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COMPARISON AND EVALUATION OF SEVERAL CHEMICALS AS AGENTS FOR ROCKET-VEHICLE PRODUCTION OF SMOKE TRAILS FOR WIND-SHEAR MEASUREMENTS

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SUMMARY

An investigation has been undertaken to determine the relative merits of several chemical substances, namely: pyrotechnic mixture (HC), phosphorus/ carbon disulfide solution (P/CS_2), titanium tetrachloride (FM), and a solution of sulfur trioxide in chlorosulfonic acid (FS), for producing smoke trails to be used in photographically obtaining detailed wind-shear measurements.

Presented herein are the results of simultaneous flight tests of three of the aforementioned smoke-producing agents along with an analysis of the factors which govern the production of a satisfactory trail. These results show that reaction of P/CS_2 to form a smoke trail is not moisture dependent. Further, the trail formed much more rapidly upon expulsion from the flight vehicle than trails from FM or FS. Also, the P/CS_2 trail was the brightest of the three. The persistence interval of the trail formed from P/CS_2 was approximately 4.5 minutes, whereas persistence interval of the trail which formed from FM was longer. Because of poor brightness over a considerable part of the FS trail, persistence interval was not determined for this fluid. Ground tests of HC revealed that use of this smoke-generating material was not feasible for in-flight production of a smoke trail for wind-shear measurements.

INTRODUCTION

Prior to flight tests of vehicles which produced smoke trails for determining small-scale wind fluctuations (refs. 1 and 2), a survey of the literature was made in an effort to determine the most suitable material for producing smoke trails. Available information was insufficient to conclusively indicate which smoke-producing material would be best for this application. However, it was found that, of all the smoke-producing agents considered practical, FS (a solution of sulfur trioxide in chlorosulfonic acid) had the greatest total obscuring power, which is usually abbreviated TOP and is defined as the area (square feet) of smoke produced from 1 pound of material and having thickness and density such that a 40-watt lamp is completely obscured. On this basis, FS was selected. Subsequently, FS produced trails whereby wind measurements could be made. However, because of the wide variation between the essentially static laboratory conditions under which TOP and other characteristics were obtained and the dynamic flight conditions under which the fluids are expelled to produce smoke trails, it was considered that information relative to smoke-producing materials was inadequate. Thus, more information about the characteristics of FS and other smoke-producing agents, after expulsion from flight vehicles, was needed.

Since the feasibility of the smoke-trail technique has been demonstrated, some consideration has been given to placing smoke generators on missiles such as Atlas on a "noninterference" basis to obtain wind measurements along their trajectories. One firm has suggested that HC (a dry pyrotechnic mixture), titanium tetrachloride (frequently designated FM), or FS would produce good trails when expelled from an Atlas at the proper rate. However, it was thought that more information about the characteristics of these materials should be obtained before engaging in a program wherein any of these agents would be carried aboard an Atlas for smoke-trail production. Heretofore, phosphorus, due to handling requirements, had not been regarded as being operationally practical but because of the high TOP of phosphorus, it was decided to include it in the aforementioned program. Therefore, it was tentatively decided to conduct a program of comparing smoke trails formed from four materials: FM, FS, phosphorus dissolved in carbon disulfide (hereafter referred to as P/CS_2), and HC. In addition, ground tests, essential to the development of a payload utilizing HC on one of the vehicles, were required. These trails would be produced by four Nike booster rocket motors fitted with 10° nose cones fired simultaneously to approximately the same altitude from launch sites near each other. Hence, atmospheric conditions encountered by each vehicle and the trail produced therefrom would be virtually identical.

This report presents the results of the simultaneous tests, under flight conditions, of three smoke-producing agents: FM, FS, and P/CS_2; in addition, results from ground tests of HC are discussed. These results consist primarily of comparison of brightness and persistence interval of the three trails as obtained from 10 sequential photographs, each of which shows all three trails.

Motion-picture supplement L-827 has been prepared and is available on loan. A request card and a description of the film are included at the back of this document.

MATERIAL CHARACTERISTICS AND REACTIONS

All agents, which were to be simultaneously expelled from similar flight vehicles for comparison of the agents' characteristics under flight conditions, react with atmospheric moisture, oxygen, or both to form small deliquescent particles consisting mainly of acids which quickly increase to maximum size and form smoke trails. Further information about each agent follows. Values of TOP cited are from reference 3.

HC (Pyrotechnic Mixture)

The dry pyrotechnic mixture (often designated HC) consisted of zinc dust, a chlorine-containing compound such as carbon tetrachloride or hexachloroethane, an oxidizer such as ammonium perchlorate or sodium perchlorate, a stabilizer such as magnesium carbonate or calcium carbonate and an agent to control burning rate such as ammonium chloride. Powdered zinc, in the presence of a proper oxidizer, ignites readily, producing considerable heat which causes reaction of previously unreacted zinc powder with carbon tetrachloride or hexachloroethane to form zinc chloride, which in turn hydrolyzes into droplets or particles, consisting mainly of hydrochloric acid and zinc hydroxide, and forms a smoke.

Reactions generally considered to occur in this process are as follows:

$$Zn + 2Cl \rightarrow ZnCl_2$$

$$ZnCl_2 + 2H_2O \rightarrow 2HCl + Zn(OH)_2$$

Total obscuring power of HC is 2100.

P/CS_2 (Phosphorus/Carbon Disulfide Solution)

The phosphorus/carbon disulfide solution P/CS_2, 83.4 percent phosphorus by weight, was prepared by adding 20 pints of carbon disulfide to a vessel containing 132 pounds of yellow phosphorus in an inert atmosphere of carbon dioxide. Phosphorus was used in a dissolved, rather than solid state, since it can more easily be expelled and because it spontaneously ignites as it is exposed to air. Solid yellow phosphorus would have required ignition, since it does not spontaneously ignite in air until approximately human body temperature is reached.

The P/CS_2 solution is atomized as it is expelled from a vehicle in flight, and carbon disulfide (being highly volatile) quickly evaporates leaving particles of solid phosphorus sufficiently small to spontaneously ignite under ambient conditions. Phosphorus burns to form solid particles of phosphorus pentoxide which under proper conditions absorb moisture to become droplets of phosphoric acid. Either the particles of phosphorus pentoxide or droplets of phosphoric acid form visible smoke trails. Therefore, phosphorus could probably be used to produce smoke trails under conditions of very low humidity.

Essential reactions for producing smoke trails from phosphorus in an atmosphere containing humidity are as follows:

$$4P + 5O_2 \rightarrow 2P_2O_5$$

$$P_2O_5 + 3H_2O \rightarrow 2H_3PO_4$$

The TOP of yellow phosphorus, the greatest of any known smoke-producing agent, is 4600, and it is assumed that only the phosphorus in P/CS_2 was effective in producing smoke. It was assumed that carbon disulfide was ineffective because during combustion it would burn into invisible gaseous products. Therefore, it was supposed that TOP of the solution would be 0.834 × 4600 or approximately 3800.

FS $\left(\text{Solution of } SO_3\text{, 55 Percent by Weight, in } ClSO_3H\right)$

The chemical warfare symbol for a solution of SO_3, 55 percent by weight, in $ClSO_3H$ is FS. When FS is exposed to moisture, it hydrolyzes into hydrochloric acid and sulfuric acid, both of which are deliquescent. Thus, small drops of FS grow into larger drops of the mixed acid, which form a smoke. Reactions essential to the process are

$$SO_3 + H_2O \rightarrow H_2SO_4$$

$$ClSO_3H + H_2O \rightarrow H_2SO_4 + HCl$$

The TOP of FS is 2550.

FM $\left(\text{Chemical Warfare Symbol for } TiCl_4\right)$

The chemical warfare symbol FM designates $TiCl_4$ which, when exposed to moisture, hydrolyzes into two deliquescent substances, hydrochloric acid and titanium hydroxide. This compound produces smoke in the same manner as FS. Effectively, the chemical reaction involved is

$$TiCl_4 + 4H_2O \rightarrow 4HCl + Ti(OH)_4$$

The agent FM can react with limited moisture to form oxychlorides and titanium oxide which are solids and can clog ports, tubing, and so forth. Therefore, equipment containing titanium tetrachloride should be kept dry. The TOP of FM is 1900.

DESCRIPTION OF VEHICLES

Each of the vehicles, one of which is shown in figure 1, consisted of a Nike booster and a smoke-producing payload. Payloads were similar to and functioned in the same manner as that of the final vehicle described in reference 2. All were identical except that the vehicle expelling P/CS_2 was equipped with an additional check valve which prevented any flow from the fluid compartment to the air reservoir. To insure that combustion of P/CS_2, after it was expelled from the vehicle, would not destroy any of the fins, it was necessary for the solution to be exhausted aft of the fins. This was done by means of a tube which ran from the base of the nose cone along the Nike motor case and terminated just aft of the nozzle exit plane. In order to maintain aerodynamic symmetry of the vehicle, a dummy tube was attached opposite the tube through which the solution flowed. Five steel bands equally spaced along the Nike motor case were used to prevent excessive vibration of the tube during flight. Since it is permissible, insofar as damage to the vehicle is concerned, to exhaust FS or FM from some point on the nose, tubing along the Nike case as just described is not necessary for these vehicles. However, to maintain aerodynamic similarity and wake conditions, FS and FM were expelled in the same manner as P/CS_2, just aft of the nozzle exit plane.

TEST PROCEDURE AND EQUIPMENT

Two of the smoke-producing agents, FS and FM, were received in liquid form ready for adding to the appropriate vehicle. The third agent, P/CS_2, was prepared by dissolving phosphorus in carbon disulfide. Since this solution was not commercially available, it was necessary to devise a new technique, which required the design and construction of special equipment for drying the phosphorus, adding carbon disulfide to dissolve the phosphorus, and piping the resulting solution into the payload compartment of the vehicle (a Nike booster fitted with a 10° cone). Description of the procedure in which the specially designed and constructed equipment was employed in preparation of the solution while in the presence of considerable safety personnel and equipment is presented in appendix A.

