REPORT NO. GESP-7181

GPHS-RTG SYSTEM EXPLOSION TEST
DIRECT COURSE EXPERIMENT 5000

1 MARCH 1984

DEPARTMENT OF ENERGY
CONTRACT NO. DE-AC01-79ET-32043

ADVANCED ENERGY PROGRAMS DEPARTMENT
GENERAL ELECTRIC

DISCLAIMER

SUMMARY

The General Purpose Heat Source - Radioisotope Thermoelectric Generator (GPHS-RTG) has been designed and is being built to provide electrical power for spacecrafts to be launched on the Space Shuttle. The objective of the RTG System Explosion Test was to expose a mock-up of the GPHS-RTG with a simulated heat source to the overpressure and impulse representative of a potential upper magnitude explosion of the Space Shuttle. The test was designed so that the heat source module would experience an overpressure at which the survival of the fuel element cladding would be expected to be marginal. Thus, the mock-up was placed where the predicted incident overpressure would be 1300 psi. The mock-up was mounted in an orientation representative of the launch configuration on the spacecraft to be used on the NASA Galileo Mission.

The incident overpressure measured was in the range of 1400 to 2100 psi. The mock-up and simulated heat source were destroyed and only very small fragments were recovered. This damage is believed to have resulted from a combination of the overpressure and impact by very high velocity fragments from the ANFO sphere. Post-test analysis indicated that extreme working of the iridium clad material occurred, indicative of intensive impulsive loading on the metal.

GESP--7181

DE86 006119

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

SECTION 1

INTRODUCTION

1.1 BACKGROUND

The General Purpose Heat Source - Radioisotope Thermoelectric Generator has been designed and is being built to provide the electrical power for the spacecraft to be used on the NASA Galileo and International Solar-Polar Missions. These missions will both be launched on the Space Shuttle. In order to obtain flight approval for the radioisotope powered generator, a series of safety analysis reports have to be prepared and presented to the Interagency Nuclear Safety Review Panel (INSRP). This panel consists of chairmen from the National Aeronautics and Space Administration, the Department of Defense (represented by the Air Force) and the Department of Energy, and having consultants and supporting groups with expertise in numerous fields. The safety analysis reports present assessments of the hazards that might result from potential accidents that can arise in the missions.

The Shuttle Range Safety Explosives Yield Ad Hoc Committee has identified and defined numerous potential accidents that have been assumed to occur in the Space Shuttle/Centaur launch vehicle that can lead to catastrophic launch pad or early ascent accidents; the mechanisms leading to these malfunctions have not been identified, however. Thus, postulated explosions of the launch vehicle are predicted to expose the GPHS-RTG to static overpressures in the 1000 - 2000 psi range with static impulses of 5.5 - 6.4 psi-sec, based on the conservative assumptions used by the ad hoc committee. Meaningful analyses of the response of a complex structure like the RTG to these blast environments have not been practicable on previous similar programs. Therefore, the capability to perform a full scale test of the RTG is highly desirable. The DIRECT COURSE event provided this capability in a readily available and cost effective test facility.

1.2 OBJECTIVE

The objective of the RTG System Explosion Test (i.e., Experiment 5000) in the DIRECT COURSE event was to expose the RTG simulant to the explosion environment (overpressure/impulse) assumed to be representative of a potential upper magnitude explosion of the Space Shuttle, recognizing, of course, that the characteristics of liquid propellant explosions are different from those of high explosives like ANFO, the latter giving sharper and faster pressure peaks and greater shattering power. The exposure of the RTG mockup to the simultaneous fireball thermal environment was a secondary objective of the test.

1.3 PURPOSE

The purpose of the RTG System Explosion Test was to determine the capabilty of the RTG to survive a representative potential explosion of the Space Shuttle on the launch pad. Information from the test will be factored into the safety analysis reports.

1.4 RELATED TESTING

Los Alamos National Laboratory (LANL) completed a series of shock tube tests at Sandia Laboratories on the GPHS modules. These tests were conducted at progressively higher overpressures to attempt to determine the failure point for the components of the module and, in particular, the iridium cladding around the radioisotope fuel pellets. In these tests, a depleted uranium dioxide fuel simulant was used in place of the live fuel. At an overpressure of 735 psi, the outer graphite member, or aeroshell, caved in, but the inner graphite impact shells with the clad fuel pellets were retained intact with negligible damage. The shot at an overpressure of 1070 psi caused all of the graphite to be stripped away from the iridium clad pellets. However, some of this could have resulted from mechanical interaction with the vermiculite material in the catch box used to stop the module as it exited the shock tube. None of the four (4) iridium clad capsules were breached. As a result of the shot at 1070 psi overpressure, testing had to be discontinued because of significant damage to the shock tube.

Testing at a higher overpressure was accomplished in the PRE-DIRECT COURSE event in which a General Purpose Heat Source (GPHS) module with lead simulants for the clad fuel elements was subjected to a static overpressure of 1300 psi. However, there were no pressure measurements made at the location of the test module in PRE-DIRECT COURSE; the 1300 psi value was a calculated value. This experiment was the precursor for the full scale RTG test to be performed in DIRECT COURSE in which exposure to a similar overpressure was to be attempted.

The GPHS test module was installed in a three module stack for purposes of the test. Two dummy modules, one on either side of the test module, were machined from solid bulk graphite and did not contain any internal cavities or fuel simulant. The three module stack was installed on a boom made from plastic pipe that hung off the main shot tower. The stack was positioned approximately 13 feet from the surface of the sphere holding the ANFO explosive and on a radial line through the sphere about five degrees (5^{o}) below horizontal.

The explosion fragmented the grapite components of the GPHS module significantly as well as the two dummy modules. A total of sixteen graphite fragments were found, ten from the dummy modules and six pieces, representing about ten percent of the graphite, from the GPHS module were recovered at distances from ground zero ranging from 420 to 1050 feet and within a sector of about 25 degrees. The four lead alloy pieces used to simulate the radioisotope fuel capsules were not found. The size of all graphite pieces found ranged from 1/4 to 2.0 inches. High speed photographic coverage of the region around the initial position of the stack of modules did not produce any useful information because of the obscuration by the fireball.

1.5 TEST APPROACH

The approach in designing this experiment was to test the RTG/heat source system in the explosion environment at which the clad fuel pellets were expected barely to survive without breaching. Based on the PRE-DIRECT COURSE test results (even though the lead simulant fuel capsules were not found) and the shock tube test results on bare GPHS modules, a conservative estimate was that the clad capsules would probably survive bare at an incident overpressure around 1200 psi. Additional protection would be provided by the RTG converter case and insulation system. Thus, for DIRECT COURSE, the RTG/GPHS test article was placed where the predicted incident overpressure would be 1300 psi.

The test specimen was a simulated RTG which is essentially a right circular aluminum cylinder containing an isotope fuel simulant of depleted uranium dioxide. The simulated fuel was preheated by an internal electric heater to the operating temperature of the GPHS at launch.

The test specimen was mounted on top of a 120 feet tower separate from the main tower for the Ammonium Nitrate-Fuel Oil (ANFO) explosive. This mounting arrangement was used to simulate the location of the RTG above the ground level on the launch pad and to position the test specimen in the 1300 psi static overpressure range. The test specimen tower was located at a ground distance of 32.5 feet from the ANFO tower to give a radial distance from the Center of Explosion (COE) of 56 feet. This distance was obtained from a calculation based on the cube-root scale-up of the PRE-DIRECT COURSE calculated value (1300 psi) to the DIRECT COURSE explosive weight. The resulting angle of approximately 35 degrees between the vertical and the line-of-sight between the COE to the test specimen was representative of the configuration in the potential launch pad accident.

The test specimen was mounted on a short section of truss structure with its longitudinal axis vertical representative of the Galileo spacecraft. The truss structure for the test specimen was mounted to the top of the tower and was instrumented with pressure transducers and time of arrival detectors to measure the overpressure and velocity. High-speed motion picture cameras were used to attempt to detect the early motion of the test specimen and to detect its exit from the fireball, should that occur.

1.6 PROGRAM SCHEDULE

The schedule for design, fabrication, test and field installation is shown in Figure 1.

SECTION 2

DESIGN

2.1 TEST SPECIMEN

The test specimen shown in Figure 2 was a simulated Radioisotope Thermoelectric Generator (RTG) containing a simulated General Purpose Heat Source (GPHS), a special design heater assembly and appropriate interior hardware and insulation. The simulated RTG was fabricated by modifying the existing Component Engineering Test Unit (CET-1).

The outer shell was approximately 48 inches long and 12 inches in diameter, consisting of a transition section (spool piece) bolted to the RTG converter shell with end closures together with seals in between. The case was a hollow cylinder with a wall thickness of about 1/8" and 8 stub fins equally spaced and running nearly the whole length. The surface for mounting the simulated RTG to the tower was at the inboard end of the case.

The spool piece, about 4" long, was bolted to the inboard end of the case and contained the two power and one instrumentation connectors. All other holes for connectors were plugged and sealed. The power and instrumentation connectors were Gulton "high reliability" hermetically sealed type. Each power connector had a single Inconel X-750 pin, size '0' (.375 dia.). The instrumentation connector had Hoskins 203 and Hoskins 225 pins (.040 dia.) which are compatible with the Tungsten-3% Rhenium vs. Tungsten-25% Rhenium thermocouples.

Bolted to each end of the case/spoolpiece assembly were ellipsoidal caps. The inboard cap contained a penetration and shut off valve for use in pressurizing the evacuating the internal chamber.

The internal structure of the RTG mock-up included the inboard and outboard supports for securing and preloading the simulated GPHS modules. Three layers of 1/4" thick repractory fiber felt insulation and a .010 inch thick molybdenum sheet lined the inside circumference of the case and both ends. Eight pounds per cubic foot density Cerafelt* insulation was air and vacuum baked at 900°C before installation to remove the phenolic binder and water vapor. Four unicouples, thermoelectric devices used in the design of the RTG, were installed through the case 90° apart at the center of the simulated isotope heat source. The 18 GPHS modules normally used in the flight design RTG's were replaced with five solid (POCO) graphite blocks each representing three GPHS modules and the electric heater and GPHS test module representing three GPHS modules.

2.2 TEST MODULE AND HEATER ASSEMBLY

Installation of the test module and heater assembly are shown in Figure 3. The Electric Heater Assembly was designed to utilize two GPHS Fine Weave

---

* Trademark of Johns-Manville Corporation

Pierced Fabric[**] graphite shells (aeroshells) as the housings. The test GPHS was installed between the two heater housings and was secured by graphite buttons in the lateral direction and by a preload in the longitudinal direction. High density (24 pounds per cubic foot) Cerafelt refractory fiber insulation surrounded the heaters on all sides except for the heater surface adjacent to the GPHS test module. A graphite spacer was used between the heater housings and graphite blocks. Tungsten-Rhenium (3% vs. 25%) thermocouples were located as shown in Figure 3. T/C-1 & T/C-2 were the primary thermocouples and were pressed against the iridium clad on the simulated fuel assembly. The secondary thermocouples (T/C-3 thru T/C-6) were located inside the insulation envelope and were intended as a back-up to the primary thermocouples. During assembly, thermocouples were installed against the iridium clads and the wires routed through the graphite shell.

The GPHS shown in Figures 4 and 5 was assembled at the Mound Plant in Miamisburg, Ohio. All of the GPHS parts were prime flight hardware except the fueled clad assemblies. A radioactive tracer was used in the iridium clads in the GPHS test module in order to facilitate locating the clads after the DIRECT COURSE event. The four capsules (IRG-91, 92, 93 and 94) with depleted UO_2 fuel simulant were irradiated in the Los Alamos Omega West Reactor within a neutron flux sufficient to produce an Iridium-192 gamma level of 20 mr/hr for each module at 10 cm. This level was chosen so that the radioactive decay would reduce the level to 10 mr/hr at 10 cm by the time of the DIRECT COURSE event, which was scheduled for mid September. The event did not occur until October 26, and the radioactive level for each capsule was calculated to be about 7 mr/hr at 10 cm.

The special design heater assembly shown on Figure 6 used four 3/8" dia. silicon carbide rods as resistance heating elements. The special order rods were 5 1/2" long with a 3 inch effective heating length. Two rods were installed in each of the two housings with alumina bushings used to isolate them electrically from the graphite housing. As shown in Figure 7, the heating elements were electrically connected in parallel within each housing and in series between housings. Electrical power leads between heaters and the power connectors in the spool piece were .147 inch dia. tungsten rod insulated with alumina sleeving. A stranded copper cable assembly was used for flexibility between the tungsten rod and the pin on the power connector. The attachment of the power leads to the heaters was through a molybdenum clamp as shown in Figure 6.

An estimate indicated that 500 watts of electrical power would be required for the heating elements to raise and maintain the temperature on the iridium clad fuel assemblies at 1075°C + 25°C. With a design factor of two being used to account for circuit variables and the simplified estimate, the electric heaters were sized at 1000 watts. The resistance of each heating element was measured and matched at assembly to obtain a resistance of .4 to .5 ohms for the elements in parallel and .8 to 1.0 ohms for the two sets of elements in series. The final installed heating element and power leads measured .90 ohms

---

[**] Trademark of Avco Corporation

at room temperature. The resistance decreased to an estimated .56 ohms at the 2300^{o}C operating temperature. Measurements were not made at temperature.

2.3 TOWER AND STRUCTURE ASSEMBLY

The structure assembly shown in Figure 8 supported the simulated RTG in a vertical position representative of the configuration in a potential launch pad accident. The test module location, as shown in Figure 9, was 32'-6" horizontally from the centerline of the ANFO tower and 120'-6" above the ground (REF. ELEV. 0'-0") which was 45'-6" below the COE. The resultant radial distance was 56 ft. at an angle of 35.5 degrees from the vertical which was intended to place the test module in the 1300 psi static overpressure range.

Figures 10 thru 12 show the support assembly and mounted components and figures 13 thru 16 show the tower being erected and its location with respect to the ANFO sphere.

The structure assembly was a bolted assembly of shortened tower sections, base plates and steel plates and angles. Braces were used between the tower and structure assembly to add rigidity. Time of arrival detectors, pressure transducers and 2-wire transmitters for thermocouples were mounted on the structure.

The structure assembly was bolted to the top of the Rohn 25G, 120 ft. (nominal, 116'-7" actual) tower. The tower was fabricated by bolting together 11 standard and 1 special 10 ft. sections; each section consisted of a 12 1/2" equilateral triangular cross section with continuous steel zig-zag cross brazing between extra heavy duty 1 1/2" steel tube side rails. The special section had double cross bracing and was used at the top where the upper structure assembly for the test article was bolted. The bottom section of tower was used to mount a control board where switch/fuse boxes, terminal boards and a mercury contactor switch were mounted. The tower assembly was rated for 85 MPH winds.

The following cables and tubes ran between the components at the top of the tower and the bottom of the tower and were strapped to the legs.

2	Heater Power Cables
4	Pressure Transducer Cables
3	Time of Arrival Detector Cables
1	8 Pair Thermocouple Cable
1	1/4" Argon Tube

The tower foundation was a 2 x 2 x 4 ft. pre-cast reinforced concrete block. A pier pin cast in the center of the foundation located the tower base plate. The top of the tower foundation was set even with the top of the ANFO tower foundation (REF ELEV 0'-0").

The tower was guyed in 3 directions (120^{o} apart) at 4 levels shown in Figure 9. Guys were anchored at three equally spaced anchor points 120 ft. from the tower. The location of the guy wire anchors were not oriented as requested, and an adjustment between the tower and structure assembly was required to rotate the simulated RTG and the time of arrival and pressure instrumentation to the correct orientation. Phillystran[*] guy cables which melt at about 700^{o}C were used at the request of DNA to eliminate the possibility of steel cables whipping around and interfering with other experiments. Phillystrain is fabricated from continuous filiment strands of Kevlar. The cables are cut to length, and the end fittings are epoxied in place by the manufacturer.

The tower, structure assembly, instrumentation and cables were assembled on the ground, and then the tower was erected and guyed in place. Continuity checks of all cables were made before and after the tower was erected.

2.4 ELECTRICAL POWER

The system for providing electrical power to the heater is shown schematically in Figure 17. Two sources of power, a generator and a battery, were required. Until 60 minutes before scheduled detonation, a military field generator (provided by DNA) and a DC power supply were used for powering the heaters. At T-60 minutes, the generator and power supply were removed and the power was switched over to battery. Number 2 copper cable was used for all power wiring between the generator, DC power supply, battery and power connectors on the simulated RTG.

The generator output was 208 VAC. to the Hewlitt Packard (HP6269B) DC power supply which had output ranges of 0-40 volts and 0-50 amps. The heat-up rate was controlled by varying the output voltage of the power supply. A manual switch in the fuse box between the power supply and RTG mock-up was opened when the generator was not in use.

The battery assembly used nine (9) heavy duty automotive batteries (120 amp hours) arranged in three (3) parallel strings of three (3) batteries in series. Battery output was rated at 36 volts and 360 ampere hours. When operating on batteries, the heat up rate was controlled by opening and closing the mercury contactor switch (Durakool #CFC2-733) by means of the remote manual control switch in the data van. When not operating on batteries, the switch on the fuse box was opened.

Figures 18 and 19 show the battery assembly on a pallet near the bottom of the tower, the two fuse boxes, and the mercury contactor switch mounted on the tower. The DC power supply was on the ground near the bottom of the tower and the generator was about 50 feet away.

2.5 INSTRUMENTATION

Two primary thermocouples were installed in contact with the iridium clad in the test module, and four back-up thermocouples were installed inside the insulation against the graphite housings of the heater assemblies as shown in Figure 3. The thermocouples were used to monitor the iridium temperature

---

[*] Trademark of Philadelphia Resins Corp.

during heat-up. Tungsten - 3% Rhenium (W3Re) vs. Tungsten - 25% Rhenium (W25Re) thermocouples were used to accommodate the 1100°C operating temperature range. The thermocouples were wired directly to the pins of the instrumentation connector in the spool piece using spring grip type sockets. In the high temperature region, alumina sleeves insulated the leads. Hoskins 203 sockets and connector pins were used with W3Re positive (+) thermocouple leads and Hoskins 225 sockets and pins with W25Re negative (-) leads.

On the outside of the simulated RTG, Hoskins 203 and 225 extension wire was connected to the pins on the instrumentation connector with spring grip type sockets. Each pair of six (6) feet long extension wires was connected to a two-wire transmitter mounted on the structure assembly. Figure 20 is a diagram of the circuitry for the thermocouple instrumentation system. The two-wire transmitters (Transpak TP620) was a special design for use with W3Re/W25Re thermocouples. The input to the two-wire transmitter was the 0-20 millivolt signal from the thermocouples at 0 to 1500°C, and the output was a 4 to 20 milliamp signal for transmission over the copper wires to the read-out equipment in the data van over a mile away. A 40VDC power supply in the data van was used to provide the small current required to power the two wire transmitters. The 115 VAC power for the DC power supply was available in the data van.

A twisted pair of #16 wire connected each transmitter to the terminal board mounted at the bottom of the tower. Two MC-12 cables containing four twisted #22 wires were laid underground to a junction box about 1000 ft. from the tower. From the junction box to the data van, 6500 ft. from the tower, a 20 pair cable was laid on top of the ground. Through these cables, the signals for four thermocouples were transmitted to the selector switch and readout equipment in the data van. The wiring through the selector switch circuit allowed only the transmitter being read to be powered. Earlier testing indicated a distortion in the transmitted signal if the transmitters were not isolated.

The system design provided that the signal for all six thermocouples would go through the transmitters and to the terminal board at the bottom of the tower. Four signals would be transmitted to the data van and the other two would be spares which could be used by changing the wires at the terminal board. Only the two thermocouples installed against the clad would be monitored as the primary thermocouples and the other two would be used as back-ups if the primary thermocouples became inoperable.

The milliamp signals from the thermocouple/transmitter were read out visually on the fluke (Model 8022B Digital Multimeter) milliamp meter and manually converted to temperature (°C) during the tests and heat-up.

The Time of Arrival Detection System (TOADS) was used previously on a similar test and at other locations on this test. The system was provided and installed by the Air Force Weapons Laboratory (AFWL), Kirtland Air Force Base, NM. The system shown in Figure 21 is based on a stop watch principle in that the piezo-electric crystals provide stop signals to the counter unit started at time zero. The counter stores the elapsed time information for each channel until the data is read out. The total system error, estimated to be about ± 0.3 microseconds or less is small compared to the practical uncertainties in the placement of the crystals. The three crystals were epoxied one foot apart in separate one-inch diameter PVC pipes mounted on the structure assembly; see Figures 8, 11, & 12.

2.6 PRESSURE TRANSDUCERS

The pressure pulse measurements were conducted by the U.S. Army Ballistic Research Laboratory (BRL). The system employed was previously used on similar tests and at other locations on this test. Pressure transducers mounted in the cylinder on top of the structure assembly (Figure 10) were used to measure the time-pressure history at the test module. The cylinder was oriented with the cylindrical surface facing the center of explosion (COE) and at an equal distance from the COE as the test module. Two Kulite Model HKS-375, 10000 psi range, transducers were installed in the cylinder pointed at the COE to measured stagnation pressure. Two Kulite Model HKS-375, 5000 psi range, transducers were installed in the cylinder at 90° to the direction of COE to measured incident (static) pressure. The Kulite transducers have a four-arm wheatstone bridge configuration with four active arms and a silicon diaphram with an integrated bridge circuit. Each transducer was connected to the recording equipment using 4-conductor shielded cable (MC-12) buried between the tower and the junction box, 1000 ft. from the tower, and using 2 pairs of the 20 pair cable laid on top of the ground from the junction box to the data van. The recording equipment was supplied from the FCDNA equipment inventory and configured by the DNA Field Support Contractor, Bendix Field Engineering, Las Vegas, NV. The equipment was housed in an instrumentation trailer located 6500 ft. from ground zero.

The data acquisition and recording system consisted of transducers, interconnecting cable, strain gage signal conditioning equipment, instrumentation amplifiers, and magnetic tape recorders. A block diagram of the data acquisition system is shown in Figure 22. B & F model 1-700 signal conditioning equipment provided the gage excitation, bridge balancing, and shunt calibration functions. Baylab Model 5503 and Dynamics Model 7525 high-gain differential amplifiers provided amplification of the transducer output signal to the input level required by the magnetic tape recorders.

During the event, the recording was operated remotely using timing signals provided via hardwire from the DNA timing and firing (T & F) trailer. Recorder operations and the instrumentation trailer status were monitored by the T & F trailer. Even though the instrumentation was controlled remotely from and monitored by the T & F trailer, project personnel manned the trailer during the event to provide back-up monitoring and to correct any malfunctions that occurred.

2.7 PHOTOGRAPHIC COVERAGE

High speed photographic coverage was provided by the White Sands Missile Range. Figures 23 and 24 show the locations of the cameras with respect to ground zero and the RTG test article and the areas of interest on which the cameras were focused. Table 1 presents other information on the cameras and film used. Cameras C1, C2 and C3 were focused on the area immediately around

TABLE 1

Camera Description and Location

Camera Number	Type	Format	Lens Size	Film Type	Frame Rate	On/Off Time-Sec	Azimuth From GZ	Distance Feet
C1	Hycam	16 MM	20"	B&W 2496	5K	-1.7 to +3	81° 48'	1430.14
C2	Hycam	16 MM	20"	B&W 2496	5K	-1.7 to +3	135° 00'	1500
C3	Hycam	16 MM	20"	B&W 2496	5K	-1.7 to +3	228° 53'	2227.05
C4	4C	35 MM	250 MM	Color (IR)	2K	-5 to +4.6	81° 00'	1430
C5	4C	35 MM	250 MM	Color (IR)	2K	-5 to +4.6	134° 00'	1575
C6	4C	35 MM	360 MM	Color (IR)	2K	-5 to +4.6	228° 30'	2227

the RTG test article on its tower for the purpose of recording the early motion or interaction with the shock front. Cameras C4, C5 and C6 were focused on an area just outside and adjacent to the anticipated extent of the fireball. The intent of looking at this area was to detect the motion of the RTG or its remains possibly exiting the fireball.

2.8 SIMULATOR

A simulator was fabricated for use in the checkouts to minimize transportation of and exposure to the radioactive simulated RTG. The simulator was a one foot square aluminum box with two sides extended to form legs. The inside wall was lined with baked out refractory fiber insulation (J-M Cerafelt). A POCO graphite block with heater rods and thermocouples constituted the heater assembly. The simulator was designed to draw electrical power for the heaters and generate a thermocouple output similar to the simulated RTG. The operation of the simulator was in the range below 300°C and did not require sealing or an inert atmosphere.

SECTION 3

ASSEMBLY AND TEST

3.1 HEATER

The special design heater was subassembled and tested at General Electric, King of Prussia, PA. The two heater housings were assembled with an instrumented (i.e., with thermocouples) empty aeroshell in between. The assembly was wrapped with insulation similar to that shown in Figure 3 and tested in a bell jar which was evacuated and backfilled with dry argon to 15-16 psia. Four (4) times each at temperature levels of 300, 500, 700, 900 and 1100°C, the bell jar was evacuated and backfilled with dry argon to remove water vapor which was absorbed by the insulation during assembly and released as the temperature increased.

Power to the heating elements was controlled by the output of the DC power supply. The power requirements were recorded at the above temperature increments. The power required to stabilize the temperature at 1100°C was 28 VDC and 33 amps or 924 watts. The assembly was cooled and was retested with similar results.

3.2 THERMOCOUPLES

The temperature measuring system was assembled and tested to calibrate the two-wire transmitters and to develop the conversion from current output to temperature. The test was assembled as shown schematically in Figure 25.

For each two-wire transmitter, the calibration was performed by adjusting the output of the millivolt generator until the desired temperature was attained on the digital thermometer. The test was repeated at temperatures of 300°C, 500°C, 700°C, 900°C and 1100°C. The test data, shown in Table 2, was plotted on a temperature versus signal current graph. The equations for the linear curves were calculated to be:

For transmitters 1, 3, 4 and 5
Degrees centigrade = 86.96 x milliamps - 260

For transmitter 2
Degrees centigrade = 87.91 x milliamps - 375

For transmitter 6
Degrees centigrade = 87.91 x milliamps - 340

These relationships were used during the heat-up to convert the signal output readings to temperature (°C)

3.3 ASSEMBLY

The simulated RTG was assembled at General Electric in a humidity controlled room to minimize absorption of water vapor in the insulation. The instrumented aeroshell was used for this operation instead of the simulated

TABLE 2 - THERMOCOUPLE TRANSMITTER CALIBRATION DATA

TEMPERATURE (°C) (METER 2160/AC)	MILLIVOLT OUTPUT (MVS-A)	MILLIAMPS (METER 8022B) TRANSMITTER					
		1	2	3	4	5	6
300	4.0	6.4	7.4	6.5	6.5	6.5	7.8
500	7.8	8.6	9.6	8.7	8.7	8.7	9.9
700	11.85	10.9	11.9	11.0	11.0	11.0	12.3
900	15.9	13.3	14.2	13.3	13.3	13.4	14.6
1100	19.9	15.6	16.5	15.7	15.7	15.5	16.9

heat source. The shell was evacuated and backfilled with dry argon and pressure decay tested before starting the heat-up for the system test. The pressure drop was 1.5 psi in 65 hours.

The system test consisted of heating and monitoring the instrumented module using the electric power and thermocouple systems. Evacuations and dry argon backfills were used at several temperature increments to remove water vapor and oxygen which was being released by the insulation at increasing temperatures. All systems operated properly, but the module temperature could not be raised above 800°C; the corresponding power input to the heaters was 40 volts and 34 amps (1360 watts).

The heater was then disassembled, a broken heater rod was replaced, and graphite cloth used between the heater rods and clamps was removed. During the system test, the resistance between the power leads and the case was found to be low, and after disassembly, graphite fibers were found shorting the power leads to the heater housing. Also, the spacers between the heater housings and the dummy graphite blocks were re-machined to reduce the contact surface (i.e., heat transfer area). Astroquartz cloth insulation was installed between the heater housings and the spacers also to reduce heat loss.

The simulated RTG was shipped to the Mound Plant in Miamisburg, Ohio, where the GPHS test module was installed. After assembly, the heater and thermocouple operation was checked by raising the assembly to 1100°C. Evacuations and argon backfills were again used to remove water vapor that was absorbed by the insulation during assembly. The power required to maintain steady state temperature at 1100°C was 32 volts and 38 amps (1216 watts). All thermocouples indicated temperatures within 10°C of each other.

SECTION 4

HANDLING AND STORAGE

The simulated RTG was shipped from General Electric, King of Prussia, PA, to the Mound Plant, Miamisburg, OH, to White Sands Missile Range (WSMR), New Mexico by exclusive use truck in a wooden crate. When it was shipped from the Mound Plant, the simulated RTG was pressurized to 10 psig, sealed in a plastic bag, and supported on packing material for shock mounting in the crate. An oversized crate was used to provide the spacing needed to reduce the radiation level at the surface of the crate. During storage at WSMR from August to October (arising from a delay of the DIRECT COURSE event), a dry argon bottle was connected to the valve assembly on the cap, and a 10 psi overpressure was maintained to prevent seepage of oxygen into the shell.

SECTION 5

INSTALLATION AND CHECK OUT

5.1 THERMOCOUPLE SYSTEM

The two wire transmitters were wired to the terminal board at the tower base using the 130 feet long 8 pair cable that would run the length of the tower after tower erection. Using the data developed in the transmitter calibration test, Section 3, voltage signals were input to the six transmitters with the millivolt generator, and the current was read out on the Fluke multimeter in the data van. The results for all six transmitters duplicated the data of the calibration tests.

5.2 ELECTRICAL POWER SYSTEM

The electrical power system was installed as shown schematically in Figure 17. The batteries were arranged on a pallet as shown in Figures 18 and 19 and electrically connected in parallel and series using standard automotive battery cables. The positive and negative cables were connected to the bottom side of the fuse/switch box on the panel with #2 stranded copper cables. The top of the fuse/switch box had been pre-wired to the mercury contactor. After the control wire for the mercury contactor was connected to the terminal board, the resistance in the circuit between the contactor and the switch in the data van measured about 200 ohms. For the contactor to operate properly, the line resistance needed to be about 20 ohms. The higher resistance was a result of the 22 gauge wire being provided instead of the 12 gauge expected. The resistance was reduced to 19 ohms by connecting several wires in parallel. Two 130 feet lengths of #2 stranded copper cable connected to the mercury contactor were strung over the length of the tower to connect to the RTG test article.

The field generator was located about 50 ft. from the base of the tower. Copper stranded cables (#2) carried the 208 VAC to the DC power supply, the power from the DC power supply to the second fuse/switch box on the panel, and from the top of the fuse/switch box to the mercury contactor.

5.3 SYSTEM CHECK-OUT

The electrical simulator was used for system checkout. The two 130 ft. long power leads were connected to the heater power leads on the simulator, and four thermocouples in the heater housing inside the simulator were connected to four two-wire transmitters. The generator operation was checked first. After the generator was started, the switch for generator power on the panel was closed and the power to the simulator was controlled by the output of the DC power supply. The temperature increase was monitored at the read-out station in the data van. The generator/DC power supply input was shut off by turning down the DC power supply, opening the switch on the fuse box and shutting off the field generator. Next the battery operation was checked. The switch for battery operation on the panel was closed. The power to the simulator was controlled by opening and closing the mercury contactor with the remote manual switch in the data van. Each time the switch was operated, the voltage across the discharge side of the mercury contactor was checked to verify proper operation. Again, the temperature was monitored at the read-out station in the data van. The maximum temperature in the heater assembly during the system check out was 300°C. The power was shut off by opening the switch on the fuse box on the panel. All functions of the electric power and thermocouple systems operated properly.

5.4 PRESSURE TRANSDUCERS AND TOAD

The four pressure transducers were installed in the cylinder and calibrated by BRL. The calibration was accomplished by statically applying the peak expected pressure to the transducer and recording the resultant signal with the tape recorder. This static pressure was applied by carefully regulating a high-pressure dry-nitrogen source to the transducer and monitoring the applied pressure with a precision dial manometer. The dial manometers were compared pre- and posttest with a standard (dead weight tester) traceable to the National Bureau of Standards to ensure calibration accuracy.

Amplifier and recorder gains were adjusted using the statically applied load to yield a predetermined FM carrier deviation. At this time, a shunt resistor was selected and inserted into the signal conditioner to establish a shunt calibration level approximately equal to the forcing function level. Both the shunt calibration level and the forcing function level were recorded on magnetic tape, and this magnetic tape was retained as the calibration standard for use in the data reduction process. The shunt calibration level was also recorded on the test data tape immediately prior to the event (T-1 minute). No gain or shunt resistance adjustments were permitted between the static calibration and the event without complete recalibration of the entire data channel.

The three time of arrival detectors were installed in the tubes on the structure assembly by AFWL and the continuity checked.

5.5 MOTION PICTURES

The motion pictures cameras were provided, installed and operated by The White Sands Missile Range Photographic Section. A crane boom was used to represent the tower during camera check out. Motion pictures were taken and reviewed to check camera angles and resolution.

5.6 TOWER

The tower, structure assembly, simulated RTG and instrumentation were assembled on the ground before the tower was erected. All cables and tubes running from the top to the bottom of the tower were taped to the tower legs. Before tower erection, all cables were continuity checked. Figures 10 thru 16 and Figures 18 and 19 show assembly in various stages.

The tower was erected by New Mexico Engineering Research Institute (NMERI) who designed and erected the ANFO tower. All the cables running down the tower were continuity checked and connected to the proper equipment at the bottom. The 1/4" rubber tube from the open valve on the simulated RTG was connected to the argon bottle. A 10 psig pressure was maintained in the simulated RTG from the time the tower was erected (Sun. 10/23) until the event (Wed. 10/26).

5.7 DRY RUN

On Monday, October 24, a dry run of all experiments was conducted by DNA. The purpose was to integrate the activities of all agencies associated with the experiments. Emphasis was placed on access to the test bed, equipment, vehicle and personnel placement and removal before the event, and access by the recovery team after the event. During the dry run, the test module in the simulated RTG was powered by both the generator and battery system to a maximum temperature of 300°C.

SECTION 6

DIRECT COURSE EVENT

EVENTS ON THE DAY OF THE DIRECT COURSE EVENT, OCTOBER 26, 1983.

0440 HRS	Started heat-up of test module using generator and DC power supply system. Heat up rate curve is shown in Figure 26. Power to heaters was manually controlled at DC power supply and temperature monitored and recorded in data van. Voice power phone set used to communicate between tower and data van.
0840 HRS (T-65 min)	Switched from generator to battery operation. Opened switch on fuse box, removed DC power supply, argon bottle and field generator from area. The temperature was monitored and recorded in the data van. Use of the manual switch to control the battery power circuit was not required. The maximum temperature reached was 1109°C.
1204 HRS (T-2 min)	Shut off power to heaters to preclude interferring with instrumentation signals. Temperature was 1097.2°C.
1205 HRS (T-1 min)	Shut off instrumentation system power to preclude interferring with other instrumentation signals. Temperature was 1075.4°C.
1206 HRS (T-0)	EVENT, detonation of 609 tons of ANFO.
1330 HRS (approx.) (T + 124 min)	Recovery team entered area to recover radioactive debris resulting from breakup of the iridium clads from the GPHS test module.

SECTION 7

RESULTS

7.1 PHYSICAL DAMAGE

The physical effects of the overpressure and fireball from the 609 tons of ANFO are shown in Figures 27 through 31. The bottom 35 feet of the tower can be seen. Beyond that only a small, occasional piece was found. Figures 30 and 31 show the Nuclear Emergency Search Team (NEST) from Los Alamos National Laboratory (LANL) recovering the radioactive material.

About 70% of the iridium from the four clads was recovered and is shown in Figure 32. Figure 33 shows the only piece of graphite recovered; this piece came from the GPHS aeroshell and may be from either the GPHS test article or one of the housings for the electric heaters.

