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U.S. Department of Energy
NEVADA OPERATIONS OFFICE

REPORT of the INVESTIGATION BOARD for the UNPLANNED FIRE at the LIQUEFIED GASEOUS FUELS SPILL TEST FACILITY on AUGUST 29, 1987

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OCTOBER 23, 1987

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I. SCOPE OF INVESTIGATION

On August 29, 1987, during the fifth test (in the Falcon Test series), involving a large volume (50 cubic meters or 13,000 gallons) spill of liquefied natural gas (LNG), large and violent rapid phase transitions (liquid phase transforming to vapor phase) occurred and were followed by the ignition of the natural gas vapor leading to a substantial fire of short duration. The test was being conducted at the Liquefied Gaseous Fuels Spill Test Facility located in Area 5 on the Nevada Test Site.

The Manager of the Nevada Operations Office, Department of Energy (DOE), formally appointed a Type B Investigation Board on September 9, 1987, involving DOE (Nevada Operations Office and Fossil Energy, HQ) and Contractor (EG&G and Lawrence Livermore National Laboratory) personnel serving as Board members (see Appendix A). The Board was charged with determining the circumstances, causes, and contributing factors leading to the unplanned ignition of the natural gas vapor.

The investigation and the report were completed in accordance with guidance provided by DOE Order 5484.1, Chapter II. The investigation was limited to determining the circumstances, causes, and contributing factors leading to the fire and made no effort to provide any new insight into the underlying phenomenon of rapid phase transitions, the initiating factor leading to the fire.

II. SUMMARY

The Department of Transportation and the Gas Research Institute sponsored a series of tests (5 to 7) involving spills of large quantities of LNG to determine the effect of physical barriers on controlling the downwind dispersion of the natural gas vapor. During the execution of the fifth test, the natural gas vapor ignited and was followed by a substantial fire of short duration. The fire burned for approximately 30 seconds until the supply of natural gas was consumed. The estimated damage to the facility included the following:

- Spill test area damage includes the replacement of scorched, blistered electrical cables for spill pipe instrumentation and control; plastic components on the spill valve; and the replacement of one "portapotty." Estimated damage: $20K.

- Test instrumentation damage includes replacement of burned cable and repair replacement of damaged measuring devices (thermocouples, gas sensors, meteorological instruments), and electronic data acquisition station. Estimated damage: $50K to $75K.

- Test-specific and expendable equipment that was damaged, but will not be replaced or repaired, includes the vapor curtain structure, the spill pond containment wall, the spill pond plastic liner, and the spill-spider. This equipment and material was purchased specifically for this test series and would have been discarded when the test series was completed. They have no residual or surplus value. (Initial value: $300K).

Large-scale tests involving spills of LNG on to water conducted previously at other locations in the United States have involved "rapid phase transitions" known as RPTs. An RPT results when a small volume of liquid natural gas instantaneously transforms into a large volume of gas or vapor. The change in volume can range from a factor of 300 to 600. When this occurs, it produces a shock wave which has characteristics similar to that produced by an explosion. The shock waves produced can have sufficient force to dislodge concrete blocks and throw them tens of feet into the air, landing at distances over 100 feet from their initial location.

In tests 3 and 5 of the series being conducted, large and violent RPTs were observed. In test 3, the number of the RPTs were less than that experienced in test 5 and were comparable in magnitude. It should also be noted that in test 1, in which the nominal values of the test parameters were similar to test 5 except the total volume and time for spill of LNG was greater by a factor of two, and the initial composition of the LNG was different, no RPTs were observed. The RPTs caused significant physical disruption to the spill test area in both tests. During test 5, the spill-spider was bent and the concrete blocks supporting it were disrupted, with many thrown about the spill pond. The wall (constructed of concrete block (8" x 8" x 16", each weighing 27 lbs), stacked one upon another without mortar) of the spill pond was badly disrupted in numerous places and the concrete blocks had been blown away and many were broken into small pieces. Over the entire spill pond, more than 700 concrete blocks had been dislodged from their initial point and many had been moved significant distances.

The details of the physical disruption prior to the fire and the fire itself were extensively documented with three video cameras, two movie cameras, and two sets of still cameras. Two of the video tapes and one of the movies clearly indicate that a strong RPT (or possibly two simultaneously) occurred in the immediate vicinity just prior (within one second) to the start of the fire. It can be logically inferred that the RPT was the initiating force that led to the fire.

The physical evidence indicates that the shock wave from this RPT (or two RPTs occurring simultaneously/doublet) was very strong. The wall of the spill pond in the area of ignition had a large opening in it created by the RPT. This section of the spill pond wall suffered the greatest damage. Two of the 9-meter- (30 feet) high poles that support the vapor curtain were sheared where they were welded to a base plate and displaced outward 1.1 cm (7/16 inches). Two 9-meter-high poles farther to the north were bent. Two of the .3 cm- (1/8-inch) diameter stainless steel guy wires (multistranded braided type cable) on the inside of the vapor curtain (one on the third pole and fifth pole) which require the application of 2,000 lbs tensile force for failure, were broken in tension. The guy wire on the fourth pole was pulled loose from the top anchor plate on the pole. Four of the six aluminum battens used to stiffen the vapor curtain were broken between poles 4 and 5. In addition, the coaxial cable used to carry the video signal from camera 3 was completely severed.

While there are ample effects of disruption resulting from the RPT, there is no obvious mechanism that resulted in the ignition of the natural gas vapor. Five different scenarios were examined and carefully compared against the information that was available. The five scenarios include direct ignition by the RPT shock wave, ignition by a catalytic source, ignition by an electrical spark from an electrical source, ignition by a friction spark from a mechanical impact, and ignition by an electrical spark from a static electricity discharge. Of the five scenarios, four appear to have a very low probability of being the source of ignition and one appears to have a high probability of being the source of ignition. The evidence available is not conclusive, but only points toward the probable cause. The major factor eliminating most of the scenarios is the apparent location of the point of ignition. The scenario that appears to be the most consistent with the evidence is an electrical spark from a static electricity discharge.

The erupting and turbulent cloud of LNG, water, ice particles, and air caused by the LNG spill itself (possibly accentuated by the associated RPTs) appears to have the capability of creating an electrostatic charge on the nonconducting fiberglass vapor curtain. The first sign of the fire appeared on the outside of the vapor curtain at or near the surface of the curtain and adjacent to pole 5. It is the consensus of the Board that the discharge of the electrostatic charge created on the vapor curtain was the most probable cause of the ignition. The most difficult fact to establish is the ground point that served as the end of the discharge. While the metal poles (9 meters high) are grounded, they do not provide an obvious discharge point. The most probable source of the spark appears to be the broken stainless steel guy wire at pole 5 which, when broken from the force of the RPT, snapped back and over the top of the vapor curtain. It probably came in contact with the curtain or the aluminum batten in the curtain to provide the spark at a point near the fifth support pole at a level equal to the location of the third batten down from the top (approximately 6 m (20 ft) above the ground).

This is the only scenario of the five that readily provides for the fire being ignited outside the curtain, at the fifth pole from the spillpipe, at or near the curtain, and at a level coinciding with the third batten down from the top.

III. FACTS

General Background

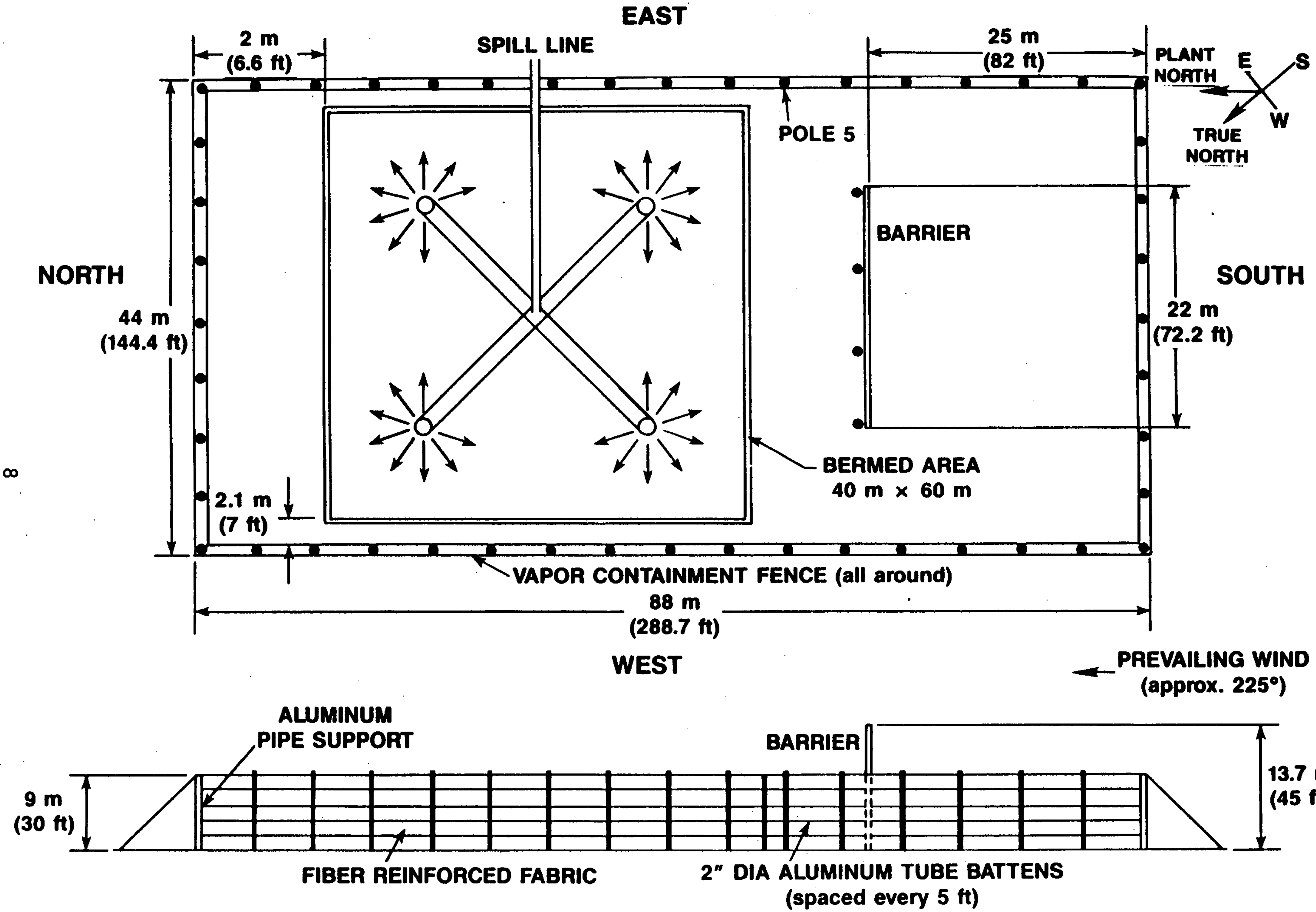
From the beginning, it was recognized that tests involving spills of LNG were potentially dangerous. The Safety Analysis Document prepared specifically for this series of tests acknowledged that RPTs could occur and could physically damage the spill test area. It was also recognized that large quantities of natural gas vapor could burn and that fire was a distinct possibility. Precautions were taken to minimize the possibilities of a fire. The method of construction utilized was one to assure that if disruption did occur, it would impact a portion of the spill test area that was of elementary construction and would minimize the financial loss.

The following are the specific quotes from the Safety Analysis Document:

> D. Spill Test Related Hazards
>
> 1. Fire or Explosion. During a spill test, the tank farm is unmanned. When the LNG is released in a spill test, large flammable amounts of natural gas will be present in and about the vapor barrier curtain. The curtain and the instrumentation in the area are at risk.
>
> 2. Wind Shifts. The potentially flammable vapors will be carried downwind by the ambient wind field. The direction or intensity of the wind may change during the test.
>
> 3. Rapid-Phase Transitions (RPTs). When LNG is spilled onto water, RPTs may occur in the pond area. The effects of an RPT are similar to a low-grade explosion and can cause mechanical damage which, in turn, may ignite the vapor cloud.

The test being conducted at the time of the fire was the fifth in a series. This particular experiment involved spilling 50 cubic meters (approximately 13,000 gallons) of liquefied natural gas from four separate nozzles (see Figure 1) at a rate of 40 cubic meters/min onto a pond 39.6 m (130 ft) x 58.5 m (192 ft) which contained water approximately 75 cm (30 inches) deep. Nominal values for the parameters for all five tests can be found in Table 1. It should be noted that the parameters for the fifth test were similar to those in the first test, except that the total volume of LNG spilled in the first test was twice that spilled in test 5, and the composition of the LNG was different.

The spill test area (see Figure 1) was surrounded by a 8.5-m (28 ft) high fiberglass curtain that was to serve as a vapor barrier for the purpose of decreasing the downwind dispersion of the natural gas vapors. Horizontal battens were emplaced in the curtain for stability.



SCHEMATIC DIAGRAM OF SPILL TEST AREA

FIGURE 1

TABLE 1
TEST PARAMETERS FOR LIQUEFIED NATURAL GAS SPILLS
SPONSORED BY GRI/DOT

	TEST NUMBER				
	1	2	3	4	5
Date of test	12 June	18 June	29 June	21 Aug	29 Aug
Time of day	19:47:56	18:09:00	18:52:02	19:27:04	18:58:00
Wind Speed (M/Sec)	1.7	3.7	3.8	4.6-5.3	2.8
Ground Pot. (Volts/Meter)	20	50	no data	10	-50 to +20
Nearest Strike within hour (Miles)	25	25	no data	25	22
Spill Rate (Cu. Meters/Min.)	40	20	20	10	40
Spill Vol. (Cu. Meters)	100	25	50	50	50
Spill Dur. (Min.)	2.5	1.25	2.5	5.0	1.25
Drive Gas Pr. (PSIG)	140	35	35	125	140
Spill Orifice (In.)	4.5	4.5	4.5	1.5	4.5
Fluid Vel. (M/Sec)	65	32.5	32.5	146	65
Water Temp. Pre/Post (Deg C)	28.4/22.4	23.6/20.6	No data	23.2/22.0	26.0/?
Gas Analysis Methane/Heavys (%)	*94.7/3.9	*95.6/3.7	**91/8.0	***84/13 91/ 8	****88/10
Del. Date	5 Jun	5 Jun 15 Jun	15 Jun 22 Jun	22 Jun 16 Jul 21 Aug	21 Aug 27 Aug
Tank Stored	C-105	C-105 C-106	C-105	C-106 C-105	C-105 C-106
Spilled From	C-105	C-105	C-105	C-106	C-106

* Sampled prior to shipment (details of composition in Appendix C)
** Sampled after testing
*** Sampled prior to test, then mixed with LNG containing 95% methane
**** Sampled prior to test

Approximately 55 seconds into the experiment, RPTs began to occur. A detailed time sequence of the experiment is provided as Figure 2. Some of the RPTs were visibly sizable and violent. RPTs had occurred in the third test that were of comparable magnitude to the ones in the fifth test. While concrete blocks were disrupted in the third test and thrown about, the damage was not as severe as that experienced in the fifth test. There were no visual observations of RPTs in tests 1, 2, and 4.

What is Known

The following is a listing of facts based on review of videotapes, movies, still photographs, and visual inspection of the facility after the fire.

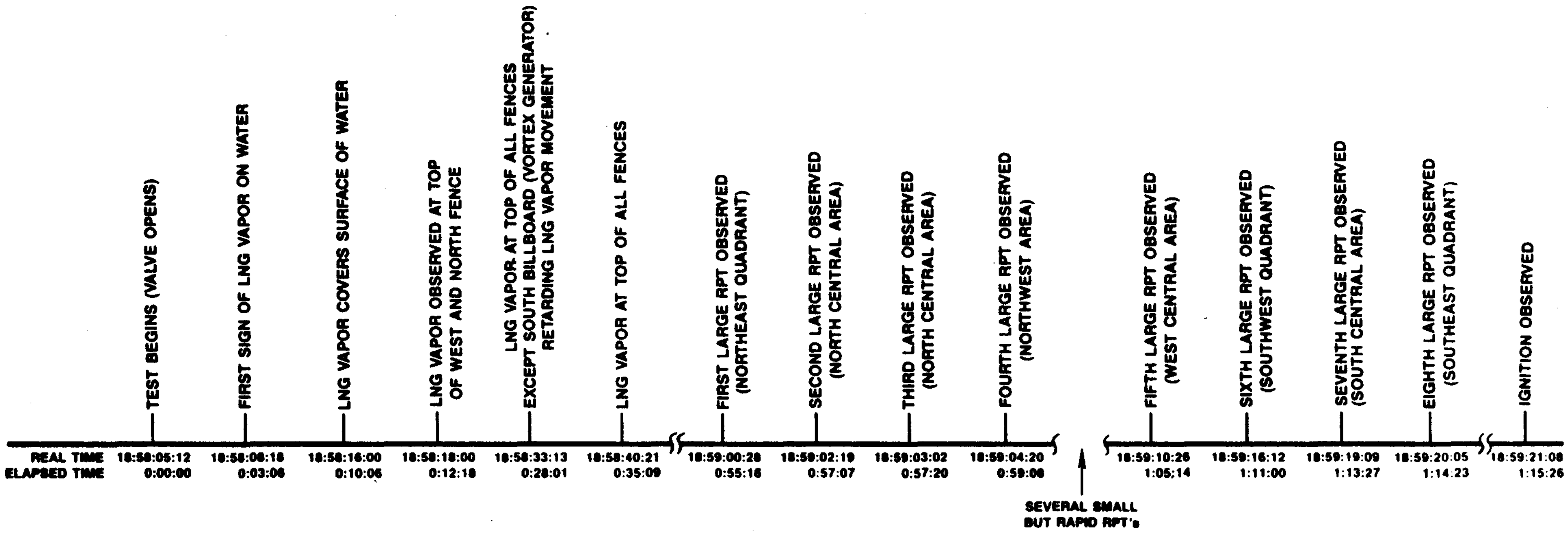
1. The entire experiment and fire was extensively recorded. Three video cameras, two movie cameras, and two sets of still cameras were utilized and were located at the positions noted in Figure 3. The videotapes recorded at 30 frames a second, and the movie cameras recorded at 24 frames a second. The still cameras were programmed at a frame rate that varied from a frame every 6 seconds to a frame every 30 seconds. The video system used a common time signal that was fed to the video channels and recorded on all three tapes. The record of time on the video is as follows: 18:59:21:08. The first number is the hour, the second the minute, the third are seconds, and the fourth is the frame number (frame numbers vary from 01 to 30). The movie cameras were keyed to a time signal from station WWV (the radio station operated by the National Bureau of Standards). There was no measured relationship between the two time signals.

2. When the experiment was initiated, the pond was well ordered; that is, there were no concrete blocks randomly distributed throughout the pond, the spill-spider was in good structural condition, and the thermal insulation was in place. Blocks were in the pond as structural support for the spill-spider. After the RPTs, many concrete blocks were dispersed around the pond, many concrete blocks were broken into small pieces, and the blocks that were providing structural support of the spill-spider were substantially disrupted. Insulation was missing from several places on the spill-spider. About 15 percent of the linear length of the insulation on the spill-spider was blown away.

3. Fifty cubic meters of LNG were spilled onto the pond starting at 18:58:05. The spill lasted between 1 minute, 20 seconds to 1 minute, 25 seconds.

