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ELECTRETS USED IN MEASURING ROCKET EXHAUST EFFLUENTS FROM THE SPACE SHUTTLE'S SOLID ROCKET BOOSTER DURING STATIC TEST FIRING, DM-3

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I. INTRODUCTION

The Space Shuttle's Solid Rocket Booster (SRB) was fired successfully during the Demonstration Model-3 (DM-3) static test at Thiokol's desert test site in Utah on October 19, 1978. The huge solid motor is the largest of its type ever developed for space flight and the first built for use on manned craft. Two of these motors will be used on each Shuttle mission. The 38.1 m (125 ft) long motor fired for approximately 2 min, reaching a thrust level of 12 596 736 N (2 832 000 lb). During the firing, 500 279 kg (1 102 926 lb) of propellant was burned.

To measure the amount of effluents released by the firing of the DM-3 rocket, air samples were taken by Thiokol's fixed flow samplers at 12 locations extending from the immediate test area to as far away as Brigham City (25 miles $\simeq$ 40 km). Marshall Space Flight Center (MSFC) electrets were placed beside each of Thiokol's air samplers. Also, electrets were placed in eight additional locations (four near-field and four far-field positions) to increase the chances of measurements.

Section II of this report presents a discussion of the instruments, background, preparation, and use of electrets and air samplers to measure exhaust effluents from SRB's. Section III presents the meteorological conditions during the DM-3 static test in Utah, Section IV reports the test results, and Section V presents the conclusions.

II. INSTRUMENTS

A. Electrets

Electrets have been known since the latter part of the 19th century. A substantial amount of work has been performed on electrets, and a few practical applications, particularly in the area of communications, have been made.

The word "electret" was derived by Oliver Heavesides in 1892 to describe a permanently polarized dielectric, which is the electrical equivalent of a permanent magnet [1]. A Japanese physicist, Eguchi, prepared the first electret in 1919 from carnauba wax [2].

Electrets have been made in a variety of ways, but the method used at MSFC's Space Sciences Laboratory is the charge injection method [3]. A dielectric sheet is passed over a plate and, as it emerges, a corona discharge is induced over the surface by applying a high-voltage current to a metal wire brush that is kept a short distance from the dielectric. Charges are injected on the dielectric, thus polarizing the dielectric. The sheet then passes through a grounded, air-cooled plate to freeze in the injected and polarized charge. Usually, charges of opposite polarity are produced on opposite sides of the sheet. The polarizing voltage is 15 kV, the temperature is 200°C, and the sample is stroked 10 times. Teflon [polytetrafluoroethylene $(C_2F_4)_n$] electrets have shown the best stability and charge retention up to 200°C. Using the charge injection technique, a surface charge of 10^{-8} C/cm^2 is easily attained.

It has been found that electrets of polymers with stable surface charges on either side are suitable devices for attracting charged particles and ions to their surface. Therefore, it was decided to use these electrets for effectively measuring charged gases, vapors, or particles in the atmosphere.

Electrets are being used to measure the effluents from the propellants in SRB's. The most widely used propellant in SRB's is ammonium perchlorate as the oxidizer with powdered aluminum filler which acts in part as a fuel and partially as a stabilizer to control the burning rate. The exhaust products from this type of fuel contain hydrogen chloride (HCl), aluminum oxide (Al_2O_3), and water (H_2O). To assess the impact of these products in the atmosphere, it is necessary to know not only their quantity but also their distribution in the ground cloud that develops at the launch site after a rocket firing [4].

Electrets of polymers have been used successfully in measuring rocket exhaust effluents. The particles in tests that have been conducted either have a positive or negative charge and are attracted to the electret's surface. These collected particles or ions on the electrets are then analyzed by taking an X-ray spectrograph of the sample. The electrets were evaluated by taking the total Cl counts obtained from the surface of the electret after exposure to pollution as a measure of the quantity of material collected by the dispersive X-ray analyses. The counts were converted to parts per million and compared with HCl measuring equipment and computed values from the NASA/MSFC Multilayer Diffusion Model [4, 5]. From these studies it was possible to identify the various effluents coming from the rockets at the time of firing. Direct comparisons of values obtained with electrets were made with the results. A comparison of measured values of HCl during 18 static tests at MSFC, with the envelope of the upper and lower bounds obtained from the NASA/MSFC Multilayer Diffusion Model, is presented in Reference 4.

The results show that electrets have multipollutant measuring capabilities, simplicity of deployment, and speed of assessment. Electrets are desirable because of their small size, light weight, long life, and low cost of manufacturing.

B. Thiokol's Fixed Flow Samplers

The linear flow in the Thiokol fixed flow air samplers is obtained by use of a wind tunnel to which the air sampler is attached. The tunnel consists of a pipe whose length [177.8 cm (70 in.)] is ten times its diameter [17.78 cm (7 in.)]. The air flow rate is calculated from the linear velocity plus the area swept out through the wind tunnel. The sampling rate was 4.88 m^3 (16 ft^3) of air/minute with Whatman No. 41 paper filters. Aluminum (Al), silica (Si), sulfur (S), and chlorine (Cl) are sampled by Thiokol's fixed flow samplers.

The Whatman No. 41 filters trap 98 percent of the 20 to 25 μ particles at a very rapid flow. X-ray fluorescence was used to determine Cl, S, Si, and Al content. Figure 1 shows Thiokol's fixed flow samplers and MSFC's electrets during the DM-3 static test.