Figure 34 shows aluminum fragments recovered from both the RTG housing or shell and the cannister for the pressure transducers. Noted on the figure are those fragments that came from the cannister that housed the pressure transducers.

7.2 TIME-OF-ARRIVAL

The arrival time for the shock wave as measured by the three time-of-arrival gauges was 5152.1, 5248.9 and 5339.5 microseconds, resulting in shock wave velocities of 10,177 and 10,873 feet per second between the gauges after correction for geometry factors. Because of the proximity of the RTG test article to the ANFO charge (i.e., a distance of approximately 38 feet to the surface of the ANFO sphere), the environment surrounding the test article was considered to be too severe and not fully developed to the extent that typical Rankine-Hugoniot relations could be used to derive the equivalent overpressure. This arises because of the complications presented by the detonation products and the effects of the charge container. However, for comparison, the shock wave velocity previously calculated by equivalent Rankine-Hugoniot relations was predicted to be 10,530 feet per second.

7.3 HIGH SPEED PHOTOGRAPHY

High speed photographic coverage of the RTG System Explosion Test in DIRECT COURSE revealed very little useful information. Figure 35 is taken from the film from Camera C1 (see Table 2 and Figures 23 and 24) and shows the first light on the test article from the fireball. Figures 36 through 39 show sequential frames from the same film showing the moment just prior to arrival of and through nearly total engulfment by the fireball. These figures do indicate that the fireball was fairly uniform, without any apparent jetting, at least in the vicinity of the RTG. Also, there are no apparent fragments headed in the general direction of the RTG prior to its engulfment by the fireball. The evidence of fragments within the fireball was obscured visibly by the fireball itself since the fragments and fireball were probably travelling at nearly the same velocity in the vicinity of the RTG test article.

7.4 OVERPRESSURE

Figures 40 through 43 show the curves resulting from the data obtained from the four pressure transducers used in the test, two (2) static pressure gauges and two (2) total pressure gauges. According to BRL, the agency performing the pressure measurements, the total pressure gauges (labeled as Stations PT-1 and PT-2 on the graphs) are believed to have been destroyed by projectiles, such as pieces of the fiberglas shell holding the ANFO explosive, before credible readings could be obtained. Consequently, only noise and ringing are seen on Figure 42 and 43. Note also that the measured impulses are an order of magnitude less than predicted which tends to indicate that the total pressure history (magnitude or duration or both) was not recorded.

The initial pulses occurring on Figures 40 and 41 for static gauges (Stations PS-1 and PS-2) are believed to be representative of the static pressure seen by the RTG test article, at least through the peak of the initial pulse. For Gauge PS-1, the maximum occurs at 2100 psi; the maximum for PS-2 is around 1460 psi. However, there is some question as to whether or not the step in the pulse from PS-1 occurring at 1260 psi might be more indicative of the static pressure seen by this gauge, possibly as a result of motion of the cannister such that this gauge might be seeing more of the stagnation pressure. The large discrepancy between the two gauges approximately four (4) inches apart and at the same radial distance from the ANFO sphere would be hard to explain unless one or both of the transducers were defective. Based on the pre-test calibration of the gauges, this does not appear to be the situation.

7.5 POST TEST ANALYSIS

Los Alamos National Laboratory performed metallographic analysis on some of the fragments from the iridium clads from the GPHS test module. Figures 44 and 45 show one of the pieces identified as #1. An enlarged cross section of a slice through the piece is shown in Figure 46. Note the extreme bending and deformation exhibited by this fragment. Figure 47 shows the crystalline structure in the same cross section.

Another fragment is shown in Figures 48 and 49 identified as #2. Metallographic sections through this fragment are shown in Figures 50 through 53. Note the necking and the extremely elongated grains plus possible fibrous structure exhibited by the section shown in Figure 52. This evidence indicates that extreme working of the clad occurred which had to result from severe impulsive loading such as by impact from another object at very high velocity or by extremely high pressure. Figure 53 shows another section through fragment #2 that exhibits local coining which also substantiates extreme loading of the metal, probably resulting from impact by another object.

Figures 54 and 55 show another iridium fragment identified as #3. Extreme bending and deformation can be seen also in this piece. Metallographic sections are shown in Figures 56 and 57. Figure 56 illustrates the degree of tearing and overall breakup of the metal structure, and Figure 57 shows another instance of coining more severe than that shown in Figure 53 from fragment #2.

Another fragment is shown in Figures 58 and 59 identified as #4. An enlarged cross action is shown in Figure 60 showing again that considerable thinning and deformation occurred. Enlarged metallographic sections are shown in Figures 61 through 63. Coining, grain elongation, and possibly fibrous structure are exhibited in the sections shown in Figures 61 and 62, adding further to the evidence that extreme loading occurred in the metal.

One final fragment identified as #6 is shown in Figure 64. An enlarged cross section is shown in Figure 65. Metallographic enlargements through this section are presented in Figures 66 through 68, showing the extensive cracking, tearing and deformation experienced by this piece.

SECTION 8

CONCLUSIONS

The degree of destruction experienced by the GPHS-RTG test article, and especially by the GPHS module, in DIRECT COURSE is believed to have resulted from the combined environment of the shock wave and impact by high speed fragments. The major portion of the damage probably occurred as a result of impact(s) by the fragments of the fiberglas container for the ANFO explosive, but there is no direct recorded evidence that this occurred; the fireball most probably obscured the presence of fragments since they were probably travelling at nearly the same velocity as the expanding fireball. Indirect evidence that this could have happened has been presented in the form of the metallographic cross sections from several of the iridium fragments from the clads around the radioisotope fuel simulant. These sections indicate considerable working of the previously recrystallized iridium clads. Working occurred to such an extent that some of the metal structure in these sections may possibly have reverted to the fibrous state.

Previous impact testing of the GPHS modules has been performed by Los Alamos to satisfy part of the design requirements. This aspect of the design requires that the cladded isotope fuel containers remain intact and prevent release of the isotropic fuel in the event of an unplanned re-entry from Earth orbit followed by impact on the Earth's surface. For design purposes, the GPHS module must survive when impact occurs at the free fall terminal velocity of the module onto an essentially unyielding surface such as granite. Numerous impact tests of the GPHS modules have been conducted onto a massive steel block in the Los Alamos cannon (a pneumatically propelled, fully enclosed, impact facility) at velocities up to 198 feet/second. Even under these conditions the iridium metal has not exhibited working to any appreciable extent. It should be noted that the potential velocity of the fiberglas fragments from the ANFO container were estimated to be in the 8000-9000 feet/second range at the location of the RTG test article.

Additional testing of the GPHS modules has been conducted by Los Alamos in the small diameter shock tube at Sandia Laboratory - Albuquerque. These explosive tests were conducted to determine the failure threshold for the GPHS clad fuel elements in order to determine their capability to survive an explosion of the Space Shuttle on the launch pad, similarly as was the purpose of the RTG System Explosion Test on DIRECT COURSE. Testing was performed up to a level of 1070 psi static overpressure and a static impulse of 3.75 psi-sec before the tests had to be terminated because of damage to the shock tube. In this final test, all of the graphite components of the GPHS module were stripped away from the iridium clad pellets. Some of this could have resulted from mechanical interaction with the vermiculite material in the catch box used to stop the module as it exited the shock tube. There was no significant damage to the iridium clads, even after one of them had penetrated through the 3/4 inch thick plywood rear wall of the catch box. The corresponding peak reflected overpressure in this test was estimated to be 7500 psi.

In the DIRECT COURSE test of the RTG, the peak reflected overpressure corresponding to the desired static overpressure of 1300 psi at the portion of the RTG test article was estimated to be around 12,150 psi. While these values are higher than those in the shock tube tests on the GPHS module (i.e., 1070 psi static overpressure and 7500 psi reflected overpressure), the DIRECT COURSE shock wave, by itself, was not expected to have caused the degree of damage experienced by the GPHS module. (It should be noted that the actual measured values of the static or free field overpressure in the DIRECT COURSE test were 1460 psi and 2100 psi, with a questionable value from one of the gauges - corresponding to the 2100 psi value - being 1260 psi.)

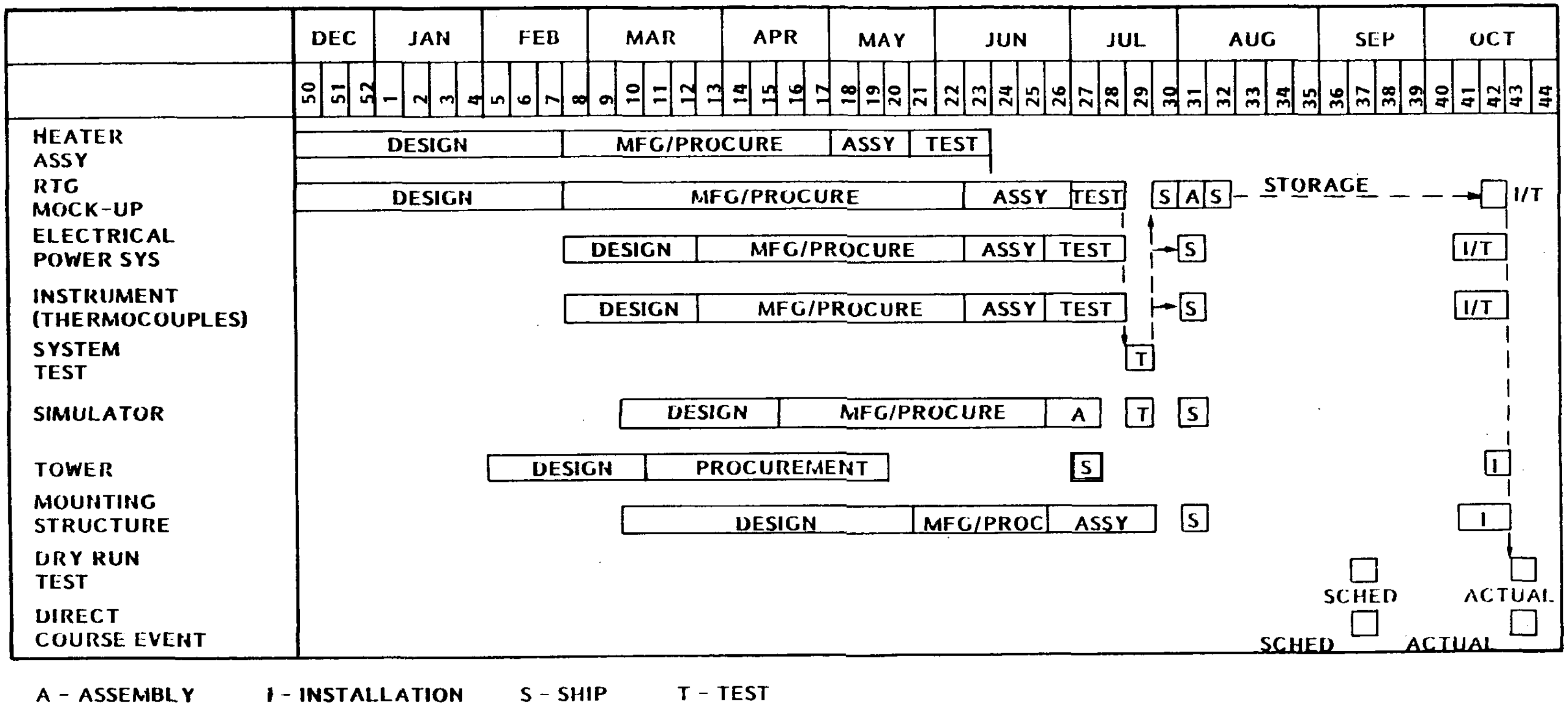


Figure 1. Program Schedule, Direct Course Event

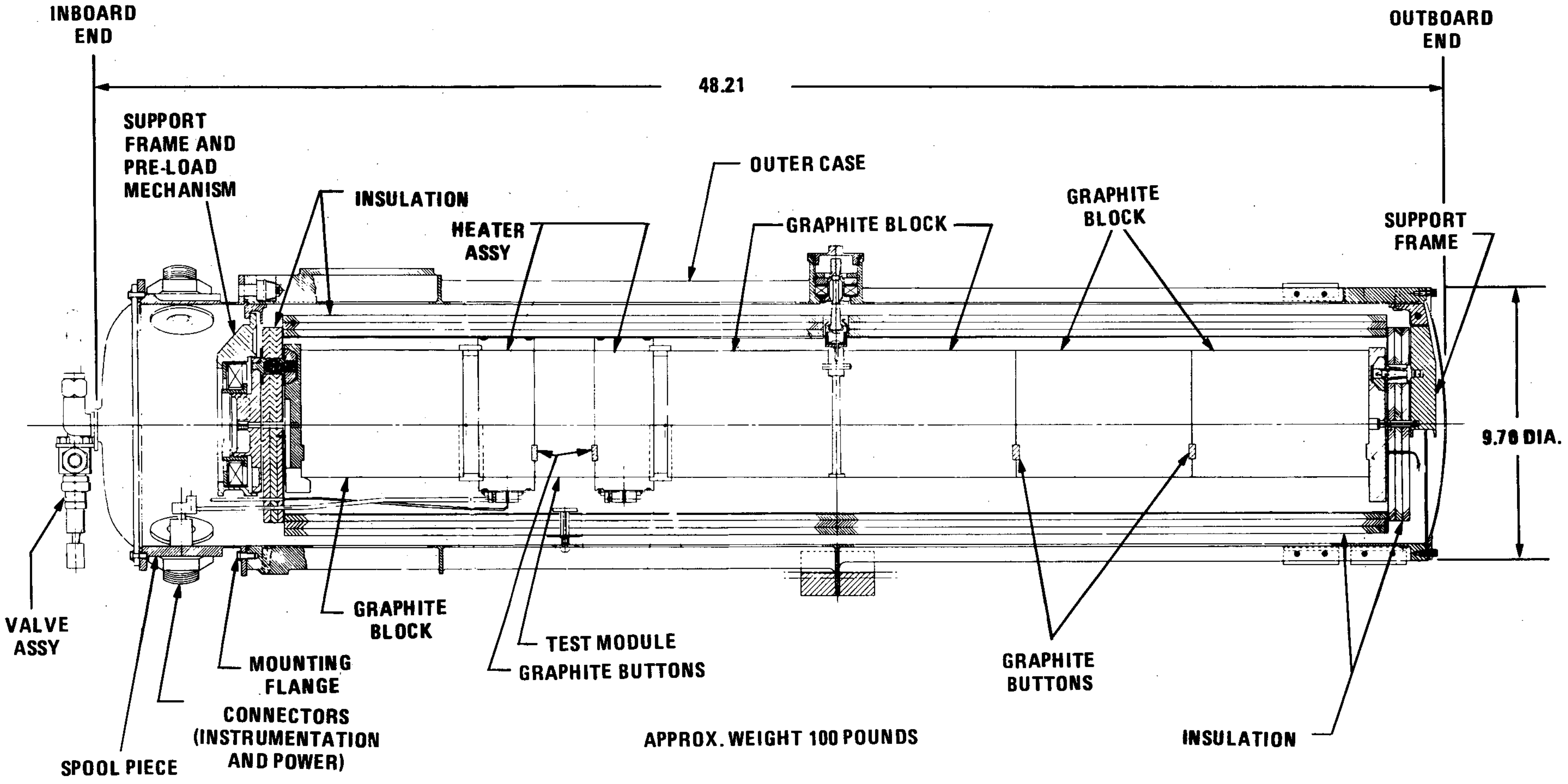


Figure 2. Radioiosotope Thermoelectric Generator (RTG) Mock-up

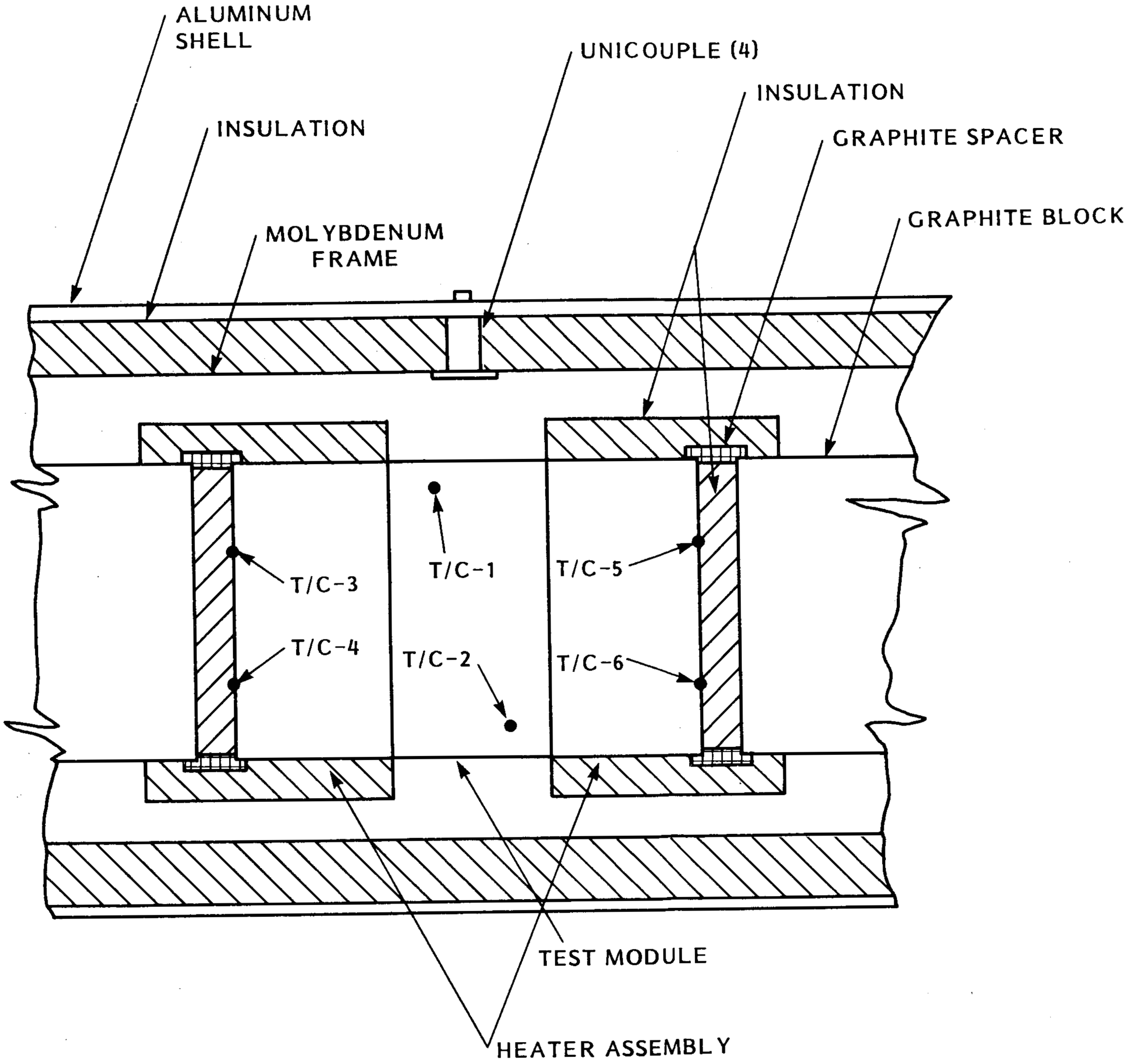


Figure 3. Test Module/Heater Assembly Installation

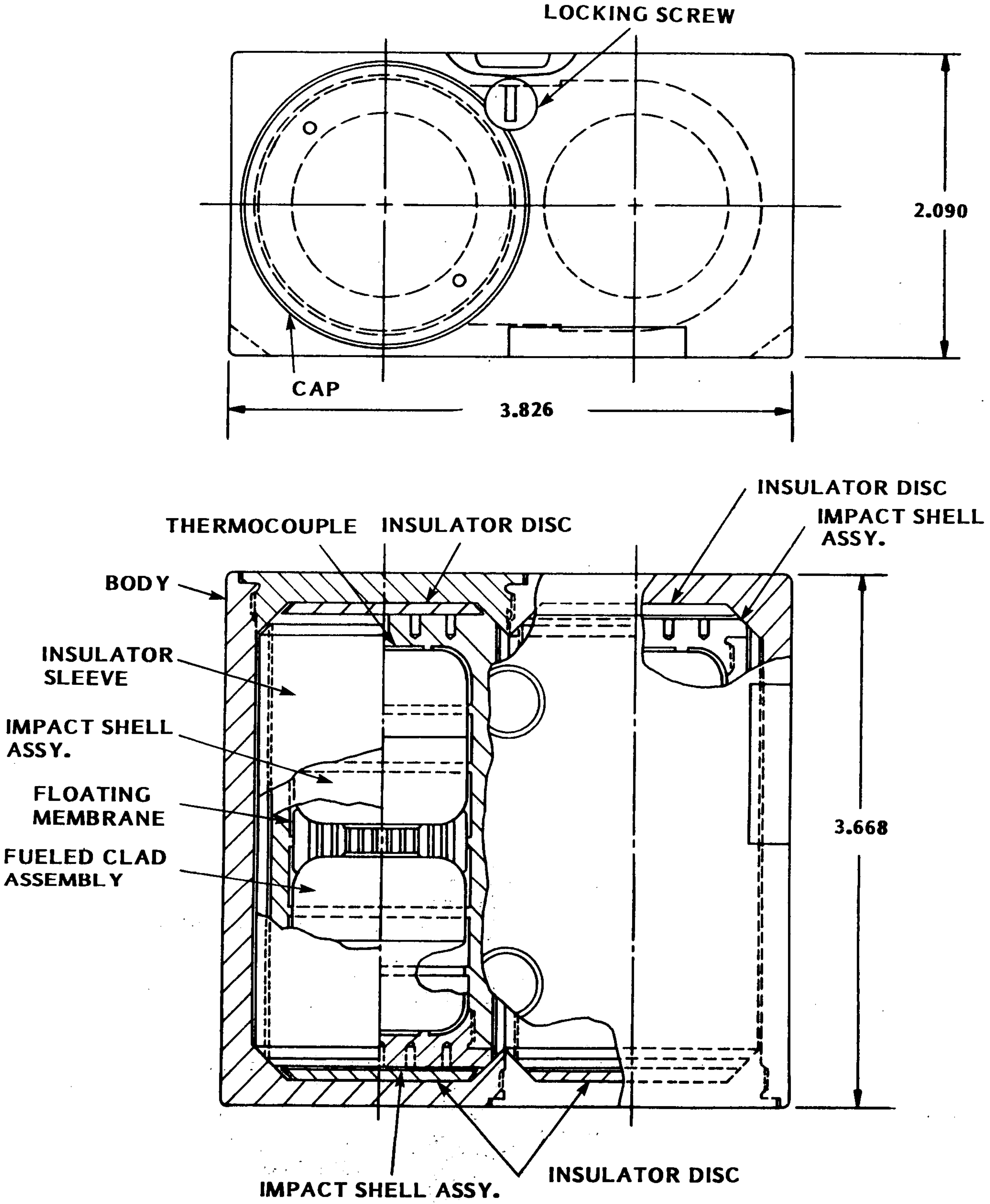


Figure 4. General Purpose Heat Source (GPHS) - Test Module

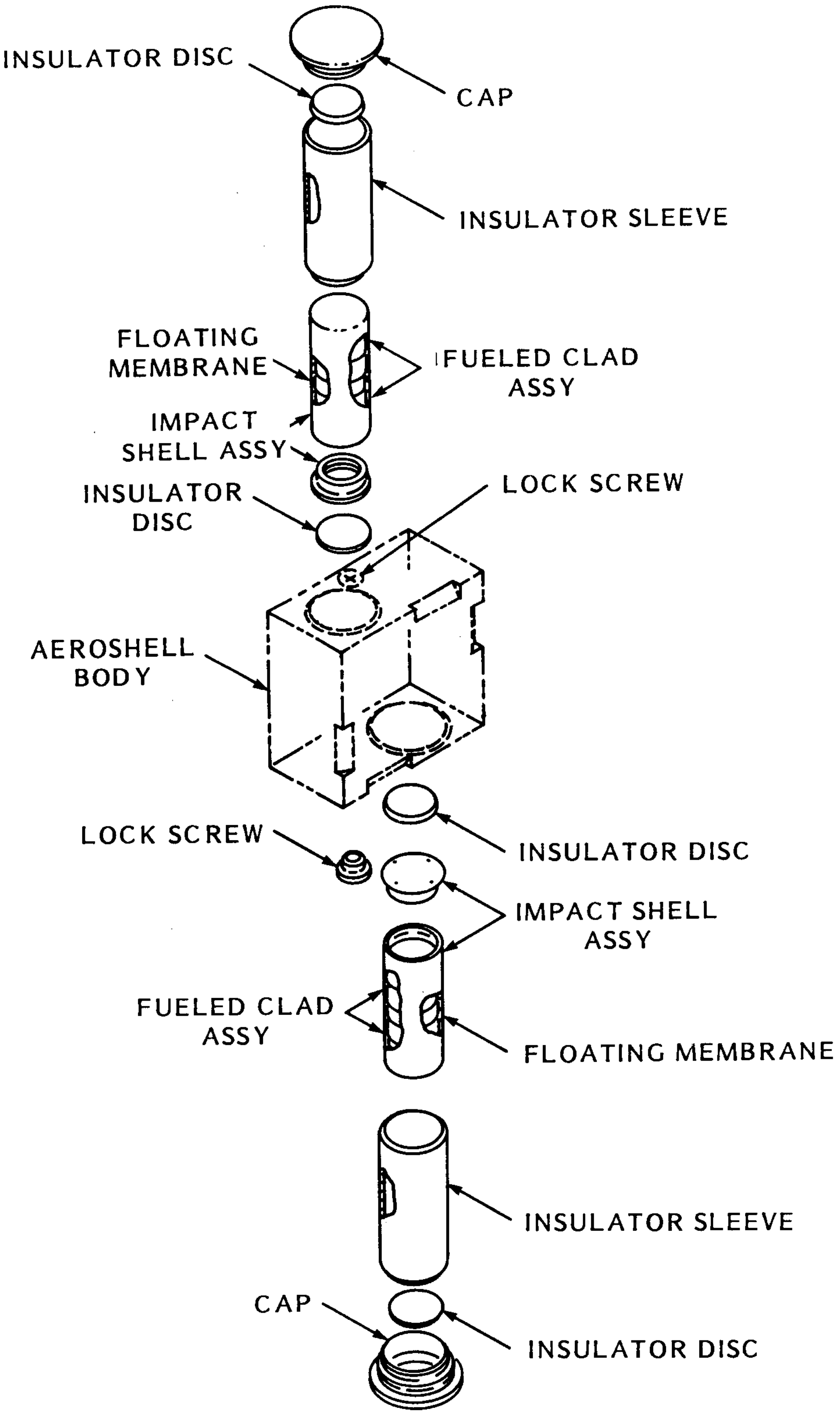


Figure 5. Exploded View of General Purpose Heat Source Test Module

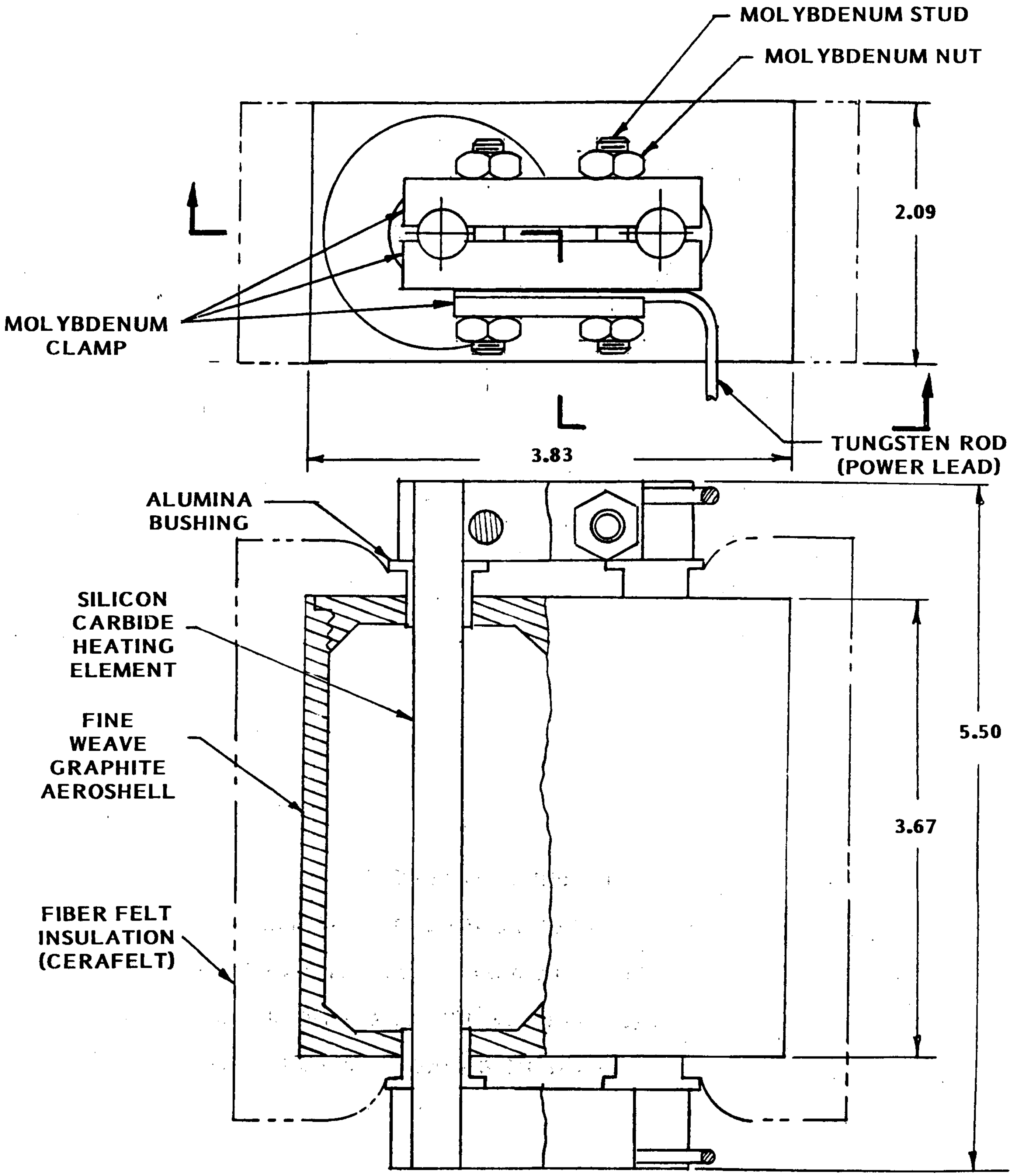
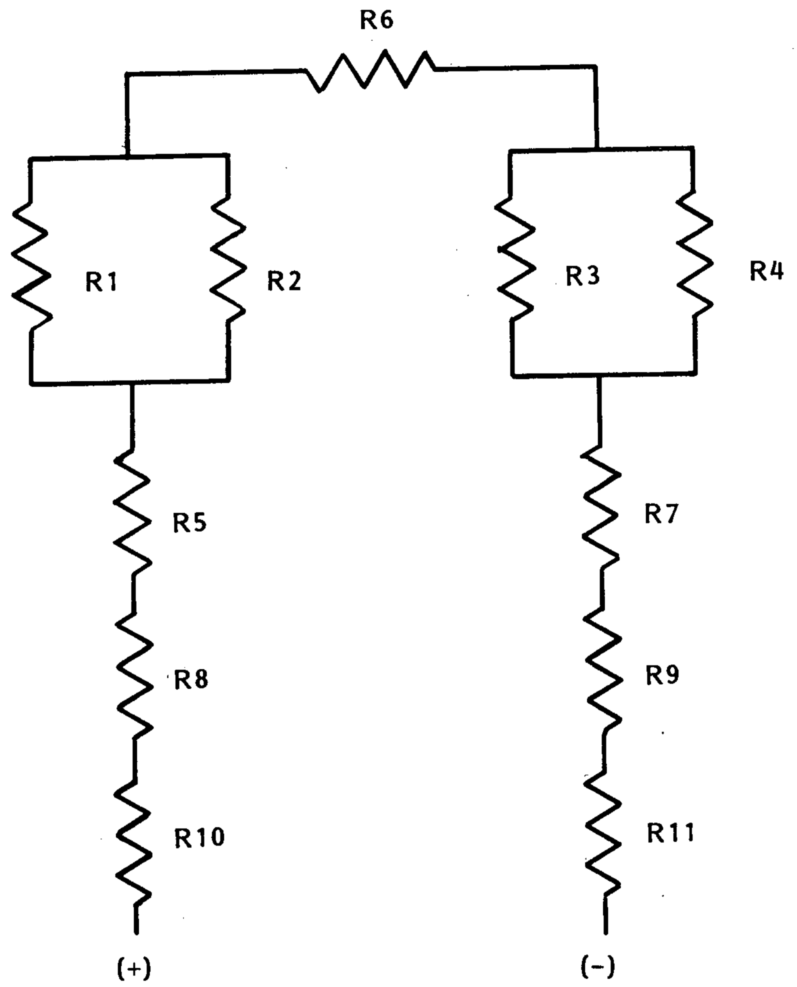


Figure 6. Heater Assembly



R1 - R4 SILICON CARBIDE HEATER ELEMENT (900 MILLIOHMS EACH)

R5 - R7 TUNGSTEN ROD POWER LEADS (2.3 MILLIOHMS (AVG.) EACH)

R8 - R9 COPPER CABLE ASSY. (1.22 MILLIOHMS EACH)

R10 - R11 INCONEL PIN (IN CONNECTOR) (0.96 MILLIOHMS EACH)

