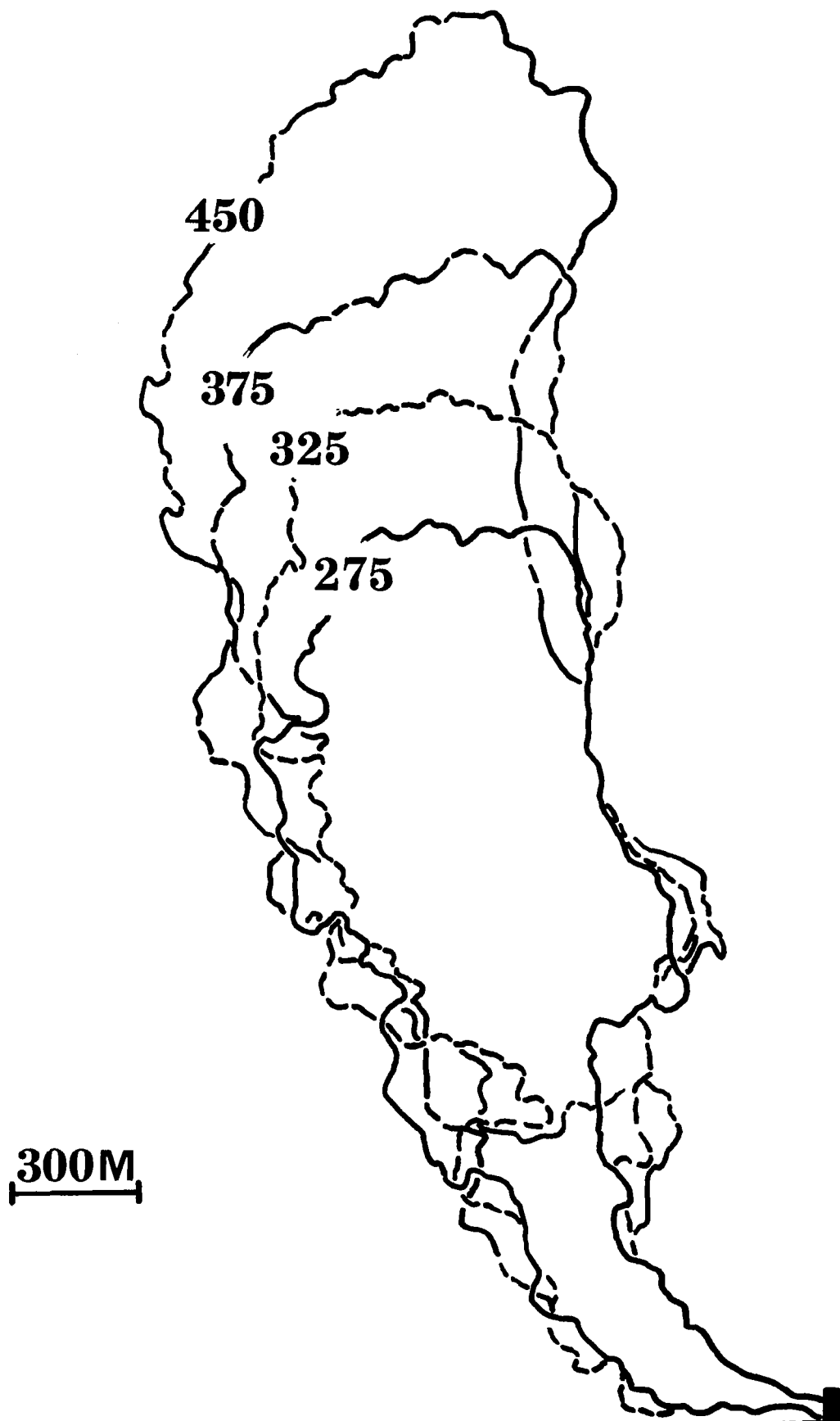


Figure 41. Rectified Cloud Geometry. Firing S-II-14.

