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UNDERGROUND DETONABLE GAS EXPLOSIONS

MIRACLE PLAY TEST SERIES

TECHNICAL SUMMARY REPORT

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by

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Defense Atomic Support Agency
Washington, D.C. 20305

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13. ABSTRACT
A program was conducted to simulate the seismic phenomena associated with underground nuclear explosions with detonable gases. The program was conducted in two phases. The first phase, an engineering design study (DASA 2316), presented the system design required to meet the physical aspects of cavity created by the SALMON Event in the Tatum Salt Dome, Hattiesburg, Mississippi, an Atomic Energy Commission installation.

The second phase consisted of a series of three detonable gas events to be conducted in the SALMON cavity. This series of detonable gas events were called MIRACLE PLAY TEST SERIES. The three events were named respectively: DIODE TUBE, HUMID WATER, DINAR COIN.

This report describes departures in the engineering design, procedure, and results of DIODE TUBE and HUMID WATER. The third event, DINAR COIN, has been cancelled.

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SUMMARY

A program was conducted to simulate with detonable gases the seismic phenomena associated with underground nuclear explosions. The program was conducted in two phases. The first phase, an engineering design study (DASA 2[illegible]10), presented the system design required to meet the physical aspects of cavity created by the SALMON Event in the Tatum Salt Dome, Hattiesburg, Mississippi, an Atomic Energy Commission installation.

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FOREWORD

This report was prepared by the General American Research Division of the General American Transportation Corporation for the Defense Atomic Support Agency (DASA), Washington, D. C., under Contract No. DASA 01-68-C-0177.

The overall management of the program was the responsibility of Dr. M. J. Balcerzak. R. J. Klima was the Program Manager. The Project Engineer for DIODE TUBE was L. G. Ullyatt. The Project Engineer for HUMID WATER was L. A. Higley.

The authors gratefully acknowledge the extensive contributions of the following engineers:

F. E. Wolosevick, GARD - Pipeline System
D. S. Schover, GARD - Electronic Systems Management and Design
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S. A. Stohl, GARD - Data Acquisition System & Valve Controllers
M. Monohan, GARD - Firing Circuit and Environmental Testing
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G. R. Reagle, GARD - Mechanical Design
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The Test Director for the MIRACLE PLAY Series was Lt. Col. Walter Davis, USAF, assigned to DASA Test Command. His continuing guidance and advice contributed to every phase of this program. His staff aggressively sought opportunities to be of assistance, and their contributions are gratefully acknowledged.

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The MIRACLE PLAY Series was conducted at the Tatum Dome Test Site (TDTS), Hattiesburg, Mississippi. This site is under the control of the Atomic Energy Commission, Nevada Operations Office, Las Vegas, Nevada. The Site Manager is L. J. Yelinek. He and his staff furnished the extensive administrative support required for this program. Logistic support at the Test Site was furnished by Reynolds Electric and Engineering Company (REECO) under contract to the AEC. The REECO Site Representative is George Carter. The earnest cooperation and aggressive support by both these gentlemen and their staffs contributed immeasurably to the success of this program.

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SECTION 1

INTRODUCTION

The General American Research Division participated in a series of underground detonable gas explosions code-named MIRACLE PLAY, a part of Project VELA-UNIFORM. This planned series consists of three experiments in simulating seismic phenomena associated with underground nuclear explosions. Two tests (DIODE TUBE, HUMID WATER) were performed in the underground cavity created by the SALMON Event in the Tatum Salt Dome near Hattiesburg, Mississippi. The third test, DINAR COIN, was cancelled. This cavity is approximately 110 feet in diameter with the center about 2700 feet below the surface. (See Appendix C.)

The planned explosive yields for the three experiments were: DIODE TUBE - 315 tons, HUMID WATER - 315 tons, and DINAR COIN - 890 tons. The first two explosions, with similar yields, would serve as a means of evaluating the repeatibility of data. It was anticipated that large amounts of water vapor would be released by the first explosion (DIODE TUBE) and might saturate the cavity walls. This saturation might affect the cavity's response characteristics. If so, the data from the second experiment (HUMID WATER) should quantify that change. Yield predictions may be found in Appendix B.

The third experiment (DINAR COIN) would provide valuable information on the effect of decoupling. Decoupling is defined by Latter[(1)*] to mean any method for reducing the seismic signal from underground explosions at constant yield, particularly through the use of a large cavity.

The first experiment (DIODE TUBE) took place February 2, 1969. The objective of DIODE TUBE was to match the equilibrium pressure increase (over initial static pressure) of the STERLING Event which was also conducted in the SALMON cavity. The equivalent energy release for the detonable gas explosion would therefore be nominally 315 tons. The observed peak amplitude of seismic data from DIODE TUBE was about one-third that observed from STERLING. A review of these results is included with this report as Appendix A.

Later analysis of the DIODE TUBE Event revealed that the gases were not completely mixed. Those considerations evolved from an extensive technical analysis, details of which are in Appendix F.

The basic engineering design for HUMID WATER was essentially the same as DIODE TUBE which has been previously reported.[(3)] The design is descriptive of the systems actually used on HUMID WATER. Specific changes are

* References noted at the end of this report.

referenced in the body of this report. Major changes will be found in the instrumentation system because of the discovery during DIODE TUBE that the cavity ambient conditions were far more adverse than anticipated. For HUMID WATER, a fully enclosed, pressure tight, acid and temperature resistant system was designed for the cavity that housed those elements necessary for the cavity monitoring, firing and data acquisition functions. These changes resulted from an extensive series of environmental tests performed by GARD.

HUMID WATER incorporated those system and procedural changes indicated by the results from the environmental tests, gas mixing analysis, and an engineering analysis of the DIODE TUBE Event.

HUMID WATER was detonated during a sudden and intense electrical storm on 19 April 1970. Diagnostic data were not recorded because the recorders which were programmed to start at a fixed point of time during the scheduled countdown had not yet been initiated when ignition occurred. The ignition of the detonable mixture ahead of schedule has been attributed to lightning.[3] All instrument circuits were functionally monitored on a continuing basis from the time the probe was inserted into the cavity until the detonation occurred. No anomalies were noted. Background noise was being monitored at several seismic gage locations at the time of ignition so that some seismic data were obtained, confirming a full scale detonation.

The objective of this report is to present the results of the two tests with special emphasis on the technical and design considerations of conducting underground detonable gas explosions.

Section 2 of this report contains conclusions and recommendations.

Section 3 describes, in detail, changes to the experimental equipment used for the HUMID WATER Event; i.e., the piping valving system, casing plug assembly, casing head assembly, data acquisition system, firing system, time reference system, valve controller system, and the tracer gas system.

Section 4 describes the procedures used during the HUMID WATER Event. Handling large quantities of methane and oxygen, more particularly at high delivery rates, requires exacting procedures and firm control. The techniques were developed for the MIRACLE PLAY Series as part of the basic engineering design previously reported.[2]

Section 5 of this report will describe the results obtained from the HUMID WATER Event. These may be compared to the results from DIODE TUBE, described in Appendix A.

SECTION 2

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of the MIRACLE PLAY Series was to determine experimentally if it was possible to simulate seismic phenomena associated with nuclear explosives by detonable gases. Data generated by these experiments would be used to gain useful information on the theory of decoupling.

The General American Research Division (GARD) participated in this series in cooperation with Advanced Research Projects Agency (ARPA), Atomic Energy Commission (AEC), Defense Atomic Support Agency (DASA), Waterways Experimental Station (WES), U. S. Coast and Geodetic Survey (USC & GS), Air Force Technical Applications Center (AFTAC) Vela Seismological Center (VSC), Environmental Research Center (ERC), Isotopes, Inc., and Physics International.

Tasks for GARD were:

1. Design, procurement and fabrication of a gas delivery system.
2. Procurement and handling of detonable gases.
3. Necessary site preparation and systems installation.
4. Diagnostic data acquisition and systems evaluation.
5. Post-shot examination and analysis of diagnostic data.

2.1 Technical Summary

Regarding the first four tasks, GARD designed and fabricated a Piping and Valving System, a Casing Plug Assembly, a Casing Head Assembly, a Data Acquisition System, a Firing System, and minor associated equipment. Additionally, GARD developed procedures necessary to operate those systems in a safe, precise manner affording necessary control over large volumes of detonable gases. Other sections of this report detail those systems (Section 3) and procedures (Section 4) in their current state of development.

The accomplishment of the task is somewhat frustrated by three eventualities. First, the unfortunate loss of diagnostic data in both DIODE TUBE and HUMID WATER; second, the cancellation of the final event (DINAR COIN); and lastly, that although planned at similar yields, DIODE TUBE and HUMID WATER actually detonated under such dissimilar conditions as to make direct comparisons difficult in most material respects.

The results of DIODE TUBE, when analyzed, revealed the need for certain corrections before HUMID WATER. The sources of the problems were two-fold. First, the assumption before DIODE TUBE was that the cavity, located in a salt dome, would be dry and free from a corrosive atmosphere. The highly corrosive atmosphere actually found created problems with the Firing and Data Acquisition Systems. Re-design of those systems for the HUMID WATER Event completely eliminated those problems.

The second problem source in DIODE TUBE was the phenomena of gas mixing that requires the heavier gas to be loaded after the lighter gas. This phenomenon was discovered as part of an independent study after DIODE TUBE.[2] By reversing the order of loading gases for HUMID WATER (oxygen over methane) the seismic signals were much larger.

2.2 Conclusions

It is established that the current state-of-the-art in conducting underground detonable gas explosions is well developed. All the systems used in HUMID WATER demonstrated reliability and flexibility. Although the Firing System and the Data Acquisition System were never actually used in the HUMID WATER Event, prior environmental testing programs proved their essential serviceability. Further, in the actual experiment, periodic checks of those circuits revealed no deterioration in function up to one hour before detonation. It is therefore reasonable to assume that the entire system would have functioned entirely as planned, had the gases not been detonated ahead of schedule by an extraneous source of ignition energy believed to be a lightning strike.

2.3 Recommendations

The best approach to the problem of reducing the risk of a lightning strike is selecting a site and scheduling the event in areas and periods of low risk. A study was made by EG&G,[4] Albuquerque, New Mexico which recommends several improvements to the system that would further reduce the risk.

The overall design concepts and procedures for producing underground detonable gas explosions are well developed, and are recommended for future use in similar applications. Any recommendations from the EG&G study that would result in reducing the vulnerability to natural hazards should be considered in future experiments.

It appears from the seismic results that the behavior of surface waves from decoupled nuclear explosions and from underground gas explosions are not related in a simple manner. To obtain a matching of the results the following three phase program is recommended.

a) Obtain experimental data on the behavior of gas detonations in a model spherical cavity. This may be accomplished using small scale laboratory apparatus.

b) Using appropriately scaled source data obtained in the above experiments and known nuclear source data, make a detailed analytic prediction for seismic results relating the behavior of the surface waves to known source parameters.

c) Confirm the theory generated by the analysis with a full scale experiment.

SECTION 3

ENGINEERING DESIGN

This section discusses the design of the various systems used for the HUMID WATER Event. Differences between the systems used on DIODE TUBE and HUMID WATER are noted. Except as noted, all design details of HUMID WATER are identical to those reported in the basic engineering design,[3] and subsequently used in DIODE TUBE.

3.1 Piping and Valving System

The piping and valving system was designed to safely permit remote control of the large volumes of oxygen, methane, and nitrogen gases loaded into the cavity. The oxygen and nitrogen was delivered to the site as a liquid in tanker trucks. The methane was supplied from a natural gas pipeline located approximately three miles from the test site, and transported to the site through a six-inch pipeline constructed for this purpose.

The piping and valving system design used for HUMID WATER was the same as that used for DIODE TUBE. A schematic of the piping and valving system is shown in Figure E-2. Changes in the basic engineering design occurred in the oxygen delivery system and the nitrogen delivery system. These changes are discussed below. The methane delivery system and the flare and vent system were the same design for HUMID WATER as they were for DIODE TUBE. Details of these systems may be found in Reference 2.

3.1.1 Oxygen Delivery System

The purposes of the oxygen delivery system were to deliver oxygen rapidly and safely to the cavity, and to insure adequate mixing of the gases in the cavity. To insure complete mixing of the gases, it was determined from the gas mixing analysis that the flow of oxygen should be as high as safety would permit. The high velocities produce a turbulent plume which entrain the gases in the cavity. The entrainment increases with increasing inlet jet velocity.

An upper limit to the inlet flow is dictated by the safety of handling oxygen. Based on the analysis, and safety in handling, it was elected to load the oxygen after the methane and at an increased delivery rate. The AEC provided a guideline for maximum flow velocities for oxygen of 350 feet per second (1.26×10^6 ft/hr), which corresponded to a flow rate of 734,000 SCFH for the oxygen fill and 440,000 SCFH for the oxygen purge.

The purpose of the oxygen purge was to remove loose material and burn any combustibles in the oxygen pipeline prior to methane fill. Consistent with this purpose, the maximum flow velocity set for gas fill operations must be exceeded to test the delivery systems and the lines. A flow delivery rate of 600,000 SCF/Hr was established for 3-1/2 minutes at the end of the purge. This test established that 440,000 SCF/Hr rates can be physically realized within delivery capabilities, and that at that rate, auto-ignition is not likely to occur. Four hundred thousand SCFH was set as the upper limit for gas fill operations.

The delivery system permitting these high flow rates was provided by Union Carbide Corporation, Linde Division, under contract to GARD. This system consisted of a large steam boiler, heat exchanger, liquid gas tanker and a liquid gas pumper truck. The heat exchanger was equipped with over-pressure safety device. This device eliminated the need for the rupture disk which was incorporated in the oxygen line for DIODE TUBE and removed for HUMID WATER. A schematic diagram of HUMID WATER oxygen delivery system is shown in Figure 1.

3.1.2 Nitrogen Delivery System

The purposes of the nitrogen delivery system were to provide an inert gas to purge the gas lines so that methane and oxygen would not come in direct contact with each other before they were mixed in the cavity and to provide a safety backup in the event of a system failure such as a pressure leak. A slow nitrogen purge would permit repairs in relative safety. Another purpose of the system was to provide the high gas pressure necessary to actuate remote equipment below ground, near the cavity.

All purging nitrogen used in HUMID WATER was delivered in transport trailers and vaporized through the same system used for the oxygen.

The high pressure (1500 psi) nitrogen required to close the shifting sleeve valve, which discontinued gas communication with the cavity, was obtained by using a high pressure nitrogen pumper truck connected to the high pressure nitrogen system. (See Figure E-1.) The high pressure pumper truck contained liquid nitrogen which was vaporized by its own system before being injected into the high pressure nitrogen line.

3.2 Casing Plug Assembly

The purpose of the casing plug assembly was to limit the effects of the explosion to the cavity. It consists of two separate subassemblies identified as the first and second operation components assembly respectively. Each component assembly was lowered and positioned within the wellhead casing in separate and distinct operations. Only those components that were changed from those detailed in the basic engineering design are discussed below.

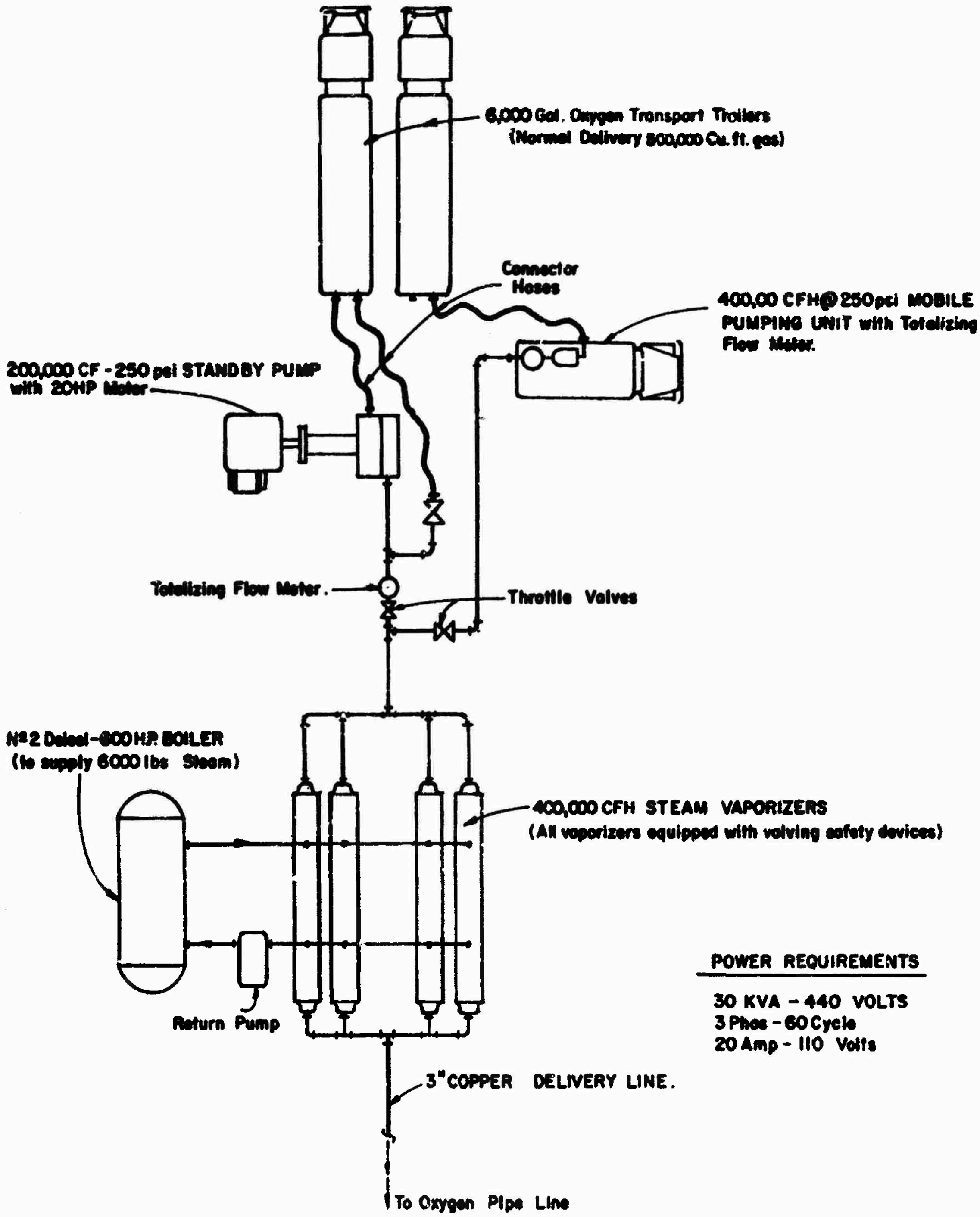


Figure I, SCHEMATIC LAYOUT OF OXYGEN SUPPLY AND GENERATING EQUIPMENT "HUMID WATER".

3.2.1 First Operation Components

The first operation components consist of the casing packer, a length of 6-5/8 inch diameter, heavy wall casing threaded to the bottom of the packer and a bellmouth fixture threaded to the bottom of the 6-5/8 inch casing. (See Figure 2.) The purpose of the casing packer is to create a firm seal with the inside of the wellhead casing. The purpose of the 6-5/8 inch casing is to transfer the gases from the packer to the cavity. The bottom four feet of the 6-5/8 inch casing contains holes through which the gas will flow during gas fill. The purpose of the bellmouth fixture is to restrict lateral movement of the instrument probe during gas fill.

The first operation components are lowered into the wellhead casing on 2-3/8" drill pipe. The packer is "set" in the wellhead casing at a predetermined depth using a setting tool.

Based upon the analysis, which suggested obtaining maximum gas flow rates within the cavity to insure good mixing, a change was made from the original design. This change consisted of making the total area through which the gases must flow directly into the cavity equal to the minimum area at any point in the system. This design would assure the maximum allowable velocity (350 ft/sec) was occurring as the gases entered the cavity. The original design, calling for slots, was amended to provide a series of 18 holes whose total area was 18.25 square inches. With due regard for friction effects, this area corresponded with the minimum restriction area located at the packer. This new configuration is shown in Figure 2.

3.2.2 Second Operation Components

The second operation components provide the electronic communication with the cavity for monitoring, firing, and recovering diagnostic data.

The second operation components (often referred to as the instrumentation string) received a great deal of development effort subsequent to DIODE TUBE. The following items will be discussed in detail:

1) Detonator Probe (Package) and Detonator Support
2) Instrument Probe
3) Instrument Probe Support
4) Crossover Assembly
5) Wellhead Connections
6) Main Instrument Cable.

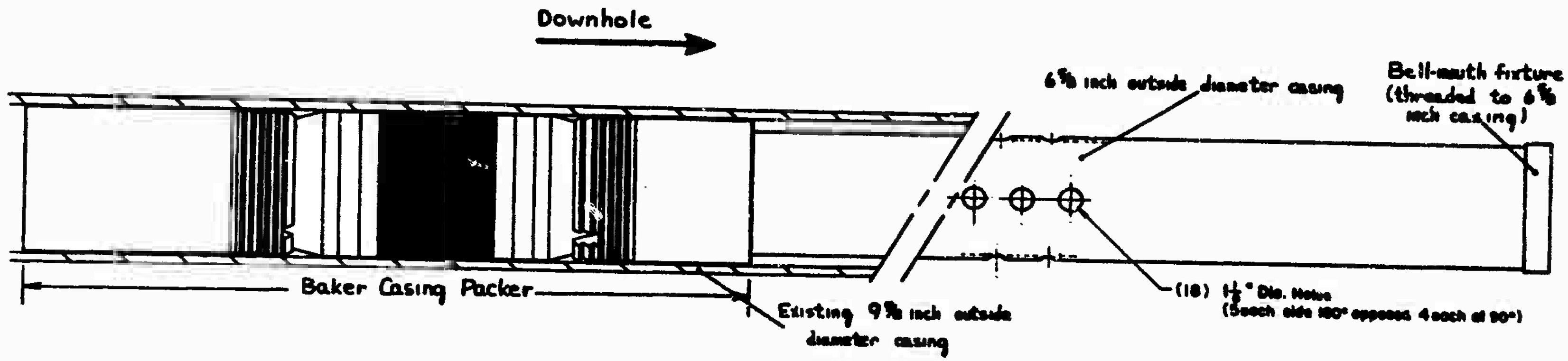


Figure 2, FIRST OPERATION COMPONENTS (Modified)

Two main problems with the second operation components were observed during DIODE TUBE. They were: (1) insufficient environmental protection to the instrument and firing circuits, and (2) prolonged in-field assembly of components. These problem areas defined overall design considerations for HUMID WATER. The first design consideration was to provide sufficient environmental protection. The second design consideration was to modularly construct the second operation components in the lab.

The overall approach to provide as much environmental protection as possible to the active circuits within the instrumentation string can be described as a completely pressure-tight encasement of the entire downhole assembly contained within the wellhead, wellhead casing, and cavity.

The ambient cavity conditions were discovered after DIODE TUBE to be far more corrosive than anticipated. (See Appendix C.) The resultant redesign effort centered upon achieving the highest possible reliability of systems in this environment. Acid resistant materials and finishes were specified on all downhole systems. As a second layer of protection, in the event of a gas or acid entry anywhere in the system, a matrix of mechanical seals and potting compounds were used that isolate the effects to a purely local area. The third layer of protection was provided by designing and encapsulating individual critical electrical systems so as to offer the best available expectation of withstanding the pressure, temperature and acid environments independently. The detailed discussion of the circuitry will be found in the system descriptions of this section.

The extreme amount of protection afforded to the instrumentation string is a critical requirement. After gas fill, when the cavity is stemmed, no other means of communication with the cavity remains for control and firing. Mechanical and electrical integrity of the instrumentation string must be maintained, dictating huge safety factors, extreme care in the emplacement and continued monitoring until successful detonation is achieved.

All individual components and subassemblies were submitted to extensive environmental tests within the laboratory. These tests simulated the environments anticipated for DINAR COIN which are more severe than those anticipated for HUMID WATER. Final engineering approval was based upon the resultsof these tests. The systems described herein were used during the HUMID WATER Event and performed satisfactorily in all respects.

3.2.2.1 Detonator Probe and Detonator Probe Support

The detonator probe, shown in Figure 3, contains the circuits necessary to arm and fire the detonators upon command. Additionally, a static pressure transducer was also included on the detonator probe to provide ambient pressure data up to the moment of detonation. A back-up, hot-wire ignitor system also on the probe provides a totally independent means for

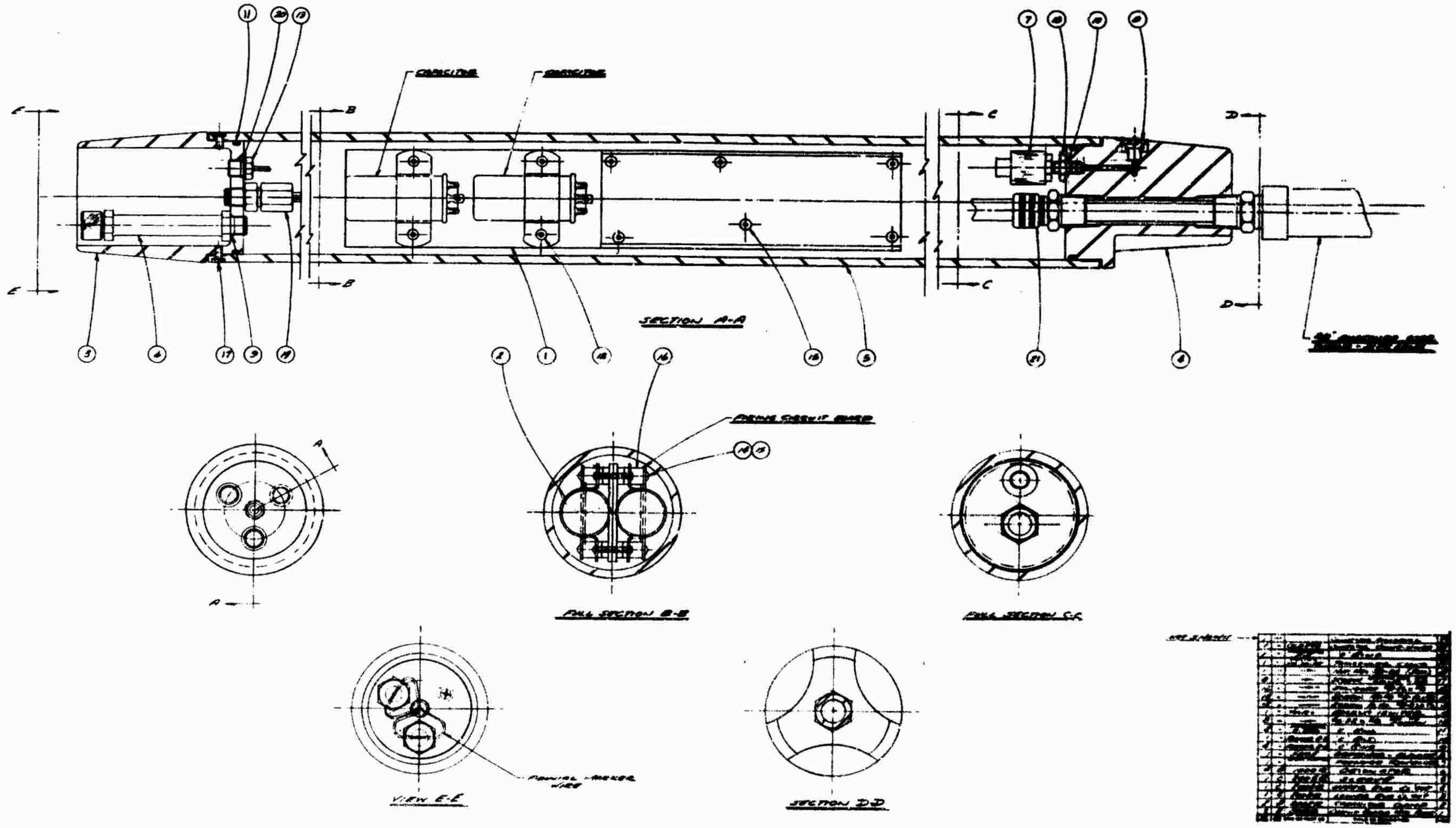


Figure 3 - Detonator Probe

detonating the cavity in the event of failure in the dual-channel primary system. This back-up ignitor was incorporated in the system as a result of events occurring on DIODE TUBE.

The detonator probe pressure case is made of cadmium plated, chromate finished steel. The slightly tapered nose permits the probe to pass over any surface irregularities during the insertion to the final location at the geometric center of the cavity, 2700 feet below the surface. Additionally, the nose piece provides protection to the exposed detonator assemblies. The four section assembled probe is approximately 3 feet long, 4 inches in diameter, with 3/16 inch thick walls.

The detonator probe support consists of a 31 foot piece of 3/4 inch high pressure, stainless steel, flexible hose. This hose provides resistance to mechanical abrasion to the cable within, and forms an integral part of the overall pressure case.

"O" rings were used to complete the pressure seal of the detonator probe. The "O" rings were packed in silicone grease to prevent potting material from entering the "O" ring grooves and disrupting the sealing mechanism. The contents were encapsulated with a clear silicone resin (Sylgard 184).

A mechanical seal was provided at the connection of the detonator probe and detonator probe support, backed up by a potting compound (Hysol XCU-M150) which has an adhesion similar to the yield strength of the cable. Although the cable itself was not the load carrying member, the strain relief provided by the potting compound, and the yield strength of the cable were adequate to support the detonator probe independently had the detonator probe support failed.

3.2.2.2 Instrument Probe

This element, shown in Figure 4, contains dynamic pressure transducers, amplifiers, a second back-up ignitor, two thermocouples, and a location (pass-through) switch assembly. Located just below the bellmouth assembly, on a line slightly below the extension of the cavity walls, its main function is to provide diagnostic data of the detonation. (See Figure 5.)

The design of the instrument probe pressure case closely resembles the detonator probe, i.e., assembled in sections, each joined with "O" rings. The modular construction facilitates assembly of interior components. The instrument probe is approximately 90 inches long by 4 inches in diameter. A slight taper at each end assures free movement over obstructions in either direction.

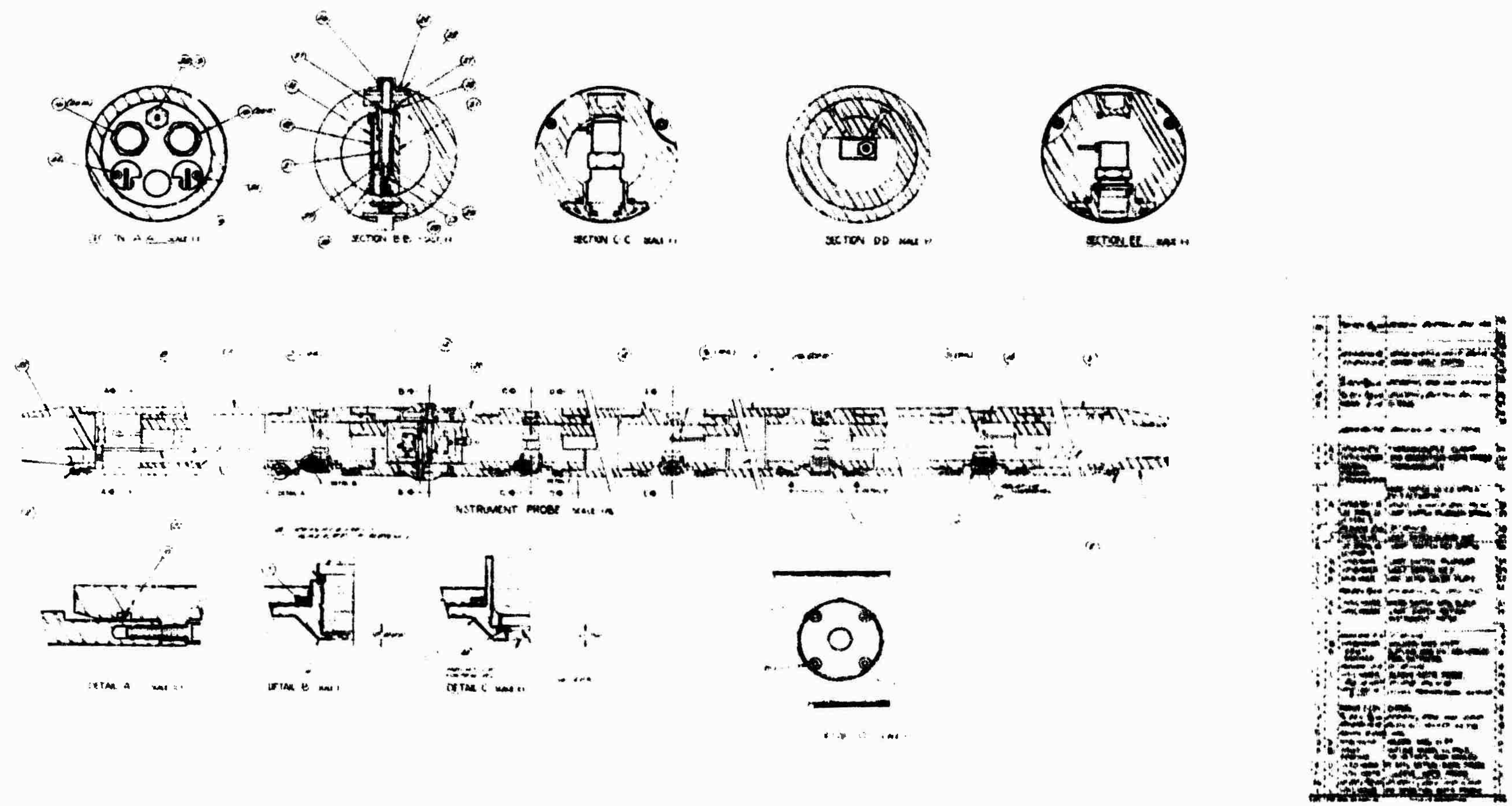


Figure 4 - Instrument Probe

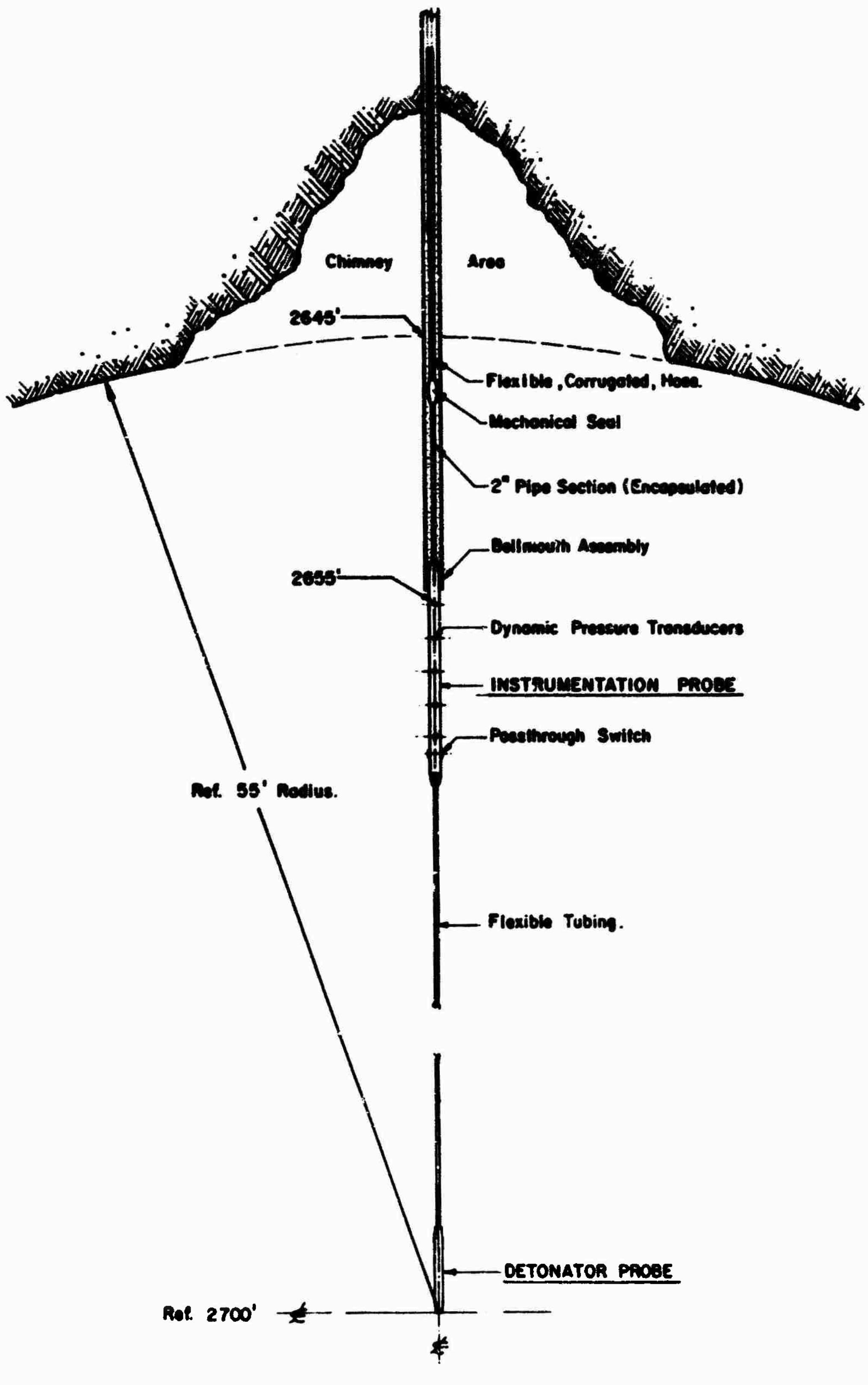


Figure 5 - Instrument Probe Location

The location switch (pass-through) provides a positive, above ground, lamp indication as the probe passes the restriction at the bellmouth. Positive location of the bellmouth can be accurately determined within approximately 0.5 feet. The lamp indication confirms that the instrument probe is not fouled somewhere within the 6-5/8" casing above the bellmouth assembly and detonator probe has also necessarily dropped free to the cavity center.

Environmental isolation of the electronics within the instrument probe is provided at both ends by mechanical seals and "O" rings at the section joints. The top seal is backed up with a strain relieving, high strength, potting compound (Hysol, XCU-M150). The remaining interior volume is completely filled with a clear silicone resin (Sylgard 184) as a back-up barrier to the corrosive environment.

Environmental tests established that all the transducers and amplifiers selected for HUMID WATER would function without external protection if exposed to 700 psig and 180°F in combination while immersed in a salt water/acid bath. This unlikely adverse environment could only occur during an actual experiment if both the instrument probe pressure case should fail, and further that the clear silicone resin should somehow permit moisture entry. Other laboratory tests developed a combination of mechanical seals, backed up with a potting compound (Hysol XCU-M150), which would withstand 450 psig and 225°F in a water bath. The combination also demonstrated that a load greater than the yield value of the cable itself (about 350 pounds) could be applied to the seal assembly without damage to its integrity. This combination was used in the rigid 2" pipe section immediately above the instrument probe.

3.2.2.3 Instrument Probe Support

Choosing a location, within the wellhead casing, for the packer is basically an engineering judgement. In the HUMID WATER case, the choice was made primarily upon three types of evidence of the structural strength of the 9-5/8" wellhead casing. These were: (1) a pass-through the casing with a TV camera, (2) a casing density log made coincident with a temperature log of the casing, and (3) the results of the casing cleaning operation prior to DIODE TUBE.

Immediately prior to the emplacement of the first operation components within the downhole casing, the casing is cleaned by a combination of scraping and brushing. During this operation on the DIODE TUBE event, severe corrosion and mechanical damage was indicated in the section of 9-5/8" casing nearest the cavity. This determination was made by inspection of the cleaning tool assembly upon retrieval from that level. The condition of the casing may be judged from the amount and type of loose material trapped in the wire brush portions of the tool. From the available evidence, the casing was judged to be capable of sealing and supporting the downhole equipment weight if the packer were placed not lower than a depth of 2515 feet. This working point was chosen for HUMID WATER. It was selected to place the top transducer of the instrument probe at a depth of 2655 feet to reduce the effects of reflections of the blast wave from the chimney area interfering with the main blast wave pressure-time record. The chimney (fractured area at the top of the cavity) extends from depths of about 2630 to 2645 feet. (See Figure 5.)

When the desired locations of both the packer and instrument probe were decided, the required length of the instrument probe support connecting the two was determined at about 140 feet (2655' - 2515' = 140').

It was suspected that splices and connections contributed to malfunctions in the electronics on DIODE TUBE. For HUMID WATER, it was determined that the main instrument cable would be continuous and unbroken from the wellhead to the instrument probe. Methods for shipment of the second operation components assembly were considered to the test site, and it was determined to limit the rigid sections of the instrument probe support to approximately 15 feet. This would accommodate the use of a 40 foot flat bed trailer. The remaining sections of the instrument probe support were flexible.

The first section of the instrument probe support from the seal assembly down to the first flexible section, consisted of two lengths of high strength, rigid tubing. Each length was terminated with a mechanical seal, and filled with a urethane potting compound (Hysol XCU-M150). The first mechanical seal was fitted with a blow-out plug just beneath the seal ring. This blow-out plug was designed such that if grout from above the packer somehow entered the annular area between the cable and the tubing, displacing the potting compound, it would be routed outside the pressure case, isolating the balance of the instrumentation string.

The remainder of the instrument probe support consisted of several lengths of high pressure flexible hose of dual wall construction (Anaconda BW21-1H-C). As a load carrying member, a 5/16 inch diameter aircraft cable was suspended within the hose, attached by welding at each joint of the flexible hose. The aircraft cable limited stretch in the hose to accurately maintain the emplaced length and eliminate possible strain on the instrument cable within.

The top of the instrument probe support was connected to the crossover assembly.

3.2.2.4 Crossover Assembly

The crossover assembly, in combination with the seal assembly, provides the means of attaching the second operation components to the first operation components. This assembly rests upon a shoulder within the packer and is designed to latch and provide a gas tight seal with the packer. The name "crossover" refers to the change in the main instrument cable position, which above the crossover is displaced to one side to pass the sliding sleeve gas valve located along the centerline. Within the crossover assembly, the cable is routed to the centerline and continues along the centerline everywhere below that point. (See Appendix A, Figure 3.) The crossover assembly also allows the gases to flow from an annular area above to the 6-5/8" casing below. The crossover assembly also contained remotely controlled gas and cementing valves. The basic design of the crossover assembly was the same for HUMID WATER and DIODE TUBE.(3)

For the HUMID WATER Event, the crossover assembly was modified to accept a static pressure transducer and a thermocouple. These instruments were designed to survive the initial blast wave and monitor the pressure and temperature decay in the cavity after detonation so that a safe period for cavity re-entry could be predicted. These added instruments were connected to the wellhead flange by an independent 4-pair cable to maintain the integrity of the main instrument cable.

3.2.2.5 Main Instrument Cable

The main instrument cable was specially fabricated by Coleman Cable and Wire Company for HUMID WATER. This new cable design was adequate, by test, to be used for DINAR COIN.

The cable consisted of 35 pair, Number 20 AWG tinned copper conductors and 2 pair, Number 20 AWG Chromel-Alumel thermocouple leads. Each pair was twisted and shielded. All pairs were joined by two layers of high temperature PVC jacketing separated by a .005" bare copper tape. The entire cable was void filled with a viscous material.

This improved, rugged cable design gave increased protection against four hazards; ambient temperature, pressure, abrasion, and moisture entry.

Approximately 2700 feet of main instrument cable was used for HUMID WATER. This cable terminated at the instrument and detonator probes on one end and at the wellhead flange (above ground) on the other.

3.2.2.6 Wellhead Connections

It was necessary to separate the main instrument cable into four separate pair groups to pass through the wellhead flange because 74 conductor connectors capable of withstanding a dynamic 3000 psi load (pressure rating of the casing head) and completely protected from moisture entry were not commercially available. To provide the same degree of protection as afforded by the original double jacket on the cable, two layers of powdered silica filled polyurethane (DuPont L 100) was used as a flexible encapsulant. The assembly was subjected to boiling salt water and pressure tests with no failure noted. These four cable branches, together with the independent 4-pair cable from the crossover assembly, were routed through the wellhead connector flange using high pressure passthrough connectors. The entire flange/connector assembly was then encapsulated with a high strength epoxy.

3.3 Data Acquisition System

The data acquisition system was designed to acquire eight dynamic pressure measurements, two static pressure measurements, and three temperature measurements from within the cavity and wellhead. During the gas fill operation, the static pressure in the cavity and at the wellhead was measured. Temperature measurements within the cavity and at the packer were also monitored.

During the detonation, peak reflected and incident blast pressure measurements were to be made. From these dynamic data, wave velocities were to be computed as well as the pressure-time history at the cavity wall. After the blast, the packer (crossover) pressure transducer and thermocouple were to monitor equilibrium pressure and temperature. A schematic diagram of the data acquisition system is shown as Figure 6.

3.3.1 Temperature Probes

Chromel-Alumel thermocouples were used in making the temperature measurements. The thermocouples were sheathed in stainless steel housings and insulated with magnesium oxide fill. Two of the three thermocouples were fed to high input impedance, zero reference, thermocouple amplifiers. (See Note 4, Figure 6.) One thermocouple was located in the packer for pre- and post-shot monitoring, and two were emplaced in the instrument probe for temperature measurements during gas filling. All the amplifiers were gain set to produce outputs from 0 to 100°C on panel meters. One of the amplifiers was provided with the capability of producing full range meter output at 200°C, 300°C, 400°C, 500°C, and 1000°C, as well as at 100°C. The circuits linearized the output to enable direct readings.

The temperature measurement recording system was arranged so that during the blast, temperatures would be recorded by the magnetic tape recorders and after the blast on pressure sensitive paper recorders. This post-shot recording would continue until cavity re-entry.