TOTAL RESISTANCE = 0.9 ± 0.1 OHMS

Figure 7. Heater Assembly Power Circuit Inside RTG Mock-up

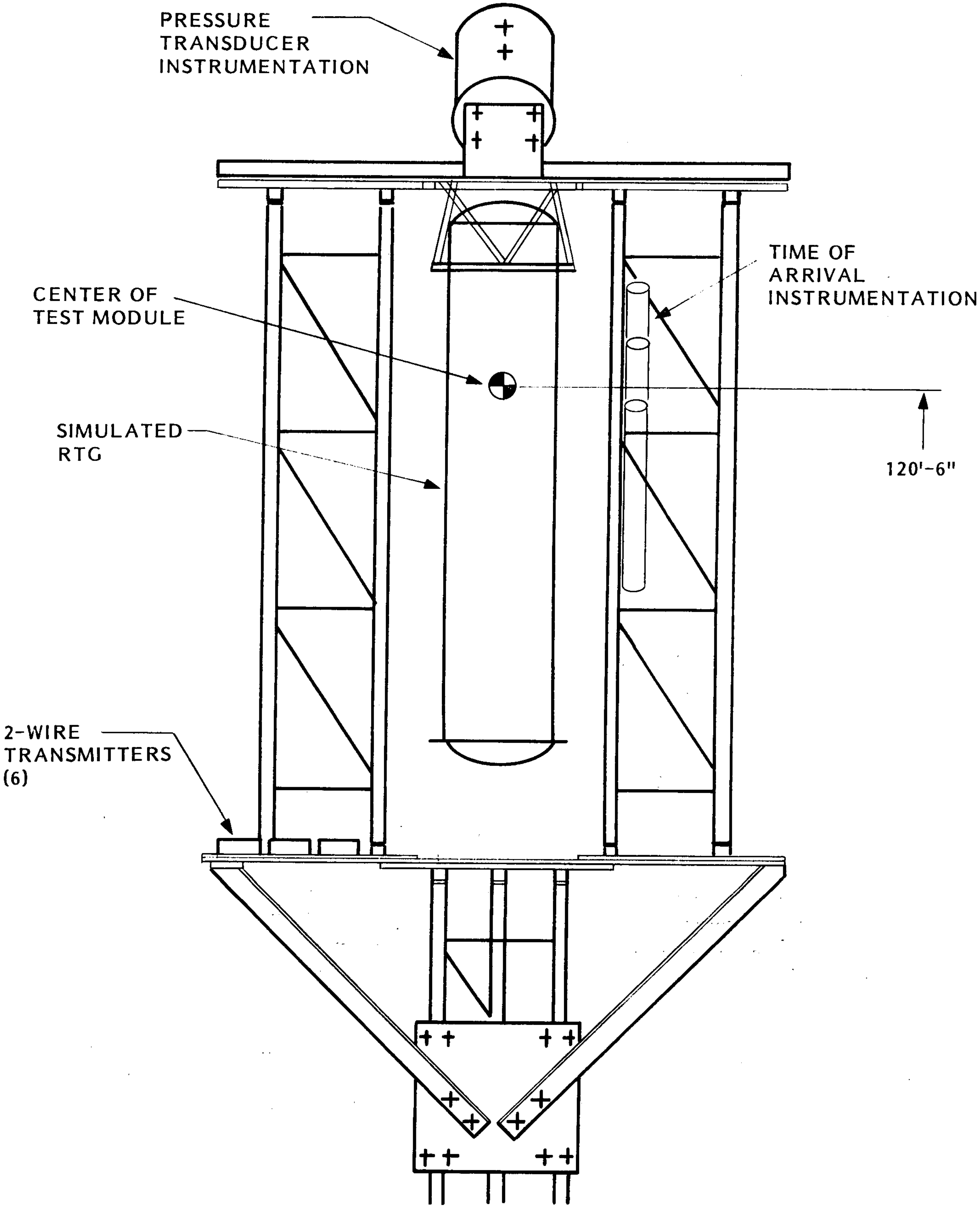


Figure 8. Structure Assembly for Supporting Simulated RTG on Top of Tower

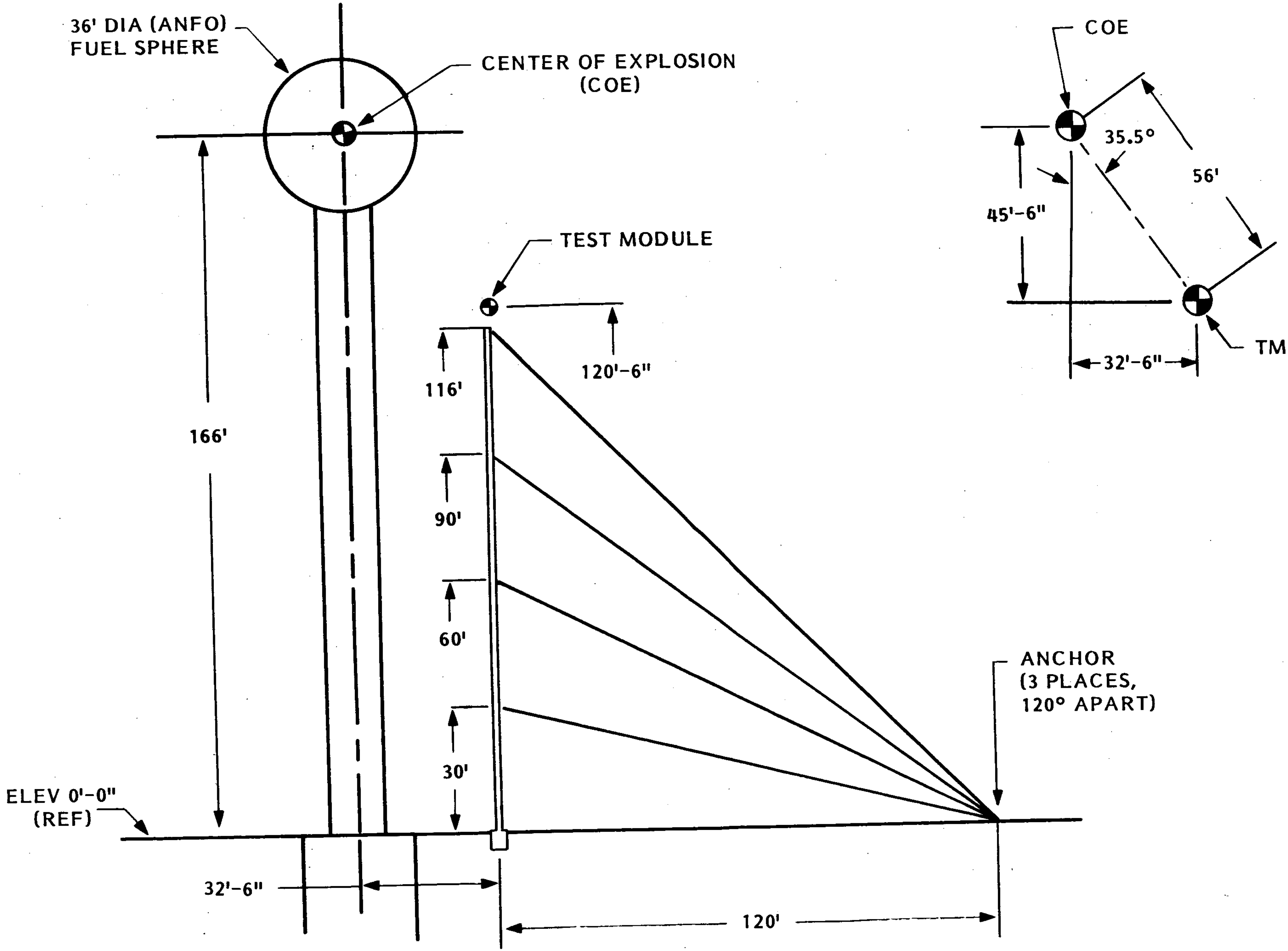


Figure 9. Position of Test Module and COE

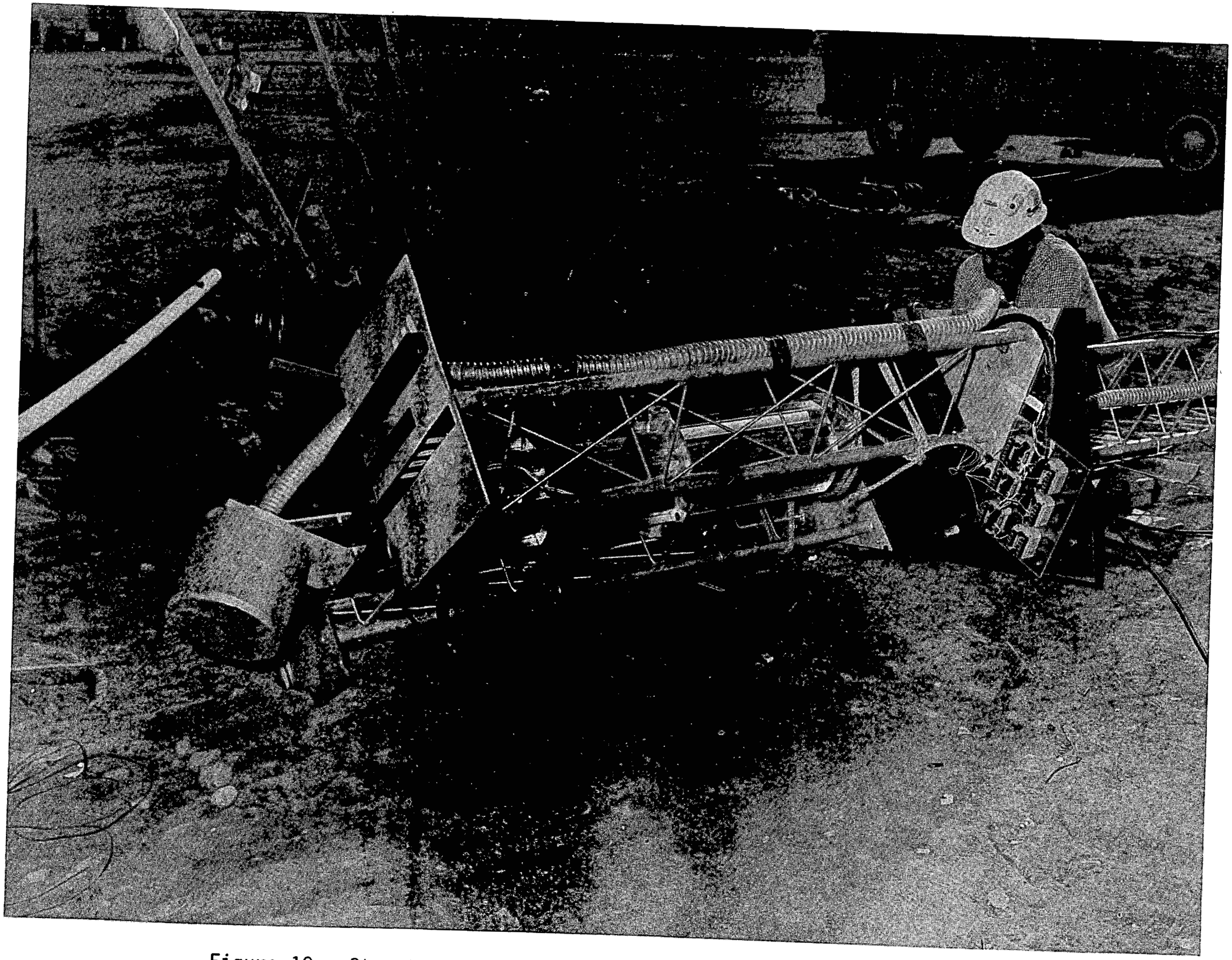


Figure 10. Structure Assembly with Simulated RTG, Pressure Transducers, Two-wire Transmitters and Time of Arrival Detectors Mounted

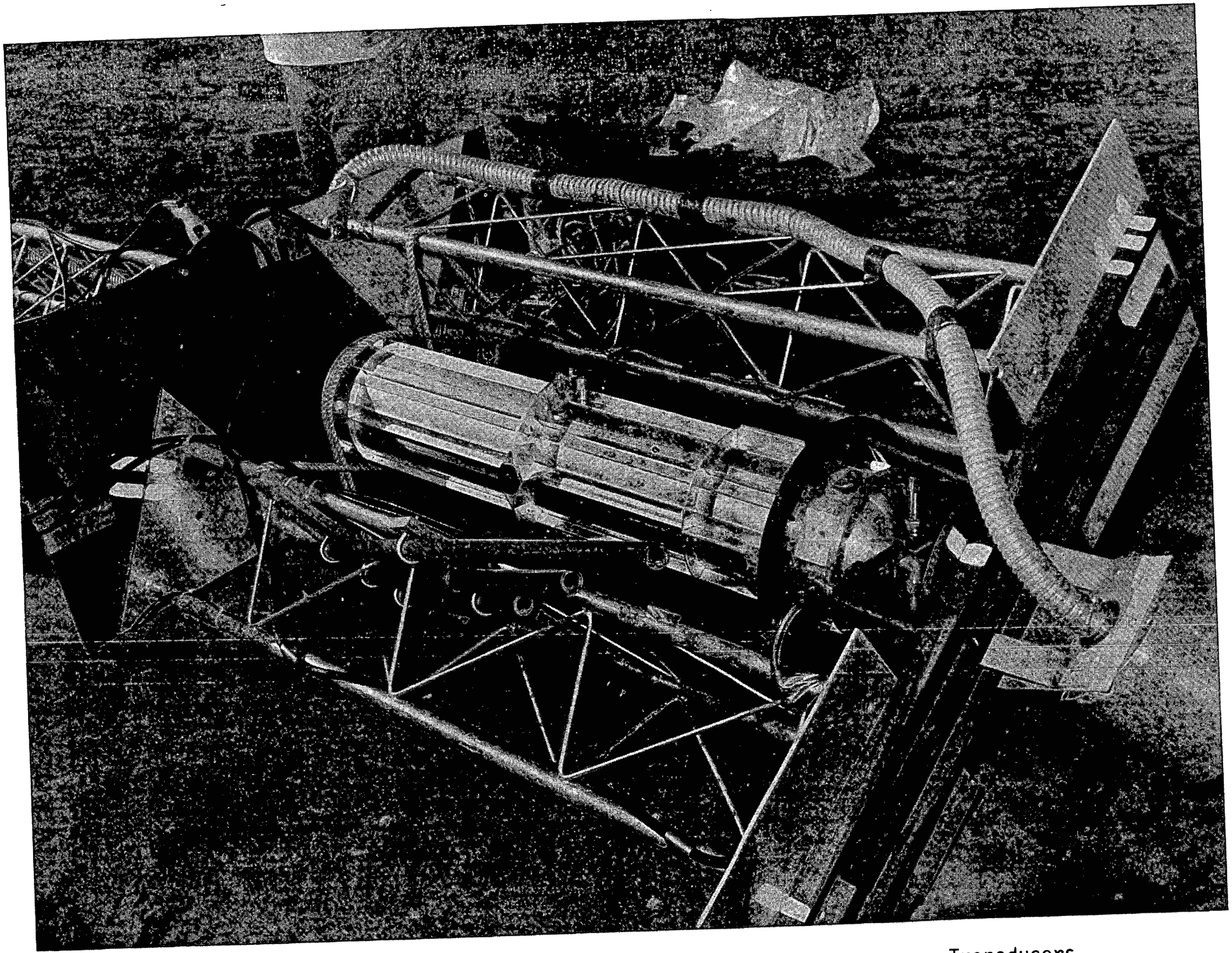


Figure 11. Structure Assembly with Simulated RTG, Pressure Transducers, Two-wire Transmitters and Time of Arrival Detectors Mounted

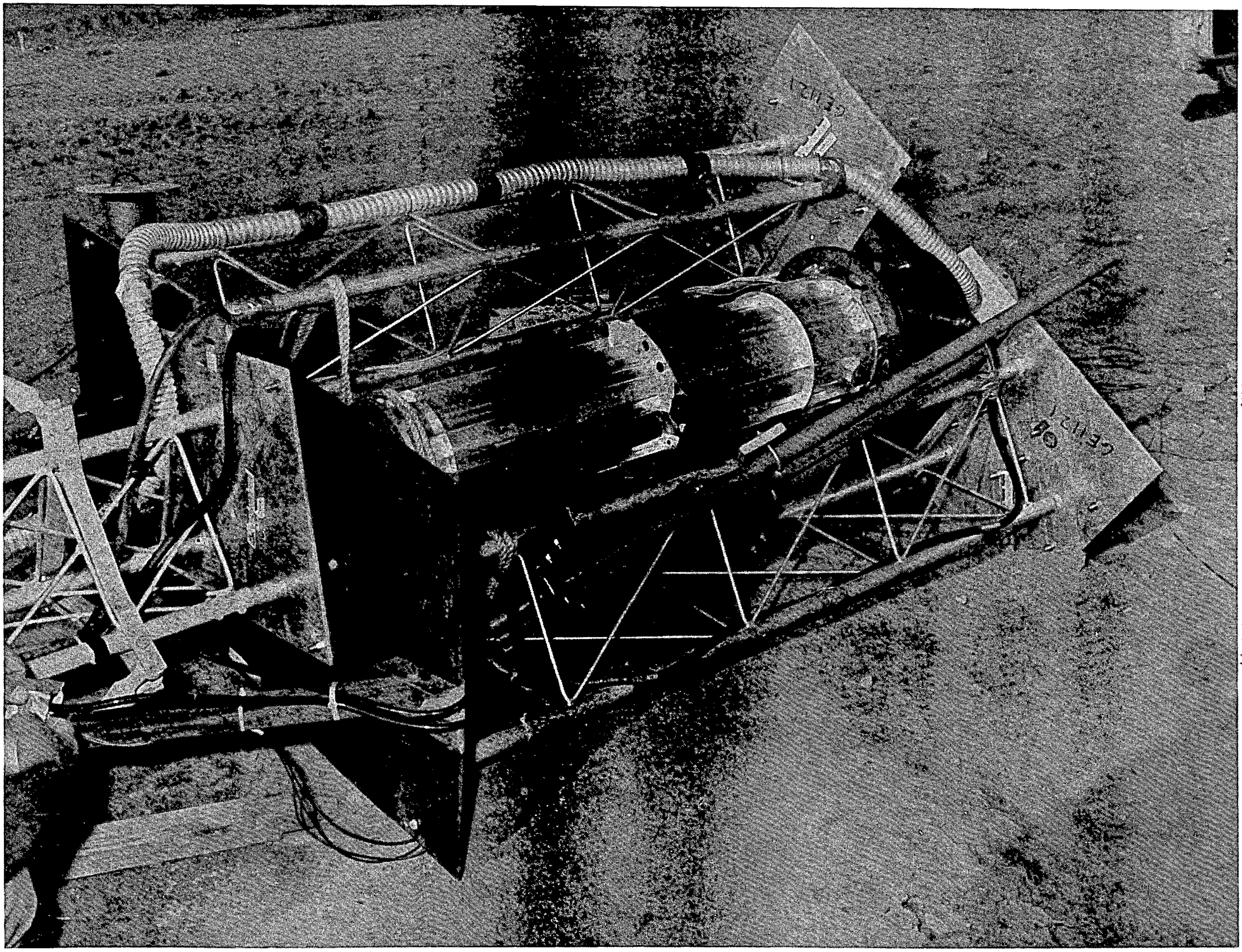


Figure 12. Structure Assembly with Simulated RTG, Pressure Transducers, Two-wire Transmitters and Time of Arrival Detectors Mounted