All the vehicles were filled with one of the smoke-producing fluids just prior to launch. During FM filling, special care was taken in order to avoid clogging of tubing by gummy residue which can form from moisture and FM; FS and P/CS_2 do not clog in this manner. Prior to filling the vehicle which carried P/CS_2, the nose cone and the filling tube connected to it were purged of air with carbon dioxide. With this vehicle horizontal, the filling tube was then connected to the dissolving apparatus and, after opening the valve at the bottom of the tank P/CS_2 flowed into the fluid compartment of the vehicle. The exhaust tube of this vehicle then was plugged to maintain the inert atmosphere of carbon dioxide in contact with the solution. A quick-disconnect coupling that functioned as a valve allowed very little spillage when the filling tube was disconnected from the vehicle fluid compartment.

After payload filling, the launchers were set at proper elevation and azimuth angles. Although simultaneous launchings at identical elevations and azimuths were originally desired, these requirements were relaxed somewhat. To prevent two vehicles from simultaneously being in the beam of any one radar, launch times and azimuth angles were varied slightly. In order that the trails of the two southernmost vehicles, whose launch sites were very close to each other, would not be so near to each other that distinguishing between them on the photographic records would be difficult, launch azimuths of these vehicles were varied by 8°. Based on past experience, it was assumed that varying azimuth by this amount would not cause any significant difference in the altitude reached by these vehicles. Also it was assumed that atmospheric conditions would not change enough in 10 seconds to appreciably alter any visible characteristics of the trails.

Launch azimuths of the vehicles were: 90° for the northernmost vehicle containing P/CS_2, 90° for the vehicle containing FS, and 98° for the southernmost vehicle containing FM. The launch elevation angle was 74.8° for all three vehicles, and all were fired from zero-length launchers for consistency in launch conditions. Starting with the northernmost vehicle and proceeding to the next one southward, one was launched every 5 seconds.

Information desired for evaluation of these flight tests was obtained from time-sequence photographs, radar magnetic tape, and rawinsonde data.

Sequential (every 6 seconds) simultaneous photographs of the trails were taken from two camera sites located at bearings from the launch site approximately 90° apart and at distances from the launch sites of approximately 10 miles. Experience to date indicates that a practical time span, insofar as accuracy in determining wind velocity, from these sequential photographs is 0.5 to 1 minute. Negatives which show the smoke trails more clearly than positives printed therefrom were read directly in obtaining wind velocity profiles. A detailed description of the photographic equipment and technique which yield wind velocity profiles and altitudes of points in the smoke trail are given in reference 1. Brightness of different trails or portions of each trail can be compared by means of photographs taken by any one of these cameras. In addition, persistence of a trail can also be determined from the time sequence photographs.

Magnetic tape which recorded data from FPS-16, SCR-584, and modified SCR-584 radars was processed to provide vehicle azimuths, elevations, and slant ranges as functions of time. This information was in turn used to compute altitudes and horizontal ranges as functions of time. Humidity, temperature, and relative humidity as functions of altitude were obtained from the rawinsonde record.

RESULTS AND DISCUSSION

HC Ground Test Results

The mixture HC, which in smoke devices is a compressed solid, generates gases and particles by surface burning. These particles upon exposure to atmospheric moisture produce smoke. This surface burning is a process similar to that occurring in solid-fuel rocket motors to produce propellant gases. Movement, cracking, or crumbling of HC could cause erratic burning, quench the burning, or cause nozzles to clog, which in turn could cause rupture of the container due to pressure buildup. Therefore, to be used aboard a vehicle in flight, the shape of the HC charge or charges and support therefor would have to be such that no movement or crumbling of HC would result from the high accelerations encountered aboard such a vehicle. This requirement and the limitation as to maximum depth of HC from the initial burning surface that would insure that all of it burned within the desired flight time would necessitate many small charges of HC. Since each of these small charges would require individual ignition, payload development began with ignition tests of HC charges of about the same size as the small blocks of HC which would be required for the payload. During many tests it was observed that ignition was random and that there were inconsistent delays between time of ignition and time that smoke was produced at the desired rate. In addition, burning rate showed no consistent variation with packing pressure. Also, it became apparent that a device necessary to provide ignition would impose a considerable weight penalty. Further, clogging of nozzles by a gummy by-product of burning was encountered. Because of these difficulties and the prospects of future difficulties that would be encountered in developing a payload employing HC to form smoke, it was decided to abandon HC as a potential payload.

Flight Test Results

The flight test results which are reported herein were directed toward the remaining materials of those originally considered: FS, FM, and P/CS_2.

Trail brightness.- The most important criteria for evaluation of the smoke trails was ability to be photographed. Factors affecting this visibility are the same as those influencing visibility. A summary of factors influencing the visibility of smoke trails is presented in appendix B.

Each of the fluids produced a trail which behaved uniquely as evidenced by comparison of figures 2(a) to 2(j) which are positive photographs of the trails from the right-hand camera site when viewed from the launchers. Although positives do not show the trails as well as the original negatives, they are presented herein for a qualitative comparison of the smoke trails. These photographs began with the time at which the vehicle expelling P/CS_2 was approximately at apogee and continued for a total interval of 4.5 minutes. From left to right the trails were produced by P/CS_2, FS, and FM, respectively.

At the time of vehicle apogee, P/CS_2 trail was bright throughout the entire length thereof, which began at the point where the vehicle started to decelerate as a result of rocket-motor burnout. At no time when this fluid was being expelled was there any noticeable delay before the trail was formed at point of expulsion. Each portion of this trail was of maximum brightness immediately after formation. Bright flame, indicative of intense combustion, was observed during the entire period of expulsion. If this fluid were expelled from a vehicle at an altitude where moisture content is insufficient for formation of trails from FS or FM, this vehicle could likely be visually detected and tracked because of the intense flame as well as the smoke trail produced.

Shortly after formation, the trail produced by FS showed an abrupt change from good visibility at lower altitudes to poor visibility (faintly visible on photographs) at higher altitudes. (See fig. 2(a).) Also, it can be seen in this figure that the lowest point visible in the FS trail is higher than the lowest point visible in the P/CS_2 trail.

The FM trail, shortly after formation, displayed characteristics similar to the FS trail; the most apparent exception being that the altitude at which an abrupt change in visibility of the upper end of the trails occurred was higher for FM than for FS. (See fig. 2(a).) The lower portion of the FM trail was very similar to the FS trail and the lowest point in each trail which could be used for determining wind velocity was at approximately 13,000 feet altitude. This altitude is considerably higher than the normal burnout altitude (approximately 6,000 feet) of these vehicles and consequently higher than the minimum altitude at which wind velocity is desired.

By the time the three vehicles had reached apogee (approximately 1.0 minute after launch) overall brightness of the trail produced by P/CS_2 was superior to that of the other two. Neither of the other trails ever achieved this brightness. Afterward, brightness of this trail decreased while that of the FM trail increased and at about 1.5 minutes subsequent to the three vehicles being approximately at apogee, brightness of these two trails was approximately the same. When the last photograph, figure 2(j) was taken (about 3.0 minutes later), the FM trail was much brighter than the P/CS_2 trail. The FS trail was never as bright as either of the other two.

Trail persistence.- In addition to brightness, another important factor for comparison and evaluation of smoke trails is persistence interval, which may be defined as the length of time that a trail is of sufficient brightness to photographically determine wind velocity.

Since wind velocity measurements are usually obtained from two exposures 30 seconds apart, a minimum persistence interval of 30 seconds is required. It is desired that a trail have this persistence interval over the entire altitude range from vehicle burnout to apogee. However, limited wind velocity measurements may be made if a trail has adequate persistence interval for only a portion of the desired altitude range.

To determine persistence intervals, initial and final points must be established. As has been previously indicated, the P/CS_2 and FS trails did not appreciably increase in brightness after $t + 1.0$ minutes (t is approximate launch time for all vehicles), and this is the earliest time for which it can be established that each of these trails has good brightness. Therefore this is the proper initial time to use for determining persistence interval of these trails. Brightness of the FM trail exceeded that of the trail formed by P/CS_2 after about $t + 2.5$ minutes. However brightness of the P/CS_2 trail was still sufficient to make wind velocity measurements until the last photograph (fig. 2(j)) was taken at approximately t + 5.5 minutes. Thus, this trail had a persistence interval of at least 4.5 minutes. Of the FS trail, only a portion at low altitude and a small portion at apogee were apparent in the final photograph. Brightness of the upper portion of the trail formed by FM gradually changed from very poor at t + 1.0 minute to very good at later times. The earliest time at which the entire trail was sufficiently bright was at about t + 2.0 minutes (fig. 2(c)). Thus, this would be the appropriate initial time for measuring persistence interval of this trail. This trail was very bright when the last photograph was taken and through visual observation it was noted that this trail was of good brightness for several minutes thereafter. Consequently, persistence interval of the FM trail was greater than that of the P/CS_2 trail. However, it should be noted that the maximum persistence interval ordinarily required is 1 minute. Movement of this trail from time of vehicle apogee to initial point of persistence interval for the complete trail is such that apparent loops in the trail and superposition of some of the trail over other portions occurred. This superposition can cause errors in measuring wind velocity with this trail. Therefore, the property of the P/CS_2 trail being bright over the entire altitude range at time of vehicle apogee compared with that of the FM and FS trails to have poor brightness over a large portion at the corresponding time is a distinct advantage.

Atmospheric effects.- By correlating quality of the three trails to relative humidity at corresponding altitudes (fig. 3) it can be seen that the altitudes where FS and FM formed no trails, poor trails, or were slow in forming adequately bright trails, coincided with altitudes where relative humidity was low. However, since there is no correlation between quality of the P/CS_2 trail and relative humidity it is apparent that little or no moisture is necessary for trail formation from P/CS_2. This fact can be substantiated by referring to the chemical equations presented previously.

