THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Meteorology and Oceanography

Final Report

SMOKE PLUME METHOD OF MEASURING UPPER WINDS

Contract Period May 6, 1966 - April 5, 1968

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I. INTRODUCTION

In October, 1965, the project director submitted an unsolicited proposal to the Department of the Army, White Sands Missile Range on the subject of "A Smoke Plume Method of Measuring Upper Winds." This outlined a three-stage extension of the technique he and his assistants had developed in 1960-62.[1] In May, 1966, the White Sands Missile Range issued a one-year contract in support of the proposed three-year study. The "Scope of Work" of this contract read as follows:

1. Expend efforts in improving the operational reliability of the titanium tetrachloride "smoke producing" rocket and extend the vertical range of the present system to its approximate height limit of 3000 to 4000 ft.

2. Concurrent modification to the rocket launchers to accommodate the improved rockets per above.

3. Develop a photographic system for sequentially recording the smoke plumes in three dimensions and the techniques in determination of wind speeds and directions vs. height, from this data.

4. Perform field testing of the complete system—rockets, rocket launchers, cameras, and data reduction techniques. This phase must be completed by tests performed at Lake Michigan and White Sands Missile Range. Tests should include multiple simultaneous firings of up to four rockets (spaced up to 1000 ft apart), followed by a second and third salvo at intervals of one to two min.

5. Investigate methods for generating "smoke trails" which are visible at night, thus extending the functional usefulness of the system at night as well as daytime operation.

6. Investigate and develop rapid analysis techniques.

7. Determine methods for obtaining temperature profiles concurrently with wind profiles obtained with above developed hardware.

8. Determine further necessary rocket modifications and launcher redesign to extend the useful height range of wind observations from 4000 ft to a minimum of 8000 ft.

In April, 1967, the funding and contract period was extended another eight months (2/3 year). The portion of the contract extension that is pertinent to this report read as follows:

"...the Government requires development of 'smoke trails' material visible at night and to extend 'smoke trail' wind profiles from 4000 ft to a minimum of 8000 ft."

In December, 1967, the contract period was extended an additional three months (to April 5, 1968) but with no addition of funds and no change in the "Scope of Work."

In the next section, the progress of research and development in each of the areas specified in the initial contract and in the contract extension is outlined.

II. RESEARCH AND DEVELOPMENT ACCOMPLISHMENTS

A. DEVELOPMENT OF A DEPENDABLE "SMOKE PRODUCING" ROCKET TO A HEIGHT LIMIT OF 3000 TO 4000 FT

The rocket selected for this phase of operations was the latest version of the rocket originally used by the project director in the development of the smoke rocket technique of 1960-62. This rocket was the Cricket, Model IV, Cold-Propellant Rocket, manufactured by Texaco Experiment Inc., Richmond, Virginia (see manual, TEI-71, May 1967 in SUPPLEMENTARY DATA).

Between 1962 and 1966 Texaco had developed, with the aid of Dr. Hay[2] the University of Western Ontario (London, Ontario) a liquid dispenser similar in principle to the titanium tetrachloride ($TiCl_4$) dispenser we had designed in 1963. Texaco advised that this liquid dispenser had been field tested and proven suitable for field use. Accordingly a number of the model IV rockets complete with liquid dispensers, and, four launchers were ordered from Texaco.

A photograph of the Cricket #4 Rocket fitted with the smoke canister payload is shown in Fig. 1. A rocket already in place in the launcher and being prepared for flight is shown in Fig. 2. A partially assembled smoke canister is shown in Fig. 3.

Briefly the operation of the smoke dispenser is as follows: The white plastic bottle is filled to the top with $TiCl_4$; and the valve mechanism is screwed onto the bottle as shown. The bottle with valve assembly is then inserted into the smoke canister base—shown in lower right of Fig. 3. The Ogive cap, is then lowered in place over its O-ring and fastened there by use of the Plexiglas locking ring shown in Fig. 3. (Several sizes of O-rings are used to seal the $TiCl_4$ and gaseous passageways.) Just prior to launching the system, the Ogive section is pressurized with gaseous CO_2 to a pressure of about 60 psi. (This operation is shown proceeding in Fig. 2.) Upon firing the rocket, an acceleration of about 70G was supposed to occur in the lower portion of the launcher causing operation of the inertial valve, which permitted the $TiCl_4$ to leave the valve system, pass into the canister base and thence to 3 jets at 120° locations around the base of the canister (Fig. 3). The rocket leaves the end of the launching tube at about 600 fps, fast enough to quickly break up the 3 fine streams of $TiCl_4$ into a single plume about 1 ft in diameter, see Fig. 4. In the next one or two sec the plume usually expands to between one and two ft in diameter due to the turbulence caused by the rocket, see Fig. 5.

In June, 1966, one month after issuing of the contract for this research, orders were placed with Texaco for the rocket launchers and rockets, with delivery promised for early August. Major delays occurred in the delivery of both the rockets and the launchers so that these were not available at The University of Michigan until late November, 1966. Since the firing of these small rockets at White Sands Missile Range would carry a very low priority rating, it was recommended that we arrange our tests at that location to occur in the last two weeks in December when the range is under nominal "shut-down conditions." In this way we would have much greater freedom for our firings. It was reluctantly agreed to make the first tests with the smoke rocket at the White Sands Missile Range during the period of December 12-28, 1966, without prior firings at The University of Michigan. In the tests conducted at White Sands, one overriding weakness showed up in the system—the unreliable operation of the smoke dispensing canister. All launchers operated satisfactorily and all rocket motors fired as planned. Several rockets were tracked to heights in excess of 3000 ft and generally the parachutes opened satisfactorily. By far the greatest weakness was in the design and operation of the $TiCl_4$ dispenser. Most of these weaknesses are described in Memorandum 1 of Supplement A.

During the next few months most of the problem areas were corrected and made to operate satisfactorily. The detailed efforts of our research and findings are given in Technical Notes 1, 2, and 3 of Supplement A. In Technical Note 4, "T-140 Valve Modifications and Their Affects on Launch Impulse Requirements" is given details of the concentrated attack on the problems of the Inertial Valve System. After redesign and laboratory testing, several full scale launches were made with the modified system. The operation was much less successful than expected—only about 40% reliability.

In view of the continued perplexing problems with the inertial valve the project director decided to set aside this system and return to the basic Plunger Valve System he had successfully used in the original smoke rocket. Details of this development are given in Technical Note 5 of Supplement A. A schematic drawing of his redesigned smoke canister is shown in Fig. 6. The basic operation of this system is as follows:

> In the upper view of Fig. 6 when the plastic bottle containing 200 cc's of $TiCl_4$ is pressurized to 60 psi by CO_2 gas, the $TiCl_4$ is kept from getting to the spray nozzles because of the small O-ring of the plunger valve. This valve is unable to move to the right due to the presence of the launch tube. Not until the rocket leaves the launch tube extension can this valve move out to its extreme position, as seen in the lower view of the figure, in which position of $TiCL_4$ can spray out the two spray nozzles located 180° apart.

Four smoke canisters utilizing the new plunger valve arrangement were fabricated. Only 10 firings of 3 of these modified valves have occurred. Nine of these firings were done in the daytime and one at night. The 9 daytime firings were 100% successful in the production of an adequate smoke plume. We are not certain if the one nighttime firing produced an adequate smoke plume or not, as the two remote photo flashes (7000 ft away) were much weaker than expected and no smoke plume was recorded. But upon rocket recovery the smoke canister appeared normal with the plunger in the pushed-out position and the plastic bottle collapsed. In view of this it is assumed that the nighttime firing was successful in the production of a smoke plume.

Thus 100% (or 90%) success has been had on the first 10 firings of the new smoke canister—a great improvement over the 30-40% success of previous firings. With careful manufacture and careful sensor preparation reliable system operation of 90% or better may be expected.

It is concluded that a reliable smoke rocket giving adequate smoke plumes from ground to heights in excess of 3000 ft has been developed. This phase of the study is considered 100% complete.

* * * * * * * *

The rocket launchers, (one of which is shown in Fig. 2) all worked well with the Model IV Crickets. To accommodate the modified smoke canisters each rocket launcher had to be modified in one simple way—employ a longer launch tube so that the plunger valve of Fig. 6 was below the top end of the launch tube when the rocket was inserted. A launch tube about 6 in. longer than the original is now employed. Details of this arrangement are given in Technical Note 5 of Supplement A.

The modifications to the rocket launchers to accommodate the improved rockets is considered 100% complete.

B. DEVELOPMENT OF PHOTOGRAPHIC TECHNIQUES FOR SEQUENTICALLY RECORDING THE SMOKE PLUMES IN THREE-DIMENSIONS, AND, THE TECHNIQUES EMPLOYED IN THE DETERMINATION OF WIND SPEEDS AND DIRECTIONS VS. HEIGHTS FROM THESE READINGS

1. Decision to Use Stereoscopic Techniques

In the 1961-62 experiments two cameras were used at right angles to one another, one 2000 ft north and the other 2000 ft west of the launcher. Radock and Morgan[3] and Tolefson and Henry[4] discussed the potential errors in wind measurement by this technique when changes in range distance were neglected. Tolefson and Henry[5] had used stereoscopic techniques for their upper level (5000 ft to 50,000 ft) wind measurements reported on in 1961. Based on the above reports; consultation with Professor R. M. Berry of The University of Michigan (an authority on photogrammetric techniques); and, consultation with Abrams Aerial Survey Corp., of Lansing, Michigan, it was decided the stereoscopic technique was much superior to the former method and we would adopt it. We would use the basic technique that Abrams used and would have them abstract the data from the photographs.

2. Aerial Stereoscopic Mapping Technique

"An Element of Stereo-Vision is brought about when an airplane flies over an area, taking photographs with the axis of the camera lens vertical. The exposures are taken so that an area on the photograph also appears on the photograph next to it. The overlapping area is suitable for stereoscopic study, only when the photographs have sufficient stereoscopic coverage and are properly set up to show the relief, or relative elevation, and structures, that appear in the area. Aerial photographs are usually taken so that they have a minimum overlap of 50%. This result is known as a spatial model. Unless every photograph has this percentage or more of overlap, it is impossible to have a complete stereoscopic coverage in a line of flight. A sure method of obtaining stereoscopic coverage is to run an overlap of about 60% in line of flight so that no two overlapping photographs ever have less than 50%."*

In most aerial mapping the airplane flies at a constant altitude of about 10,000 ft (above ground); the axis of the camera is kept vertical; and picture taking frequency is at about 6000 ft intervals. The negatives are usually 9 in. X 9 in. with the camera having a focal length of 6 in. Accordingly, the pictures have a field of view of approximately 15,000 ft by 15,000 ft, with an overlap of about 9000 ft from photo to photo, see Fig. 7a.

For the accurate abstraction of data the analyst must know the exact elevation and/or, the separation of two or more points in each stereo pair. With clear distinct negatives, calibrated lenses, precision stereo plotting equipment, and careful, experienced analysts, Abrams Aerial Survey Corp. routinely draw maps with 2-ft contour lines from photographs taken from a 10,000 ft elevation; and can plot maps with 1-ft contours, if necessary. Thus, with good and calibrated equipment in the hands of professionals, points in space some 8000-12,000 ft from the cameras can be located with an accuracy of ±0.5 ft in each of the 3 orthogonal directions, that is, to one part in 20,000. This accuracy has been verified by the use of standard surveying instruments. Such accuracy is greater than our needs in this problem of the movement of a smoke trail.

A much fuller treatment of the analysis of stereoscopic pictures is given by one of us in Section I of Appendix B and by the other references of Supplement B.

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*"Manual of Stereoscopy," 18 pages, December 1965. Abrams Instrument Corporation, Lansing, Michigan.

3. Application of These Aerial Techniques to Photographing Smoke Plumes for Ground Locations

Upon recommendations of Abrams Aerial Corp., it was decided to have the camera line 3300 ft from the rocket launch line, with the cameras 2000 ft apart. Since the wind usually has a west to east component we decided to place the 4 rocket launchers in a true east-west line with the cameras 3300 ft to the south of the rocket launchers (sun behind the cameras), see Fig. 7b. The rocket launchers were located 300 ft apart, launcher #1 being 900 ft west of launcher #4. The axes of both cameras were pointed upward 20°—in order that full plume height would be visible in all photographs. A survey crew was utilized to lay out the positions and elevations of the rocket launchers and the cameras.

With a distance of 3300 ft between cameras and smoke plumes instead of 10,000 ft the potential accuracy of reading a point in space was reduced from ±0.5 ft to approximately ±0.2 ft. Although we were using cameras with matched focal length (152.4 ±0.2 mm) we did not have the camera lenses or the platens calibrated by the National Bureau of Standards. Nor was the height of the tower exactly measured. So the accuracy of locating a point in space in the plane of the smoke plume was probably ±0.4 ft instead of the potential value of ±0.2 ft. The matter of accuracy will be further discussed in the present section as well as in Appendix B.

Two "used" but "fully reconditioned" K-17C cameras fitted with lenses of focal length 152.4 ±0.2 mm were purchased, along with a spare magazine for each camera. The cameras were equipped with high speed motors that permitted taking pictures at 1.5 sec intervals. Standard intervalometers were not employed in the picture taking as the repetition rate of the pictures would be too variable. Instead, a repeat cycle timer driven by a 2 rps motor which in turn was driven from an inverter of 24 V dc input to 110-V 60.0 ±0.5 cps output. Thus the repetition rate of the pictures was maintained at 2.00 sec per frame ± 1%.

Communication between the launch director and the control tower was by standard short wave radio; between the launch director and the camera crew by "citizens band" radio transmitter—receivers; and between launch director and the operators at the four launchers by field telephone. When the launch director learned that all four launchers were ready for firing and the cameras were in readiness, he instructed the camera operators to start the cameras; then 10 sec later he closed the switch which operated the solenoid values at each of the four launch sites, so that all rockets were launched simultaneously. Simultaneous photographs by the two cameras were made about 10 sec prior to launch until at least 30 sec (sometimes up to 200 sec) following the firing of the rockets. Under stable ground conditions pictures of the smoke plume both near the ground and near apogee could be obtained from the photographs taken 8 to 16 sec after launch; but when the turbulence was severe near the ground the smoke trail of the first 500 ft might not last over 6 to 8 sec and would have disappeared before the rocket reached apogee. Under such conditions, photographs of the early part of the flight were analyzed for the lower portion of the flight and the later pictures for the upper portion of the flight.

4. Firings at the White Sands Missile Range, December 15-22, 1966

Prior to the arrival of The University of Michigan Group, a careful survey and layout of the area had been made by WSMR engineers. The launch line of 4 launchers was made in a true east-west direction with the 500-ft tower located about midpoint between the #3 and #4 launchers. The camera line was 3300 ft to the south of the launch line. The 4 marker positions of the launchers at 300 (±0.5) ft apart as well as the 500-ft vertical tower aided considerably in setting up and analyzing the stereo pairs of photographs by Abrams.

The major findings from the White Sands Missile Range tests may be summarized as follows:

(a) The overall system worked well, and proved to be quite feasible. The layout of rocket launchers 300 ft apart in an east-west line with the cameras to the south gave good pictures and needed no revision. The communication system was quite adequate needing only minor revision.

(b) The presence of a 500-ft tower aided considerably in two ways: (i) as an exact height difference of 500.0 ft, (ii) as a vertical indicator—it showed that the two camera vertical elevation angles were off from 20.0° by 0.8 to 1.4°, respectively.

(c) Subsequent analysis of the smoke plumes showed that the rockets were reaching a height of 3200-3500 ft as specified.

(d) The density of the smoke plume was adequate from ground to apogee.

(e) The main weakness of the system was found to be the unreliable operation of the smoke canister as discussed in Section II-A.

(f) The camera supports were found to have insufficient rigidity—subsequent analysis showed that azimuth and elevation angles fluctuated by as much as ±1° from the mean position, from exposure to exposure.

(g) Some of the negatives were found to be fuzzy around the edges.

(h) The 2-4 min spacing between successive salvos was found to be inadequate for two reasons—the operators at the launchers required at least 5 min to properly prepare the launcher with another rocket for firing, and, a period of at least 5 to 10 min was frequently required for the smoke to clear sufficiently at upper levels before starting a new series.

5. Analysis of One Pair of Smoke Plumes at WSMR, 1130 MST, December 19, 1966

Figures 8, 9, and 10 show smoke plumes at 3, 15, 27 sec after rockets in launchers #1 and #4 were made (900-ft separation). From the corresponding negatives of these pictures positive plates were prepared and these were analyzed by Abrams. In Appendix B is tabulated the data obtained from the camera negatives of Figs. 8, 9, and 10, plus two other pairs of photos thus making up a sequence taken at 0, 6, 12, 24, and 48 sec after that Fig. 8. In Table I is shown one of the tables given in Appendix B—that of the left smoke trail of Fig. 9.

Using the positive glass plates and the survey showing the accurately measured distances between cameras, launch location, and tower, Abrams read the X and Y positions of the centerline of each trail at 200-ft height intervals. While the trail width remained less than 2 ft in diameter the stereo plotter operator recorded the position of the centerline to ±0.1 ft. The writers had some doubt that this resolution was justified but when the stereo pairs of a typical trail were examined in the stereo analyzer the view is similar to that sketched in Fig. 11, R1 and L2. When the right and left views of the trail are adjusted to intercept on cross hairs, (R2 and L2), the position of the centerline of the trail is read to the nearest 0.1 ft and is repeatable within ±0.1 ft. Thus recording the position of the centerline to the nearest 0.1 ft is justified where position differences will later be obtained.

In Fig. 12 is shown the simultaneous wind speed and wind direction variation of the two smoke plumes between various pairs of photographs. In Fig. 13 the variation of wind speed and of direction vs. time is shown for each of the plumes separately. (Complete report by Armendariz, Rider, and Gill in SUPPLEMENT A.)

Although most of the abstracted data (see Table I) is recorded to the nearest 0.1 ft, and the relative position is probably accurate to ±0.3 ft, one is not justified in recording the change in X position or change in Y position at a given elevation (say Z = 2000.0 ft) to the nearest 0.1 ft because of the 3-dimensional movement of each parcel of smoke. One would be justified, however, in recording differences to the nearest 1 ft with an accuracy of ±1 ft. In the case of Figs. 8 and 9, or, Figs. 9 and 10 with pictures 12 sec apart, the corresponding accuracy of wind speed measurement is about ±1/12 fps, say to ±0.1 fps. The reader might question this but upon examination of the above reference paper and of Fig. 12, in the height region 1500 to 2000 ft (where a peak speed of 15 to 18 fps is attained) it appears that recording wind speeds to the nearest 0.1 fps is justified. Likewise recording of wind direction to ±2-4° appears justified.

Since smoke particles have such a small inertia they faithfully follow all wind speed and direction changes in the speed range we are considering. Since the stereoscopic technique has such potential accuracy this method of measuring upper wind movements may have the greatest accuracy of any system yet developed.

TABLE I

ORTHOGONAL COORDINATES OF CENTERLINE OF "SMOKE" TRAIL AT SELECTED HEIGHTS ABOVE GROUND (LEFT "SMOKE" TRAIL OF FIG. 9, 15 SEC AFTER LAUNCH, 11:30 LDT, DECEMBER 19, 1966, WHITE SANDS MISSILE RANGE)

X (ft)	Y (ft)	Z (ft)	Stereo Code (3)
2383.0	959.0	562.0	
2408.0	963.7	672.7	4
2405.8	982.4	728.6	4
2381.8	973.1	744.8	4
2375.2	971.2	779.3	4
2392.2	976.8	800.0	4
2377.1	988.3	851.8	3
2361.7	971.7	926.3	3
2362.8	998.9	1000.0	3
2367.2	942.8	1087.0	
2374.0	919.8	1148.3	
2377.6	916.0	1200.0	
2378.3	915.2	1232.2	
2379.2	920.5	1279.0	
2371.8	906.5	1387.2	
2373.0	908.0	1400.0	
2388.0	918.2	1542.9	
2395.9	927.6	1600.0	
2384.8	954.2	1717.0	
2386.9	960.5	1773.7	
2373.4	972.0	1800.0	
2374.2	1037.7	1916.4	
2391.9	1063.7	2000.0	
2400.5	1078.8	2028.9	
2410.2	1083.5	2070.3	
2430.8	1130.8	2200.0	
2448.3	1145.9	2224.2	
2460.2	1152.4	2312.1	
2491.3	1163.3	2357.1	
2500.0	1167.4	2400.0	
2501.7	1168.6	2415.3	
2509.0	1225.5	2521.3	
2500.1	1239.6	2578.0	

TABLE I (Concluded)

X (ft)	Y (ft)	Z (ft)	Stereo Code (3)
2499.1	1247.8	2600.0	
2492.8	1284.6	2708.2	2
2484.8	1307.5	2770.9	2
2480.2	1315.3	2829.0	2
2477.8	1328.8	2888.0	2
2485.8	1357.9	2955.0	3
2487.9	1377.4	2977.5	4
2487.7	1377.8	2996.7	4
2490.3	1384.0	3000.0	4
2493.1	1389.0	3040.0	4
2508.9	1453.7	3200.0	4
2512.2	1471.8	3238.1	4

NOTES:

(1) Tabulated data is for centerline of smoke trail at (a) 200 ft intervals above ground (Z column), (b) additional levels, for determining limits of shear zones and for determining vertical components of wind.

(2) X and Y distances are measured from a hypothetical bench mark located 3152.1 ft west and 1000.0 ft south of the centerline of the tower. X distances are measured in a true east direction, and Y distances are measured in a true north direction from this bench mark.

Z distances are measured in a true vertical direction from a point at the base of the tower 500.0 ft below the top edge of the tower.

(3) The code for the Stereo Quality of Point measurement is:

none	good	$< \pm 0.1$ ft
(2)	second quality,	± 0.1 ft
(3)	poor,	$\pm (0.1 - 1)$ ft
(4)	very poor,	± 2 ft

6. Systems Modifications Following the White Sands Missile Range Tests

Although the 2K17C cameras had been sold to us "fully reconditioned" the WSMR tests showed that the cameras were not in good operating condition. After the WSMR tests the cameras were thoroughly examined in our laboratory and found to be deficient in 3 or 4 areas. The cam which is used to open and close the vacuum line to the platen of the cameras was out of phase so that the vacuum was not applied to the platen during picture taking operations. This was corrected. In one camera the main lens was found to be loose and to have a small chip at the lens edge. The chipped portion was coated with lampblack paint and the lens tightened. Subsequent testing showed both cameras to give clear, distinct pictures quite acceptable to our needs.

To overcome the weakness caused by a lack of rigid support for the cameras, we tried to locate suitable commercial tripods for our needs. Not being as successful as we had hoped to be, we designed a rugged tripod arrangement complete with "panhead"—see Figs. 14 and 15. The photographs taken with the cameras subsequently at Willow Run Airport appeared to be markedly superior in quality, and in maintenance of position, than did those taken at White Sands Missile Range. Although Abrams have not analyzed any of the data from these pictures, we are confident they are much superior to those previously obtained.

In order that each photograph might include the location, date, time, and, run number on it, a board was mounted ahead of each camera that contained the necessary data—see Fig. 14. Prior to each firing the necessary pertinent information was tabulated on each of these two boards.

7. Willow Run Tests, May 1967

The Willow Run Tests may be summarized as follows:

The cameras worked very well, with excellent focus of all plumes.

The tripods worked well—no movement in camera field-of-view from picture to picture.

The timing, film exposure, etc., were all excellent.

The communication system and the electrical operation of the installation were very satisfactory—no changes necessary.

The continued unreliability of the smoke canisters (as mentioned in the previous section) caused the termination of the series.

But the complete stereo-photographic technique of recording the successive positions of the smoke plume and the accurate method of obtaining upper level winds worked very well.

8. Conclusions

The development and perfecting of a method for sequentially recording the positions of smoke plumes and of analyzing the data with an adequate accuracy is considered to be 100% complete.

C. DEVELOPMENT OF A NIGHT LIGHTING SYSTEM FOR THE USE OF "SMOKE ROCKETS" AT NIGHT

1. Purpose of System

Since different rocket types need to be fired at night as well as by day, data on winds at levels above the ground are needed for nighttime operations as well as for daytime. Thus there is a need to make the "smoke" plumes photographable by night.

2. Possible ways of making "smoke" plumes photographically visible at night

For the April 1967 extension of the contract the following methods of night lighting a Cricket "Smoke Rocket" plume at the WSMR were proposed:

(a) "Searchlight Technique. For this system a powerful searchlight would be located 1-2 miles back from the smoke rocket launcher and behind the stereoscopic cameras. The beam of the searchlight would be programmed to sweep a vertical path from the base of the smoke plume to its apogee at a steady rate, taking say 2 sec to go from ground to 4000 ft; and repeat the cycle at say 6-sec intervals. The cameras would be on time (or bulb) exposure during the 2-sec period of the vertical plume sweep; the camera shutters closed after exposure; film advanced; and camera shutter opened just prior to start of next sweep, 6 sec later. Army surplus searchlights (used for automatic tracking of aircraft at night during World War II) are available with a suitable beam intensity and with a programmer that might be adapted to our needs. The beam width and searchlight location could be set to take care of plume movements for winds up to 20 mph.

(b) "The Armed Services have developed flash cartridges which when ejected from photo reconnaissance aircraft are ignited 2 sec after ejection, illuminating the ground with sufficient intensity for the aircraft to photograph the ground.* Two sizes of these are manufactured, the larger of which permits photographing ground installations from a height of 8000 ft. This flash cartridge weighing less than 5 lb should be suitable for our needs it being ignited at ground level

*"Installation and Maintenance of Aerial Photographic Equipment," U.S.A.F. Manual 95-3, December 1961.

say 700 ft behind our cameras and about 4000 ft back from the smoke plume. These flash cartridges are equipped with a propulsion charge that would eject them approximately 70 to 100 ft into the air before ignition—thus the complete smoke plume should be illuminated. With the low turbulence usually encountered at night the smoke plume near the ground is likely to be photographable from 10 to 20 sec after rocket firings, so successive pictures at 5-sec intervals should be adequate. A rack of four flash cartridges fired at 5, 10, 15, and 20 sec after launching the smoke rocket should provide a sequence of good photographs from which wind movements up to the height of the smoke plume could be obtained. With these high-intensity flashes it may be possible to photograph plumes up to 8000 ft or higher.

(c) "Electronic flash tubes are also used by photo reconnaissance aircraft at night.* These tubes provide very high intensity light for a short time, and the larger capacity units would likely be adequate for our needs. The complete system of batteries, converter, huge condensers and electronic parts are both bulky and expensive. Accordingly, the simpler inexpensive flash cartridges referred to in (b) above would seem to be more suited to our immediate needs.

(d) "High intensity flares that burn at a relatively steady rate for 10 to 20 sec are available. These may be raised by a rocket (the Cricket has carried such a system) to the desired height, ejected, ignited, and the whole assembly descend by parachute. With the "smoke" plume illuminated by such a flare a sequence of stereoscopic pictures could be taken.

> "Of the four systems mentioned the photoflash and electronic flash techniques appear to be much superior to the other two methods, when one considers their simplicity and reliability of operation, as well as cost. With the markedly smaller outlay of funds for the photoflash technique and its apparent adequacy of operation, present plans are to develop this system (unless an electronic flash unit is made available to the project at nominal cost).
>
> "For the nighttime operations it may be necessary to replace the K17C aerial cameras with other aerial cameras as we understand the K17C cameras are not easily adapted to time exposure operation. Time exposures are necessary as synchronization of camera shutter with photoflash for camera exposures of say 1/50 sec is practically impossible since the period of ignition of the flash varies by as much as ±1/5 sec from its nominal value of 2 sec after ejection. It may be cheaper and more reliable to purchase other war surplus aerial cameras fitted with time exposure shutters than to try to modify the K17C for such duty."

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*"Installation and Maintenance of Aerial Photographic Equipment," U.S.A.F. Manual 95-3, December 1961.

3. Development of Flash Cartridge Technique of Illuminating "Smoke" Plumes

After careful consideration of the various night lighting techniques listed above, it was decided to try the Flash Cartridge Technique as it offered excellent possibilities of providing an economical and adequate system of night lighting smoke plumes.