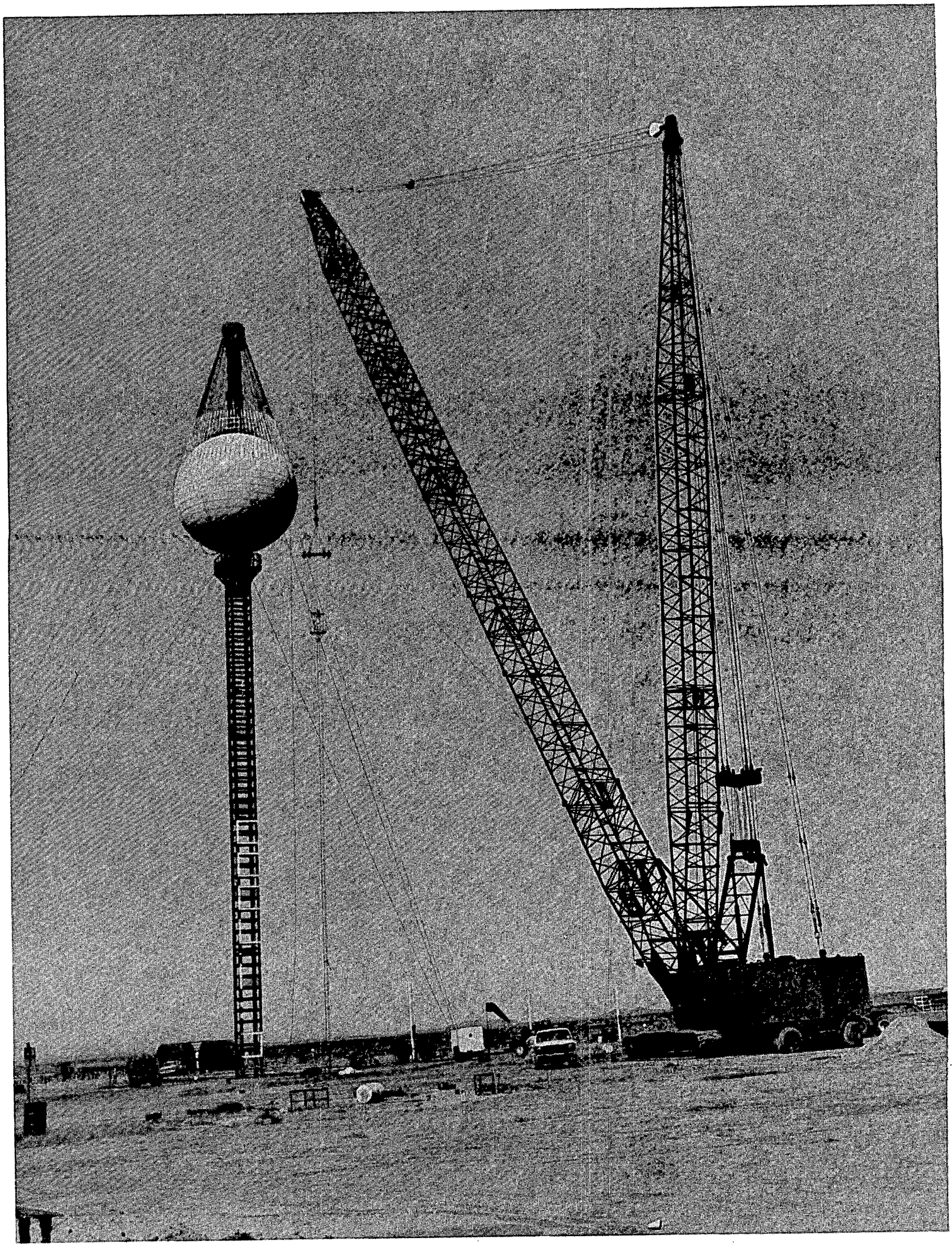


Figure 13. Test Specimen Support Tower Being Erected

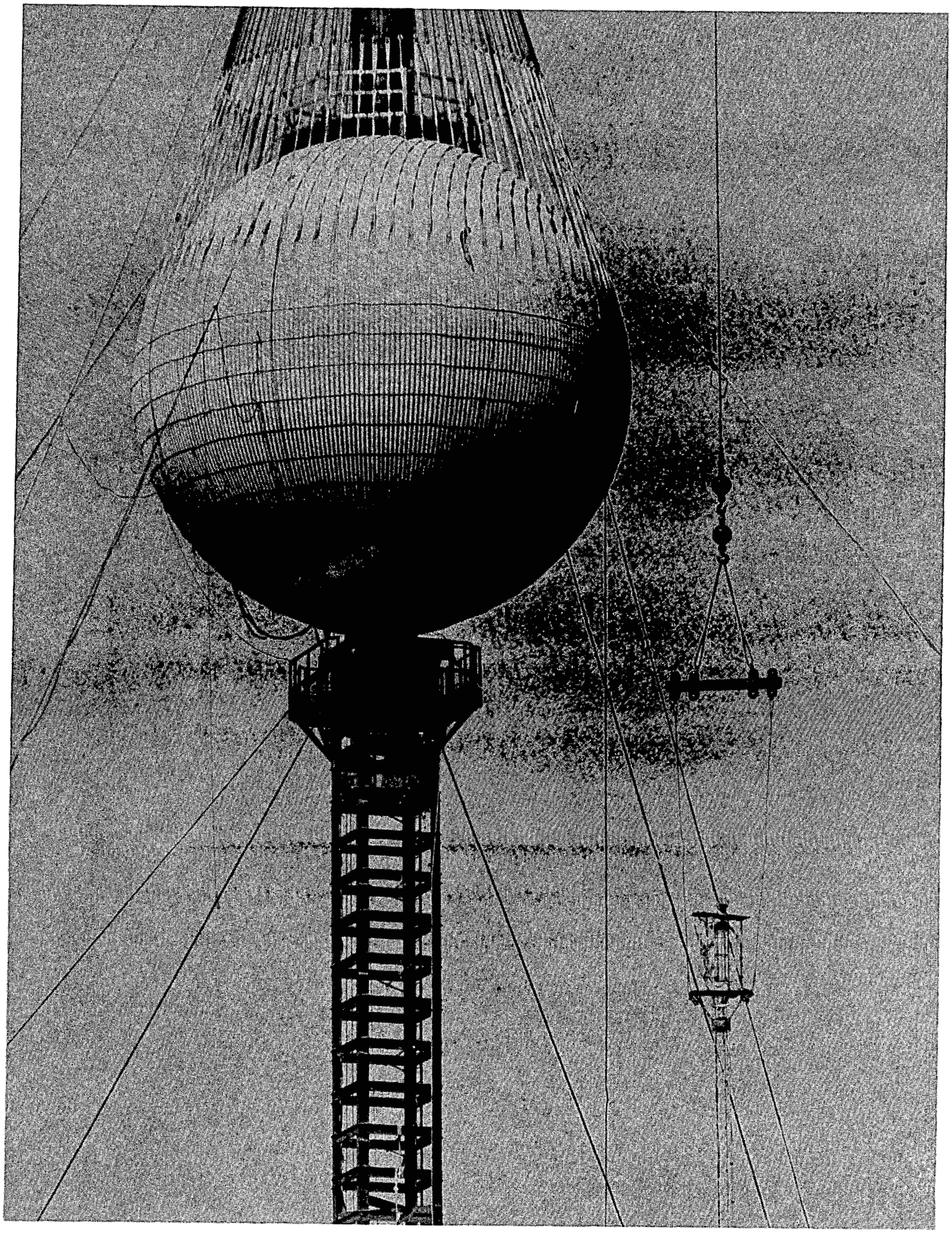


Figure 14. Crane Rigging on Tower During Erection

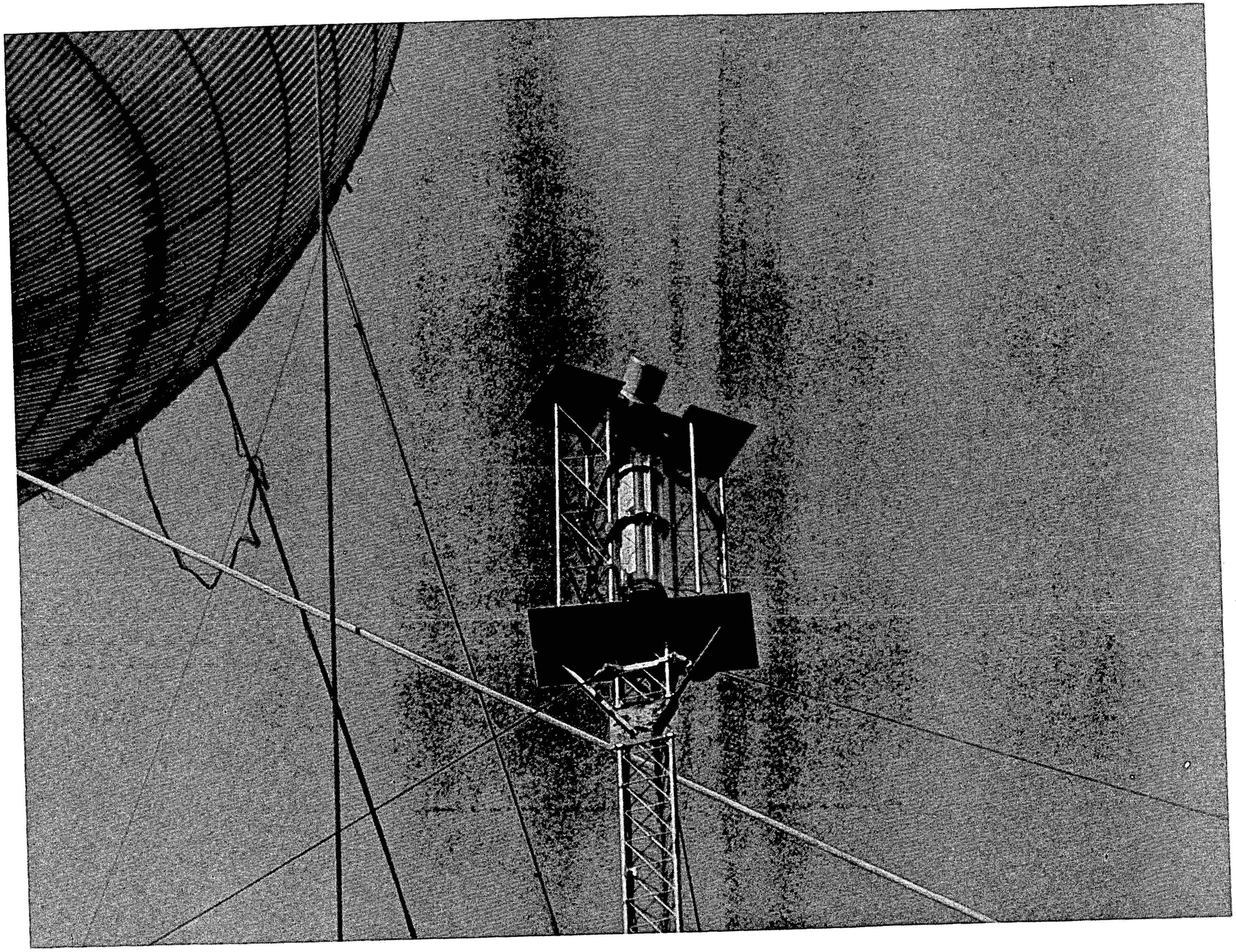


Figure 15. Structure Assembly and Mounted Components After Tower was Erected

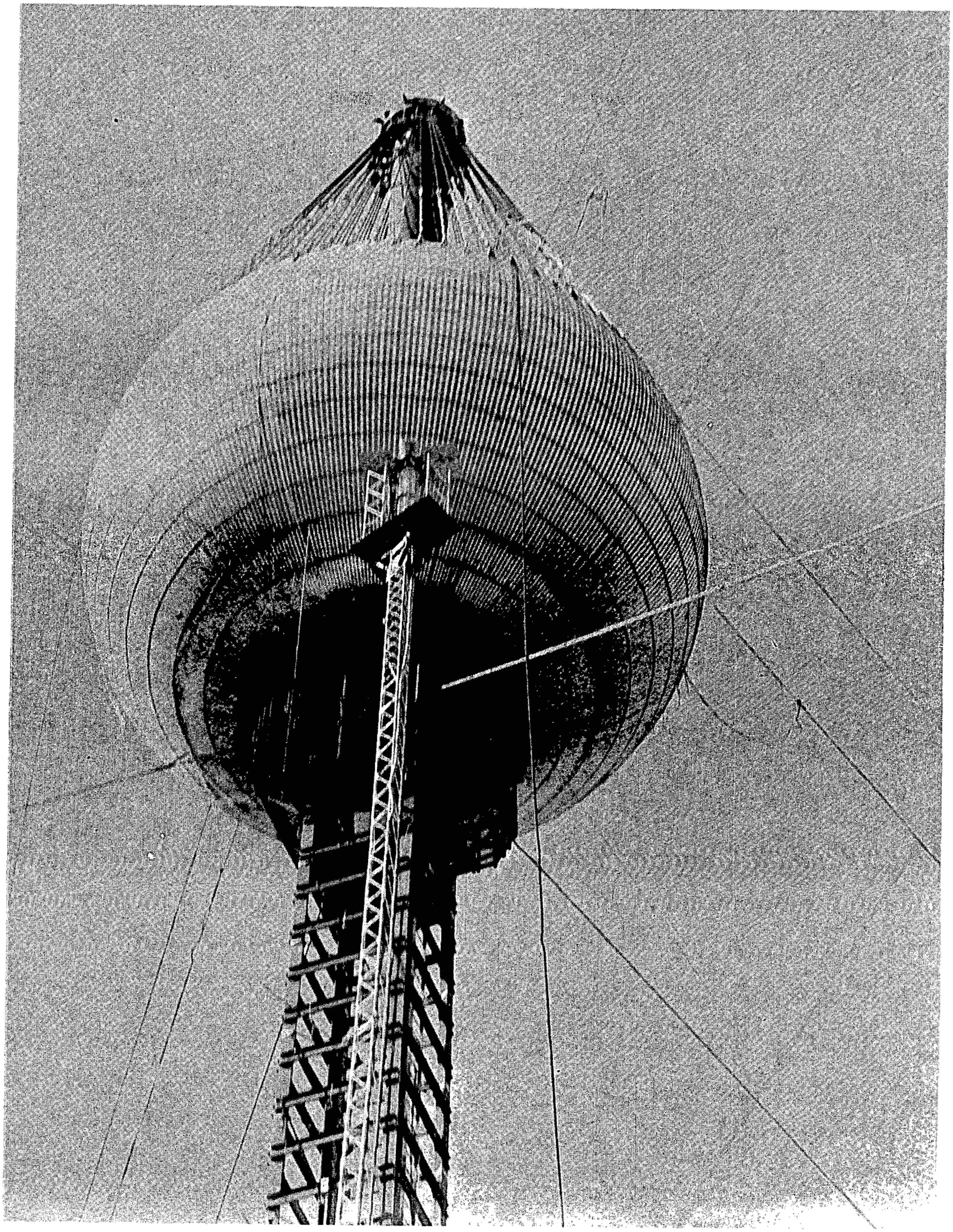


Figure 16. Test Specimen and ANFO Sphere

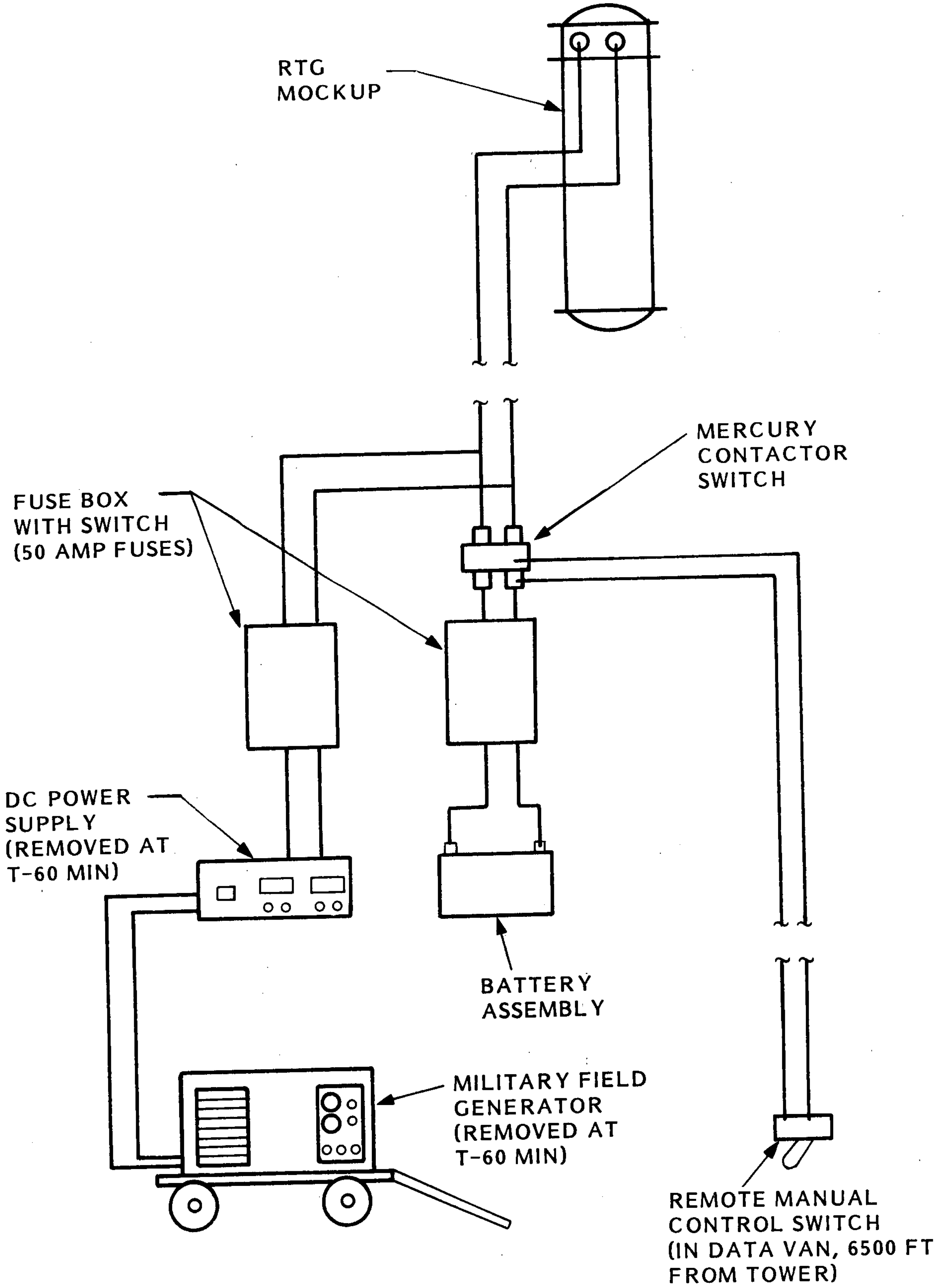


Figure 17. Electrical Power System for Heaters

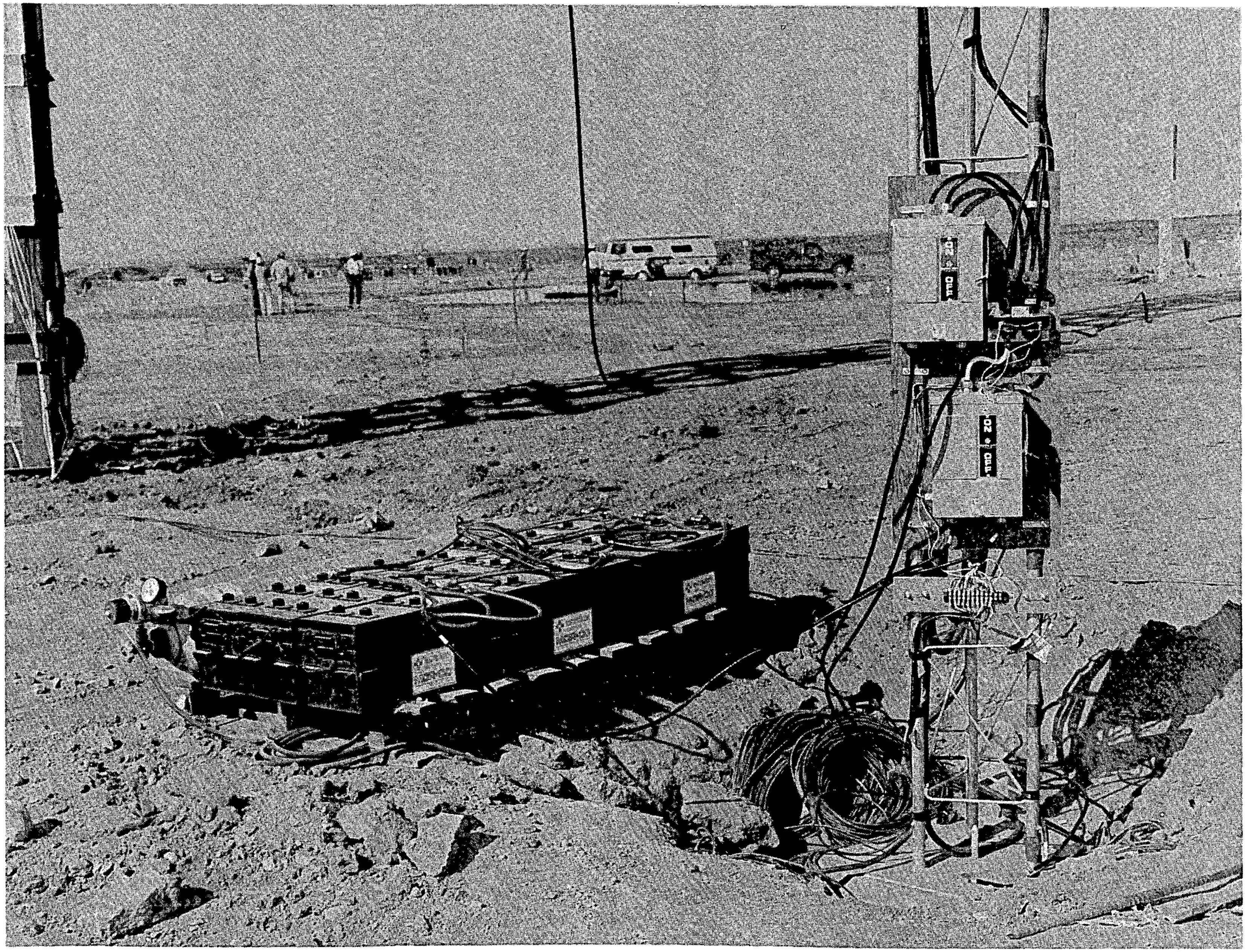


Figure 18. Components at the Bottom of the Tower

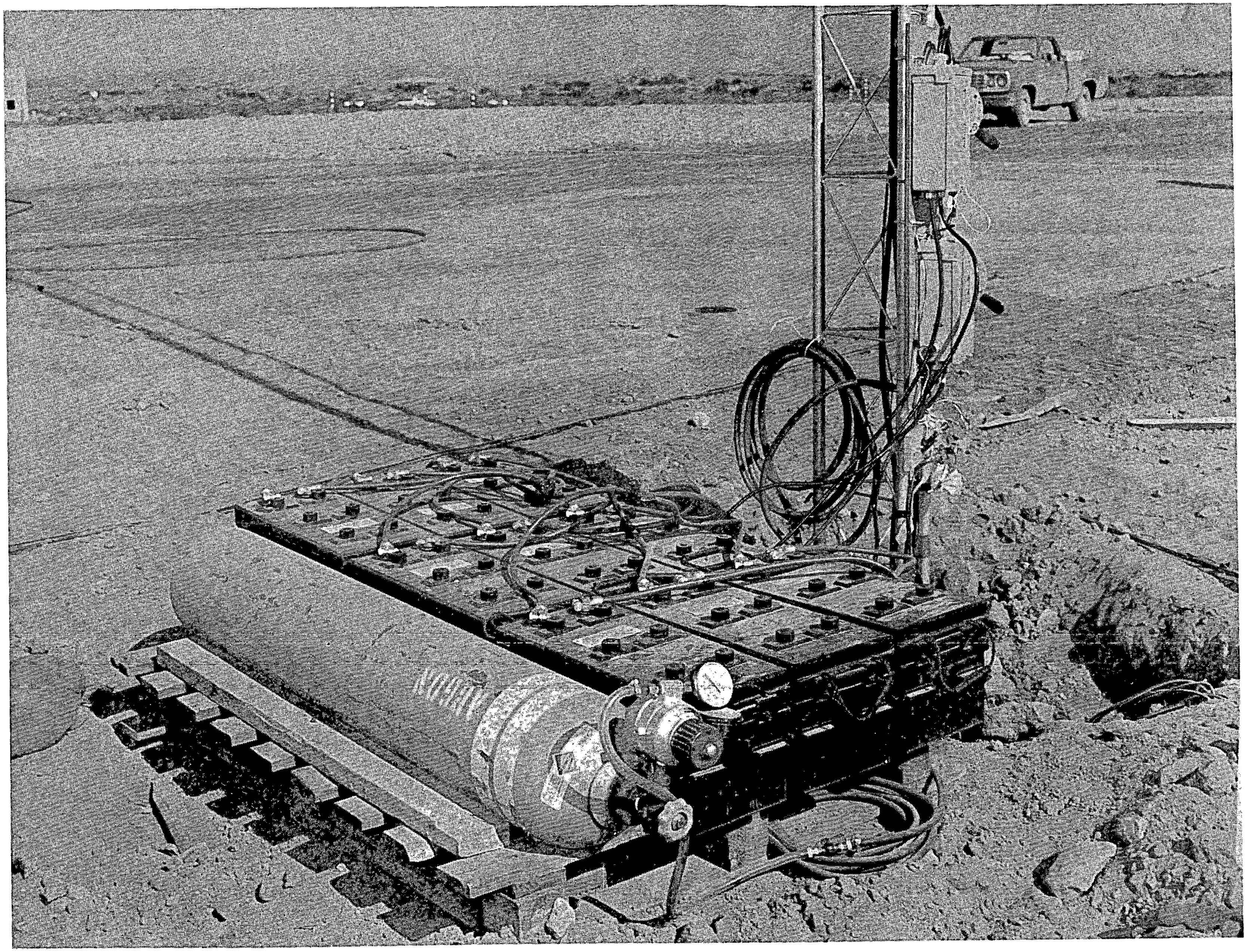


Figure 19. Components at the Bottom of the Tower

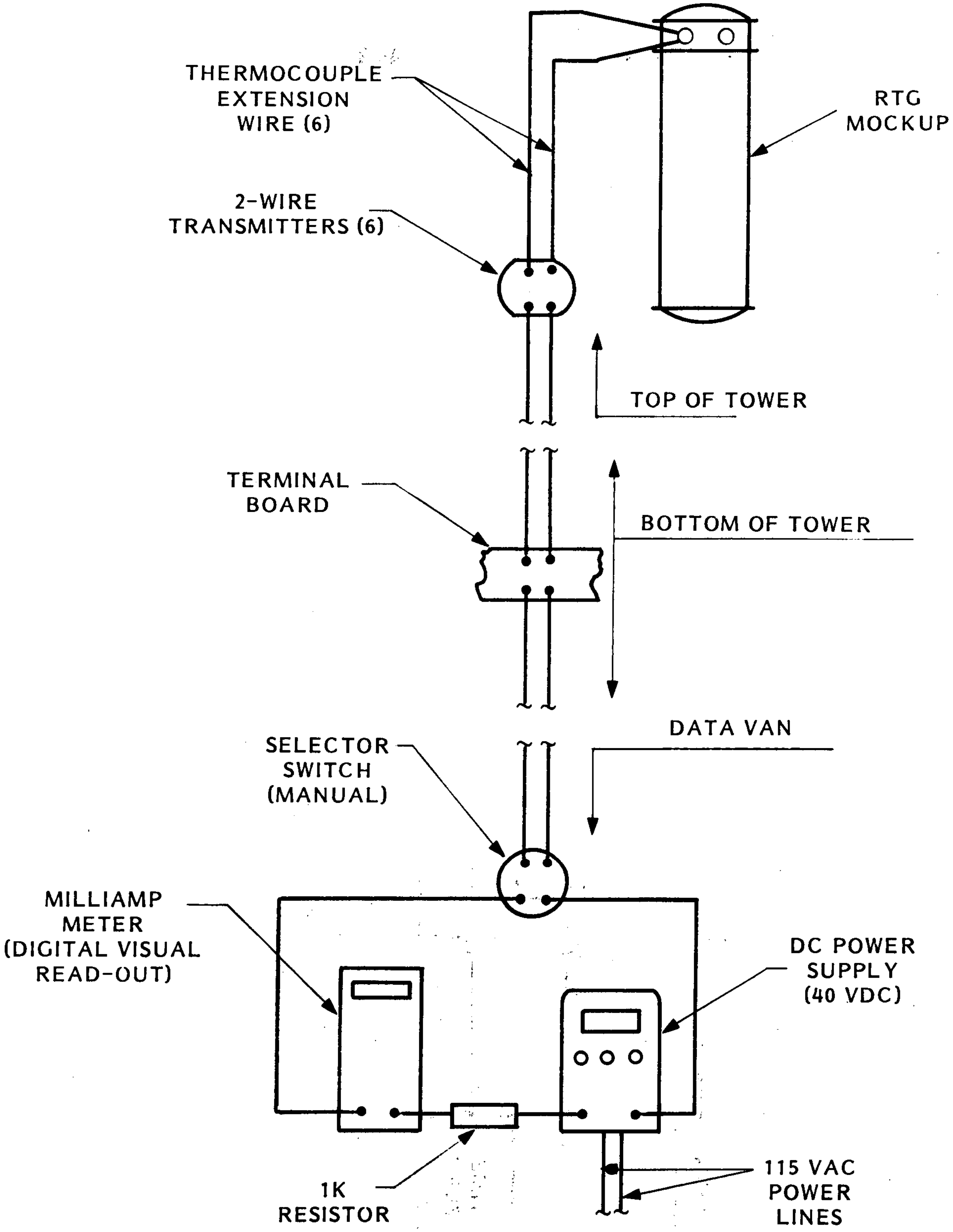


Figure 20. Thermocouple Instrumentation System

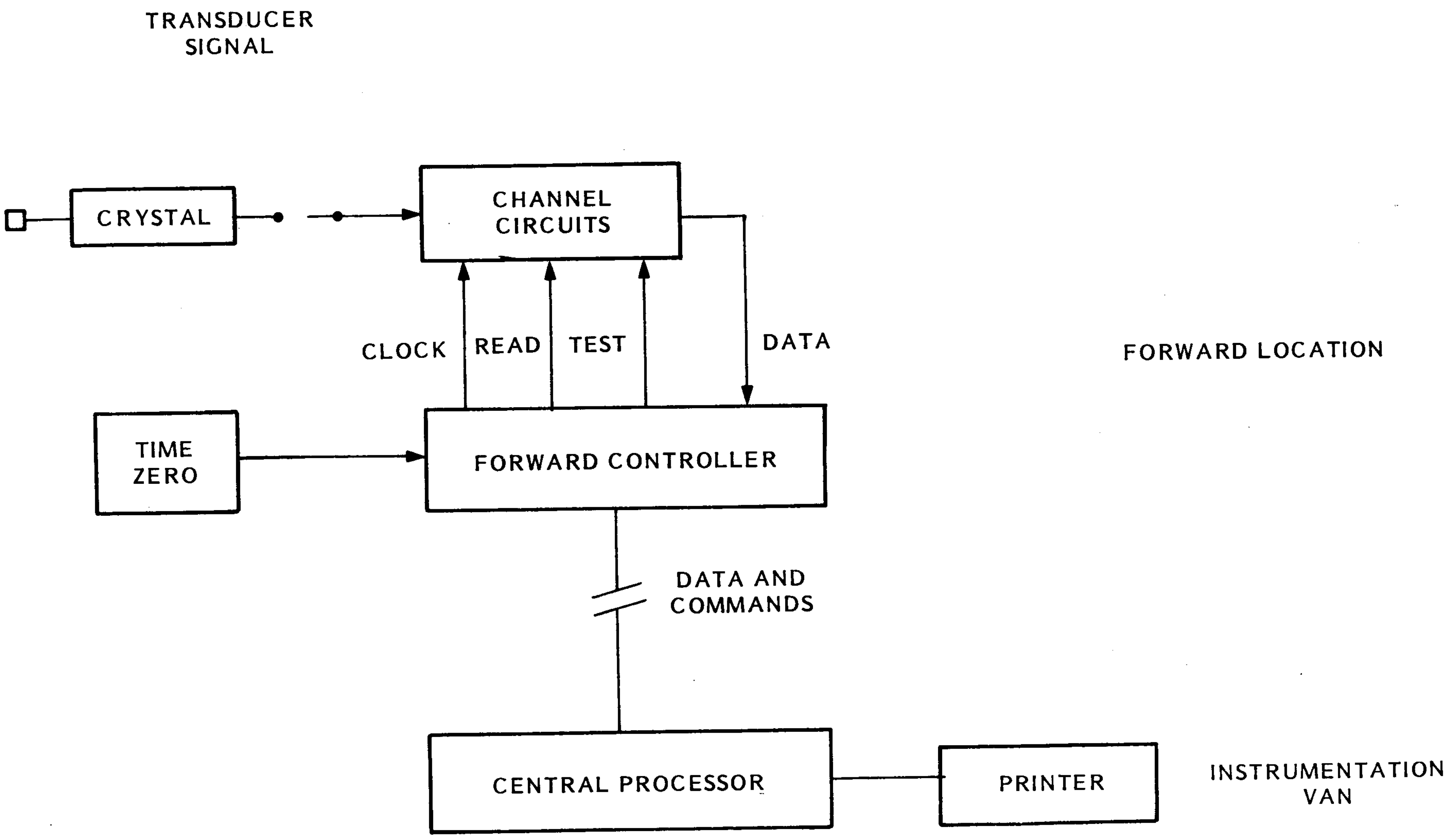


Figure 21. AFWL Digital Time of Arrival Detection (TOAD) System

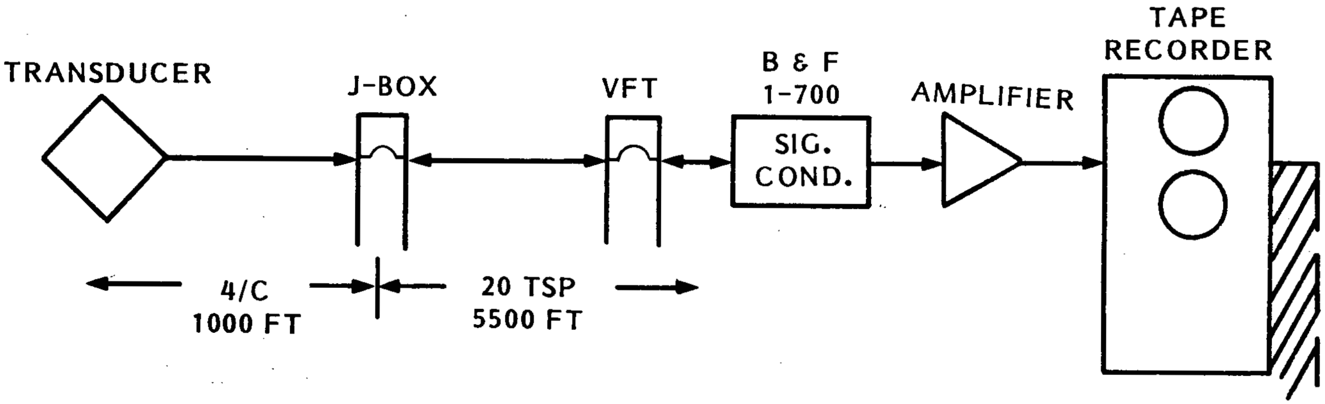


Figure 22. Data Acquisiton System for Pressure Transducers