3.3.2 Detonation Pressure Measurements

The pre-shot, temperature related, failure of the Bytrex pressure transducers during the gas fill of the DIODE TUBE Event led to a search for a more reliable detonation pressure measurement system. The search

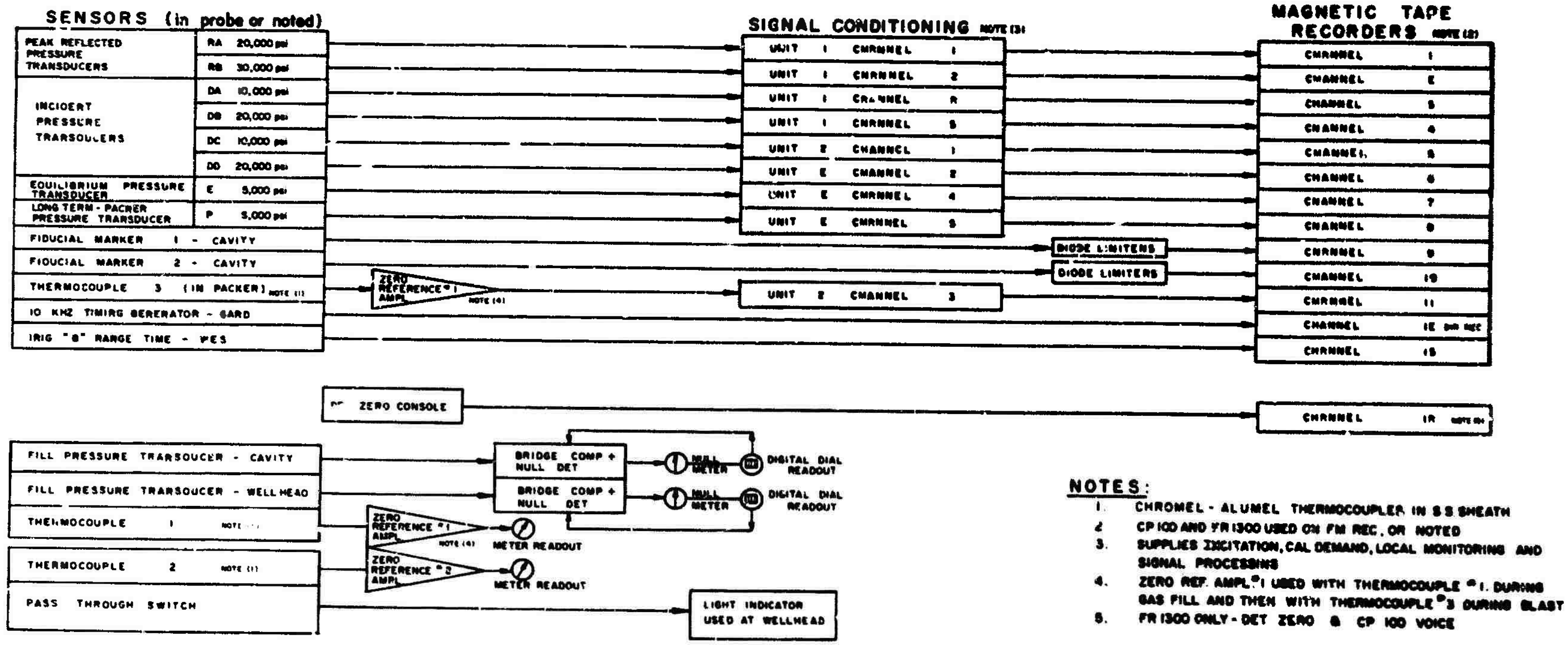


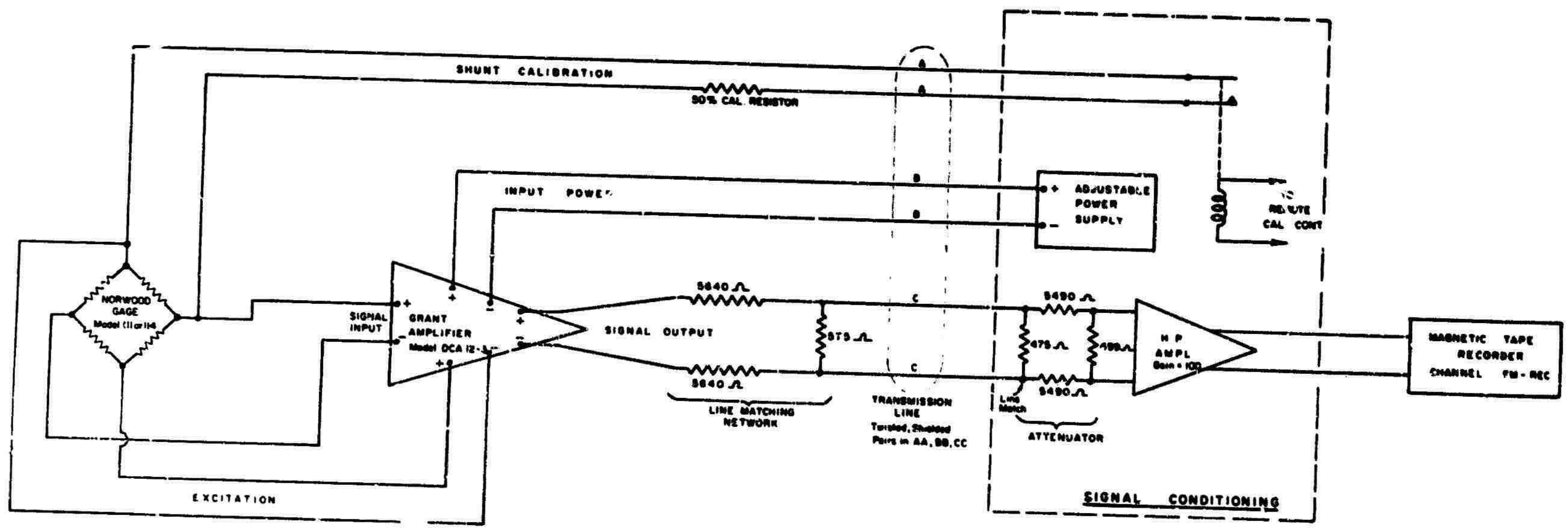
Figure 6 - HUMID WATER Signal Sensoring, Conditioning and Recording Instrumentation System Diagram

started by considering the bonded strain gage type of pressure transducer manufactured by the Norwood Gage Group of the American Standard Company, in Monrovia, California. The gage was noted as being designed to perform under the stringent operating conditions expected. However, the output signal from these devices is only three millivolts per volt of excitation. Without some form of amplification, this output would have been too low for use in HUMID WATER. Further investigation revealed that an amplifier, used with the Norwood transducers by the Sandia Corporation on sled tests, might raise the output of the gages to a useful level above noise and perform adequately. Laboratory tests at GARD indicated that these amplifiers, made by Grant Electronics in Los Angeles, California, would survive the environment and provide useful signals over the mile length of cable at a high signal/noise ratio. The Norwood gages and Grant amplifiers were used to measure detonation pressures for the HUMID WATER Event.

The six detonation (dynamic) pressure transducers were all located in the instrument probe. (See Figures 4 and 6 for details.) The two peak reflected pressure gages were located in the instrument probe nose piece, facing the center of the cavity. Of the five gages located along the side of the instrument probe, the bottom four were incident pressure gages. The top gage, along the side, measures equilibrium pressure. An 1/8" thick layer of ablative silicone resin covered the sensitive equilibrium pressure gage disphragm to permit the gage to survive the initial detonation temperature.

A typical detonation pressure measurement channel is shown in Figure 7. The pressure transducer, the high gain amplifier, a 50% shunt calibration resistor, and a line matching network were encased in the instrumentation probe housing. Six electrical conductors are required for each transducer system. Two conductors allow module excitation, two carry the output signals, and two provide for the 50% shunt calibration.

All six conductors terminate in an assigned signal conditioner channel. The signal conditioners contained differential input amplifiers, floating power supplies in each channel and a remote calibration capability. The excitation conductors deliver direct current power to the Grant amplifier from the signal conditioner power supply. The Grant amplifier incorporates a voltage regulator from which the bridge circuits of the Norwood gages are excited. The gage outputs provide signals to the differential inputs of the Grant amplifier. The amplifier output is fed to a line matching network which feeds the long transmission line (about 1 mile) leading to the signal conditioner channel. The other two conductors from the Norwood/Grant combination are fed via a 50% calibration resistor through the line to the signal conditioner channel. The signal conditioner, on demand, provides a short circuit across one leg of the sensing bridge of the Norwood transducer. Electronically, this causes a gage output exactly equivalent to 50% of full scale, permitting calibration checks, remotely and on demand, at any time prior to the detonation.



Figu-e 7 - Typical Blast Pressure Measurement Channel

The signal conditioner amplifier is gain adjusted to provide a 1-1/2 volt full scale signal for records on an FM channel on both magnetic tape recorder.

3.3.3 Static Pressure Measurements

Static pressure measurements were made during gas fill. A Servonics capsule transducer with potentiometer output was used in two locations. One unit was encased in the detonator probe, and another unit was mounted at the wellhead. Each unit was used in a null bridge circuit. The circuits are shown in Figure 8. A calibrated position-numbered-multiturn-dial is mechanically coupled to a matching potentiometer. The potentiometer arm is moved to correspond to the relative position of the transducer potentiometer arm so that a null current results in the meter circuit wired between both potentiometer arms. Each system was individually calibrated so that the number appearing on the multiturn dial corresponded to a pressure.

3.4 Firing Circuit System

The firing circuit system consists of two units: the above-ground control unit, and firing circuit unit in the cavity. (See Figure 9.) Each unit is redundent, affording the reliability of an independent, dual channel, system.

3.4.1 Firing Circuit Unit

Two Firing Circuit Units, located in the center of the cavity, are enclosed by the detonator probe. Each unit is independently controlled by a separate firing channel. Each unit consists of a filter network, a neon bulb, a silicon controlled rectifier (SCR) firing unit, two parallel firing capacitors, a Safe/Arm relay, and detonator. A typical channel is described in the right hand half of Figure 9.

Extensive filtering networks, designed into the circuit, guard against premature firing due to spurious high frequency signals. Protection against false firing by transient low frequency signals is provided by the neon bulb which effectively blocks the passage of all voltage signals below its illumination level.

The charge capacitors store the detonator ignition energy at a level of about 200 volts. Upon receiving the trigger pulse, the gate circuit of the SCR opens, permitting the SCR to conduct. Conduction of the SCR permits the capacitors to discharge through the SCR, thereby firing the detonator.

The type of detonator used to explode the detonable gas mixture is a Holex Type No. 4800 which contains 195 milligrams of equivalent PETN. Ensign-Bickford Primacord (400 gr/ft) was used as a booster for the detonator. Total explosive charge is in the order of 140 grains of PETN.

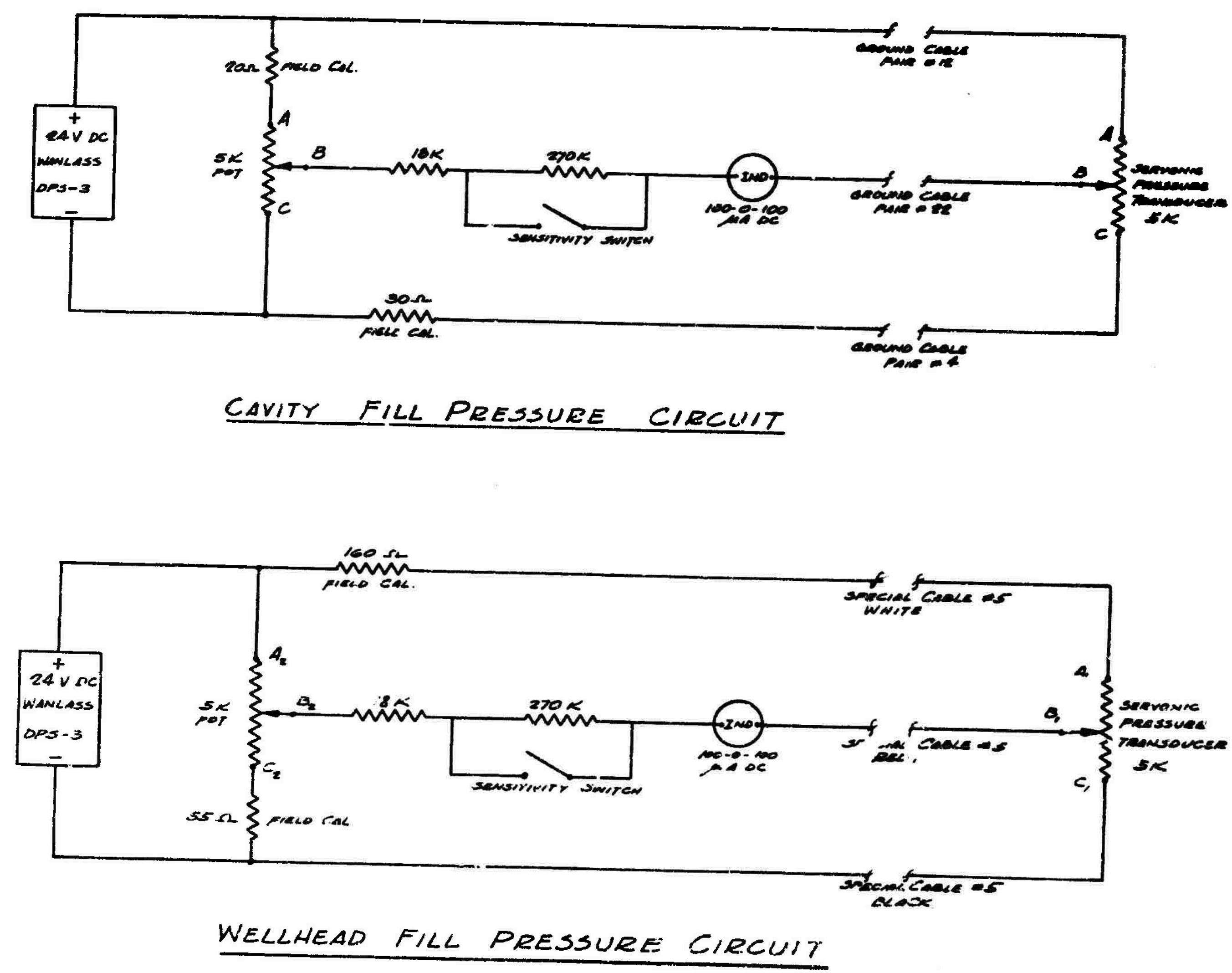


Figure 8 - Cavity Fill Pressure Circuit and Wellhead Fill Pressure Circuit

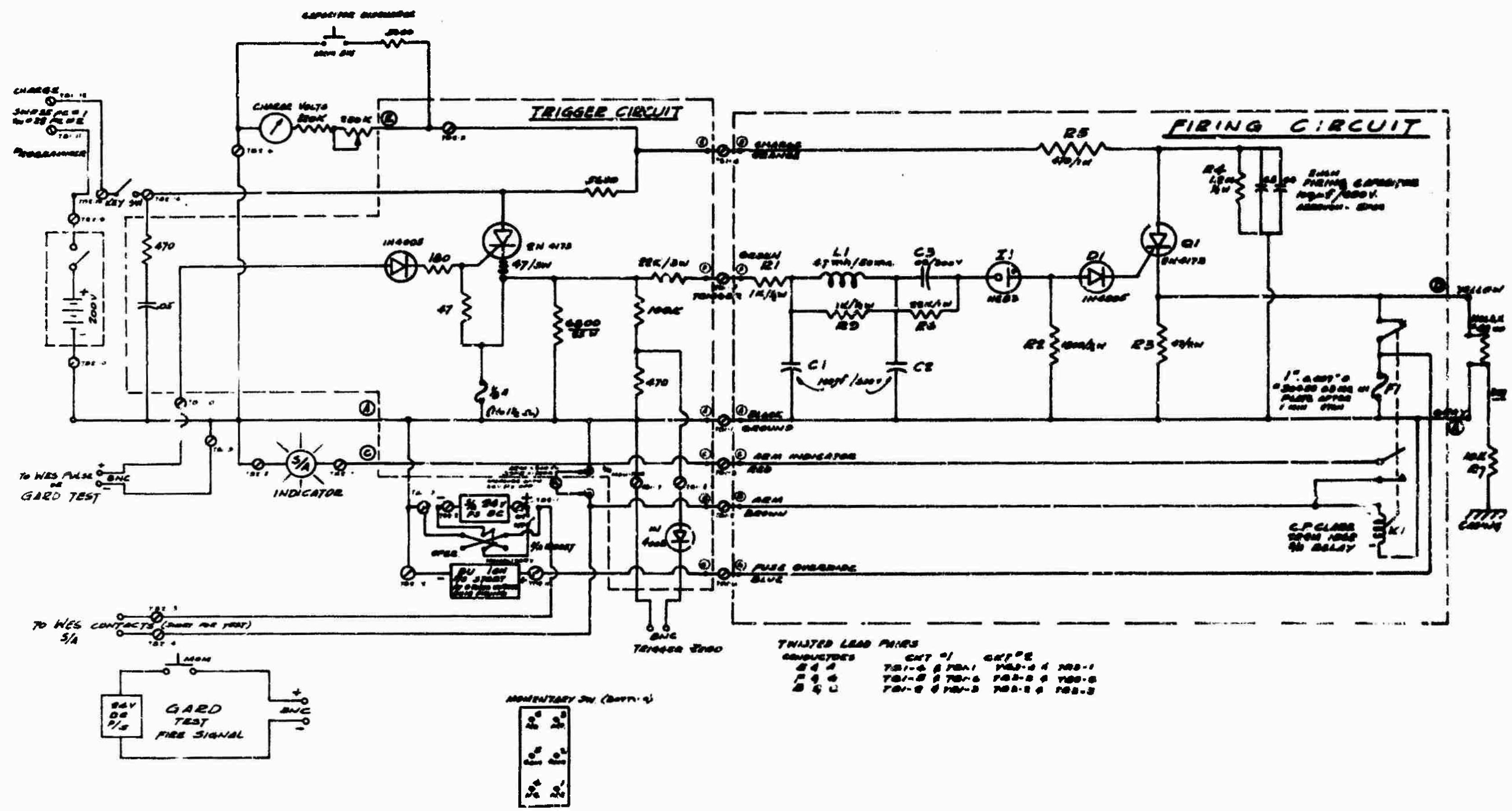


Figure 9 - Trigger and Firing Circuits

Two detonators and boosters are located in the detonator probe nose piece as assemblies in a stainless steel housing. Each detonator assembly is linked independently to its corresponding firing circuit.

The complete firing circuit unit, less the pressure case and encapsulation, was tested in a methane/oxygen mixture at 15 and 40 atmospheres of pressure. In this test, the units functioned properly, detonating the gas mixture. Other environmental tests included boiling salt water and static pressure of 700 psig. In the latter tests, the explosives were substituted by dummy loads. The unit successfully passed all environmental tests, protected only by the encapsulant (Sylgard 184). The outer pressure case provided an additional margin of reliability.

3.4.2 Ground Control Unit

The Ground Control Unit, located above ground 2000 feet from ground zero (wellhead casing) consists of two identical channels, each having a 200 volt direct current power source, a charge-monitoring voltmeter, a Safe/Arm indicator, a 24 volt direct current power source, and a trigger circuit. A typical unit is shown in the left half of Figure 9. The operational description can be followed on Figure 9. Unit operation consists of the following sequence of control steps:

1) Initial conditions: All power off. Charge line E is discharged. Waterways Experimental Station (WES) timing programmed contacts are open. Trigger line F is shorted to ground through 125 milliampere fuse.

2) Turn Arm power on (24 volts direct current). Turn Charge power on (200 volts direct current). Close key lock switch.

3) At -42 seconds, WES provides a programmer start signal.

4) At -30 seconds, the programmer contacts on charge line E are closed. The firing capacitors charge toward 100 percent. The charge monitoring voltmeter indicates the state of charge.

5) At -3 seconds, WES programmed contact on Arm line B is closed. Energy to the Safe/Arm relay causes a contact closure that lights the Safe/Arm indicator. Simultaneously, another contact opens to remove the safety short circuit from the detonator.

6) At 0 seconds, the WES firing pulse opens the gate circuit of the SCR, applying 200 volts across the 125 milliampere fuse. The fuse opens, permitting the trigger pulse to be applied to the firing circuit via line F. The trigger level (200 volts) breaks down the neon bulb, raises the SCR gate so that the SCR conducts, thus permitting the firing capacitors to discharge through the detonator to cause detonation.

3.5 Time Reference System

A time reference system was provided at the Tatum Dome Test Site by the U. S. Army Corps of Engineers Waterways Experimental Station (WES). The system is the Inter-Range Instrumentation Group Format B (IRIG B). This series of coded signals designates range time in milliseconds to an accuracy of microseconds. The time was correlated with transmission from the National Bureau of Standards Station WWV located in Colorado.

An additional timing reference signal was supplied by GARD. This 10 kilohertz signal is produced by an accurate time-marker-generator unit. Both IRIG B and the 10 kilohertz signal were fed to channels on the recorders so that they would provide all reference timing required to analyze the event data.

3.6 Valve Control System

The valve control system provided for remote, single location, control over the piping and valving system. Power failures occurred during critical oxygen fill time during the DIODE TUBE Event. These random power failures caused the GARD valve control system to lock up the valves even though oxygen vaporization was continuing. Oxygen pressure continued to build up in the delivery lines. To overcome this undesired operation, a new valve control system was designed, fabricated, and installed for HUMID WATER. In case of power failure, all valves continue to stay in their last ordered condition. The manual overrides are still available to change valve condition, if desired, in the event of power failure.

During the design of the new valve control system, additional features were incorporated such as elimination of any possible overshoot on valve operation command. An improved local/remote control lock-up arrangement was developed and the display improved to clearly indicate valve status in bright lighting conditions. This new valve control system is shown in Figure 10.

The system is segregated into three locations: the motor operators which are mounted above the valves; a "local" control box near ground zero; and the remote control box located in the GARD instrumentation shack.

The valve operators are reversible alternating current motors equipped with end-of-travel limit switches. One side of each limit switch connects to a steering diode at completion of an open or closed function. Connection of the switch to its appropriate diode provides the report-back information indicating valve position.

The "local" control box contains the main circuit breaker and a key lock switch that controls the selection of the valve control point, (i.e., local or remote). One latching relay per valve is included as well as display lamps and the control switches.

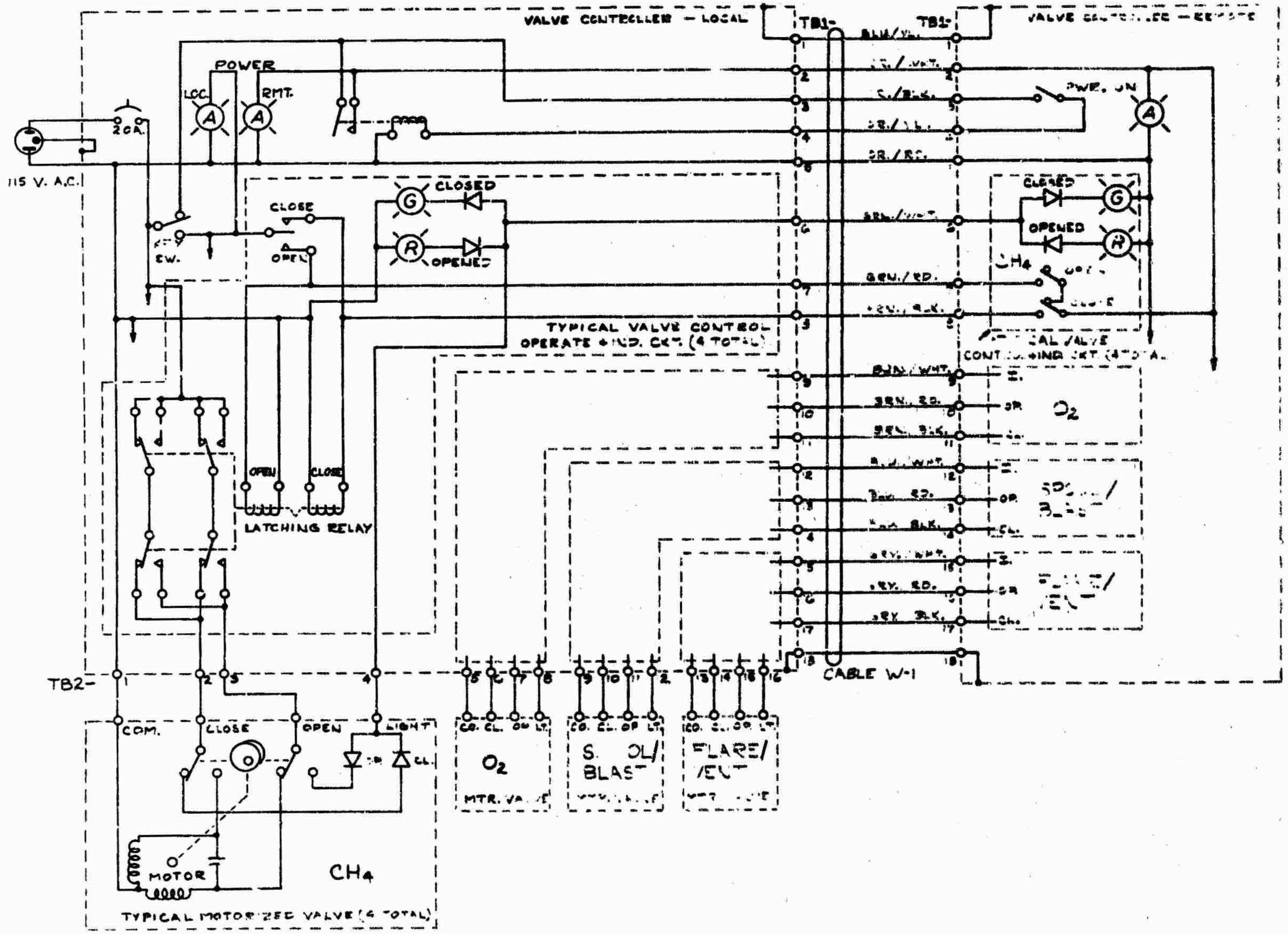


Figure 10 - Valve Control System

The remote control box contains a power "on" switch, four valve control switch arrangements consisting of one "open" and one "close" switch per valve and a lamp display that indicates valve condition.

During gas fill, the local control box key switch selector is set to remote control. The valve open/close control is then accomplished in the instrumentation shack. When control resides at one location the other location cannot override.

3.7 Tracer Gas System

The tracer gas used for the HUMID WATER Event was SF_6 provided by Isotopes, Incorporated. This gas was to be used in DINAR COIN as a means of estimating damage to the cavity walls and was being utilized in DIODE TUBE on a trial basis.

GARD provided an access in both the oxygen and methane gas fill piping system. One access point was located near the manual control valve in the methane pipeline, and the other near the manual control valve at the entrance of the oxygen pipeline.

The addition of SF_6 to methane-oxygen mixtures produces the same degrading effects on detonation as the addition of CO_2.(5) The limits of flammability of methane in air are unaltered by up to 20,000 PPM concentration of CO_2 by volume.(6) Therefore, the addition of 10 pounds (or 18 PPM) of SF_6 to the HUMID WATER detonable mixture had no measurable effect.

SECTION 4

PROCEDURE

The procedures used in the HUMID WATER Event were improved upon from those used in DIODE TUBE. The basic program organization was modified so that area (mechanical, electrical, etc.) responsibility could be assigned. Log books were maintained by each area, and procedures written for major operations. All assembly and test of equipment possible was accomplished in the laboratory, before going into the field.

Important changes were made in the gas fill procedure, in that the order in which the gases were loaded was reversed, and the oxygen delivery rates greatly increased. These changes, combined with changes in the equipment systems described in Section 3 of this report, account for the other differences in the procedure of the two experiments.

A schedule of the major activities for HUMID WATER is shown as Table 1. The descriptive paragraphs that follow explain the work content of the activities shown on the schedule.

4.1 Pipeline and Valve Renovation

Between the DIODE TUBE and HUMID WATER Events, the pipeline system suffered extensive damage due to a hurricane. This required major repairs to return it to its original condition. In addition to hurricane damage, the climatic conditions in the test site area corroded the ball valve seats such that repairs were necessary. The valves were renovated by the manufacturer concurrently with pipeline repair.

Required repairs to the pipeline included replacement of severely damaged sections, rebuilding weakened or broken support structures, alignment of bent sections, removal of felled trees that bridged the pipeline, and improvement of access roads.

4.2 Laboratory Preparation

The increased sophistication of the equipment described in this report for HUMID WATER, as compared to the designs used in DIODE TUBE,[2] and the desire to reduce the in-field effort, made it necessary to complete the assembly of all the systems within the laboratory, insofar as that was practical. Further, this philosophy was adopted to preclude or limit in-field problems and to provide a better environment for assembling and potting. This had an additional value, as laboratory tests could be performed on entire systems, verifying their proper function. In-field preparation, other than for "installed" equipment such as the pipelines, etc., therefore was limited to making cable inter-connections, check-outs, and what might be described a "bolt-together" operation.

Table 1. SCHEDULE OF ACTIVITIES - HUMID WATER

ACTIVITY	WEEK ENDING (1970)								
	2/28	3/7	3/14	3/21	3/28	4/4	4/11	4/18	4/25
Valve Renovation	█	█	█	█					
Pipeline Renovation	█	█	█	█					
Laboratory Preparation	█	█	█	█					
Transport Equipment					█				
In-field Preparation						█			
Emplacement							█	█	
MFP/FF Test								█	
Gas Fill									█
Stem									█
Conduct Test									█

The entire second operation component assembly, described in Section 3, was assembled and checked in the laboratory. The MIRACLE PLAY Console, containing the firing system ground control units and the static pressure and temperature monitoring controls, was constructed as a complete unit. Also fabricated as complete assemblies, were the valve controllers and signal conditioners.

The first and second operation component assemblies were packaged and loaded upon a 40 foot flat bed trailer for delivery to the test site. The other assemblies were transported from the laboratory to the test site in a 14 foot commercial moving van with the balance of the experimental equipment needed that was not left in place after DIODE TUBE or shipped directly from the manufacturer.

4.3 In-Field Preparation of Equipment

The pipelines were inspected, and repaired as necessary. All pipelines were cleaned and pressure checked. All valves were re-installed and checked for proper operation, both manually and remotely driven where such options existed.

The casing head assembly, consisting of a blowout preventor and associated hardware,[2] was cleaned, checked for proper operation, and pressure checked. See Appendix D for details of this procedure.

The 2-3/8" tubing string which was used to lower all equipment in the wellhead casing, was cleaned by sandblasting and protected from corrosion by a single coating of automotive primer. This operation removed all of the oil preservatives that would be a potential fire hazard in an oxygen atmosphere, and most of the loose particles that might create static charge buildup.

Equipment systems, assembled in the laboratory, were installed, interconnected, and checked for proper operation. The oxygen purge of the oxygen pipeline and wellhead casing described in Section 3 was completed using approximately 140,000 SCF of gas. Following the purge, the cavity was vented to equilibrium with the atmosphere through the venting systems.

4.4 Emplacement Procedure

Most of the techniques used are standard within the oil field practice. Advice, and supervision of the drill rig crew, was furnished by the consultant firm of Fennix and Sisson, Inc., Las Vegas, Nevada. Detailed descriptions of step-by-step procedures are included with this report in Appendix D. They may be briefly summarized by:

a) Mobilize and degrease rig.
b) Pressure test casing head assembly.

c) Temperature log casing and cavity.
d) Clean wellhead casing.
e) Emplace casing plug assembly.
f) Demobilize rig.
g) Close sliding sleeve valve after gas fill.
h) Stem casing.

4.5 Mandatory Full Power, Full Frequency Test

This test was performed immediately prior to lowering the second operation components. The test consists of all participating agencies utilizing shot-day procedures to evaluate timing and firing control systems, and discover potential problems in communications or data recovery. For this test, the detonator assemblies, normally in the nose cone of the detonator probe, were not in place to prevent damage to the probe. A special set of detonators, sand bag covered, were connected to the detonator probe with a short patch cord. After successful completion of the test, detonator assemblies were installed in their normal location, the probe encapsulation completed, and the encapsulation permitted to cure over-night before lowering the following day.

4.6 Gas Fill Procedures

The gas fill procedure may be summarized by the following sequence:

1) Nitrogen purge
2) Load methane
3) Nitrogen purge
4) Load oxygen
5) Nitrogen purge.

The initial nitrogen purge (2000 SCF) provides an inert atmosphere for starting methane flow, thereby preventing a possible detonable mixture developing above ground. Methane flow was continuous in the second step above, stabilized about 150,000 SCF/Hr. Hourly readings were taken, after stabilization, of flow rate and total delivery until approximately 100,000 SCF from the desired total. At that point, methane flow was stopped, all gas volume calculations reviewed and verified, then the precise balance added. Precisely 2,965,000 SCF of methane was delivered in 21 hours total elapsed time.

An intermediate nitrogen purge (25,000 SCF) removes all methane from the portions of the pipeline system and wellhead casing that will be in contact with the oxygen to follow. This prevents above ground detonable gas mixtures.

Oxygen flow was discontinuous as the arrival of liquid oxygen tankers could not be scheduled rapidly enough to supply a continuous demand of 400,000 SCF/Hr. With the approval of the Test Director, after the cavity pressure had increased sufficiently, flow rates were permitted to increase approximately 10%. This, due to the increased pressure head, would not result in exceeding any prior approved maximum oxygen velocity in the system. The oxygen fill was completed approximately 13 hours ahead of schedule, or in 29 of the 42 schedule hours for a total delivery of 4,561,000 SCF.

After the final nitrogen purge (50,000 SCF) minor leaks in the wellhead flanges were nearly stopped by tightening the flange bolts. The net pressure loss rate was then established to be at most 3 psi/hr. After closing the sliding sleeve valve and stemming, the pressure was increased to 230 psig (with nitrogen) in the area above the grout thereby creating a pressure differential to insure that no cavity gas would flow upward during the 24 hours required to cure the grout. The entire gas filling procedure required 56 hours, including equipment change-over times.

4.7 <u>Conduct Test</u>

The control of the HUMID WATER initiation was to have been transferred to a timer/stepping switch within the MIRACLE PLAY Console. This console would have been started by a Waterways Experimental Station time marker signal. The planned operation of all systems is described in Section 3. Detonator zero was scheduled for 0500 hours (CST) 21 April 1970. Detonation occurred, probably due to a lightning strike, about 1245 hours (CST), 19 April 1970. Therefore, these procedures were not followed. A discussion of the actual events will be found in Section 5 - Results.

4.8 <u>Re-Entry</u>

After the cavity gases have cooled sufficiently to reduce the pressure to a safe level, gas communication to the surface is established by milling out the 2-3/8" tubing string. These gases are vented through a treatment plant and periodic samples taken and analyzed. The balance of the procedures listed below are to clear the wellhead casing to permit re-use of the cavity.

1. Pick up 1-7/8" mill with check valve on 1" tubing and run into 2-3/8" O.D. tubing.

2. Mill cut cement, cementing sleeve, floating piston, and baffle collars using conventional water circulation. Switch returns from water tank to filtration plant when communication is established with the cavity.

3. Bleed down cavity through filtration plant.

4. Pull 1" tubing and remove 2-3/8" O.D. wellhead equipment.

5. Cut 2-3/8" tubing at cement top. Break cables, pull tubing and cables.

6. Run 7" washpipe on 4-1/2" drill pipe and wash out cement. Cut and retrieve tubing and cable in maximum length sections permitted by hole conditions.

7. Attempt to disengage seal assembly. If unsuccessful, mill out.

8. Mill cut and attempt to retrieve packer and 6-5/8" casing.

SECTION 5

RESULTS

5.1 Event Description

All of the procedures outlined in Section 4 were followed through the stemming of the downhole casing. The stemming procedure was completed about 0230 hours, CST, 19 April 1970. The stemming would require approximately 24 hours to cure. During this curing cycle, a minimum work force would maintain a continuous monitoring and control function. Basically this force consisted of representatives of the AEC, DASA and GARD. Additionally, there were safety and security teams. The safety team had members proficient in Industrial Safety, Radiation Safety, and Firefighting.

The last complete check of all GARD control and data acquisition circuits revealed no anomalies. This check was reported as of 1130 hours, CST, 19 April 1970.

A sudden, but intense, local storm commenced about noon, accompanied by frequent lightning strikes, one of which struck somewhere in the general vicinity of ground zero and created a considerable air blast within the monitoring and control building located about 2000 feet from ground zero. The time was observed to be 1245 hours, CST, 19 April 1970. The GARD representative immediately went to a position from which he could observe the GZ area. There were no anomalies noted, e.g., flying debris, fires, etc. The DASA representative started immediately to check to static pressure and temperature readings. Significant changes from the last recorded readings were noted. A warning to evacuate the GZ area was given to prevent injury to personnel pending a more complete analysis.

A GARD representative checked the Arm/Safe relay circuit and found a shorted indication. The absence of an open circuit made it mandatory that power be removed from all circuits having potential communication with the cavity until the exact status could be determined.

Later circuit analysis showed all circuits were somehow shorted to one another. Small gas bubbles began to appear around the wellhead casing in the wet soil. These were sampled and contained some carbon monoxide, but mostly nitrogen. The samples were indicative but inconclusive evidence of a detonation.

It was determined that safety would permit the monitoring of thermocouples. These readings, presented later in this section, gave strong indications of a detonation, but were not accepted as proof of a detonation as they were consistent with a hypothetical fusing of the main cable at some point above the cavity due to electrical arcing created by the lightning.

A positive determination that a detonation occurred was made when a preliminary report of a seismic recording, observed at the warehouse location (about 5 miles northeast of ground zero) indicated amplitudes much larger than normal for lightning induced ground motion and at the same time as the intense lightning strike.

Diagnostic data was not recorded, due to the detonation occurring substantially before the scheduled event. Recording time is severely limited, thus continuous monitoring of those data channels during the 24 hours required to cure the grout would not have been practical.

Enough facts were observed to verify most of the basic requirements of the experiment. Large quantities of explosive gases can be loaded separately and mixed in underground cavities safely and with precision. They can be detonated, and will release large amounts of energy. Inspection of the residual cavity gases suggest that the detonation was thermochemically near that predicted.

5.2 Cavity Temperature

Figure 11 is a plot of the temperatures recorded by thermocouples located at the packer and instrument probe. No readings were recorded from approximately two minutes after the lightning "strike" for about five hours due to equipment power down directed as a safety measure until the effects of the lightning strike could be analyzed. A small positive bias on the order of several degrees is expected in this data due to small induced voltages in the relatively long lead lines (about one mile). The data seems to indicate a detonation occurred and rather rapid cooling to the equilibrium conditions of the cavity.

5.3 Seismic Data

Some seismic data was recovered due to the fortunate circumstance that some of the seismographs, intended to record this experiment, were operating at the time of the unintentional detonation. Johns[7] reports the preliminary analysis of the seismic data taken at recording stations at about 70 km from GZ. These gauges were recording during the time the gas detonated. The first P wave signal amplitudes were not recorded, but only inferred from comparison with other shot records. The amplitudes of the HUMID WATER Event were, in most modes of comparison, larger than those in the STERLING Event. A factor of 1.5-2 in the amplitudes would approximately describe the ratio, but caution is advised since the spectral content of the signals in HUMID WATER was slightly different from STERLING.

This data infers a detonation occurred, as no other phenomenon (e.g. diffusion flame) would have produced ground motion of this magnitude short of an earthquake. An earthquake exactly coincident with other observed

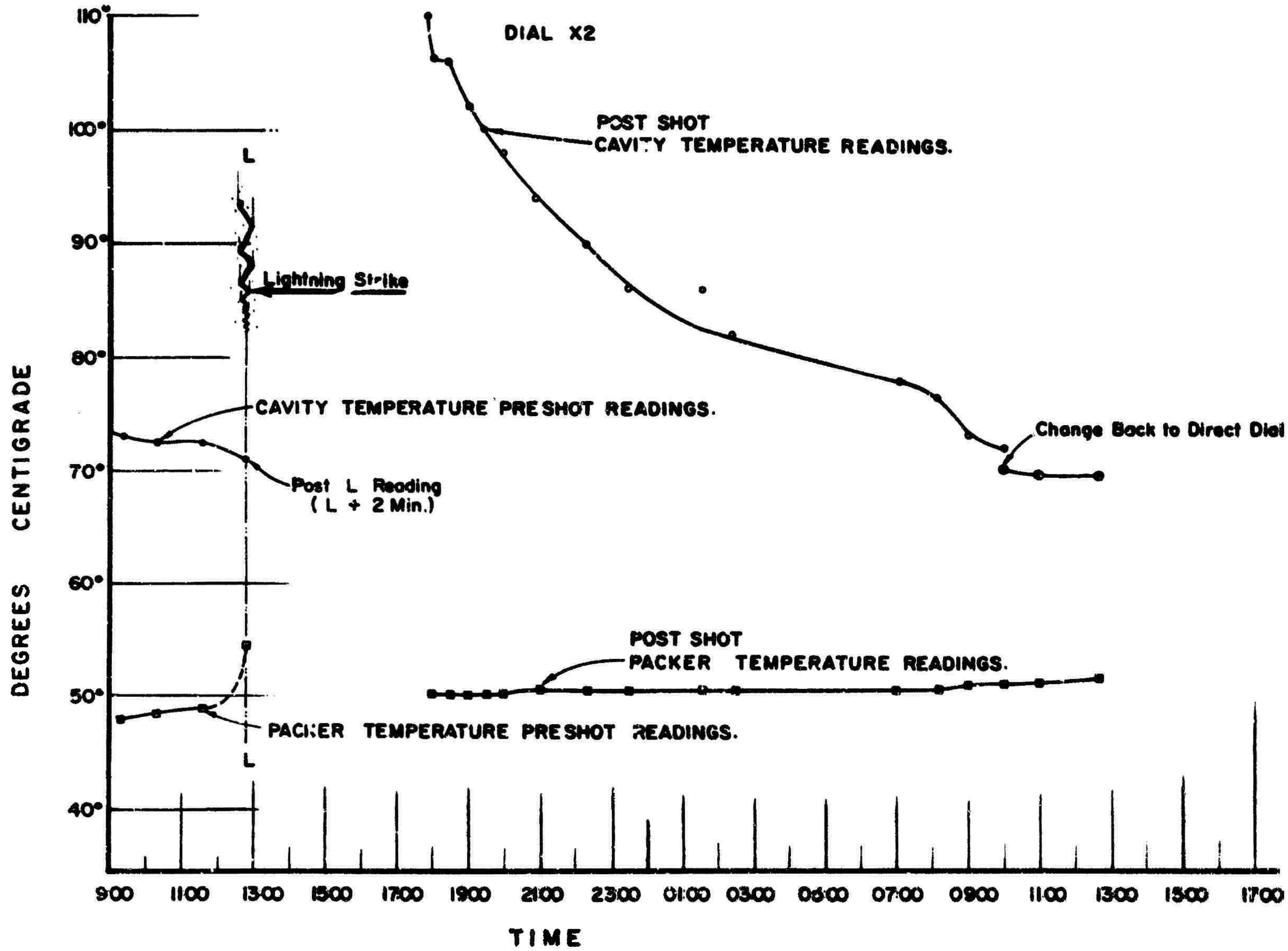


Figure 11, PRESHOT AND POST SHOT, CAVITY AND PACKER, TEMPERATURE HISTORY.

phenomena (e.g. lightning, temperature and pressure changes) is extremely improbable. Analysis of this data is made more difficult by considerable background noise, due to the local storm, superimposed upon the seismic records.

5.4 Analysis of Cavity Bleed-Down Gases

Subsequent to confirmation that a detonation had in fact occurred, the cavity was re-entered with techniques described in Section 4.8. The cavity pressure upon entry was 140 psi. Table 2 presents periodic analysis of the venting gas samples which include about 60% CO_2, indicating a rather complete, full-scale, reaction. Differences in relative percentages of residual gases observed after DIODE TUBE (see Appendix A) are consistent with the difference in initial O_2/CH_4 ratios (DT = 1.96, HW - 1.6).

TABLE 2

GAS ANALYSIS (%)

DATE/TIME (CST)	H_2S	H_2	CH_2	CO	CO_2	O_2	N_2
2 May 1970/1100	8.6	11.0	2.5	4.0	60.2	1.0	12.5
3 May 1970/1100	8.0	13.7	3.0	3.8	57.1	1.1	13.3
5 May 1970/1515	8.0	13.7	3.0	3.6	59.0	1.5	12.0
4 May 1970/1000	5.3	11.5	3.5	4.5	62.5	1.6	11.9
4 May 1970/1700	5.2	10.6	3.5	4.0	62.0	1.4	11.3
5 May 1970/1600	5.9	10.3	3.8	3.7	61.0	1.3	13.0

The significant amount of H_2S probably is due to a reaction with the calcium sulfate impurity present in the cavity walls.[8]

5.5 Evaluation of Experimental Procedure

The emplacement program discussed in Section 4 proceeded smoothly as planned. All the equipment was conservatively designed, and adequate in all respects for its intended use.

The gas fill procedures and equipment performed in all respects equal to, or exceeding, expectations. A flow rate demand 110% of that planned was placed upon the oxygen delivery system without evidence of stress. Methane delivery was maintained within approximately 1% of the desired flow rate, without difficulty or service interruptions.

Stemming the wellhead casing went without incident. The casing plug assembly functioned properly sealing the cavity, and there was no evidence of any loss of stemming material into the cavity. Backup procedures are necessary as a precaution in the event a positive seal is not obtained, but were not used in either HUMID WATER or DIODE TUBE. Leakage, even after the detonation, was confined to small cracks in the grout outside the 9-5/8 inch wellhead casing.

The second operation components, containing the diagnostic instrumentation, was exposed to the cavity environment from the 15th to 19th of April. During that four days to the detonation, no evidence of moisture entry or system failure was noted. Insulation resistance values did not shift. (A shift would normally be observed if moisture entry occurred.)

Periodic checks of above-ground equipment revealed no problems. The Mandatory Full Power, Full Frequency Test was completed successfully on the first try, verifying the ability of all systems to work together.

The detonation mechanism, probably due to lightning, was studied by E.G. and G., Albuquerque, New Mexico.[3] Analysis confirms it was due to lightning although the exact mechanism is yet unknown. No evidence, despite a thorough search, was ever found of a direct strike on any component of the system. All hypotheses of mechanisms by which some part of the control system itself was responsible have been rejected after evaluation of the evidence.

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APPENDIX A

OPERATION MIRACLE PLAY

DIODE TUBE EVENT

Summary of Analytical Considerations

APPENDIX A

OPERATION MIRACLE PLAY

DIODE TUBE EVENT

Summary of Analytical Considerations

This appendix describes the analytical investigations conducted by General American Research Division of General American Transportation Corporation concerning the DIODE TUBE Event of the MIRACLE PLAY Series. Included are the predictions of the theoretical pressure waveforms, the theoretical detonation parameters, and summaries of investigation of the several hypotheses suggested to account for the observed seismic behavior.

The DIODE TUBE Event was an underground detonable gas explosion conducted by the DASA Field Test Command for the Advanced Research Projects Agency (ARPA). The detonable gas mixture, consisting of methane and oxygen, was exploded in a 55-foot radius spherical cavity, whose center was 2700 feet below the ground surface. The cavity is located in the Tatum Salt Dome, near Hattiesburg, Mississippi, and was created by a nuclear explosion, denoted as the SALMON Event. One objective of DIODE TUBE was to match certain parameters of a nuclear event (STERLING) previously detonated in the same cavity.

