

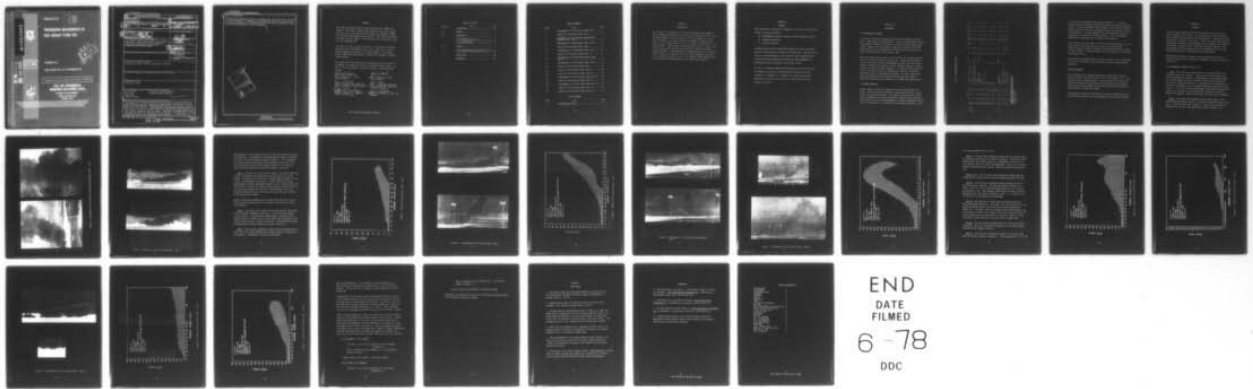
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CIVIL AND ENVIRONMENTAL ENGINEERING DEVELOPMENT OFFIC--ETC F/G 4/1  
PHOTOGRAPHIC MEASUREMENTS OF USAF AIRCRAFT PLUME RISE.(U)  
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# PHOTOGRAPHIC MEASUREMENTS OF USAF AIRCRAFT PLUME RISE

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NOVEMBER 1977

FINAL REPORT JULY 1977 TO NOVEMBER 1977

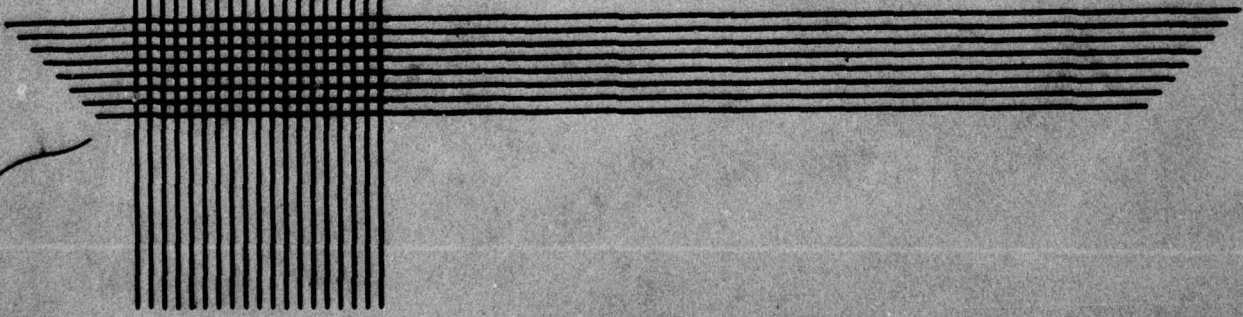
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## CIVIL AND ENVIRONMENTAL ENGINEERING DEVELOPMENT OFFICE

(AIR FORCE SYSTEMS COMMAND)

TYNDALL AIR FORCE BASE  
FLORIDA 32403





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micrometeorology apparently account for these plume rise variations. Since the 13 tests performed are inadequate to understand the causes for the plume rise and ground separation, it is recommended that this study be extended in order to provide an explanation for this phenomenon.

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PREFACE

This study was performed under Program Element 62601F, CEEDO JON 19002A47. The project engineers and authors are 2d Lt Paul D. Music and 2d Lt John S. Hunt, who have been temporarily assigned to CEEDO while awaiting undergraduate pilot training. This work was performed at Tyndall and Nellis AFBs. Inclusive dates of this work were 1 July 1977 to 22 November 1977.

Capt Dennis F. Naugle is project officer. He provided the guidance which led to the development of this report. Maj Peter S. Daley provided numerous technical and editorial comments. Maj Joseph B. Hooten, CEEDO Staff Meteorologist, computed all atmospheric stability classifications.

This report has been reviewed by the information office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

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## SECTION I

### INTRODUCTION

The Air Force has developed an Air Quality Assessment Model (AQAM) to predict downwind concentrations of pollutants released by various sources. The AQAM considers all major emission sources but emphasizes aircraft exhaust emissions. Aircraft emissions are assumed to emanate from a specific initial exhaust plume and then to disperse in accordance with a Gaussian model. Recent studies conducted at Williams AFB, Arizona, gave rise to serious doubt concerning the validity of volume dispersion presently assumed. Since AQAM and all airport models rely on an assumed initial volume, it is important that the current assumption be proven valid or improved to make it valid. The following study comprises data from a plume rise study designed to help resolve this problem.

## SECTION II

### METHODS

Three techniques to determine the geometry and location of the aircraft exhaust plume were considered:

- (1) Photographic tracking of plumes from smoke-equipped aircraft.
- (2) Infrared photography.
- (3) Infrared detection.

A detailed study of these techniques revealed that there was several possible solutions which would provide accurate data. The chosen solution was to photographically track plumes from smoke-equipped F-102 drones stationed at Tyndall AFB, Florida and smoke-equipped T-38 Thunderbird aircraft stationed at Nellis AFB, Nevada.

The use of an external smoke-producing device which injects oil into the exhaust stream was not chosen primarily because of the time necessary to incorporate it. However, this technique should be considered for future testing since it is applicable for a wide variety of aircraft.

### SECTION III

#### PROCEDURES

##### T-38 THUNDERBIRD AIRCRAFT

One series of tests was conducted using the Nellis-based T-38 Thunderbirds. These tests had two advantages. First, all Thunderbird aircraft have equipment capable of producing a continuous visible exhaust smoke stream. Second, the meteorological conditions in Nevada are much different from those in Florida where the other series of tests was conducted, thus providing a wider range of data.

During the tests at Nellis AFB, the T-38 was set on a trim pad with the nose of the aircraft directed into the wind. Cameras were positioned such that the plume could be photographed with both still and motion cameras. Markers were placed at 30-meter intervals behind the aircraft to assist in measuring plume dimensions. The smoke was then turned on, with the aircraft at idle, for approximately three to five minutes during which time all photographs were taken. The Nellis AFB Weather Station provided hourly and special meteorological data (Table 1). Atmospheric stabilities were computed by the CEEDO Staff Meteorologist.

##### F-102 DRONE AIRCRAFT

Another series of tests was conducted using the Tyndall-based F-102 drones. The drones were positioned on a north-south trim pad, facing north into the prevailing wind. The engines were then run up to idle speeds to prepare for the smoke production. Cameras were positioned on either side of the trim pad approximately 100 meters downstream from the exhaust nozzle and 50 to 100 meters from the exhaust centerline. Both

TABLE 1. METEOROLOGICAL DATA

NAME	DST	Mean Solar Time	(1977) Date	Cloud Cover (in 100's of Feet), 70 Scattered, Est 100 Broken, 250 Broken	Vis Vis	Weather Vis	WD	WS (Kt)	WS M/Sec	Press in Hg	Temp F	DP F	Hum %	Stab	
30° 14' N 85° 35' W	0900	0900	11 Oct 77	70 Scattered, Est 100 Broken, 250 Broken	7		040	02	1	30.00	67	55	--	B	
	* 0930	0830	11 Oct 77	Est 100 Broken	---								65		
		1000	---	70 Scattered, 100 Scattered, 250 Scattered	10		100	02	1	30.01	75	59	--		
		1400	---	Est 70 Broken, 100 Broken, 250 Overcast	7 Light Rain		Calm	Calm	---	29.99	72	59	--		
	* 1445	1345	11 Oct 77	Est 70 Broken	---										
		1500	---	30 Scattered, 70 Overcast	---									64	B
	* 1000	0900	0930	45 Scattered, 70 Broken	7	5 Light Rain	360	02	1	29.99	69	61	--		
	* 1500	1400	1430	Est 90 Broken	7		360	09	4.5	30.06	62	55	68	C	
	0900	0800	0831	Clear	10		360	12	6	30.00	70	51	50	D	
		1500	1431	35 Scattered, 300 Thin-Scattered	10		330	06	3	30.05	65	44	48	D	
	0900	---	---	Clear	10		330	08	4	30.20	54	42	--	B	
	* 0930	0830	0901	Clear	---										
		1000	---	Clear	10		360	04	2	30.20	56	45	--		
		1300	---	Clear	10		330	09	4.5	30.15	66	48	--	C	
* 1330	1230	1301	Clear	---											
	1400	---	Clear	10		330	06	3	30.11	66	49	--			
36° 11' N 125° 11' W	* 1000	0900	14 Oct 77	5 Thin Scattered	35 Smoke		Calm	Calm	0	30.06	72	37	28	B	
	1500	---	19 Oct 77	50 Scattered, 250 Scattered	35		080	15	7.5	29.88	80	46	--		
	* 1530	1430	1505	50 Scattered	---								29	D	
	1600	---	19 Oct 77	10 Scattered, 150 Broken, 250 Broken	35		050	14	7	29.87	77	59	--		
	* 0900	0800	0835	10 Scattered, 140 Scattered	35		Calm	Calm	0	29.93	63	55	75	B	
	* 1100	1000	1035	10 Scattered, 140 Scattered	35				.5	29.94	70	55	59	A-B	
	* 1300	1200	1235	10 Scattered, 140 Scattered	35		Calm	Calm	0	29.91	75	50	41	A	

\*Denotes times in which data was collected. If time was not during an observation period, wind speed and direction were interpolated. All other parameters were assumed the same as the prior observation period.

\*\*Instrument calm < 2 knots

still and motion photographs were taken of each test. In order to measure the plume dimensions from the photography, cones were placed at 75-meter intervals downstream from the nozzle. This procedure presented problems when the winds were not perpendicular to the exhaust centerline of the aircraft. In these instances, the plume dimensions could not accurately be determined from the photographs. Also, the distance markers were occasionally not as visible as anticipated.

After engine run-up, the smoke was turned on and photographed. The F-102 drones did not have the capability to provide continuous smoke stream; instead, the smoke is produced for two seconds and then stopped for three seconds. The meteorological data were supplied by the Tyndall AFB weather station.