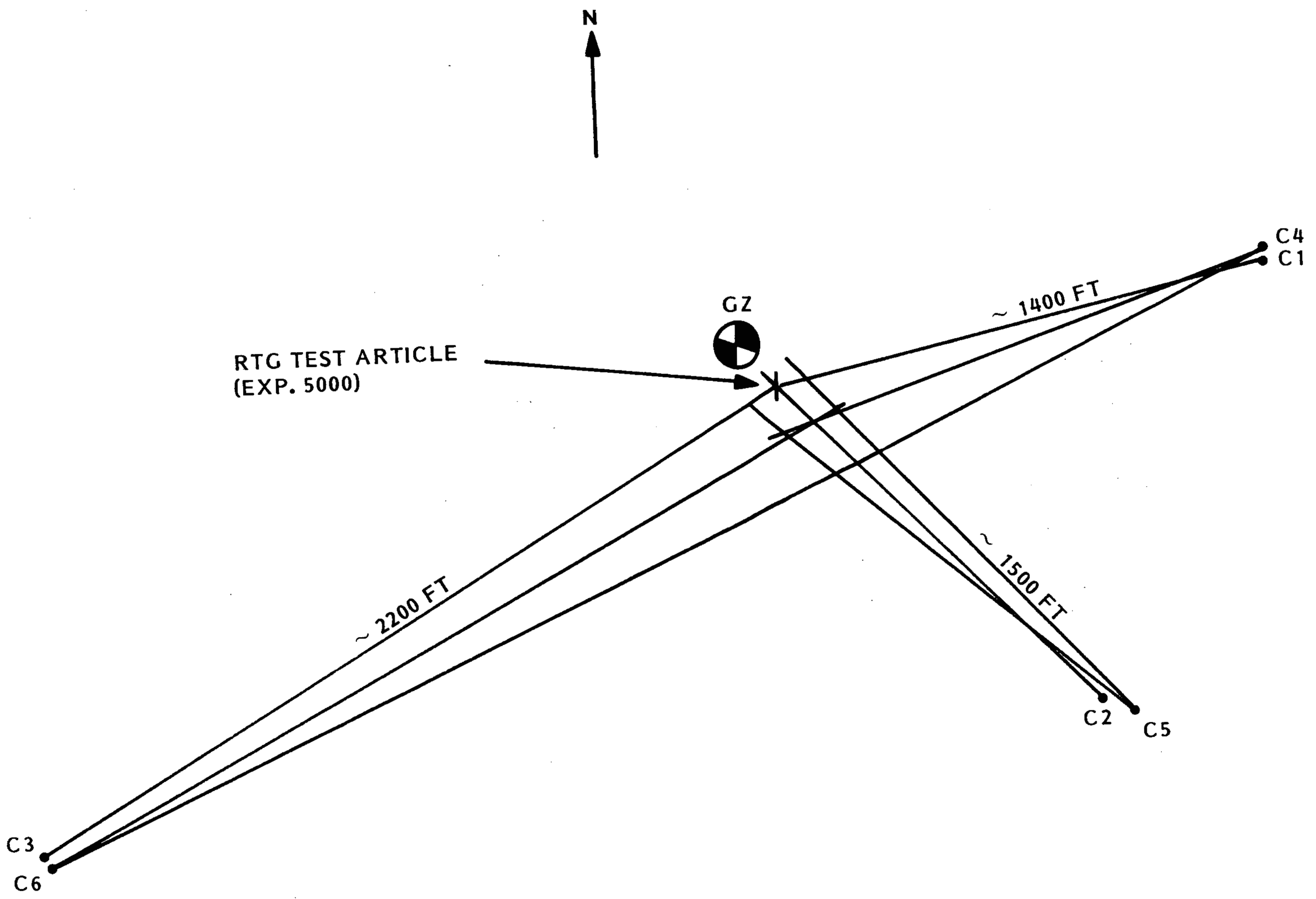


Figure 23. Camera Locations

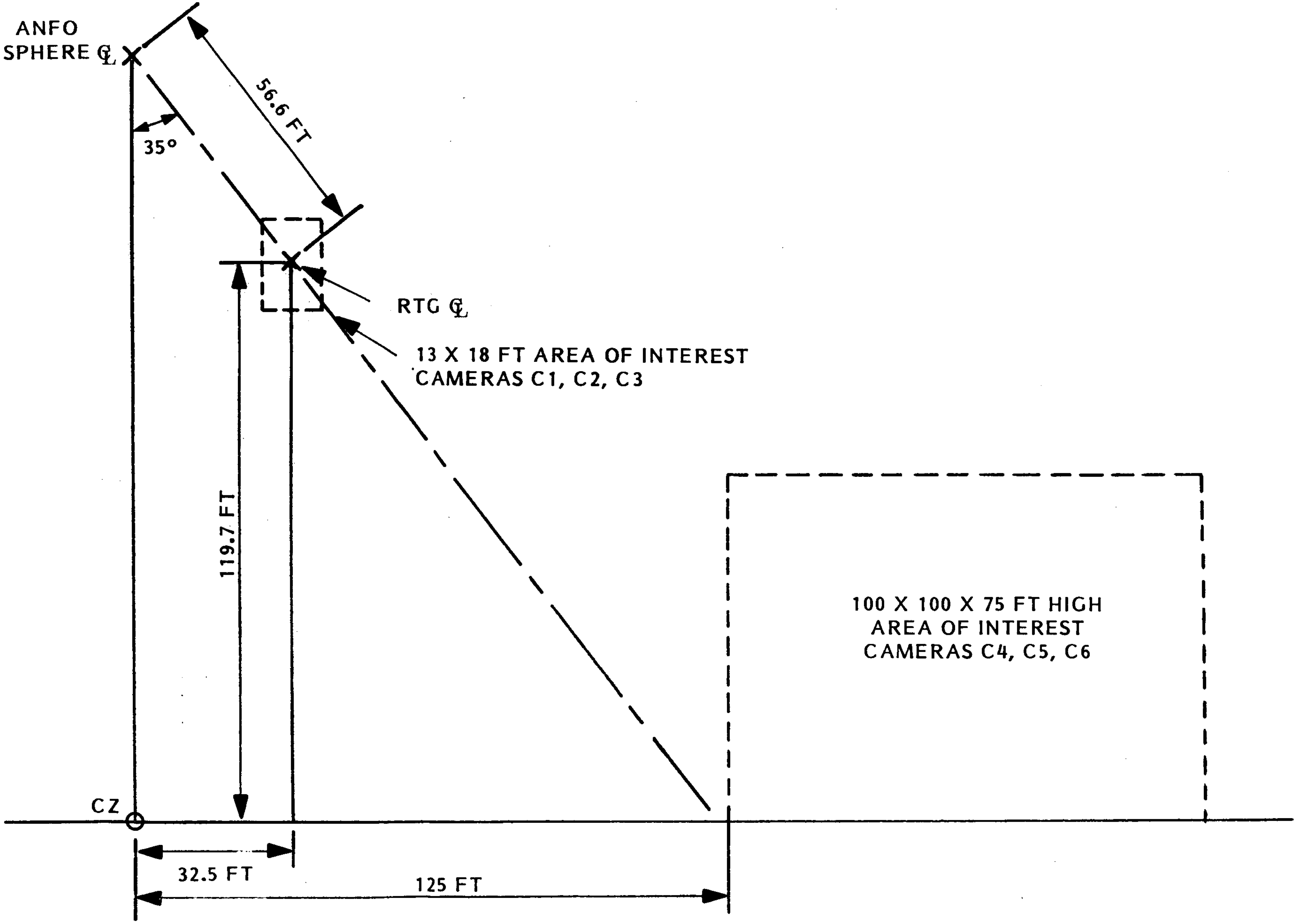


Figure 24. Camera Areas of Interest

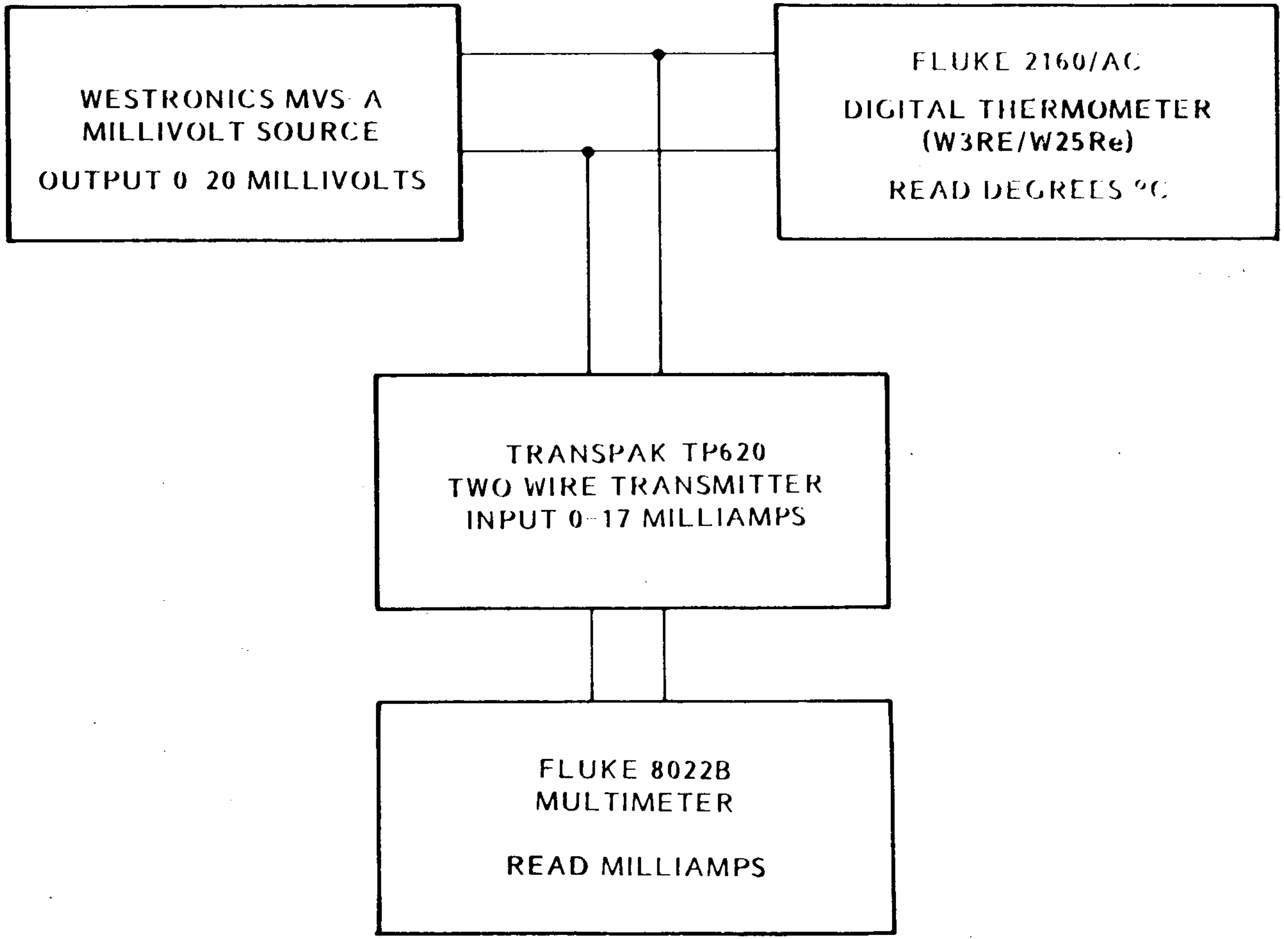


Figure 25. Test Arrangement for Calibration of Thermocouple System

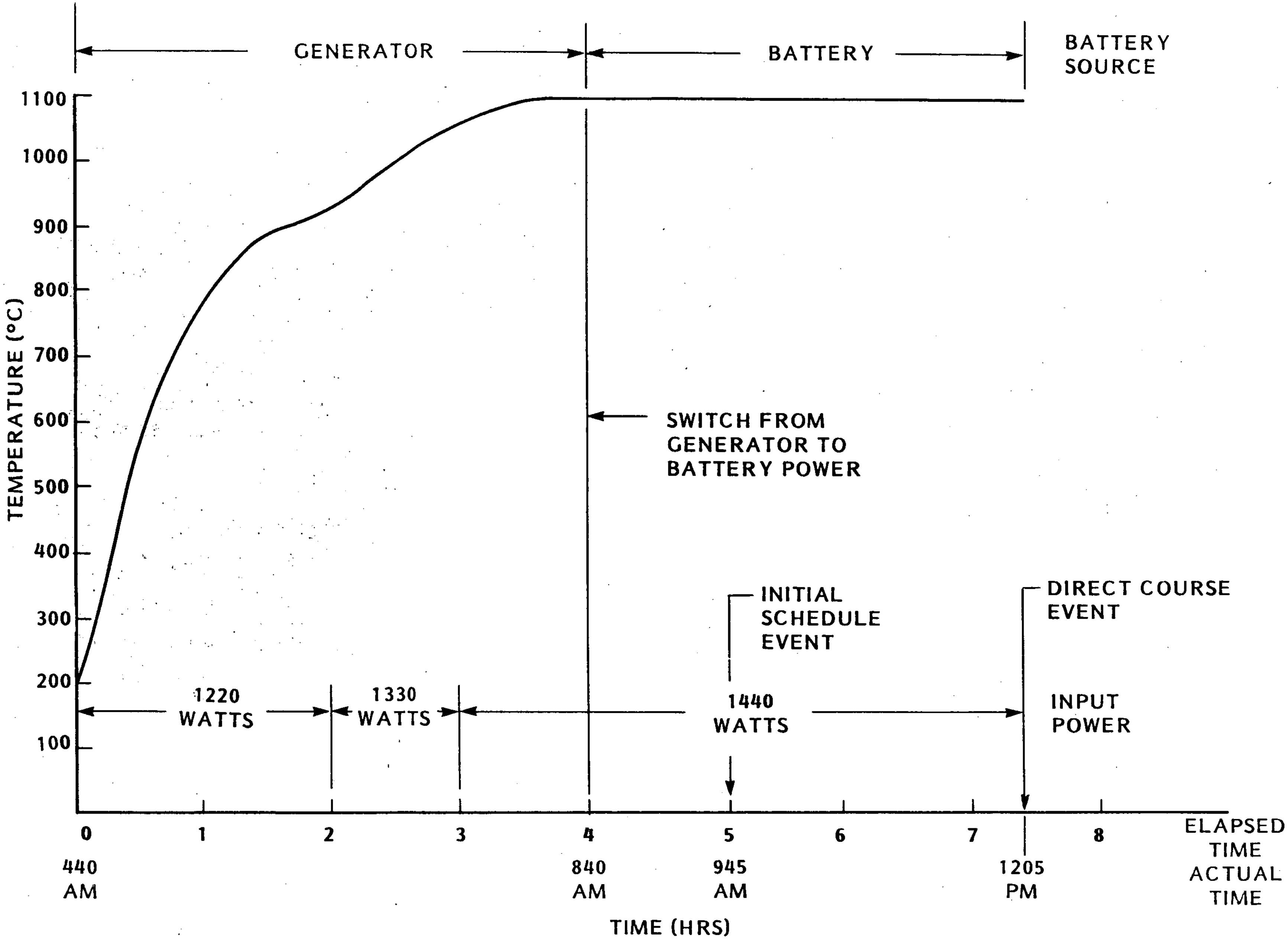


Figure 26. Test Module Heat-up Rate

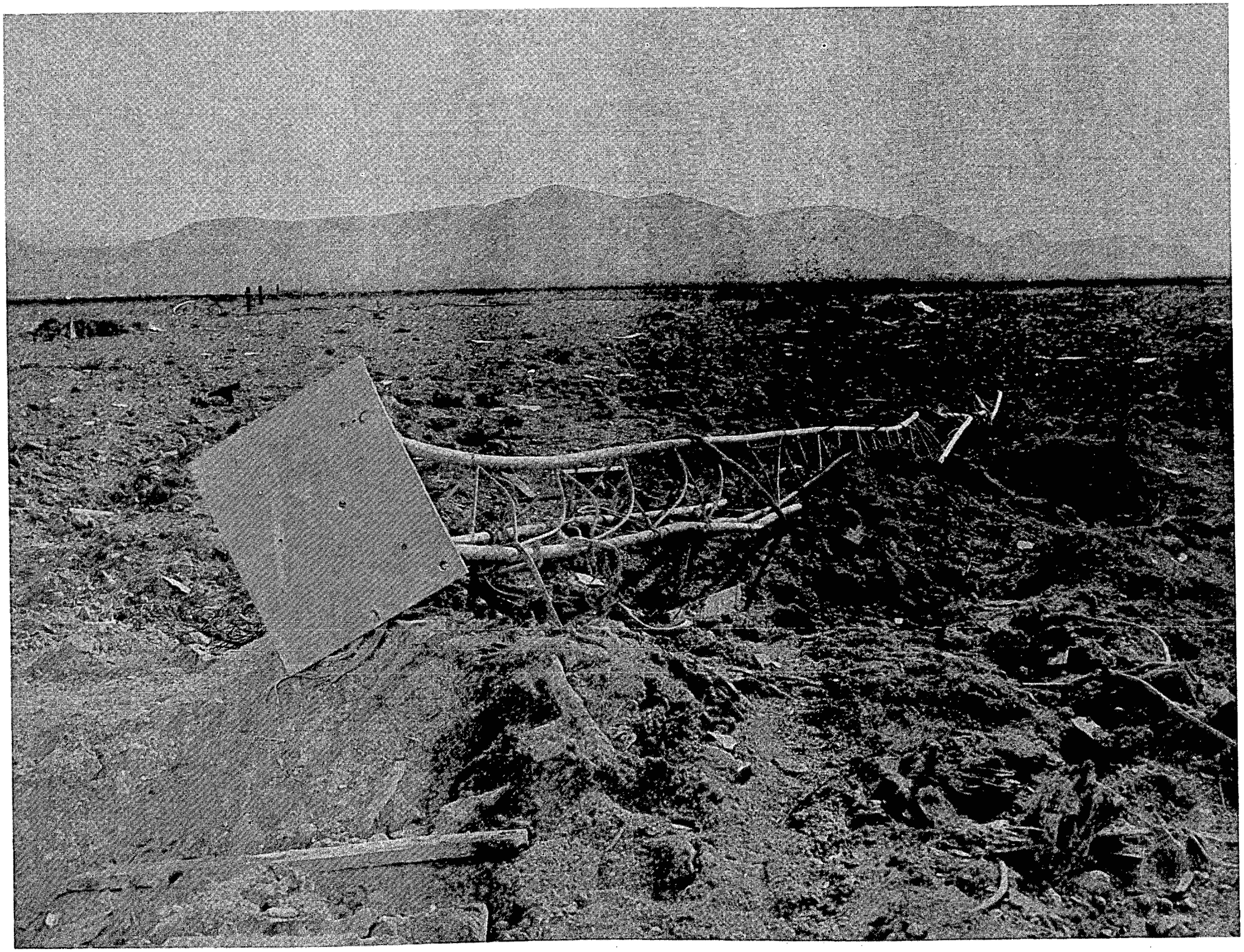


Figure 27. Bottom Section of Tower, After Detonation

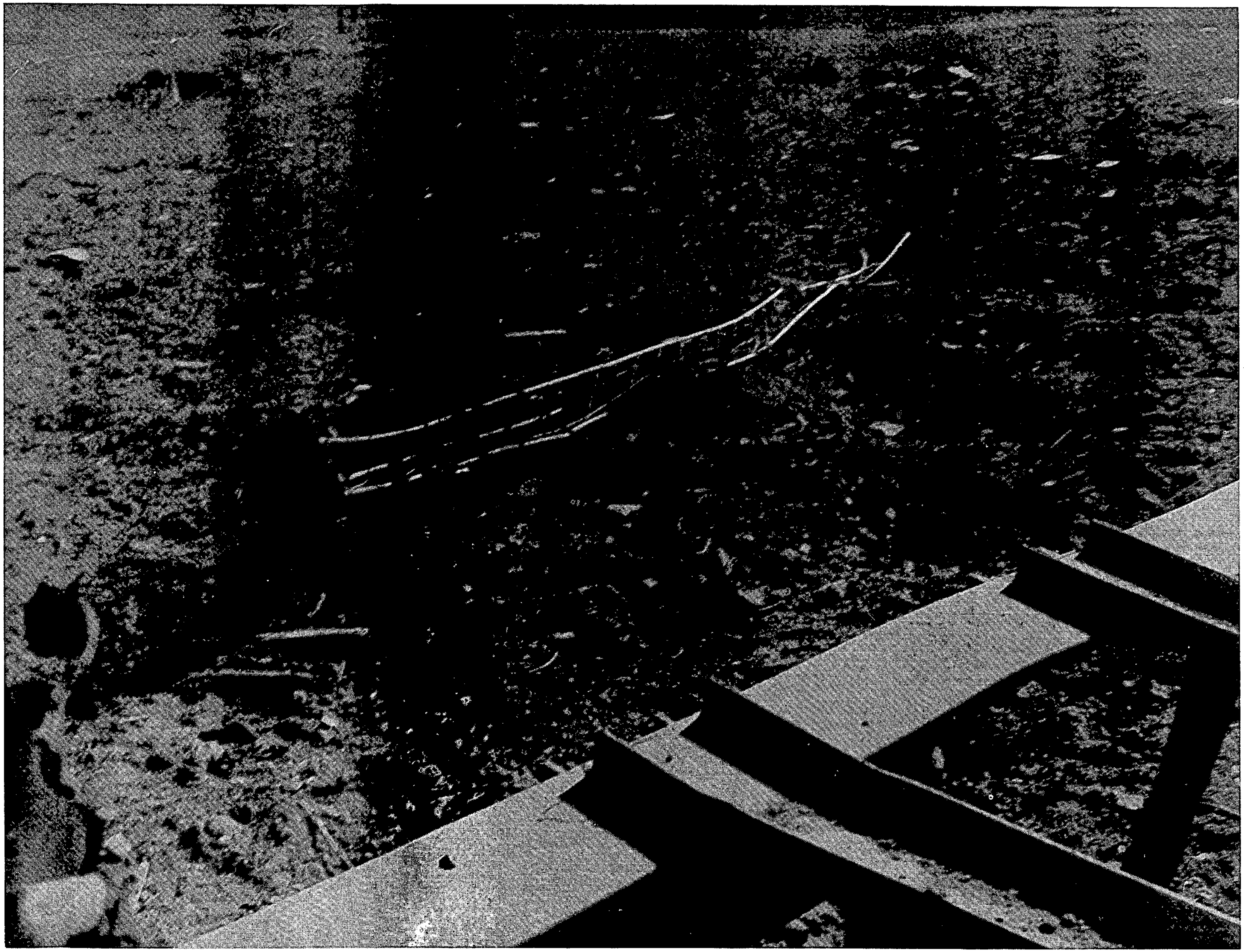


Figure 28. RTG Tower and ANFO Tower, After Detonation

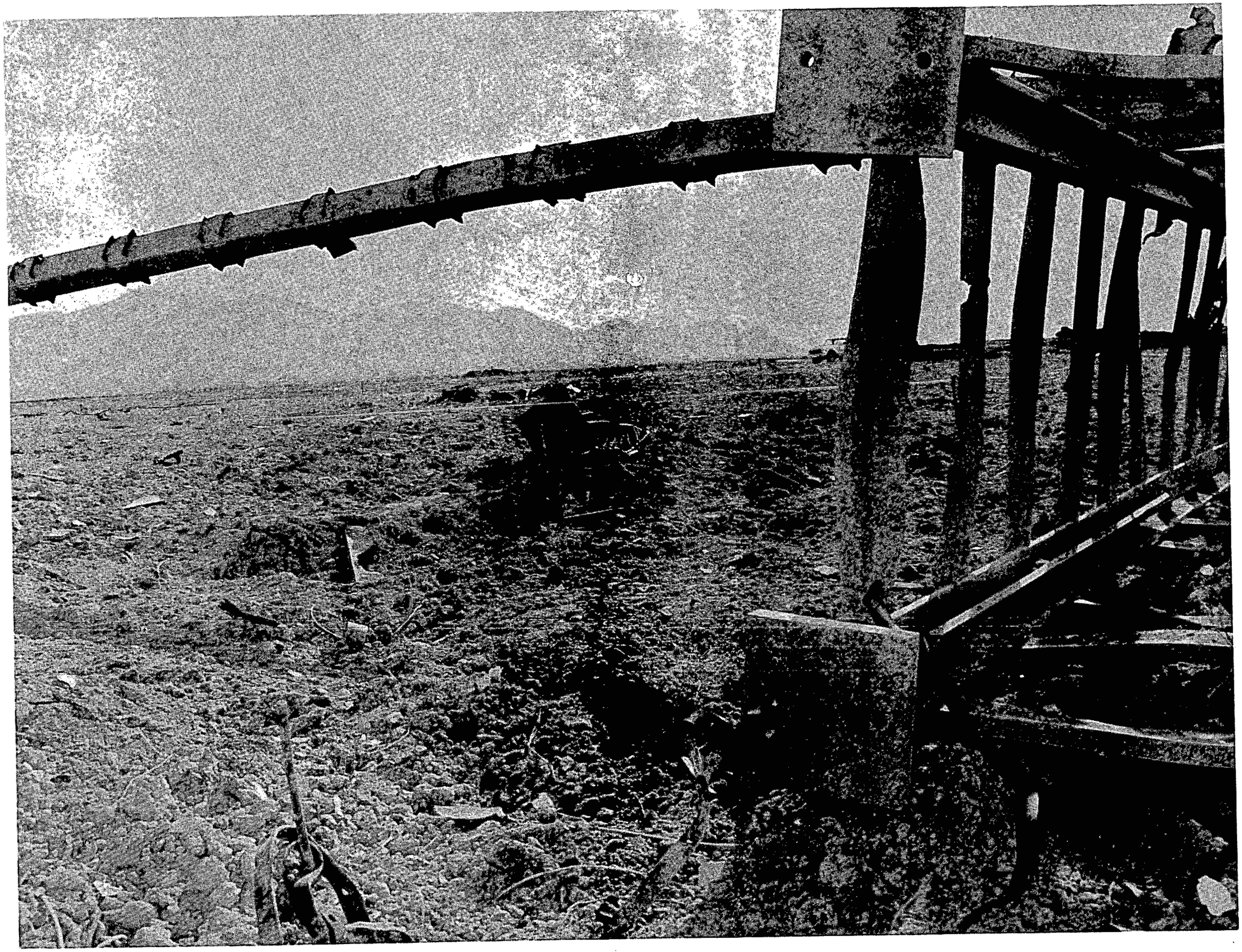


Figure 29. ANFO Tower in Foreground and RTG Tower, After Detonation

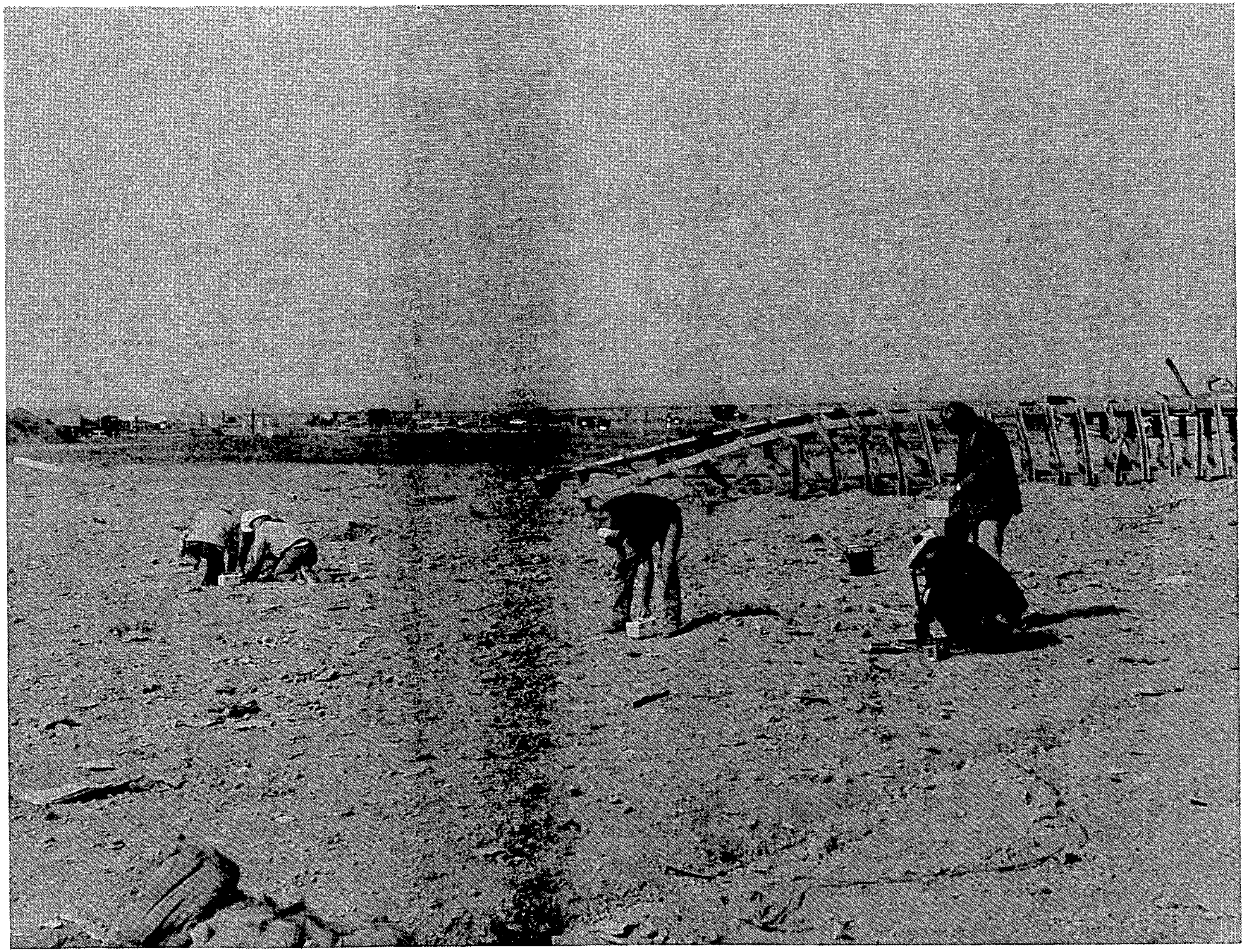


Figure 30. Nuclear Emergency Search Team Recovering Debris.
RTG Tower is Shown on Right

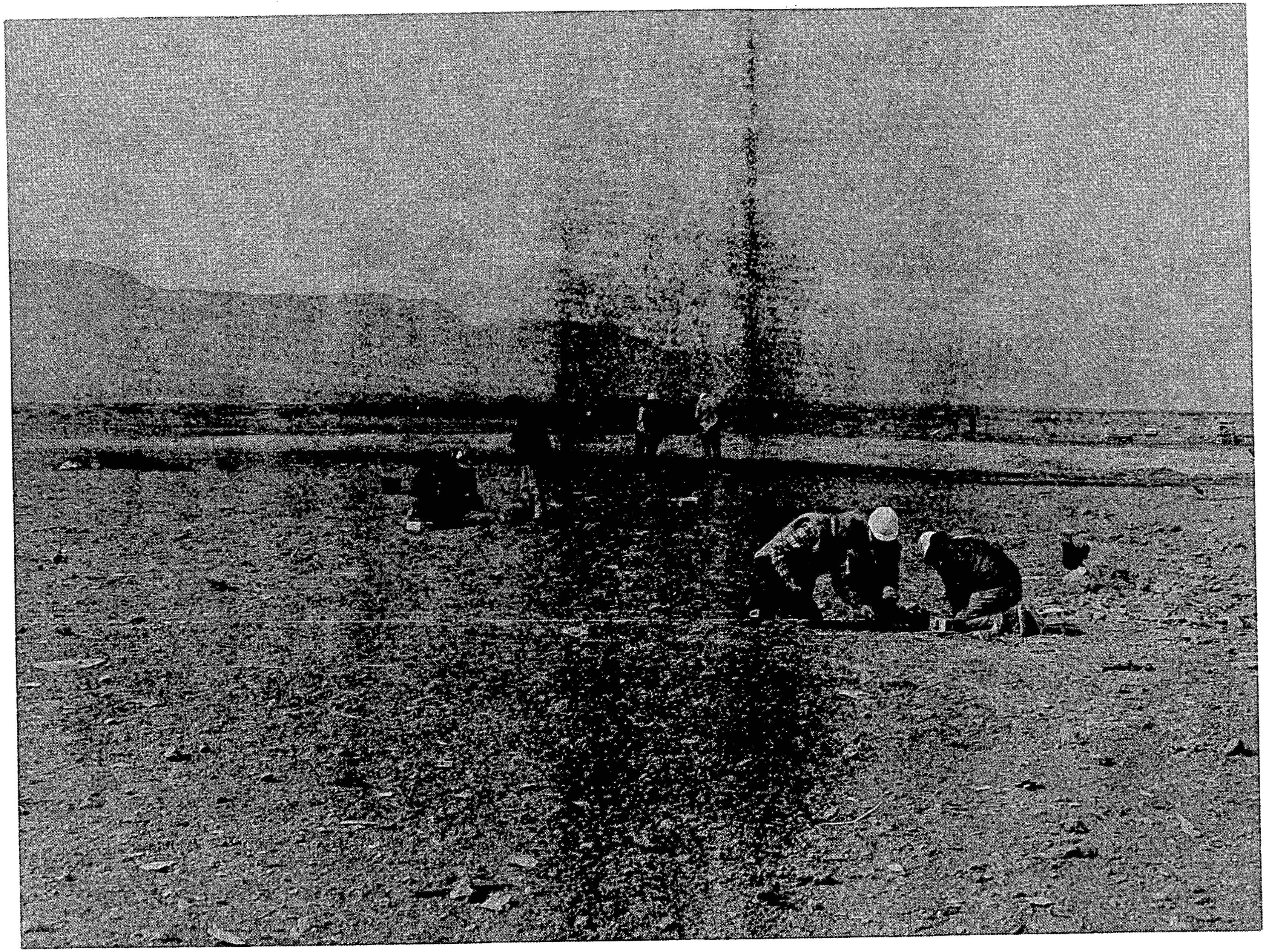


Figure 31. Nuclear Emergency Search Team Recovering Debris

Figure 32. Iridium Fragments Recovered (70% of Total)