4. Very large and violent RPTs occurred in the following sequences:

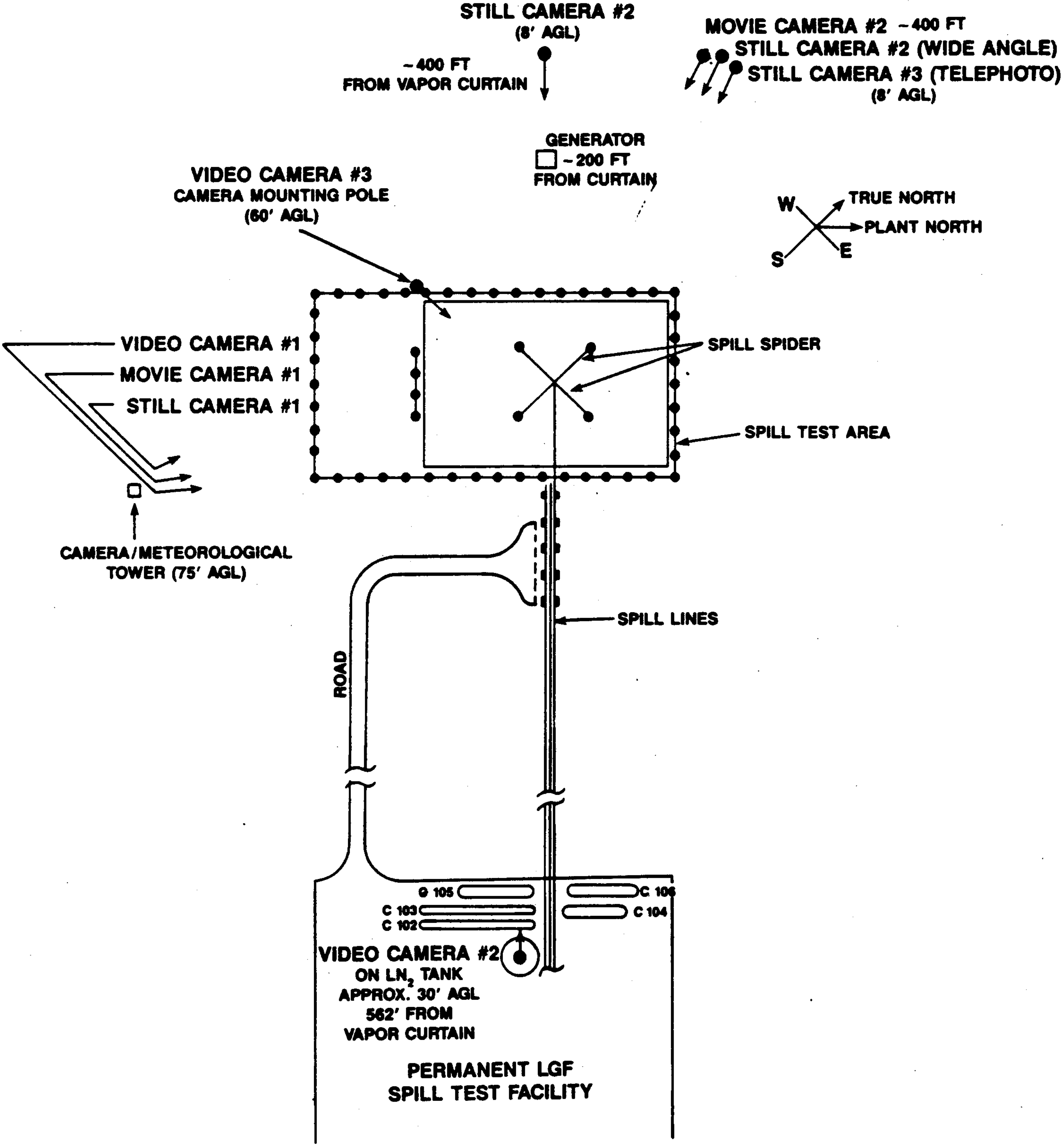
   1st: N.E. quadrant approximately 55 seconds into test.
   2nd: N. central area - T = 57 seconds.



NOTE: REAL TIME EXPRESSED IN HOURS/MINUTES/SECONDS/30th OF SECONDS
ELAPSED TIME EXPRESSED IN MINUTES/SECONDS/30th OF SECONDS

SEQUENCE OF EVENTS IN TEST 5

FIGURE 2



AGL: ABOVE GROUND LEVEL

SCHEMATIC DIAGRAM OF
LIQUEFIED GASEOUS FUELS SPILL TEST FACILITY

FIGURE 3

3rd: N. central area - T = 58 seconds.
4th: N.W. area - T = 59 seconds.

Numerous small RPTs occurred from 1 minute, 4 seconds through 1 minute, 10 seconds, based on sound recordings but they were not visibly observable.

5th: W. central - T = 1 minute, 5 seconds.
6th: S.W. quadrant - T = 1 minute, 11 seconds.
7th: S. central quadrant - T = 1 minute, 14 seconds.
8th: S.E. quadrant - T = 1 minute, 15 seconds. This RPT produced two separate plumes indicating that two RPTs might have occurred simultaneously in close proximity to one another.

5. Ignition occurred at approximately T = 1 minute, 16 seconds after the start of the spill.

6. The last series of violent RPTs appeared to be following along the south wall, with the last RPT adjacent to the ignition location.

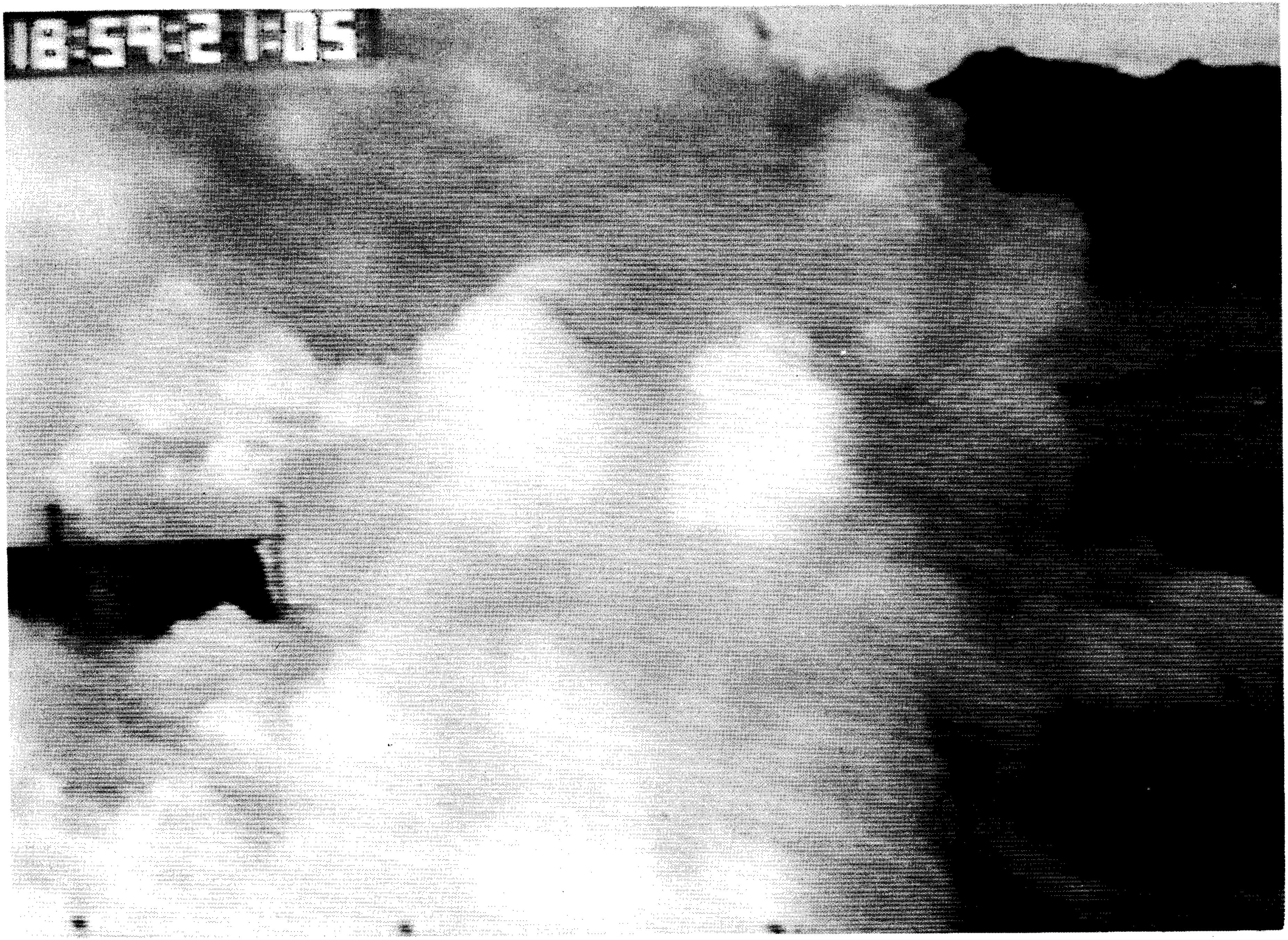
7. The RPTs created minor shock waves that produced noticeable movements in the vapor curtain. This was obvious in the films taken from both angles and in the still photos. No physical damage to the curtain or its supporting structure could be observed in the films as a result of the shock wave, but some damage did occur to the curtain as a result of flying debris.

8. The RPT (or RPTs) adjacent to the location of the fire initiation appeared to be strong. This was evident in the fact that four of the six horizontal battens were broken; that poles 4 and 5 south of the spillpipe had the welds holding them to the base sheared and moved out by 1.1 cm (7/16 inches); that 0.3-cm- (1/8-inch) diameter stainless steel guy wires inside the vapor curtain on poles 3 and 5 were broken in tension and guy wire on pole 4 was pulled loose from the anchor plate at the top of the pole; and the wall was significantly damaged, having more than 15 blocks blown out of the wall.

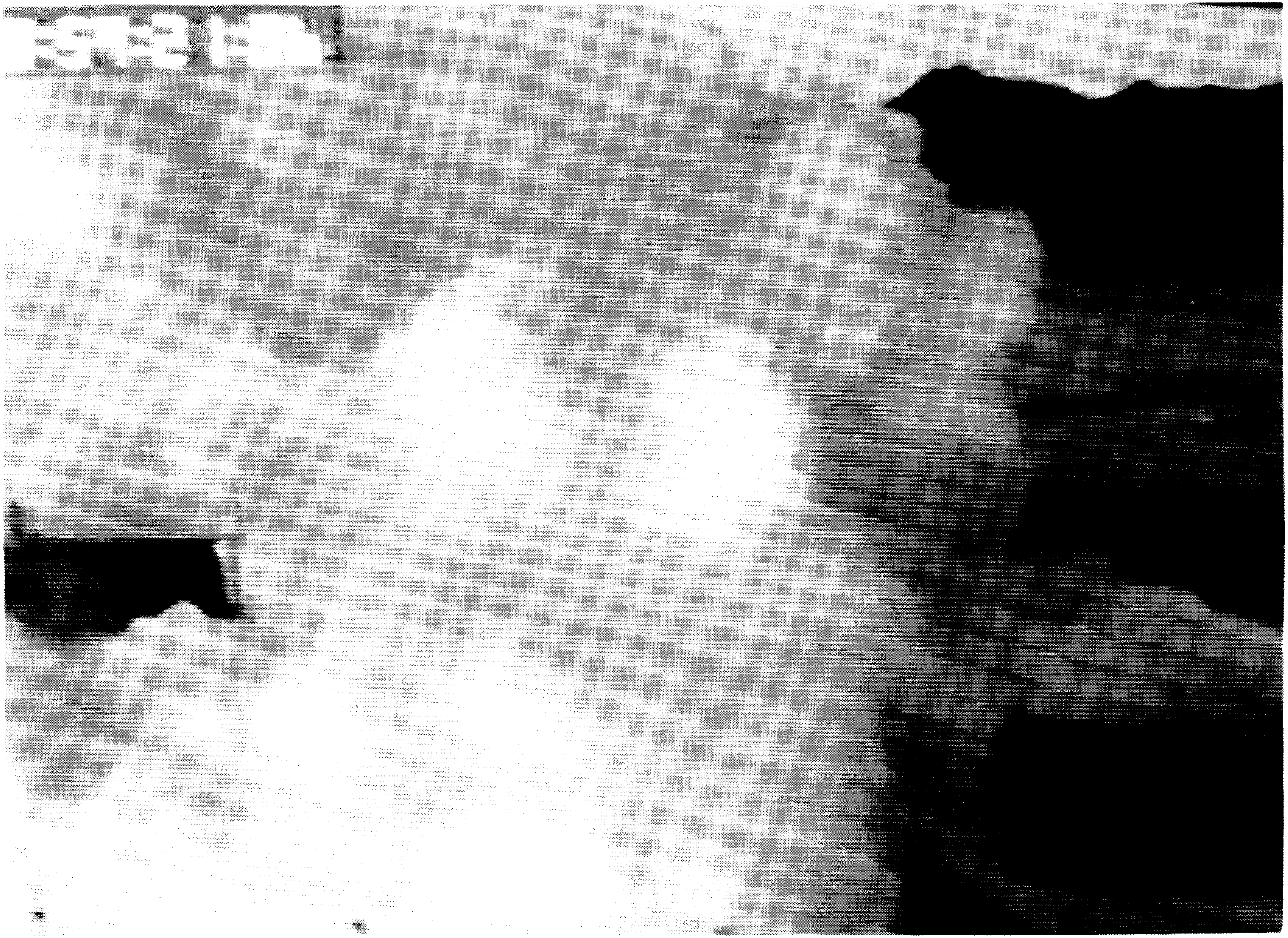
9. Ignition appears to have occurred at 18:59:21:08 (based on images from video camera 2) or 1 minute, 16 seconds into test. Figures 4a through 4s show the sequence of photos taken by the three video cameras and movie camera 1 from just before ignition to just after ignition.

10. Ignition occurs approximately 1 second after RPT No. 8 was observed, which appeared to be a doublet.

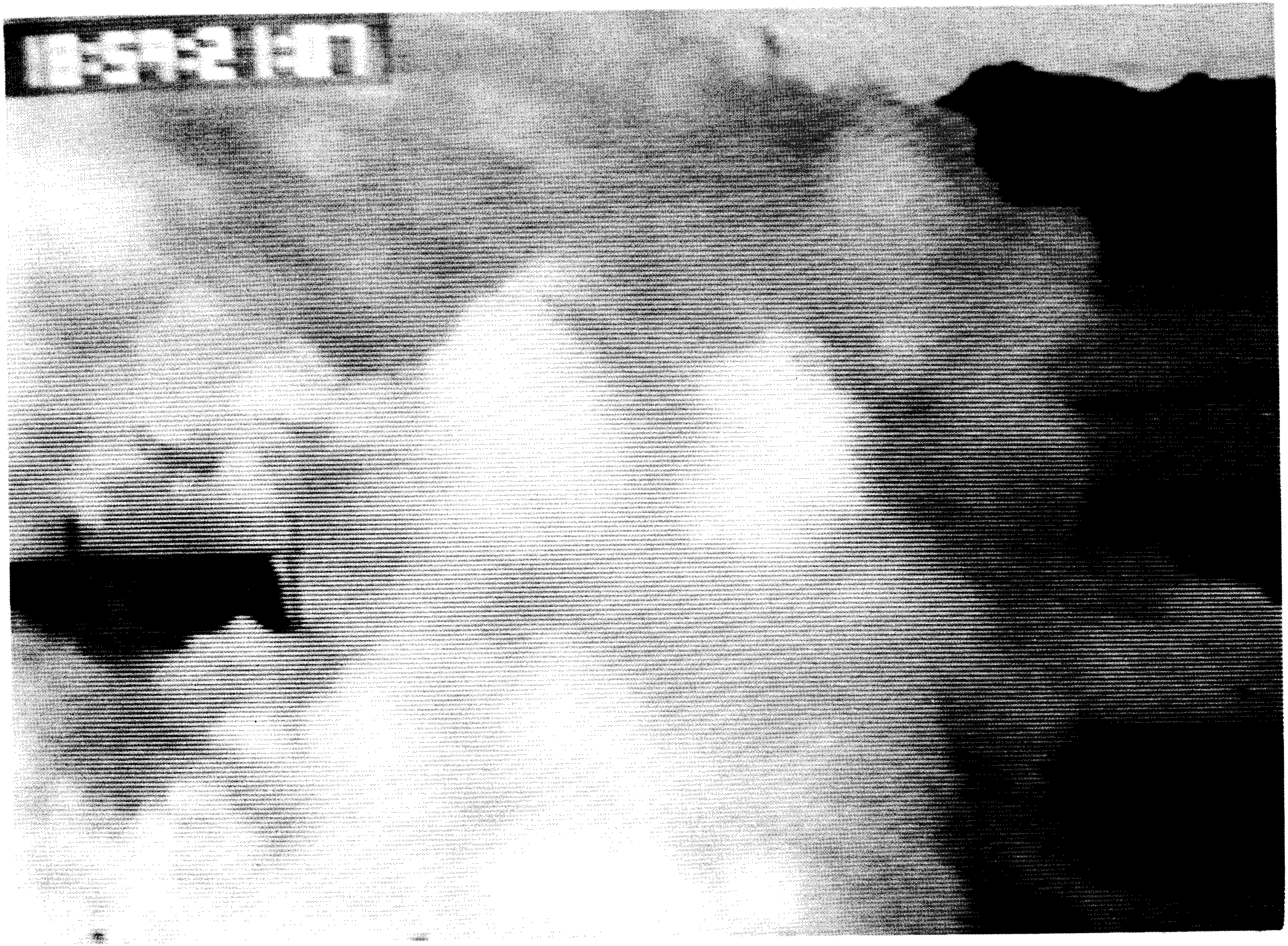
11. Broken interior guy wires were found over the top batten for poles 3 and 5. Both guy wires appeared to have failed in tension. The guy wire from pole 3 was generally discolored by