Examination of the seismic records obtained from this detonation reveal certain anomalies. Comparison of data from the DIODE TUBE and STERLING Events reveals that, although the wave shape of the STERLING data was reproduced in the DIODE TUBE Event, at least for the long range recording stations, the amplitudes of the DIODE TUBE signals are generally lower by roughly seventy percent. On this basis standard decoupling theory predicts that the magnitudes of the explosive yield of DIODE TUBE should be less than that of the STERLING Event by the same percentage.

Several significant parameters describe and characterize the detonation of a gas mixture or of a nuclear device. Among these are the peak reflected pressure at the cavity wall, the equilibrium pressure of either the burnt, detonated mixture or shocked air and nuclear debris before heat losses occur, the initial pressure, the difference between the peak reflected pressure and the initial pressure, the total energy released by the detonation, the size of the cavity in which the detonation occurs, and the periods between the successive shock reflections at the cavity wall. These last two parameters may be combined and expressed as a mean long time oscillation frequency and the mean sound velocity in the heated residual gas mixture.

When matching of nuclear detonations and gas detonations is attempted, no more than two of the listed parameters can be matched. When those two are selected, the ratios of the remaining terms are fixed. Functional relationships among the various detonation parameters exist, since the physical process and its mathematical description are well known. The DIODE TUBE and STERLING Events occurred in the same cavity, so that the matching of one of the parameters, the cavity size, is imposed. The second parameter selected was the difference between the equilibrium pressure and the initial pressure.

The DIODE TUBE Event was a nominal 315-ton (TNT energy equivalent) gas explosion with its parameters chosen so that the difference between the equilibrium pressure and the initial pressure matched that of the STERLING Event, a 380-ton nuclear explosion in the same cavity. Figure A-1 shows the predictions of the pressures exerted at the cavity wall for these two events. The gas calculations are scaled from the detonation calculations of Ostrem and Fugelso [(1)*] for the specific case of a methane-oxygen-air mixture with $O_2/CH_4 = 1.97$, at initial pressure equal to 15.8 atmospheres including the initial volume of air at 1 atmosphere. The detonation pressure to initial pressure ratio was 20 and the detonation velocity was 8250 ft/sec. The nuclear pressure profile was obtained by the application of standard cube root scaling to Patterson's calculation[(2)] of a 100-ton TNT equivalent nuclear detonation in a 14.5-meter radius cavity.

The theoretically calculated detonation parameters for the DIODE TUBE detonations are presented in Table A-1, where the detonation pressure, peak reflected pressure, equilibrium pressure and other thermodynamic quantities are calculated from the thermochemical analysis described by Balcerzak and Johnson[(8)]. These numbers are calculated for the gas mixture actually piped into the hole. Three sets of data are presented since the pressure of the gas in the cavity is known fairly precisely but the cavity volume is not. The sets correspond to the mean and the probable extremes of the cavity volume.

The gases for the DIODE TUBE event were loaded into the cavity, oxygen first, followed by the methane. The drill hole was sealed. The arming device for the down hole ignition system failed and the detonator proved inoperative. The mixture was ignited by applying a high voltage current across the ignition system, causing either a spark to jump the arming system gap or to burn away the insulation of the electrical leads. This emergency ignition system did produce a detonation someplace within the cavity.

Preliminary examination of the seismic data obtained by several agencies (WES, AFTAC(VSC), USGS) indicates that according to standard decoupling and seismic wave propagation theory, the apparent yield produced by the gas explosion is on the order of one-third the predicted yield. Figure A-2 shows two sets of comparable seismic records for the DIODE TUBE and STERLING Events; the top record of each pair being that of the STERLING Event and the bottom one being the DIODE TUBE record. These particular records were taken by the U.S. Geological Survey, using similar instrumentation at distances of 16 and 28 kilometers from the epicenter.[(3)] The shape of the

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* See References at the end of this Appendix

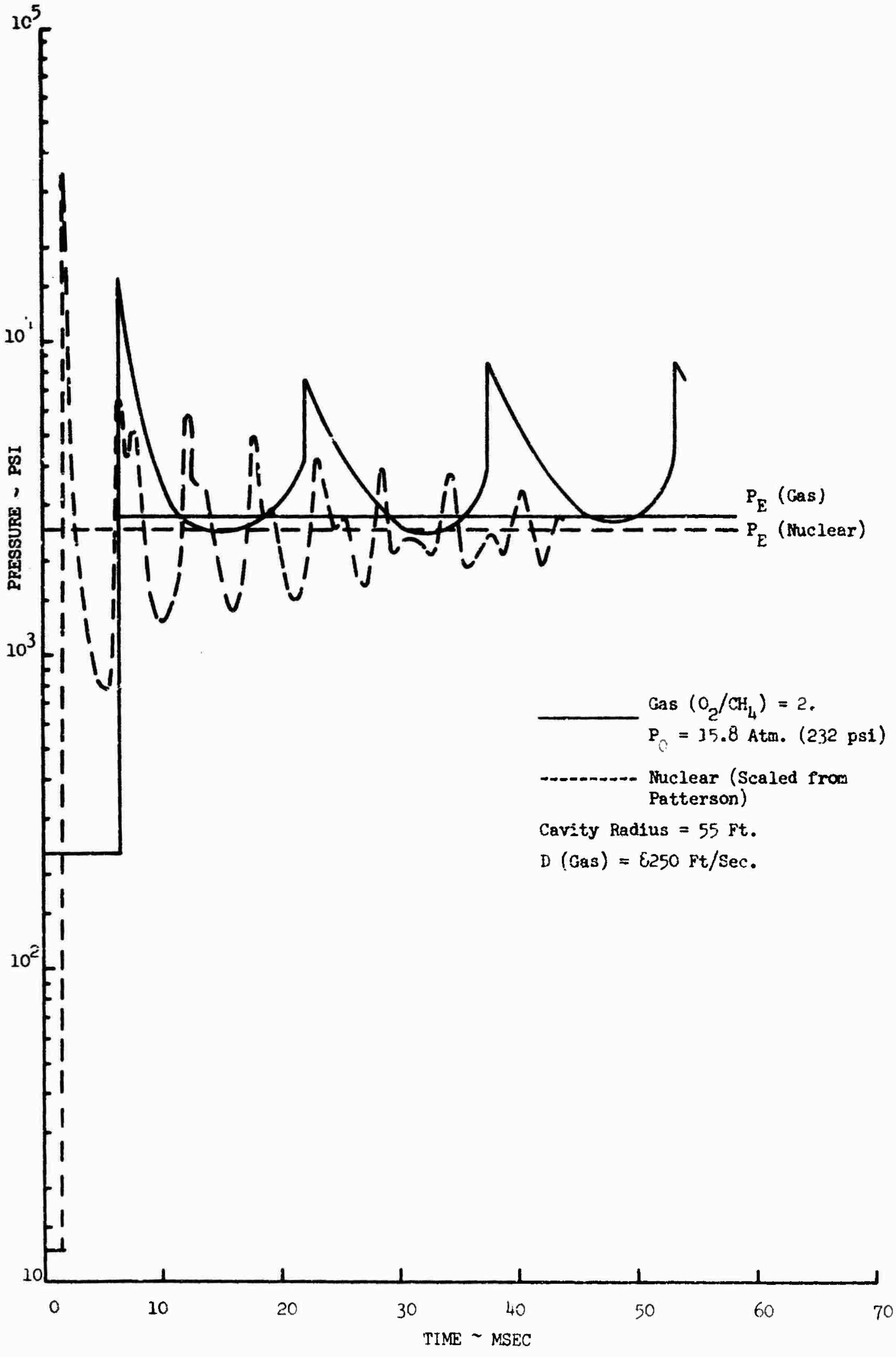

Figure A-1. CAVITY WALL PRESSURE LOADING PREDICTION FOR GAS AND NUCLEAR DETONATIONS

THEORETICAL CALCULATIONS

	CAVITY VOLUME (FT^3)		
	650,000	670,000	690,000
INITIAL PRESSURE (ATM)	15.8	15.4	14.9
DETONATION PRESSURE (PSI)	6520	6320	6123
PEAK REFLECTED PRESSURE (PSI)	16805	16291	15781
EQUILIBRIUM MINUS INITIAL PRESSURE (PSI)	2389	2338	2240
(BARS)	165	161	154
EQUILIBRIUM PRESSURE (PSI)	2635	2578	2472
(BARS)	182	178	170
MIXTURE RATIO: MOLES O_2/CH_4	1.969	1.970	1.972
ENERGY RELEASED (FT.LB.)	10.33 x 10"	10.31 x 10"	10.26 x 10"
EQUIVALENT TNT YIELD (TONS OF TNT)	335	334	333

TABLE A-1

THEORETICAL PREDICTIONS FOR GAS DETONATION OF OXYGEN AND METHANE IN DIODE TUBE EVENT

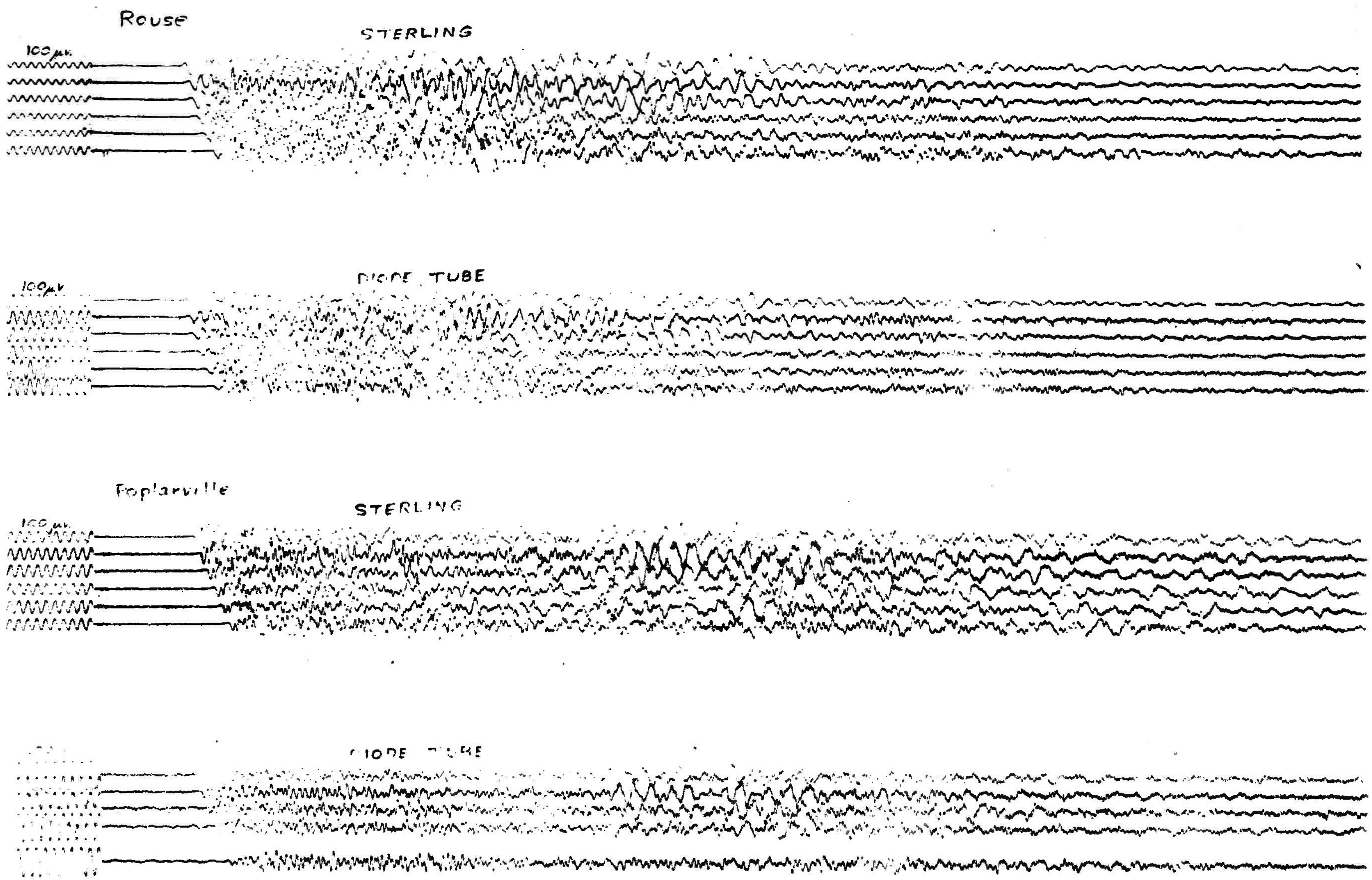

Figure A-2. SEISMIC RECORDS AT POPLARVILLE AND ROUSE STATIONS FOR STERLING AND DIODE TUBE EVENTS seismic signals received at both locations agree in most details for most of the period covered in the records. The amplitudes of these motions are approximately in the ratios of 3 to 1, the STERLING amplitudes being larger. (The amplitude scale on the graphs is indicated by the calibration signal to the left.)

Because of extensive modifications in the downhole circuits required to cause ignition, all source instrumentation designed to measure the initial and equilibrium pressure and the transient explosive pressure in the cavity were disconnected prior to detonation to prevent damage to secondary equipment. No direct verification of the source pressures during the detonation was made. Prior experience with methane-oxygen detonations obtained in the operation of a detonation shock tube facility, in a sonic boom simulation facility, in surface explosions of the gas mixture in balloons and in a preliminary detonability test at an initial pressure of 15 atmospheres indicate that the experimental pressure in the cavity should have been nearly equal to that predicted.

Several hypotheses were made to explain the drastically lower seismic signals. First, some of the gas mixture may have leaked out of the cavity, mainly through the several other instrumentation holes near the cavity. These other holes were plugged and sealed prior to the gas fill; however, the plugs could have failed. Second, detonation anomalies may have occurred as small amounts of water vapor and H_2SO_4 were initially present in the gas mixture. The possibility of a lower order detonation preferentially occurring at the actual initial mixture composition, initial temperature (70°C) and pressure must be considered. Third, the gas mixture could have been stratified during the gas loading and thus an incomplete mixing might have occurred. A fourth possibility is that gross errors in measuring the gas loading could have been made, either in O_2 or CH_4 systems or in the cavity pressure and temperature monitoring system. A fifth hypothesis is that the actual ignition point of the detonation took place at a point other than the center of the cavity. The final hypothesis notes the peak reflected pressure for the STERLING Event is estimated as being about three times that of the gas explosion, although the equilibrium pressures of the two explosions are about the same. The peak reflected pressures for both explosions exceed the yield strength of the surrounding medium. Under this condition, the seismic effects due to the rapidly decaying spike are normally thought to be attenuated, this attenuation removing all effects of the spike which might propagate to large distances. It is possible, though, that the distant seismic signals are strongly affected by the spike pressures, whose effect, in cases of this sort, is normally neglected because, (1) the spike is of short duration and the resulting "high frequency" component would rapidly be attenuated during its propagation as a seismic wave and (2) the spike pressure causes the cavity wall to yield plastically and the wave energy would be absorbed in plastic deformation and thus no appreciable signal would be propagated. Thus the last conjecture is that the spike pressure and its effects are not so rapidly attenuated and that the seismic signal is in some manner proportional to the peak pressure of the detonation.

Of the several hypotheses ventured, selection and verification of those pertinent to this problem are precluded by insufficient explosive sources data.

GARD has examined several features pertaining to these hypotheses. These analyses are given below. The mixing analysis of the methane and oxygen in the spherical cavity is discussed in detail in Appendix F. In that appendix the mixing procedure used in the DIODE TUBE event was predicted to be incomplete. Only a third of the volume would be sufficiently mixed to be considered a detonable mixture.

The prediction of thermochemical data was made under the assumtions that (1) the initial and final states of the explosive mixture can be represented as perfect gases, (2) the detonation satisfies the Chapman-Jouguet condition, (3) the reactions in the detonation front take place with infinitely fast rates, (4) the burnt gas mixture is in equilibrium at the detonation pressure and temperature. One term which enters into the calculations is the adiabatic exponent. The detonation pressure is approximately proportional to - 1; the values of for the burnt gas mixture therefore must be known very precisely. Typical values of for the hot burnt gas mixture are about 1.2 contrasted to values about 1.4 for the initial mixture. The computed values of are in agreement with those reported by Lewis and Von Elbe.[(4)] Experimental determination of the detonation pressure has been made for several of these gas mixtures at initial pressures up to 5 atmospheres in GARD's detonation shock tube facility, where the theoretical and experimental detonation pressures agreed to within 10%. From this experience it is concluded that the thermochemical calculations as presented here are an accurate prediction for the detonation of the uniform gas mixture.

The next problem investigated by GARD was the accuracy of the amount of gas actually loaded into the cavity. The gases were loaded into the cavity from a gas supply at the surface through a downhole assembly.

Figure A-3 presents a schematic representation of the downhole assembly from the sliding sleeve valve down to the detonator package. The diagram to the left shows the gas inlet port in the sleeve valve, the cable crossover, the packer seal assembly, the packer, and the 6-5/8 inch inner casing. The diagram to the right shows a continuation of the inner casing, the ports for gas entry into the cavity, the instrument probe, and the detonator package. The arrows designate the path of gas flow.

When gas flow into the cavity is complete, nitrogen pressure is used to shift the sliding sleeve closed. Once the sliding sleeve has closed, a pressure check valve in addition to a mechanical latch prevents the valve from re-opening.

The instrumentation cable was potted into the crossover assembly using high strength epoxy. This was done to form a seal around the cable to withstand the high temperature, high pressure cavity gases following the detonation. The cable was potted for some distance into the crossover assembly and additional potting was poured onto the top of the crossover.

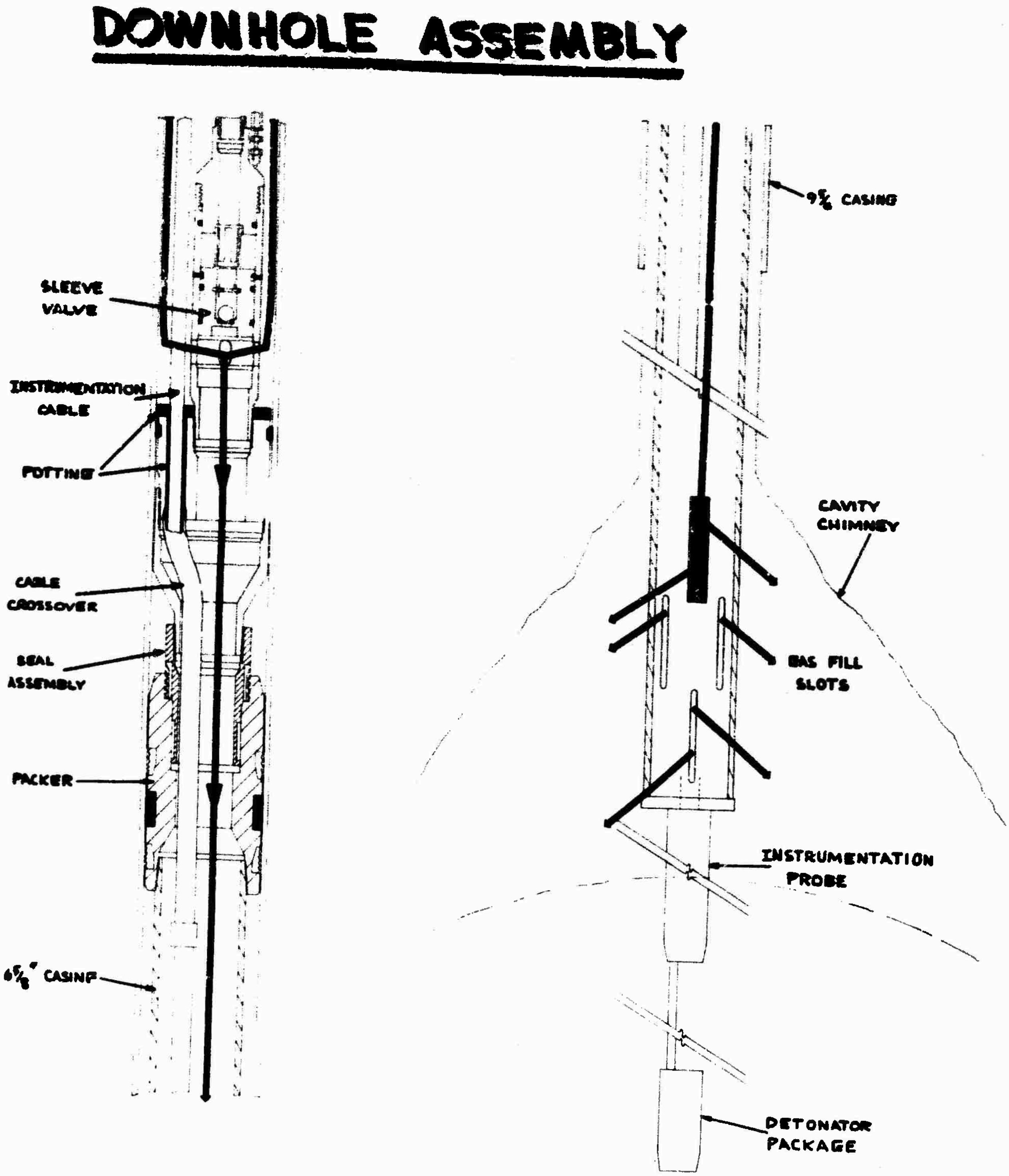

Figure A-3. GAS LOADING DOWNHOLE ASSEMBLY FOR DIODE TUBE

The packer seal assembly and packer are production items manufactured by Baker Oil Tools, Inc. The packer seals against the existing 9-5/8 inch outer casing with a hard Buna N seal. The packer seal assembly latches into the top of the packer and seals using molded chevrons.

The inner casing extends for a distance of approximately 125 feet to the top of the instrumentation probe. Five feet above the probe are gas entry slots which permit flow of gas into the cavity. As noted, these slots are 1/2 inch x 12 inches and are 12 in number (4 slots per row, 3 rows).

The instrumentation probe contains the source verification pressure transducers and the thermocouple. Suspended from the probe is the detonator package containing the gas fill pressure transducer, the firing circuit boards, and the 3 detonators. The detonator package hangs some 40 feet below the instrumentation probe, near the center of the cavity (working point at 2700 feet below grade).

The gas was loaded into the cavity with the oxygen going into the cavity first, followed by the methane. Figure A-4 shows the time history of gas volume added to the cavity. Significant changes during the gas fill, such as the start time of the methane fill are indicated. The oxygen and nitrogen were brought to the site in tanks in the liquid form, while the methane was brought to the site via pipelina from the United Gas Company main line. The nitrogen and oxygen are almost completely pure. Table A-2 presents the chemical analysis of the natural gas as received from the United Gas Company.

TABLE A-2

ANALYSIS OF THE NATURAL GAS

GAS	% BY VOLUME
Methane	96.11
Nitrogen	1.66
Carbon Dioxide	1.13
Ethane	0.33
Propane	0.29
Isobutane	0.10
Normal Butane	0.14

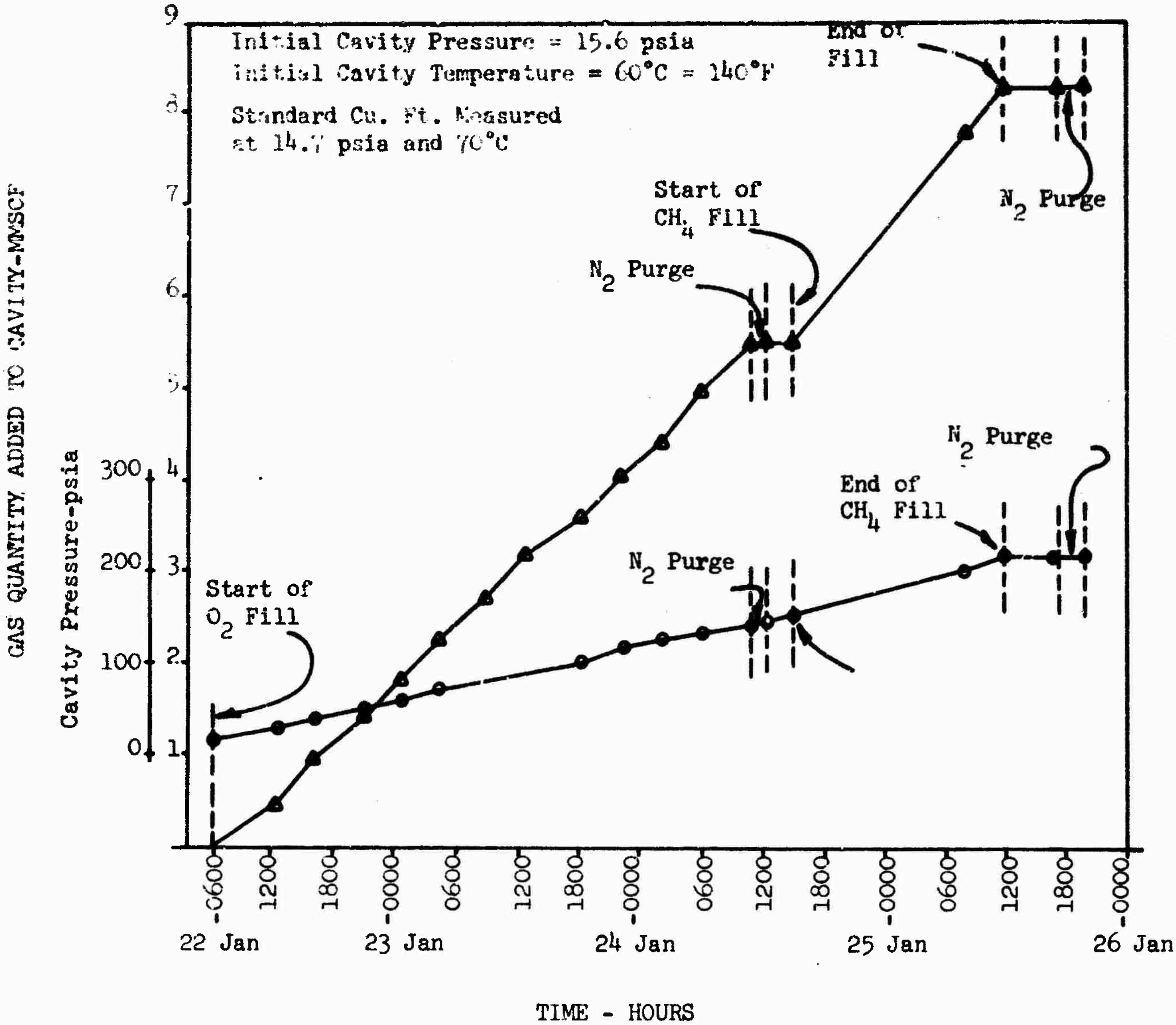

Figure A-4. GAS LOADING HISTORY

GAS		% BY VOLUME
Oxygen		NIL
Others		0.24
Specific gravity @ 14.73 psia	=	0.5873
Line temperature	=	78 deg. F

The measured volume of gas pumped into the cavity was 8.44 million standard cubic feet, of which 5.6 million standard cubic feet were oxygen. The oxygen fill was completed in 51 hours and 20 minutes and the natural gas fill took 21 hours and 45 minutes. Two methods were used to measure the volume of the gas added to the cavity. First, the flow rate was approximately measured; second, the cavity pressure was recorded and this pressure together with the measured cavity temperature and estimated cavity volume, gave a measure of the gas volume. The pressure transducers in the cavity failed during the latter part of the oxygen fill, after which time the pressures were monitored by transducers near the wellhead.

Figure A-5 presents actual test data taken during oxygen and natural gas fill. During this period cavity temperature remained relatively stable. The resultant curve faired through the data points is a straight line, which indicates that little or no cavity leakage of gas occurred during fill. The natural gas volumes obtained from the supplier were corrected to the standard conditions of 14.7 psia and 70 deg. F.

Figure A-6 presents accuracies of the various systems used in computing the volume of gas which has entered the cavity. The line labelled Pressure Monitoring includes the accuracy of the gas fill pressure transducer, gas fill pressure meter, and gas fill pressure transducer calibration. Based on these estimates, the pressure monitoring system is stated as being accurate to within ± 4 percent of full scale.

The center line, which shows the accuracy of the actual gas loading systems, includes the following: during oxygen fill, either the liquid level gauges or the liquid weight was used to compute volume. If the level gauges were used, the accuracy is estimated to be about ± 3 percent. If the gauge was inoperable, the weight of the liquid oxygen in the tanker excluding the amount left in the tanker (estimated) was used to obtain a volume. The accuracy of this method, including the truck scales and quantity remaining estimate is about 2.5 percent. During natural gas fill, a meter certified accurate to within 2 percent was used to obtain gas volume.

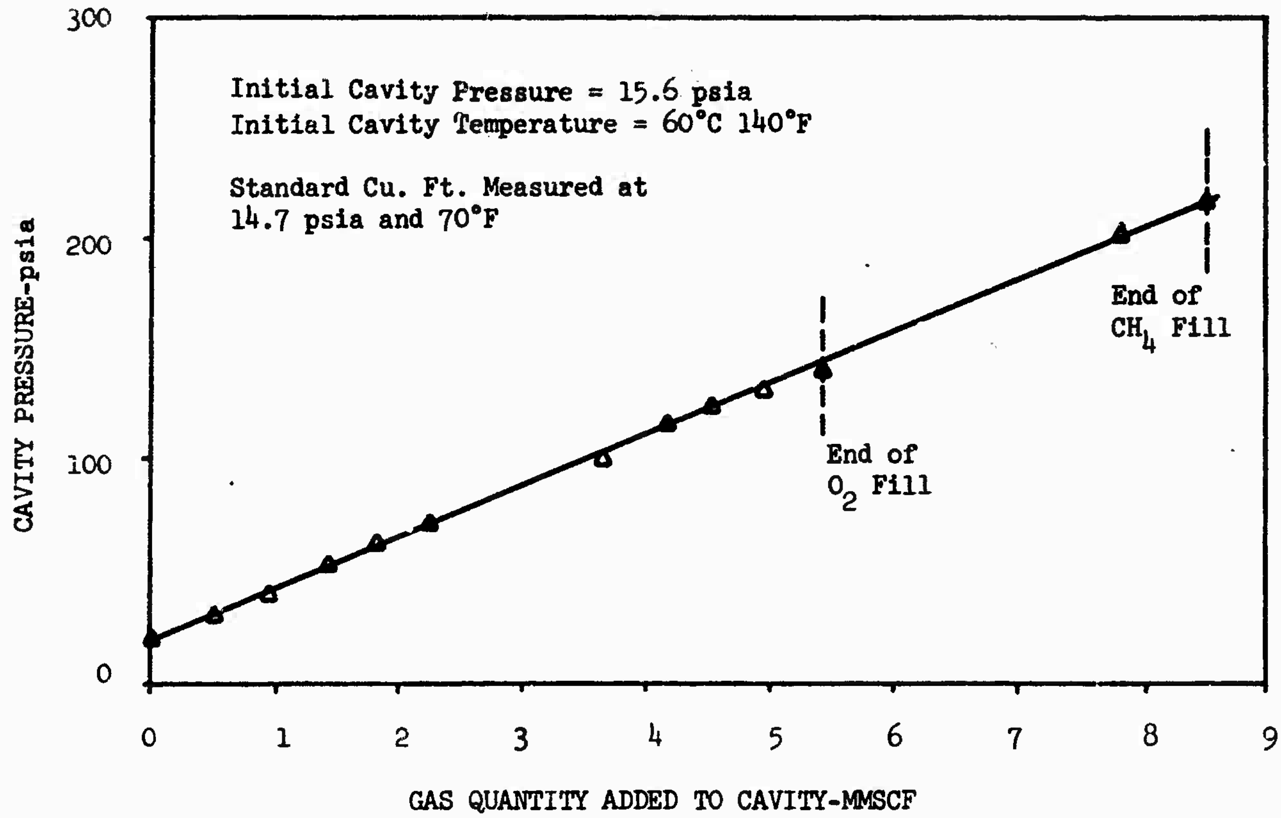

Figure A-5. CAVITY PRESSURE HISTORY

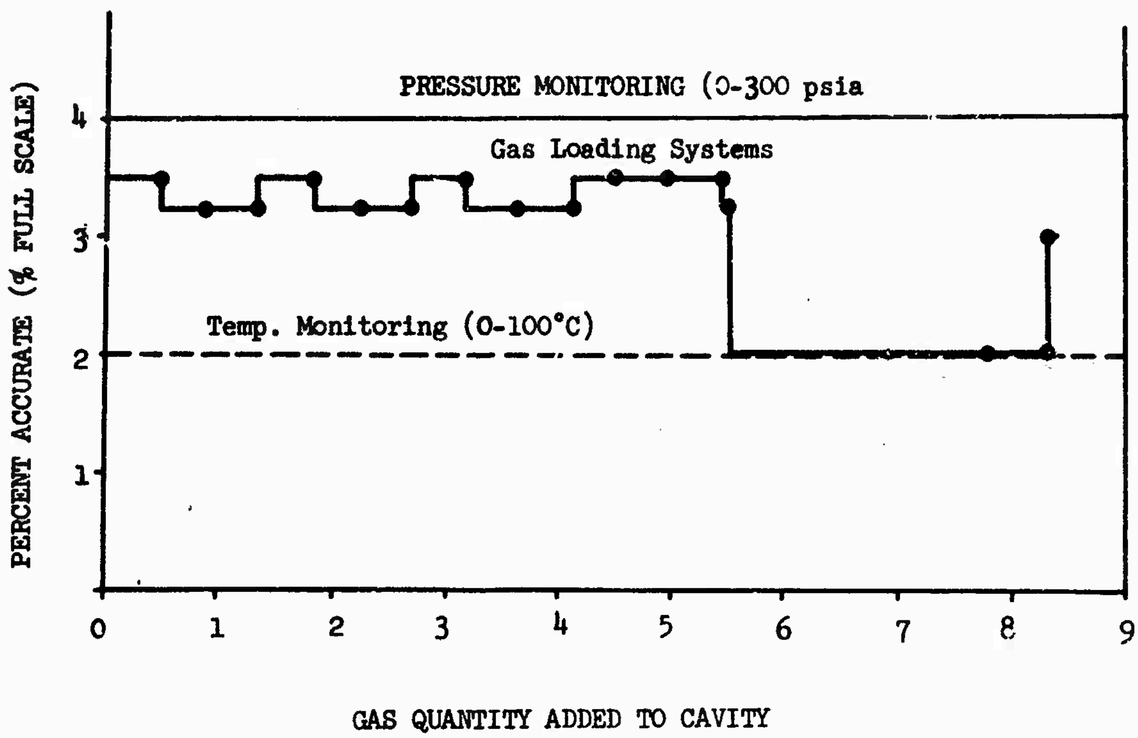

Figure A-6. LOADING SYSTEM ACCURACY

The bottom line, which shows the accuracy of the temperature monitoring system, includes the accuracy of the thermocouple amplifier and the thermocouple calibration. Accuracy is better than 2 percent of full scale.

Figure A-7 shows the improvement in the solution to the cavity volume as gas fill proceeds. The data appears to finally oscillate about a volume of 660,000 feet.

Formula used to calculate cavity volume is derived from the perfect gas law. Cavity volume calculations were made following the unloading of each tanker of oxygen and at two selected times during natural gas fill.

In the absence of diagnostic information on the detonation, it is necessary to rely on data obtained during gas filling and some deductions using previous experience to ascertain that a detonation of the predicted yield actually occurred.

It has been verified that 5.6×10^6 SCF of oxygen and 2.84×10^6 SCF (standard condition, 70 deg. F and 14.7 psia) were added to the cavity. This is an oxygen-to-fuel ratio of 1.97 (by volume). The amount of oxygen initially in the cavity prior to gas loading (about 0.13×10^6 SCF) does not significantly alter this ratio.

It has been reported in the literature [5,6] that detonation will occur for 1.5 O_2/CH_4 3.0. GARD experimental evidence shows a slightly broader range for detonation: 1.25 O_2/CH_4 3.5. It should be noted that the flammability limits are considerably broader. The stated mixture ratio does, however, insure a detonation once ignition has been established in the gas mixture.

The detonability limits for methane and oxygen mixtures are 1.25 O_2/CH_4 3.5 and the flammability limits are 0.65 O_2/CH_4 18. Using the filling rates for O_2 as 150,000 SCF/Hr and for methane as 130,000 SCF/Hr, and using the total volumes of O_2 and CH_4 to be added as 5.6×10^6 SCF and 2.84×10^6 SCF, we find that it takes 12.3 hrs of methane fill to reach detonability limits, if all the oxygen is added first. The flammability limit of the mixture is reached after 2.3 hours of methane fill.

It is possible that some water vapor was present in the cavity prior to detonation. Since the saturation pressure for water vapor is only 2.2 psia at 138 deg. F (the equilibrium temperature of the gas mixture prior to detonation), the detonable mixture could only contain less than one percent (by volume) water vapor. This amount could have only a negligible effect on the detonation.[4]

Because the oxygen and methane were delivered to the cavity separately, the quality of the resultant mixture must be considered. The gas velocity entering the cavity was about 72 fps (calculated from delivery rate). This results in Reynold's numbers greater than 275,000 for oxygen and 140,000 for methane. The probability of turbulent mixing is therefore high. Experience during DISTANT PLAIN with the 20-ton hemisphere explosion indicated no

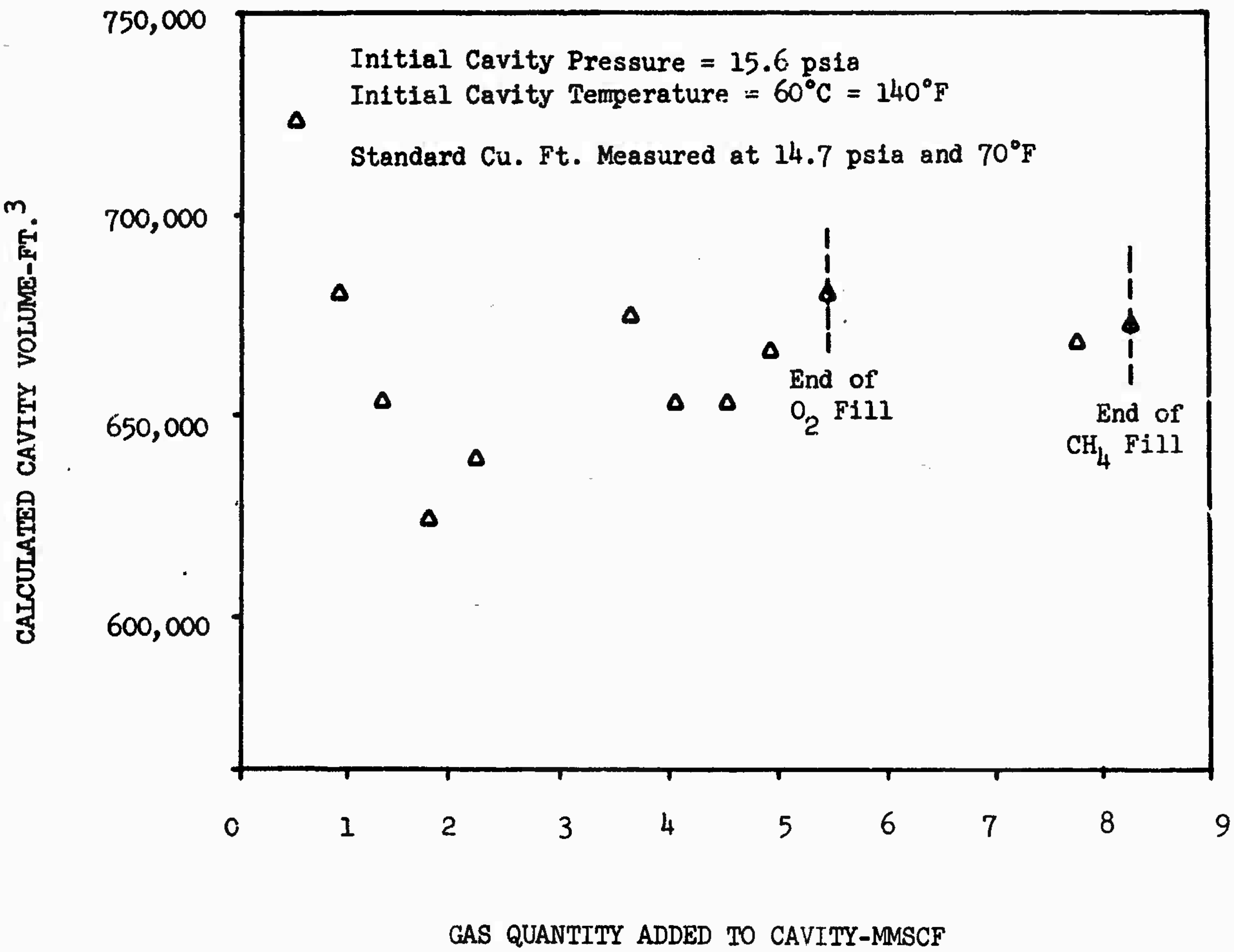

Figure A-7. CALCULATED CAVITY VOLUME

difficulty with gas mixing. In that experiment, oxygen was also loaded first and the fuel (propane) last. The loading rates were lower and the hold between fill completion and detonation was only about one hour. Data from that experiment confirms that the predicted yield was obtained. Extrapolation of that experience to DIODE TUBE gives good evidence to expect that proper mixing took place. Once mixing is complete, the possibility of stratification due to gravity is low.

The process of mixing of the methane-oxygen, besides being time dependent in this case, involves molecular diffusion, thermal diffusion, and turbulent flow. A complete analysis of the turbulent mixing was done at a later time and is presented in Appendix F.

Because the methane and oxygen were loaded into the cavity as separate units, the concentrations of the component gases initially would vary widely over the cavity. This state gives rise to the molecular diffusion process wherein mass transport results from a difference in a chemical potential in the mixture. The diffusion coefficient,[7] the proportionality constant between the diffusion flux and the gradient of the potential causing diffusion, in a binary gas system can be estimated by

$$D_{12} = \frac{0.001858\, T^{3/2} \quad (M_1 + M_2) / M_1 M_2 \quad ^{1/2}}{P \quad {}_{12}^{2} \quad {}_{D}}$$

for equimolar mixtures. There T is the absolute temperature (°K), M and M_2 are the molecular weights of the component gases, P is the absolute pressure in atmospheres and $_{12}$ is the molecular force constant while is the collision integral. These last two quantities are given in tables by Reid and Sherwood. The above expression, valid up to about 20 atmospheres pressure, shows that the diffusion rate is inversely proportional to the pressure.

The diffusion coefficient for the methane-oxygen mixture at 5 atmospheres initial pressure, is sufficiently low, if the gases are completely separated, to preclude significant mixing by molecular diffusion in a weeks time.

In addition to the molecular diffusion process, the method of gas loading provided another mixing mechanism. The flow energy possessed by the incoming methane is sufficient to allow the methane to penetrate a significant distance into the cavity. For a flow rate of about 130,000 cubic feet per hour through a 6-inch diameter pipe, the jet formed by the incoming methane reaches a diameter of about 25 feet (about 25 percent of the cavity diameter) at the cavity midpoint. The induced flow at this position is calculated to be about 3 million cubic feet per hour.[9]

Thirdly, the inlet temperature of the gases was on the order of 60° F, about 80°F less than the cavity wall temperature. Because of the large surface area involved, thermal gradients may play a significant role in mixing.

The absence of a completely homogeneous mixture throughout the cavity may not seriously impede the detonation process. The quantities of methane and oxygen injected into the cavity yield an oxygen-to-methane mole ratio of slightly under 2.0. A variation of this ratio from 1.5 to 2.5 causes a corresponding three percent variation in the energy releases and a five percent variation in the detonation pressure. Detonation will occur at 15 atmospheres initial pressure for mixtures within these composition limits.

From the analysis of turbulent mixing presented in Appendix F, it is concluded that turbulent mixing is the dominant mechanism. Incomplete mixing is noted when oxygen is added first and methane second, while almost complete mixing is obtained when the loading sequence is reversed. In the former case, which was the procedure used in the DIODE TUBE approximately one-third of the mixture is within the detonable limits, with a layer of pure methane on top and a layer of pure oxygen on the bottom.

The reaction rate of oxygen and methane at 130 deg. F and 215 psia is so low[4] that no measurable reaction could take place within one week (the time between termination of gas loading and detonation).

When the DIODE TUBE cavity was re-entered, the pressure in the cavity was approximately 161 psia (Lt. Col. Davis, Personal Communication, Lt. Col. Reign, Personal Communication). The residual gas mixture in the hole was removed at a rate of 300 scm and processed through a filtering plant where the gas mixture is analyzed. A typical analysis of the gas composition was 78% CO_2, 0.5% CO, 4% O_2, the percentages by volume. Water, in the liquid form, was being removed from the cavity at a rate of 40 gal/hr. The variation of the gas mixture ratios was CO: 77% - 80%, CO: 0.4% - 0.8%, O: 2.4% - 4.8%. The pressure at the wellhead was 58 psia and the temperature of the gas mixture was 54°C = 317°K. The temperature in the cavity is slightly higher than 54°C. No initial re-entry temperature data was taken.

The composition of the analyzed residual gas mixture is quite different from the burnt gas mixture anticipated at the detonation front. A short analysis of the anticipated gas mixture follows. The initial mixture is air, methane and oxygen, including one volume of air at one atmosphere pressure and a sufficient volume of methane and oxygen to bring the total mixture pressure to 15.8 atmospheres (for a cavity volume - 650,000 cu. ft.). The initial temperature of the gas mixture was taken to be 330°K = 60°C, which is the ambient temperature of the cavity. The molar methane-to-oxygen ratio of the total mixture was 0.508 and the mole fraction of air was 0.0765. When this mixture was detonated the detonation pressure was calculated to be 6520 psi (= 44 atm) the detonation temperature being 4270°K. This pressure and temperature combination occur at the detonation front. The thermochemical analysis assumes that the burnt gas mixture is in equilibrium behind the detonation fromt. Table A-3 gives the composition of the mixture at the detonation conditions.