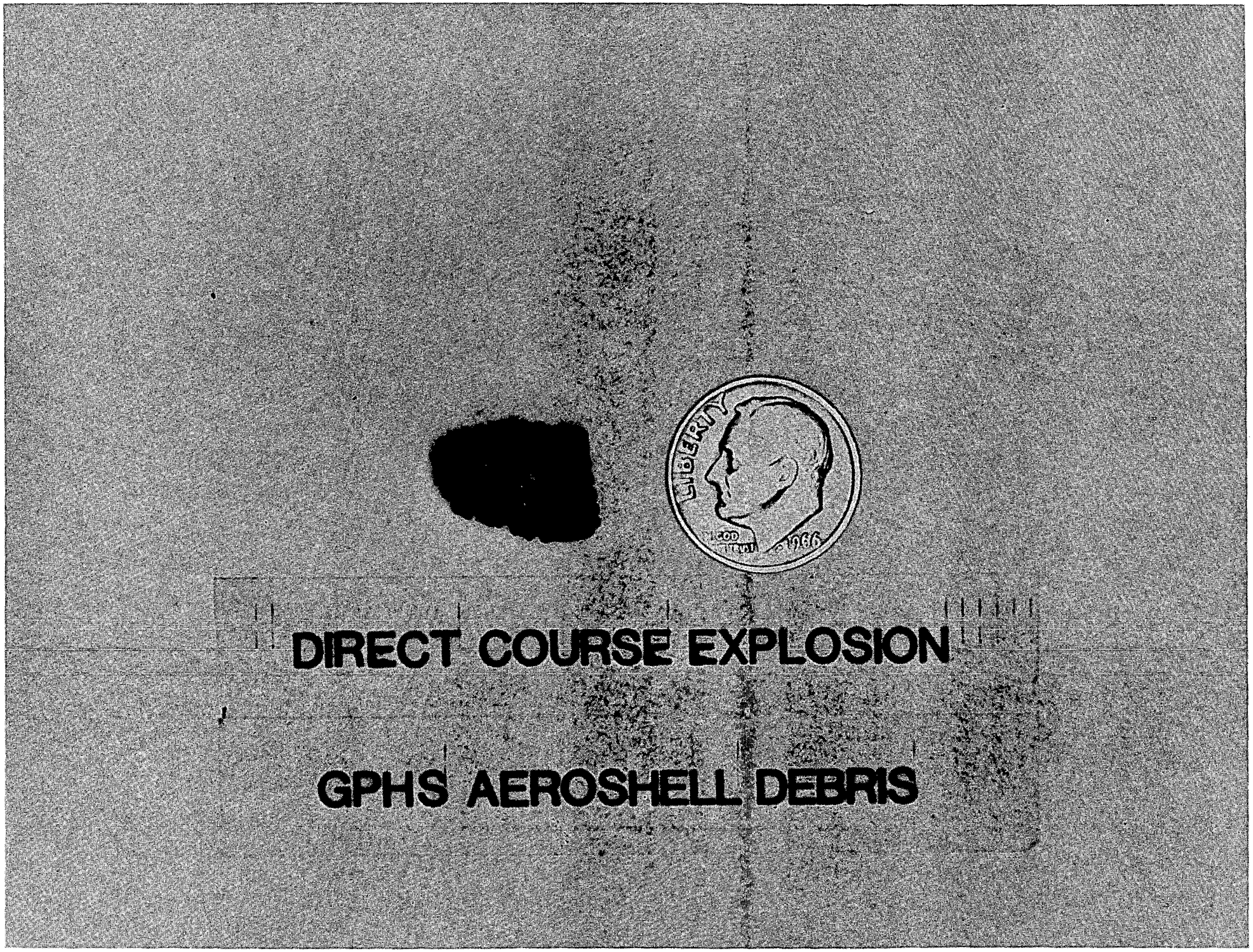


Figure 33. Fragment From GPHS Aeroshell

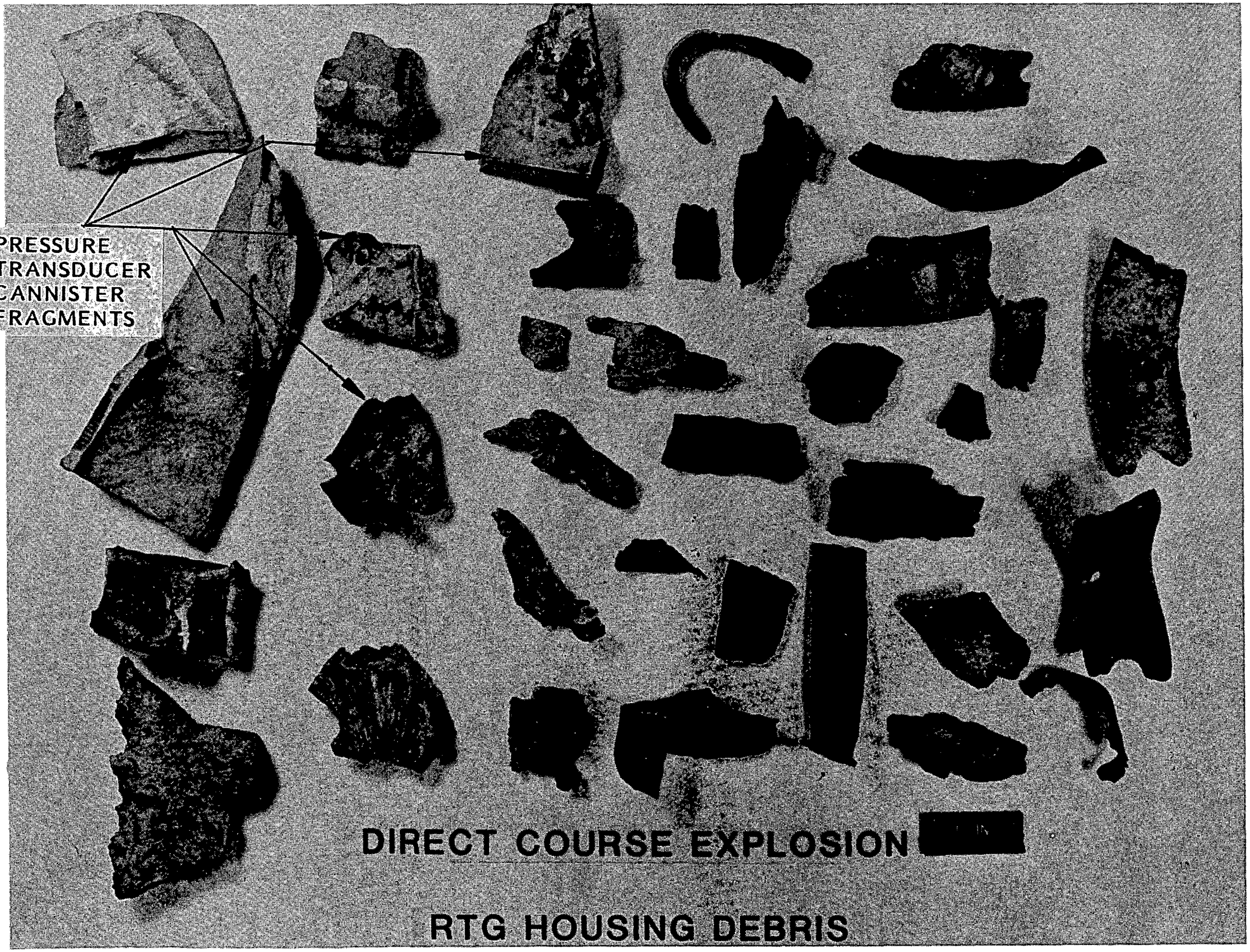


Figure 34. Aluminum Fragments Recovered

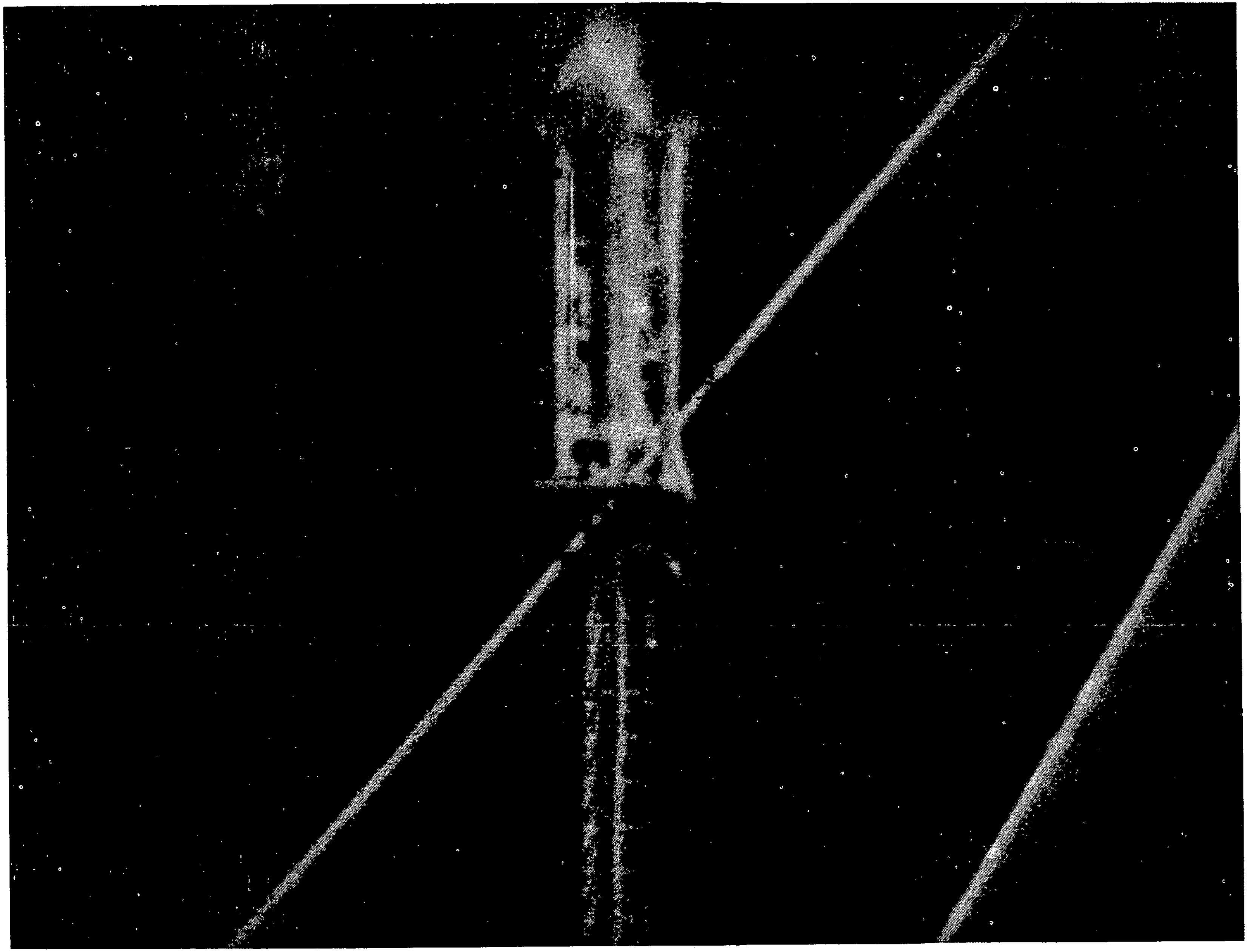


Figure 35. First Light From Fireball on RTG Test Article

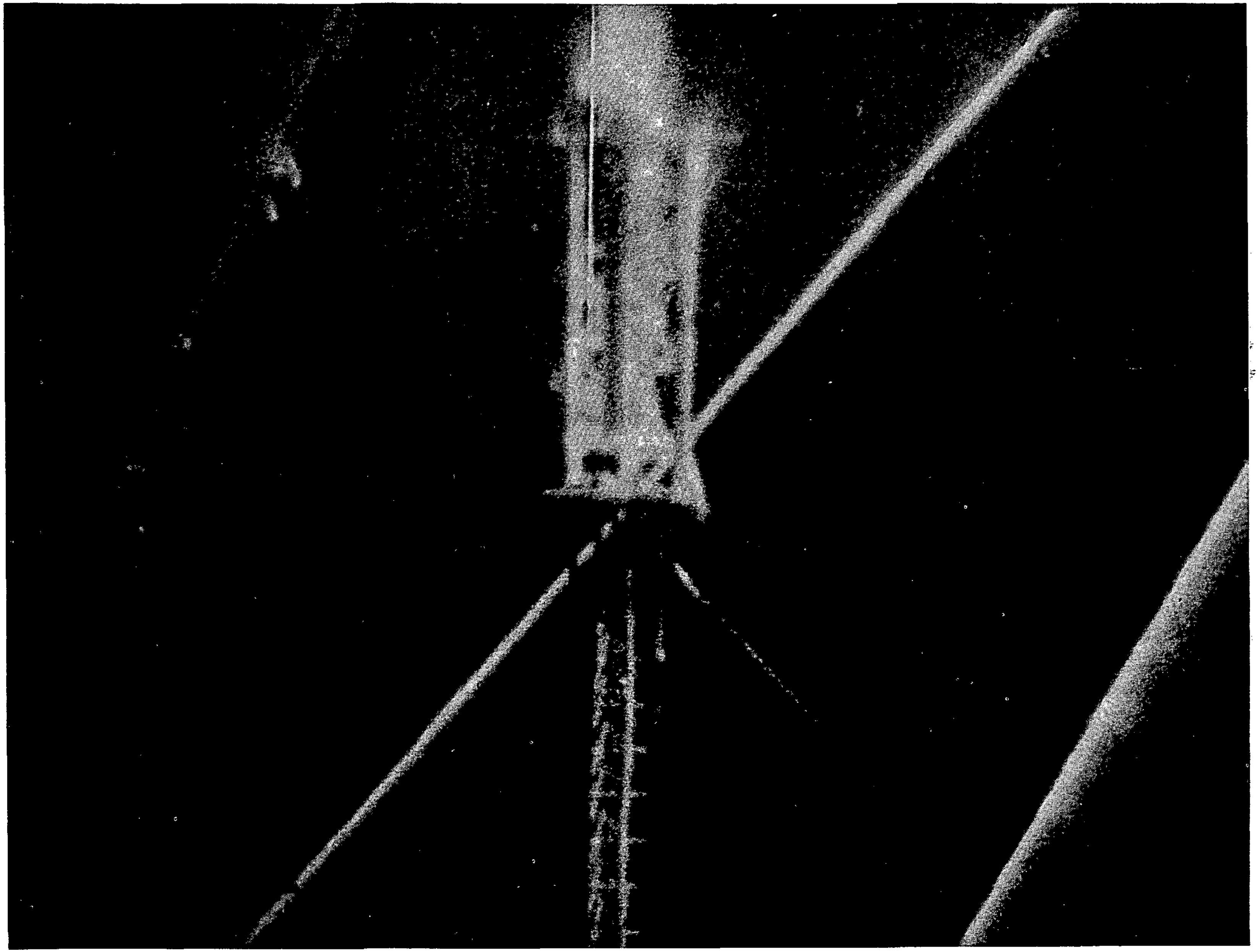


Figure 36. RTG Immediately Prior to Arrival of Fireball

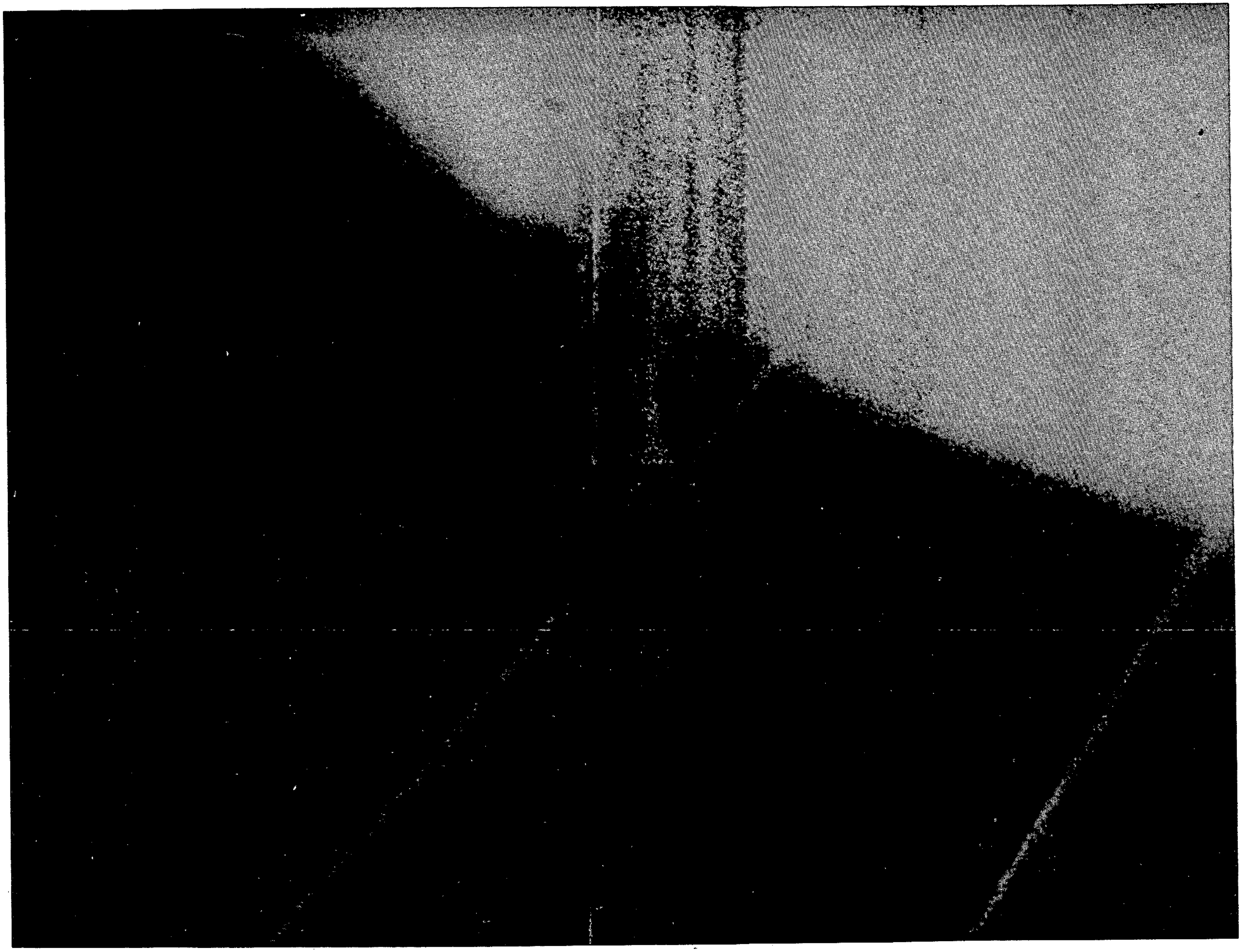


Figure 37. Fireball Approaching RTG Test Article

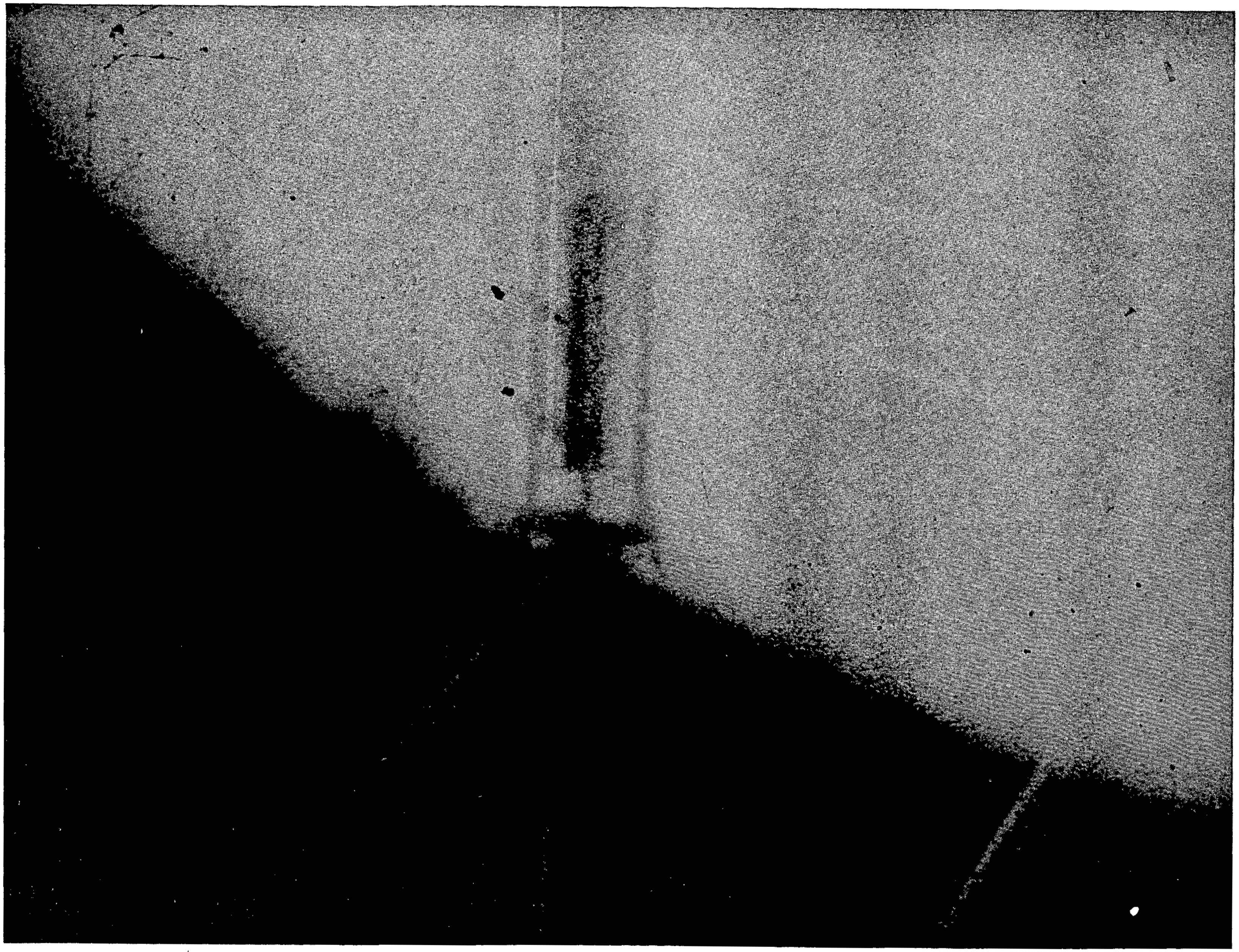


Figure 38. Fireball Contacting RTG Test Article

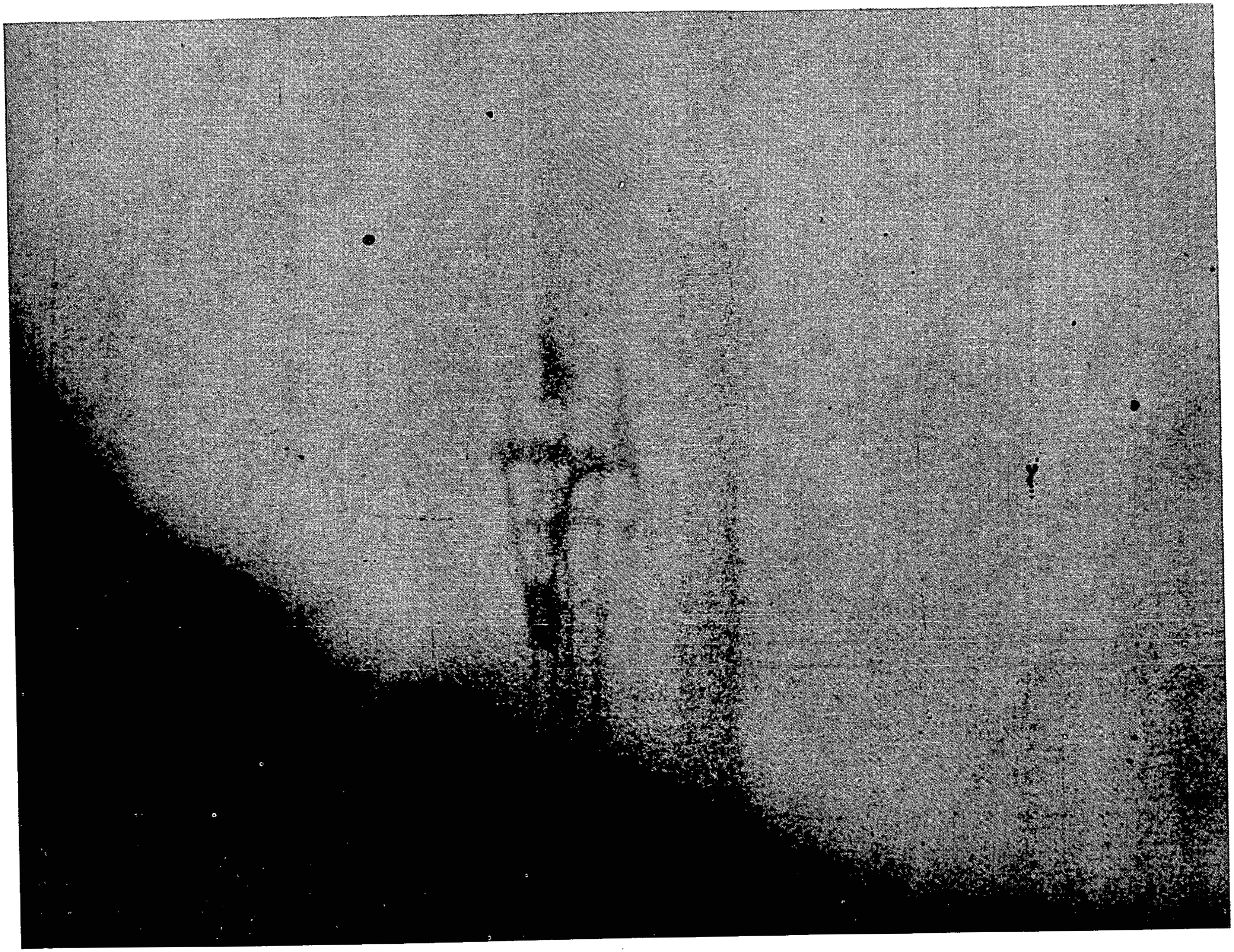


Figure 39. RTG Test Article Nearly Engulfed by Fireball

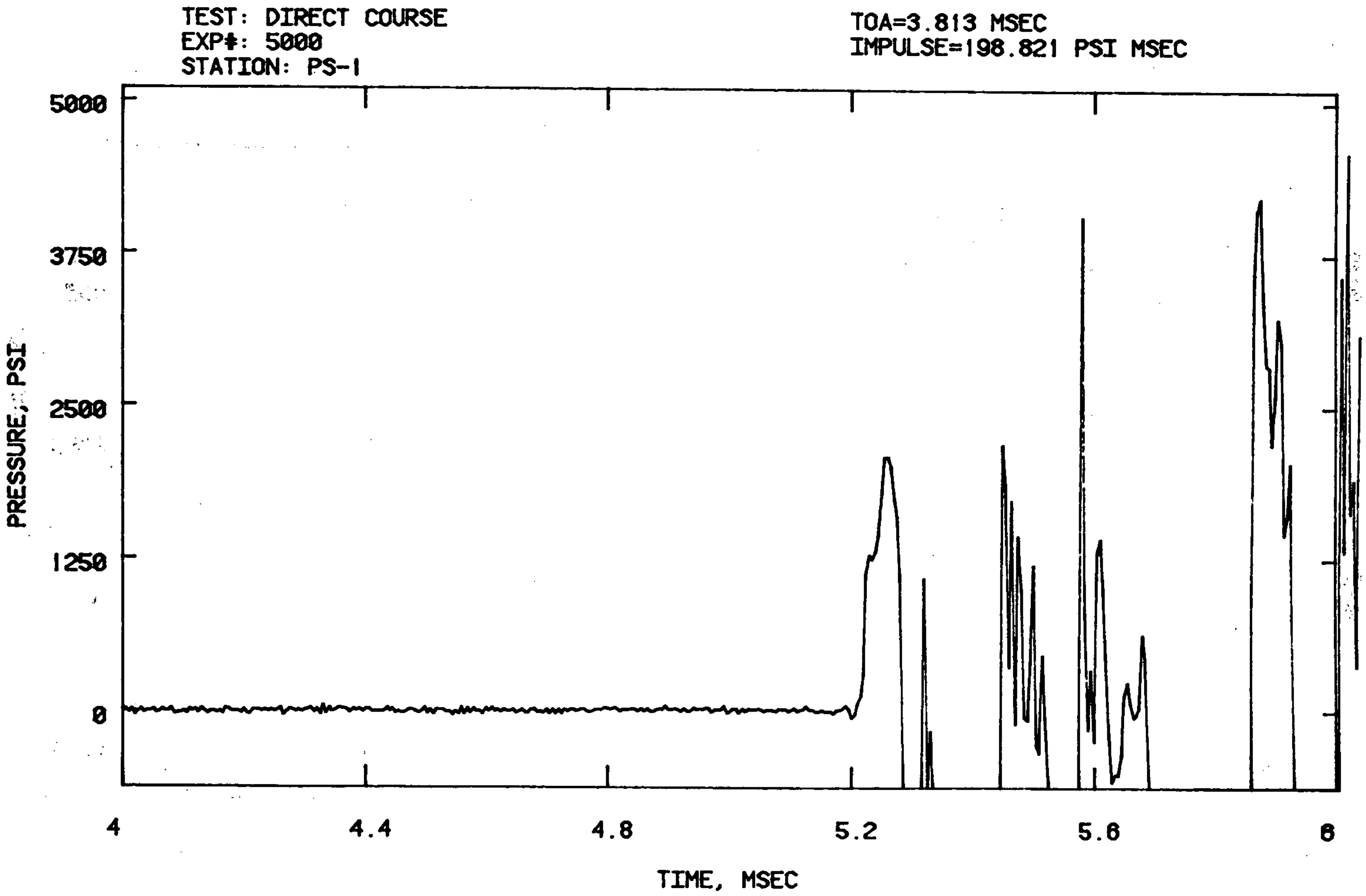


Figure 40. Static Overpressure Record: Gauge PS-1

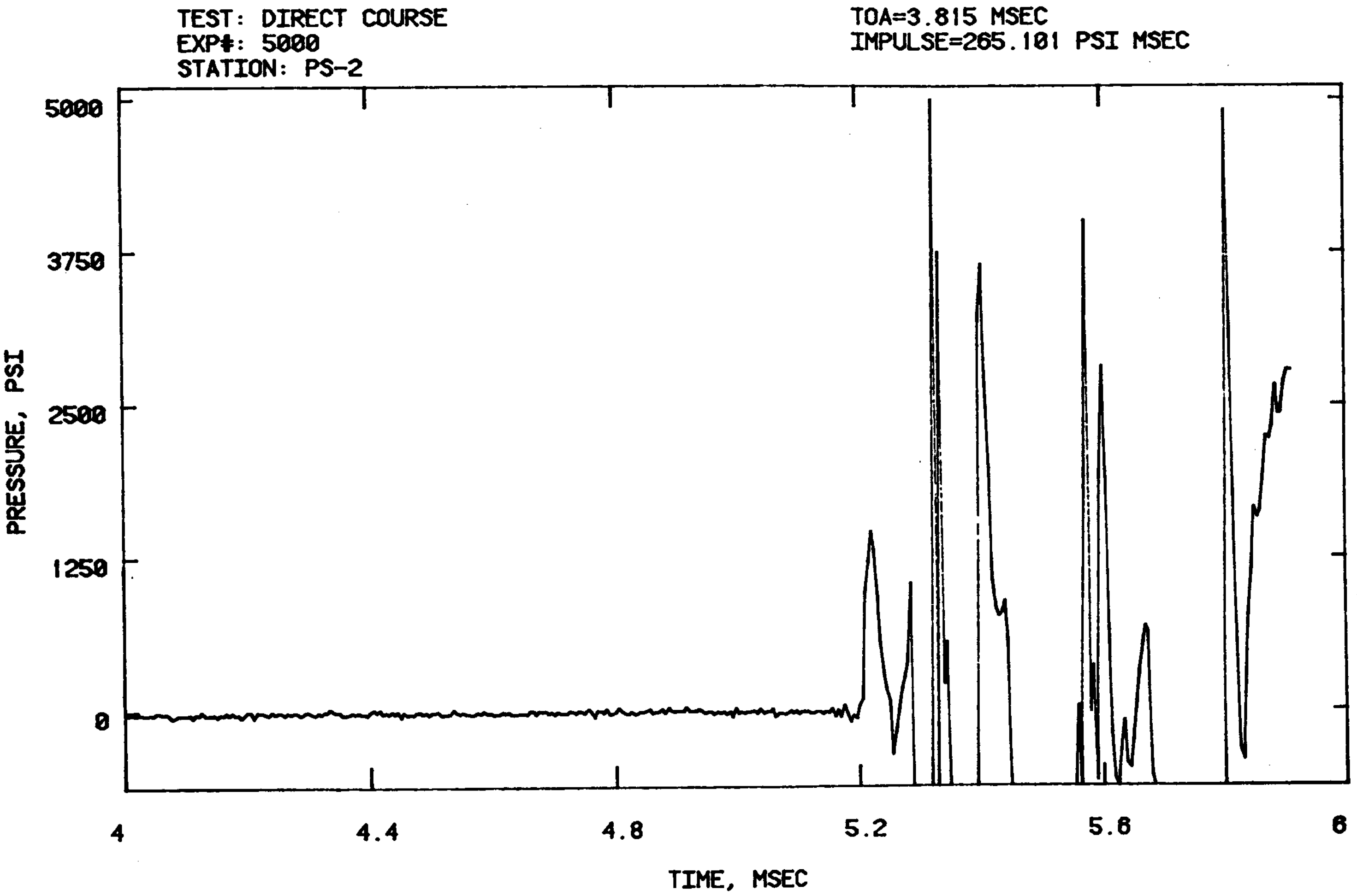


Figure 41. Static Overpressure Record: Gauge PS-2

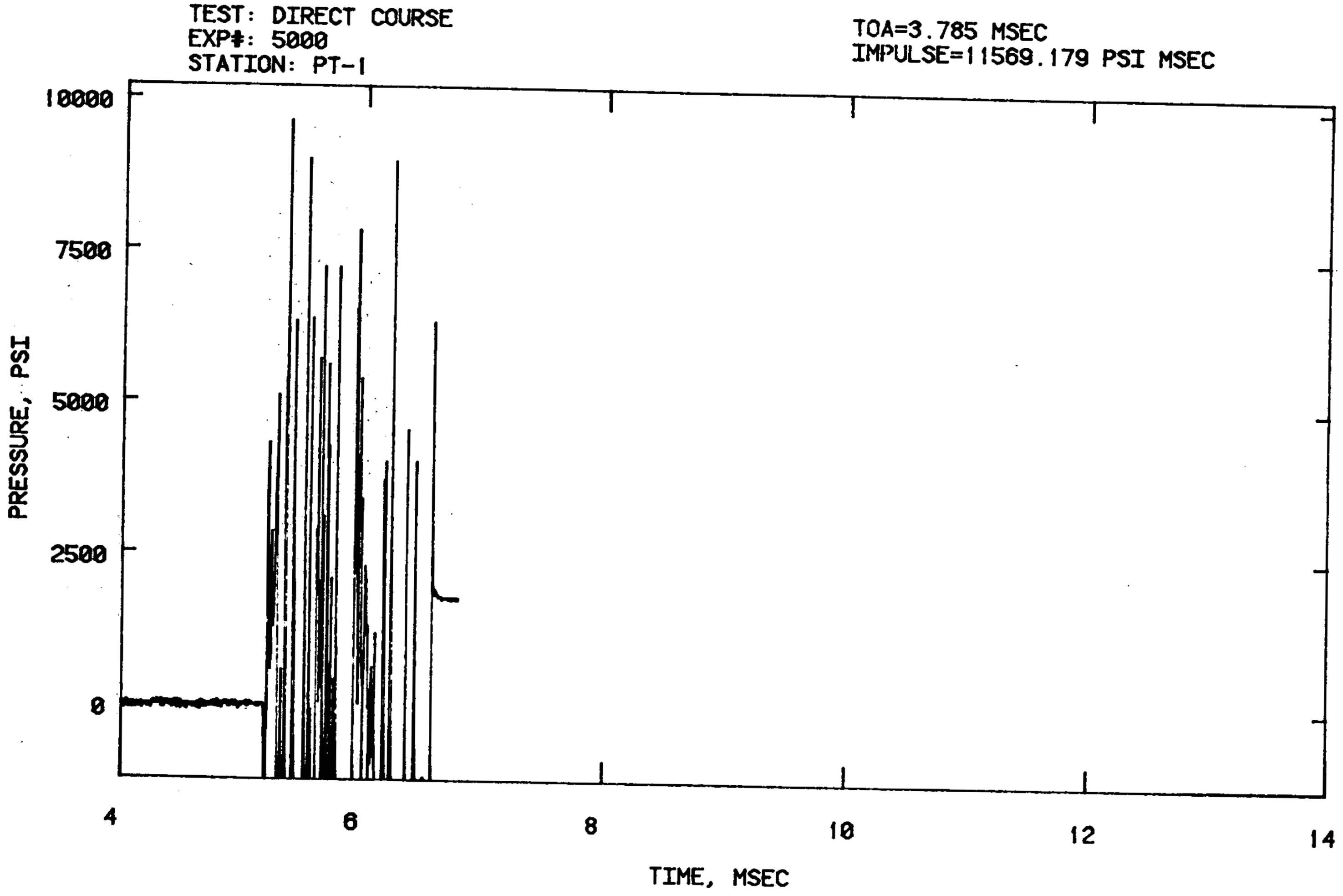


Figure 42. Total Overpressure Record: Gauge PT-1

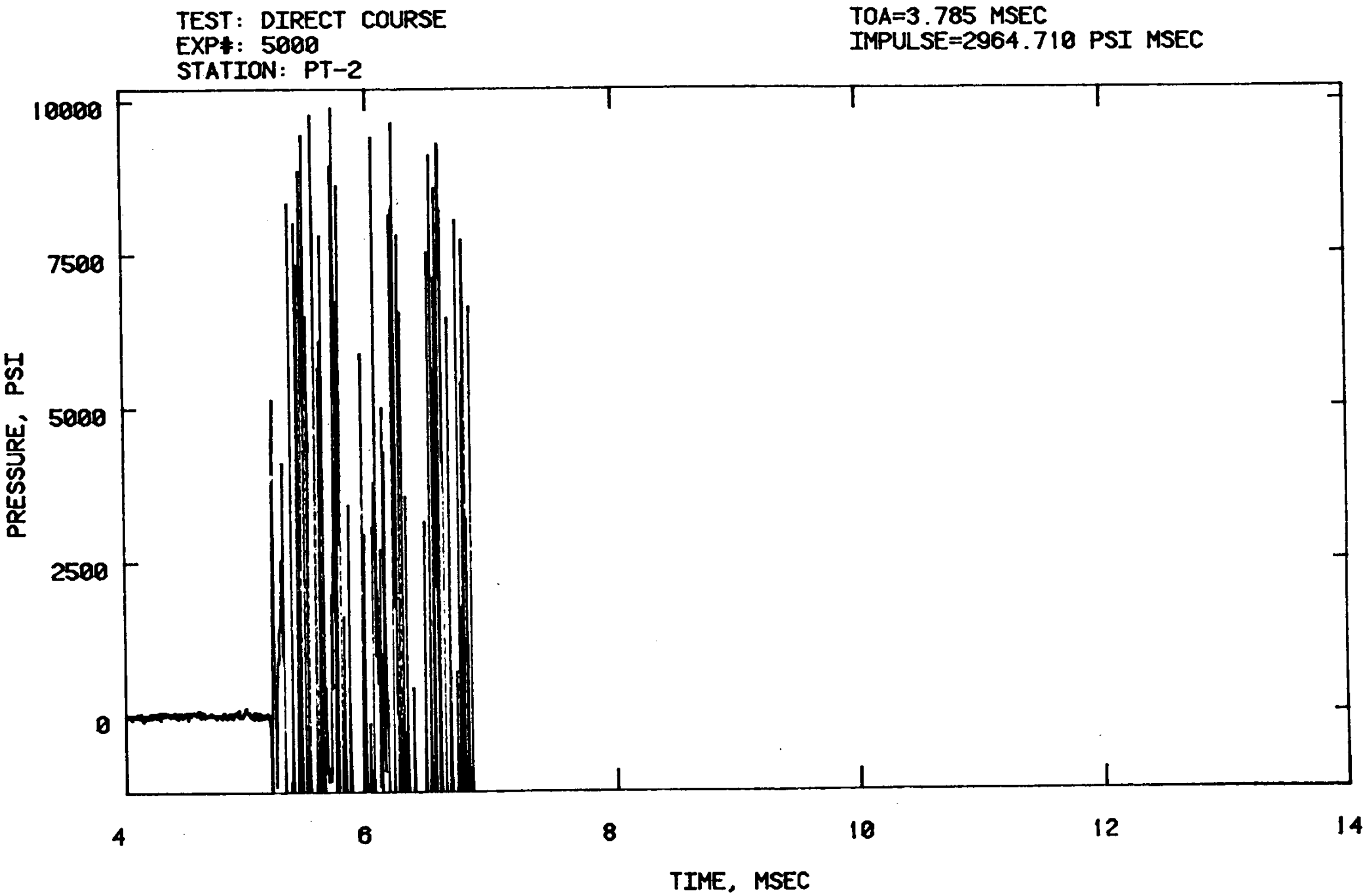


Figure 43. Total Overpressure Record: Gauge PT-2