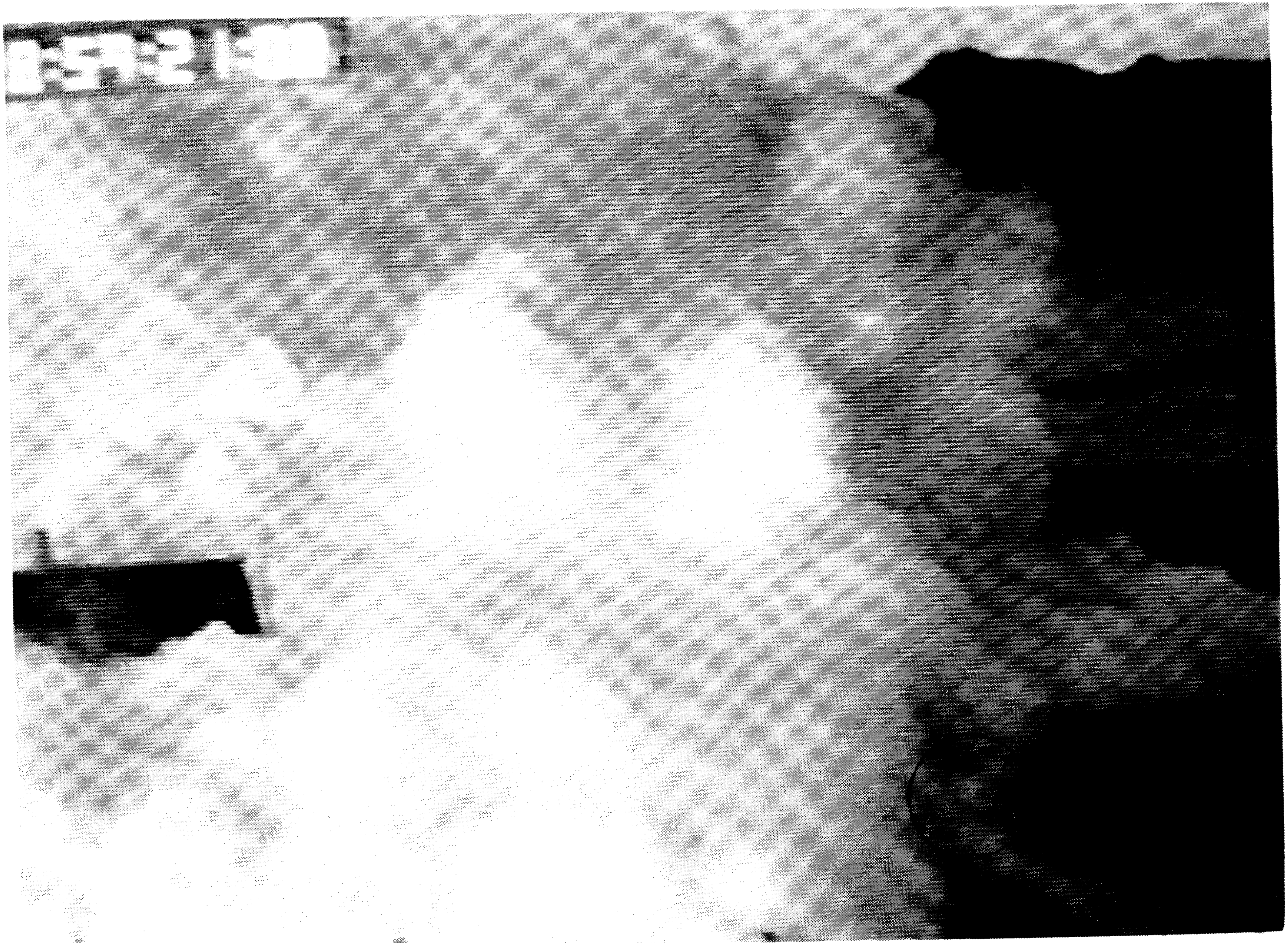
SPILL TEST AREA: VIDEO CAMERA 1
3/30 OF SECOND BEFORE IGNITION
FIGURE 4a



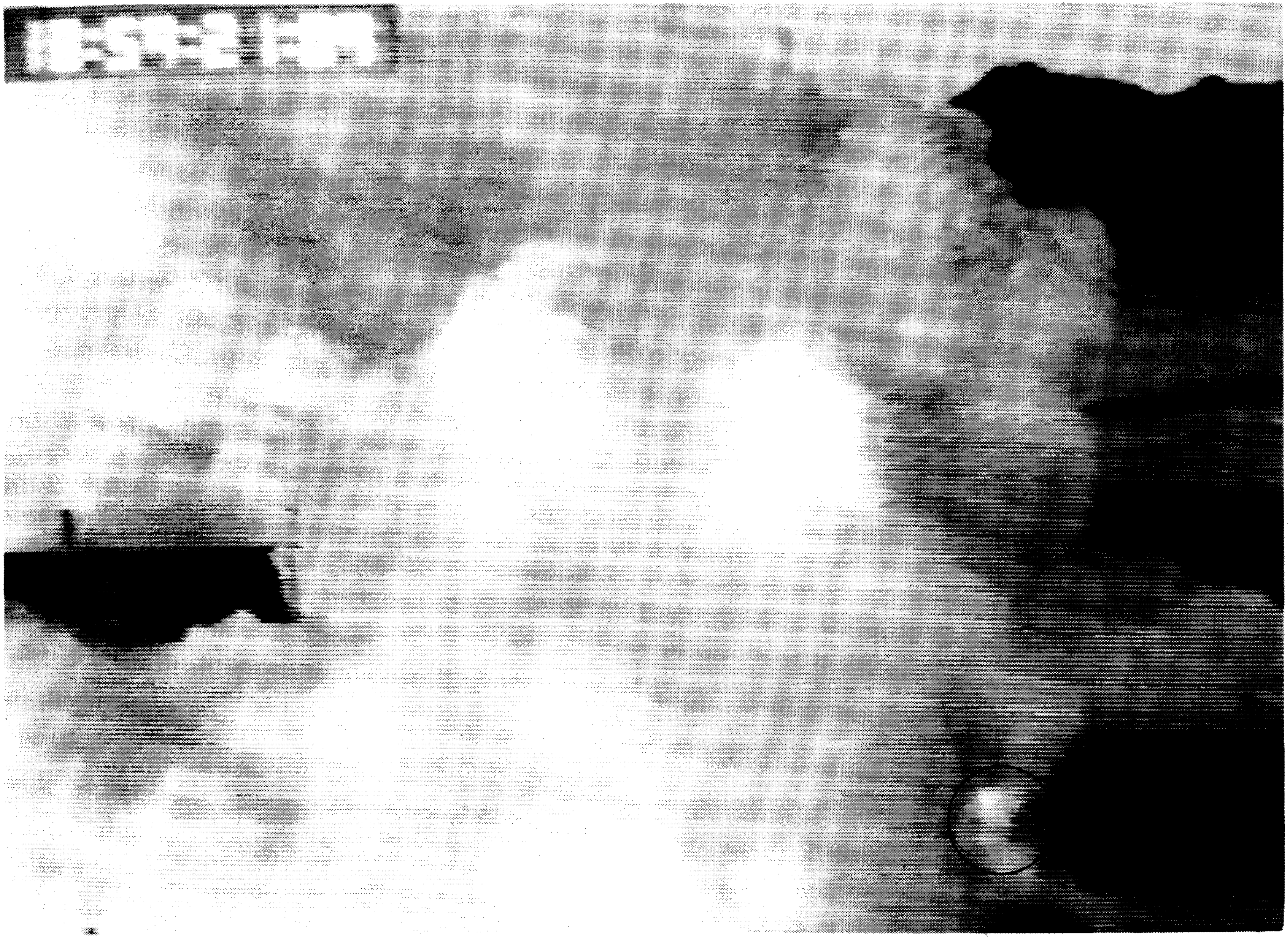
SPILL TEST AREA: VIDEO CAMERA 1
2/30 OF SECOND BEFORE IGNITION
FIGURE 4b



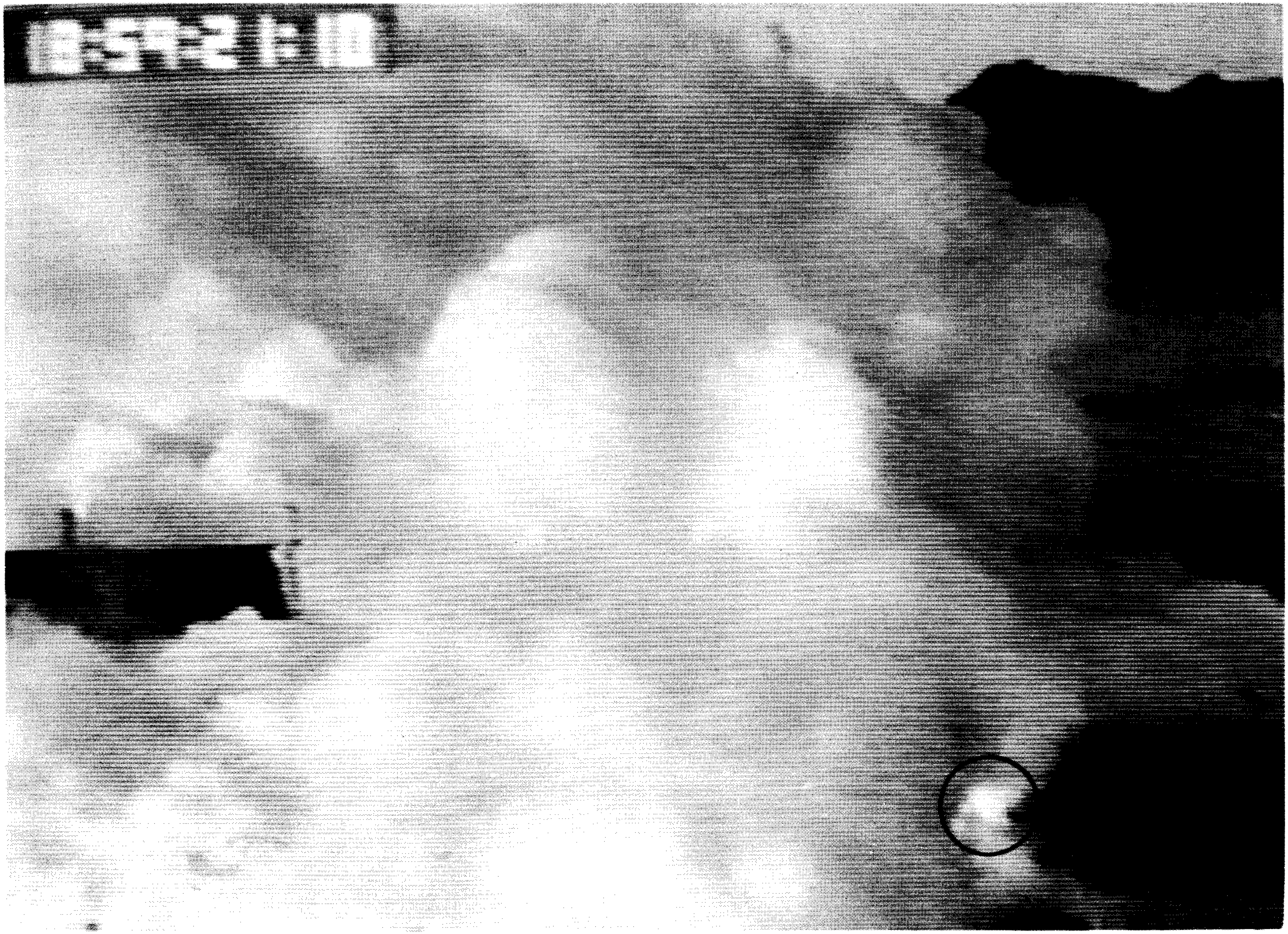
SPILL TEST AREA: VIDEO CAMERA 1
1/30 OF SECOND BEFORE IGNITION
FIGURE 4c



SPILL TEST AREA: VIDEO CAMERA 1
AT IGNITION
FIGURE 4d



SPILL TEST AREA: VIDEO CAMERA 1
1/30 OF SECOND AFTER IGNITION
FIGURE 4e



SPILL TEST AREA: VIDEO CAMERA 1
2/30 OF SECOND AFTER IGNITION
FIGURE 4f

SPILL TEST AREA: VIDEO CAMERA 2
3/30 OF SECOND BEFORE IGNITION

FIGURE 4g

SPILL TEST AREA: VIDEO CAMERA 2
2/30 OF SECOND BEFORE IGNITION
FIGURE 4h

SPILL TEST AREA: VIDEO CAMERA 2
1/30 OF SECOND BEFORE IGNITION
FIGURE 4i

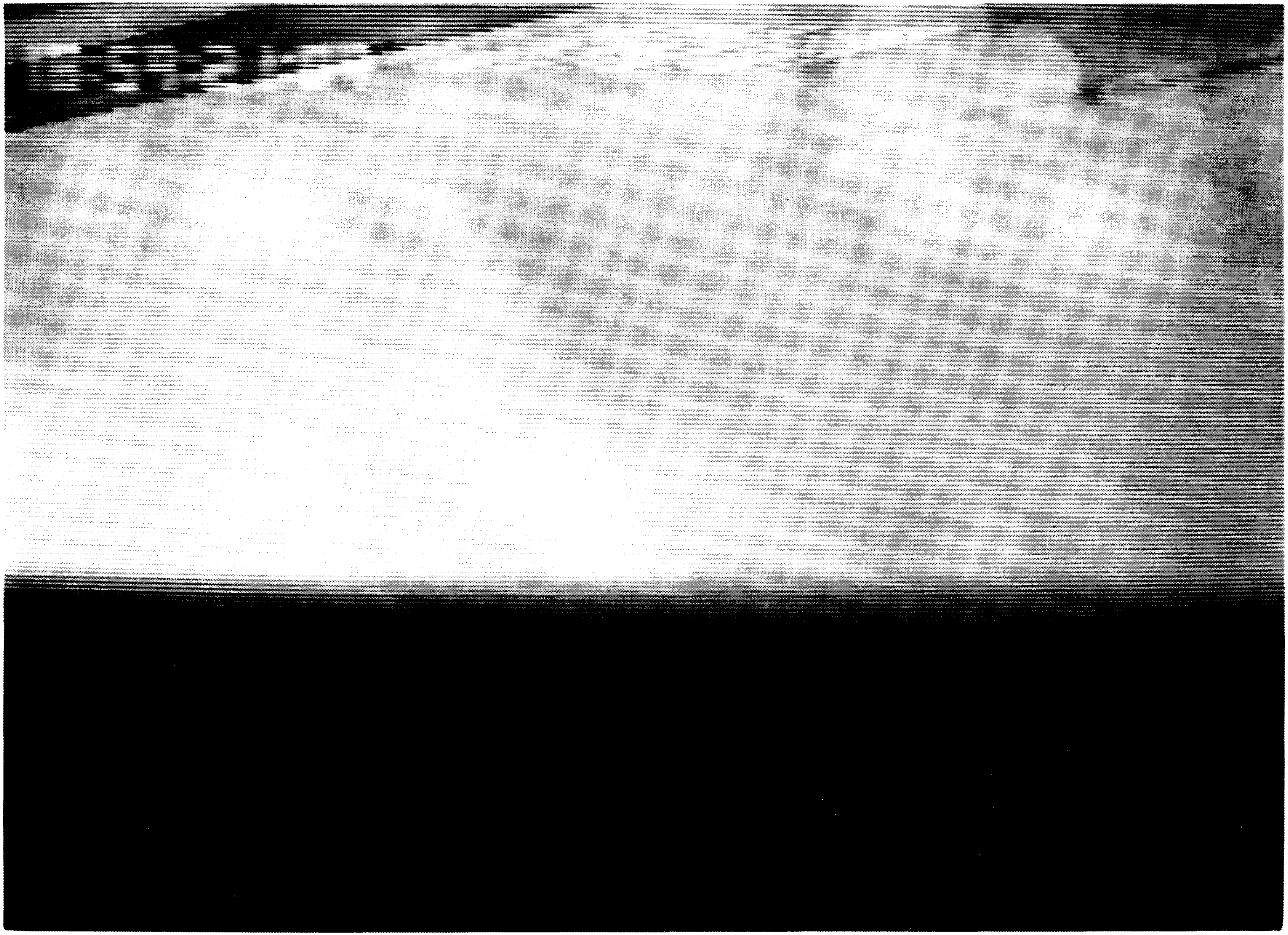
SPILL TEST AREA: VIDEO CAMERA 2 AT IGNITION