The U.S.A.F. utilize three sizes of flash units for photographing ground installations at night. These three sizes permit photographing from the following approximate height limits—40,000, 8000, and 4000 ft.* We selected the M-123 cartridge for our tests, which is the unit used by reconnaissance aircraft flying at heights up to 8000 ft. Table II gives general technical data on this cartridge, and on the M-112 cartridge used at elevations up to 4000 ft.

TABLE II

CHARACTERISTICS OF THE M-112 AND M-123A1 CARTRIDGES

	M-112	M-123
Total weight	16.4 oz	4.3 lb
Outer case weight	4.4 oz	1.3 lb
Flash powder weight	7 oz	1.7 lb
Length	7.73 in.	8.45 in.
Diameter	1.57 in.	2.885 in.
Muzzle velocity	130 fps	70 fps
Peak candlepower	110 million	265 million
Candlepower-second	1.2 million	6.0 million
Time to peak	.003 sec	.004 sec
Duration of flash	.030 sec	.040 sec

The Air National Guard kindly loaned to us several Model M-123 cartridges for our testing. They were a model with a delay time of 6 sec between ejection of the propulsion charge and ignition of the flare. Since the ejection speed is a nominal 70 fps, if the flare were ejected at an elevation angle of 45° to 60° it would rise into the air and land on the ground before the flare was ignited. We consulted with the manufacturer to modify these cartridges to remove the propulsion charge and to eliminate the delay fuze, having in mind igniting the flash cartridge at a fixed level say 10 ft above ground. The manufacturer, Crane Ordinance Depot, was very interested in our problem and kindly offered to assemble 8 or 10 flash cartridges of the standard M-123 flash

*"Installation and Maintenance of Aerial Photographic Equipment," U.S.A.F. Manual 95-3, December 1961.

size but without the propulsion charge or delay fuze and at no cost to The University of Michigan. These units were delivered to our laboratories early in 1968.

It was considered that the simpler systems would meet our needs better for the following reasons:

(a) The time period between successive flashes could be controlled within ±0.1 sec instead of ±1 sec (as the 6-sec delay fuzes vary in burning time by ±0.5 sec). (This improvement in control of time period between successive flashes was very important as it relates directly to the accuracy of the wind-speed measurements.)

(b) The position of the flare would be fixed in space within a few feet of the ground rather than varying from ground level to 50 ft or more in the air.

(c) Protection of operators and observers in the area would be simplified by the ground firing, both with regard to eyesight and to sound.

4. Camera Modifications

The shutters of the K17C cameras were rewired so as to permit taking either instantaneous (daytime) or time exposure (nighttime) photographs. Being able to do this, we did not buy other aerial cameras fitted for time exposures.

Two film types were used for the nighttime photographs:

(a) Kodak #2475 Recording Film, Estar Base, Exp. Index ~ 1200.

(b) Kodak Tri-X, Aerocon, Exp. Index = 200.

The photographic department of Wallops Island Missile Range kindly loaned a roll of the high-speed film to us for our tests.

5. Daytime Tests of Flash Cartridge

In March, 1968, two of the simplified Flash Cartridges as supplied by Crane Ordinance Depot were tested at our Willow Run test site. The units were supported at heights of about 6 ft above ground, and spaced about 10 ft apart. A 16-mm Cine Kodak Special was employed to photograph the two successive flashes. By this means we hoped to ascertain the approximate fireball diameter, and the approximate flash duration. Unfortunately there was an error made in film placement so all photos were out of focus—so we were unable to accurately measure fireball dimensions.

The two tests yielded the following information:

(a) Effective flash duration was about 0.1 sec (for about 90% light output).

(b) Estimated fireball diameter, 10-12 ft.

(c) Sound report—men could operate without ear plugs at 200 ft from flash unit.

(d) Firing of first unit did not cause firing of second unit located 10 ft away.

(e) Electrical circuit employed for the safe firing of units worked perfectly.

6. Nighttime Tests of Flash Cartridges

The nighttime test was conducted at a carefully selected and prepared site satisfying the following conditions:

(a) Remote from any heavily travelled highway—so that high intensity flashes would be unlikely to cause any automotive or airplane accidents.

(b) Direct viewing of fireball would be cut off on three sides by trees; and on the fourth side by a crescent shaped man-made screen 50 ft long by 8 ft in height (starting 2 ft above ground and extending to 10 ft above ground).

(c) Protection of operators by 15 ft high embankment.

(d) Flash units 5 ft above ground and 12 ft apart.

(e) Planned firing time between 11:00 p.m. and 4:00 a.m. when minimum number of observers would be present.

The actual site selected is shown in Fig. 16. It will be noted that the following components were in an almost straight line, West Camera to Flash Units (about 1200 ft); Flash Units to Rocket Launcher (about 6000 ft); Rocket Launcher to East Camera (about 8000 ft). Trees protected East Camera from direct viewing of the flash units; and West Camera was located with an angular separation between flash units and rocket launcher of about 10°—so that both fireball and smoke plume should be recorded on the film. East Camera was loaded with Kodak Tri-X film having an Exp. Index of 200 and at maximum lens opening of f/8; West Camera with Kodak #2475 Recording Film (Exp Index 1200) and at maximum lens opening of f/8.

The test was conducted in the presence of a WSMR representative about 11:30 p.m. on March 29, 1968.

The sky was overcast with a ceiling estimated at 4000 ft or more. Since rain started some 30 min after the test and became heavy about 60 min after test, the cloud cover must have been nimbo-status.

The smoke rocket was launched and presumably operated normally; about 10 sec later the first flash unit was ignited; and 10 sec later the second flash unit was ignited. The sequence of events went normal but neither camera recorded the smoke position nor did operating personnel see an illuminated smoke plume.

East Camera recorded neither the smoke plume or the silhouttes of distant trees, although the camera operator saw both flashes faintly illumine a small portion of the skyline. West Camera failed to record the smoke plume but had a much larger area illumined by the flash unit than expected—the condition of very humidity caused the film to be fogged for a solid angle of about 15° radius from the flash unit at the West Camera site, so photographing of any smoke plume was eliminated.

Owing to rain starting within 30 min of the first rocket launch, testing was terminated for the night and no further tests were conducted later.

We were disappointed neither camera nor observer recorded the smoke plume. Subsequent research showed that the U.S.A.F. normally use cameras with apertures of f/2.5 or f/2.8 for nighttime aerial photos instead of cameras with an f/8 lens. Such cameras would increase the light intensity on the film by a factor of 10—an order of magnitude increase in light intensity.

One camera was located to take pictures of a directly lighted smoke plume; the other by an indirect lighting—to see which system was preferable for our operation. Since neither camera recorded a smoke plume this question of preferred camera position remains unresolved.

7. Conclusions Re Flash Cartridge Technique of Night Lighting Smoke Plumes

Although the one nighttime test of the system failed to record any smoke plume the writers believe the system is sound and should be developed. It is recommended that flash cartridges be increased in weight of active materials by a factor of 4 to 10; and that aerial cameras having maximum aperture of not less than f/2.8 be used. A reduced distance between flash units and rocket launcher is recommended (for increased light intensity of smoke plume near the ground); and a relocation of both cameras so that direct illumination of objects or atmosphere near the flash units cannot interfere with the photographing of any smoke plumes.

The development of a night lighting system for the use of "smoke rockets" at night is considered to be 60 to 70% complete.

D. DEVELOPMENT AND TESTING OF A SMOKE ROCKET SYSTEM TO EXTEND THE USEFUL HEIGHT RANGE TO AT LEAST 8000 FT ABOVE GROUND

1. Design Concepts

(a) We decided to continue the use of $TiCl_4$ as the tracer material for several reasons:

(i) Its efficiency as a "smoke" producing agent is high and no markedly superior materials (in regard to volume of dense smoke per unit mass of chemicals used) were found in the literature.

(ii) Being a liquid it is much easier to adjust its rate of ejection than is a powder.

(iii) With our intimate knowledge of the characteristics and handling of this chemical, it was natural to continue its use in this extension of the work.

(b) To provide smoke during both the acceleration and deceleration phases of the Cricket Rocket we had developed a pressurized smoke canister, but had run into more problems of liquid ejection than is desirable for a simple, reliable, smoke rocket. With a larger rocket and higher acceleration and deceleration rates the problems of the pressurized canister would be sure to increase rather than decrease, so the method of liquid ejection was given very careful consideration. It was desirable to design a payload section that would be simple and reliable in operation providing adequate smoke during both acceleration and deceleration phases of the rocket ascent.

For the following reasons, it was decided to test a two-stage $TiCl_4$ dispenser, one stage for use during the acceleration phase of the rocket ascent, the second stage during the deceleration phase of the ascent:

(i) Ample forces should be available to dispense the $TiCl_4$ during the acceleration phase, due both to the high g force during the complete acceleration phase, and, due to the dynamic head pressure that rapidly develops as the speed of the rocket increases.

(ii) Tolefson and Henry[5] had already developed a simple, reliable $TiCl_4$ payload for the deceleration phase of a rocket ascent. We would utilize their basic techniques.

(c) For the design of the payload section of the proposed new two-stage smoke dispenser, consideration was given to the following factors:

(i) Allocating the volumes of the two chambers of $TiCl_4$ roughly according to the height intervals each will be in use, that is, if acceleration is expected from ground to 1000 ft, and deceleration from 1000 ft to above 8000 ft, then 12-1/2% (1/8) of the total $TiCl_4$ volume should be allocated to the acceleration phase and the remainder to the deceleration phase.

(ii) Since accurate wind speed and direction data is more essential in the lowest few hundred feet of the atmosphere than it is in the upper region of the smoke rocket ascent, it is preferable to err on providing a little extra smoke during the acceleration phase of our smoke rocket with some loss of density during the deceleration phase instead of the reverse. Accordingly in the illustration given in (i) above we would consider it preferable to allocate about 15% of the liquid volume for the acceleration phase and 85% to the deceleration phase in the initial design of the payload.

(iii) With a 10:1 or more change in speed of the rocket between 50 ft above ground and burnout, it would be very difficult to design a simple liquid metering system which would maintain a relatively uniform emission rate (say within ±50% of the mean) per 100 ft of altitude throughout the acceleration phase. To permit keeping the system simple it would be best to expect to emit an average of 2 to 4 times as much $TiCl_4$ per 100 ft of height as we averaged for the Cricket Rocket. The Cricket Rocket dispensed about .75 lb of $TiCl_4$ (200 cc) in going from ground to 3200 ft in altitude, or about 0.24 lb per 1000 ft in height. For an adequate plume to 8000 ft with a safety factor of 2 to 4, we should then have a payload of 4 to 8 lb of $TiCl_4$. Allowing an equal weight for the two-compartment liquid container (including nose cone, ducts, metering valves, etc.) our total payload at launch would be about 8-16 lb.

Thus the rocket selected should have a minimum capability of lifting an initial payload of 8 lb (decreasing at apogee to 4 lb) to a height of at least 8000 ft; preferably it should have a capability of lifting an initial payload of 16 lb (decreasing at apogee to about 8 lb) to a height of at least 10,000 ft.

2. Selection of Rocket Motor

The following matters and features were considered in the selection of a rocket motor for the proposed two-stage "smoke" rocket:

(a) A mass produced, well tested, reliable, adaptable, and inexpensive rocket motor should be selected, if possible.

(b) An uncomplicated rocket launcher (unlike the Arcas system) capable of being operated by one man was desirable.

(c) A solid propellant rocket, easily prepared for firing and easily aborted in case of emergency was desirable.

In the selection of a suitable rocket motor Dr. Harold Allen, of the High Altitude Engineering Laboratory, The University of Michigan, and Mr. Wm. L. Lord of Test Rocket Group, NASA, Wallops Island, Va. were most helpful. They both recommended the "2.75" FFAR Test Rocket." This rocket was well rated in the report RH-TR-65-1, Meteorological Rocket Program, Volume I, "Meteorological and Sounding Rocket State-of-the-Art Study," by J. R. Brasfield. Good technical data on its use is given in the Bureau of Ordnance Publication OP 1793 "2.75 in. Folding-Fin Aircraft Rocket." Final decision to use this vehicle was based on the outstanding report "The 2.75 in. FFAR Test Rocket" by Wm. L. Lord, Cary F. Milliner, and Robert F. Stengel, NASA Wallops Station, September 1963 (26 pages, 30 figures). This report outlined a careful study these men conducted to determine the payload capability, thrust accelerations; impact predictability; flight stability, etc., of this rocket. One sentence of their report reads as follows: "After a period of 14 months, during which approximately 200 rockets were fired, the rocket has been found to be safe, reliable and readily trackable by Wallops."

Some of the features of this rocket applying to our use were:

(a) It is in mass production (by the thousands); is routinely available to military establishments; and costs less than $50 complete.

(b) It is very adaptable to our needs. It has an overall length of 42 in. (without payload); diameter of 2.75 in., and a weight of 18 lb.

(c) It has a payload capability of 8 lb to 18,000 ft; 16 lb to 15,000 ft; and 24 lb to 12,000 ft—see Fig. 17. Thus this rocket motor had ample weight payload capability for our needs.

(d) It is fired from a small, inexpensive, and easily portable launcher that can be carried by two men.

(e) Eighty of the rockets were available at WSMR and 24 were assigned to this project.

3. First Models of "FFAR Smoke Canister" and Tests at the Keweenaw Range, (Copper Harbour, Mich.)

The first models of the smoke canister were not designed as prototype production smoke canisters but rather as test vehicles designed to:

(a) Test the operational feasibility of the two-stage design.

(b) Check for approximate orifice sizes.

(c) Determine adequacy of smoke plumes near the start and end of the deceleration phase.

It was planned to fire these from Wallops Island, Va., and to use time lapse cameras to record the data.

Six smoke canisters were fabricated, three with a payload of about 13 lb $TiCl_4$; and three with a payload of 5 lb $TiCl_4$. The two sizes were identical in diameter and in components, the one being almost twice as long as the other. One of each is shown in the photograph of Fig. 18. The design drawing of the longer unit is shown in Fig. 19.

During the acceleration phase of the rocket three major factors contribute to the liquid pressure at the $TiCl_4$ orifices. These are:

(a) The acceleration forces of the rocket.

(b) The instantaneous depth of $TiCl_4$ column above the orifices.

(c) The dynamic air pressure created by the instantaneous forward speed of the rocket.

Use of the Wallops Island report ("The 2.75 in. FFAR Test Rocket," Fig. 24), indicated we could expect the acceleration forces to increase from say 30 g at launch to about 40 g at burnout—an increase of about 30%. The depth of liquid should decrease at this same time from full depth to about 0.1 full depth (allowing 10% safety factor). Thus the pressure contribution of (a) and (b) above would decrease during the acceleration phase from a maximum at start to about 13% (130 x 0.1) of maximum, at burnout, whereas the speed of the rocket has increased at least 10-fold between 50 ft above launcher and burnout. So the net result of the combined pressure of (a) and (b) above is to produce a large volume of smoke in the first 100 ft of ascent quickly tapering off to a very small volume of smoke during the last 100 ft of the acceleration phase—an undesirable condition. During this same period the dynamic pressure of the tip of the nose cone has increased as the square of the rocket speed from zero at launch to a maximum at burnout. The rate of $TiCl_4$ emission (lb/sec) should likewise increase from 0 at launch to maximum at burnout. Accordingly, it was desirable to minimize the combined effects of (a) and (b) and maximize the effect of (c). Since (a) and (c) are relatively fixed (determined by rocket performance) (b) was the variable that could be adjusted. To minimize this pressure we should keep the initial height of $TiCl_4$ liquid to a minimum. By increasing the outside diameter of the payload section from 2.75 in. to 4.00 in. the cross-sectional area of the rocket was more than doubled, thus decreasing the height of $TiCl_4$ to less than half for any given volume of liquid. This is the reason for the "smoke" canister being 4 in. in diameter instead of 2.75 in.

As shown in the design drawing of Fig. 19, two tubes project ahead of the rocket nose cone, one to provide full dynamic head pressure to the top surface of the $TiCl_4$ in the lower chamber during the acceleration phase of the rocket; the other to provide full dynamic head to the underside of the $TiCl_4$ column in the upper chamber during the deceleration phase of the rocket ascent. During the acceleration phase of the ascent, no $TiCl_4$ is forced out the upper orifices of the rocket.

In these experimental smoke canisters two orifices were provided for emission of $TiCl_4$ during the acceleration phase and two for the deceleration phase. The hole size selected for these nozzles for the first tests was 11/32 in. (.341 in.). This size was based on computations of expected pressures and on laboratory tests. It was planned to use larger or smaller sizes in future tests, based on the experimental results of the first firings. Although the flow from these two pairs of orifices would be very rapid it was expected the $TiCl_4$ would be broken up into very small droplets by the intense shear next to the rocket body and the severe turbulence in its wake. These tiny droplets would form many smaller titanium oxide particles that would respond to any wind movements in their environment.

It was planned to make the firings of the first FFAR Smoke Rockets at Wallops Island, Va., where such rockets are routinely followed by tracking radars. But with the relative infrequency of clear skies in December and January in that sea-coast area and the relative low priority of these rockets, the project director decided there was a better chance of making successful firings under suitable weather conditions from The University of Michigan Keweenaw Range (near Copper Harbour on Lake Superior) for a given expenditure of funds than there would be from the Wallops Island Range. In addition, there was a reluctance on our part to make the first firings of a wholly untested "smoke" canister in the presence of many rocket professionals such as would likely occur at Wallops Island.

Two of the short version of smoke canister ((b) of Fig. 18) and two of the longer version ((c) of Fig. 18) and shown in Fig. 19 were fired from the Keweenaw Range on November 29, 1967. Messrs. Stohrer and Sweeney were assisted in these tests by Dr. Harold Allen of The University of Michigan High Altitude Laboratory. Unfortunately, the weather was not perfect; also the main camera (to be located about one half mile from the launch site) failed to operate in the sub-freezing temperatures. However 35 mm cameras did record most of the important features of the flights, but no accurate computations of height were possible from these photographs.

Several representative photographs of the Keweenaw tests are shown in Figs. 20-23. In the first two firings with the short versions of the smoke canister both $TiCl_4$ reservoirs were essentially full in each case when the rockets were launched. Both firings were essentially 100% successful with adequate "smoke" at take-off; during the whole acceleration phase, and during the deceleration phase as long as the $TiCl_4$ lasted. (Examination of Figs. 21(d) and 22(e) suggests that the shorter version of canister did not have sufficient $TiCl_4$ for the upper portion of the deceleration phase of the ascent.) There was ample smoke at all levels, and there was no apparent break in the plume during the transition period between acceleration and deceleration. There was some spiralling of both rockets during their ascents, indicating some misalignment of parts or weakness in design.

In the firing of the first longer version of the smoke canister (Fig. 22) again 100% success was achieved insofar as visual observations and photographs showed. An excellent smoke plume from ground to near apogee was obtained. For the second firing of the longer version (Fig. 23) there was insufficient $TiCl_4$ available to fill both acceleration and deceleration chambers. The acceleration reservoir was nearly filled but the deceleration reservoir was only about one half filled (not accurately measured owing to sub-freezing temperatures). In the ascent of this rocket two significant performance differences occurred, the rocket spiralled more in its ascent, and there was a definite break in the smoke plume between the acceleration and deceleration phases—see Fig. 23(d). The firing of the incompletely filled smoke canister was advantageous in this experimental flight as it demonstrated two things:

(a) That there indeed was two distinct phases (acceleration and deceleration) to the $TiCl_4$ emission.

(b) That the blunt-nosed stocky smoke canisters were somewhat unstable in flight.

The cause of the break in the smoke plume may have been due to one or both of the following reasons:

(a) The $TiCl_4$ in the almost filled lower reservoir was all dispensed before the acceleration phase was complete. (This seems unlikely as Stohrer believes the reservoir was more than half filled with $TiCl_4$ which would be more than the corresponding volume of $TiCl_4$ in ascents #1 and #2, and there was no apparent break in the smoke plume of those two ascents.)

(b) In the transition period between acceleration and deceleration the $TiCl_4$ in the upper chamber had to move from the lower portion of the reservoir to the upper portion where the two outlet ports or orifices were located. Although this transition period would be only a fraction of a second, it must have been sufficient to cause a distinct break in the emission of $TiCl_4$.

The main conclusions to be drawn from the firings of the four 2.75 in. FFAR Smoke Rockets are:

(a) The two-compartment design with its two-phase operation worked perfectly on all four firings. It thus appears to be a very practical smoke canister to provide a continuous smoke plume from launch to near apogee.

(b) A simple, uncomplicated design is possible without the problems of pressurized chambers, moving parts, O-rings, etc.

(c) The volume of $TiCl_4$ was adequate in the larger unit (13.5 lb) to provide ample smoke throughout the ascent, both during the acceleration and deceleration phase.

(d) The orifice sizes for the acceleration phase were probably somewhat too large as more than adequate smoke was produced near the ground, and very adequate smoke during the complete acceleration phase. The orifice size for the deceleration phase was likewise adequate, but data is too meager to say if the size was too large as we do not know if the plume terminated near or significantly below apogee.

(e) A smoke-canister rocket-motor combination of greater stability, aerodynamically speaking, is desirable. (The use of a smoke canister of the same diameter as the rocket body; a more tapered nose cone; and, eliminating the projection of the two pressure tubes ahead of the nose cone are obvious improvements.)

(f) The smoke canister design could be improved to permit: (1) easier and more rapid filling with $TiCl_4$ prior to launch, (2) an equally simple but more reliable method of keeping the four orifices closed until the rocket is launched.

(g) The 2.75 in. FFAR rocket motor lived up to expectation in its reliability, ease of handling, and performance.

4. Proposed Design Changes for Second Model of "2.75 in. FFAR Smoke Rocket"

Based on the Keweenaw tests; further study of the report "The 2.75 in. FFAR Test Rocket"; and other work, the following design changes of modifications were proposed for the second model of the FFAR smoke canister:

(a) An outside diameter of 2.75 in., the same as the rocket motor. (Although this reduction in diameter would require doubling the overall length of the smoke canister for a given volume of payload, this increase in length should not cause instability of operation as payloads of this diameter and greater in length than those anticipated have been successfully flown at Wallops Island. To compensate for the doubled $TiCl_4$ hydraulic pressures the orifice size must be appropriately reduced.)

(b) A nose cone with a taper of 3.75:1 (height to diameter ratio) instead of 1.25:1 would improve dynamic stability; markedly decrease the dynamic drag on the rocket, and markedly increase expected peak altitude for a given payload.

(c) A redesigned nose cone to make the filling of the canister with $TiCl_4$ easier and better.

(d) The use of a ring of twelve small orifices instead of two large orifices for both upper and lower chambers, to reduce the possibility that large drops of liquid $TiCl_4$ might remain in the rocket wake to fall freely like rain and thus not respond to wind movements. (From the Keweenaw firings there is no indication of this occurring but from some special Cricket test firings at low rise rates and at 60° elevation angles liquid $TiCl_4$ drops fell 200 to 400 ft before evaporating. During such free fall of the drops they are not moving with the wind and the system produces a sheet of smoke rather than a narrow plume of smoke. To markedly reduce the chances that any $TiCl_4$ drops larger than a few microns in diameter are left behind the rocket, it is desirable to use a series of small orifices instead of two large orifices.)

(e) Design the components of the canister so that the $TiCl_4$ payload can be easily changed simply by changing the length of the cylindrical tube; and, that the proportion of the two chambers can be easily varied by simply changing the position of the bulkhead in the tube.

(f) A simpler but equally reliable method of sealing off the $TiCl_4$ orifices until rocket launch occurs.

5. Second Model of 2.75 in. FFAR Smoke Rocket

The design drawings of this smoke canister are shown in Fig. 24; full size blueprints in the Supplemental Data. The two compartment design and most essential parts are shown in the upper half of Fig. 24 including the two orifices for each of acceleration and deceleration phases. In the lower half of Fig. 24 the modification to the 12 orifices for each of the two phases is shown. The ease with which the total volume of ratios of volumes may be changed is apparent from the drawings. Likewise the sizes of orifices may be changed easily, simply by using larger or smaller drills. The canister is easily filled when in the erect position by placing the tapered end of a funnel in the tip end of the cone—both $TiCl_4$ chambers are filled at the same time.

The first fabricated model of the new design is shown in Fig. 18(a) along with the earlier FFAR Smoke Canisters and the Cricket Smoke Rocket. This model has a payload capacity of 12 lb $TiCl_4$ with a gross weight upon launch of 19 lb. A computer analysis of this payload indicates an expected apogee of about 14,000 ft. A comparison of the three 2.75 in. FFAR rockets with payloads is given in Table III. From this table it will be noted that the rocket is expected to reach well above the minimum design height of 8000 ft, and it is expected that by firing several rockets with assorted orifice sizes and variations in the volumes of $TiCl_4$ for both phases a good smoke plume from ground to 12,000 ft or higher will be obtained.

Considerable effort was spent by the project director in designing a simple, efficient, and reliable method of closing the two rings of $TiCl_4$ orifices until the rocket was launched. The system should have the following desirable features:

(a) Seal all holes from $TiCl_4$ leaks.

(b) Prevent any air from getting to $TiCl_4$ until instrument launched.

(c) Easy to apply with a minimum likelihood of failure prior to launch.

(d) Quick action upon rocket launch, without the use of auxiliary electric circuits of complex mechanical design.

(e) Assembly parts not corroded by extended exposure to $TiCl_4$.

The currently accepted design of the sealing method is shown in Fig. 25. Details of the design and operation are clear from a study of various photos. The stretchable band is made from a length of 1 in. wide x 1/16 in. thick section of "Viton" sheeting cemented to form the double thickness strap shown. ("Viton" stretches like rubber and is impervious to $TiCl_4$.) In use, the snap ends of the two chains will terminate on a rigid ring or band attached to the rocket launcher. Some design changes will likely be found desirable following some actual firings but the basic concepts are believed to be valid.

To provide data on the expected performance of this second version of the 2.75 in. FFAR Smoke Rocket, Messrs. Stohrer and Brock of our group ran a computer analysis of this rocket design for several gross payloads at launch angles of 80°, 75°, and 45°. This data is graphically represented in Fig. 26. The actual computations are given in Appendix C. The more important features of the analysis are listed in Table IV.

TABLE III

FFAR SMOKE CANISTER DATA

Details	First Model: Short Version	First Model: Longer Version	Second Model
Gross height, in.	17	29-1/2	47
Net height (less threaded portion), in.	15	27-1/2	44-1/2
Outside diameter, in.	4	4	2-3/4
Cylindrical tube section, in.	9-3/4	22-1/4	36
Weight of $TiCl_4$ in lower chamber, lb	.65	20	1.8 (est.)
Weight of $TiCl_4$ in upper chamber, in.	4.55	11.5	10.2 (est.)
$TiCl_4$ payload, lb	5.1	13.5	12
Net Weight of Canister, lb	7	9.25	7
Launch weight of Canister, lb	12	23	19
Portion of ascent, by height, rocket is in acceleration phase (estimated), %	16	16	11
Portion of payload, by weight, for acceleration phase, %	13	15	15
Estimated apogee height, ft	10,000	8000	14,000
Number of orifices and diameter for			
(a) acceleration phase, in.	two; 0.341	two; 0.341	ten; .062
(b) deceleration phase, in.	two; 0.341	two; 0.341	ten; .062

TABLE IV

COMPUTER SIMULATION OF 2.75 IN. FFAR SMOKE ROCKET FLIGHTS

Canister Model	Run No.	Firing Angle (deg.)	Head Weight (ft)	Burnout Height (ft)	Apogee Height (ft)	Apogee Time (sec)	Impact Distance (ft)	Impact Time (sec)
First	3	75	16	978	9,629	22.4	7,258	51.2
Second	2	80	0	2,108	21,384	33.0	11,716	72.0
Second	5	75	2	2,126	19,241	30.5	15,180	68.3
Second	4	75	8	1,500	17,449	30.5	14,672	66.0
Second	6	45	8	1,081	10,016	22.8	29,440	49.8
Second	1	75	16	1,041	15,215	29.7	13,953	62.5

It is expected the second Model 2.75 in. FFAR Smoke Rocket will be fired at an elevation angle of 75° to 80° and will weigh 16 lb or more. The impact point then may be expected not to exceed about 3 miles (15,000 ft) in light winds. When firing at a 75° angle $TiCl_4$ emission should terminate at less than 90% apogee height (in order to avoid marked initial curvature of the upper portion of the smoke plume). Good smoke plumes to at least 12,000 ft are expected.