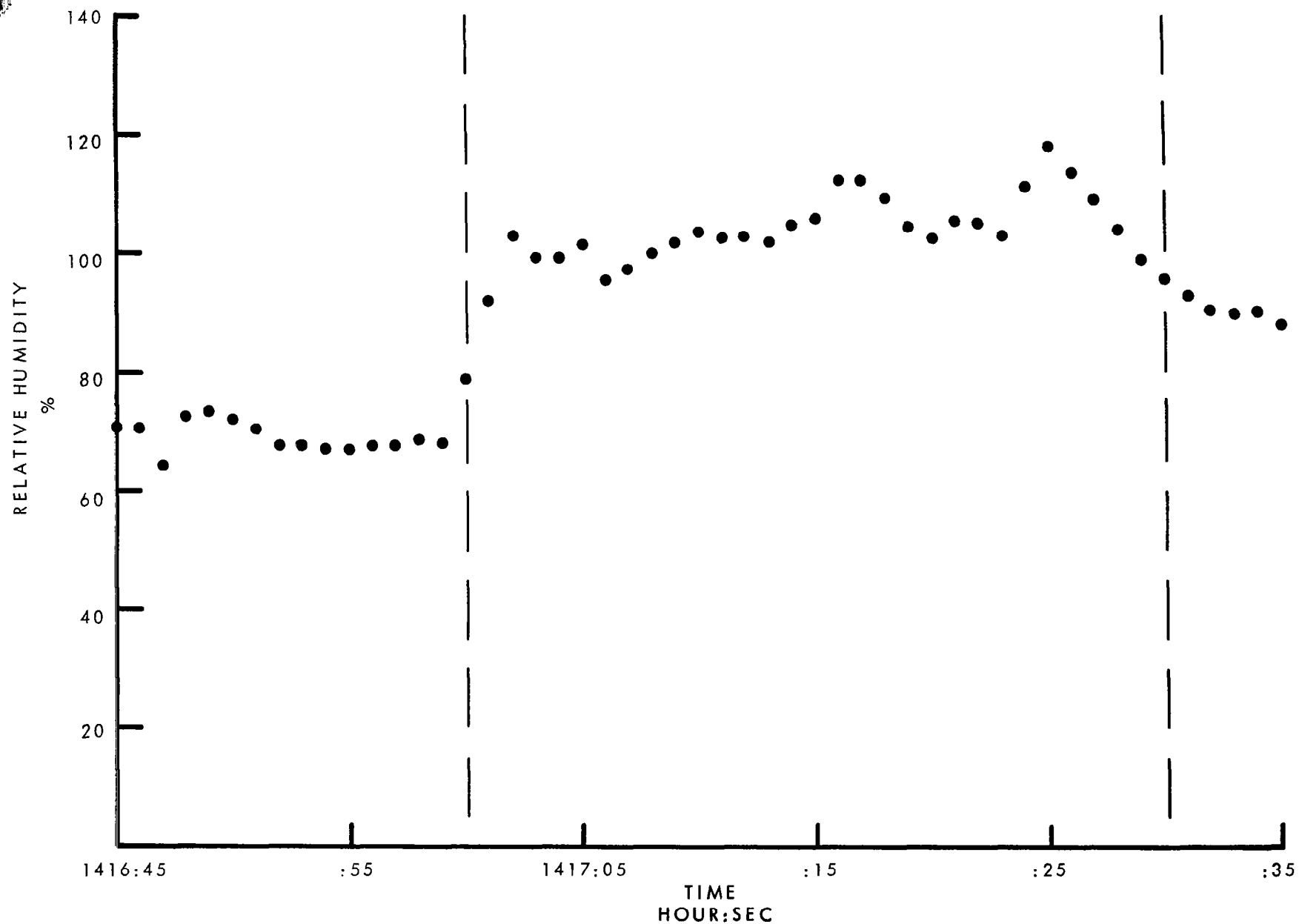
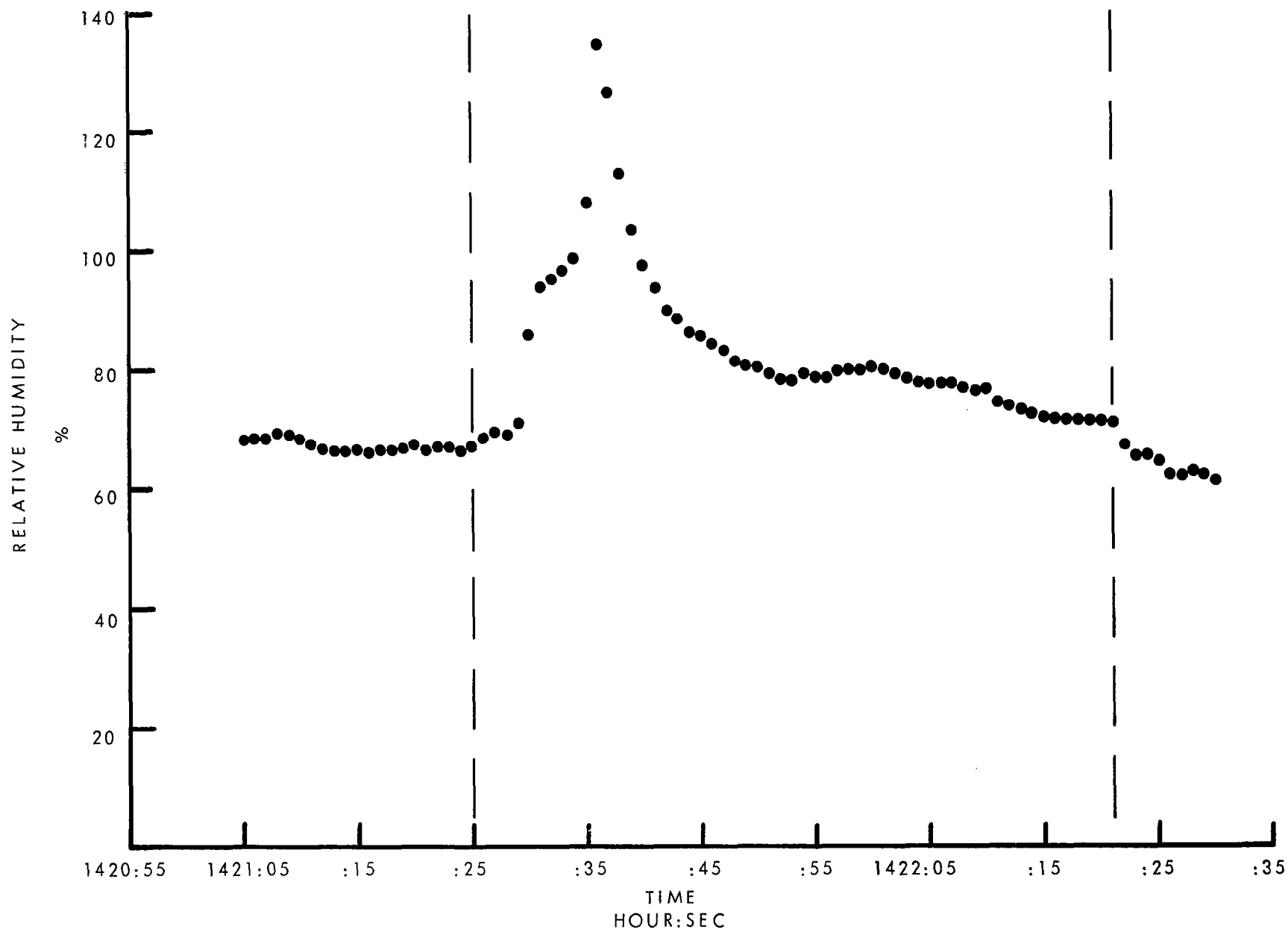


Figure 42. Relative Humidity In Cloud. Pass 1.  
Firing S-II-14. MSU Aircraft.