TABLE A-3

EQUILIBRIUM COMPOSITION OF BURNT GAS AT p = 444 atm, T = 4270°K

	Mole Fraction		Mole Fraction
H_2	0.0709	O_2	0.0628
N_2	0.0414	OH	0.1096
CO_2	0.1009	NO	0.0179
CO	0.1581	H	0.0315
H_2O	0.3767	O	0.0302
CH_4	0.000		1.0000

When the detonation wave and its subsequent reflected shocks have died down, but before any heat has been conducted away from the cavity, the pressure of the burnt gas mixture is approximately 0.42 P_D = (0.42) x (6520) psi = 2750 psi (= 187 atm). If the mixture composition is frozen at that of the detonation composition, the temperature in the gas mixture can be estimated by the perfect gas law. In 1 cubic foot there are 0.0433 lb-moles of high temperature detonation products. Thus

$$T_E = \frac{P_E V}{NR} = \frac{(2740(\text{psi}) \times (1\ \text{ft}^3))\ 5/9\ {}^{\circ}\text{K}/{}^{\circ}\text{R}}{(0.043\ \text{Moles}) \times (10.73\ \text{psi-ft}^3/{}^{\circ}\text{R-lb Mole})} = 3280^{\circ}\text{K}$$

This temperature is somewhat lower than the detonation temperature, but well above the ambient. The temperature in the cavity is reduced to ambient temperature in less than 48 hrs, if the initial temperature in the cavity is of the order of 4000°K. Since the DIODE TUBE cavity had much longer to cool before re-entry took place, we may assume that the temperature of the cavity was reduced to ambient conditions, i.e., the final temperature of the gas mixture should be about 60°C.

Two significant changes in the gas mixture will occur if the temperature is dropped from 4270°K to 340°K. First, the composition of the equilibrium mixture will change drastically as the temperature is lowered. Second, any water vapor present will condense. Let us examine the first change. The equilibrium reactions affected most by the drop in temperature from 4270° to, say, 373°K are

	2H	H_2O
	2O	O_2
	OH + 1/2 H_2	H_2O
	CO + 1/2 O_2	CO_2
also	NO	1/2 N_2 + 1/2 O_2

At T = 4270°K the equilibrium composition favors the left hand side of these reactions. For temperatures below 2500°K the equilibrium strongly favors the right hand side. For low temperatures then all the atomic H, O and OH disappear, as does the CO, if sufficient oxygen is available. Thus for the indicated composition at 4270°K, the equilibrium composition at T = 373°K is approximately given in Table A-4. The approximate composition is computed by eliminating O, H, NO, and OH from the composition and replacing them by their respective products. One mole of mixture at 4270°K becomes 0.79 mole at 373°K.

TABLE A-4

APPROXIMATE EQUILIBRIUM COMPOSITION AT T=373°K

	Mole/Mole at 4270°K	Mole Fraction
H_2	0.016	0.020
N_2	0.050	0.063
CO_2	0.269	0.342
CO	0.000	0.000
H_2O	0.447	0.566
CH_4	0.000	0.000
O_2	0.007	0.009
OH	0.000	0.000
NO	0.000	0.000
O	0.000	0.000
	0.789 moles/mole	1.000

The pressure of the gas mixture has dropped due to constant volume cooling and due to the change in the number of moles present. From the perfect gas law at T = 3280°K

$$P_E = \frac{1 \text{ mole } (3280^\circ K)\ R\ (\text{psi-ft}^3/\text{mole}^\circ K)}{Vn\ (ft^3)} = 2740 \text{ psi}$$

Vn = Volume of 1 mole.

Now 373°K is the boiling point of H_2O at a total pressure of 1 atm. At total pressure of the order of 17 atm, the boiling point is 210°C. The partial pressure of the resultant gas taken from T = 4270°K or T = 333°K is independent of the boiling point of the water. More precision about noting where the water vapor condensed could be made but it would have made no difference in the final pressure calculated. For calculation purposes then, it is assumed that the water vapor condenses at 373°K.

The pressure, $\bar{P}_{373}$, of the gas mixture at T = 373°K is calculated similarly to the pressure at T = 3280°K.

$$\bar{P}_{373} = \frac{(0.79 \text{ mole})\ (373^\circ K)\ R\ (\text{psi-ft}^3/\text{mole }^\circ K)}{Vn\ (\text{ft}^3)}$$

From the two previous relations

$$\bar{P}_{373} = \frac{(373)\ (0.79)\ (2740)}{(3280)} \text{ psi} = 246 \text{ psi}$$

At T 373°K, the water vapor will condense, and with the assumption that the liquid volume is negligible, the gas pressure will be further reduced, since 56.4% of the gas mixture is water vapor

$$\bar{P}_{373} = 246 \times .436 + \text{vapor pressure of } H_2O$$

$$= 117 \text{ psi} + P_{H_2O} = (117 + 15) \text{ psi} = 132 \text{ psi}$$

Further cooling to 60°C = 333°K yields final gas pressure 105 psi. The vapor pressure is 3 psi thus

$$P_F = 108 \text{ psi}$$

The residual gas mixture is 4.6% H_2, 14.5% N_2, 78° 8% CO_2, and 2.1% O_2. A more precise computation of the mixture would possibly yield small amounts of CO.

The total process of the detonation and cooling that we have considered is:

Initial reagents (P_o, T_o, n_o) Detonation →

Products behind detonation front (P_D, T_D, n_D) Expansion to Equilibrium →

Detonation products (P_E = .42 P, T_E, n_D) Cooling at constant volume by conduction of heat →

Detonation products (P_{373}, 373°K, n_D) Reverse reaction →

Final products including water (P_{373}, 373°K, n_F) Cooling →

Final state (P_E, 333°K, n_F)

A final pressure of 108 psi at T = 60° was computed compared with 161 psi measured. If T = 100°C the computed pressure is 132 psi. The neglected heats should raise the calculated pressures slightly. If the computation is valid, this indicates that no gas has been lost from the cavity by leakage. The predicted compositions of the outflowing gas agree very well.

Certain aspects of explosions in spherical cavities and their relationships to the propagation of elastic waves in the surrounding medium were reviewed. First, the blast source was characterized by the several parameters that would influence elastic wave propagation. Second, a review of the spherically symmetric elastic wave solution comparing a step load and a nuclear explosion illustrated typical qualitative differences in waveforms that might be expected. Third, a brief comparison of waveforms between symmetric and asymmetric detonation initiation demonstrated the qualitative difference that would be expected.

The seismic records expected from this type of loading are expected to be quite sensitive to the choice of the matched parameters. When the difference between the equilibrium and initial pressure is matched, the final displacement should agree closely. Also, the lower frequency components of the motion should show agreement. By low frequency components, it is meant those Fourier components with wave lengths long compared to the cavity radius. For this chosen matching, the peak reflected pressure due to the nuclear blast is larger than that expected for the gas detonation; the peak nuclear pressure is a function of the initial air density in the cavity. STERLING Event peak pressure expected was approximately three times that expected in the DIODE TUBE Event. The mean period between successive reflections for the nuclear shot considered here is roughly 2/5 that of the gas detonation. The transient early phases of the motion and the oscillatory part of the wave (which has a high frequency by the previous standard) determine the high frequency components. These high frequency components are normally noticed in the early phases of the wave train that would be observed at some point in the elastic medium.

This point is illustrated by a computation of Patterson [2] wherein the elastic motion at the wall of a spherical cavity in response to a nuclear pressure pulse was compared to the response generated by a step pulse with the same equilibrium pressure. (See Figure A-8.) The presence of the transient spike and subsequent pressure oscillations induces high frequency components superimposed on the response to the step pulse. For very small times after the signal arrival, the spike response is large compared to the step response. At times larger than the initial spike decay time, the step response is dominant, although a small oscillatory component remains.

The firing circuits downhole also failed prior to ignition, presumably due to the cavity environment. The detonation was effected by imposing a high voltage across the detonator circuit leads, after about one minute of application of about 2000 volts, detonation occurred. This voltage induced current flow somewhere in the cavity. The two most probable locations for this detonation point are at the original detonator or at the instrumentation package near the top of the cavity.

PEAK PRESSURE (SPIKE) DETERMINES

PEAK ACCELERATION
HIGH FREQUENCY COMPONENTS

EQUILIBIRUM PRESSURE DETERMINES

FINAL DISPLACEMENTS
LOW FREQUENCY COMPONENTS

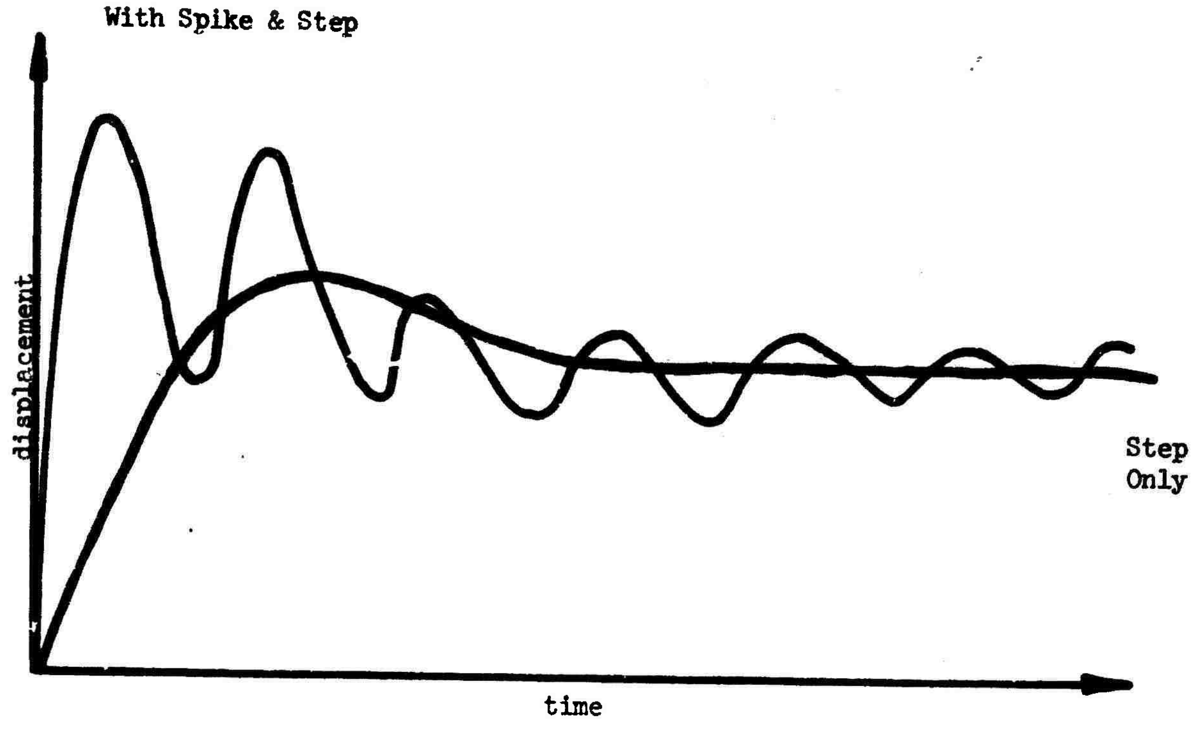

Figure A-8. SCHEMATIC RESPONSE TO CAVITY PRESSURE

Possible variations of positioning of the detonator in the spherical cavity leads to possible variations of the seismic source. Two cases, first, the normal position of the detonator being at the center of the cavity and second, the detonator being at the edge of the cavity directly over the center are considered. Qualitatively examining the types of load distributions obtained on the cavity wall and for the specific gas and cavity materials, some comments on the nature of the seismic phenomenon inititated can be made.

Spherically symmetric placing of the detonator generates one elastic wave, and a P wave which propagates symmetrically. The magnitude of the peak driving pressure is 2.6 P_D. A symmetric detonation, typified by detonation at the top, yields both P and S waves. The strength of the peak pressure at the cavity wall is, in general, significantly lower than those expected in the spherical case.

First, let us examine the spherical detonation case. After initiation, a spherical wave of constant velocity and strength propagates outward. When this detonation wave reflects from the wall, a converging shock wave is initiated. This imploding shock wave converges on a point, interacts with itself and continues as a diverging shock wave until it again strikes the exterior wall, where upon another convergent shock wave is generated. The pressure profile at any point is a repetition of a spike decay. The pressure on the first spike is roughly 2.6 times the detonation pressure, subsequent spikes are smaller by a factor of 2 and the mean pressure is on the order of 0.42 times the detonation pressure. (See Figure A-9.) This pressure generates one spherical elastic wave of the primary type (P-wave).

Now consider the detonator positioned at the top of the cavity. The detonation wave again propagates spherically and at constant strength and velocity. Figure A-10 shows several steps in the evolution of the detonation front and of the generated elastic waves. To determine the nature of the emitted elastic waves, the phase velocity of the detonation front of the cavity wall and its peak pressure is estimated. The trace velocity along the cavity wall is

$$V = \frac{D}{\theta/2}$$

. where θ is the latitude measured from the top. The instantaneous angle of incidence (on a regular reflection and small amplitude of reflection assumption, i.e., no Mach stem type reflection) is

$$\frac{\pi}{2} - \frac{\theta}{2}$$

The angle of incidence increases as the detonation grows. For angles of incidence less than 60°, the peak reflected pressure is almost the same as the incident pressure which, in this instance is the detonation pressure.

As the detonation wave progresses from its initiation point, a number of elastic waves are generated in the surrounding medium. A P wave is sent

CENTER IGNITION

SPHERICALLY SYMMETRIC WAVEFORM

P WAVE ONLY

SOURCE PRESSURE PEAK = 2.6 P_D

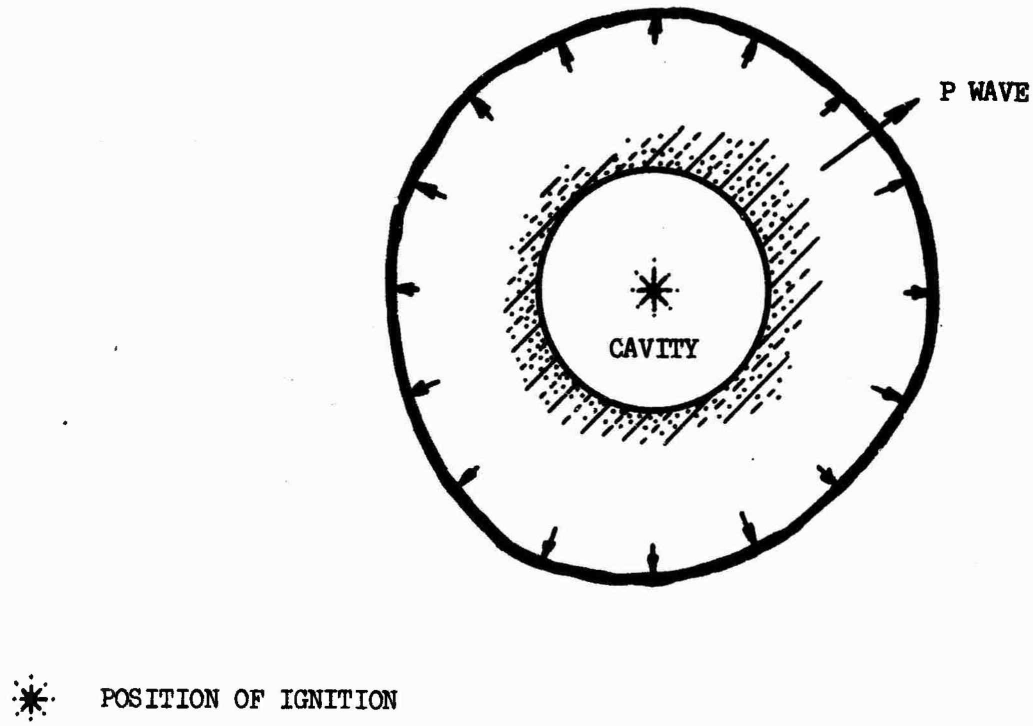

Figure A-9. ELASTIC WAVE PATTERN RADIATED AFTER CENTRAL IGNITION

ASYMMETRIC WAVE FORMS BOTH P & S WAVES

P WAVES PROPAGATE VERTICALLY

S WAVES PROPAGATE LATERALLY

SOURCE PRESSURE PEAK

P_D IN TOP 2/3 OF CAVITY

2.6 P_D IN BOTTOM 1/3 OF CAVITY

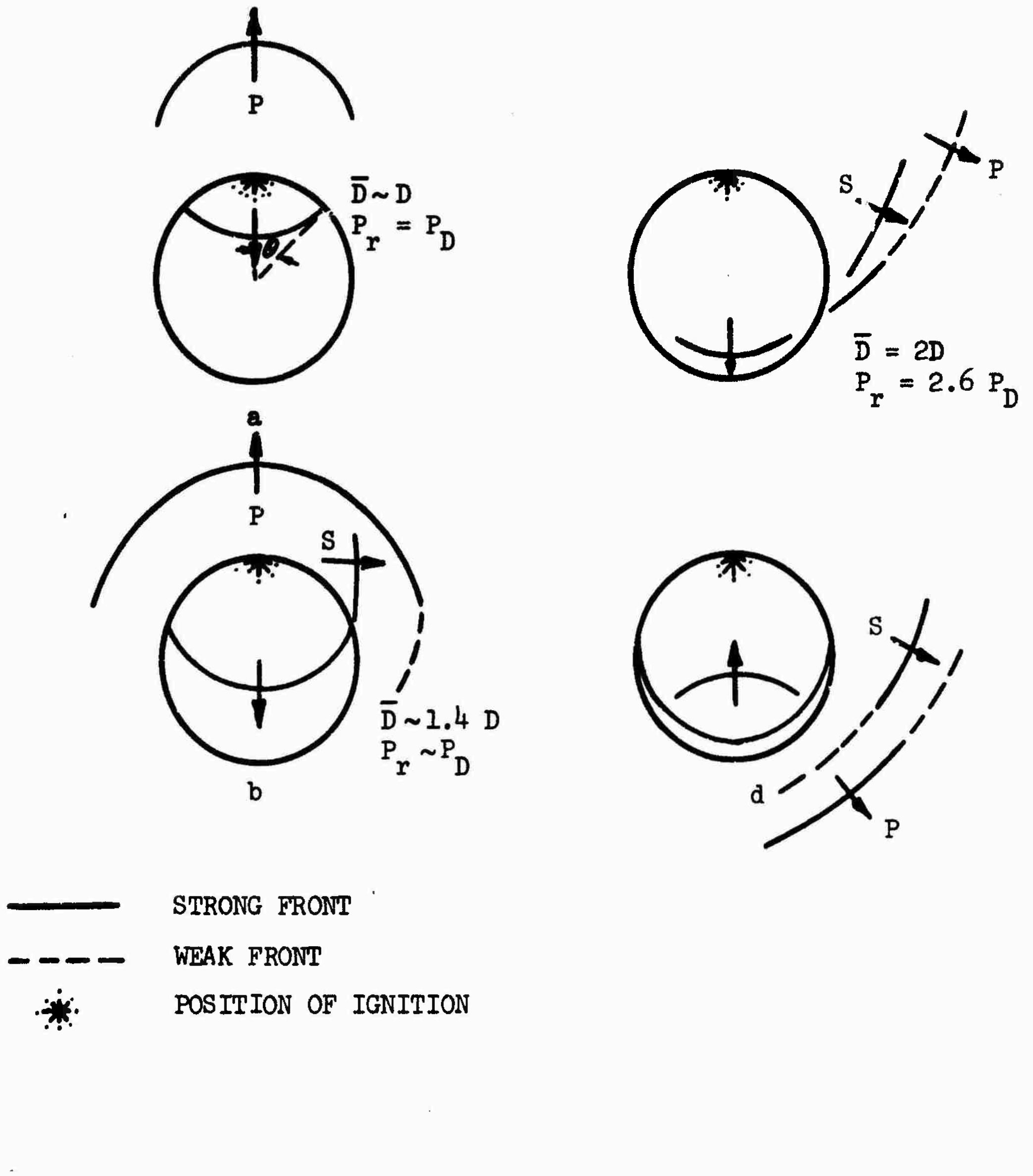

Figure A-10. GENERATION OF ELASTIC WAVE PATTERN RADIATED AFTER TOP-CENTER IGNITION upwards. As the detonation sweeps over the cavity in the range $0^\circ \leq \theta \leq 180^\circ$ the trace velocity is transseismic, since $D \approx 8250$ fps, C_p for salt is 14300 fps and $C_s \approx 8400$ fps. The cavity pressure becomes superseismic at $\theta \approx 110^\circ$. For the transseismic conditions an appreciable percentage of seismic energy is generated as a shear wave with a very sharp front. The P wave in the shadow zone from the detonating points is rather weak. In this region of maximum shear generation, the pressure at the wall is nearly the detonation pressure. As the detonation wave progresses further, the trace velocity becomes superseismic (for $\theta > 110^\circ$) and the pressure at the wall becomes larger as reflection conditions approach normal reflection. The interface velocity now favors the generation of P waves, and since the source pressure is increased, the conclusion is that significantly larger P waves are propagated away in the vertical direction.

We thus see that detonation at the top of the cavity leads to the redistribution of propagated seismic waves, both in direction and in character.

Conclusions From the DIODE TUBE Event.

Source data at ignition time is lacking for the DIODE TUBE event due to failure of the ignition system. From pre-shot and post-shot data, the following conclusions are warranted: (1) the correct portions and amounts of methand and oxygen were added to the cavity, (2) no appreciable amount of gas leaked from the cavity, (3) a combustion, detonation or a combination of detonation and compustion occurred, using up the entire initial contents of the cavity. Two possible sources of the measured lower seismic yield are (1) an off-center ignition point and (2) incomplete mixing.

From these latter two points, modifications in the ignition system to ensure center detonation and in the gas loading sequence to ensure complete mixing were recommended for the HUMID WATER event.

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APPENDIX B

GAS CALCULATIONS

EVENT HUMID WATER

APPENDIX B

HUMID WATER - GAS CALCULATIONS

B-1 Explosive Yield Predictions

Following is an explosive yield prediction for the HUMID WATER Event based on the final cavity conditions after filling with methane and oxygen.

Initial Conditions - The initial pressure measured at the wellhead prior to gas loading was 14.5 psia. This converts to a cavity pressure of 15.9 psia by compensating for a 2700-foot gravity head. (See paragraph B-2.) The initial cavity temperature was measured at 61°C.

It is assumed that prior to oxygen purge, the cavity contained a 20%-oxygen and 80%-nitrogen air mixture at cavity pressure and temperature. After purging with 139,000 SCF of oxygen, the cavity atmosphere contained 216,997 SCF oxygen (34.5%) and 412,546 SCF nitrogen (65.5%).

The following amounts of gases were in the cavity following the filling operation:

initial "air"	=	629,543 SCF
nitrogen purge	=	75,000 SCF
added oxygen	=	2,965,000 SCF
methane	=	4,561,000 SCF
Total Volume	=	8,230,543 SCF

Except for the initial "air" volume (which is calculated based on initial cavity pressure and temperature), these are metered volumes.

It is assumed that at ignition time, the temperature of this gas mixture was 61°C (the initial cavity temperature). Based on this temperature and the total gas volume, the cavity pressure is calculated to be 208 psia (14.15 atm).

The mole ratio of oxygen to methane (based on total oxygen in the cavity) is calculated to be 1.613. Initial gas weight is 277.5 tons.

Thermochemical Analysis - Computer results for these initial conditions are shown in Table B-1. The equilibrium pressure minus the initial pressure is 160 bars. The yield is calculated to be 317.5 tons (TNT energy equivalent). Peak reflected pressure is 15,500 psia and the equilibrium pressure is 2525 psia.

Table B-1. THERMOCHEMICAL ANALYSIS FOR THE DETONATION OF OPERATION MIRACLE PLAY - HUMID WATER

208 psia, 61°C

Lbs. PETN/cu. ft.	= 0.0000	No. of carbon atoms in fuel gas	= 1.0
Lbs. Poly Sleeve/lb. PETN	= 0.0000	No. of hydrogen atoms in fuel gas	= 4.0
Moles fuel gas/mole oxygen	= 0.6200	No. of oxygen atoms in fuel gas	= 0.0
Mole fraction of air	= 0.0626	Heat of formation of fuel gas	= -17.88
Moles H_2 gas/mole oxygen	= 0.0000	Initial pressure of gas	= 14.150

Detonation Pressure, psi	= 6016.79	Total lb-moles of products	= 0.4098374E-01
Detonation temperature, °K	= 4241.32	Apparent mol.wt. of products	= 0.2051148E 02
Detonation velocity, fps	= 8508.26	Specific heat ratio of products	= 1.218725
Particle velocity of products, fps	= 3760.80	Gas constant of products, btu/lb/deg.	= 0.9681794E-01
Sonic velocity of products, fps	= 4747.46	Total weight of products, lbs	= 0.8406375E 00

B-2 Wellhead Pressure Correction for Cavity Pressure

Equilibrium equation for gas column: where p = pressure,

z = vertical height (ft.)

$$\frac{dp}{dz} = -\rho \qquad \rho = \frac{m}{ft^3}$$

Assume:

1) perfect gas law
2) uniform temperature
3) uniform moisture in column

$$p = \rho \frac{R_o}{M} T = \rho RT \qquad R = \frac{R_o}{M}$$

$$\frac{dp}{dz} = -\frac{p}{RT}$$

where: R_o = gas constant

M = molecular weight

T = degrees Rankine

Integration from center of cavity to wellhead:

$$p_{cav} = p_{wh} \quad \exp\left(\frac{h}{RT}\right)$$

Consider 3 cases:

1) Column contains air at 140°F $(.20\ O_2 + .80\ N_2)$

$$M = .2 \times 32 + .8 \times 28$$

$$= 28.8$$

$$R = \frac{1545}{28.8} = 53.7$$

$$p_{cav} = p_{wh} \quad \exp\left(\frac{2700}{53.7 \times 600}\right)$$

$$p_{cav} = 1.088\ p_{wh}$$

2) Column contains methane at 70°F

$$M = 16.$$

$$R = \frac{1545}{16} = 96.5$$

$$p_{cav} = p_{wh} \exp\left(\frac{2700}{96.5 \times 530}\right)$$

$$p_{cav} = 1.055\ p_{wh}$$

3) Column contains O_2 at 50°F

$$M = 32$$

$$R = \frac{1545}{32} = 48.3$$

$$p_{cav} = p_{wh} \exp\left(\frac{2700}{48.30 \times 510}\right)$$

$$p_{cav} = 1.116\ p_{wh}$$

APPENDIX C

CAVITY DESCRIPTION

APPENDIX C

CAVITY DESCRIPTION

C-1 General

Figure C-1 shows the general representation of the cavity and environs. The cavity walls are 90-93% Sodium Chloride, with Calcium Sulfate the principal impurity.* The cavity volume is about 660,000 cubic feet, as determined by GARD, and slightly pear shaped by melt and debris dropped from the top to partly fill the bottom (see Appendix A). A "chimney" about the area where the casing enters the cavity has been left by previous explosions. The cavity major diameter is approximately 110 feet with the center located near 2700 feet from the surface.

C-2 Chemical Analysis of Wellhead Water Samples

Two samples of water received from Isotopes, Inc., a Teledyne Company, were analyzed for chloride, sulfate, and nitrate ions on January 5, 1970. The results were:

a. Sample labeled "wellhead, 1700 hrs, 2-24-69, Process H_2O":

Chloride (Cl^-)		6.5 g/l
Sulfate ($SO_4^{=}$)		3.8 g/l
Nitrate (NO_3^-)		none
pH (acidity)	=	2.6

b. Sample labeled "1300 hrs, 2-24-69, #1 Waste Tank":

Chloride (Cl^-)		48.6 g/l
Sulfate ($SO_4^{=}$)		5.0 g/l
Nitrate (NO_3^-)		none
pH (acidity)	=	3.9

These samples, although quite different because they were taken before and after the processing plant, indicate a highly corrosive atmosphere within the cavity.

Significant quantities of water have been added to the cavity by various methods, including the residuals from the DIODE TUBE detonation, resulting in a great deal more moisture than previously reported.[5] Small quantities of water have been added by milling operations during the DIODE TUBE re-entry and perhaps small leaks in the wellhead casing permitting entry of ground water.

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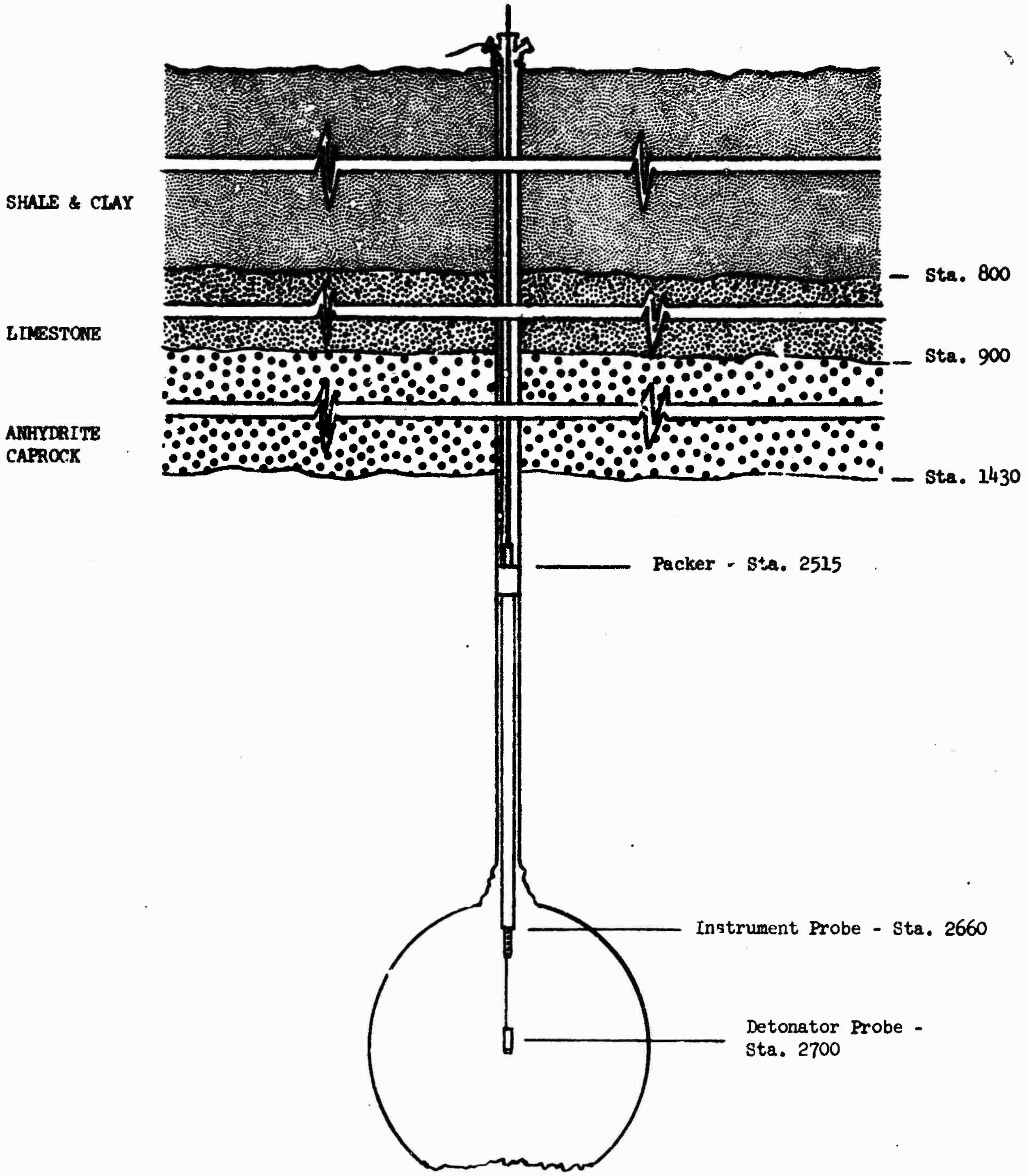
* Werth, G. and P. Randolph, "The SALMON Seismic Experiment," Journal of Geophysics Research, Vol. 71, 1966, page 3406.



SALMON CAVITY - TATUM SALT DOME

Figure C-1

C-3 Temperature Log of the Cavity

Figures C-2a through C-2n show the observed temperatures from the original log of the cavity and casing as observed via thermocouples affixed to a centralizing fixture lowered slowly through the casing into the cavity. Significant convection occurs within the cavity in its natural state. Television logs have shown that gases rise up the casing where they are cooled, condensed, and return back into the cavity. These convection currents probably bias the temperature log down, at least within the cavity. It is also probable that the motion of the thermocouple results in measurement of transient temperatures rather than steady state. This is particularly evident in the slowly rising temperature after the probe is stopped in Figures C-2m and C-2n.

After emplacement of the instrumentation string, thus largely inhibiting the natural convection, a stabilization temperature was observed of about 72°C near the top of the cavity. This compares to the 61°C apparent stabilization temperature observed during the temperature logging. A 12 hour observation of the temperature decay after the detonation indicates that cavity temperatures again appear to converge, while cooling, upon the higher temperature (72°C - see Section 5).

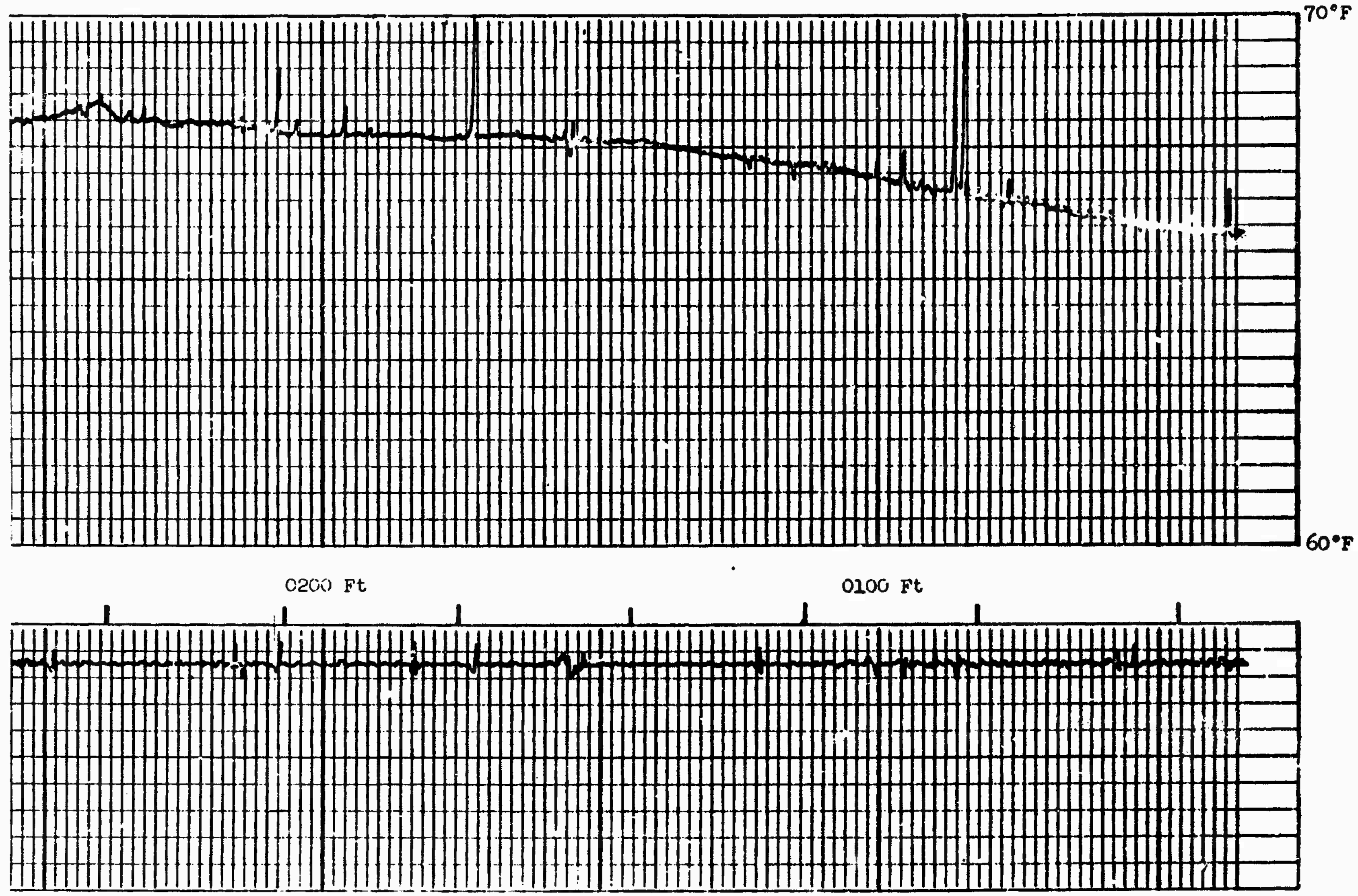


Figure C-2a. TEMPERATURE LOG

Figure C-2b.

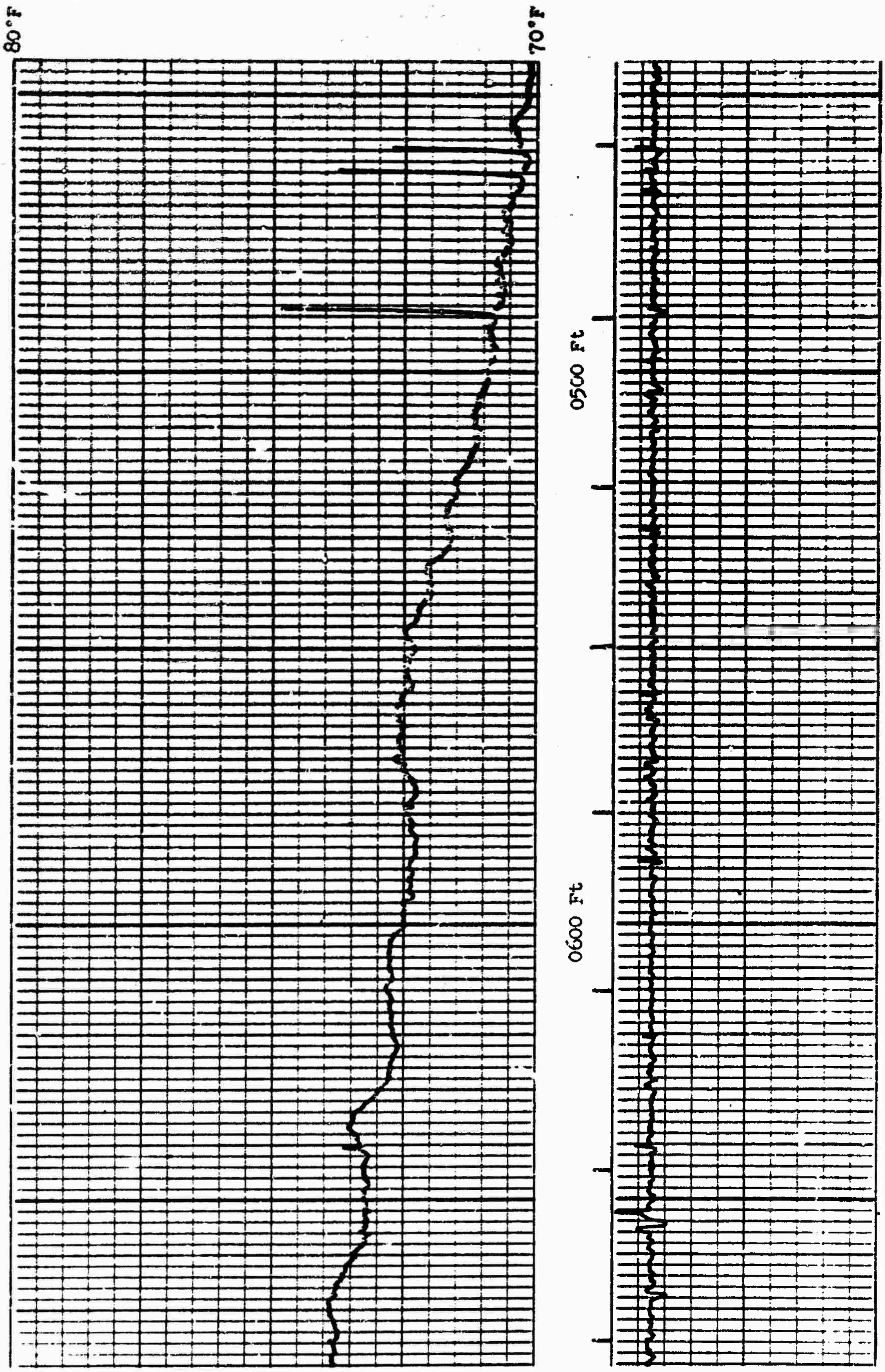


Figure C-2c.

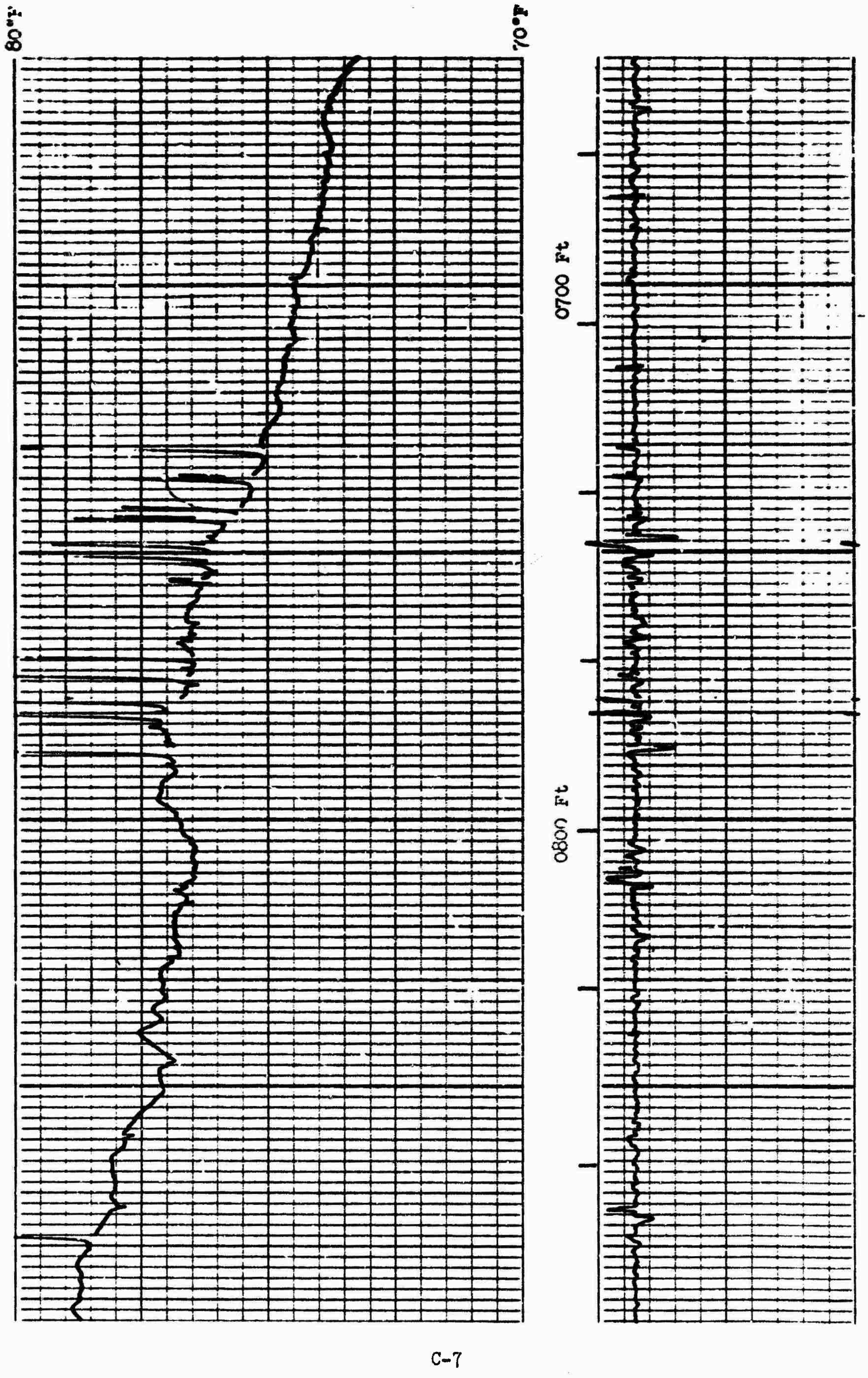


Figure C-2d.

Figure C-2e.

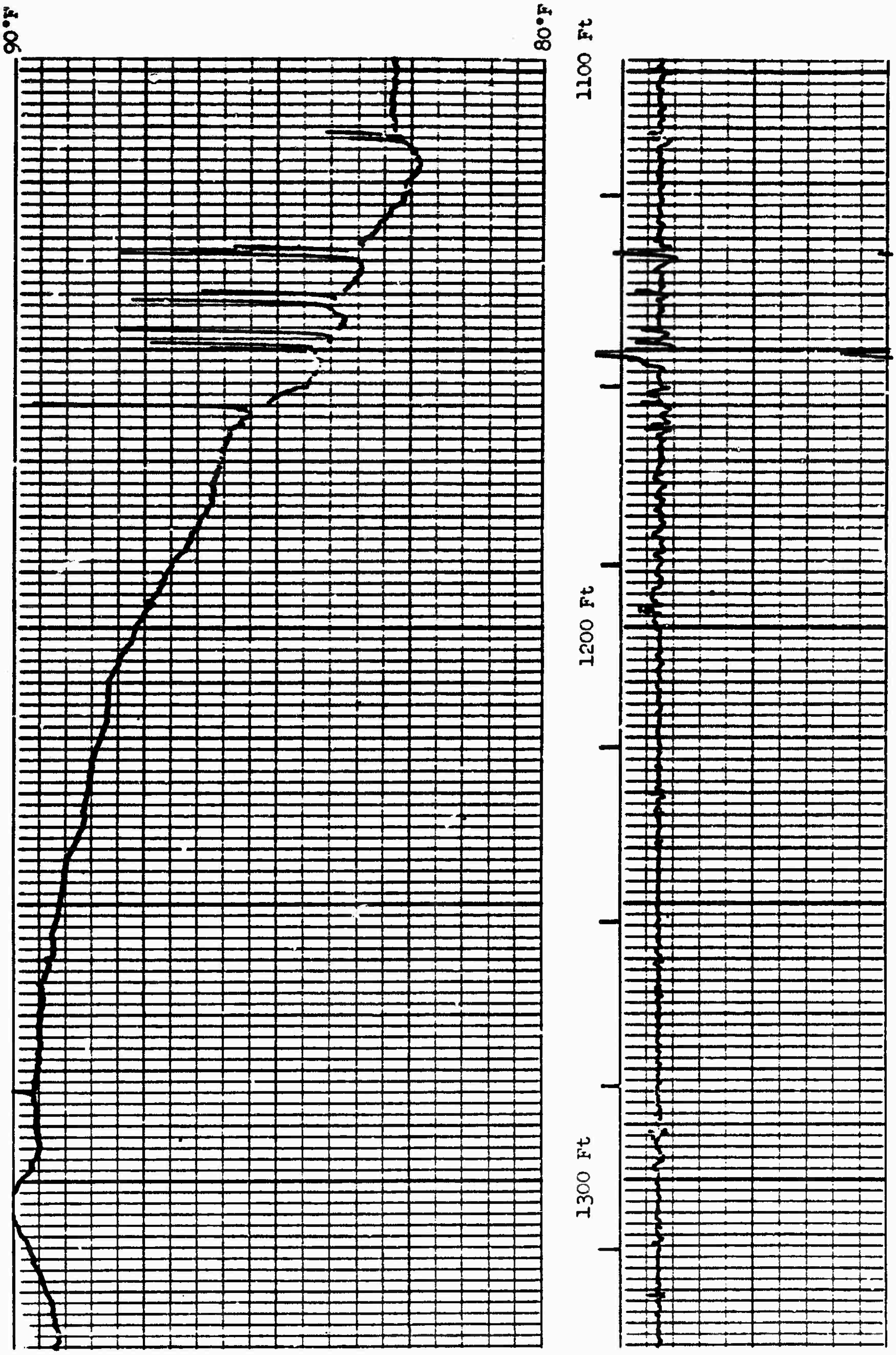


Figure C-2f.