FIGURE 4j

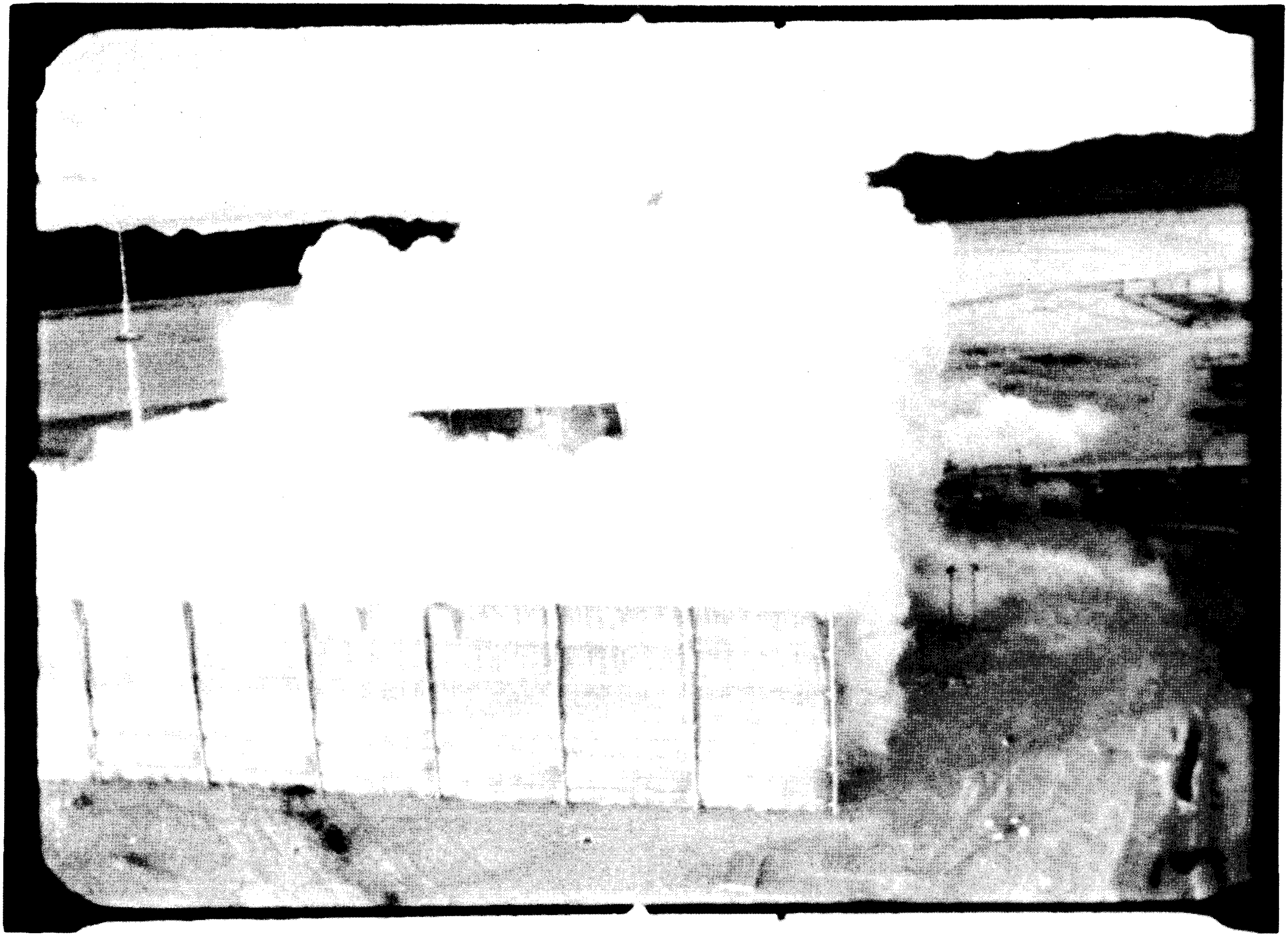
SPILL TEST AREA: VIDEO CAMERA 2
1/30 OF SECOND AFTER IGNITION
FIGURE 4k

SPILL TEST AREA: VIDEO CAMERA 2
2/30 OF SECOND AFTER IGNITION
FIGURE 4I

SPILL TEST AREA: VIDEO CAMERA 3
AT IGNITION
FIGURE 4m

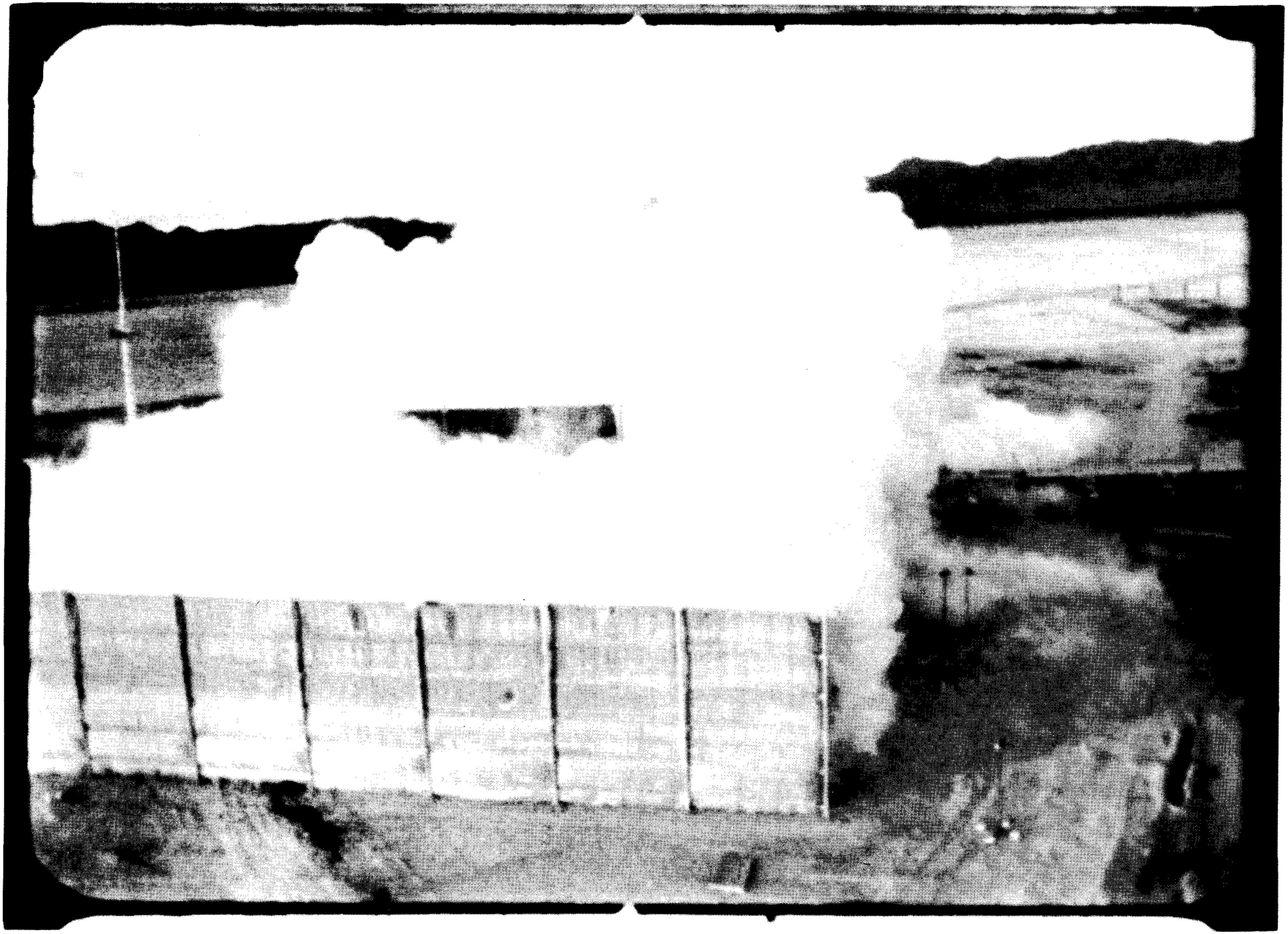


SPILL TEST AREA: VIDEO CAMERA 3
1/30 OF SECOND AFTER IGNITION
FIGURE 4n



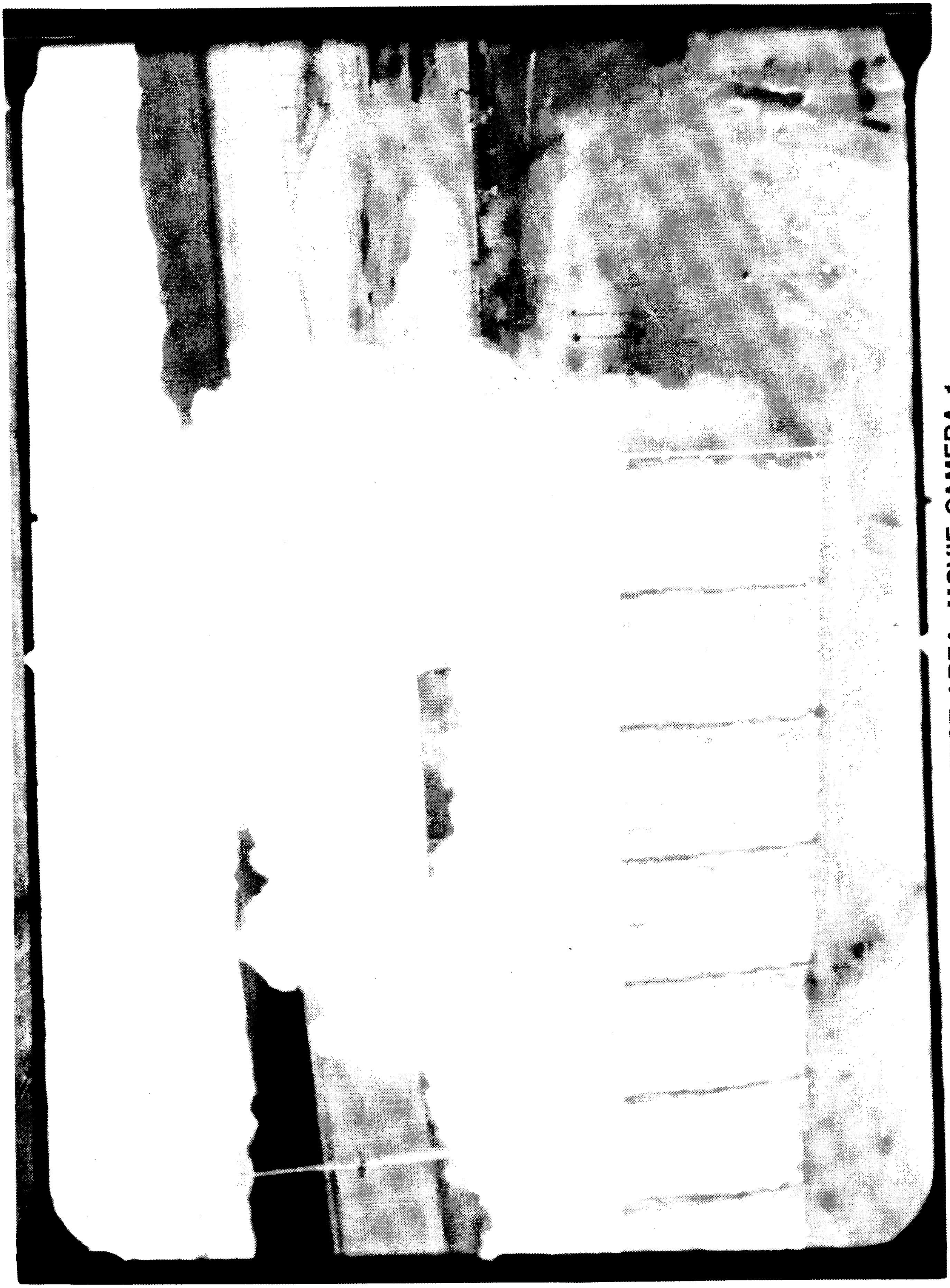
SPILL TEST AREA: MOVIE CAMERA 1

FIGURE 4o



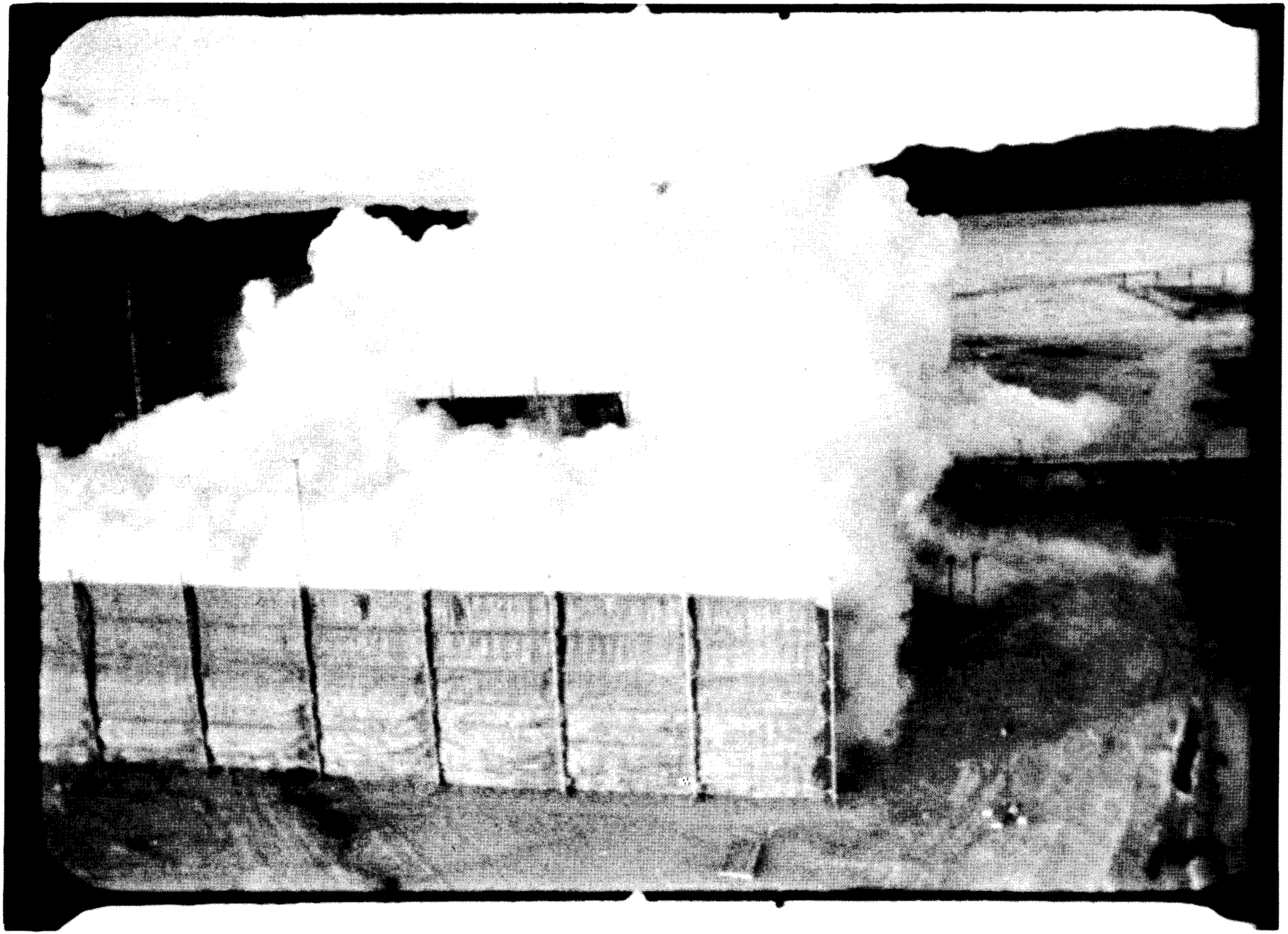
SPILL TEST AREA: MOVIE CAMERA 1

FIGURE 4p



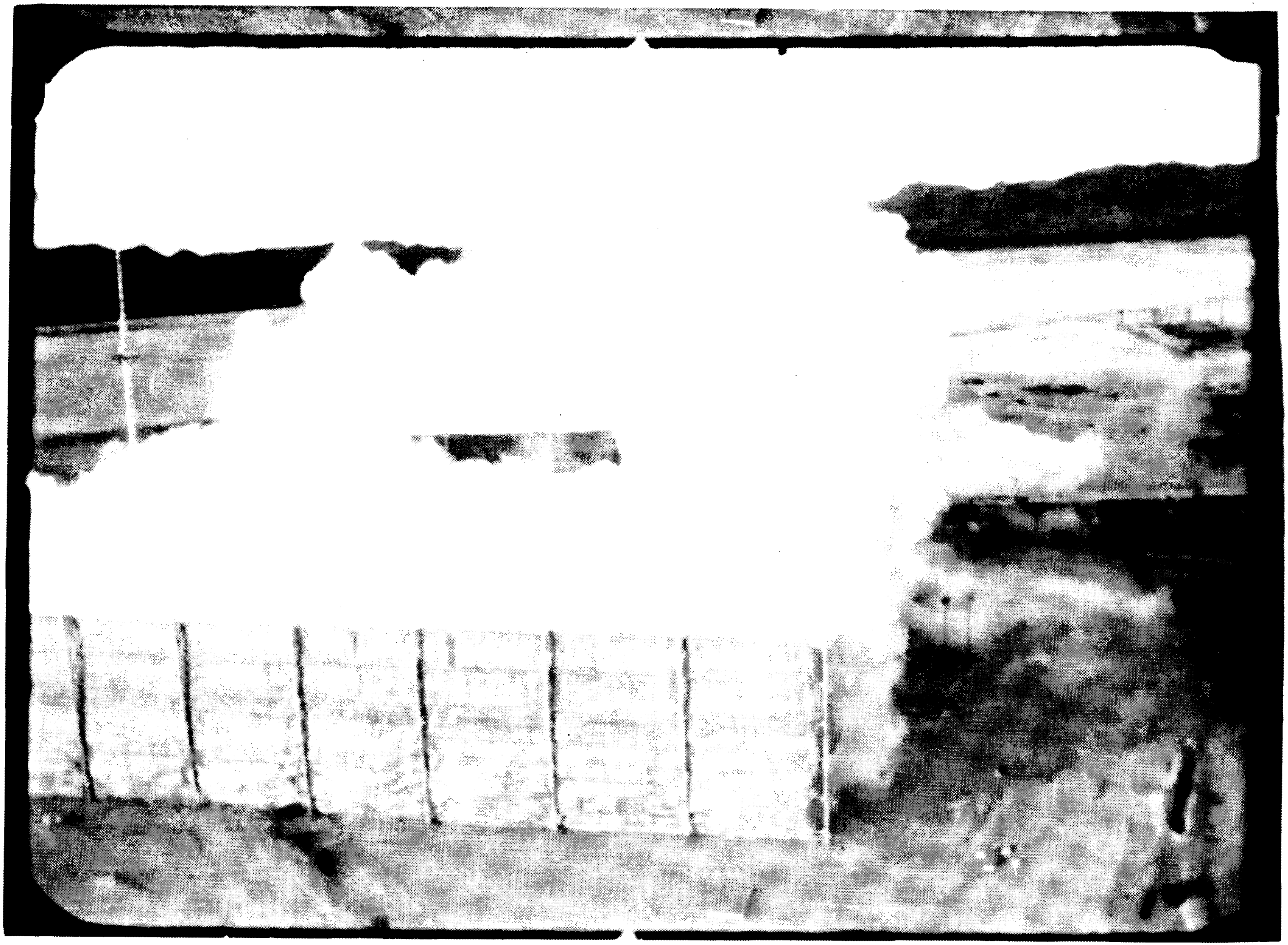
SPILL TEST AREA: MOVIE CAMERA 1

FIGURE 4q



SPILL TEST AREA: MOVIE CAMERA 1

FIGURE 4r



SPILL TEST AREA: MOVIE CAMERA 1

FIGURE 4s

the fire. The guy wire from pole 5 that flipped up and over the vapor curtain was only discolored on the frayed ends above the break. The other broken end of the guy wire for pole 5 which remained on the inside of the vapor curtain and on the ground showed no discoloration on the frayed end.

12. The spill-spider in the center of the pond was significantly damaged by the RPTs. Damage can be seen in Figure 5. For the general facility configuration, see Figure 1. Approximately 15 percent of the linear pipe length had the insulation blown off.

13. In the location where the RPTs occurred on the edge of the pond, the concrete block wall was heavily damaged. Blocks were either pushed back over the earth-berm behind the block wall into the 7-ft-wide space between the pond and the vapor curtain or thrown completely beyond the vapor curtain. The 1/2-inch-diameter reinforcing rods used to align the concrete blocks in the vicinity of the fire ignition point were bent outward at an angle of 15° to 20°. The rods were not encased in concrete. Figure 6 provides several views of the damage at this point.

14. Several pieces of block (approximately 2 pounds each) were found directly east of the spill test area approximately 130 feet away from the fence.

15. The vapor curtain between poles 4 and 5 was generally intact below the third batten (counting from the top--see Figure 7). Above the third batten, little remained of the curtain. The final status of the curtain can be seen in Figure 8.

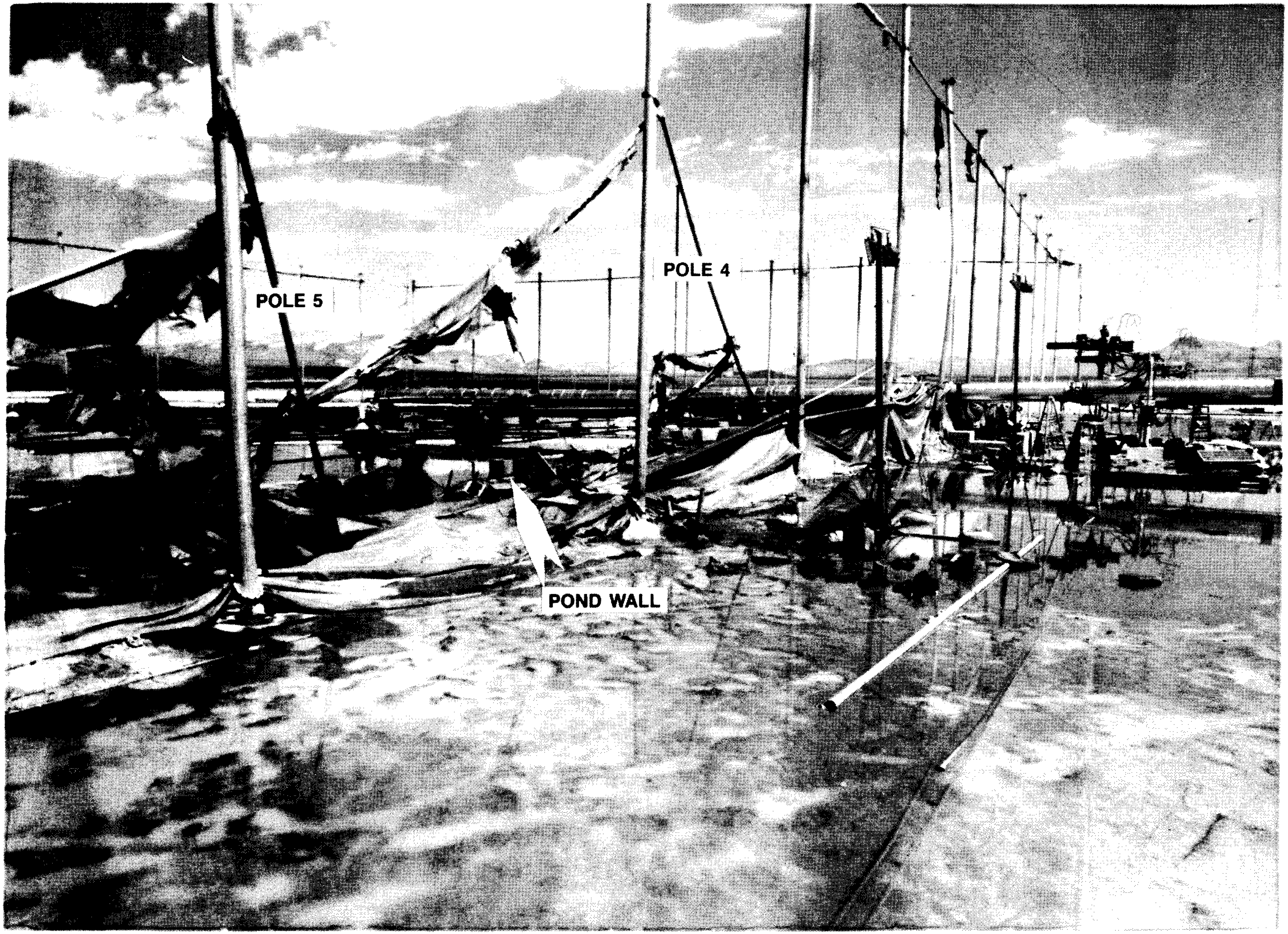
16. The vapor curtain between pole 4 and pole 5 was missing between the first two batten sections from the top, and a rectangular hole (3' high x 5' long) was observed at bottom corner of pole 4. Concrete blocks were found outside of the curtain in this area.

17. At pole 4, interior guy wire support (chain) had instrumentation wiring pressed against it, with each cable stripped approximately two inches. The signal cable from video camera 3 was broken at this point. Camera 3 lost its video signal in videotape frame 18:59:21:09, or one frame after ignition became visible outside the curtain. The force of the RPT disrupting the spill pond wall was the most likely cause of the broken signal cable. (Ref. Figure 4n for last partial frame).

18. Aluminum battens 2, 4, 5, and 6 (Ref. Figure 7) in the support structure between poles 4 and 5 were found broken and separated at approximately 1/3 the distance into the curtain from pole 4. At the breaking points, aluminum was broken as if from bending.

