NASA Technical Memorandum 78778

NASA-TM-78778 19790007278

Launch Vehicle Effluent Measurements During the August 20, 1977, Titan III Launch at Air Force Eastern Test Range

David C. Woods, Richard J. Bendura, and Dewey E. Wornom

JANUARY 1979

NASA

NASA Technical Memorandum 78778

Launch Vehicle Effluent Measurements During the August 20, 1977, Titan III Launch at Air Force Eastern Test Range

David C. Woods, Richard J. Bendura,
and Dewey E. Wornom
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1979

SUMMARY

The airborne effluent measurements and cloud physical behavior for the August 20, 1977, Titan III launch are summarized in this paper. The Titan vehicle was launched at 1029 eastern daylight time from launch complex 41 at the Air Force Eastern Test Range (AFETR), Florida. The monitoring program included airborne effluent measurements within the launch cloud and visible and infrared imaging measurements of cloud physical behavior. Effluent measurements included concentrations of hydrogen chloride (HCl), chlorine (Cl_2), nitrogen oxide (NO), nitric oxide (NO_x), and particulates (solid and liquid) as a function of time in the exhaust cloud. For each sampling pass the nonvolatile particle mass concentration was measured as a function of particle diameter over a size range of 0.05 to 25 μm and particle number density was measured over a size range of 0.5 to 7.5 μm.

Measurement results showed incloud gaseous effluent values to be similar to those measured at previous launches. For example, maximum incloud HCl concentrations ranged from about 30 parts per million by volume (ppm) several minutes after launch to 1 to 2 ppm at 100 minutes after launch. Maximum Cl_2 ranged from about 40 to 45 parts per billion by volume (ppb) several minutes after launch to less than 10 ppb by 20 minutes after launch. Maximum NO_x concentrations were about 1100 ppb several minutes after launch and between 100 to 300 ppb after 100 minutes. Integrating nephelometer measurements showed maximum incloud particle concentrations to be about 1100 $\mu g/m^3$ several minutes after launch and between 100 to 200 $\mu g/m^3$ by 100 minutes. Particle sizing measurements (mass concentration as a function of size) showed the incloud particle distribution to be generally bimodal in the range of 0.05- to 25-μm diameter, with concentration peaks generally at about 0.1 μm and about 1 to 3 μm. Visible and infrared imaging data on cloud physical behavior were limited to about the first 16 minutes after launch.

The purpose of the paper is data presentation. These data will be useful in the development of diffusion models for predicting exhaust cloud behavior under various meteorological conditions. Some comparisons of data with those from previous Titan III launches are presented.

INTRODUCTION

Since 1972, the National Aeronautics and Space Administration (NASA) has been conducting launch vehicle effluent (LVE) measurements at selected NASA and Air Force launches for the purpose of investigating the effect of launch vehicle emissions (mainly, solid rocket motor emissions) on tropospheric air quality. This tropospheric program is aimed at measuring and predicting the impact of ground clouds produced after launch on the surface air quality. The LVE monitoring program is conducted by the Langley Research Center (LaRC) with intercenter support from Marshall Space Flight Center (MSFC) and John F. Kennedy Space Center (KSC). The goal of the LVE program is to assess the applicability and accuracy of diffusion models for predicting the dispersion of exhaust effluents from NASA's current and future launch vehicles. The objectives of the program are to develop data to be used in the establishment of potential launch constraints and to develop in-house expertise in the areas relating to the environmental impact of launch activities. The approach employed to meet these objectives is that of measuring rocket exhaust products (produced by large, solid rocket motor launch vehicles) at surface level and within the stabilized ground cloud formed in the troposphere as a result of the launch. These exhaust products are mainly HCl and particulates (aluminum oxide (Al_2O_3) and debris). These measurements are then used to make direct comparisons with the diffusion models and NASA computer codes that are used to predict effluent composition and concentrations.

From 1972 to midyear 1974, LaRC monitored six launches (refs. 1 to 5) for purposes of developing the measurement techniques and operational procedures to be used during full-scale (land, sea, and airborne) monitoring of launches in late 1974 and 1975. Four launches during this time period were selected as the tests in which full-scale measurement and modeling programs would be attempted and model-measurement results compared. The HCl data obtained during the four launches are reported in reference 6, and the May 1975 launch results are discussed in detail in reference 7. Following the completion of the four full-scale launch monitoring activities, LaRC discontinued such large-scale monitoring but has continued the airborne sampling in the ground cloud at a rate of about two launches per year.

The measurement results for the August 20, 1977, Titan III launch are summarized in this paper. The Titan vehicle was launched from launch complex 41 (LC-41) at the Air Force Eastern Test Range (AFETR), Florida. Launch time was 1429 universal time (1029 eastern daylight time). The LVE monitoring experiment included airborne effluent measurements within the launch cloud and visible and infrared imaging measurements of cloud physical characteristics.

SYMBOLS

t_0 — reference time after launch for concentration-time plots for airborne data, min:sec after launch

T — time relative to launch; T - 0 is launch

Abbreviations:

CS-27200 — camera site, Air Force facility number 27200

FSSP — forward scattering spectrometer probe

LC-41 — launch complex 41

LVE — launch vehicle effluent

ppb — parts per billion by volume

ppm parts per million by volume

QCM quartz crystal microbalance cascade impactor

SRM solid rocket motor

UCS universal camera site

VAB camera site, Vertical Assembly Building

EXHAUST CLOUD DESCRIPTION

A brief description of the ground cloud sampled by the aircraft is presented in this section. Refer to reference 5, 7, 8, or 9 for a more detailed cloud discussion.

The Titan III launch vehicle consists of a three-stage core using a liquid propulsion system and two solid rocket motors (SRM) attached on opposite sides of the core. Only the SRM boosters (first 10 to 20 sec of burn) contribute effluents to the ground cloud because the liquid propulsion system is ignited at altitude. Each SRM booster has a mass-flow rate at lift-off of about 4160 kg/sec and remains relatively constant for the first 20 seconds. This initial exhaust from the SRM boosters generates a ground cloud in the immediate vicinity of the launch pad and, as a result of buoyant forces, rises to a stabilization altitude where it then drifts and diffuses with the prevailing winds. Stabilization typically occurs within 15 minutes after launch at altitudes between 1000 and 2000 meters, depending upon cloud buoyancy, meteorology, and the mixing-layer height. Initially the cloud is composed of species from the SRM engine exhaust, debris from the launch pad, and species generated during high-temperature afterburning reactions in the exhaust plume. However, as the cloud rises, stabilizes, and drifts with the wind, it entrains large quantities of atmospheric air, and by the time stabilization occurs, less than 1 percent of the cloud mass is engine exhaust. Main constituents of the stabilized ground cloud are listed in table I. Shown are incloud concentrations at about 10 to 15 minutes after launch and the sources for each specie.

MEASUREMENT PROGRAM

The airborne sampling strategy and instrumentation used in the LVE program have been discussed in previous papers. (See refs. 5, 7, and 10.) A description of the visible photography and infrared imaging instrumentation are available in references 7 and 11. Therefore, only a brief summary of the measurement program is presented herein.

Airborne Sampling Plan

The sampling platform, a twin-engine light aircraft, was airborne at approximately T - 30 minutes where T - 0 is launch. Range safety required the aircraft to be in a holding pattern at an altitude of approximately 1000 meters, approximately 8 km west of the launch pad. Just before launch the aircraft was released from the holding pattern and radar vectored to perform the sampling mission. The sampling plan used by the aircraft was a series of basic downwind and crosswind penetrations of the exhaust cloud, each at a constant altitude through the center of the cloud as determined visually by the flight crew. For this mission, 31 penetrations of the exhaust cloud were made from about T + 4 minutes to T + 103 minutes. After the 31st pass, sampling was terminated because of the low fuel reserve remaining onboard the aircraft. The flight parameters associated with each sampling pass are listed in table II.

Airborne Instrumentation

The sampling aircraft (ref. 10) was equipped to monitor HCl, suspended particulates, NO, NO_x, and Cl_2. Routine flight parameters (altitude, heading, airspeed, etc.) were also measured. Aircraft position was obtained by ground radar track of the onboard S-band transmitter beacon. As discussed in reference 10, all effluent air samples were taken into the aircraft through specially designed sampling probes located in the nose of the aircraft. These probes extended forward of the flow-field disturbance created by the aircraft nose, thus collecting undisturbed, free-stream sampling air. The characteristics of the effluent monitoring instrumentation from which data were obtained for this mission are described in table III. The operations of the instruments are described in references 10, 12, 13, 14, 15, and 16 as listed in table III. To a limited extent the elemental composition as a function of particle size was determined from postflight analysis of particles collected in the QCM instrument.

Cloud Imaging Systems

Metric-tracking units (ref. 11) and time-sequence cameras were located at sites UCS-9, UCS-2, and CS-27200 (see fig. 1) for purposes of obtaining records of cloud track, rise, growth, and volume. A motion-picture camera was located at site VAB. Infrared scanners (ref. 7) located at sites CS-27200 and VAB provided additional cloud physical data. Operational problems of identifying the exhaust cloud from ambient clouds were experienced at all cloud imaging sites. Typically only 15 to 20 minutes of usable data were obtained at each site.

DATA RESULTS

The data obtained during the August 20, 1977, LVE measurement operation are presented in this section. Where appropriate, similar data from previous launches are shown for comparison.

Meteorology

Figure 2 shows the meteorological data for the launch. These data are from a rawinsonde released at T - 13 minutes and T - 0. A notable feature of the data is the nearly constant wind direction (230° to 250°) from about the surface to 3-km altitude.

Cloud Physical Parameters

As stated previously, weather conditions were responsible for limited cloud imaging data at all tracking sites. Metric-tracking data were obtained for about 16 minutes, and infrared data for about 20 minutes. Poor resolution for the infrared data beyond T + 20 minutes was due to signal attenuation by ambient water vapor. For similar reasons time-sequence and motion-picture data were obtained for only a few minutes after launch. The data obtained by the imaging systems are discussed in the following paragraphs, and where appropriate the data are used to compare the aircraft radar tracked position (during each sampling pass) with the main exhaust cloud as tracked optically.

Figure 3 shows the 16 minutes of cloud trajectory data from the metric-tracking cameras. The bars on the data indicate the uncertainties in the cloud location as determined from the three tracking cameras. (See ref. 5 for a discussion of data analysis techniques.) The aircraft location for several of the earlier sampling passes is also shown. Figure 4 is a plot of the aircraft location (table II) at the midpoint of each sampling pass. These data, the optical-track data of figure 3 and the wind-direction data of figure 2, indicate a cloud trajectory of about 58° from LC-41. Figure 5 shows the cloud-rise data (metric-tracking camera) and the sampling altitude (at midpoint of a pass) of the aircraft for each of the first six sampling passes. The aircraft data and the optical-track data compare favorably after 6 minutes and show a cloud stabilization altitude (center) between 1.2 and 1.3 km at 10 minutes. Based on the aircraft sampling altitude (table II), the cloud decreases in altitude to about 1 km at 30 minutes and remains there for the duration of the sampling (T + 103 min). Obviously from the data of figures 3 to 5, both the optical-tracking teams and the aircraft-sampling crew were following the same cloud. The consistency of the aircraft position data (fig. 4) indicates that the aircraft crew had no difficulty in identifying the launch exhaust cloud during the approximate 100 minutes of effluent sampling.

Because of poor exhaust cloud contrast with the ambient background and infrared signal attenuation by ambient moisture, cloud volume could not be calculated from either the optical or infrared tracking data. However cloud volume was approximately calculated from the residence time of the aircraft in the cloud. The results are shown in figure 6. Comparison of these calculations with the conventional volume calculations (using the optical and infrared data) for launches where both techniques can be applied ($T < 20$ min) indicates that the aircraft determined cloud volumes are generally within a factor of 0.5 of those determined by the more accurate optical data. Error analysis for later time periods (where no camera data exist) indicates that the aircraft technique is accurate within a factor of 3.

Figures 7 and 8 show a comparison of the August 1977 cloud data with those of other Titan III clouds (all at the Florida launch site). Figure 7 shows the envelope of cloud-rise data measured for nine previous Titan III launches. The

August 1977 measurements are well within the data envelope after stabilization. As shown from previous Titan III data, the initial rise rate of the cloud is 4 to 5 m/s and essentially independent of the existing meteorology; however cloud stabilization altitude differs among launches and is dependent on the prevailing meteorology and thermodynamics of the atmosphere. Cloud-volume comparison is shown in figure 8. Note the scale break in the time axis. The data envelope of figure 8 is from five previous Titan III launches and is mainly calculated from the optical and infrared data. Considering the potential factor of 3 uncertainty in the August 1977 volume calculations and the different meteorological conditions for the launches, the volume agreement is reasonable.

Airborne Effluent Measurements

Concentration-time data.- Incloud effluent concentrations of HCl, Cl_2, particles (nephelometer), and NO_x measured during each sampling pass are shown in figure 9. Analyses indicate that most NO_x is NO. Zero time t_0 for the abscissa of each plot is shown in the subtitle of the figure and is given in minutes and seconds after launch. The following points should be considered in the interpretation of the data of figure 9:

(1) As a result of operational difficulties, Cl_2 data were not obtained during pass 1, and Cl_2 data are not shown beyond pass 8 as Cl_2 concentrations were below 10 ppb (detection limit). In addition, NO_x data are not shown for passes 9 to 31 because noise in the NO-NO_x instrument output negates the usefulness of these data. However, analysis of the data indicated that maximum NO_x concentration during each of these passes was of the order of 100 to 300 ppb.

(2) No correction for sampling line time-delay effects of the various instruments has been applied to the data. Generally the nephelometer and HCl instruments respond together whereas the Cl_2 and NO_x data lag by about 10 seconds because the NO_x and Cl_2 instruments are located in the aft passenger cabin, whereas the other two instruments are located in the nose compartment of the aircraft.

(3) All 31 sampling passes are of the main exhaust cloud formed at launch. Little difficulty was experienced by the aircraft crew in locating and identifying the launch cloud. Problems encountered at some previous launches (ref. 16) of the existence of multiple clouds and the identification of which cloud was sampled on successive passes did not occur.

For this mission, maximum observed HCl concentration of approximately 30 ppm occurred during pass 2 (T + 5 min). Approximately 15 minutes after launch, maximum HCl was about 5 ppm, and at completion of the sampling (T + 100 min), HCl had decayed to 1 to 2 ppm. Figure 9 shows Cl_2 concentrations (sharp peaks) as high as 80 ppb; however, as discussed in reference 14, some minor Cl_2 instrumentation problems occurred with the result that maximum Cl_2 concentrations were most likely of the order of 40 to 55 ppb. By T + 20 minutes, these Cl_2 concentrations decayed to below 10 ppb. Maximum NO_x concentrations of 1100 ppb (T + 5 min) decayed to approximately 500 ppb at 15 minutes and by completion of the mission (T + 100 min) were 100 to 300 ppb. Maximum particulate concentration (nephelometer) was of the order of 1100 $\mu g/m^3$ (pass 2) and decayed to 100 to 200 $\mu g/m^3$ by pass 30. Data from all 31 passes are plotted in figure 9 by using a 1-second data interval. The data are listed in the appendix at 2-second intervals.

The August 1977 airborne data are compared with those of previous Titan III launches in figure 10. The comparison is only for the first 50 minutes after launch. (Data from previous launches did not exceed 50 min.) The solid lines represent the envelope of maximum observed concentrations in each sampling pass for the previous Titan III launches. As shown in the figure, the August 1977 data are within the previous data envelope.

Particle-sizing data.- The average particle size distribution over the path length through the exhaust cloud was measured with the QCM and FSSP instruments for each sampling pass. See reference 16 for a discussion of the data-reduction techniques. As noted in reference 16, the QCM instrument (like the nephelometer) is responsive mainly to the nonvolatile particulates in the LVE cloud. The liquid aerosols (including most of the water on the surface of the solid particulates) are vaporized prior to encountering the QCM sensing crystals by the heated sample inlet probe. The QCM data for each sampling pass are shown in table IV. Data are not shown for the 0.2-μm sizing stage as this channel of the QCM was inoperative. Most data show a bimodal size distribution with peaks at approximately 0.1-μm diameter and 1- to 3-μm diameter. These results are similar to those observed for the May 1977 launch (ref. 16). Figure 11 is a plot of the data of table IV. Elemental and morphological analyses of particles collected by the various stages of the QCM were performed postlaunch with scanning electron microscopy. The type of analyses and some typical results from previous launch effluent samples are discussed in reference 17. Particles collected on sizing stages 6.3, 12.5, and 25 μm were relatively few in number, mostly irregular in shape, and contained the elements sodium (Na), magnesium (Mg), aluminum (Al), sulfur (S), chlorine (Cl), potassium (K), tin (Sn), calcium (Ca), titanium (Ti), iron (Fe), and zinc (Zn) in varying amounts. Particles on sizing stages 0.8, 1.6, and 3.2 μm are spherical in shape. These particles were of similar elemental composition as the 6.3- to 25-μm particles, and many particles were surrounded by stains (on the collecting crystal), possibly suggesting these particles may have been wet at the time of collection. Particles on the 0.4-μm stage were both amorphous and spherical, not surrounded by stains, and showed the presence of Na, Al, Cl, Ca, and Fe. Particles collected on sizing stages 0.05, 0.1, and 0.2 μm were dominated by agglomerates. These agglomerates were probably formed after impaction because they are large compared with the sizing range of these stages. These particles contained all the elements found in the 6.3- to 25-μm sizes with the exception of Ti and Sn. Generally spherical particles have been associated with the Al_2O_3 exhaust particles (usually rich in Al and Cl), whereas the amorphous particles show numerous elements and have been attributed to launch debris and ambient particulates entrained within the cloud.

As discussed in reference 16, the FSSP instrument is sensitive to both the solid and liquid aerosols in the LVE cloud. The FSSP data for each of the 31 sampling passes are shown in figure 12 and table V. The data are presented in aerosol percentage and represent the number of aerosols in a given size interval divided by the number of aerosols sampled in all size intervals. The previous passes (first 11 or 12 min) show a size distribution biased to the larger size aerosols. For example, passes 1, 2, and 3 show a sizable percentage of aerosols in the 4- to 6-μm-diameter range as compared with those aerosols below 1 μm. However as time increases, the size distribution changes such that at about pass 9 (T + 20 min), the smaller aerosols (1 μm or less) dominate. At pass 9 and beyond, 50 percent of the aerosols are 1 μm or less in diameter. Because the FSSP does not detect particles below 0.5-μm diameter, the bimodal distribution (peak at 0.1-μm diameter) observed from the QCM data is not seen in the FSSP results.

Note that the operating principles of the various particle instruments (nephelometer, QCM, and FSSP) are different. The instruments are sensitive over different particle size ranges, and the instrument responses are affected by different factors. Direct comparisons of data from the three different instruments are not a simple matter. For example, the response of the integrating nephelometer is strongly dependent upon the particle size distribution (ref. 18) over a range of approximately 0.2-μm to 10-μm diameter and is essentially zero outside this range. The response is complicated even more by the effects of the light refraction characteristics of the particles (ref. 19). These factors must be considered before comparing integrating nephelometer data with QCM data. If the QCM data are compared with the FSSP data, the following three factors must be considered:

(1) The QCM cascade impactor measures aerodynamic size and is therefore sensitive to mass density of the individual particles, whereas the FSSP measures geometrical size and is sensitive to particle shape and refractive index.

(2) The QCM cascade impactor measures over a size range from 0.05-μm diameter to 25-μm diameter, whereas the range of the FSSP (selected for sampling) is from 0.5- to 7.5-μm diameter.

(3) The QCM inlet is heated so that most of the liquid component is removed from the sample. This is not the case for the FSSP.

Thus differences are expected between the mass concentration as measured with the QCM (sum of all stages) and the mass concentration as derived from the scattering coefficient measurements made with the integrating nephelometer. Because the FSSP measures particle-number concentration as a function of size over a range from 0.5- to 7.5-μm diameter and the QCM measures mass concentration as a function of size over a range from 0.05- to 25-μm diameter, it is not possible to make direct comparisons of the data from the two instruments. For these reasons, no attempt is made in this paper to compare quantitatively results from the various particle instruments. Future activities should be focused in that direction.

CONCLUDING REMARKS

The data presented herein were obtained during the August 20, 1977, Titan III launch vehicle effluent (LVE) measurement program. Most data are presented in both tabular and graphical form and in a format easily used and referenced for the reader. No data analyses are presented, and data discussion is limited to only those instances where the lack of such discussion would result in possible improper interpretation of the data. Comparison of the August 20, 1977, data with those of previous LVE measurement data suggests that the data set is representative of that from other Titan III launches.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
November 9, 1978

APPENDIX

TABULATION OF AIRBORNE HCl, Cl_2, NO_x, AND NEPHELOMETER

PARTICULATE DATA

Tables VI to XXXVI are tabulations of the airborne effluent data shown graphically in figure 9. Tabulations are for 2-second intervals. Only those data from figure 9 taken when the aircraft was sampling the launch cloud are tabulated.

REFERENCES

1. Gregory, Gerald L.; Hulten, William C.; and Wornom, Dewey E.: Apollo Saturn 511 Effluent Measurements From the Apollo 16 Launch Operations - An Experiment. NASA TM X-2910, 1974.

2. Hulten, William C.; Storey, Richard W.; Gregory, Gerald L.; Woods, David C.; and Harris, Franklin S., Jr.: Effluent Sampling of Scout "D" and Delta Launch Vehicle Exhausts. NASA TM X-2987, 1974.

3. Gregory, Gerald L.; and Storey, Richard W., Jr.: Effluent Sampling of Titan III C Vehicle Exhaust. NASA TM X-3228, 1975.

4. Stewart, Roger B.; Sentell, Ronald J.; and Gregory, Gerald L.: Experimental Measurements of the Ground Cloud Effluents and Cloud Growth During the February 11, 1974, Titan-Centaur Launch at Kennedy Space Center. NASA TM X-72820, 1976.

5. Bendura, Richard J.; and Crumbly, Kenneth H.: Ground Cloud Effluent Measurements During the May 30, 1974, Titan III Launch at the Air Force Eastern Test Range. NASA TM X-3539, 1977.

6. Gregory, Gerald L.; Wornom, Dewey E.; Bendura, Richard J.; and Wagner, H. Scott: Hydrogen Chloride Measurements From Titan III Launches at the Air Force Eastern Test Range, FL, 1973 Through 1975. NASA TM X-72832, 1976.

7. Gregory, Gerald L.; and Storey, Richard W., Jr.: Experimental Measurements of the Ground Cloud Effluents and Cloud Growth for the May 20, 1975, Titan IIIC Launch at Air Force Eastern Test Range, Florida. NASA TM-74044, 1977.

8. Gomberg, Richard I.; and Stewart, Roger B.: A Computer Simulation of the Afterburning Processes Occurring Within Solid Rocket Motor Plumes in the Troposphere. NASA TN D-8303, 1976.

9. Stephens, J. Briscoe; and Stewart, Roger B.: Rocket Exhaust Effluent Modeling for Tropospheric Air Quality and Environmental Assessments. NASA TR R-473, 1977.

10. Wornom, Dewey E.; Woods, David C.; Thomas, Mitchel E.; and Tyson, Richard W.: Instrumentation of Sampling Aircraft for Measurement of Launch Vehicle Effluents. NASA TM X-3500, 1977.

11. Ehling, Ernest H., ed.: Range Instrumentation. Prentice-Hall, Inc., c.1967.

12. Gregory, Gerald L.: Measurement Techniques Investigated for Detection of Hydrogen Chloride Gas in Ambient Air. NASA TN D-8352, 1976.

13. Gregory, Gerald L.; Hudgins, Charles H.; and Emerson, Burt R., Jr.: Evaluation of a Chemiluminescent Hydrogen Chloride and a NDIR Carbon Monoxide Detector for Environmental Monitoring. 1974 JANNAF Propulsion Meeting, Volume I, Part II, CPIA Publ. 260 (Contract N00017-72-C-4401), Appl. Phys. Lab., Johns Hopkins Univ., Dec. 1974, pp. 681-704. (Available from DDC as AD B002 590.)

14. Gregory, G. L.; Emerson, Burt R., Jr.; and Hudgins, Charles H.: Summary of Airborne Chlorine and Hydrogen Chloride Gas Measurements for August 20 and September 5, 1977 Voyager Launches at Air Force Eastern Test Range, Florida. NASA TM-78673, 1978.

15. Woods, David C.: Rocket Effluent Size Distribution Made With a Cascade Quartz Crystal Microbalance. NASA paper presented at the 4th Joint Conference on Sensing of Environmental Pollutants (New Orleans, La.), Nov. 7-11, 1977.

16. Gregory, Gerald L.; Bendura, Richard J.; and Woods, David C.: Launch Vehicle Effluent Measurements During the May 12, 1977, Titan III Launch at Air Force Eastern Test Range. NASA TM-78753, 1978.

17. Chuan, R. L.; and Woods, D. C.: Morphology and Elemental Composition Analysis by Size of Rocket Particulate Effluent. 4th Joint Conference on Sensing of Environmental Pollutants, American Chem. Soc., 1977. pp. 610-613.

18. Charlson, R. J.; Ahlquist, N. C.; Selvidge, H.; and MacCready, P. B., Jr.: Monitoring of Atmospheric Aerosol Parameters With the Integrating Nephelometer. J. Air Pollut. Control Assn., vol. 19, no. 12, Dec. 1969, pp. 937-942.

19. Woods, David C.: The Effects of Particle Size Distribution and Refractive Index on Aerosol Mass Concentration Measurements Made With an Integrating Nephelometer. Blacks in Technology - Beyond the Bicentennial, CP 101, Natl. Tech. Assoc., Aug. 1977.