III. METEOROLOGICAL DATA

A. General Synoptic Conditions

Fifty-six hours prior to the test firing at 1400 MDT (Thursday, October 19, 1978), two high pressure areas dominated most of the nation. The stronger of these, centered over the eastern Great Lakes, stretched northeastward across Canada and southwestward to Texas and New Mexico. The other, located over eastern Alberta, had surged southward along the eastern slopes of the Rockies during the preceding day. At 0600 MDT (Tuesday, October 17, 1978) the frontal boundary separating the two air masses swung southward from a low pressure trough over east-central Canada, across the Dakotas and Nebraska, then westward to a point along the Utah-Idaho border. Relatively lower pressure

Figure 1. MSFC's electret (single arrow) and Thiokol's air sampler (double arrow).

existed over much of the remainder of the western U.S. from southern California northward along the Pacific coast and over interior sections across portions of Nevada, Utah, Idaho, and western Montana. The Salt Lake City area had overcast skies with light northwesterly winds.

The main synoptic feature at 500 mb was a relatively sharp trough aligned southwestward from west-central Canada to the northern California coast and offshore over the eastern Pacific. A secondary trough was indicated over northern Mexico to the west of a ridge of high pressure over Texas and Louisiana. The 1200 GMT radiosonde data from Salt Lake City, situated on the east side of the major trough, reflected southwest winds of 15.44 m/s (30 kt) at the 500 mb level. By Wednesday morning the axis of the massive high dominating the eastern half of the country a day earlier had moved near the eastern seaboard. The cold frontal boundary had been displaced southeastward across the nation's midsection and was located within a narrow surface trough running from the central Great Lakes region across Iowa and eastern Kansas to New Mexico. The cold high centered over eastern Alberta on Tuesday had tracked southeastward to the Dakotas. Low pressure troughing was still evident northward over California as well as southern portions of Nevada and Utah and northern Arizona. Salt Lake City was under partly cloudy skies with some shower activity in the area and light southerly winds at the surface.

At 500 mb, the western trough was now aligned from the western Great Lakes west-southwestward to northern Utah, then southwest well off the northern Baja California coast where it appeared to be closing off. Winds at Salt Lake City, along the trough axis, were now westerly at 12.87 m/s (25 kt). Nearly zonal flow existed east of the trough over the northern half of the U.S. with speeds decreasing southward to near the Gulf coast. By Thursday morning the cold front lay in a weak trough from New England southwestward across Texas. The center of the high over the northern Plains on Wednesday had settled southward over western Kansas and was dominating most of the remainder of the country as it bridged eastward across the frontal boundary to the Atlantic coast and westward to the Pacific. Northern Utah and surrounding areas were experiencing clear skies at 0600 MDT. Winds were calm in Salt Lake City.

A closed-off low had established itself over the eastern Pacific, west of northern Baja, at 500 mb with the trough extending northeastward to another low centered over Nevada. Ridging was occurring over south-central portions of the nation, northwestward over the Pacific northwest, bending westward around the Nevada low to the coast. Salt Lake City, on the east side of the Nevada low, was reporting southwest winds at 15.44 m/s (30 kt).

B. Localized Atmospheric Conditions

Throughout the morning hours on the day of the firing (Thursday), Salt Lake City was recording clear skies, good visibility, and very light (mostly southeasterly) winds. By 1400 MDT the station had scattered cloudiness, a temperature of 21.1°C (70°F), and northerly winds of 4.63 m/s (9 kt). A cumulonimbus cloud formation was observed to the distant west-southwest. The exhaust cloud from the SRB was visible to the distant north-northwest from the Salt Lake City forecast office at 1414 MDT. A vertical wind profile from Salt Lake City, extracted from a radiosonde run made at 1715 MDT, yielded uniform south-southwest winds from 641 m (2103 ft) through 3652 m (11 981 ft). Speeds varied from 4.12 m/s (8 kt) and 8.75 m/s (17 kt) at the 641 m (2103 ft) and 938 m (3077 ft) levels, respectively, to between 10.8 m/s (21 kt) and 13.38 m/s (26 kt) through 2660 m (8727 ft). Within the remainder of the layer, 15.44 m/s (30 kt) speeds were common, reaching a maximum of 17.50 m/s (34 kt) at 3652 m (11 981 ft). Surface winds were north-northwest at 5.15 m/s (10 kt), backing to west-northwest and decreasing to 1.54 m/s (3 kt) at 390 m (951 ft).

Diurnal temperature ranges over the area from Tuesday until the time of the firing varied from 5° to 23°C (42° to 73°F). No measurable precipitation was recorded at the Salt Lake City forecast office during the period of record; however, a trace of precipitation fell between 0600 MDT Tuesday and 0600 MDT Wednesday. A few additional showers developed nearby during the late afternoon and early evening hours on Wednesday.

Much of Utah experienced another precipitation episode on Friday and into Saturday as the upper level Pacific trough tracked eastward across the western states. Although local amounts of precipitation ranged near an inch over southern Utah, Salt Lake City again received only a trace.

IV. TEST RESULTS

A. Thiokol's Fixed Flow Samplers

As with previous test firings, air samples were taken during the firing of DM-3 to measure the amount of rocket exhaust effluents. Samples were taken at 12 locations extending from the immediate test area to as far away as Brigham City.

