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FINAL REPORT

SIMULATED LIGHTNING TEST

SHUTTLE .03 SCALE MODEL

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Prepared by Don W. Clifford

Don W. Clifford
Group Engineer, Lightning Simulation Laboratory

Approved by Leon E. McCrary

Leon E. McCrary
Sr. Group Engineer, Physics Laboratories

MCDONNELL AIRCRAFT COMPANY

Box 516, Saint Louis, Missouri 63166 — Tel. (314)232-0232

MCDONNELL DOUGLAS

IN CONCURRENCE

A. H. Bay
Manager, Materials Laboratories

J. C. Bass
Project Laboratory Engineer

ABSTRACT

Lightning Attach Point tests were conducted on a 0.03 scale model of the Space Shuttle launch configuration (Orbiter, External Tank and Solid Rocket Boosters). A series of 250 long spark tests (15 to 20 foot sparks) determined that the Orbiter may be struck on the nose, windshield brow, tail and wingtips during launch but not on the main engine nozzles which have been shown to be vulnerable to lightning damage. The Orbiter main engine and SRB exhaust plumes were simulated electrically with physical models coated with graded resistance paints. The tests showed that the exhaust plumes from the SRB provide additional protection for the main engine nozzles. However, the tests showed that the Orbiter Thermal Protection System (TPS), which has also been shown to be vulnerable to lightning damage, may be struck during launch. Therefore further work is indicated in the areas of swept stroke studies on the model and on TPS panels. Further attach point testing is also indicated on the free-flying Orbiter.

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SIMULATED LIGHTNING TEST-SHUTTLE .03 SCALE MODEL

1.0 INTRODUCTION. Preliminary tests have shown that the Space Shuttle Orbiter Thermal Protection System (TPS) and Space Shuttle Main Engine (SSME) nozzles are vulnerable to catastrophic damage if struck directly by lightning. A strike to either of these vulnerable areas during launch would presumably abort the mission since the TPS is essential to surviving the high temperature entry conditions and the SSME's are essential for orbital insertion. This test program was designed therefore to indicate whether the Orbiter TPS or SSME's are in lightning strike zones on the Shuttle launch vehicle configuration.

The Space Shuttle Model Lightning Attach Point Test utilized the MDC Lightning Test Facility and a 0.03 scale wind tunnel model (including External Tank, SRB's and Orbiter) to determine where lightning may strike the Shuttle during launch. Various configurations of simulated plumes were designed based on inputs from a brief research study. These plumes were built and appended to the aluminum and steel model to evaluate their effect on lightning attach point behavior. The test was conducted by suspending the 840 pound model (with and without plumes) between the high voltage output probe of the MDC 4.2 million volt generator and ground (rod-plane gap). The model was rotated through a series of angles with respect to the probe to simulate the different directions from which lightning may come. High voltage sparks (15-20 feet long) were generated to the model in each position, and the arc attachment points were recorded by photography.

This work was conducted in the Engineering Physics Laboratory of McDonnell Aircraft Company under Intercomponent Work Order No. 2GA, Supplement No. 1, to McDonnell Douglas Technical Service Co. (MDTSC).

2.0 TEST ARTICLE

2.1 SHUTTLE MODEL. An existing .03 scale model of the Space Shuttle including Orbiter, External Tank (ET) and 2 Solid Rocket Boosters (SRB) was used for this test program. The model was constructed of steel and aluminum for wind tunnel testing and weighs approximately 840 pounds. The Model is designated as Model No. 17 in the NASA-RIC inventory and represents an early configuration of the Shuttle, which does not conform to the present configuration in many regards, e.g. ET nose protrusion, ET length, diameter and surface detail, and Orbiter surface detail. It is fairly certain that these details affect the capture angles of the ET nose and Orbiter extremities. However, it is not believed that any major attach points on the Orbiter were missed, nor would the attach points and capture angles of the aft hardware and plumes be affected. It was necessary to remove some out of date surface detail from the model, and cover over the holes with conductive tape. Photographs of the model are shown in Figures 1, 7 and 10 beginning on page 23.

2.2 PLUMES. In order to obtain realistic lightning attach point data for the Shuttle Launch configuration, it was desired to account for the effect of the exhaust plumes of the Space Shuttle Main Engine (SSME) and the Solid Rocket Motors (SRM). Several workers in the field were contacted and a brief literature search was conducted in an effort to establish the electrical, thermal and aerodynamic properties of the plumes as a basis for simulating the plumes physically. Obviously there is no existing experimental data on the plumes since the engines have not been built yet. In fact, some of the design parameters are still in a state of flux although the general characteristics of the engines are defined. Recourse was taken therefore to the consideration of analytical predictions and experimental data on similar existing engines. The data therefore carry a fair degree of uncertainty and consequently the simulated plumes are an approximation of the effected configuration.

2.2.1 SRM Plumes. Most of the plume data available are for solid rocket engines. Impedance curves for a Minuteman exhaust were furnished by Rockwell International (1, 2)* with a general statement that the SRB plumes are expected to be conductive for 1000 feet. Discussions with Mr. Bob Dunn at Marshal SFC [3] revealed that the SRM's are more nearly identical to the Titan strap-ons with very similar expansion ratios and fuel compositions. However, the SRMs are slightly larger so Dunn suggested factoring actual Titan plume data upward by the ratio of the engine diameters, i.e. 146/120, or 1.22. From Reference 4, the conductive length of the Titan solid booster plumes was measured to be 650 feet. Therefore, applying the scaling factor would yield a conductive length for the SRM plumes of 790 feet. This number is consistent with Krider's treatment of the Relaxation Time [5], which is the ratio of the permittivity of the plume to its conductance. Using the conductance data from Reference 2 and assuming a value of 10^{-9} to 10^{-10} for the permittivity, at about 800 feet the plume will exhibit a relaxation time of 10^{-5} seconds. With an electron concentration of $10^8 e\text{-}cm^{-3}$, fields less than 10^4V/m changing in times longer than 10^{-6} seconds will be excluded from the exhaust. Quoting Reference 5, "Thus, as far as lightning is concerned, the blackbody part of the exhaust can be considered a metallic extension of the vehicle."

*Parenthetical numbers designate references listed at the end of the report.

Further insight into the solid rocket plume characteristics was gained from the data from Nanevicz[4] which indicated a charging current of 50-100μamps produced by the Titan rocket exhaust. The vehicle potential was measured to be 20Kv just before the conductive part of the plume broke contact with the ground at 650 feet. The effective resistance of the plume can thus be calculated directly from Ohm's Law as about 10^8 ohms or an average of 10^6 ohms/meter. The Apollo data in Reference 5 indicated the highly conductive blackbody portion of the plume extended about one-third the length of the conductive plume so that most of the resistance of the plume could be attributed to the portion aft of the blackbody section. It must be cautioned however, that the engine may act as a constant current source regardless of the resistance of the plume and that the Apollo plume spatial characteristics may or may not be reflected in the solid propulsion plume.

Another important variable is the effect of altitude on the configuration of the plumes. Curves of plume diameter vs. altitude have been furnished by Rocketdyne and JSC[6]. The data for the SRM's show that from sea level to 20,000 feet the plume expands to only 1.4 times the exit plume diameter. By 32,000 feet it has expanded by 2.3 times and by 80,000 feet it has expanded to about 5 times its sea level diameter. Because of this wide variance it is proposed that a worst case plume be defined. We know that although lightning activity can extend up to 80,000 feet, 90 percent of all strikes to aircraft occur below 25,000 feet[7]. The Apollo 12 strikes occurred at altitudes of 6,000 and 14,400 feet [5]. Since the plumes do not change appreciably between sea level and 30,000 feet, it was decided to use the sea level plume dimensions in the simulation.

In summarizing the SRM plumes, they were determined to be over-expanded plumes extending 790 feet beyond the exit plane (about 4 vehicle lengths) with a maximum radius of 1.3 times the nozzle exit plane radius. The conductivity is much higher (essentially metallic) for the first one-third of the plume but with an average value over the length of 10^{-4} mhos/cm.

2.2.2 <u>SSME Plumes</u>. Rocketdyne and JSC have furnished analytical data describing the plume diameters and plume conductivity. Early computer runs at Rocketdyne yielded no conductivity data but the program was modified to account for N_2 dilution and was rerun. The JSC curves show the plumes to be essentially cylindrical and non-intersecting at altitudes below 20,000 feet. However, there is no plume length data since the calculations cut off at the first Mach disc which is only one or two nozzle diameters away. Dunn of Marshall SFC suggests that about 5 nozzle diameters might be a reasonable length to assume for the underexpanded, high expansion ratio SSME exhaust. Phillips of Rocketdyne suggests two plume cycles or about 45 feet. SSME exit diameter is only approximately 100 inches which would result in a 42 foot plume following Dunn's suggestion. These two sources were therefore in excellent agreement on this critical point.

The Rocketdyne data showed the SSME plume diameter oscillating along its length and is included as Appendix A. However, Rocketdyne agreed that a cylindrical approximation would be reasonable. The Rocketdyne conductivity analysis using N_2 dilution showed a surprisingly high conductivity of 10^{-5} mho/cm, essentially constant along the plume axis.

No other existing data have been found on ionization or conductivity of H_2-O_2 engines except that discussions with Bill Balwanz of NRL [8] revealed that, in general, liquid engine ionization is about 1/1000 of solid engines, and hydrogen engines can be expected to be even lower than most other liquids. The exhaust will be very transparent and clean burning with no carbon particles to react with the atmosphere and burn, as in kerosene engines; the chemical product is primarily H_2O and molecular H_2, in concurrence with the earlier Rocketdyne data. The ionization is generally too low to measure in liquid exhausts experimentally. The plume simulation finally adopted was based on a compromise, assuming that the SSME exhaust will have a conductivity less than .1 to .01 times the SRM value.

Data from Rockwell [9] concerning the SSME orientation angles show that the upper engine is angled 16° away from the longitudinal axis of the vehicle in pitch; the two lower engines are angled 10° away from the axis in pitch and are each angled 3.5° away from the axis in yaw.

Summarizing the SSME plume data, at low altitudes the plumes are essentially well collimated cylinders possibly around 45 feet long, transparent and poorly conducting with an average conductivity on the order of 10^{-5} mho/cm or less.

2.2.3 Plume Simulation. One set of SSME plumes and three sets of SRM plumes were fabricated for this test; the SSME plume set was the same for each test using plumes. The SRM plume configurations are designated as A, B and C for ease of reference and are described as follows:

Configuration: A - 6-foot length, graded resistance

B - 6-foot length, fully conductive

C - 12-foot length; first 6-foot length fully conductive; second 6-foot length graded resistance.

The simulated plumes for the SRM's were constructed of plywood, phenolic and styrofoam as shown in the sketch of Figure 2. The foam was wrapped with glass tape and then sprayed with a coating of Krylon for sealing purposes. The plumes were then painted with graded resistance paints designed to produce an equivalent conductivity of 10^{-4} mho/cm. The fully conductive configuration was obtained by wrapping the basic 6-foot conductive plume with aluminum foil. The SRM plumes were constructed in two interconnecting 6-foot sections and when threaded into the SRB model base and cantilevered out horizontally, the 12-foot plumes exhibited a total deflection of the tip of less than 4-6 inches. A photograph of the graded resistance plumes is shown in Figure 3.

The SSME plumes were constructed of styrofoam and treated in the same way to produce an equivalent conductivity of 10^{-5} mho/cm. The actual length of the model SSME plumes was 15 inches.

3.0 TEST SETUP

The test setup is shown in Figure 4 which shows the Shuttle model with one section of SRM plumes and full SSME plumes installed. The model is suspended by a 3/4 inch polypropylene line passing through brackets attached to the ET body. The line passes over pulleys at the tops of 2 40-foot utility poles and down to winches attached at the base of the poles. The output electrode is suspended and controlled in the same way but with lighter 1/4-inch nylon lines. Additional light tie-lines were used as necessary to anchor probe and model to prevent movement by the wind.

The MDC 4.2 million volt simulator is a 42 stage marx surge generator which is charged to a maximum voltage of 100kV per stage; the stages are discharged in series through spark gap switches to produce the high voltage output. The generator is housed in a 36 foot high fiberglass tower enclosed by plexiglass sheets. For maximum voltage operation the tower is filled with a mixture of gaseous Freon-114 and air which serves as a dielectric medium to prevent premature electrical breakdown or internal arcing. The output of the generator is affixed to an output resistor which limits the spark current and slows the output voltage ramp.

The output voltage waveform for holdoff (no flashover) is shown in Figure 5. The voltage rises to crest in less than 0.5 μsec. and decays to half value in 40 μsec. During flashover tests to the model, timing waveforms as shown in Figure 6 were taken to show the flashover time and streamer formation time. The positive pulse is generated when the tower erects and the negative pulse is produced when the arc closes.

4.0 TEST PROCEDURE

4.1 GENERATOR CHECKOUT. Prior to model testing the generator was charged with Freon and test shots fired: a) into an output voltage divider to record the output waveform, and b) across the test gap to demonstrate arc distance and to set photographic exposure settings.

4.2 MODEL POSITIONING. The first test sequence consisted of conducting model attach point studies through the pitch axis with no plumes attached. The model was suspended by metallic brackets affixed to the external tank, as shown in Figure 7. Three-quarter inch polypropylene lines attached to the model brackets were used to support the weight of the structure and to winch the model to an initial test height of 6 feet; nylon lines fore and aft were used to rotate the model through the range of test angles shown in Figure 8. The model was initially positioned vertically with the high voltage probe positioned at an average distance of 9 feet above the model along the longitudinal axis. During the test sequence, the model was rotated in pitch by adjustment of the nylon positioning lines tied fore and aft on the model. The angular displacement was measured by sighting through a protractor mounted on one of the utility poles supporting the model.

As shown in Figure 8, the model was rotated through 180° so that the last position was with the nose down and the high voltage probe positioned above the aft end. As the tests proceeded, the angular orientation was adjusted in steps small enough to determine all probable attach points in that plane.

Because of the extensive length of the SRM plumes, which extend approximately 4 vehicle lengths behind the nozzle exit plane, it is impractical to simulate the full plume length for a test of this type. The .03 scale model of the Shuttle launch configuration is 6-feet long and the full length of the scaled plume would be 24 feet, resulting in a total length of vehicle and plumes of 30 feet all of which would have to be suspended in mid-air and rotated precisely. It was therefore decided to simulate the plumes in two increments of 6-feet, which, when coupled with the no-plume configuration, should yield data which show the effect of plume length on attach point distribution. It was anticipated that little difference would be seen between the 6 and 12 foot plumes, (the assumption was confirmed by the test results) indicating that the simulation of the full plume length was unnecessary.

In addition to variations in plume length, it was also decided to investigate variations in SRM plume conductivity, especially over the first section of the plume (nearest the vehicle) where the Minuteman and Apollo data both indicated minimum electrical impedance. The conductivity variation was to be obtained by wrapping the resistive plume with aluminum foil.

Consequently, following the baseline (no plumes) sequence, the model was lowered and graded resistance simulated plumes were attached to the SSME and SRM nozzles (plume configuration A). The SSME plumes were full scale length (15 inches) and the SRB plumes were 6 feet long or 25 per cent of full plume length.

With the plumes attached, the model was hoisted to a centerline height of 12 feet above the ground and again rotated to the vertical position (Figure 9). The model with plumes was then tested through the critical angles of pitch as before. Additional tests were conducted by shifting the high voltage probe laterally (as if rolling the model) and evaluating attach points from that angle in an attempt to strike the main engine plumes.

The next plume configuration to be tested was Configuration B, the fully conductive SRM plumes, one vehicle length in dimension with the basic SSME plumes. The first 6-foot SRM graded resistance plumes were wrapped with aluminum foil for this test and selected angles were evaluated to determine if any changes in attach point behavior could be observed in critical areas. The areas to be tested were determined by evaluation of the observed attach points in the previous tests.

The final plume configuration to be tested (Configuration C) was the 2-vehicle length (12 foot) SRM plumes with the basic SSME plumes. A graded resistance extension, six feet in length, was attached to the base plumes already installed on the SRM's. A fully conductive base plume section (metallic) was used. For this sequence, the model height above ground was reduced and the critical test angles evaluated in a nose down attitude as shown in Figure 9C.

Following the completion of the pitch angle series of tests, the model was reconfigured to the first plume case (SSME plumes and six foot resistive SRM plumes) and the attachment brackets changed for the roll angle series. The bracket attachment scheme for roll is shown in Figure 10. The model was hoisted to an elevation of six feet with the longitudinal axis horizontal and the Orbiter on top. The high voltage probe was positioned directly above the model in the plane of the wing tips (trailing edge). The model was then rotated through 180° roll in steps as shown in Figure 11. Following this sequence, the high voltage probe was shifted laterally as necessary to pick up additional attach point information fore or aft of the wing tips.