These tests were conducted twice a day for one week, once in the morning and once in the afternoon, thus providing a variety of meteorological conditions.

#### PLUME MEASUREMENTS

Plume dimensions were obtained from slides and 16mm films using the distance markers, the aircraft length (T-38 = 14.0 meters, F-102 = 20.7 meters) and other reference points. Several events of each trial were analyzed, and average height-distance relationships were calculated. These measurements were made by projecting the slides and tracing the plume outlines on large chart paper.

This dimensional data was then entered on a Hewlett Packard 9862 calculator plotter to obtain the charts presented in the following section.

## SECTION IV

### RESULTS

Five tests were conducted at Nellis AFB, Nevada, and eight were conducted at Tyndall AFB, Florida. Six of these (four at Nellis AFB and two at Tyndall AFB) provided the best photographs. A selection of these photographs is included in the report. Many of the other tests provided valuable data; however, the photographs did not reproduce well enough to be included. Several of the 13 tests were discarded because the contrast between the white plume and the cloud background was poor, and accurate data could not be obtained from the photographs.

Meteorological data were obtained from the base weather stations at Tyndall and Nellis AFB to calculate the atmospheric stability categories (see Table 1).

#### T-38 THUNDERBIRD AIRCRAFT (TESTS 1 TO 5)

Test 1. The first test conducted at Nellis AFB provided the most surprising plume rise (Figure 1). There was no wind during the test, and the atmosphere was unstable. Ground separation began approximately two aircraft lengths behind the aircraft, and the plume continued to rise from the same point (Figure 2). The plume rose to approximately 50 to 60 meters and began to form a mushroom cloud which continued to grow (Figure 3). This was the most extreme plume rise condition encountered; however, the stationary aircraft continually feeding the plume may produce this apparent "chimney effect" where the plume rise is enhanced.

Test 2. The second test conducted at Nellis AFB (Figure 4) also showed ground separation; however, it was not as distinct as that of the first. Second test winds were greater (7 meters per second) and the atmosphere was neutral. The plume did not begin to separate until

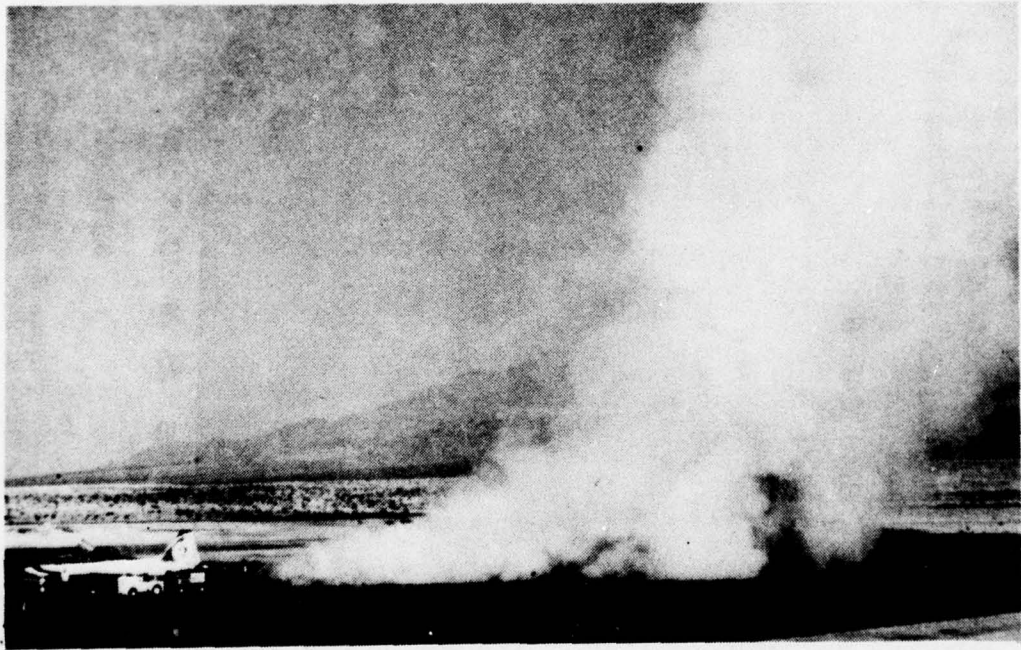
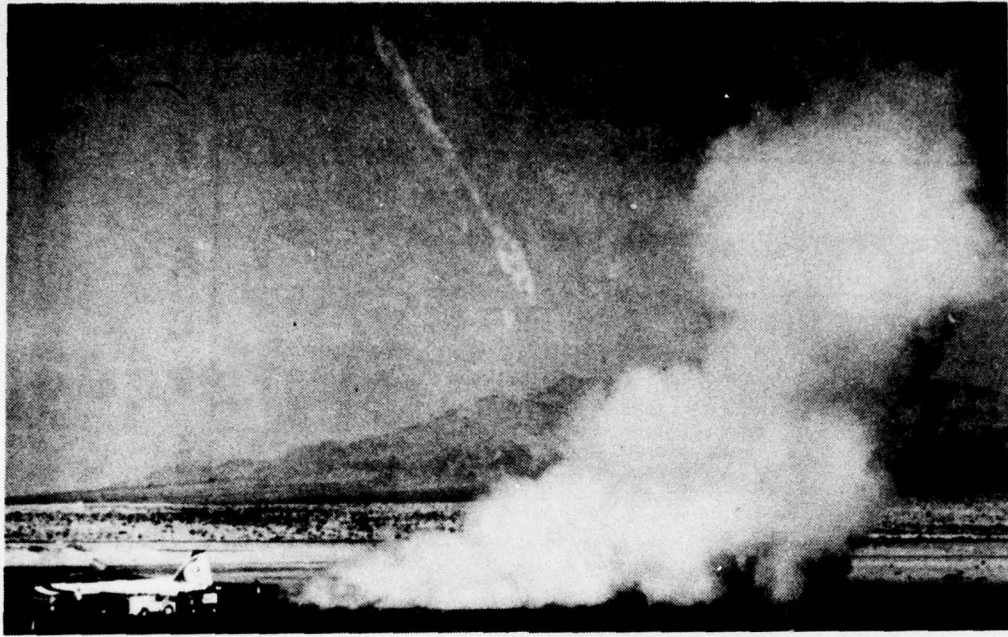