These samples showed that the test firing had no significant effect on the air quality in the areas sampled. The sample sites were the same as those for the previous DM-2 test [6] except that a sample was taken at the Howell Well, and the portable generator was moved north of Plant 3 so it was generally east of the test site. The sampling time varied from 2 to 10 hours. Background samples were taken at six sites the day before the firing; most of these samples were run for approximately 24 hours. As in the two previous firings, the samples were taken with Thiokol's fixed flow samplers; the sampling rate was 4.88 m^3 (16 ft^3) of air/minute with Whatman No. 41 paper filters. After sampling, the following tests were run on each filter:

1) Each filter was weighed before and after sampling.

2) X-ray fluorescence was used to determine Cl, S, Si, and Al.

3) The filters were leached with water and the pH of each solution was measured.

The samples taken at sites 1 and 8 were averaged as a background for all other remote sites where a background was not taken. The background data were subtracted from the test data. All of the test data are very low and indicate no significant increase in contamination during the firing. Figures 2 and 3 illustrate the far-field and near-field deployment of instruments.

The highest measurement was obtained by the sampler at Plant 3 (site 11), 8 km at a 113-deg heading from the static test site. After background corrections, 0.0048 mg/m^3 of Cl and 0.0017 of S were measured. No measurement of Si and Al was obtained. Converting the 0.0048 mg/m^3 of Cl to ppm results in 0.0016 ppm. The next highest measurement was at Plant 78 (site 12), 6.43 km at a 330-deg heading from the static test site, where 0.0016 mg/m^3 of Cl, 0.0016 of S, 0.003 of Si, and 0.0007 of Al were sampled. Converting the 0.0016 mg/m^3 of Cl to ppm results in 0.0008 ppm. At site 5, approximately 300-deg heading and 100 m from the static test firing, 0.0012 mg/m^3 of Cl, 0.0020 of S, 0.019 of Si, and 0.0016 of Al were sampled. Converting the 0.0012 mg/m^3 of Cl to ppm results in 0.0004 ppm. Again, there was no measurement of significant rocket exhaust effluents at the test sites sampled.

There is no indication from the pH measurements that there was any HCl contamination. In fact, in most cases the pH increased. If HCl had been present, the pH would have decreased.

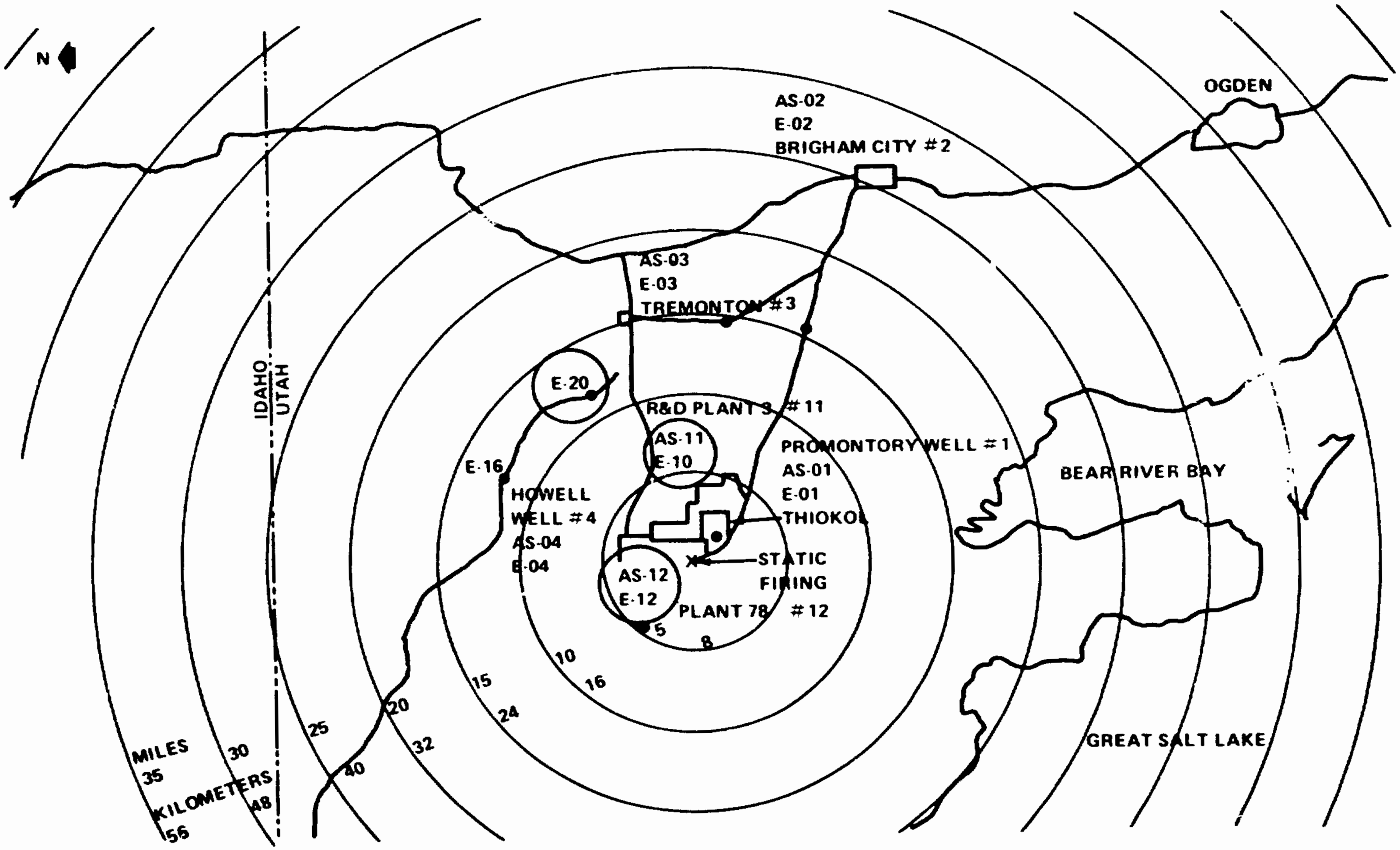


Figure 2. Far-field deployment of instruments.