4.3 FIRING AND DATA TAKING PROCEDURES. During the initial setup, a series of test firings of the generator was made with no model in the gap. This firing sequence was used to set the photographic exposure of the two main data cameras. Two Orbit model reflex type cameras with Polaroid film holders were used to photograph each arc attachment test from 2 orthogonal angles. The photographs from the test series were labeled and the attach points recorded on a data sheet.

The generator firing sequence for a given test consisted of first positioning the model in the desired angular position, then loading and cocking the cameras. After the test area was evacuated, the generator was charged to the desired operating voltage and fired (about 1-2 minutes required). Test personnel then entered the test area to reload and cock the cameras. This firing sequence was repeated up to ten times for each model orientation. Where data was less critical, fewer firings were used and visual recording of attach points were used instead of photography after the first shot. However, where there was much chance for visual error, photographs were taken.

5.0 TEST RESULTS

The results of the lightning attach points tests are summarized by the Attach Point Capture Angle diagrams in Figures 12 - 16. These diagrams illustrate the attach points (termination of dark lines on the vehicle) and the capture angle of each attach point in that azimuth (defined by the cone angle whose apex is at the attach point). For example, in Figure 12, the attach points are the ET noze, the Orbiter nose, eyebrow and vertical fin tip, and the SRB nozzle. The Orbiter nose may be struck by lightning approaching from 50° to 60° while the brow may be struck from 50° to 75°. The azimuth is the longitudinal plane of symmetry, designated as 0° roll. The open regions indicate "protected" zones where no direct strikes were recorded. Figures 17 - 22 show representative attach point photographs in the various model/plume configurations. A complete tabulation of all shots is included as Appendix B to this report.

Figure 23 illustrates streamering photographs which were used to supplement the direct strike data by showing where streamers are being generated on the model. The heavier the streamer activity, the greater the likelihood of drawing a direct strike. The photographs were produced by providing a short auxiliary air gap out of the field of view of the cameras for the arc to flashover. The streamers observed in the photos were produced by the high fields which exist before the auxiliary gap flashes over.

6.0 DISCUSSION OF TEST RESULTS

As stated earlier, this test program was designed specifically to determine the likelihood of the Orbiter TPS and Main Engines being struck by lightning in the event of a flash to the vehicle during launch. It was not designed to closely identify every attach point and associated capture angle on the Shuttle. For example, no specific effort was made to strike the SRB nose or to define the switchover angle from ET nose to the body on the backside of the vehicle (opposite the Orbiter).

The reasons why complete 4 mapping was not conducted were partly technical and partly a result of program limitations. Technically, the fact that a very heavy (840 lbs.) wind tunnel model was used greatly complicated the support and orietation of the model. A light weight model could have been mounted on a gimballed support structure which would allow orientation in combinations of pitch and roll or pitch and yaw, thus allowing a complete mapping. However, the heavy model had to be supported by brackets mounted on axes passing through the center of gravity, thereby restricting the planes of rotation to the longitudinal and lateral azimuths passing through the CG. This restriction was overcome to some degree by movement of the high voltage probe out of the plane of rotation. This was done during both the pitch and roll series in an attempt to direct strikes to the Main Engine nozzles or plumes.

The primary objectives of the program were achieved in that the Orbiter extremities and windshield brow were observed to be Zone 1 (Direct Strike) attach points showing that the TPS regions on the top and sides of the Orbiter are in the Zone 2 category (swept-stroke region) and may be struck during launch. However, it was clearly demonstrated by direct strike and by streamering tests that the Main Engines are effectively shielded from direct strikes by the Orbiter vertical fin and the SRB plumes, and are not therefore Zone 1.

The strikes to the Orbiter nose and brow, however, place the entire fuselage (top and sides) in the Zone 2 category. Because of the restrictions on model orientation, no information was obtained on strikes to the leading edge of the Orbiter wing. Therefore, it is not known with certainty whether the top of the wing is in a swept-stroke zone or not. At least the inboard section of the wing should probably be considered as Zone 2 because of the large initial sweep angle of the wing (greater than 45°).

Although it was shown that the SSME's are not subject to direct strike attachment, the fact that the fuselage is subject to swept strokes raises the question of whether a swept stroke might attach to a main engine bell after sweeping the length of the fuselage and hang on long enough to either burn through the wall by high coulomb heating or blast through the wall by a high current restrike. Windblown swept stroke tests on the model would be required to answer the question of wehther the Main Engines are Zone 2.

7.0 CONCLUSIONS

Summarizing briefly the conclusions reached from the test data, it is felt that the test program has demonstrated conclusively that although the Orbiter may be struck by lightning on the nose, windshield eyebrow, vertical fin tip and wing tips during launch, the main engines are protected and may be considered safe from direct lightning strikes. These results are based, of course, on the accuracy of the Shuttle model and exhaust plume data furnished for the test. The Orbiter and External Tank configurations have undergone changes since the model was built and the plume data are subject to uncertainties. However, the data obtained leave room for some uncertainty and the test results are probably valid in spite of the limited changes.

The direct strike testing was supplemented by streamering tests which served to increase confidence in the conclusion that the SSME's will not be struck directly. The photos show a very heavy umbrella of streamers from the vertical fin and SRB plumes shielding the main engines. Only very light (almost imperceptible) streamering was observed from either the main engine plumes or the engine bells themselves.

Other observations from the test include the following:

1. Little difference was seen between the 6 ft and 12 ft plumes, thus substantiating the assumption that it was not necessary to simulate the full plume length. Higher electrical conductivity of the SRB plumes enhances the shielding of the main engines by taking strikes from the Orbiter vertical fin and providing a more overlapping umbrella.
2. Strikes to the Orbiter nose and eyebrow place the entire Orbiter fuselage in a swept-stroke zone during launch. It is conceivable that a stroke could still sweep aft from a forward attachment and

ultimately contact and hang on to a main engine bell. The engine bell could then experience a high coulomb continuing current and/or high peak current.

3. Although most exit points of direct strikes to the Orbiter appeared to be from the ET nose or SRB nozzles or skirts, direct strikes were observed on the belly of the ET. With further work, strike attach points could probably have been observed on the SRB walls or noses as well.

4. No attach point tests were conducted on the Orbiter alone. Therefore, the attach points observed during this test apply only to the launch configuration.

8.0 RECOMMENDATIONS

Based on the results of this test, the following recommendations are made:

8.1 In order to fully answer the question of possible lightning damage to the Main Engines, a series of swept stroke tests should be conducted on the launch configuration model. Although models cannot be used in swept stroke tests to determine dwell time or skip distance across a surface, a model can be used to identify trailing edge hangon points for swept strokes. The model would be mounted in the swept stroke facility windstream (headed into the wind) and rotated through various angles of roll as shown in Figure 24. High speed and still photography would be used to observe and record the windblown arc behavior in each roll position, especially at the aft end of the Orbiter. The test should be conducted with SSME and SRB plumes attached. Minor configuration modifications to prevent hangon to the SSME's should be evaluated.

8.2 It is recommended that an additional attach point test series be conducted on the Orbiter alone. The launch configuration strikes to the Orbiter cannot be assumed to be valid for the free flying Orbiter and the critical systems during entry include neither the TPS nor the Main Engines which were focussed on during the past test series. The lighter weight and smaller size of the Orbiter alone would allow mounting on a gimbal support so that a complete mapping could be conducted. The resulting data would be used to define probable current flow paths through the vehicle and to scope the necessary protection required for external sensors, dielectric or composite structural areas and internal avionics sensors.

8.3 Since the nose, brow, vertical fin and wingtips of the Orbiter have been shown to be Zone 1 attach points, it is recommended that a TPS damage evaluation program be conducted based on the zonal information provided by this program. Based on the Model Lightning Current Waveform provided in the Space Shuttle Lightning Protection Criteria Document (Reference 10) the following evaluations should be made:

A. High current damage tests should be conducted on structures in the Direct Strike zones using 200 kiloamp strikes. Full scale structural mockups, complete with TPS, should be used for these tests. However, only the region immediately around the strike point need be mocked up. For example, the windshield brow mockup might consist of a 36-inch long section of windshield molding (18 inches each side of centerline) and a 24-36 inch wide section of metallic fuselage structure extending aft of the molding. Several (8-12) TPS tiles should be attached as in the flight configuration, although the entire panel need not be covered with tiles for the TPS damage evaluation. Controlled 200 kiloamp high current strikes conducted to the TPS section of the panels will then give a true indication of the degree of damage which can be anticipated in the direct strike zones.

B. Swept stroke damage tests should be conducted on simulated fuselage structures representative of the nose and brow regions. Full-scale mockups of the fuselage structure extending back six feet from the nose and brow attach point regions should be exposed to windblown continuing current arcs and to high current restrikes.

These panels should be 4 to 6 feet across and about 6 feet long, molded to the proper curvature and incorporating surface detail such as antenna mountings, access doors, fasteners, and proper skin thickness. The panels should be covered with the proper surface insulation over their full area.

The panels should be mounted as shown in Figure 24B and exposed to a windblown arc, which initially attaches to the leading edge of the panel and is subsequently blown back across the panel by the windstream. The arc current should be several hundred amps (based on the Model Lightning Strike continuing current component) and should accurately simulate high coulomb burnthrough damage to the metal substrate. The arc dwell time, skip distance and damage to the TPS should also accurately simulate actual strike conditions, for either launch or descent phases of the mission. The tests should be run with and without high current restrikes since either or both cases may occur in flight.

The data can be used to predict the damage to both metal substructure and to the TPS. It can also be used to determine whether protection is needed for components such as antennas, probes, etc, mounted in swept stroke regions. Although the TPS design may not be subject to change as a result of the tests, minor changes in the substructure and component mounting configurations may be indicated which could easily be incorporated, perhaps eliminating the possibility of catastrophic damage or the need to specifically protect individual components if they are shown to be adequately protected by the TPS. In addition, the damage observed on the TPS can be used to good advantage in the repair program recommended below.

C. It is recommended that a series of high current damage tests be conducted on TPS panels to determine degree of damage as a function of current level. Since the vehicle is unlikely to see the severe Lightning Model current levels [10] during launch, (99 per cent of all strikes are less severe) it would be desirable to obtain data on the probable level of damage which can be expected. Average lightning current levels (which would likely predominate in any strikes experienced under realistic launch conditions) are closer to 20 kiloamps than 200 kiloamps and the damage should be accordingly much less. The data from this test series can be used to check against thermal and aerodynamic conditions to determine the impact on mission success. The data can also be used to provide guidelines to possible EVA repair procedures.

9.0 SUMMARY OF RESULTS

Lightning Attach Point studies have been completed on a 0.03 scale model of the Space Shuttle Launch configuration (Orbiter, External Tank and Solid Rocket Boosters). A series of 250 long spark tests (15 to 20 foot sparks) determined that the Orbiter may be struck directly during launch on the nose, windshield brow, tail and wingtips but not on the main engine nozzles which have been shown to be vulnerable to lightning damage. The Orbiter main engine and SRB exhaust plumes were simulated electrically with physical models coated with graded resistance paints. The tests showed that the exhaust plumes from the SRB provide additional protection for the main engine nozzles. However, the tests showed that the Orbiter Thermal Protection System (TPS), which has also been shown to be vulnerable to lightning damage, may be directly struck during launch. Therefore further work is indicated in the areas of swept stroke studies on the model and on TPS panels. Further attach point testing is also indicated on the free-flying Orbiter.