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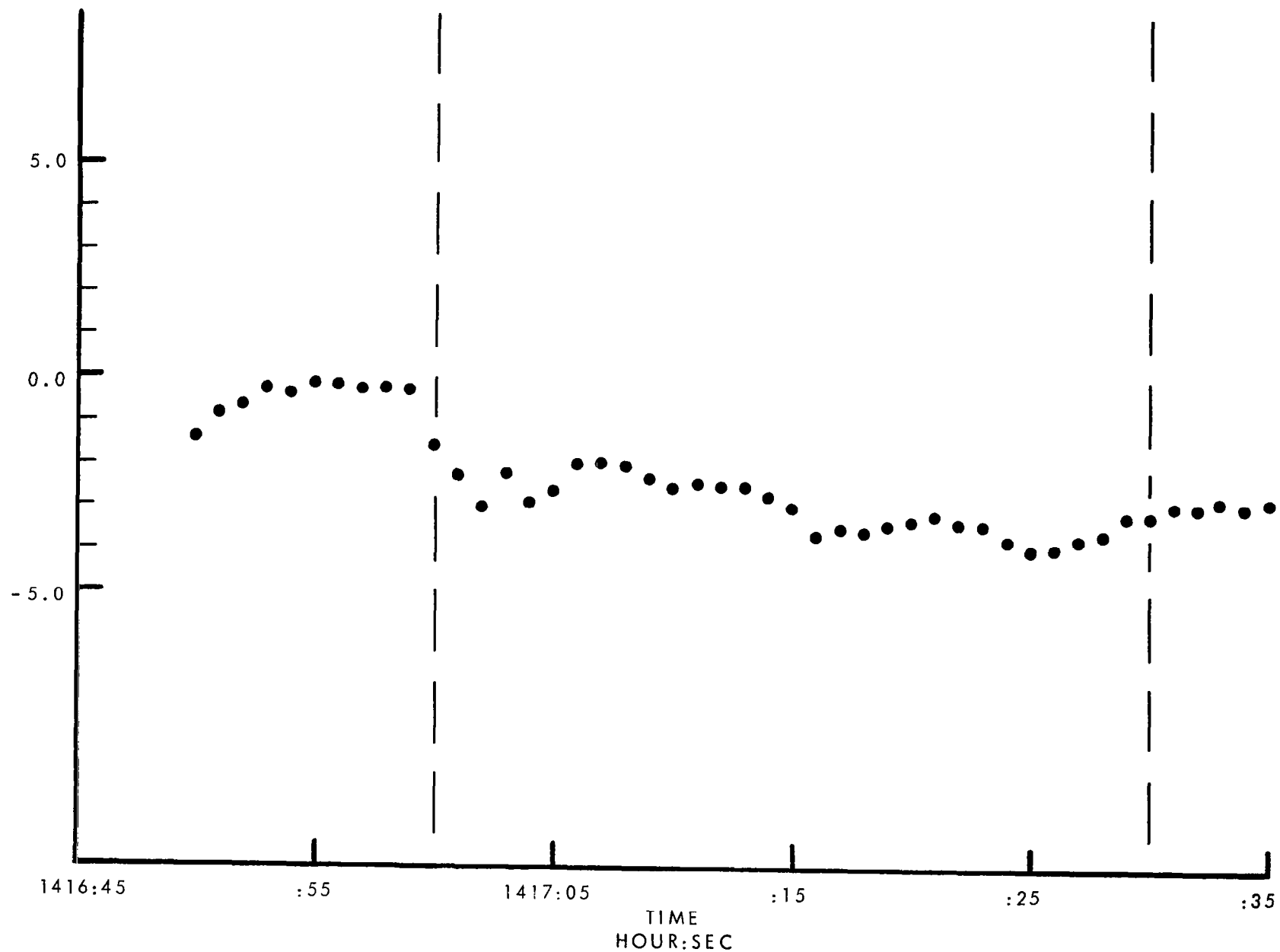


Figure 44. Disturbed Temperature In Cloud. Pass 1.  
Firing S-11-14. MSU Aircraft.

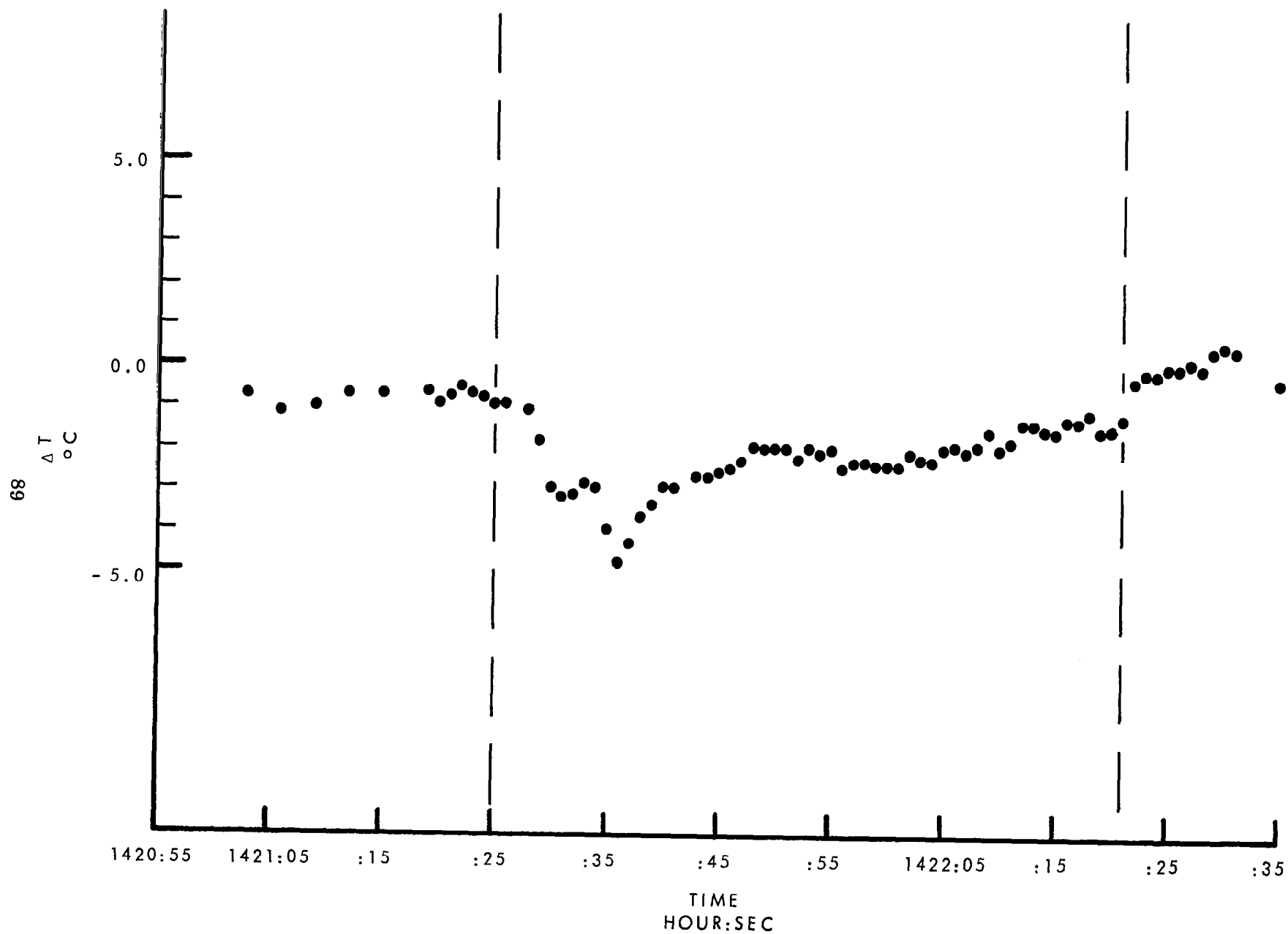


Figure 45. Disturbed Temperature In Cloud. Pass 2.  
Firing S-II-14. MSU Aircraft.