Figure C-2g.

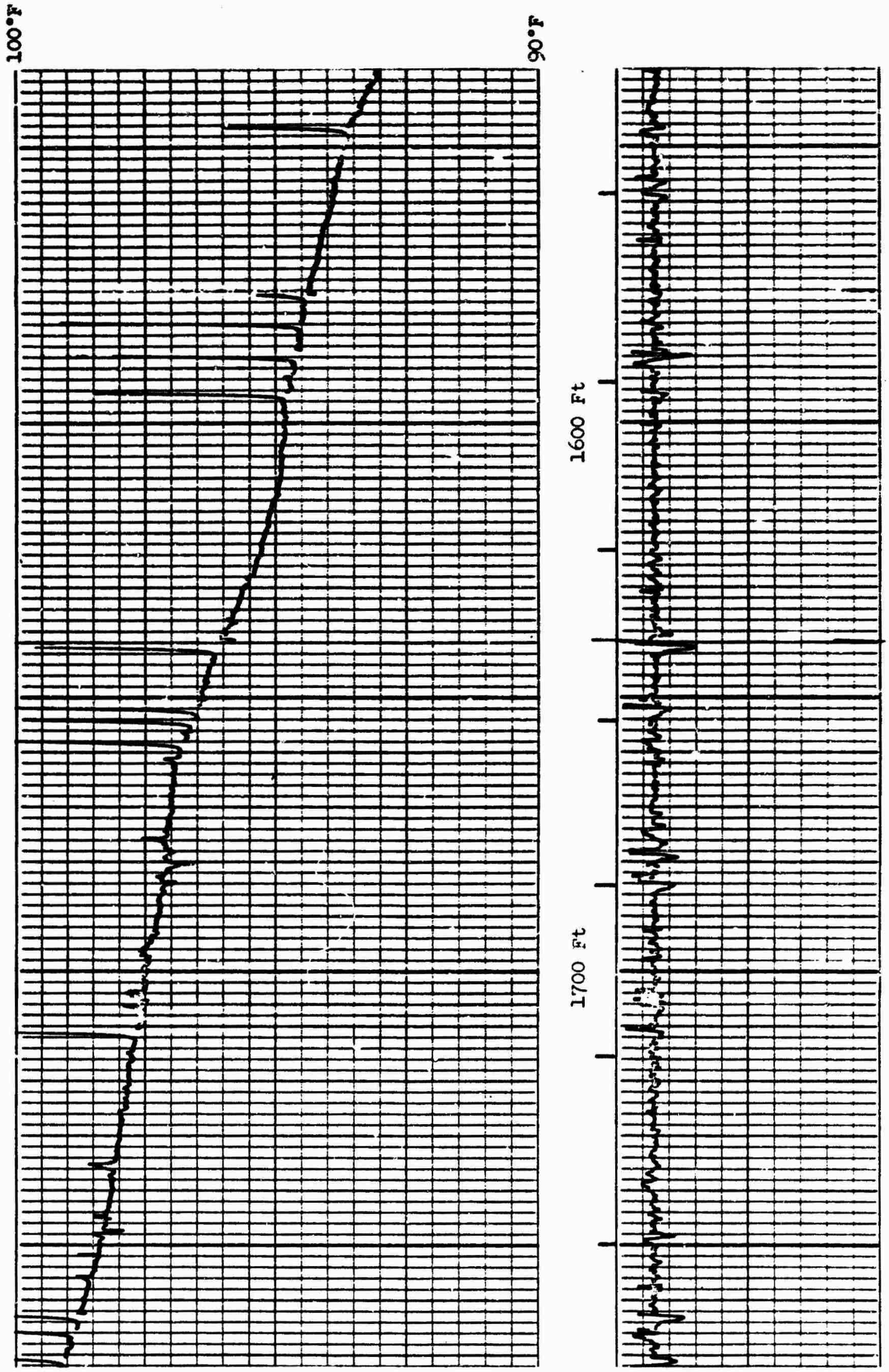


Figure C-2h.

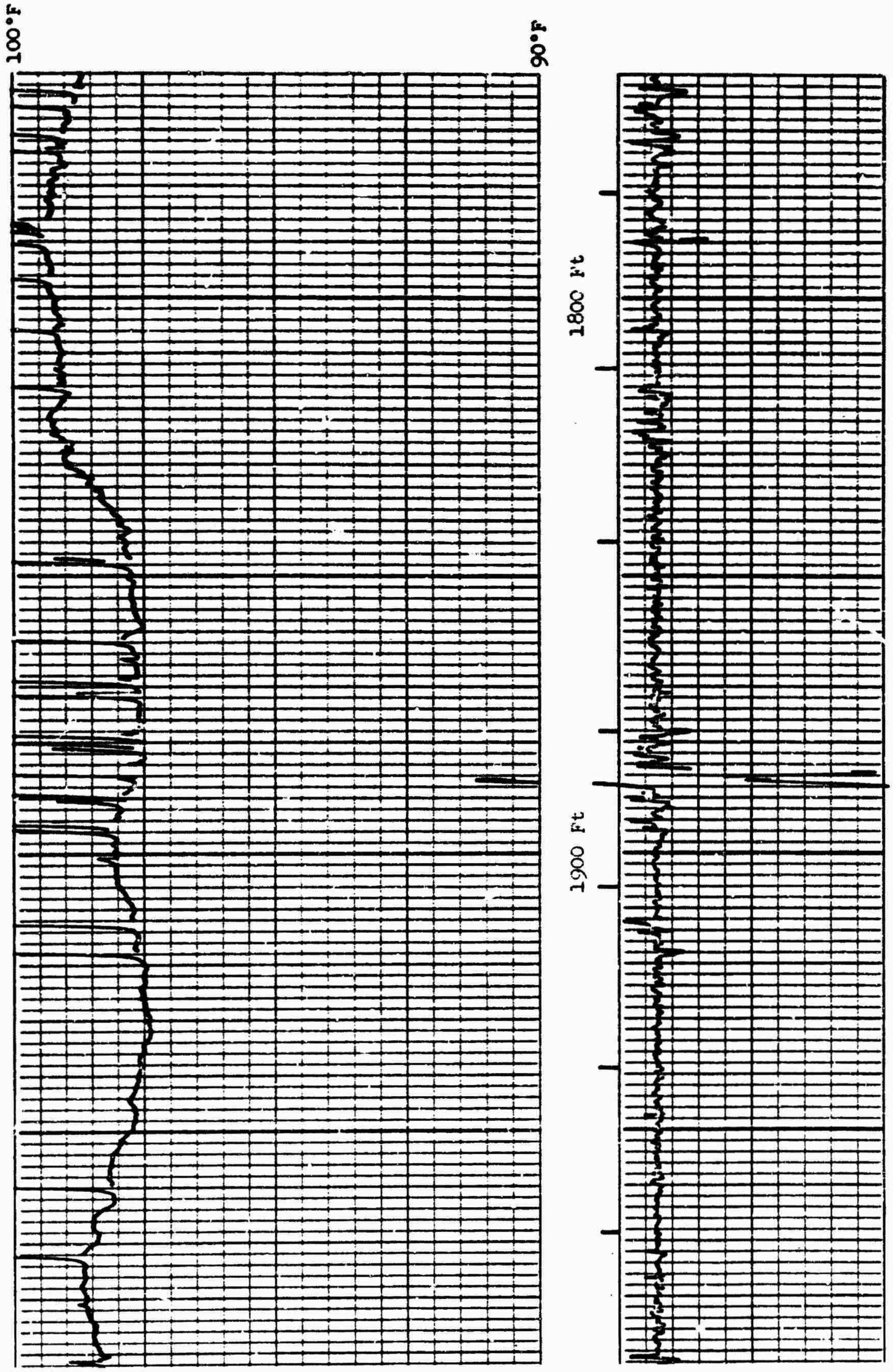


Figure C-21.

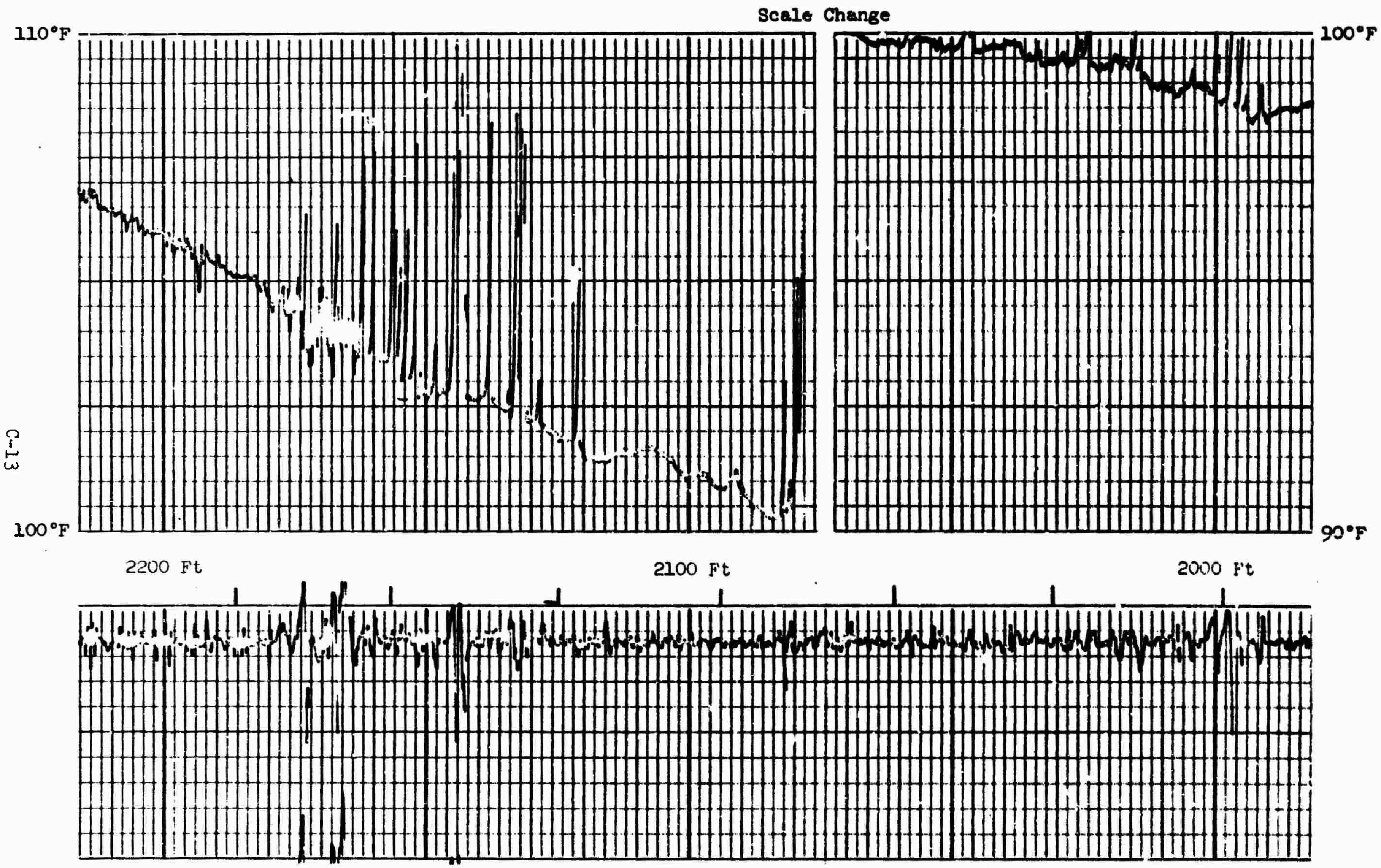


Figure C-2j.

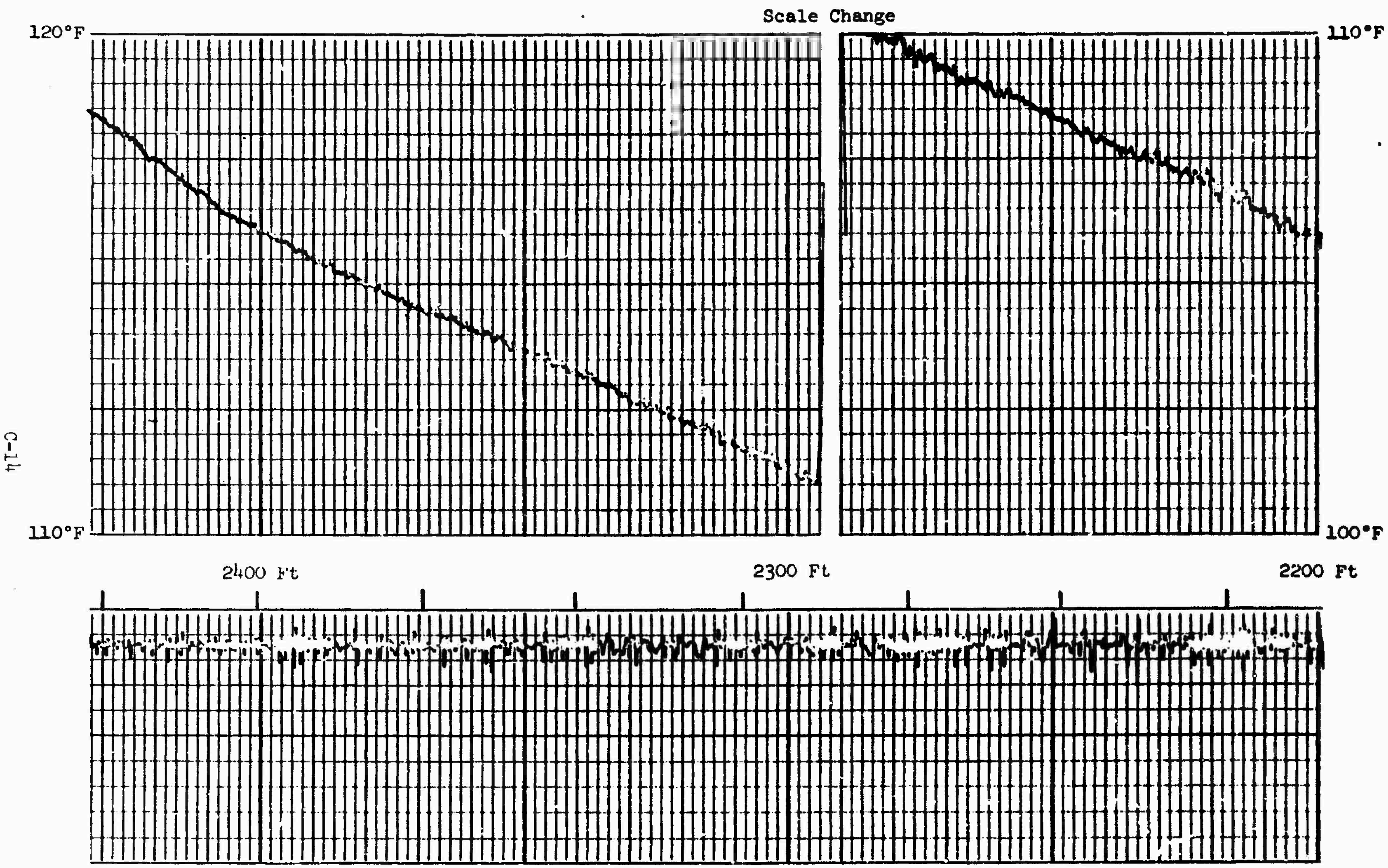
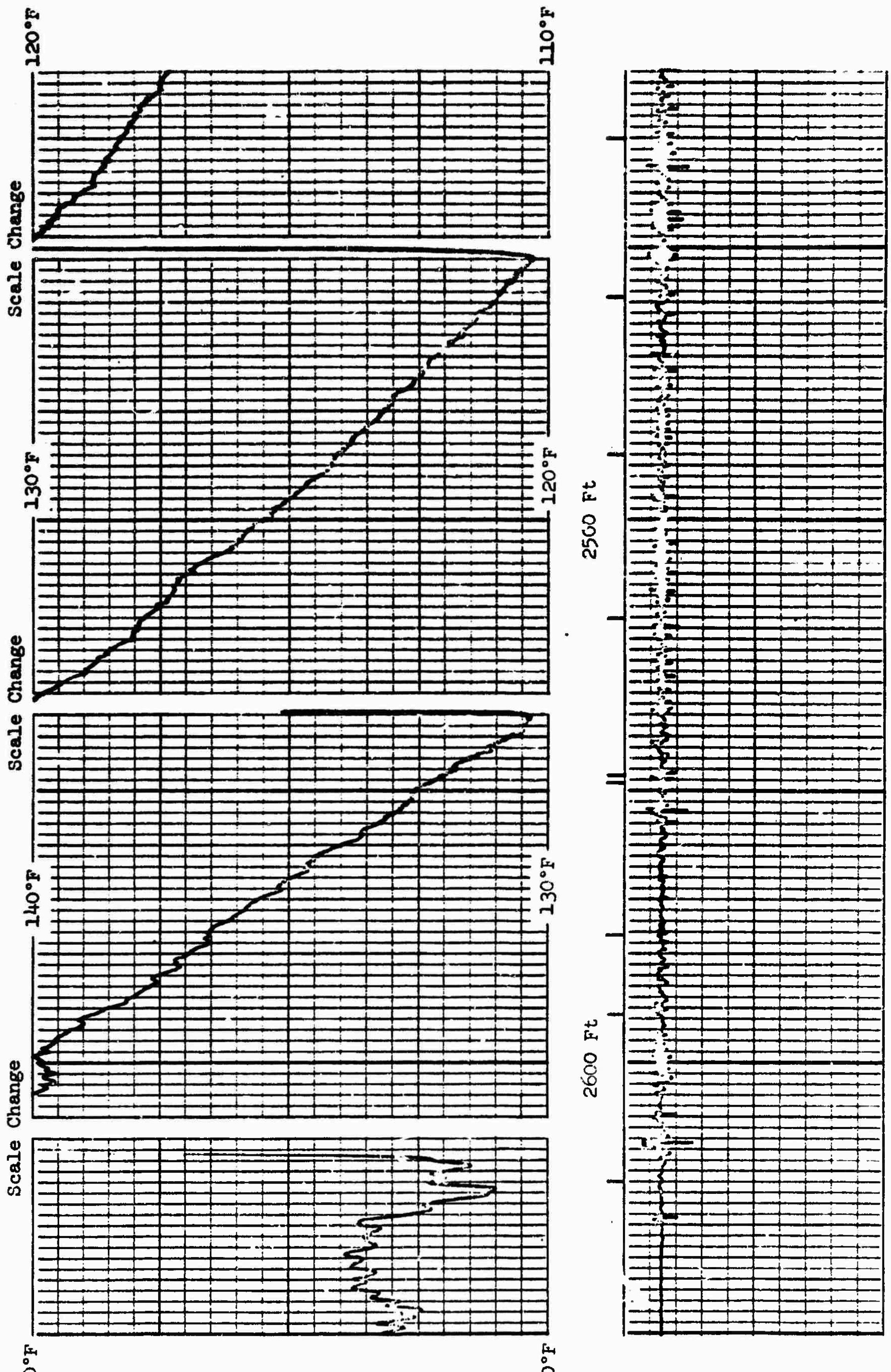


Figure C-2k.



120°F
110°F
Scale Change
130°F
120°F
Scale Change
140°F
130°F
Scale Change
150°F
140°F
2500 Ft
2600 Ft

Figure C-21.

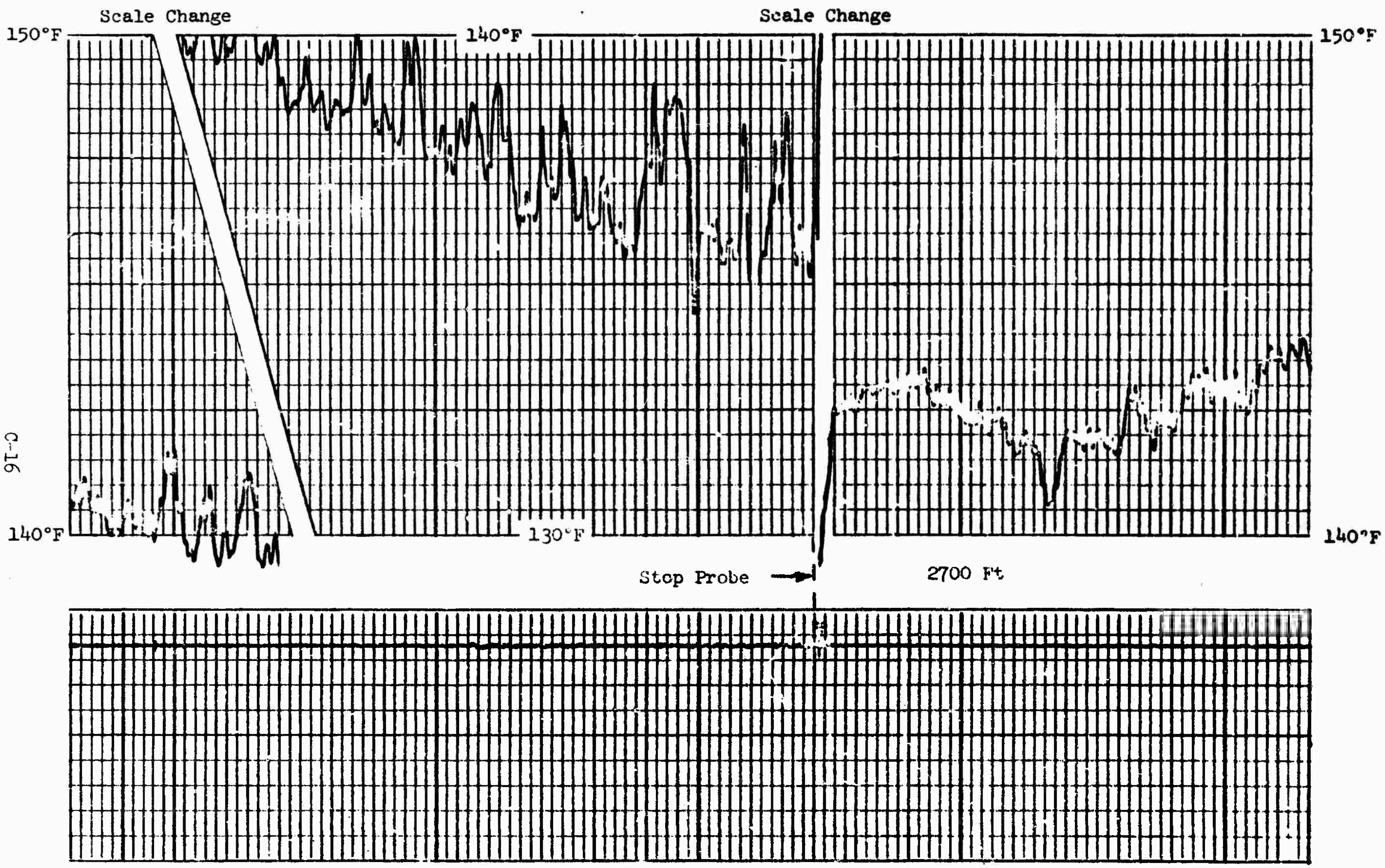

Scale Change
150°F
140°F
Scale Change
150°F
140°F
130°F
140°F
Stop Probe
2700 Ft

Figure C-2m.

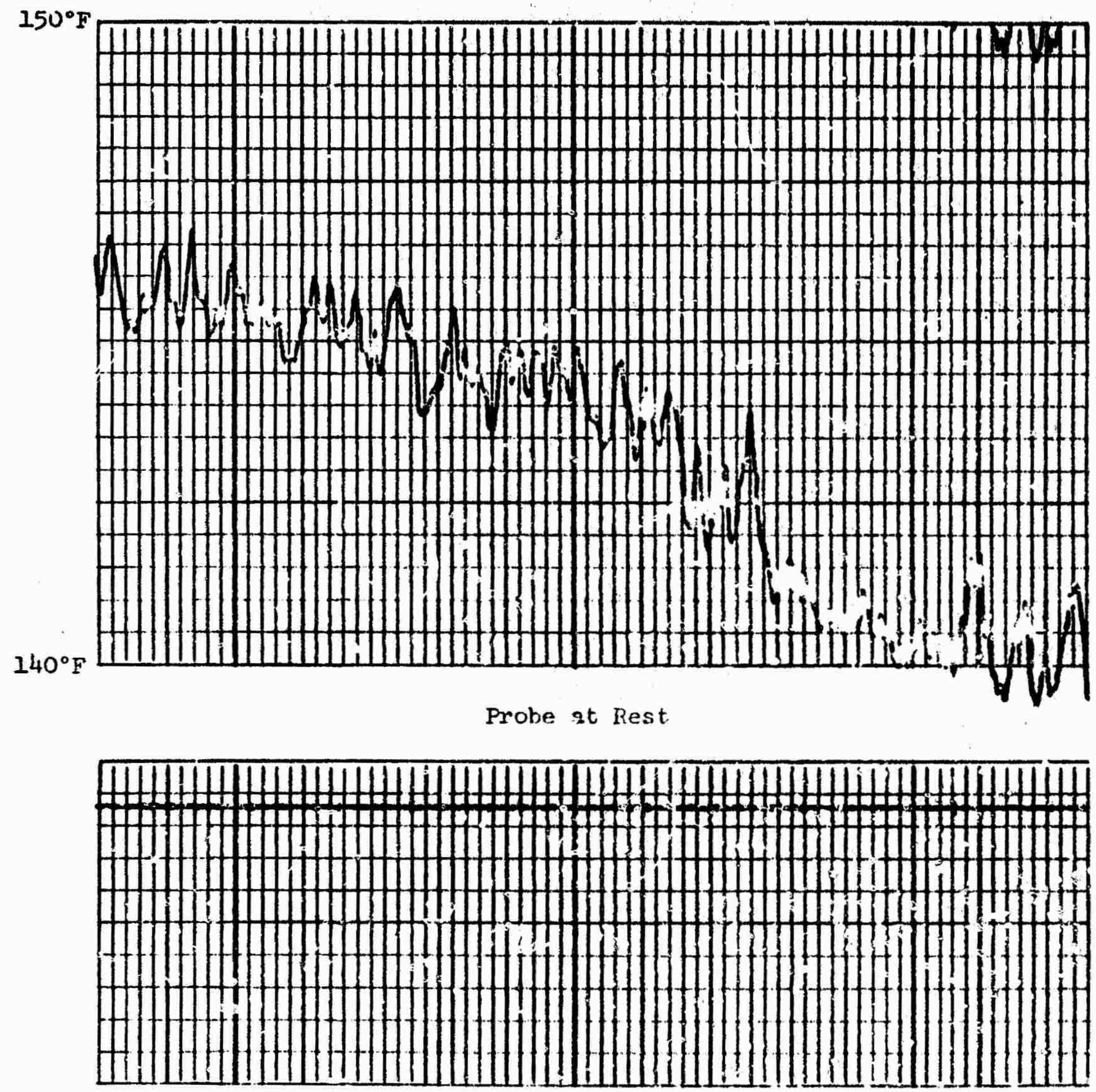


Figure C-2n.

APPENDIX D

EMPLACEMENT PROGRAM

EVENT HUMID WATER

Prepared by

Fennix and Sisson, Inc.
Los Vegas, Nevada

Rev. 30 March 1970

HUMID WATER EMPLACEMENT PROGRAM

D-1. Move in and steam clean rig.

D-2. Mobilize rig over hole. Test blowout preventer in accordance with approved procedure. Rig up logger and run temperature log.

D-3. Pick up 7-3/4" mandrel, one joint of 4-1/2" drill pipe, casing scraper, and two wire brushes. Run assembly on 2-3/8" tubing, reciprocating several times as each joint is added. Use teflon tape for thread lubricant. Run mandrel to 2645'. (All measurements from ground level.) Pull back up and work scraper and brushes through pipe from 2505' to 2525'. Reciprocate 10 to 15 times through this section, rotating tubing about 30° between each stroke. Pull out of hole and stand pipe back in doubles taking care that pipe is kept clean. Make steel line measurement of pipe while pulling.

D-4. Close blind rams and purge casing with oxygen.

D-5. Pick up 6-5/8" casing tail pipe as specified by GARD. Attach tail pipe to Baker DAB 9-5/8" packer. Run packer with hydraulic setting tool on 2-3/8" tubing. Position packer with locator shoulder at 2515'. Fill tubing with water to actuate top slips and pull up to set packer as directed by Baker Engineer. Swab unit may be required to release setting tool from packer. Pull setting tool taking care that pipe is kept clean. Make steel line measurement of pipe while pulling and number each stand in sequence pulled.

D-6. Place 6' diameter sheave against wellhead. Place 3-1/4" diameter flexible tubing of downhole module across sheave immediately above instrument pod. At no time during handling should the flexible tubing be permitted to bend less than a 3' radius. Close sheave and attach to hook or bails. Secure flexible tubing to sheave hangar by rope so that the flexible tubing can't slide and sheave can't turn. Secure the valve seal assembly on forklift and align and anchor flexible tubing to same. Carefully pick up sheave until instrument pod and detonator package are hanging over hole while moving the forklift forward and manually controlling the flexible tubing to prevent excessive bending and maintaining its clean condition.

D-7. Conduct full power test. The Test Director will install the detonator nose cone.

D-8. Lower sheave allowing detonator package and instrument pod to enter hole while moving forklift back from hole to control slack in flexible tubing. Attach catline to flexible tubing on uphole side of sheave. Unrope flexible tubing and pull toward hole with catline. Move forklift toward hole to control downhole progress as catline pulls toward hole. GARD will provide a special shoulder sub located approximately 45' below seal assembly. Attach flexible tubing clamp under shoulder and support clamp on blowout preventer.

D-9. Lower sheave to ground while controlling flexible tubing to prevent excessive bending. Remove flexible tubing from sheave. Put elevators around pickup sub on valve seal assembly. Tie cables to lift sub and loop back to crossover sub. Support loop to prevent bending beyond 3' minimum radius.

D-10. Raise valve seal assembly into derrick and pick up weight from clamp. Remove clamp and lower assembly into hole. Untie cable loop. Install spider and slips and hang assembly from landing sub. Spider and slips must have open segment to allow clearance for one 1-1/2" cable and one 3/4" cable.

D-11. Place both cables over 6' sheave and pick up sheave with crane. Orient sheave to permit easy placement of cables against tubing.

D-12. Run assembly on 2-3/8" tubing with centralizers at every fourth connection. Support cables from centralizers with kellem grips. Install cementing valve at approximately 2440'. Thoroughly tape cable to entire length of tubing. Have short pup joints in tubing string at calculated landing depth so that minimum tubing head height will be achieved. Do not attempt to release from packer after stab-in because rotation could damage cable. Electrical circuits will be monitored continuously during lowering. Electrical signalling system will indicate position of instrument pod while passing through packer and bell-mouth. Pull on string after set-down as directed by Baker Engineer to check latching.

D-13. Cable ends will be split into several flexible pigtails with pre-installed connectors. These pigtails will be brought out through the northern outlet of the Y spool. Excess pigtail will be coiled within that 6" outlet arm and the connectors will be fastened and potted to the special flanged cover. If additional room for excess cable is required, a spool extension will be connected to the outlet. Land tubing on spider and slips.

D-14. Close 2-3/8" pipe rams. Back coupling off tubing and install 2" ball valve. Install 2" flow tee in ball valve and flanged ball valve on side outlet of flow tee. Install companion flange with tapped bull plug on valve and connect 1/2" N_2 line. Last 20' of line will be flexible hose. Install 1/2" valve in flow tee top plug. Leave both ball valves open and demobilize rig. Arrange 1/2" nitrogen line so that pressure cannot build up in it or be unintentionally applied to it.

D-15. Fill cavern with gas as described in GARD's "Gas Fill Operation Procedure". (See Appendix E.) The Test Director, assigned by TC/DASA, will be responsible for handling the oxygen, methane and tracers (see Planning Directive, NVO-64). The fill period will end with N_2 purge of the casing.

D-16. Shut off N_2 purge to casing and begin to apply N_2 pressure to tubing through 1/2" line. Bring tubing pressure up to 1500 psi. Resume flow of purge N_2 to casing. Bring casing pressure up to 400 psi and close off fill line. Monitor pressure on wellhead gauge to determine if there is leakage into the cavern.

D-17. Close both ball valves on tubing head, open 1/2" valve on flow tee. Remove top plug from flow tee and drop cementing valve tripping ball. Replug tee and close 1/2" valve and let tripping ball pass into tubing. Wait 10 minutes for ball to fall. Open flange ball valve and bleed tubing down to fill pressure plus 50 psi. Close screwed ball valve. Bleed annulus pressure back to fill pressure plus 50 psi.

D-18. Bleed pressure from 1/2" N_2 fill line. Remove flexible hose. Install 1/2" tee between blowout preventer outlet gauge and gauge valve. Install flexible hose between 1/2" tee and 1/2" valve on top of flow tee. Open gauge valve but leave 1/2" valve on top of flow tee closed. Remove tapped bull plug from companion flange and connect Dewell cementing line to flange.

D-19. Prepare cement composed of 48% portland, 48% flyash, and 4% bentonite by volume measurement in a Paddle mixer. Open screwed ball valve. Pump two barrels of jelled water to open cementing sleeve followed by approximately 178 cubic feet of cement to provide 400 feet of steaming. Close flanged ball valve and open 1/2" valve on flow tee. (Exact volumes required in accordance with approved TNP Containment Plan will be calculated when emplaced tubing tally is available.)

D-20. Bleed N_2 pressure on casing down to fill pressure plus 50 psi and hold 24 hours.

D-21. Fire when ready.

BACKUP PROCEDURES

A. If small, but significant leakage is detected in step #16, proceed as follows:

  a. Complete step #17 and #18 as described.

  b. Pump 10 barrels of jelled water into tubing. Close flanged ball valve and open 1/2" valve on flow tee.

  c. Maintain N_2 pressure on casing at final fill pressure plus approximately 50 psi for 2 hours. If no leakage is evident, bring pressure up to 400 psi.

  d. If no leakage is evident at the higher pressure, bleed pressure back, reset valves, and complete steps #19 and #20.

B. If purge pressure does not build up in step #16 after pressuring tubing, proceed as follows:

  a. Repeat step #16 but bring tubing pressure up to 3000 psi. If valve closes, proceed with program as written.

  b. If valve does not close, continue slow N_2 purge down casing. Remove flanged section of 3" line between blowout preventer outlet valve and flare. Connect cementing line to valve.

  c. Pump coarse lost circulation material and jelled water into casing through blowout preventer. Control purge gas pressure within 50 psi above final cavity fill pressure until sufficient volume of L.C. material has been pumped to fill all of 6-5/8" casing and packer assembly.

  d. Begin pumping fine L.C. material and heavy mud. Let purge gas pressure rise to 400 psi as seal develops. Maintain 400 psi casing pressure for 8 hours after complete seal is developed to obtain good compaction of plug.

  e. Bleed casing pressure back to fill plus 50 psi and proceed with steps #17, #18, #19 and #20.

BLOWOUT PREVENTER TEST
PROJECT MIRACLE PLAY

The Shaffer double gate preventer will be degreased and equipped with blind rams and 2-3/8" pipe rams prior to installation on the wellhead. Water with good quality permanent type anti-freeze solution will be used as hydraulic fluid. Nitrogen bottles will be installed on the Hydril accumulater for emergency use. The accumulator and control panel will be placed approximately 100 feet southeast of the wellhead. The blowout preventer test will follow installation of GARD's 10" check valve and piping to the south outlet of the 12" wellhead spool and the installation of GARD's 3" line to the bottom outlet of the Shaffer blowout preventer. The blowout preventer test will precede downhole pumping of any oxygen or methane. A blind flange will be installed on the north outlet of the 12" wellhead spool for test purposes. The test will be conducted as follows:

Step 1 - Set retrievable bridge plug in 9-5/8" casing below 12" spool and fill wellhead with water.

Step 2 - Install 1/2" tee between gauge and valve on GARD's 3" line from blowout preventer. Close blind rams and GARD's 3" valve. Open 1/2" valve below tee and pump water into wellhead with Baker hand pump. Bring pressure up to 3000 psi and hold for 15 minutes. If leakage occurs, make repairs and retest until complete sealing is accomplished.

Step 3 - Close 1/2" gauge valve with 3000 psi on system and disconnect hand pump. Inspect 1/2" valve for leakage.

Step 4 - Re-connect pump and open 1/2" valve. Place bullplugged tubing pup in preventer and close pipe rams.

Step 5 - Open blind rams and pump water pressure back to 3000 psi. Hold pressure for 15 minutes and inspect for leakage. If leakage occurs, make repairs and retest until complete sealing is accomplished.

Step 6 - Bleed off pressure, open rams, and retrieve bridge plug.

APPENDIX E

GAS FILL

PROCEDURES

EVENT HUMID WATER

Prepared by

General American Research Division
General American Transportation Corporation

20 March 1970

Rev. 13 April 1970

APPENDIX E

HUMID WATER GAS FILL OPERATIONAL PLAN

E-1. **General Requirements**

A. Two men (buddy system) will work together on all operations.

B. Communications will be maintained between all groups associated with this phase of the program.

C. During cavity gas fill operations the GARD Instrumentation Shack will be the control point (CP) Telephone No. 794-6404.

E-2. **Assumptions**

A. The pipeline from the United Gas Co. mainline to the motor CH_4 valve, 6-MOBV-G-5 will be filled with CH_4 at atmospheric pressure.

B. The 8" line from the E-14 pad to the motor O_2 valve, 8-MOBV-02, and the X section will be filled with O_2 at atmospheric or slightly greater pressure.

E-3. **Preparation**

A. Confirm all site valves are in a closed position.

B. Inspect BOP for closure.

C. Position and set up the SF_6 feed system for operation at the bleed plug near the manual CH_4 valve, 6-MABV-G-4.

D. Purge the O_2 line and X section through the flare vent line with 1000 SCF of N_2.

E. Remove HPN2 gage and open .50-MAV-N-4 and remove handle. Open valves 2-MABV-N-5 and 2-MABV-N-6 at the BOP. Assure valve .5-MAV-N-7 is closed.

F. Verify that all valves in the pressure monitoring manifold on the 3" flare and vent line are open.

E-4. **Natural Gas Fill**

A. Obtain permission of Technical Director and Test Manager to proceed.

B. Verify that the United Gas Company's natural gas valve is open and manned by U.G. personnel at the mainline distribution point. Set for estimated flow rate of 150K SCF/hr.

C. Open Manual natural gas valve, 6-MABV-G-4.

D. Open motor natural gas valve, 6-MOBV-G-5.

E. Open motor spool valve, 8-MOSBV-3.

F. Open and adjust SF_6 feed system into the CH_4 pipeline.

G. Establish flow rate of 150K SCF/hr; adjust SF_6 inject rate.

H. When cavity pressure is 75 PSIA, notify the Technical Director.

I. Final adjustment will be made under the supervision of the Technical Director.

J. Stop natural gas flow by closing the manual valve at the United Gas Company's main distribution point when permission is given by the Technical Director. Close the SF6 feed system into the CH4 pipeline. Close the motor CH4 valve, 6-MOBV-G-5.

E-5. Nitrogen Purge and Venting of CH4 Pipeline

A. Prepare to begin nitrogen flow at station E-14.

B. Open manual nitrogen valve .50-MAV-N-2. Reinstall 02 bleed plug.

C. Simultaneously, begin nitrogen flow and open manual nitrogen valve .75-MAV-N-1.

D. When N2 pressure in 02 lines is 120 PSIG, open motor oxygen valve 8-MOBV-0-2.

E. Purge X section, wellhead, and downhole casing. Volume of N2 will be at least 25,000SCF.

F. Shut down N2 flow and close motor spool valve, 8-MOSBV-3.

G. Close motor 02 valve, 8-MOBV-0-2.

H. Open motor vent valve, 3-MOBV-VF-6.

I. Vent CH4 pipeline to atmoshpere through flare stack by opening motor CH4 valve, 6-MOBV-G-5. Ignite flare with sparker.

J. After gas flow roar from vent stack ceases, close the manual CH4 valve, 6-MABV-G-4.

K. Five (5) minutes after completing step J, close SF6 valve and remove CH4 bleed plug. Uncouple the SF6 feed system from the CH4 pipeline. Move the SF6 feed system to the E-14 pad and connect to SF6 inlet to the 8" service pipeline.

L. Open the motor 02 valve, 8-MOBV-0-2.

M. Start flowing N2.

N. Purge the X section, the vent line, and the section of the CH4 pipeline between the manual CH4 valve 6-MABV-G-5, with nitrogen. Volume of N2 will be at least 1500 SCF.

O. Close motor vent valve 3-MOBV-VF-6. Continue purge for additional 1000SCF.

P. To stop nitrogen purge, simultaneously close nitrogen valve .75-MAV-N-1 and stop N2 flow.

Q. Close manual CH4 valve, 6-MABV-G-5.

R. Secure nitrogen pumper.

S. When the pressure in the 8" pipeline reaches atmospheric pressure, close the motor 02 valve, 8-MOBV-0-2.

E-6. Oxygen Fill (Commence on approval from Technical Director and Test Manager)

A. Check that valve .75-MAV-N-3 is closed. Verify that valves 2-MAV-N-5, 2-MAV-N-6 are open.

B. Insure SF6 feed system is ready for operation.
C. Prepare to begin 02 flow.
D. Open manual 02 valve, 3-MABV-0-1.
E. Open motor 02 valve, 8-MOBV-0-2.
F. Slowly begin 02 flow. When pressure in 02 line exceeds 125 PSIG, open motor spool valve, 8-MOSBV-3.
G. Increase 02 flow to maximum as directed by Technical Director. Open and adjust SF6 feed system into oxygen flow. As necessary, Linde may operate manual 02 valve, 3-MABV-0-1 during transfer of liquid oxygen.
H. When cavity pressure is 180 PSIA, notify the Technical Director. Final adjustments will be made under the supervision of the Technical Director.
I. When permission is granted by Technical Director close manual 02 valve, 3-MABV-0-1, and stop 02 flow. Close SF6 feed system.

E-7. Nitrogen Purge

A. Prepare to begin nitrogen flow at station E-14.
B. Open manual N2 valve, .50-MAV-N-2.
C. Simultaneously begin nitrogen flow and open manual N2 valve, .75-MAV-N-1, when N2 line pressure exceeds 02 line pressure.
D. Purge oxygen line, X section, wellhead section and downhole casing with nitrogen. Volume will be at least 50,000 SCF.
F. Shut down N2 flow and close manual N2 valve, .75-MAV-N-1, to stop nitrogen purge.

NOTE: Procedures for items 8 and 9 are complementary to the Emplacement Plan and will require close coordination with the Site Manager and his staff.

E-8. Sliding Sleeve Valve Operation

A. Prepare hi-pressure N2 pumper. (Commence with approval of Technical Director)
B. Replace HPN2 gage. Replace handle and open manual N2 valve, .50-MAV-N-4.
C. Open manual N2 valve, .75-MAV-N-3, to shift sliding sleeve. Raise pressure to 1500 PSIG.
D. Close manual N2 valve, .75-MAV-N-3.

E-9. Downhole Casing Pressure Test

A. Start N2 pumper, build pressure to 250 PSIG; open manual N2 valve .75-MAV-N-1 and increase N2 pressure to 250 PSIG.
B. Simultaneously close manual N2 valve, .75-MAV-N-1 and shut down N2 pumper.

C. Observe gages LPN2 and wellhead pressure transducer for any gross pressure decrease in casing and if a decrease occurs, determine approximate rate of leakage.

D. Inform Technical Director of results of step C before proceeding.

E. Close valve .5-MAV-N-2. Cautiously remove LPN2 gage. A party of three (one rad safe) will take gage to GZ. At GZ close all three pressure monitoring manifold valves. Cautiously interchange gages. Open gage valve & pressure monitoring manifold valve. Leave valve to pressure transducer closed. All personnel return to station E-14. Install wellhead gage on N2 manifold. Open .5-MAV-N-2.

F. Start N2 pumper. Build pressure to 250 PSIG: open manual N2 valve .75-MAV-N-1 and increase N2 pressure to 400 PSIG.

G. Simultaneously close manual N2 valve .75-MAV-N-1 and shut down N2 pumper.

H. Observe replaced LPN2 gage for any gross pressure decrease in casing and if a decrease occurs, determine approximate rate of leakage.

I. Inform Technical Director of result of step H before proceeding.

J. Close motor spool valve 8-MOSBV-3 and motor 02 valve 8-MOBV-0-2.

K. A party of three (including one rad safe) will go to GZ and closely monitor wellhead pressure gage and determine rate of pressure decrease if any.

L. Inform Technical Director of result of step K before proceeding.

M. Close motor spool valve 8-MOSBV-3 and motor 02 valve 8-MOBV-0-2.

N. Slowly & cautiously drop wellhead pressure to 250PSIG by cracking manual vent valve, 3-MAV-VF-7.

O. Drop cementing ball (reference Emplacement Plan).

P. Open motor vent valve, 3-MOBV-VF-6 and open motor oxygen valve, 8-MOBV-0-2 to bleed 02 line.

Q. Close manual N2 valve .5-MAV-N-2.

R. Bleed 2 3/8" tubing to 250 PSIG (HPN2 gage) by opening manual N2 valve .75-MAV-N-1 and manipulating manual N2 valve .75-MAV-N-3. Close both valves at 250 PSIG.