TABLE I.- CLOUD CONSTITUENTS

Specie	Source	Nominal maximum concentration
N_2	Ambient air	Ambient values
O_2	Ambient air	Ambient values
H_2O	Ambient air; launch pad water; exhaust	Ambient values
CO_2	Ambient air; plume afterburning	Ambient values
Particles	Exhaust; pad debris	1000 to 3000 $\mu g/m^3$
HCl	Exhaust	5 to 40 ppm
CO	Ambient air; exhaust	<1 ppm
$NO-NO_x$	Plume afterburning	200 to 800 ppb
Cl_2	Plume afterburning	20 to 40 ppb

TABLE II.- AIRCRAFT FLIGHT PARAMETERS

Pass no.	Sampling altitude, m (a)	Type of pass	Aircraft location from LC-41 (b)		Time of pass after launch, min (c)
			km	deg	
1	766 ± 14	Downwind	1.6	56	3.5
2	1061 ± 55	Crosswind	2.4	47	5.1
3	1271 ± 17	Downwind	3.5	55	6.8
4	1385 ± 47	Crosswind	----	---	8.7
5	1313 ± 8	Downwind	6.9	53	11.4
6	1337 ± 10	Crosswind	8.6	54	13.4
7	1329 ± 10	Downwind	9.9	59	15.4
8	1373 ± 13	Crosswind	11.0	55	17.5
9	1190 ± 16	Downwind	12.8	58	21.2
10	1232 ± 26	Crosswind	15.2	57	24.1
11	1081 ± 15	Downwind	15.6	59	27.0
12	1055 ± 9	Crosswind	17.3	58	29.7
13	982 ± 6	Downwind	19.5	58	34.0
14	979 ± 8	Crosswind	20.6	58	37.0
15	983 ± 3	Downwind	23.0	59	40.2
16	986 ± 4	Crosswind	26.0	58	44.1
17	992 ± 5	Downwind	31.6	59	48.2
18	991 ± 4	Crosswind	----	---	51.7
19	993 ± 4	Downwind	32.1	58	55.1
20	994 ± 4	Crosswind	33.6	57	58.6
21	994 ± 3	Downwind	36.4	58	63.3
22	994 ± 5	Downwind	40.7	59	70.4
23	994 ± 4	Crosswind	42.2	58	73.5
24	993 ± 5	Downwind	----	---	78.3
25	995 ± 4	Crosswind	----	---	81.4
26	996 ± 6	Downwind	----	---	85.3
27	995 ± 5	Crosswind	----	---	88.7
28	993 ± 3	Downwind	----	---	92.8
29	992 ± 5	Crosswind	----	---	96.9
30	995 ± 6	Downwind	59.0	59	100.5
31	998 ± 4	Crosswind	58.8	58	103.3

[a]Sampling altitude ± Altitude variation during pass.
[b]Aircraft location at midpoint of sampling pass.
[c]Time when aircraft at midpoint of sampling pass.

TABLE III.- INSTRUMENT CHARACTERISTICS

Measured specie	Instrument	Reference	Range	Detection limit	Response to 90-percent reading, sec
HCl	Chemiluminescent	10, 12, 13	0.5 to 200 ppm	0.5 ppm	1
Cl_2	Chemiluminescent	14	0.01 to 10 ppm	0.01 ppm	1
$NO-NO_x$	Chemiluminescent	10	0.002 to 5 ppm	0.002 ppm	1.5
Particles	Cascade quartz crystal microbalance	15, 16	0.05- to 25-μm diam	10 $\mu g/m^3$	5
Aerosols	Forward scattering spectrometer probe	16	0.5- to 7.5-μm diam	1 particle	---
Particles	Nephelometer	10, 16	0.2- to 10-μm diam	100 particles	.2

TABLE IV.- PARTICULATE MASS CONCENTRATION ($\mu g/m^3$) AS FUNCTION

OF PARTICLE SIZE (QCM DATA)

Pass no.	Particle diameter, μm										
	0.05	0.1	0.2 (a)	0.4	0.8	1.6	3.2	6.3 (b)	12.5 (b)	25 (b)	Σ-stages (c)
1	35	104	---	22	17	125	12	0	0	0	315
2	162	207	---	36	27	48	81	45	18	0	624
3	141	104	---	15	15	30	60	30	15	7	417
4	36	122	---	58	14	22	18	7	14	22	313
5	67	25	---	21	25	34	13	0	8	8	201
6	22	79	---	36	29	43	43	7	0	0	259
7	33	75	---	25	25	8	66	8	4	17	261
8	45	54	---	36	30	36	6	6	-6	-12	213
9	130	187	---	58	58	72	43	43	-14	-14	591
10	39	97	---	39	27	27	5	5	-5	-5	239
11	29	59	---	7	22	15	59	7	7	0	205
12	19	51	---	6	19	6	19	12	6	6	144
13	31	21	---	13	13	13	13	0	0	0	104
14	21	50	---	13	17	8	46	4	4	4	167
15	26	57	---	13	13	9	13	0	0	0	131
16	19	42	---	14	14	9	47	0	0	7	152
17	25	59	---	4	17	13	8	-4	-8	-4	126
18	22	43	---	13	22	4	43	4	0	0	151
19	16	31	---	14	8	6	2	-2	-4	-6	77
20	14	38	---	10	10	7	58	0	0	10	147
21	10	17	---	4	6	3	10	7	0	0	57
22	22	39	---	9	9	9	30	0	-4	-4	118
23	19	42	---	8	12	8	27	4	0	0	120
24	32	53	---	21	16	21	37	5	-5	0	185
25	16	39	---	12	12	12	31	4	-4	0	126
26	23	34	---	11	11	4	19	0	0	0	102
27	18	36	---	7	14	7	40	0	0	0	122
28	25	52	---	15	19	15	15	12	0	0	153
29	4	31	---	16	16	12	31	0	0	0	110
30	22	28	---	12	12	12	6	0	0	0	92
31	0	27	---	---	5	5	49	0	0	0	86

[a] 0.2-μm stage inoperative.
[b] Negative data plotted as 0 in figs.
[c] Negative data are not included in summation.

TABLE V.- AEROSOL DISTRIBUTION (PERCENT) AS FUNCTION OF PARTICLE DIAMETER (FSSP DATA)

Pass no.	Particle diameter, μm														
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
1	5.5	3.8	3.6	4.3	5.6	5.9	6.4	8.3	10.3	10.6	10.7	9.1	7.9	6.6	1.5
2	5.7	6.0	5.3	4.7	5.5	6.0	6.3	6.7	7.5	7.0	8.0	8.9	9.5	10.2	1.8
3	2.6	1.8	2.2	2.9	4.2	6.5	9.9	12.8	14.4	13.4	11.3	8.2	5.4	3.4	1.0
4	10.8	11.8	17.6	17.5	11.0	6.1	4.3	3.7	2.8	2.3	2.1	2.4	2.7	2.3	2.6
5	8.2	6.1	6.0	6.3	5.7	6.9	7.4	9.3	8.6	8.3	6.3	5.3	4.8	5.7	5.1
6	13.6	10.7	9.0	7.4	7.2	5.4	5.8	5.7	4.8	6.2	4.8	3.8	6.0	4.5	5.1
7	11.4	7.4	6.9	6.8	5.8	6.5	6.5	5.9	7.6	5.9	6.4	7.3	5.3	4.7	5.6
8	17.8	6.6	5.9	6.1	7.1	6.1	7.0	5.6	5.7	5.7	5.8	5.7	5.2	5.1	4.7
9	35.3	13.1	9.2	8.2	3.2	5.0	4.8	2.2	4.0	3.3	2.0	2.4	2.9	2.3	2.2
10	41.9	15.9	9.2	8.4	4.7	3.1	2.8	2.3	2.0	1.8	1.5	1.5	1.6	1.6	1.5
11	42.2	14.2	9.6	6.7	3.8	3.5	3.6	2.6	2.4	2.2	1.9	1.8	2.1	1.5	1.7
12	36.2	12.3	9.3	7.9	4.6	3.7	4.2	3.1	2.7	3.3	2.5	2.0	2.8	3.0	2.1
13	36.6	14.2	9.4	8.4	5.0	3.3	3.4	3.2	2.6	2.5	2.3	2.3	2.4	2.1	2.3
14	38.0	13.2	8.3	7.4	5.0	3.8	4.2	3.4	2.9	2.4	2.4	2.2	2.3	2.5	2.0
15	33.5	13.6	9.2	7.7	5.3	4.2	3.2	2.8	3.4	2.6	2.4	2.8	3.3	2.9	2.9
16	27.8	14.7	11.2	7.8	5.1	4.1	4.8	3.6	3.6	3.3	3.3	2.2	2.8	2.7	2.9
17	37.1	12.6	9.5	8.0	5.5	4.4	3.3	2.6	2.8	2.7	2.3	2.1	3.0	2.1	2.0
18	33.1	13.3	9.3	7.6	4.9	4.3	3.8	3.3	3.6	2.7	2.5	3.3	2.9	2.9	2.7
19	34.0	12.6	10.0	8.1	5.6	4.0	3.5	3.4	3.2	2.9	2.6	2.5	2.7	2.5	2.5
20	28.2	14.1	11.0	7.4	5.5	3.9	3.6	3.8	3.5	3.4	3.2	3.1	2.9	3.1	3.1
21	32.7	13.5	9.4	7.2	5.2	4.6	3.6	3.4	3.5	3.1	3.2	2.7	3.0	2.5	2.3
22	33.4	13.0	9.0	7.2	4.7	3.8	4.2	3.9	3.2	3.2	3.0	2.5	3.2	2.9	2.8
23	33.3	13.6	8.4	7.0	5.2	4.6	3.7	3.7	3.3	3.2	3.2	2.7	3.3	2.6	2.3
24	30.1	14.8	9.7	7.0	5.3	4.0	3.5	4.0	3.0	3.0	3.2	3.1	3.1	3.0	3.2
25	34.3	13.1	9.9	7.3	6.0	4.0	4.3	3.5	2.8	2.6	2.3	2.8	2.1	2.2	2.9
26	28.8	12.2	9.6	7.7	5.1	5.0	4.9	3.4	3.3	3.5	3.3	2.9	3.8	2.8	3.6
27	25.4	13.0	9.4	6.2	5.8	4.2	5.6	3.6	4.5	4.6	4.1	3.1	3.8	3.5	3.1
28	33.7	14.6	10.3	6.9	5.1	4.2	3.8	3.3	2.8	2.2	2.1	2.7	2.6	2.7	3.1
29	27.8	13.4	9.7	7.4	5.9	4.9	5.0	4.9	3.6	3.7	2.8	2.6	2.6	2.9	2.8
30	31.3	11.6	10.2	6.4	5.2	4.6	4.6	4.0	3.5	3.2	3.8	2.8	3.0	3.0	2.8
31	22.2	10.8	10.1	7.5	6.2	5.7	5.9	4.9	3.8	3.5	3.3	3.7	4.2	4.0	4.2

TABLE VI.- AIRBORNE DATA SAMPLING PASS 1

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb (a)	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
0	0.6		83	-1
2	.6		139	1
4	.6		80	3
6	.7		110	3
8	10.7		134	63
10	10.9		85	349
12	14.9		99	371
14	26.1		79	473
16	11.2		81	880
18	9.4		33	685
20	7.5		60	657
22	3.7		382	503
24	2.3		755	248
26	1.8		805	117
28	1.5		1005	60
30	1.3		849	35
32	1.2		525	27
34	1.1		357	23
36	1.1		222	23
38	1.0		137	22
40	1.0		154	21
42	1.0		134	24
44	.9		197	25
46	.9		125	25
48	.9		132	26
50	.9		80	27

[a]No data; malfunction.

TABLE VII.- AIRBORNE DATA SAMPLING PASS 2

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
0	0.7	2	151	8
2	.7	2	161	8
4	4.0	2	71	10
6	6.8	2	204	240
8	21.4	6	153	386
10	7.9	14	112	472
12	10.0	20	122	348
14	24.5	22	210	383
16	27.3	43	110	781
18	16.6	13	170	1061
20	11.9	31	404	961
22	8.6	28	657	805
24	4.4	36	738	614
26	3.1	20	469	326
28	2.4	13	673	162
30	2.0	8	1062	84
32	1.7	1	1040	52
34	1.5	1	747	37
36	1.4	1	552	32
38	1.2	0	314	30
40	1.2	0	104	28
42	1.1	0	45	28
44	1.1	0	61	30
46	1.0	0	54	30
48	1.0	0	133	31
50	1.0	0	155	30

TABLE VIII.- AIRBORNE DATA SAMPLING PASS 3

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
10	0.9	3	123	8
12	7.1	3	143	66
14	6.8	3	109	170
16	13.5	3	82	193
18	16.7	9	65	379
20	21.3	21	84	469
22	19.8	19	65	536
24	15.2	21	129	544
26	15.8	21	335	518
28	6.4	28	425	396
30	5.7	21	530	196
32	5.1	15	640	94
34	3.1	9	802	50
36	2.2	2	811	33
38	1.9	1	691	21
40	1.7	1	557	18
42	1.5	0	350	16
44	1.4	0	209	16
46	1.3	0	156	14
48	1.2	0	169	14
50	1.1	0	149	15

TABLE IX.- AIRBORNE DATA SAMPLING PASS 4

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
0	0.2	3	217	4
2	.2	3	80	2
4	.2	3	162	5
6	.1	3	282	-1
8	.5	3	88	49
10	4.3	3	136	169
12	9.3	4	185	413
14	14.0	5	173	621
16	14.4	8	226	751
18	3.7	45	215	595
20	2.2	80	165	291
22	3.8	37	233	174
24	5.5	13	317	243
26	4.9	1	458	240
28	4.6	6	613	248
30	5.8	19	558	337
32	2.2	14	385	351
34	1.4	14	277	185
36	1.1	17	379	92
38	1.0	7	467	51
40	.9	0	420	36
42	.6	0	431	24
44	.7	0	423	19
46	.6	0	369	24
48	.6	0	231	20
50	.5	0	145	20

TABLE X.- AIRBORNE DATA SAMPLING PASS 5

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
10	0.6	2	160	-1
12	.6	2	174	0
14	1.1	3	232	1
16	3.6	4	176	140
18	2.3	3	153	157
20	2.1	3	203	176
22	3.9	10	172	175
24	6.9	6	121	210
26	7.0	5	149	284
28	7.1	6	185	316
30	3.4	15	379	278
32	3.2	30	334	208
34	3.0	61	215	204
36	2.8	18	289	151
38	1.9	5	489	154
40	1.5	7	582	83
42	1.4	5	504	41
44	1.3	5	433	22
46	1.1	1	296	12
48	1.1	1	290	12
50	1.0	1	272	12

TABLE XI.- AIRBORNE DATA SAMPLING PASS 6

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
10	0.5	5	149	1
12	.8	5	171	17
14	1.4	4	127	50
16	4.0	4	214	255
18	2.4	4	193	400
20	4.7	4	147	365
22	6.2	13	126	375
24	7.3	16	83	350
26	6.8	9	139	337
28	7.5	18	213	317
30	7.5	32	384	329
32	7.8	32	382	325
34	6.3	66	405	298
36	4.4	31	516	270
38	2.5	29	557	200
40	1.8	30	528	101
42	1.5	15	563	54
44	1.3	4	549	32
46	1.2	1	539	23
48	1.1	0	471	17
50	1.0	0	383	15
52	1.0	0	274	12
54	.9	0	143	11

TABLE XII.- AIRBORNE DATA SAMPLING PASS 7

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
0	0.6	4	168	-3
2	.7	4	153	0
4	.7	4	217	1
6	.7	4	177	2
8	.9	4	208	13
10	.9	3	163	81
12	1.6	3	167	114
14	4.3	3	160	216
16	5.3	5	128	429
18	6.7	6	173	536
20	3.8	11	171	509
22	1.9	21	173	312
24	1.7	22	251	155
26	1.5	15	202	126
28	1.2	5	330	74
30	1.1	0	489	40
32	1.1	1	468	22
34	1.1	0	344	16
36	1.0	1	271	12
38	.9	1	213	13
40	.9	0	183	15

TABLE XIII.- AIRBORNE DATA SAMPLING PASS 8

Reference time, sec	HCl concentration, ppm	Cl_2 concentration, ppb	NO_x concentration, ppb	Particle concentration (nephelometer), $\mu g/m^3$
0	0.2	5	196	-3
2	.2	4	176	0
4	.1	4	147	2
6	.1	3	172	3
8	.2	2	210	9
10	1.1	2	147	88
12	2.4	2	89	274
14	2.6	2	195	340
16	1.5	4	192	264
18	2.9	11	255	215
20	4.1	10	251	286
22	5.2	5	277	336
24	5.3	7	315	332
26	4.9	12	292	283
28	5.1	19	301	285
30	4.5	22	281	309
32	4.6	19	252	328
34	3.4	21	394	311
36	2.5	17	492	211
38	2.0	15	503	138
40	1.1	10	464	74
42	.8	7	484	37
44	.7	5	457	24
46	.6	3	487	19
48	.5	1	405	16
50	.5	1	288	16

TABLE XIV.- AIRBORNE DATA SAMPLING PASS 9

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), μg/m^3
0	0.4	84
2	.3	63
4	.4	59
6	.7	102
8	1.3	191
10	1.1	176
12	1.2	180
14	1.1	142
16	1.7	171
18	2.0	231
20	2.0	255
22	2.0	258
24	3.4	286
26	4.0	369
28	4.7	429
30	4.2	459
32	2.0	361
34	3.8	373
36	2.0	287
38	1.6	182
40	1.1	104
42	.9	56
44	.6	31
46	.6	22
48	.6	17
50	.5	19

TABLE XV.- AIRBORNE DATA SAMPLING PASS 10

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
0	0.2	-1
2	.2	1
4	.2	0
6	.2	8
8	1.0	101
10	1.5	195
12	2.1	245
14	2.8	311
16	2.5	348
18	2.1	302
20	2.3	276
22	2.5	276
24	2.3	262
26	3.1	283
28	3.1	288
30	3.6	319
32	3.6	328
34	3.2	318
36	3.7	271
38	3.0	242
40	2.5	197
42	2.5	171
44	3.1	184
46	2.8	203
48	1.4	159
50	1.1	85
52	.9	47
54	.8	30
56	.7	23
58	.6	22
60	.6	17
62	.6	16
64	.5	16
66	.5	16

TABLE XVI.- AIRBORNE DATA SAMPLING PASS 11

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), μg/m^3
0	0.2	-1
2	.2	-1
4	0	3
6	.2	7
8	.6	68
10	1.1	164
12	1.3	205
14	1.5	216
16	1.6	223
18	1.5	214
20	1.7	207
22	1.4	191
24	1.5	156
26	1.7	155
28	1.9	166
30	2.2	233
32	1.9	238
34	1.7	210
36	1.0	157
38	.8	79
40	.7	38
42	.4	21
44	.5	14
46	.5	11
48	.5	10
50	.4	10

TABLE XVII.- AIRBORNE DATA SAMPLING PASS 12

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.2	-6
12	.2	-3
14	.2	3
16	.2	13
18	.4	39
20	.7	83
22	.7	120
24	.9	122
26	.9	120
28	1.4	151
30	1.4	211
32	2.1	237
34	2.1	306
36	1.6	291
38	1.2	183
40	1.8	202
42	1.1	195
44	.8	105
46	.7	52
48	.6	25
50	.3	14
52	.4	9
54	.4	5
56	.4	7
58	.4	7
60	.3	7

TABLE XVIII.- AIRBORNE DATA SAMPLING PASS 13

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.1	-1
12	.1	-3
14	.1	-2
16	.1	-2
18	.2	14
20	.2	30
22	.1	14
24	.4	45
26	.6	114
28	.8	172
30	1.6	203
32	1.9	287
34	1.8	292
36	1.5	256
38	1.8	243
40	1.8	249
42	1.4	214
44	1.1	162
46	1.3	130
48	1.6	158
50	2.2	219
52	2.1	280
54	2.3	275
56	2.0	273
58	2.0	256
60	1.1	217
62	.8	113
64	.5	53
66	.6	27
68	.5	18
70	.5	14

TABLE XIX.- AIRBORNE DATA SAMPLING PASS 14

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.2	1
12	.2	7
14	.2	10
16	.2	12
18	.2	18
20	.4	44
22	.4	79
24	.4	87
26	.7	85
28	.7	96
30	.7	85
32	.9	90
34	1.1	93
36	1.8	130
38	1.8	175
40	2.3	208
42	2.5	234
44	2.3	240
46	2.0	233
48	1.9	205
50	1.3	180
52	1.5	153
54	2.0	168
56	1.8	188
58	1.7	189
60	1.3	169
62	1.0	113
64	.8	96
66	.6	60
68	.5	39
70	.4	30

TABLE XX.- AIRBORNE DATA SAMPLING PASS 15

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
0	0.1	10
2	.1	10
4	.1	10
6	.2	10
8	.3	52
10	.8	97
12	1.5	176
14	1.8	217
16	1.9	231
18	2.1	239
20	2.2	244
22	1.7	235
24	1.5	196
26	1.5	173
28	1.2	154
30	1.0	106
32	.8	77
34	.7	52
36	.8	47
38	1.1	84
40	1.5	131
42	1.5	153
44	.9	136
46	.7	82
48	.6	48
50	.5	33

TABLE XXI.- AIRBORNE DATA SAMPLING PASS 16

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.1	11
12	.1	10
14	.1	9
16	.1	11
18	.4	56
20	.9	124
22	1.4	175
24	1.7	210
26	1.4	202
28	1.3	193
30	1.5	177
32	1.8	187
34	1.8	203
36	1.4	190
38	1.0	140
40	.8	93
42	.9	84
44	.7	93
46	.7	73
48	.7	72
50	.5	62
52	.4	40
54	.4	28
56	.4	22
58	.3	19
60	.2	19

TABLE XXII.- AIRBORNE DATA SAMPLING PASS 17

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.1	14
12	.4	33
14	.9	122
16	1.4	175
18	1.7	206
20	1.3	206
22	1.2	178
24	1.2	167
26	1.4	162
28	1.3	165
30	1.6	160
32	1.5	175
34	1.5	173
36	1.6	165
38	1.9	186
40	1.7	197
42	1.7	188
44	1.7	180
46	1.7	165
48	1.5	171
50	1.6	159
52	1.6	165
54	1.0	141
56	.9	91
58	.7	66
60	.6	46
62	.6	34
64	.5	28
66	.4	26
68	.4	25
70	.4	25

TABLE XXIII.- AIRBORNE DATA SAMPLING PASS 18

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
20	0.1	13
22	.2	11
24	.2	25
26	.4	51
28	.6	83
30	.5	96
32	.5	79
34	1.1	104
36	1.5	153
38	1.7	191
40	1.7	200
42	1.5	196
44	1.5	177
46	1.3	169
48	.9	139
50	1.0	104
52	.8	100
54	.9	88
56	1.0	96
58	1.0	105
60	.8	111
62	.6	78
64	.6	50
66	.5	38
68	.4	27
70	.4	22

TABLE XXIV.- AIRBORNE DATA SAMPLING PASS 19

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
0	0.6	8
2	.6	8
4	.6	8
6	.6	18
8	.6	25
10	.5	32
12	.7	58
14	.7	77
16	1.2	85
18	1.7	160
20	1.9	200
22	2.0	206
24	2.0	205
26	2.1	200
28	1.7	198
30	1.6	188
32	1.7	184
34	1.6	182
36	1.3	153
38	1.4	128
40	1.4	126
42	1.9	134
44	2.1	177
46	2.2	203
48	2.1	212
50	1.9	200
52	1.3	171
54	.9	118
56	.8	69
58	.6	43
60	.6	32

TABLE XXV.- AIRBORNE DATA SAMPLING PASS 20

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
20	0.2	16
22	.2	37
24	.2	49
26	.3	58
28	.9	107
30	1.0	165
32	.9	165
34	1.0	157
36	1.2	174
38	1.3	186
40	1.2	183
42	.9	154
44	.9	124
46	.8	109
48	.7	96
50	.7	84
52	.6	73
54	.6	62
56	.6	58
58	.5	57
60	.4	38
62	.4	26
64	.3	21
66	.3	18
68	.2	17
70	.3	18

TABLE XXVI.- AIRBORNE DATA SAMPLING PASS 21

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.1	16
12	.2	35
14	.1	68
16	.2	65
18	.7	106
20	1.0	160
22	1.0	183
24	1.2	182
26	1.2	184
28	1.2	181
30	1.2	172
32	1.4	171
34	1.5	182
36	1.2	178
38	1.4	162
40	1.6	172
42	1.6	191
44	1.2	169
46	1.4	152
48	1.2	157
50	.9	122
52	.6	83
54	.6	51
56	.7	48
58	.8	83
60	.7	87
62	.5	64
64	.5	40
66	.4	30
68	.4	26
70	.4	24

TABLE XXVII.- AIRBORNE DATA SAMPLING PASS 22

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.1	10
12	.1	15
14	.1	18
16	.1	20
18	.1	29
20	.1	32
22	.2	50
24	.3	65
26	.3	72
28	.5	99
30	.7	110
32	1.0	123
34	1.1	137
36	1.0	133
38	1.0	121
40	1.0	111
42	1.0	108
44	1.0	104
46	1.0	102
48	1.1	101
50	1.2	103
52	1.1	108
54	1.1	104
56	1.0	98
58	.9	88
60	.7	71
62	.6	52
64	.5	38
66	.5	30
68	.4	23
70	.3	23