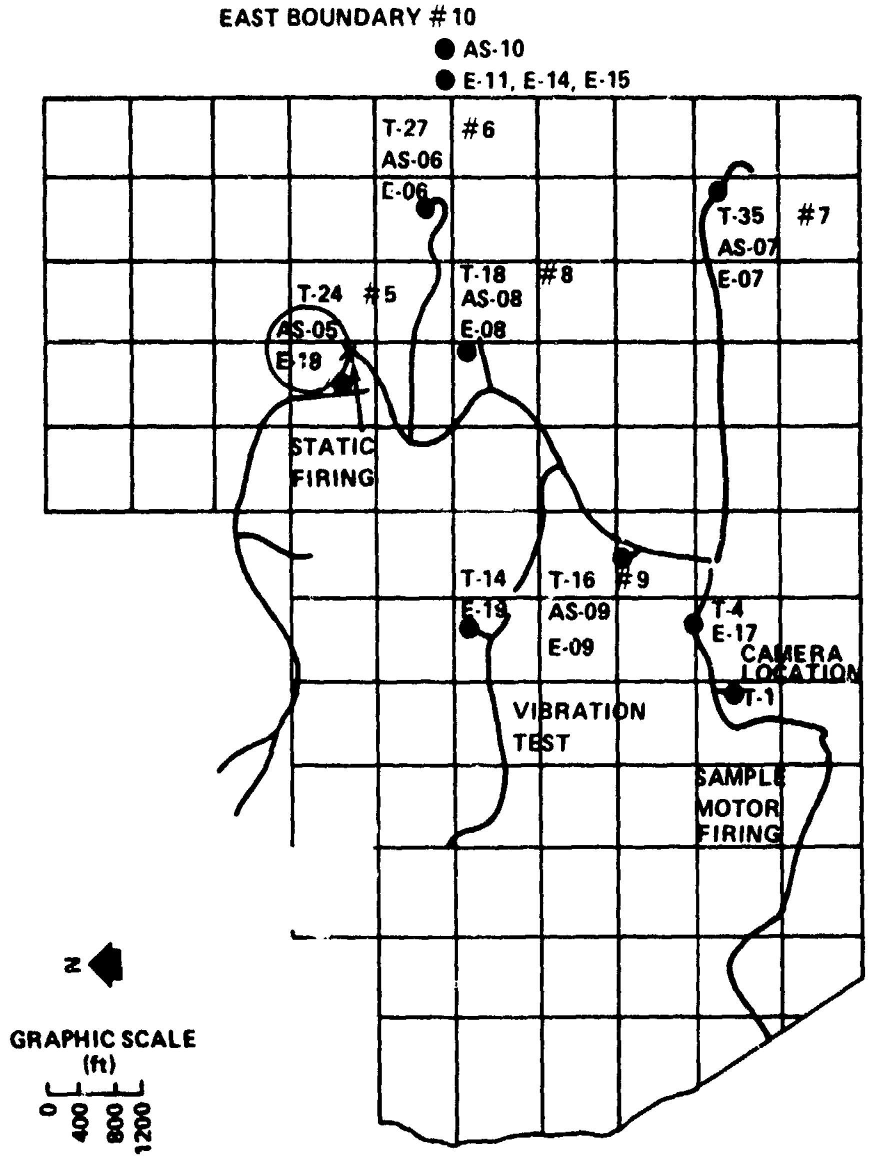


Figure 3. Near-field deployment of instruments.

According to the National Weather Service in Salt Lake City, there was a weak temperature inversion at approximately 3657 m (12 000 ft) at the time of firing. The cloud went up to about this level and then flattened out and moved in a northeasterly direction as it dispersed. The major fallout from the cloud missed the samplers that were near the test site. The far-field sampler nearest the cloud's path was in Tremonton; however, when the cloud reached this point, it was well dispersed, so very little, if any, contamination was detected [7]. Figures A-1 through A-4 in the Appendix illustrate the exhaust cloud rise during the DM-3 static test firing.

B. MSFC's Electrets

At sites 11, 12, and 5 (Figures 2 and 3) the electret counts obtained from X-ray spectroscopy for Cl, corrected for background, were 334, 543, and 368, respectively (Tables 1, 2, and 3). As previously indicated, the fixed flow sampler measurements of 0.0048, 0.0016, and 0.0012 mg/m^3 for Cl were converted to ppm of 0.0016, 0.0008, and 0.0004, respectively, at these sites. The average of the counts from the MSFC electrets is 415. Likewise, the average of Thiokol's air samplers is 0.0009 ppm. An additional measurement (Table 4) was obtained by an electret placed at site 20, approximately 20 km northeast from the test site (Figure 2). With no power available at this site, the electret, a passive instrument, was the only measurement device possible. A total of 550 counts was obtained from X-ray spectroscopy. Equating the previously calculated average counts of 415 from the electrets and 0.0009 ppm from Thiokol's samplers, the 550 counts obtained at site 20 convert to 0.0011 ppm. Again, there was no significant amount of rocket exhaust effluents.