S. When N2 flow from vent stack ceases, close motor vent valve 3-MOBV-VF-6, and motor 02 valve 8-MOBV-0-2.

T. Proceed with emplacement plan. To bleed ½" N2 line, open manual N2 valves .75-MAV-N-1 and .75-MAV-N-3. To bleed annulus, use manual flare/vent valve 3-MAV-VF-7. After stem is in place, check 02 line pressure (LPN2), bleed if necessary, and remove 02 bleed plug.

E-10. Emergency Procedures

A. In case of an emergency during the oxygen fill:

1. Immediately stop the oxygen pumper at Station E-14.

2. Immediately close the motor spool valve 8-MOSBV-3 and the motor oxygen valve 8-MOBV-0-2.

3. Alert the emergency team.

4. Close manual oxygen valve 8-MABV-0-1.

5. If emergency is a fire or potential fire remove as much as possible the combustibles from the area of the fire.

6. If emergency is a fire or potential fire, respond with appropriate agent to control fire.

7. Notify the Technical Director, GARD Project Engineer and AEC Safety. Do not proceed with oxygen fill until permission is granted by these persons.

B. In case of an emergency during the natural gas fill:

1. Immediately close motor spool valve 8-MOSBV-3 and the motor natural gas valve 6-MOBV-G-5.

2. If possible have the manual natural gas valve at the United Gas Company's mainline distribution point closed.

3. Alert the emergency team.

4. Close the manual natural gas valve 6-MABV-G-4.

5. If emergency is a fire or a potential fire, remove as much as possible the combustibles from the area of the fire.

6. If emergency is a fire or a potential fir , respond with appropriate agent to control fire.

7. Notify the Technical Director, GARD Project Engineer, and AEC Safety. Do not proceed with natural gas fill until permission is granted by these persons.

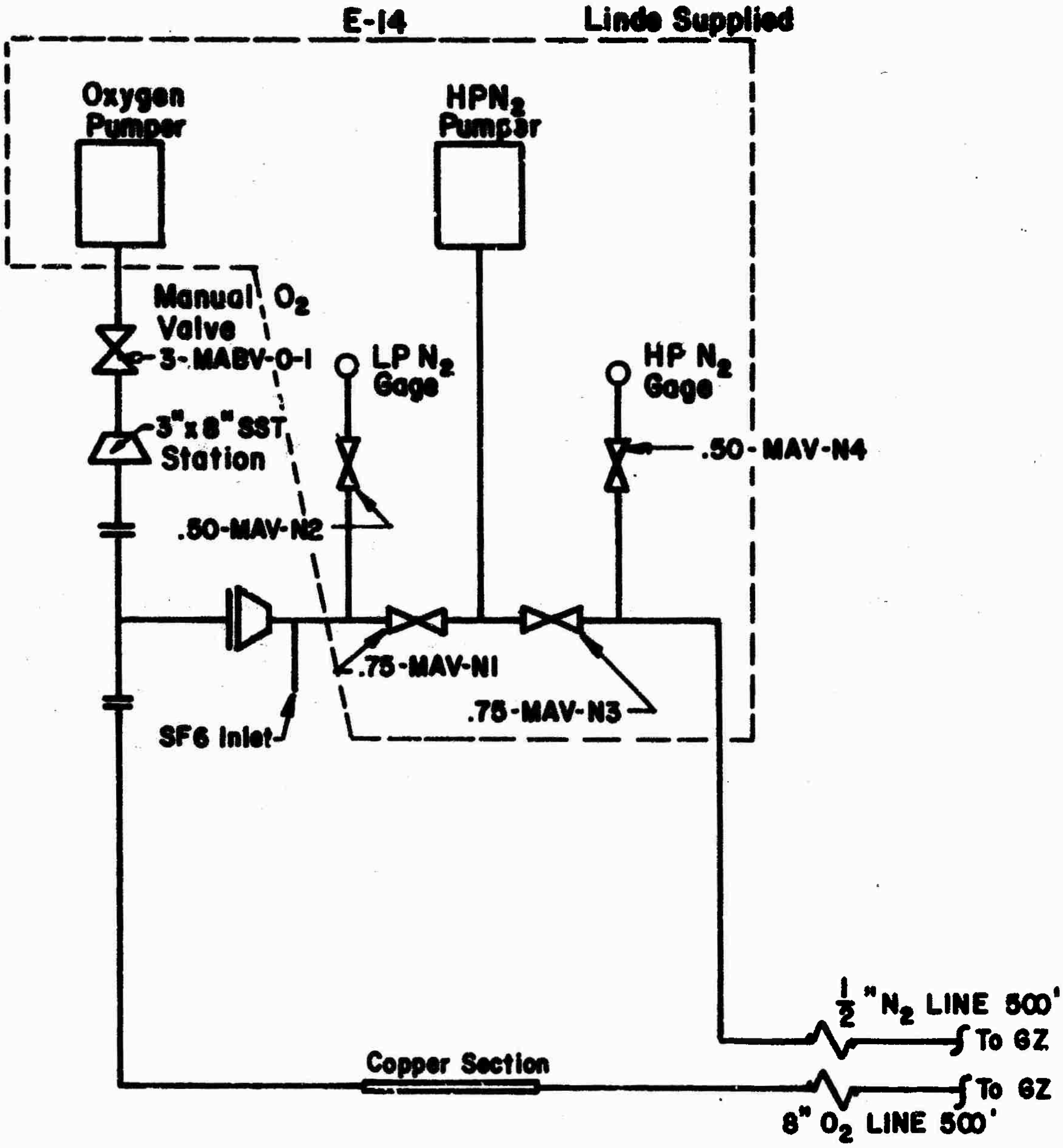


Figure E-1, CONTROL VALVES FOR OXYGEN, METHANE, AND NITROGEN SUPPLY SYSTEM.

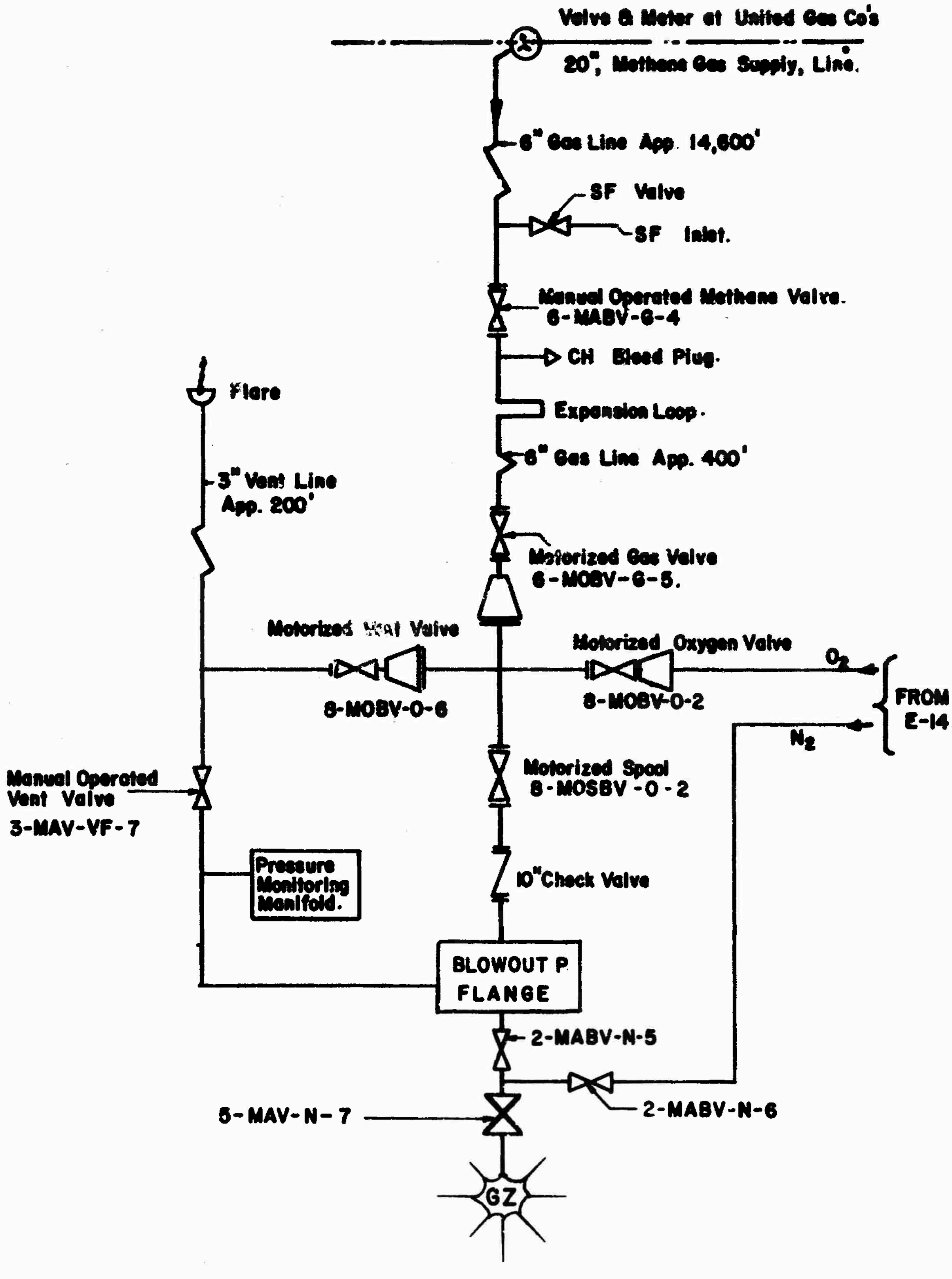


Figure E-2 PIPELINE SYSTEM.

APPENDIX F

THE MIXING OF GASES IN A SPHERICAL CAVITY

Operation MIRACLE PLAY

by

L. B. Holmes

L. E. Fugelso

ABSTRACT

The mixing of gases in a large spherical cavity to obtain a detonable mixture has been analyzed for several different loading procedures. The methods analyzed make use of convection and mixing in the cavity produced by the action of a turbulent buoyant source at the top of the cavity.

Excellent mixing is produced by the action of a heavy turbulent plume which extends to the floor of the cavity. The plume entrains and displaces a large volume flux of gas producing free convection in the cavity. If a large density gradient exists in the cavity, the plume may not penetrate to the cavity floor. In this case, the mixing takes place only to the depth of penetration of the plume.

Relatively poor mixing is obtained by the action of a light plume which penetrates to a shallow depth into the cavity before it is reversed by buoyant forces. The mixing established by the light plume is confined to a region near the source. The efflux from the light plume displaces the heavier mixture originally at the top of the cavity. This displacement forms a steep gradient between the light gases at the top of the cavity and the compressed heavier gas.

When alternate volumes of gas are loaded into the cavity, mixing is alternately produced by heavy and light plumes. Excellent mixing is produced by the heavy plume while the poor mixing by the light plume produces steep density gradients. These gradients in turn confine the action of the next heavy plume to the region above the gradient. For these reasons this method of loading cannot yield better results than the action of a single heavy plume.

ACKNOWLEDGEMENTS

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THE MIXING OF GASES IN A SPHERICAL CAVITY

Background

General American Research Division participated in an underground gas detonation experiment, Diode Tube Event of Miracle Play Test Series under DASA Contract DASA01-68-C-0177. The purpose of this experiment was to match the seismic signals of a previous nuclear explosion, Sterling, using a gas detonation in the same cavity. Investigation of the seismic data from Diode Tube Event indicates that the peak amplitudes of the seismic signals from Diode Tube are one-third of what was expected. In reviewing the program, questions were raised concerning the quality of gas mixing (implying an explosive yield less than predicted) obtained in Diode Tube Event. Reported herein is an evaluation of the mixing of gases which takes place in a large spherical cavity for several different loading procedures, including those used for Diode Tube Event and those proposed for Humid Water and Dinar Coin Events.

The cavity, into which the gases were to be mixed, existed in the Atomic Energy Commission's Tatum Dome Test Site near Hattiesburg, Mississippi. Its roughly spherical shape (110 ft. diameter) had been produced by a previous nuclear explosion, Project Salmon, at that site. A solidified pool of salt on which rested a layer of rubble formed the floor of the cavity. At the top, chunks of the ceiling had fallen out to form a chimney. A 6-5/8 inch diameter steel casing protruded into the chimney, 2650 feet below the well head. This casing contained a 1-1/2 inch diameter instrumentation cable and valving for the gases. The gases flowed out of the casing into the chimney area through slots cut into the side of the casing.

Methods of Loading

This analysis deals with the problem of mixing large quantities of gases into an explosive mixture. A detonable mixture of methane and oxygen was to be obtained in a 110 ft. diameter spherical cavity, approximately one-half mile underground. Safety considerations generally precluded mixing the gases at ground level and transporting them down to the cavity. Thus, alternate methods were devised.

In Diode Tube Event, the heavy gas (oxygen) was loaded into the cavity first, then the methane. Other methods of loading the gases to obtain mixing in the cavity are: 1) to load all of the lighter gas (methane) first, then the oxygen or 2) to load methane and oxygen in alternate small volumes using an inert gas (nitrogen) to purge the pipe line between volumes.

Method of Solution

The gases in the cavity are mixed by several different mechanisms. The method of solution has been to treat the problems of turbulent diffusion, forced and free convection and molecular diffusion individually. By this means it can be shown that the dominant mixing mechanism during the loading process is diffusion and buoyant free convection produced by a forced plume.

The gases enter the cavity through openings cut into the 6-5/8 inch diameter casing which protrudes into the chimney of the cavity. The gas enters the cavity with sufficient velocity to produce a turbulent jet (See Appendix 1) which entrains cavity gas.

For the flow conditions used in Diode Tube Event the entrance momentum flux was insufficient to support significant convective velocities which would mix the gases by large scale forced circulation (See Appendix 2).

The entering jet may be heavier or lighter than the proximate cavity gas. When the direction of mean motion is induced by buoyancy forces, this type of continuous turbulent source is called a plume. The plume tends to induce a circulation of the mixed gases in the cavity. The extent of this circulation depends on the direction taken by the plume due to its buoyancy. The gases entrained and mixed in the plume are transported to the position that the plume terminates. The plume gas issuing from the plume spreads laterally at its density level displacing the cavity gases originally there.

ENTRAINMENT AND CONVECTION BY A FORCED PLUME

The methods analyzed make use of convection and mixing in the cavity produced by the action of a turbulent buoyant source in the top of the cavity. A model for turbulent buoyant convection from a source in a confined region, introduced by W. D. Baines and J. S. Turner(1), is applied in this analysis. Their model incorporates a turbulent plume which persists to and is terminated at the boundary of the cavity. The gas mixture issuing from the plume spreads laterally at its density level displacing the gas originally there. Mixing takes place by turbulent diffusion in the plume. Convection outside of the plume is produced by displacement by the gases issuing from the plume and by entrainment into the plume.

The main differences between the model of W. D. Baines and J. S. Turner and the one applied here is that in this case the displacement of the gases in the cavity is accompanied by their compression as the pressure in the cavity increases. This compression is directly related to convection in the cavity.

In this analysis the source is finite and has an associated mass and momentum flux. The molecular weights of the source and cavity gases differ initially by a factor of 2. Sources of mass momentum and buoyancy have been analyzed by B. R. Morton[2] who shows that they can be related to a virtual point source of buoyancy and momentum only. Increasing the mass and momentum of the source in a stably stratified atmosphere has the effect at first of reducing the total penetration of the plume. This indicates that the spreading and mixing occurring in a turbulent forced plume is affected by the initial momentum and mass flux.

In the analysis which follows, it is assumed that the momentum forces associated with the inlet jet are insufficient to over balance the stabilizing buoyant forces and drive the cavity gases into a large scale circulation. Appendix 2 shows that the momentum at the inlet, for the cases which will be considered, is insufficient to produce rapid circulation, assuming Stokes flow, of a uniform gas in the cavity. The calculated circulation would have been even less if the stabilizing buoyancy forces were included.

Equations for the Axisymmetric Plume

The theory of turbulent gravitational convection from maintained sources was developed by B. R. Morton, G. I. Taylor, and J. S. Turner[3]. The mean velocity and mean density for an axisymmetric plume are given by

$$U\,(s,\ r) = U(s)e^{-r^2/b^2} \qquad (1)$$

$$[\,\rho - \rho_o\,]\,(s,\ r) = [\,\rho - \rho_o\,]\,(s)e^{-r^2/b^2} \qquad (2)$$

where $U(s)$ is the centerline mean velocity, $\rho(s)$ and $\rho_o(s)$ are centerline mean densities inside and outside of the plume, respectively, and $b(s)$ is a characteristic plume radius.

The conservation of mass and momentum, where the coordinate systems under consideration is shown in Figure 1, are given by

$$\frac{d}{ds}\left[(\rho - \rho_o)\frac{ub^2}{2}\right] = -b^2 U \frac{d\rho_o}{ds} \tag{3}$$

$$\frac{d}{ds}\left[b^2 u^2 \left(\frac{\rho_o + 2\rho}{6}\right)\cos\Theta\right] = gb^2(\rho - \rho_o) \tag{4}$$

$$\frac{d}{ds}\left[b^2 u^2 \left(\frac{\rho_o + 2\rho}{6}\right)\sin\Theta\right] = 0 \tag{5}$$

where Θ is the angle between the direction of the plume trajectory (s) and the acceleration of gravity (g).

Batchelor's assumption that the entrainment at some position in the plume is proportional to a characteristic velocity at that position is given by

$$\frac{d}{ds}(b^2 u) = 2\alpha\, bu \tag{6}$$

where α is the experimentally determined entrainment coefficient. Equations 3-6 result from integration of the equations over the plume cross section.

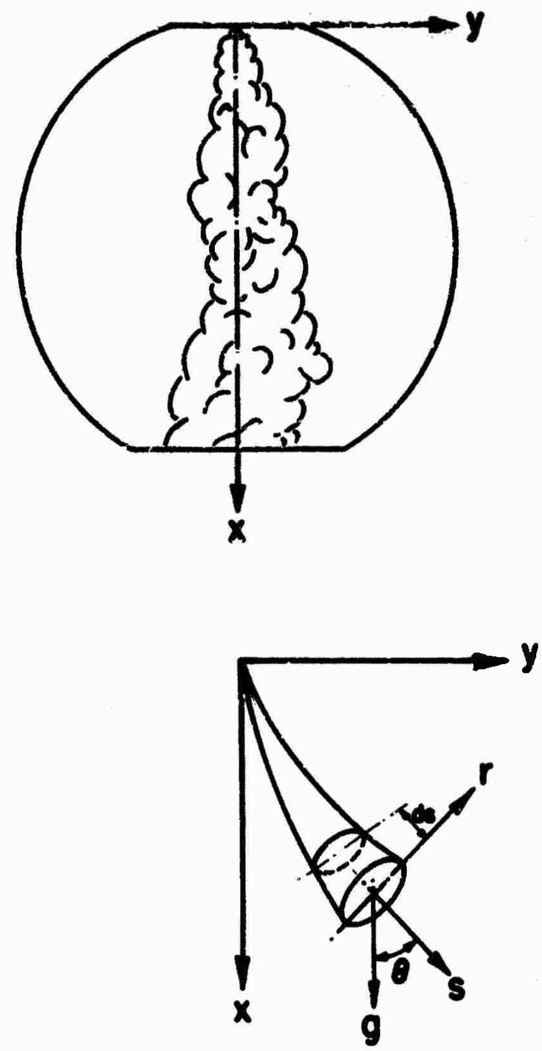

Figure 1. COORDINATE SYSTEM FOR AN AXISYMMETRIC PLUME

Conservation of mass in the cavity outside of the plume is given by

$$\frac{\partial \rho_o}{\partial t} + U \frac{\partial \rho_o}{\partial x} + \rho_o \frac{\partial U}{\partial x} = 0 \qquad (7)$$

where U is the convective velocity and

$$\pi R^2 \left(1 - \frac{b^2}{R^2}\right) U = \pi \left(1 - \frac{V_a}{V}\right) u_1 b_1^{\,2} - \pi u b^2 \qquad (8)$$

The nomenclature for equation 8 is shown in Figure 2. R is the radius of the cavity at the depth x, $\pi u_1 b_1^{\,2}$ is the inlet volume flux and V_a/V is the ratio of the volume above the section at x to the total volume of the cavity.

The transition of the jet mean velocity and mean density profiles from being uniform at the nozzle exit to fully developed Gaussian at a position downstream has been analyzed by C.duP. Donaldson and K. E. Gray[4] using a momentum integral method. The core or uniform property region decreases due to turbulent diffusion with distance along the trajectory(s). The core region is shown schematically in Figure 3 ending at a distance s_c along the trajectory. For low Mach number flow and density ratios of 2, the length of the core region is found to be of the order of the nozzle radius (See Appendix 1). The change of momentum of the jet due to buoyancy over the distance s_c is negligible compared to the assumed inlet momentum. In order to treat the transition region, the momentum will be assumed to be constant and equal to the inlet momentum.

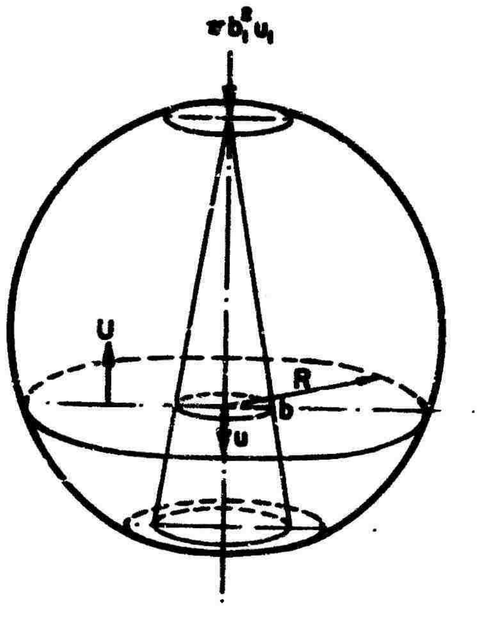

Figure 2. CONSERVATION OF MASS IN A SPHERICAL CAVITY.

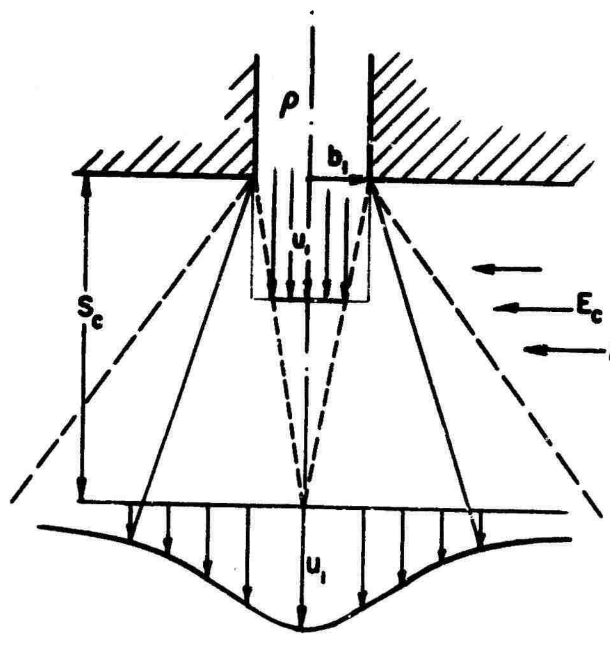

Figure 3. FLOW TRANSITION AT THE NOZZLE EXIT.

It is convenient to assume that the characteristic plume dimension for the density profile is given by b/λ in the core region where λ is a parameter. The mass and momentum fluxes at $s = s_c$ are given by

$$Z_c = \frac{\pi(\rho + \lambda^2 \rho_o)\, ub^2}{\lambda^2 + 1} \qquad (9)$$

$$W_c = \frac{\pi(2\rho + \lambda^2 \rho_o)\, u^2 b^2}{2(2 + \lambda^2)} \qquad (10)$$

If the entrainment over the distance s_c is given by E_c then the volume flux Y_c is given by

$$Y_c = \pi b_1^{\,2}\, u_1 + E_c \qquad (11)$$

and the momentum and mass fluxes are

$$Z_c = \rho_1\, b_1^{\,2}\, u_1 + \rho_o\, E_c \qquad (12)$$

$$W_c = \rho_1\, b_1^{\,2}\, u_1^{\,2} \qquad (13)$$

Solution of equations 9 - 13 simultaneously yields E_c and λ^2. One obtains

$$E_c = \lambda^2\, u_1\, b_1^{\,2}$$

$$\lambda^2 = -1/2 + \sqrt{1/4 + \frac{2\rho}{\rho_o}}$$

These parameters in conjunction with equations 11 to 13 define the boundary conditions for the Gaussian axisymmetric plume in terms of known conditions at the nozzle.

Initially, the cavity contains a known number of moles of gas. At the beginning of the computation, it is assumed that the plume is already established in the cavity gas. The inlet gases issue from openings cut into the side of a 6-5/8 inch diameter casing at approximately 20° to the axis of the cavity. It is assumed that loading the light gas forms four distinct plumes while loading the heavy gas forms a single plume. In the case of the heavy gas, the individual plumes quickly join up due to the rapid entrainment of the gas between them.

Numerical Solution

The differential equations in terms of trajectory, (s), and time, (t), were non-dimensionalized and converted to pure difference equations. These were programmed in FORTRAN IV for the IBM 1130 computer. Mathematical singularities in the problem were isolated and computed separately. Two cases of a finite source were solved numerically; one with positive buoyancy and one with negative buoyancy. The cavity boundary was a 110 ft. diameter sphere truncated 3 ft. from the top (ceiling) and 7 ft. from the bottom (floor). The entrance nozzle was at the center of the ceiling.

The entrainment coefficient, α , has been experimentally determined. Values reported in the literature for liquids and gases range from 0.058 to 0.082[5]. H. Rouse, C. S. Yih, and H. W. Humphreys[6] measured $\alpha = 0.058$ for plumes in air. This value, used in this analysis, seems to be the one most generally accepted.

Light Plume; Methane Source

Initially, the cavity contains 9 atmospheres of oxygen. Methane is added at 336 lbm-moles/hr until the cavity pressure reaches 15 atmospheres. The methane issues into the cavity at an angle of 20° off the axis of the cavity from 4 nozzles with 1/8 ft. radii.

The computation shows that the plume initially penetrates only 1 ft. deep into the pure oxygen. As the lighter plume gas accumulates at the top of the cavity, the penetration increases to a maximum of 3 ft. Meanwhile the methane added to the cavity continues to compress the pure oxygen deeper into the cavity without further entrainment from the pure oxygen region. The concentrations of oxygen vs depth in the cavity at selected times during the methane loading are shown in Figure 4.

Heavy Plume; Oxygen Source

For this case the cavity contains 6 atmospheres of methane. Oxygen is loaded into the cavity at 336 lbm-mole/hr until the cavity pressure reaches 15 atmospheres. The oxygen issues into the cavity along the vertical axis through a single nozzle with a 1/4 ft. radius. The plume extends to the floor of the cavity entraining a large volume flux of cavity gas. For the initial plume the entrainment is 311 times the volume flux at the nozzle. Outside of the plume the first traces of plume gas reach 98% of the cavity height in 1/3 hour. The pattern of mixing is unchanged after this first front approaches the ceiling of the cavity. The concentration of oxygen vs depth in the cavity is shown in Figure 5 for several selected times. The natural convection produced by the plume provides a very effective means of mixing the gases. The fractional

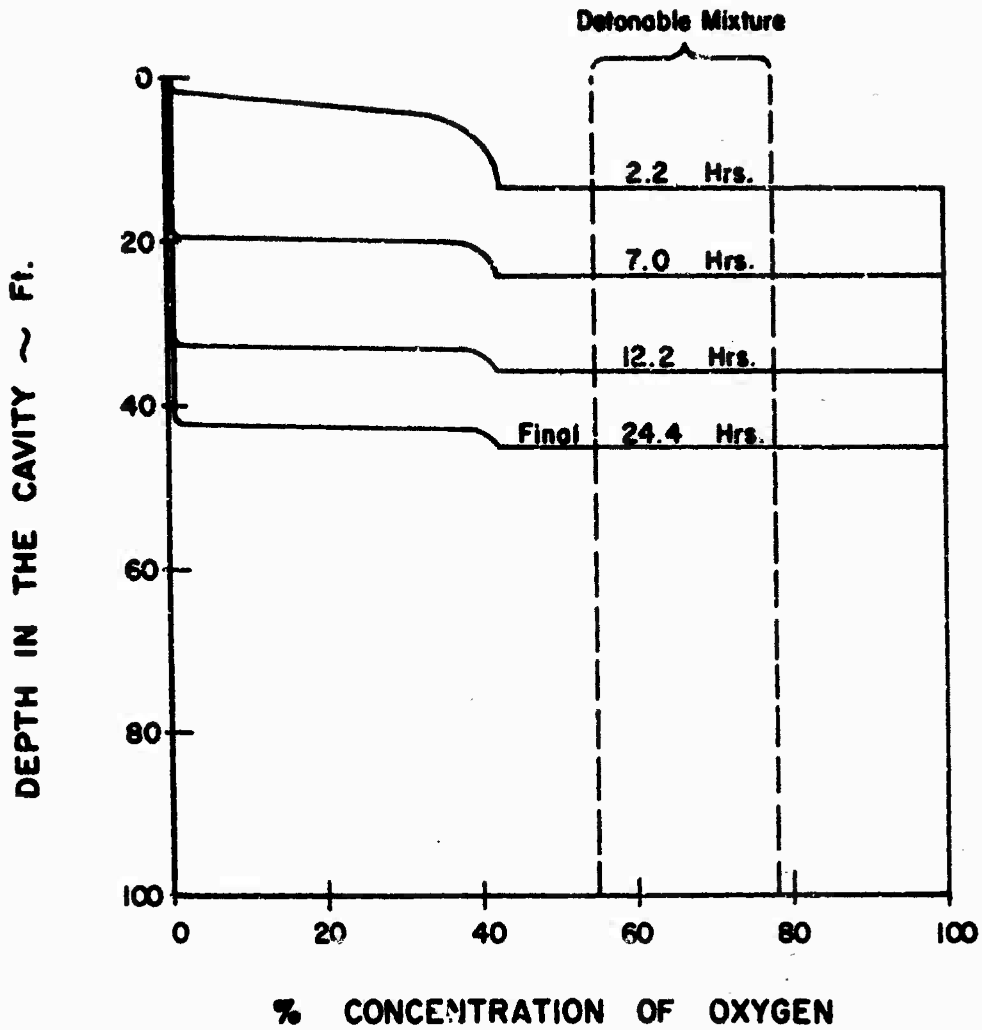

Figure 4. LIGHT PLUME; CONCENTRATION OF OXYGEN IN A SPHERICAL CAVITY.

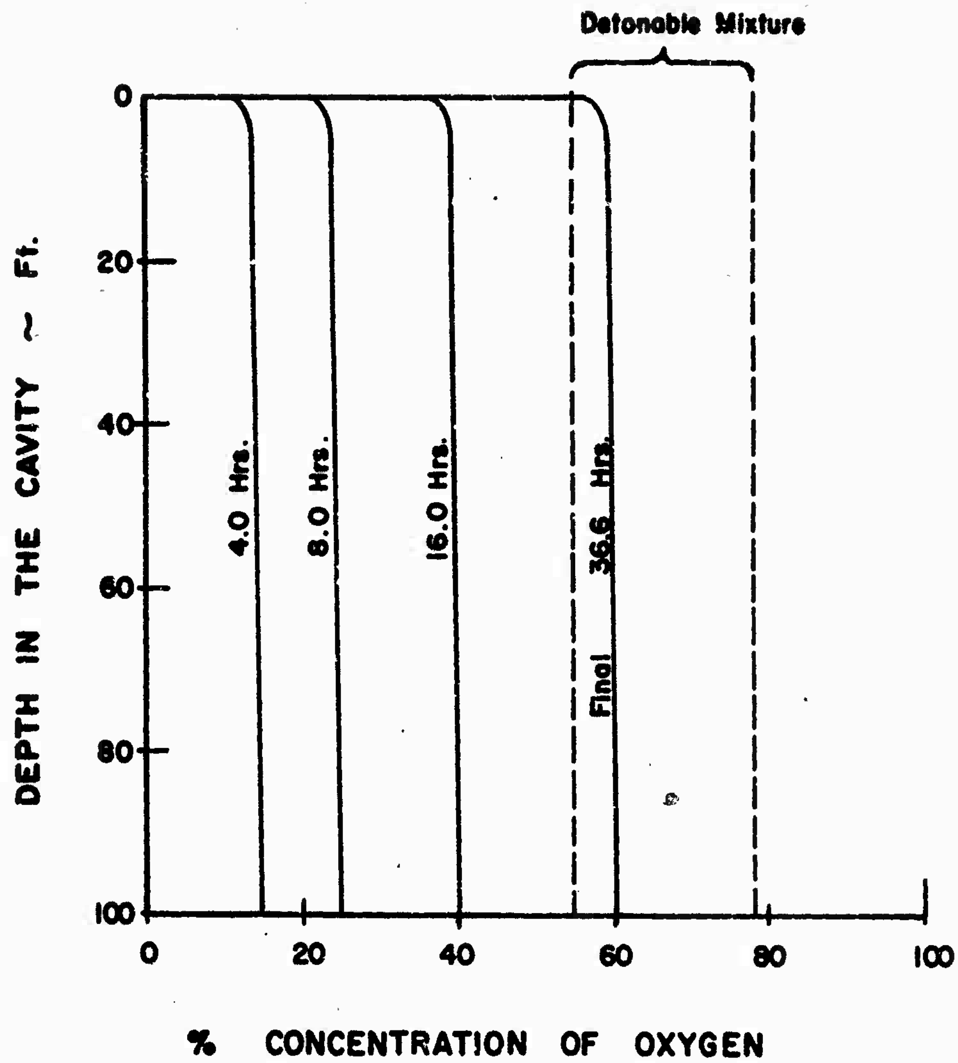

Figure 5. HEAVY PLUME; CONCENTRATION OF OXYGEN IN A SPHERICAL CAVITY.

change in concentration over 98% of the cavity height is les than 10% by the time only 1/10 of the total oxygen has been added to the cavity.

Details of the plume are shown in Figure 6. Initially the plume expands rapidly as a turbulent momentum jet, then less rapidly, characteristic of a turbulent buoyant plume. The concentration of oxygen is such that the weight of the plume gases are always heavier than the cavity gas except at the floor of the cavity where they are equal.

The buoyancy of the plume gas decreases rapidly downstream of the nozzle. If initially there existed a significant density gradient with depth in the cavity, the plume buoyancy would reverse before reaching the cavity floor. The position at which the plume terminates in this case cannot be predicted by this analysis.

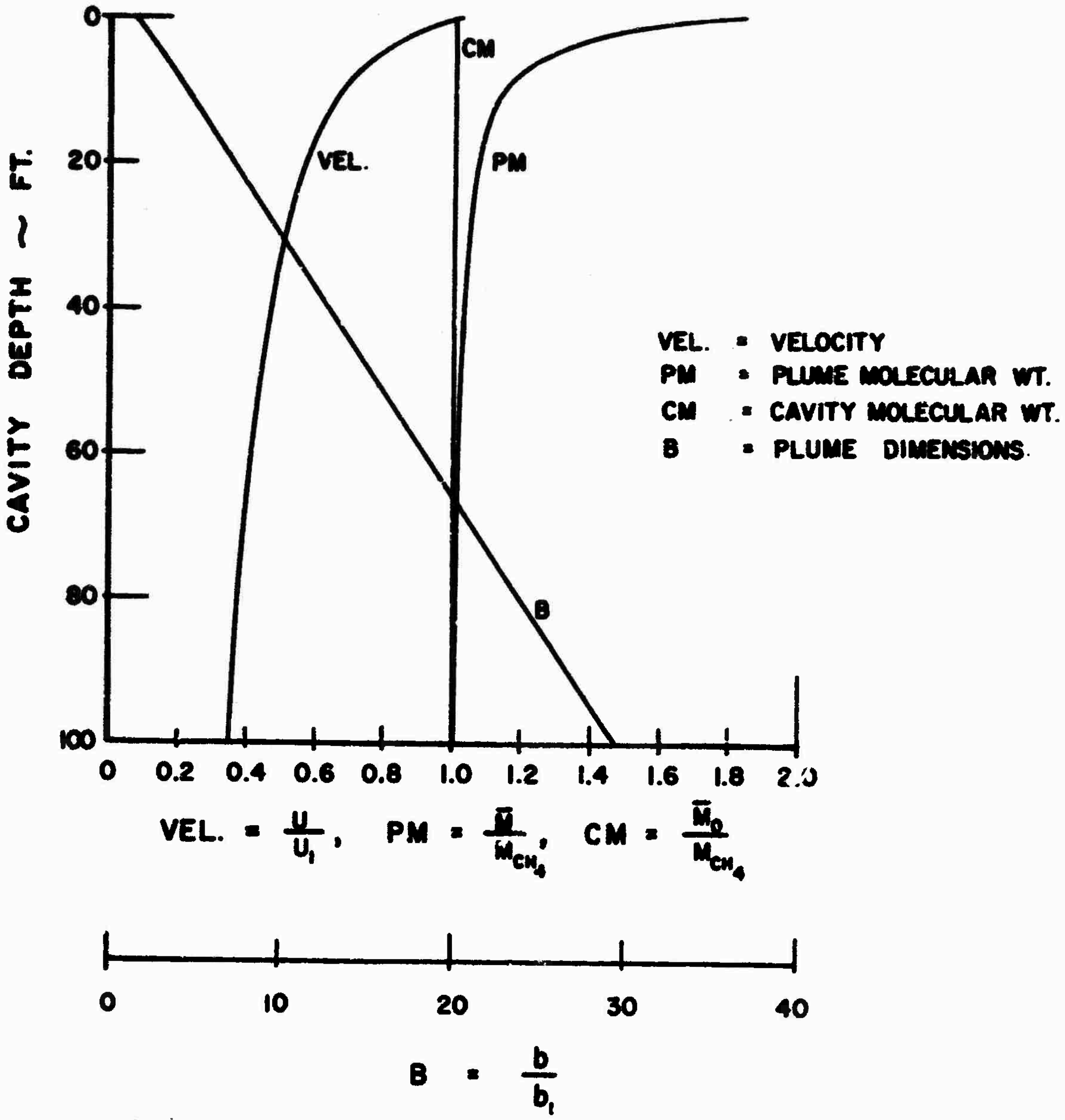

Figure 6. HEAVY PLUME IN A SPHERICAL CAVITY

Alternate Heavy and Light Plumes

Alternate heavy and light plumes formed by alternately loading small volumes of the gases, can be analyzed using the methods and model already described provided one assumes that the heavy plume terminates at a position of neutral buoyancy. In application to the mixing produced, this assumption is probably quite accurate because observations of plumes in the atmosphere show that the plumes penetrate only slightly into the layer where the buoyancy reverses [5].

For this method of loading (alternate slugs), most of the mixing in the cavity takes place by the action of the heavy plume. Thus good mixing can be expected above the position of the steep density gradient in the cavity while the heavy gas is being loaded. Poor mixing occurs while the light gas is being loaded. If the first volume added to the cavity is heavy gas it will be compressed to the floor of the cavity and if the last volume is light gas, it will be concentrated at the ceiling.

Discussion

The method of loading used in Diode Tube Event corresponds to that described under the section: Light Plume; Methane Source. The results show that very little mixing takes place from the action of the light plume, resulting in a small volume of inflammable gas in a disk on a central plane of the sphere (see Figure 4). During the methane loading time (one day) molecular diffusion contributes very little to the mixing. However, in Diode Tube Event, the gases remained in the cavity approximately 10 days before they were detonated. If one computes the mixing due to molecular diffusion

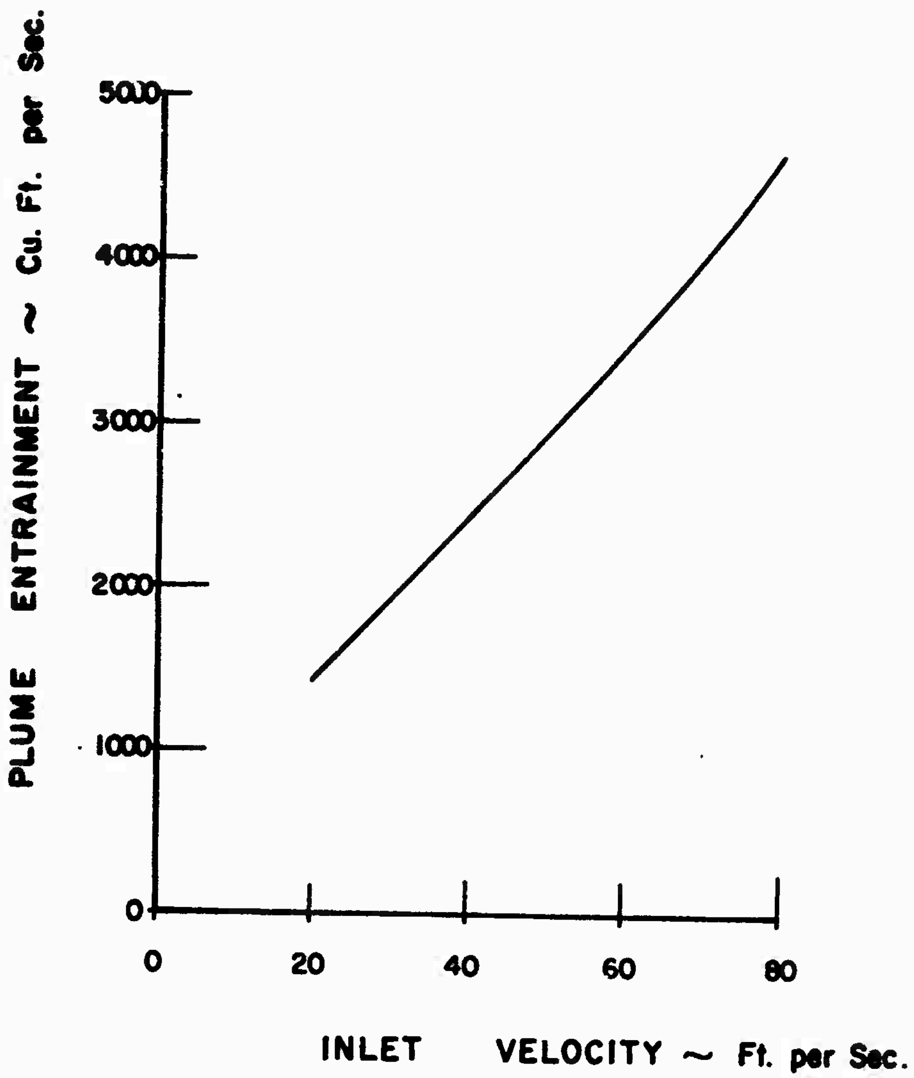

Figure 7. ENTRAINMENT BY HEAVY PLUME.

over a 10 day period (see Appendix 3) one obtains 7% of the cavity volume within the detonability limits with approximately 25% of the volume within the limits of inflammability. This conservative estimate of the mixing could account for the decreased yield of explosive implied by the seismic signal amplitudes obtained in Diode Tube Event.

The excellent mixing obtained by the action of the heavy plume occurs because of the large volume flux entrained by the plume which penetrates the full depth of the cavity. Loading the oxygen last also has the advantage that the individual gases are in contact over the longer oxygen fill time, 36 hours.

The mixing can be further improved by increasing the velocity of the gas entering the cavity. Figure 7 shows the volume flux entrained by the initial plume in the cavity for varying inlet velocities. The velocities shown in Figure 7 straddle those pertaining to Diode Tube Event (~40 ft/sec). The entrainment of cavity gas due to the initial plume varies approximately linearly in this velocity range. Inlet velocities are limited, by safety regulations for oxygen handling, to approximately 400 ft/sec.

Recommendation

General American Research Division recommends loading all of the methane into the cavity,then all of the oxygen for Humid Water and Dinar Coin Events. The heavy turbulent plume formed by this method of loading takes advantage of excellent natural mixing in the cavity. The simplicity of the method provides safety in handling and has economic advantages.

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APPENDIX 1

MOMENTUM JET

Free jets become turbulent for Reynolds numbers (R_c) approximately equal to 30[1]:

$$R_e = \frac{UD}{\nu}$$

where U is the velocity, D is the diameter and ν is the kinematic viscosity of the jet source. Using the values pertinent to Diode Tube Event, one obtains, for the methane jet,

$$r \times 10^3 < R_{jet} < 25 \times 10^3$$

This range of values is greater than R_c by more than a factor of 100, indicating that the entrance jet is turbulent.

An excellent review article on the mixing occurring in a turbulent free jet was given by W. Forstall and A. H. Shapiro[2]. The theory originated by H. B. Squire and J. Trouncer[3] has been extended by C.duP. Donaldson and K. E. Gray[4] to include the compressible free mixing of two dissimilar gases. A simplification of this theory applies to the present problem.

The axially symmetric turbulent free jet may be divided into two regions (see Figure 3): 1) the core region, and 2) the fully developed region. In the core region, the momentum transfer has not diffused to the center of the jet, so that at the center of the core region, the mean axial velocity is essentially constant. At the start of the fully developed region, the core has diminished to zero and the radial velocity profile is Gaussian.

Following Donaldson and Gray, one can write for any section of the jet,

$$\frac{d}{ds} \int^{r^*} \rho u r \, dr + u(r^*) \frac{d}{ds} \int^{r^*} \rho u r \, dr + r^* \tau^* = 0. \tag{1}$$

This equation states that the rate of change in axial momentum is equal to the mass added at velocity $u(r^*)$ plus the Reynolds stress acting at r^*.

If the arbitrary radius r^* is allowed to increase without limit, equation (1) becomes

$$\int_0^\infty \rho u^2 r \, dr = \text{constant}. \tag{2}$$

An equation which satisfies the species conservation and momentum conservation simultaneously is given by

$$C = u/u_1 \tag{3}$$

where C is the mass fraction of the jet gas and u is the mean velocity of the jet. Assuming the perfect gas law for a mixture of ideal gases and a constant pressure in the jet, one obtains

$$\rho = \frac{\bar{M}P}{RT} \tag{4}$$

and

$$\bar{M} = \frac{1}{C\left(\frac{1}{M_1} - \frac{1}{M_2}\right) - \frac{1}{M_1}} \tag{5}$$

where ρ, $\bar{M}$, P, T are the density, molecular weight of the mixture, pressure, and temperature and R is the universal gas constant.

The Reynolds stress is assumed to be given by;

$$\tau^* = \frac{K}{2} \rho (r^* - r_c) u_c \frac{\partial u}{\partial r} \tag{6}$$

where r_c is the core radius, u_c is the centerline velocity and K is a constant evaluated by experiment.