TABLE XXVIII.- AIRBORNE DATA SAMPLING PASS 23

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), μg/m^3
10	0.3	13
12	.2	21
14	.2	31
16	.2	32
18	.2	33
20	.3	50
22	.5	63
24	.7	102
26	1.1	125
28	1.2	154
30	1.2	172
32	1.1	173
34	1.1	157
36	1.3	148
38	1.3	156
40	1.2	147
42	1.3	143
44	1.4	146
46	1.4	152
48	1.3	148
50	1.3	139
52	1.3	138
54	1.3	127
56	1.4	131
58	1.1	138
60	.8	105
62	.7	73
64	.7	56
66	.6	51
68	.5	37
70	.4	28

TABLE XXIX.- AIRBORNE DATA SAMPLING PASS 24

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
20	0	9
22	.2	11
24	.1	30
26	.3	65
28	.3	94
30	.2	74
32	.4	75
34	.7	119
36	1.2	168
38	1.3	192
40	1.3	192
42	1.3	185
44	1.1	181
46	1.1	178
48	1.5	176
50	1.4	175
52	1.2	158
54	1.2	137
56	1.0	119
58	.9	99
60	.8	82
62	.8	71
64	.8	67
66	.7	62
68	.7	58
70	.6	53
72	.7	45
74	.6	52
76	.6	52
78	.6	51
80	.5	43

TABLE XXX.- AIRBORNE DATA SAMPLING PASS 25

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.2	17
12	.2	30
14	.2	38
16	.2	50
18	.7	81
20	1.1	130
22	1.2	161
24	1.1	165
26	1.2	154
28	1.2	157
30	1.3	159
32	1.3	154
34	1.2	152
36	1.1	142
38	1.0	129
40	1.1	119
42	1.2	123
44	1.1	123
46	1.1	119
48	1.0	117
50	1.0	112
52	1.0	109
54	.9	105
56	1.0	102
58	.9	100
60	1.1	109
62	1.1	120
64	.8	108
66	.6	71
68	.5	42
70	.5	30

TABLE XXXI.- AIRBORNE DATA SAMPLING PASS 26

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
20	0.2	34
22	.2	44
24	.3	58
26	.4	70
28	.7	103
30	.9	137
32	1.3	161
34	1.6	181
36	1.8	197
38	1.7	195
40	2.0	181
42	1.9	180
44	1.5	158
46	1.2	129
48	1.2	105
50	1.2	91
52	1.0	84
54	1.0	78
56	.9	70
58	.9	67
60	.8	66
62	.8	58
64	.7	53
66	.2	49
68	.6	42
70	.5	33
72	.5	26
74	.5	24
76	.4	23
78	.4	22
80	.4	21

TABLE XXXII.- AIRBORNE DATA SAMPLING PASS 27

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.1	19
12	.4	67
14	.4	87
16	.8	101
18	1.1	150
20	1.3	165
22	1.5	178
24	1.7	180
26	1.7	176
28	1.3	160
30	1.0	126
32	.8	94
34	1.0	84
36	1.1	105
38	.9	109
40	.8	89
42	.8	79
44	.7	70
46	.7	70
48	.8	73
50	.8	86
52	.7	86
54	.6	69
56	.7	71
58	.6	61
60	.7	73
62	.6	84
64	.7	76
66	.6	83
68	.5	57
70	.5	36

TABLE XXXIII.- AIRBORNE DATA SAMPLING PASS 28

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.2	19
12	.2	33
14	.2	38
16	.3	51
18	.3	56
20	.4	57
22	.5	74
24	.7	102
26	.8	116
28	.9	135
30	1.1	142
32	1.2	148
34	1.2	149
36	1.3	146
38	1.5	151
40	1.4	158
42	1.6	160
44	1.7	161
46	2.0	163
48	2.2	170
50	2.2	181
52	2.4	183
54	2.1	179
56	1.8	158
58	1.5	128
60	1.4	107
62	1.2	95
64	1.1	88
66	1.2	85
68	1.2	80

TABLE XXXIII.- Concluded

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
70	1.0	76
72	1.1	70
74	1.2	74
76	1.2	81
78	1.1	78
80	1.2	74
82	1.2	78
84	1.3	81
86	1.3	86
88	1.2	82
90	1.1	75
92	1.3	77
94	1.7	102
96	1.9	138
98	1.8	149
100	1.8	141
102	1.6	126
104	1.5	109
106	1.3	97
108	1.1	86
110	.8	67
112	.7	47
114	.6	34
116	.6	27
118	.5	25
120	.5	23

TABLE XXXIV.- AIRBORNE DATA SAMPLING PASS 29

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
0	0.2	9
2	.1	8
4	.1	10
6	.2	12
8	.2	22
10	.2	35
12	.4	59
14	.7	94
16	1.1	130
18	1.2	150
20	1.3	153
22	1.1	144
24	1.1	127
26	1.3	124
28	1.4	145
30	1.3	152
32	1.3	145
34	1.2	135
36	1.0	122
38	1.1	107
40	1.3	117
42	1.3	123
44	1.1	124
46	1.1	116
48	1.1	109
50	1.1	107
52	1.0	101
54	.9	90
56	1.0	82
58	1.0	96
60	1.0	103
62	.9	98
64	.7	75
66	.6	48
68	.5	32
70	.5	25

TABLE XXXV.- AIRBORNE DATA SAMPLING PASS 30

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), μg/m^3
10	0.2	9
12	.2	19
14	.2	35
16	.4	54
18	.3	87
20	.3	79
22	.4	61
24	.4	53
26	.6	72
28	.8	98
30	1.0	123
32	1.1	141
34	1.4	153
36	1.6	161
38	1.7	169
40	1.8	171
42	1.8	173
44	1.9	167
46	2.0	168
48	1.9	172
50	1.8	159
52	1.7	142
54	1.5	124
56	1.5	109
58	1.5	107
60	1.5	103
62	1.5	102
64	1.2	98
66	1.2	83
68	1.0	70
70	1.1	69
72	1.1	72
74	.9	66
76	.9	57
78	.8	56
80	.8	55
82	.6	45
84	.6	33
86	.5	24
88	.6	25
90	.7	38

TABLE XXXVI.- AIRBORNE DATA SAMPLING PASS 31

Reference time, sec	HCl concentration, ppm	Particle concentration (nephelometer), $\mu g/m^3$
10	0.1	12
12	.2	22
14	.1	29
16	.3	46
18	.3	60
20	.5	85
22	.5	93
24	.6	98
26	.6	100
28	.5	94
30	.5	72
32	.6	69
34	.8	84
36	.9	105
38	.8	113
40	.9	98
42	.8	100
44	.6	78
46	.5	46
48	.4	28
50	.4	20
52	.4	16
54	.3	15
56	.3	12
58	.3	13
60	.2	12

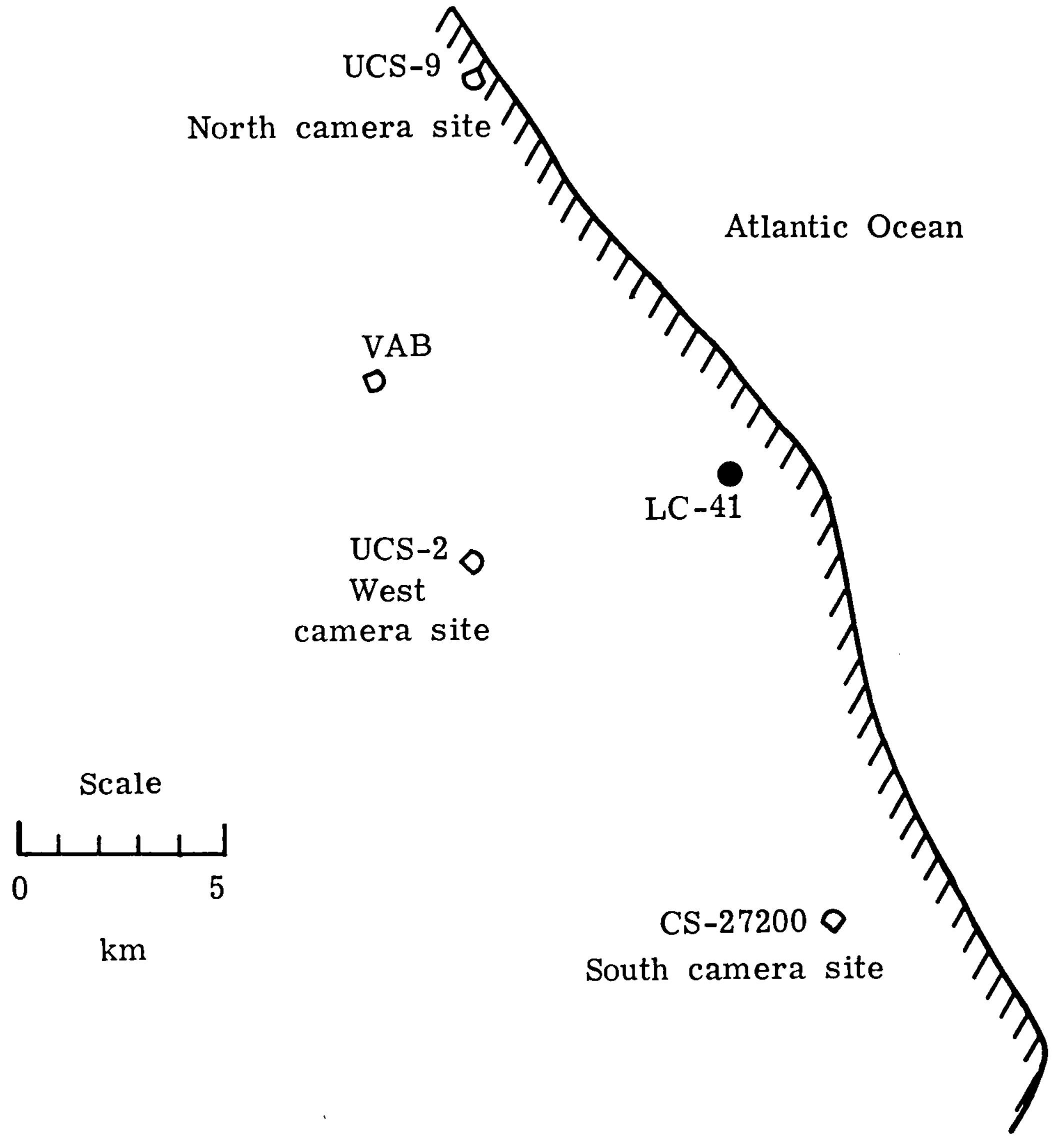


Figure 1.- Map showing locations of tracking-camera sites.

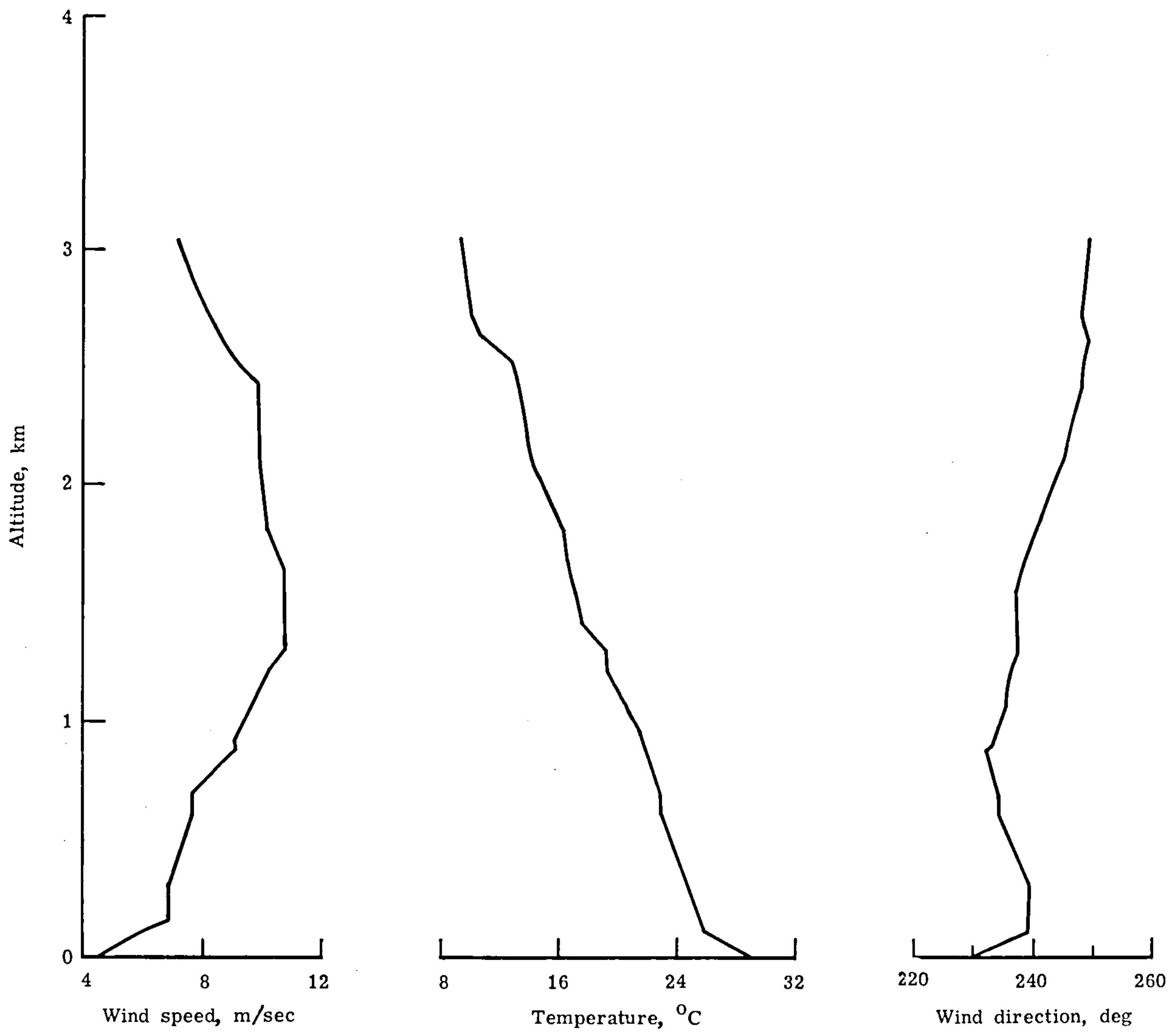


Figure 2.- Meteorological data from rawinsonde sounding measurements at T - 13 min at Kennedy Space Center on Aug. 20, 1977.

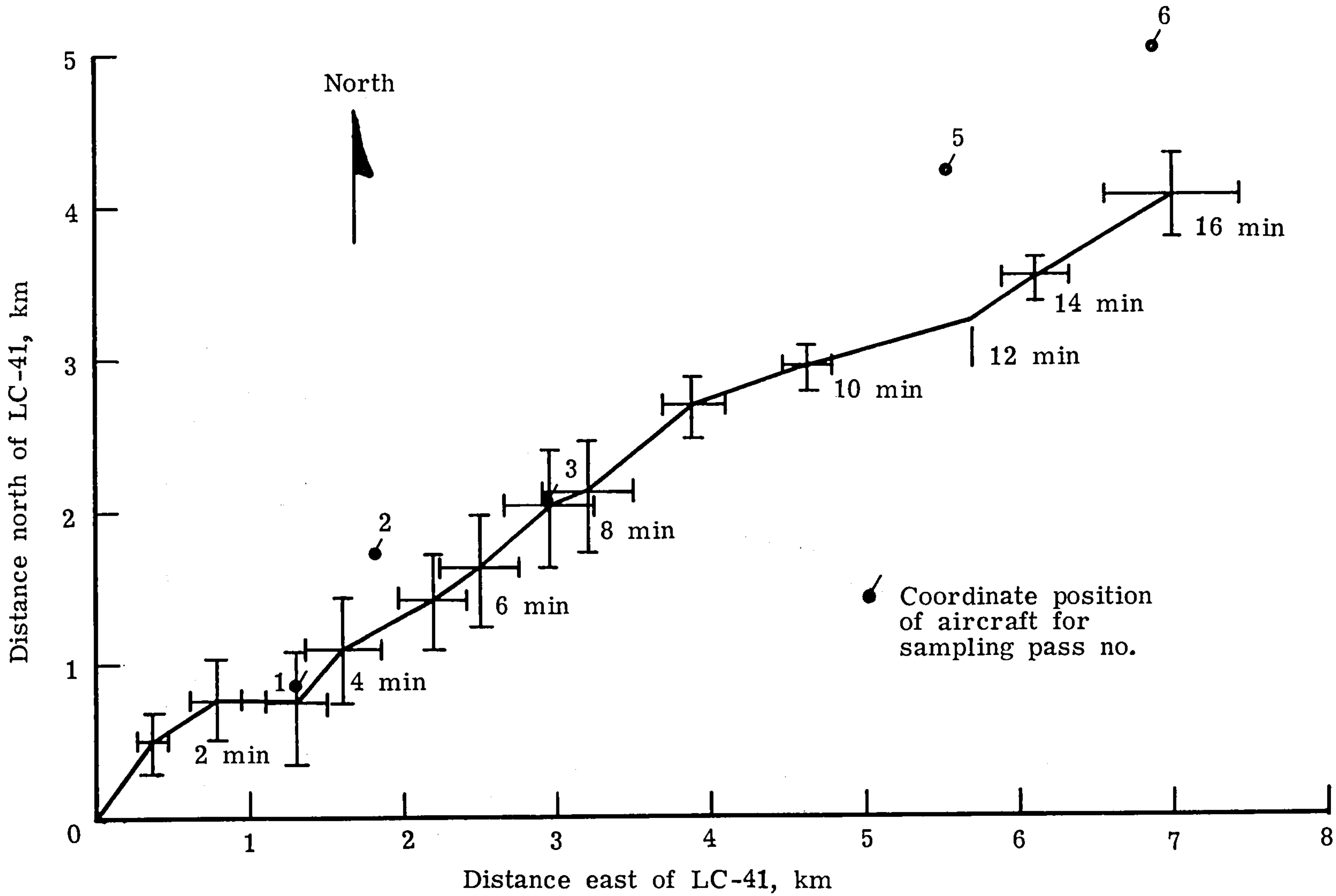


Figure 3.- Ground track of exhaust cloud from metric-tracking camera data.

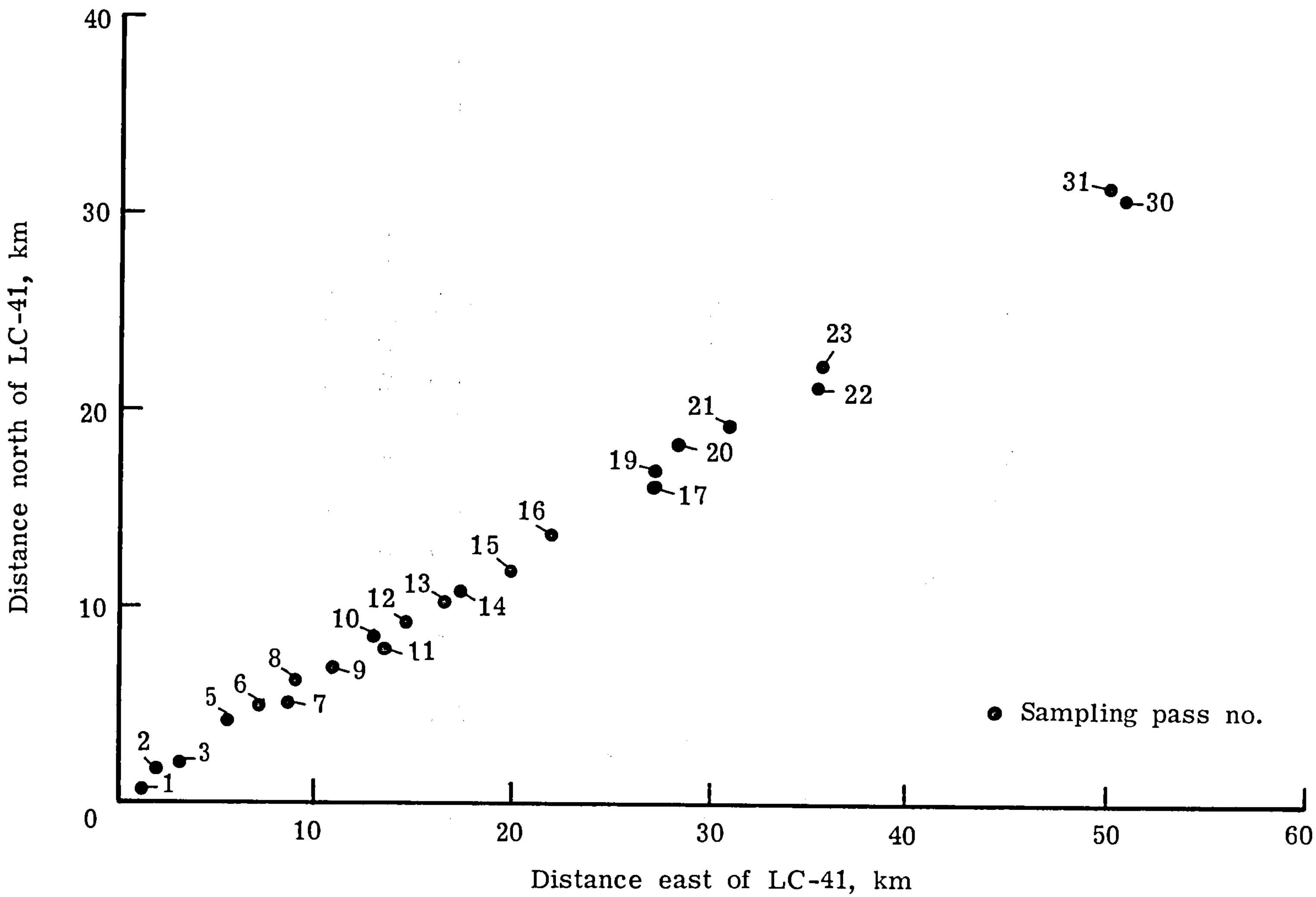


Figure 4.- Aircraft location at midpoints of sampling passes.

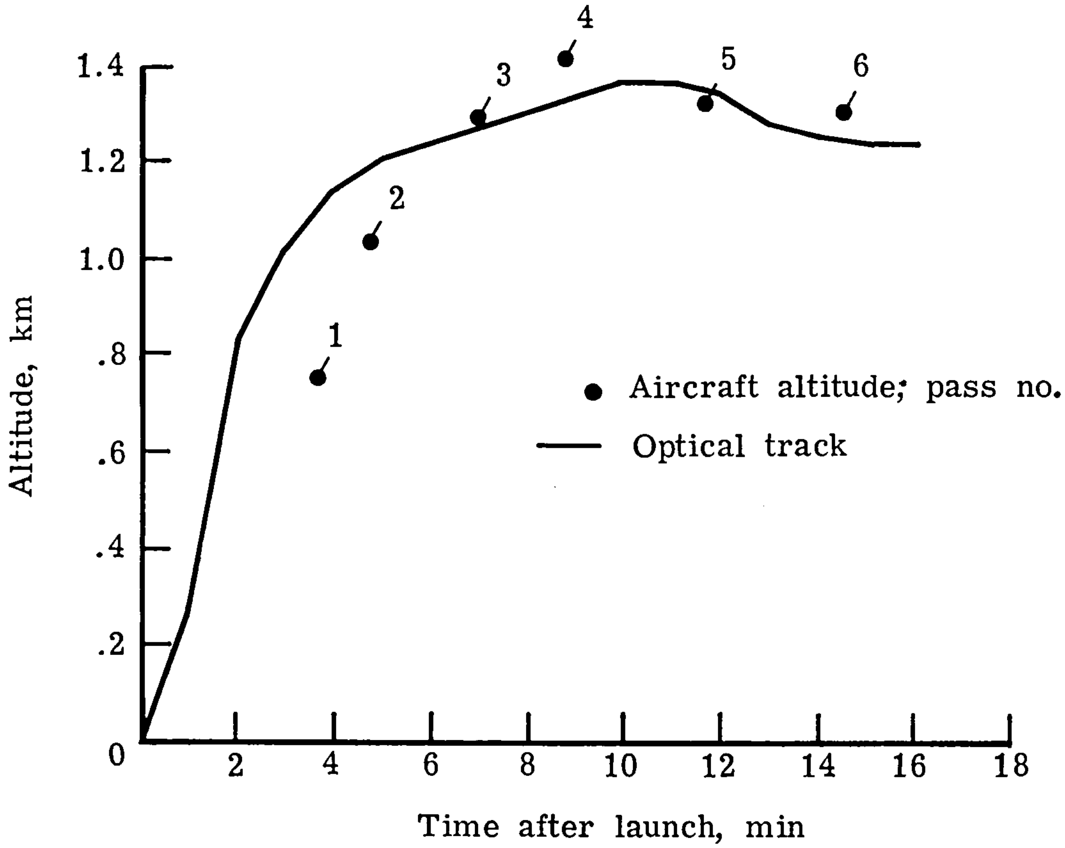


Figure 5.- Ground-cloud altitude as function of time after launch.