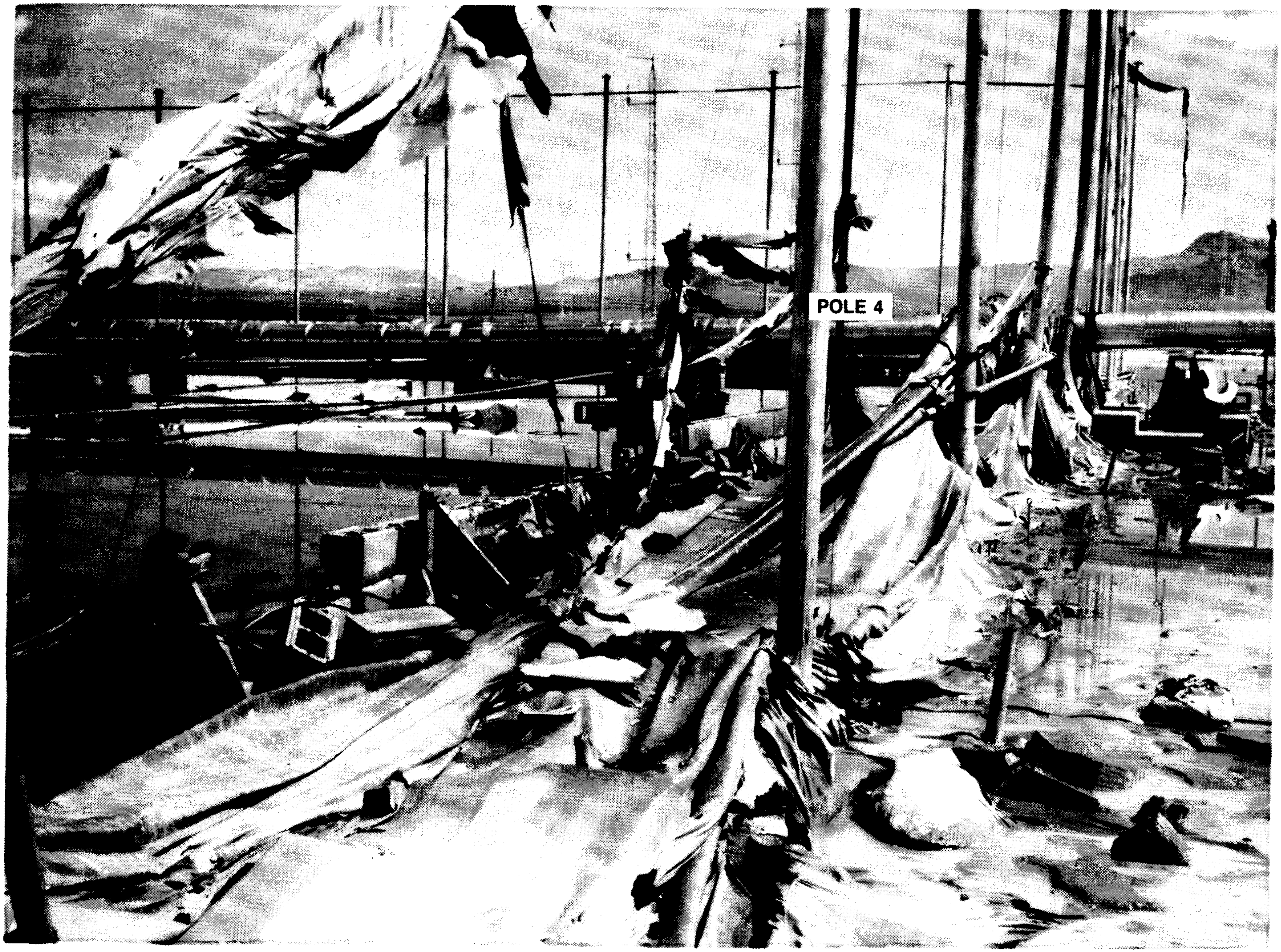
SPILL-SPIDER DAMAGE

FIGURE 5



SPILL-POND WALL DAMAGE

FIGURE 6a

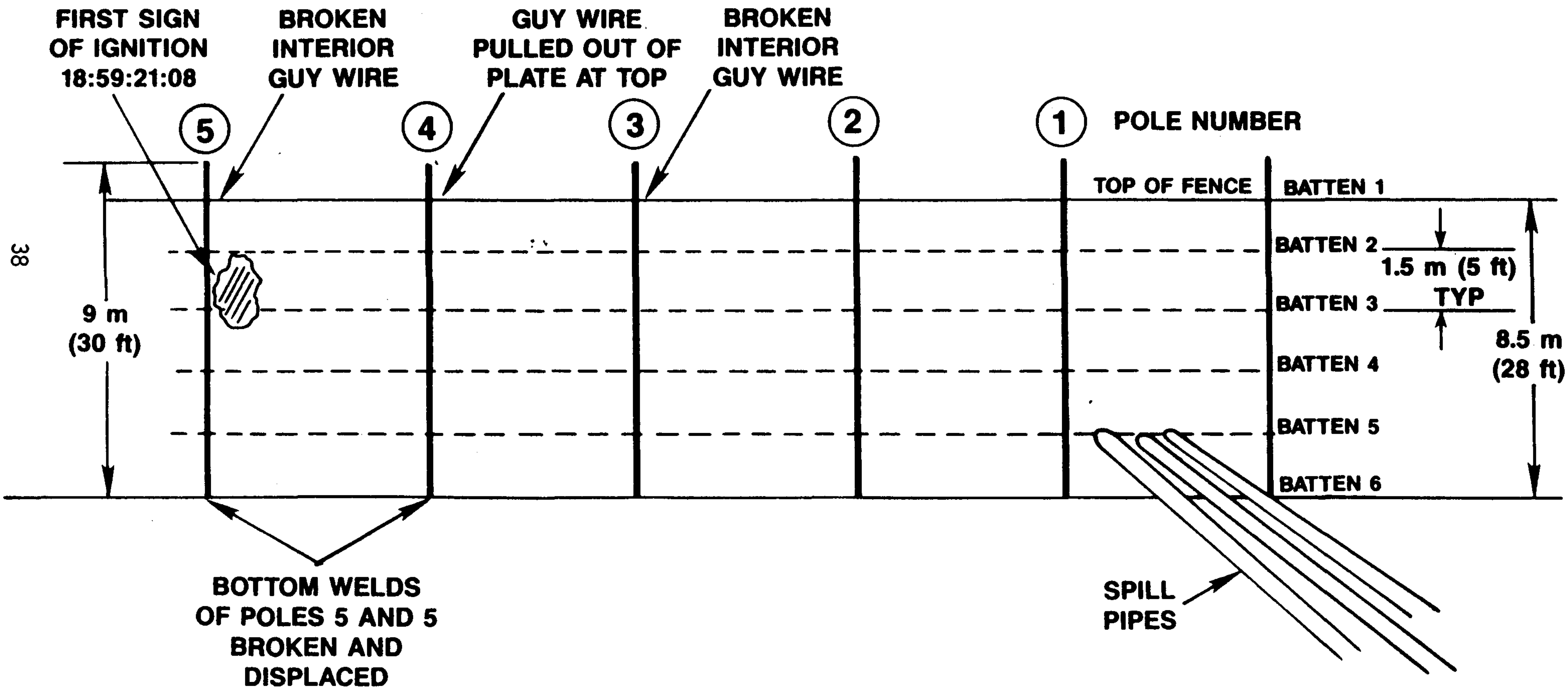


SPILL-POND WALL DAMAGE

FIGURE 6b

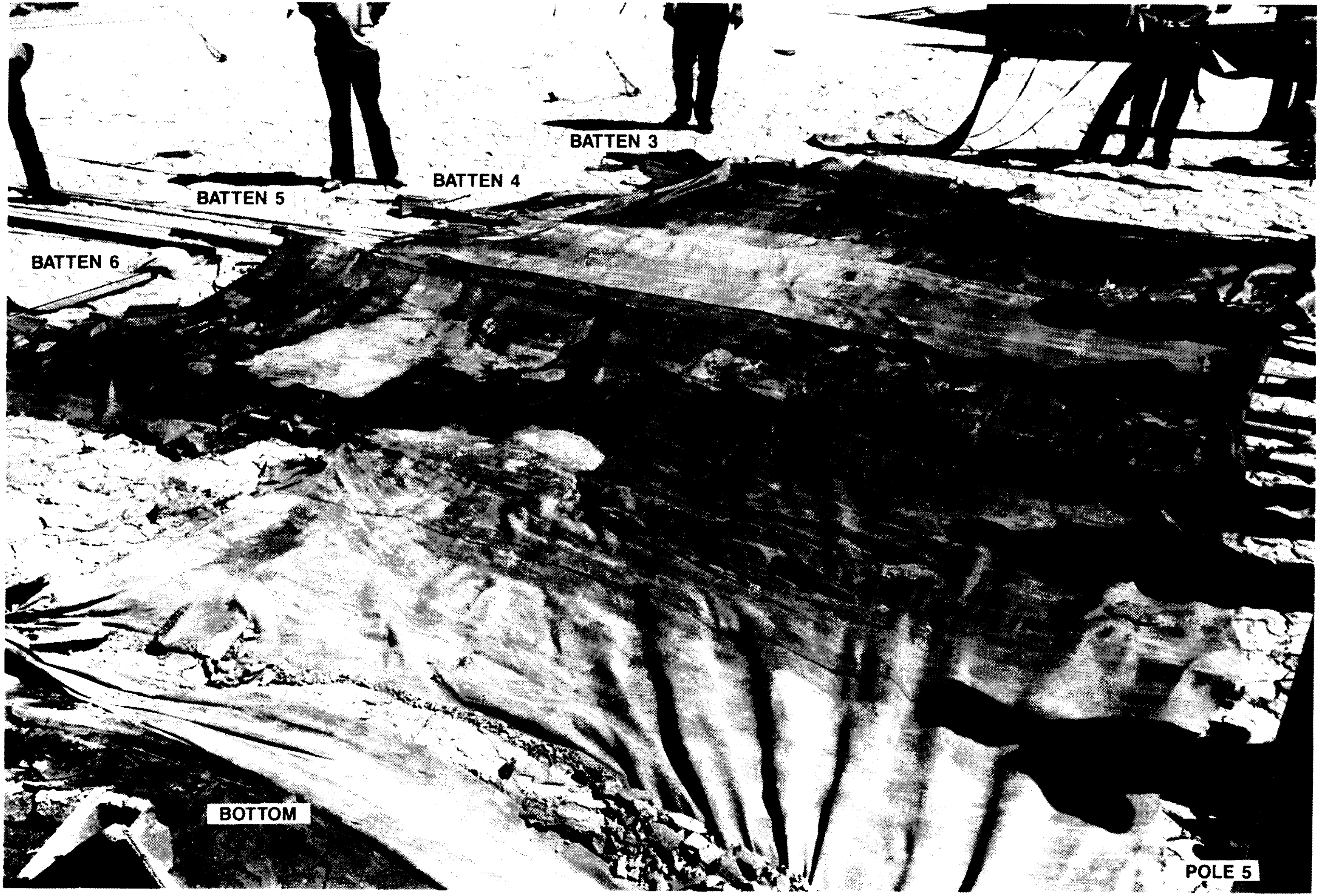
SPILL-POND WALL DAMAGE

FIGURE 6c



SCHEMATIC DIAGRAM OF VAPOR CURTAIN

FIGURE 7



VAPOR CURTAIN AFTER FIRE

FIGURE 8

19. The view from video camera 2 appears to show that the ignition of the fire was outside the vapor curtain at about pole 5 and approximately 1/3 the way down from the top of the curtain. The point of ignition can be seen in Figure 9. The concept that the fire started outside the vapor curtain is supported by the fact that pictures from video camera 2, well after ignition, do not show the appearance of a hole in the curtain from light of the fire burning inside the curtain shining through such an opening. Figure 10 shows the curtain at 18:59:30:03. No light can be observed from behind the curtain where the fire is burning, indicating no hole is present.

20. All camera angles were insufficient to determine if the point of ignition was at the vapor curtain or a few feet out from the front of the vapor curtain. However, they do indicate that the fire started close to the curtain. There is no evidence supporting initial ignition occurring inside the curtain.

IV. ANALYSIS

Numerous mechanisms were considered for the ignition of the fire. Table 2 outlines the potential mechanisms considered. In addition to these mechanisms, determining the location of the point of ignition of the fire was a factor of prime importance. Two mechanisms (combustion with a cool flame and combustion with a hot flame) were considered for the initiation of the fire. It was initially believed possible that the ignition might not have occurred at the point where it was first visible as seen in frame 18:59:21:08 from video camera 2.

It was hypothesized that the flame could have started inside the curtain perhaps with a cool flame, propagated through a hole in the vapor curtain at a point 6 meters (20 feet) above the ground, and then achieved combustion conditions where it was visible outside the curtain. The hypothesis was examined extensively. The following is a summary of the factors that were considered to support or reject the hypothesis concerning the identification of the exact location of the point of ignition.

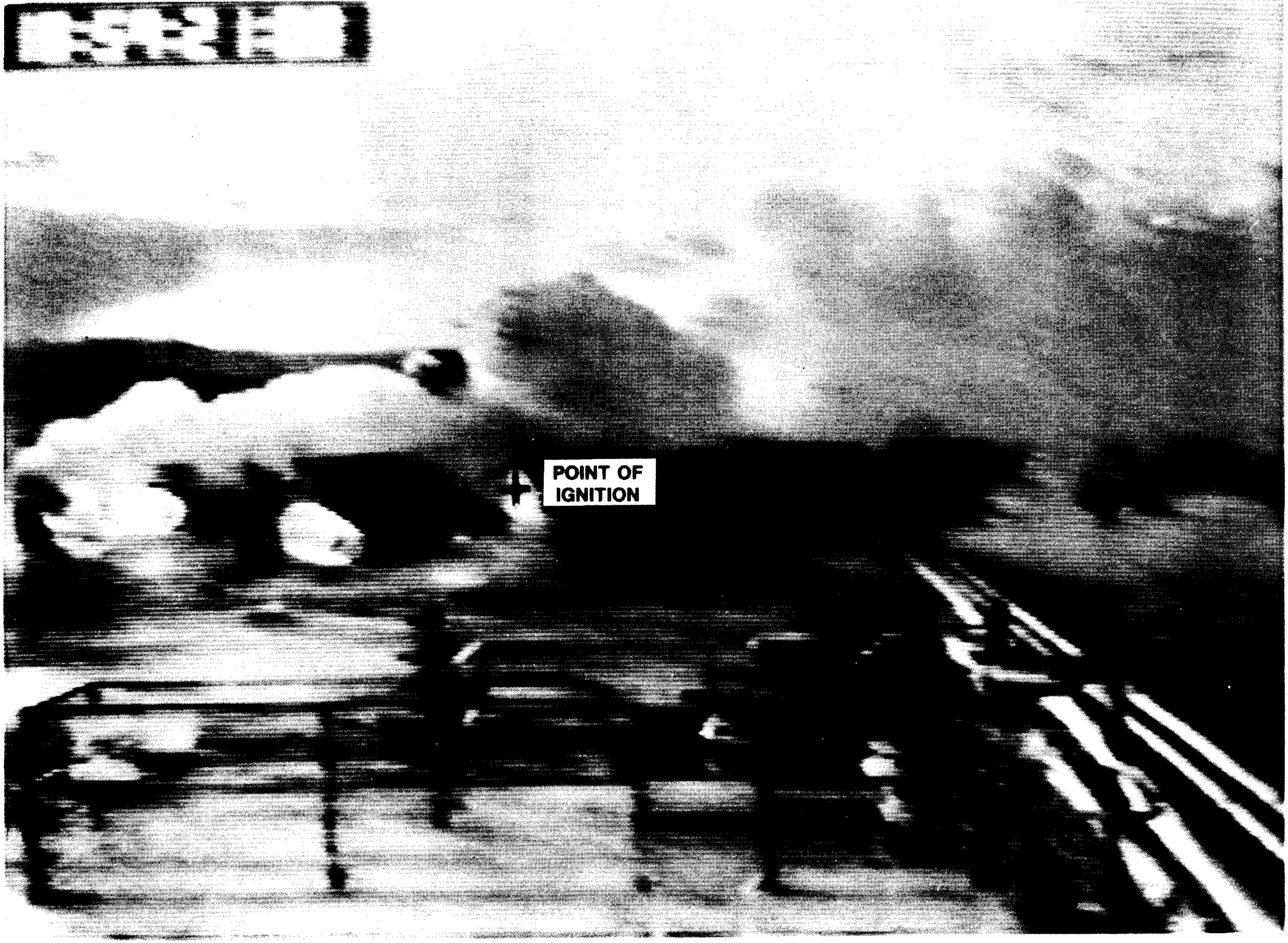
Evidence that supports the view that the fire ignited on the inside of the vapor curtain.

1. More conditions suitable for ignition of the fire are on the inside of the curtain.

2. Flammable composition is possible due to the turbulence caused by the RPTs.

3. Small RPT-like plume occurred on the inside just prior to ignition.

4. No well-defined mechanism that would readily demonstrate that the fire started outside.



IDENTIFICATION OF POINT OF IGNITION

FIGURE 9a

IDENTIFICATION OF POINT OF IGNITION

FIGURE 9b

VAPOR CURTAIN DURING FIRE

FIGURE 10

TABLE 2

POSSIBLE MECHANISM FOR IGNITION

1. Direct ignition by RPT shock wave
2. Catalytic ignition
3. Electrical spark from an electrical source
    - Broken TV signal cable
    - Abraided thermocouple cables
    - Abraided heat flux cables
4. Friction spark from mechanical impact
    - Steel rebar and concrete blocks
    - Stainless steel guy wire and concrete block
5. Electrical spark from static electricity discharge
    - Charge created on vapor curtain by air and vapor flow

Evidence that supports the view that the fire ignited outside of the vapor curtain.

1. First visual observation of flame is on the outside of the vapor curtain.

2. The flame front appears to roll up the outside of the curtain, rolls over the top, and into the inside of the curtain.

3. No visible evidence that flames propagated up in a turbulent environment on the inside of the curtain. If the fire started on the inside and propagated through a hole one-third the way down from the top, the fire would have to have been that close to the top of the curtain on the inside, with a mixture that was just as flammable as that on the outside.

4. No evidence of multiple points of ignition on the inside.

5. No observation of a hole in the curtains, from "back-lighted" condition, for which flames could penetrate from the inside to the outside.

6. Definitely had appropriate flammable limits on the outside.

The hypothesis that the fire ignited inside the curtain was rejected in favor of the view that the fire ignited outside the curtain. The major factor was the nature of the propagation of the fire. The visual record indicates that after ignition, the fire moved up the outside of the curtain and over the top, igniting the vapor on the inside. There appeared to be no simultaneous appearance of a flame on the inside of the curtain. It was felt that if there was fire initially on the inside within 10 feet of the top of the curtain, with the dynamic condition due to turbulence from the RPTs, the fire would have found numerous locations where a cool flame could encounter the proper gas mixture that would allow rapid propagation upward. If it had started on the inside, it could be reasonably expected that it would have propagated upward to the top on the inside before it did so on the outside. There is no evidence of this effect (see Figure 4).

A consensus was reached that the point of ignition was on the outside of the curtain at the point observed in frame 18:59:21:08 shown on camera 2. The next question was, considering the ignition scenarios proposed, which ones would be capable of igniting the natural gas vapor at pole 5 approximately 1/3 of the way down from the top of the vapor curtain, a distance of 6 meters (20 feet) above the ground.

The following is a systematic discussion of the various scenarios presented in Table 2:

Scenario 1 -- Direct ignition by RPT shock wave

Evidence that favors or supports this scenario.

1. A very strong RPT (or doublet) occurred adjacent to the point of ignition.

2. Turbulence in gas mixture could provide gas composition within proper flammable characteristics.

Evidence that does not support this scenario.

1. No published or available information or theories indicating or documenting that RPTs have caused direct ignition.

2. Spatial separation between point of RPT and point of ignition is incompatible. The RPT occurred close to the wall at the pond surface which could be about 7 feet from the base and on the inside of the vapor curtain. Ignition appeared to have occurred on the outside of the vapor curtain at a point 6 meters (20 feet) above ground level.

3. RPTs of similar strength occurred in this test and in test 3 in conditions of similar geometry and no fire resulted.

4. There is no indication that an RPT could create a shock wave with sufficient compression to heat the mixture to a point of ignition.

Evaluation of the Board: This is a very low probability cause of the fire and the evidence does not support a logical conclusion that this mechanism was the probable cause of the fire.

Scenario 2 -- Catalytic Ignition

(Note: Catalytic ignition is a surface-related phenomena; the Board felt that a new or fresh surface was required for this scenario. The new, possibly significant, surfaces created were the concrete blocks that were broken and the stainless steel guy wires broken in tension.)

Evidence that favors or supports this scenario for concrete blocks.

1. Many blocks were broken creating many new, fresh surfaces.

Evidence that does not support this scenario for concrete blocks.

1. Concrete blocks were broken in test 3 and there was no fire.

2. Many concrete blocks were broken in test 5 which produced many surfaces which should result in multiple points of ignition.

3. Spatial separation between points where blocks were fractured and the point of ignition is incompatible. Blocks appeared to be

fractured on the inside of the vapor curtain while ignition point was on the outside of the curtain.

4. No previous evidence exists that indicates that concrete blocks can function as a catalyst for the ignition of natural gas vapor.

5. There is no evidence that material contained in the blocks were of a nature to create a catalytic surface even when broken.

Evaluation of the Board: While this is a very low probability cause of the fire and the evidence does not support a logical conclusion that this mechanism was the probable cause of the fire.

Evidence that favors or supports this scenario for stainless steel guy wires.

1. The tensile failure of the braided stainless steel guy wire produces fresh metal surfaces at the end of many small-diameter wires.

2. The end of the frayed guy wire was discolored by oxides from elevated temperature oxidation.

3. Guy wire found in the vicinity of the ignition.

Evidence that does not support this scenario for stainless steel guy wires.

1. Two wires broke and flipped over the top batten with only one ignition.

2. Broken wire with fresh surfaces passed through many combustible mixtures on its way up and out of the vapor cloud on the inside of the curtain. It is not clear why it would be delayed over a second until it reached the outside of the vapor curtain.

3. The fresh surface area on the ends of the broken stainless steel wires is very small, indicating that the surface to volume ratio needed to support the catalytic reaction would not be easily satisfied.

4. No previous evidence exists that indicates that stainless steel can function as a catalyst for the ignition of a natural gas vapor.

5. The time of reactivity in a new surface of stainless steel is not known.

Evaluation of the Board: While this is a plausible cause of the fire, the evidence does not support the logical conclusion that this mechanism was the probable cause of the fire.

Scenario 3 -- Electrical spark from an electrical source

Two different electrical sources were considered which included a spark from the broken coaxial cable for video camera 3 and from the instrumentation cables (thermocouples and heat flux gages).

Evidence that favors or supports this scenario for the broken coaxial cables.

1. Coaxial signal cable was broken.

Evidence that does not support this scenario for the broken coaxial cables.

1. Camera 3 remained on for 1/30 of a second after the ignition has occurred. The fire was well ignited in frame in 21:08 and the signal from camera 3 is not terminated until halfway through frame 21:09 (see Figures 4m and 4n).

2. Spatial separation between the points of the cable break and the point of ignition is incompatible. The cable break occurred near the ground on the inside of the vapor curtain. Ignition appeared to have occurred on the outside of the vapor curtain at a point 6 meters (20 feet) above the ground level.

3. With the low voltages used in the video signal, it is believed that there would not be sufficient energy in a spark to ignite the vapor cloud.

4. Low probability for a combustible mixture near the ground on the inside of the curtain.

Evaluation of the Board: While this is a plausible cause of the fire, the evidence does not support the logical conclusion that this mechanism was the probable cause of the fire.

Evidence that favors or supports the scenario for shorted cables from heat flux sensors and thermocouples.

1. Instrumentation wiring abrasion did occur.

Evidence that does not support the scenario for shorted cables from heat flux sensors and thermocouples.

1. Spatial separation between the location of the abraded wires where a short could have occurred and the point of ignition is incompatible. The abraded wires are near the ground on the inside of the vapor curtain. The ignition point appeared to have occurred in the outside of the vapor curtain at a point 6 meters (20 feet) above the ground level.

2. With the low voltages used in the instrumentation, it is believed there would not be sufficient energy in a spark to ignite the vapor cloud. It was also noted that the 1/4 amp fuse in the circuit was not "blown." Thermocouple leads are known to have insufficient energy to create a suitable spark.

3. Low probability for combustible mixture near the ground on the inside of the curtain.

Evaluation of the Board: While this is a plausible cause of the fire, the evidence does not support the logical conclusion that this mechanism was the probable cause of the fire.

Scenario 4 -- Friction spark from a mechanical impact

Evidence that favors or supports this scenario for concrete block and steel rebar impact.

1. The two materials are known to spark when forced against one another with a rapid shearing action created by impacts.

2. Many blocks were displaced from positions where rebar was used to align the wall and the rebar was bent outward indicating strong and significant interactions between the block and the rebar.

Evidence that does not support the scenario for concrete block and steel rebar interaction.

1. Spatial separation between the location of the rebar and the point of ignition is incompatible. The rebar is near the ground on the inside of the vapor curtain. The ignition point appears to be outside of the vapor curtain at a point 6 meters (20 feet) above the ground level.