06  
RELATIVE HUMIDITY  
%

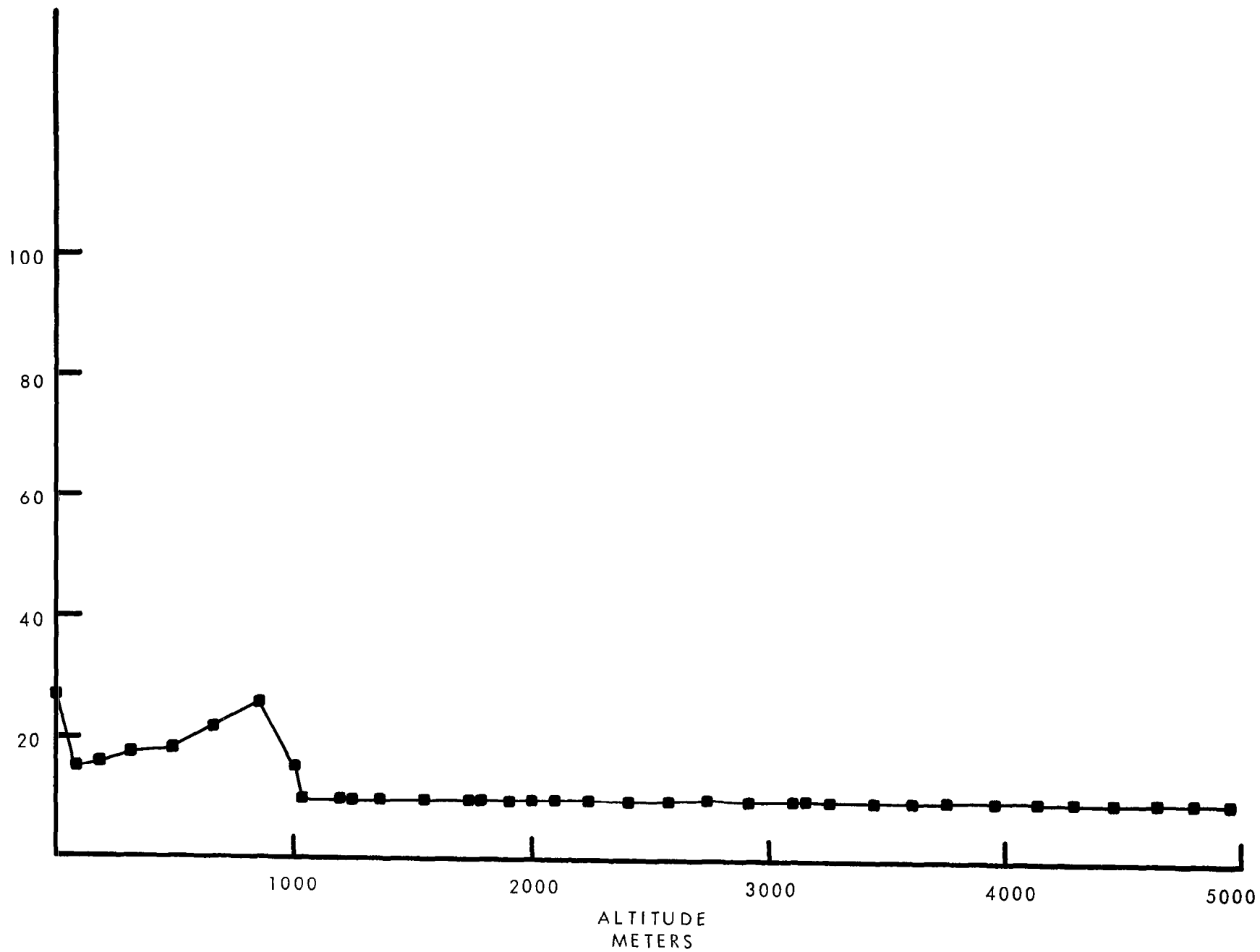


Figure 46. Radiosonde Relative Humidity Sounding.