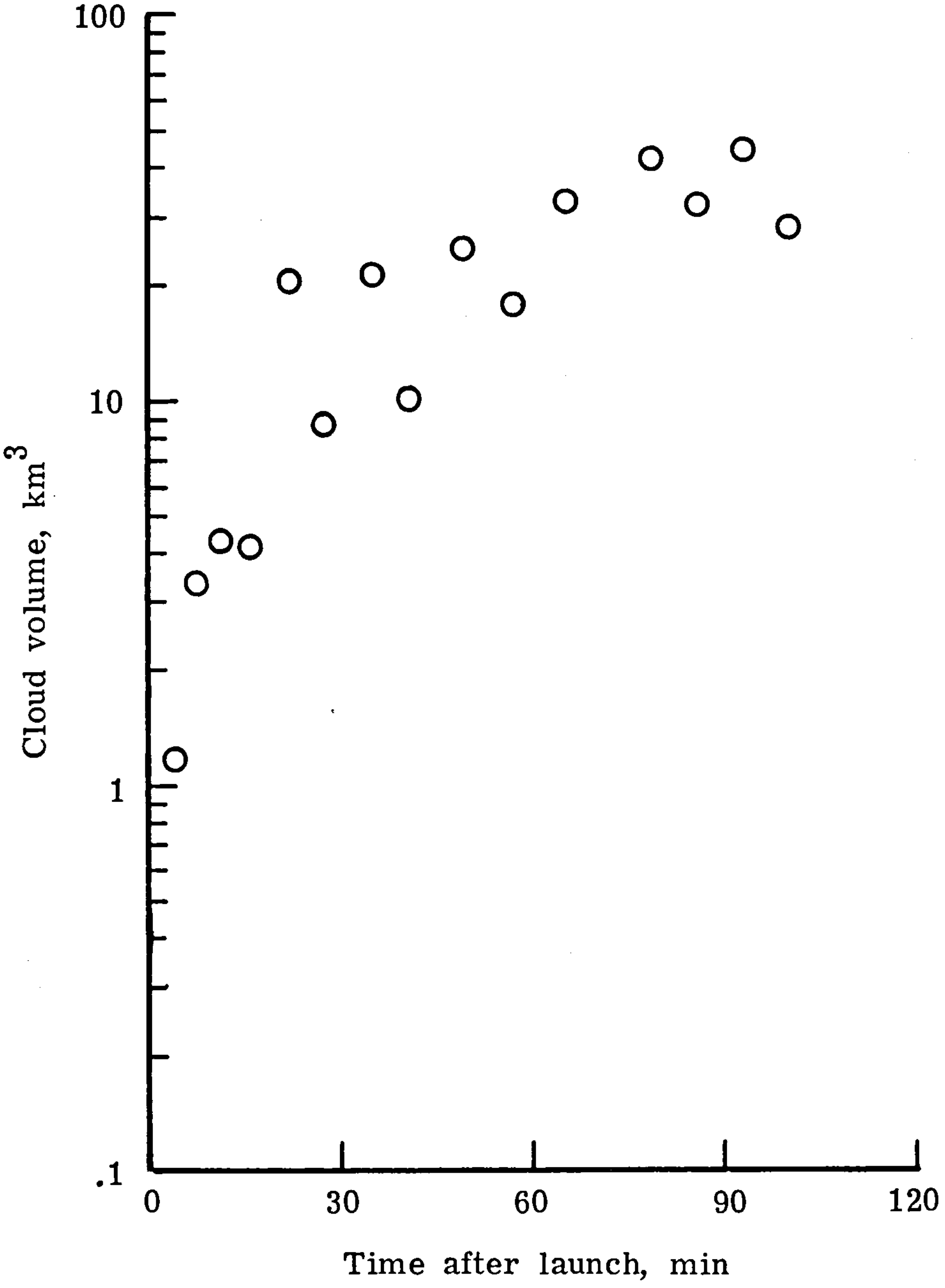


Figure 6.- Cloud volume data (from aircraft transit time) as function of time after launch.

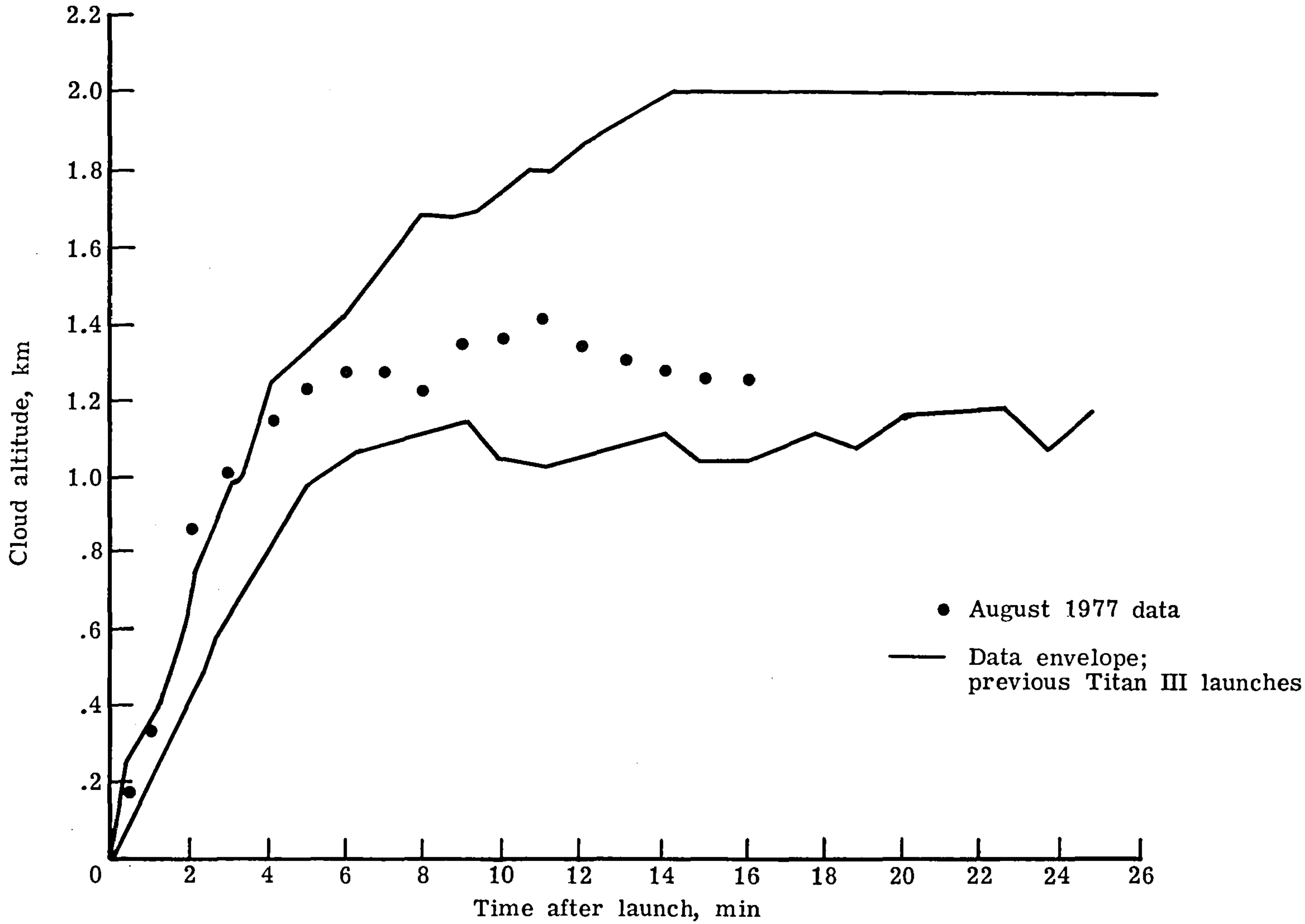


Figure 7.- Cloud rise and stabilization height; Titan III launches.

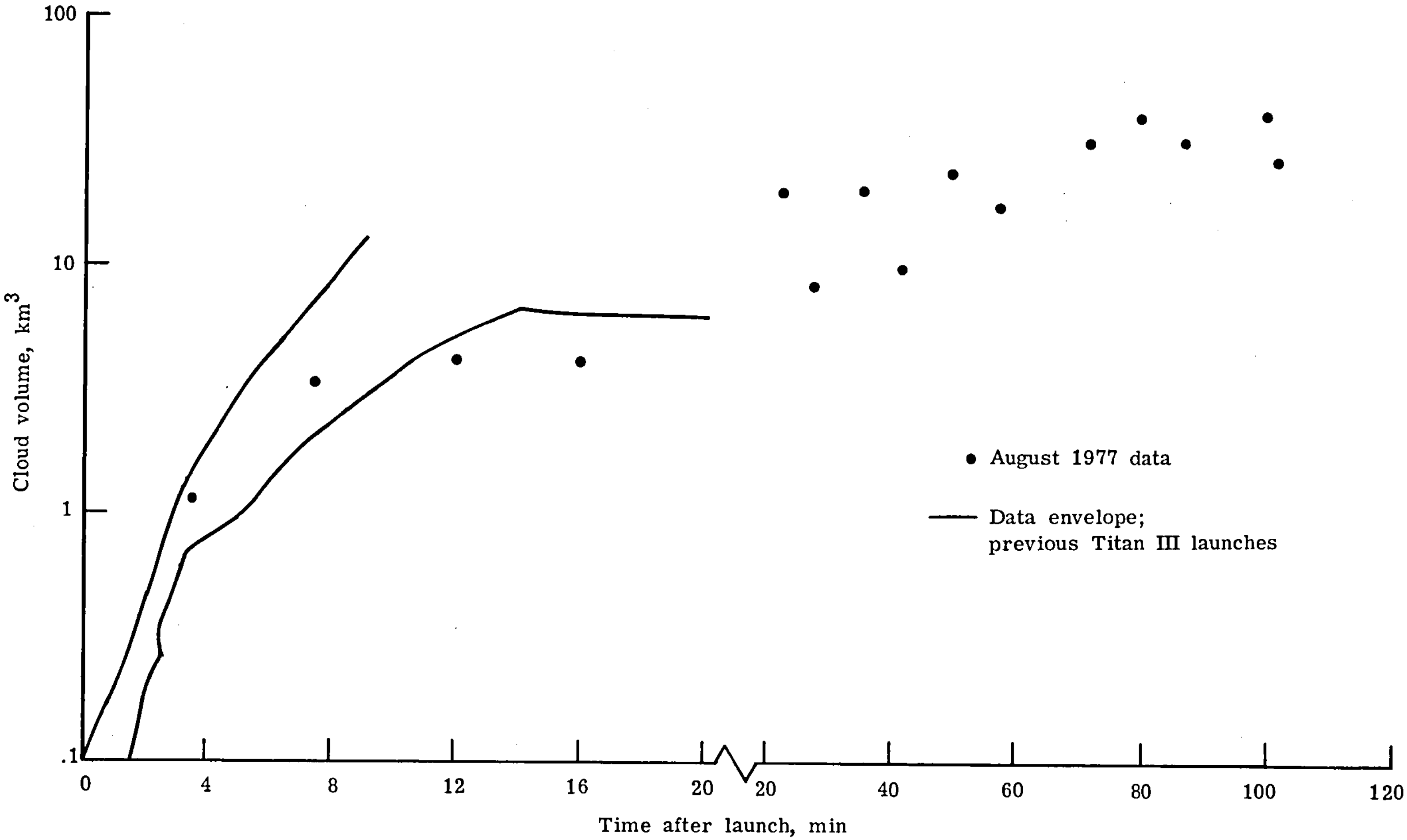
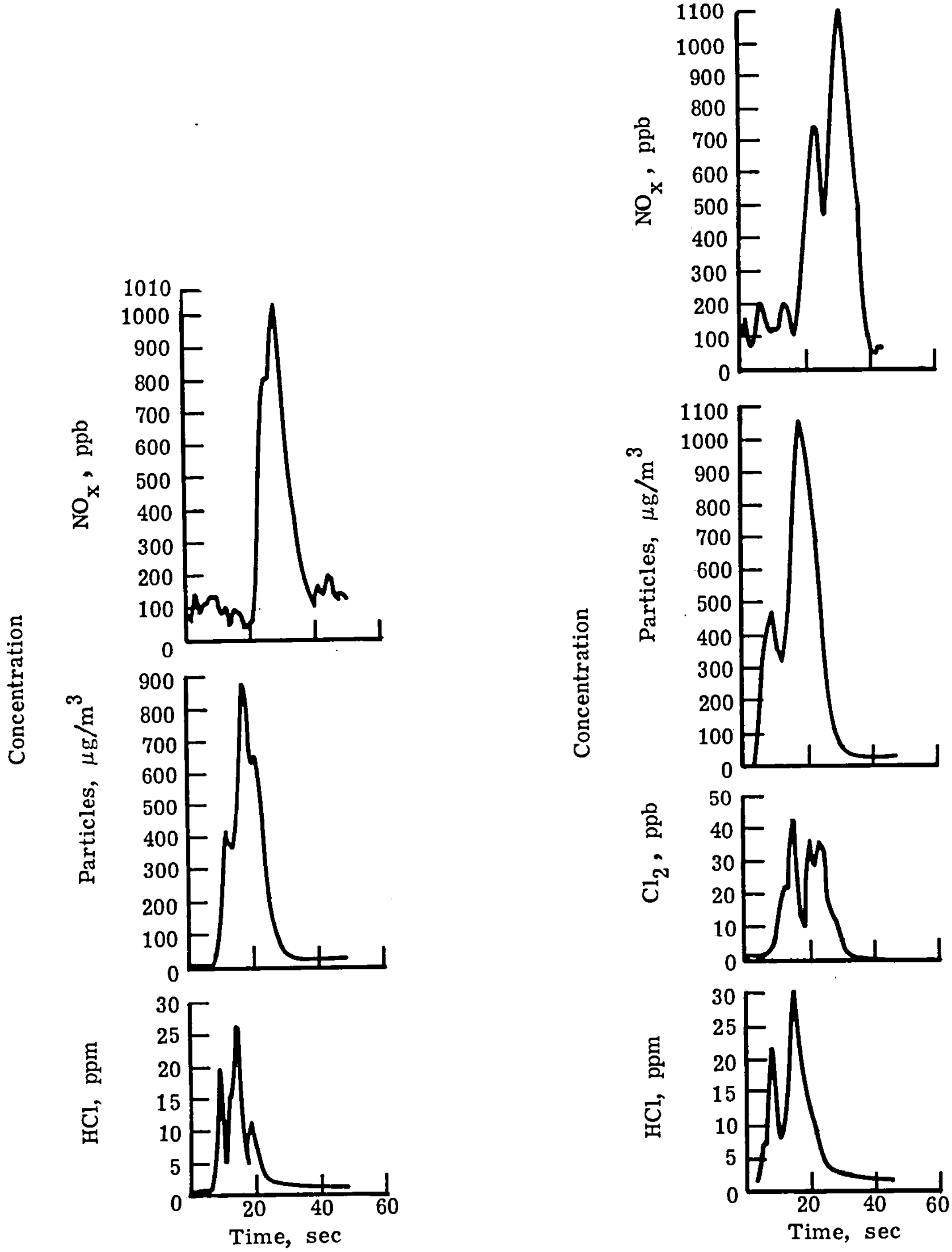


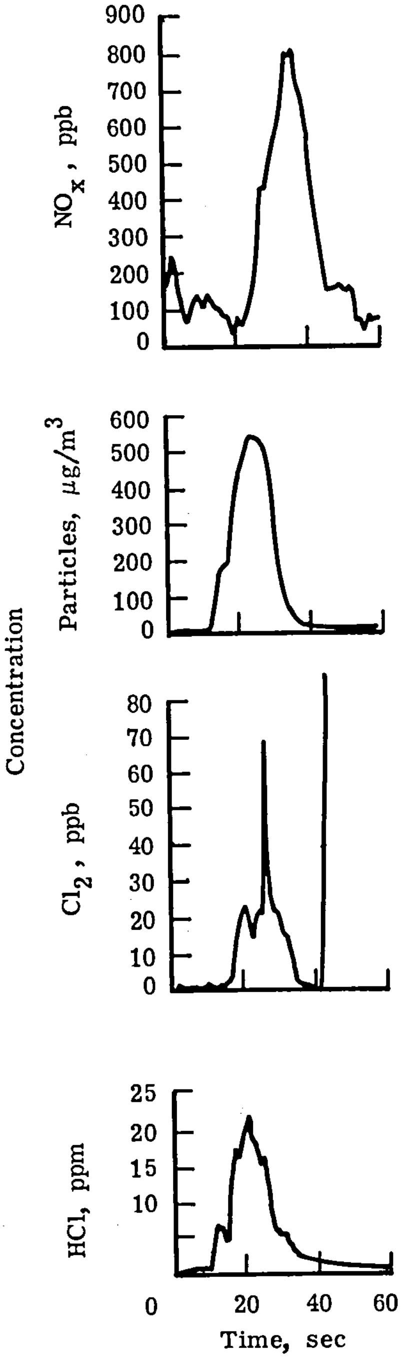
Figure 8.- Cloud volume; Titan III launches.



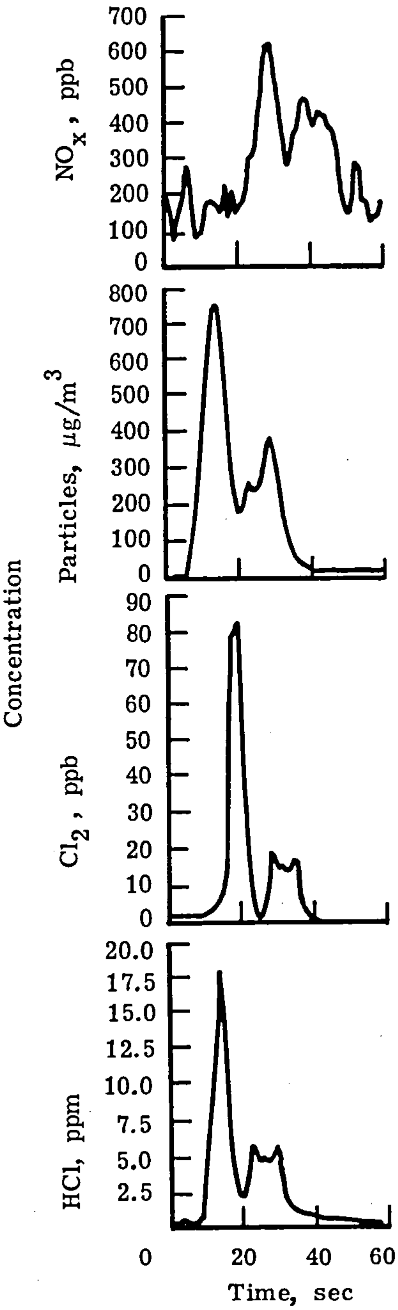
(a) Pass 1; t_0 = 3 min 14 sec.

(b) Pass 2; t_0 = 4 min 46 sec.

Figure 9.- Effluent concentrations as function of time in cloud from airborne sensors.

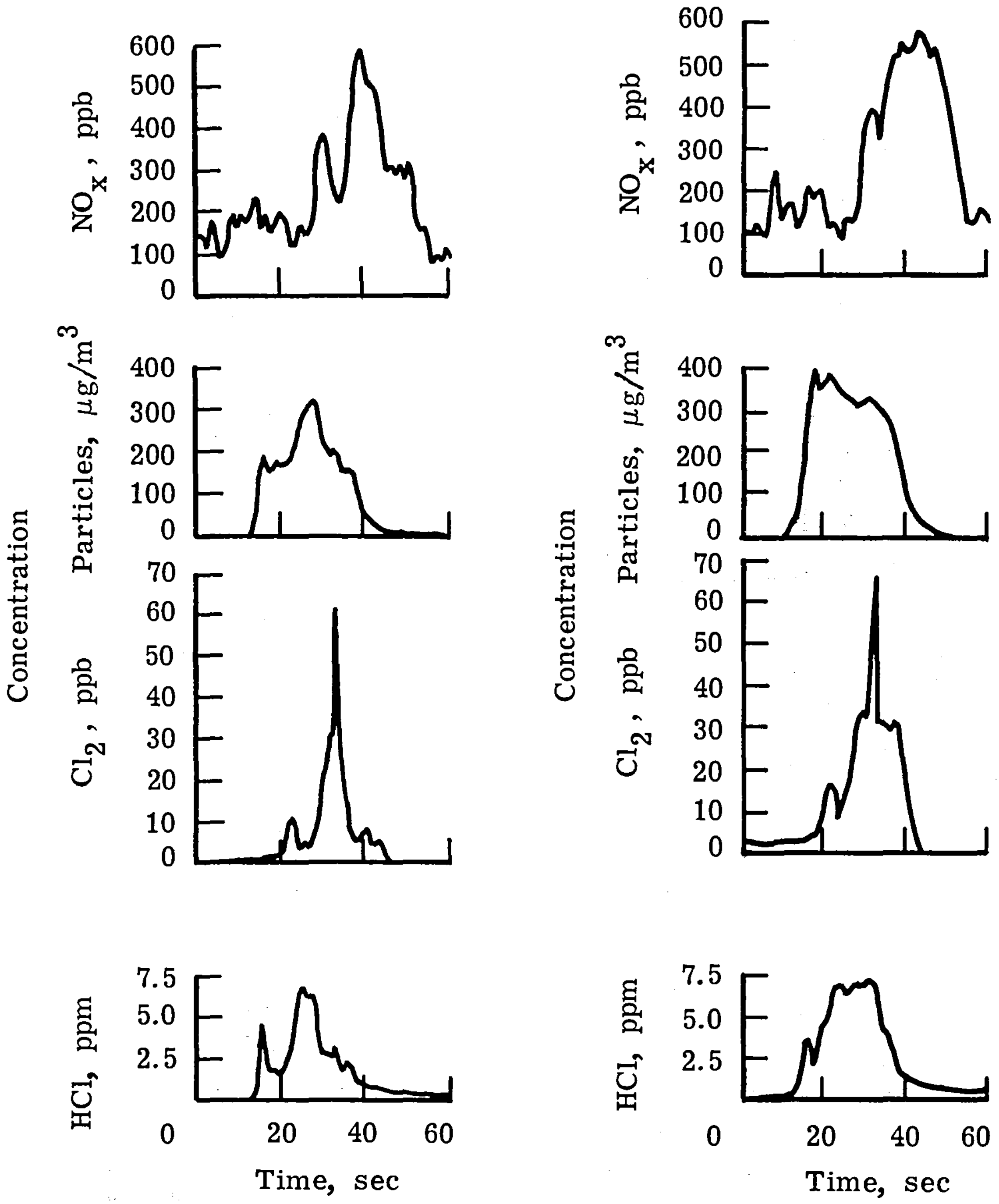


(c) Pass 3; t_0 = 6 min 24 sec.



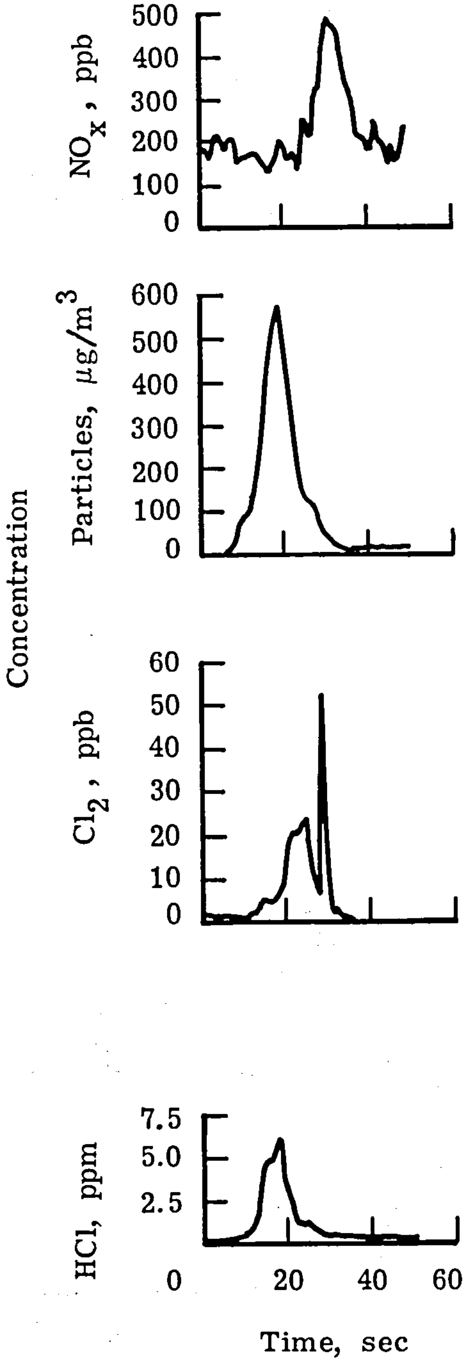
(d) Pass 4; t_0 = 8 min 14 sec.

Figure 9.- Continued.

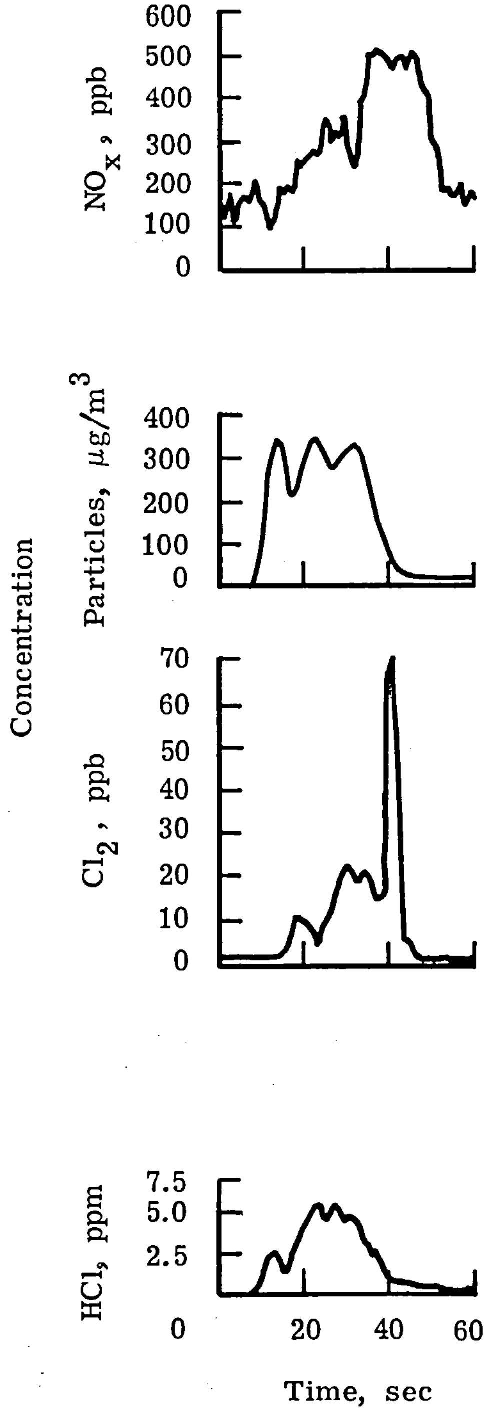


(e) Pass 5; t_0 = 10 min 56 sec.　　(f) Pass 6; t_0 = 12 min 56 sec.