2. It is believed that a friction spark from this type of interaction would not have sufficient energy to ignite the natural gas vapor.

3. Similar block displacements and bent rebar in other locations around the pond in test 5 and in test 3 without ignition.

4. Low probability for a combustible mixture near the ground on the inside of the curtain.

Evaluation of the Board: While this is a plausible cause of the fire, the evidence does not support the logical conclusion that this mechanism was the probable cause of the fire.

Evidence that favors or supports this scenario for concrete block and stainless steel guy wire impact outside the vapor curtain.

1. Spatial relationship is favorable in that stainless steel guy wire is located in very close proximity to where fire is considered to have ignited.

2. Many concrete blocks were dislodged and several were blown over the top of the curtain.

3. Flammable mixture well established by virtue of ignition.

Evidence that does not support the scenario for concrete block and stainless steel guy wire outside the vapor curtain.

1. The cross section of the guy wire and a concrete block or part of a block for interaction is extremely low.

2. Inconclusive evidence of mechanical abrasion on the outside guy wire at pole 5.

3. No evidence of localized heating to indicate point of ignition.

4. For the fire to ignite at a level equal to the third batten would require that the block strike the guy wire (extending from the top of the 9 meter pole at a 45° angle) at a distance of approximately 3 meters out from the curtain. Photographic evidence indicates that fire started much closer to the curtain than 3 meters (10 feet).

5. It is believed that a spark from this type of interaction would not have sufficient energy to ignite the natural gas vapor.

Evaluation of the Board: While this is a plausible cause of the fire, the evidence does not support the logical conclusion that this mechanism was the probable cause of the fire.

<u>Scenario 5 -- Electrical spark from static electricity discharge</u>

Evidence that favors or supports this scenario.

1. Curtain is made of a nonconductive material that has a very high resistivity.

2. LNG spill and RPT produced a turbulent cloud of ice particles, water, natural gas, and air in a very close proximity to the curtain and could have developed a static charge on the curtain.

3. The energy in static electric charges are well known to have sufficient energy to ignite combustible mixtures of gases.

4. The vapor was obviously in a flammable mixture range as evidenced by the fire.

5. The metal battens for support to the curtain were electrically isolated from the 9-meter-high support poles that were grounded.

6. The broken stainless steel guy wire, which was grounded, was hanging on the outside of the top batten. The broken guy wire could have easily served as the discharge point. It was close to the curtain and in the vicinity of pole 5.

7. Broken guy wires were only found in test 5, indicating that static charges possibly created at other times may not be readily discharged to a grounded point.

Evidence that does not support this scenario.

1. Despite potential for static electricity being created in the spill test area, no evidence was noted previously.

2. No obvious path to ground to promote discharge.

3. Guy wire was broken on pole 3 and it established the same configuration as on pole 5, but there was no evidence of ignition.

4. Curtain was likely wet from the water spray from the RPT and might not hold a static charge.

Evaluation of the Board: The Board concluded that the argument for this scenario was the only one that was supportable. There was a unanimous consensus by the Board that this was the most probable cause of the fire.

V. CONCLUSION

Findings

1. A Safety Analysis Document had been prepared specifically for these tests and it fully recognized the potential for RPTs and that a fire could occur.

2. The test and the fire were well documented. Without the extensive video tapes and movie, it would have been extremely difficult to establish the probable cause.

3. Operational procedures were in place that would not allow the test to be conducted with personnel in close proximity to the spill test area. There was no risk to people or the permanent part of the facility (storage tanks and control room) at the time of the occurrence.

4. Sufficient planning regarding the structure and configuration of the spill test area had been completed to make the probability of fire extremely low.

5. The construction method of the spill test area was of an elementary nature that would minimize financial loss from RPTs and if a fire were to occur.

6. Numerous variables contribute to the occurrence of RPTs which include initial LNG composition, spill duration, spill substrate, rate of vaporization, and horizontal and vertical momentum of LNG. The significance of each of these variables in promoting RPTs is not well understood.

7. LNG compositions were measured; however, the analyses were not always available on the days of the tests. These data were not used as criteria in determining whether to conduct a test.

8. While initial LNG composition is a factor that influences the potential for RPTs, the importance of this parameter is not well understood. When LNG is spilled on a substrate such as water, it has an initial composition and the predominant constituent is methane. Once spilled, the composition of the LNG continually changes as the constituents evaporate at different rates. Methane, which has the lowest boiling temperature, dissipates at the highest rate. With time, the remaining LNG become richer in hydrocarbons of high molecular weight (ethane, propane, butane, etc.). The role LNG composition, the initial composition and that at any given time, plays in occurrence of RPTs is not understood.

9. Water was selected for the substrate in which to spill LNG because of its good heat capacity and good thermal conductivity that provided the characteristics to support the desired high and sustained evaporation rates of LNG to meet the test requirements. The test requirements were established jointly by GRI and DOT.

10. The four previous test spills of LNG were conducted without a fire. Three of the test spills were conducted without an occurrence of RPTs.

11. The experimental parameters in the first test spill were similar to the last test spill, although the total volume of LNG was larger in test 1 by a factor of two, and the composition of the LNG was different. No RPTs were visually observed in test 1.

12. While variables that contribute to or promote the occurrences of RPTs have been identified, with the current state of the art, it is not possible to predict when RPTs will actually occur or their magnitude.

13. The decision to proceed with each test in the series was made after consultation between the sponsor and the LLNL staff. They reviewed the results of previous tests and established the nominal test conditions for the next test. After consultation with the Scientific Advisory Panel, a conscious decision was made to proceed with the test following the agreed-upon conditions. The potential risks of pursuing the test were understood.

14. The decision to execute a specific test, using the conditions established jointly with the sponsor, was made by the Test Controller with input from the Test Director and the Scientific Advisory Panel. The conditions in the spill test area were within the agreed-to values at the start of the test.

15. A violent and powerful RPT (or doublet) occurred in the immediate vicinity of and just prior to the ignition of the natural gas vapor. This RPT created significant disruption to the spill test area structures.

16. The ignition of the fire was at or very near the vapor curtain on the outside at a point one third of the way down from the top at the fifth pole south of the spill line.

Probable Cause

Although there was substantial information about the conditions prior to the fire, the information was not of a nature that would allow a clear determination of the cause of the fire. The identification of the most probable cause was based on a systemmatic evaluation of the facts in the context of five different scenarios. The evidence available is not conclusive, but only points to the probable cause. Within this context, there was a unanimous consensus among the Board members and technical advisors to the Board that the following were the most probable causes:

1. RPTs were a major contributing factor to the ignition of this fire for two reasons: (a) they contributed to the conditions necessary to establish the static electric charge on the vapor curtain; and (b) they created significant damage, including the necessary force to break the guy wire that eventually became the ground point for the discharge of the static electricity.

2. The most probable source of the ignition of the fire was a static electric discharge, resulting from the broken stainless steel guy wire interacting with the curtain or aluminum battens on the outside of the curtain producing a spark.

Judgment of Needs

The following judgments are presented within the context that a research program of similar nature to the Falcon series of tests will be continued. Although the probability of fire is very low with the existing operational practices and test area configuration, several actions could be taken to further reduce the probability of a fire occurring. Before one takes these actions, the cost-benefit relationship should be carefully considered. The proposed actions are as follows:

1. Reduce the probability for the occurrence of RPTs. Numerous variables contribute to the occurrence of RPTs and the significance of each is not well understood. They include LNG chemical composition, spill duration, spill substrate (water), rate of vaporization and horizontal and vertical momentum of LNG. These variables need to be evaluated to determine which ones have the greatest potential for promoting RPTs and the controls that could be placed on these variables to minimize the potential for RPTs. It also should be noted that if experimental variables for similar tests fall within the conditions that increase the probability for RPTs, this should not be viewed as an imperative to change if the conditions are necessary to obtain other pertinent data about hazardous materials.

2. Reduce the potential for creating a static electric charge or static spark. This could be accomplished by utilizing a vapor curtain that is electrically conductive and grounded. If an electrically conductive curtain cannot be found, then the battens used to stiffen the curtain should be electrically bonded and grounded. Locations of electrical ground should be well controlled; the diameter of guy wires could be increased to minimize potential for breaking and producing a highly mobile ground that could contribute to a random discharge of a static electric charge.

3. Reduce the potential for creating a friction spark from mechanical impact actions of materials in the test area. Some specific actions that could be taken are the removal of the carbon steel reinforcing bar that is in the pond wall, cement the bricks in the pond wall to make it more difficult for them to be knocked out of position by nearby RPTs, and encase the stainless steel guy wires in plastic or teflon sleeves. With regard to the spillpond construction, cement could be eliminated if sandbags were used to weight the wall from the top and support it from behind. The chains at the bottom to which the stainless steel guy wires are connected should be covered with earth or protected by some means.

4. Reduce the potential for creating an electrical spark from instrumentation cables. Some actions that could be taken are to remove all unnecessary electrical cables from inside the vapor curtain; for essential cables, protect them using nonsparking conduit or bury them below ground.

Board of Investigation

Unplanned Fire at the Liquefied Gaseous Fuels Spill Test Facility on August 29, 1987

Dr. Donald L. Vieth

Dr. Donald L. Vieth
Acting Deputy Assistant Manager for
Environment, Safety, and Health
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Francis A. Leone

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U.S. Department of Energy
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APPENDIX A

LETTER APPOINTING BOARD

Department of Energy
Post Office Box 98518
Las Vegas, NV 89193-8518

SEP 9 1987

D. L. Vieth, Acting Deputy Assistant Manager for Environment, Safety & Health, NV
L. J. Ferderber, Assistant Deputy Associate Director for Nuclear Testing, LLNL, Livermore, CA
J. A. Michael, Deputy General Manager, EG&G/EM, Las Vegas, NV
R. W. Svab, Fire Protection Engineer, EG&G/EM, Las Vegas, NV
F. A. Leone, HQ (FE-15) GTN

INVESTIGATION BOARD--LIQUEFIED NATURAL GAS VAPOR CLOUD IGNITION

You are hereby appointed as members of a Panel to conduct a Type B investigation and submit a formal report on the circumstances, causes, and contributing factors to the unplanned ignition of the liquefied natural gas (LNG) vapor cloud at the Liquefied Gaseous Fuels Spill Test Facility, Nevada Test Site, on August 29, 1987.

Dr. Donald Vieth will serve as Chairman of the Board. Other individuals who will participate in the investigation in varying capacities are listed on the Attachment. The investigation and report will be in accordance with the provisions of DOE Order 5484.1, Chapter II.

The Board shall have the authority to consult with, enlist the aid of, and take statements from any and all personnel whose authority, responsibility, function, and activity might bear directly or indirectly on this event and who can contribute to understanding the causes of the occurrences and can provide input to recommendations for corrective actions.

Mr. Shed R. Elliott, Director, Safety and Health Division for the Nevada Operations Office, will provide appropriate assistance and will review the draft report for completeness prior to publication.

The report of the investigation, with appropriate recommendations, is to be submitted to me by October 9, 1987.

Nick C Aquilina

Nick C. Aquilina
Manager

SHD:DRM-678

Enclosure:
As stated

cc w/encl:
R. W. Barber, HQ (EH-33) GTN
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D. R. Martin, SHD, NV

LIQUEFIED GASEOUS FUELS SPILL TEST FACILITY (LGFSTF)

TYPE B INVESTIGATION PURSUANT TO UNPLANNED FIRE DURING EXPERIMENT ON AUGUST 29, 1987

INVESTIGATION PANEL MEMBERS

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Mr. Tom Brown

Dr. Ron Koopman

Mr. Harold Gray

ITINERARY FOR

LIQUEFIED GASEOUS FUELS SPILL TEST FACILITY (LGFSTF) TYPE B INVESTIGATION MEETING

THURSDAY, SEPTEMBER 10, 1987

6:45 a.m.	Arrive at Maxim Hotel *
7:00 a.m.	Depart for Nevada Test Site
8:10 a.m.	Arrive badge office
8:20 a.m.	Depart for LGFSTF
8:45 a.m.	Arrive LGFSTF
9:00 a.m.	Begin meeting - introductions - review of purpose of meeting
9:15 a.m.	Review experiments
11:00 a.m.	Consider information provided regarding fire - Review and discussion of data - Brainstorm - Outline information desired and course of action
Noon	Lunch
1:15 p.m.	Visit site of fire
2:15 p.m.	Continue review and discussion
3:15 p.m.	Summarize situation
4:00 p.m.	Adjourn - return to Las Vegas
6:00 p.m.	Arrive Las Vegas - hotel/airport

* Guest will be met by Don Vieth with 14-passenger van

APPENDIX B

LETTERS FROM TECHNICAL ADVISORS TO THE BOARD

DLV 1/22

ACTION Amesh
INFO
AMA
AMESH ✓
AMOE

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CRYOGENICS
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Boulder, Colorado 80303
303/494-6926

September 13, 1987

Dr. Donald L. Vieth
U.S. Department of Energy
Nevada Operations Office
P.O. Box 14100
Las Vegas, NV 89114-4100

Re: P.O. Number 1926 L

Dear Don:

In reflecting on discussions held during our meeting of September 10, I will attempt to summarize my views related to the accidental ignition that took place at the LGFSTF on August 29, 1987. Upon my return to Boulder I continued to consider several aspects of our tentative conclusions without materially altering the basic concepts we jointly developed.

In order to initiate combustion, natural gas must be mixed with air within suitable composition limits and be provided with an ignition source of sufficient energy. In a spill test, the first requirement is known to exist in large portions of the atmosphere. Potential sources of ignition in the regions adjacent to the spill and near the ensuing vapor cloud can be somewhat more subtle. For a methane-air mixture, the minimum ignition energy at one atmosphere is about 0.30 mJ with an autoignition temperature of about 1000 F. (Other pertinent hydrocarbons are in a similar range.) These physical characteristics are sufficiently low to readily permit ignition to take place - even under somewhat subtle circumstances. Under certain instances both the composition limits and ignition temperature can be somewhat less stringent. There is little evidence that combustion of a natural gas-air mixture in free space can develop into a detonation, although the configuration of the surrounding area (confinement), combined with a further restriction in composition limits, can influence such an evolution. For the subject incident, there is no evidence of detonation taking place.

Upon inspection of evidence at the test site in its present condition and after viewing video tapes and 16-mm motion picture films taken during the event, several pertinent observations give insight to the sequence of events taking place before, at and after the incident. Approximately one minute after the 50 cubic meter LNG spill, numerous intense rapid phase transitions (RPT's) took place. Although RPT's are not unexpected when spilling LNG on the surface of water, two facts are relevant - such events were only observed to have occurred in one of the previous four spill tests and the events of the present test appeared more abundant and perhaps more intense. In the film records, significant movement of the 35 foot high fabric vapor curtain was observed in synchronization with RPT events (caused by the associated pressure waves). The RPT's caused considerable damage to the concrete block wall forming the water pool. Damage to the fabric vapor curtain was seen in the film records at about the height of the top row of concrete blocks. Inspection of the site following the incident indicated considerable damage to the water containment wall and displacement of the concrete blocks over wide areas - portions of blocks were some distance outside of the curtain. It is highly likely that blocks (and/or portions thereof) were propelled through the curtain by the effects of the RPT's prior to ignition.

Immediately preceding the observation of ignition, at least two violent RPT's took place adjacent to the curtain panel where the fire was first seen. The observable flame occurred approximately 20 feet above the ground and <u>at</u> the location of the 5th pole from the pipeline. The flame appeared to take place at or near the curtain as opposed to a distance inside or outside of the curtain. The visibility of the flame is attributed to the ignition of a rich hydrocarbon mixture. (There was some speculation that the flame could possibly have occurred inside the curtain at near ground level. The lack of visual evidence could be rationalized by the initiating point being obscured from the points of observation or due to the occurrence of a cold flame of non-luminous intensity. It was the general opinion that initiation of the flame at a distance inside the curtain is improbable.) The flame front rapidly grew outside the curtain from the visual point of ignition. The downward flame front proceeded more rapidly than the upward front due to gaseous concentration differences. On reaching the top of the curtain, the flame appeared to roll over the top before rapidly spreading-adding additional impetus to ignition taking place at or outside of the curtain. Additionally, inspection of the curtain revealed considerable heat discoloration to the top portions of the outside of the curtain (with apparent bleed-thru to the inside) but no appreciable discoloration to the inside at low level. The top portions of the curtain between batten 1 and 3 had been consumed by fire. The propagation of the flame throughout the combustible cloud took place very rapidly - indicating extremely turbulent conditions.

Electrical sources located inside the curtain (and at the elevation of the fourth concrete block) adjacent to the curtain panel where external initiation was observed to occur were reported to be limited to the TV signal cable from camera #3, thermocouple leads and heat flux instrument leads. No electrical leads contained sufficient energy to cause ignition. The TV signal from camera #3 was interrupted (cable broken) about 1.5 frames <u>after</u> ignition was observed outside of the curtain by other cameras. None of the leads indicated that they had been burned.

Additional information requested from test site personnel includes an as-built drawing of electrical lead placement adjacent to the subject curtain panel (and their electrical energy) and readings taken during the spill test by thermocouples and gas concentration instruments located within the curtain enclosure.

Each vertical curtain pole is supported by three guy wires - two inside the curtain and one external to the curtain. One of the inside guy wires from pole 5 was broken by tensile failure. The force necessary to cause failure was attributed to the pressure wave associated with the RPT's that preceded ignition as the pressure was projected against the large curtain area. The top portion of the wire was propelled vertically at the time of failure in such a manner that it flew over the top horizontal batten. The top portion of the tensile break shows blue discoloration due to heat while the lower portion of the break shows no such discoloration. This implies that the top portion of the wire was exposed the fire after separation. Internal guy wire failures also occurred at other adjacent poles.

The actual mechanism of ignition can only be inferred by evidence available from the film records and from inspection of the site after the incident. The task group considered a number of potential ignition mechanisms, most of which were eliminated as being highly improbable for initiating ignition in the known test site configuration and known environmental conditions. Two potentially possible ignition sources were isolated and reviewed at more length. These basic concepts relate to ignition caused by a spark initiated by mechanical impact and to ignition by discharge of static electricity.

Mechanical impact - One proposed ignition mechanism involves a concrete block (or portion thereof) being propelled outside or thru the curtain striking the external stainless steel guy wire from the pole. The mechanical impact of the concrete block on the wire must create a spark of sufficient energy to ignite combustible gas in the area. (Pertinent guy wires will be closely inspected by test site personnel for indication of impact with concrete.)

Although the impact of stainless steel on concrete is known to produce a spark, the energy contained in the spark may be questionable. In technical literature distributed at the meeting, the practical danger from mechanical sparks appears to be controversial. I suggest a further action item to more thoroughly investigate the extent of hazard associated with such sparks in a natural gas-air environment. Additional information is needed to conclude this scenario.

Static electricity - A second proposed ignition mechanism involves the discharge of static electricity built up on the fabric curtain. It is known that a difference in electrical potential can be generated between two materials of differing dielectric properties and insulated from each other. A static charge buildup on the curtain could have been achieved by several possible mechanisms, but the most probable would be attributed to gas cloud dynamics within the curtained area. It is postulated that turbulence of the vapor cloud (especially containing many small ice crystals) in rapid motion against the fabric curtain could produce such an effect. The curtain and battens are insulated from the vertical poles by teflon sheets wrapped on the battens in the region of the pole. (The purpose of the teflon was to reduce sliding friction against the pole during relative motion while raising the curtain.) It is possible then to create a situation where the fabric curtain and the battens are suspended at a different electrical potential from the grounded vertical aluminum poles.

The actual ignition (discharge) mechanism is somewhat less definitive but two possibilities were proposed: 1) The broken internal guy wire being rapidly propelled over the top batten would be at the same electrical potential as the pole. The guy wire striking the curtain or batten could cause static discharge. (The electrical conductivity of the fabric curtain is somewhat in question but was reported to be non-conducting by the manufacturer.) and 2) Perhaps a more likely mechanism would be due to rapid relative (lateral) movement between the batten and the pole (probably at the precise time when the internal guy wire broke) causing the batten to contact the pole beyond the region protected by the insulating teflon sheet. A static discharge would then occur between the batten and the pole with sufficient energy to cause ignition.

Perhaps a relevant question is why the ignition did <u>not</u> occur during other spill tests. There must have been a unique event that took place in the subject test. It is highly probable that this event was the proximity of at least two RPT's occurring immediately adjacent to the curtain causing sufficient damage to initiate the series of events leading to the incident. For the static electricity scenario, it is possible that a static charge was established on the curtain during preceding tests, but there was insufficient disturbance at the curtain, insufficient static build up and/or lack of a combustible mixture at the critical location.

The above comments summarize my thoughts following the meeting. I will call you after I receive and review your preliminary report.