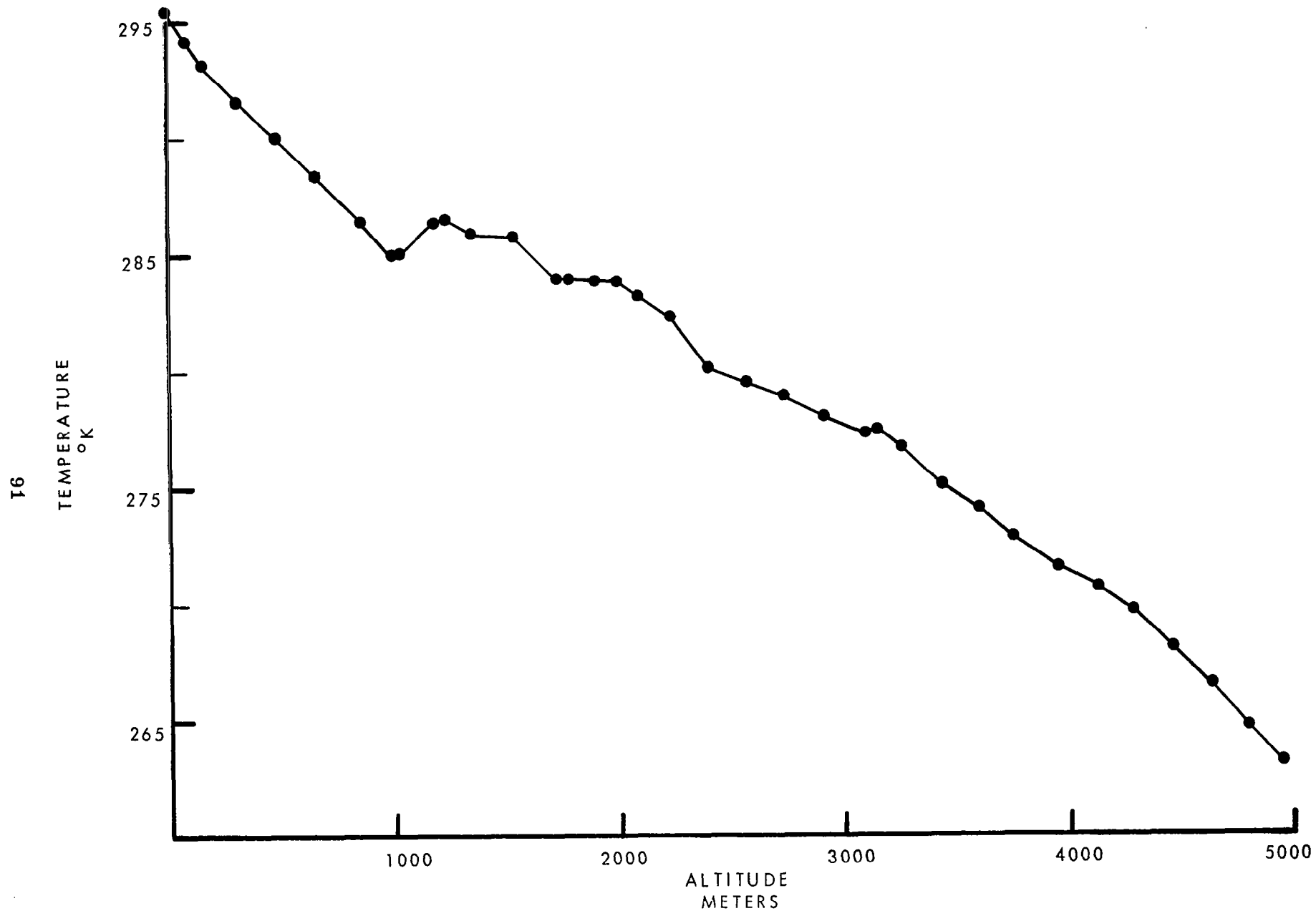


Figure 47. Radiosonde Temperature Sounding  
Firing S-11-15.



Figure 48. Cloud Photograph 50 Seconds After Ignition. Firing S-11-15.

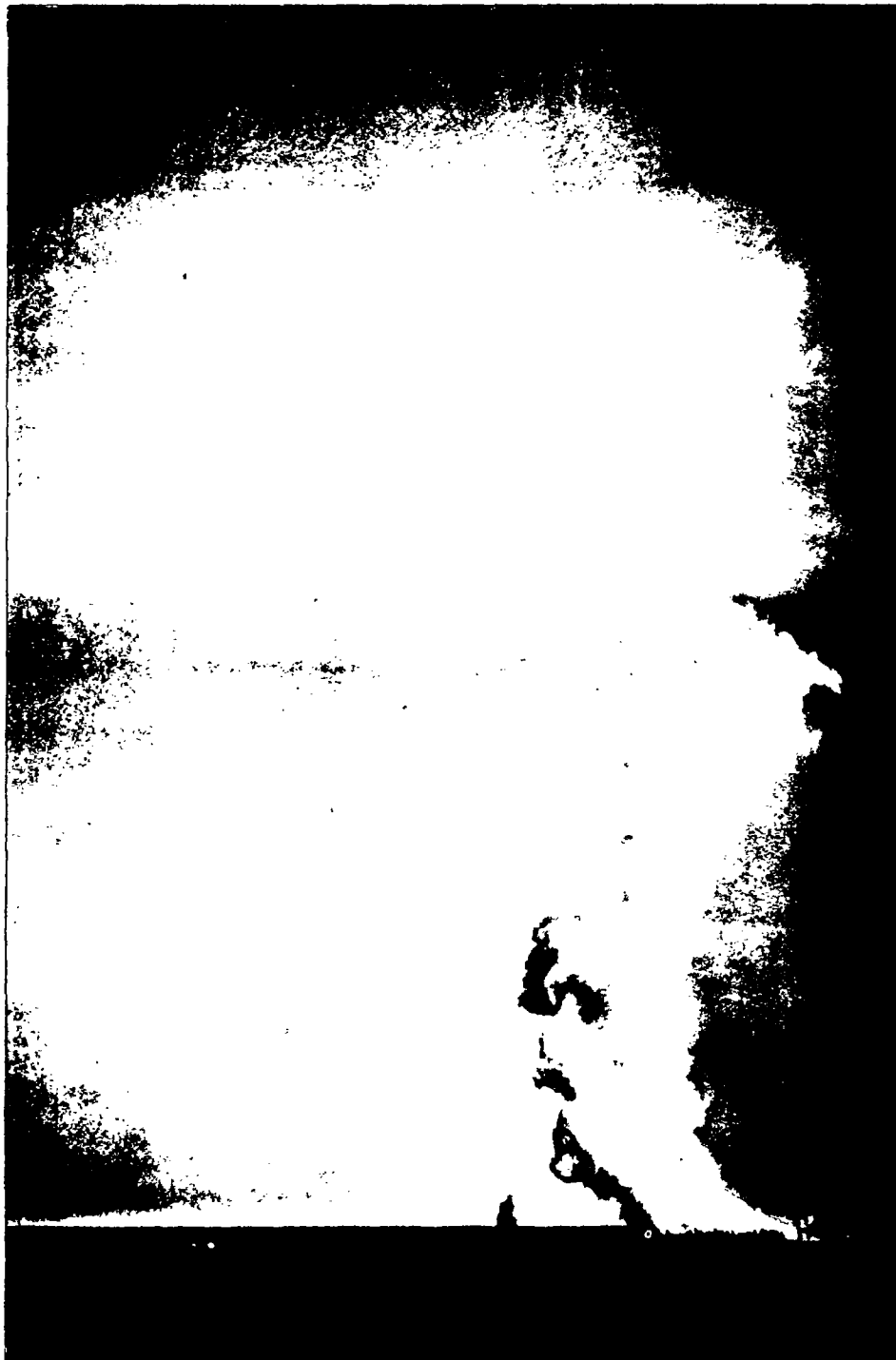


Figure 49. Cloud Photograph 200 Seconds After Ignition. Firing S-II-15.