Figure 9.- Continued.

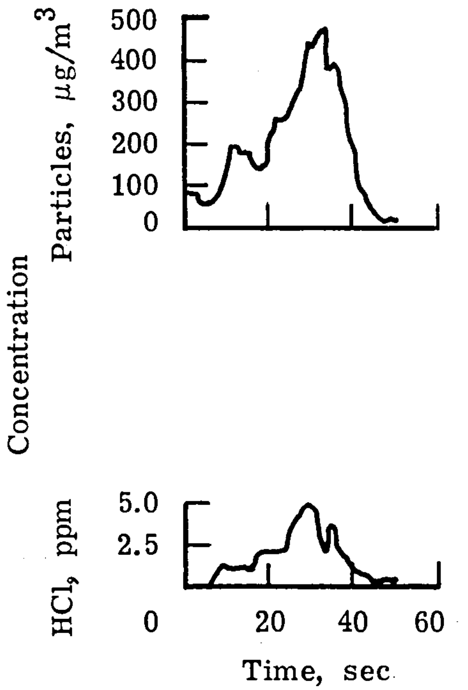


(g) Pass 7; t_0 = 15 min 4 sec.

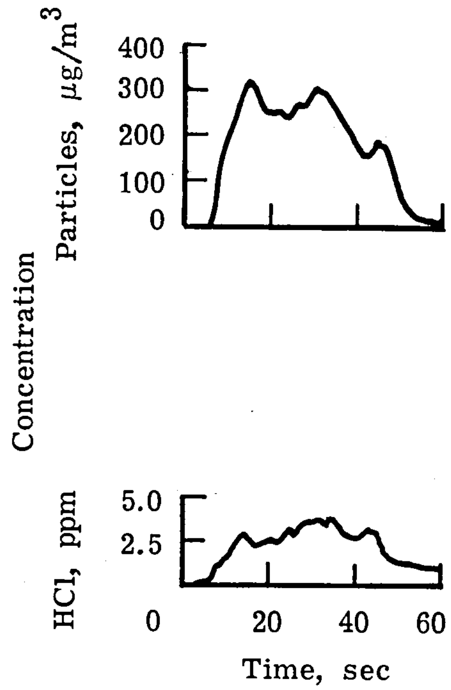


(h) Pass 8; t_0 = 17 min 4 sec.

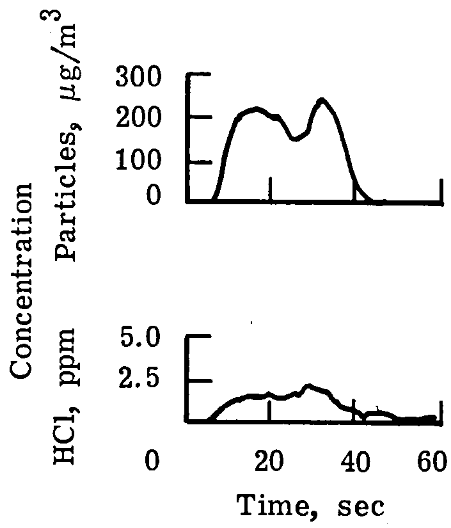
Figure 9.- Continued.



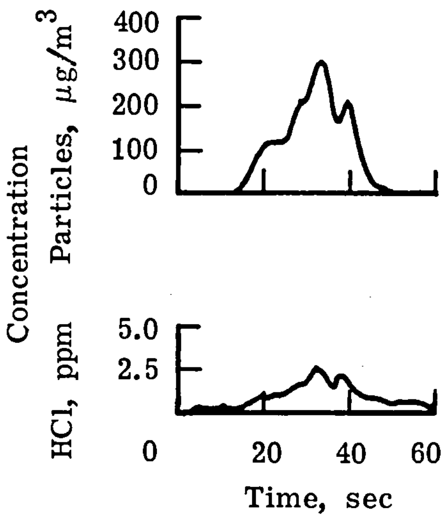
(i) Pass 9; t_0 = 20 min 18 sec.



(j) Pass 10; t_0 = 23 min 36 sec.

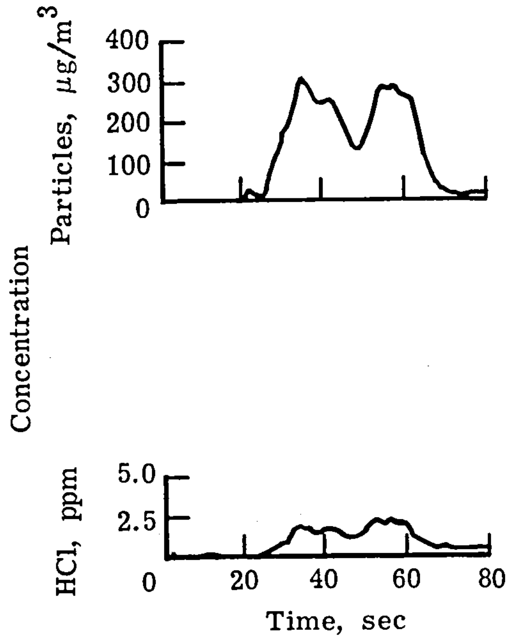


(k) Pass 11; t_0 = 27 min 37 sec.

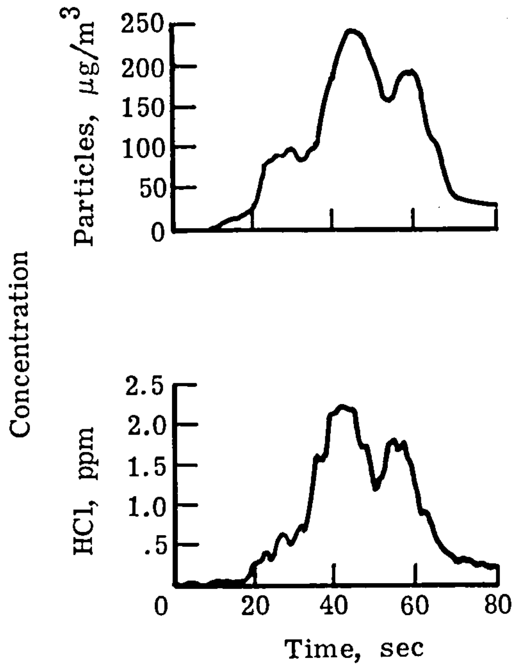


(l) Pass 12; t_0 = 29 min 8 sec.

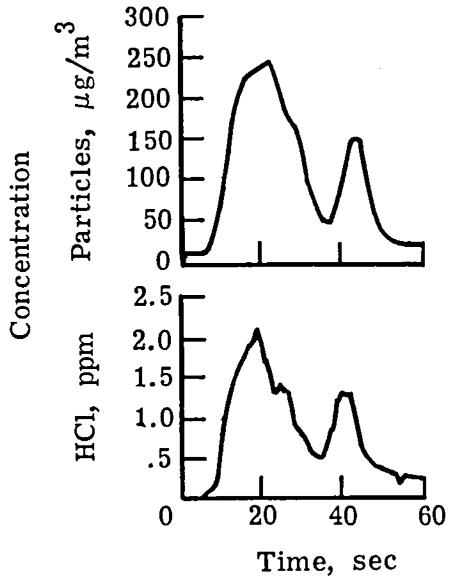
Figure 9.- Continued.



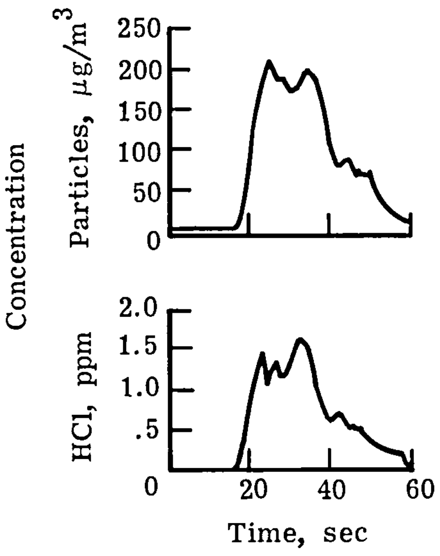
(m) Pass 13; t_0 = 33 min 16 sec.



(n) Pass 14; t_0 = 36 min 17 sec.

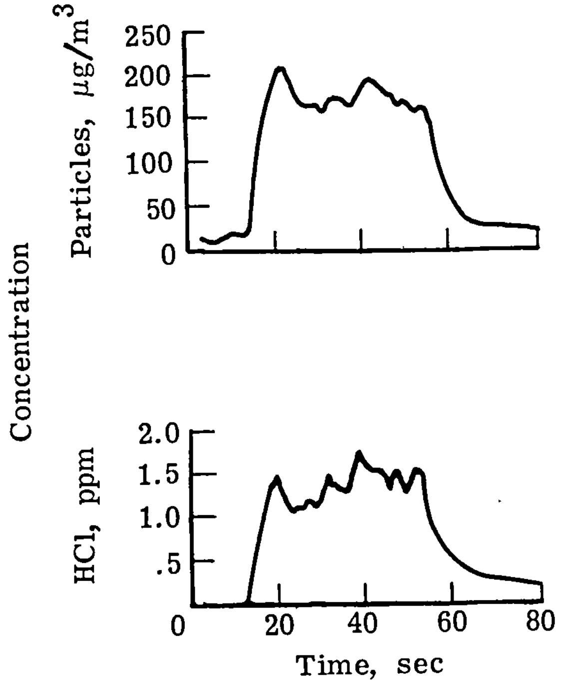


(o) Pass 15; t_0 = 39 min 40 sec.

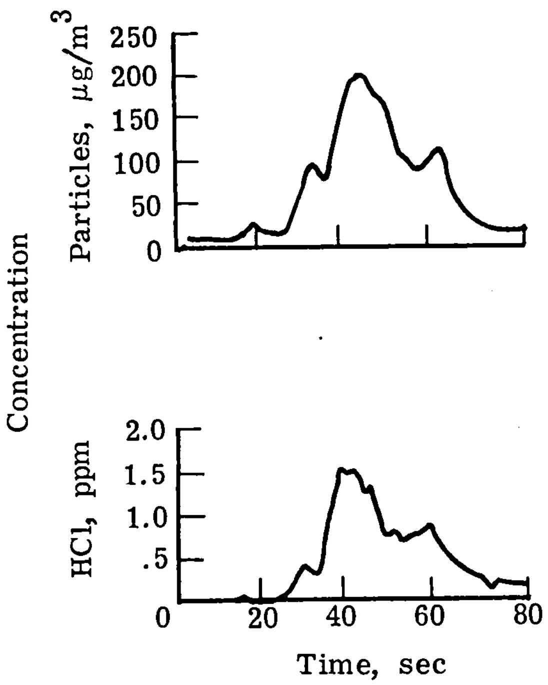


(p) Pass 16; t_0 = 43 min 28 sec.

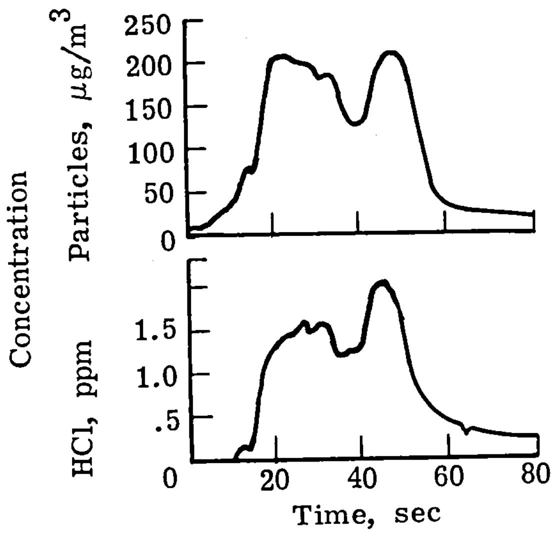
Figure 9.- Continued.



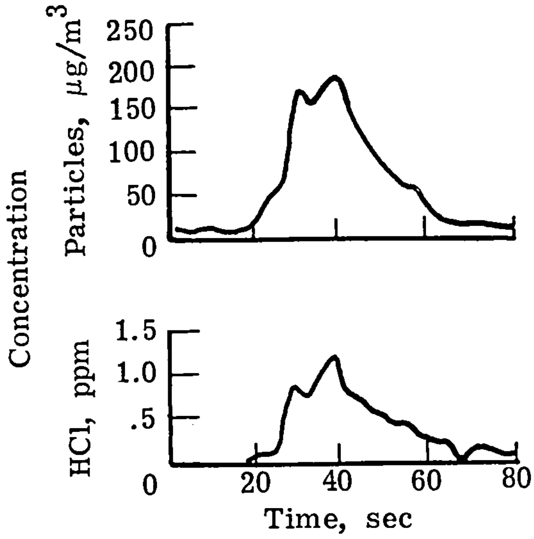
(q) Pass 17; t_0 = 47 min 38 sec.



(r) Pass 18; t_0 = 51 min 0 sec.

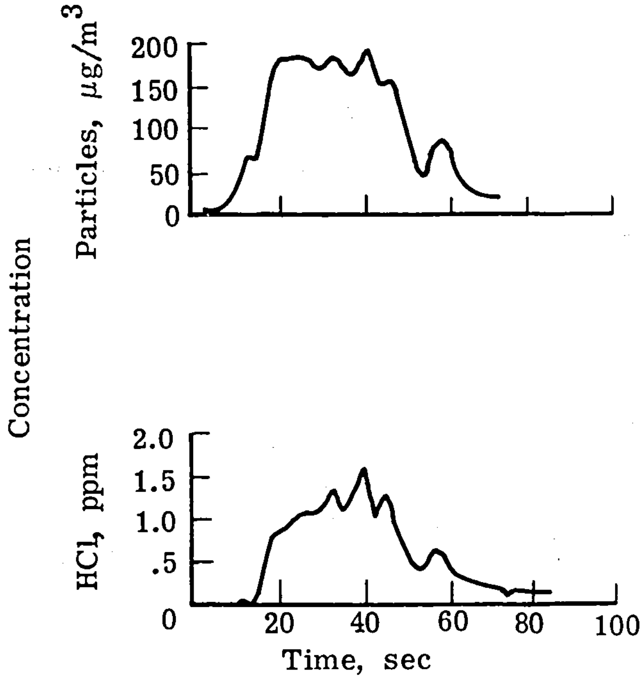


(s) Pass 19; t_0 = 54 min 30 sec.

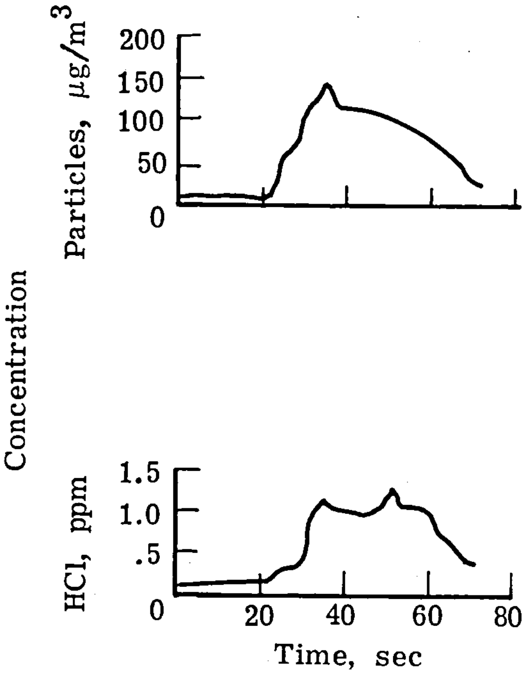


(t) Pass 20; t_0 = 57 min 50 sec.

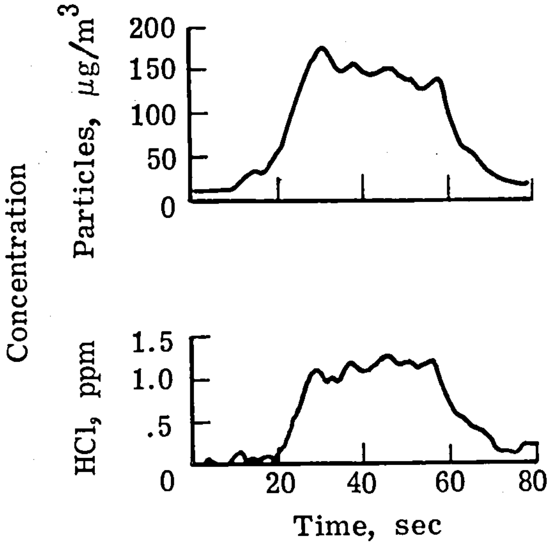
Figure 9.- Continued.



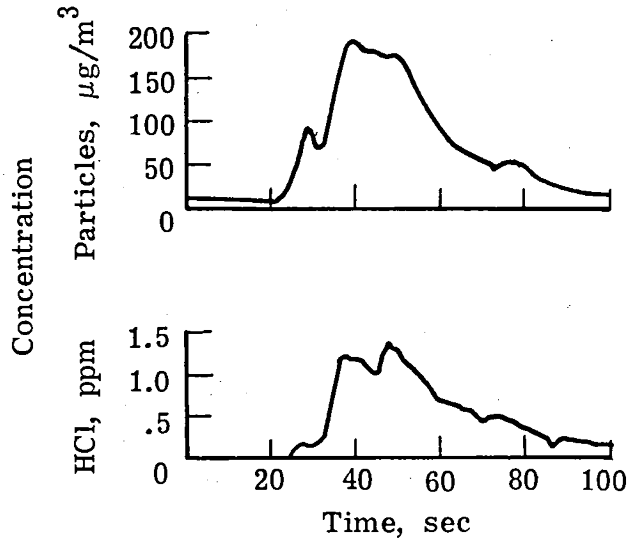
(u) Pass 21; t_0 = 62 min 40 sec.



(v) Pass 22; t_0 = 69 min 40 sec.

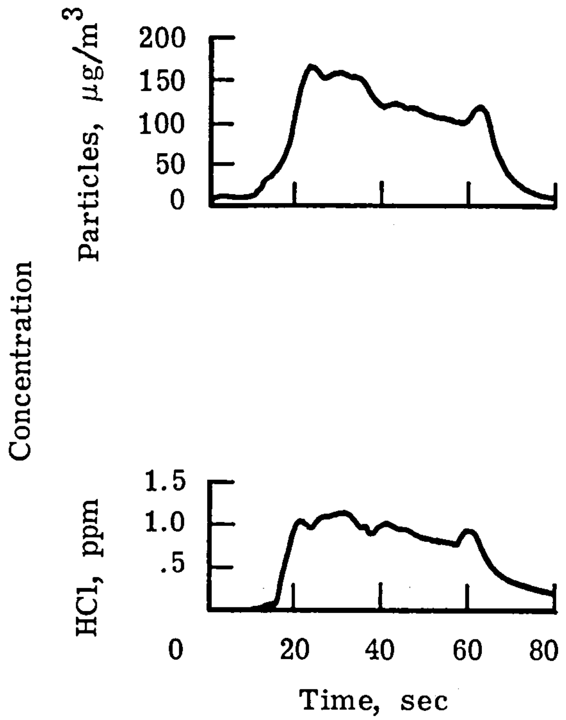


(w) Pass 23; t_0 = 72 min 50 sec.

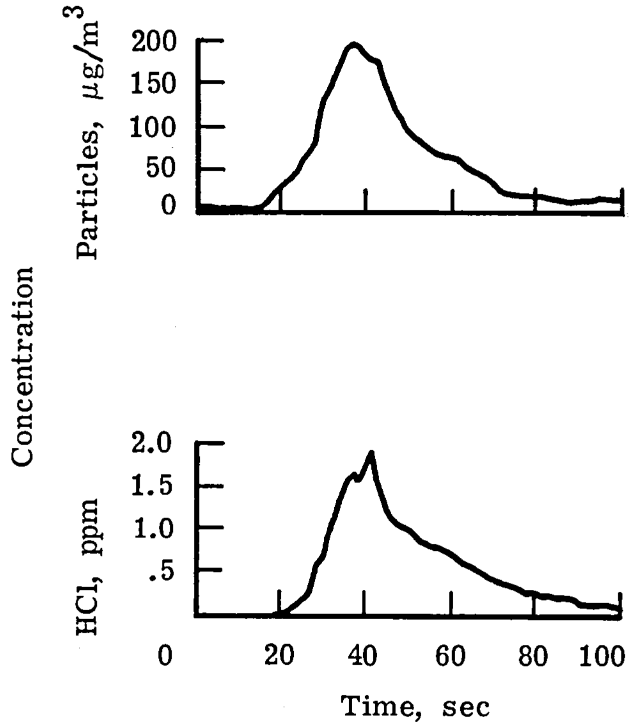


(x) Pass 24; t_0 = 77 min 20 sec.

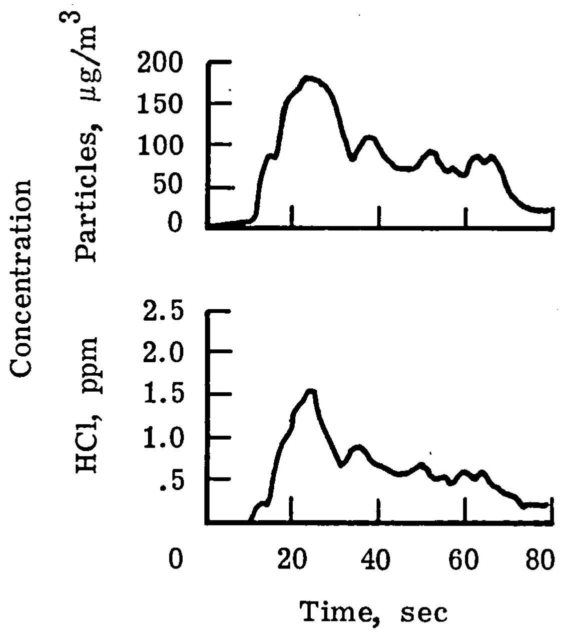
Figure 9.- Continued.



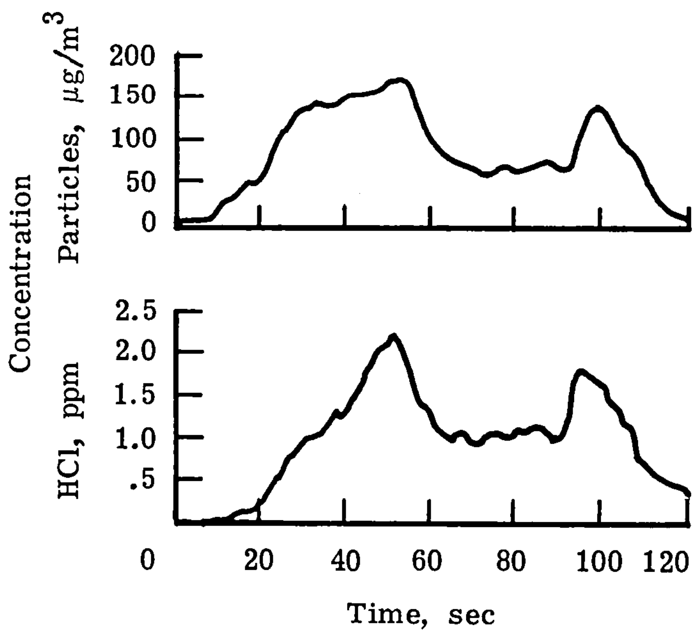
(y) Pass 25; t_0 = 80 min 40 sec.



(z) Pass 26; t_0 = 84 min 30 sec.

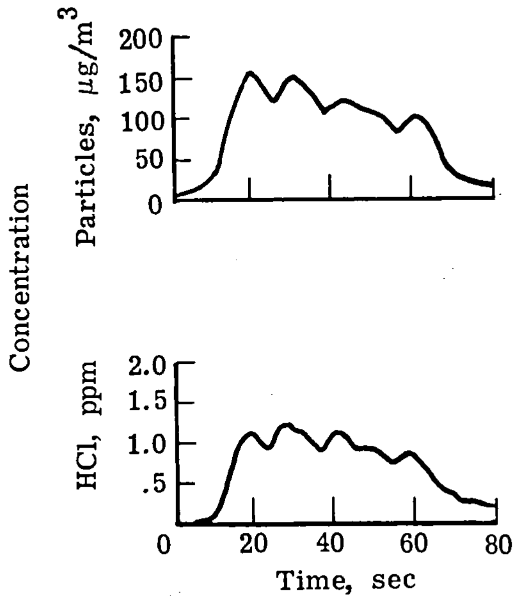


(aa) Pass 27; t_0 = 88 min 0 sec.