Figure 1. Photographs of T-38 Aircraft Plume: Test 1

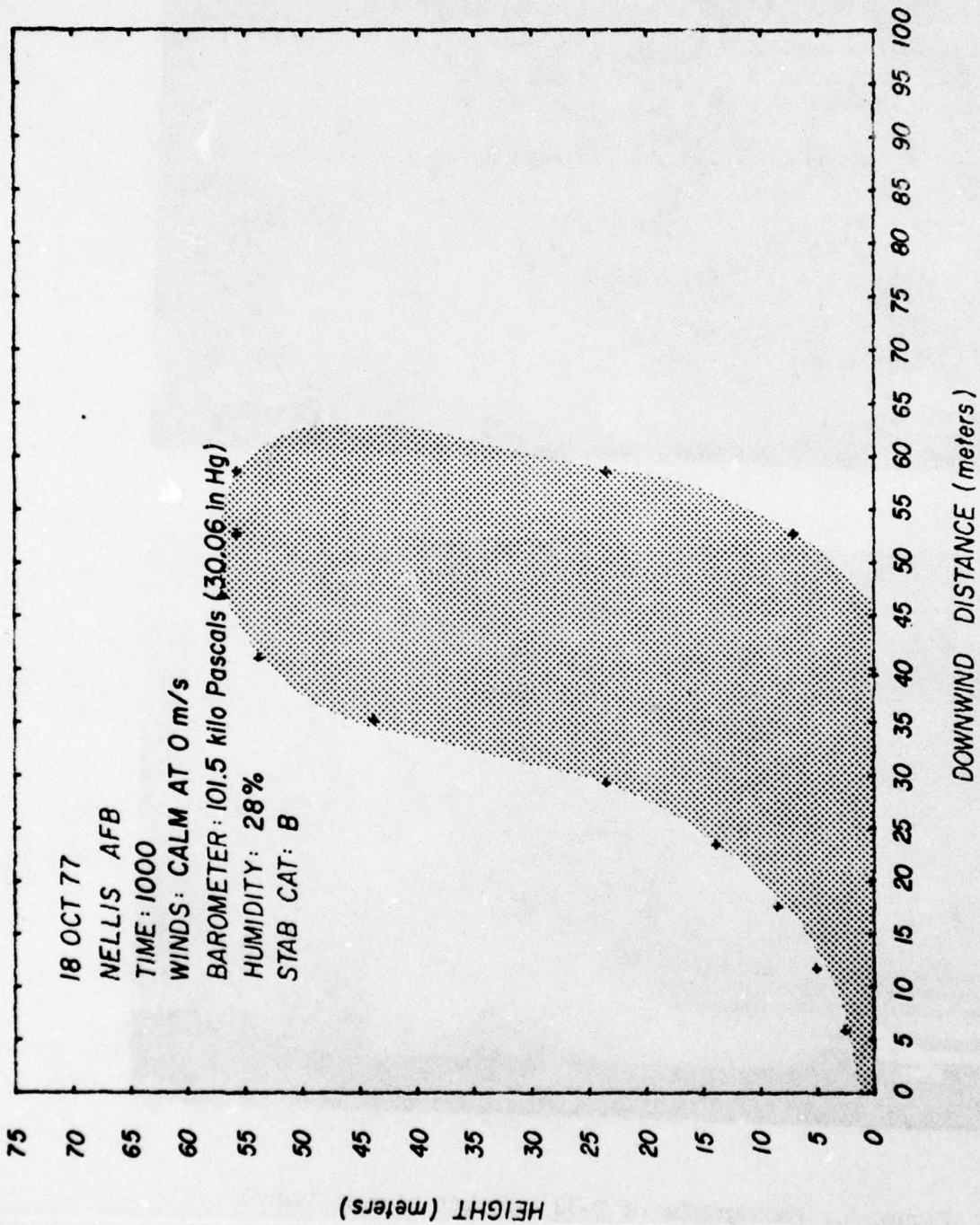


Figure 2. Graph of T-38 Aircraft Plume: Test 1

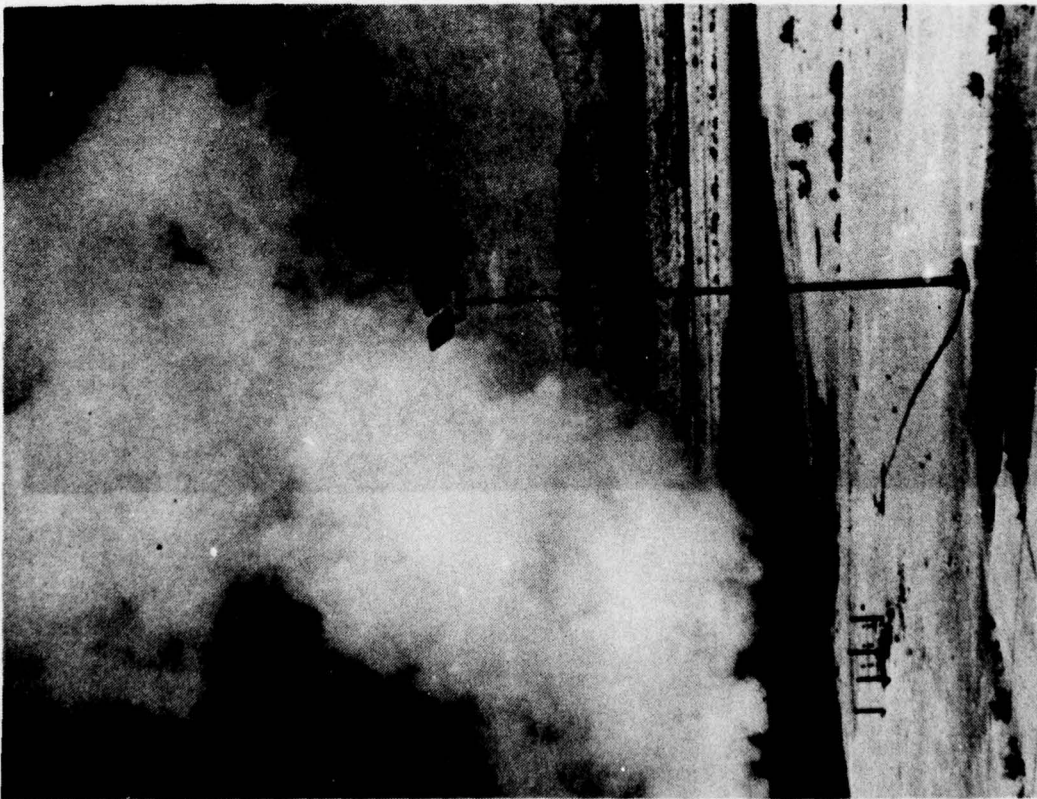
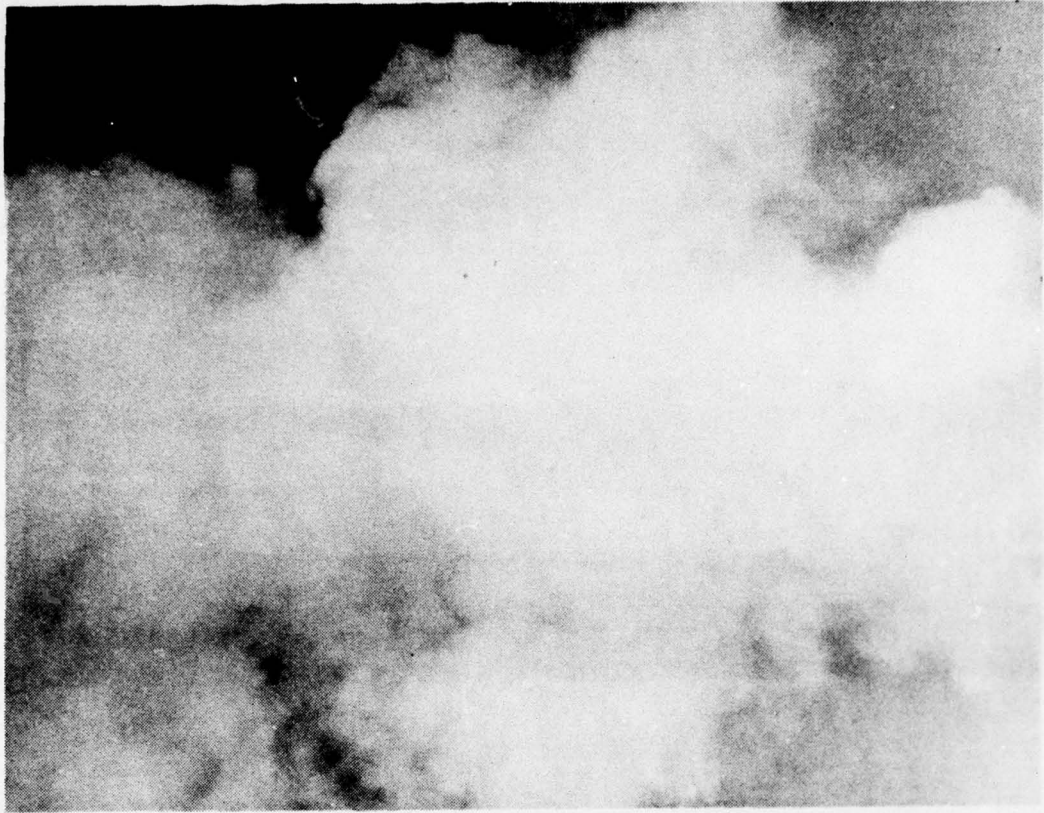


Figure 3. Photographs of T-38 Aircraft Plume Forming Mushroom Cloud: Test 1

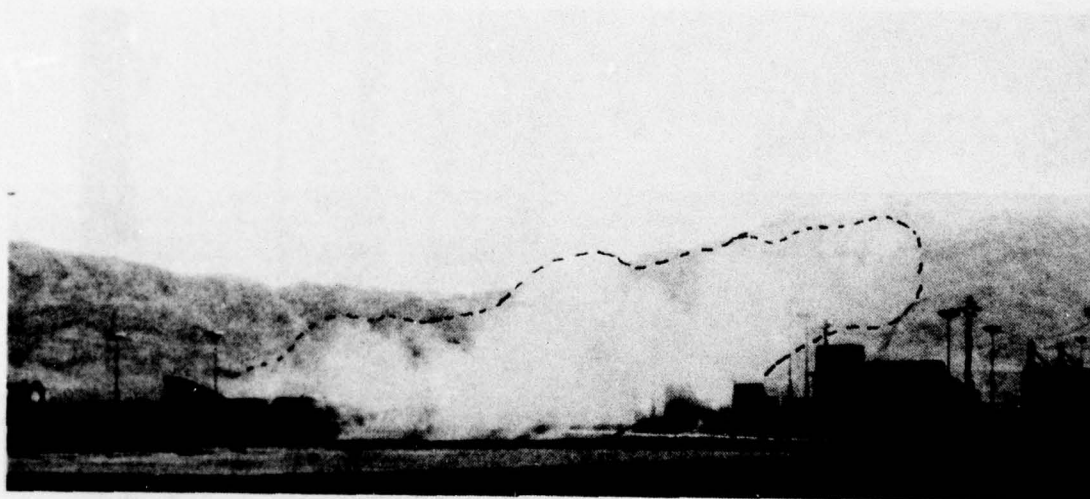
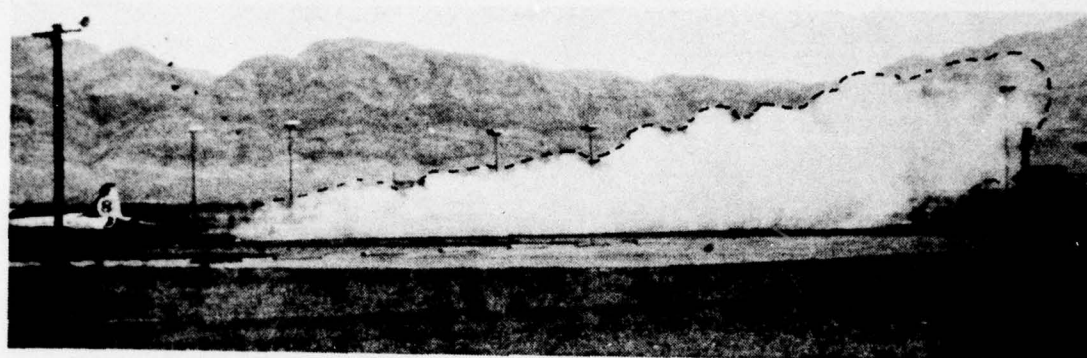


Figure 4. Photographs of T-38 Aircraft Plume: Test 2

approximately 50 meters behind the aircraft and then rose slowly (Figure 4 bottom photo). The diameter of the plume does not begin to increase until over 10 meters behind the aircraft (Figure 5). This retarding of the plume spread and the delayed ground separation may be due to the high wind velocity acting with the buoyant effects of the plume as vector quantities which would describe the shape of the plume.

Test 3. The next test at Nellis AFB (Figure 6) also had interesting results. The winds at the observation site were reported as calm; however, at the test site there was an obvious breeze estimated at up to 3 knots. The atmosphere was unstable. Ground separation occurred approximately 50 meters downstream (Figures 6 and 7), just as during the previous test. However, the ground separation point coincided with the point where the concrete met the sand. The difference in the heat absorption characteristics of the concrete and sand may have an effect on the rise at this location.

Another interesting phenomena which occurred during the start of this test was that the plume began to loop several times before it lifted (see Figure 8).

Test 4. The fourth test at Nellis AFB was made during slight winds and very unstable atmospheric conditions. In this case the greatest looping occurred. Looping began at approximately 50 meters off the ground (Figure 9 top photo), and then the entire loop continued to rise (Figure 9 bottom photo), forming a large arch. Ground separation began at approximately 45 meters behind the aircraft (Figure 10).

Test 5. The last test conducted at Nellis AFB was performed during high winds which quickly spread out the plume to where it could not be photographed. Consequently, this test was discarded.