V. CONCLUSIONS

The purpose of this research was to evaluate the electret, a new contamination detection device developed by MSFC, in conjunction with Thiokol's fixed flow air sampler during the DM-3 static test firing in Utah.

The assessment of the effectiveness of the electret resulted in the following conclusions.

At sites 11, 12, and 5, Thiokol's fixed flow air samplers measured 0.0048, 0.00016, and 0.00012 mg/m^3 of Cl. These measurements converted to 0.0016, 0.0008, and 0.0004 ppm, or an average of 0.0009 ppm. Alongside the fixed flow measurements, the electret counts from X-ray spectroscopy were 334, 543, and 368 counts, or an average of 415 counts.

An additional electret was placed at site 20, approximately 20 km northeast of the static test site. The electret was the only measurement device, because no power was available at this site. After subtracting the background count, 550 counts were obtained from X-ray spectroscopy. Equating the average electret counts of 415 and the average calculated 0.0009 ppm from the fixed flow samplers, the 550 counts obtained at site 20 equal 0.0011 ppm. Again, no significant amount of rocket exhaust effluents was measured. In addition, simplicity in deployment of the electrets (no power necessary) makes the electret a valuable complementary device in detecting rocket gas effluents.

TABLE 1. ELECTRET QUANTITATIVE RESULTS OBTAINED FROM X-RAY SPECTROSCOPY AT SITE 11[a]

X–RAY ENERGY (keV)	TOTAL TEST COUNTS (1000 s)	SYMBOL	BACKGROUND COUNTS
1.480	58617	Al	–
1.709	106247	Si	129303
2.595	685	Cl	351
6.370	6924	Fe α	4912
7.027	701	Fe β	326
8.009	12873	Cu α	7596
8.878	1494	Cu β	825

a. SITE 11 RESULTS FOR THIOKOL'S FIXED FLOW SAMPLER:
TOTAL: 0.009 mg/m^3
Cl: 0.0048 mg/m^3
S: 0.0013 mg/m^3
Si AND Al: NEGATIVE

TABLE 2. ELECTRET QUANTITATIVE RESULTS OBTAINED FROM X-RAY SPECTROSCOPY AT SITE 12[a]

TOTAL TEST

X-RAY ENERGY (keV)	COUNTS (1000 s)	SYMBOL	BACKGROUND COUNTS
1.480	43417	Al	—
1.709	135945	Si	129303
2.082	771	Au	996
2.250	2225	S	1618
2.595	894	Cl	351
3.307	1960	K	897
3.657	7535	Ca	169
5.410	1400	Cr_{α}	1234
5.860	190	Cr_{β}	—
6.370	5877	Fe_{α}	4912
7.027	964	Fe_{β}	326
8.009	9701	Cu_{α}	7596
8.878	1103	Cu_{β}	825

a. SITE 12 RESULTS FOR THIOKOL'S FIXED FLOW SAMPLER:
TOTAL: 0.022 mg/m^3
Cl: 0.0016 mg/m^3
S: 0.0016 mg/m^3
Si: 0.003 mg/m^3
Al: 0.0007 mg/m^3

TABLE 3. ELECTRET QUANTITATIVE RESULTS OBTAINED FROM X-RAY SPECTROSCOPY AT SITE 5[a]

X-RAY ENERGY (keV)	TOTAL TEST COUNTS (1000 s)	SYMBOL	BACKGROUND COUNTS
1.480	47353	Al	–
1.709	119011	Si	129303
2.082	781	Au	996
2.595	719	Cl	351
3.657	1587	Ca	169
5.410	1990	Cr_α	1234
5.860	169	Cr_β	–
6.370	6288	Fe_α	4912
7.060	46	Fe_β	326
7.432	1019	Ni	968
8.009	12553	Cu_α	7596
8.878	1512	Cu_β	825

a. SITE 5 RESULTS FOR THIOKOL'S FIXED FLOW SAMPLER:
TOTAL: 0.075 mg/m^3
Cl: 0.0012 mg/m^3
S: 0.0020 mg/m^3
Si: 0.019 ng/m^3
Al: 0.0016 mg/m^3

TABLE 4. ELECTRET QUANTITATIVE RESULTS OBTAINED FROM X-RAY SPECTROSCOPY AT SITE 20[a]

X–RAY ENERGY (keV)	TOTAL TEST COUNTS (1000 s)	SYMBOL	BACKGROUND COUNTS
1.480	54208	Al	—
1.709	154685	Si	129303
2.082	555	Au	986
2.250	1691	S	1618
2.595	901	Cl	351
3.307	4963	K	897
3.657	3300	Ca	169
5.410	1100	Cr α	1234
5.860	264	Cr β	—
6.370	6314	Fe α	4912
7.027	613	Fe β	326
7.432	—	Ni	968
8.009	12767	Cr α	7596
8.878	1805	Cu β	825

a. NO THIOKOL FIXED FLOW SAMPLER MEASUREMENTS.