Sincerely,

Dudley B. Chelton

Dudley B. Chelton

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September 16, 1987

Dr. Donald L. Vieth
U.S. Department of Energy
Nevada Operations Office
P.O. Box 14100
Las Vegas, NV 89114-4100

Re: P.O. Number 1926L

Dear Don:

In continuing to consider various aspects of the LNG incident that occurred at the LGFSTF, I have several additional thoughts regarding the vapor curtain structure in the region of the 4th and 5th vertical support poles. Examination of the evidence during the field inspection trips indicated several important points that may warrant additional thought. Specifically, 1) the horizontal aluminum battens between poles 4 and 5 had been broken near their midpoints, 2) vertical poles 4 and 5 had failed at their ground level base plates and 3) one guy wire on poles 3, 4 and 5 displayed tensile failure.

Horizontal battens - The horizontal battens used to provide some curtain support and to provide lateral rigidity for the assembly are composed of 2" aluminum tubes. Most (or all) of the battens between poles 4 and 5 failed near their midpoints without obviously damaging the fabric curtain. (The top fixed batten did not appear to be damaged and remained in place.) The appearance of the tube failures seemed unusual in that there was very little bending as I would have expected.

It would not be unusual to break the relatively thin-wall aluminum tubing if appropriate forces were applied, but I would expect the break to show signs of bending and flattening. Instead, the breaks were ragged with little deformation - perhaps even similar to brittle or torsion failure. Did these breaks take place when pressure forces were applied by the RTD's or when the curtain collapsed? Were other factors involved?

As I verbally mentioned on September 14, failure of the battens may allow sufficient lateral movement of the curtain assembly to permit metallic contact between the batten and the vertical pole. Such contact may be pertinent to the static electricity ignition scenario since it would provide a means of discharging the difference in potential between the curtain and the grounded vertical pole. The time when the batten failure took place would obviously influence its participation (if any) in the ignition process. If the battens broke during collapse of the curtain it would influence their ability to allow lateral movement at the proper time to cause a spark.

Vertical poles - The 48 thirty-foot high vertical poles form the ructural support for the fiber reinforced fabric vapor curtain. The uminum poles (5" schedule 5 pipe?) are welded onto base plates at the top d bottom. Poles 4 and 5 (numbered clockwise from the LNG pipeway) ppeared to have experienced some minor bending outward from the spill area ut more significantly both separated from their bottom base plates at the eld location. Other poles displayed more significant bending (concave from the inside to outside of the enclosure) without being broken at their bases. The mode of failure is surprising to me. A general pressure force on the curtain would impose uniform loading on the pole with the pole acting as a cantilevered beam clamped at the base plate. Although the maximum stress on the pole is indeed at the base plate weld, I would expect greater deformation in higher portions of the pole and flattening before breaking at the weld. (As I recall, a pole that required replacement after test #3 failed in just such a mode. It was lying in the field to one side of the site.) Perhaps the mechanics of calculating the stresses and deflections would verify the physical results observed. Is the possible that the nature of the failure is providing additional information of which we are not taking advantage? Perhaps the existing pressure forces were applied only to the lower part of the poles and not along its length. Perhaps the torn part of the curtain near the base of pole 5 is due to higher pressures at the base.

Guy wires - Each vertical pole is supported by three guy wires formed from (1/8"?) stainless steel cables - two inside the curtain enclosure and one outside. One cable had been broken on poles 3, 4 and 5 (perhaps others?). The failures are typical of that caused by tensile stress and are not in themselves unusual for pressure loading on the curtain. I did not observe, however, if the guy wire failures displayed a directional aspect that might focus on the origin (location) of the pressure source, i.e. were the forces that caused failure coming from a common direction. If there is a directional dependence, is there a corresponding direction to bending of the vertical poles? The latter was not obvious at the site inspections. If there appears to be a directional effect, what would it mean? Would it serve merely to indicate the location of the RPT's that preceded ignition or would it indicate the occurrence of a different (additional) event taking place?

Unfortunately, the above comments seem to raise more questions then proposing solutions, but they may warrant additional consideration during our next meeting or perhaps another look at the test site.

I have been reviewing various sources for information on the energy available in a static discharge. National Fire Protection Association Recommended Practice on Static Electricity, NFPA No.77, clearly indicates that potential can exist for ignition of a combustible mixture.

Sincerely,

Dudley

Dudley B. Chelton

cc: Harold Gray

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September 26, 1987

Dr. Donald L. Vieth
U.S. Department of Energy
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Las Vegas, NV 89114-4100

Re: P.O. Number 1926L

Dear Don:

Following the meeting of September 24 in Las Vegas, I am in agreement with general statements and conclusions expressed by the Investigating Board and the technical advisors regarding the incident that occurred at LGFSTF on August 29. The preponderance of evidence and technical knowledge supports a highly probable cause of ignition. Rapid phase transitions (RPT's) occurred adjacent to the area of interest immediately prior to ignition. Although these RPT's influenced the sequence of events that led to ignition, the probable cause of the incident was attributed to the discharge of static electricity from the fabric vapor curtain to ground potential. The possibility of establishing a static charge on non-conducting fabric material has ample precedent. The severity of RPT damage to the facility in the area of poles 4 and 5 was contributory to the release of the static charge.

The detailed mechanism for the static electrical discharge was reduced to three possibilities: 1) contact of the frayed end of the electrically-grounded broken guy wire from pole 5 with the surface of the fabric curtain, 2) contact of the electrically-grounded broken guy wire (along its length) with exposed parts of the electrically-isolated battens adjacent to pole 5 and 3) lateral movement of the battens permitting contact of uninsulated portions of the batten with the grounded pole 5. Although the final selection is not definitive at this time, all may be plausible depending on the ability of the battens to become electrically charged. I have enclosed a copy of NFPA Recommended Practice on Static Electricity (NFPA No. 77). Chapter 2 and Section 7312 are particularly informative.

Several other ignition scenarios, all considered plausible, were unanimously agreed to be of low probability. Although these scenarios were considered in detail, sufficient evidence and technical support were not present to establish credibility in the existing circumstances.

As a result of the investigative analysis, several constructive recommendations were developed to reduce the probability of recurrence in similar experiments. The recommendations were synthesized from pertinent factors of the low probability (but plausible) scenarios as well as the highly probably scenario. The basic approach was to consider steps to reduce possible escalation of RPT related damage within the enclosure and to reduce potential ignition sources from and within the enclosure.

I look forward to reviewing the draft of the Final Report when it becomes available.

Sincerely,

Dudley B. Chelton

Dudley B. Chelton

cc: Harold Gray
w/o enclosure

Western LNG Terminal Associates

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October 9, 1987

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Dr. Donald L. Vieth
Department of Energy
P.O. Box 14100
Las Vegas, NV 89114-4100

Dear Don:

First let me begin by saying that I am convinced that the fire which occurred during Test #5 on August 29, 1987 did, in fact, originate at, or immediately adjacent to the surface of the vapor barrier. I concur with our earlier consensus that the initial ignition was from a single source approximately 20 feet high at, or near, the main support pole #5.

My original thought was that, even though the evidence indicates the fire first at that point, the fire probably started at a point near ground level between the impound area and the vapor fence where instrument and video cables were destroyed and where considerable other physical damage occurred. If a near-invisible flame stared at that point and traveled up the inside of the vapor curtain it could, in fact, first show through a small hole in the curtain at the 20 foot elevation. The films, however, show clearly that he flame rose over the vapor curtain from the outside.

This means that my invisible flame would have had to begin its rise from a torn area near the bottom - outside of the curtain near pole #5. If this was the case, I think it <u>very</u> unlikely that the first visible flame would show as a point source which all evidence indicates. Therefore, the fire did not start at, or near, ground level either inside or outside the vapor fence. Also, since the fire did not first rise inside the fence, it could not have originated from anywhere inside. We are limited now to an initial ignition at or immediately adjacent to the outer area of the vapor fence. By visual evidence we are also limited to a point at, or immediately downwind of support pole #5 and at, or very near, the height of the third batten counting down from the top.

Regarding the physical elements required to start the fire, there was, near the point of ignition, the main support pole #5, the vapor fence, horizontal battens in loops of the vapor fence, and a broken 1/2" guy wire which was hanging from he top of pole #5 and down the outside of the vapor fence. There was no evidence of other objects but it is possible that something (such as part of a block) penetrated the vapor fence at the time of ignition.

To release a spark sufficient to initiate combustion, we now need an electrical charge and a ground. The support pole and hanging guy wire are obvious grounds. There has been much discussion about the ability of the vapor curtain to build up a static charge collected from the violent RPT forces and the large vapor cloud turbulence, especially with the cold cloud having a high probability of containing significant quantities of ice particles.

One expert opinion was that the static charge is only a surface effect and therefore would only be contained on the inside surface of the vapor fence and since the fire did not start inside the fence, the static charge from inside the impounding area could not cause a fire outside. The vapor fence was a woven glass cloth indicating that the surfaces were interconnected. The batten loops, made of the same cloth, were attached to the outer surface of the vapor fence by double stitching through the curtain creating additional common surface area contact. The glass cloth had a surface finish of silicon, graphite and teflon and it seems logical that a large static charge build-up from inside the vapor fence would build throughout surfaces of the woven material. The charge would then naturally be contained in the aluminum battens which had nearly full-surface contact with the vapor fence loops. The most probable events are therefore the vapor fence or the batten hitting either the guy wire or the support pole.

Many of the phenomena of RPT violence were similar in tests #3 and #5. There was no fire in test #3 and the only major differences between the two tests were that test #5 had guy wires snapped and thrown over the top of the vapor fence from inside to outside and that test #5 then had a fire in the immediate vicinity where the guy wire from support pole #5 would lean against the batten and vapor fence at pole #5. It seems most probable that it was the guy wire touching the batten or the vapor fence on the outside surface which created the ignition source.

Don, I have received a few inquiries from LNG facility operators asking about the conditions at the time of the fire. Since there are over 100 operating LNG facilities in North America, I feel it is important that we briefly mention that the research spill conditions simply do not exist at these LNG facilities.

In these research tests, large quantities of LNG were spilled into an impounding area which was prepared with a surface of circulating water to increase boiloff. RPT's can <u>only</u> occur when LNG spills on significant amounts of water. LNG facilities <u>do not</u>

have water in impounding areas. It is important, however, that facility operators be aware of the potential for static electric charges from other sources and protect the facilities accordingly.

Yours very truly,

L. E. Bell

LEB:aw

J. REED WELKER

P. O. Box 116
Fayetteville, AR 72702

8 October 1987

Dr. Donald L. Vieth
U. S. Department of Energy
Nevada Operations Office
P. O. Box 98518
Las Vegas, NV 89193-8518

Dear Don:

The accidental ignition of the vapor cloud near the end of Test 5 of the LNG test series (on 29 August 1987) represents an example of the kind of problem that can occur when flammable mixtures of fuel and an oxidizer are present. If research into the behavior of large flammable vapor clouds is to be conducted, it must be conducted with the actual materials present. Our present knowledge of modeling of vapor clouds is just not sufficient for studying the effects without using the actual materials. Too many of the physical parameters interact in ways that we cannot yet predict. If we then wish to extend our knowledge of the behavior of LNG clouds, we must accept the risk that an accidental ignition will occur. It was known before the tests started that there was a risk of ignition and that if a fire occurred, damage to some parts of the facility could be expected. The "permanent" portions of the spill facility, including the storage tanks and the control systems, were located a distance away from the spill area to minimize the chance of substantial loss, and all personnel were kept an even farther distance from the spill area during active testing.

The tests being run were specified to have a high vaporization rate of the LNG. One way to obtain a high vaporization rate was to spill the LNG on water, a surface for which it is known that the heat transfer and vaporization rates are high. It is also known that LNG spilled on water can result in rapid phase transitions (RPT's) and that the RPT's can have fairly violent reactions. RPT's have occurred in previous tests, especially when the LNG was rich in heavier components. The nature of the present tests was such that some weathering of the LNG in the storage tanks could be expected, and it was no real surprise that RPT's occurred. No RPT had led to ignition in earlier large or small scale LNG spill tests, and there was no reason to believe that ignition by the direct effects of an RPT would occur in these tests. However, ignition did occur, and our meetings of 10 September and 24 September brought together a substantial body of information and experience to attempt to determine why the vapor cloud ignited in Test 5 when other clouds had not ignited earlier in these tests or in other test series that have been conducted elsewhere.

The immediate attention centered on the events that led to and followed the occurrence of RPT's because the ignition seemed to be so closely related to the RPT's. It also seemed imperative to consider the vapor curtain because it was the one element in the tests that was different from any previous test series. It thus seems logical to infer that ignition was somehow related to the presence of the curtain. Several plausible ignition mechanisms were considered, and most were rejected as being lower probability than the one the panel finally agreed was the most likely. Since our meetings, I've thought about the ignition and believe that the mechanism we considered to be the ignition source is indeed the most probable one: ignition by static discharge from contact of a broken guy wire with either the aluminum support batten or the curtain itself. Our conclusion was based substantially on the photographic record from video cameras. Indeed, were it not for those records, I doubt that we could have concluded that the static discharge mechanism was the most likely. With the video tape records, the preponderance of evidence supports our conclusion.

One of the things I considered after our meetings was the chance that ignition might have been caused by the shock wave from the RPT's. A rough estimate of the pressure rise required to initiate direct ignition shows it to be in the range of 30 to 50 atmospheres. I haven't seen much data on the pressure rises generated by RPT's, but I recall that the pressures are in the range of about 10 to 20 atmospheres (at points very near the center of the RPT's location). In addition, had an RPT had sufficient pressure rise to cause ignition, there would have been many such cases in the past. Thus, it appears that the pressure rise is just not high enough to cause direct ignition. Overpressures on the order of 10 atm can damage structures, of course, so the displacement of concrete blocks and damage to the spill spider could have been expected.

It's also well known that discharges of static electricity can ignite flammable vapor-air mixtures. Static charges can build up rather easily on nonconducting surfaces, particularly in dry air, when there is wind blowing, and when there are solid particles in the air. The energy released by a small static discharge is not large, but the ignition energy of methane-air mixtures can be as low as 0.3 millijoules. For mixtures that are not at stoichiometric concentrations, the ignition energy is higher, but still in the range of a few millijoules; a static discharge can easily provide that much energy. The only thing that is required is a path by which the discharge can take place. Normally, the path cannot be through the insulating material because it does not conduct a charge readily.

The one difference between Test 5 and all other tests in which RPT's occurred was that a mechanism for grounding was available. In Test 5, the cables that anchored the poles supporting the curtain broke or pulled loose in three locations. The cable on Pole 5 was the apparent source of ground and the apparent source of ignition. I believe the most likely contact point for ignition was the aluminum batten. There are two reasons: first, had ignition occurred by contact of cable and curtain, there would have been an approximately equal chance of ignition at Pole 3, and second, ignition would have been more likely to have occurred at some location away from the point where the pole and batten meet. The combination of bare cable and bare batten occurred only at points near the poles, so ignition might have occurred at Pole 3 as well. However, the probability of contact of batten and cable is less than that of curtain and cable, so ignition probability would be reduced. In Test 5, ignition might have occurred at either Pole 3 or Pole 5; it happened at Pole 5.

The presence of RPT's seems to be required in this test series to lead to ignition. The reason is simply that without the RPT's, there will be no breaking of the cables, and therefore no ground source to allow static discharge. The curtain will still build up a charge, but it does not have a path for sparking, thus causing ignition. Thus, while neither the RPT's nor the curtain alone seems capable of causing ignition, the combination could result in ignition if the RPT's were large enough and near enough the curtain to cause a support cable to break, and if the cable happened to contact the batten at a point where it was bare.

The question of whether ignition could have been forecast, and thus prevented, will inevitably be asked, and although it is not a strictly technical question, I'd like to address it. It was known that the RPT's had a good chance of occurring. It is also known that nonconductors build up static charges readily. What could not have been reasonably forecast was that the support cables would break in such a way that one of them could contact an ungrounded batten and spark. Thus, I think that in pushing the frontiers of knowledge forward a combination of events that could not have been predicted occurred. In the future, of course, steps can be taken to reduce the probability of another ignition from the same causes. However, if more tests are run, there may be other as yet unknown mechanisms that will cause ignition. Prudence will continue to dictate that tests be run with regard to that possibility, and equipment and personnel should be kept in locations where damage or injury will be minimized or prevented if a fire does occur.

Sincerely,

J. Reed Welker

J. Reed Welker

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October 12, 1987

Mr. Donald L. Vieth
Deputy Assistant Manager for
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Dear Don:

I would like to submit my views on the "Investigation of Unplanned Ignition of Liquified Natural Gas Vapor Cloud".

The report summarizes the findings extremely well and the Board has performed a thorough investigation.

The instrumentation was excellent and camera and sensor locations provided data sufficient to identify the most probable cause with a high degree of certainty. Conversely, a perhaps logical cause of ignition, a broken camera or instrument wire can almost certainly be ruled out. Without these good data, the existing analysis would have been difficult if not impossible.

It should be noted that the test was well planned, not only because of the good instrumentation but that no damage occurred outside the immediate test area. Also there were no lives endangered during or after the test.

Any spill of fuel (LNG) must assume that an ignition source could exist. The test preparation did make this assumption. Ignition was not intentional nor desired for this test but adequate provisions were made and there was no indication of negligence or omission. In fact, a great deal was learned and new information was developed to guide future tests.

Once the flame started there was deflagration (rapid burning) but we should emphasize that there was not recorded detonation (shock wave). This was predicted and confirmed by test 5.

Rapid Phase Transitions (RPT) are very unfamiliar entities to both the scientific community as well as the non-scientific community. It is <u>critical</u> for us to convey what did and what did not happen in this test. In the jargon of the mathematician, the RPT's were a necessary but not sufficient cause of the fire. The RPT was not the source of ignition. The cause was a spark. However, the large forces from the RPT's did provide the necessary circumstances to permit a fire.

continued . . .

DOT and DOE have the regulatory responsibility for LNG safety and they place a heavy burden on the industry. I feel it is in the nations best interest to establish reasonable safety data. Thus, I want to encourage (most certainly not discourage) the continued use of NTS for this useful and important purpose.

In conclusion, test 5 was well planned and extremely well instrumented. Unexpected ignition can and does occur when handling fuel and oxidizers and adequate planning went into these tests. More tests would be useful and justified to help in establishing LNG safety criteria. A fundamental understanding of RPT's should be an important scientific objective but it probably is not critical in establishing LNG safety criteria. We know they can exist and must plan accordingly. The criteria for future tests should be to learn the maximum about LNG spills not explicitly to prevent what happened in test 5.

Richard H. Kropschot
Associate Director and
Head, Engineering Division

institute

October 9, 1987

Dr. Donald L. Vieth
Acting Deputy Assistant Manager for
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U. S. Department of Energy
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Dear Don:

The purpose of this letter is to pass along my comments on the October 5 draft report of the Board investigating the fire at the Liquefied Gaseous Fuels Spill Test Facility (LGFSTF). The report represents a thorough, carefully completed account of the Board's deliberations. I feel that you did an excellent job in pulling the report together over a very short time period.

The following comments address specific report sections:

- (Recommendation 2 in the Cover Letter and Pages 67 and 69 of the Report) Actions to reduce the probability of RPTs could be recommended _if_ RPTs would conflict with the research goals. Care should be taken not to prevent future research on RPTs. Also, empirical evidence from these experiments and others does not support the contention that LNG chemical makeup, in of itself, is responsible for generating RPTs. While the mechanism for RPTs put forth by Enger and Hartmann suggests that collapse and superheating of heavy fractions of LNG play the key role in the phenomenon, other experiments involving spills on water such as the China Lake spill series have shown that LNGs with relatively high methane concentrations (approximately 91% at China Lake) can easily produce RPTs. In the case of the spills at the LGFSTF, the RPTs appear to be a function of spilling on water (by far the most important factor), LNG chemical makeup, spill duration, slower than anticipated rates of vaporization (which allow enrichment of spilled LNG with heavies), horizontal and vertical momentum of LNG, and confinement against obstacles. We feel that unfavorable conditions for a number of these variables caused the RPTs. We can only explain the production of RPTs in Spill 5 and lack of them in Spill 1 when we consider all of these variables. In formulating a recommendation, I suggest that examination of all of these variables be taken into account during the test planning stage.

- (Page 5 of the Report) Discussions with Livermore staff during the September 24 meeting brought to light that costs of instrument damage are well below the initial estimates of $50K to $75K. I was told that data station damage was confined to the exterior case; the interior components were not damaged. It was previously thought that these systems were completely destroyed. I was told that estimated instrumentation damage was approximately $20K when the limited damage to the station(s) was taken into account.

- (Page 6) To my recollection, there was no consensus that RPTs in Spill 5

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were stronger that those in Spill 3 (I happen to believe that they were stronger). A comment of Page 14 suggests a "comparable magnitude."

- (Pages 8 and 56) The perceived location of the ignition and fire was, in fact, used as a means of eliminating a variety of ignition sources, including RPT generated ignition (Page 8). The logic of the Board did proceed in that sort of linear fashion. However, the suggestion that RPTs could directly ignite the cloud requires a number of tenuous assumptions in order to rationalize an ignition mechanism. Other ignition sources, both inside and outside the fence, make use of well known and understood mechanisms. Placing RPT ignition on a par with these other mechanisms (in these sections and others) represents a radical departure from the current understanding of RPTs. If we were to consider an event tree description of ignition, RPT ignition would require a more complex event tree than any other potential ignition source, and unlike the other potential sources, there would be no basis for formulating probabilities along critical branches. In terms of the Board evaluation on Page 56, the plausibility of RPT ignition as the cause of the fire has to be significantly less than other plausible ignition sources. With each mention of RPT ignition, I suggest including a caveat that clarifies the lack of an observed mechanism.