The shapes or patterns of the trails, which were produced by winds encountered, showed remarkable similarity. This similarity can be seen by comparing corresponding portions of all three trails on any photograph of figure 2, and would seem to strongly indicate that response of the smoke trails to wind is nearly perfect as had been assumed earlier.

Vehicle performance.- Trajectories of the vehicles which produced the three trails are shown in figure 4. In this figure it can be seen that the vehicle which expelled P/CS_2 achieved a considerably higher altitude than either of the other two vehicles. As previously mentioned, a bright flame could be seen issuing aft of this vehicle. It is probable that the energy from combustion of P/CS_2 was sufficient to significantly decrease the pressure differential between the low pressure base region and the relatively high pressure region in the adjacent free stream. Therefore the drag of this vehicle was appreciably reduced enabling the achievement of a higher altitude.

Operational Considerations

In addition to the discussion of the results of the flight tests and ground tests, it should also be pointed out that FS and FM were used as received and required only a few man-hours for adding to appropriate vehicles, whereas considerable time and effort were necessary to prepare and load P/CS_2. Also, the nature of the materials handled in preparation of P/CS_2 required the presence of safety personnel and equipment which were not required for the other two fluids used.

CONCLUSIONS

Flight tests employing three chemical smoke-producing agents have been conducted under essentially identical conditions of lighting, sky background, moisture, and vehicle flight environment. Three vehicles carrying phosphorus/carbon disulfide (P/CS_2), titanium tetrachloride (FM), and FS (a solution of sulfur trioxide in chlorosulfonic acid) were launched nearly simultaneously (5 seconds apart). Analysis of photographs of the trails produced by the three fluids along with flight preparation experience and ground tests of pyrotechnic mixture, HC, has resulted in the following conclusions:

1. The mixture HC is not a suitable material for flight usage in the production of a smoke trail for wind-shear measurements.

2. Of the three materials, P/CS_2 formed the brightest trail.

3. Brightness of the FM trail was greatest after about 2.5 minutes subsequent to the time of vehicle apogee and greater than that of the P/CS_2 trail after about 1.5 minutes subsequent to vehicle apogee.

4. Both P/CS_2 and FM produced trails of good visibility well in excess of the minimum persistence interval required; the P/CS_2 trail showing necessary persistence for at least 4.5 minutes and the FM trail interval being somewhat longer.

5. The FS trail never attained the brightness of the other two trails and, except for a small portion at apogee, was not visible at high altitude.

6. The solution, P/CS_2, demonstrated the advantages over the other fluids of forming a satisfactory trail irrespective of moisture conditions, and forming a trail more rapidly.

7. Use of P/CS_2 requires additional safety measures and preparation that are not associated with the use of FS or FM.

8. The agent FM has a tendency to clog tubing, whereas the other two fluids do not.

9. The three simultaneously produced trails exhibited identical shape variation with altitude, thereby verifying the previous assumption that the response of a smoke trail to wind movement is nearly perfect.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 20, 1964.

APPENDIX A

DESCRIPTION OF PROCEDURE FOR PREPARATION OF PHOSPHORUS/CARBON DISULFIDE SOLUTION

Phosphorus was poured from the metal cans, in which it had been immersed in water, into the dissolving tank (fig. 5) which also contained enough water to cover the phosphorus. Except for the brief time required for it to fall, the phosphorus was contained in an inert medium from the time it was received until it was expelled to form a smoke trail.

After all the phosphorus had been poured into the dissolving tank, the port through which it had been poured was closed. A carbon dioxide cylinder was then connected to the dissolving apparatus which was checked for leaks with the carbon dioxide pressure at about 5 pounds per square inch gage. When it had been ascertained that there were no gas leaks, the dissolving apparatus, which included the tank and all piping connected to it, was purged of air by allowing carbon dioxide to flow through the system for several minutes. Water, which would have interfered in the dissolving of phosphorus in carbon disulfide, was then drained from the tank after which carbon dioxide flowed throughout the tank then out the drain pipe until the phosphorus appeared to be dry. Next, carbon disulfide was poured into the closed funnel which was subsequently purged of air by allowing carbon dioxide to flow through it. Carbon disulfide then was drained into the tank to begin dissolving phosphorus after which the basket containing solid phosphorus within the tank was intermittently agitated until all traces of solid phosphorus disappeared. The solution was kept in the dissolving tank pressurized to about 5 pounds per square inch gage with carbon dioxide until the solution was added to the vehicle just prior to launch.

APPENDIX B

FACTOR AFFECTING SMOKE-TRAIL VISIBILITY

In general, visibility of a smoke trail depends on angle of subtense of trail, brightness of trail, brightness of sky background, and obscuration of the trail by the atmosphere between trail and observer.

From a given observation point, the angle of subtense of the trail is a function of the diameter of the trail. For instance, at an altitude of 200,000 feet a trail 1 foot in diameter subtends an angle of 1 second to an observer on the ground directly below it.

The brightness of a trail depends upon the particle density, which is defined as the number of particles per unit volume of the trail, and the size distribution of these particles. It is assumed that particle size distribution is not influenced by particle density and that particle density varies linearly as the amount of smoke-producing agent dispensed per unit volume. Particle size distribution affects the brightness of a trail because light-scattering ability of these particles varies with size. Generally, the maximum scattering efficiency is obtained from particles equal in size to the wave length of the incident light. Thus, particles of a uniform size of about 0.7 micron would appear red and particles about 0.4 micron would appear blue. These phenomena are approximated in nature by the normally blue sky and the red sunset. Since sunlight, the illumination for the sky and the smoke trails, consists of light of many wave lengths, no particle size has maximum efficiency for scattering every component of this illumination. However, particles with a diameter of 0.55 micron (ref. 3) to 0.6 micron (ref. 4) are the most efficient particle size for scattering incident light of the composition of sunlight. Visible light has wave lengths in the approximate range of 0.4 to 0.7 micron, and it is considered that particles in this same size range have very good light-scattering ability. However, because of the high viscosity and surface tension of fluids used for producing smoke trails, particles in the smoke trails are of such size distribution that a large percent of these particles are much larger than the most efficient size for scattering light.

Neglecting varying atmospheric conditions (such as haze) and assuming a standard value for sun illumination, brightness at any point in the sky, as observed from any point on earth, may be computed as a function of the elevation angle of the sun. Table II of reference 4 presents sky brightness as a function of sun elevation angle at a point in the sky with elevation of 30°, the sun being at an azimuth angle 45° from the point and sun illumination being 12,700 foot-candles. This point is referred to as target point. Brightness of sky at target point as a function of sun elevation angle is repeated in columns 1 and 2 of table I of this report. This table shows that the brightness of the target point increases as the angular distance of the sun from the point decreases and it is assumed that this behavior also pertains to any point in the sky. The lowest sun elevation listed in the table, -6°, is the lowest at which the sun would illuminate a smoke trail at an altitude of 60,000 feet.

Trail brightness and background brightness are often not considered as two separate properties, but are considered to jointly determine the property known as brightness contrast which is defined by $C = (B_t - B_b)/B_b$ where B_t and B_b are trail brightness and background brightness, respectively. Figure 6, obtained from reference 4, presents the relation between brightness contrast and angle of subtense necessary for visibility of bright-line targets as determined from laboratory tests. Smoke trails usually appear as bright-line targets. At brightness contrasts greater than zero, the line target is brighter than the background, and for brightness contrasts less than zero, the background is brighter than the line target. From the figure it can be seen that at angles of subtense less than approximately 0.3 second, the brightness contrast necessary for visibility increases rapidly as angle of subtense decreases. Also, at angles of subtense greater than 0.8 second, the brightness contrast necessary for visibility is low and decreases slowly as angle of subtense increases. Under adverse conditions encountered in field tests (ref. 3), higher contrasts were necessary for visibility at a particular angle of subtense than were necessary under laboratory conditions. However, it is considered that these two cases represent extremes for visibility requirements. According to reference 3, a trail subtending an angle of 1 second should be visible to the naked eye if the contrast were 4 or more. Assuming that a brightness contrast of 4 is necessary and substituting in the formula $C = (B_t - B_b)/B_b$, brightness B_t necessary for a trail to be visible at the target point of table I may be computed as a function of elevation angle of the sun. Values of brightness B_t so computed are presented in column 3 of table I. Considering the reflectivity of the trails to be 100 percent, these trail brightness values may be divided by the sun illumination to compute the percent backscattering needed for trails, under the same illumination conditions as the target point, to be visible when the sun is at the various elevations listed in column 1. These percentages are listed in column 4 of table I. Since light-scattering ability or brightness of a trail depends on the particle density of the trail or weight of smoke chemical dispensed per unit volume, the advantage of a predawn firing can be seen from column 4 of table I if it is desired to minimize the weight of chemicals used for producing visible smoke trails.

So far, only the efficiency of particles as light scatterers has been discussed with no mention of direction of scatter. However, in general, it can be said that with the sun in the same general direction as the smoke trail, forward scattering is desirable, and, with the sun behind the observer, backscattering is desirable. In viewing a square centimeter of smoke consisting of particles approximately 0.6 micron in diameter and numbering less than 10^6 behind the square centimeter, light will be scattered more strongly in the forward direction than in the backward direction, according to reference 3. When this number (of particles) is exceeded, secondary scattering becomes appreciable, and the forward component decreases, while the backward component increases. When the number of particles behind 1 square centimeter is of the order of 10^8, 90 percent of the light is backscattered, and when this number is 10^9, 100 percent of the light is backscattered.

Obscuration by the intervening medium between the trail and the observer can be attributed mainly to haze. It is assumed that this haze consists of particles which are about the same size as fog particles, or an average of 0.5 micron. This size is approximately as efficient in light scattering as the size for which scattering efficiencies are given; thus whenever the number of particles behind 1 square centimeter of area appreciably exceeds 10^9, a smoke trail of infinite brightness could not be seen through this area.