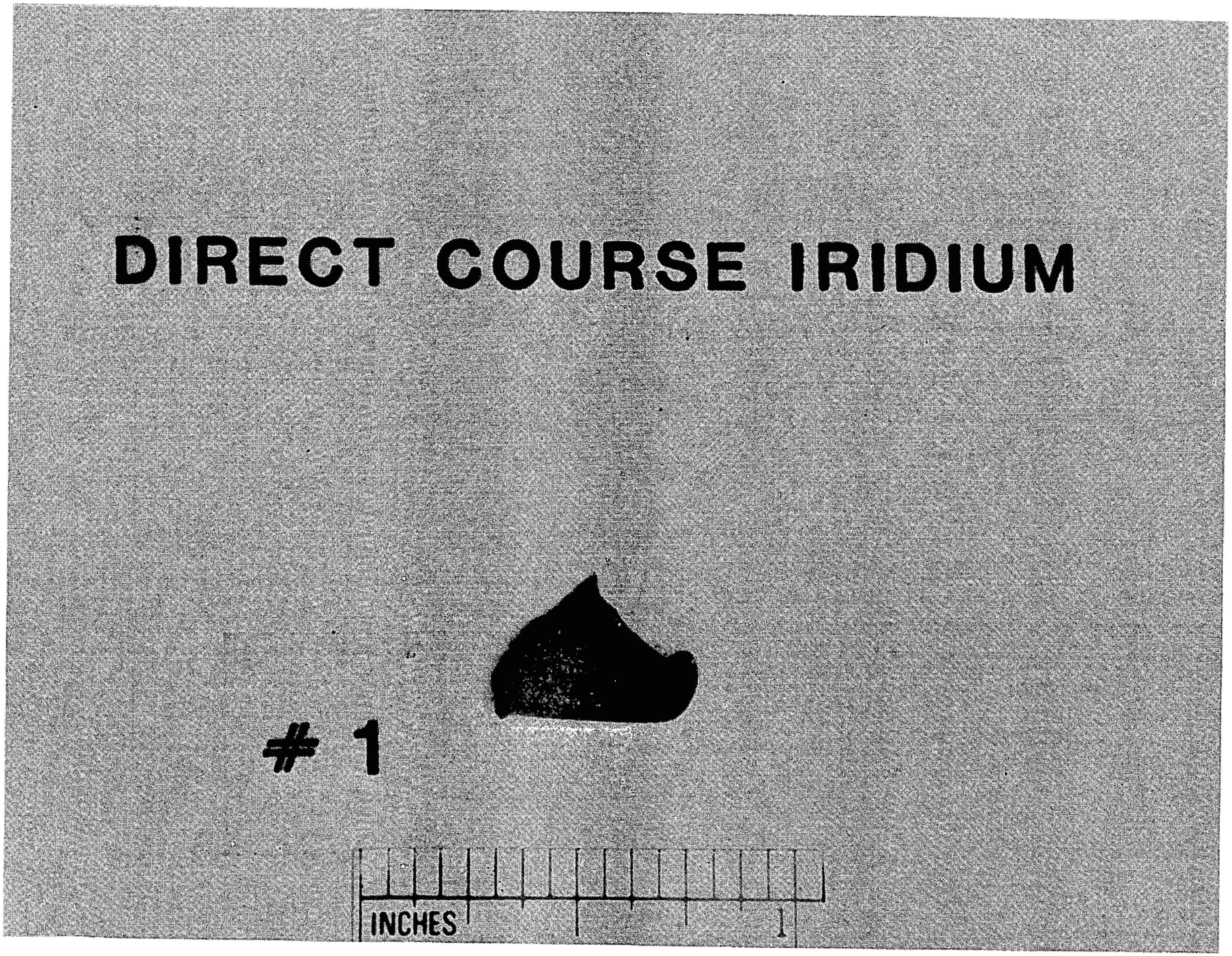


Figure 44. Iridium Fragment #1

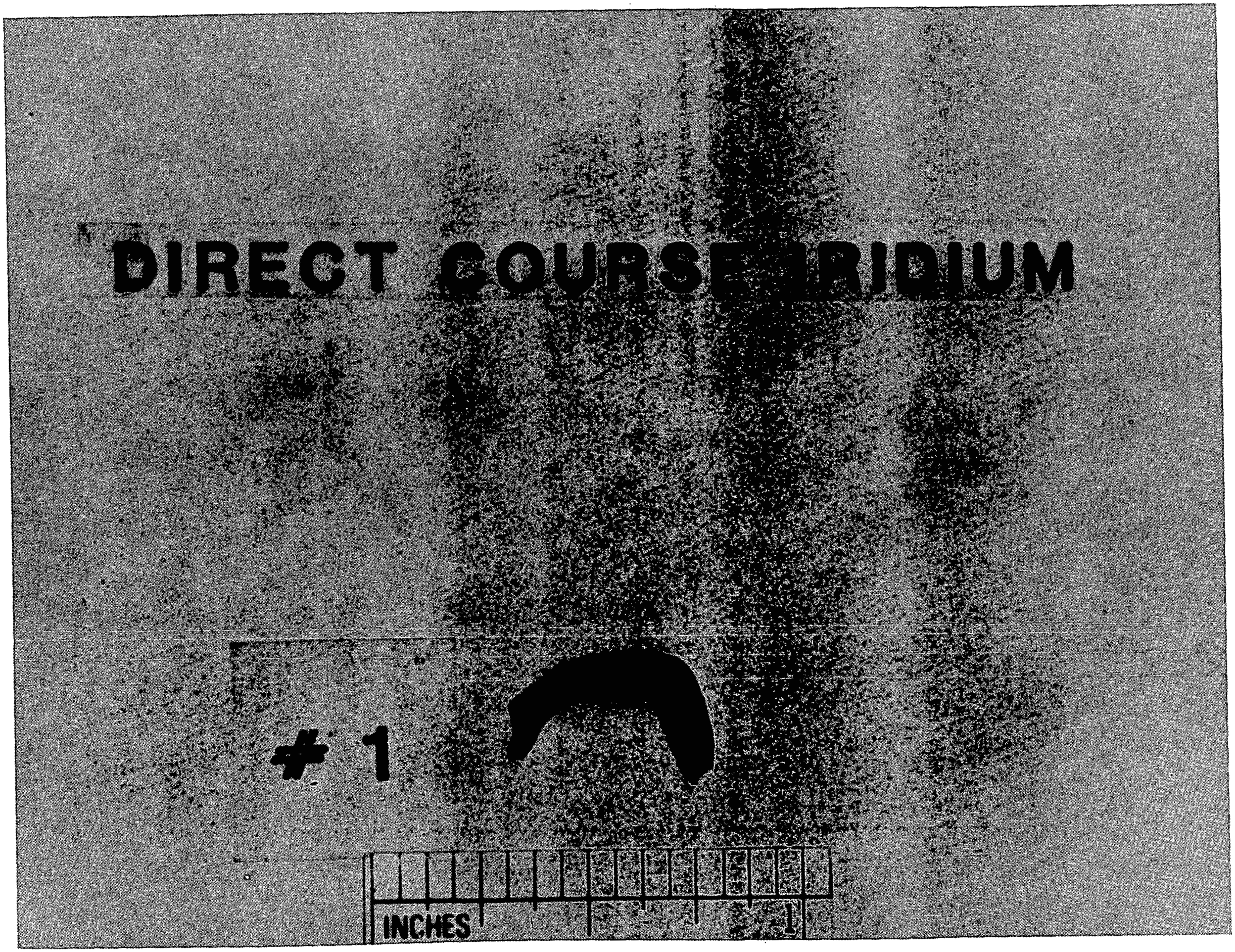


Figure 45. Alternate View - Iridium Fragment #1

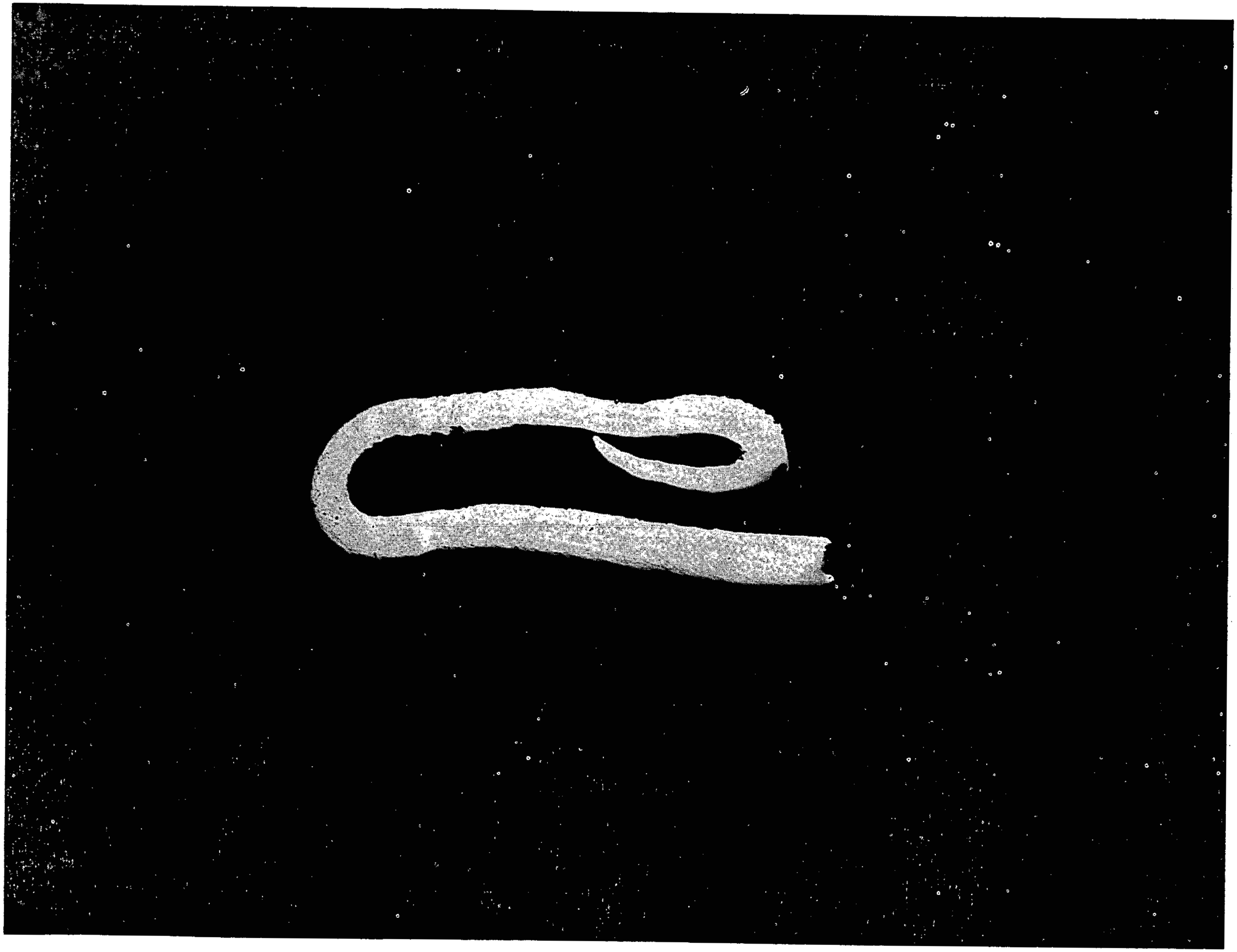


Figure 46. Cross Section - Fragment #1

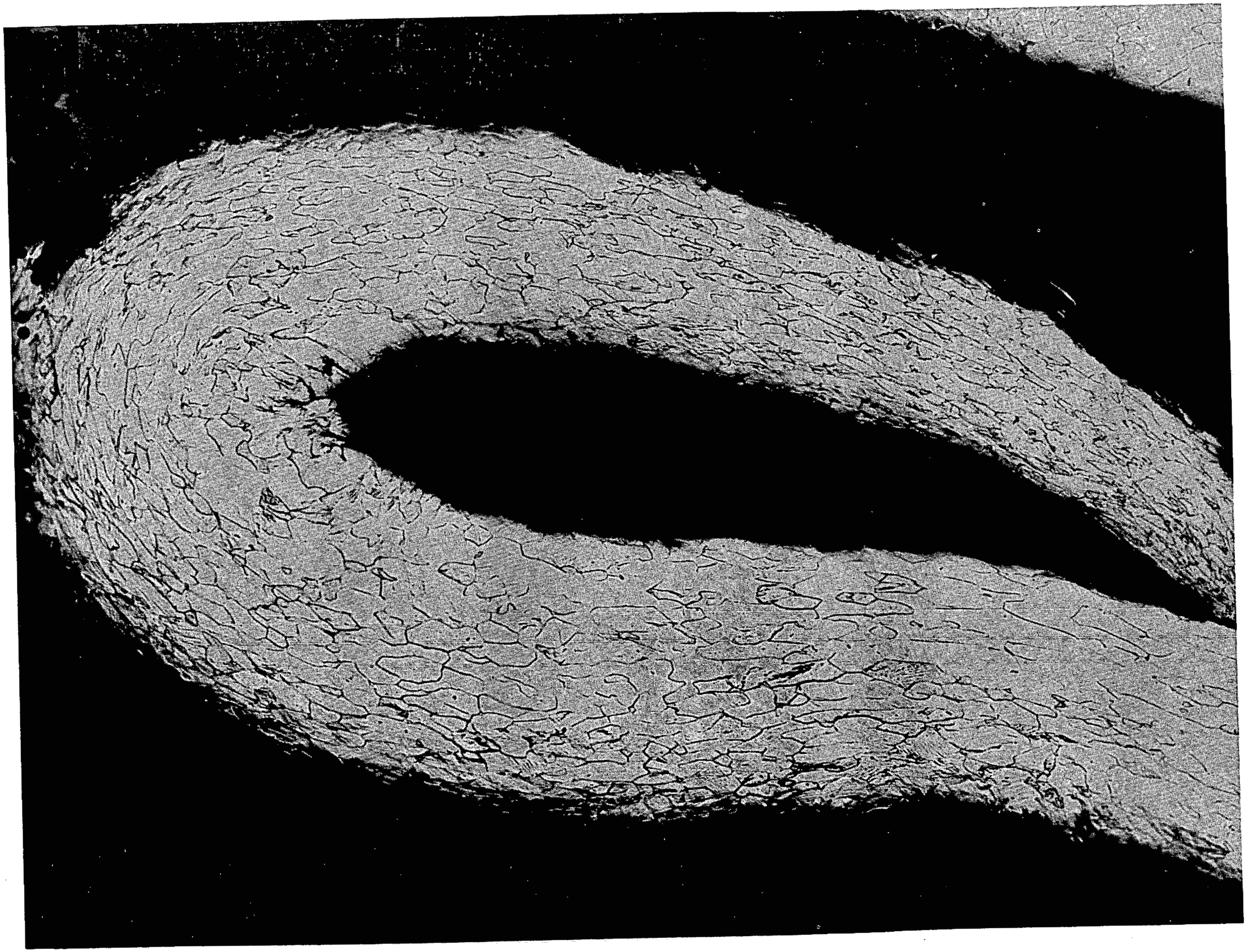


Figure 47. Metallographic Section - Fragment #1

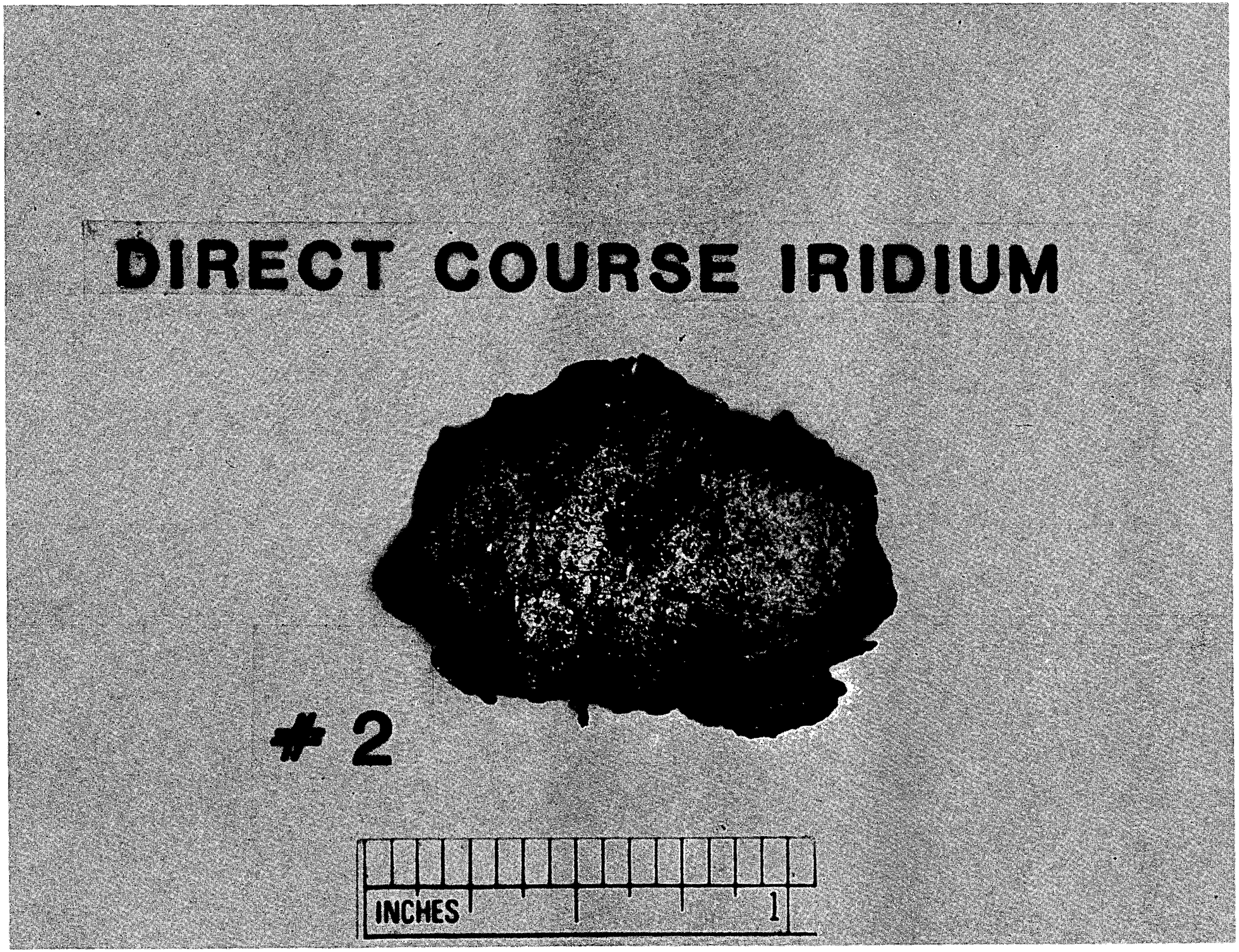


Figure 48. Iridium Fragment #2

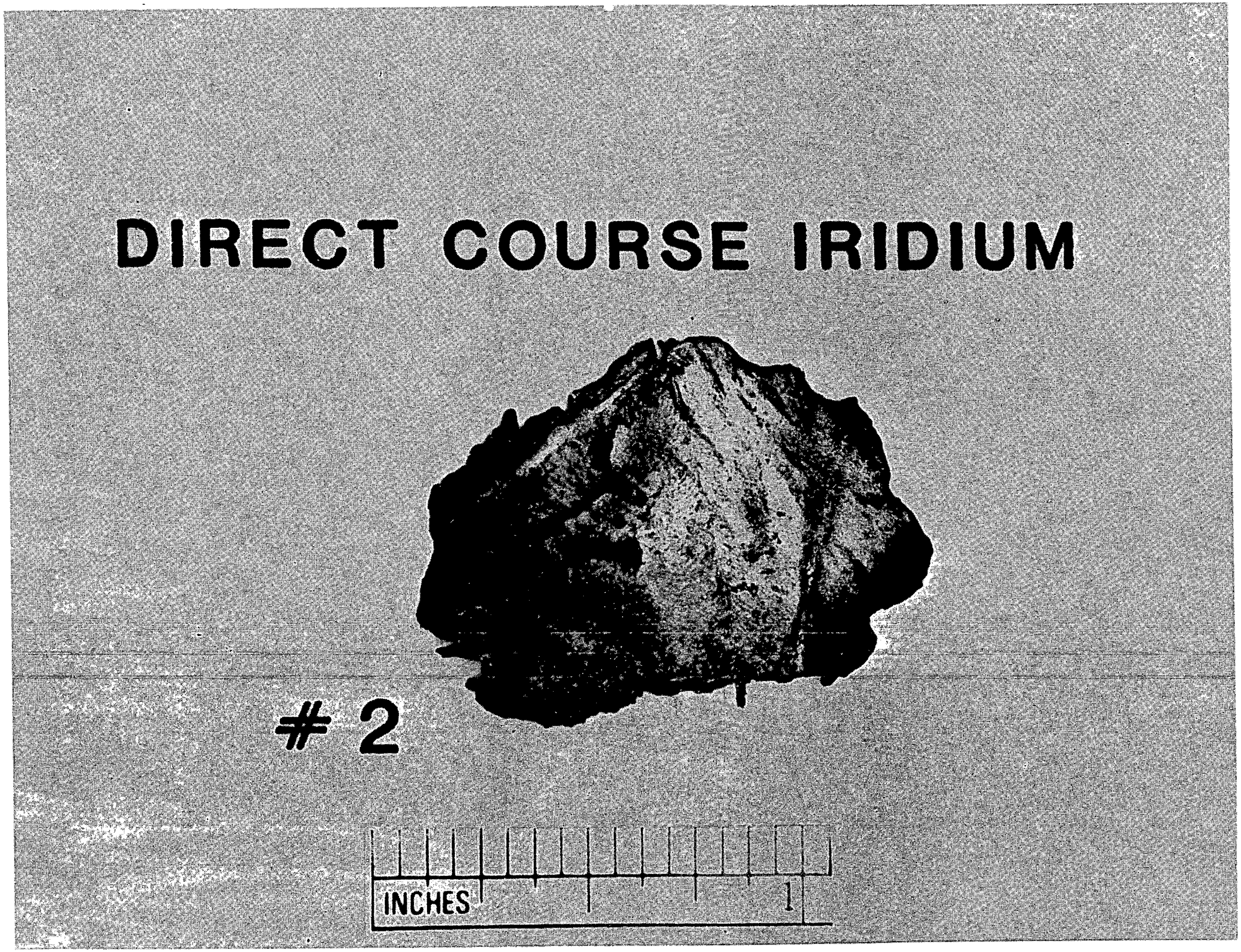


Figure 49. Alternate View - Fragment #2

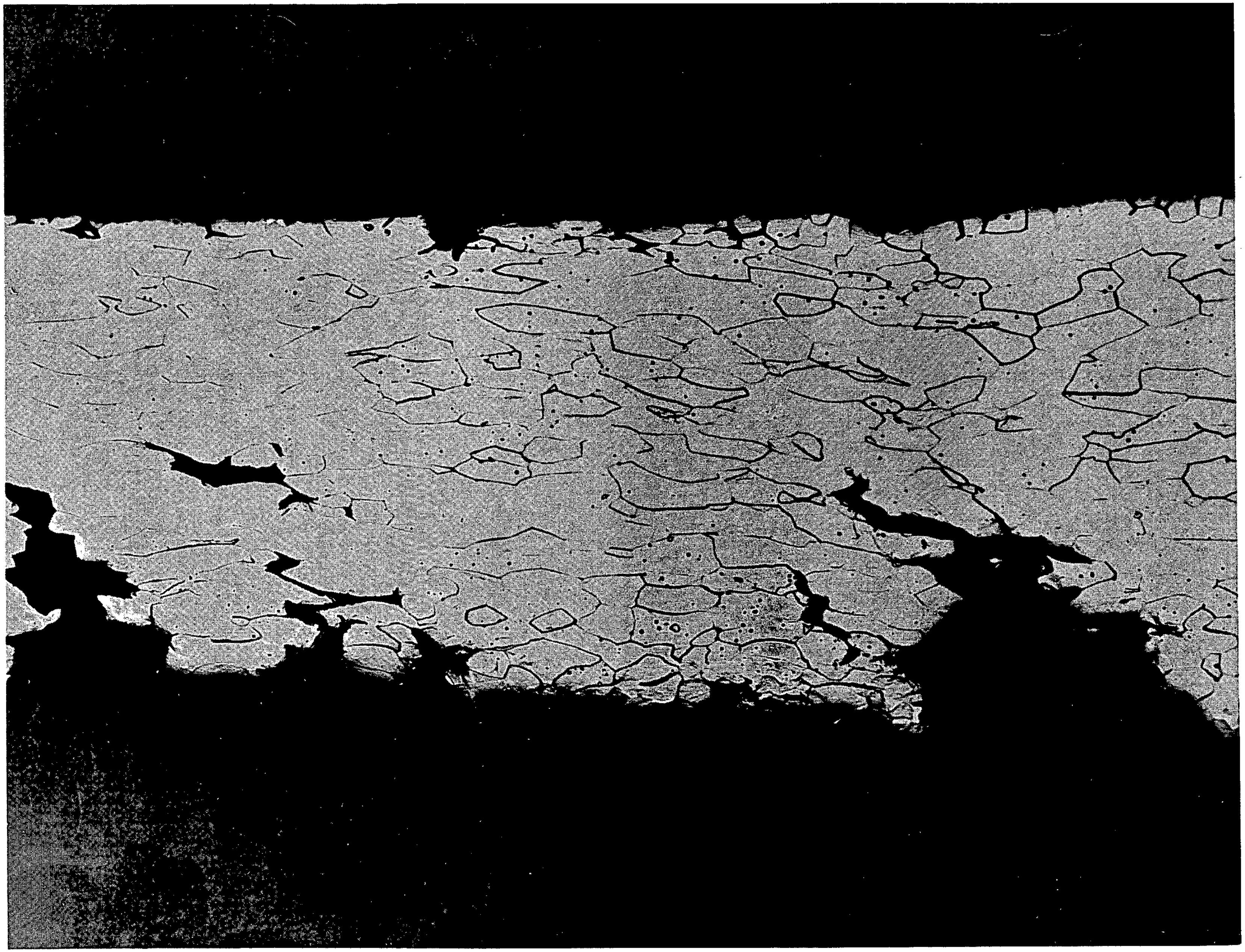


Figure 50. Metallographic Section - Fragment #2

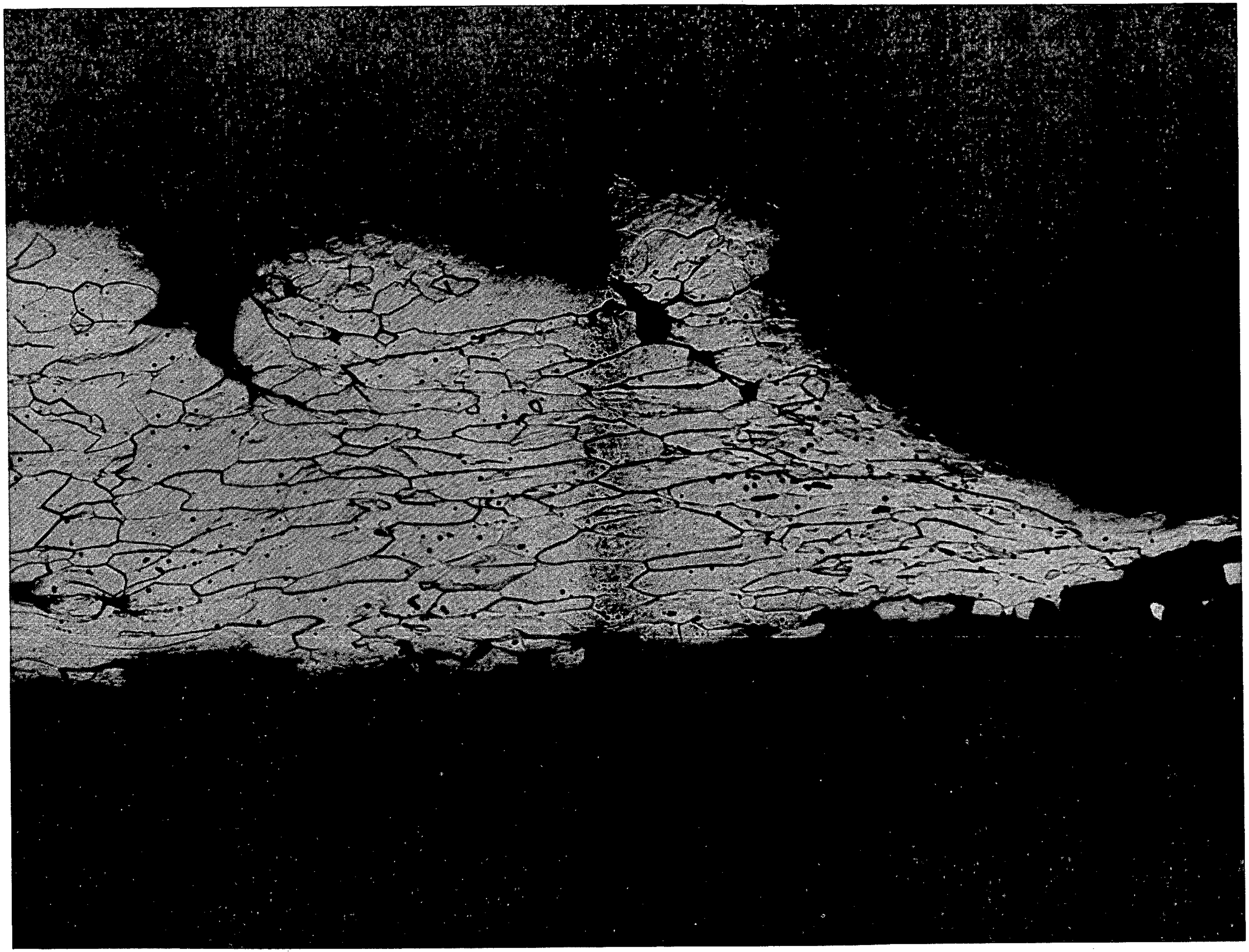


Figure 51. 2nd Metallographic Section - Fragment #2

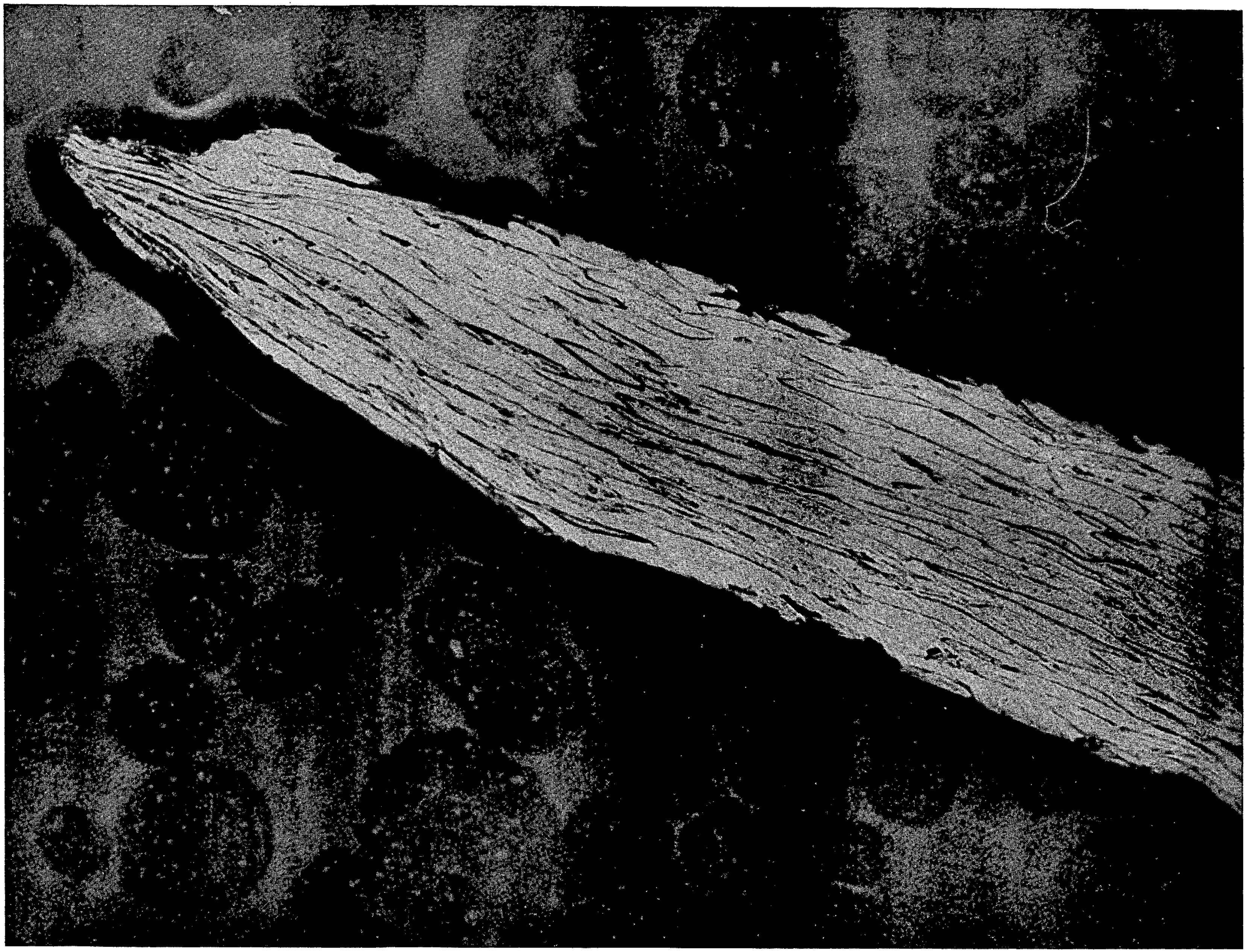


Figure 52. 3rd Metallographic Section - Fragment #2

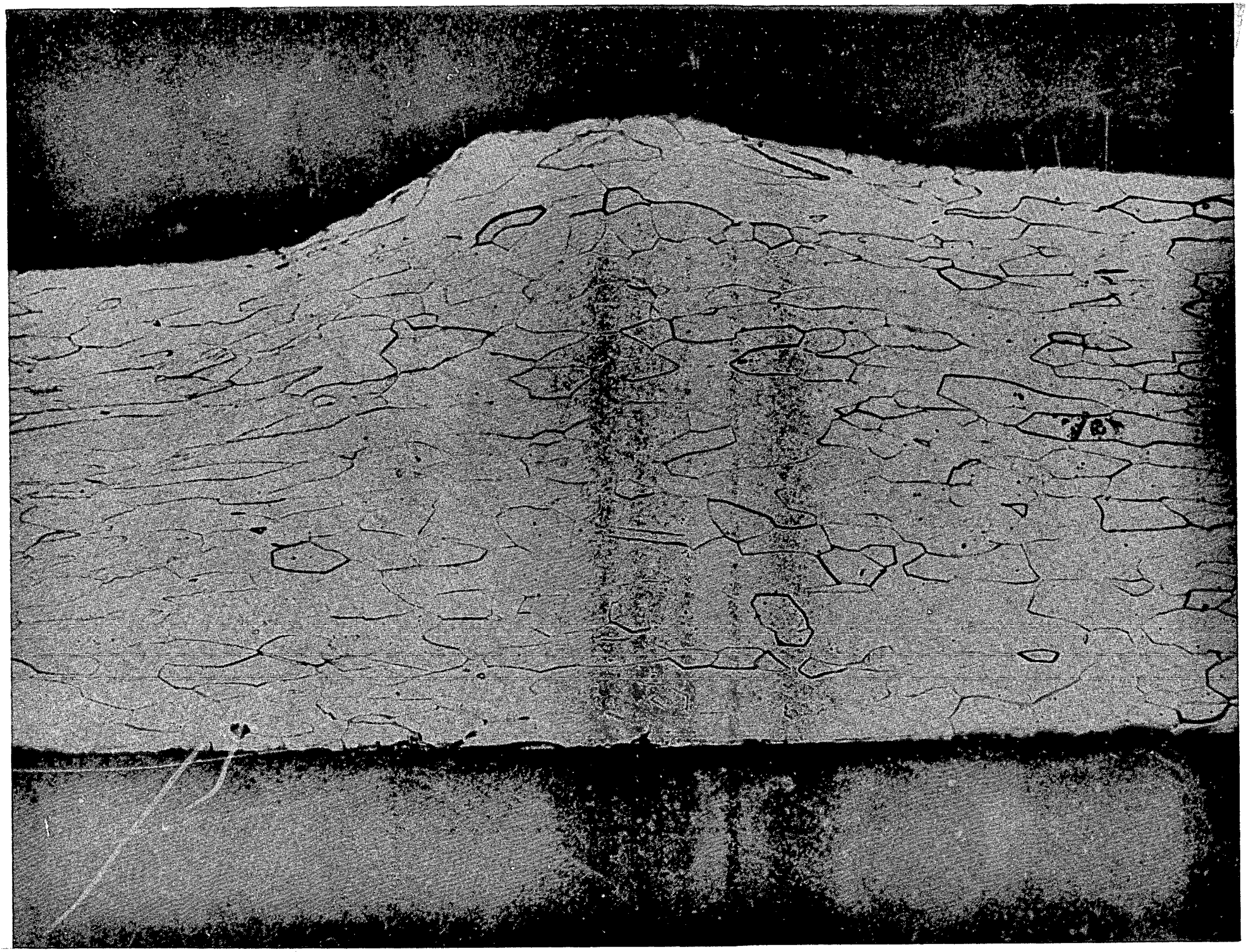


Figure 53. 4th Metallographic Section - Fragment #2

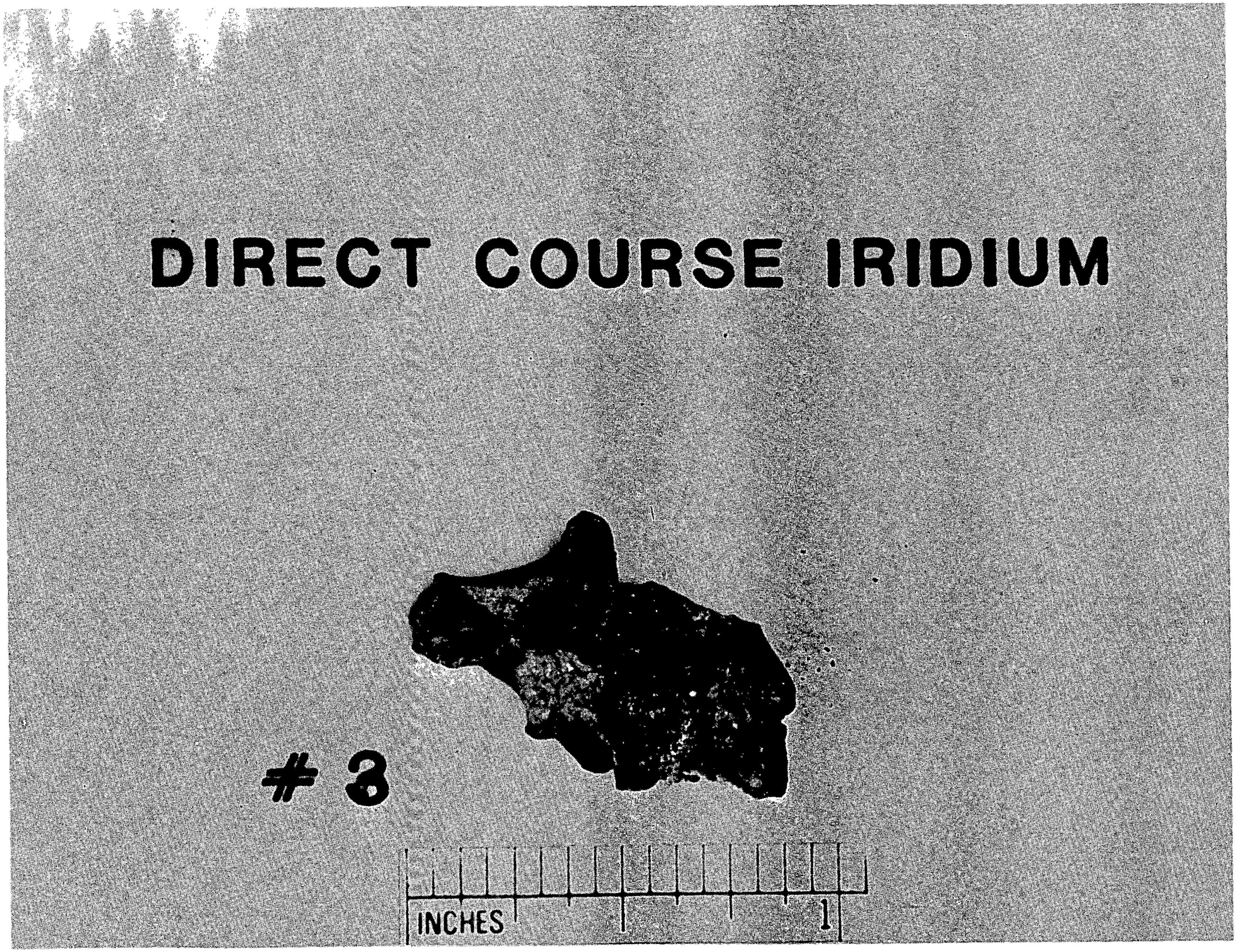


Figure 54. Iridium Fragment #3

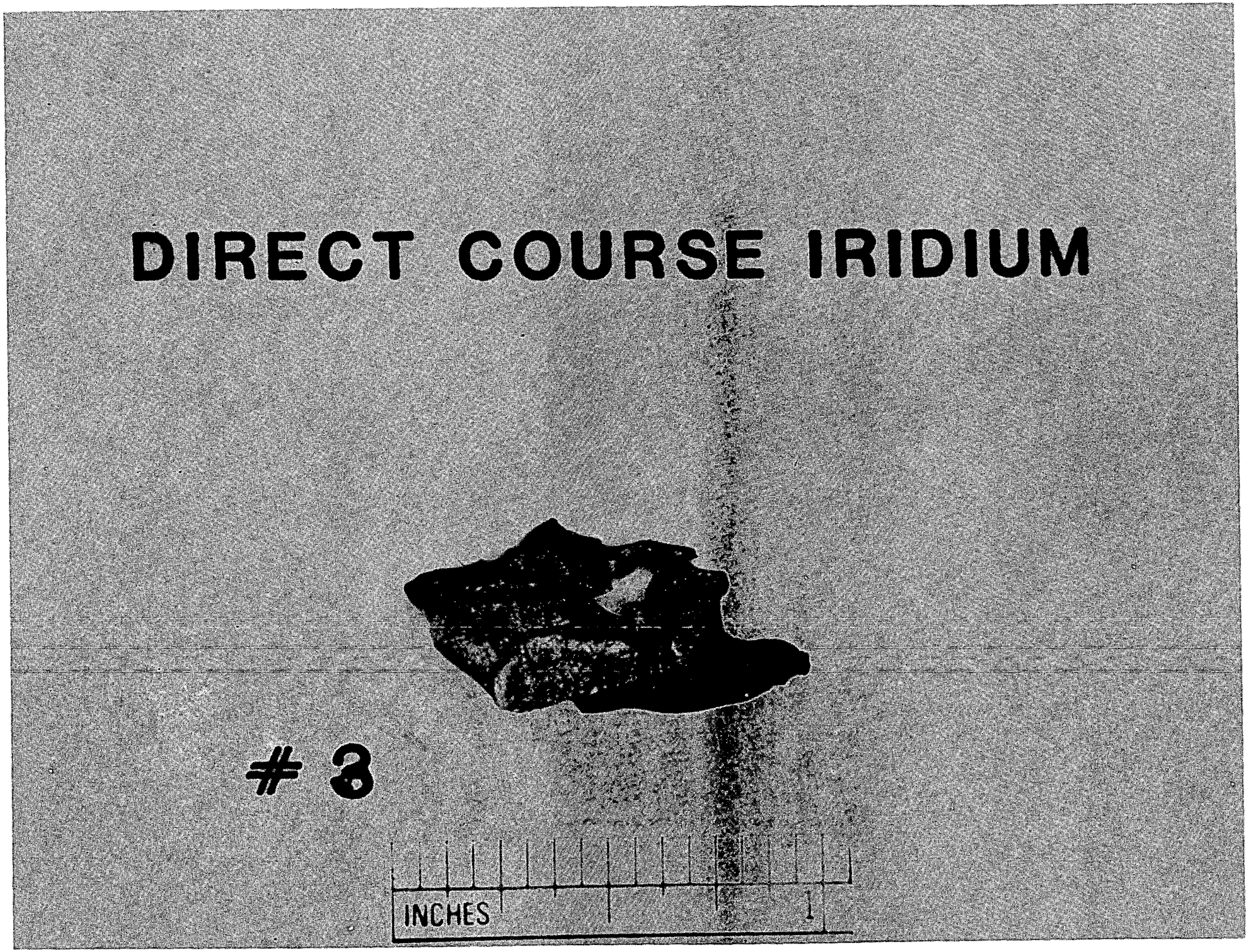


Figure 55. Alternate View - Fragment #3

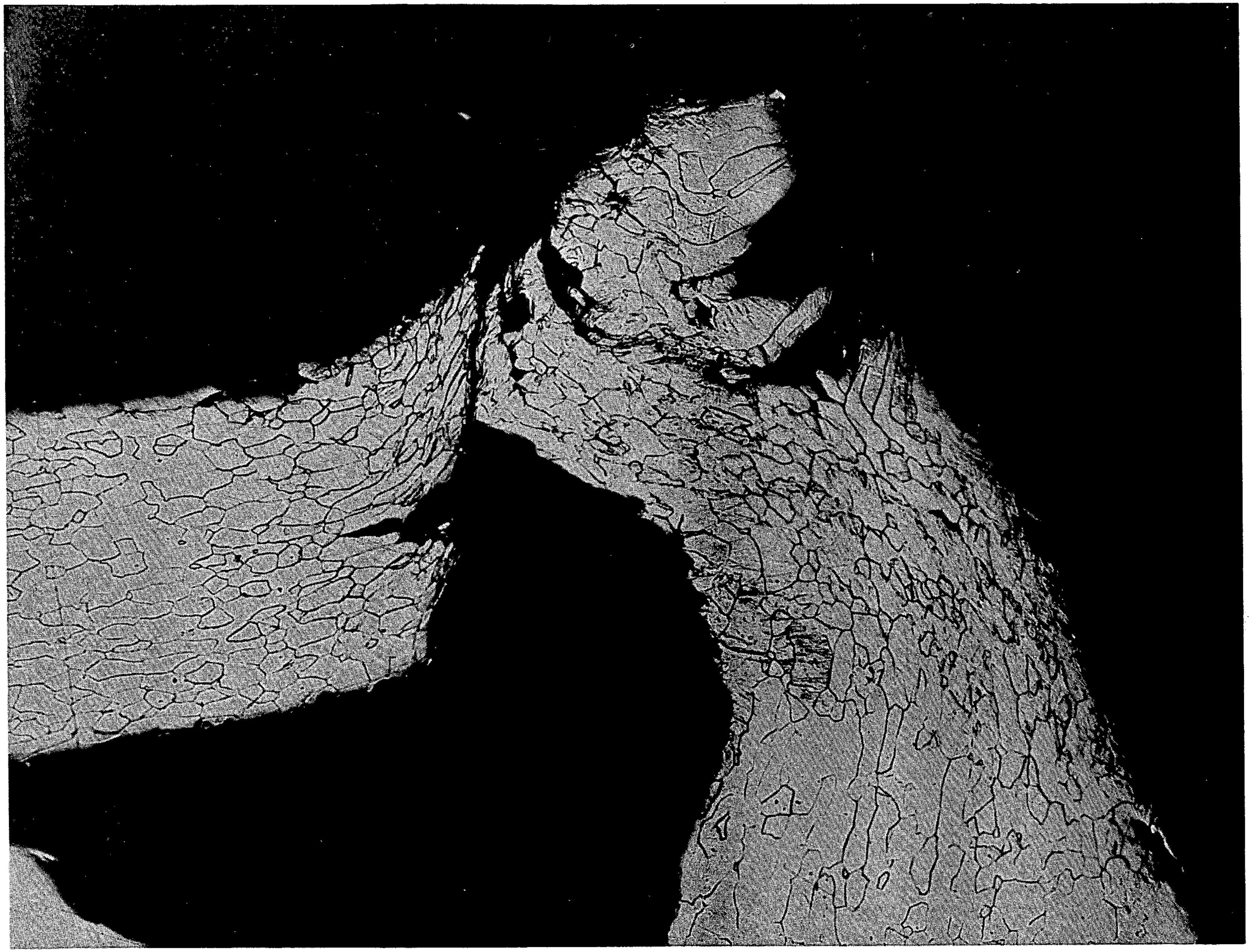