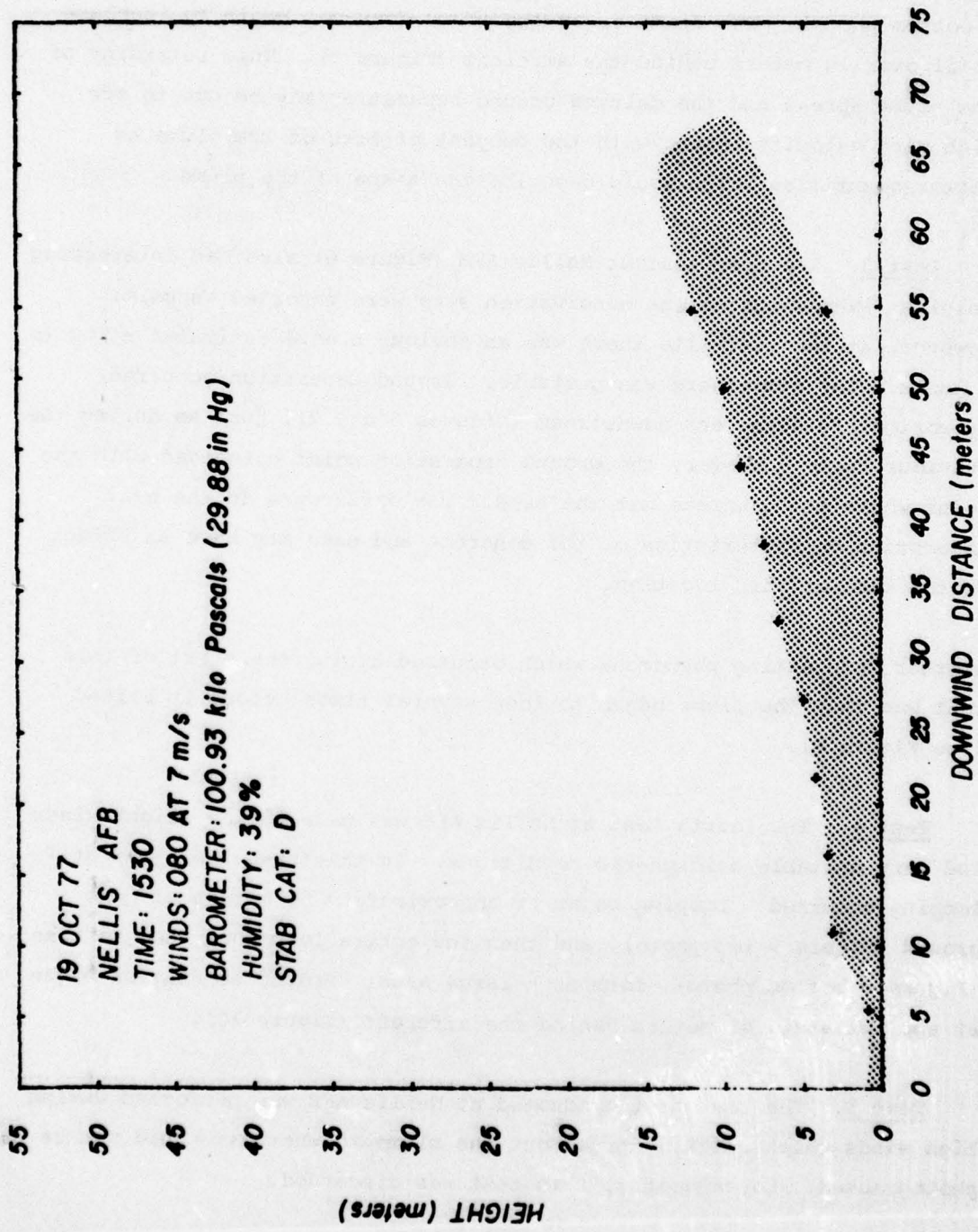


Figure 5. Graph of T-38 Aircraft Plume: Test 2

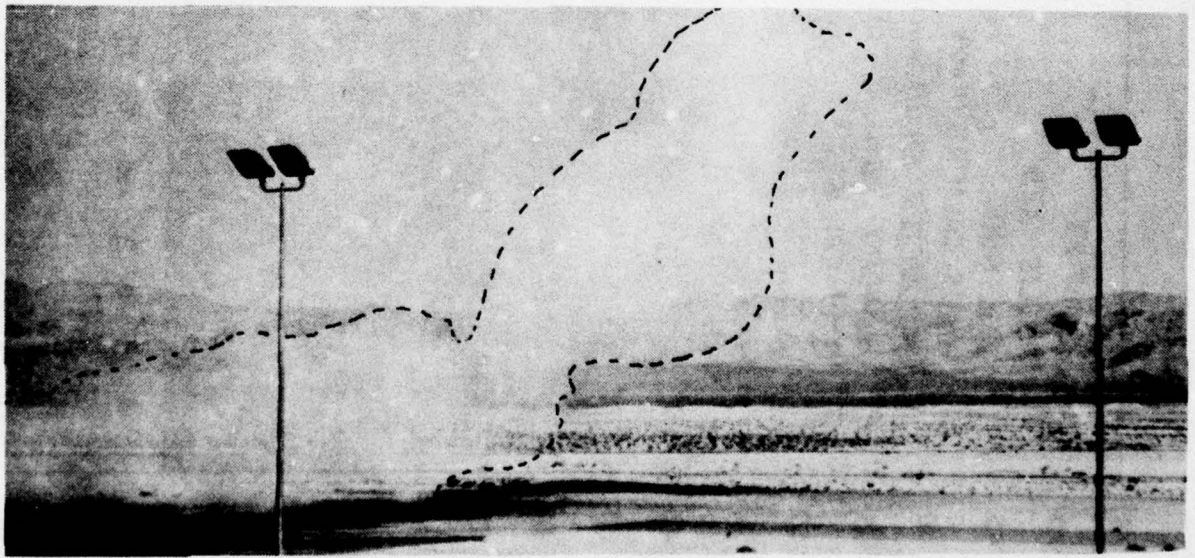
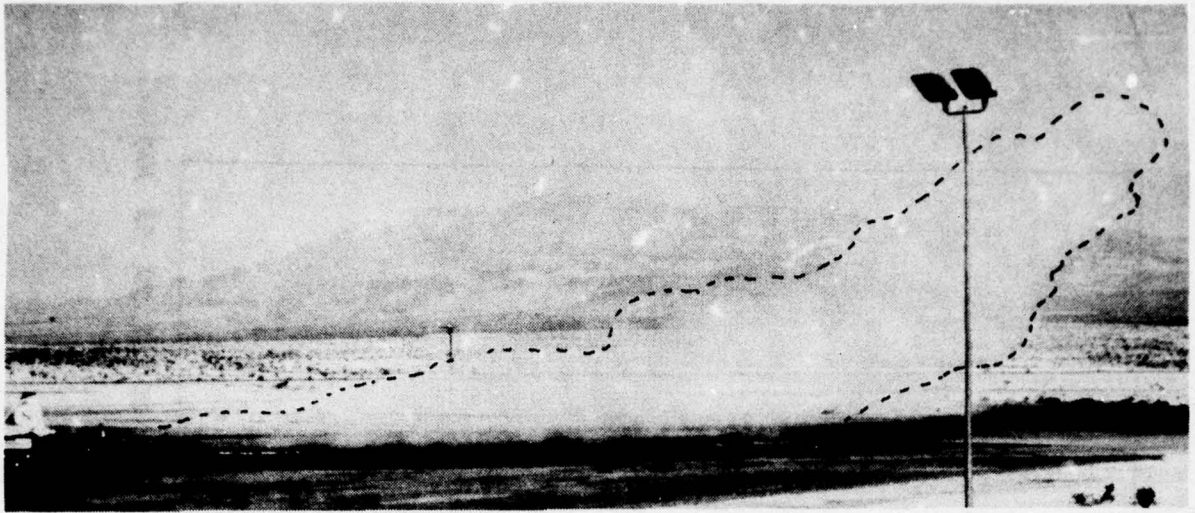