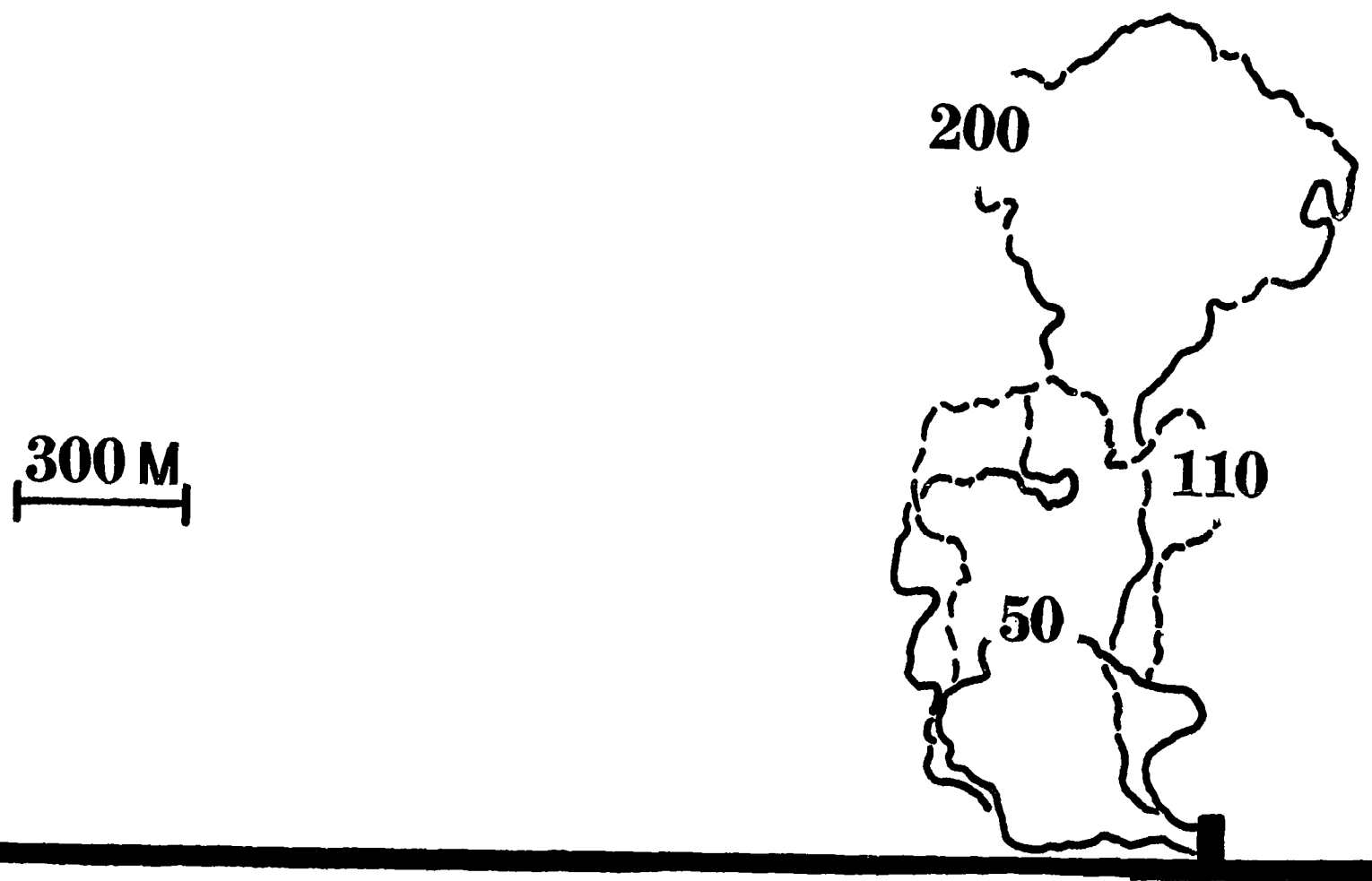


Figure 50. Rectified Cloud Geometry. Firing S-11-15.

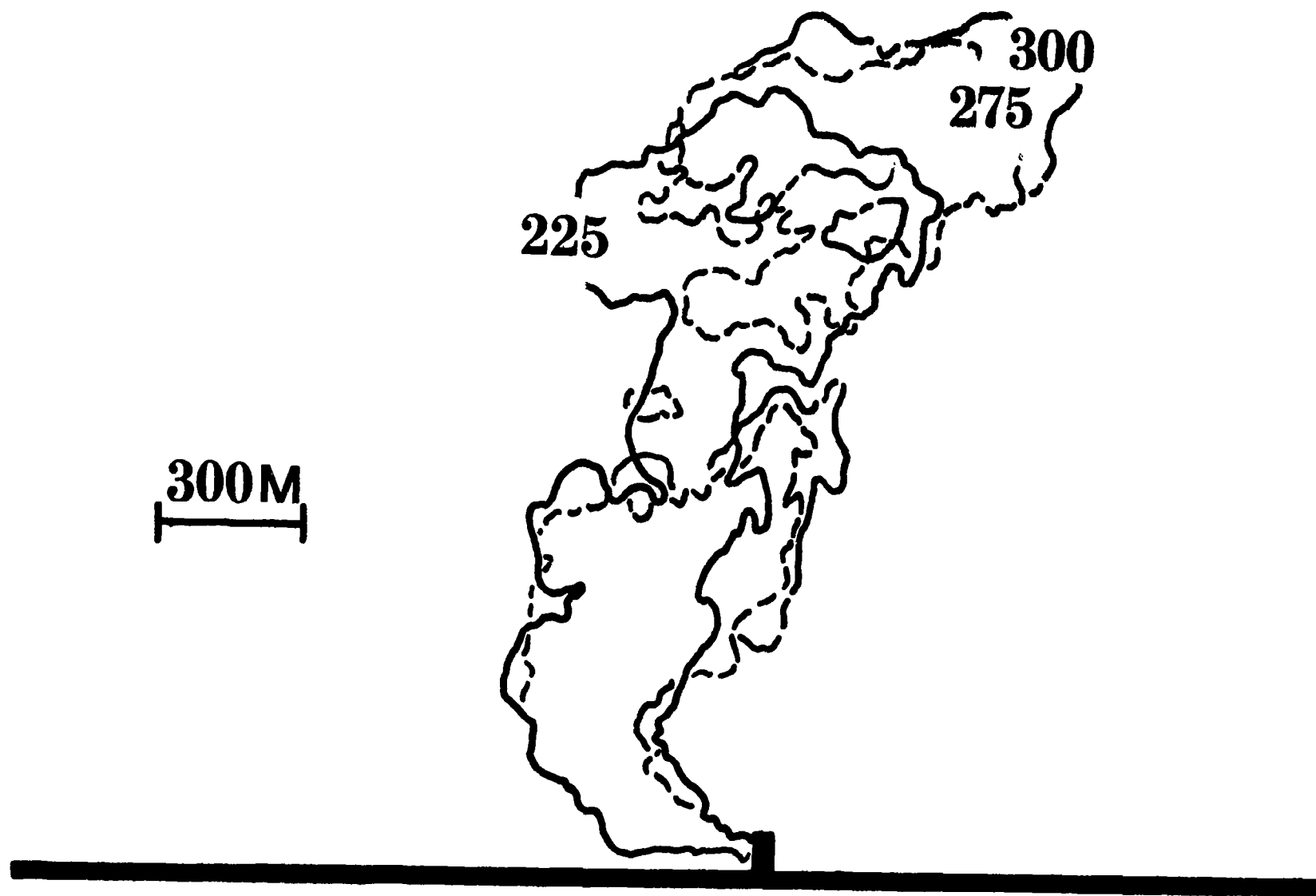


Figure 51. Rectified Cloud Geometry. Firing S-11-15.