6. Conclusions Concerning the "Development of a Smoke Rocket System to a Useful Height Range of at Least 8000 ft Above Ground"

The following conclusions have been reached:

(a) A simple, inexpensive reliable rocket motor is available to provide such a smoke rocket.

(b) A simple, uncomplicated two stage smoke canister has been developed which will provide adequate smoke from launch to apogee.

(c) With the firing of about ten smoke canisters of the model shown in Fig. 25 (with the models varying in size and number of orifices; in the volumes of liquid for each stage; and possibly changing the nose cone ratio to 5:1), it is believed a finalized design can be reached that provides excellent smoke from ground to at least 12,000 ft above ground.

The development of a smoke rocket system to a useful height range of at least 8000 ft above ground is believed to be about 80% complete.

III. CONCLUSIONS

Referring to the "Scope of Work" specified in the contract and outlined in the Introduction, the following conclusions are drawn:

1. The development of a dependable smoke rocket to heights of 3000-4000 ft is considered to be 100% complete.

2. Modifications to the rocket launchers to accommodate the improved rockets is 100% complete.

3. An adequate method of sequentially photographically recording the smoke plumes in three dimensions has been developed and perfected. Analysis of these photographs (by using equipment developed for analyzing aerial stereo photographs) permits obtaining wind speed and direction measurements to the full height of the plume with greater accuracy than anticipated. As set up at White Sands Missile Range and utilizing photographs taken 6, 12, and 24 sec apart of a representative smoke plume, in the height range 500 to 3000 ft above ground where wind speed was in the range 10 to 20 ft sec^{-1}, the precision of measuring wind speeds was about ±0.2 to ±0.4 ft sec^{-1}, and of wind direction ±2° to ±4° azimuth. This is markedly better than can be obtained with pilot balloons, owing to their inherent self-induced oscillations.

The development of this system is considered to be 100% complete.

4. Field testing of the complete system, firing up to 4 smoke rockets simultaneously and having up to 3 salvos spaced 2-4 min apart was attempted at both WSMR and in Michigan, but with only mediocre results. In both cases, the operational reliability of the smoke canister was the overriding weakness. Although individually usable and sometimes double or triple plumes were obtained this phase of the study must be considered very incomplete. With the much improved reliability of the new Cricket smoke canister, these tests could be conducted with a much greater probability of success. However this phase of the study might be conducted with the newer FFAR smoke rocket, which should have a greater reliability than the Cricket smoke rocket, and should reach much greater heights.

This phase of the study might be considered to be 25% complete.

5. For the night lighting of the smoke plumes the basic method has been developed but the current light intensity is too low and cameras with larger apertures are needed. There is no apparent problem to fabricate flash units of 4 to 10 times the light output of the first units tested and this procedure is recommended. There are a number of aerial reconnaissance cameras manufactured for the USAF that have lens apertures of f/2.5 (e.g., the K24 and K46) that are

designed for nighttime photography, and these should be much better than the pair of K17C cameras of f/8 that we used. With these two major improvements and the use of the high-speed film, we are confident there would be no problem to photograph smoke plumes to at least 4000 ft.

This phase of the study might be considered to be 60% complete.

6. A number of ideas on the "rapid analysis techniques" of smoke plumes have been considered. But the development of dependable smoke plumes has taken major priority. Accordingly one must consider this phase of the study to be 100% incomplete.

7. As in item 6, this phase of the study has had very little attention and may be considered to be 100% incomplete.

8. The development of equipment to extend the smoke trail method to at least 8000 ft has progressed very well. An inexpensive, reliable, and easily handled rocket motor is available and has been used that has ample weight capabilities for our needs. A two-stage smoke canister (to supply a smoke plume for both the acceleration and deceleration phases of the ascent) has been designed, tested, and proven to supply adequate smoke for heights up to at least 6000 ft. Design changes have been made and a new model is now ready for testing. We are confident that the new model will provide excellent smoke plumes from ground to at least 10,000 ft.

This phase of the study is considered to be 75% complete.

IV. ACKNOWLEDGMENTS

In the execution of this contract three outside individuals or groups of individuals, stand out in the minds of the authors for major assistance "beyond the call of duty":

1. Mr. William Lord and his associates at NASA, Wallops Island—for help in the selection of rocket motors for the higher level smoke rockets, and in making tentative arrangements for rocket firings at Wallops Island.

2. Messrs. George Niles and James Lenhardt and their associates of the FAA, Central Region—for careful consideration of our needs to fire the Cricket Smoke Rockets in the Ann Arbor area; assisting us in the safe launching of these from the Willow Run Airport; and granting us permission and making arrangements for the safe firing of the FFAR rockets from the Keweenaw Range in Northern Michigan.

3. Mr. Lightfoot of the Crane Ordnance Depot—for fabricating and supplying several special flash cartridges for our night lighting test at no cost to us.

In addition to the above the project director wishes to express his appreciation to the Atmospheric Sciences Laboratory in the way Messrs. Rachele and Armendariz have monitored the work on this project. The director had some reservations with regard to accepting a contract with a division of the U. S. Army as he was concerned that the Army might be very rigid in requiring full accomplishments of all areas mentioned in the contract; of such close supervision of the contract that the director and his assistants would feel "fenced in"; and, that all major capital expenditures would need written justification. All of these fears were unfounded. Working relationships with the Atmospheric Sciences Laboratory have always been pleasant but businesslike. The project director believes markedly less would have been accomplished on the project had it not been for the excellent working relationship between his group and Messrs. Rachele and Armendariz. He would have no hesitation in considering another contract with this group.

V. REFERENCES

1. Gill, Gerald C., Eugene W. Bierly, and Jal. N. Kerawalla. "An Inexpensive Rocket Technique for Obtaining Low Level Wind Profiles," J. Applied Meteorology, Vol. 2, No. 4, pp. 457-462, August 1963.

2. Hay, D. R. and K. Naito. "An Investigation of Clear Air Stratification with Radar and Elevated Instruments," Radar Science, J. of Res. NBS/USNC-VSSI, Vol. 69D, No. 6, pp. 877-880, June 1965.

3. Radok, Uwe and Peter Morgan. Comments on "An inexpensive rocket technique for obtaining low level wind profiles," J. Applied Meteorology, Vol. 4, No. 4, p. 551, August 1965.

4. Tolefson, Harold B. and Robert M. Henry. Additional comments on "An inexpensive rocket technique for obtaining low level wind profiles," J. Applied Meteorology, Vol. 5, No. 2, pp. 225-226, April 1966.

5. Tolefson, Harold B. and Robert M. Henry. "A Method of Obtaining Detailed Wind Shear Measurements for Application to Dynamic Response of Missile Systems," J. Geophy. Res., Vol. 66, pp. 2849-2862, 1961.

6. Lord, William L, Cary F. Milliner, and Robert F. Stengel. "The 2.75 in. FFAR Test Rocket," a preliminary report from NASA, Wallops Island, 26 pages plus 30 figures, September 1963.

Fig. 1. Photograph of "Cricket" model IV rocket fitted with a "smoke" canister payload.

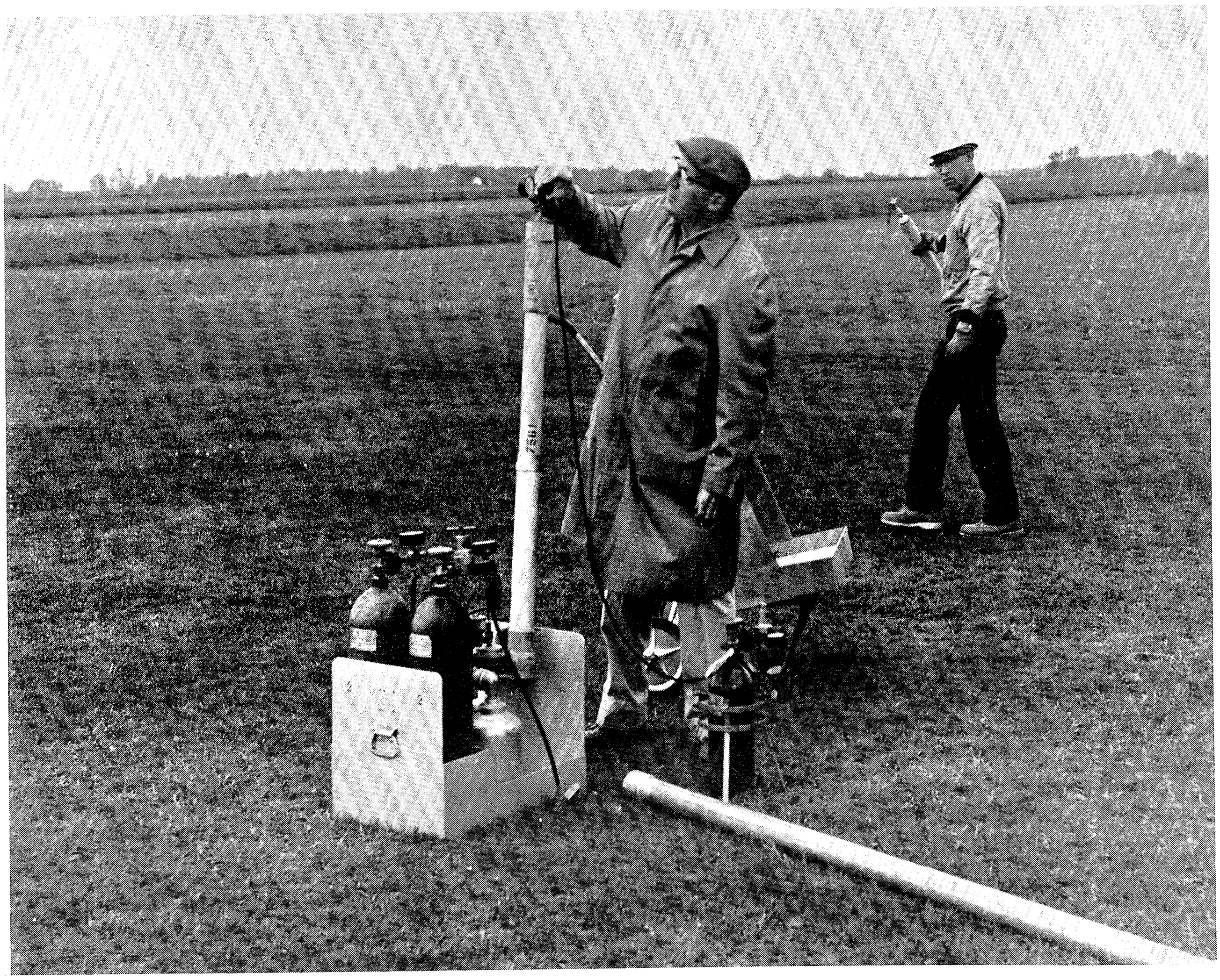


Fig. 2. Photograph of portable launcher, Cricket "smoke" rocket and auxiliary equipment. Rocket is in launch tube with safety shield over "smoke" canister, which is being pressurized. After pressurizing, 10 ft extension tube is installed before launching.

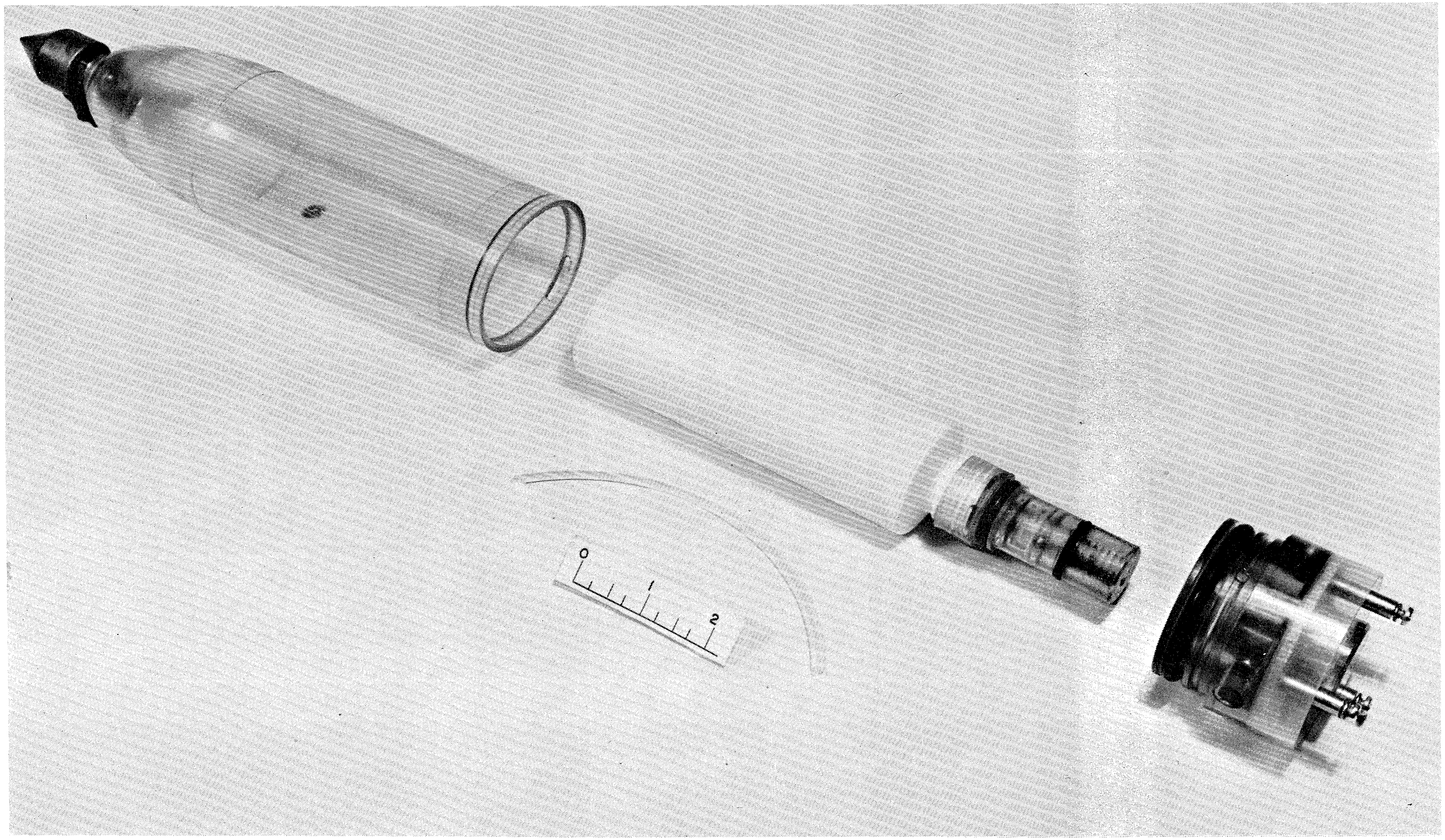


Fig. 3. Photograph of separated parts of Texaco's Cricket 1966 smoke canister.

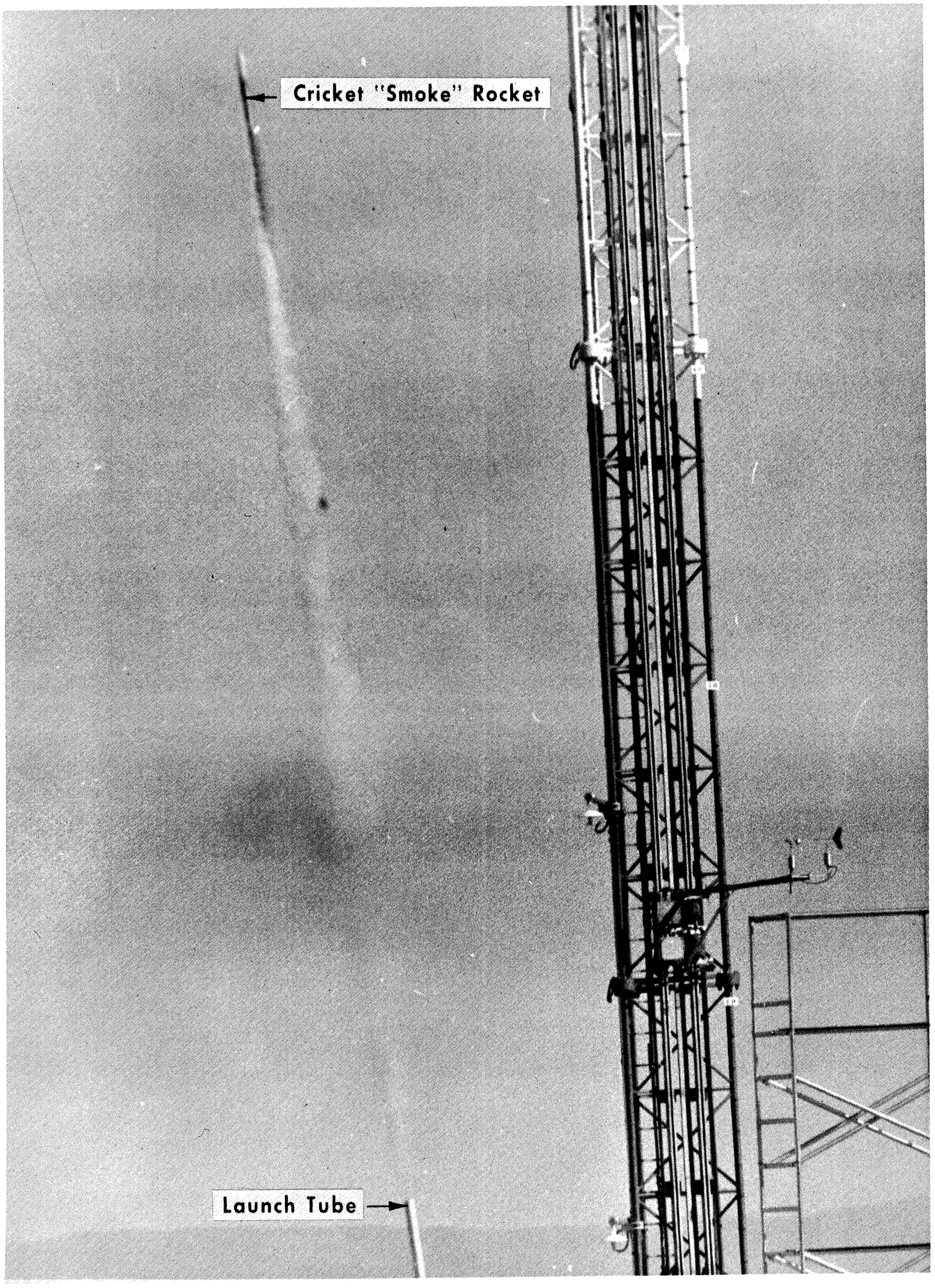


Fig. 4. Photograph of "smoke" rocket, smoke trail, extension tube of launcher, and part of 500 ft tower (WSMR) a fraction of a second after launch.

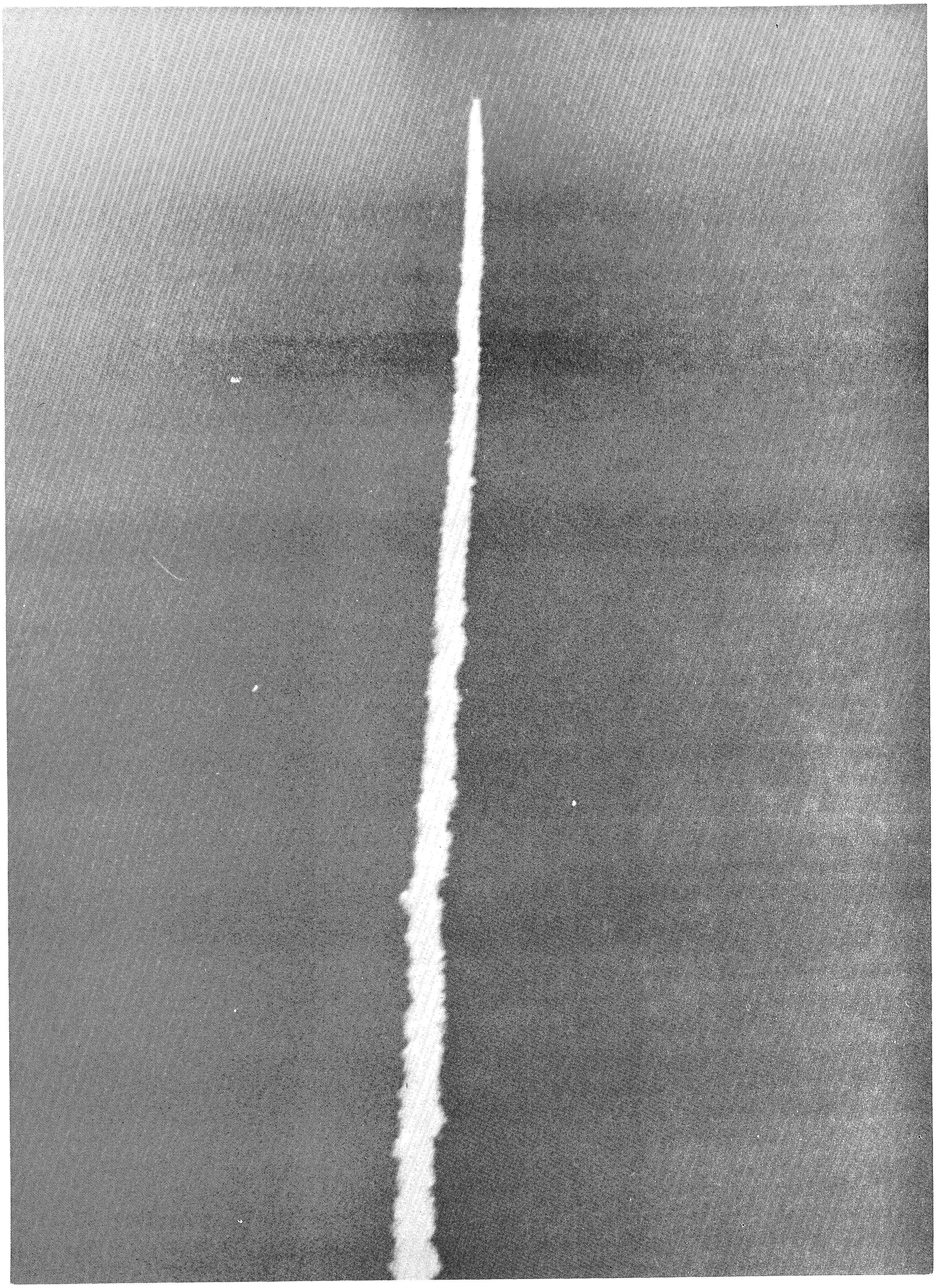


Fig. 5. Same rocket and smoke trail as in Fig. 4, but one or two seconds later.

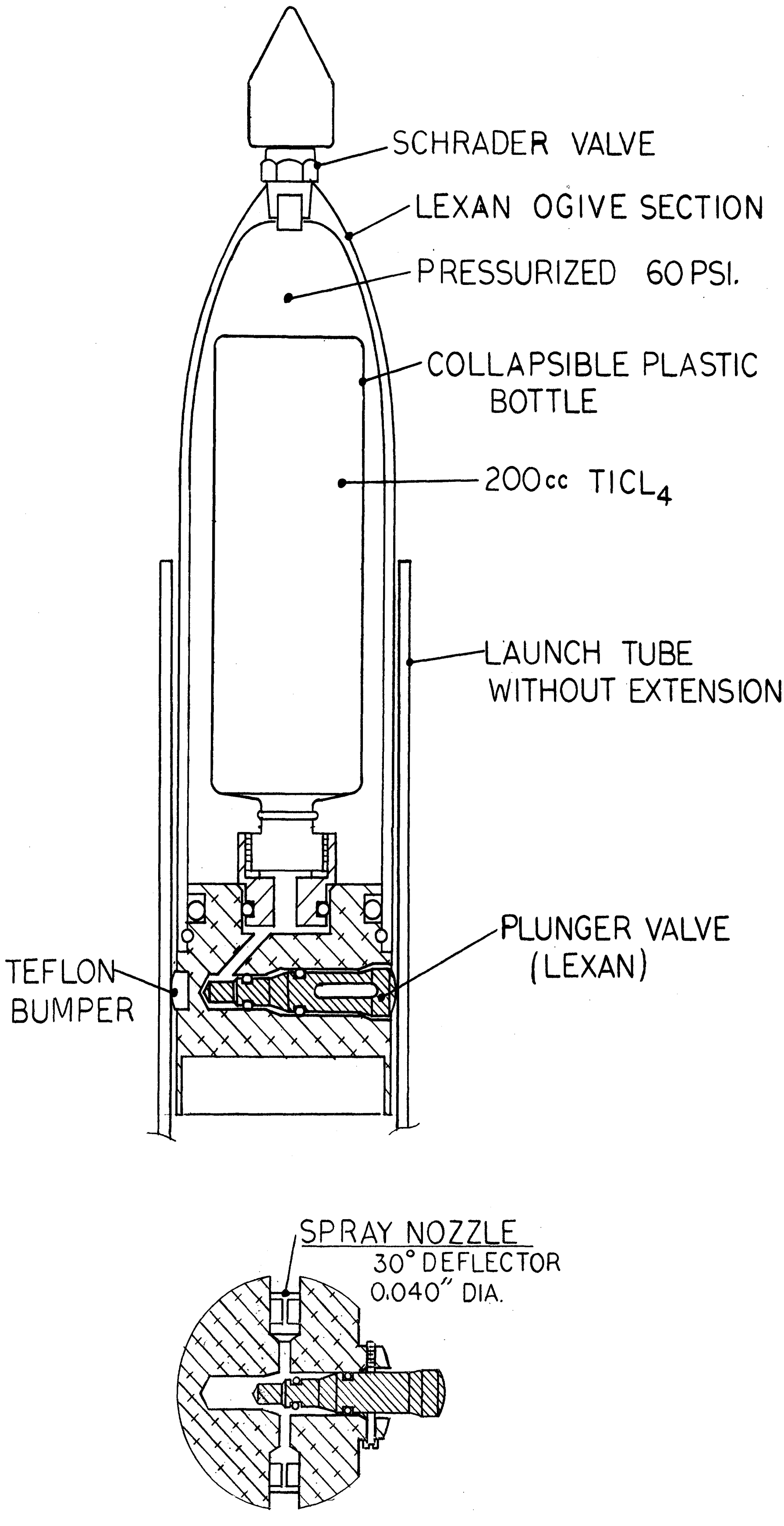


Fig. 6. Schematic drawing of "smoke" rocket canister fitted with the "plunger valve" liquid release mechanism. In the upper drawing the "smoke" canister is shown in the rocket launcher being prepared for launch. The plunger valve is held in the closed position until the canister leaves the end of the launch tube extension. In the lower drawing, the plunger valve is shown in the open, or operated, position.

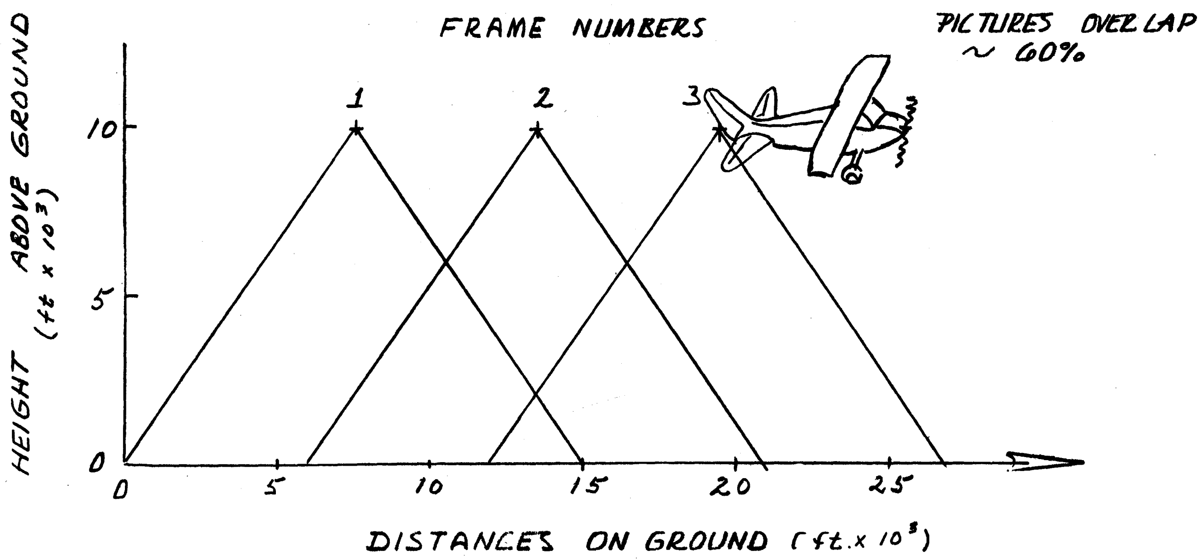


Fig. 7(a). Aerial mapping routine.