Figure 56. Metallographic Section - Fragment #3

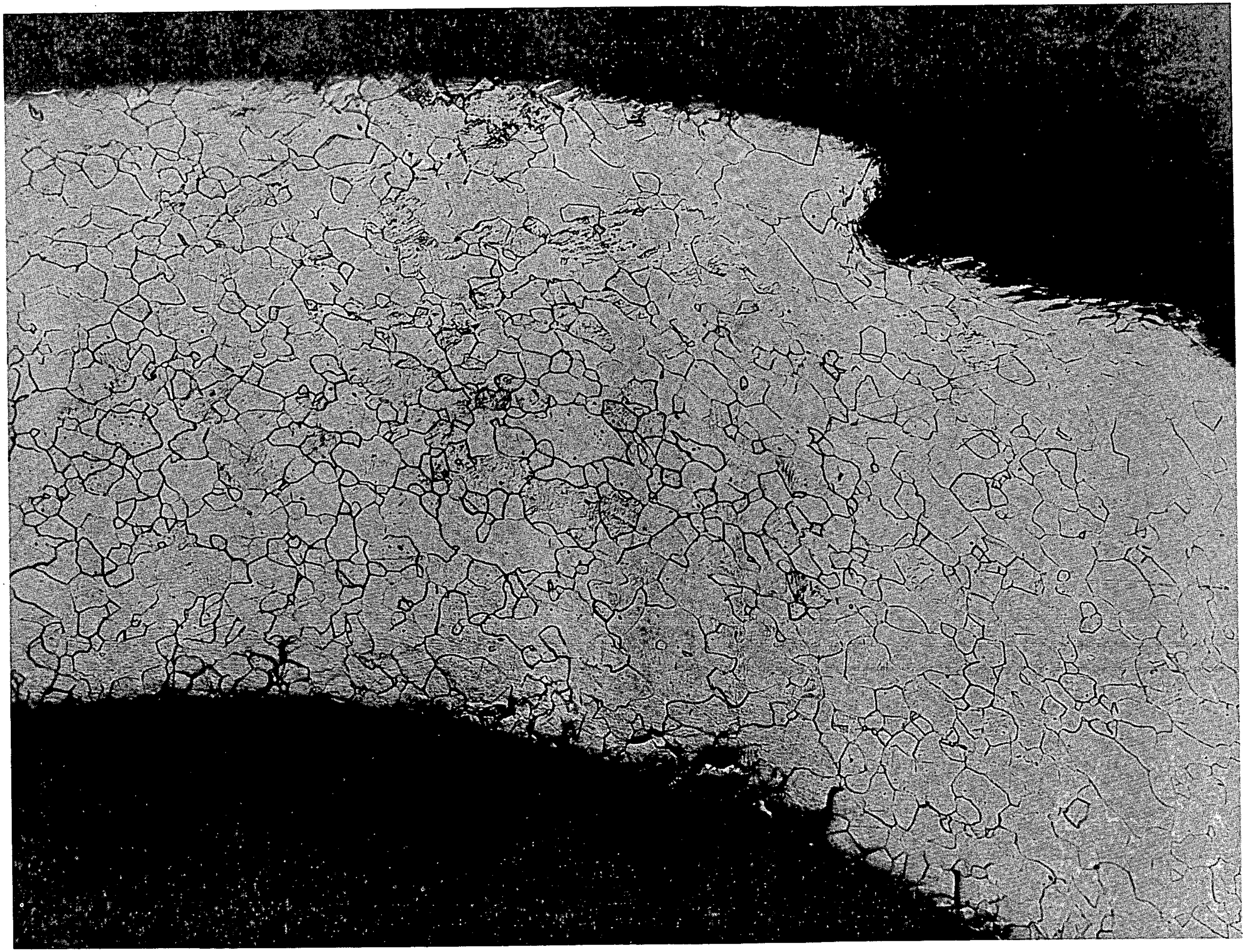


Figure 57. 2nd Metallographic Section - Fragment #3

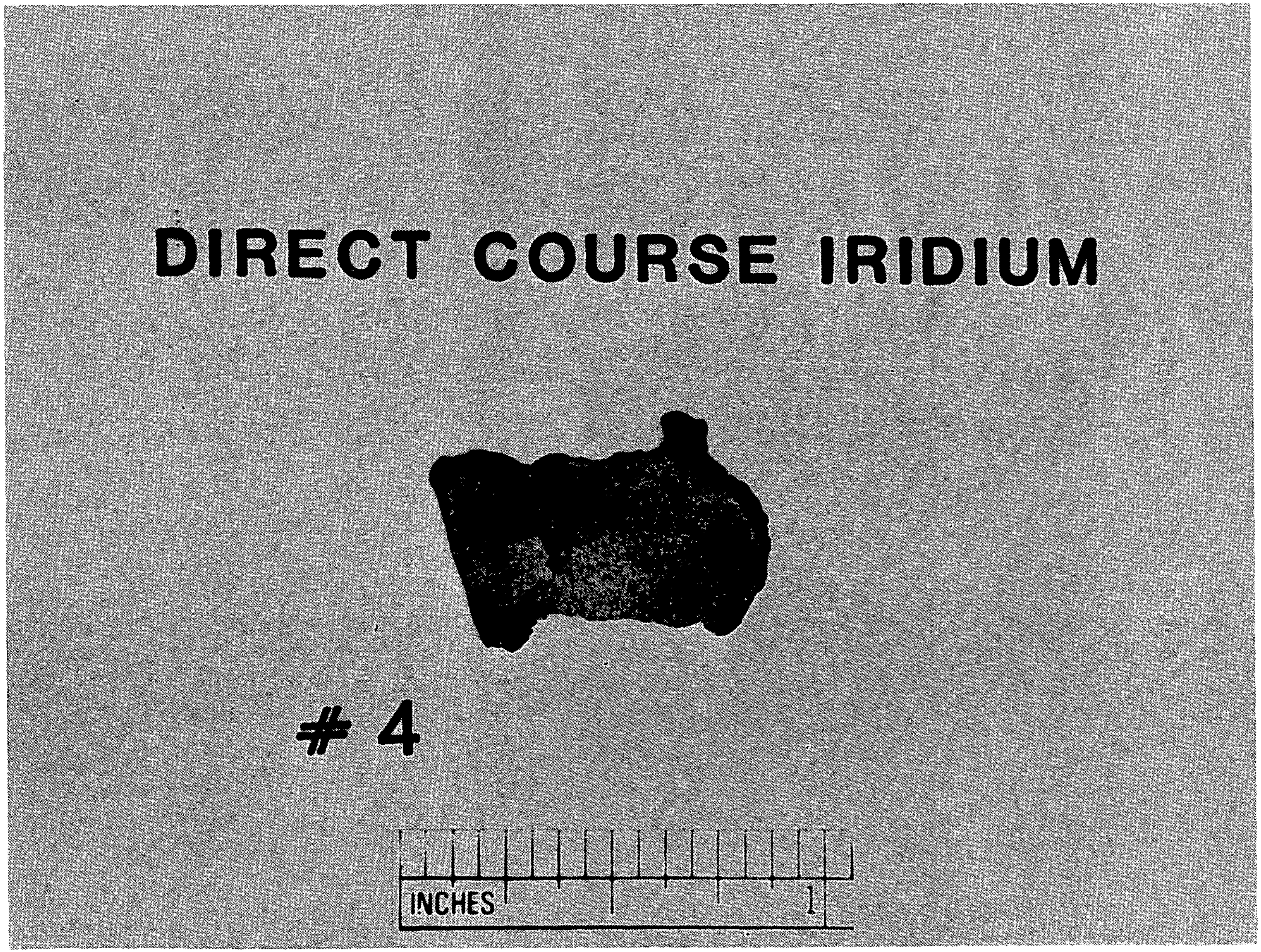


Figure 58. Iridium Fragment #4

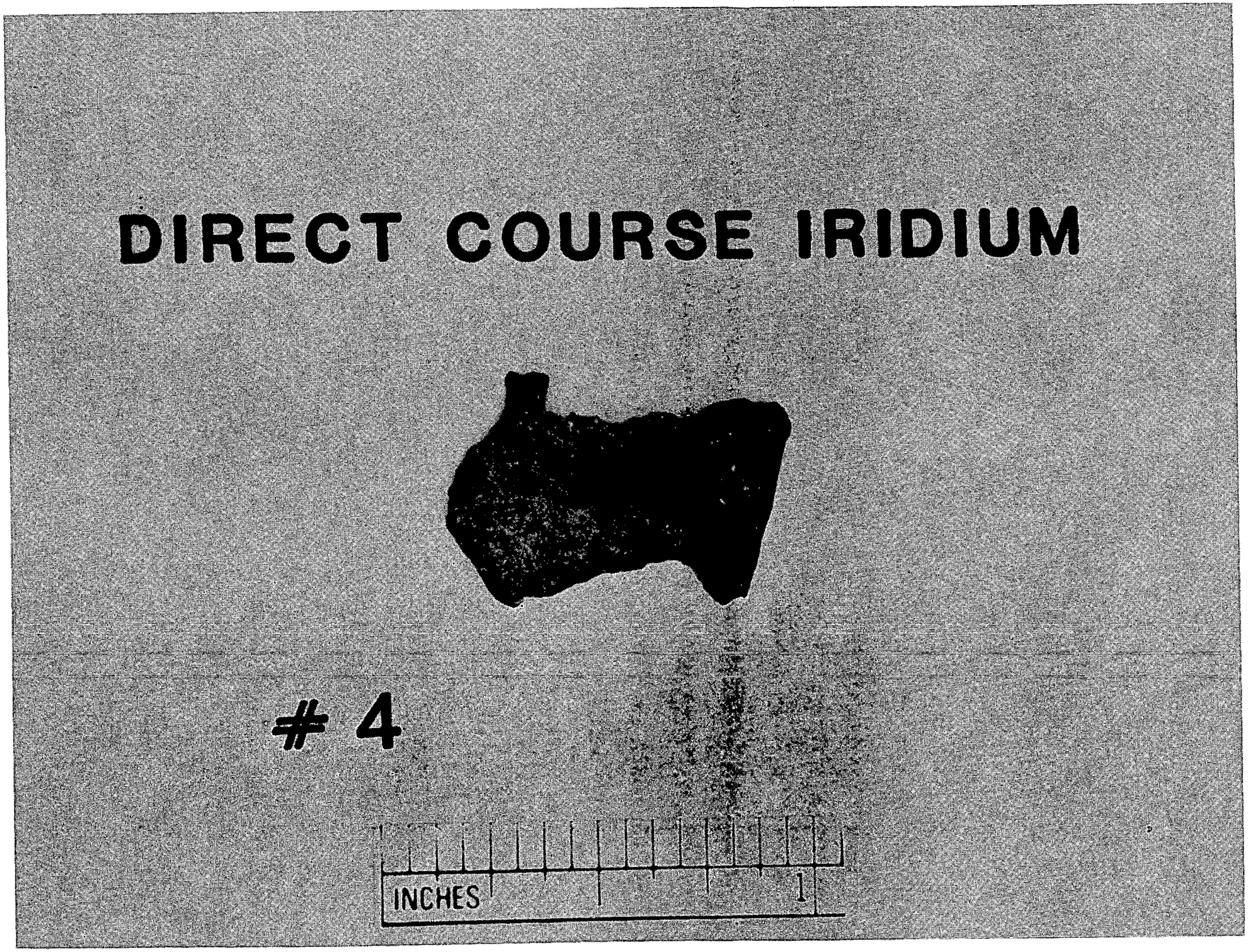


Figure 59. Alternate View - Iridium Fragment #4

Figure 60. Cross Section - Fragment #4

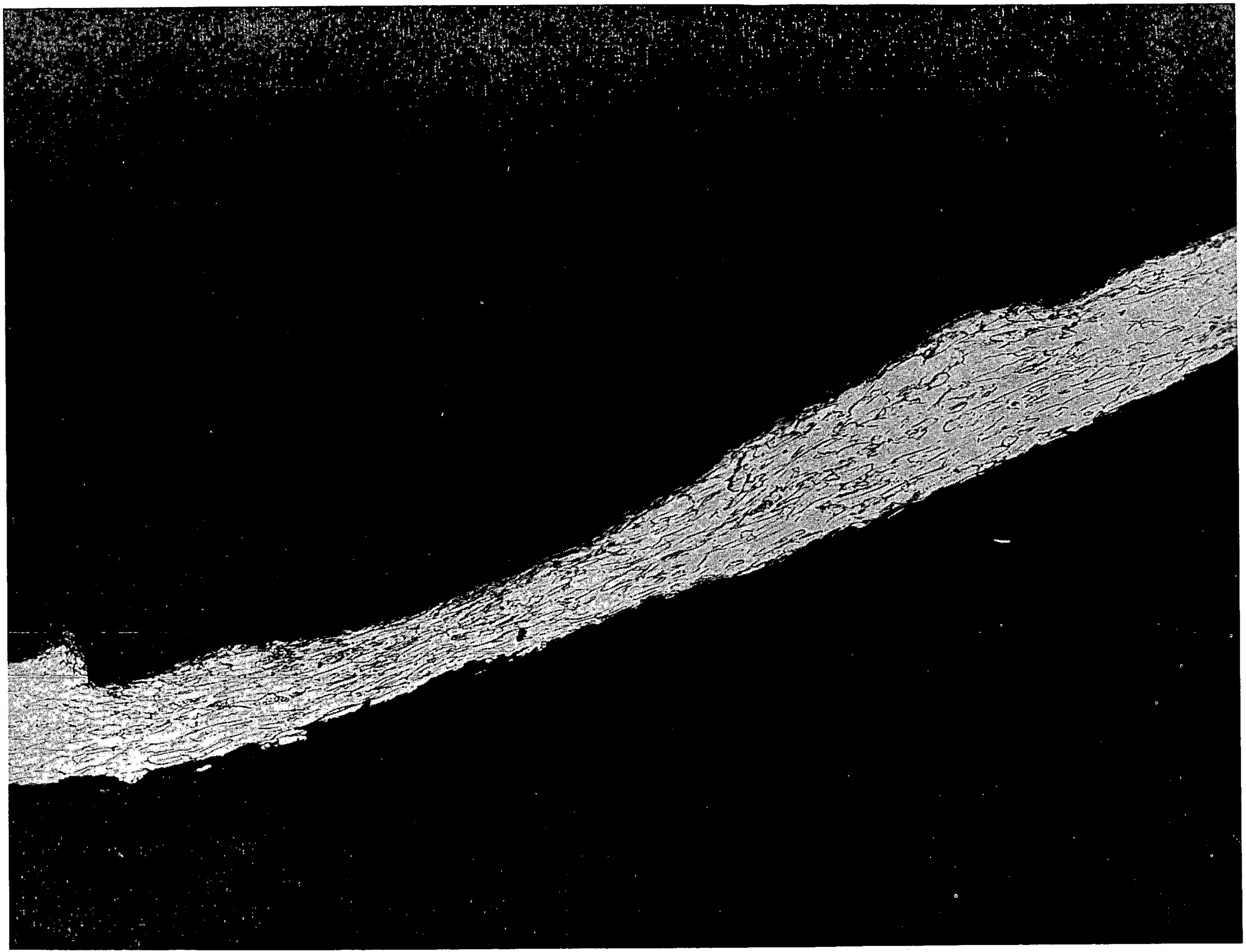


Figure 61. Metallographic Section - Fragment #4

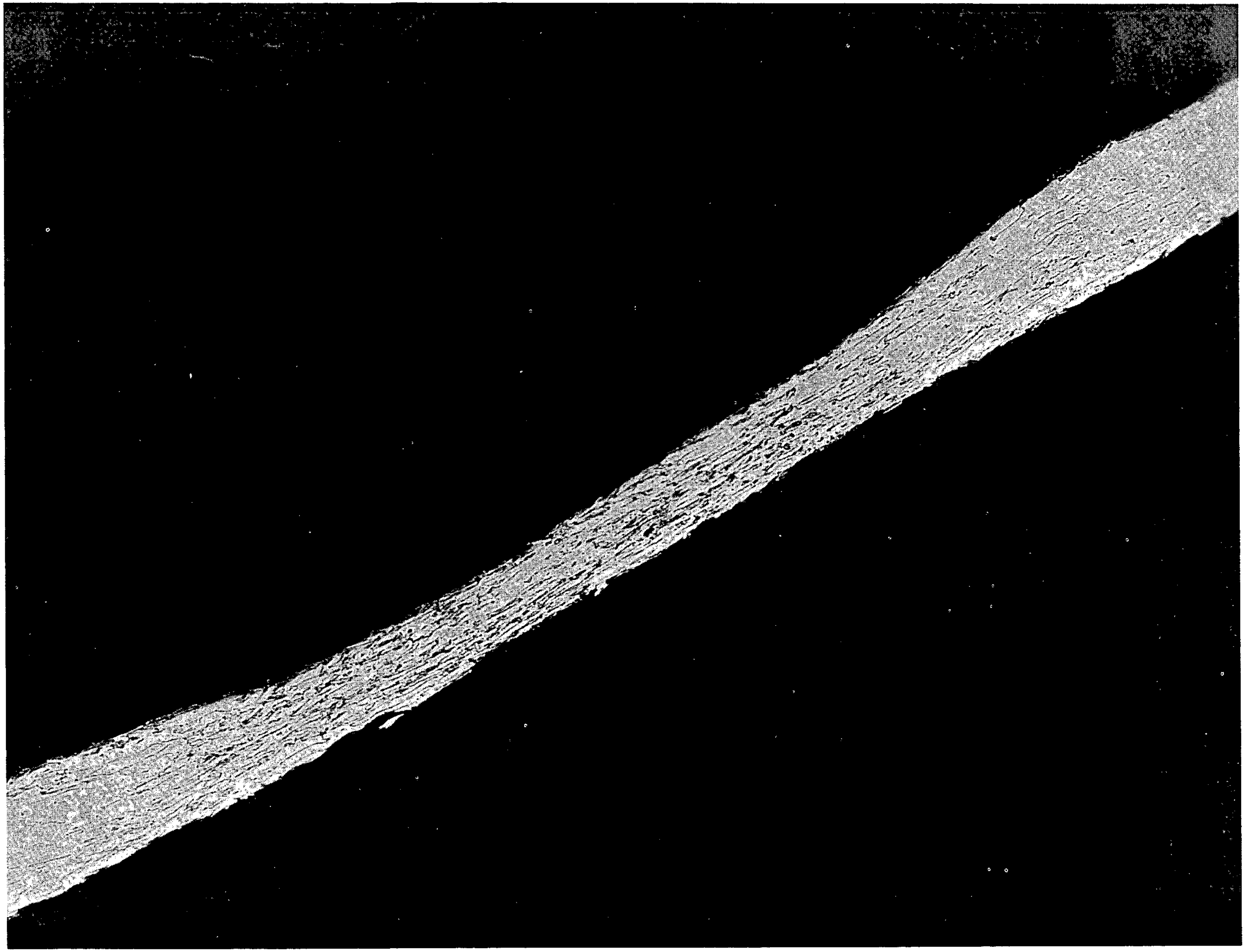


Figure 62. 2nd Metallographic Section - Fragment #4

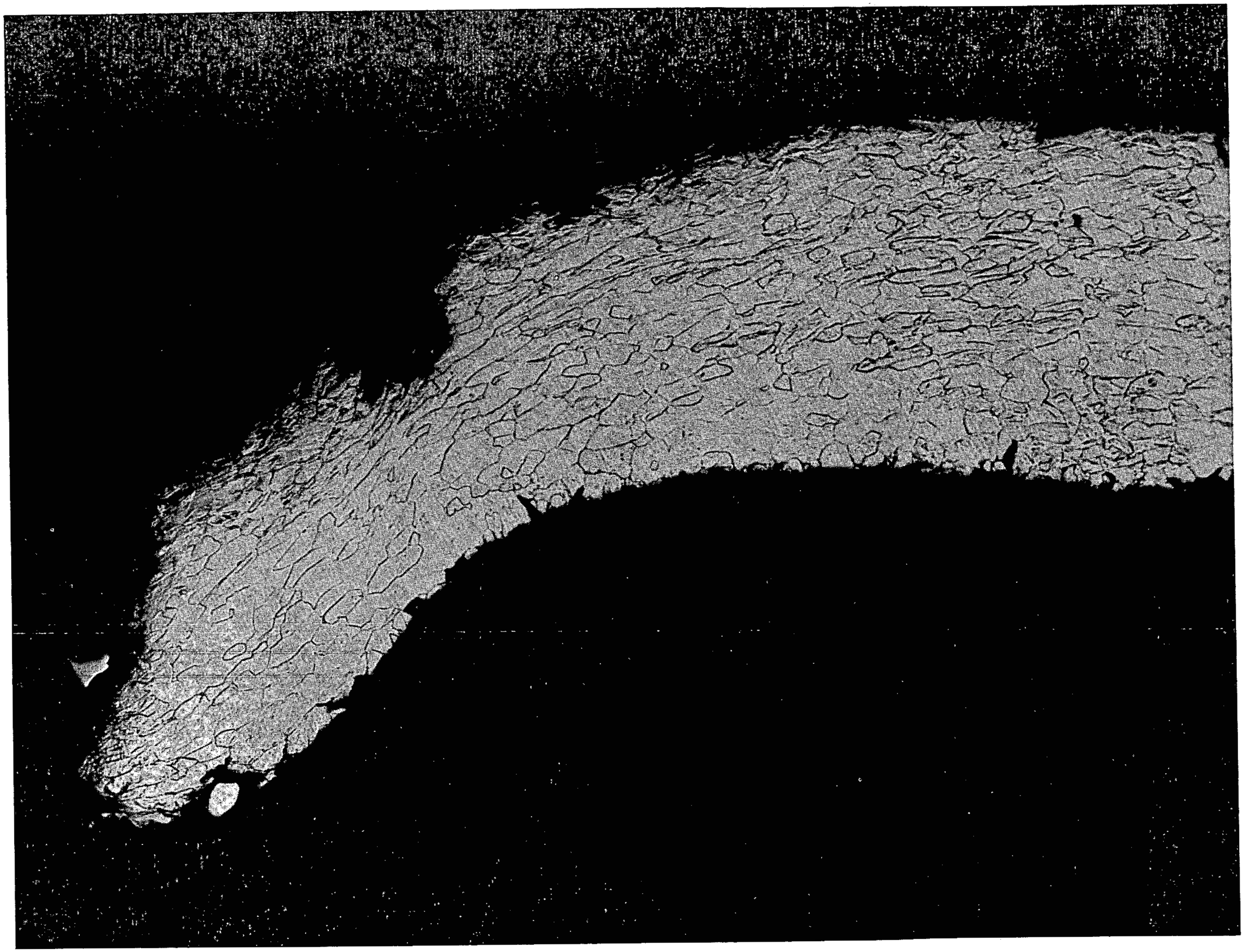


Figure 63. 3rd Metallographic Section - Fragment #4

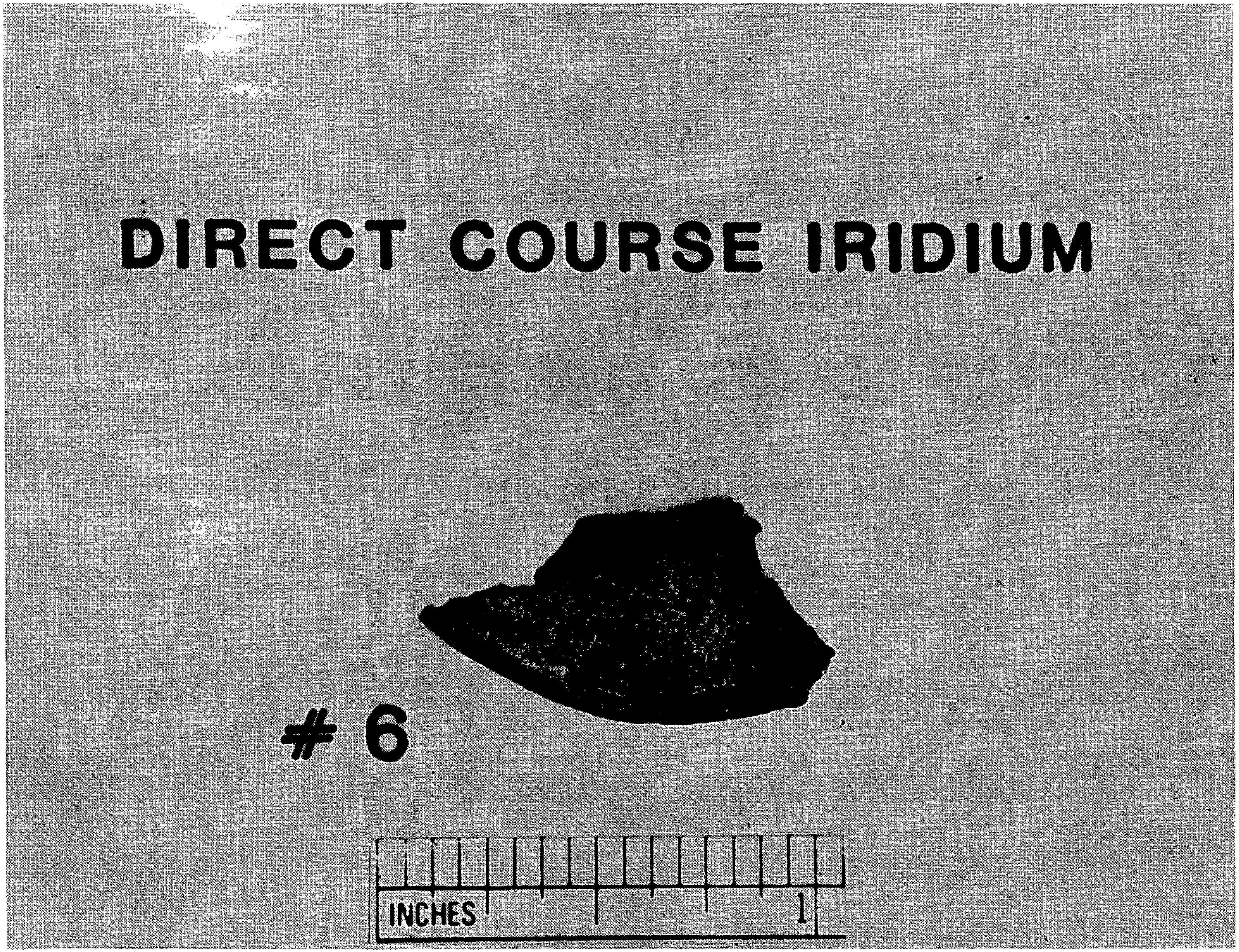


Figure 64. Iridium Fragment #6

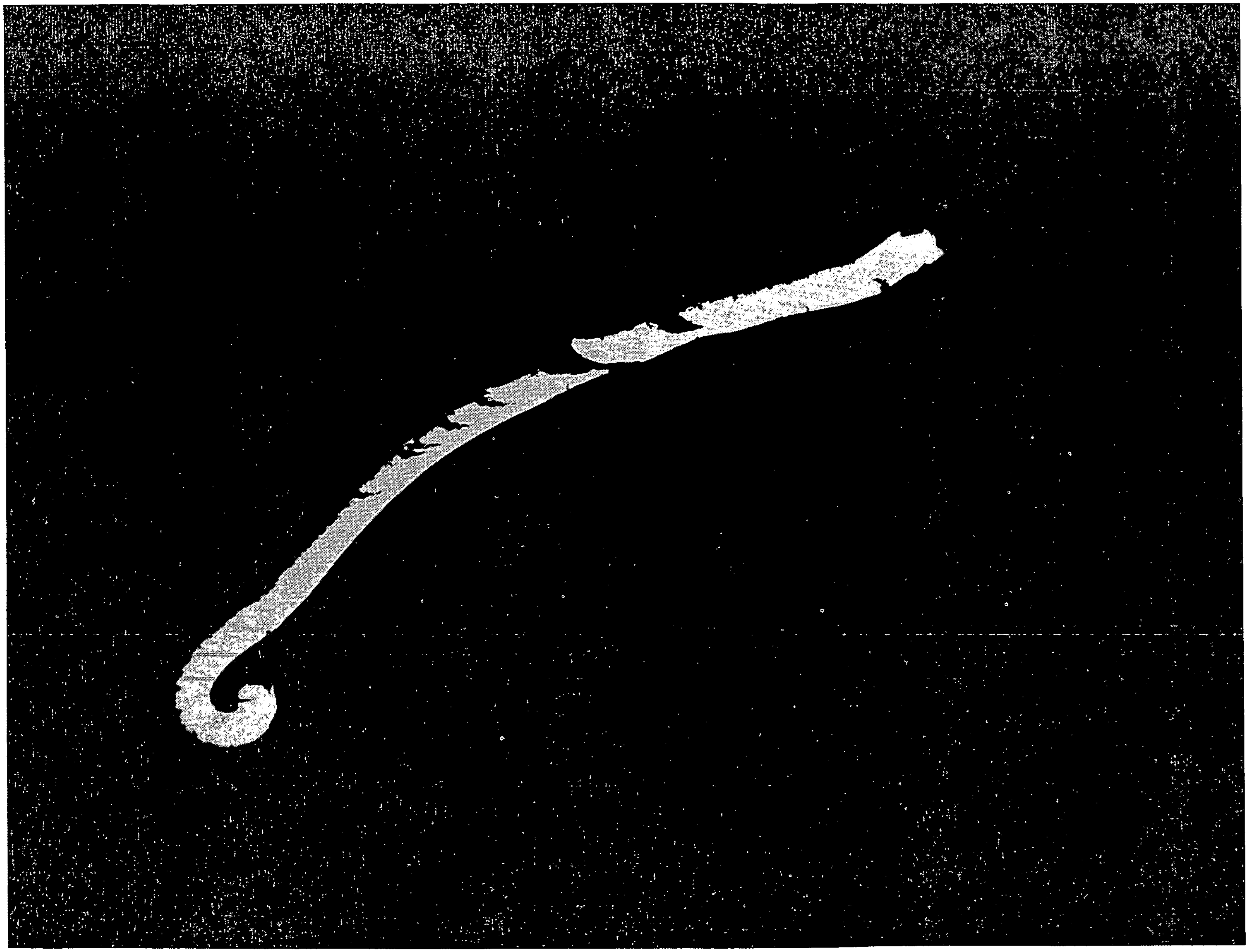


Figure 65. Cross Section - Fragment #6

Figure 66. Metallographic Section - Fragment #6

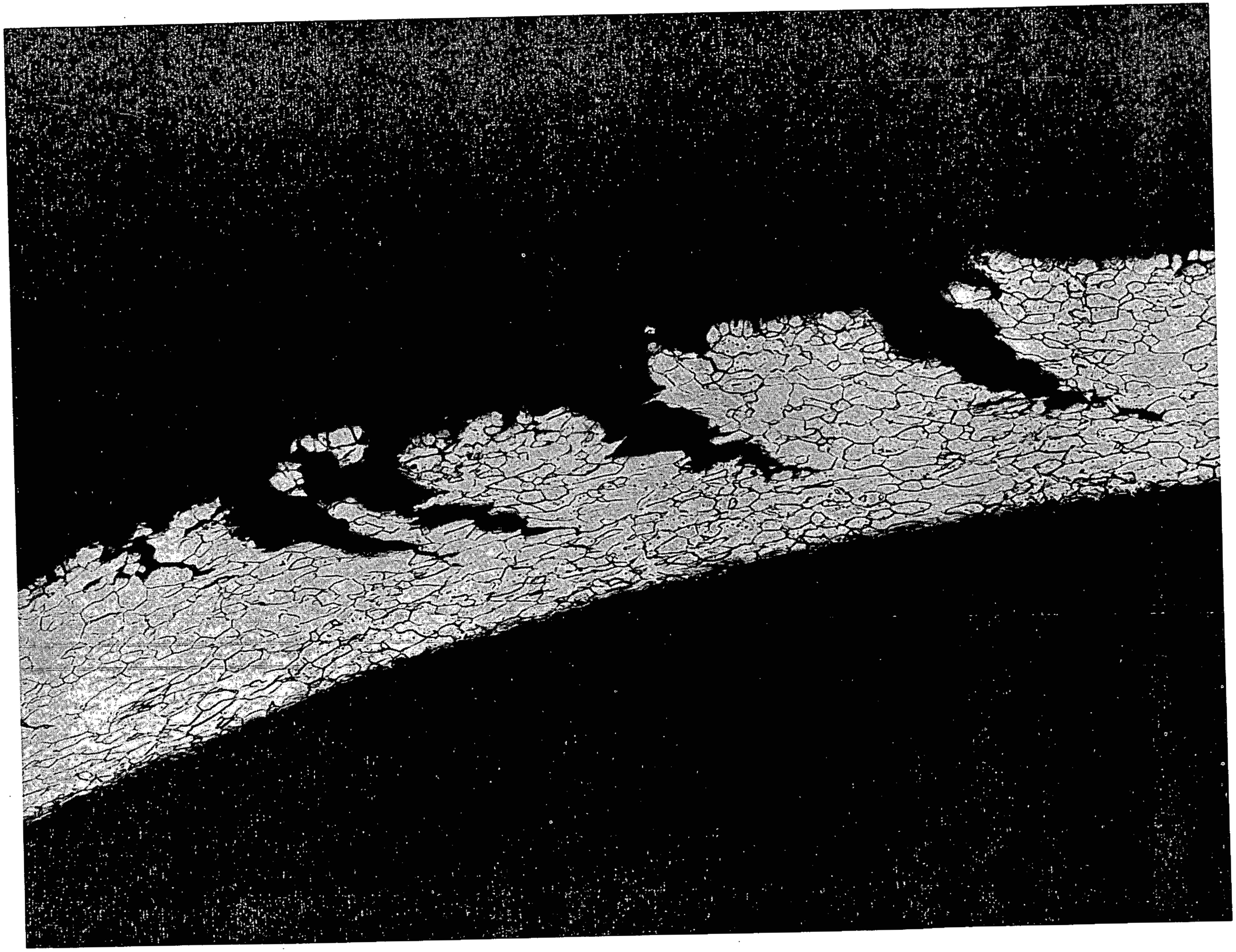


Figure 67. 2nd Metallographic Section - Fragment #6

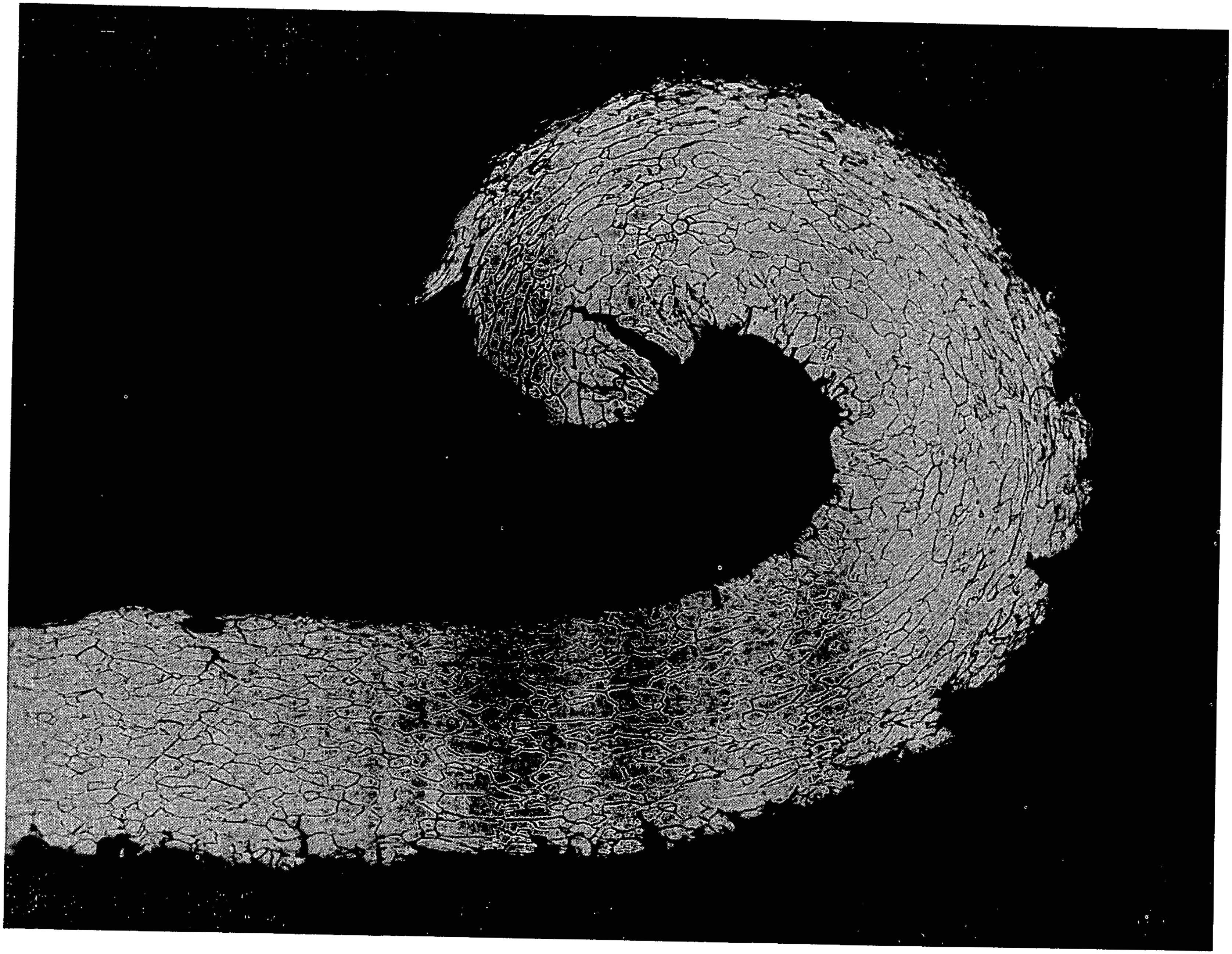


Figure 68. 3rd Metallographic Section - Fragment #6