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TABLE I.- LIGHT-SCATTERING REQUIREMENTS FOR A SMOKE TRAIL

SUBTENDING AN ANGLE OF 1 SECOND

[Target elevation, 30°; azimuth angle of sun, 45°; sun illumination, 12,700 foot-candles]

1 Sun elevation, deg (a)	2 Sky brightness, B_b, foot-lamberts (a)	3 Required smoke brightness, B_t, foot-lamberts (b)	4 Required scattering of incident light, percent
-6	0.3	1.5	0.012
-3	12	60	.47
0	72	360	2.84
3	207	1035	8.15
5	314	1570	12.4
15	660	3300	26.0
30	1050	5250	41.3
60	675	3375	26.6
90	552	2760	21.7

[a]From reference 4.

[b]For brightness contrast of 4.

TABLE I.- LIGHT-SCATTERING REQUIREMENTS FOR A SMOKE TRAIL

SUBTENDING AN ANGLE OF 1 SECOND

[Target elevation, 30°; azimuth angle of sun, 45°; sun illumination, 12,700 foot-candles]

1 Sun elevation, deg (a)	2 Sky brightness, B_b, foot-lamberts (a)	3 Required smoke brightness, B_t, foot-lamberts (b)	4 Required scattering of incident light, percent
-6	0.3	1.5	0.012
-3	12	60	.47
0	72	360	2.84
3	207	1035	8.15
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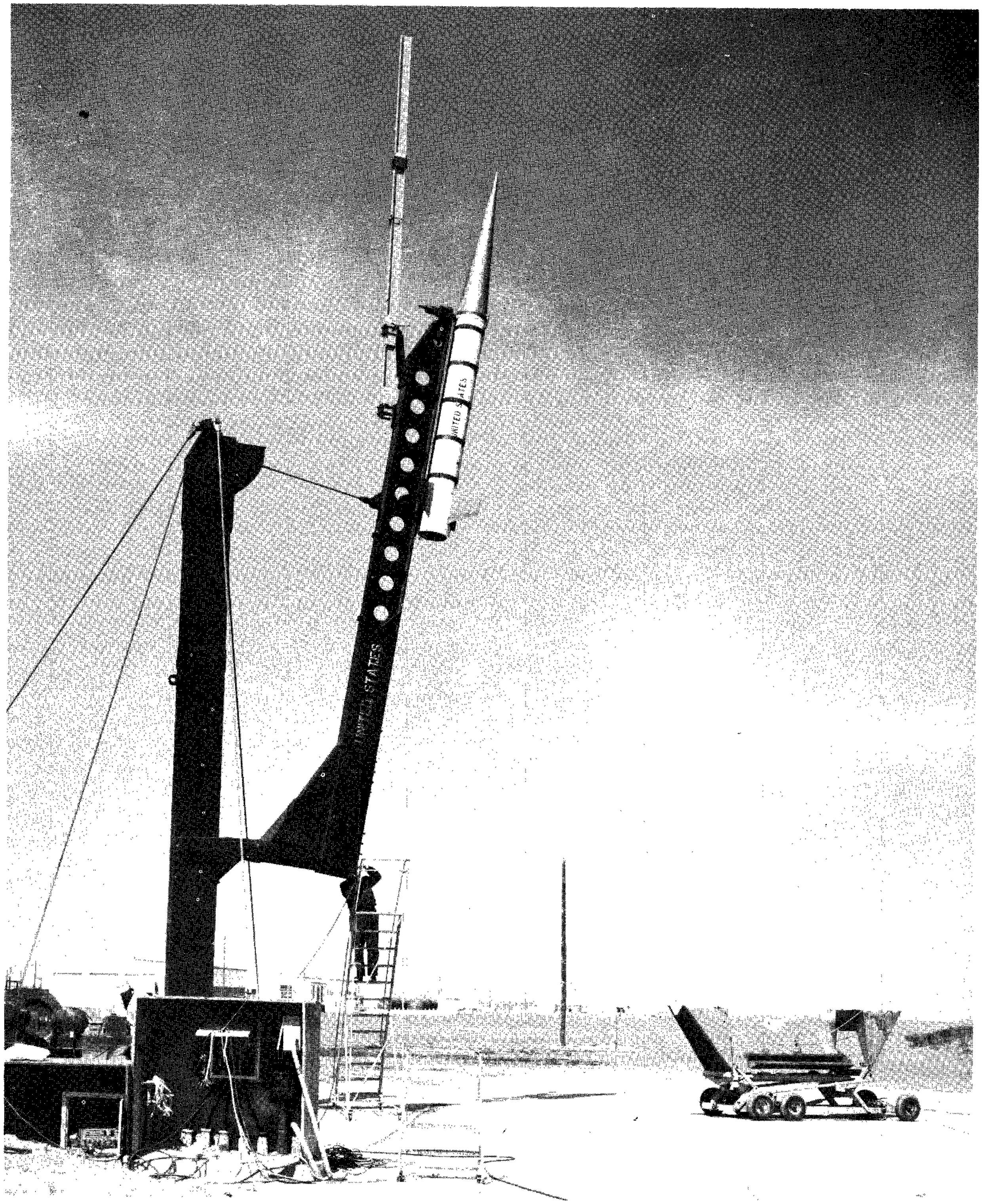
15	660	3300	26.0
30	1050	5250	41.3
60	675	3375	26.6
90	552	2760	21.7

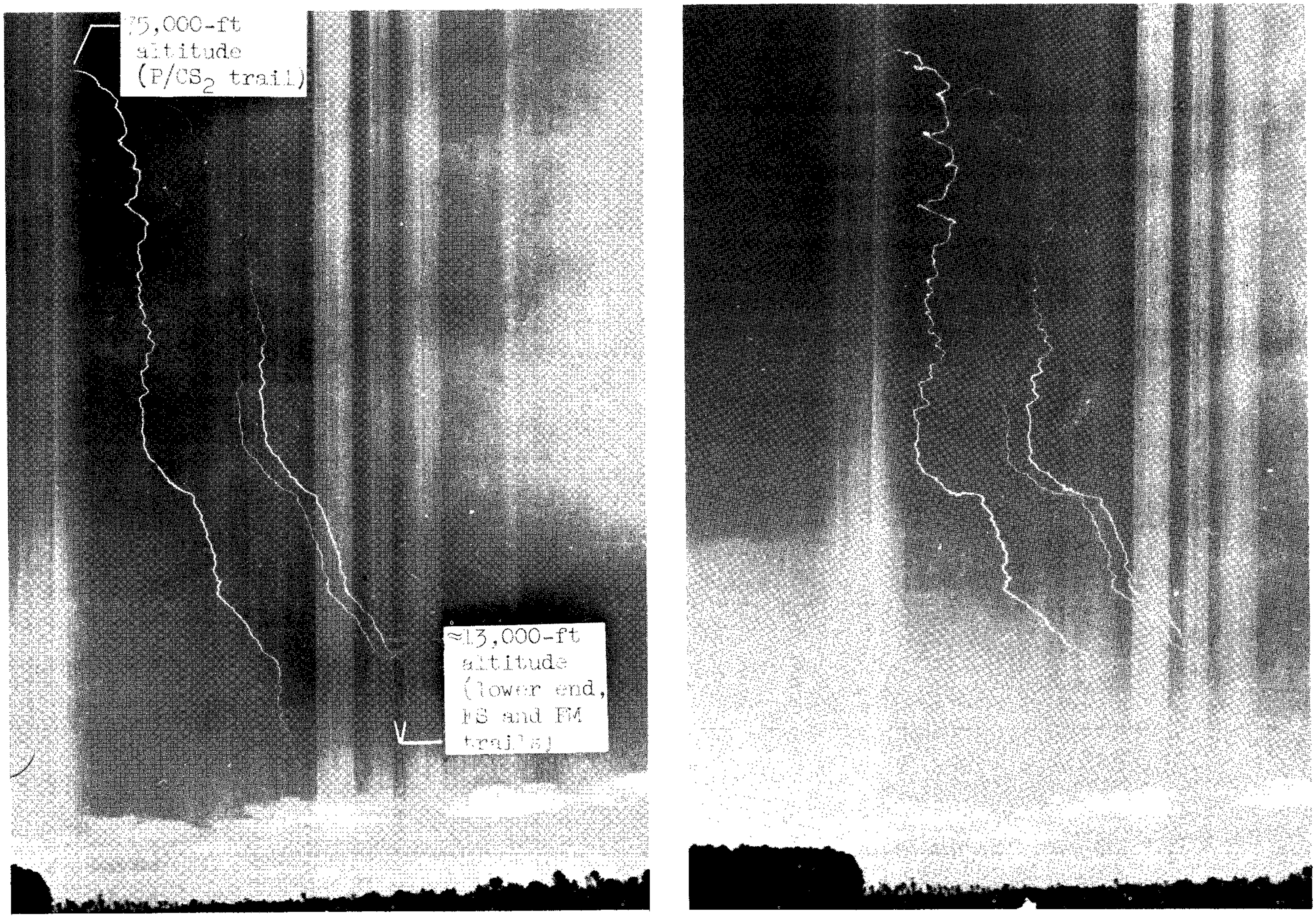
[a]From reference 4.

[b]For brightness contrast of 4.



L-63-3959

Figure 1.- One of three externally identical smoke-producing vehicles on launcher.