Figure 6. Photographs of T-38 Aircraft Plume: Test 3

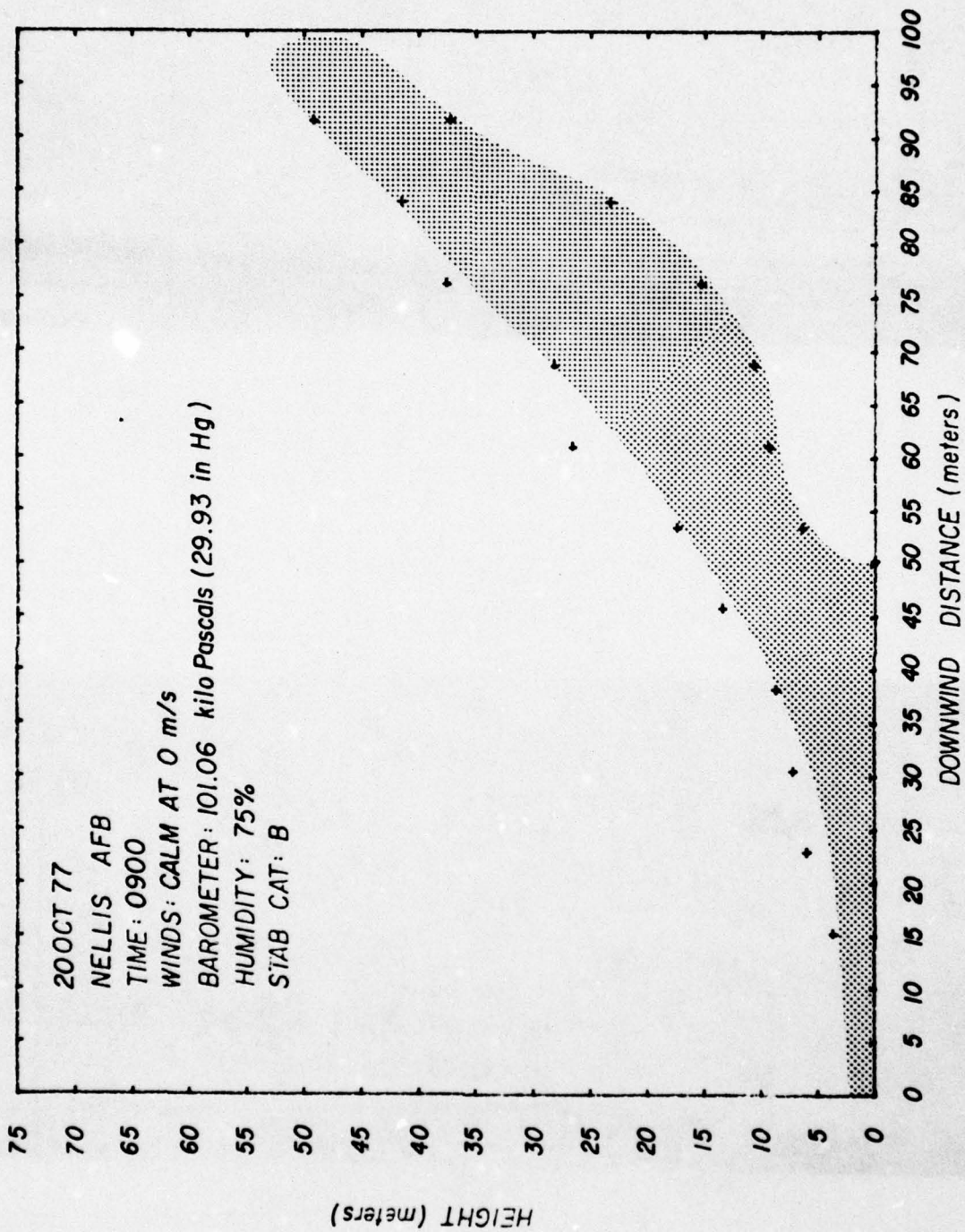


Figure 7. Graph of T-38 Aircraft Plume: Test 3

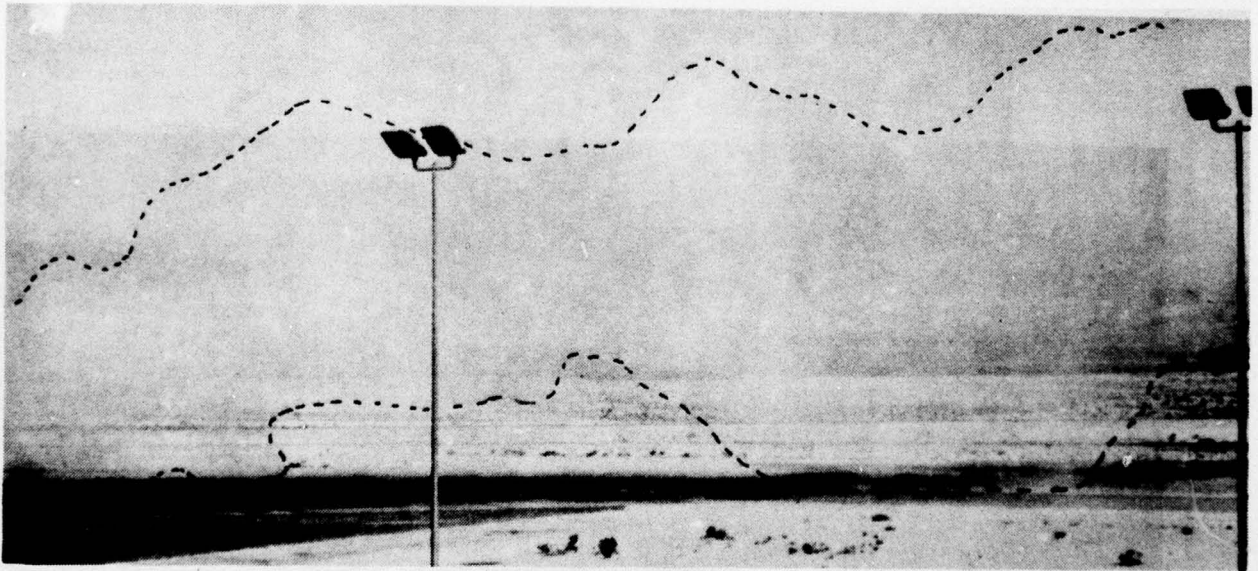
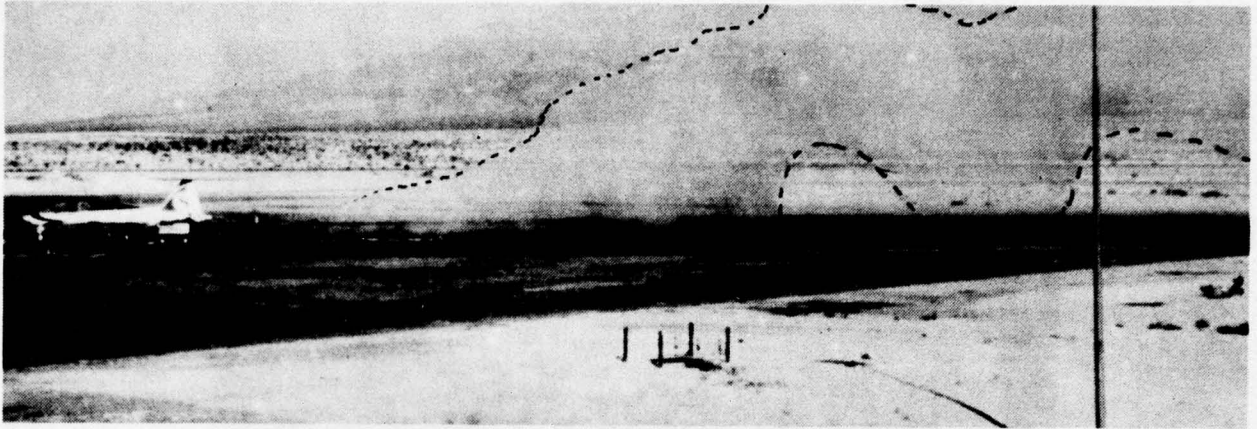


Figure 8. Photographs of T-38 Aircraft Looping Plume:  
Test 3

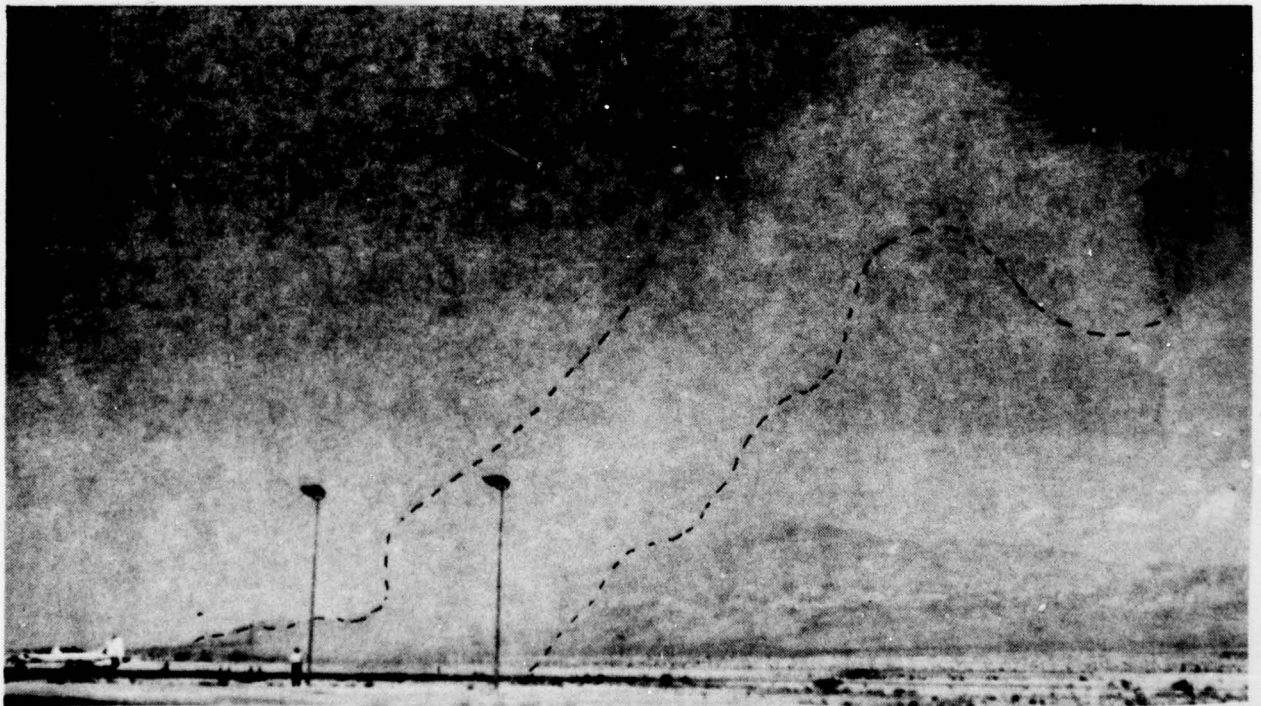
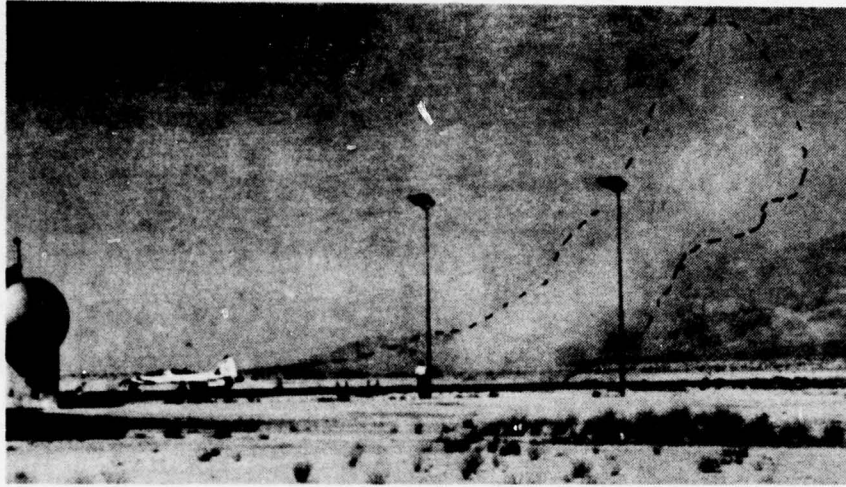