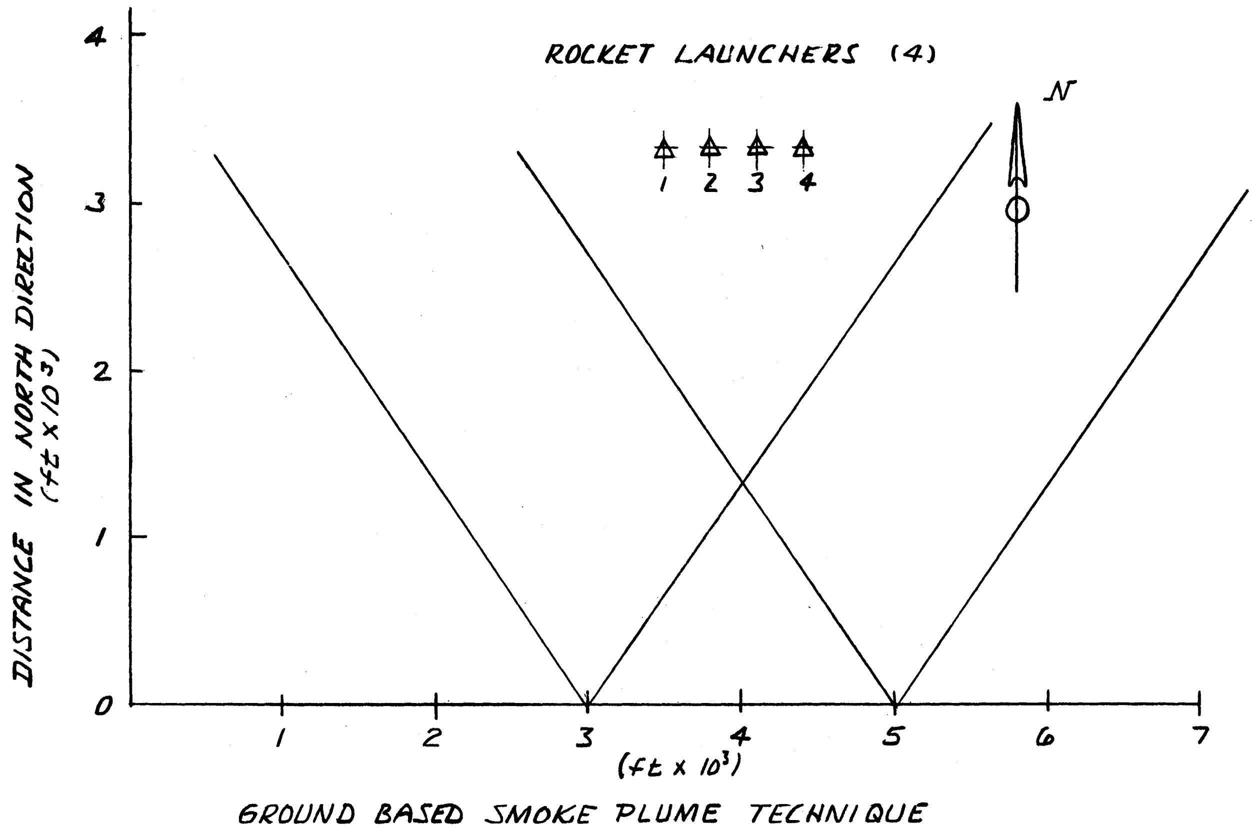


Fig. 7(b). Stereoscopic photography.

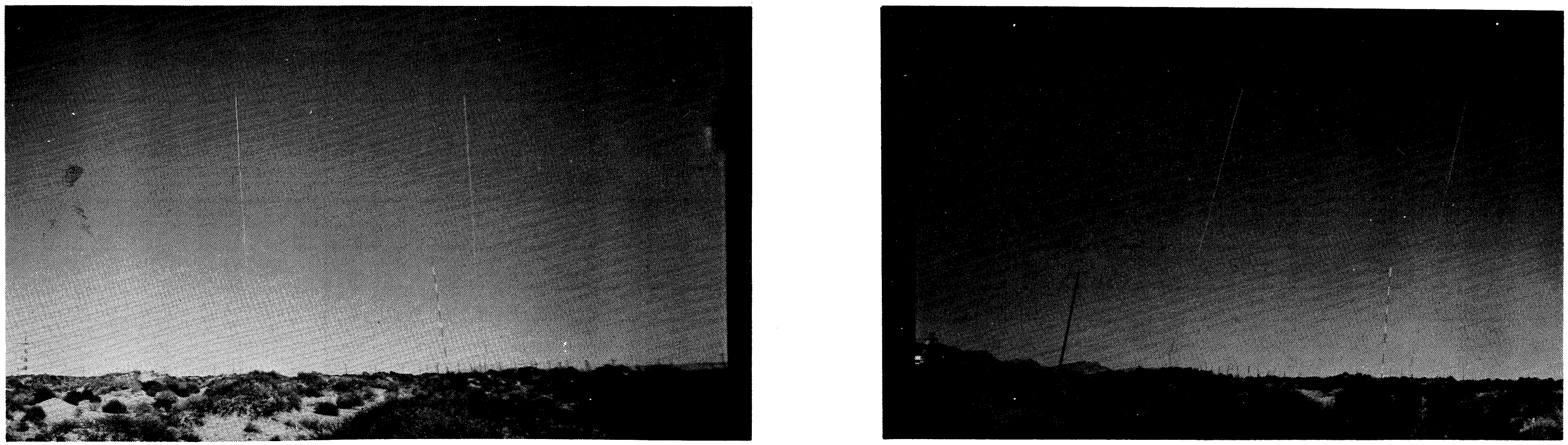


Fig. 8. Simultaneous photographs of two smoke trails 3 sec after launch. (Separation of cameras - 2000 ft; camera line to launch line - 3300 ft; separation of two launchers - 900 ft; tower height - 500 ft. Note: (1) fiducial points on camera negatives near top right edge of left camera, and near top left edge of right camera, (2) fuzziness of left photograph, right trail caused by vacuum not being applied to camera platen.)

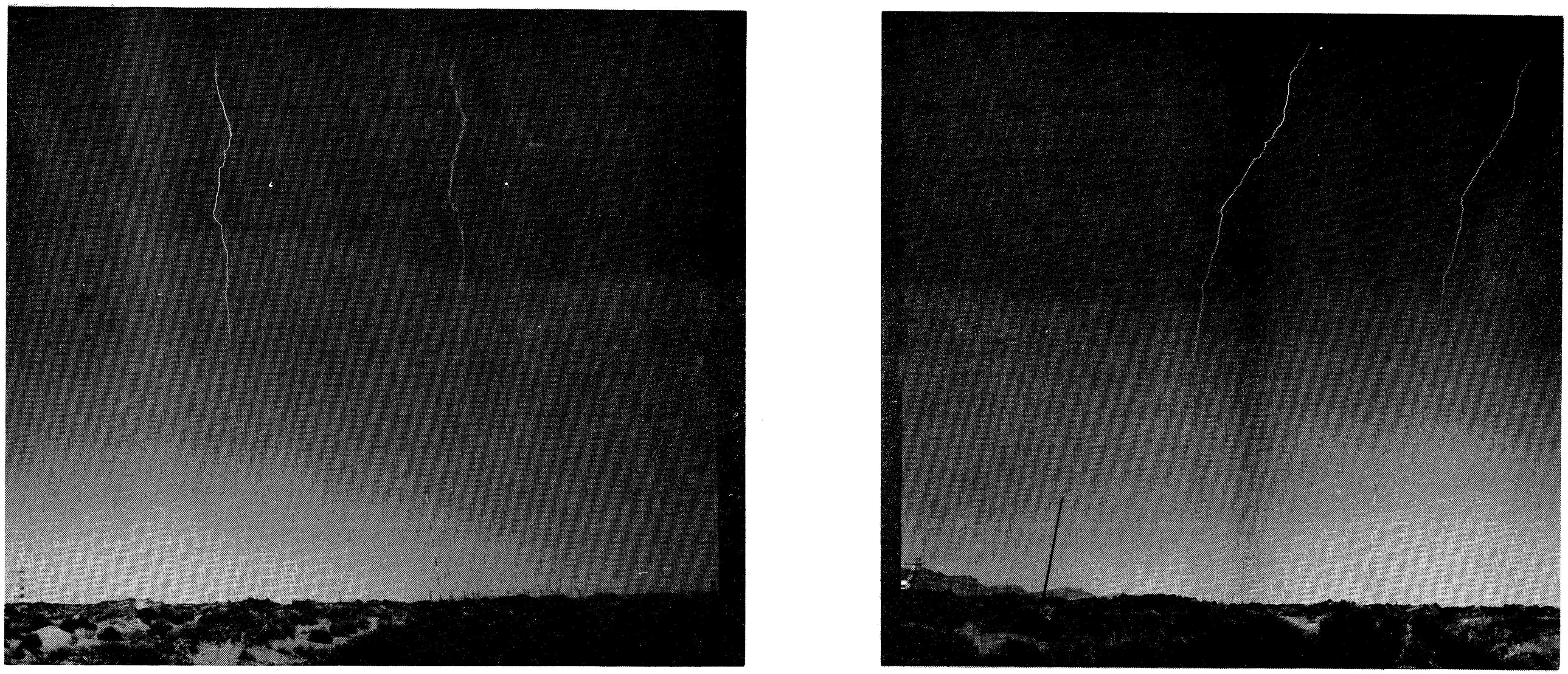


Fig. 9. Simultaneous photographs of same two smoke trails as in Fig. 8, but 12.0 sec later. (15 sec after launch)

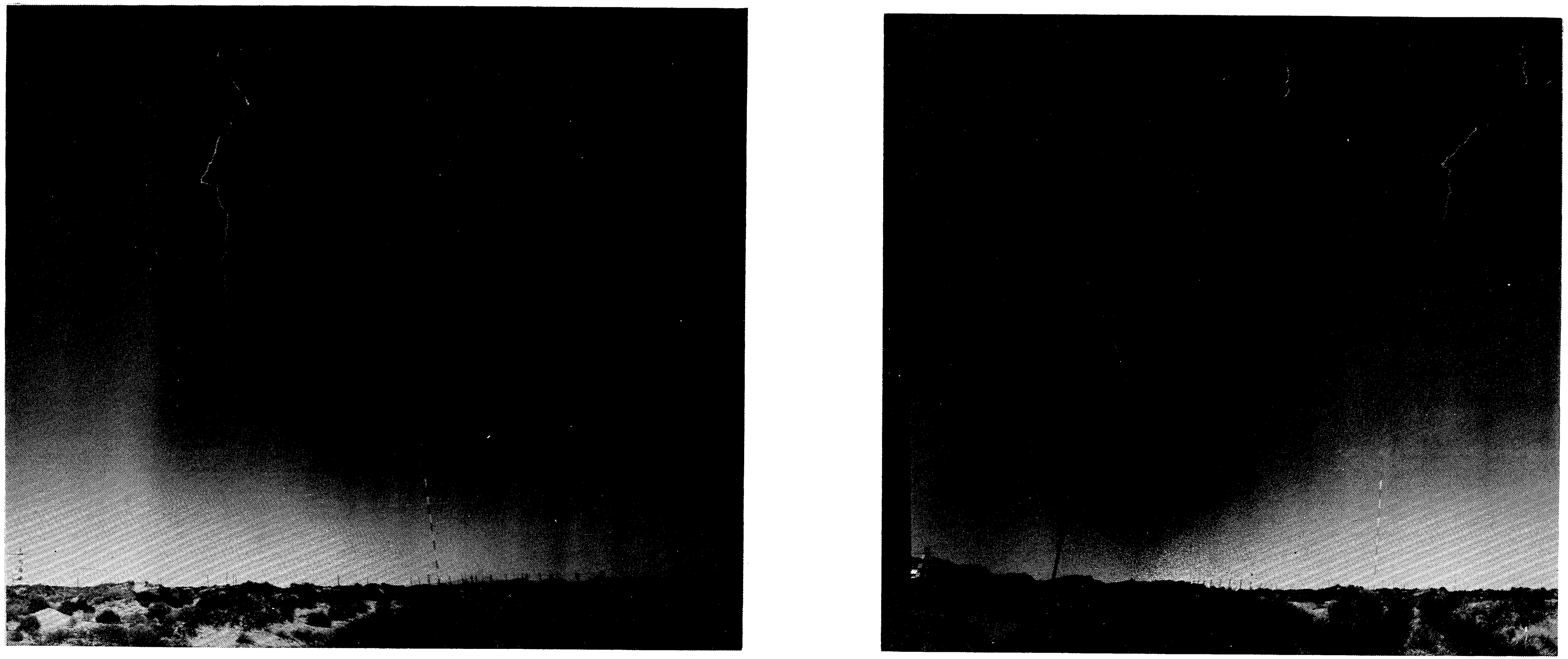


Fig. 10. Simultaneous photographs of same two smoke trails as in Fig. 8, but 24.0 sec later. (27 sec after launch)

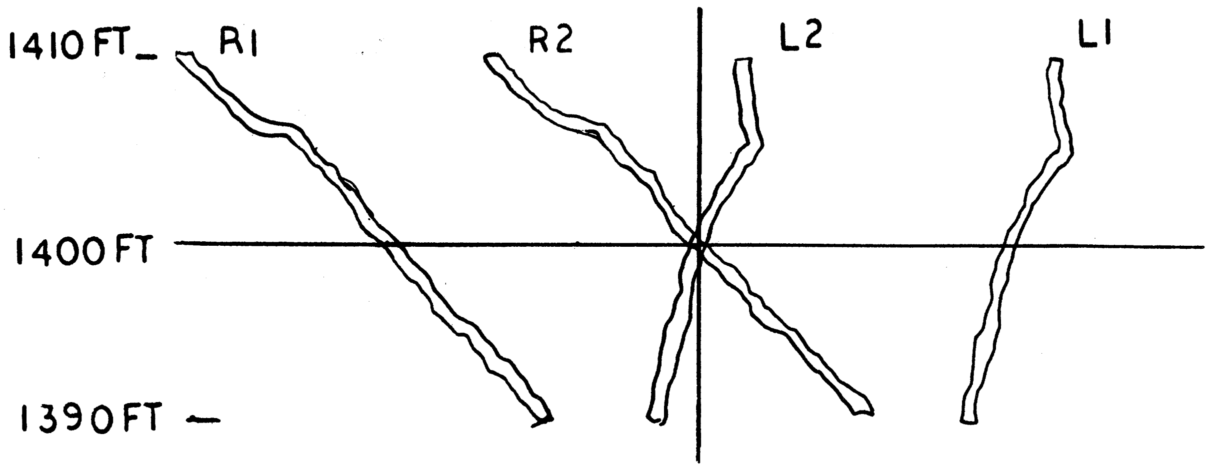


Fig. 11. View in stereo plotter of a smoke trail as seen by two cameras. R1 and L1 is view before X and Y dials turned; R2 and L2 is view when X and Y positions may be read for Z = 1400 ft.

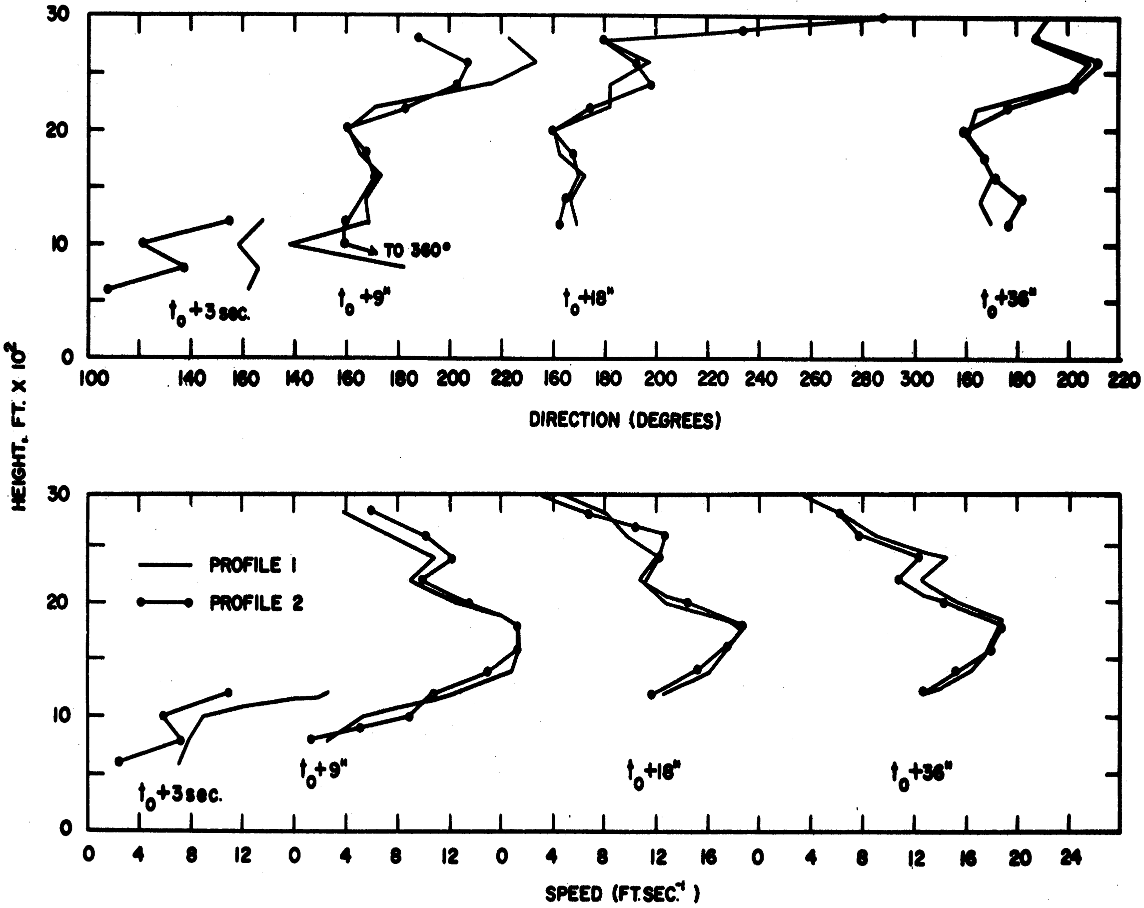


Fig. 12. Distance variation of wind profiles derived from smoke trails at two locations separated by 900 ft at White Sands Missile Range. December 19, 1966, 1130 MST.

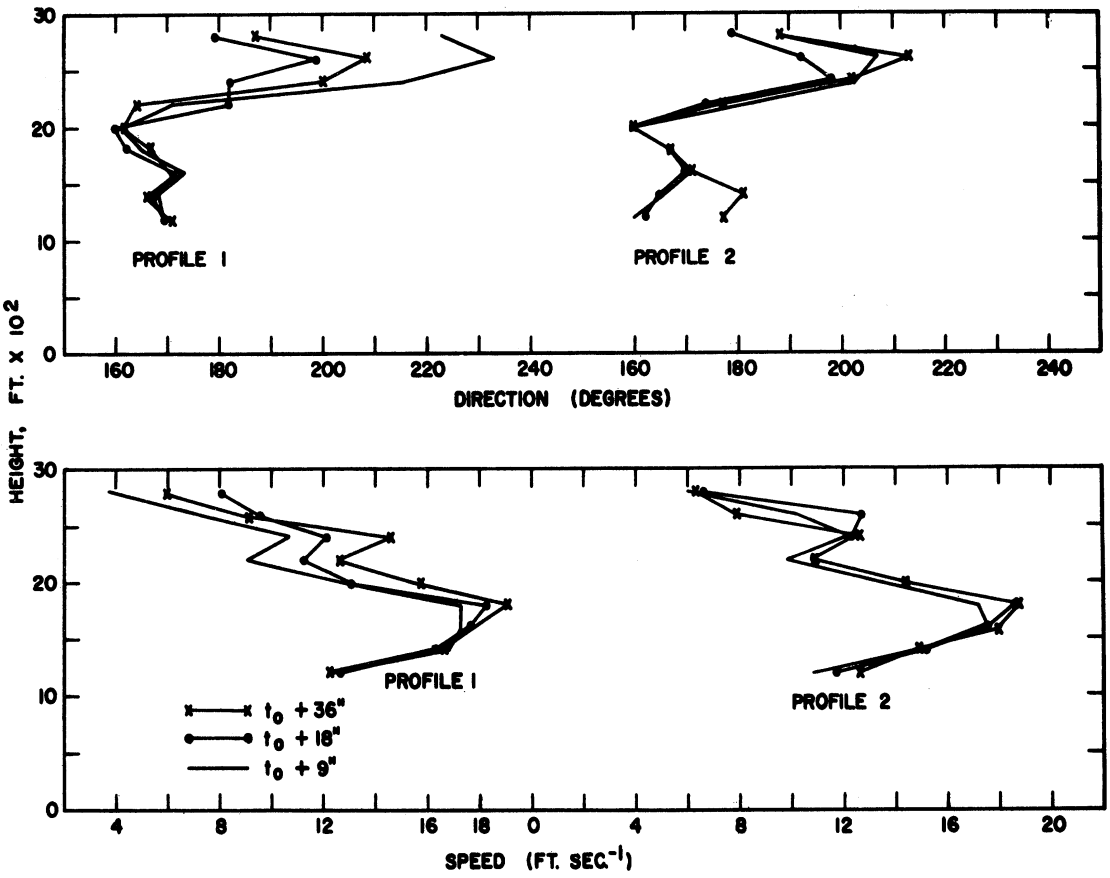


Fig. 13. Time variation of wind profiles derived from smoke trails at two locations separated by 900 ft at White Sands Missile Range. December 19, 1966, 1130 MST.

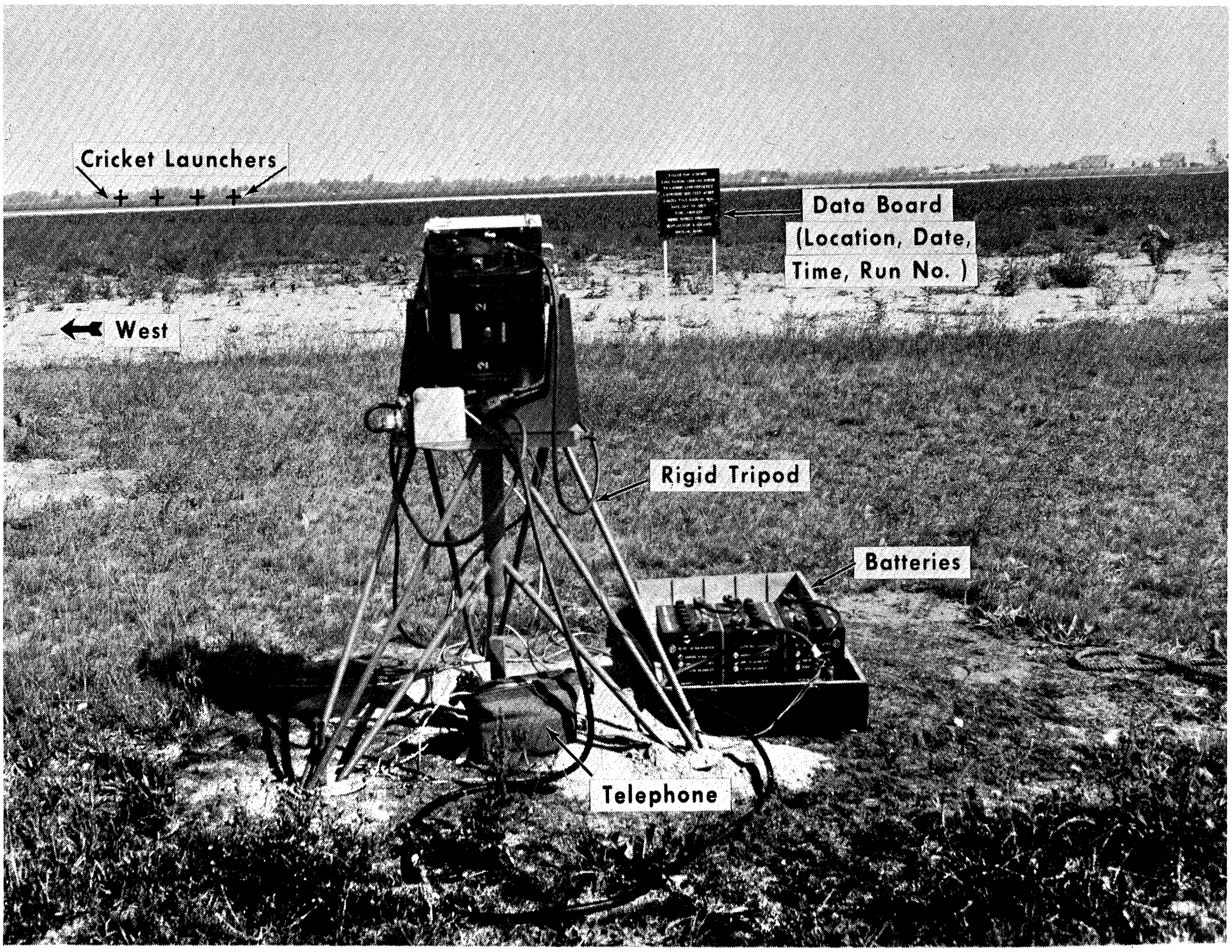


Fig. 14. East camera installation, Willow Run Airport. (Camera line 3300 ft south of launch line. Launchers 300 ft apart.)

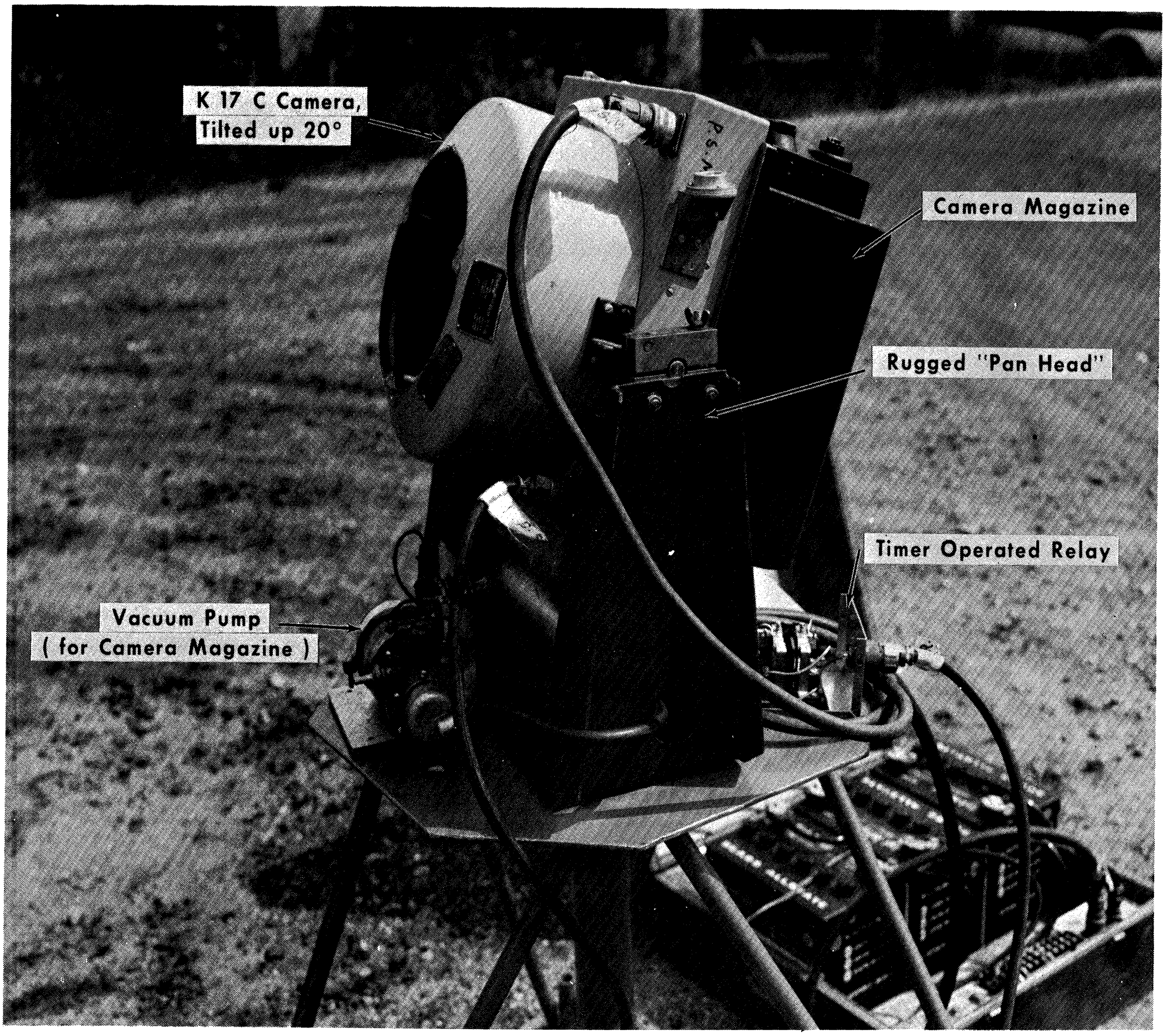


Fig. 15. Close-up of camera system.