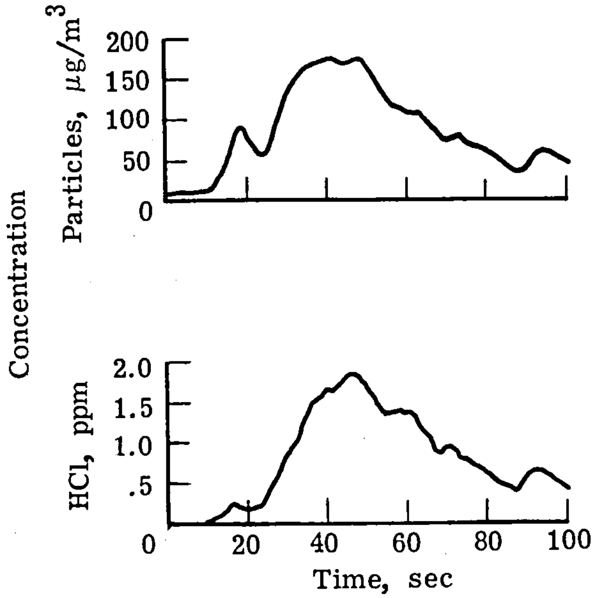


(bb) Pass 28; t_0 = 91 min 44 sec.

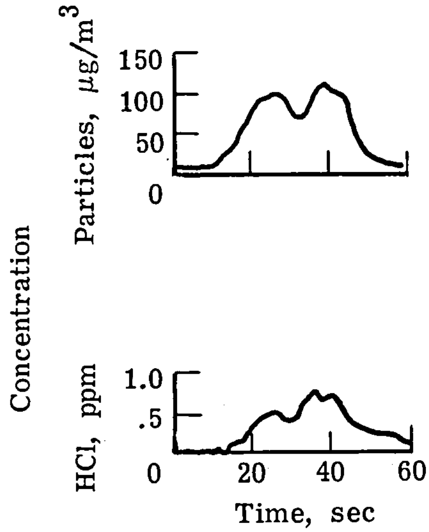
Figure 9.- Continued.



(cc) Pass 29; t_0 = 96 min 14 sec.



(dd) Pass 30; t_0 = 99 min 24 sec.



(ee) Pass 31; t_0 = 102 min 44 sec.

Figure 9.- Concluded.

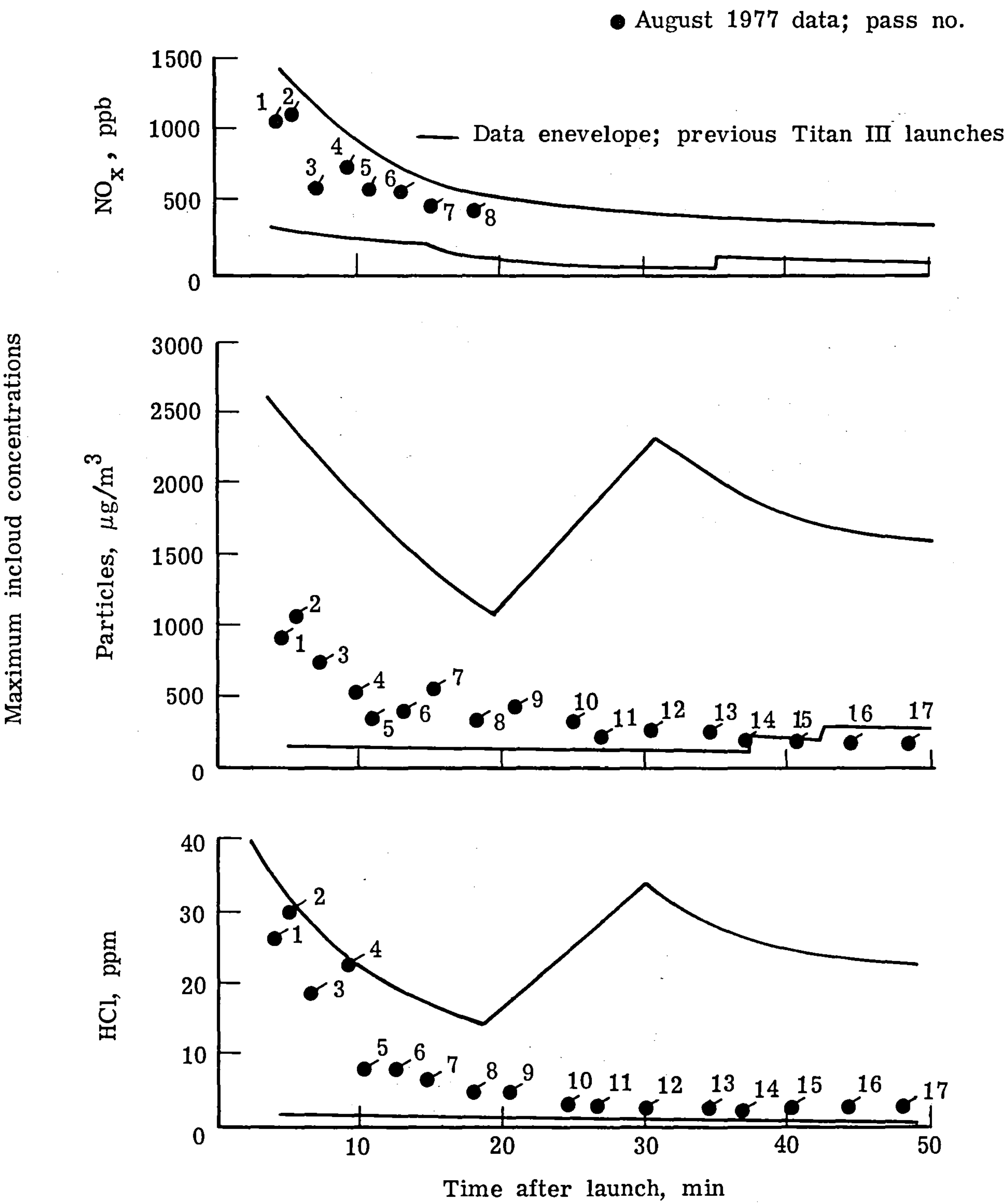


Figure 10.- Comparison of maximum effluent concentrations per pass with previous Titan III data.

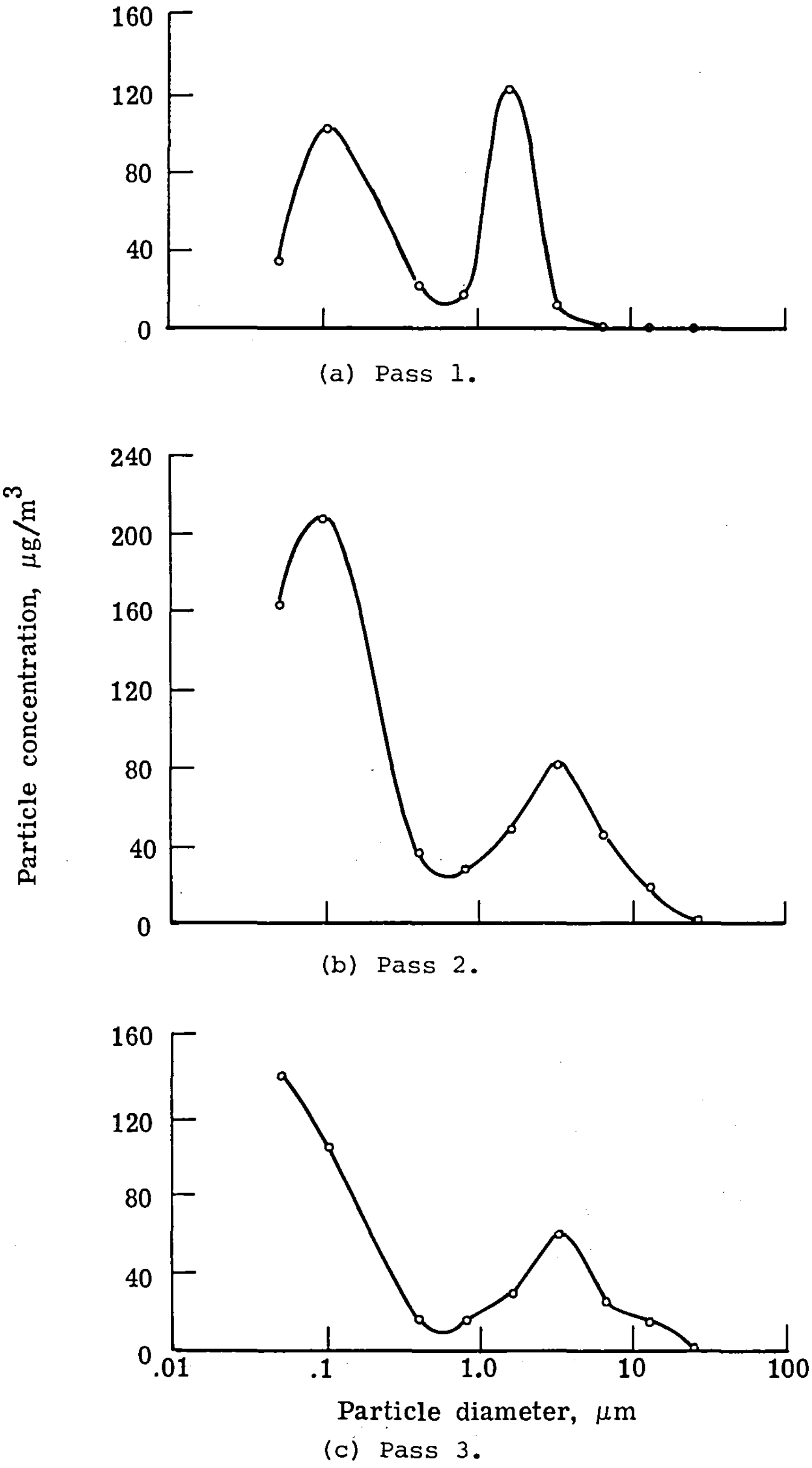


Figure 11.- Mass concentration as function of particle aerodynamic diameter determined from QCM measurements.

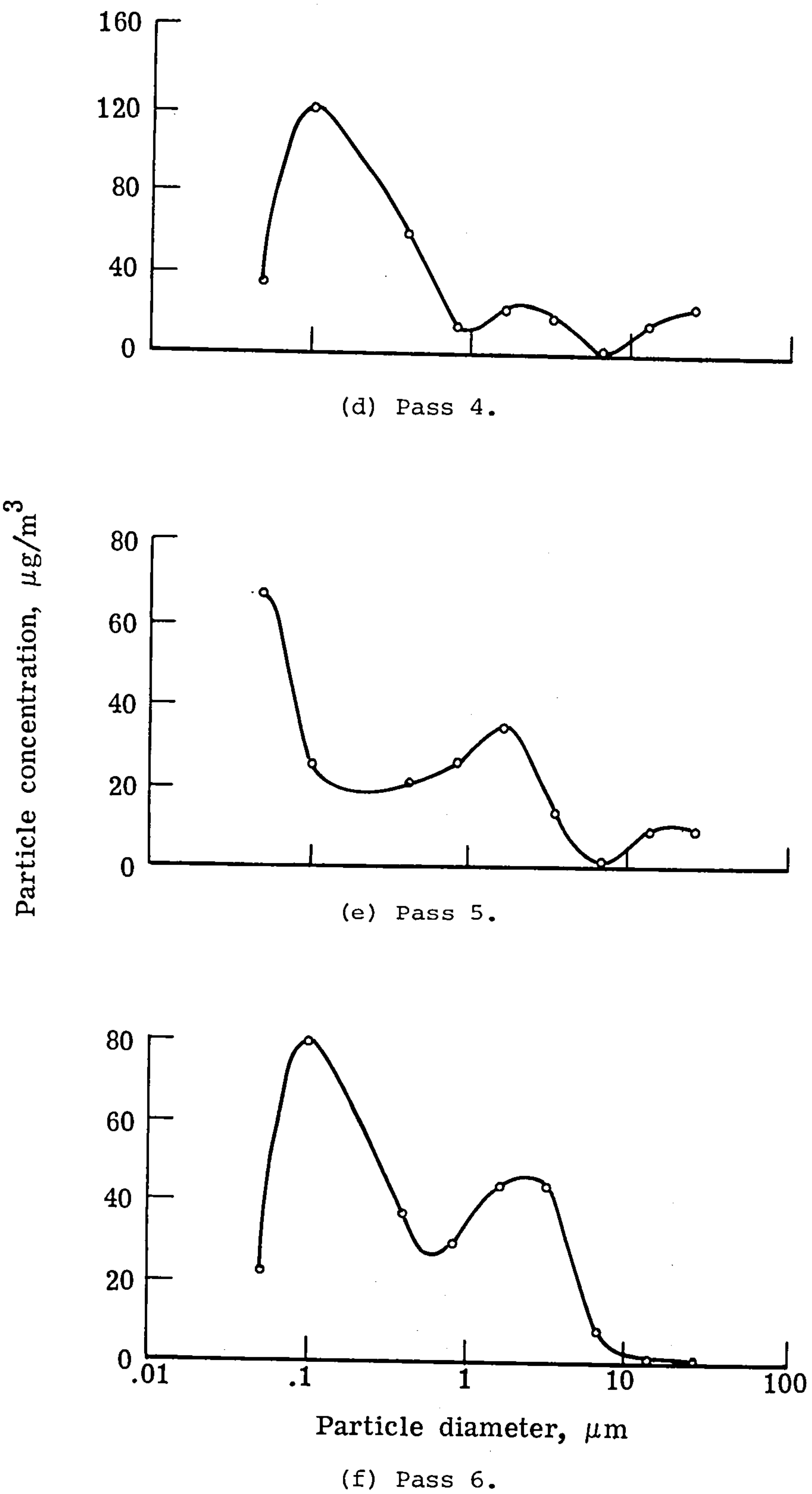


Figure 11.- Continued.

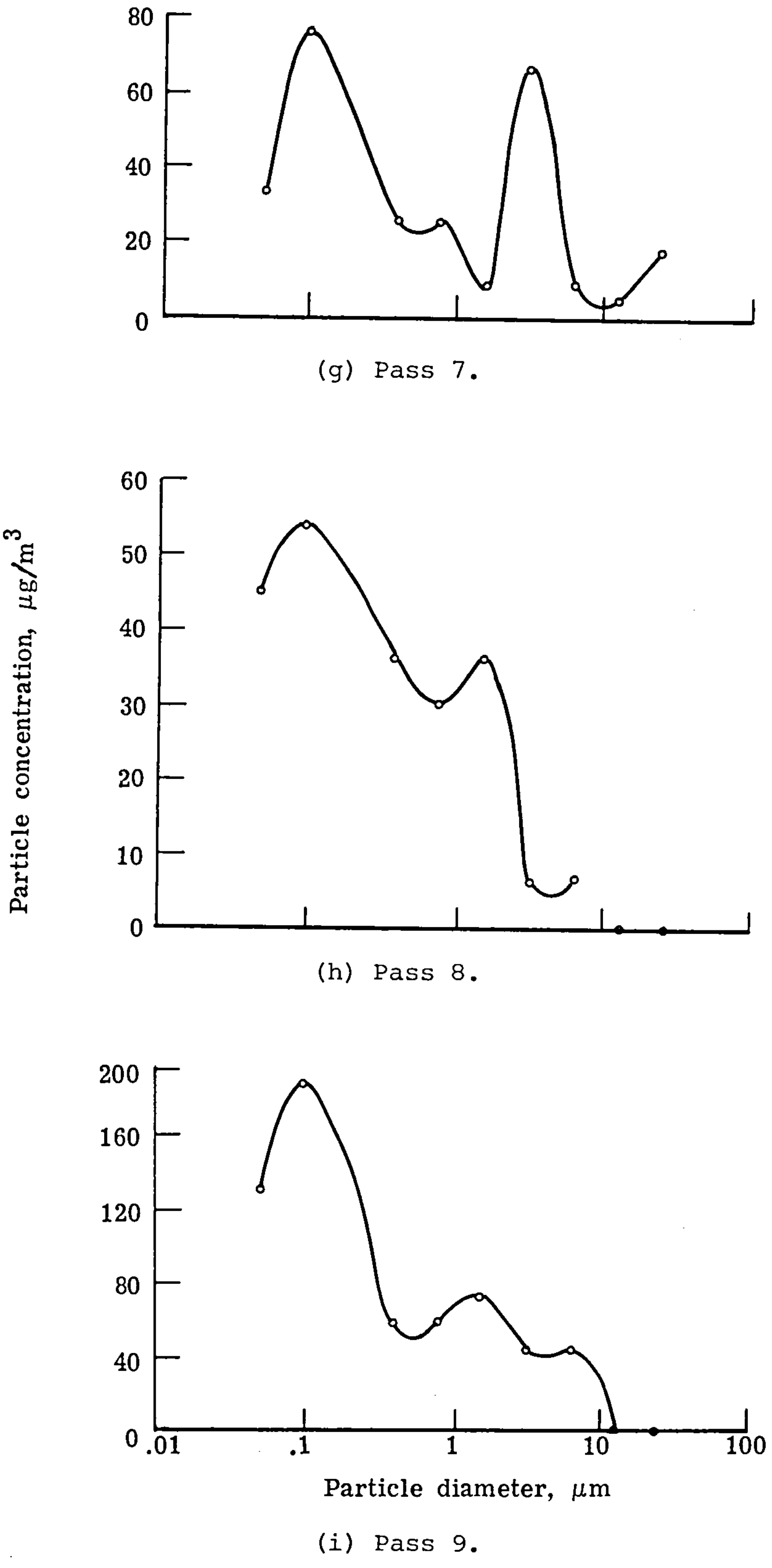
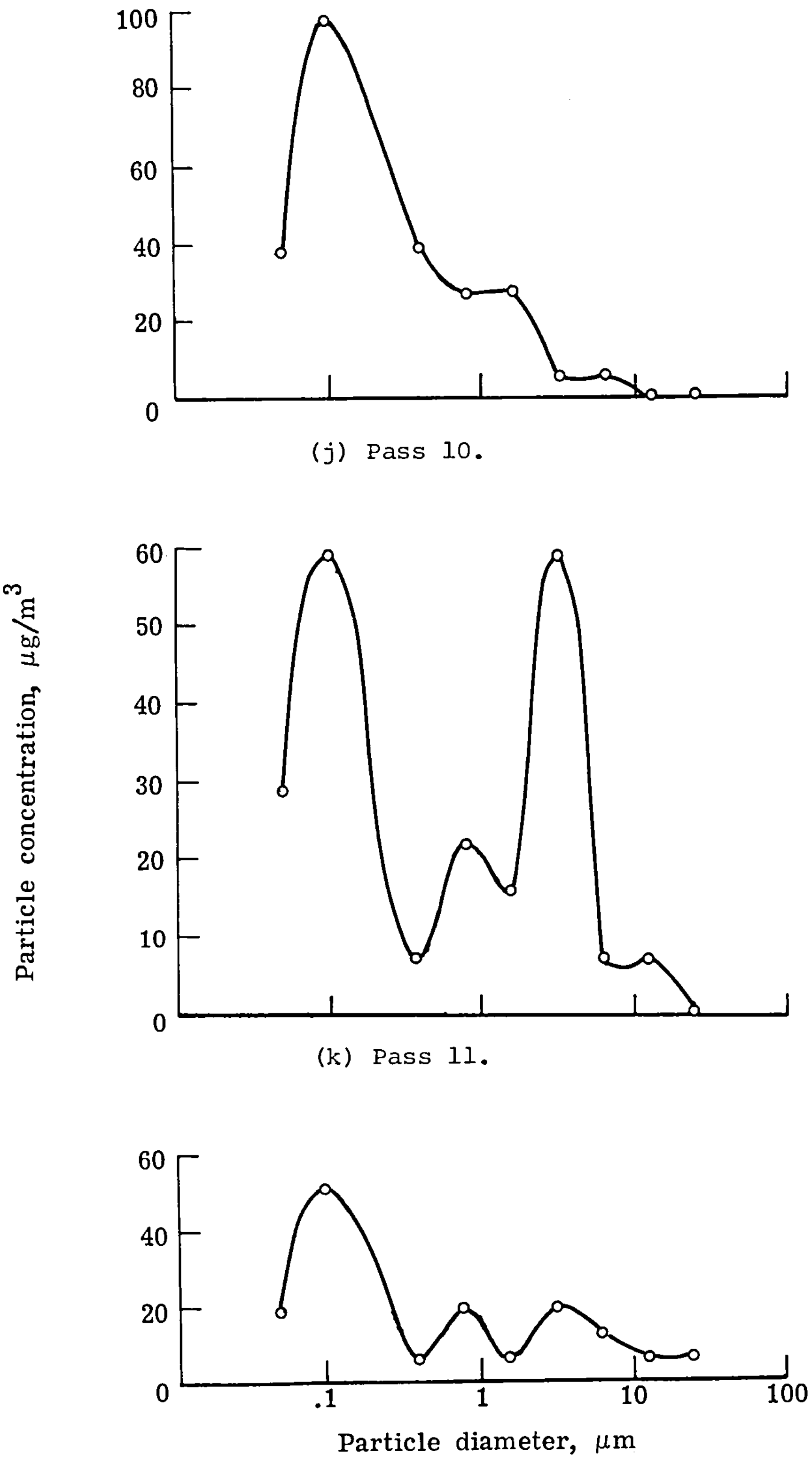


Figure 11.- Continued.

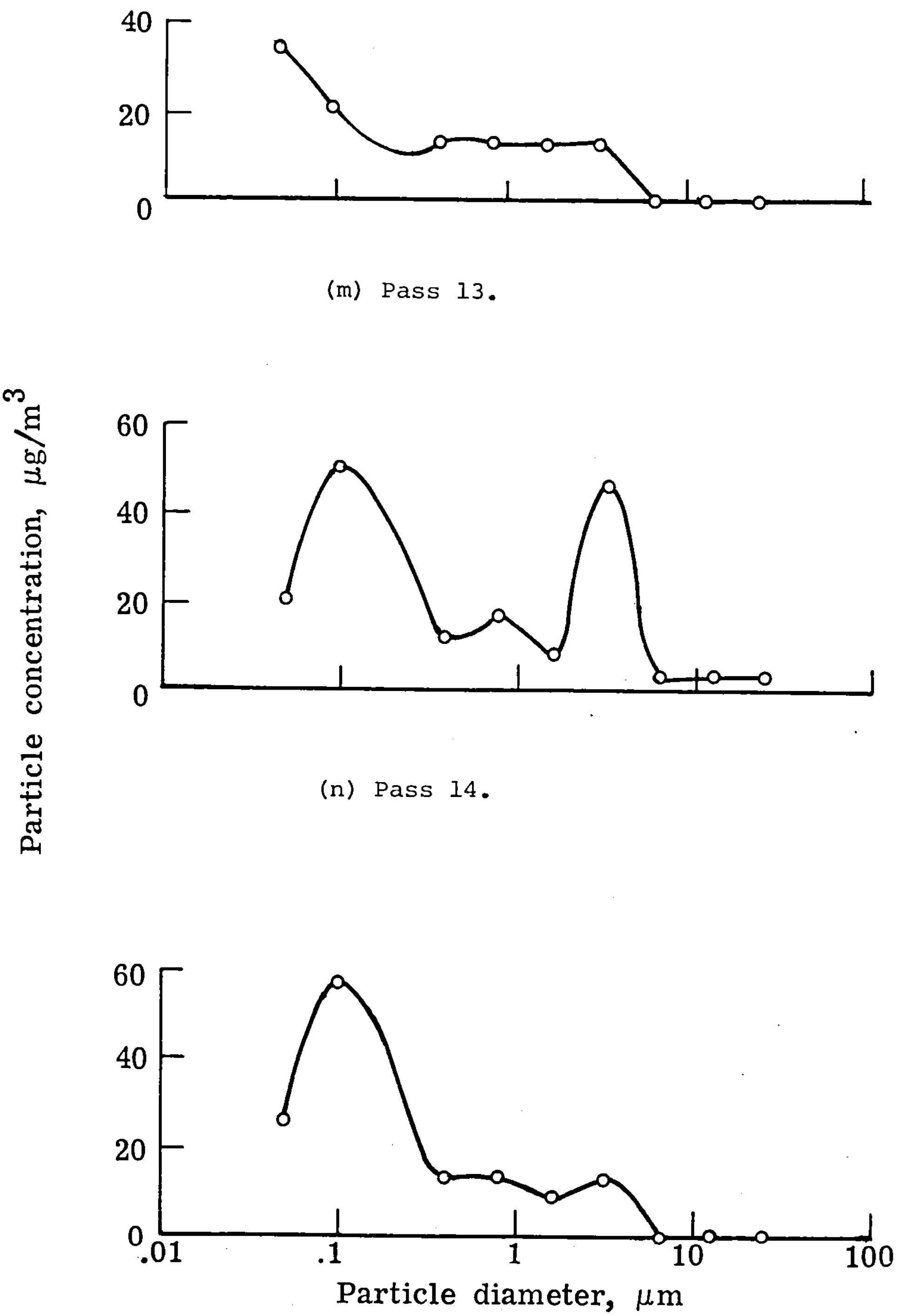


(j) Pass 10.

(k) Pass 11.

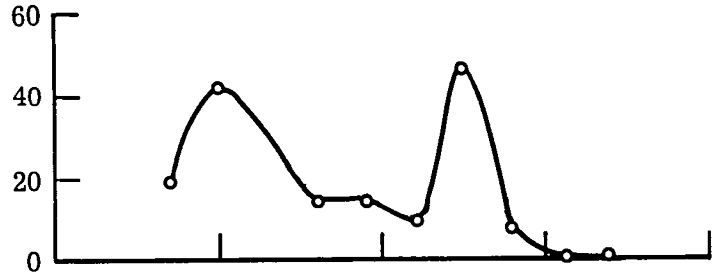
(l) Pass 12.

Figure 11.- Continued.