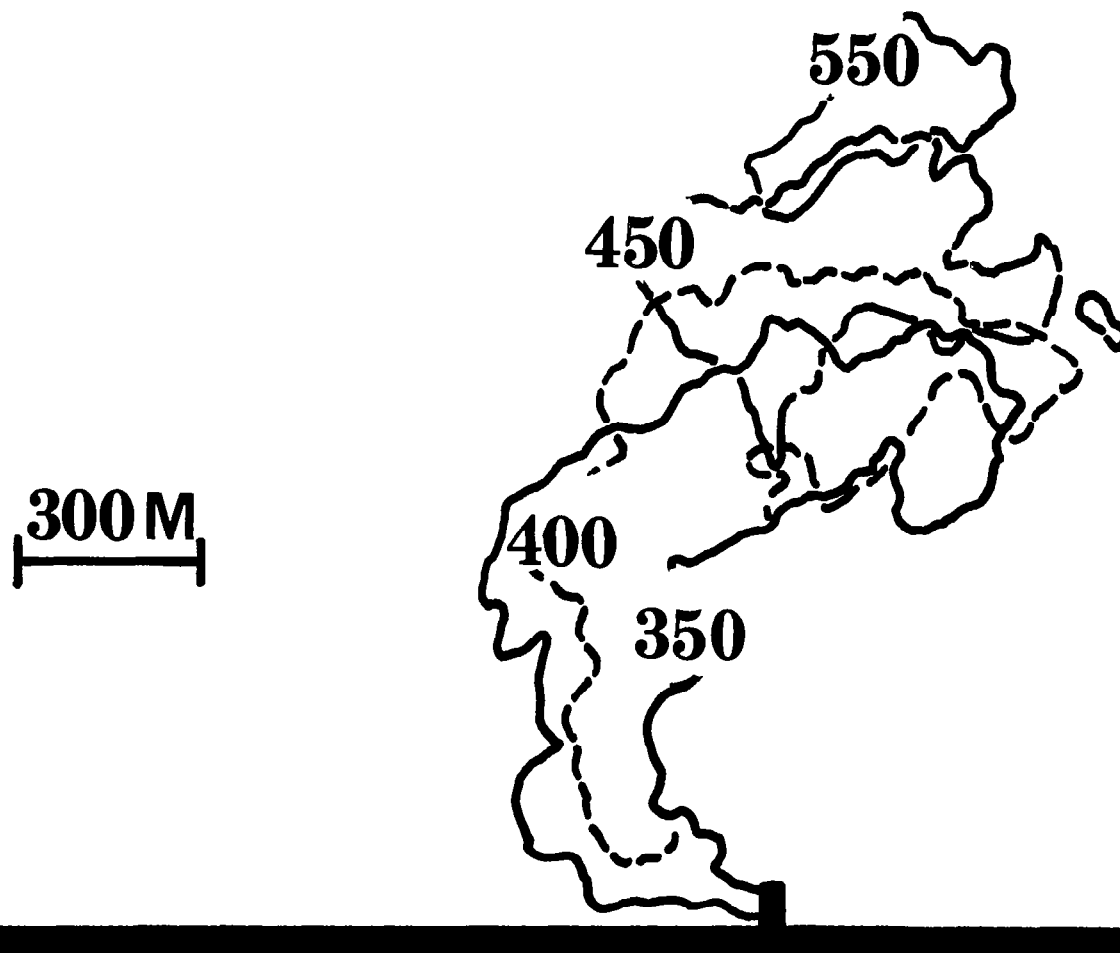


Figure 52. Rectified Cloud Geometry. Firing S-II-15.