- (Page 11) The spill parameters were specifications. We are currently trying to determine how well the spills met these specifications in practice. Until this is completed, we are not treating the spill parameters as spill data.

- (Page 18) Did the Board think that there was a ninth RPT (i.e., after the doublet)?

- (Page 44) I do not recall any evidence of an "ignition overpressure." The term suggests that a vapor cloud explosion might have occurred. Vapor cloud explosion is a very controversial concept since it has never been observed in published experiments, and many in the LNG industry maintain that they cannot occur as a result of an LNG spill.

- (Page 65) One additional factor that does not support the electrostatic discharge scenario is that the potential could be generated only where the batten directly contacted the fabric. This limits the surface area of the fence that could be responsible for charging the batten and lowers the probability of ignition (see John Cece's comments on static charge in the transcript).

This concludes my comments on the draft report. If you have any questions concerning my comments, please do not hesitate to call.

Sincerely,

Ted A. Williams

Ted A. Williams
Project Manager,
Environment and Safety
Research Department

cc: S. Wiersma

APPENDIX C

COMPOSITION OF LNG FOR VARIOUS TESTS

FALCON 1

SOUTHERN NATURAL GAS — A SONAT COMPANY

TRANSMISSION DEPARTMENT-BIRMINGHAM ALABAMA
CHROMATOGRAPHIC ANALYSIS REPORT

SAMPLE FROM: TRUSSVILLE LNG
STATION IDENT#: N/A
LOCATION: TRUSSVILLE AL
OPERATOR: TRUSSVILLE UTILITIES
METER NUMBER: N/A
CYLINDER NUMBER: COSMODYNE
SAMPLE PRESSURE: 200
TEMPERATURE: N/A

MEAS.BTU: N/A
MEAS.GRAVITY: N/A
FLOW RATE(MCF/D): N/A
SAMPLED BY: A. MALONE
DATE SAMPLED: 5/28/87
ANALYZED BY: MR & CB
DATE ANALYZED: 5/29/87
LABORATORY: SNG PINSON AL

COMPONENT		MOLE %	IDEAL BTU/FT3 14.73 DRY	GROSS BTU 14.73 DRY	IDEAL GRAVITY FACTORS	SPECIFIC GRAVITY AIR=1
XYGEN	O2	0.1273	0.0	0.00	1.1048	0.0014
ITROGEN	N2	0.4798	0.0	0.00	0.9672	0.0046
ARBON DIOXIDE	CO2	0.0388	0.0	0.00	1.5195	0.0006
ARBON MONOXIDE	CO	0.0000	321.1	0.00	0.9671	0.0000
THANE	C1	94.7257	1012.1	958.72	0.5539	0.5247
HANE	C2	3.9196	1773.0	69.49	1.0382	0.0407
OPANE	C3	0.5937	2523.3	14.98	1.5225	0.0090
O-BUTANE	IC4	0.0551	3260.7	1.80	2.0068	0.0011
RMAL BUTANE	NC4	0.0485	3269.8	1.59	2.0068	0.0010
O-PENTANE	IC5	0.0074	4009.7	0.30	2.4910	0.0002
MAL PENTANE	NC5	0.0041	4018.9	0.16	2.4910	0.0001
ANES +	C6+	0.0000	5360.8	0.00	3.3627	0.0000
AL		100.00		1047.04		.5834
UE CORRECTED FOR Z=.9978				1049		.5844

ONENT		MOLE %	LIQUID EQUIV@ 15.025	C2+GPM @15.025	C3+GPM @15.025	IC5+GPM @15.025
E	C2	3.9196	0.27281	1.069		
NE	C3	0.5937	0.28107	0.167	0.167	
ANE	IC4	0.0551	0.33369	0.018	0.018	
ANE	NC4	0.0485	0.32161	0.016	0.016	
TANE	IC5	0.0074	0.37323	0.003	0.003	0.003
TANE	NC5	0.0041	0.36944	0.002	0.002	0.002
S+	C6+	0.0000	0.45733	0.000	0.000	0.000
		4.6284		1.275	0.206	0.005

MARY		BTU@14.73	BTU@15.025
CORRECTED FOR Z= .9978	DRY:	1049	1070
	WET:	1031	1052

RUN ON SIGMA 2000 - SPECIAL ANALYSIS FOR TRUSSVILLE UTILITIES

LL HEXANES-PLUS FACTORS BASED ON AVERAGE COMPOSITION OF 40% HEXANES, NES AND 20% OCTANES. CALCULATED BTU AND GRAVITY REFERENCE AGA GAS NT COMMITTEE REPORT #5. CALCULATED GPM'S FROM NGPA 2145-84 FACTORS.

Falcon 2

SOUTHERN NATURAL GAS — A SONAT COMPANY

TRANSMISSION DEPARTMENT-BIRMINGHAM ALABAMA
CHROMATOGRAPHIC ANALYSIS REPORT

SAMPLE FROM: TRUSSVILLE TRUCK SKID
STATION IDENT#: N/A
LOCATION: TRUSSVILLE AL
OPERATOR: TRUSSVILLE UTILITIES
METER NUMBER: N/A
CYLINDER NUMBER: COSMODYNE
SAMPLE PRESSURE: 195
TEMPERATURE: N/A

MEAS.BTU: N/A
MEAS.GRAVITY: N/A
FLOW RATE(MCF/D): N/A
SAMPLED BY: N/A
DATE SAMPLED: 6/12/87
ANALYZED BY: C BOWMAN
DATE ANALYZED: 6/12/87
LABORATORY: SNG PINSON AL

COMPONENT		MOLE %	IDEAL BTU/FT3 14.73 DRY	GROSS BTU 14.73 DRY	IDEAL GRAVITY FACTORS	SPECIFIC GRAVITY AIR=1
OXYGEN	O2	0.0158	0.0	0.00	1.1048	0.0002
NITROGEN	N2	0.0970	0.0	0.00	0.9672	0.0009
CARBON DIOXIDE	CO2	0.0402	0.0	0.00	1.5195	0.0006
CARBON MONOXIDE	CO	0.0000	321.1	0.00	0.9671	0.0000
METHANE	C1	95.6068	1012.1	967.64	0.5539	0.5296
ETHANE	C2	3.6823	1773.0	65.29	1.0382	0.0382
PROPANE	C3	0.4498	2523.3	11.35	1.5225	0.0068
ISO-BUTANE	IC4	0.0526	3260.7	1.72	2.0068	0.0011
NORMAL BUTANE	NC4	0.0462	3269.8	1.51	2.0068	0.0009
ISO-PENTANE	IC5	0.0074	4009.7	0.30	2.4910	0.0002
NORMAL PENTANE	NC5	0.0000	4018.9	0.00	2.4910	0.0000
HEXANES +	C6+	0.0019	5360.8	0.10	3.3627	0.0001
TOTAL		100.00		1047.91		.5786
VALUE CORRECTED FOR Z=.9979				1050		.5796

COMPONENT		MOLE %	LIQUID EQUIV@ 15.025	C2+GPM @15.025	C3+GPM @15.025	IC5+GPM @15.025
ETHANE	C2	3.6823	0.27281	1.005		
PROPANE	C3	0.4498	0.28107	0.126	0.126	
I-BUTANE	IC4	0.0526	0.33369	0.018	0.018	
N-BUTANE	NC4	0.0462	0.32161	0.015	0.015	
I-PENTANE	IC5	0.0074	0.37323	0.003	0.003	0.003
N-PENTANE	NC5	0.0000	0.36944	0.000	0.000	0.000
HEXANES+	C6+	0.0019	0.45733	0.001	0.001	0.001
TOTAL		4.2402		1.168	0.163	0.004

[illegible]MARY

		BTU@14.73	BTU@15.025
[illegible]UES CORRECTED FOR Z= .9979	*DRY:*	*1050*	*1071*
	WET:	1032	1053

REMARKS: RUN ON SIGMA 2000 SPECIAL ANALYSIS FOR TRUSSVILLE UTILITIES

NOTES: ALL HEXANES-PLUS FACTORS BASED ON AVERAGE COMPOSITION OF 40% HEXANES, 40% HEPTANES AND 20% OCTANES. CALCULATED BTU AND GRAVITY REFERENCE AGA GAS

FALCON 3

SAMPLE FROM: TRUSSVILLE TRUCK SKID
STATION IDENT#: N/A
LOCATION: TRUSSVILLE AL
OPERATOR: TRUSSVILLE UTILITIES
METER NUMBER: N/A
CYLINDER NUMBER: COSMODYNE
SAMPLE PRESSURE: N/A
TEMPERATURE: N/A

MEAS.BTU: N/A
MEAS.GRAVITY: N/A
FLOW RATE(MCF/D): N/A
SAMPLED BY: A. MALONE
DATE SAMPLED: 6/26/87
ANALYZED BY: C BOWMAN
DATE ANALYZED: 7/8/87
LABORATORY: SNG PINSON AL

COMPONENT		MOLE %	IDEAL BTU/FT3 14.73 DRY	GROSS BTU 14.73 DRY	IDEAL GRAVITY FACTORS	SPECIFIC GRAVITY AIR=1
OXYGEN	O2	0.3911	0.0	0.00	1.1048	0.0043
NITROGEN	N2	1.5454	0.0	0.00	0.9672	0.0149
CARBON DIOXIDE	CO2	0.0519	0.0	0.00	1.5195	0.0008
CARBON MONOXIDE	CO	0.0000	321.1	0.00	0.9671	0.0000
METHANE	C1	92.7146	1012.1	938.36	0.5539	0.5135
ETHANE	C2	4.4340	1773.0	78.61	1.0382	0.0460
PROPANE	C3	0.6782	2523.3	17.11	1.5225	0.0103
ISO-BUTANE	IC4	0.0851	3260.7	2.77	2.0068	0.0017
NORMAL BUTANE	NC4	0.0764	3269.8	2.50	2.0068	0.0015
ISO-PENTANE	IC5	0.0113	4009.7	0.45	2.4910	0.0003
NORMAL PENTANE	NC5	0.0065	4018.9	0.26	2.4910	0.0002
HEXANES +	C6+	0.0055	5360.8	0.29	3.3627	0.0002
TOTAL		100.00		1040.35		.5937
VALUE CORRECTED FOR Z=.9978				1043		.5948

COMPONENT		MOLE %	LIQUID EQUIV@ 15.025	C2+GPM @15.025	C3+GPM @15.025	IC5+GPM @15.025
ETHANE	C2	4.4340	0.27281	1.210		
PROPANE	C3	0.6782	0.28107	0.191	0.191	
I-BUTANE	IC4	0.0851	0.33369	0.028	0.028	
N-BUTANE	NC4	0.0764	0.32161	0.025	0.025	
I-PENTANE	IC5	0.0113	0.37323	0.004	0.004	0.004
N-PENTANE	NC5	0.0065	0.36944	0.002	0.002	0.002
HEXANES+	C6+	0.0055	0.45733	0.003	0.003	0.003
TOTAL		5.2970		1.463	0.253	0.009

BTU SUMMARY VALUES CORRECTED FOR Z= .9978		BTU@14.73	BTU@15.025
	DRY:	1043	1064
	WET:	1025	1046

REMARKS: RUN ON SIGMA 2000 SPECIAL ANALYSIS FOR TRUSSVILLE UTILITIES

NOTES: ALL HEXANES-PLUS FACTORS BASED ON AVERAGE COMPOSITION OF 40% HEXANES, 40% HEPTANES AND 20% OCTANES. CALCULATED BTU AND GRAVITY REFERENCE AGA GAS MEASUREMENT COMMITTEE REPORT #5. CALCULATED GPM'S FROM NGPA 2145-84 FACTORS.

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#########################################   POST FALCON 3
# TO: KOOPMAN(0515-32)                  #   
#########################################   PRE FALCON 4

LIQ. NAT. GAS

MASS SPECTROMETRIC ANALYSIS NO.   70955.
DONE ON 13-JUL-87 AT 15:04:53  CALCULATED ON 13-JUL-87 AT 15:18

       COMPOUND                       CONCENTRATION STD DEV.
                                      MOLE (VOLUME) PCT.      renormalize *

1    NITROGEN          N2 . . . . . . . .  21.20     0.46          0.0
2    CARBON DIOXIDE    CO2 . . . . . . . .  0.032    0.011         0.041
3    METHANE           CH4 . . . . . . . . 71.58     0.46         90.8
4    ETHANE            C2H6  . . . . . . .  6.18     0.05          7.84
5   N-BUTANE           N-C4H10 . . . . . .  0.228    0.008         0.29
6    PROPANE           C3H8  . . . . . . .  0.72     0.03          0.91
7    PROPYLENE         C3H6  . . . . . . .  0.054    0.008         0.068
                                           ======                 -----
           TOTAL                          100.00                 100.0

      VARIANCE =  3.16 PERCENT


NOTE: UNCERTAINTIES ARE ONE STD. DEV. FROM THE 'REGRESSION,
      ANALYSIS AND DO NOT INCLUDE CONTRIBUTIONS DUE TO
      INTENSITY MEASUREMENTS WHICH ADD ABOUT +/-.2% 'OF THE.
      CONCENTRATION.


      COMPUTED VALUES LESS THAN 0.01 PERCENT HAVE BEEN OMITTED.
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* renormalize by removing nitrogen which was inadvertantly left in the sampler divide by .788

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****************************************
* TO: KOOPMAN(0515-32)                 *
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FALCON 4

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LIQ NAT GAS

MASS SPECTROMETRIC ANALYSIS NO.    71134.
DONE ON 10-AUG-87 AT 15:02:06  CALCULATED ON 11-AUG-87 AT 08:50

     COMPOUND                        CONCENTRATION STD DEV.
                                     MOLE (VOLUME) PCT.

 1   NITROGEN         N2 . . . . . . . .    0.62     0.11
 2   OXYGEN           O2 . . . . . . . .    0.118    0.002
 3   CARBON DIOXIDE   CO2 . . . . . . . .   0.037    0.003
 4   CARBON MONOXIDE  CO . . . . . . . .    0.10     0.09
 5   METHANE          CH4 . . . . . . . .  83.94     0.11
 6   ETHANE           C2H6 . . . . . . .   12.92     0.02
 7   N-BUTANE         N-C4H10 . . . . .     0.200    0.006
 8   PROPANE          C3H8 . . . . . . .    1.771    0.008
 9   ISOBUTANE        I-C4H10 . . . . .     0.223    0.006
10   ISOPENTANE  C5H12 . . . . . . . . .    0.063    0.003
                                           ======
       TOTAL                               99.99

     VARIANCE =  0.64 PERCENT


NOTE: UNCERTAINTIES ARE ONE STD. DEV. FROM THE 'REGRESSION,
      ANALYSIS AND DO NOT INCLUDE CONTRIBUTIONS DUE TO
      INTENSITY MEASUREMENTS WHICH ADD ABOUT +/-.2% 'OF THE.
      CONCENTRATION.


      COMPUTED VALUES LESS THAN 0.01 PERCENT HAVE BEEN OMITTED.


      COMPONENTS OMITTED  EQUAL TO  0.01 PERCENT OF THE SAMPLE

      RESULTS ARE NORMALIZED' AFTER THESE COMPOUNDS ARE REMOVED.
         ( 1)  WATER  H2O
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FALCON 5

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    ****************************************
    * TO: KOOFMAN(0515-32)                 *
    ****************************************

    LIQ GAS

    MASS SPECTROMETRIC ANALYSIS NO.    71303.
    DONE ON 10-SEP-87 AT 07:58:31  CALCULATED ON 10-SEP-87 AT 09:54

         COMPOUND                  CONCENTRATION STD DEV.
                                   MOLE (VOLUME) PCT.

1   NITROGEN         N2 . . . . . . . .    1.22      0.10
2   CARBON DIOXIDE   CO2 . . . . . . . .   0.035     0.005
3   METHANE          CH4 . . . . . . . .  87.89      0.21
4   ETHANE           C2H6  . . . . . . .   9.38      0.03
5   BUTANE  N-C4H10 . . . . . . . . . . .  0.172     0.016
6   PROPANE          C3H8  . . . . . . .   1.145     0.017
7   PROPYLENE        C3H6  . . . . . . .   0.020     0.005
8   ISOBUTANE       I-C4H10  . . . . . .   0.072     0.019
9  PENTANE C5H12 . . . . . . . . . . . . . 0.051     0.008
                                          ======
          TOTAL                           100.00

    VARIANCE =  0.94 PERCENT


TE: UNCERTAINTIES ARE ONE STD. DEV. FROM THE 'REGRESSION,
    ANALYSIS AND DO NOT INCLUDE CONTRIBUTIONS DUE TO
    INTENSITY MEASUREMENTS WHICH ADD ABOUT +/-.2% 'OF THE.
    CONCENTRATION.


   COMPUTED VALUES LESS THAN 0.01 PERCENT HAVE BEEN OMITTED.


   COMPONENTS OMITTED  EQUAL TO  0.01 PERCENT OF THE SAMPLE

   RESULTS ARE NORMALIZED' AFTER THESE COMPOUNDS ARE REMOVED.
      ( 1)  WATER  H2O
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SOUTHERN NATURAL GAS — A SONAT COMPANY
TRANSMISSION DEPARTMENT-BIRMINGHAM ALABAMA
CHROMATOGRAPHIC ANALYSIS REPORT

SAMPLE FROM: TRUSSVILLE PUMP SKID
STATION IDENT#: N/A
LOCATION: TRUSSVILLE ALA
OPERATOR: TRUSSVILLE UTILITIES
METER NUMBER: N/A
CYLINDER NUMBER: COSMODYNE
SAMPLE PRESSURE: 240
TEMPERATURE: N/A

MEAS.BTU: N/A
MEAS.GRAVITY: N/A
FLOW RATE(MCF/D): N/A
SAMPLED BY: C CATHERS
DATE SAMPLED: 9/15/87
ANALYZED BY: C BOWMAN
DATE ANALYZED: 9/18/87
LABORATORY: SNG PINSON ALA

COMPONENT		MOLE %	IDEAL BTU/FT3 14.73 DRY	GROSS BTU 14.73 DRY	IDEAL GRAVITY FACTORS	SPECIFIC GRAVITY AIR=1
OXYGEN	O2	0.0175	0.0	0.00	1.1048	0.0002
NITROGEN	N2	0.0894	0.0	0.00	0.9672	0.0009
CARBON DIOXIDE	CO2	0.0398	0.0	0.00	1.5195	0.0006
CARBON MONOXIDE	CO	0.0000	321.1	0.00	0.9671	0.0000
METHANE	C1	93.6094	1012.1	947.42	0.5539	0.5185
ETHANE	C2	5.3039	1773.0	94.04	1.0382	0.0551
PROPANE	C3	0.7418	2523.3	18.72	1.5225	0.0113
ISO-BUTANE	IC4	0.0922	3260.7	3.01	2.0068	0.0019
NORMAL BUTANE	NC4	0.0812	3269.8	2.66	2.0068	0.0016
ISO-PENTANE	IC5	0.0118	4009.7	0.47	2.4910	0.0003
NORMAL PENTANE	NC5	0.0070	4018.9	0.28	2.4910	0.0002
HEXANES +	C6+	0.0060	5360.8	0.32	3.3627	0.0002
TOTAL		100.00		1066.92		.5908
VALUE CORRECTED FOR Z=.9977				1069		.5919

COMPONENT		MOLE %	LIQUID EQUIV@ 15.025	C2+GPM @15.025	C3+GPM @15.025	IC5+GPM @15.025
ETHANE	C2	5.3039	0.27281	1.447		
PROPANE	C3	0.7418	0.28107	0.208	0.208	
I-BUTANE	IC4	0.0922	0.33369	0.031	0.031	
N-BUTANE	NC4	0.0812	0.32161	0.026	0.026	
I-PENTANE	IC5	0.0118	0.37323	0.004	0.004	0.004
N-PENTANE	NC5	0.0070	0.36944	0.003	0.003	0.003
HEXANES+	C6+	0.0060	0.45733	0.003	0.003	0.003
TOTAL		6.2439		1.722	0.275	0.010

BTU SUMMARY VALUES CORRECTED FOR Z= .9977		BTU@14.73	BTU@15.025
	DRY:	1069	1090
	WET:	1050	1072

REMARKS: RUN ON SIGMA 2000 SPECIAL ANALYSIS FOR TRUSSVILLE UTILITIES

NOTES: ALL HEXANES-PLUS FACTORS BASED ON AVERAGE COMPOSITION OF 40% HEXANES, 40% HEPTANES AND 20% OCTANES. CALCULATED BTU AND GRAVITY REFERENCE AGA GAS MEASUREMENT COMMITTEE REPORT #5. CALCULATED GPM'S FROM NGPA 2145-84 FACTORS.