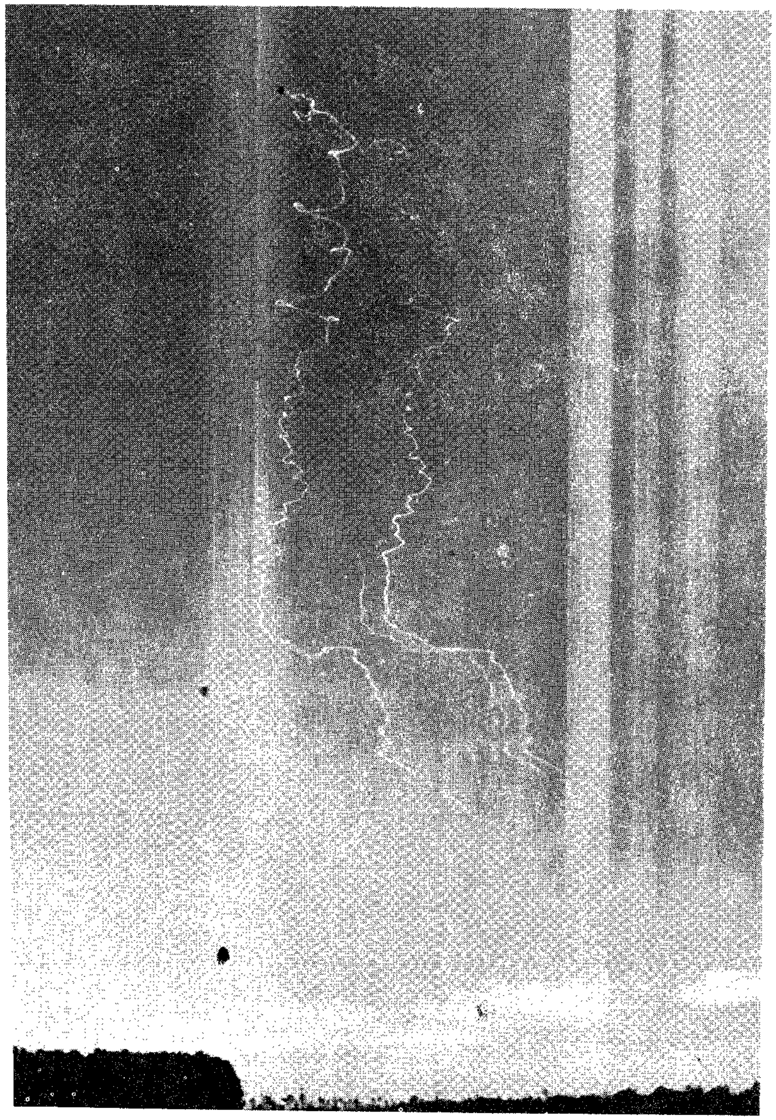
L-64-3059

(a) All vehicles approximately at apogee about 1 minute after vehicles were launched.

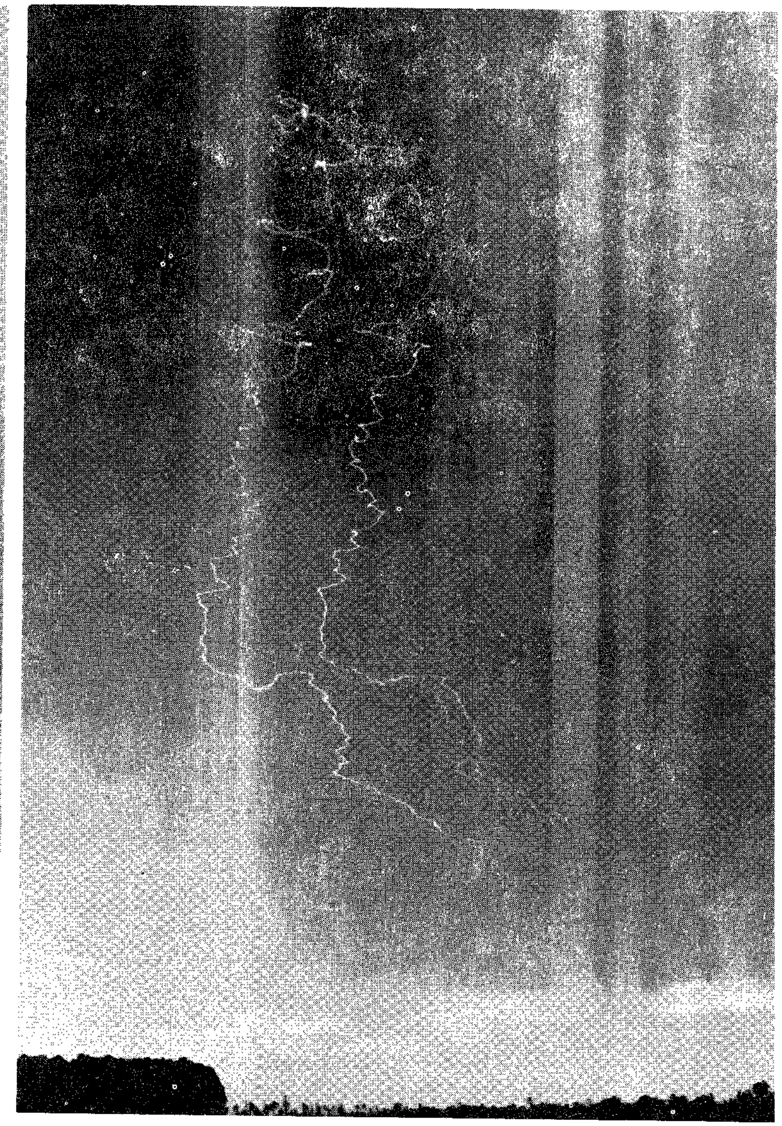
L-64-3060

(b) Approximately 1.5 minutes after launch.

Figure 2.- Sequential photographs of 3 smoke trails produced simultaneously from left to right by P/CS_2, FS, and FM, respectively.

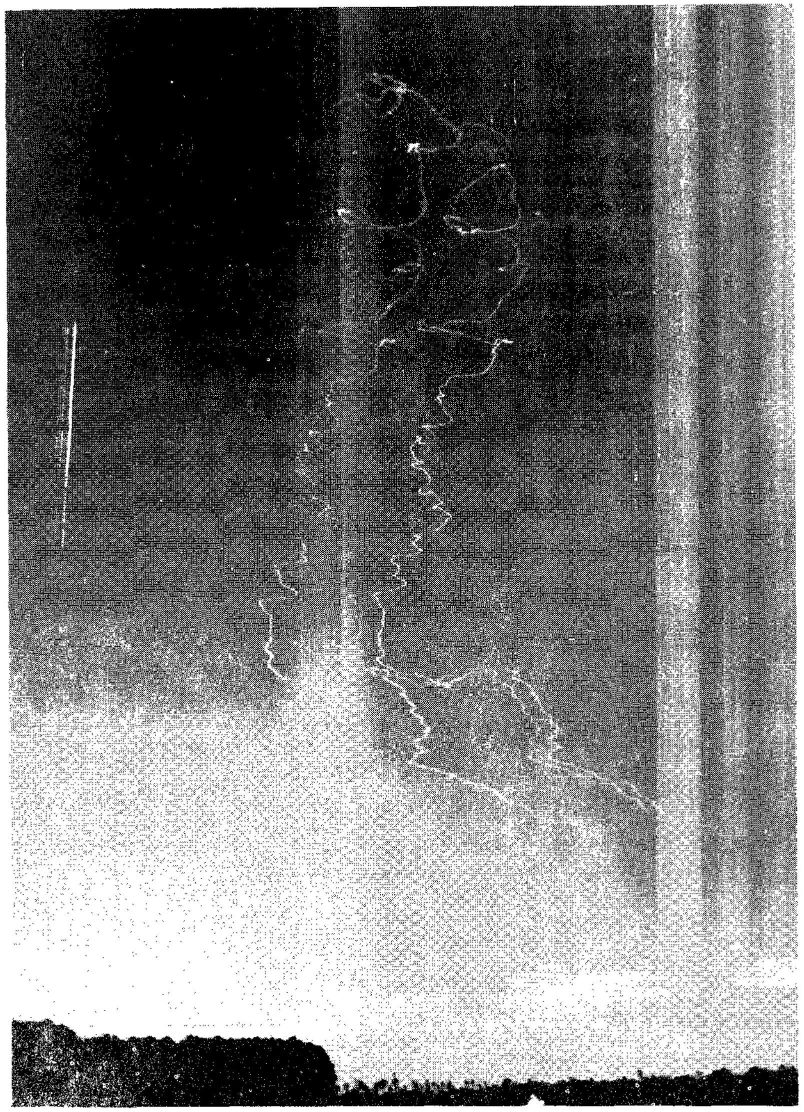


L-64-3061
(c) Approximately 2.0 minutes after launch.

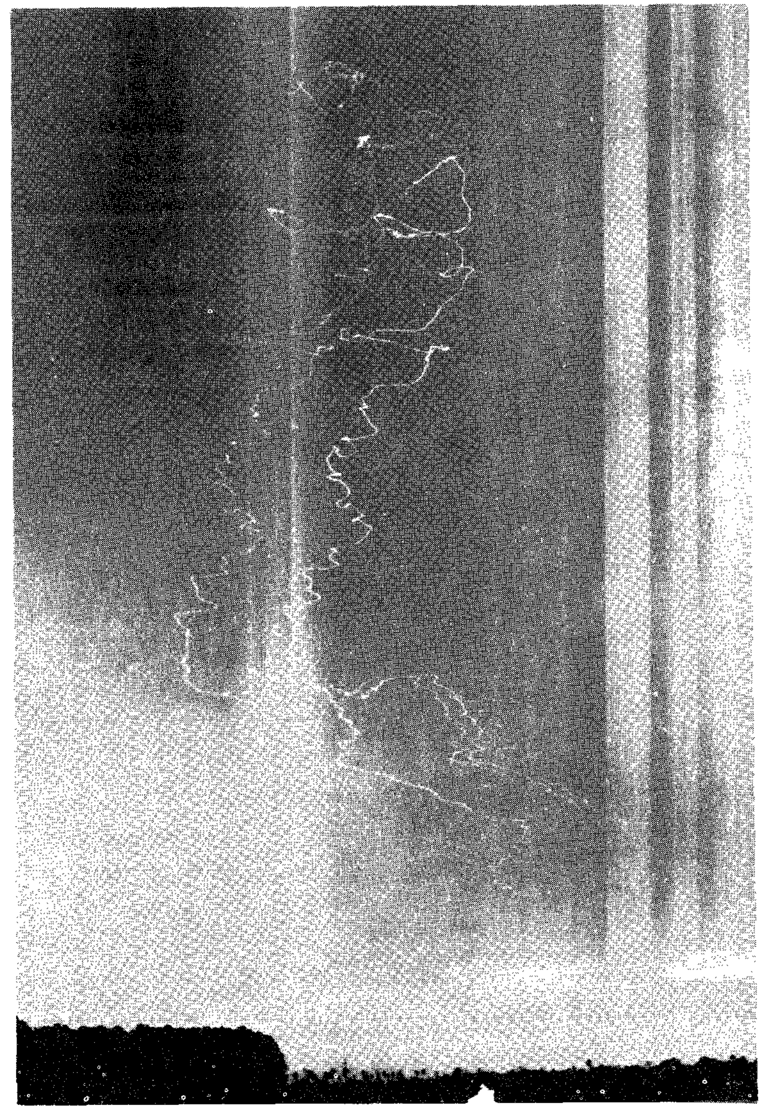


L-64-3062
(d) Approximately 2.5 minutes after launch.