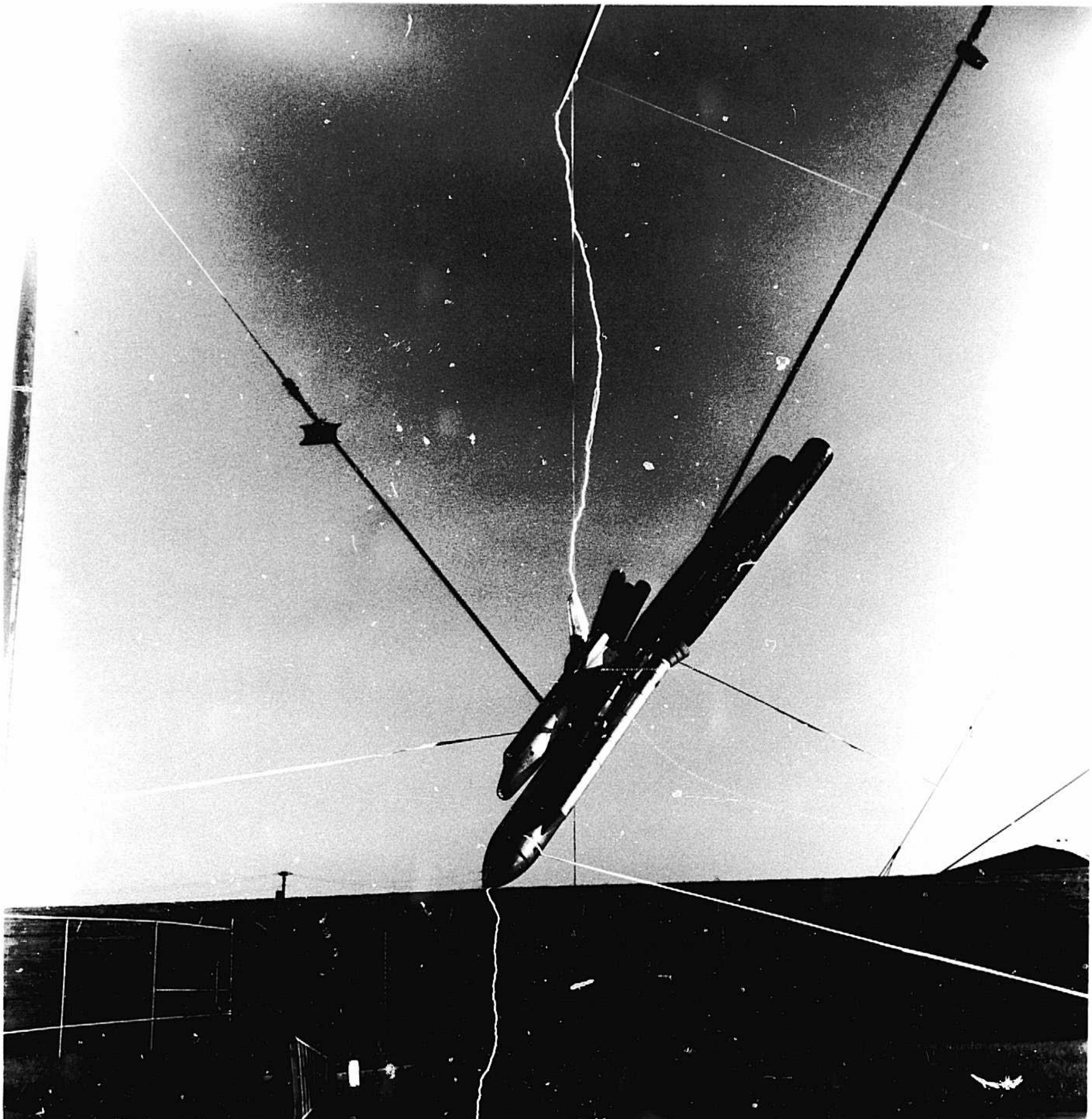


FIGURE 1 - .03 SCALE SHUTTLE MODEL SUSPENDED FOR TEST

D4E-587551

FIGURE 1

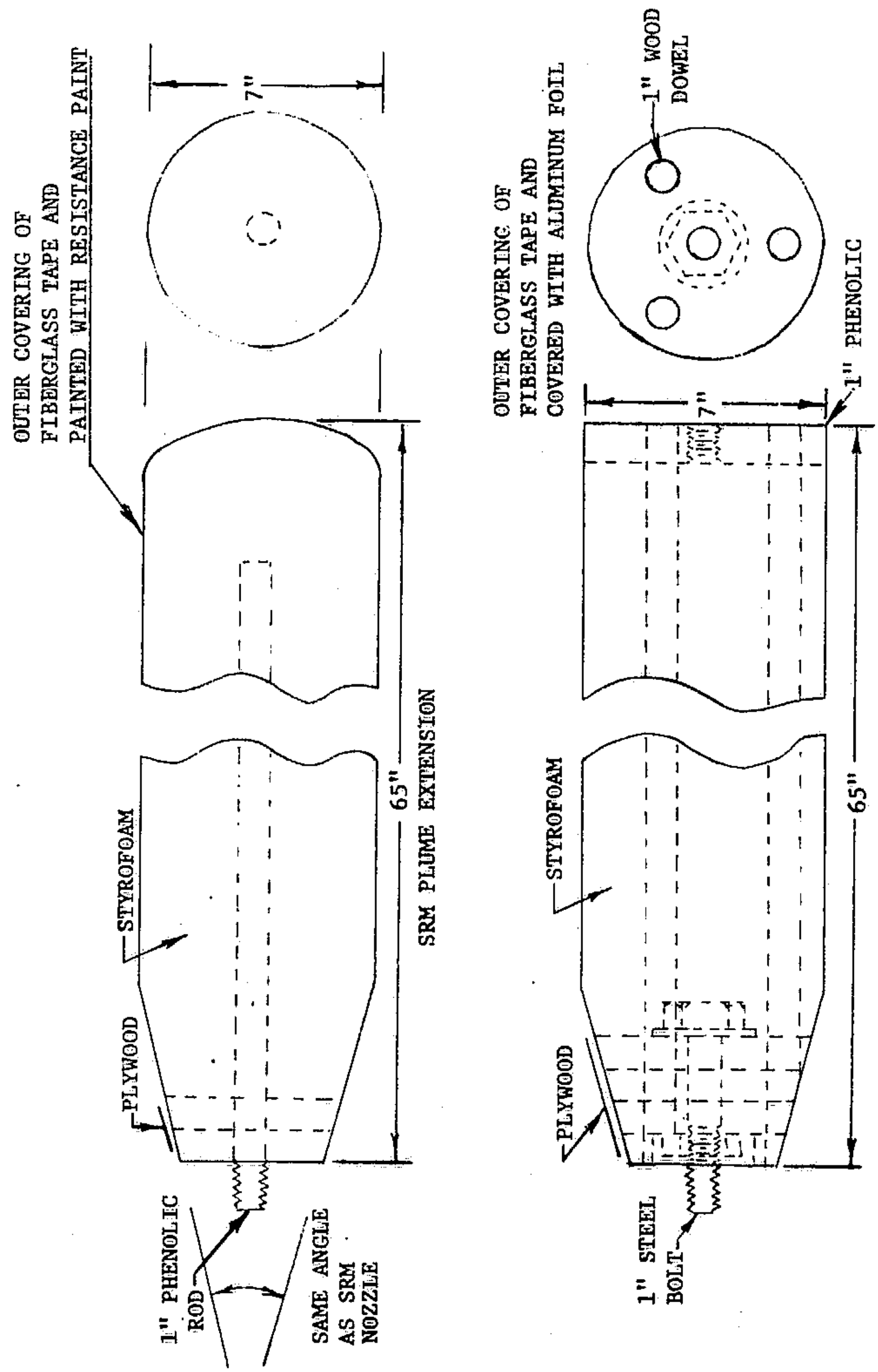


FIGURE 2 - SIMULATED SRM PLUMES

FIGURE 2

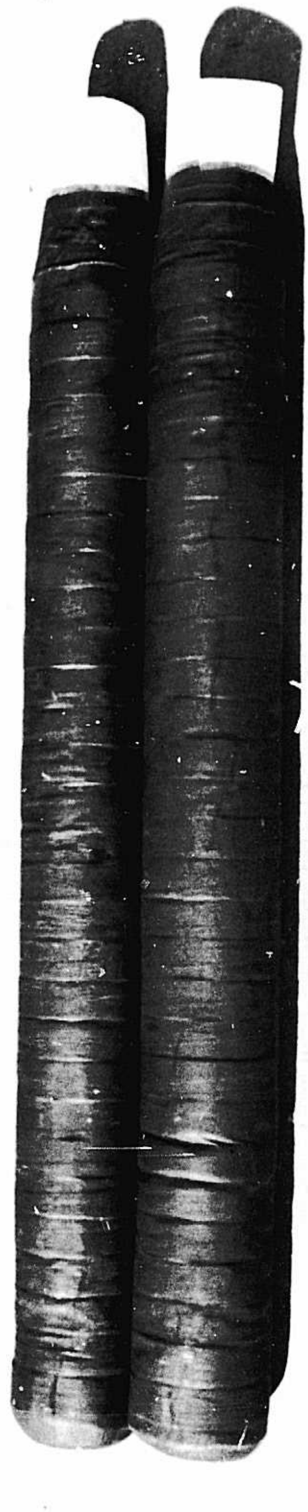


FIGURE 3 - GRADED RESISTANCE SRB PLUMES

12-6274-1

FIGURE 3

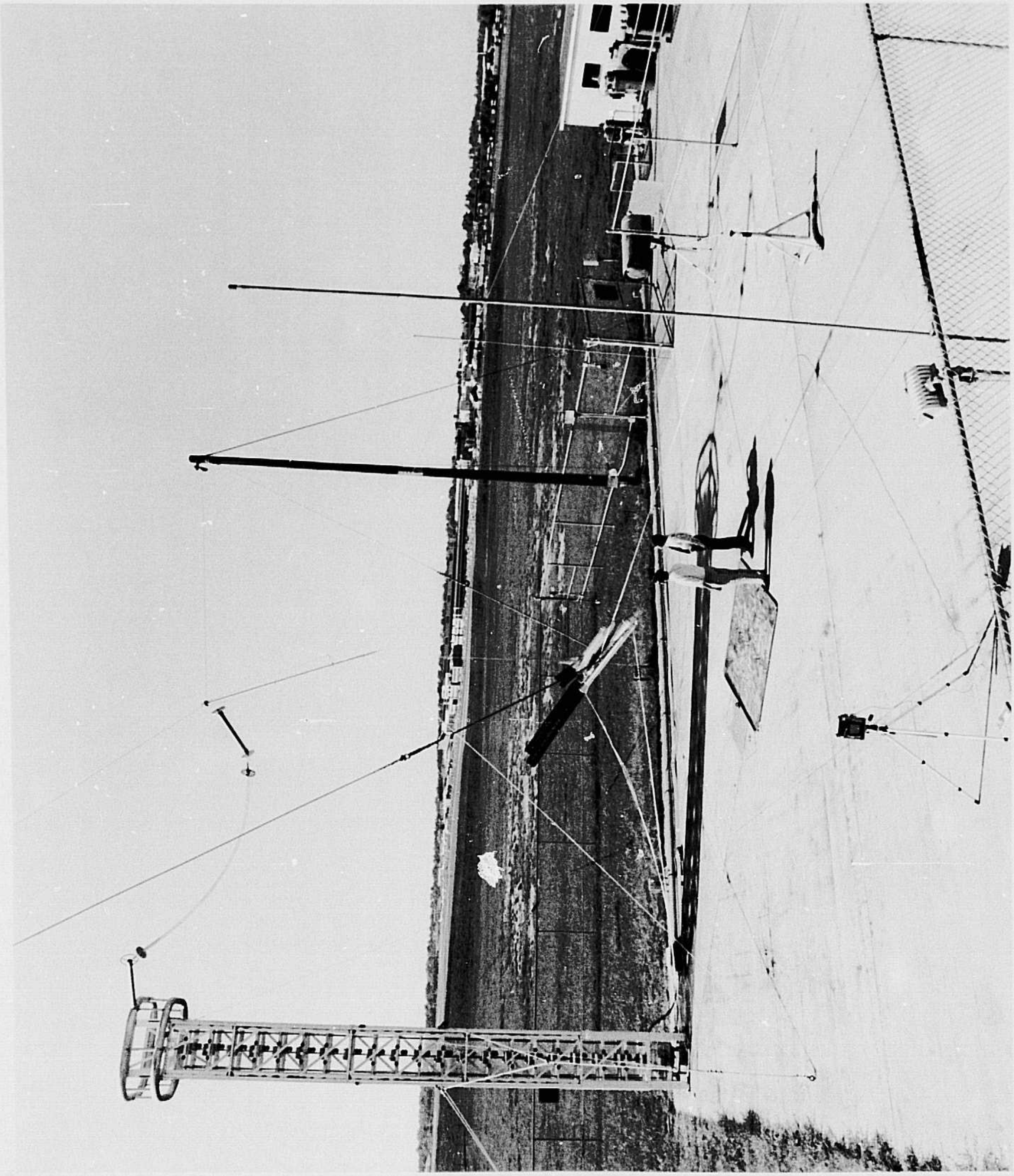
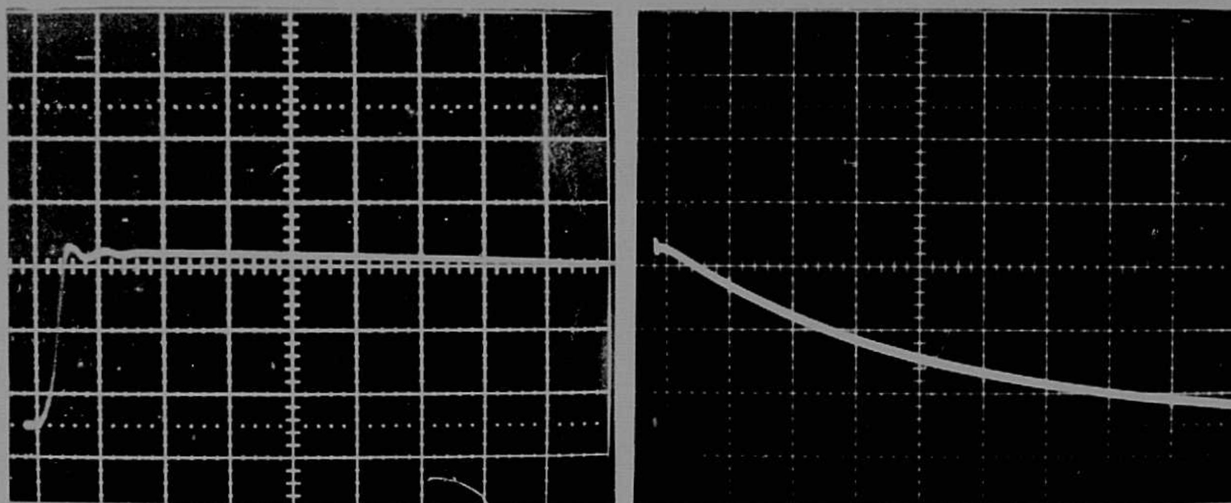


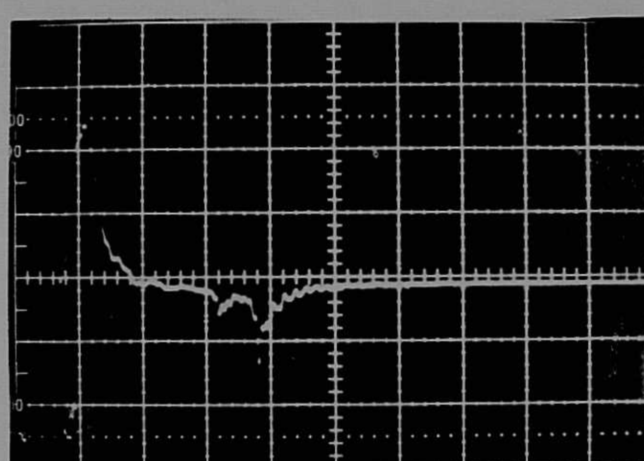
FIGURE 4 - SIMULATED LIGHTNING TEST SETUP



A. 1μsec/div. - Holdoff Condition

B. 20μsec/div. - Holdoff Condition

FIGURE 5 - HIGH VOLTAGE WAVEFORMS



1 μsec/div - Positive Peak is Generator Erection

Negative Peak at 2.8μsec is Gap Flashover

FIGURE 6 - HIGH VOLTAGE FLASHOVER TIMING WAVEFORM

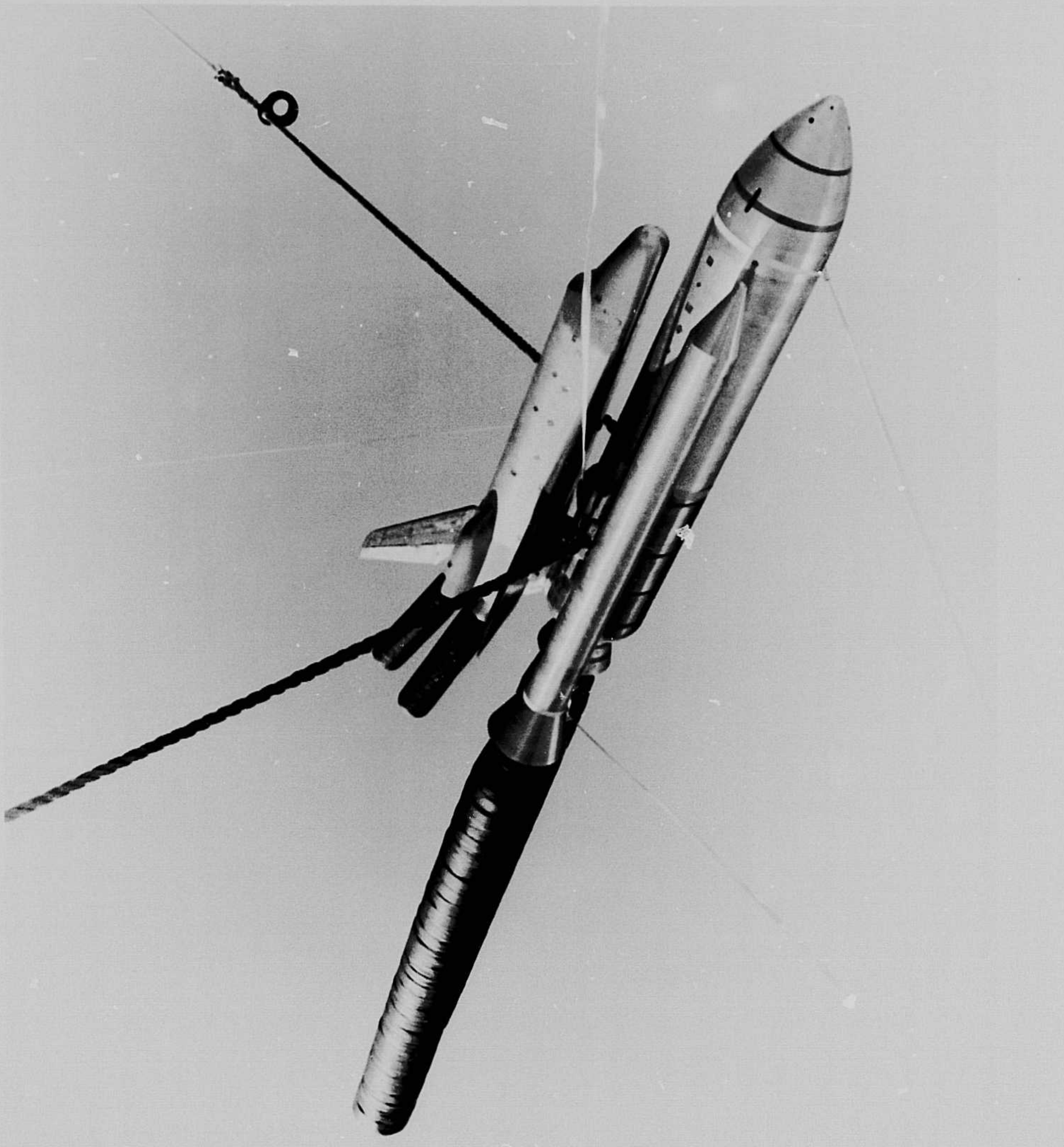
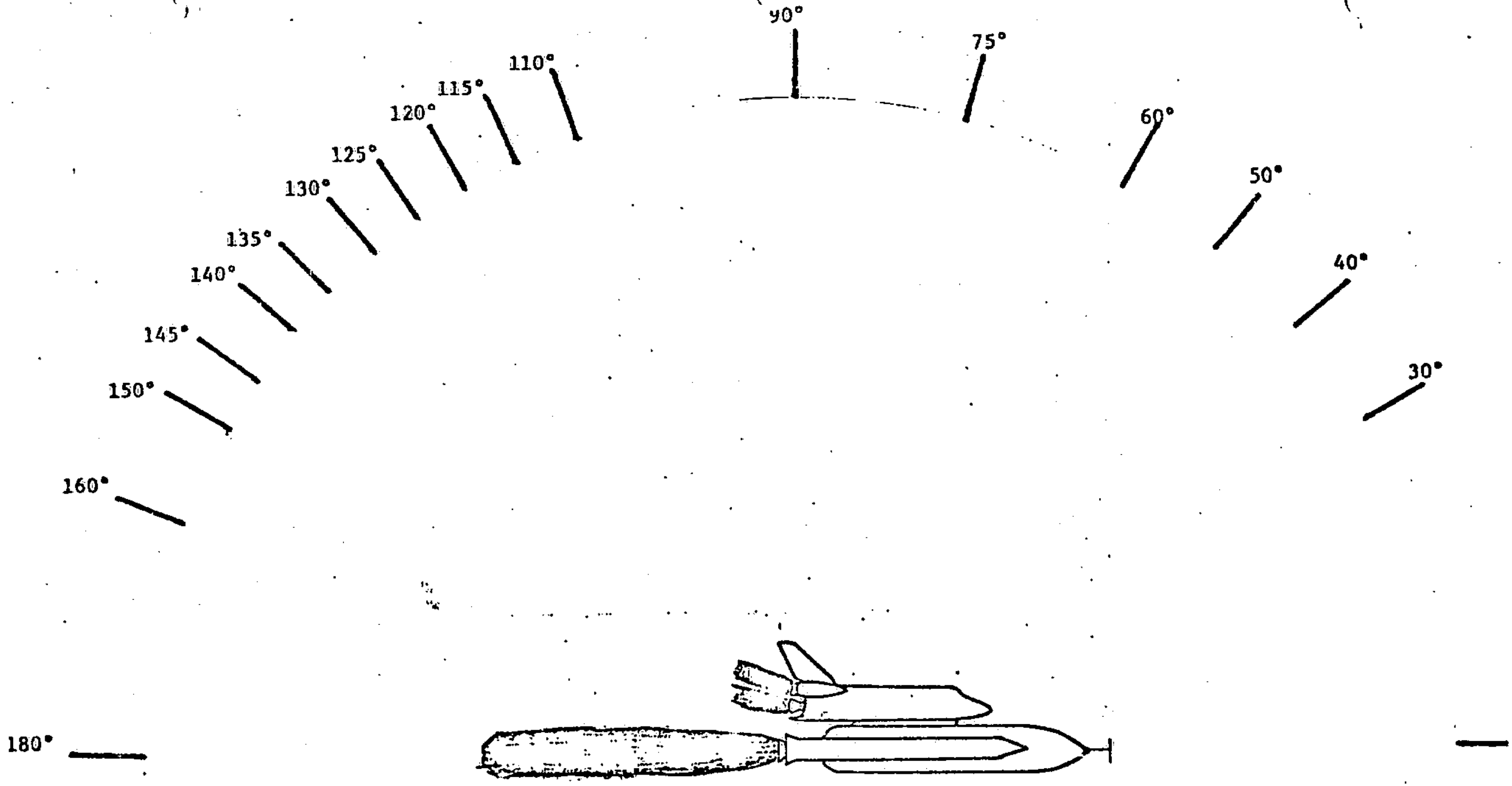