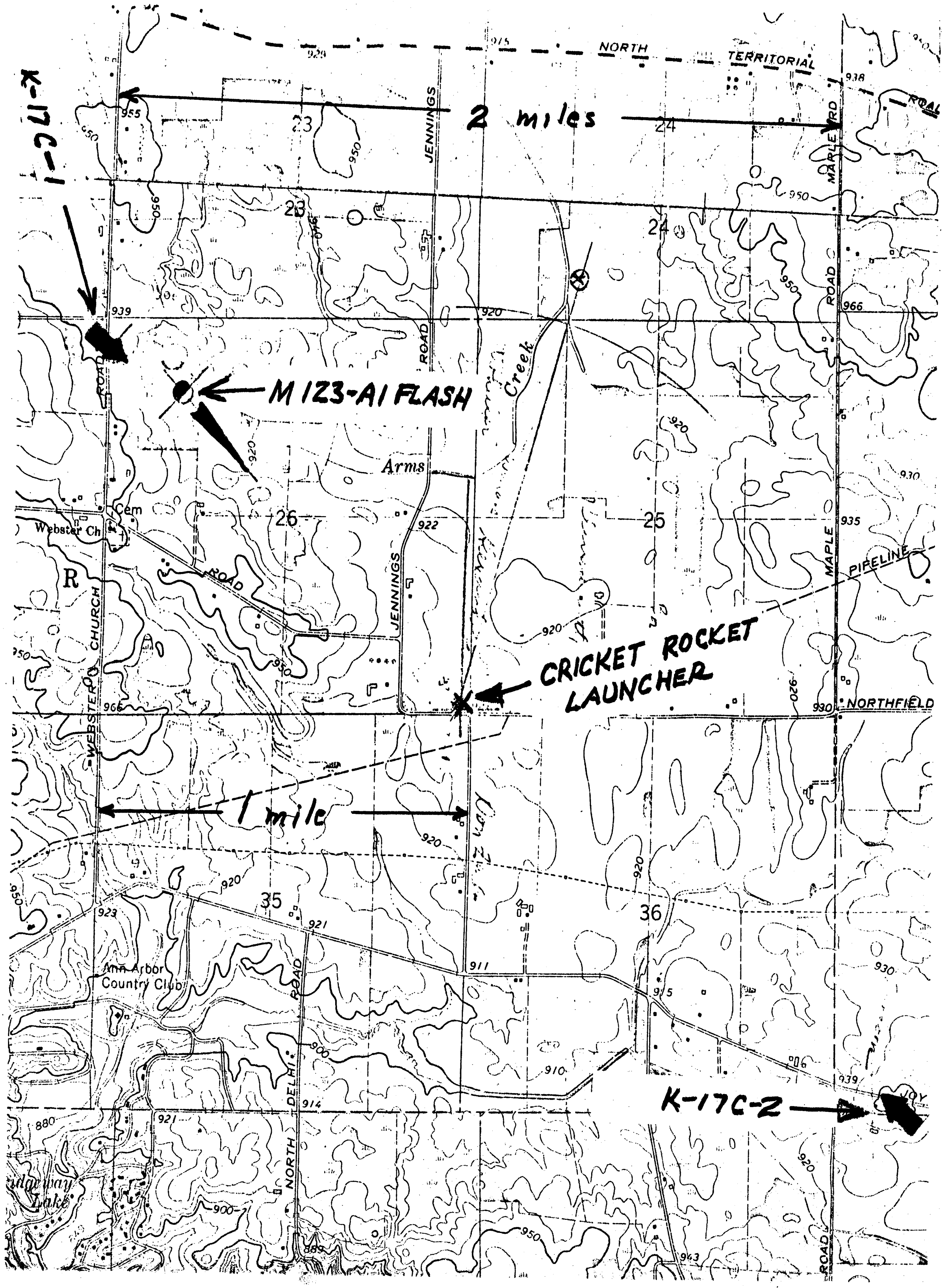


Fig. 16. Launch site for night firing of Cricket smoke rocket.

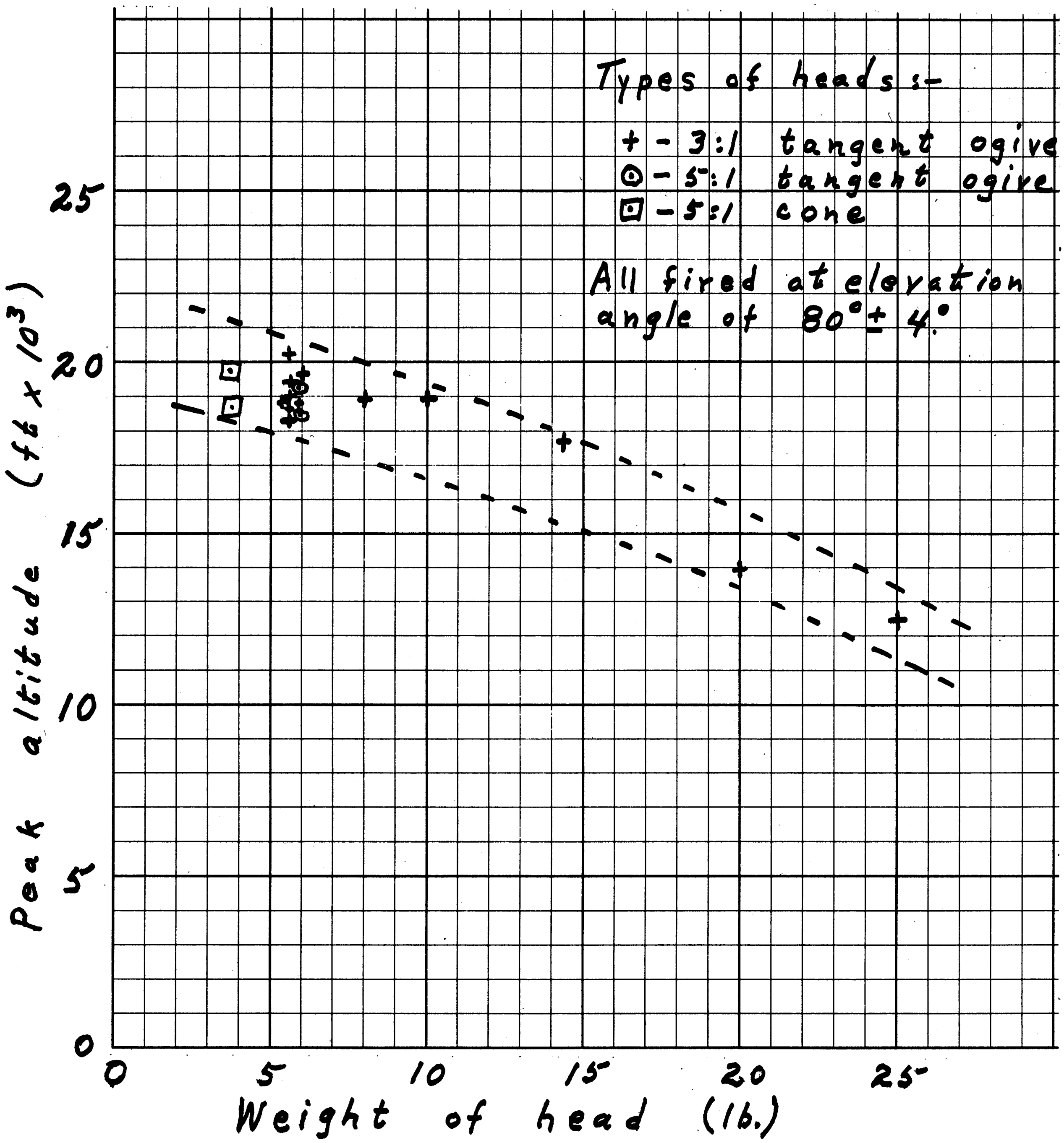


Fig. 17. Payload weight vs. apogee of 2.75 in. FFAR rockets for nose cones of three different shapes. Note little difference in performance of three shapes—all acceptable. (Data from report by Lord, Milliner, and Stengel)

(a) (b) (c) (d)

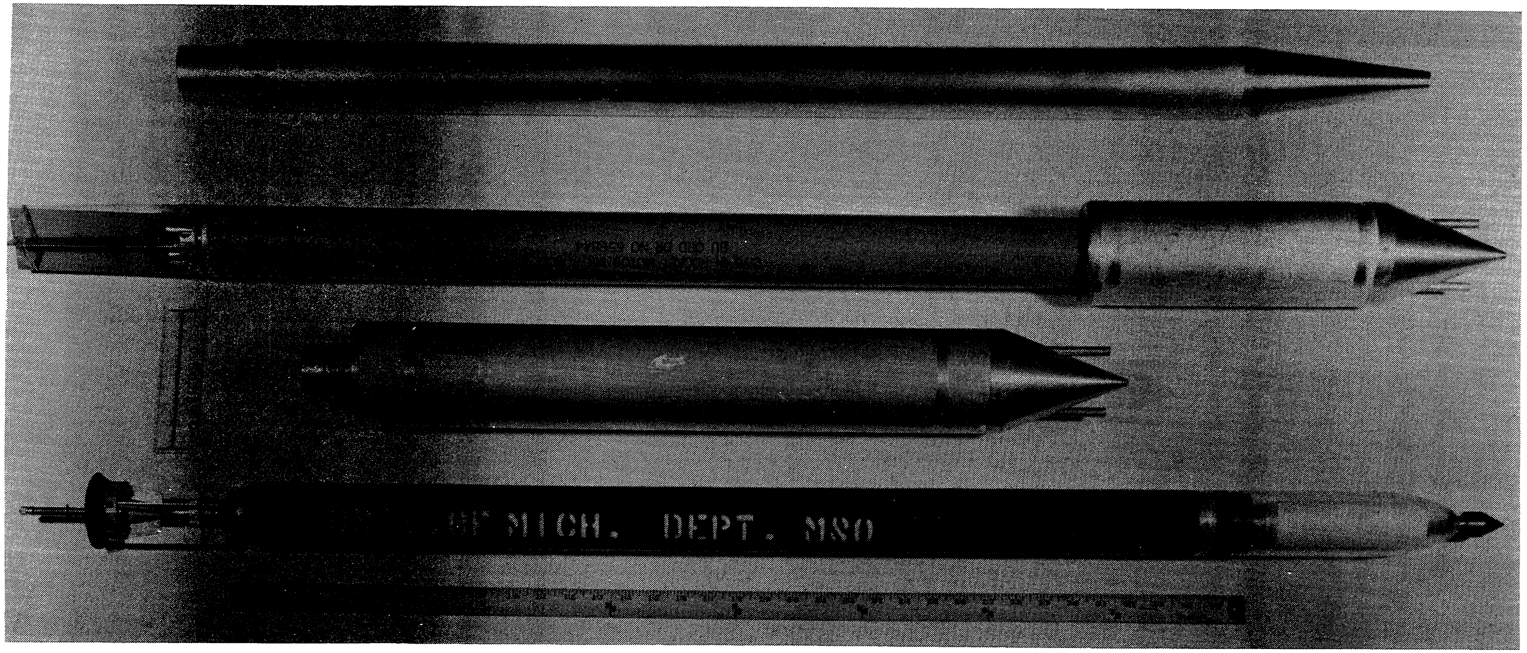


Fig. 18. Models of various "smoke rockets" developed on this contract. (a) Second model 2.75 in. FFAR smoke rocket, developed but not tested. (b) First model 2.75 in. FFAR smoke rocket, shorter version, attached to FFAR rocket (5 lb $TiCl_4$). (c) First model 2.75 in. FFAR smoke rocket, longer version (13-1/2 lb $TiCl_4$). (d) Cricket smoke rocket, complete.

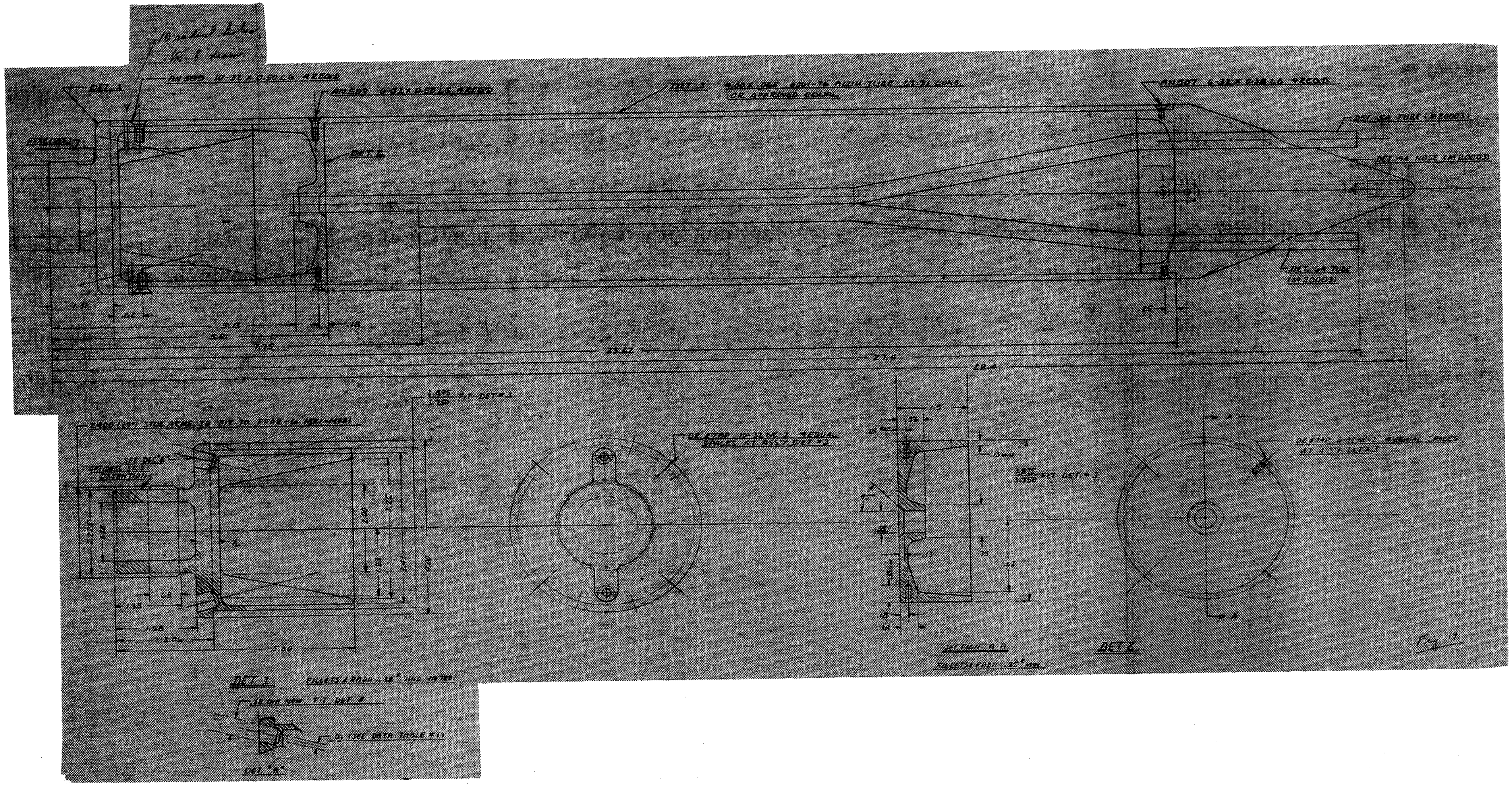


Fig. 19. Design drawing of first model 2.75 in. FFAR smoke canister (longer version).

(a) (b) (c)

Fig. 20. Preparation for launching 2.75 in. FFAR smoke rockets. (a) Filling short version with $TiCl_4$ (canister screwed on rocket and latter in launcher). Note launcher angle 5° off vertical. (b) Attaching nose cone to short version just prior to launch No. 2. (c) Completing launch preparations of longer version of smoke canister. Note smallness and simplicity of launcher—essentially a steel tube held nearly vertical with lower end sealed and supporting a coaxial electrical plug for firing rocket remotely.

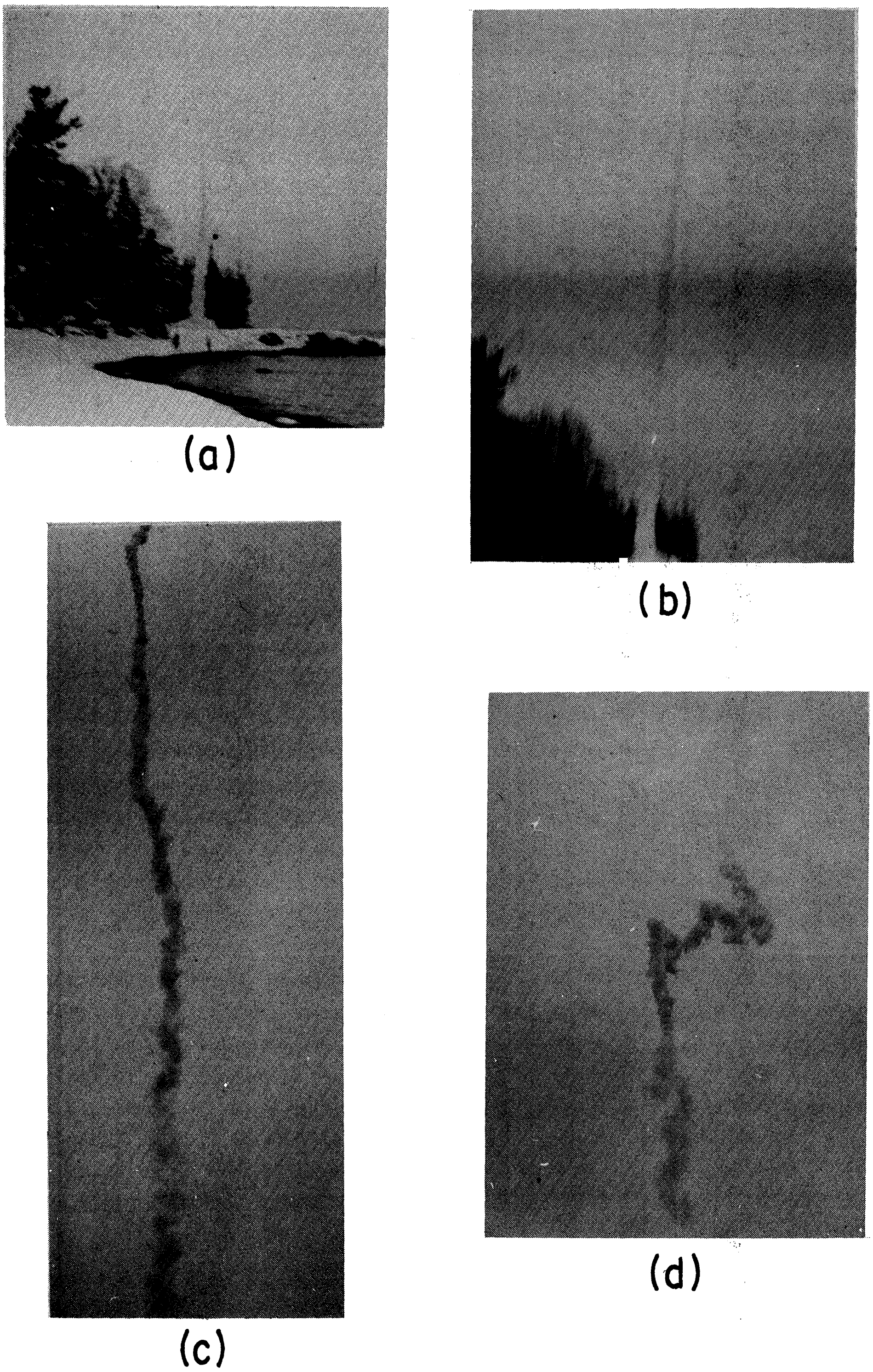


Fig. 21. Smoke plumes from shorter versions of first model of FFAR smoke rocket. (a) Launch No. 1—note adequate smoke plume forming. (b) Launch No. 2—again note adequate smoke plume forming. (c) Typical portion of plume, 10 sec after No. 2 launch—adequate volume of smoke. (d) Top portion of plume, 3 min after No. 2 launch—believe all $TiCl_4$ ejected from upper portion of smoke canister significantly below rocket apogee, confirming need for larger volume of $TiCl_4$ than is in short version of canister.

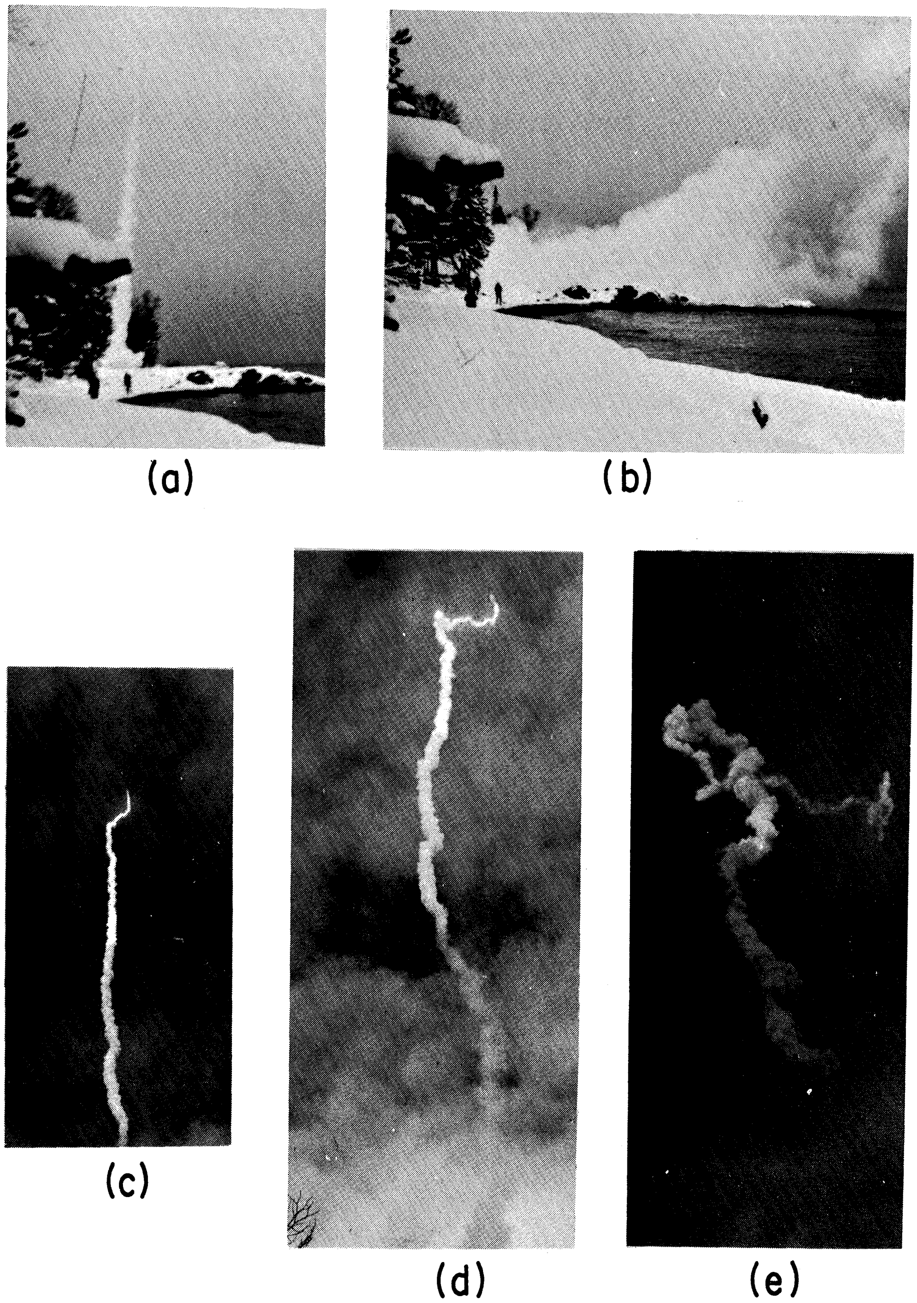


Fig. 22. Smoke plume from longer version of first model of FFAR smoke rocket—full quota of $TiCl_4$. (a) Launch No. 3—note more than adequate volume of smoke near ground. (b) Launch site 25 sec after No. 3 launch—markedly larger volume of smoke than needed. (Confirms engineering design that doubling height of $TiCl_4$ liquid would markedly increase $TiCl_4$ emission rate near ground.) (c) Upper portion of No. 3 launch about 12 sec after launch. (d) Upper portion of No. 3 launch about 20 sec after launch. (e) Upper portion of No. 3 launch about 45 sec after launch—smoke trail probably reaching to near apogee and 2000 to 4000 ft higher than in (d). Note strong shear layer at level just below top of photos (c) and (d).