Figure 9. Photographs of T-38 Aircraft Plume: Test 4

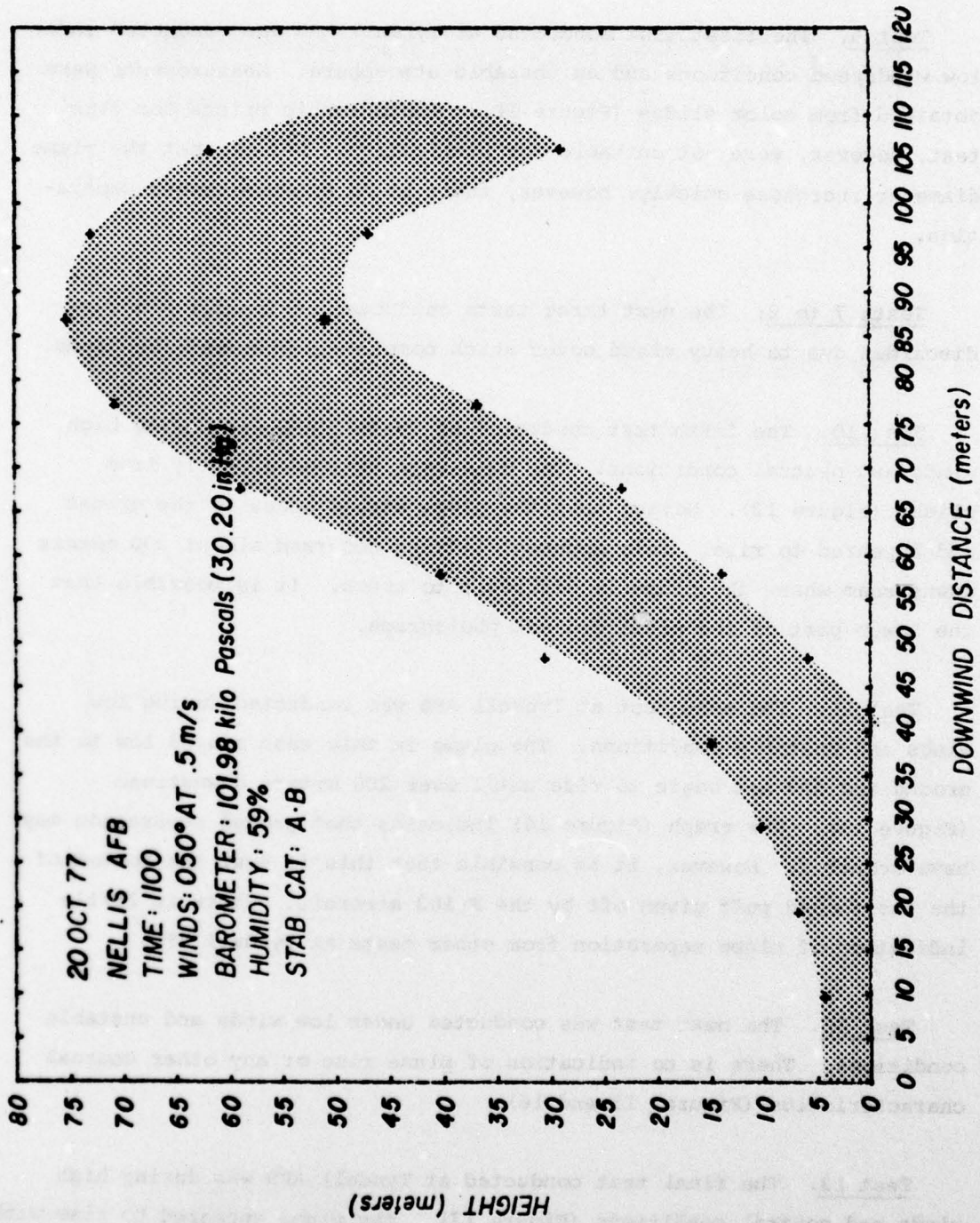


Figure 10. Graph of T-38 Aircraft Plume: Test 4

F-102 DRONE AIRCRAFT (Tests 6 to 13)

Test 6. The first test conducted at Tyndall AFB was conducted under low windspeed conditions and an unstable atmosphere. Measurements were obtained from color slides (Figure 11). Photographic prints for this test, however, were not suitable for publication. Notice that the plume diameter increases quickly; however, there is no visible ground separation.

Tests 7 to 9: The next three tests conducted at Tyndall AFB were discarded due to heavy cloud cover which completely obscured the plume.

Test 10. The fifth test conducted at Tyndall AFB was during high winds and neutral conditions. The data were derived directly from slides (Figure 12). Notice that the plume stayed close to the ground and appeared to rise. This apparent lifting occurred almost 200 meters downstream where the plume is difficult to track. It is possible that the lower part of the plume did not photograph.

Test 11. The next test at Tyndall AFB was conducted during low winds and unstable conditions. The plume in this case stayed low to the ground and did not begin to rise until over 200 meters downstream (Figure 13). The graph (Figure 14) indicates that ground separation may have occurred. However, it is possible that this is just the bottom of the two-second puff given off by the F-102 aircraft. There is little indication of plume separation from other tests at Tyndall AFB.

Test 12. The next test was conducted under low winds and unstable conditions. There is no indication of plume rise or any other unusual characteristics (Figures 15 and 16).

Test 13. The final test conducted at Tyndall AFB was during high winds and neutral conditions (Figure 17). The plume appeared to rise with