FIGURE 7 - SUPPORT BRACKET INSTALLATION
FOR PITCH ROTATION

12-6275-3

FIGURE 7



Pitch Angles (Negative) for Initial Study

FIGURE 8 - PITCH ANGLE ORIENTATIONS

FIGURE 8

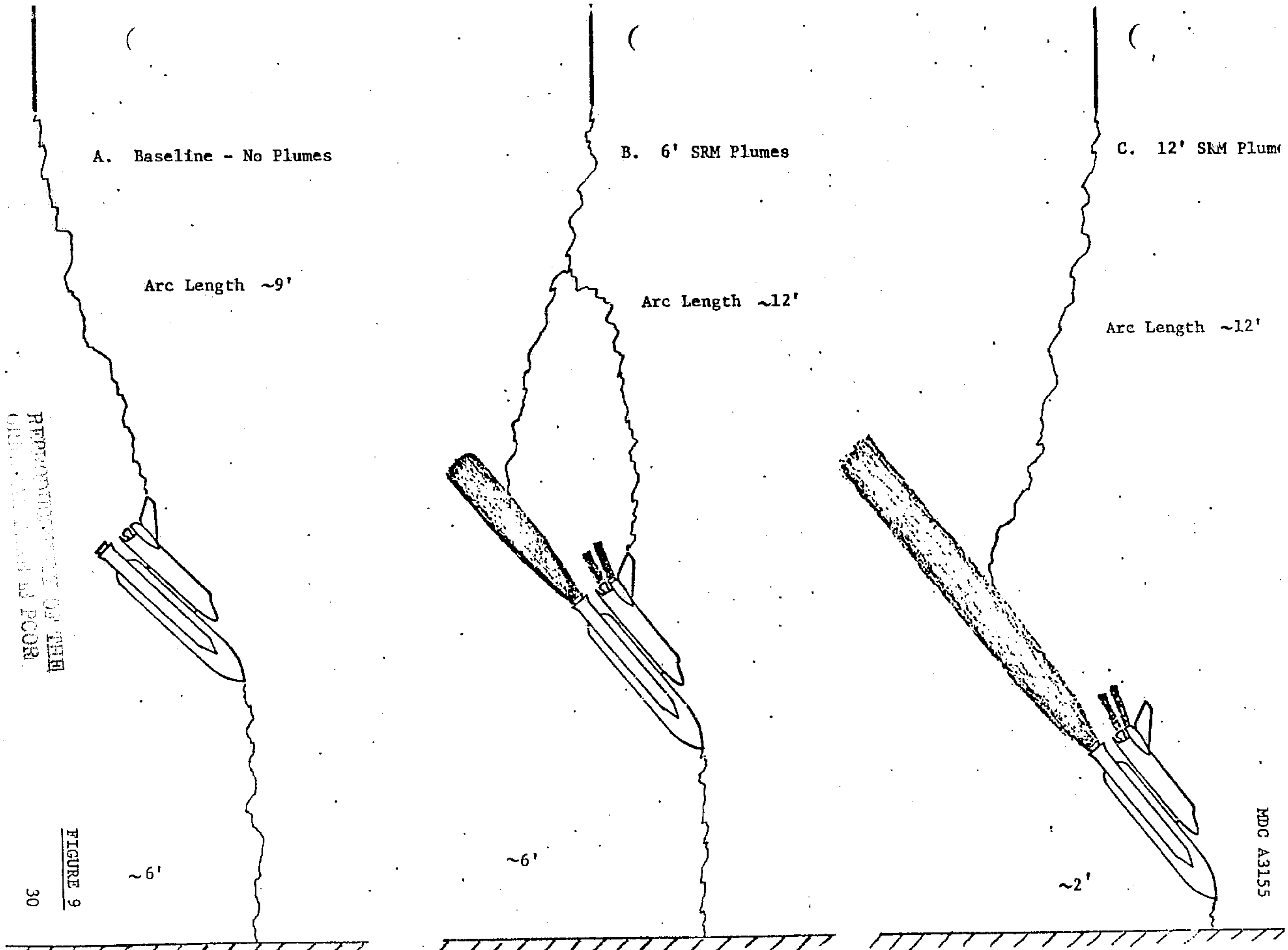


FIGURE 9 - SHUTTLE MODEL LIGHTNING ATTACH POINT STUDY - MODEL ELEVATIONS FOR PLUME TEST

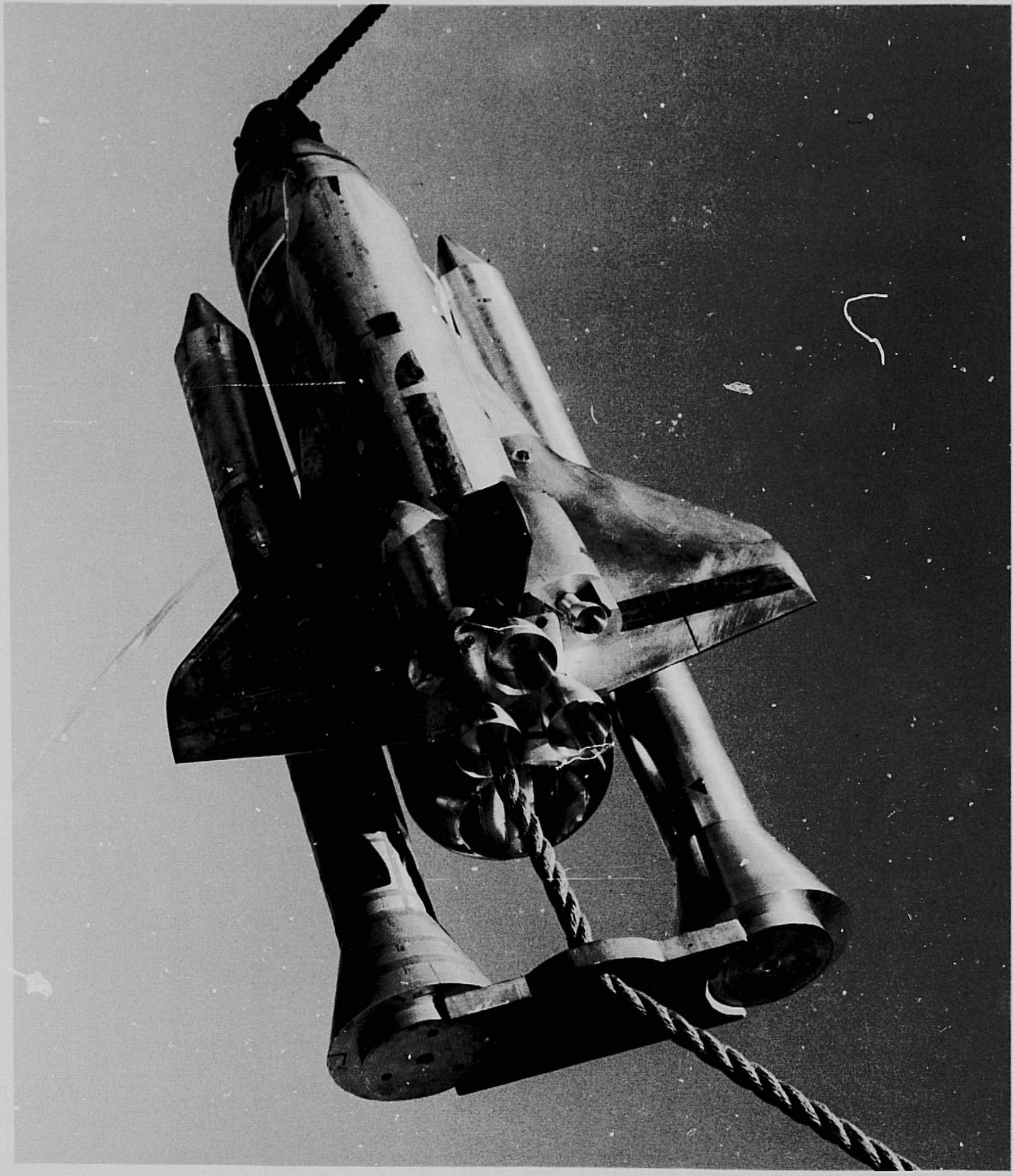


FIGURE 10 - ROLL AXIS BRACKET INSTALLATION

12-6276-2

FIGURE 10

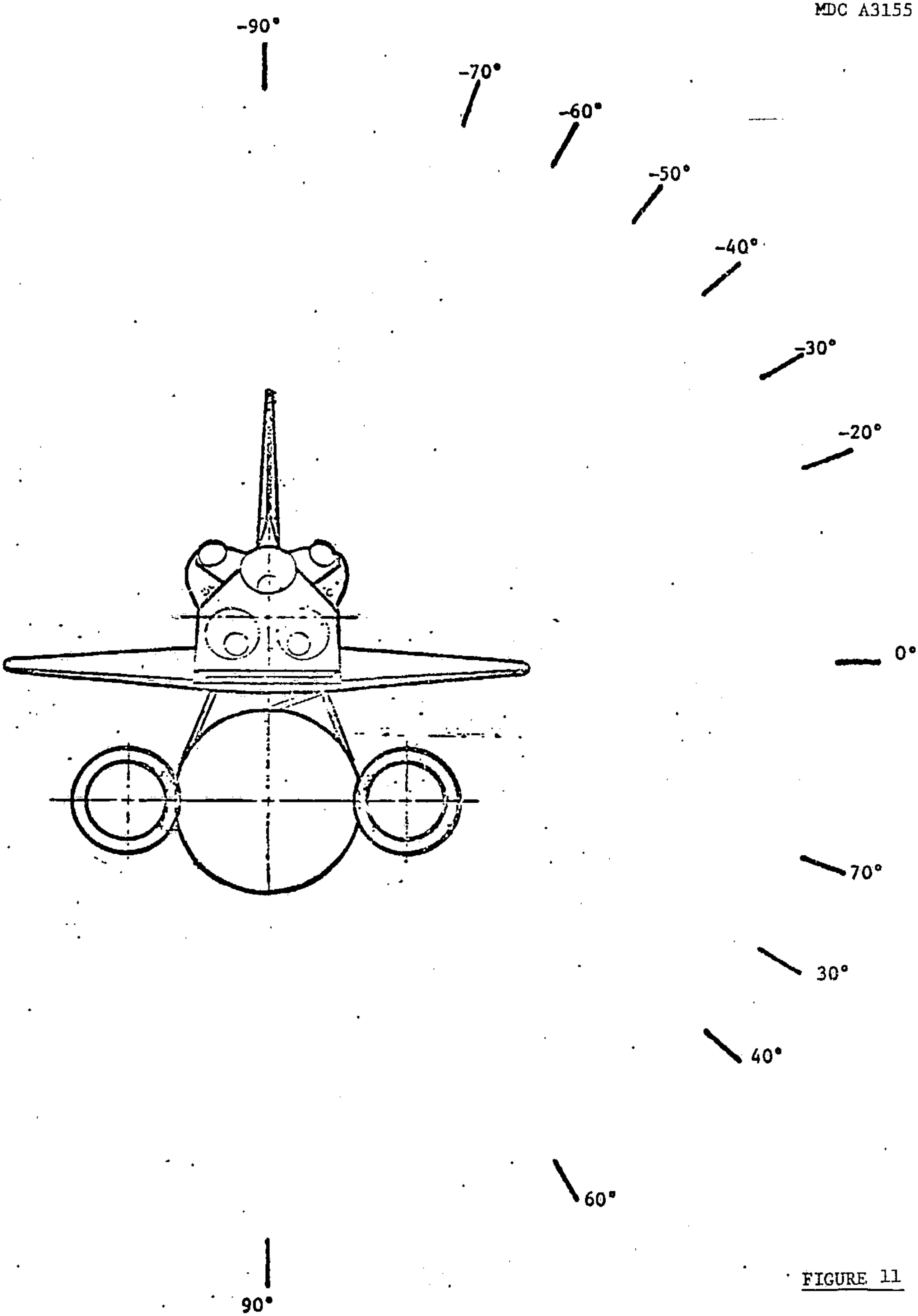


FIGURE 11

FIGURE 11 - ROLL ANGLE ORIENTATIONS

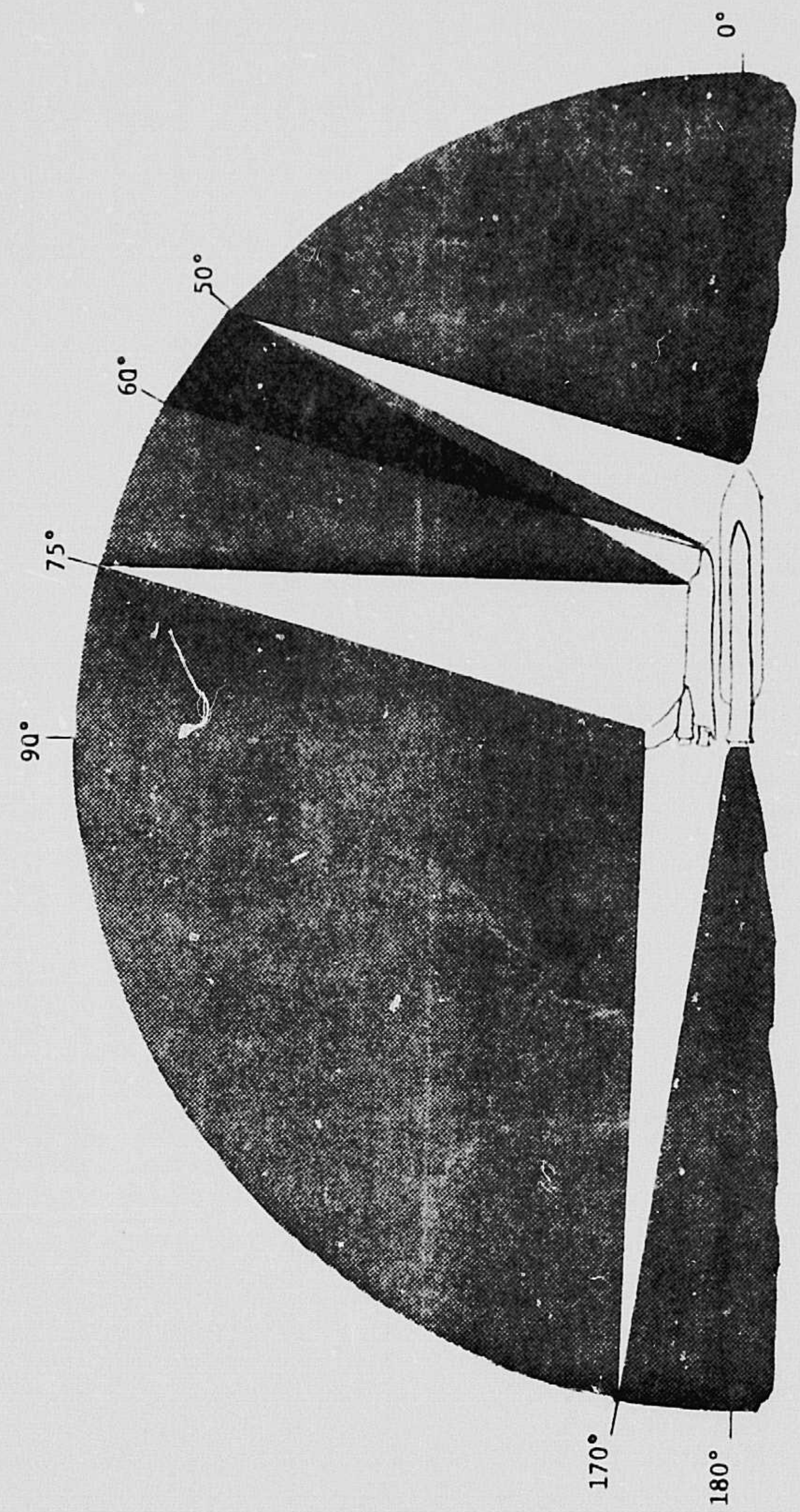