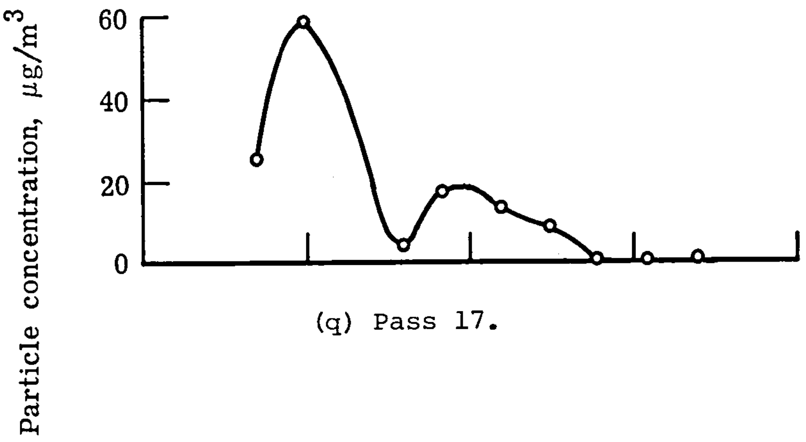


(o) Pass 15.

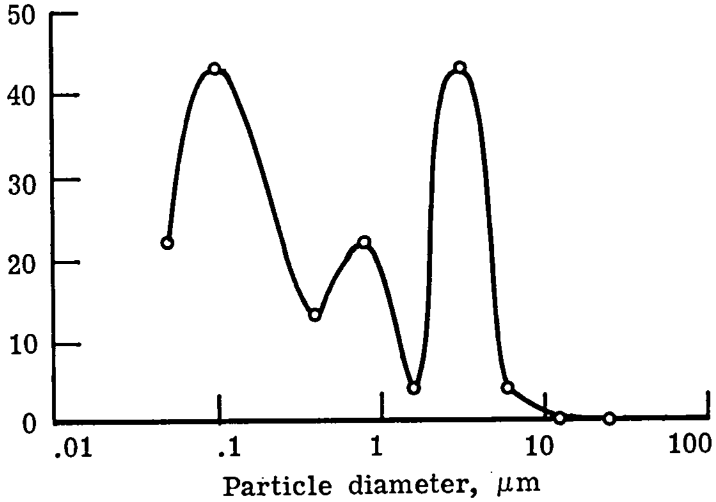
Figure 11.- Continued.



(p) Pass 16.

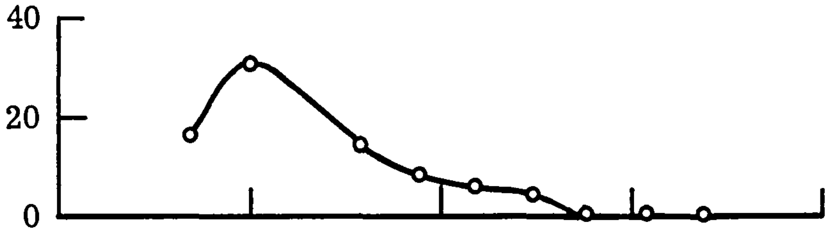


(q) Pass 17.

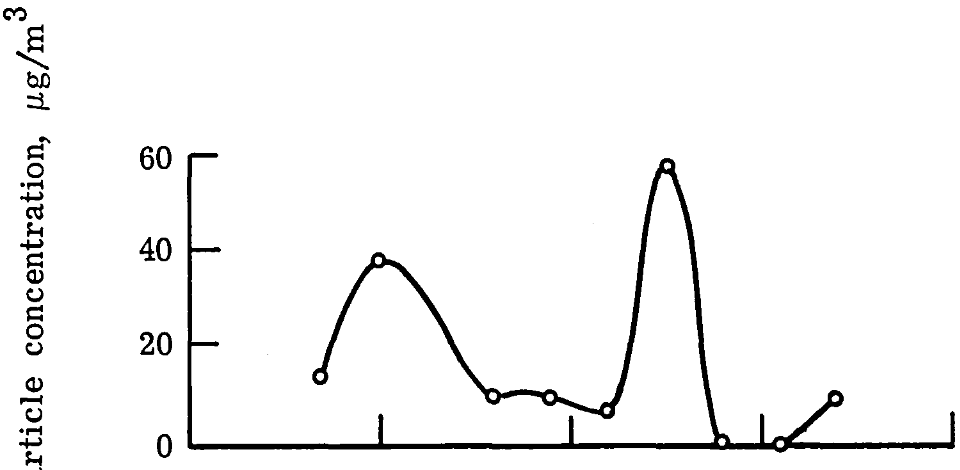


(r) Pass 18.

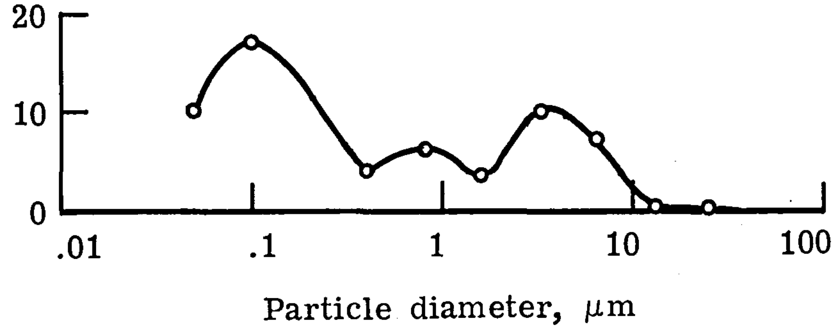
Figure 11.- Continued.



(s) Pass 19.

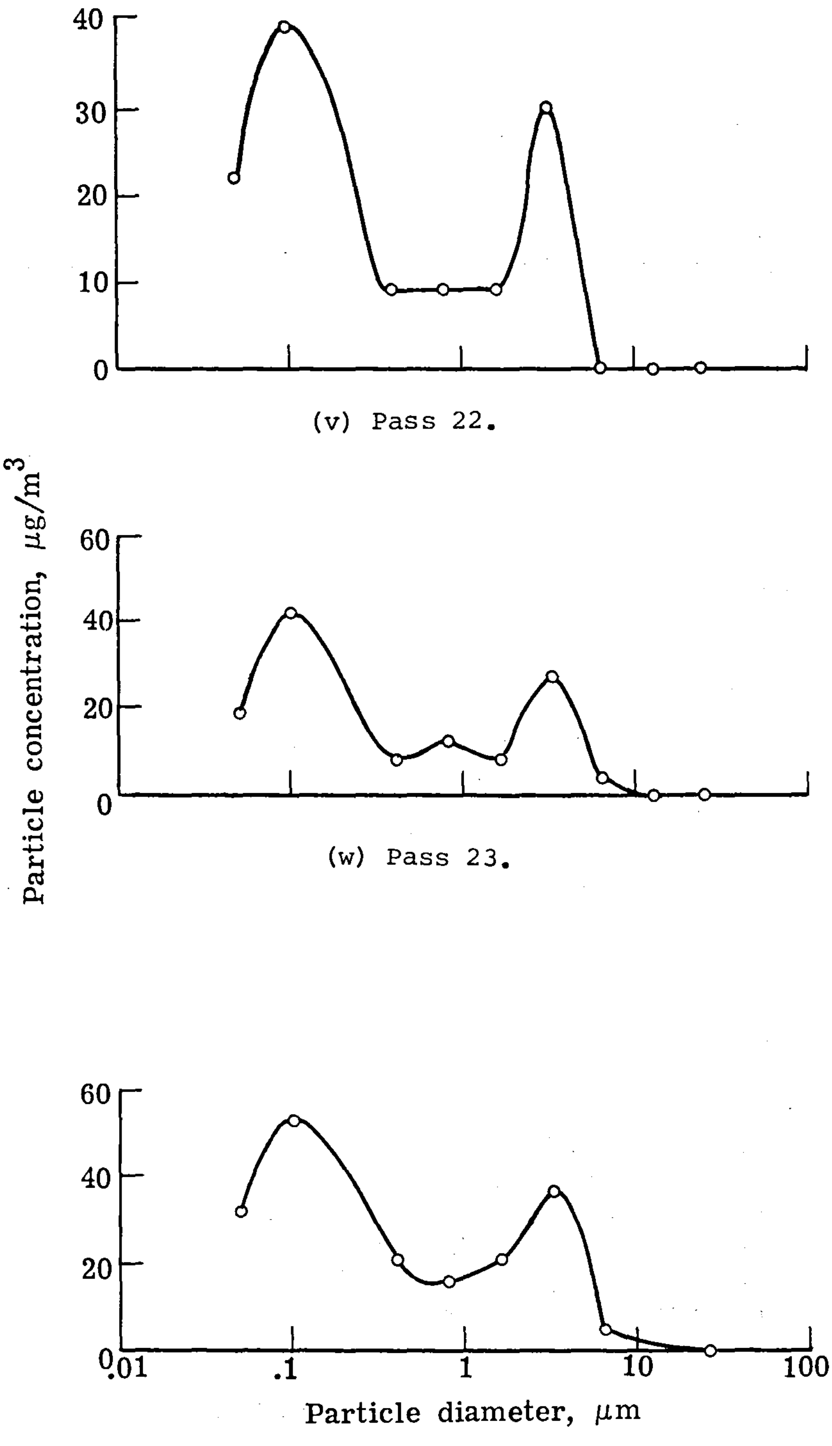


(t) Pass 20.



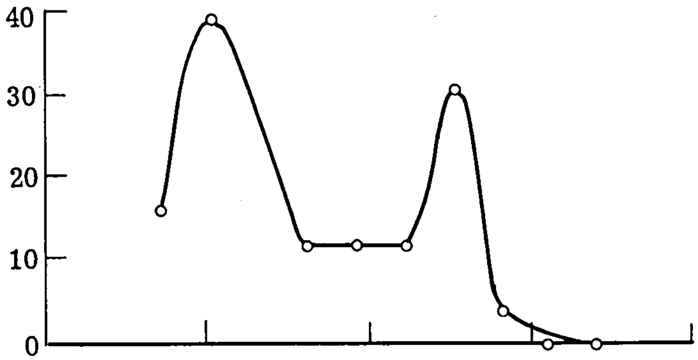
(u) Pass 21.

Figure 11.- Continued.

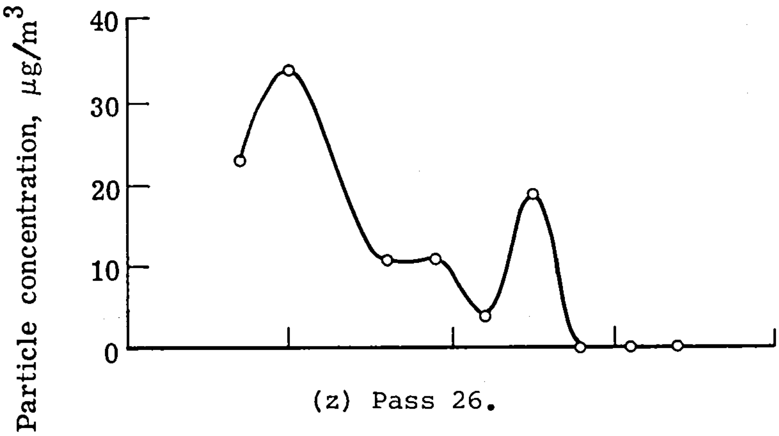


(x) Pass 24.

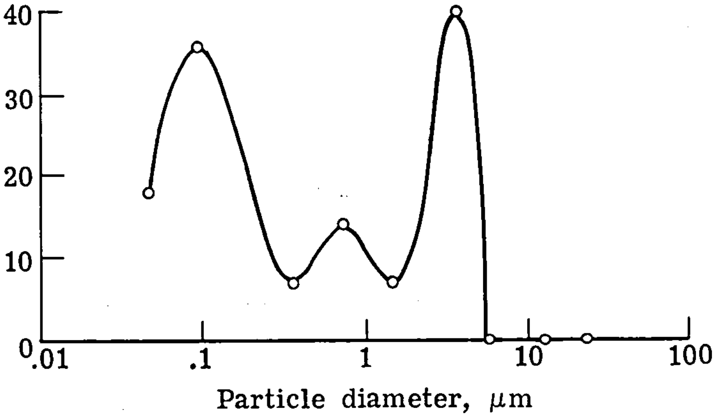
Figure 11.- Continued.



(y) Pass 25.

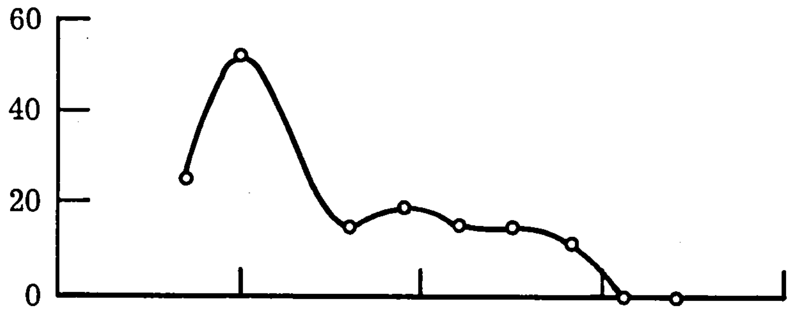


(z) Pass 26.

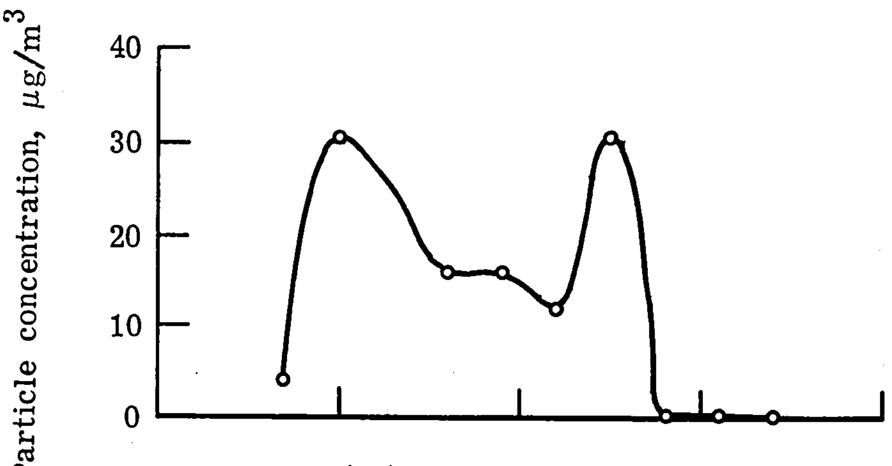


(aa) Pass 27.

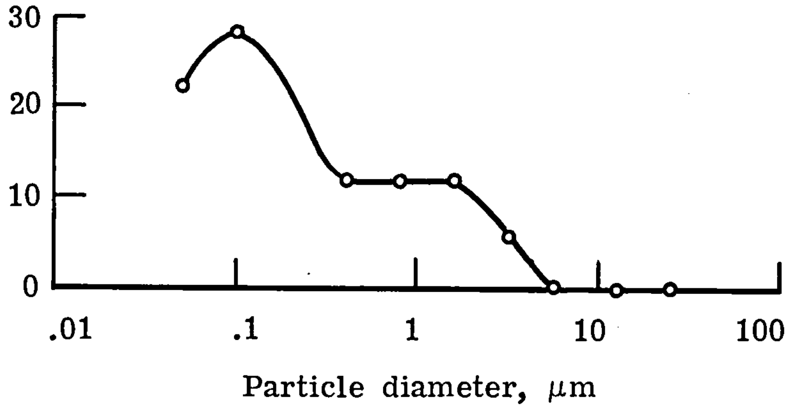
Figure 11.- Continued.



(bb) Pass 28.

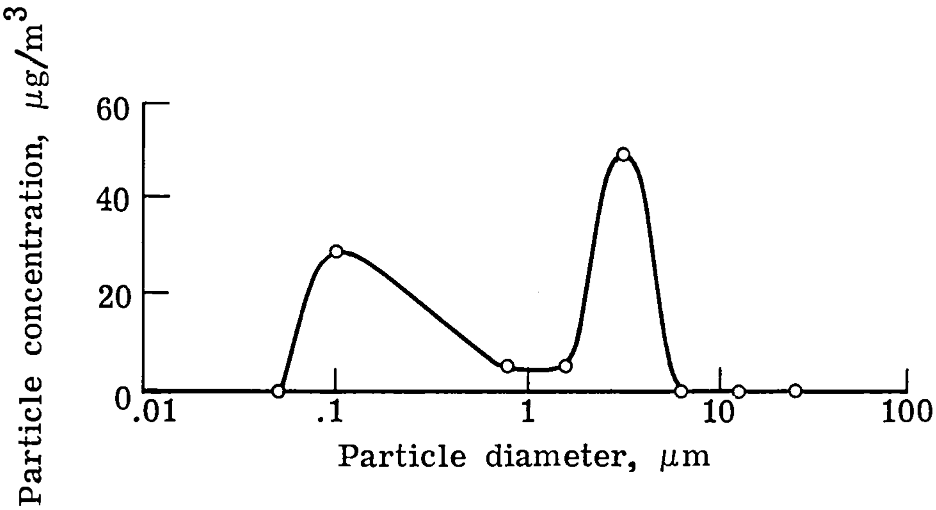


(cc) Pass 29.



(dd) Pass 30.

Figure 11.- Continued.



(ee) Pass 31.

Figure 11.- Concluded.

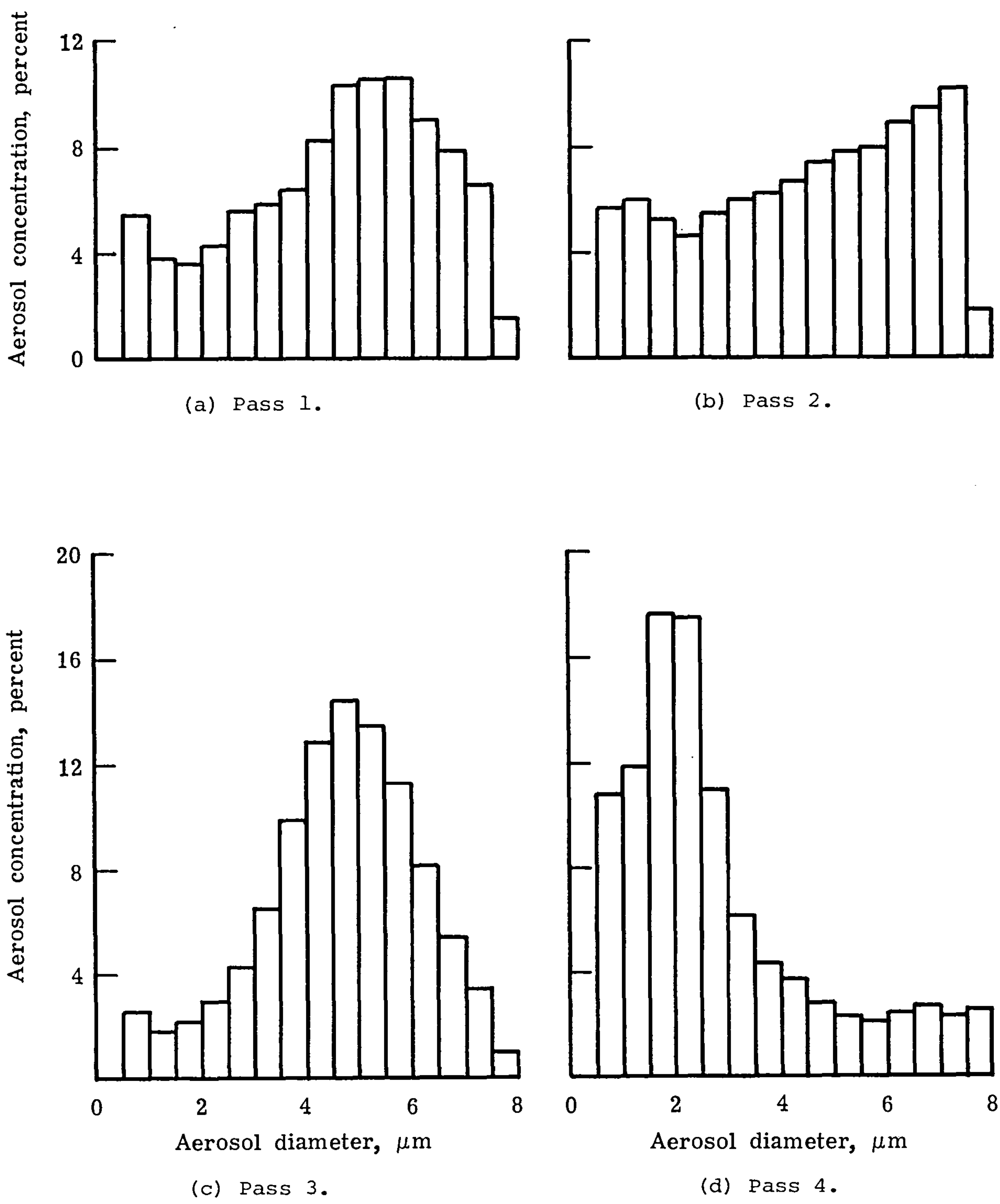
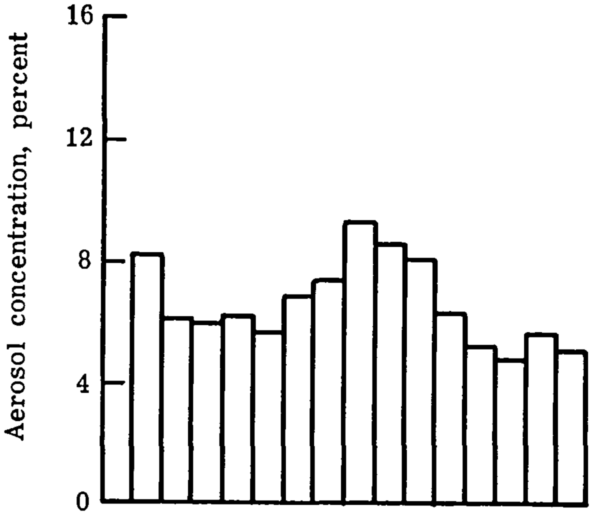
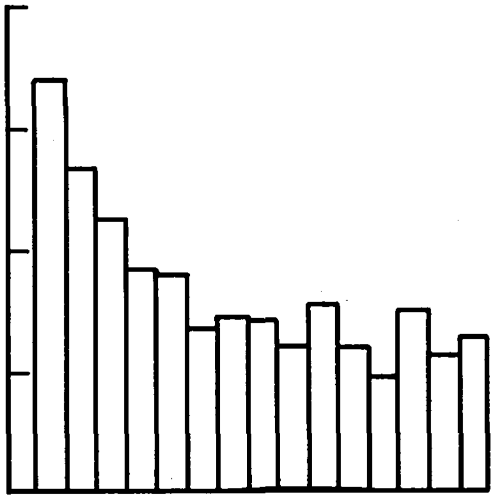


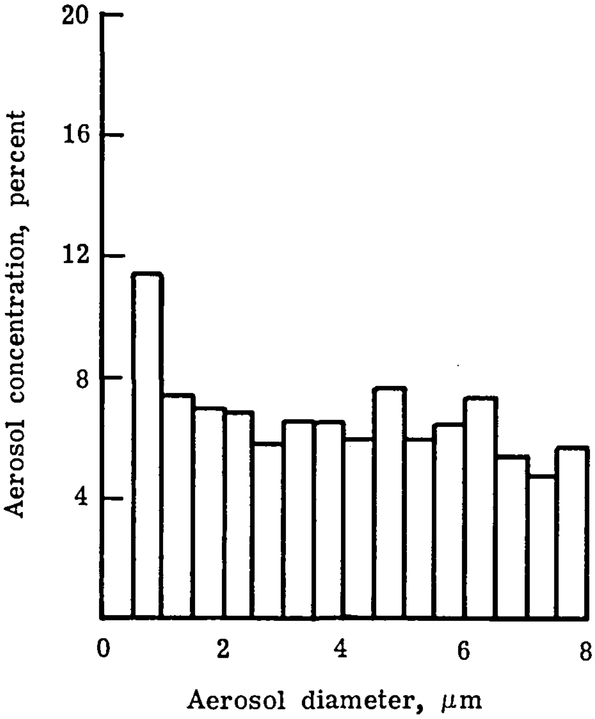
Figure 12.- Relative aerosol number concentration as function of diameter from FSSP measurements.



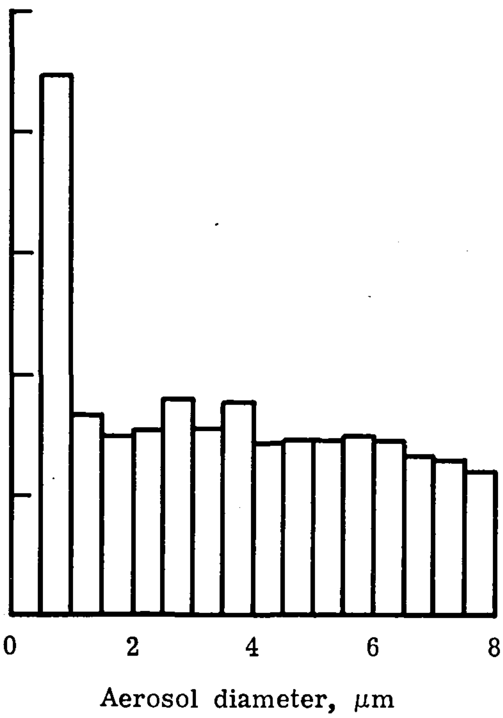
(e) Pass 5.



(f) Pass 6.