APPENDIX

PHOTOGRAPHS OF ROCKET PLUME/FIRE AT VARIOUS STAGES OF BURN

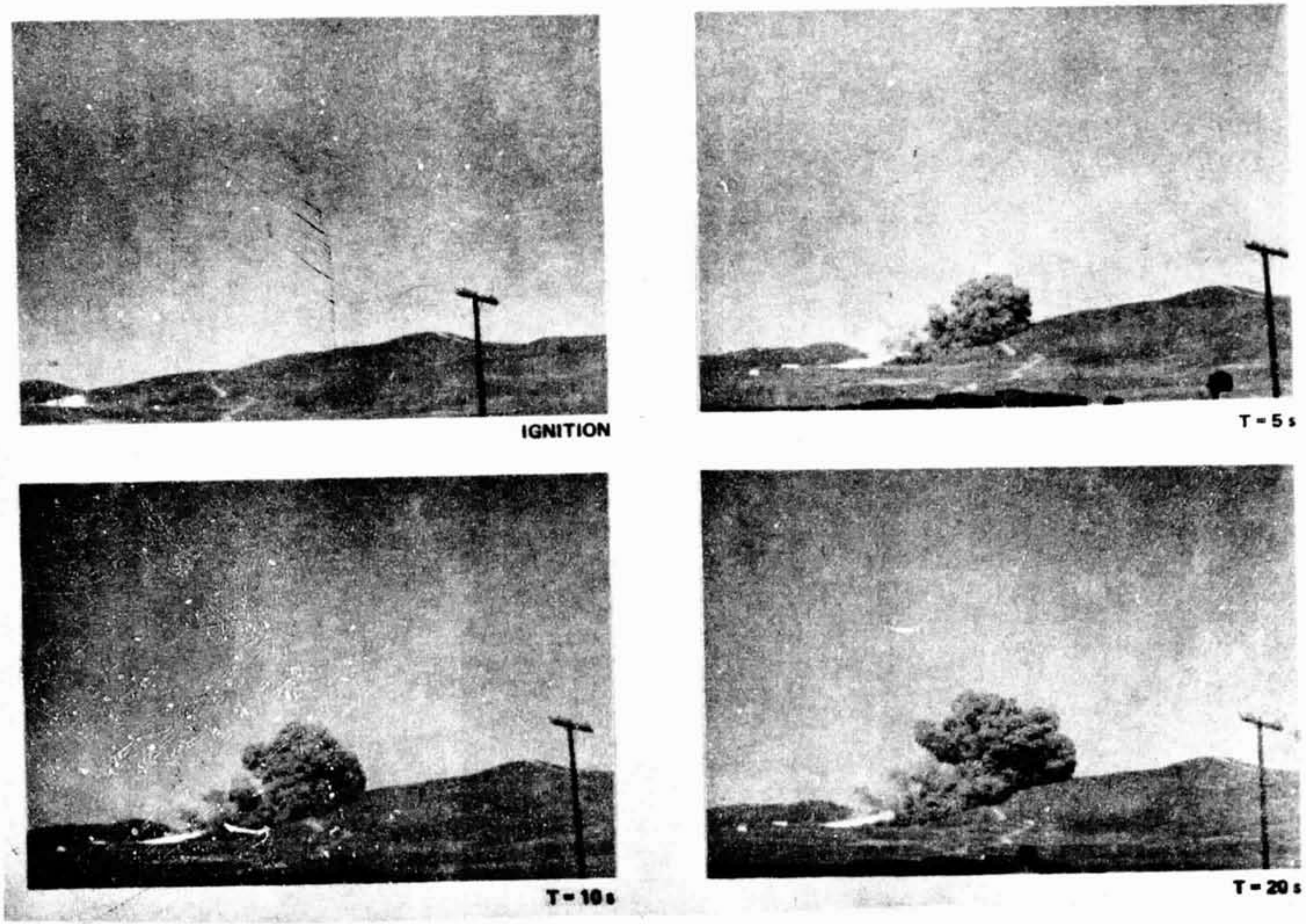


Figure A-1. Rocket plume/fire at time of ignition, 5, 10, and 20 s.