FIGURE 12 - CAPTURE ANGLE DIAGRAM-PITCH AXIS, NO PLUMES

FIGURE 12

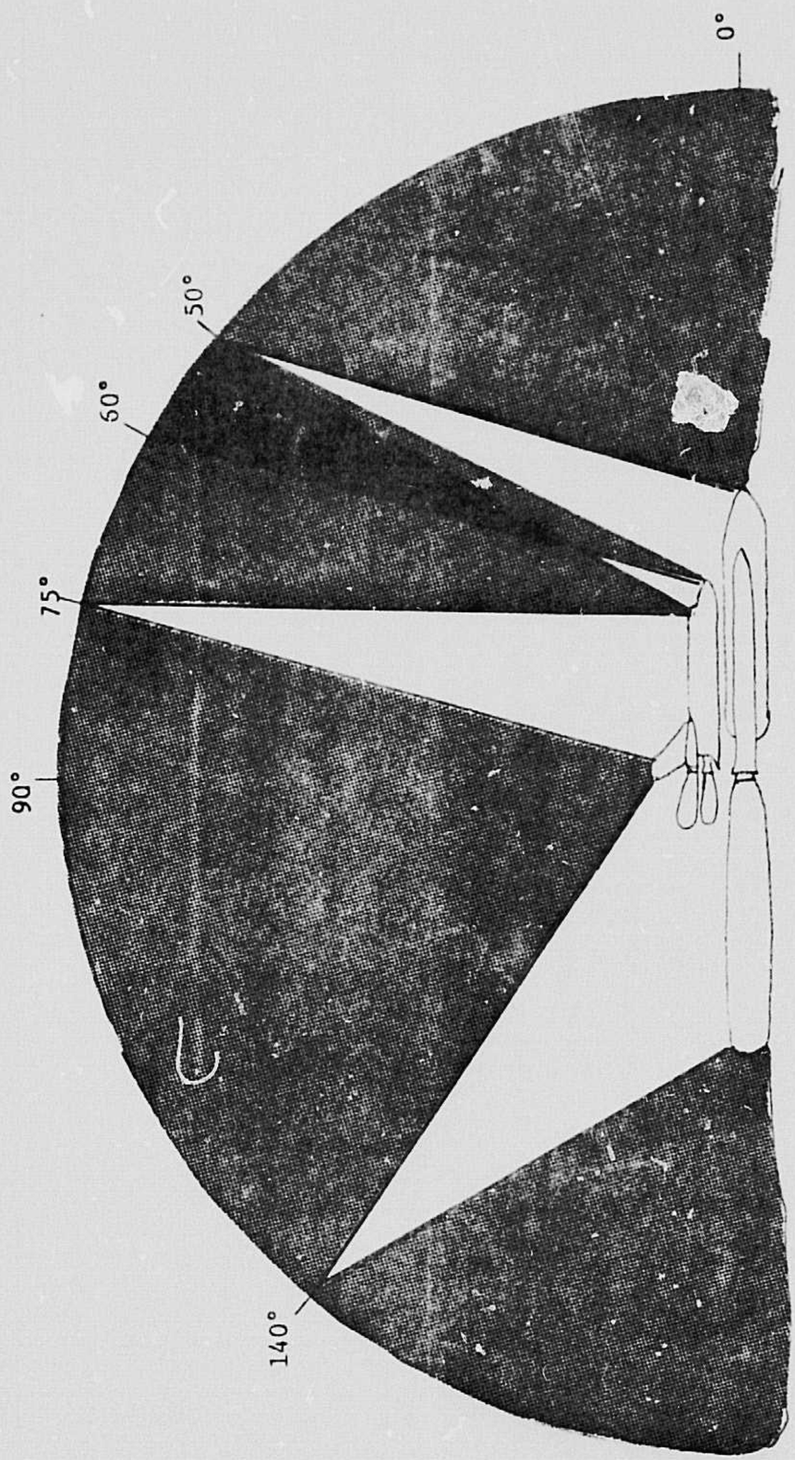


FIGURE 13 - CAPTURE ANGLE DIAGRAM - PITCH AXIS,
6' RESISTIVE SRB PLUMES

FIGURE 13

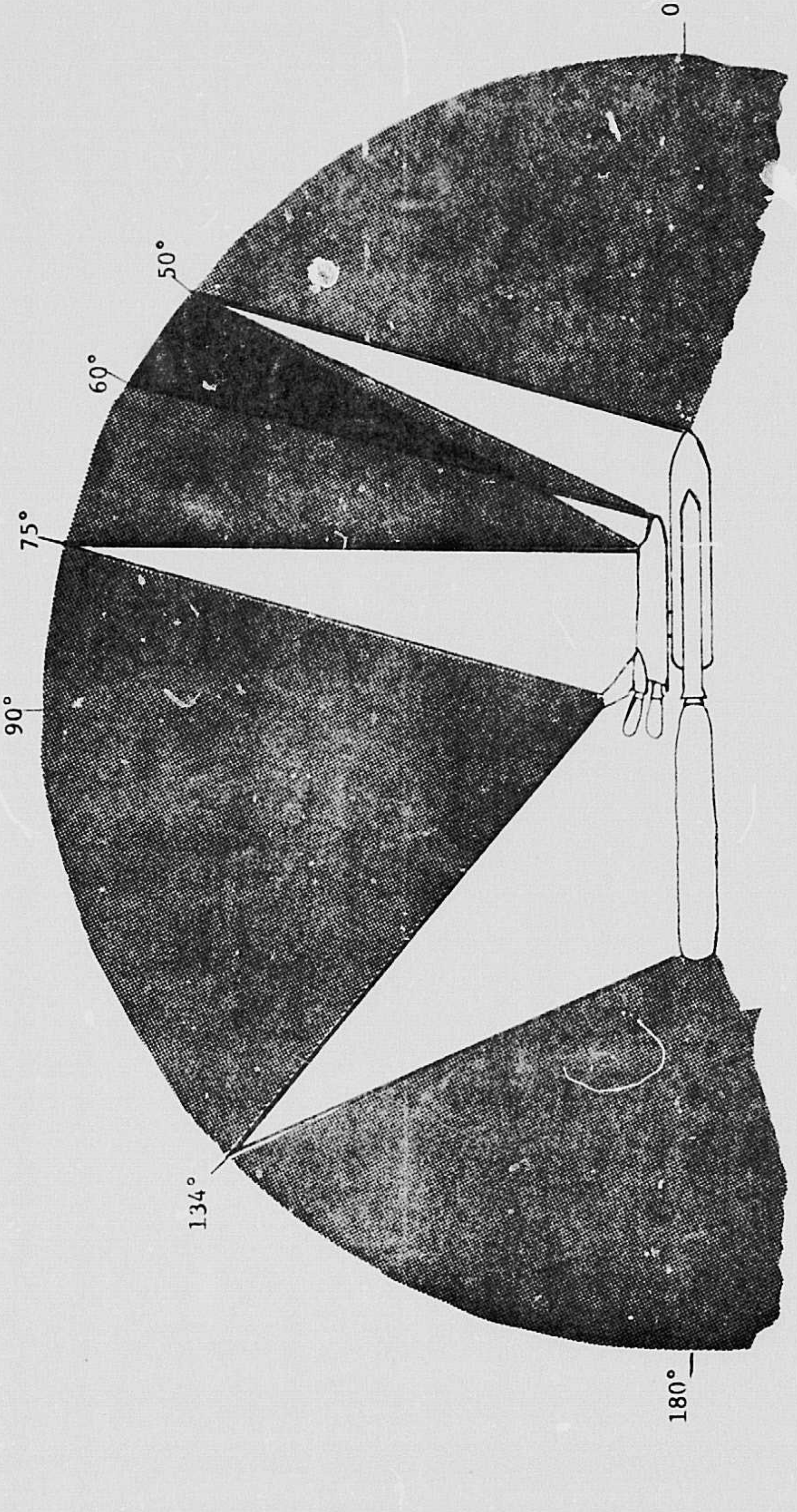


FIGURE 14 - CAPTURE ANGLE DIAGRAM - PITCH AXIS, 6' CONDUCTIVE SRB PLUMES

FIGURE 14

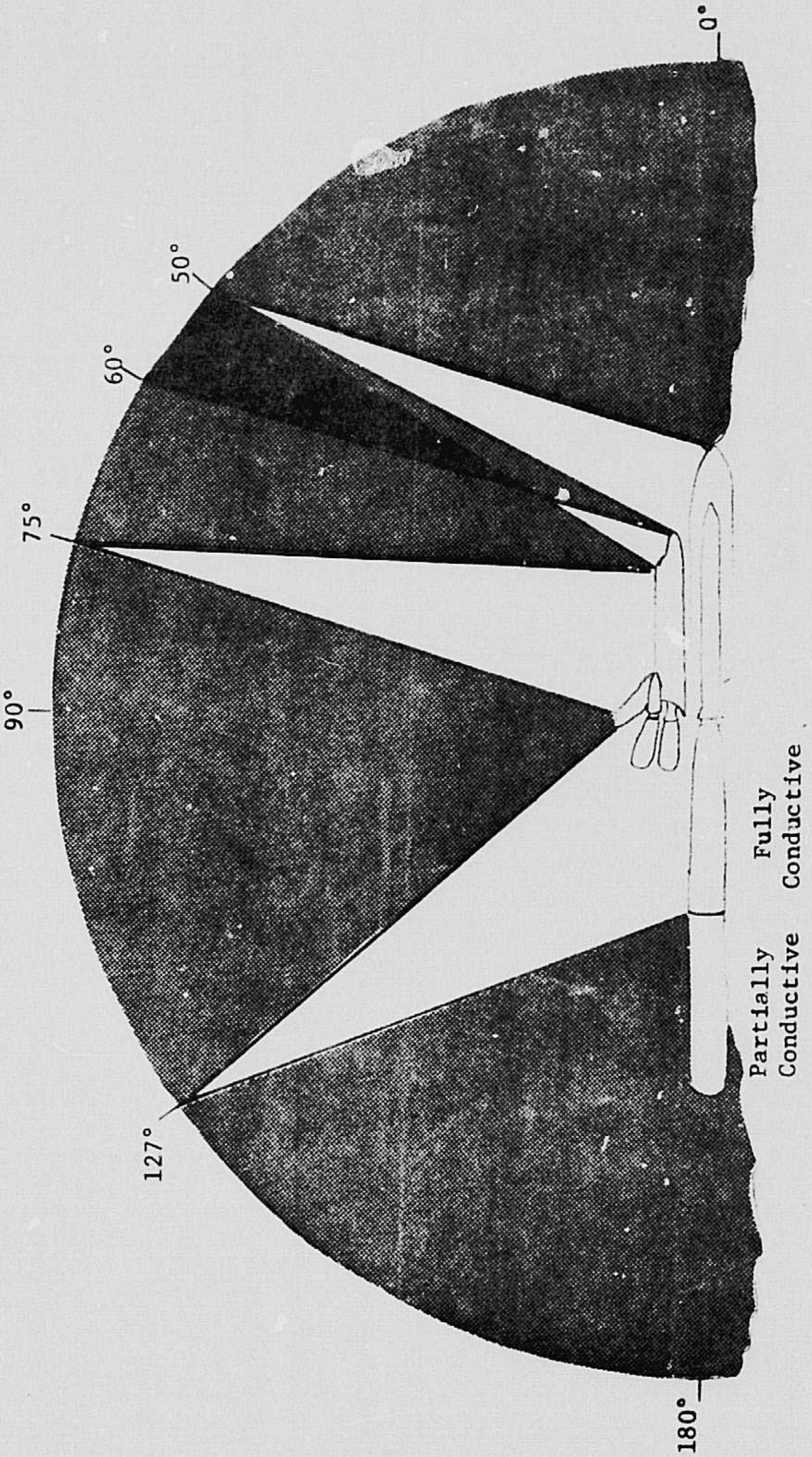


FIGURE 15 - CAPTURE ANGLE DIAGRAM - PITCH AXIS, 12' PLUMES

FIGURE 15

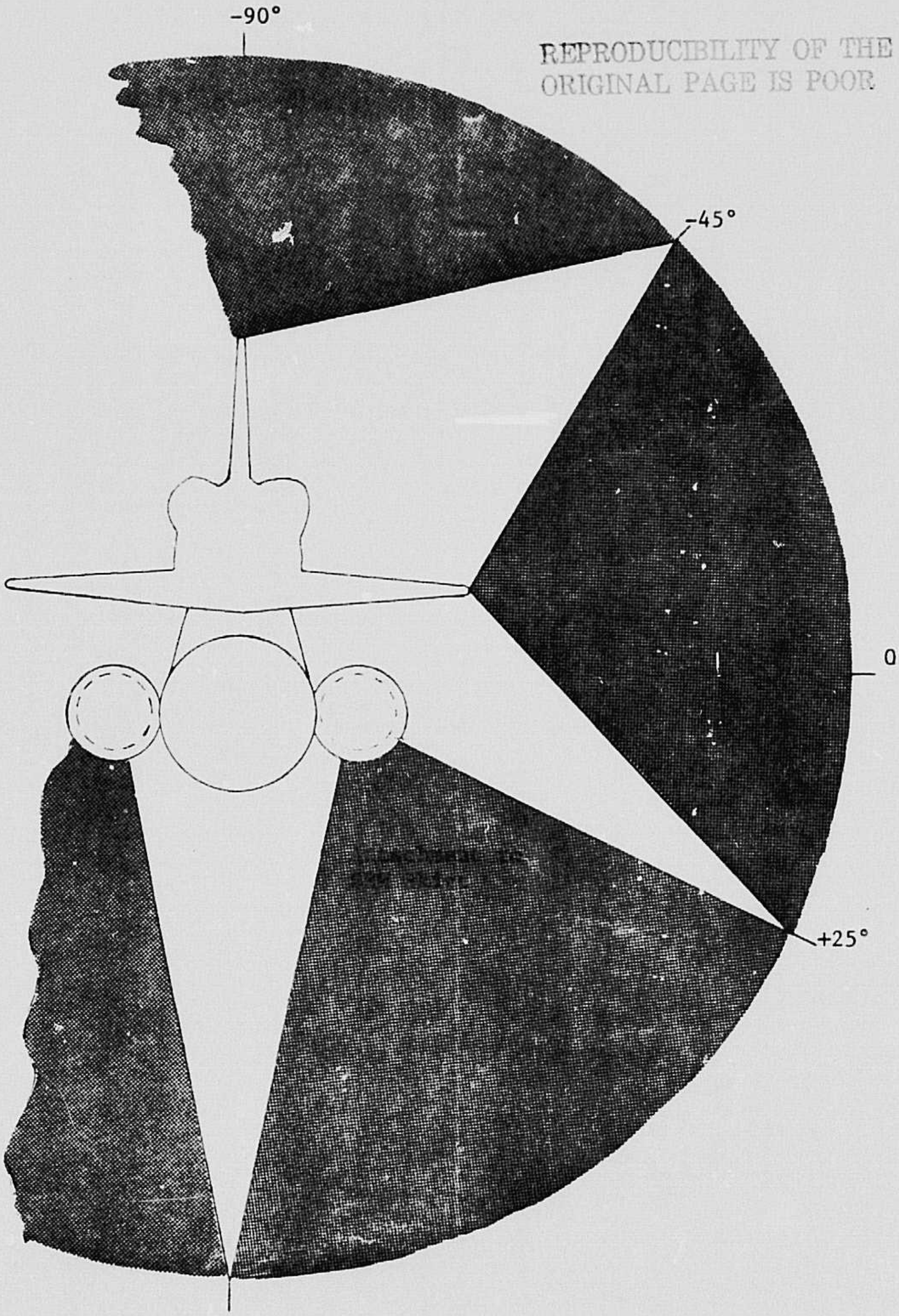
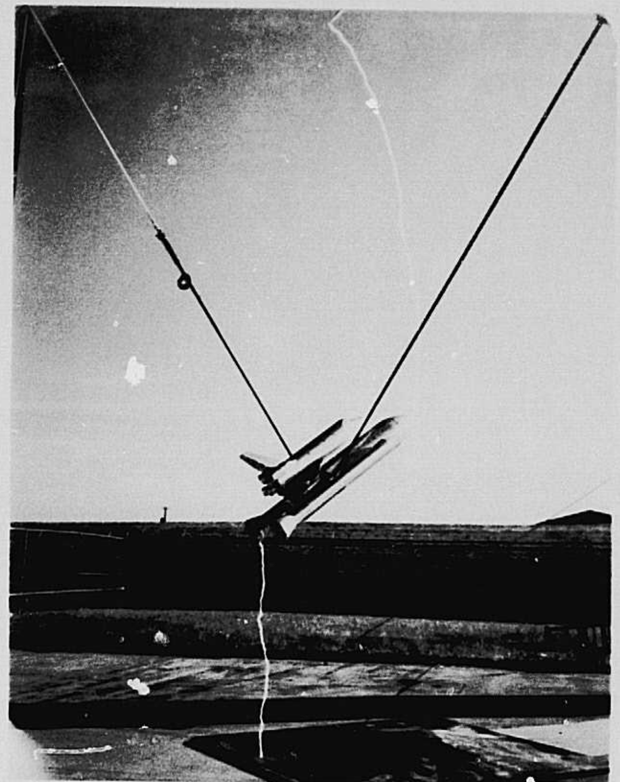