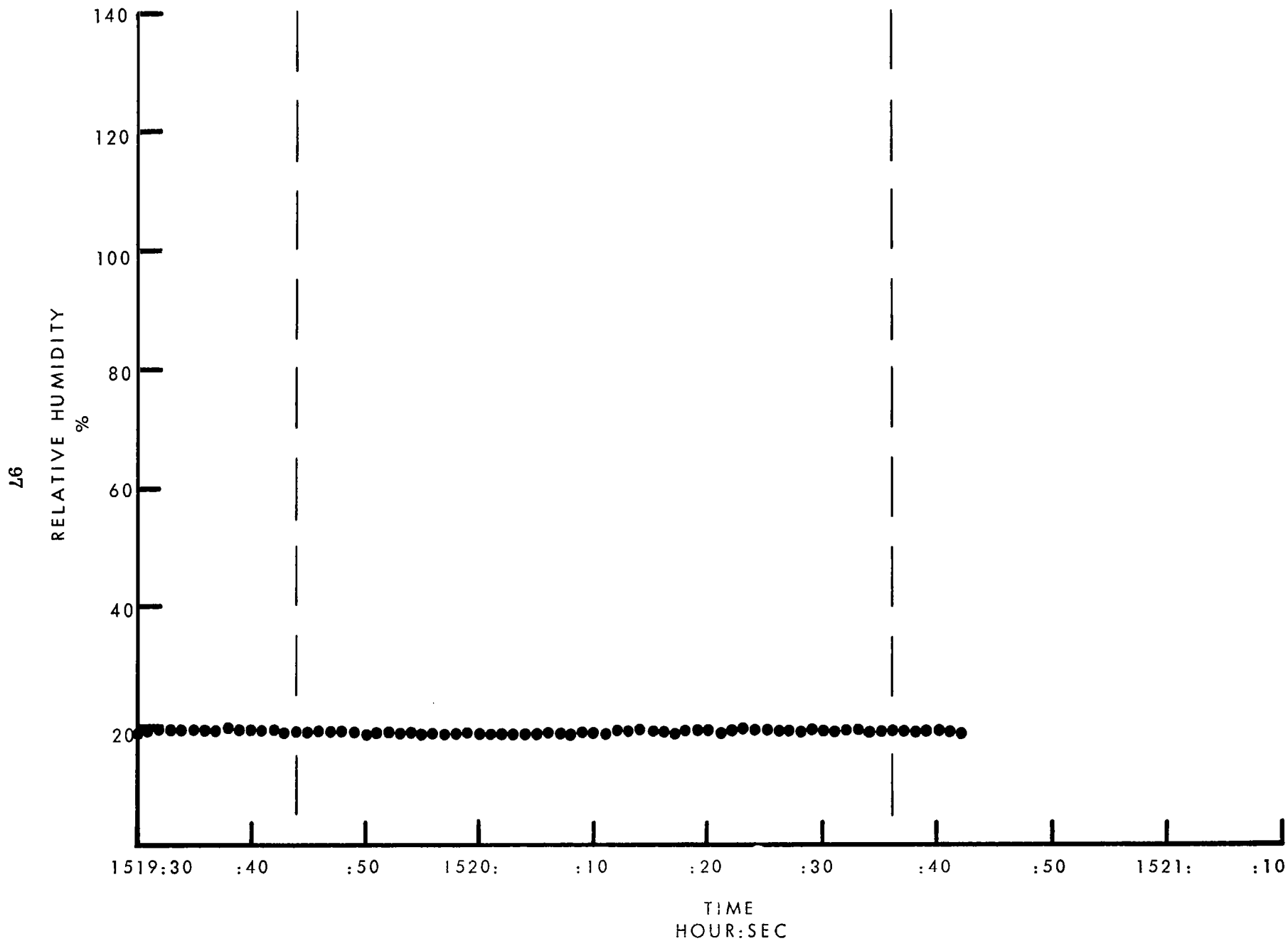


Figure 53. Relative Humidity In Cloud. Pass I.  
Firing S-II-15. MSU Aircraft.

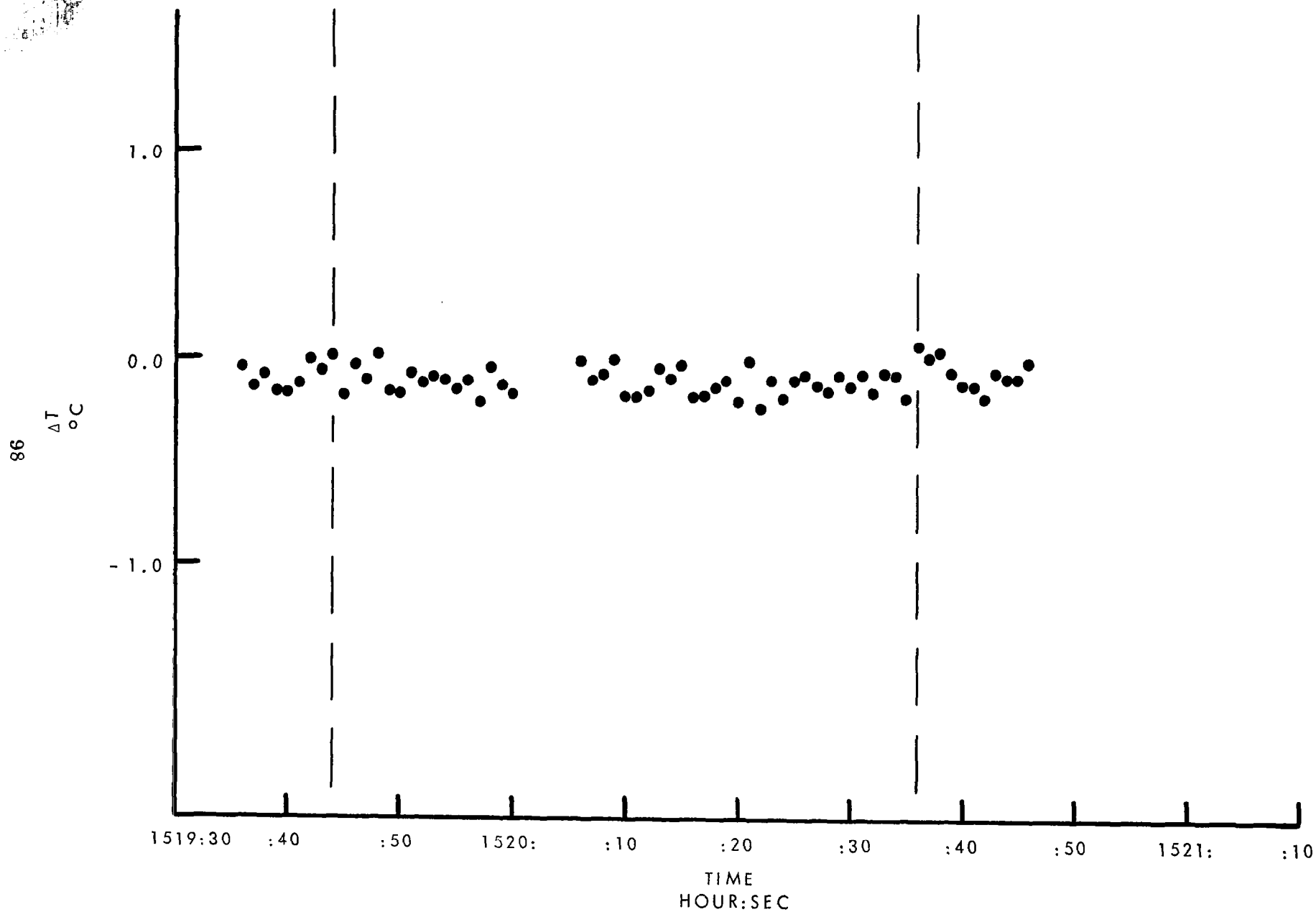


Figure 54. Disturbed Temperature In Cloud. Pass 1.  
Firing S-II-15. MSU Aircraft.

## BIBLIOGRAPHY

- (1) Berry, F.A., Bollay, E. and Beers, N.R., Handbook of Meteorology, McGraw-Hill Book Company, New York, 1945.
- (2) Smith, M.R. and Johnson, R.A., "Application of Aerospace Data Acquisition Technology to Atmospheric Meteorological Investigations," Technology Utilization Ideas for the 70's and Beyond, Vol. 26, American Astronautical Society, 1970.