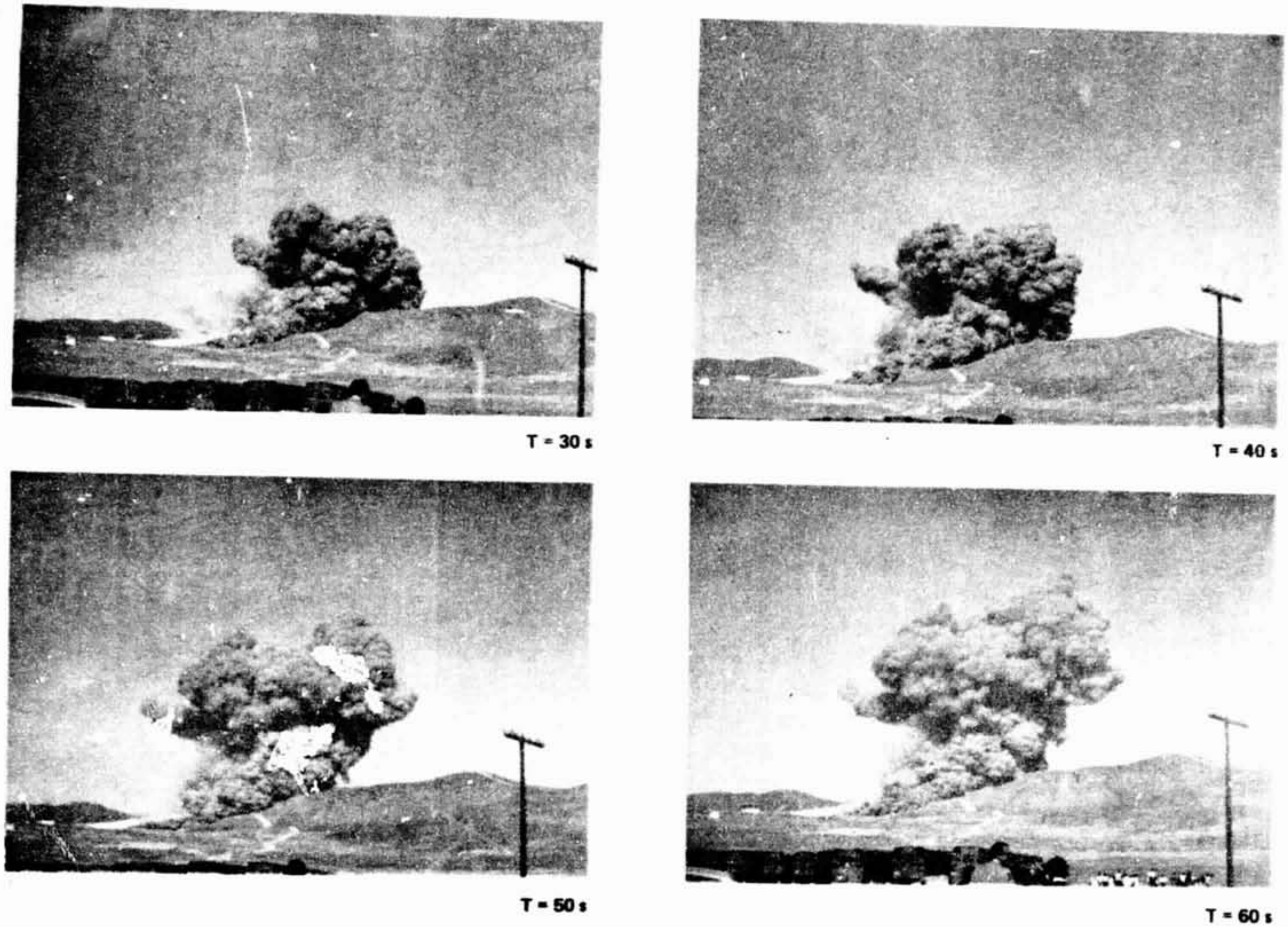


Figure A-2. Rocket plume/fire at 30, 40, 50, and 60 s.