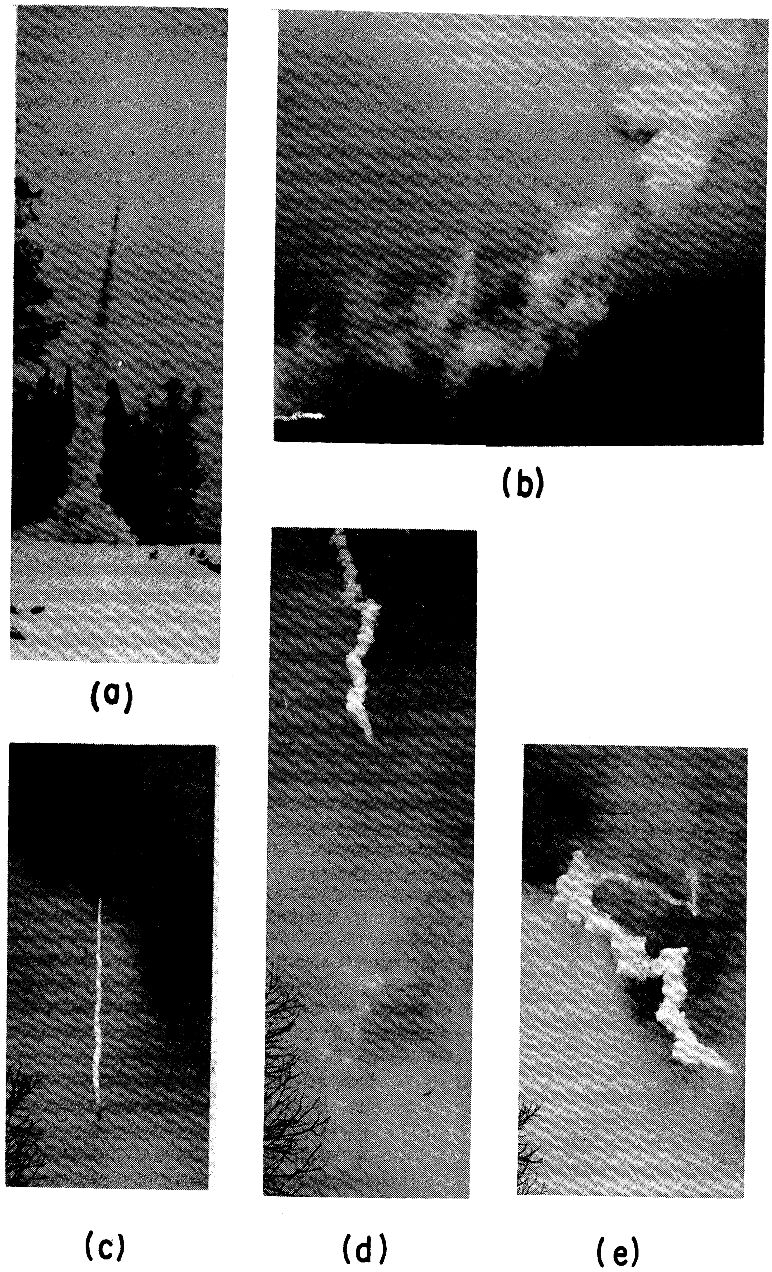


Fig. 23. Smoke plume from longer version of first model FFAR smoke rocket—full quota $TiCl_4$ in lower chamber; about 1/2 quota in upper chamber. (a) Launch No. 4—note more than adequate volume of smoke near ground. (b) Launch site 25 sec after launch—note more than adequate volume of smoke. (c) Midportion of ascent (say 1000 to 3000 ft above ground) about 10 sec after No. 4 launch. Note break in plume at phase shift from acceleration to deceleration—for explanation see text. (d) Phase shift portion of plume about 20 sec after No. 4 launch. Note distinct break between thin smoke of latter portion of acceleration phase (lower part of photo) and dense smoke of deceleration phase (upper portion of photo). (e) Upper portion of ascent, about 45 sec after No. 4 launch. Note distinct but weak smoke trail of upper portion of ascent, indicating main supply $TiCl_4$ exhausted from upper chamber well before apogee. Weak trace probably due to $TiCl_4$ vapor leaving both upper and lower orifices as air rushes through both chambers.

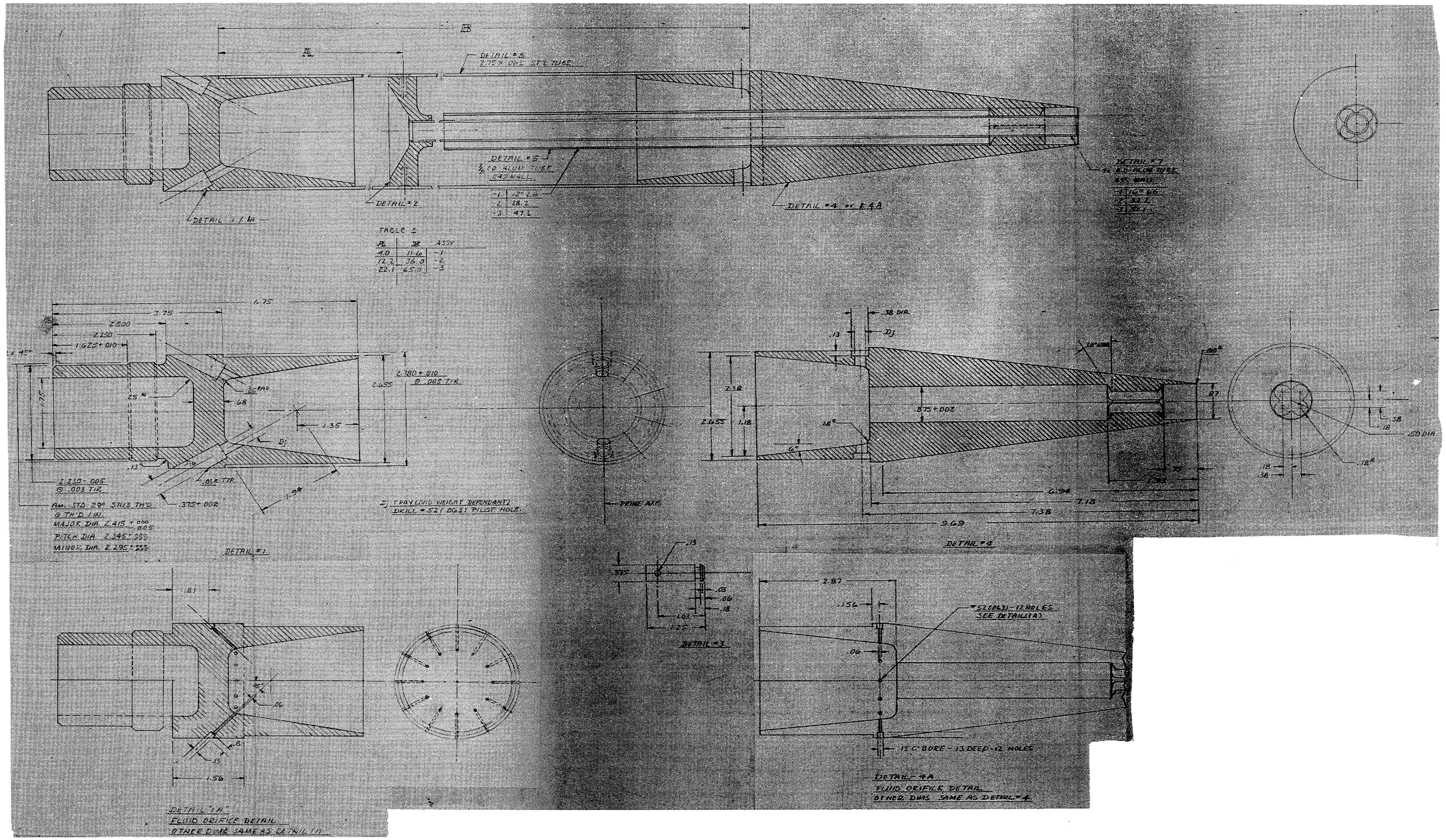


Fig. 24. Composite design drawing of second model 2.75 in. FFAR smoke canister.

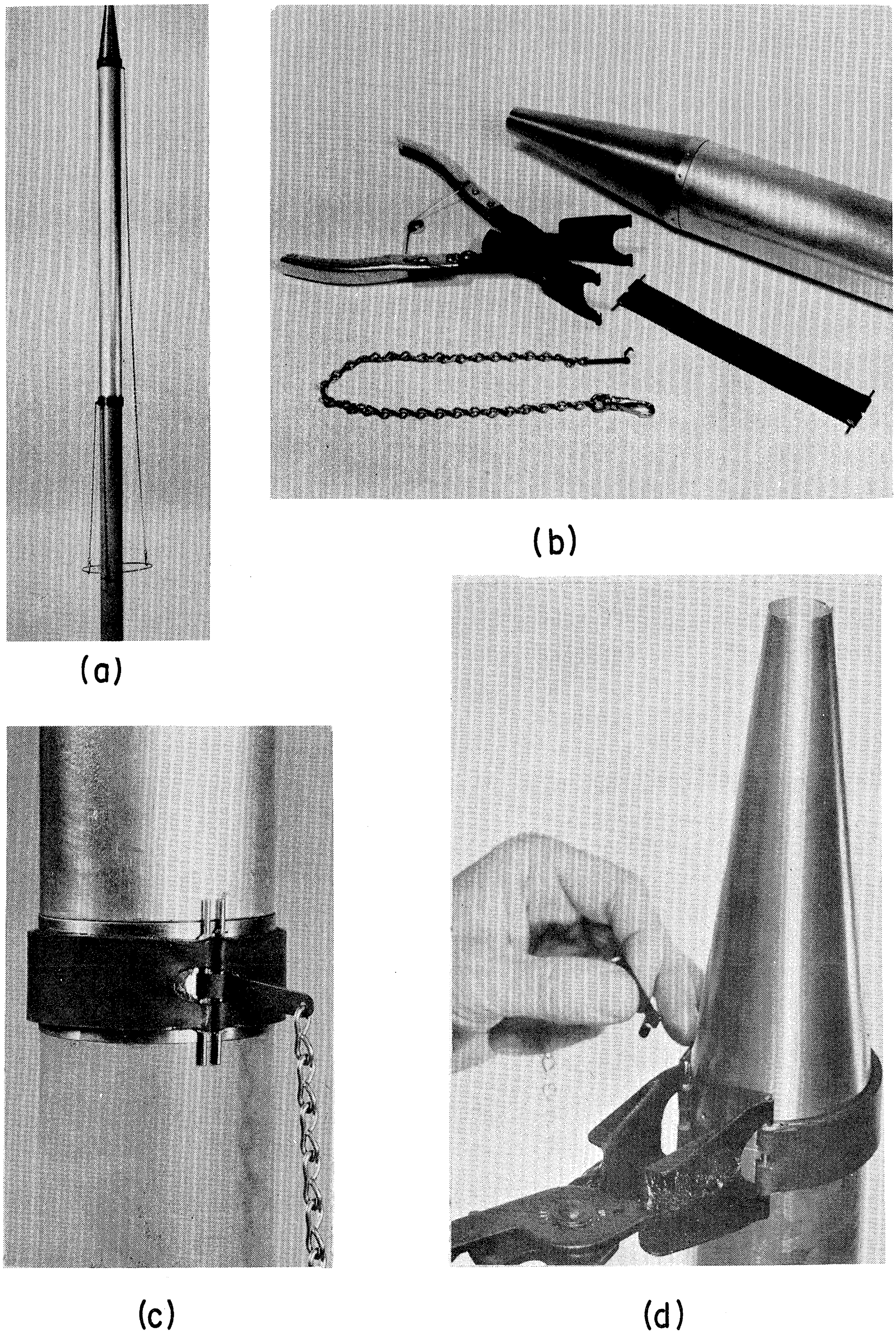


Fig. 25. Second model of 2.75 in. FFAR smoke rocket showing elastic bands used to seal upper and lower orifices. (a) Elastic ("Viton") bands, quick-release clips, and light chains in place, ready for filling with $TiCl_4$. Lower anchor ring would be rigidly fastened to outside of launcher tube. (b) Shows details of Viton strap, quick-release clip on chain, and special pliers for assembly. (c) Close-up of strap and quick-release clip in place. (d) Operator installing strap and clip on upper orifices.

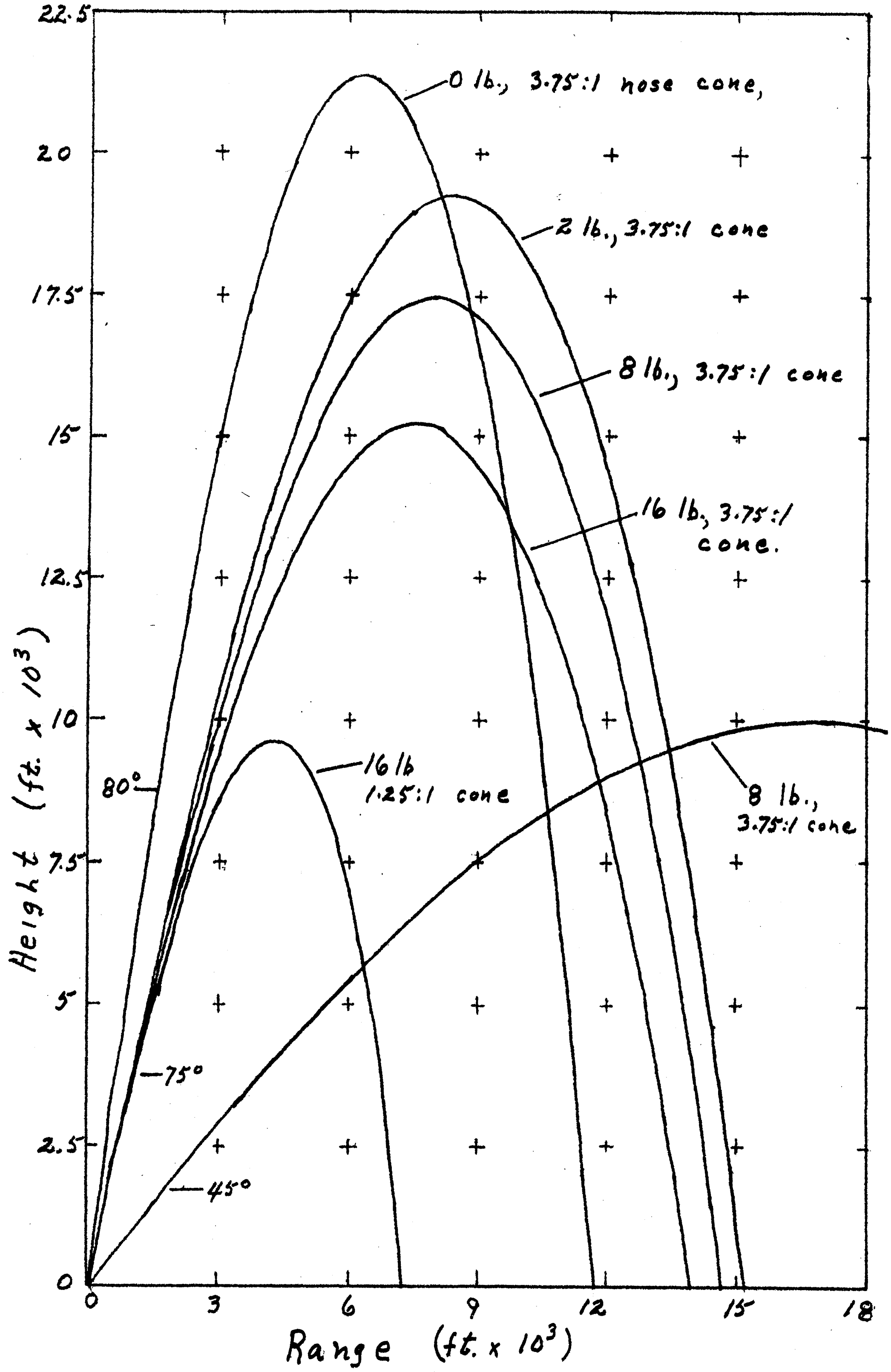


Fig. 26. Computer simulation of expected performance of first and second models of 2.75 in. FFAR smoke rockets. First model had 1.25:1 nose cone and was 4.00 in. diameter; second model 3.75:1 nose cone and was 2.75 in. diameter. Weights given are for total head weight. For other data see Table III.

SUPPLEMENTARY DATA

(Articles, manuals, selected chapters, and books supplied to, or referenced for, WSMR as part of the final report—but not bound with this report.)

A. Data associated with the Cricket rocket

1. Cricket, Model IV, Cold-Propellant Rocket, Operating and Maintenance Instructions, TEI-71, May 1967.

2. Appendix A, Cricket Rocket Trajectory Analysis, P5-642.

3. "A Smoke Rocket Technique for Daytime Wind Measurements to Three Thousand Feet," by Gerald C. Gill, Albert W. Stohrer, and Timothy L. Sweeney, paper presented at the Unguided Rocket Ballistics Meteorology Conference, New Mexico State University, Oct. 31 - Nov. 2, 1967.

4. "Wind Profiles and Shear Derived from Smoke Trails," by Manuel Armendariz, Laurence V. Rider, and Gerald C. Gill, paper presented at the Unguided Rocket Ballistics Meteorology Conference, New Mexico State University, Oct. 31 - Nov. 2, 1967.

5. Technical Notes #1, 2, 3, 4, and 5 on development of Cricket Smoke Rocket.

6. Fabrication drawings of Cricket smoke cannister fitted with "plunger valve" liquid release mechanism (Fig. 6 of report). "Liquid Dispenser Smoke Payload, Cricket," drawing #M 20005. Design—G. C. Gill; drawn by—A. W. Stohrer.

B. Data associated with the development of the stereoscopic technique of recording and analyzing smoke plumes.

1. "Photogrammetry," second edition, by Francis H. Moffitt, Int. Textbook Co., 540 pp, 1967.

2. "The Physical Aspects of Aerial Photography," by G. C. Brock, Dover Publications Inc., 267 pp, 1967.

3. "Information Capacity of Photographic Materials," by G. C. Higgins, Eastman Kodak Co.

4. Assorted design drawings of "rigid tripod" for aerial cameras, by Albert Stohrer.

C. Data associated with the photographing of smoke plumes at night.

1. Installation and Maintenance of Aerial Photographic Equipment, USAF Manual 95-3, December 1961, Chapter 7. (This chapter discusses night lighting techniques and equipment.)

D. Data associated with the development of the smoke rocket technique to heights of at least 8000 ft.

1. Meteorological Rocket Program, Vol. I, "Meteorological and Sounding Rocket State-of-the-Art Study," by J. R. Brasfield, Report #RH-TR-65-1, July 1965.

2. 2.75" Folding-Fin Aircraft Rocket, Description and Instructions for Use, OP 1793, Bur. of Ordnance Publ., September 1954.

3. "The 2.75" FFAR Test Rocket," by Wm. L. Lord, Cary F. Milliner, and Robt. F. Stengel, NASA, Wallops Island, unofficial report, Sept. 1963.

4. Fabrication drawings of second model of 2.75 in. FFAR rocket smoke canister, "Liquid Dispenser Smoke Payload FFAR," Drw. #M 20006, 20007—designed by G. C. Gill and A. W. Stohrer.

APPENDIX A

NOTES ON PROBLEMS WITH SMOKE ROCKETS AT WHITE SANDS MISSILE RANGE, DECEMBER 15-21, 1966

NOTE: Part numbers referred to in the following are their part numbers found in "Rough Draft, Cold—Propellant Rocket System," of Texaco Experiment Inc., dated October 26, 1966.

I. Payload Section

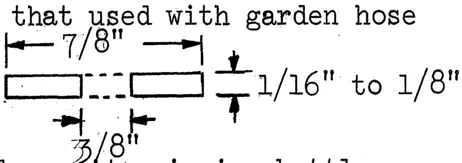
(a) Threads on Valve Sleeve C-7 do not mate bottles B well—threads on C-7 roughly turned, (appears as if saw tooth in cross-section instead of good mate to bottle threads), and terminate in rough manner at inner end. This results in cross-threading too easily—one should remember that working with gloves and with a fuming acid trying to fit a soft bottle to a poorly threaded part leaves much to be desired. Result is leaky seal for $TiCl_4$—often half of $TiCl_4$ was out of bottle into Nose A2 before firing.

Another problem here is in holding Bottle B tight enough, even at its base or its top, to give much turning torque without squeezing liquid out of bottle. Also difficult to hold Valve Sleeve C-7 tight enough with other hand without withdrawing Valve Sleeve C-7 from Base D-2. If this removed, difficult to avoid gloves touching greased o-rings C-6 and C-8 and possibly getting dirt on them.

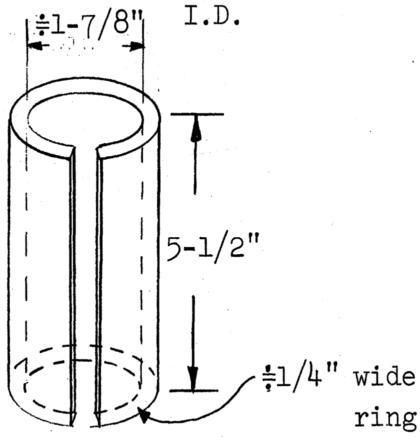
Suggested correction techniques:

(i) Improved threads on Valve Sleeve C-7

(ii) Use of Viton washer of shape similar to that used with garden hose fittings (we have a sheet of .075 in. Viton on order, to try out this idea.)



(iii) Provide a simple bottle holder that will permit gripping bottle more firmly without it partially collapsing when screwing into place. (Holder when squeezed tightens on full length of bottle. Have just tried a second bottle, top cut off; slit down side and bottom; and most of bottom cut away—believe it will work satisfactorily.)



(iv) Provide a pair of "pliers" with rubber or plastic covered jaws to grip Valve Sleeve C-7, while C-7 is still inserted into D-2.

(b) "Stainless Steel" balls C-3 rusted badly with $TiCl_4$—gave rise to many failures of rocket to make "smoke"—probably reason for 30-60% of failures. Rust caused friction not only in axial guides that each had to slide in, but friction with Inertial Weight C-4 and inner groove of C-7.

<u>Suggested correction technique</u>:

(v) Use balls that do not corrode at all under conditions of use, and which are compatable with other needs. (We have obtained some balls of same diameter of unhardened Stainless Steel; Lexan; pyrex glass; and expect some of teflon—all to be tested as soon as possible, for inertness to $TiCl_4$ for not flattening under pressure, and for suitability in this application.)

(c) Fluorlube Grease #GR-362 (Fischer Scientific cat. #F-20) withstood $TiCl_4$ fine, but was considered too viscous for use on balls and on Lexan part C-2. Believe high viscosity prevented balls from closing in radially fast enough when Inertial Weight C-4 depressed upon rocket firing so that inertial weight returned to socket with no subsequent emission of $TiCl_4$ and thus another failure. Since thin fluid lubricant should be suitable for balls and O-rings, consider the high viscosity of grease a definite liability rather than an asset.

The unlabelled second type of lubricant supplied by Texaco Experiment Inc. (in tube form) broke down quickly when tried—became brown in a minute or so, later formed dry white paste that was a nuisance to clean off and did no good. Kel-F, #90 Grease (3-M Co.) stood up well to $TiCl_4$, but was too viscous for our needs.

Removal of all O-rings, thorough cleaning, and relubrication was a time consuming job. Also chance of cutting O-rings.

<u>Suggested correction technique</u>:

(vi) Use inert fluid lubricant say SAE 10-30 viscosity on balls and on all O-rings—thin enough to be applied with a small brush; a lubricant for all sliding surfaces; that does not combine with water (in later washing); that does not react with Lexan, Viton, or balls; stands up to $TiCl_4$; and does not clog $TiCl_4$ passageways.

(We have four samples of Dow Corning fluorosilicone on the way for testing:

Fluids #FS-1265

3 grades, Viscosities 300
1000
10,000

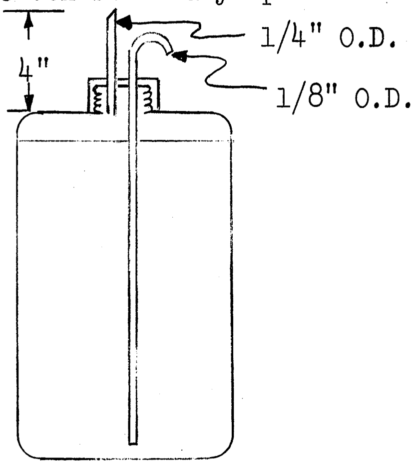
Grease #FS-1292, penetration = 280, and hope to run tests during next two weeks. These are materials one of their chemical engineers recommended for this application.)

(d) Lexan appeared to stand up well (excepting when contacted by acetone); likewise Viton "O" rings—no change needed. Same true of high density polyethylene bottles—none failed even after several hours exposure to $TiCl_4$.

In the three or four failures of Lexan parts, these had been attacked by the acetone—latter spilled down rocket when charging motor. In one or two cases of cracks appearing in Lexan nose cone A-2 around Valve Stem A1-3 where it is cemented into place, fractures may have been caused by impact with ground, instead of by chemical reaction with acetone—time will tell. But in two cases where Base D-2 attacked by acetone, fractures in nose cone as noted above occurred, suggesting both caused by acetone. (Fractures caused rapid loss of gas pressure and may have been reasons for some failures to produce smoke.)

<u>Suggested correction technique</u>:

(vii) When using acetone filling bottle TEI Part #938, use modified pour cap TEI Part #939 that greatly reduces spilling of acetone. Likewise hold inverted rocket with fluid absorbing cloth so if any spilled it will not reach Lexan payload below.



Suggested modified pour cap.

(e) Desirable all Lexan parts be interchangeable. Most of Nose Cones A-2, and Bases D-2 are interchangeable, but several C-2 parts will not fit into part C-7; whereas others are too loose.

There is more variability in freedom of movement of the balls in the ball guides than there should be, even when new—all balls should roll under gravity from one end of guide to the other without difficulty.

(f) Rusting of the Inertial Weight C-4 was not as disastrous as that of the balls C-3, but was significant. Also part C-4 would easily bind in the passageway of Sleeve C-7.

Suggested correction technique:

(viii) Use Inertial Weight of material not attacked by $TiCl_4$—maybe brass. Or coat C-4 with material not attacked by $TiCl_4$, say teflon coating. (A somewhat smaller diameter of metal part would be needed to allow for teflon coating—but desirable keep mass as high as it is now, or even greater—suggest section where diameter is greater (.459 in.) to be made longer, also this part should have slightly smaller diameter, and rounded edges—to reduce binding in passageway.

(g) Locking Strip E worked well, except bent end broke off several times.

(h) $TiCl_4$ got into some clocks—primarily from dripping from three orifices, I expect. This caused rusting of clocks, and need for washing out clocks in water, then drying. Latter could contribute to rusting as well.

Suggested correction technique:

(ix) After winding clock to desired extent suggest one turn of tape (drafting), around rocket to close all holes that would permit $TiCl_4$ getting to clock. (Must be careful not to use too thick tape to cause binding of rocket in launch tube, or other problems.)

II. Other Rocket Sections

(a) Sometimes shrouds of parachute broke—probably due to weakening by exposure to $TiCl_4$. Must watch this.

Lanyard broke on at least one occasion. When checking for repeat firing best to replace lanyard if in doubt.

(b) Upon recovery of nozzle plug after firing, small O-ring usually no longer in groove, but near center of plug. What does this signify?

APPENDIX B

STEREO PHOTOGRAMMETRIC COLLECTION
(Albert Stohrer)

SECTION B

The collection of position data through the use of a pair of cameras deployed as a stereo pair is in wide current usage in aerial mapping and surveying. The methodology for collecting and abstracting data is extensively developed and can provide spacial resolutions of position to within 1.0 ft at ranges between 3000 to 4000 ft. The geometrical models that are used in the aerial mapping techniques can be rotated to provide a terrestrial stereo model as shown in Fig. B-1.

In an x, y, z stereo space, the objective is to find the coordinates of the point p(i) given the angles Θ_1, Φ_1, Θ_2, Φ_2, and the baseline length a. The length OA along the z axis is the arbitrary base line length dictated by the scale of the experiment. A camera (in this case one yielding a 9 in. x 9 in. negative) is placed at each point where z = 0 and z = a. The lens axes are arranged so that they are parallel to the O}x coordinate axis. Each lens nodal point then becomes a center of projection. The plane b, c, d, e, represents the film plane in both cameras. This plane, in the Fig. B-1 is translated into the quadrant in front of the projection centers to reduce confusion resulting from image inversion. Each camera is provided with a set of four fiducial marks that locate the center of the photograph and provide an origin of coordinates on the photograph.

The geometry of the camera permits us to derive a set of equations to define the magnitudes of the angles Θ_1, Θ_2, Φ_1, and Φ_2. To make this clear we consider the camera in more detail. In Fig. B-2, a ray a-b passes through the N.P. (nodal point) of the taking lens and forms a point image at y = 0. The skew line c-d from any random point in space passes through the N.P. and is imaged at c. The distance from N.P. to a is by definition the focal length (f) of the lens. The displacement of the point c from z = 0 is then a measure of the z parallax and the displacement from y = 0 the y parallax. Division by f (the lens focal length) provides the tangent of the angles $\Theta_{1,2}$ and $\Phi_{1,2}$.

We can write an expression for the tangent of Θ_1 and Φ_1 as follows:

$$\tan \Theta_1 = \frac{/y/}{f}, \quad \tan \Phi_1 = \frac{/z/}{f}$$

the nodal point (N.P.) and the two slopes define a unique line in space to the point P(i).