The velocities in the core and fully developed regions are given by

$$u = u_c e^{-\lambda \frac{r^2 - r_c^2}{r_5^2 - r_c^2}} \qquad r \geq r_c \tag{7a}$$

$$u = u_c e^{-\lambda r^2/r_5^2} \tag{7b}$$

where r_5 is a characteristic radius at which the velocity is given by

$$u_5 = \frac{u_c}{2}$$

Substituting $r^* = r_5$ in equation (1) and combining with equations 2 - 7a yields an equation which can be solved in closed form for the length of the core region (S_c).

One obtains

$$S_c = \frac{(1-I)(1 + \frac{\delta}{2})}{(1+\delta) K \lambda a} \left[-2 - \frac{1}{\sqrt{\frac{a}{a-1}}} \ln \frac{1 - \sqrt{\frac{a}{a-1}}}{1 + \sqrt{\frac{a}{a-1}}} + \sqrt{1-a} \right] \tag{8}$$

where

$$\delta = \left(\frac{M_2}{M_1} - 1 \right)$$

$$I = \frac{\left[\delta + (2 + \delta) \ln \frac{1 + \frac{\delta}{2}}{1 + \delta} \right]}{\delta - \ln(1 + \delta)}$$

and

$$a = \frac{\lambda \delta^2}{(1 + \delta)[\ln(1 + \delta) - \delta]}$$

Reference 4 gives K = .45 while for a methane jet into oxygen,

$$\delta_{CH_4} = 1$$

and for an oxygen jet into methane,

$$\delta_{O_2} = -\frac{1}{2}$$

Substitution of these values into equation (8) yields the core length for an incompressible momentum jet. These values are shown in Figure 1, represented by the straight line portion of the curve.

Equations 1 - 7b may be combined to obtain:

$$\frac{dx}{dv} = \frac{\delta\ (1 + v/2)}{(1 + v)\ K\ (1 + \delta)^{1/2}\ \lambda^{3/2}} \left[\frac{1}{[v - \ln(1 + v)]^{3/2}} - \frac{1}{v[v - \ln(1 + v)]^{1/2}} \right]$$

where $v = \delta \frac{u_c}{u_1}$ and $x = \frac{s}{r_1}$

This equation was solved by numerical integration. (The program, written in Fortran IV, appears at the end of this appendix.) The results of the computations are shown in Figure 1.1 which shows the mass fraction of the jet gas as a function of distance along the jet, in jet nozzle radii.

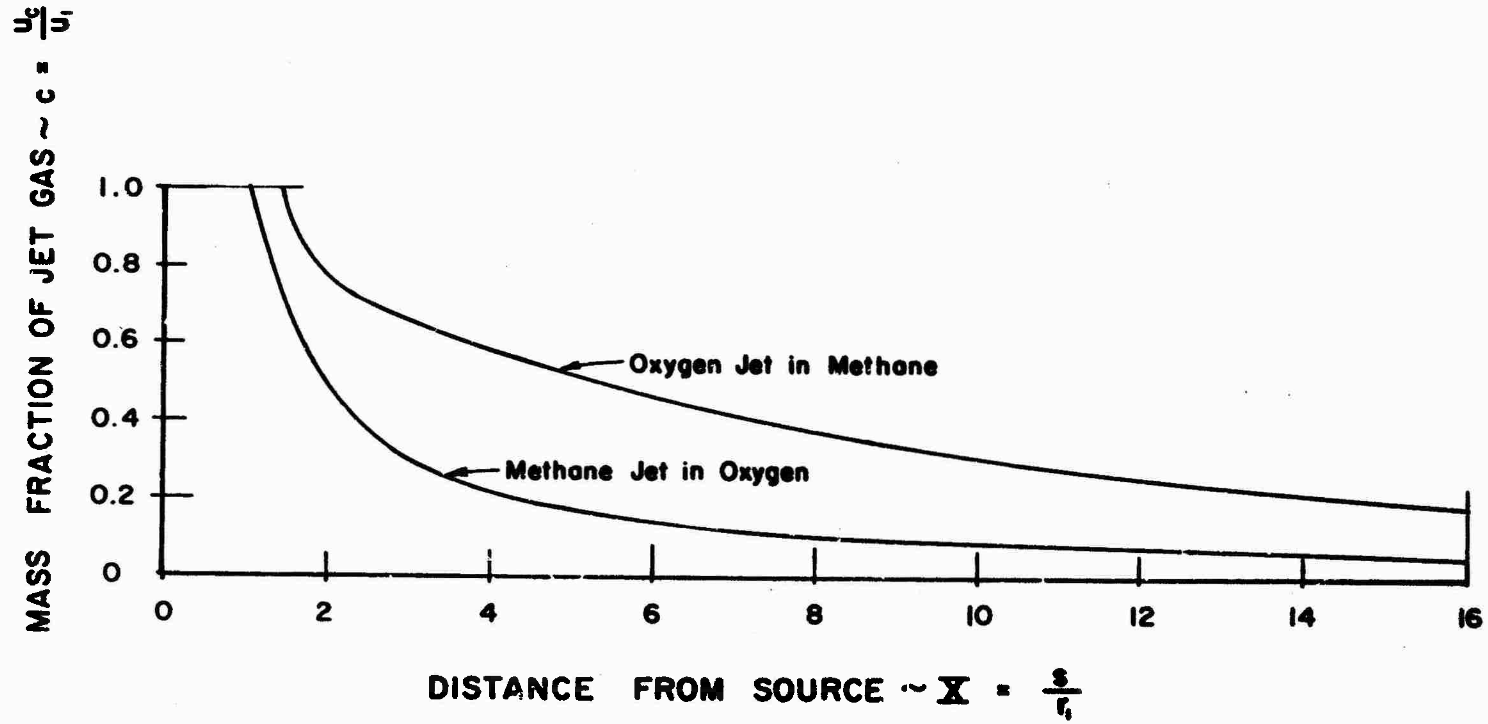

Figure 1.1 ENTRAINMENT BY A MOMENTUM JET MASS FRACTION OF JET GAS VS DISTANCE ALONG JET.

```
// JOB T
// FOR
*EXTENDED PRECISION
*ONE WORD INTEGERS
*LIST ALL
      SUBROUTINE HOLME (F,V)
      F=V*(1.&V)*(V-ALOG(1.&V))**(0.5)*(V-ALOG(1.&.5*V))/((1.&V/2.)
     1*ALOG(1.&.5*V))
      RETURN
      END
// DUP
*STORE      WS  UA  HOLME
// FOR
*IOCS(CARD,1132PRINTER)
*EXTENDED PRECISION
*ONE WORD INTEGERS
*LIST ALL
    5 READ(2,1) DELTA
      READ(2,1)B
      FACT=-1
    1 FORMAT (E14.6)
      WRITE (3,35) DELTA
   35 FORMAT(10X,'DELTA = 'F14.4,/)
      X=.0001
      V = DELTA
      DO 20 I=1,100
    6 WRITE (3,2) X,V
    2 FORMAT (10X,'X = ',F15.4,'  V = ',F14.6,/)
      XNEXT = .0001*10.**(I*B)
      DX = XNEXT - X
      IF (ABS(V)-.0001*ABS(DELTA))4,4,3
    3 CALL HOLME (F1,V)
      VT= V & F1*DX*0.5
      CALL HOLME (F2,VT)
      VT = V & F2*DX*0.5
      CALL HOLME (F3,VT)
      VT = V & F3*DX
      CALL HOLME (F4,VT)
      V = V & FACT*(F1 & 2.0*F2 & 2.0*F3 & F4)*DX/6.
   20 X = XNEXT
    4 CONTINUE
      CALL EXIT
      END
// XEQ
  -.500000E&00
   .100000E+00
// XEQ
  -.500000E&00
   .500000E-01
```

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APPENDIX 2

CONVECTION IN A SPHERICAL CAVITY

Introduction

An estimate of the convective motion in the spherical cavity due to the momentum in the free jet will be made. The free jet, which actually adds mass to the cavity, will be replaced by a source of momentum in the form of a small sphere of radius c on which the fluid velocities are specified, where c << d and d is the radius of the cavity.

The gas inside the cavity will be assumed to be homogeneous and the flow will be assumed to be steady and axisymmetric. The equations of motion applicable to this flow are the equations representing conservation of mass and momentum given by

$$\rho \, \underline{v} \cdot \nabla \, \underline{v} = -\nabla P + \mu \, \nabla^2 \, \underline{v} \qquad (1)$$

and

$$\nabla \cdot \underline{v} = 0 \qquad (2)$$

where ρ , $\underline{v}$, P and μ are the density, velocity, pressure, and viscosity, respectively.

If the Reynolds number of the flow is small, $R_e = \frac{VD}{\nu} < 1$, then the dynamic stress on the left hand side of (1) may be neglected with respect to the viscous stresses. The restriction on the flow that $R_e < 1$ will certainly be in error near the source (as already discussed in relation to turbulent jets), but near the walls of the cavity, where the velocities are much lower than at the momentum source, low Reynolds number flow will be approximated.

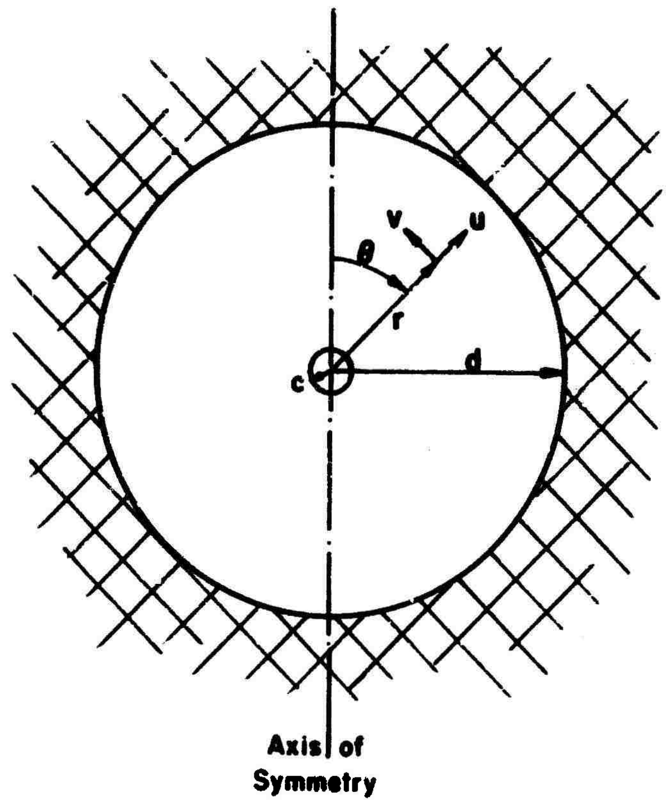

Figure 2.1 COORDINATE SYSTEM IN A SPHERICAL CAVITY.

For flow at low Reynolds number, the equations reduce to[1]

$$\nabla^2 \underline{\omega} = 0 \qquad \underline{\omega} = \nabla \times \underline{v} \tag{3}$$

$$\nabla \cdot \underline{v} = 0 \tag{4}$$

<u>Analysis</u>

In terms of a spherical coordinate system with axial symmetry whose origin is centered in the sphere and whose axis of symmetry is vertical (see Figure 2.1), the equations become

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(\frac{r^2 \partial\omega_\phi}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial\omega_\phi}{\partial\theta}\right) - \frac{\omega_\phi}{r^2 \sin\theta} = 0 \tag{5}$$

$$\frac{1}{r}\left\{\frac{\partial}{\partial r}(rv) - \frac{\partial u}{\partial\theta}\right\} = \omega_\phi \tag{6}$$

$$0 = \frac{1}{r^2}\frac{\partial(r^2 u)}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\, v) \tag{7}$$

with boundary conditions $u = v = 0$ at $r = d$ and u, v are specified on a spherical surface about the momentum source.

Equation (5) is the vector Laplace equation which is separable in the spherical coordinate system[2].

$$\omega = r^n S_n \quad \text{where } S_n = S(\theta) \text{ only.} \tag{8}$$

Substituting (8) into (7) and setting $\mu = \cos\theta$, one obtains

$$\frac{d}{d\mu}\left\{(1-\mu^2)\frac{dS_n}{d\mu}\right\} + \left\{n(n+1) - \frac{m^2}{1-\mu^2}\right\}\delta_n = 0 \tag{9}$$

where $m = 1$

This is Legendre's associated equation which has a solution in terms of Legendre's associated polynomials $P_n^m(\mu)$. (3) One obtains

$$\omega_\phi = \sum_{n=0}^{\infty} \left\{ \begin{matrix} b_n & r^n \\ a_n & r^{-n-1} \end{matrix} \right\} P_n^m(\mu) \tag{10}$$

Substituting equation (10) into equation (6) and cross differentiating equation (6) and (7) to separate u and v gives,

$$\frac{(1-\mu^2)^{1/2}}{r} \frac{\partial^2}{\partial\mu^2}\left[(1-\mu^2)^{1/2} v\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \frac{\partial}{\partial r}(rv)\right] = \sum_{n=1}^{\infty}\left[(n+3)b_n r^n + (2-n)a_n r^{-n-1}\right] P_n^1(\mu)$$

and (11)

$$\frac{1}{r}\frac{\partial^2}{\partial r^2}(r^2 u) + \frac{1}{r}\frac{\partial}{\partial\mu}\left[(1-\mu^2)\frac{\partial u}{\partial\mu}\right] = \sum_{n=1}^{\infty}(b_n r^n + a_n r^{-n-1})\frac{\partial}{\partial\mu}(1-\mu^2)^{1/2} P_n^1(\mu) \tag{12}$$

The general solutions to equations (11) and (12) are given by

$$u = \sum_{n=0}^{\infty}\left\{ \begin{matrix} \beta_n r^{n-1} + b_n \dfrac{n(n+1)}{(n+2)(n+3)-n(n+1)} r^{n+1} \\ \alpha_n r^{-n-2} + a_n \dfrac{n(n+1)}{(1-n)(2-n)-n(n+1)} r^{-n} \end{matrix} \right\} P_n$$

$$v = \sum_{n=0}^{\infty}\left\{ \begin{matrix} \dfrac{\beta_n r^{n-1}}{n} + b_n \dfrac{n+3}{(n+3)(n+2)-n(n+1)} r^{n+1} \\ -\dfrac{\alpha_n}{n+1} r^{-n-2} + a_n \dfrac{2-n}{(2-n)(1-n)-n(n+1)} r^{-n} \end{matrix} \right\} P_n^1 \tag{13}$$

where the terms with coefficients α and β are from the solution of the homogeneous equation and those with coefficients a and b from the particular solution.

The Momentum Source

The momentum source is determined by specifying a continuously varying velocity on the surface of a sphere. In principle, the momentum source can be placed anywhere within the cavity boundary but the solution is greatly simplified if the sphere representing the source is chosen to be concentric with the spherical cavity.

The velocities u and v on the surface of the source corresponding to a point source momentum at the sphere center can be specified in terms of a series of Legendre Polynomials. (4)

One obtains

$$u\Big|_{r=c} = \sum_{m=0} F_m P_m \qquad\qquad (14)$$

$$v\Big|_{r=c} = \sum_{m=0} G_m P_m'$$

where F and G are functions of c only.

The Solution

At the cavity boundary (r = d) the velocities are zero.

$$u\Big|_{r=d} = 0 \qquad\qquad (15)$$

$$v\Big|_{r=d} = 0$$

These are sufficient boundary conditions to determine a_n, b_n, α_n and β_n from equation (13) uniquely. One obtains

$$a_n^* = na_n = \frac{4n(1-2n)\left[\frac{F_n}{n+1} + G_n\right] c^{1-n} (d^{2n+3}-c^{2n+3}) + 2(1-2n)(2n+3)\left[F_n - nG_n\right](d^2-c^2)c^{n+2}}{(1-2n)(2n+3)(d^2-c^2) - 4(d^{2n+3}-c^{2n+3})(d^{1-2n}-c^{1-2n})}$$

$$b_n^* = nb_n = -2n\left[\frac{F_n}{n+1} + G_n\right]\frac{c^{1-n}}{d^2-c^2} - a_n^*\left(\frac{2}{1-2n}\right)\left(\frac{d^{1-2n}-c^{1-2n}}{d^2-c^2}\right) \qquad (16)$$

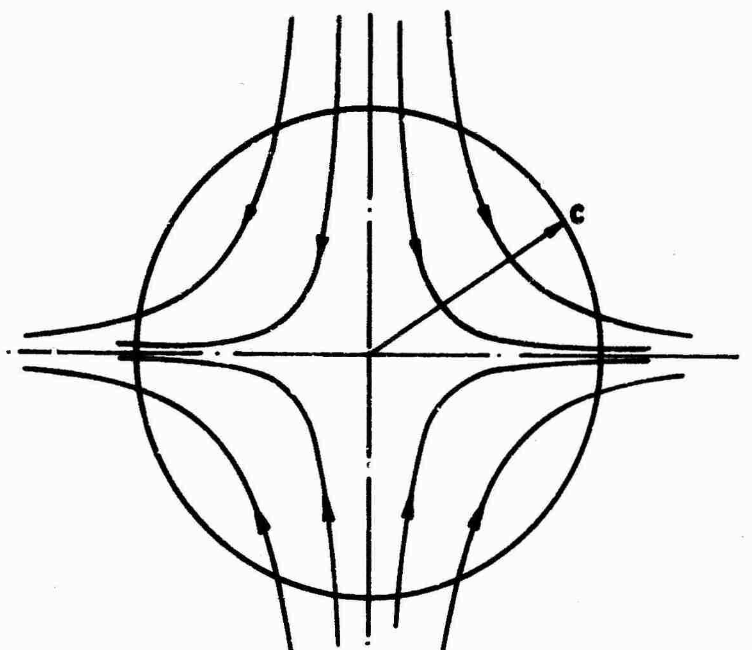

Figure 2.2 AXISYMMETRIC STAGNATION POINT FLOW

$$\alpha_n = \frac{b_n^* \, (n+1)}{(2n+1)(2n+3)} \, d^{2n+3} + a_n^* \, \frac{(n+2)}{2(2n+1)} \, d^2$$

(16) Cont'd

$$\beta_n = -b_n^* \, \frac{n+1}{2(2n+1)} \, d^2 - a_n^* \, \frac{n+1}{(1-2n)(2n+1)} \, d^{1-2n}$$

If axisymmetric stagnation flow is assumed, the inner boundary conditions can be expressed by two Legendre polynomials and one associated Legendre polynomial. The axis of symmetry is assumed to coincide with the vertical axis (see Figure 2.2).

On the boundary of the sphere, v = c, the velocities u and v are given by

$$u \Big|_{r=c} = kc \, (P_o - 2P_2) \qquad v \Big|_{r=c} = -kc \, P_2^1 \qquad (17)$$

where k is a parameter which can be used to match the physical conditions of the jet. Using equations (15), (16), and (17), the flow in the cavity can be determined. The velocities u and v are given by

$$\frac{u}{kc} \approx \left(\frac{2r}{d^3} + \frac{1}{r^2} - \frac{3}{d^2}\right) c^2 \, P_o + \left(\frac{25}{2} \frac{r}{d^3} - \frac{15}{2} \frac{r^3}{d^5} + \frac{3c^2}{r^4} - \frac{5}{r^2}\right) c^2 \, P_2 \qquad (18)$$

$$\frac{v}{kc} \approx \left(\frac{25}{4} \frac{r}{d^3} - \frac{25}{4} \frac{r^3}{d^5} - \frac{c^2}{r^4}\right) c^2 \, P_2^1$$

where terms of order $\epsilon^2 = \left(\frac{c}{d}\right)^2$ have been neglected in determining the series coefficients.

The flow parameter k and radius of the source c must yet be evaluated to determine the flow in the cavity. From equation (17),

$$u(\theta)\Big|_{r=d} = 0 \qquad \text{when } \theta = \frac{2\pi}{5}, \frac{3\pi}{5}$$

The constant k can be adjusted so that the mass flow rate into the spherical source at r = c equals the mass flow rate in Diode Tube Event (336 lbm-mole/hr). Simultaneously c can be so chosen to match the velocities in the inlet pipe corresponding to Diode Tube Event. One obtains

$$50 < k < 100 \ \frac{1}{\text{sec}} \qquad c = .268 \text{ ft.} \tag{19}$$

From equation (18) it can be seen that near the cavity wall v behaves as:

$$\frac{v}{kc}\Big|_{R \approx 1} \approx \frac{25}{4}\,\epsilon^2\,(R-R^3)\,P_2^1 \tag{20}$$

where $R = \frac{r}{d}$. P_2^1 has a maximum value of 1/2 at $\theta = \pi/4$. Substituting equations (19) into (18), one obtains

$$1/2 \text{ ft/hr} < v(\pi/4, .9) < 1 \text{ ft/hr}$$

at $R = \frac{r}{d} = .9$

and

$$4 \text{ ft/hr} < v(\pi/4, .5) < 8 \text{ ft/hr}$$

at $R = .5$

The convection velocities due to inlet momentum are seen to be very low, corresponding to Diode Tube Event. The stabilizing forces of buoyancy which have not been included in the analysis, but which actually exist in the cavity, would further limit the forced convection.

Equation (18) may also be used to estimate the radius at which u and v are zero in the mixing region. This is the radius which describes a circle through which all of the streamlines in the cavity pass. R_o is found to be 1/10. This further substantiates the limited effect of the momentum in the jet.

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1. G. K. Batchelor, "An Introduction to Fluid Mechanics", Cambridge University Press (1967).

2. P. M. Morse and H. Feshbach, "Methods of Theoretical Physics", McGraw-Hill Book Co., Inc. (1953).

3. E. W. Hobson, "The Theory of Spherical and Ellipsoidal Harmonics", Cambridge University Press (1931).

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APPENDIX 3

MIXING BY MOLECULAR DIFFUSION

In Diode Tube Event, there was a 10 day period of time between loading the detonable gases and their ignition. The methane loading, which took approximately 1 day, brought the cavity pressure up to 15 atmospheres. If it is assumed that the gases, at 15 atm., are initially separated at a 40 ft. depth in the cavity, an estimate of the molecular diffusion occurring in the cavity during the 10 day period can be made.

It will be assumed that the portion of the spherical cavity over which significant molecular diffusion takes place can be described by an infinite cylinder. The solution obtained will show that the diffusion distance, over 10 days, is short enough to justify these assumptions.

The diffusion equation is given by

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \tag{1}$$

where D is the diffusion coefficient, c is the mole fraction of one constituent, and x and t are distance from the interface and time, respectively.

A similarity solution of this equation which satisfies the boundary condition is

$$c = \frac{1}{2}\left(1 - \operatorname{erf}\left(\frac{x}{\sqrt{4Dt}}\right)\right) \tag{2}$$

The diffusion coefficient is given by R. C. Reid and T. K. Sherwood[1].

$$D = \frac{.001858\ T^{3/2}\left[(M_1 + M_2)/M_1 M_2\right]^{1/2}}{P_o\ \sigma_{12}^{2}\ \Omega} \tag{3}$$

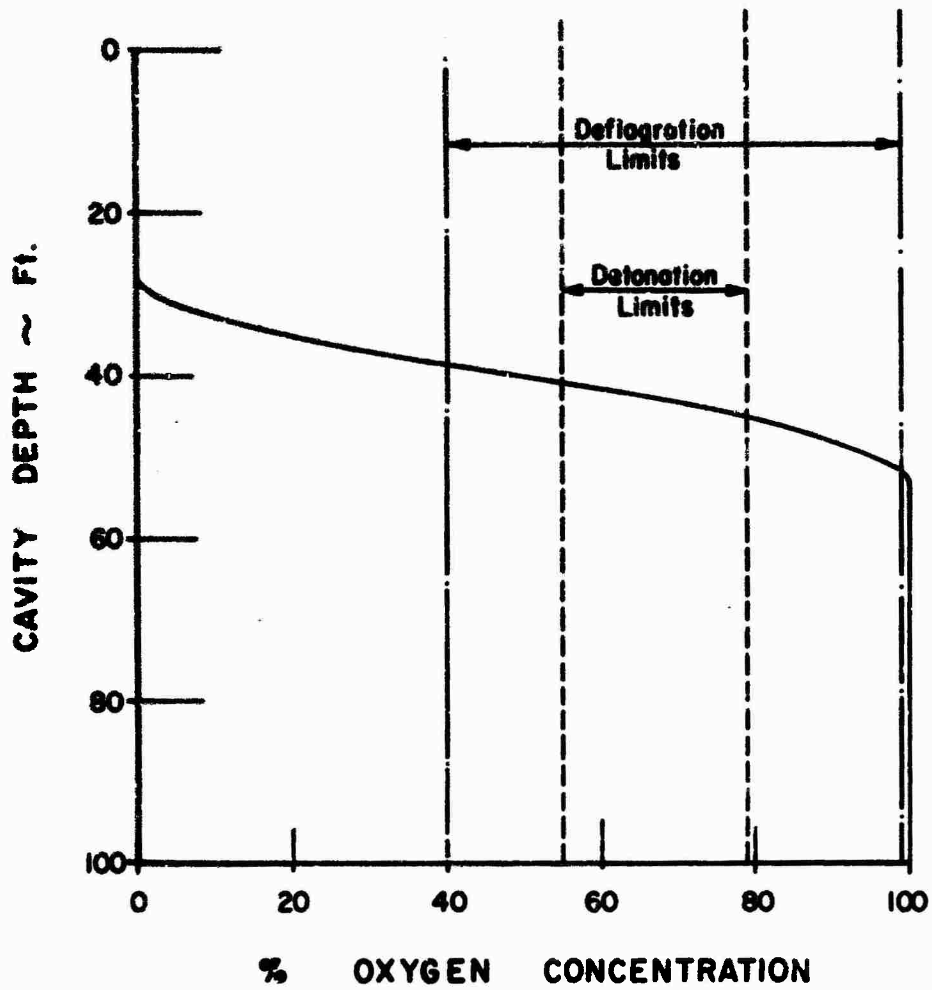

Figure 3.1 MOLECULAR DIFFUSION

where T is the absolute temperature in °K, P_o is the pressure in atmospheres, M_1 and M_2 are the molecular weights of the gases, and σ_{12} and Ω_o are empirically determined constants.

The conditions pertaining to Diode Tube Event are given by:

$$T = 330°K$$
$$P_o = 15 \text{ atm}$$
$$M_{CH_4} = 16$$
$$M_{O_2} = 32$$
$$\Omega_D = .96$$
$$\sigma_{12} = 3.627$$

One obtains

$$D = .02 \text{ cm}^2/\text{sec}$$
$$T = 10 \text{ days}$$

and

$$c = \frac{1}{2} \left(1 - \text{erf}\left(\frac{x}{2.62 \text{ m}}\right)\right) \quad (4)$$

Equation (4) is evaluated in terms of the curve in Figure 3.1 as it is applied to mixing in the spherical cavity. The limits of detonability and inflammability are also indicated in the figure. This curve shows that a disc of detonable gases lies between 41 and 46 ft. The gases in this disc represent 7% of the total volume of the sphere. 25% of the total volume is within the limits of inflammability.

BIBLIOGRAPHY FOR APPENDIX 3

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APPENDIX 4

PROGRAM WITH COMPUTER PRINT-OUT FOR THE HEAVY AND LIGHT PLUMES

Nomenclature

T	=	(real time hr.)/9.75
H	=	depth in cavity = h/D
CM	=	molecular wt. cavity gas = $\bar{M}_o/M_{CH_4}$
DCM/DX	=	$\frac{d(CM)}{dx}$
B	=	plume dimension = b/b_1
VEL	=	velocity of plume gas = u/u_1
PM	=	molecular wt. plume gas = M_o/M_{CH_4}
S	=	distance along plume = s/D
X	=	depth in cavity = x/D
R	=	radial dimension = y/D
QNET	=	net volume flux in plume at section X
PLVOL	=	volume of plume up to section at X

```
*DELETE                 QUAD
// FOR
*EXTENDED PRECISION
*ONE WORD INTEGERS
      SUBROUTINE QUAD(YK,Y,XK,X,J)
      DIMENSION Y(30),X(30)
      IF (J-2) 1,1,2
 1    J1=J
      J2=J-1
      JS=J+1
      GO TO 3
 2    JS=J
      J1=J-1
      J2=J-2
3     A0=Y(J2)/((X(J2)-X(J1))*(X(J2)-X(JS)))
      A1=Y(J1)/((X(J1)-X(J2))*(X(J1)-X(JS)))
      A2=Y(JS)/((X(JS)-X(J2))*(X(JS)-X(J1)))
      YK=A0*(XK-X(J1))*(XK-X(JS))+A1*(XK-X(J2))*(XK-X(JS))+A2*(XK-X(J2))
     1*(XK-X(J1))
      RETURN
      END
// DUP
*STORE       WS   UA   QUAD
// JOB
// DUP
*DELETE                 LBHOP
// FOR
*EXTENDED PRECISION
*ONE WORD INTEGERS
      SUBROUTINE LBHOP (PY,VEL,H,V,CONST,P)
      DIMENSION V(8)
      C=SQRT(V(3)**2+P*P)
      D=(4.*V(1)*V(2)-V(1)**2*V(7))/(6.*C)
      H=CONST*SQRT(D)
      VEL=V(1)/(D*CONST**2)
      PY=2.*V(2)/V(1)-V(7)
      RETURN
      END
// DUP
*STORE       WS   UA   LBHOP
// DUP
*DELETE                 LBHGP
// FOR
*EXTENDED PRECISION
*ONE WORD INTEGERS
      SUBROUTINE LBHGP (G,V,F,DUXX,P,CONST)
      DIMENSION G(8), V(8)
      C=SQRT(V(3)**2+P*P)
      D=(4.*V(1)*V(2)-V(1)**2*V(7))/(6.*C)
      G(1)=SQRT(V(1)**2/D)
      G(2)=SQRT(V(1)**2/D)*V(7)
      G(3)=F*D*2.0*(V(2)/V(1)-V(7))
      G(4)=1.0
      G(5)=V(3)/C
      G(6)=P/C
      G(7)=DUXX*V(3)/C
      G(8)=CONST**2*D
      RETURN
      END
// DUP
*STORE       WS   UA   LBHGP
```

```
// JOB
// DUP
*DELETE             LBHMP
// FOR
*IOCS(CARD,1132PRINTER)
*EXTENDED PRECISION
*ONE WORD INTEGERS
*ARITHMETIC TRACE
*TRANSFER TRACE
C                    SIMULTANEOUS DIFFERENTIAL EQUATIONS                 LBHML001
C                27 JANUARY 1970                                          LBHML002
C                                                                         LBHML003
      DIMENSION V(8),G(8),DGA(8),DGB(8),DGC(8),MTIM(100),PLR(40),VO(40)  LBHML004
      DIMENSION PL(8,40),PL1(40),PL2(40),PL5(40),PL6(40),Y(40),PL3(40)   LBHML005
      DIMENSION X(100), H(100), U(100), UP(100), DUX(100), DUPX(100)     LBHML006
      DIMENSION PL4(40)
C                                                                         LBHML007
    9 FORMAT (I2,I4,4F7.0)
   10 FORMAT(I2,10F7.0)                                                   LBHML008
   11 FORMAT(1H1,'BUOYANT PLUME IN A SPHERICAL CAVITY')                   LBHML009
   12 FORMAT(1H0,'INPUT DATA',//,11X,'MOLECULAR WEIGHT OF JET',I7,/,11X  LBHML010
     1,'SPACE STEPS IN CAVITY',F10.0                                      LBHML011
     2,/,11X,'INITIAL COS(THETA)',F19.6,/,11X,'FINAL NUMBER OF MOLES'     LBHML012
     3F10.0,/,11X,'MOLES IN SLUG OF METHANE',F7.0,/,11X,'MOLES IN SLUG OLBHML013
     4F OXYGEN',F8.0,/,11X,'INITIAL MOLES IN CAVITY',F8.0,/,11X,'ENTRAINLBHML014
     5MENT COEFFICIENT',F12.4,/,11X,'MOLE FLOW RATE PER SECOND',F10.4)   LBHML015
   13 FORMAT(1H ,10X,'RADIUS OF ENTRANCE JET',F13.4)                      LBHML016
   14 FORMAT(1H0,'TIME =',F9.6,/,1X)                                      LBHML017
   15 FORMAT(1H0,/,5X,'B',6X,'VEL',6X,'PM',9X,'S',7X,'X',7X,'R',7X,'CM',LBHML018
     129X,'Y',9X,'Z',10X,'W',8X,'VOL',/,)                                 LBHML019
   16 FORMAT(1H ,F7.2,F9.4,F11.6,3F8.3,F11.6,F28.3,F10.3,F10.0,F10.3)    LBHML020
   17 FORMAT(1H0,3X,'XMAX',5X,'SXMAX',5X,'CMAVE',//,2F8.3,F11.6,///,3X,  LBHML021
     1'ONET',6X,'X',7X,'PLVOL',/,1X)                                      LBHML022
   18 FORMAT(1H ,2F8.3,F10.3)                                             LBHML023
   19 FORMAT(1H0,/,3X,'M',6X,'H',10X,'CM',7X,'DCM/DX',/,1X)               LBHML024
   20 FORMAT(1H ,I3,3F11.6)                                               LBHML025
   21 FORMAT(1H0,   'DS DECREASED TO ',E16.8)                             LBHML026
   22 FORMAT (1H0,'XTA DOES NOT CONVERGE')                                LBHML027
   23 FORMAT (1H0,/,6X,'JET MOLECULAR WEIGHT IS',I3)                      LBHML028
   24 FORMAT (1H0,5X,'BOUNDARY VALUES',/,)                                LBHML029
C                                                                         LBHML030
      CALL TSTOP                                                          LBHML031
  100 READ(2,10 ) MJW,STEP,CS1,FN,SLMN,SLON,CN,AA,DNT,B1                  LBHML032
      READ(2,9 ) NPRNT,NPROF,DEPTH
C                                                                         LBHML034
      MPRNT=NPRNT                                                         LBHML035
      MJ=MJW/16                                                           LBHML036
      CS=CS1                                                              LBHML037
C                                                                         LBHML038
      GO TO (130,110),MJ                                                  LBHML039
C                                                                         LBHML040
  110 CS=1.0                                                              LBHML041
      Z=2.0                                                               LBHML042
      TS=0.0                                                              LBHML043
      IN=1                                                                LBHML044
      VAL=1.0
      DO 120 J=1,100                                                      LBHML045
      H(J)=1.0                                                            LBHML046
  120 U(J)=1.0                                                            LBHML047
      SMN=CN+SLON+SLMN                                                    LBHML048
```

```
      SON=CN+SLON                                                       LBHML049
      TNO=0                                                             LBHML050
      GO TO   150                                                       LBHML051
C                                                                       LBHML052
  130 Z=1.0                                                             LBHML053
        IN=0                                                            LBHML054
      VAL=0.0
      DO 140 J=1,100                                                    LBHML055
      H(J)=0.0                                                          LBHML056
  140 U(J)=2.0                                                          LBHML057
      SON=CN+SLON+SLMN                                                  LBHML058
      SMN=CN+SLMN                                                       LBHML059
      TNO=CN                                                            LBHML060
C                                                                       LBHML061
  150 Y(1)=1.0                                                          LBHML062
      DO 152 I=1,100
  152 DUX(I)=0.0
      WAG=0.0
      T=0.0                                                             LBHML074
      MTIM(1)=0                                                         LBHML097
      MFIN=0                                                            LBHML098
C                                                                       LBHML063
      CALL DATSW (2,LITE)
      GO TO (153,157),LITE
  153 READ (2,20) MFIN,T
      READ (2,20)(MTIM(M),H(M),U(M),DUX(M),M=1,MFIN)
  157 CONTINUE
      WRITE(3,11 )                                                      LBHML064
      WRITE (3,12 ) MJW,STEP,CS,FN,SLMN,SLON,CN,AA,DNT                  LBHML065
      WRITE (3,13   ) B1                                                LBHML066
C                                                                       LBHML067
      SN=SQRT(1.0-CS**2)                                                LBHML068
      SXMAX=1.0                                                         LBHML069
      DX=1.0/STEP
      Q=2.0*STEP+1.0                                                    LBHML071
      KMAX=Q                                                            LBHML072
      LF=30                                                             LBHML073
      S=0.0                                                             LBHML075
      DO 160 I=1,MFIN
      DUPX(I)=DUX(I)
  160 UP(I)=U(I)
C                                                                       LBHML078
      CONST=200.*AA/B1                                                  LBHML079
      W=CONST**2*MJ*CS                                                  LBHML080
      V(1)=Y(1)                                                         LBHML081
      V(2)=Z                                                            LBHML082
      V(3)=W                                                            LBHML083
      V(4)=0.0                                                          LBHML084
      V(5)=0.0                                                          LBHML085
      V(6)=0.0                                                          LBHML086
      V(7)=U(1)                                                         LBHML087
      V(8)=0.0                                                          LBHML088
C                                                                       LBHML089
      DO 170 I=1,8                                                      LBHML090
  170 PL(I,1)=V(I)                                                      LBHML091
C                                                                       LBHML092
      N=0                                                               LBHML093
      NS=1                                                              LBHML094
      DT1=CN*2.85E-05/(DNT*4100)                                        LBHML095
      DT=DT1                                                            LBHML096
```

```
      XMAX=1.0
      MSTO=1
C                                          TIME STEP LOOP
  180 N=N+1
C
      MFIN1=MFIN
      MFIN=MFIN+1
C
  220 DO 230 J=1,8
  230 V(J)=PL(J,1)
C                                          SET V(M) AT S = 0.0
  239 DO 260 J=1,MFIN
      J0=J+1
      DIF = H(J0)-0.01*XMAX
      IF(H(J)-.01*XMAX)   240,   270,   250
  240 DIF = -DIF
  250 IF(DIF)   270,   280,   260
  260 CONTINUE
      V(7)=PL(7,1)
      GO TO   290
C
  270 V(7)=U(J)
      GO TO   290
C
  280 V(7)=U(J0)
C
  290 P=CONST**2*MJ*SN
      RN=1.+DNT*T/(2.85E-05*CN)
      CC=1./(16.*B1**2)
      U1=(DNT*.2187666E+06)/(CN*RN*B1**2*CC)
      F=.30912E+14*AA**4/(U1**2*B1**4)
      HH=B1**2*U1/28.5
      CNT=RN*CN
      PL(7,1)=V(7)
      GO TO (291,292) ,NPROF
  291 ALL=0.0
      GO TO 293
  292 ALL=SQRT(.25+2.*MJ/PL(7,1))-.5
  293 V(1)=1.+ALL
      V(2)=MJ+ALL*V(7)
      PL(2,1)=V(2)
      PL(1,1)=V(1)
      CALL LBHDP (PM,VEL,B,V,CONST,P)
C
      IF(MPRNT-NPRNT)   310,   300,   300
C
  300 WRITE(3,11 )
      WRITE (3,14 ) T
      WRITE(3,19  )
      WRITE(3,20 )  (MTIM(M), H(M), U(M), DUX(M), M=1,MFIN1)
      WRITE(3,15 )
      WRITE (3,16 ) B,VEL,PM,PL(4,1),PL(5,1),PL(6,1),PL(7,1),PL(1,1),
     1PL(2,1),PL(3,1),PL(8,1)
C
  310 DO 770 K=2,KMAX
C                                          INTERPOLATE TO OBTAIN DUXX
      IF(K-3)   320,   320,   330
  320 DS=.5*DEPTH/STEP
      GO TO 340
  330 DS=1.0*DEPTH/STEP
```

```
  340 IF(M-2)    390,  390,  350
C                    BRACKET V(5) WITH H(M) AND INTERPOLATE, DUXX(V(5))
  350 DO 380 M=2,MFIN
      M1=M-1
      DIF = H(M1)-V(5)
      IF(H(M)-V(5))    360,  410,  370
  360 DIF=-DIF
  370 IF(DIF)    400,  420,  380
  380 CONTINUE
C
  390 DUXX=0.0
      GO TO    430
C
  400 V5=V(5)
      CALL QUAD(DUXX,DUX,V5,H,M1)
      GO TO    430
C
  410 DUXX=DUX(M)
      GO TO    430
C
  420 DUXX=DUX(M1)
C                                           INTEGRATE PLUME EQUATIONS
  430 CALL LBHGP (G,V,F,DUXX,P,CONST)
C
      IF (ABS(G(5))-0.9)    440,  450,  450
C
  440 DS=0.5*DEPTH/STEP
  450 K1=K-1
C
      DO 460 J=1,9
      DGA(J)=G(J)*DS
  460 V(J)=PL(J,K1)+DGA(J)/2.0
C
      CALL LBHGP (G,V,F,DUXX,P,CONST)
C
      DO 470 J=1,9
      DGB(J)=G(J)*DS
  470 V(J)=PL(J,K1)+DGB(J)/2.0
C
      CALL LBHGP (G,V,F,DUXX,P,CONST)
C
      DO 480 J=1,9
      DGC(J)=G(J)*DS
  480 V(J)=PL(J,K1)+DGC(J)
C
      CALL LBHGP (G,V,F,DUXX,P,CONST)
C
      DO 490 J=1,9
      DGD   =G(J)*DS
      DG    =(DGA(J)+2.0*DGB(J)+2.0*DGC(J)+DGD    )/6.0
      PL(J,K)=PL(J,K1)+DG
  490 V(J)=PL(J,K)
      PLKK1=PL(3,K)-PL(3,K1)
      GO TO (492,493) ,MJ
  492 PLKK1=-PLKK1
  493 IF (PLKK1)    494,  495,  495
  494 PL(3,K)=PL(3,K1)
  495 CONTINUE
C                         DETERMINE CM(S) IN TERMS OF X
      PLX=PL(5,K)
```

```
      ARG=1.0                                                           LBHML208
C                                                                       LBHML209
      GO TO (510,500),MJ                                                LBHML210
C                                                                       LBHML211
  500 ARG=-1.0                                                          LBHML212
C                                                                       LBHML213
  510 DO 570 M=1,MFIN                                                   LBHML214
C                                                                       LBHML215
      M0=M+1                                                            LBHML216
      XM=H(M)                                                           LBHML217
      XM0=H(M0)                                                         LBHML218
      PLXM=PLX-XM                                                       LBHML219
      PLXM0 = PLX-XM0                                                   LBHML220
C                                                                       LBHML221
      IF(ABS(PLXM)-0.0000001)  590,  520,  520                          LBHML222
C                                                                       LBHML223
  520 IF(ABS(PLXM0)-0.0000001)  580,  530,  530                         LBHML224
C                                                                       LBHML225
  530 INX=1                                                             LBHML226
C                                                                       LBHML227
      IF  (ARG*PLXM)  540,  540,  560                                   LBHML228
C                                                                       LBHML229
  540 IF  (ARG*PLXM0)  560,  560,  550                                  LBHML230
C                                                                       LBHML231
  550 INX=2                                                             LBHML232
C                                                                       LBHML233
  560 GO TO (570,640),INX                                               LBHML234
C                                                                       LBHML235
  570 CONTINUE                                                          LBHML236
C                                                                       LBHML237
      GO TO (630,710),MJ                                                LBHML238
C                                                                       LBHML239
  580 MM=M0                                                             LBHML240
      GO TO   600                                                       LBHML241
C                                                                       LBHML242
  590 MM=M                                                              LBHML243
C                                                                       LBHML244
  600 IF(MM-MFIN)   620,  610,  610                                     LBHML245
C                                                                       LBHML246
  610 IF(MM-1)   620,  620,  650                                        LBHML247
C                                                                       LBHML248
  620 PL(7,K)=U(MM)                                                     LBHML249
      GO TO   710                                                       LBHML250
C                                                                       LBHML251
  630 PL(7,K)=2.0                                                       LBHML252
      IF  (PLX)    631,  635,  635
  631 PL(7,K)=PL(7,1)
  635 GO TO   710                                                       LBHML253
C                                                                       LBHML254
  640 IF(ARG*(PLX-H(MFIN1)))   650,  650,  680                          LBHML255
C                                                                       LBHML256
  650 MFIN2=MFIN-2                                                      LBHML257
      DUMY=0.0                                                          LBHML258
C                                                                       LBHML259
      IF(MFIN2)   670,  670,  660                                       LBHML260
C                                                                       LBHML261
  660 DUMY=ARG *(U(MFIN1)-U(MFIN2))*(PLX-H(MFIN1))/(H(MFIN1)-H(MFIN2))  LBHML262
      IF  (ARG*DUMY) 670,661,661
  661 DUMY=0.0
C                                                                       LBHML263
```