FIGURE 16 - CAPTURE ANGLE DIAGRAM - ROLL AXIS, 6' RESISTIVE SRB PLUMES

FIGURE 16

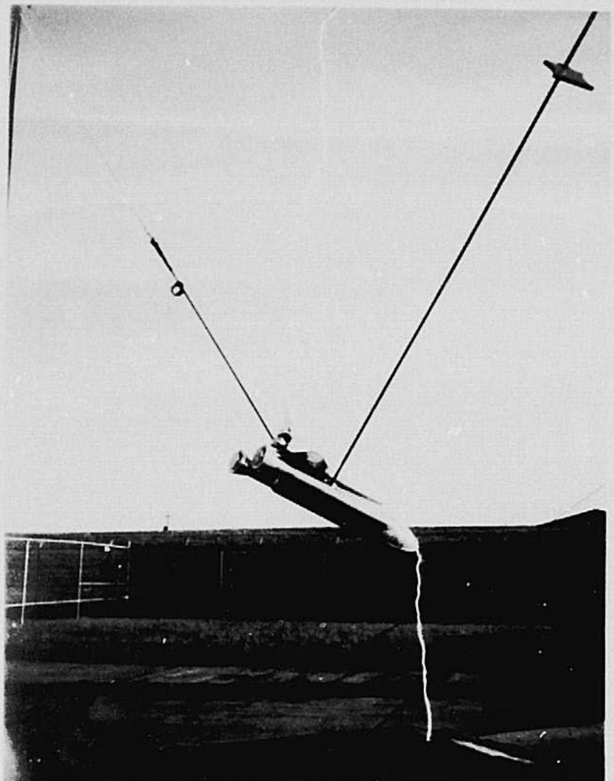

(50°) (Pitch) Shot #14


(50°) (Pitch) Shot #17

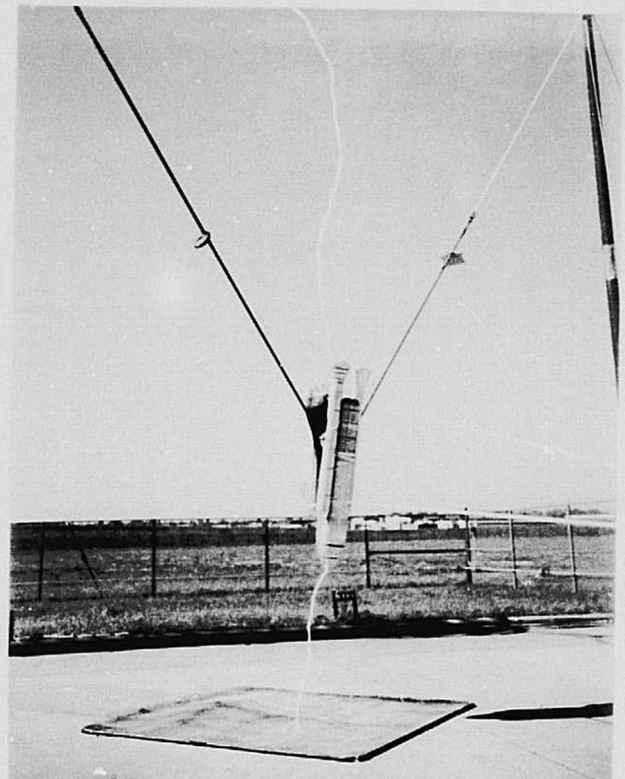

(50°) (Pitch) Shot #20


(75°) (Pitch) Shot #30

FIGURE 17 - ATTACH POINT PHOTOS

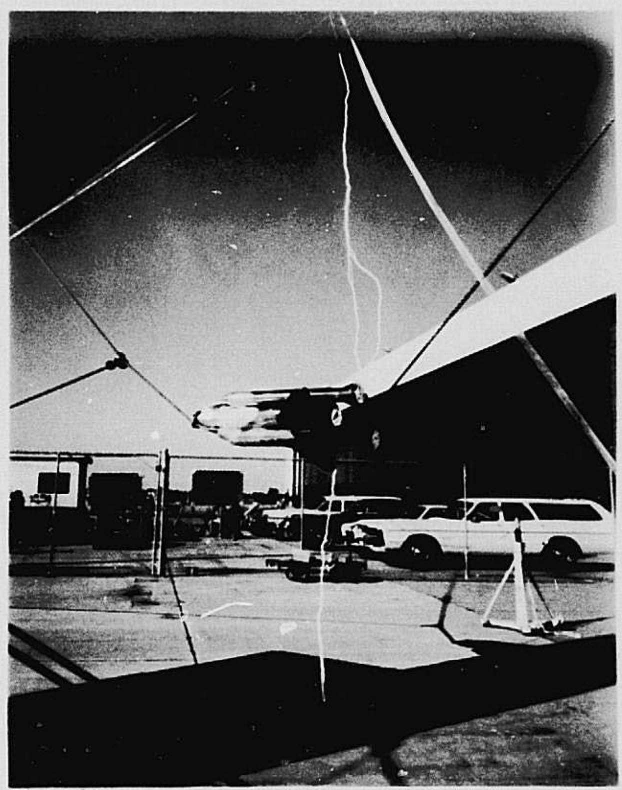


(110°) (Pitch) Shot #38



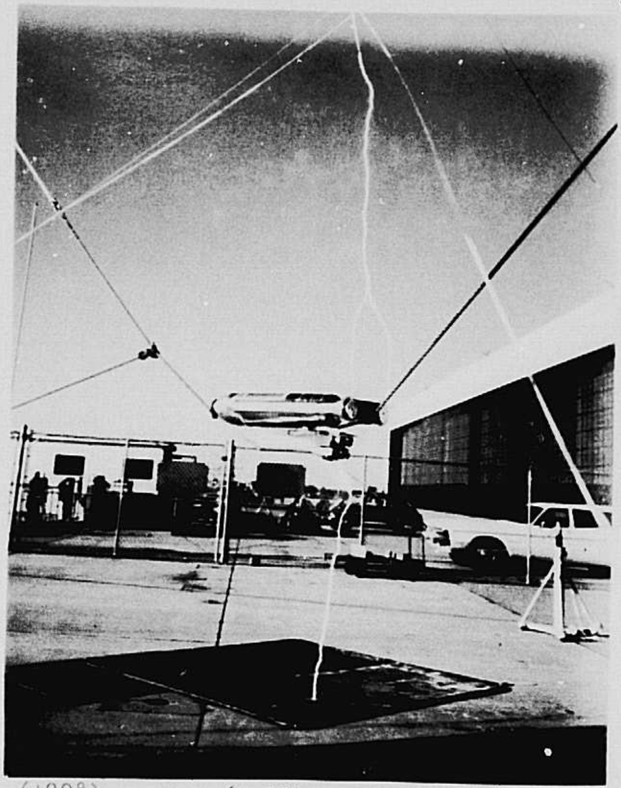
(170°) (Pitch) Shot #68

(+10°) (Roll) Shot #122

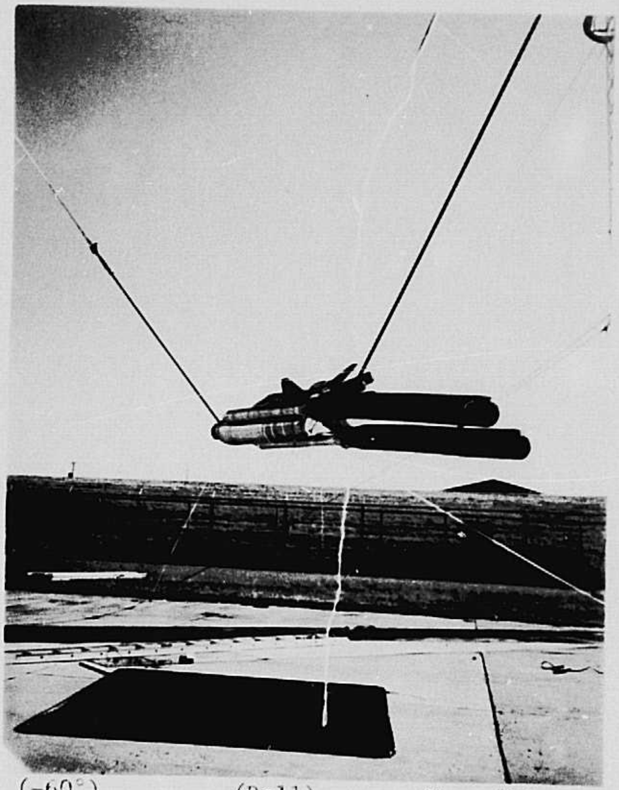


(+40°) (Roll) Shot #135

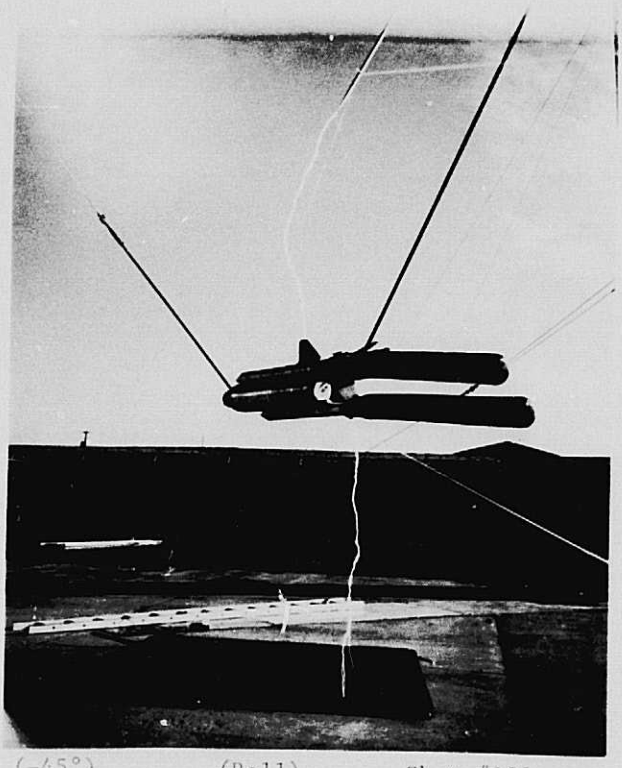
FIGURE 18 - ATTACH POINT PHOTOS



(+90°) (Roll) Shot #152



(-60°) (Roll) Shot #92

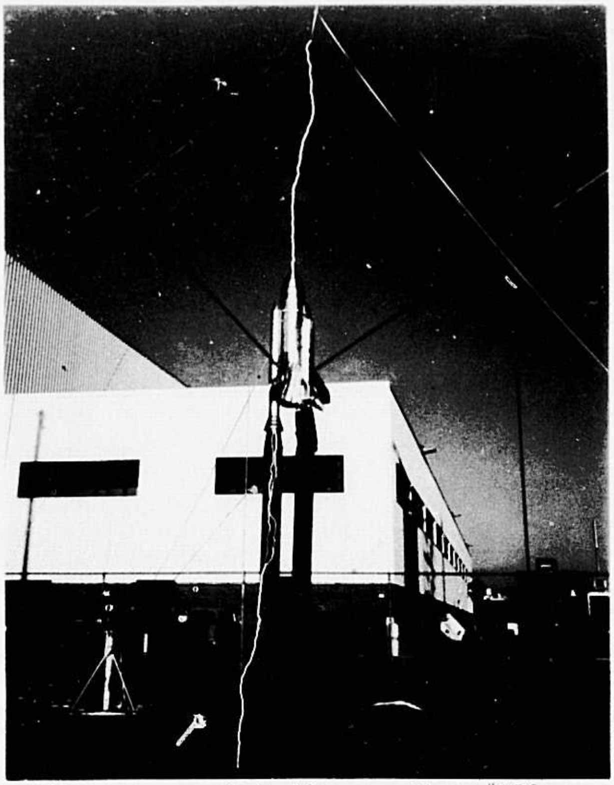


(-45°) (Roll) Shot #108

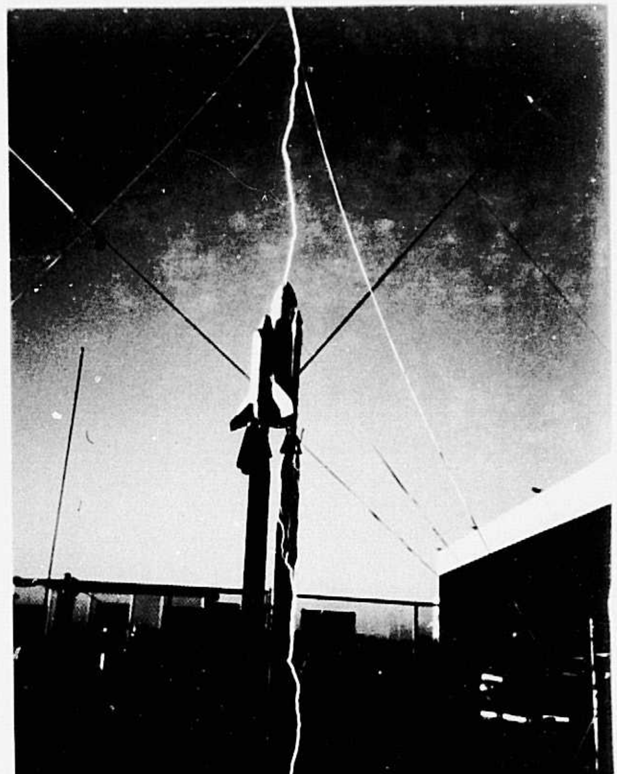
(+50°) (Roll) Shot #117

D4E-588933

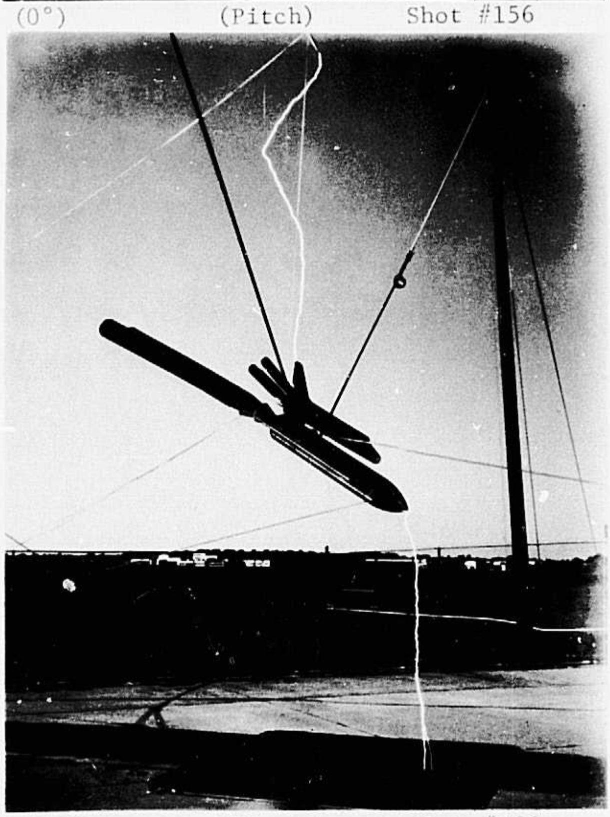
FIGURE 19 - ATTACH POINT PHOTOS



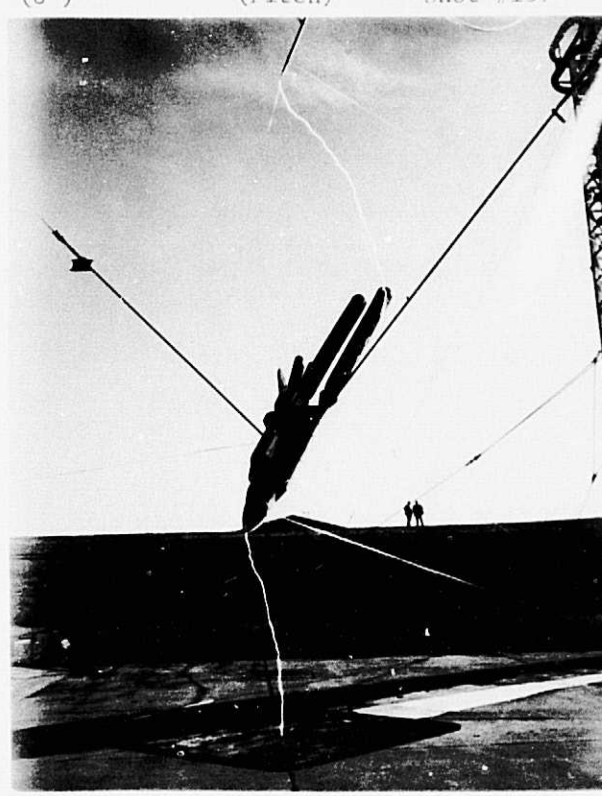
(0°) (Pitch) Shot #156



(0°) (Pitch) Shot #157



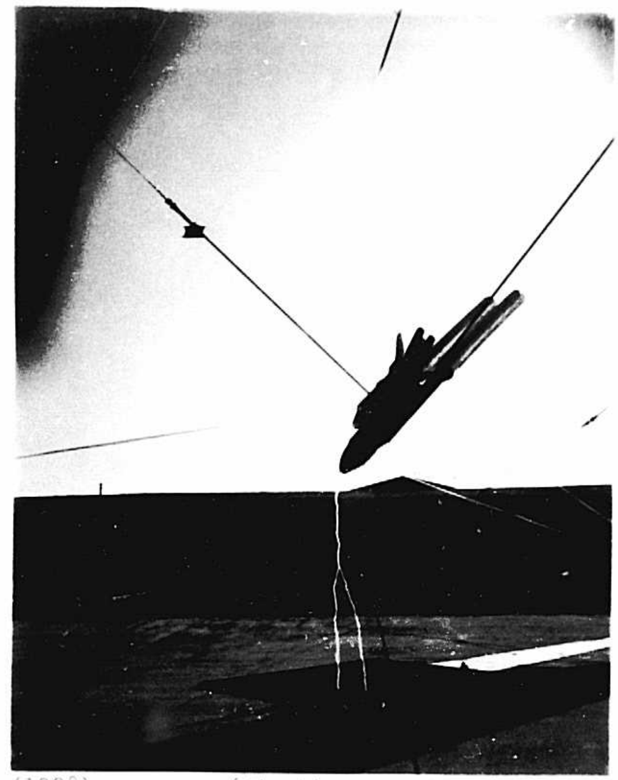
(125°) (Pitch) Shot #166



(145°) (Pitch) Shot #175

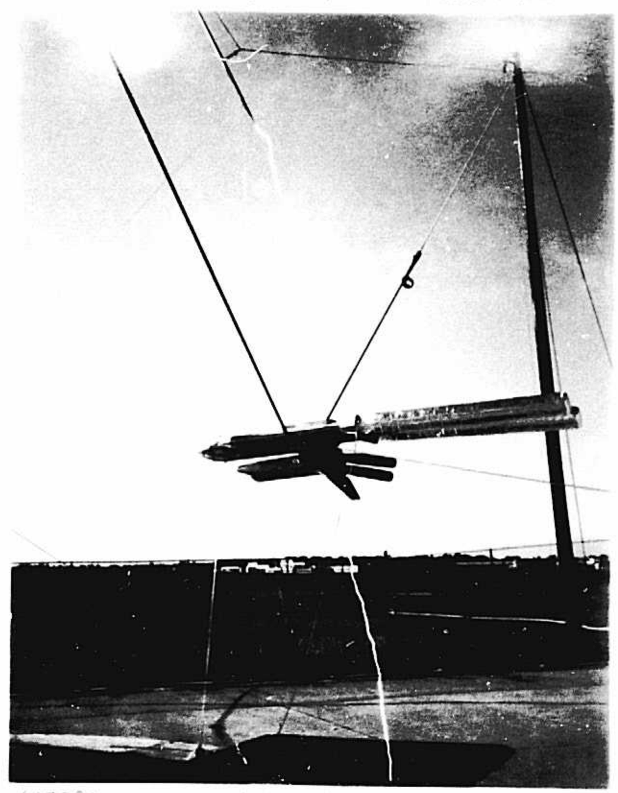
FIGURE 20 - ATTACH POINT PHOTOS

(150°) (Pitch) Shot #163



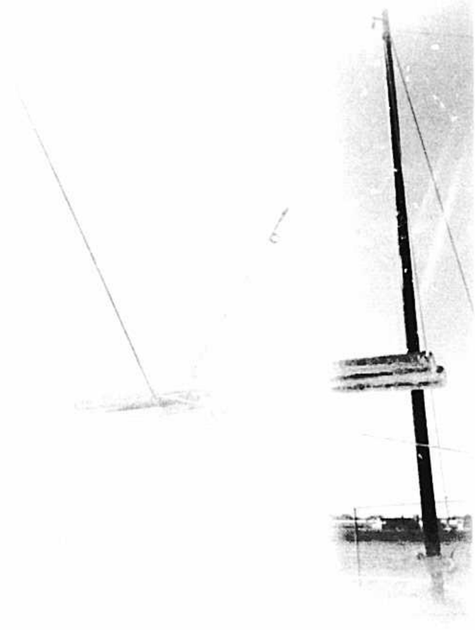
(130°) (Pitch) Shot #195

([illegible]°) (Pitch) Shot #197



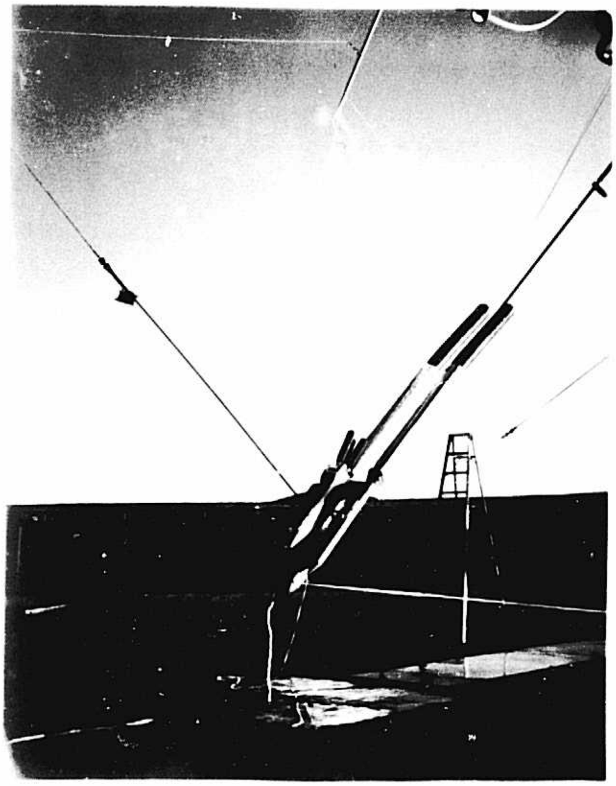
(270°) (Pitch) Shot #[illegible]

MCDONNELL AIRCRAFT COMPANY



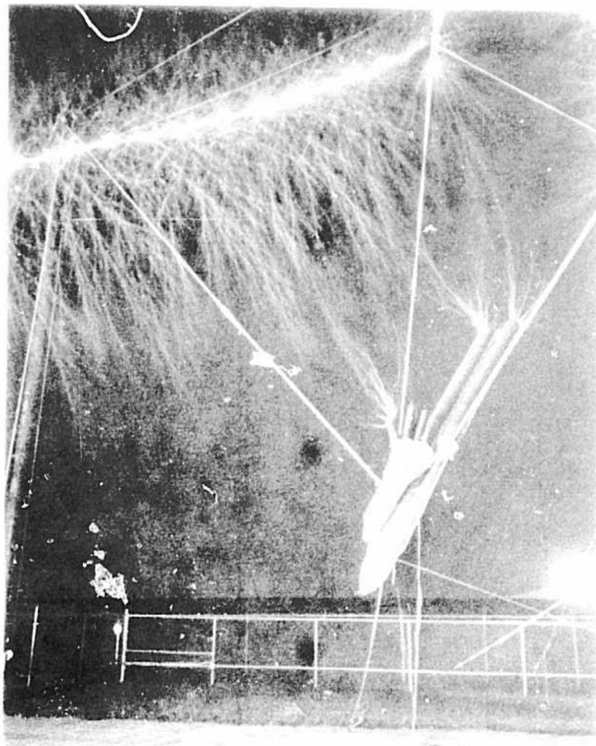
(270°) (Pitch) Shot #209

(127°) (Pitch) Shot #213

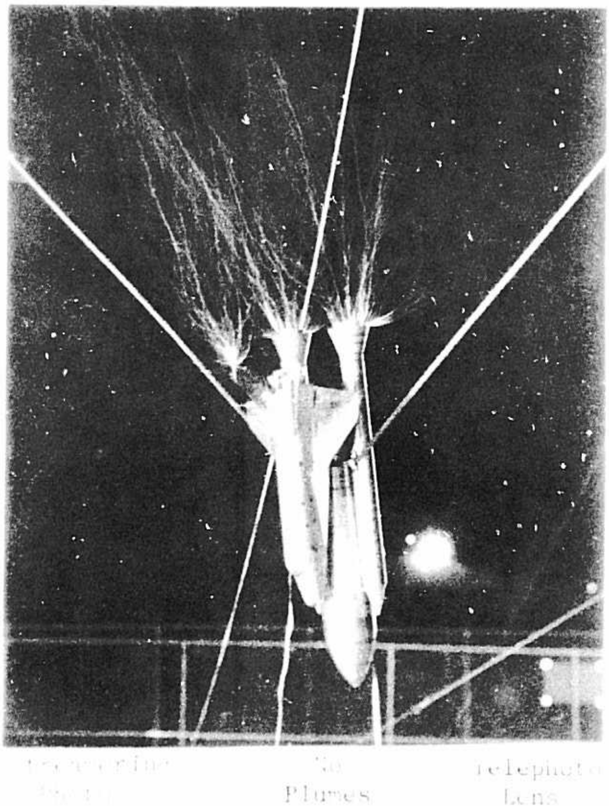


(133°) (Pitch) Shot #219

Streamering Photo — Short Plumes — Telephoto Lens



Streamering Photo — Short Plumes — [illegible]



Streamering Photo — No Plumes — Telephoto Lens

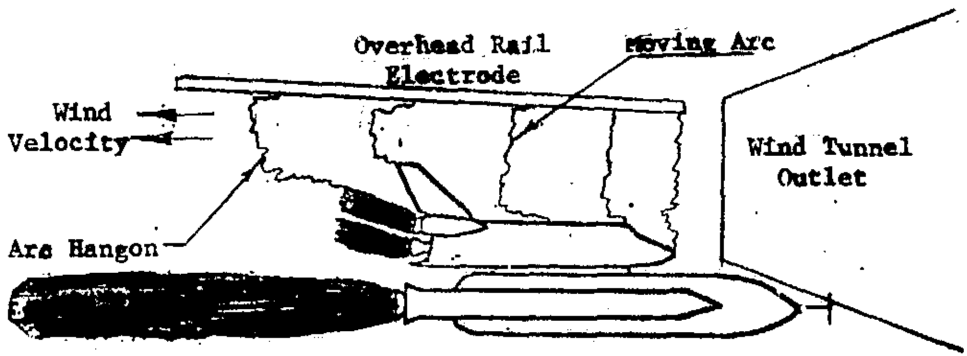


FIGURE 24A - SWEPT STROKE LIGHTNING HANGON TEST ON SHUTTLE MODEL

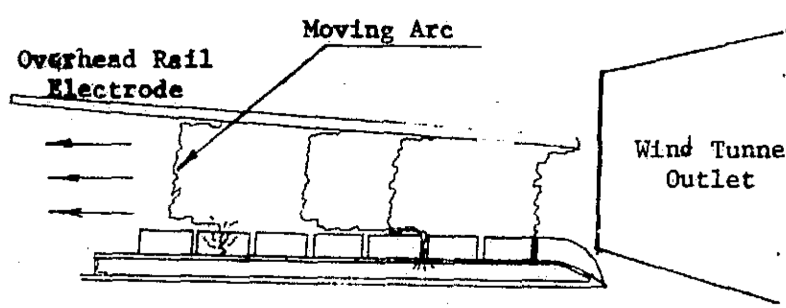


FIGURE 24B - SWEPT STROKE LIGHTNING TEST ON TPS PANEL

FIGURES 24A, 24B

APPENDIX A

SSME EXHAUST PLUME DATA FOR LIGHTNING MODEL STUDY

Inclusive pages: 47 - 51

PLUME CONDUCTIVITY. A value for plume conductivity was calculated from the relationship

$$\text{Conductivity} = \frac{Ne^2}{m\, g_r}$$

where N = electron density/CM^3

e = electron change

m = electron mass

and g_r = electron collision frequency.