Figure 2.- Continued.

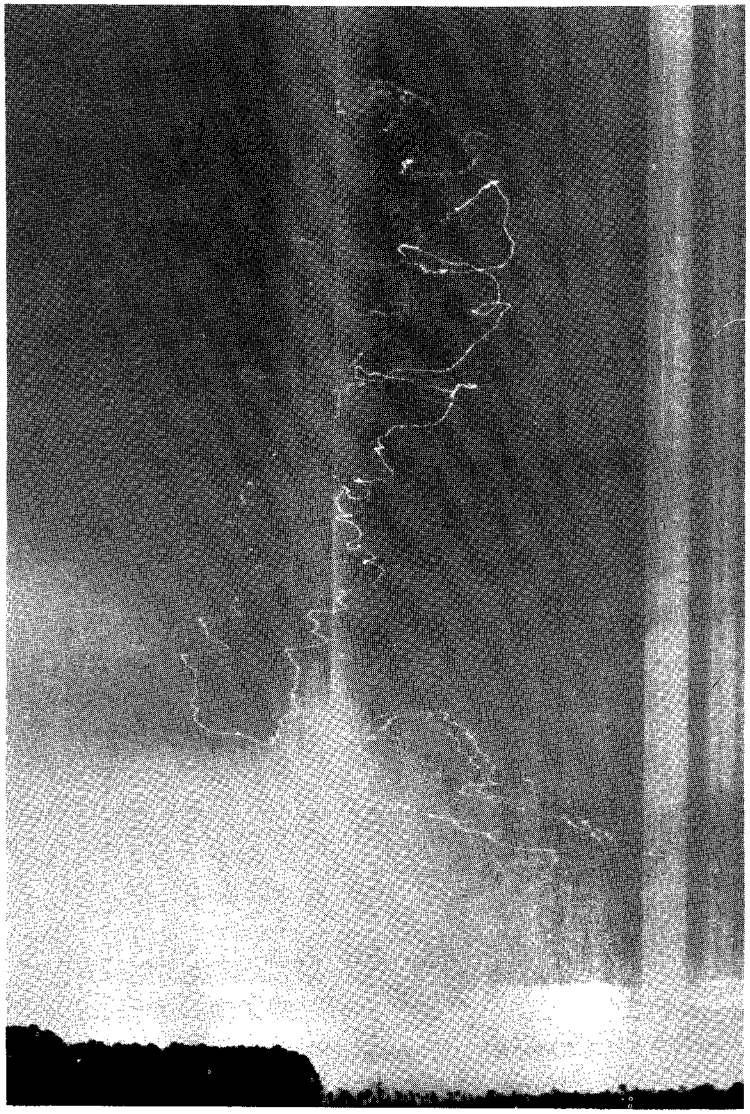


L-64-3063
(e) Approximately 3.0 minutes after launch.

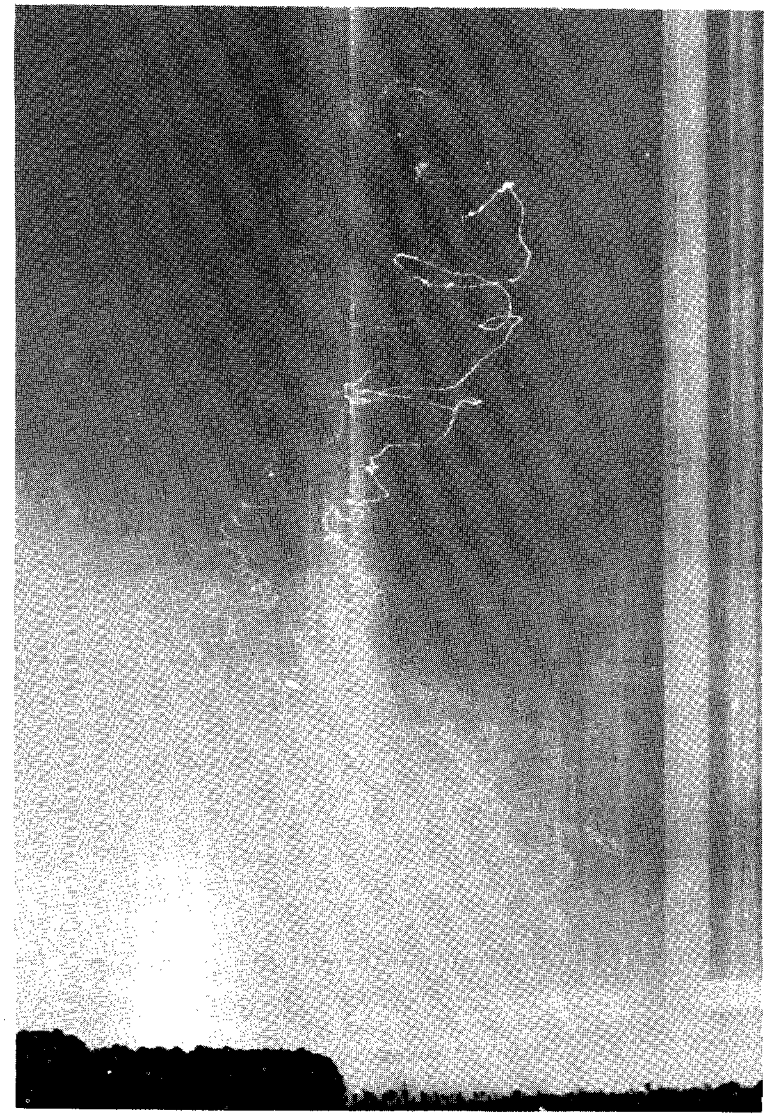


L-64-3064
(f) Approximately 3.5 minutes after launch.

Figure 2.- Continued.

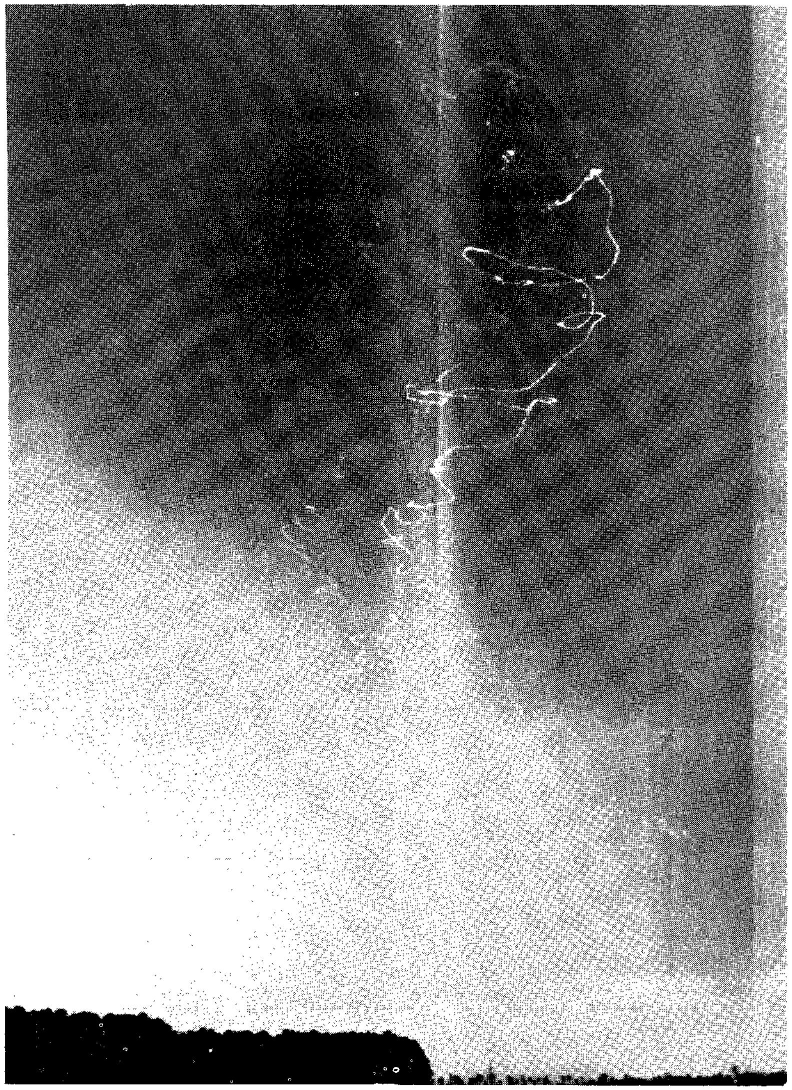


L-64-3065
(g) Approximately 4.0 minutes after launch.