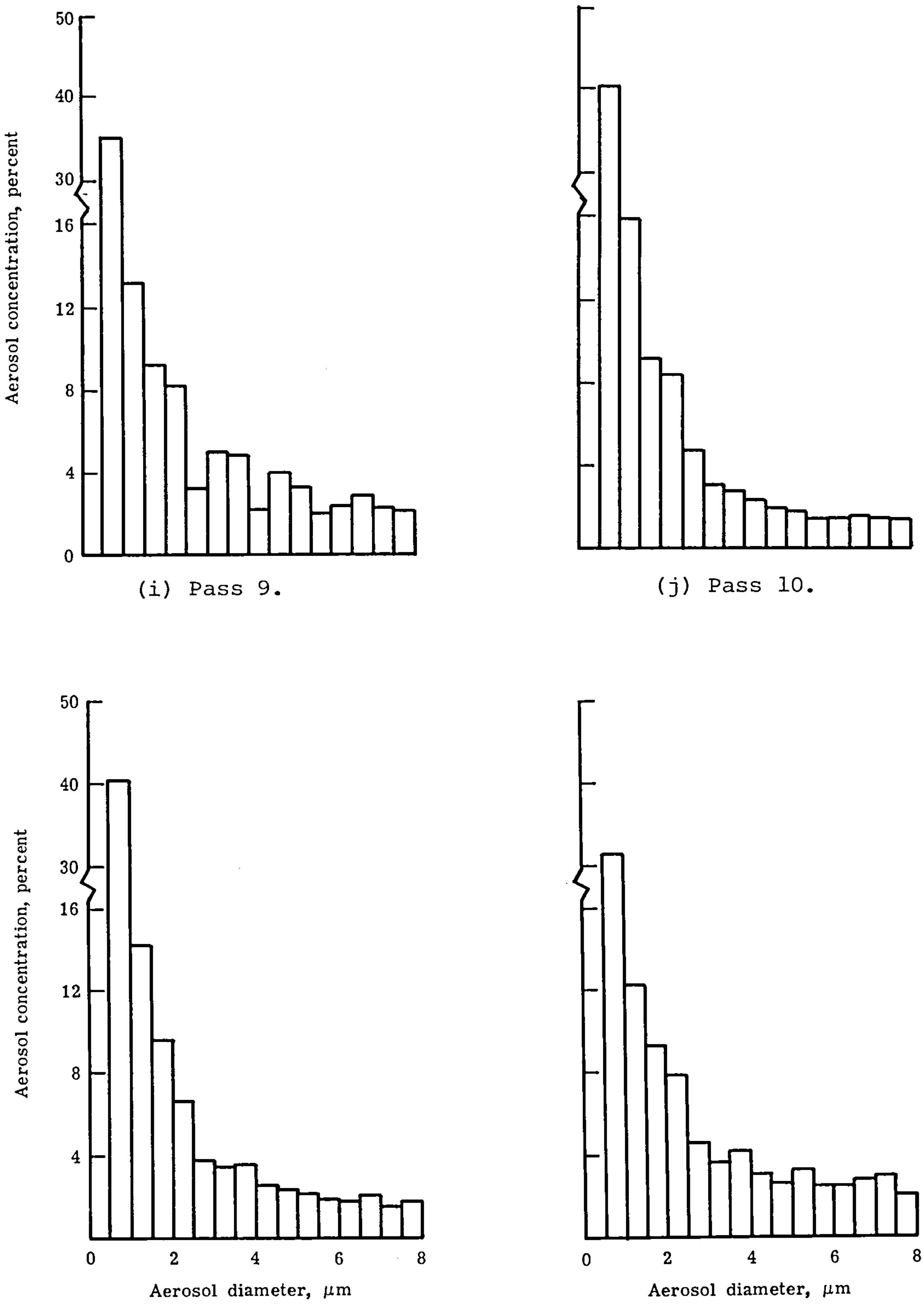


(g) Pass 7.



(h) Pass 8.

Figure 12.- Continued.



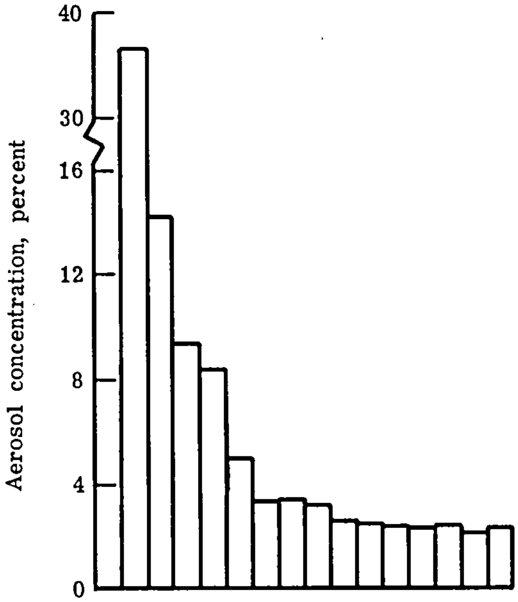
(i) Pass 9.

(j) Pass 10.

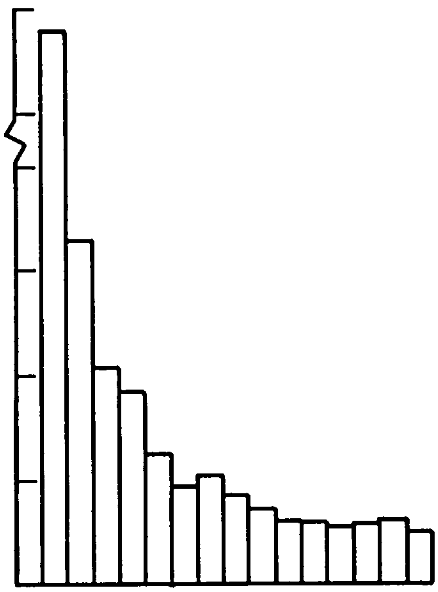
(k) Pass 11.

(l) Pass 12.

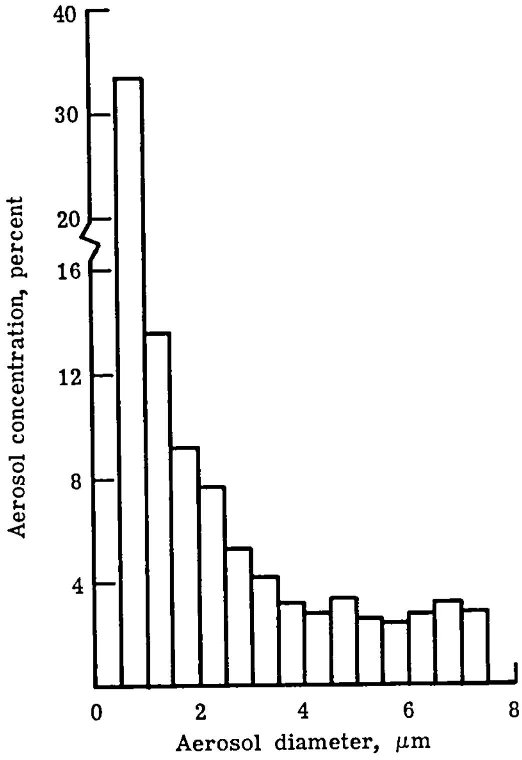
Figure 12.- Continued.



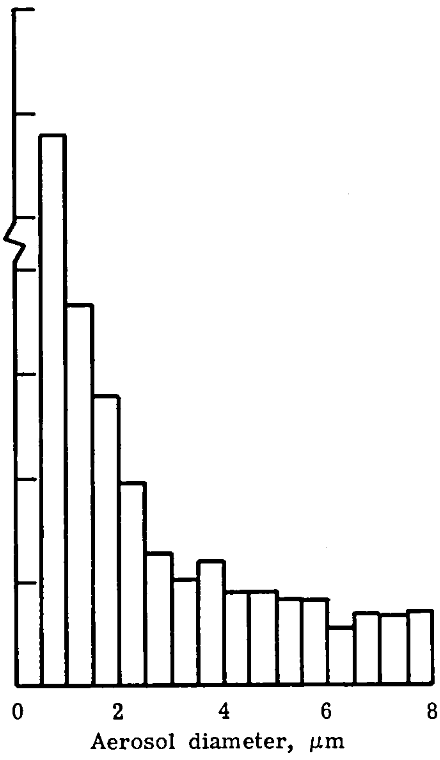
(m) Pass 13.



(n) Pass 14.

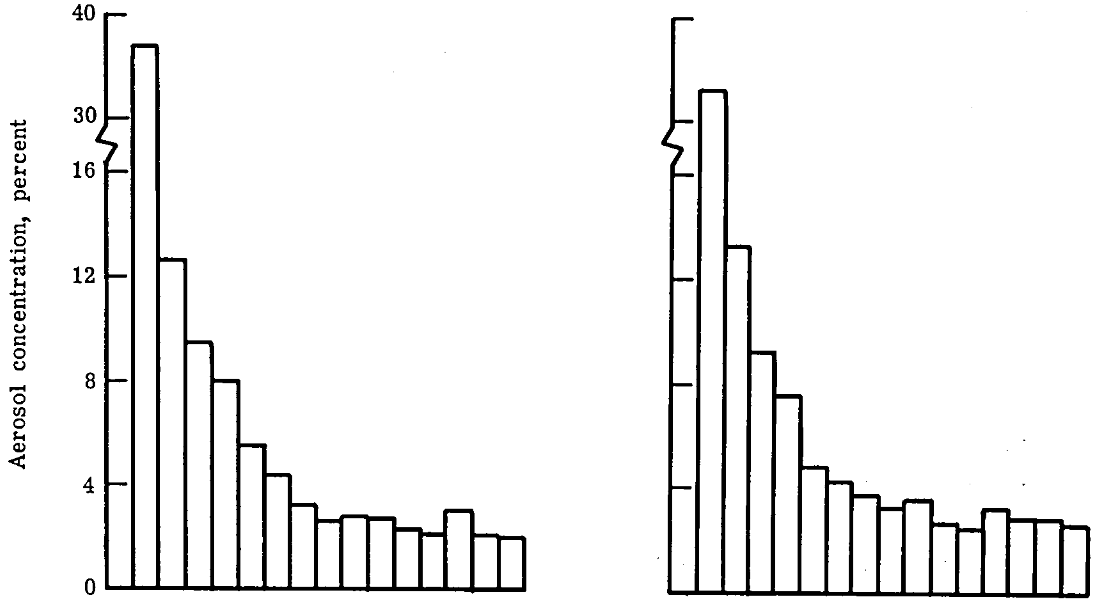


(o) Pass 15.



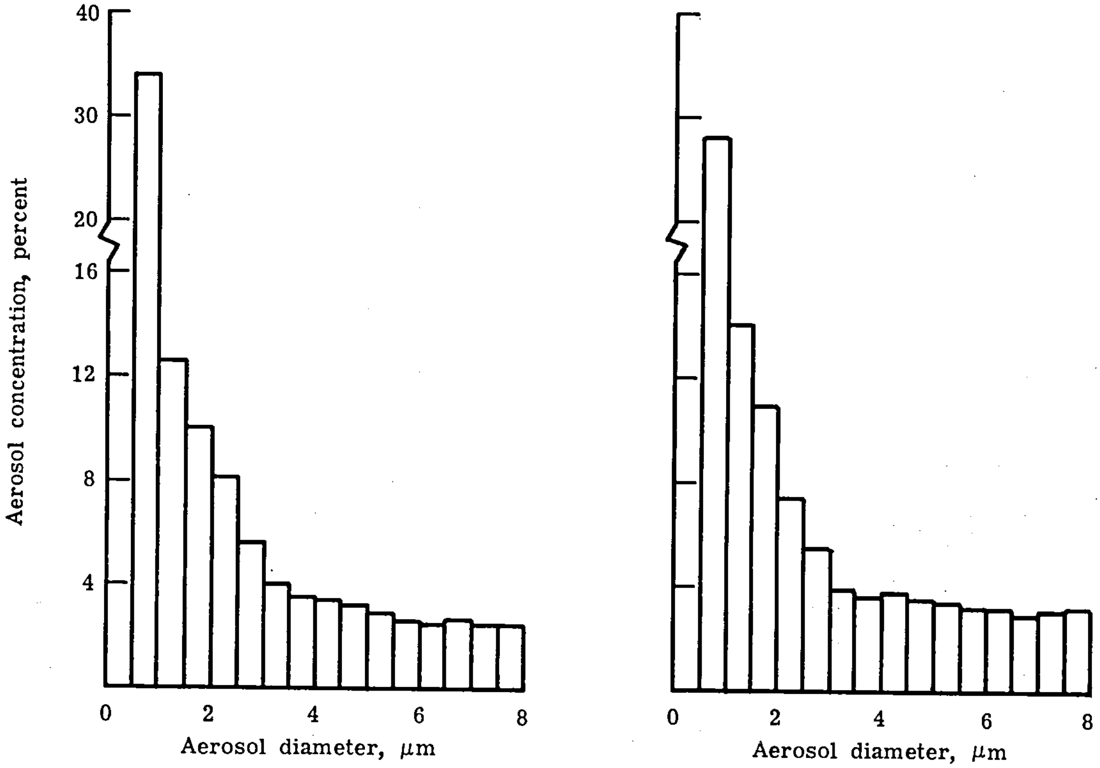
(p) Pass 16.

Figure 12.- Continued.



(q) Pass 17.

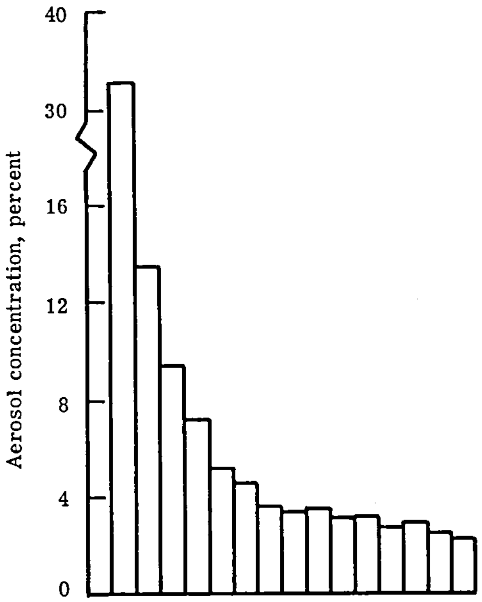
(r) Pass 18.



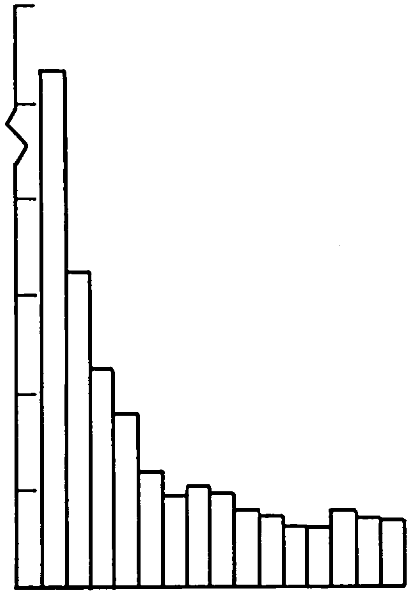
(s) Pass 19.

(t) Pass 20.

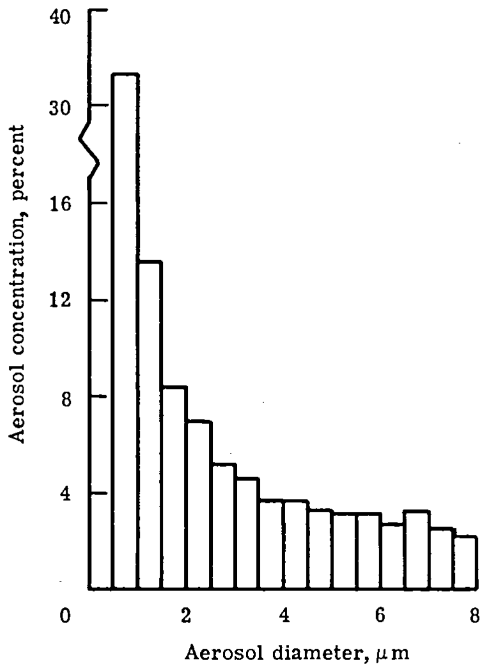
Figure 12.- Continued.



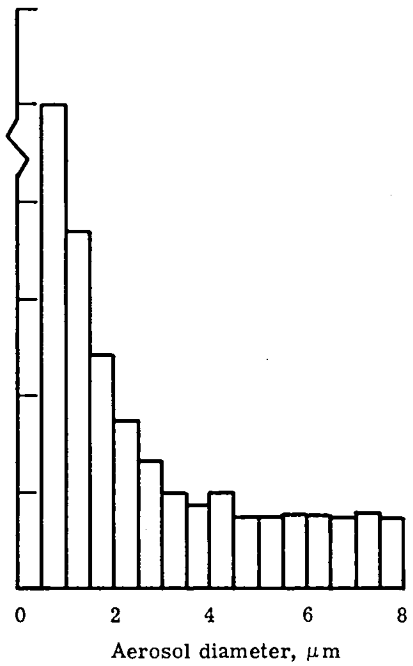
(u) Pass 21.



(v) Pass 22.

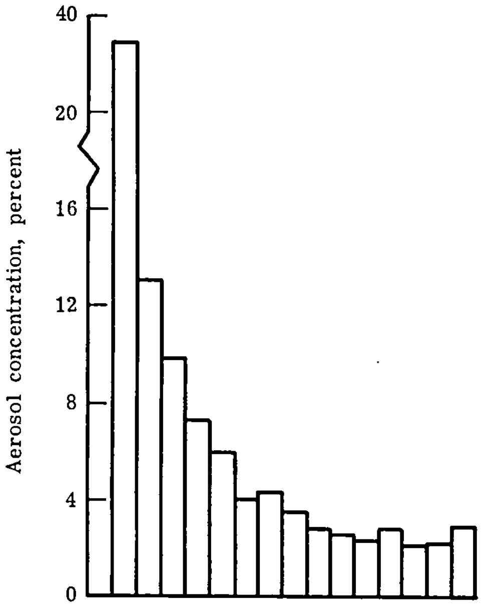


(w) Pass 23.

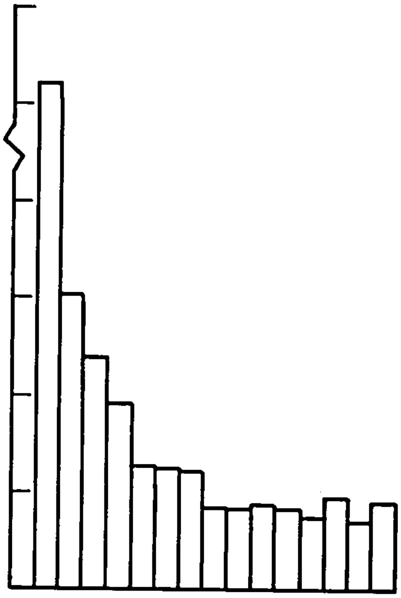


(x) Pass 24.

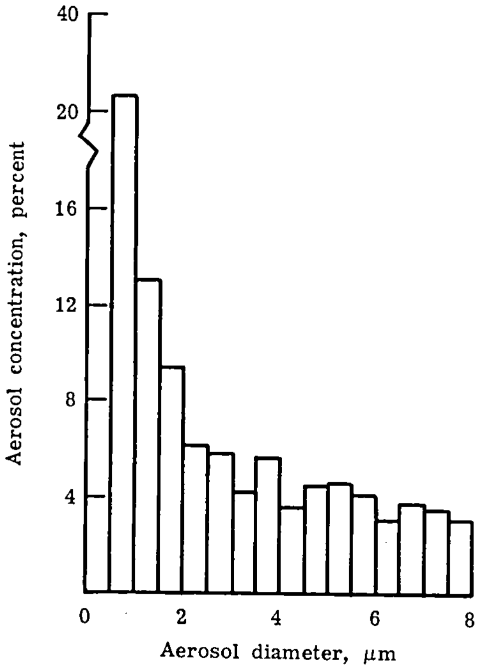
Figure 12.- Continued.



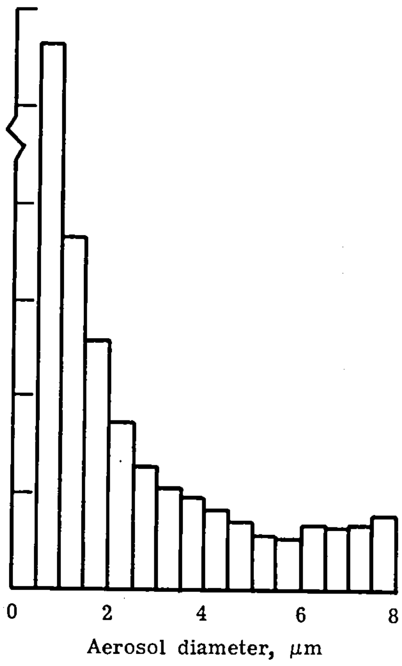
(y) Pass 25.



(z) Pass 26.

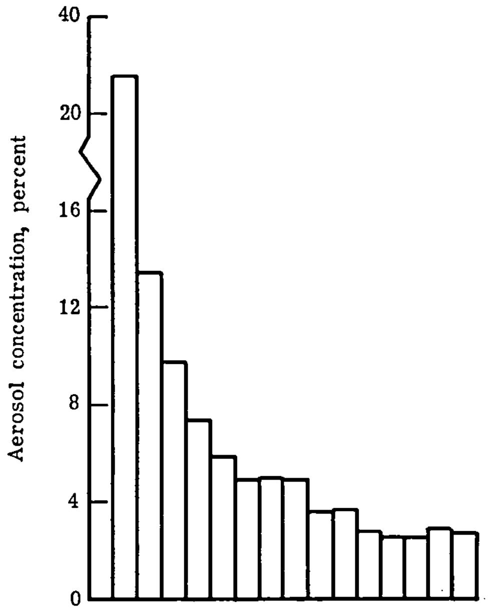


(aa) Pass 27.

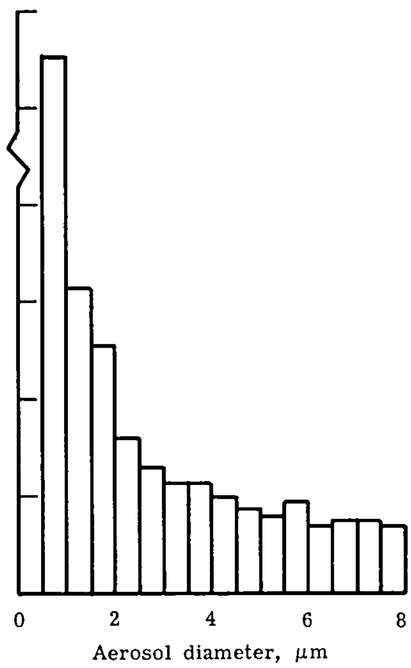


(bb) Pass 28.

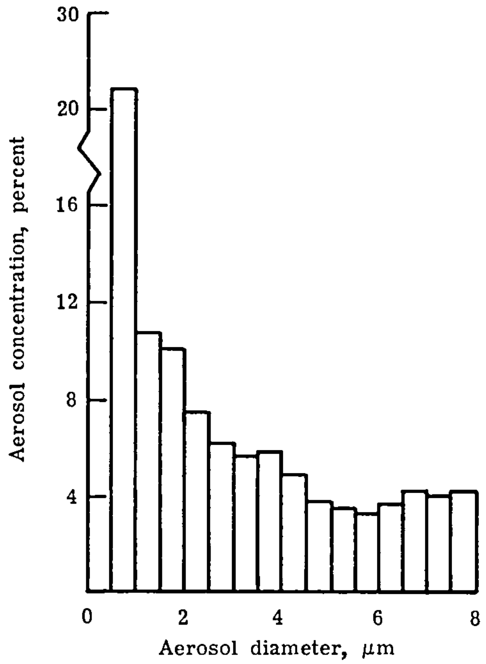
Figure 12.- Continued.



(cc) Pass 29.



(dd) Pass 30.



(ee) Pass 31.

Figure 12.- Concluded.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-78778		

4. Title and Subtitle	5. Report Date
LAUNCH VEHICLE EFFLUENT MEASUREMENTS DURING THE AUGUST 20, 1977, TITAN III LAUNCH AT AIR FORCE EASTERN TEST RANGE	January 1979
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
David C. Woods, Richard J. Bendura, and Dewey E. Wornom	L-12551
	10. Work Unit No.
9. Performing Organization Name and Address	989-15-20-01
NASA Langley Research Center Hampton, VA 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Rocket exhaust cloud measurements made in the troposphere for the August 20, 1977, Titan III launch from the Air Force Eastern Test Range are presented. Included are airborne effluent measurements within the launch cloud and visible and infrared measurements of cloud physical behavior. Airborne effluent measurements included concentrations of HCl, Cl_2, NO, NO_x, and particulates as a function of time during each sampling pass through the exhaust cloud. The particle size distribution was measured for each pass through the cloud. Mass concentration as a function of particle diameter was measured over the size range of 0.05- to 25-μm diameter, and particle number density was measured as a function of diameter over a size range of 0.5 to 7.5 μm. Effluent concentrations were similar to those of previous launch monitorings. Maximum HCl concentrations in the cloud ranged from about 30 ppm several minutes after launch to about 1 to 2 ppm at 100 minutes. Maximum Cl_2 concentrations were about 40 to 55 ppb and by 20 minutes were less than 10 ppb. A tabulated listing of the airborne data is given in the appendix. Usable cloud imaging data were limited to the first 16 minutes after launch.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Airborne sampling Effluent sampling Rocket vehicle exhaust Titan III booster exhaust	Unclassified - Unlimited Subject Category 45

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	87	$6.00

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

NASA-Langley, 1979

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return