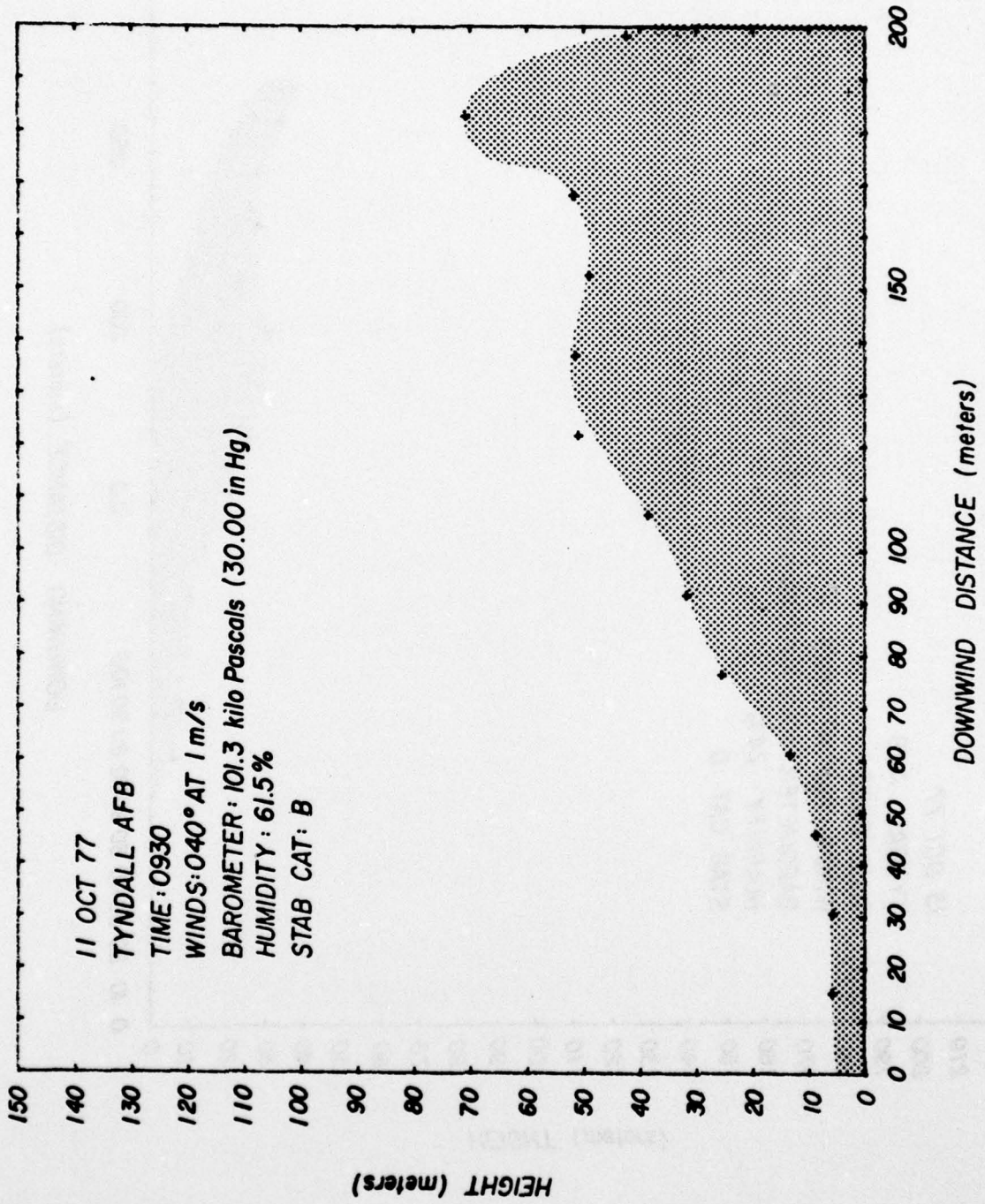


Figure 11. Graph of F-102 Aircraft Plume: Test 6

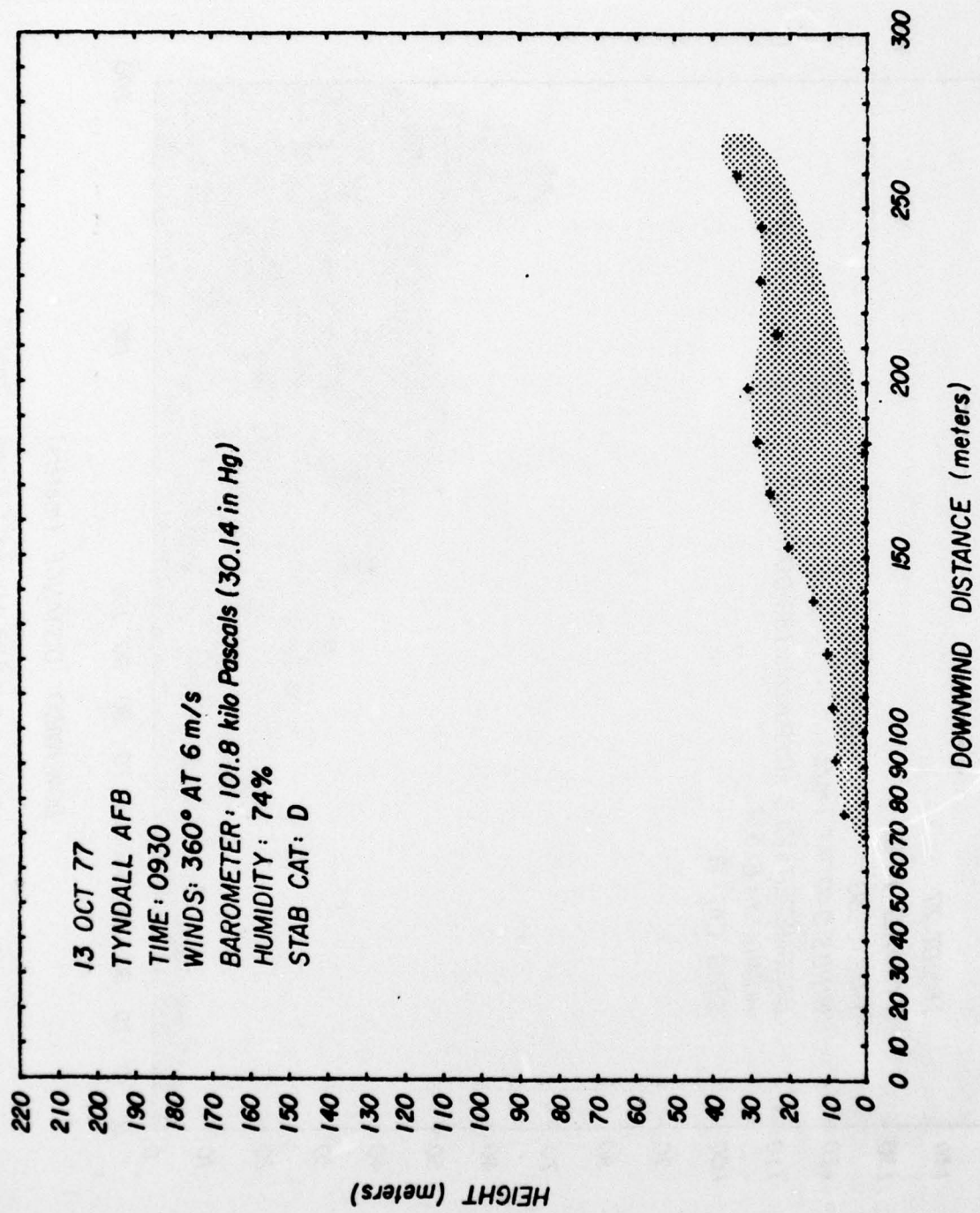


Figure 12. Graph of F-102 Aircraft Plume: Test 10

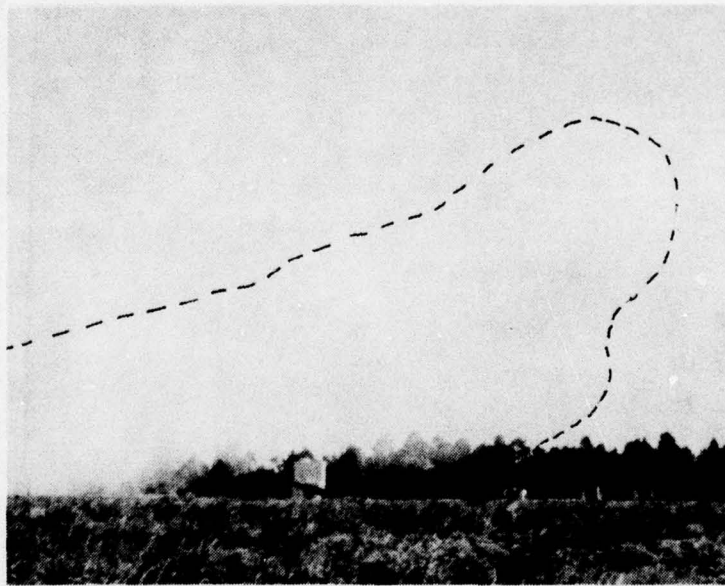
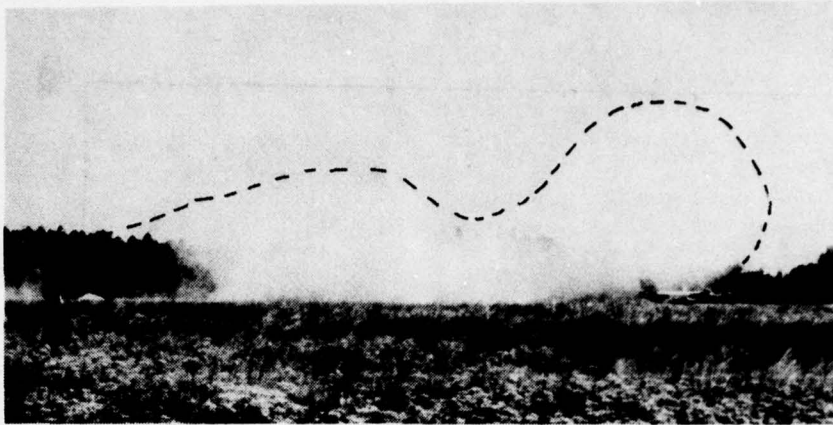


Figure 13. Photographs of F-102 Aircraft Plume: Test 11

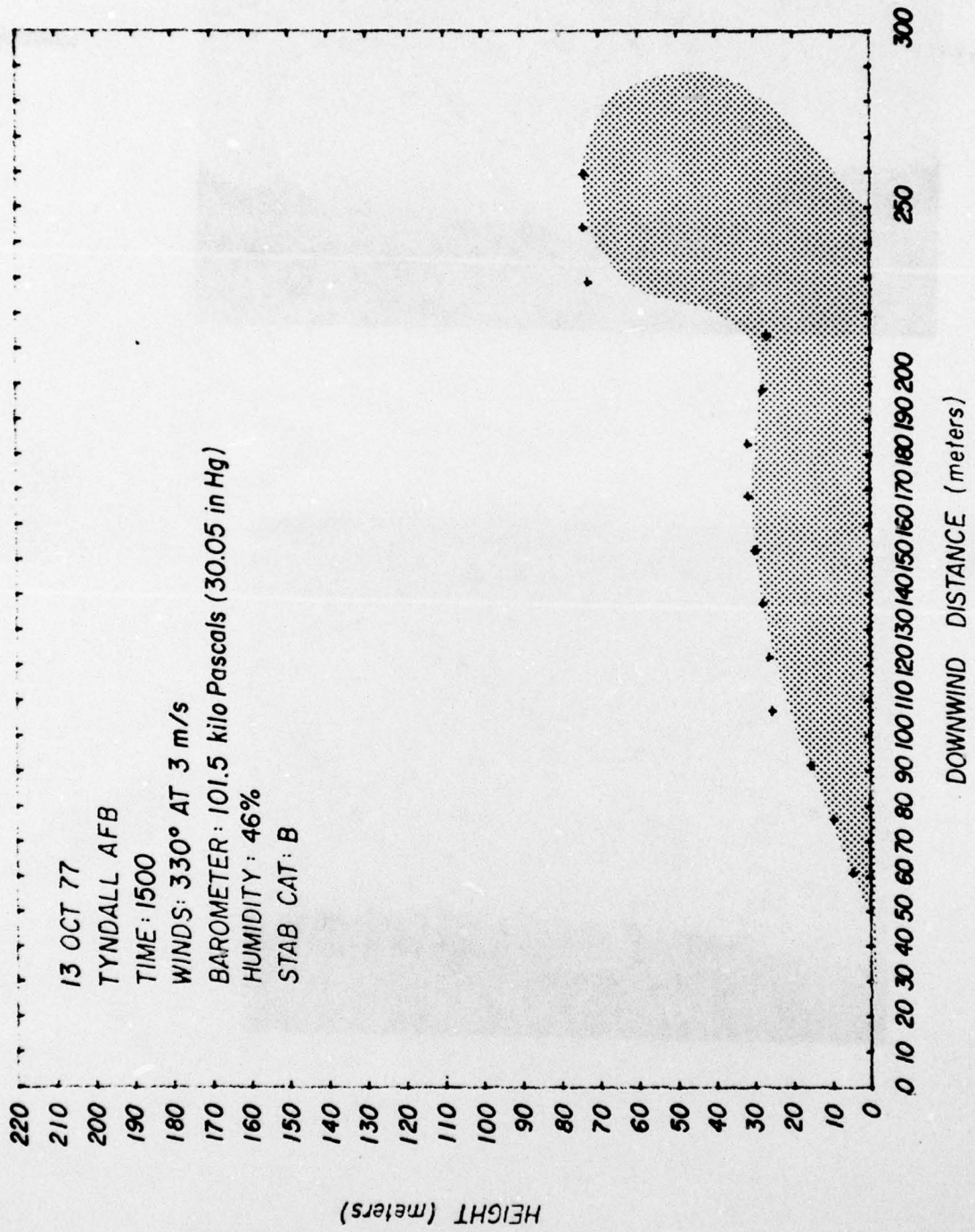


Figure 14. Graph of F-102 Aircraft Plume: Test 11

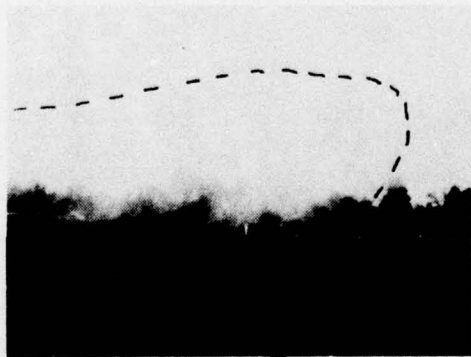
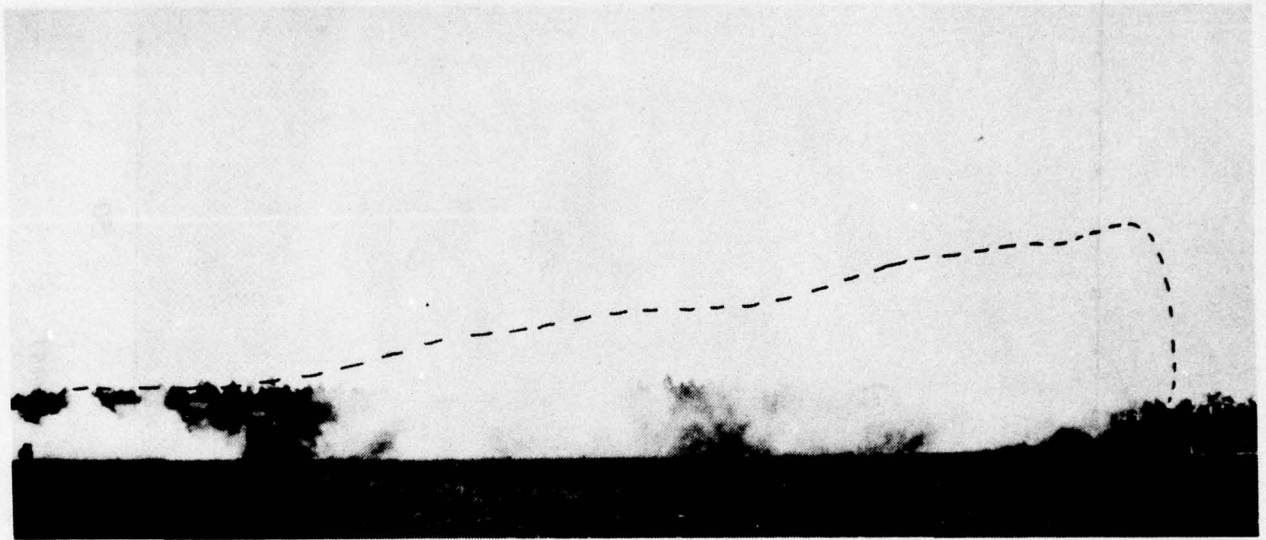