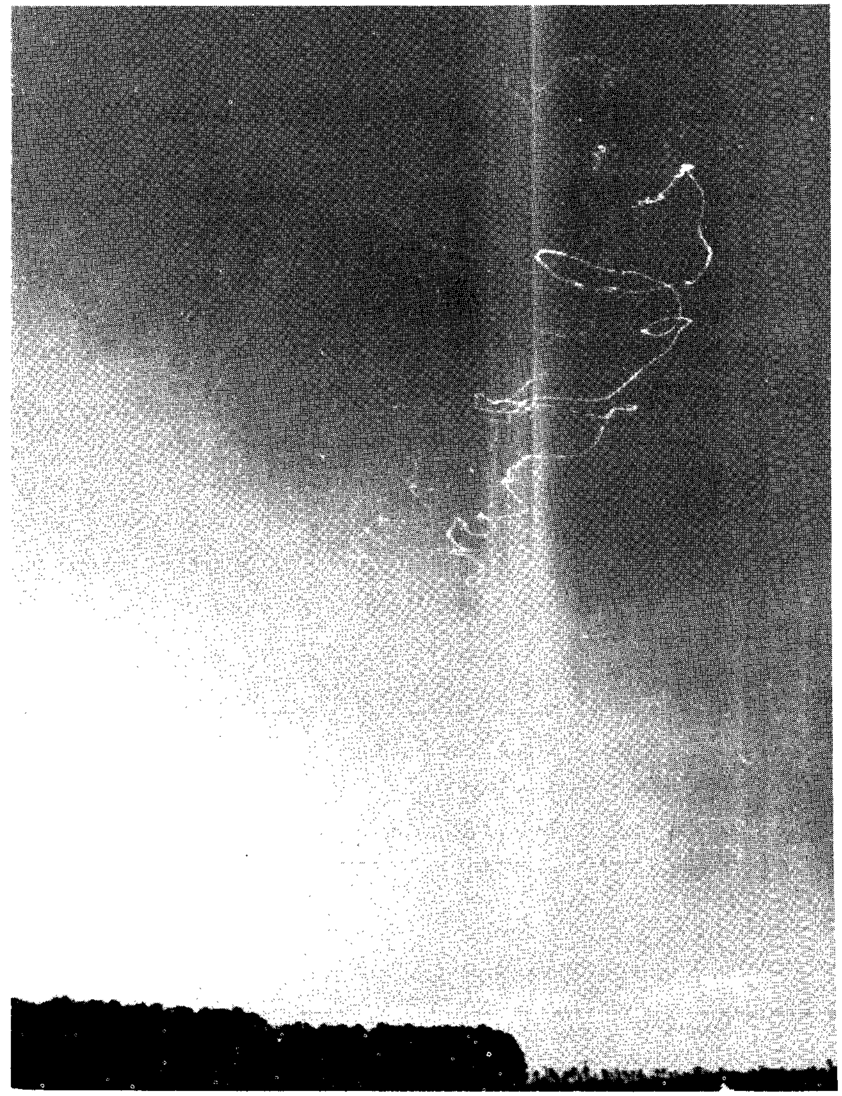


L-64-3066
(h) Approximately 4.5 minutes after launch.

Figure 2.- Continued.



L-64-3067
(i) Approximately 5.0 minutes after launch.



L-64-3068
(j) Approximately 5.5 minutes after launch.

Figure 2.- Concluded.

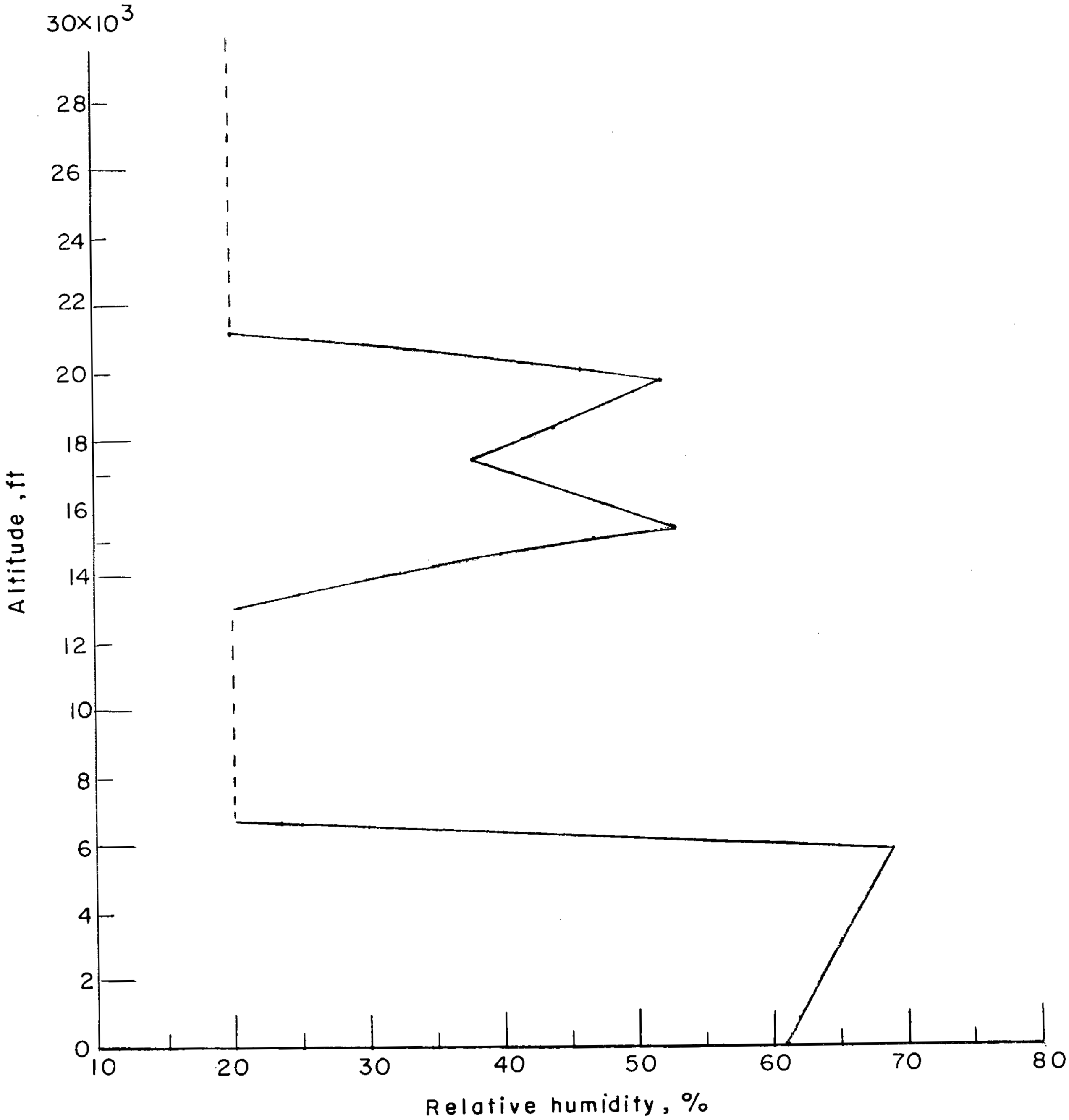


Figure 3.- Relative humidity as a function of altitude at time of vehicle flights. Relative humidity is below 20 percent in altitude range bounded by dashed line and at all altitudes above 21,200 feet.