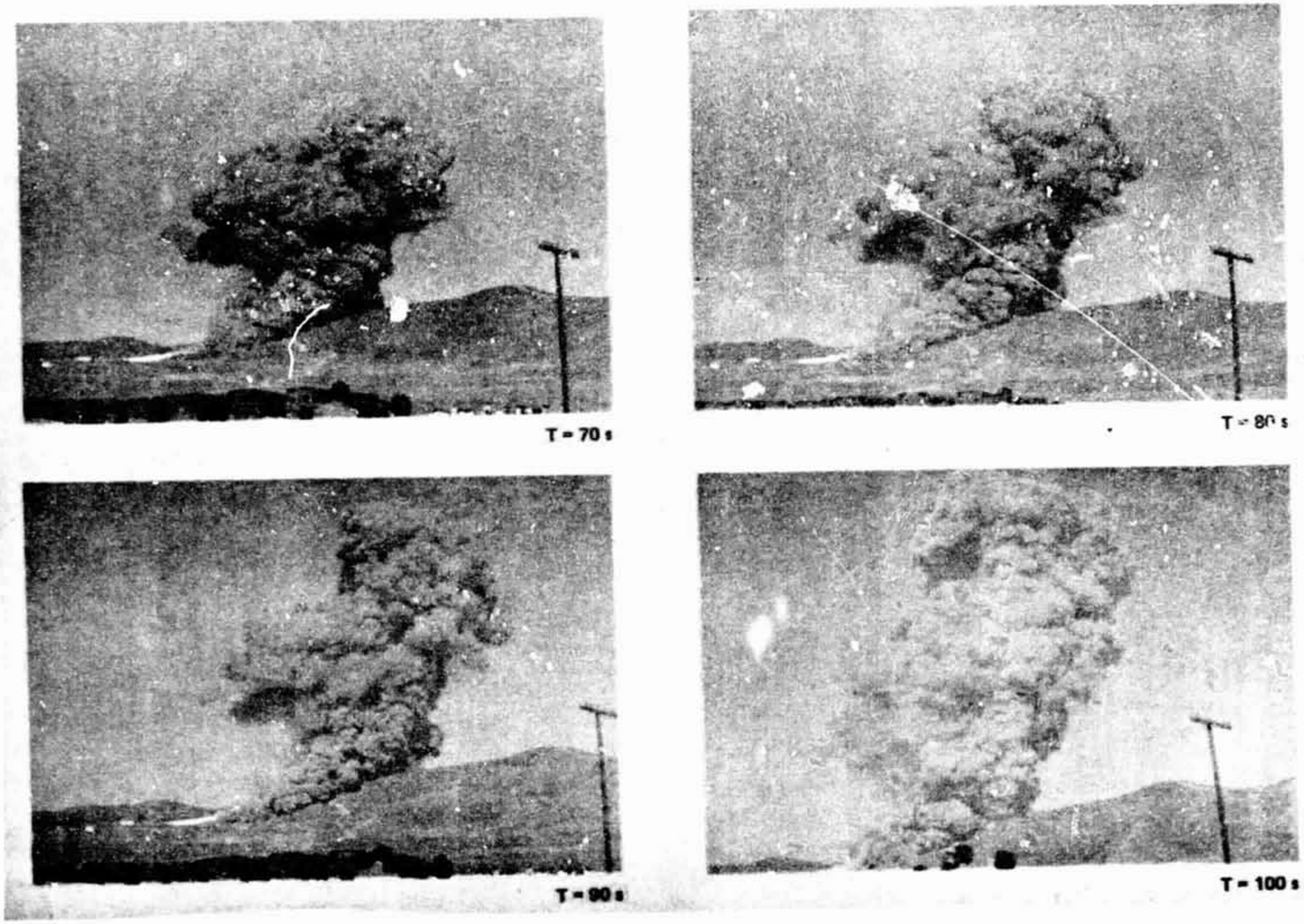
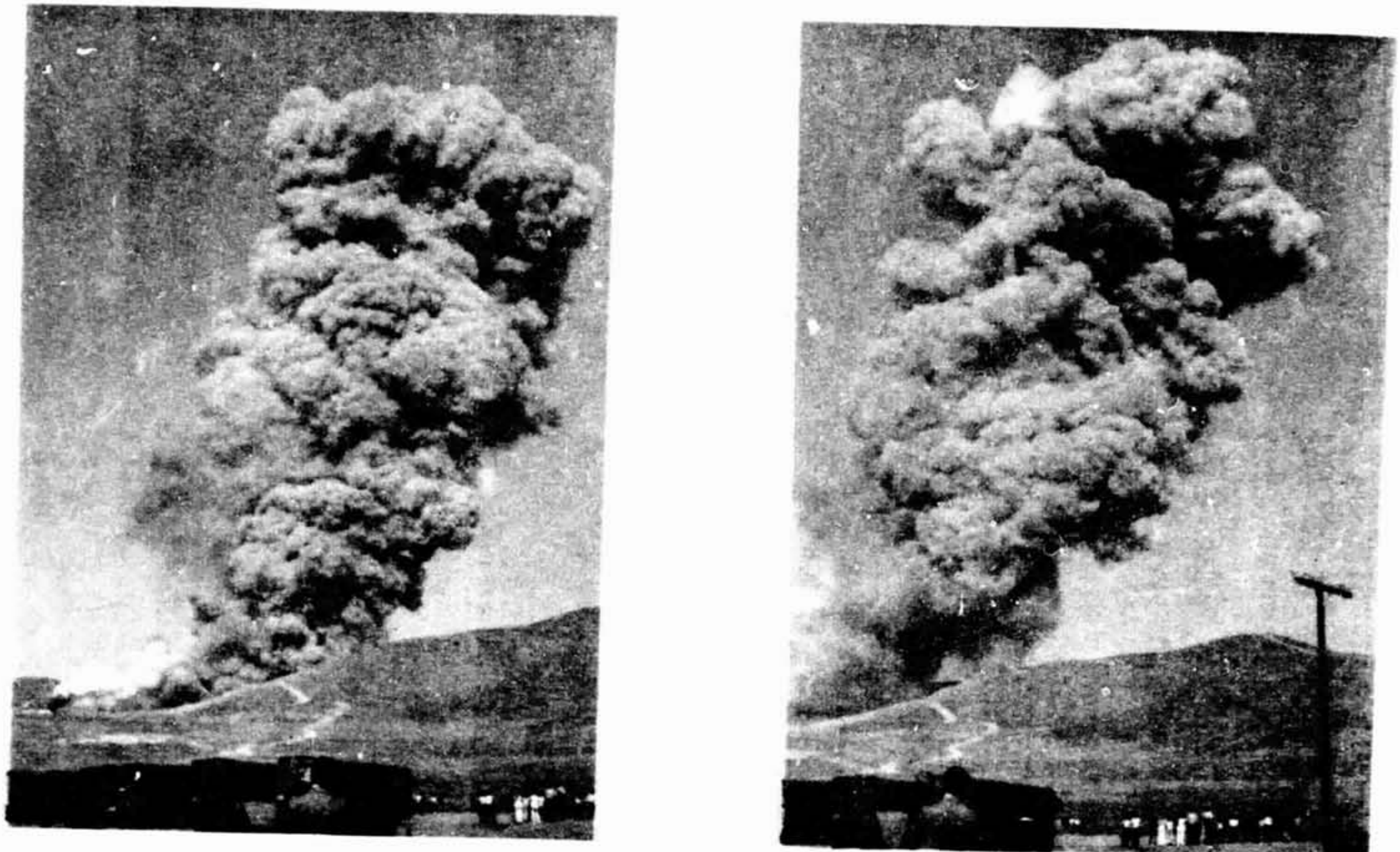


Figure A-3. Rocket plume/fire at 70, 80, 90, and 100 s.



T = 110 s   T = 120 s

Figure A-4. Rocket plume/fire at 110 and 120 s.

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APPROVAL

ELECTRETS USED IN MEASURING ROCKET EXHAUST EFFLUENTS FROM THE SPACE SHUTTLE'S SOLID ROCKET BOOSTER DURING STATIC TEST FIRING, DM-3

By Michael Susko

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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