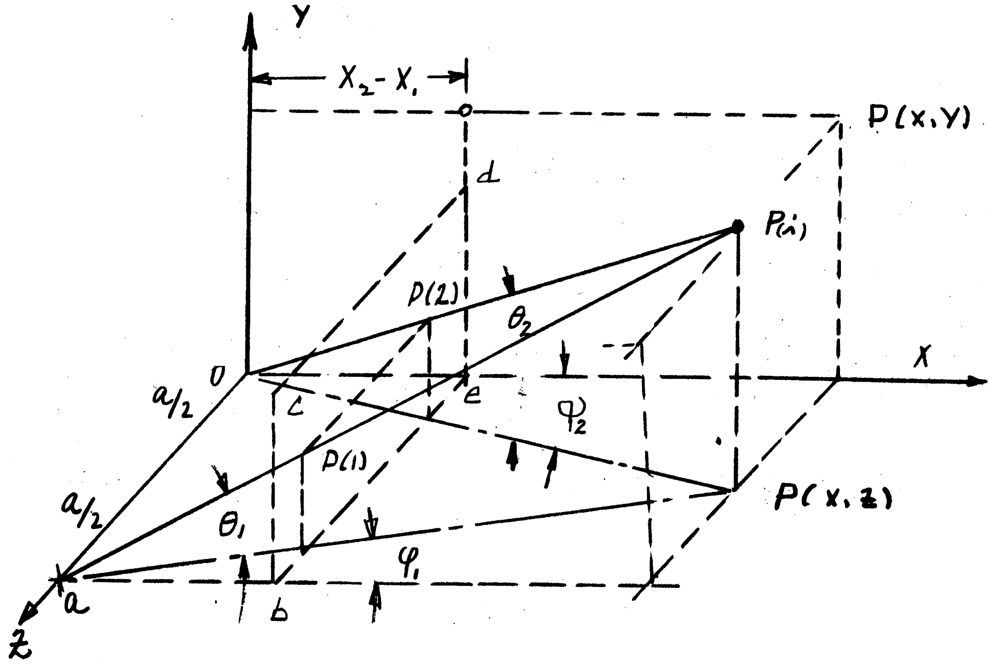


Fig. B-1. Terrestrial stereo model.

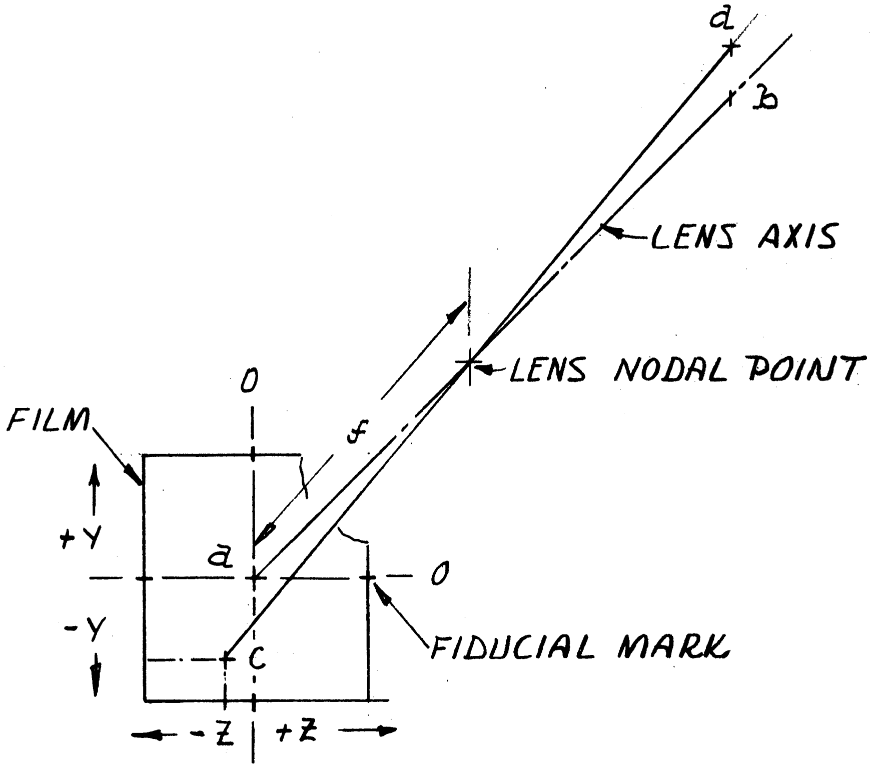


Fig. B-2. Film coordinates.

An alternative method of describing a line in space is to use the general definition of a line in space as a linear combination of two planes in space. In this case the two known points are the N.P. for the lens and the image of p_i in the film plane. Each of these points has a triple of values (x_i, y_i, z_i) associated with it.

The set of equations:

$$A_1x + B_1y + C_1z + D_1 = 0; \ (u)$$

$$A_2x + B_2y + C_2z + D_2 = 0; \ (u)$$

represents a straight line if:

$$u + kv = 0$$

where k is an arbitrary constant. Since the geometry of the cameras is fixed, the location of the N.P. and the film image of the point in space define for each camera a line to the point in space (i.e.,(a, p_1, p_i) and $(0, p_2, p_i)$) (Fig. B-1). The photographs constitute two projections of the original experimental scene reproduced point by point.

To make effective use of the stereograms as a quantitative measure of position we employ a stereo plotter (Fig. B-3). This device provides a means for positioning the photographs in the same relative position they had when exposed but moves them closer together to permit simultaneous viewing by an observer. Under these conditions, an operator can fuse the separate images into a single three-dimensional view of the original scene at a reduced scale.

The stereo plotter is provided with an indexing point that appears in the optical trains associated with both of the photographs. Each of these indexing points is the projection of a point in space. When these two projections are fused they are in effect a floating index that is positioned at will in the scene under examination. The y, z parallax of the projections of the floating mark are then the parallax of the point in space. If we place the floating mark on a definable point in the scene, the plotter readout is the position of the point in the model space.

In Fig. B-4 is a schematic diagram of the C-8, showing the projection system, the rotations of the two cameras, the three motions of each measuring mark, designated bx, by, and bz, the viewing systems, and the measuring system. A pair of conjugate (related) points are projected through the camera lenses and the auxiliary lens systems, and come to a focus on reference mirrors m and m'. These reference mirrors contain the measuring marks. From the reference mirrors, the images of the points, together with the measuring marks, are brought to the eye pieces by means of the optical trains.

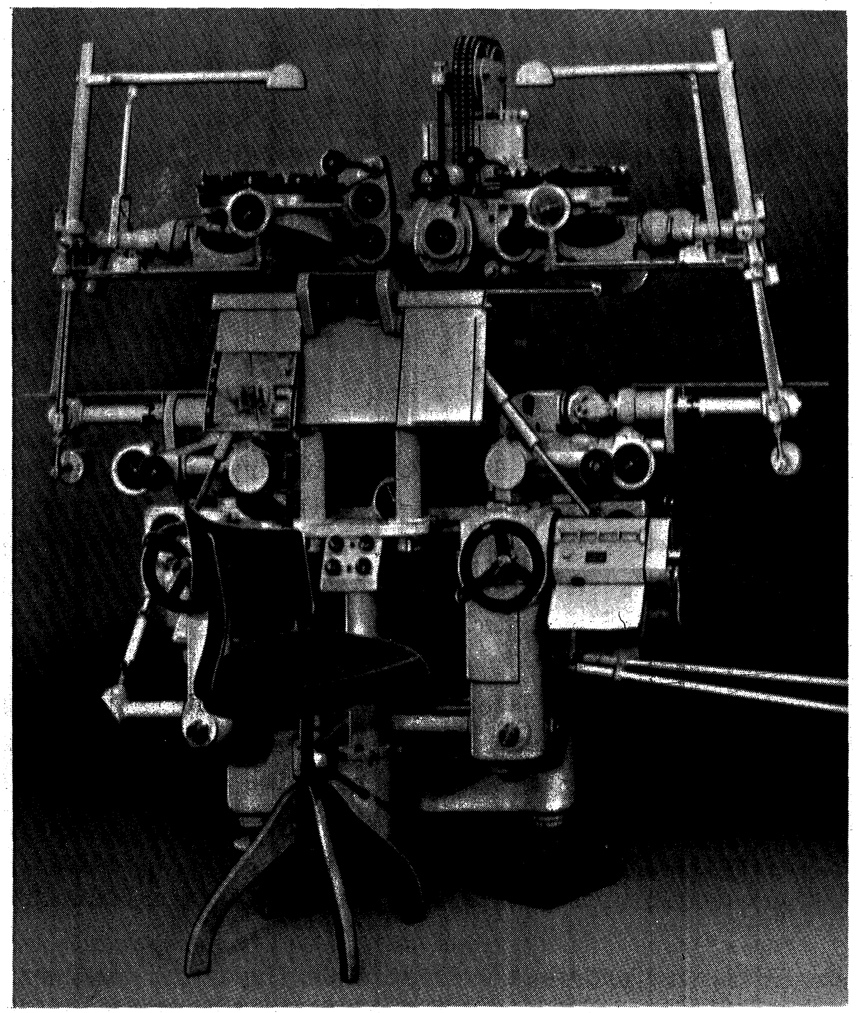


Fig. B-3. Stereoscopic plotting instruments.

EQUATION OF A LINE THROUGH TWO POINTS

The equation of a line in space in terms of its direction cosines can be written $lx + my + nz = p$ where l, m, and n are the direction cosines defined as follows:

$$l = \frac{x_2 - x_1}{d}$$

$$m = \frac{y_2 - y_1}{d}$$

$$n = \frac{z_2 - z_1}{d}$$

and

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

In the case under study, the two given points are the nodal point of the lenses and the film images of the point in space.

The lens nodal point can be determined from survey data for each camera in the stereo pair. For the case of a film plane perpendicular to the z, x surface at a distance 152.4 mm in front of the (z, y) plane, $x_2 - x_1$ is equal to a constant for all values of y and z. Also for the computations of l, m, and n we can remain within the confines of the camera.

Example computation for a hypothetical point:

$x_2 - x_1 = 15.24$ cm = f $\qquad 15.24^2 = 232.25$

$y_2 - y_1 = 10$ cm $\qquad 10^2 = 100.00$

$z_2 - z_1 = 5$ cm $\qquad 5^2 = 25.00$

$\qquad 357.25$

$$d = (357.25)^{1/2}$$

$$l = \frac{15.24}{19.40} = 0.786$$

$$m = \frac{10.00}{19.40} = 0.515$$

$$n = \frac{5.0}{19.40} = 0.258$$

The term p is 0 if the line passes through the origin of the coordinate system.* For the given point the equation for L(1) is $0.786x + 0.515y + 0.258z = 0$. For a line L(2) with consistant y and (-z) displacements, we can write another equation and finally arrive at a solution for $p_i(x_i, y_i, z_i)$. This operation presupposes that the pair of point images is available along with their spacial coordinates. In theory this is simple and direct, but in practice degenerates into a trial and error solution. The use of the stereo plotter avoids this stepwise iteration process by providing a three-dimensional reproduction of the original scene at a reduced scale.

STEREO PHOTOGRAPHS

If two photographic exposures are taken so that an area on one photograph also appears on another photograph from a slightly different angle; then the overlapping areas contain enough information to reconstruct the scene in perspective relief. Any region not covered by the overlap is not in perspective relief. These simultaneous views of the scene from two points of projection also occurs in most normal vision and provides the visual relief we use in the preception of depth or range.

STEREOSCOPIC VISION

Stereoscopic vision (usually referred to as stereo-vision) is necessary in order to obtain stereoscopic effects. Stereo-vision is the ability of a person to combine two perspective images of an object, in such a manner as to create a mental impression of relief or three-dimensional effect. Each of the two perspective images of the same object must be produced from a somewhat different angle, such as two photographs taken from different camera stations. The resultant photographs are known as a stereo-pair.

Thus, it follows that persons with monocular vision cannot see stereoscopically. This is not to say that all persons having binocular vision can see stereoscopically either. An elderly person often has much more difficulty in seeing stereoscopically than a younger person, because the eye muscles have become set and will not relax easily. Some people can never see stereoscopically from a stereo-pair even though they have normal vision in both eyes.

*If the line does not pass through the origin then p is the perpendicular distance from the line to the origin of coordinates.

STEREOSCOPES

The simplest optical instruments for viewing objects in three dimensions are stereoscopes. These may be of the mirror (reflecting) type, the prism type, or the lens (refracting) type. The first recorded stereoscope was a mirror type developed by Robert Wheatstone in 1838. A few years later, Sir David Brewster developed a lens stereoscope.

The stereoscope is an optical apparatus which enables us to look at the same time upon two photographic images nearly the same, but taken from a small difference of angular view. Each eye looks upon one picture only; and as in ordinary vision, two images are conveyed to the brain which unite into one, the objects being represented with enhanced relief. The stereoscope is constructed in accordance with the visual phenomena which convey to the mind impressions of the relative forms and positions of an object. When a near object having three dimensions is viewed, a different perspective representation of it is seen by each eye. Between the two views, there is distinct binocular parallax. Certain parts are seen by the right eye (the left being closed), that are invisible to the left eye, and vice versa. These two visual impressions are simultaneously perceived by both eyes, and are combined into one image, producing the impression of perspective and relief. We can exploit this ability to reconstruct the experimental scene in a quantitative way by introducing the notion of a parallax equation. The parallax equation provides us with the information for determining the position differences between objects in a stereo scene.

From proportional parts of similar triangles we can write:

$$\frac{x}{f} = \frac{p}{H - h}$$

or

$$\frac{x_i}{f} = \frac{p}{H - h_1}$$

multiply by f for:

$$x = \frac{Pf}{H - h}$$

or

$$x_1 = \frac{Pf}{H - h_1}$$

the range difference (in case of the current study the movement between frames)

$$\Delta x = x_1 - x = \frac{Pf}{H - h_1} - \frac{Pf}{H - h}$$

Multiply by $(H - h_1)$ and $(H - h)$ on the right side, rearrange, and factor

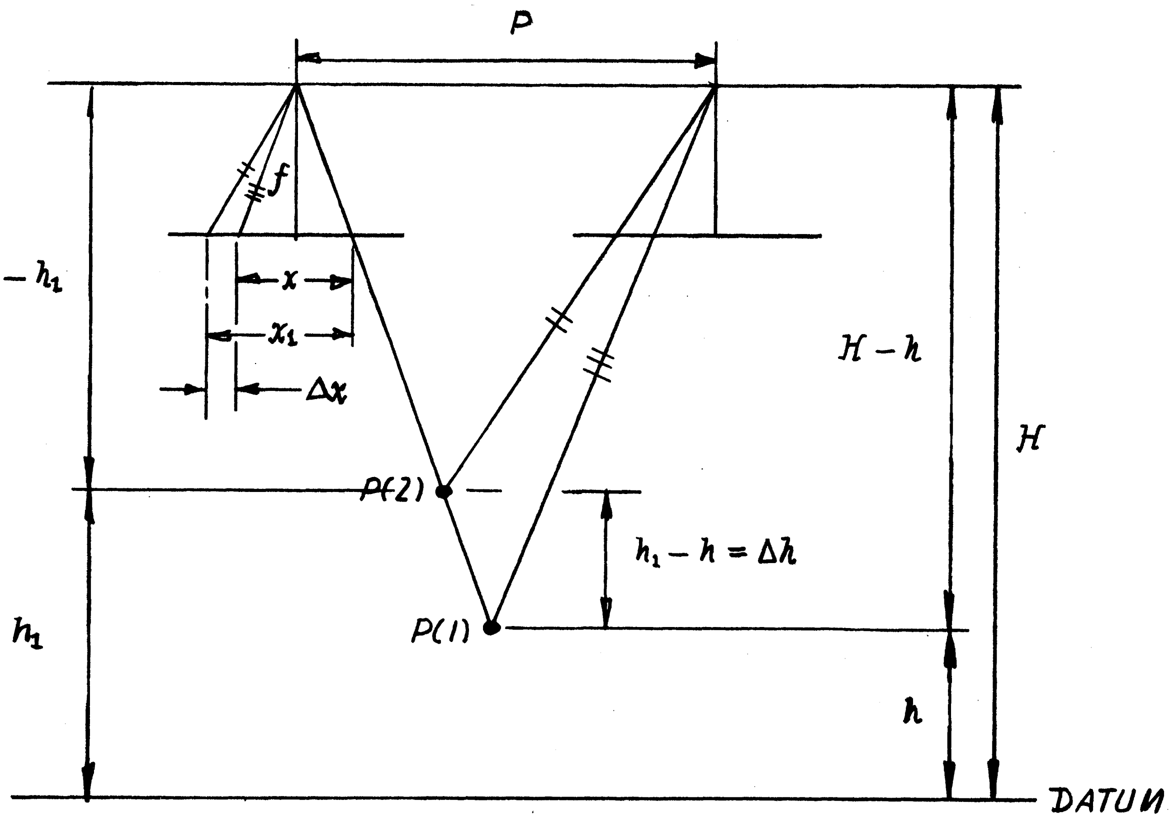


Fig. B-5. Parallax geometry.

where:

- p = distance between camera positions (base line)
- f = focal length of lens
- H = range to the datum distance
- h = range to the object of interest
- h_1 = range difference between objects
- Δh = object dimension
- x = base height
- x_1 = crest height
- Δx = height differential on deflection

$$\Delta x = \frac{Pf((H - h) - (H - h_1))}{(H - h)(H - h_1)}$$

then

$$\Delta x = \frac{Pf(h_1 - h)}{(H - h)(H - h_1)}$$

Since $hh_1 \ll H$ and $h_1 \simeq h$ we can write; $H^2 - 2Hh + h^2$ which factors to $(H - h)^2$ with small error then

$$\Delta x = \frac{Pf(\Delta h)}{(H - h)^2}$$

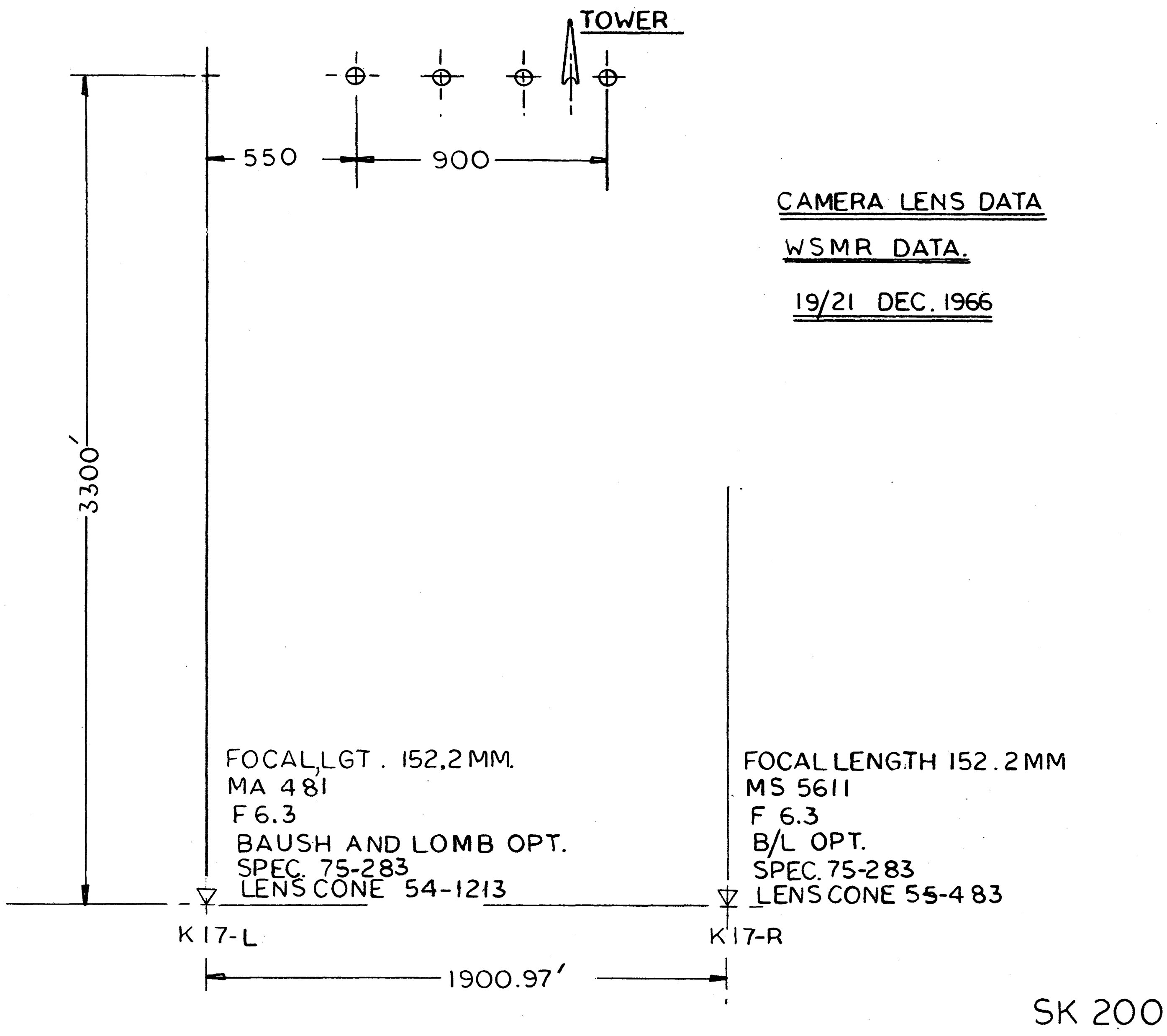
or

$$\Delta h = \frac{(H - h)^2}{Pf} \Delta x \quad .$$

Further, if h = 20 ft and H = 3000 ft then $(H - h) \simeq H$ and a further useful approximation is $\Delta h = H^2/Pf \cdot \Delta x$. In the current problem H, P, and f are given and Δx is a measured value from the stereophotos. For $h \doteq 20$ ft, H = 3000 ft, H = (H - h) to within 1/2%; for h = 200 ft, H = 3000 ft, H = (H - h) to within 7-1/2%; and h should be retained. The retention of h in the stereoplotter is incorporated in the original design of the instrument. The transfer from the original scene involves a change of scale that depends on the range to the plane of the experiment. For a range of 3600 ft the final model scale is 800 ft equals 1.0 in. The stereoplotting machines can measure to 1 part in 1000 routinely and provide a position fix on a point to an uncertainty of ±1 ft. With great care, 1 part in 10,000 can be achieved and the uncertainty becomes 0.08 ft.

A partial list of errors to be considered in the context of system errors are:

Systematic:	Surveying errors Camera alignment Lens distortion Focal Plane distortion Film shrinking or stretching Camera imperfections Earth curvature
Random:	Reading errors Film shear stress distortions System resolution and contrast Computation errors Timing Errors Tracer errors Index refraction fluctuations and distortion Vertical motion of the airmass


TOWER
550
900
3300'
CAMERA LENS DATA
WSMR DATA.
19/21 DEC. 1966
FOCAL,LGT . 152,2 MM.
MA 481
F 6.3
BAUSH AND LOMB OPT.
SPEC. 75-283
LENS CONE 54-1213
K 17-L
FOCAL LENGTH 152.2 MM
MS 5611
F 6.3
B/L OPT.
SPEC. 75-283
LENS CONE 55-4 83
K 17-R
1900.97'
SK 200

USA ERDA SURVEY CONTROL & INSTRUMENTATION POINTS

SHEET NO.

LOCATION	4 Launchers at L.C. #36 and Camera Sites.			TO OTHER STATIONS		DATE OF SURVEY Nov. 1966
NAME	COORDINATES WSTM			STATION		REMARKS
L 1	X	503,443.62				* Elevation is on the top of stake ** Elevation is on the top 500' Tower Base
	Y	191,085.58				
	H	*4,034.00				
L 2	X	503,743.62				Elevation of the light on 500' Tower is 4538.77'
	Y	191,085.58				
	H	*4,035.29				
L 3	X	504,043.62				
	Y	191,085.58				
	H	*4,035.47				
L 4	X	504,343.62				
	Y	191,085.58				
	H	*4,030.74				
Photo C.P.	X	503,893.62				
	Y	187,785.58				
	H	*4,031.05				
K17C-1	X	502,893.62				
	Y	187,785.58				
	H	*4,032.36				
K17C-2	X	504,893.62				
	Y	187,785.58				
	H	*4,025.07				
Center of Tower	X	504,224.34				
	Y	191,170.71				
	H	**4,037.00				

SELWS LE Form 1129
1 JAN 64

SK 200

USA ERDA SURVEY CONTROL & INSTRUMENTATION POINTS

SHEET NO

LOCATION: 4 Launchers at L.C. #36 and Camera Sites				TO OTHER STATIONS		DATE OF SURVEY Dec. 1966
NAME	COORDINATES WSTM			STATION		REMARKS
K17C-2 (New Site)	X	504,794.59				*** Top of Camera mount plate.
	Y	187,799.49				
	H	4,035.94 ***				
K17C-1						
	H	4036.48	***			

SELWS LE Form 1129
1 JAN 64

SK200 ~~3 OF 3~~

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SHORT LIST OF AVAILABLE CAMERAS

KS72A	day/nite	f/2.8	6 in. lens
K56	day	f/4.5	3 in. lens
K47	nite	f/2.5	12 in. lens
K46	nite	f/2.5	7 in. lens
K24	day/nite	f/2.5	7 in. lens
K17	day	f/6.3	6 in. lens
P-2	day/nite	f/2.5	70 mm

APPENDIX C

TABULAR DATA FROM ABRAMS ANALYSIS OF TWO SMOKE PLUMES SHOWN IN FIGS. 8, 9, 10 OF THE REPORT

As indicated in Section B of Research and Development Accomplishments, the 9 in. x 9 in. negatives of the stereo photographs were made available to Abrams Aerial Survey Corp. (Lansing, Mich.) to make positive photographic plates which were analyzed on their Galileo Santoni Stereocartograph. The data they abstracted from five pairs of photographs is tabulated below.

The following notes apply to this tabulated data:

(1) Tabulated data is for center line of smoke trail at (a) 200 ft intervals above ground (Z column), (b) additional levels, for determining limits of shear zones and for determining vertical components of wind.

(2) X and Y distances are measured from a hypothetical bench mark located 3162.1 ft west and 1000.0 ft south of the center line of the tower. X distances are measured in a true east direction, and Y distances are measured in a true north direction from this bench mark.

Z distances are measured in a true vertical direction from a point at the base of the tower 500.0 ft below the top edge of the tower.

(3) The code for the Stereo Quality of Point measurement is:

none	good,	< ± 0.1 ft
(2)	second quality,	± 0.1 ft
(3)	poor,	± (0.1 - 1) ft
(4)	very poor,	± 2 ft

(4) Break = break in smoke plume = edge of shear layer.
Ar Obs = area obscured—usually smoke too diffuse or not discernible from background haze.