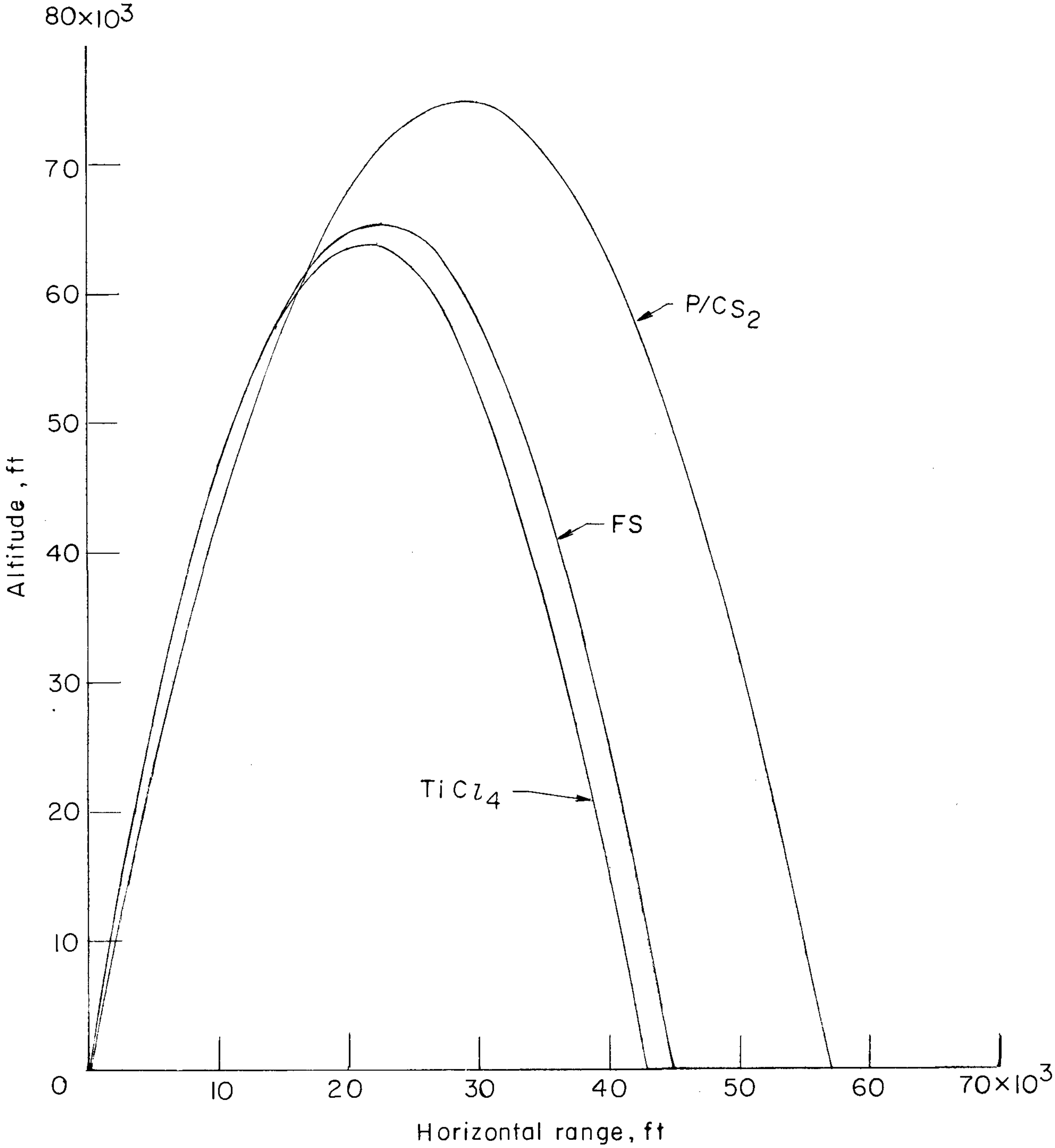


Figure 4.- Trajectories of three smoke-producing vehicles flown simultaneously with type fluid expelled from corresponding vehicle indicated.

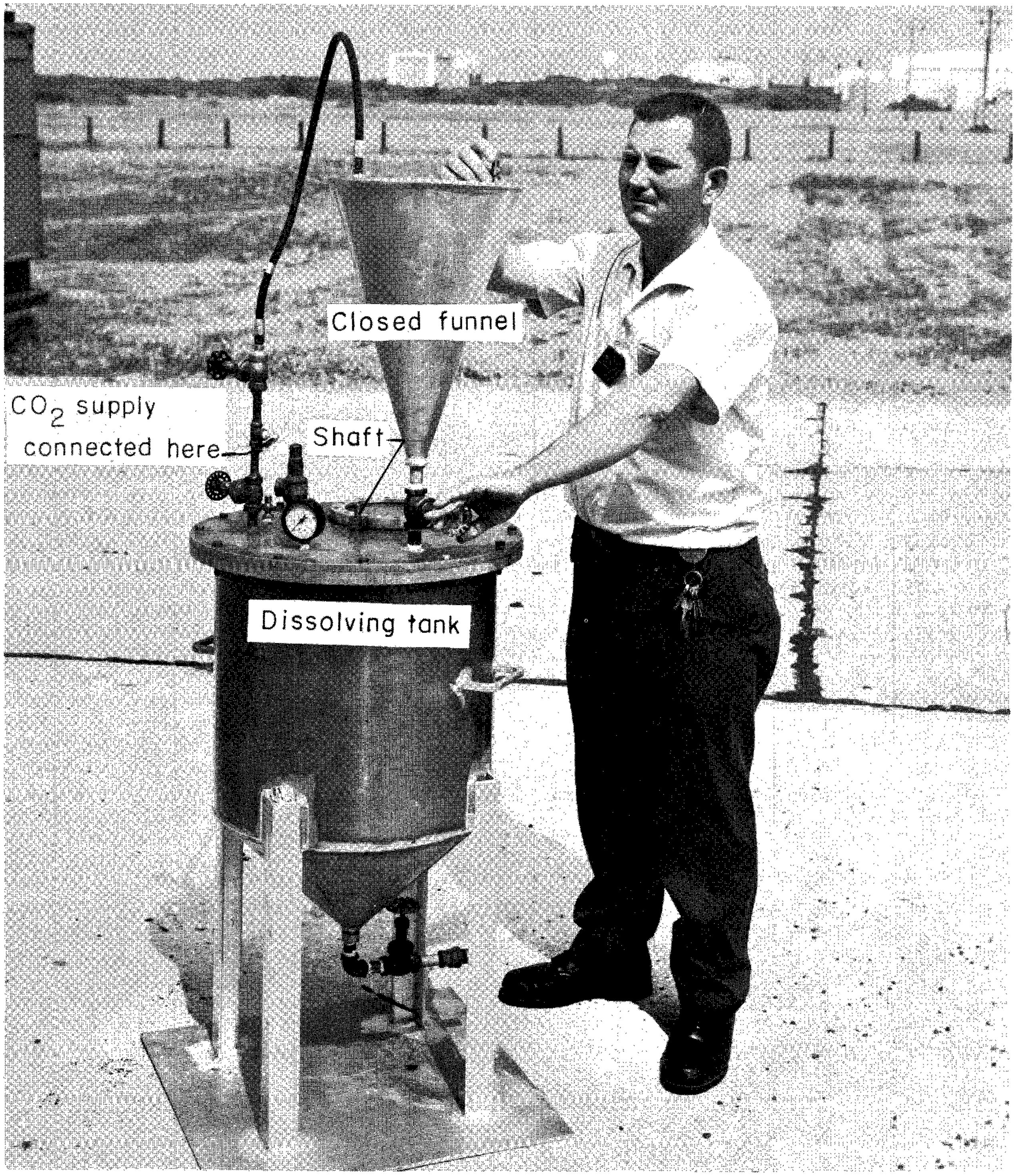


Figure 5.- Apparatus for dissolving phosphorus in carbon disulfide. L-63-7936

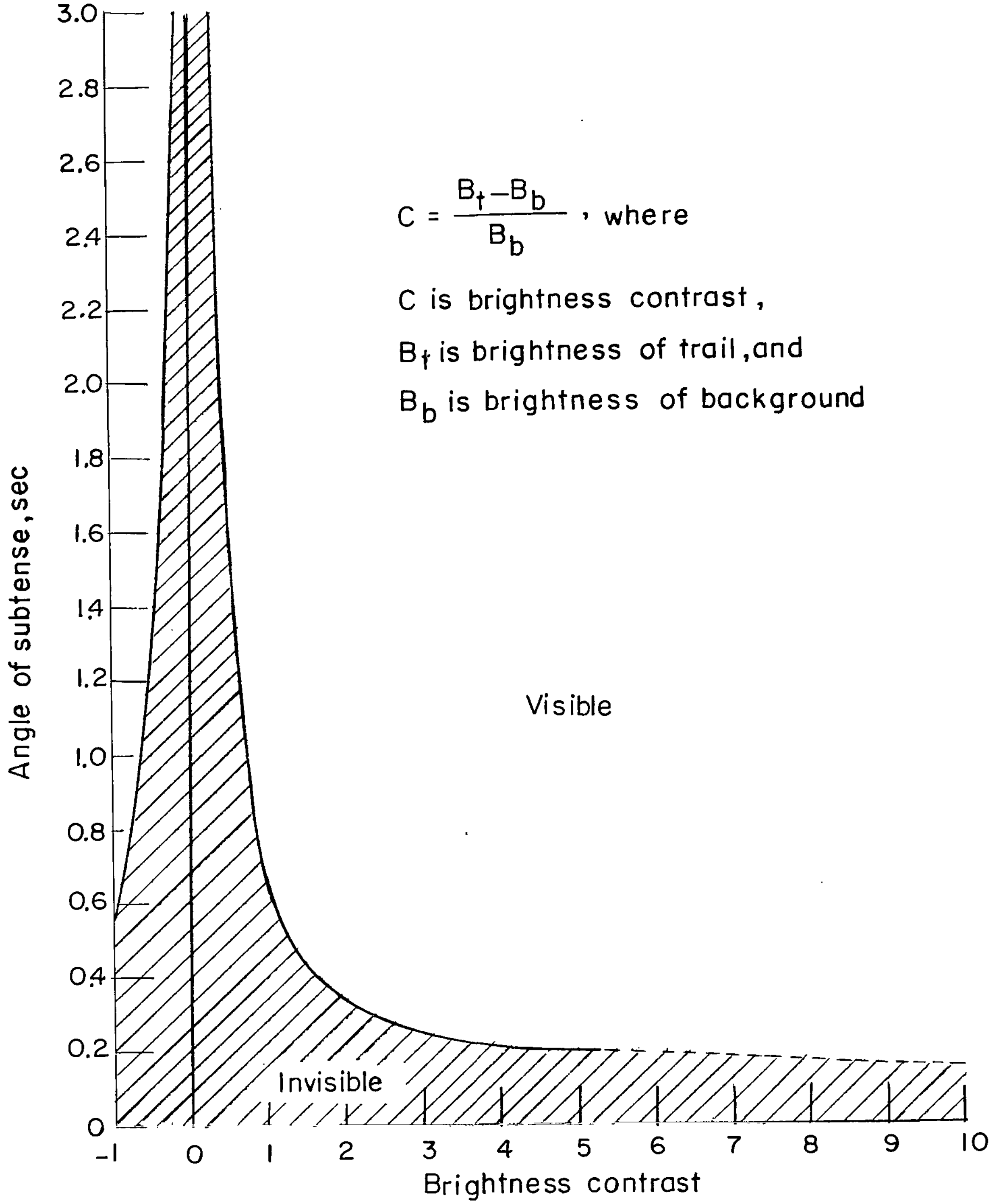


Figure 6.- Minimum brightness contrast and angle of subtense required for visibility of bright line targets under laboratory conditions. (From ref. 4.)

A motion-picture film supplement L-827 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 22 min, color, silent) shows the dissolving and loading of phosphorus plus the tracking of three simultaneously produced smoke trails.

Requests for the film should be addressed to:

Chief, Photographic Division
NASA Langley Research Center
Langley Station
Hampton, Va. 23365

C U T

Date ____________________

Please send, on loan, copy of film supplement L-827 to TN D-2277.

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City and State ____________________ Zip code

Attention: Mr. ____________________

Title ____________________

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07

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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