The resultant value is 3×10^{-5} mho/cm, and is essentially constant along the plume axis, despite the oscillatory nature of the plume. The ratio of N to g_r remains relatively constant because g_r is a function of N.

The SSME exhaust was thought to be a poor conductor, as the combustion products are essentially molecular water and hydrogen. (The conductivity of distilled water is 2×10^{-6} mho/cm, and for saturated NaCl solution 2×10^{-1} mho/cm.) However, though lacking in free ions, the exhaust contains a high concentration of free electrons, as determined by a N-element performance analysis program commonly used at Rocketdyne. This program was perturbed by introducing N_2 diluents into the propellants at percentages of 0.1% and 1% (to create NO ions) with negligible effect. Therefore the 3×10^{-5} conductivity value is felt adequate and within sensible bounds for simulation purposes.

PLUME GEOMETRY. Single Engine SSME plume geometry for sea level, 30K ft and 88K ft altitudes was created from a Rocketdyne Plume Analysis IBM program, which iterates the plume jet boundary with respect to the internal shock structure, based upon combustion properties along the thrust axis. Data is computed normalized to the MCC throat radius, and was converted manually to dimensional coordinates as presented in Table A1. A smooth curve graphic representation of these data points is included for information purposes as Figure A1.

For modeling purposes, Rocketdyne has recommended the following:

a) There is negligible effect on the outer plume boundary for the 3 engine cluster combination even though the inner plume boundaries will intersect at some altitude between sea level and 25K ft.

b) For conductivity simulation, the model could be represented by either a thin wall (hollow) shell of material having a constant volumetric conductivity, or a solid dielectric shape with an applied surface conductor. The bulk of the combustion products is concentrated adjacent to the jet boundary, with very low pressure (and density) effluents in the central portion of the exhaust.

The geometric shapes generated by the IBM program were further checked by a GE program (Jet Dimensional Prediction by Integral Method) with adjustments made for entropy.