Figure 15. Photographs of F-102 Aircraft Plume: Test 12

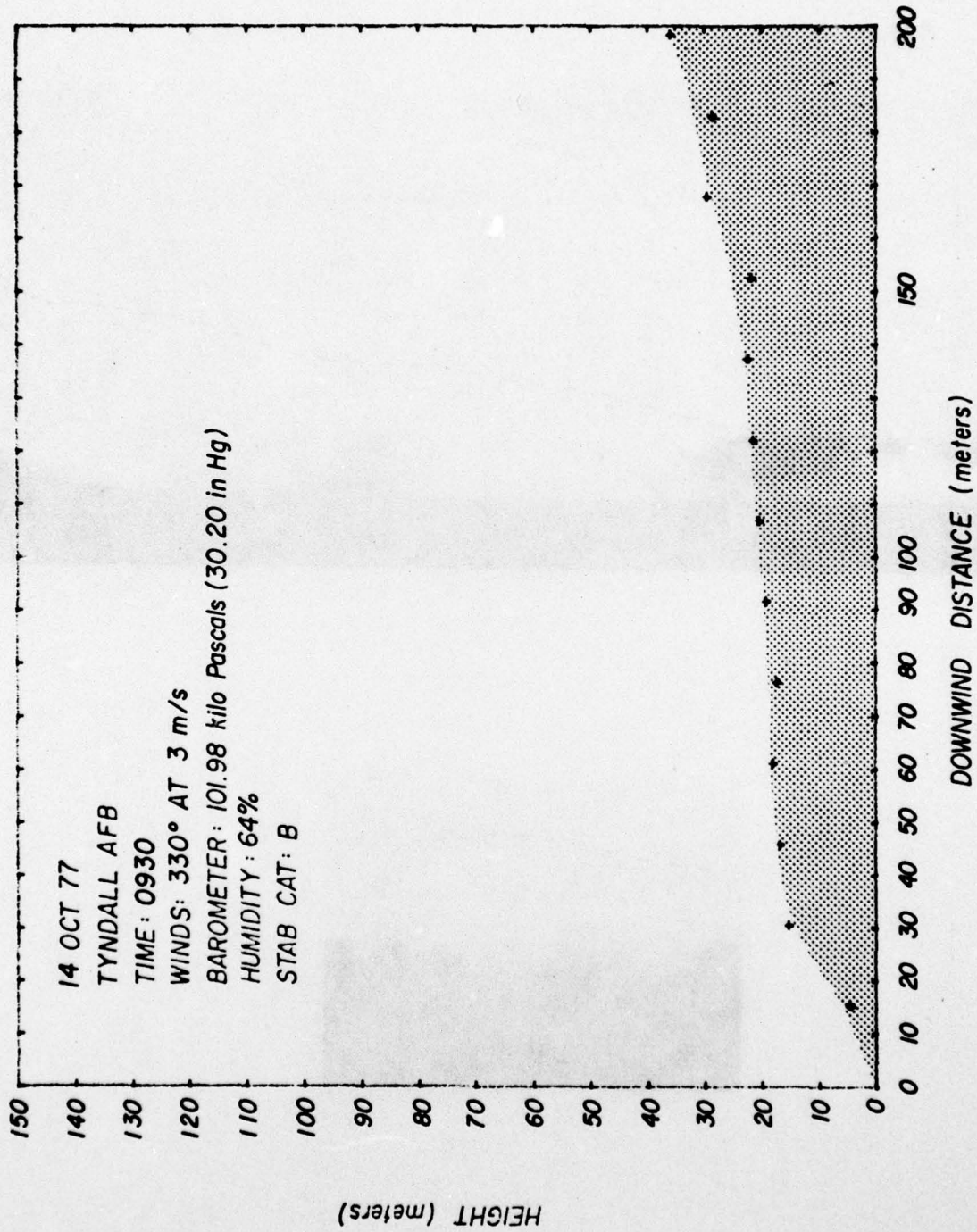


Figure 16. Graph of F-102 Aircraft Plume: Test 12

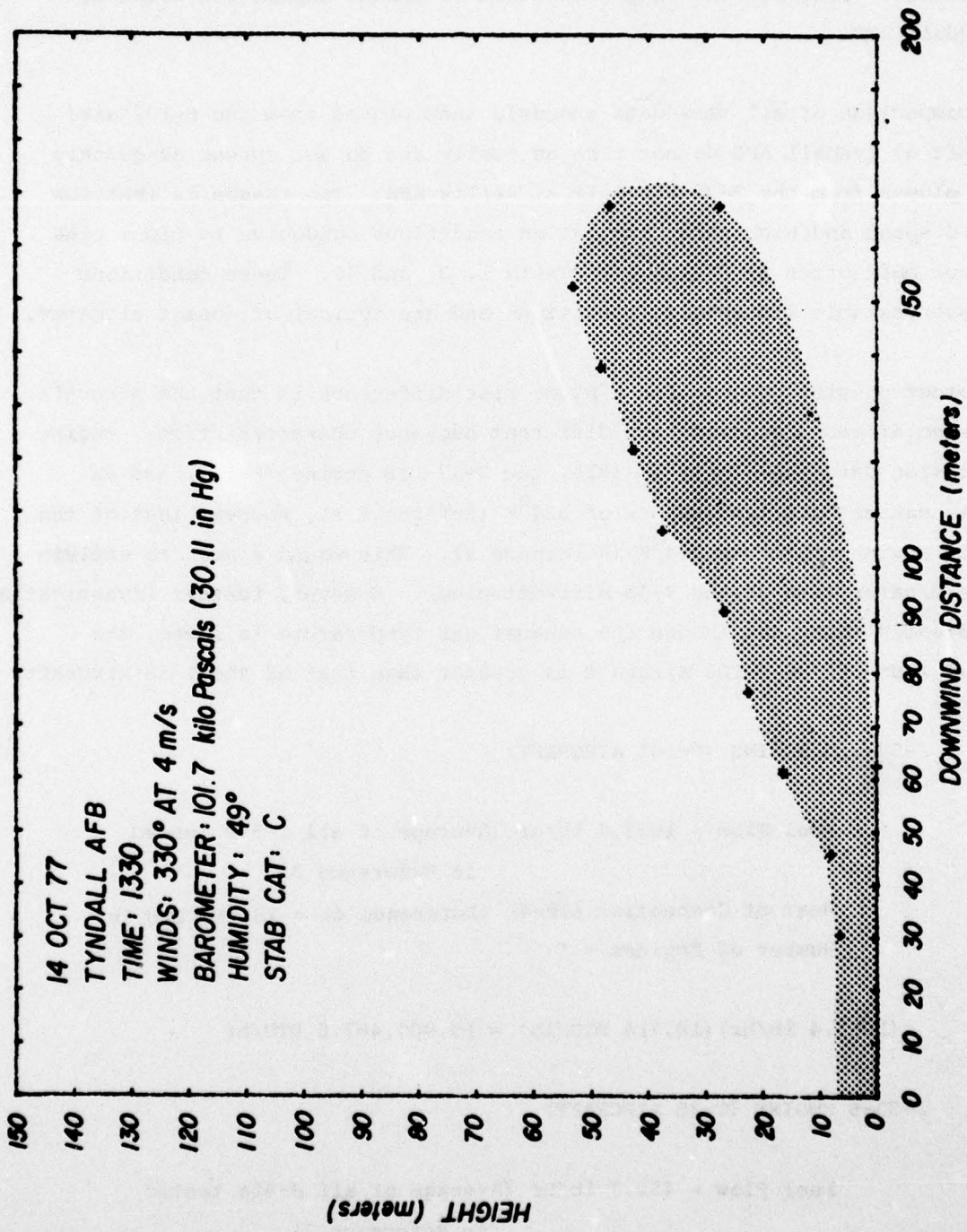


Figure 17. Graph of F-102 Aircraft Plume: Test 13

some ground separation. This separation occurred approximately 60 meters behind the aircraft but the plume never attained a significant attitude. This was the only indication of ground separation noted at Tyndall AFB.

A comparison of all test data suggests that plumes from the F-102 aircraft at Tyndall AFB do not rise as easily and do not spread as quickly as plumes from the T-38 aircraft at Nellis AFB. One reason is that low wind speed and high solar insulation conditions conducive to plume rise occur most often at Nellis AFB (Tests 1, 3, and 4). These conditions cause unstable atmospheric conditions and are typical of desert climates.

Another possible reason for a plume rise difference is that the aircraft tested at each location have different buoyancy characteristics. Engine emission data show that, at idle, the J-57-21B engine (F-102) has an idle exhaust gas temperature of  $324^{\circ}\text{F}$  (Reference 1), whereas that of the J-85 engine (T-38) is  $764^{\circ}\text{F}$  (Reference 2). This would appear to explain the greater rise of the T-38 aircraft plume. However, further investigation indicated that even though the exhaust gas temperature is lower, the heat flux of the F-102 aircraft is greater than that of the T-38 aircraft.

J-57-21B ENGINE (F-102 AIRCRAFT)

Fuel Flow = 1063.4 lb/hr (Average of all J-57s tested  
in Reference 3)

Heat of Combustion (JP-4) (Reference 4) = 18,714 BTU lb

Number of Engines = 1

$$(1063.4 \text{ lb/hr})(18,714 \text{ BTU/lb}) = 19,900,467.6 \text{ BTU/hr}$$

J-85-5 ENGINE (T-38 AIRCRAFT)

Fuel Flow = 452.7 lb/hr (Average of all J-85s tested  
in Reference 3)

Heat of Combustion (JP-4) (Reference 4) = 18,714 BTU/lb  
Number of Engines = 2

$$(2)(452.7 \text{ lb/hr})(18,714 \text{ BTU/lb}) = 16,943,655.6 \text{ BTU/hr}$$

Therefore, the influence of aircraft type and exhaust parameters could not be determined from these studies.

## SECTION V

### CONCLUSIONS

1. The greatest plume rise and ground separation were observed under low winds and high insolation conditions, where the atmosphere is unstable (Tests 1, 3, and 4).
2. Plumes did rise under all conditions, but the rate was greatly retarded as wind velocity increased (Tests 2 and 10).
3. Aircraft type has an undetermined effect on plume rise. While the higher exhaust temperature of the T-38 aircraft appears to explain the higher plume rise observed in the Nellis AFB studies, the total heat flux of the T-38 aircraft is less than that of the F-102 aircraft. This contradiction could not be resolved with the limited data available.
4. Under zero wind conditions for a stationary aircraft, there is an apparent chimney effect where the buoyancy of the plume is continually enhanced (Test 1) by subsequent exhaust gases.
5. Smoke photographing is an effective means of plume tracking if the nose of the aircraft is pointed into the wind, distance markers are visible, and perpendicular distances of the cameras from the exhaust centerline are known.
6. White smoke is not visible against a white, cloud-covered sky. Colored smoke will make the plume more visible and is important at locations such as Tyndall AFB which frequently have a hazy sky background.

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USA CERL	1
Naval Postgraduate School/Code 41A	1
Argonne National Laboratory	1
2d Lt. Paul D. Music	2
AUL/LSE 71-249	1
US EPA/MOA	1
FAA/AEQ	2
Det 1 HQ ADTC/WE	2
Det 1 HQ ADTC/ECA	4
Det 1 HQ ADTC/ECW	1
Det 1 HQ ADTC/PRT	1
AFCEC/DEE	1
2d Lt. John S. Hunt	2
Naval Air Propulsion Center/ Code PE 71: AFK	1
Det. HQ ADTC/EC	1