TABLE I

SMOKE PLUME COORDINATES
#1 AND #4 ROCKETS LAUNCHED AT WHITE SANDS MISSILE RANGE,
11:30 HR, 19 DEC., 1966

(Stereo Pair #010; Time After Launch = 3 sec)

West Plume Center Line (ft)				East Plume Center Line (ft)			
Notes	X	Y	Z	Notes	X	Y	Z
	2384.1	926.6	60.0		3279.5	912.9	71.0
Break	2379.1	950.0	200.0		3294.1	927.6	200.0
Break	2392.0	956.8	216.0		3308.1	951.7	400.0
	2392.1	984.7	400.0		3339.0	973.6	600.0
	2399.0	1008.6	600.0		3363.5	992.8	800.0
	2403.5	1038.8	800.0		3388.8	1013.5	1000.0
	2407.1	1069.4	1000.0		3416.3	1035.3	1200.0
	2415.1	1097.8	1200.0				

TABLE II

(Stereo Pair #013; Time After Launch = 9 sec)

West Plume Center Line (ft)				East Plume Center Line (ft)			
Notes	X	Y	Z	Notes	X	Y	Z
	2377.3	871.0	93.5		3262.5	899.0	60.0
Area	2371.0	870.3	166.3		3288.0	887.0	106.0
Obscured	2395.1	963.7	493.4	Area	3262.0	875.0	175.0
	2385.9	959.0	544.0	Obscured	3305.1	960.0	506.0
	2381.0	963.4	572.0		3326.0	969.5	600.0
	2389.2	963.5	575.0		3354.0	959.5	770.0
	2386.1	969.0	600.0		3334.0	960.5	800.0
	2391.8	992.8	800.0		3367.5	983.0	852.0
Break	2382.5	994.0	931.2		3358.8	995.6	1000.0
Break	2388.0	1018.5	1000.0	Break	3363.0	983.0	1042.5
	2392.0	989.0	1200.0	Break	3407.0	990.8	1086.0
	2394.3	1006.4	1400.0		3389.0	975.4	1200.0
	2408.5	1031.7	1600.0		3416.0	983.3	1400.0
Break	2406.8	1059.0	1765.1		3452.0	1002.8	1600.0
	2400.9	1072.7	1800.0		3480.5	1032.0	1800.0
	2416.2	1136.3	2000.0		3508.7	1090.2	2000.0
	2439.0	1184.1	2200.0		3561.0	1137.7	2200.0
	2462.2	1219.5	2400.0		3612.0	1173.2	2400.0
	2464.5	1274.0	2600.0		3649.0	1219.0	2600.0
	2467.0	1327.6	2800.0		3690.8	1272.0	2800.0

TABLE III

(Stereo Pair #016; Time After Launch = 15 sec)

West Plume Center Line (ft)				East Plume Center Line (ft)			
Notes	X	Y	Z	Notes	X	Y	Z
	2383.0	959.0	562.0		3322.5	954.0	610.0
(4)	2408.0	963.7	672.7		3338.0	968.0	814.0
(4)	2405.8	982.4	628.6		3341.0	937.0	1075.0
(4)	2381.8	973.1	744.8		3365.0	941.0	1135.8
(4)	2375.2	971.2	779.3	Break	3361.5	915.6	1184.1
(4)	2392.2	976.8	800.0		3366.3	913.2	1200.0
(3)	2377.1	988.3	851.8	Break	3387.1	904.3	1309.1
(3)	2361.7	971.7	926.3	Break	3390.9	907.0	1346.1
(3)	2362.8	998.9	1000.0		3394.6	896.3	1400.0
	2367.2	942.8	1087.0	Break	3418.0	900.0	1505.5
	2374.0	919.8	1148.3		3436.2	899.9	1600.0
	2377.6	916.0	1200.0	Break	3445.1	911.8	1670.1
	2378.3	915.2	1232.2	Break	3453.3	933.0	1762.2
	2379.2	920.5	1279.0		3458.0	931.9	1800.0
	2371.8	906.5	1387.2		3460.8	932.0	1812.3
	2373.0	908.0	1400.0		3450.7	954.5	1871.8
	2388.0	918.2	1542.9		3481.9	1014.7	2000.0
	2395.9	927.6	1600.0		3523.3	1050.0	2122.8
	2384.8	954.2	1717.0		3539.8	1076.2	2183.7
	2386.9	960.5	1773.7		3562.3	1078.7	2197.5
	2373.4	972.0	1800.0		3564.2	1079.1	2200.0
	2374.2	1037.7	1916.4		3613.9	1110.6	2322.1
	2391.9	1063.7	2000.0		3626.8	1101.9	2372.9
	2400.5	1078.8	2028.9		3640.8	1106.0	2400.0
	2410.2	1083.5	2070.3		3660.2	1114.8	2458.8
	2430.8	1130.8	2200.0	(4)	3676.7	1164.6	2600.0
	2448.3	1145.9	2224.2	(4)	3695.5	1236.3	2800.0
	2460.2	1152.4	2312.1	(4)	3768.3	1308.8	3000.0
	2491.3	1163.3	2357.1				
	2500.0	1167.4	2400.0				
	2501.7	1168.6	2415.3				
	2509.0	1225.5	2521.3				
	2500.1	1239.6	2578.0				
	2499.1	1247.8	2600.0				
(2)	2492.8	1284.6	2708.2				
(2)	2484.8	1307.5	2770.9				
(2)	2480.2	1315.3	2829.0				
(2)	2477.8	1328.8	2888.0				
(3)	2485.8	1357.9	2955.0				
(4)	2487.9	1377.4	2977.5				
(4)	2487.7	1377.8	2996.7				
(4)	2490.3	1384.0	3000.0				
(4)	2493.1	1389.0	3040.0				
(4)	2508.9	1453.7	3200.0				
(4)	2512.2	1471.8	3238.1				

TABLE IV

(Stereo Pair #022; Time After Launch = 27 sec)

West Plume Center Line (ft)				East Plume Center Line (ft)			
Notes	X	Y	Z	Notes	X	Y	Z
(4)	2321.0	897.2	1047.0		3319.1	780.0	1192.0
(3)	2331.1	831.4	1088.9		3324.8	779.4	1200.0
(2)	2343.0	809.0	1119.1		3344.6	766.8	1231.1
(2)	2334.0	783.2	1145.1		3344.5	767.5	1248.0
	2357.3	729.2	1165.2		3348.5	758.0	1279.8
	2350.2	768.0	1200.0		3353.5	751.8	1292.0
	2350.0	757.7	1239.0		3355.0	752.8	1334.1
	2344.1	767.7	1271.0		3356.0	721.7	1387.6
	2344.9	748.3	1312.0		3349.6	720.0	1400.0
	2341.1	744.9	1339.0		3341.5	717.4	1422.0
	2341.0	727.8	1356.9		3358.0	708.6	1460.8
	2327.0	717.9	1383.9		3372.1	713.0	1493.2
	2330.0	720.4	1400.0		3390.3	700.5	1527.5
	2344.0	723.0	1419.0		3398.0	691.9	1600.0
	2344.0	717.9	1427.0		3403.0	707.2	1681.8
	2354.0	720.8	1436.0		3416.0	713.4	1693.5
	2346.0	718.3	1448.9		3402.1	727.8	1752.5
	2352.9	700.2	1545.1		3407.0	714.9	1800.0
	2365.9	717.2	1600.0		3408.2	714.8	1807.0
	2370.0	719.0	1624.5		3369.1	752.3	1840.8
	2338.1	737.0	1769.1		3375.1	754.8	1865.1
	2306.1	762.0	1800.0		3362.1	786.6	1883.1
	2297.1	779.0	1814.0		3405.3	843.2	1968.0
	2290.8	871.6	1900.9		3421.2	850.4	2000.0
	2331.0	891.8	1986.1		3484.8	898.0	2126.5
Break	2337.9	918.2	2000.0		3493.1	934.9	2169.6
	2367.0	912.7	2058.3	(2)	3547.8	939.5	2190.6
	2395.7	967.8	2173.2	(2)	3550.0	950.7	2200.0
Break	2434.5	995.7	2200.0	(2)	3577.0	969.7	2231.8
	2463.0	992.6	2286.9	(2)	3623.5	985.4	2316.5
	2549.8	984.5	2382.5		3651.8	949.0	2355.1
	2556.0	1022.0	2400.0	Break	3686.5	966.2	2400.0
	2563.2	1093.3	2501.2		3717.0	966.0	2455.0
	2540.0	1107.5	2553.8		3709.0	1016.9	2600.0
	2536.0	1140.2	2600.0	(2)	3717.0	1095.4	2663.2
	2522.0	1164.3	2668.0	(3)	3713.0	1117.1	2687.0
	2498.0	1208.5	2733.1	(3)	3714.9	1138.0	2722.8
	2480.1	1214.2	2800.0	(3)	3689.0	1143.9	2767.0
	2465.0	1227.0	2869.7	(3)	3696.9	1156.9	2800.0
	2478.2	1288.5	2936.0	(4)	3698.5	1179.7	2858.8
	2485.8	1332.5	2959.8	(4)	3699.0	1216.0	2868.9

TABLE IV (Concluded)

West Plume Center Line (ft)				East Plume Center Line (ft)			
Notes	X	Y	Z	Notes	X	Y	Z
Break	2489.6	1340.5	3000.0	(4)	3724.0	1219.3	2895.1
	2516.1	1398.7	3064.1	(4)	3718.3	1232.2	2925.8
	2524.0	1400.0	3074.0	(4)	3741.5	1276.6	2944.0
(2)	2525.1	1416.5	3119.1	(4)	3786.1	1314.8	3000.0
(2)	2526.0	1416.5	3174.2	(4)	3822.0	1347.0	3044.1
(2)	2526.0	1429.2	3211.8				

TABLE V

(Stereo Pair #034; Time After Launch = 51 sec)

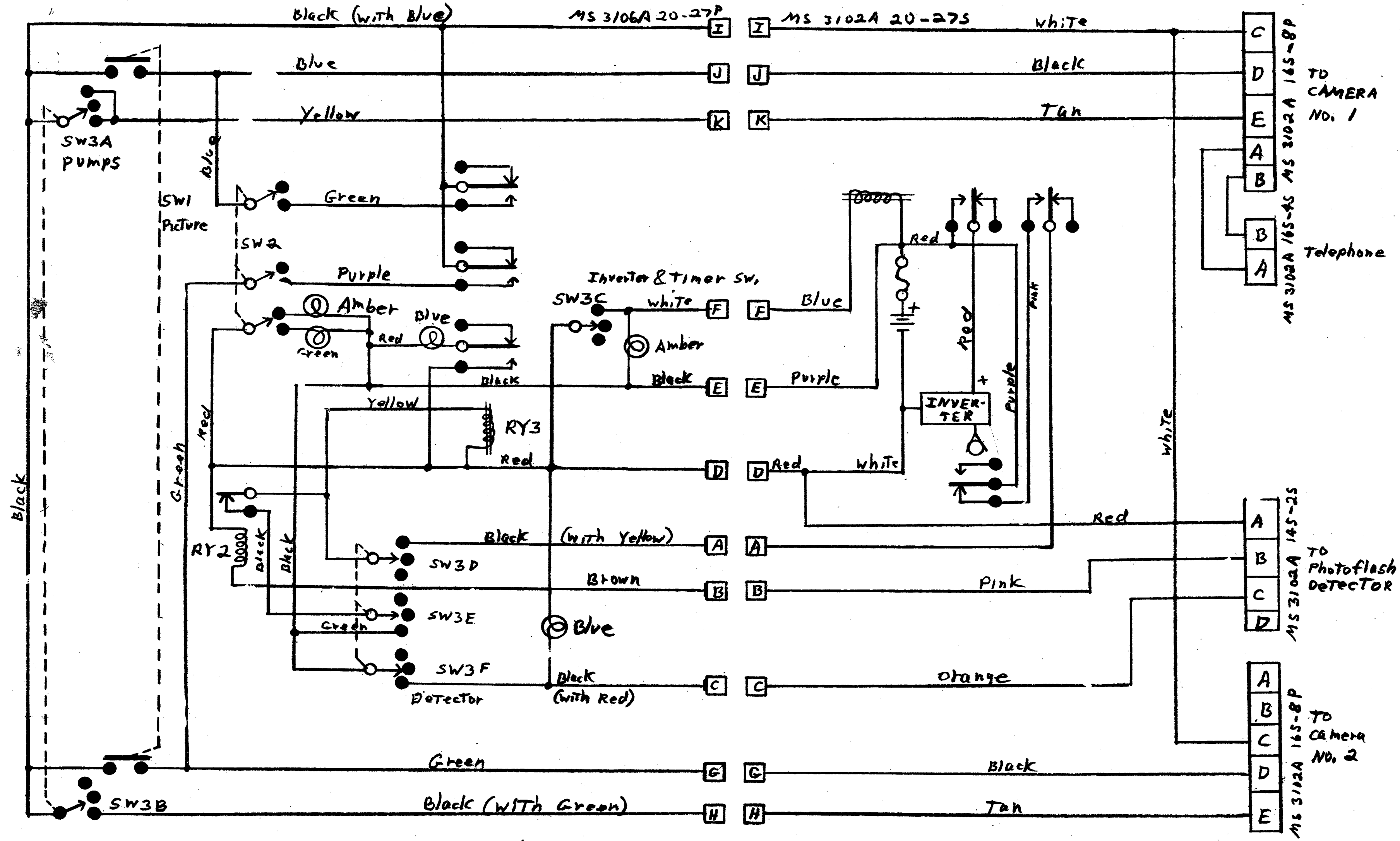
West Plume Center Line (ft)				East Plume Center Line (ft)			
Notes	X	Y	Z	Notes	X	Y	Z
(4)	2269.0	585.2	1112.0	(4)	3287.0	492.5	1174.5
(3)	2272.8	573.9	1121.0		3307.2	477.3	1200.0
(2)	2240.0	556.8	1125.1		3308.3	474.6	1211.3
	2267.1	496.2	1160.0		3300.0	472.4	1231.7
	2303.1	491.3	1179.5		3312.9	462.1	1248.9
	2299.1	476.1	1200.0		3301.1	442.6	1278.0
	2288.5	443.7	1246.9		3294.5	437.8	1327.0
	2276.9	450.5	1289.0		3274.1	395.9	1357.0
	2271.5	403.7	1329.0		3283.2	366.2	1382.0
	2268.2	400.4	1348.3		3257.8	355.8	1400.0
	2261.8	358.5	1373.0		3247.5	352.0	1411.5
	2234.3	336.5	1400.0		3258.5	330.5	1447.8
	2234.0	332.5	1406.8		3291.0	335.5	1481.2
	2258.1	337.4	1434.0		3322.1	302.3	1516.5
	2269.0	327.7	1443.0		3335.0	266.3	1595.8
	2283.2	326.5	1451.5		3331.0	266.0	1600.0
	2273.5	323.9	1459.0		3322.0	264.4	1626.4
	2272.5	314.1	1466.1		3323.8	280.8	1687.8
	2284.9	316.0	1472.1		3344.8	288.2	1696.5
	2290.1	305.8	1481.2		3340.0	309.2	1702.5
	2281.1	283.6	1560.6		3309.1	315.4	1751.9
	2298.0	291.0	1573.1		3303.1	279.0	1796.0
	2301.1	290.3	1600.0		3306.1	278.0	1800.0
	2307.9	290.1	1661.9		3311.1	279.4	1816.0
	2244.0	314.8	1749.1	(3)	3258.1	296.7	1836.1
	2234.8	295.6	1787.1	(4)	3198.1	403.0	1883.1
	2201.6	315.0	1800.1	(4)	3272.1	511.4	1962.1
	2159.0	357.6	1831.2		3302.7	523.3	2000.0
	2122.7	425.9	1855.0		3313.9	528.4	2015.8
	2117.2	481.8	1869.1		3362.9	573.6	2062.1
	2184.8	544.2	1954.0		3398.8	588.3	2109.8
	2216.1	570.0	2000.0		3424.2	599.6	2137.8
	2224.0	574.5	2015.0	(4)	3437.0	623.1	2178.0
	2243.2	602.0	2014.9	(4)	3435.0	674.5	2197.5
	2260.0	612.0	2042.0				
	2281.0	603.0	2070.0				
	2306.5	645.0	2118.8				
	2317.1	646.7	2143.2				

TABLE V (Concluded)

West Plume Center Line (ft)				East Plume Center Line (ft)			
Notes	X	Y	Z	Notes	X	Y	Z
	2353.8	704.6	2200.0	↓	3536.1	694.8	2200.0
	2428.0	749.0	2220.0		3597.2	715.4	2263.0
	2453.0	719.5	2233.0	Smoke Dispersed	3703.0	743.0	2325.0
Smoke	2488.1	738.8	2267.8		3735.0	662.0	2348.0
Dispersed	2488.0	715.2	2306.0		2798.5	689.0	2400.0
	2568.9	733.4	2302.1	Break	Impossible	Very Poor	
	2610.0	706.0	2355.5	Break	to Read	Stereo	
	2669.8	686.4	2396.1		3817.0	806.0	2571.0
	2676.6	695.0	2400.0		3809.0	862.0	2600.0
	2714.0	842.4	2471.8	Very Poor Stereo	3797.0	900.7	2636.0
	2640.0	911.5	2574.0		3797.0	907.0	2678.0
	2639.8	948.6	2600.0	↑	3720.0	1011.0	2800.0
	2586.8	1017.8	2702.1				
	2556.1	1091.9	2742.8				
Break	2495.9	1075.8	2800.0				
(4)	2488.5	1109.0	2853.0				
(4)	2464.8	1094.5	2902.5				
(4)	2461.2	1188.2	2935.5				
(4)	2479.0	1280.3	3018.0				
(4)	2500.8	1284.8	2987.8				
(4)	2501.1	1287.0	2992.0				
(4)	2502.0	1289.8	3000.0				
(4)	2507.2	1321.0	3079.8				
(4)	2524.5	1388.7	3080.1				
(4)	2578.8	1427.5	3129.0				
(4)	2576.0	1388.0	3200.0				
	2574.0	1375.5	3228.2				

APPENDIX D

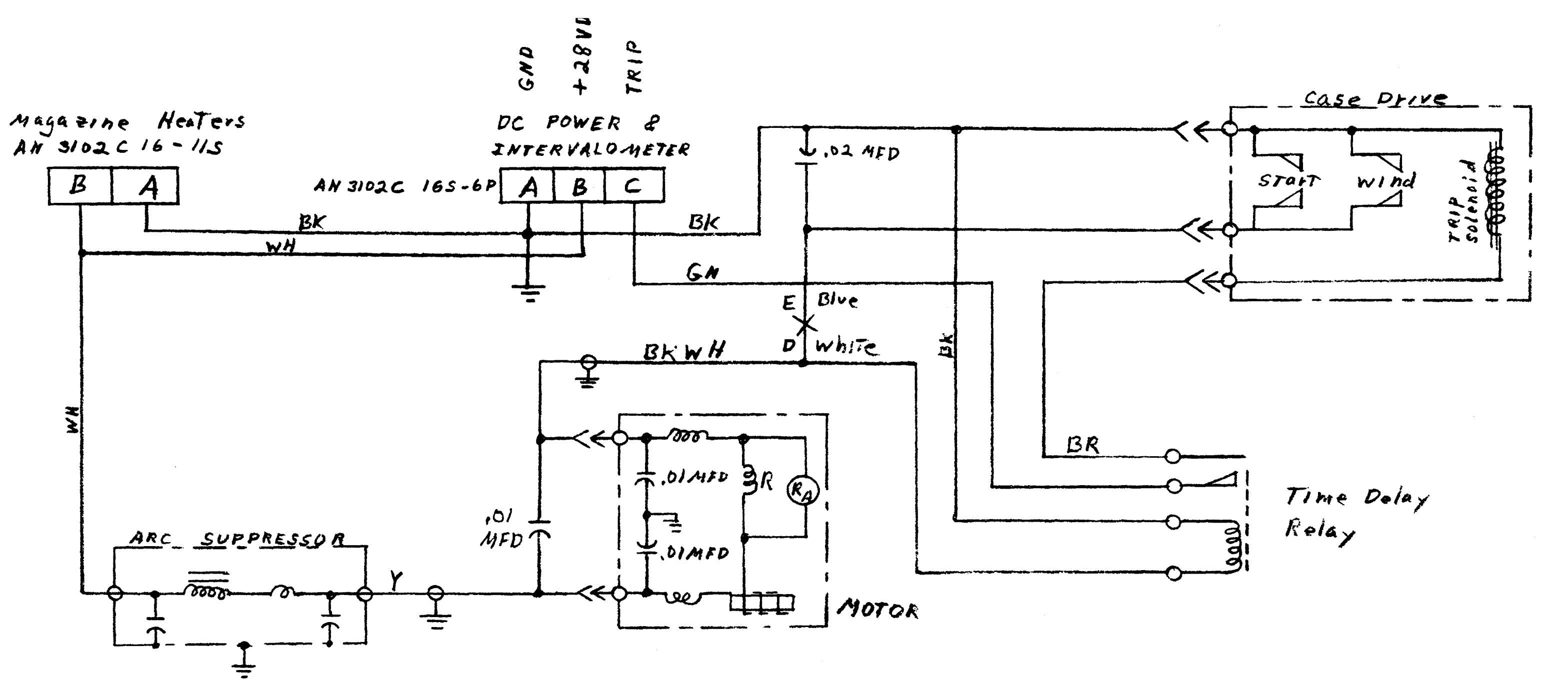
WIRING DIAGRAMS OF EQUIPMENT
by T. L. Sweeney



DAY-NIGHT STEREOGRAPHIC CAMERA CONTROL

Jan. 1968

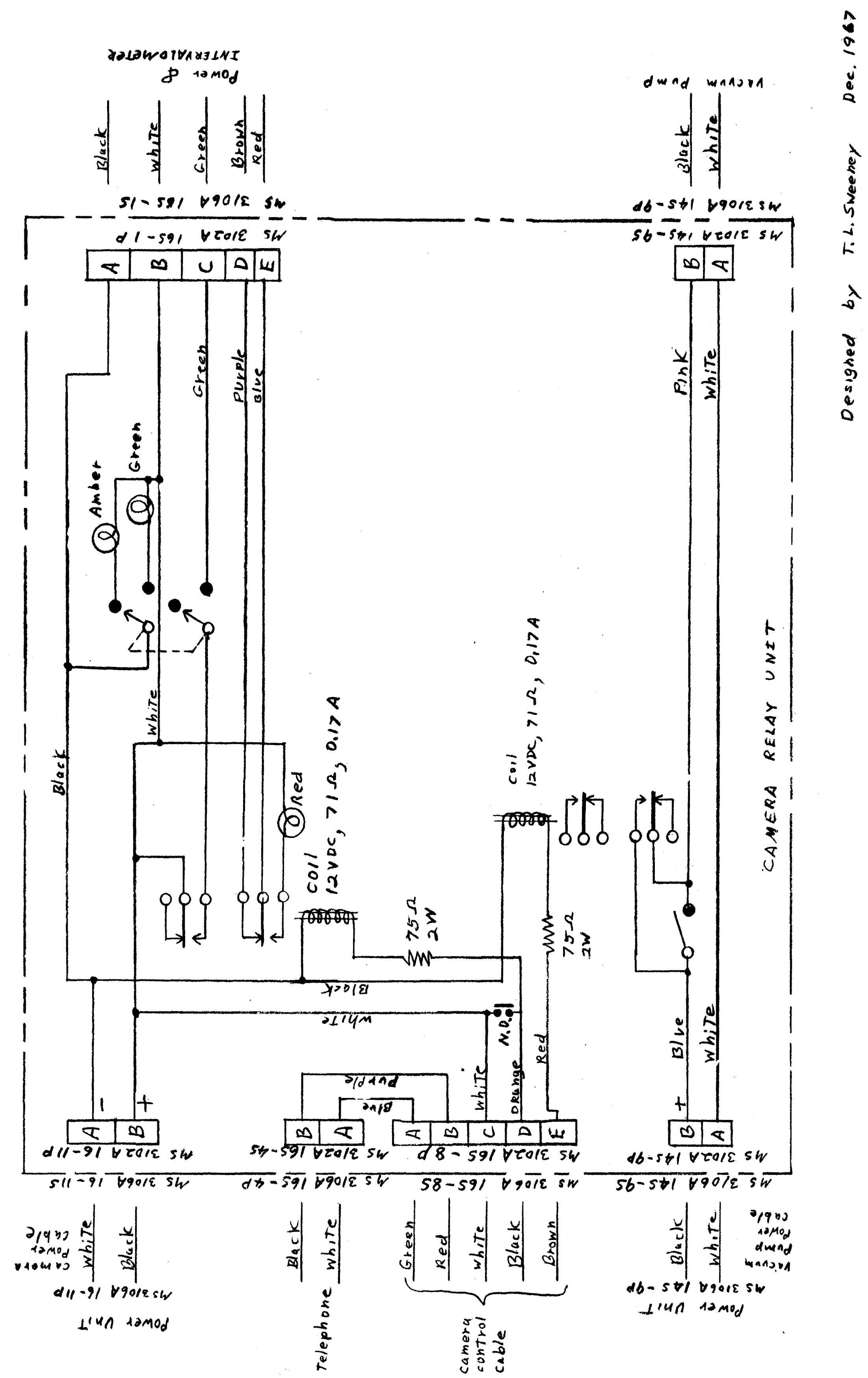
Designed by T. L. Sweeney



Points E & D Terminate in Intervalometer connector.

K17C AERIAL RECONNAISSANCE CAMERA
(Modified)

T. L. Sweeney Jan. 1968


CAMERA RELAY UNIT
Designed by T. L. Sweeney Dec. 1967
Power & INTERVALOMETER
Vacuum pump
Power Unit
Telephone
camera control cable
camera power cable
vacuum pump power cable
MS 3106A 16S-1S
MS 3102A 16S-1P
MS 3106A 14S-9P
MS 3102A 14S-9S
MS 3102A 16-11P
MS 3106A 16-11S
MS 3102A 16S-4S
MS 3106A 16S-4P
MS 3102A 16S-8P
MS 3106A 16S-8S
MS 3102A 14S-9P
MS 3106A 14S-9S
Coil 12VDC, 71 Ω, 0.17 A
75 Ω 2W
Amber
Green
Red
N.O.

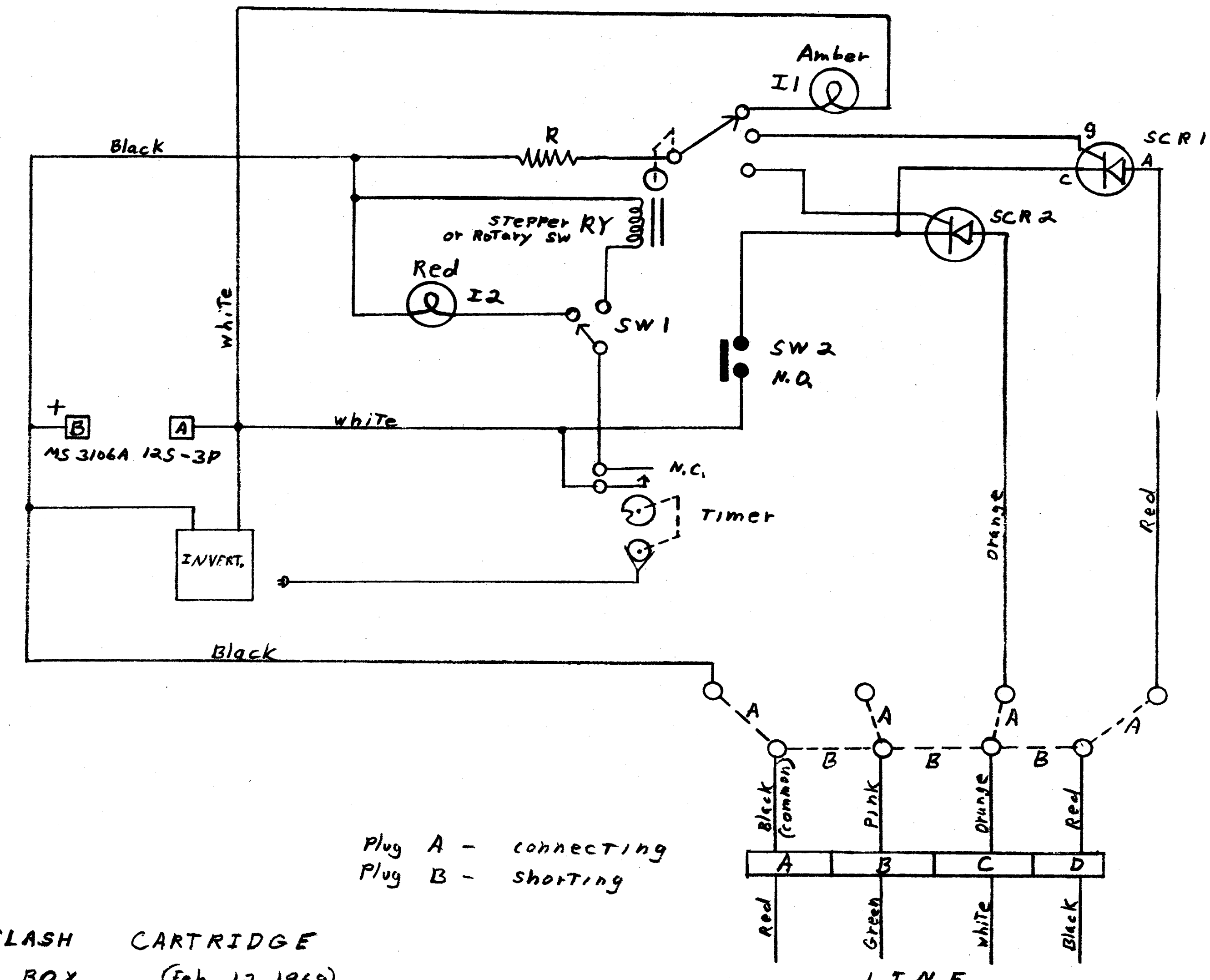


PHOTO FLASH CARTRIDGE
FIRING BOX (Feb. 12, 1968)

Designed by T. L. Sweeney