TABLE A1 -

SSME SINGLE ENGINE EXHAUST PLUME DIMENSIONS

(JET BOUNDARY)

*SUBTRACT 121.2 FOR DIST. FROM EXIT

AXIAL COORD (INCH) FROM THROAT	PLUME RADIAL COORD Y (INCHES) VS ALTITUDE		
	SEA LEVEL (1)	30,000 FT (2)	88,000 FT (2)
X*	Y	Y	Y
	A (Exit)		
128.7	43.8	46.3	47.4
141.6	42.5	47.9	
154.5	39.9	48.4	56.6
167.4	36.1	48.9	
180.2	30.9	48.9 A	64.9
193.1	25.7	48.4	
206.0	21.1	46.9	72.1
218.9	15.9	45.8	
231.7	15.5 B	45.1	76.7
244.6	16.5	43.3	
257.5	23.2	41.7	81.4
270.4	29.9	40.1	
283.2	36.1	37.6	85.0
296.1	41.2	36.5	
309.0	44.8	34.0	87.5
321.9	46.9	33.5	
334.7	47.9 C	31.4	90.1
347.6	47.6	30.4	
360.5	46.3	29.9	91.4
373.4		29.3	
386.2		28.8 B	91.9
399.1		29.9	92.4 A
437.7			91.9
463.5			90.9
489.2			90.1
515.0			87.5
540.7			85.0

TABLE A1 (Cont'd)

(Cont'd)

AXIAL COORD (INCH) FROM THROAT	PLUME RADIAL COORD Y (INCHES) VS ALTITUDE			
X*	SEA LEVEL Y	30,000 FT Y	88,000 FT Y	
566.5			81.4	
592.2			76.7	
618.0			68.9	
643.7			64.4	
669.5			60.3	
695.2			58.7	
721.0			57.7	
746.7			56.6	
772.5			55.6	B
798.2			56.6	

A = 1ST CYCLE CREST

B = 1ST CYCLE NODE

C = 2ND CYCLE CREST

(1) For SEA LEVEL PLUME, 2nd and subsequent cycles are symmetic and identical to B to C 1/2 cycle.

(2) For 30K and 88K PLUMES, 2nd and subsequent cycles are symmetric and identical to A to B 1/2 cycle.

TABLE A1

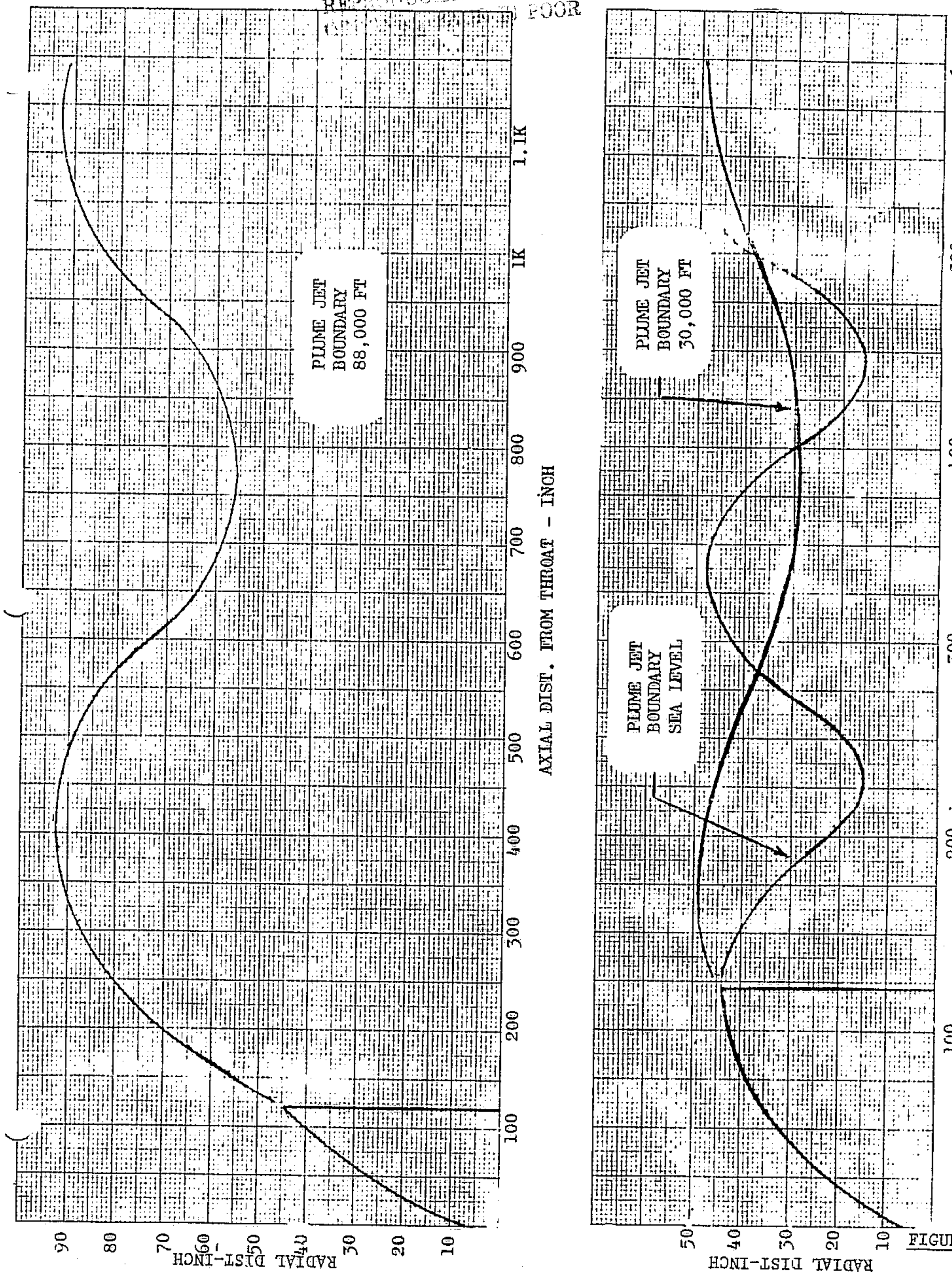


FIGURE A1 - SSME PLUME BOUNDARIES

FIGURE A1

APPENDIX B

RAW DATA SHEETS

Inclusive pages: 53 - 60

TABLE B1 -

SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 1 Oct 74

ATTITUDE PITCH - B PLANE

WITNESSES MR NATE SCOTT
EHS
DWC

SHOT #	ANGLE	ATTACH POINTS	DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
1	0°	Ext tank nose - Rt SRB nozzle	8½'	5'		80KV
2	0	" "	↓	↓		80
3	0	" " streamer L. SRB nozzle	↓	↓		77
4	30°	" - L. SRB skirt	9'	5'3"		77KV
5	30	" R. SRB	↓	↓		77
6	30	" L. SRB	↓	↓		77
7	30	" L. SRB	↓	↓		↓
8	30	" - L. SRB skirt	↓	↓		↓
9	40	" - "	9¼'	5½		77'
10	40	" R. SRB	↓	↓		↓
11	40	" "	↓	↓		↓
12	40	" L. SRB	↓	↓		↓
13	40	" R. - SRB skirt	↓	↓		↓
✓ 14	50	Orbiter nose - L. SRB skirt	9½'	5¾		↓
15	50	Orbiter eyebrow - R. SRB skirt	↓	↓		↓
16	50	Ext tank nose - L. SRB skirt	↓	↓		↓
✓ 17	50	" - "	↓	↓		↓
18	50	Orbiter nose - R. SRB skirt	↓	↓		↓
19	50	" "	↓	↓		↓
✓ 20	50	Orbiter eyebrow - L & R. SRB skirts	↓	↓		76
21	60	" - L. SRB skirt	9¾'	6'		↓
22	60	Orbiter nose - "	↓	↓		↓
23	60	" R. SRB skirt	↓	↓		↓
24	60	" - "	↓	↓		↓
25	60	" "	↓	↓		↓
26	75	Orbiter Tail - L. SRB skirt	10'	6½'		↓
27	75	" "	↓	↓		↓
28	75	Orbiter eyebrow & tail streamer - R. SRB skirt	↓	↓		↓
29	75	Orbiter tail - R. SRB skirt	↓	↓		75
✓ 30	75	" - "	↓	↓		75
31	90	" - "	9¾	6¾'		78
32	90	" - R. SRB skirt & streamer L. SRB skirt	↓	↓		78
33	90	" - R SRB skirt	↓	↓		↓
34	90	" "	↓	↓		↓
35	90	Orbiter tail - Ext tank nose & streamers L & R SRB skirts	↓	↓		↓
36	110	" - Ext tank nose	9½	↓		78

TABLE B1 (Cont'd)

(Cont'd)

TABLE B1 -
SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 1 Oct 74
ATTITUDE PITCH - B PLANE

WITNESSES
SJSS
DWC

SHOT #	ANGLE	ATTACH POINTS		DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
37	110°	Orbiter tail - Ext tank nose		9½	6 3/4		78KV
38	110	"	"	↓	↓		↓
39	110	"	"				
40	110	"	"				
41	120	"	"				71KV
42	120	"	"				↓
43	120	"	"				
44	120	"	"				
45	120	"	"				
46	130	"	"	~9	~6		72
47	130	"	"	↓	↓		72
48	130	"	"				72
49	130	"	"				72
50	130	"	"				↓
51	140	"	"				
52	140	"	"				
53	140	"	"				
54	140	"	"				
55	140	"	"				72

(Cont'd)

TABLE B1 -
SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 4 Oct 1974

ATTITUDE PITCH - B PLANE

WITNESSES MR. PERCY MIGLICCO
EJS
DWC

SHOT #	ANGLE	ATTACH POINTS	DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
56	140°	Orbiter tail - Ext tank nose	~9½	~6¼		75
57	140	" "				
58	150	" "				
59	150	Orbiter tail - Ext tank nose				
60	150	" "				
61	150	" "				
62	160°	" "	~9	~6		
63	160°	" "				
64	160°	Orbiter tail - Ext tank nose				
65	160	" " "				
66	160°	" " "				
67	170°	R. SRB nozzle - "				
68	170°	L. SRB nozzle - "				
69	170	Orbiter tail - "				
70	170	" "				
71	170	" "				
72	170° + 3 ft right		~9½			
73		SRB R. nozzle - Ext tank nose				
74		R. SRB skirt - " visual				
75		R. SRB nozzle & orbiter tail - Ext tank nose				
76		~~R. SRB~~ R. SRB - "				
77	170° + 4 ft out & 4 ft [illegible]	Orbiter tail - "				
78		" - "				
79		" - "				
80	180-B plane	R SRB nozzle - "	9'			
81		" "				
82		" "				75
83		" "				80
84		R. SRB - Ext tank nose				
85		R. SRB & L SRB [illegible] "				
86	[illegible] SRB plane 155°	check on ability of plane				
87						

TABLE B1 (Cont'd)

SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 4 Oct 74 WITNESSES MR. NATE SCOTT

ATTITUDE Roll - C (3ft) and B plane &HS DWC

SHOT #	ANGLE	ATTACH POINTS	DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
87	-90°C	Orbiter Tail — Ext tank nose	~ 3'	~ 7'		80KV
88	-90C	" — "				80
89	-90C	Orbiter tail — Ext tank nose				76KV
90	-90°C	" — "				76KV
91	-60C	" - R. SRB skirt				78KV
92	-60C	" — "				
93	-60C	" — "				
94	-60C	" — "				
95	-60C	" — "				
96	-45C	" — "				
97	-45C	" — "				
98	-45C	" — "				
99	-45C	Orbiter Tail - R. SRB skirt				
100	-45°C	" — "				
101	-30C	attach to support rope "				
102	-30B	Orbiter L wing tip - "				
103	-30B	" — "				
104	-30B	" — "				
105	-30B	" — "				
106	-30B	Orbiter wing tip - R. SRB skirt				
107	-45B	Orbiter Tail "				
108	-45B	Orbiter R wing tip "				
109	-45B	Orbiter Tail "				
110	-45B	" — "				
111	-45B	Orbiter wing tip - R. SRB skirt				
112	-10B	" " " - Orbiter wing tip				
113	-10B	" " " — " " "				
114	-10B	" " " — " " "				
115	-10B	" " " — " " "				
116	-10B	" " " — " " "				
117	+50°B	L SRB skirt — Orbiter tail				
118	+50B	" — "				
119	+50B	" — "				
120	+50B	" — "				
121	+50B	" — "				

(Cont'd)

TABLE B1 -

MDC A3155

SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 7 Oct 74

ATTITUDE Roll – B plane

WITNESSES MR. NATE SCOTT
ENS

SHOT #	ANGLE	ATTACH POINTS	DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
122	+10 B	Orbiter wing tip – Orbiter wing tip	9 ft	6 ft.		75KV
123	+10 B	" "				
124	+10 B	" "				
125	+10 B	" "				
126	+10 B	" "				
127	+25 B	" "				
128	+25 B	" "				
129	+25 B	R. SRB skirt – Orbiter L wing tip				
130	+25 B	Orbiter wing tip – Orbiter wing tip				
131	+25 B	" "				
132	+40 B	R. SRB skirt · Orbiter L wing tip				
133	+40 B	Orbiter wing tip – "				
134	+40 B	R. SRB skirt – "				
135	+40 B	" – "				
136	+40 B	" – Orbiter tail				
137	+45 B	" – Orbiter L wing tip				
138	+45 B	" – "				
139	+45 B	" – "				
140	+45 B	" – "				
141	+45 B	" – Orbiter tail				
142	+50 B	" – "				
143	+50 B	" – "				
144	+50 B	" "				
145	+65 B	" – "				
146	+65 B	" "				
147	+65 B	" "				
148	+65 B	" "				
149	+65 B	" "				
150	+90 B	" "				
151	+90 B	L SRB skirt – "				
152	+90 B	L & R. SRB skirts – "				
153	+90 B	R. SRB skirt "				
154	+90 B	" "	9	6 ft		

TABLE B1 (Cont'd)

SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 7 Oct 74
ATTITUDE Pitch - B plane - [illegible]

WITNESSES
EHS
DWC

SHOT #	ANGLE	ATTACH POINTS	DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
155	0°	Ext tank nose - R SRB plume	9 ft	12 ft [illegible]		75KV
156	0°	" L SRB plume	↓	↓		↓
157		" R SRB plume	↓	↓		↓
158	150°	R SRB plume - Ext tank nose	10 ft - plume	5½		↓
158	150°	" "	↓	↓		↓
159	150	" "	↓	↓		↓
160	150°	" "	↓	↓		↓
161	150°	" "	↓	↓		↓
162	150°	" "	↓	↓		↓
163	150°	R SRB plume [illegible] L plume - Ext tank nose	↓	↓		↓

SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 8 Oct 74 WITNESSES ENS / BH

ATTITUDE Pitch [illegible] Points

SHOT #	ANGLE	ATTACH POINTS		DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
164	125°	[illegible] Tail	Ext Tank nose	[illegible]	6		75KV
165	125°	"	"				
166	125	"	"				
167	125	"	"				
168	125	"	"	↓			
169	130°	"	"	10' - tail	6		
170	135°	"	"	9'3" plume / 10' - tail	6		
171	135°	"	"				
172	135°	"	"				
173	135°	"	"				
174	135°	"	"	↓			
175	145	L. SRB plume	"	8'3" plume / 10' tail			
176	145	"	"				
177	145°	"	"				
178	145°	"	"				
179	145°	"	"	↓			
180	145°	"	"	9'3" plume / 11'1" tail			
181	145°	"	"				
182	145°	"	"	↓			
183	145°-A 3ft	"	"	7' plume / 9'9" tail			
184	145°-A 3ft	"	"	↓			
185	140 B	Orbiter tail	"	7'10" plume / 9'2" tail			
186	140°	"	"				
187	140°	"	"				
188	140°	Orbiter tail & L. SRB plume	— Ext tank nose				
189	140°	L SRB plume	"				
190	140°	Orbiter tail	"	↓	↓		↓

SPACE SHUTTLE MODEL LIGHTNING ATTACH TESTS

DATE 9 Oct 74

WITNESSES ENS, AY, DWC.

ATTITUDE PITCH - METAL PLUMES B PLANE

	SHOT #	ANGLE	ATTACH POINTS		DISTANCE PROBE MODEL	DISTANCE MODEL GROUND	ARC TIME	CHARGE VOLTS
	191	130°	Orbiter tail -	Ext tank nose	9'0" plume 9'0" tail	6'		75KV
	192	130°	"	"				
	193	130°	"	"				
	194	130°	"	"				
✓	195	130°	"	"				
	196	130°	"	"				
✓	197	141°	R SRB plume	"	7'6" plume 9'0" tail			
	198	141°	"	"				
	199	141°	"	"				
	200	141°		"				
	201	141°		"				
	202	134°	L SRB plume	"	8'6" plume 9'0" tail			
	203	134°	R SRB plume	"				
	204	134°	Orbiter tail	"				
	205	134°	L SRB plume	"				
	206	134°	R SRB plume	"				
	207	-270°	ET body	Orbiter Tail	11'-Tank	6' tail		
✓	208	-270°	"	"	"	"		
✓	209	-270	"	"	"	"		
EXTENDED PLANE	210	*127°	Orbiter Tail	ET Nose	10'4" plume	30"		
	211	127°	"	"	"			
	212	127°	Conductive plume	"	"			
✓	213	127°	Orbiter Tail		"			
	214	127°	"		"			
	215	127°	"		"			
	216	127°	"		"			
	217	133°	Conductive plume	ET nose	11'6 tail 9'10" mid plume			
	218	133°	"	"				
✓	219	133°	"					

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10. JSC-07636, "Space Shuttle Lightning Protection Criteria Document" September, 1973.