NOT REPRODUCIBLE

```
  670 PL(7,K)=U(MFIN1)+DUMY
      GO TO   710
C
  680 MT=M+2
C
      IF(MT-MFIN)    700,   700,   690
C
  690 PL(7,K)=U(M)
      GO TO   710
C
  700 PL(7,K)=PLXM*(U(MM)-U(M))/(XMM-XM) + U(M)
C
  710 V(7)=PL(7,K)
C
      CALL LBHDP (RM,VEL,R,V,CONST,P)
C
      IF(MPRNT-NPRNT)   730,   720,   720
C
  720 WRITE (3,16 ) R,VEL,RM,PL(4,K),PL(5,K),PL(6,K),PL(7,K),PL(1,K),
     1PL(2,K),PL(3,K),PL(8,K)
C
  730 XX=V(5)
      RB=SQRT((1.07-XX)*(XX+0.031))
      KF=K
C                                           DETERMIN THE FINAL VALUE OF Z, Y
C                                           X, S, RB, ON THE TRAJECTORY
      IF(V(5))    740,   780,   750
  740 IF(RB-V(6))    830,   780,   790
  750 IF (ABS(1.0-V(5))-.0001)     780,   780,   751
  751 IF(1.0-V(5))    800,   780,   760
  760 IF(RB-V(6))    830,   780,   770
C
  770 CONTINUE
C
      GO TO    880
C
  780 VF1=PL(1,K)
      VF2=PL(2,K)
      VF3=PL(3,K)
      VF8=PL(8,K)
      XF=V(5)
      GO TO    880
C
  790 XF=0.0
      GO TO    810
C
  800 XF=1.0
C
  810 DO 820  J=1,K
      PL2(J)=PL(2,J)
      PL1(J)= PL(1,J)
      PL8(J)=PL(8,J)
       PL3(J)=PL(3,J)
  820 PL5(J)=PL(5,J)
      J=KF
C
      CALL QUAD (VF3,PL3,XF,PL5,K)
      CALL QUAD (VF8,PL8,XF,PL5,K)
      CALL QUAD(VF1,PL1,XF,PL5,K)
      CALL QUAD(VF2,PL2,XF,PL5,K)
```

```
      GO TO   880
C
  830 C=SQRT(V(3)**2+P*P)
      DD=(V(5)**2+V(6)**2-1.04*V(5)-.0321)/(2.*V(5)*P/C+(2.*V(5)-1.04)*
     1V(3)/C)
      RB=V(6)-DD*P/C
C
      DO 840 J=1,K
      PL2(J)=PL(2,J)
      PL1(J)=PL(1,J)
      PL3(J)=PL(3,J)
      PL8(J)=PL(8,J)
  840 PL6(J)=PL(6,J)
      J=KF
C
      CALL QUAD (VF3,PL3,RB,PL6,K)
      CALL QUAD (VF8,PL8,RB,PL6,K)
      CALL QUAD(VF1,PL1,RB,PL6,K)
      CALL QUAD(VF2,PL2,RB,PL6,K)
C
      XT=V(5)-DD*V(3)/C
      IF(XT-.52)    850,   850,   860
  850 FACT=-1.0
      GO TO    870
  860 FACT=1.0
  870 XF=.52+FACT*SQRT(.3025-RB**2)
C
  880 V(1)=VF1
      V(2)=VF2
      V(3)=VF3
      V(4)=0.0
      V(5)=XF
      V(6)= RB
      V(8)=VF8
C
      CALL LBHDP (PM,VEL,B,V,CONST,P)
C
      IF(MPRNT-NPRNT)    900,   890,   890
C
  890 WRITE(3,24   )
      DUMMY=1.0
      XX=XF
      RB=SQRT((1.07-XX)*(XX+0.03))
      WRITE  (3,16  )  B,VEL,PM,DUMMY,XF,RB,PM,VF1,VF2,VF3,VF8
C
C                                           DETERMINE MAXIMUM X ON S TRAJECTORY
  900 DO 910 I=1,KF
      PL5(I)=PL(5,I)
  910 X(I)=PL(4,I)
C
      DO 950 K=2,KF
      K1=K-1
      PLN=PL5(K)
      PLN1=PL5(K1)
      IF(PLN-PLN1)     920,    920,    950
  920 IF(K-3)     960,    960,    930
  930 KO=K+1
      IF(KO-KF)     940,    940,    970
  940 K2=K-2
      K3=K-3
```

```
      DUMY1=X(K2)-X(K1)
      DUMY2=X(K2)-X(K)
      DUMY3=X(K1)-X(K)
      A0=PL5(K2)/(DUMY1*DUMY2)
      A1=PL5(K1)/(-DUMY1*DUMY3)
      A2=PL5(K)/(DUMY2*DUMY3)
      SXMAX=(A0*(X(K)+X(K1))+A1*(X(K)+X(K2))+A2*(X(K1)+X(K2)))/
     1(2.*(A0+A1+A2))
      CALL QUAD (XMAX,PL5,SXMAX,X,K)
      GO TO   980
C
  950 CONTINUE
C
      XMAX=XF
      GO TO   980
C                                               STEP IS TOO SMALL
  960 DS=DS/2.0
C
      WRITE(3,21 ) DS
      GO TO   980
C
  970 XMAX=PLN
C
  980 DX=XMAX/STEP
      GO TO (9811, 9811),MJ
 9811 DEPTH=3.0*XMAX
      DPTH1=DEPTH
      IF(DEPTH-1.0)    982,  981,  981
  981 DEPTH=1.0
C
  982 CMAVE=(CNT+INO+IN*DNT*(T-TS)/2.85E-05)/CNT
C
      IF(MPRNT-NPRNT)  1000,  990,  990
C
  990 WRITE(3,17 ) XMAX,SXMAX,CMAVE
C
 1000 Q=STEP+1.0
      LMAX=IFIX(Q)
C                                         DETERMINE NET VOLUMN AND VOLUMN FLUX
C                                         AS A FUNCTION OF X
      DO 1010 MP=1,LMAX
 1010 X(MP)=(MP-1)*DX
C
      DO 1020 I=1,KF
      PL8(I)=PL(8,I)
      PL4(I)=PL(4,I)
      PL5(I)=PL(5,I)
 1020 PL1(I)=PL(1,I)
      KF1=KF-1
      KF2=KF-2
      DV=(PL8(KF1)-PL8(KF2))/DS
      VT=DV*XF&VF8
C
      DO 1190 L=1,LMAX
      XL=X(L)
C
      DO 1040 J=2,KF
      XJ=PL(5,J)
      XJ1=PL(5,J-1)
      IF(XL-XJ)  1030, 1040, 1040
```

```
1030 IF(XL-XJ1)  1040, 1050, 1060
1040 CONTINUE
     YP=PL(1,KF)
     VP=PL(8,KF)
     GO TO  1070
C
1050 YP=PL(1,J-1)
     VP=PL(8,J-1)
     GO TO  1070
C
1060 JT=J
     IF (PL4(J)-SXMAX)    1062,  1062,  1061
1061 JT=J-1
1062 CALL QUAD (ST,PL4,XL,PL5,JT)
     CALL QUAD (YP,PL1,ST,PL4,J)
     CALL QUAD (VP,PL8,ST,PL4,J)
C
1070 GO TO (1090,1080),MJ
C
1080 YN=0
     VN=0.0
     GO TO  1150
C
1090 DO 1110 J=2,KF
     XJ=PL(5,J)
     XJ1=PL(5,J-1)
     IF(XL-XJ)  1105, 1105, 1110
1105 IF(ABS(XL-XJ)-.1E-03)    1100,  1100, 1110
1100 IF(XL-XJ1)  1140, 1130, 1110
1110 CONTINUE
C
     IF(XL-XF)  1120, 1120, 1140
C
1120 YN=VF1
     VN=DV*XL
     GO TO  1150
C
1130 YN=PL(1,J-1)
     VN=VT-PL(8,J-1)
     GO TO  1150
C
1140 JT=J
     IF (PL6(J-2)-SXMAX)   1141,  1142,  1142
1141 JT=J+1
1142 CALL QUAD (ST,PL4,XL,PL5,JT)
     CALL QUAD (YN,PL1,ST,PL4,J)
     CALL QUAD (VN,PL8,ST,PL4,J)
     VN=VT-VN
C
1150 VO(L)=(VP+VN)
     Y(L)=(YP-YN)
     GO TO (1160,1170),MJ
1160 Y(LMAX)=0.0
     VO(LMAX)=VT
C
1170 IF(MPRNT-MPRNT)  1190, 1180, 1180
C
1180 WRITE (3,18 ) Y(L),XL,VO(L)
C
1190 CONTINUE
```

```
C                                         FIND SHIFT IN POSITION OF        LBHML481
C                                         CONVECTED GAS IN CAVITY          LBHML482
      CALL TSTRT
      ID=0                                                                 LBHML483
      MSTRT=0                                                              LBHML485
C                                                                          LBHML486
      DO 1410 M=1,MFIN                                                     LBHML487
C                                                                          LBHML488
      XH=H(M)                                                              LBHML489
      XHO=H(M+1)
      DXH=ABS(XH-XHO)
C                                                                          LBHML490
      IF(ID)  1200, 1200, 1240                                             LBHML491
C                                                                          LBHML492
 1200 GO TO (1220,1210),MJ                                                 LBHML493
C                                                                          LBHML494
 1210 IF(XH-2.024)  1410, 1230, 1230                                       LBHML495
 1220 IF(.976      -XH)  1410, 1221, 1221                                  LBHML496
 1221 IF (M-MFIN)     1222,  1230,  1230
 1222 IF (DXH-.01*XMAX)     1223,  1223,  1230
 1223 H(M+1)=XH
      GO TO 1410
C                                                                          LBHML497
 1230 ID=1                                                                 LBHML498
C                                                                          LBHML499
 1240 XHT=XH                                                               LBHML500
      XTG=XH                                                               LBHML501
      MSTRT=MSTRT+1                                                        LBHML502
      MTIM(MSTRT)=MSTRT                                                    LBHML503
C                                                                          LBHML504
      DO 1250 L=1,LMAX                                                     LBHML507
C                                                                          LBHML506
      IF( X(L)-XH  )  1250, 1260, 1270                                     LBHML508
 1250 CONTINUE                                                             LBHML509
      L=LMAX                                                               LBHML510
C                                                                          LBHML511
 1260 YI=Y(L)                                                              LBHML512
      VH=VO(L)                                                             LBHML513
      GO TO 1271
C                                                                          LBHML515
 1270 CALL QUAD (YI, Y, XH , X, L)                                         LBHML516
      CALL QUAD(VH,VO,XH,X,L)                                              LBHML517
C                                                                          LBHML520
 1271 DO 1350 JJ=1,10
      DO 1272 LL=1,LMAX
      IF (X(LL)-XTG)     1272,   1273,   1274
 1272 CONTINUE
      LL=LMAX
 1273 VTG=VO(LL)
      GO TO 1275
 1274 IF(XTG-XMAX)     12742,  12741,  12741
12741 VTG=VO(LMAX)
      GO TO 1275
12742 CALL QUAD (VTG,VO,XTG,X,LL)
 1275 DO 1276 LL=1,LMAX
      IF (X(LL)-XHT)     1276,   1277,   1278
 1276 CONTINUE
      LL=LMAX
 1277 VHT=VO(LL)
      GO TO 1280
```

```
 1279 IF (XHT-YMAX)    12792,  12791,  12791
12791 YHT=YMAX
      GO TO 1280
12792 CALL QUAD (YHT,V),XHT,X,LL)
 1280 XX=XHT
      VR=((XX+.03)**2*(.54-XX/3.0)-.[illegible]-3)/.2157[illegible]
C
C
C
 1300 AMIM=(XH+.03)**2*(.54-XH/3.0)
      [illegible]=XH*DT*(1.0-VR-YT)*CC
      C0UT =(.54-XTG/3.0)
      XT=SQRT((AMIM+[illegible]-1.0E-04*B1**2*(VR-VTG))/C0UT)-.03
      XHT=SQRT((AMIM+[illegible]*.5-1.0E-04*B1**2*(VR-VHT))/C0UT)-.03
C
      DUMMY=.625E-05
      IF(XHT)   1310, 1340, 1320
C
 1310  XHT=0.0
      GO TO  1340
C
 1320 IF(XHT-1.)  1340, 1340, 1330
C
 1330 XHT=1.0
C
 1340 XTA=ABS(XT-XTG)
C
      IF (XTA-.005*XMAX)  1360, 1360, 1350
C
 1350 XTG=XT
C
      WRITE (3,22 )
C
 1360 IF(M-MFIN)     1364,  1363,  1364
 1363 YM=YT
      AIM=2-IM
      YTT=VF1/ABS(1.0-VR-YM)
      UP(MFIN)=AIM+(VF2/VF1-AIM)*YTT
 1364 CONTINUE
C
      IF (XT)  1370, 1400, 1380
C
 1370 XT=0.
      GO TO  1400
C
 1380 IF (XT-1.)  1400, 1400, 1390
C
 1390 XT=1.
C
 1400 H(MSTRT)=XT
C
 1410 CONTINUE
      MFINN=MFIN+1
      UP(MFINN)=UP(MFIN)
C
      T=T+DT
      MFT=MFIN-MSTRT
      DUPX(MFIN)=0.0
      DUPX(MFINN)=0.0
      MSTO=MSTRT+1
```

```
      DO 1490 M=1,MSTO                                              LBHML579
      MMET=M+MET                                                    LBHML580
      UP(M)=UP(MMET)                                                LBHML581
 1490 DUPX(M)=DUPX(MMET)                                            LBHML582
      HMST=H(MSTRT)/XMAX                                            LBHML566
      GO TO (1420,1430),MJ                                          LBHML567
 1420  HMST=1.-HMST                                                 LBHML568
 1430 IF (HMST-.55)     1450, 1440, 1440                            LBHML569
 1440 IF (HMST-.73)     1470,  1460,  1460                          LBHML570
 1450 NS=NS/2                                                       LBHML571
      IF (NS)     1451,  1451,  1452
 1451 NS=1
 1452 GO TO 1470                                                    LBHML572
 1460  NS= NS+NS                                                    LBHML573
 1470 DT= NS*DT1                                                    LBHML574
      MFIN=MSTRT                                                    LBHML583
      MFIN1=MFIN-1                                                  LBHML584
C                                                                   LBHML585
      IF(MFIN1)   1510, 1510, 1490                                  LBHML586
C                                                                   LBHML587
 1490 DO 1500 J=1,MFIN1                                             LBHML588
      J1=J+1                                                        LBHML589
 1500 DUPX(J)=(UP(J)-UP(J1))/(H(J)-H(J1))                           LBHML590
      DUPX(MFIN)=MAG*(UP(MFIN)-UP(MFIN1))/(H(MFIN)-H(MFIN1))        LBHML591
      UP(MFINN)=U(MFIN)+DUPX(MFIN)*(H(MFINN)-H(MFIN))               LBHML592
C                                                                   LBHML593
C                                                                   LBHML594
 1510 DO 1520 M=1,MFINN                                             LBHML595
      U(M)=UP(M)                                                    LBHML596
 1520 DUX(M)=DUPX(M)                                                LBHML597
      GO TO (15210, 1523) ,MJ
15210 IF (MFIN-17)     1523,    15211,  15211
15211 DO 15214 M=1,MFIN
      XH=H(M)
      XH0=H(M61)
      IF (XMAX-XH0)     15214,  15213,  15213
15213 IF (XMAX-XH)     15215,  15214,  15214
15214 CONTINUE
15215 MOUT=M-1
      DO 15216 M=MOUT,MFIN
      H(M)=H(M61)
      U(M)=U(M61)
15216 DUX(M)=DUX(M61)
      MFIN=MFIN-1
      MSTRT=MFIN
 1523 MFINN=MSTRT+1
      CALL TSTOP
      DO 1525 M=MFINN,100
 1524 H(M)=VAL
 1525 CONTINUE
 1528 TSMN=CNT-SMN                                                  LBHML598
      TSON=CNT-SON                                                  LBHML599
C                                                                   LBHML600
      IF(F -CNT)   1640, 1640, 1530                                 LBHML601
 1530 IF(TSMN)    1550, 1540, 1540                                  LBHML602
C                                                                   LBHML603
 1540 MJ=2                                                          LBHML604
      VAL=1.0
      MJW=32                                                        LBHML605
      WRITE (3,23   ) MJW                                           LBHML606
```

```
      MPRNT=MPRNT-1                                                    LBHML607
      SON=SON+SLON+SLON                                                LBHML608
      DEPTH=1.0
      TS=T                                                             LBHML609
      IN=1                                                             LBHML610
      GO TO  1570                                                      LBHML611
C                                                                      LBHML612
 1550 IF(TSON)  1650, 1560, 1560                                       LBHML613
C                                                                      LBHML614
 1560 MJ=1                                                             LBHML615
      VAL=0.0
      MJW=15                                                           LBHML616
      WRITE(3,23  ) MJW                                                LBHML617
      MPRNT=NPRNT-1                                                    LBHML618
      TNO=TNO+SLON                                                     LBHML619
      SON=SON+SLON+SLMN                                                LBHML620
      DEPTH=DPTH1/2
      IN=0                                                             LBHML621
C                                                                      LBHML622
 1570 MFIN=MFIN+1                                                      LBHML623
      MFINN=MFIN+1                                                     LBHML624
      NS=NS/2
      IF (NS-1)   1571,  1572,  1572
 1571 NS=1
 1572 DO 1580 MM=1,MFIN                                                LBHML625
      NM=MFINN-MM                                                      LBHML626
      X(NM)=H(MM)                                                      LBHML627
      UP(NM)=U(MM)                                                     LBHML628
 1580 DUPX(NM)=DUX(MM)                                                 LBHML629
      DO 1590 M=1,MFIN                                                 LBHML630
      H(M)=X(M)                                                        LBHML631
      U(M)=UP(M)                                                       LBHML632
 1590 DUX(M)=DUPX(M)                                                   LBHML633
C                                                                      LBHML634
      GO TO (1620,1600),MJ                                             LBHML635
C                                                                      LBHML636
 1600 DO 1610 M=MFINN,100                                              LBHML637
 1610 H(M)=1.0                                                         LBHML638
      CS=1.0                                                           LBHML639
      Z=2.0                                                            LBHML640
      B1=0.25                                                          LBHML641
      GO TO  1650                                                      LBHML642
C                                                                      LBHML643
 1620 DO 1630 M=MFINN,100                                              LBHML644
 1630 H(M)=0.0                                                         LBHML645
      CS =CS1                                                          LBHML646
      Z=1.0                                                            LBHML647
      B1=0.125                                                         LBHML648
C                                                                      LBHML649
 1640 MPRNT=NPRNT                                                      LBHML650
      GO TO  1690                                                      LBHML651
 1650 IF(MPRNT-NPRNT)  1690, 1660, 1700                                LBHML652
C                                                                      LBHML653
 1660 MPRNT=0                                                          LBHML654
      CALL DATSW(0,LITE)                                               LBHML655
      GO TO (1670,1690),LITE                                           LBHML656
 1670 PAUSE 1111                                                       LBHML657
      CALL DATSW(1,LITE)                                               LBHML658
      GO TO (1680,100),LITE                                            LBHML659
C                                                                      LBHML660
```

```
 1680 READ(2,9 ) NPRNT,NPROF,DEPTH
C                                                              LBHML652
 1692 NPRNT=NPRNT+1                                            LBHML653
      GO TO   180                                              LBHML665
C                                                              LBHML666
 1700 CALL EXIT                                                LBHML667
      END                                                      LBHML668
// DUP
*STORE      WS  UA  LBHMP

// JOB
// XEQ LBHMP
32     20  1.000  20500  8200  12300  8200  .0540  .0933    .25
 1   2   1.00
```

BUOYANT PLUME IN A SPHERICAL CAVITY

INPUT DATA

MOLECULAR WEIGHT OF JET	32
SPACE STEPS IN CAVITY	20.
INITIAL COS(THETA)	1.000000
FINAL NUMBER OF MOLES	20500.
MOLES IN SLUG OF METHANE	8200.
MOLES IN SLUG OF OXYGEN	12300.
INITIAL MOLES IN CAVITY	8200.
ENTRAINMENT COEFFICIENT	0.0580
MOLE FLOW RATE PER SECOND	0.0933
RADIUS OF ENTRANCE JET	0.2500

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.000000

M	H	CM	DCM/DX
0	1.000000	1.000000	0.000000

B	VEL	PM	S	X	R	CM
1.57	1.0269	1.780776	0.000	0.000	0.000	1.000000
2.30	0.8788	1.426867	0.025	0.025	0.000	1.000000
3.03	0.7873	1.275812	0.050	0.050	0.000	1.000000
3.75	0.7249	1.195735	0.075	0.075	0.000	1.000000
4.46	0.6790	1.147514	0.100	0.100	0.000	1.000000
5.88	0.6144	1.093975	0.150	0.150	0.000	1.000000
7.29	0.5696	1.065999	0.200	0.200	0.000	1.000000
8.69	0.5358	1.049340	0.250	0.250	0.000	1.000000
10.09	0.5090	1.038529	0.300	0.300	0.000	1.000000
11.49	0.4870	1.031070	0.350	0.350	0.000	1.000000
12.89	0.4684	1.025682	0.400	0.400	0.000	1.000000
14.29	0.4523	1.021649	0.450	0.450	0.000	1.000000
15.68	0.4383	1.018542	0.500	0.500	0.000	1.000000
17.08	0.4259	1.016092	0.550	0.550	0.000	1.000000
18.47	0.4148	1.014123	0.600	0.599	0.000	1.000000
19.86	0.4048	1.012512	0.650	0.649	0.000	1.000000
21.26	0.3957	1.011177	0.700	0.699	0.000	1.000000
22.65	0.3873	1.010056	0.750	0.749	0.000	1.000000
24.05	0.3797	1.009105	0.800	0.799	0.000	1.000000
25.44	0.3726	1.008290	0.849	0.849	0.000	1.000000
26.83	0.3660	1.007586	0.899	0.899	0.000	1.000000
28.23	0.3598	1.006973	0.949	0.949	0.000	1.000000
29.62	0.3541	1.006435	0.999	0.999	0.000	1.000000

BOUNDARY VALUES

29.62	0.3541	1.006435	1.000	0.999	0.268	1.006435

XMAX	SXMAX	CMAVE
0.999	1.000	1.000000

QNET	X	PLVOL
2.561	0.000	0.000
7.251	0.049	0.275
13.558	0.099	0.988
21.282	0.149	2.336
30.303	0.199	4.516
40.534	0.249	7.721
51.908	0.299	12.145
64.369	0.349	17.982
77.873	0.399	25.427
92.381	0.449	34.672
107.859	0.499	45.912
124.277	0.549	59.341

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.026270

M	H	CM	DCM/DX
1	0.127433	1.003218	0.123602
2	0.131401	1.003708	0.056991
3	0.140825	1.004245	0.036192
4	0.173010	1.005410	0.033767
5	0.209465	1.006641	0.024204
6	0.250596	1.007637	0.021337
7	0.296056	1.008620	0.018799
8	0.349239	1.009608	0.016717
9	0.409593	1.010617	0.014569
10	0.480091	1.011653	0.011939
11	0.568279	1.012699	0.007707
12	0.689390	1.013632	0.000000

B	VEL	PM	S	X	R	CM
1.57	1.0269	1.780776	0.000	0.000	0.000	1.000000
2.30	0.8824	1.426610	0.025	0.025	0.000	1.000000
3.02	0.7918	1.275407	0.050	0.050	0.000	1.000000
3.74	0.7297	1.195302	0.075	0.075	0.000	1.000000
4.45	0.6837	1.147100	0.100	0.100	0.000	1.000000
5.87	0.6197	1.089052	0.150	0.150	0.000	1.004577
7.35	0.5612	1.062608	0.200	0.200	0.000	1.006322
8.84	0.5169	1.047607	0.250	0.250	0.000	1.007622
10.34	0.4819	1.038177	0.300	0.300	0.000	1.008682
11.85	0.4524	1.031846	0.350	0.349	0.000	1.009621
13.38	0.4265	1.027415	0.400	0.400	0.000	1.010457
14.94	0.4030	1.024215	0.450	0.449	0.000	1.011206
16.54	0.3813	1.021844	0.500	0.500	0.000	1.011884
18.18	0.3609	1.020070	0.550	0.550	0.000	1.012481
19.86	0.3416	1.018785	0.600	0.599	0.000	1.012943
21.57	0.3238	1.017812	0.650	0.649	0.000	1.013329
23.32	0.3073	1.017081	0.700	0.699	0.000	1.013632
25.09	0.2922	1.016764	0.750	0.749	0.000	1.013632
26.80	0.2799	1.016487	0.800	0.799	0.000	1.013632
28.47	0.2698	1.016244	0.849	0.849	0.000	1.013632
30.10	0.2613	1.016031	0.899	0.899	0.000	1.013632
31.72	0.2537	1.015847	0.949	0.949	0.000	1.013632
33.32	0.2468	1.015687	0.999	0.999	0.000	1.013632

BOUNDARY VALUES

33.32	0.2468	1.015687	1.000	0.999	0.268	1.015687

XMAX	SXMAX	CMAVE
0.999	1.000	1.010378

QNET	X	PLVOL
2.561	0.000	0.000

7.261	0.049	0.274
13.596	0.099	0.984
21.360	0.149	2.327
30.377	0.199	4.525
40.480	0.249	7.817
51.576	0.299	12.431
63.588	0.349	18.599
76.440	0.399	26.570
90.059	0.449	36.611
104.372	0.499	49.013
119.308	0.549	64.090
134.798	0.599	82.187
150.780	0.649	103.662
167.202	0.695	128.879
184.023	0.749	156.209
201.233	0.799	191.914
218.851	0.849	230.156
236.887	0.899	273.101
255.346	0.949	320.932
274.224	0.999	373.864

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.075144

M	H	CM	DCM/DX
1	0.009418	1.017685	0.065015
2	0.025179	1.018710	0.059025
3	0.042589	1.019738	0.054025
4	0.061794	1.020775	0.047488
5	0.083119	1.021788	0.042627
6	0.106034	1.022790	0.038372
7	0.132522	1.023784	0.034579
8	0.161081	1.024771	0.031047
9	0.192061	1.025752	0.027864
10	0.227097	1.026728	0.024806
11	0.266770	1.027697	0.022010
12	0.310012	1.028662	0.018966
13	0.361157	1.029621	0.016309
14	0.419039	1.030575	0.013702
15	0.488839	1.031523	0.012593
16	0.573089	1.032584	0.008491
17	0.691740	1.033592	0.000000

B	VEL	PM	S	X	R	CM
1.57	1.0258	1.789756	0.000	0.000	0.000	1.017685
2.29	0.8822	1.437888	0.025	0.025	0.000	1.018698
3.02	0.7905	1.288187	0.050	0.050	0.000	1.020138
3.74	0.7267	1.209298	0.075	0.075	0.000	1.021402
4.46	0.6788	1.162125	0.100	0.100	0.000	1.022508
5.90	0.6092	1.110355	0.150	0.150	0.000	1.024388
7.34	0.5588	1.083797	0.200	0.200	0.000	1.025956
8.80	0.5190	1.068344	0.250	0.250	0.000	1.027281
10.28	0.4858	1.058573	0.300	0.300	0.000	1.028429
11.78	0.4569	1.052055	0.350	0.349	0.000	1.029409
13.30	0.4311	1.047525	0.400	0.400	0.000	1.030254
14.85	0.4077	1.044274	0.450	0.449	0.000	1.030991
16.44	0.3860	1.041859	0.500	0.500	0.000	1.031664
18.07	0.3654	1.040024	0.550	0.550	0.000	1.032293
19.76	0.3458	1.038669	0.600	0.599	0.000	1.032812
21.48	0.3273	1.037657	0.650	0.649	0.000	1.033237
23.24	0.3102	1.036884	0.700	0.699	0.000	1.033592
25.04	0.2942	1.036580	0.750	0.749	0.000	1.033592
26.77	0.2814	1.036314	0.800	0.799	0.000	1.033592
28.46	0.2709	1.036080	0.849	0.849	0.000	1.033592
30.11	0.2620	1.035875	0.899	0.899	0.000	1.033592
31.74	0.2541	1.035697	0.949	0.949	0.000	1.033592
33.36	0.2470	1.035545	0.999	0.999	0.000	1.033592

BOUNDARY VALUES

33.36	0.2470	1.035545	1.000	0.999	0.268	1.035545

XMAX	SXMAX	CMAVE
0.999	1.000	1.029126

QNET	X	PLVOL
2.544	0.000	0.000
7.230	0.049	0.273
13.538	0.099	0.983
21.240	0.149	2.335
30.187	0.199	4.539
40.263	0.249	7.810
51.368	0.299	12.372
63.414	0.349	18.464
76.319	0.399	26.337
90.006	0.449	36.257
104.403	0.499	48.511
119.438	0.549	63.414
135.034	0.599	81.315
151.125	0.649	102.587
167.651	0.699	127.613
184.564	0.749	156.786
201.854	0.799	190.387
219.539	0.849	228.575
237.633	0.899	271.515
256.141	0.949	319.391
275.059	0.999	372.425

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.124019

M	H	CM	DCM/DX
1	0.016332	1.037542	0.059489
2	0.032592	1.038509	0.053765
3	0.050470	1.039470	0.048679
4	0.070101	1.040426	0.043973
5	0.091689	1.041375	0.039860
6	0.115412	1.042321	0.035967
7	0.141502	1.043259	0.032571
8	0.170226	1.044195	0.029251
9	0.201964	1.045123	0.026276
10	0.237126	1.046047	0.023467
11	0.276289	1.046966	0.020803
12	0.320204	1.047880	0.017942
13	0.370830	1.048788	0.015415
14	0.429412	1.049691	0.012935
15	0.498817	1.050589	0.010443
16	0.584273	1.051481	0.007582
17	0.701276	1.052369	0.000000

B	VEL	DM	S	X	R	CM
1.57	1.0257	1.790268	0.000	0.000	0.000	1.018710
2.28	0.8926	1.419815	0.025	0.025	0.000	1.038057
3.03	0.7835	1.283459	0.050	0.050	0.000	1.039445
3.77	0.7138	1.212006	0.075	0.075	0.000	1.040641
4.50	0.6638	1.169258	0.100	0.100	0.000	1.041707
5.95	0.5935	1.122222	0.150	0.150	0.000	1.043536
7.40	0.5437	1.098010	0.200	0.200	0.000	1.045066
8.87	0.5045	1.083901	0.250	0.250	0.000	1.046349
10.35	0.4718	1.074969	0.300	0.300	0.000	1.047459
11.86	0.4433	1.069005	0.350	0.349	0.000	1.048414
13.39	0.4179	1.064850	0.400	0.400	0.000	1.049238
14.95	0.3948	1.061886	0.450	0.449	0.000	1.049958
16.55	0.3733	1.059692	0.500	0.500	0.000	1.050601
18.20	0.3530	1.058098	0.550	0.550	0.000	1.051124
19.88	0.3340	1.056871	0.600	0.599	0.000	1.051601
21.62	0.3160	1.055970	0.650	0.649	0.000	1.051980
23.39	0.2993	1.055219	0.700	0.699	0.000	1.052359
25.21	0.2834	1.054949	0.750	0.749	0.000	1.052369
26.97	0.2706	1.054722	0.800	0.799	0.000	1.052369
28.68	0.2601	1.054521	0.849	0.849	0.000	1.052369
30.36	0.2512	1.054345	0.899	0.899	0.000	1.052369
32.01	0.2435	1.054192	0.949	0.949	0.000	1.052369
33.65	0.2364	1.054061	0.999	0.999	0.000	1.052369

BOUNDARY VALUES

33.65	0.2364	1.054061	1.000	0.999	0.268	1.054061

XMAX	SXMAX	CMAVE
0.999	1.000	1.047176

ONET	X	PLVOL
2.543	0.000	0.000
7.235	0.049	0.273
13.482	0.099	0.994
21.066	0.149	2.372
29.851	0.199	4.613
39.727	0.249	7.935
50.595	0.299	12.564
62.370	0.349	18.740
74.970	0.399	26.717
88.319	0.449	36.770
102.345	0.499	49.190
116.975	0.549	64.298
132.143	0.599	82.439
147.782	0.649	103.985
163.836	0.699	129.329
180.251	0.749	158.889
197.011	0.799	192.974
214.135	0.849	231.751
231.638	0.899	275.384
249.524	0.949	324.060
267.793	0.999	377.999

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.221768

M	H	CM	DCM/DX
1	0.013953	1.072358	0.059580
2	0.029067	1.073258	0.053877
3	0.045662	1.074152	0.048935
4	0.063830	1.075041	0.044346
5	0.083729	1.075924	0.040352
6	0.105535	1.076804	0.036708
7	0.129401	1.077680	0.033094
8	0.155388	1.078547	0.030283
9	0.184312	1.079416	0.027165
10	0.215995	1.080277	0.024480
11	0.251020	1.081134	0.021912
12	0.289943	1.081987	0.019493
13	0.333489	1.082836	0.016814
14	0.383076	1.083680	0.014467
15	0.441050	1.084519	0.012163
16	0.510202	1.085353	0.009843
17	0.594425	1.086182	0.007157
18	0.709019	1.087006	0.000000

B	VEL	PM	S	X	R	CM
1.56	1.0235	1.807060	0.000	0.000	0.000	1.053251
2.27	0.8917	1.443085	0.025	0.025	0.000	1.073016
3.02	0.7825	1.310512	0.050	0.050	0.000	1.074365
3.76	0.7130	1.241173	0.075	0.075	0.000	1.075537
4.49	0.6632	1.199746	0.100	0.100	0.000	1.076580
5.94	0.5932	1.154236	0.150	0.150	0.000	1.078362
7.39	0.5434	1.130851	0.200	0.200	0.000	1.079843
8.85	0.5043	1.117211	0.250	0.250	0.000	1.081110
10.34	0.4715	1.108611	0.300	0.300	0.000	1.082183
11.84	0.4429	1.102866	0.350	0.349	0.000	1.083114
13.38	0.4175	1.098877	0.400	0.400	0.000	1.083916
14.94	0.3942	1.096015	0.450	0.449	0.000	1.084620
16.55	0.3726	1.093926	0.500	0.500	0.000	1.085229
18.19	0.3523	1.092386	0.550	0.550	0.000	1.085744
19.88	0.3332	1.091196	0.600	0.599	0.000	1.086222
21.63	0.3149	1.090348	0.650	0.649	0.000	1.086580
23.41	0.2980	1.089642	0.700	0.699	0.000	1.086937
25.24	0.2820	1.089330	0.750	0.749	0.000	1.087006
27.03	0.2687	1.089126	0.800	0.799	0.000	1.087006
28.77	0.2578	1.088946	0.849	0.849	0.000	1.087006
30.46	0.2486	1.088788	0.899	0.899	0.000	1.087006
32.14	0.2406	1.088650	0.949	0.949	0.000	1.087006
33.80	0.2334	1.088532	0.999	0.999	0.000	1.087006

BOUNDARY VALUES

33.80	0.2334	1.088532	1.000	0.999	0.268	1.088532
XMAX	SXMAX	CMAVE				

0.999	1.000	1.081335

QNET	X	PLVOL
2.511	0.000	0.000
7.177	0.049	0.270
13.400	0.099	0.988
20.960	0.149	2.359
29.722	0.199	4.591
39.575	0.249	7.901
50.421	0.299	12.515
62.171	0.349	18.676
74.746	0.399	26.637
88.067	0.449	36.673
102.061	0.499	49.079
116.657	0.549	64.176
131.787	0.599	82.308
147.383	0.649	103.859
163.385	0.699	129.230
179.740	0.749	158.840
196.425	0.799	193.031
213.455	0.849	231.998
230.844	0.899	275.912
248.600	0.949	324.957
266.721	0.999	379.355

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.319517

M	H	CM	DCM/DX
1	0.016752	1.104039	0.049230
2	0.031504	1.104765	0.044852
3	0.047018	1.105488	0.040993
4	0.065155	1.106207	0.037482
5	0.084231	1.106922	0.034261
6	0.104984	1.107633	0.031392
7	0.127319	1.108340	0.028687
8	0.152030	1.109043	0.026221
9	0.178712	1.109743	0.023877
10	0.207841	1.110439	0.021693
11	0.239730	1.111130	0.019626
12	0.274785	1.111818	0.017664
13	0.313522	1.112503	0.015514
14	0.357384	1.113183	0.013635
15	0.407019	1.113860	0.011796
16	0.464078	1.114533	0.009969
17	0.531222	1.115202	0.008113
18	0.613280	1.115868	0.005917
19	0.725183	1.116530	0.000000

B	VEL	PM	S	X	R	CM
1.56	1.0235	1.807060	0.000	0.000	0.000	1.053251
2.25	0.9123	1.410724	0.025	0.025	0.000	1.104445
3.05	0.7702	1.301030	0.050	0.050	0.000	1.105586
3.82	0.6896	1.244228	0.075	0.075	0.000	1.106576
4.57	0.6359	1.210270	0.100	0.100	0.000	1.107462
6.04	0.5649	1.172764	0.150	0.150	0.000	1.108985
7.50	0.5163	1.153343	0.200	0.200	0.000	1.110251
8.98	0.4788	1.141946	0.250	0.250	0.000	1.111332
10.46	0.4476	1.134709	0.300	0.300	0.000	1.112264
11.97	0.4205	1.129860	0.350	0.349	0.000	1.113069
13.51	0.3963	1.126483	0.400	0.400	0.000	1.113764
15.08	0.3741	1.124065	0.450	0.449	0.000	1.114367
16.69	0.3536	1.122293	0.500	0.500	0.000	1.114891
18.34	0.3343	1.120966	0.550	0.550	0.000	1.115355
20.04	0.3160	1.119965	0.600	0.600	0.000	1.115760
21.79	0.2986	1.119231	0.650	0.649	0.000	1.116086
23.59	0.2822	1.118651	0.700	0.699	0.000	1.116381
25.44	0.2668	1.118304	0.750	0.749	0.000	1.116530
27.29	0.2532	1.118151	0.800	0.799	0.000	1.116530
29.08	0.2421	1.118015	0.849	0.849	0.000	1.116530
30.83	0.2328	1.117895	0.899	0.899	0.000	1.116530
32.54	0.2248	1.117790	0.949	0.949	0.000	1.116530
34.25	0.2176	1.117700	0.999	0.999	0.000	1.116530

BOUNDARY VALUES

34.25	0.2176	1.117700	1.000	0.999	0.268	1.117700

XMAX SXMAX CMAVE

0.999 1.000 1.113130

QNET	X	PLVOL
2.511	0.000	0.000
7.192	0.049	0.270
13.307	0.099	1.010
20.453	0.149	2.430
29.122	0.199	4.735
38.616	0.249	8.142
49.047	0.299	12.877
60.332	0.349	19.181
72.394	0.399	27.311
85.142	0.449	37.543
98.564	0.499	50.175
112.533	0.549	65.528
127.003	0.599	83.955
141.909	0.649	105.847
157.190	0.699	131.618
172.794	0.749	161.705
188.687	0.799	196.507
204.873	0.849	236.281
221.368	0.899	281.201
238.180	0.949	331.459
255.312	0.999	387.279

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.422154

M	H	CM	DCM/DX
1	0.022177	1.133691	0.054528
2	0.036588	1.134477	0.051643
3	0.052022	1.13[illegible]274	0.044842
4	0.069155	1.13[illegible]042	0.042621
5	0.087749	1.136834	0.037347
6	0.108120	1.137595	0.034840
7	0.130214	1.138365	0.031835
8	0.154325	1.139133	0.028856
9	0.180063	1.139893	0.026482
10	0.209498	1.140656	0.021115
11	0.241392	1.141330	0.023422
12	0.275468	1.142128	0.016853
13	0.314420	1.142784	0.016276
14	0.357333	1.143483	0.016758
15	0.405350	1.144288	0.013191
16	0.462194	1.145037	0.011034
17	0.529242	1.145777	0.008911
18	0.611334	1.146509	0.006488
19	0.723415	1.147236	0.000000

B	VEL	PM	S	X	R	CM
1.55	1.0199	1.835193	0.000	0.000	0.000	1.115868
2.25	0.8916	1.486670	0.025	0.025	0.000	1.133845
3.00	0.7850	1.359449	0.050	0.050	0.000	1.135169
3.73	0.7167	1.293167	0.075	0.075	0.000	1.136291
4.46	0.6674	1.253683	0.100	0.100	0.000	1.137292
5.90	0.5976	1.210436	0.150	0.150	0.000	1.138995
7.35	0.5476	1.188309	0.200	0.200	0.000	1.140405
8.81	0.5083	1.175499	0.250	0.250	0.000	1.141531
10.29	0.4752	1.167402	0.300	0.300	0.000	1.142541
11.79	0.4469	1.162014	0.350	0.350	0.000	1.143363
13.32	0.4212	1.158172	0.400	0.400	0.000	1.144198
14.89	0.3974	1.155478	0.450	0.450	0.000	1.144877
16.50	0.3754	1.153521	0.500	0.500	0.000	1.145455
18.15	0.3547	1.152063	0.550	0.550	0.000	1.145962
19.85	0.3351	1.150964	0.600	0.600	0.000	1.146408
21.61	0.3164	1.150166	0.650	0.649	0.000	1.146760
23.41	0.2989	1.149530	0.700	0.699	0.000	1.147084
25.26	0.2824	1.149164	0.750	0.749	0.000	1.147236
27.10	0.2681	1.148996	0.800	0.799	0.000	1.147236
28.89	0.2563	1.148847	0.849	0.849	0.000	1.147236
30.63	0.2465	1.148715	0.899	0.899	0.000	1.147236
32.34	0.2380	1.148601	0.949	0.949	0.000	1.147236
34.04	0.2303	1.148503	0.999	0.999	0.000	1.147236

BOUNDARY VALUES

34.04	0.2303	1.148503	1.000	0.999	0.268	1.148503

XMAX SXMAX CMAVE

0.999	1.000	1.144228

QNET	X	PLVOL
2.458	0.000	0.000
7.087	0.049	0.266
13.294	0.099	0.973
20.856	0.149	2.325
29.635	0.199	4.532
39.516	0.249	7.809
50.400	0.299	12.383
62.200	0.349	18.493
74.837	0.399	26.389
88.226	0.449	36.354
102.289	0.499	48.589
116.955	0.549	63.714
132.153	0.599	81.782
147.811	0.649	103.283
163.867	0.699	128.632
180.265	0.749	158.262
196.970	0.799	192.568
213.987	0.849	231.802
231.334	0.899	276.137
249.019	0.949	325.763
267.044	0.999	380.906

BUOYANT PLUME IN A SPHERICAL CAVITY

INPUT DATA

MOLECULAR WEIGHT OF JET	16
SPACE STEPS IN CAVITY	20.
INITIAL COS(THETA)	0.938000
FINAL NUMBER OF MOLES	20500.
MOLES IN SLUG OF METHANE	8200.
MOLES IN SLUG OF OXYGEN	12300.
INITIAL MOLES IN CAVITY	12300.
ENTRAINMENT COEFFICIENT	0.1000
MOLE FLOW RATE PER SECOND	0.0933
RADIUS OF ENTRANCE JET	0.1250

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.000000

M	H	CM	DCM/DX
0	0.000000	2.000000	0.000000

B	VEL	PM	S	X	R	CM
1.00	1.0000	1.000000	0.000	0.000	0.000	2.000000
1.15	0.8221	1.088733	0.000	0.000	0.000	2.000000
1.30	0.6960	1.159884	0.001	0.001	0.000	2.000000
1.45	0.6004	1.218516	0.001	0.001	0.000	2.000000
1.61	0.5243	1.267795	0.002	0.002	0.000	2.000000
1.93	0.4078	1.346107	0.003	0.003	0.001	2.000000
2.29	0.3190	1.405328	0.004	0.004	0.001	2.000000
2.49	0.2807	1.429654	0.005	0.005	0.002	2.000000
2.72	0.2449	1.451102	0.006	0.005	0.002	2.000000
2.98	0.2110	1.470008	0.006	0.006	0.002	2.000000
3.30	0.1785	1.486627	0.007	0.006	0.003	2.000000
3.68	0.1476	1.501153	0.008	0.007	0.003	2.000000
4.11	0.1212	1.513794	0.008	0.007	0.004	2.000000
4.41	0.1079	1.524993	0.009	0.007	0.004	2.000000
4.32	0.1191	1.535669	0.009	0.007	0.005	2.000000
4.06	0.1336	1.546610	0.010	0.007	0.006	2.000000
3.83	0.1535	1.557962	0.011	0.006	0.006	2.000000
3.67	0.1715	1.569582	0.011	0.006	0.006	2.000000
3.57	0.1872	1.581303	0.012	0.005	0.007	2.000000
3.49	0.2006	1.592988	0.013	0.005	0.007	2.000000
3.45	0.2120	1.604535	0.013	0.004	0.007	2.000000
3.41	0.2302	1.626948	0.014	0.003	0.008	2.000000
3.41	0.2434	1.648188	0.016	0.002	0.008	2.000000
3.44	0.2532	1.668108	0.017	0.000	0.008	2.000000
3.50	0.2603	1.686675	0.018	-0.000	0.009	2.000000

BOUNDARY VALUES

3.48	0.2590	1.682991	1.000	0.000	0.179	1.682991

XMAX	SXMAX	CMAVE
0.007	0.009	2.000000

QNET	X	PLVOL
-2.154	0.000	-0.000
-2.034	0.000	0.005
-1.917	0.000	0.010
-1.802	0.001	0.015
-1.688	0.001	0.021
-1.577	0.001	0.026
-1.468	0.002	0.032
-1.360	0.002	0.038
-1.255	0.003	0.044
-1.150	0.003	0.050

-1.048	0.003	0.056
-0.947	0.004	0.063
-0.848	0.004	0.070
-0.750	0.004	0.077
-0.653	0.005	0.085
-0.558	0.005	0.093
-0.464	0.006	0.103
-0.371	0.006	0.114
-0.277	0.006	0.126
-0.184	0.007	0.141
0.000	0.007	0.182

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.077893

N	M	CM	DCM/DX
1	0.069810	1.424876	2.733572
2	0.051317	1.374870	6.914415
3	0.046341	1.339086	8.700969
4	0.042814	1.308395	14.800133
5	0.040797	1.278540	9.639707
6	0.038309	1.254562	15.862177
7	0.036994	1.233696	19.909158
8	0.036116	1.216208	11.567925
9	0.034805	1.201046	12.041642
10	0.033093	1.187651	7.484743
11	0.032092	1.175672	5.225323
12	0.030049	1.164998	10.058167
13	0.029093	1.155378	52.538040
14	0.027593	1.076589	-4.280621
15	0.025861	1.084859	-0.665606
16	0.023501	1.086297	0.294450
17	0.019994	1.085264	0.233202
18	0.013962	1.083857	0.000000

B	VEL	PM	S	X	R	CM
1.00	1.0000	1.000000	0.000	0.000	0.000	1.083857
1.30	0.7553	1.019002	0.001	0.001	0.000	1.083857
1.61	0.6060	1.030878	0.003	0.003	0.001	1.083857
1.92	0.5049	1.039016	0.005	0.005	0.001	1.083857
2.23	0.4317	1.044944	0.007	0.006	0.002	1.083857
2.86	0.3318	1.052986	0.011	0.010	0.003	1.083857
3.50	0.2662	1.058201	0.014	0.013	0.005	1.083857
4.17	0.2191	1.061861	0.018	0.017	0.006	1.084606
4.88	0.1826	1.064674	0.022	0.020	0.008	1.085428
5.65	0.1526	1.066945	0.025	0.023	0.009	1.086038
6.06	0.1394	1.067898	0.027	0.025	0.010	1.084940
6.48	0.1277	1.068661	0.029	0.027	0.011	1.078388
6.78	0.1219	1.068701	0.031	0.028	0.012	1.139686
8.97	0.0725	1.072949	0.033	0.030	0.013	1.166247
9.83	0.0621	1.075751	0.035	0.030	0.015	1.167448
7.99	0.0972	1.078620	0.036	0.029	0.016	1.156182
7.71	0.1086	1.080063	0.038	0.027	0.017	1.076741
7.99	0.1049	1.080092	0.040	0.025	0.017	1.083755
8.15	0.1047	1.080405	0.042	0.024	0.018	1.085783
8.36	0.1051	1.080584	0.044	0.022	0.019	1.086036
8.78	0.1000	1.080894	0.047	0.019	0.021	1.085096
9.22	0.0968	1.081138	0.051	0.015	0.022	1.084372
9.68	0.0936	1.081320	0.055	0.012	0.024	1.083857
10.19	0.0906	1.081470	0.058	0.009	0.025	1.083857
10.58	0.0880	1.081610	0.062	0.005	0.026	1.083857
11.02	0.0857	1.081738	0.066	0.002	0.028	1.083857
11.45	0.0835	1.081851	0.070	-0.001	0.029	1.083857

BOUNDARY VALUES

11.31	0.0842	1.081814	1.000	0.000	0.179	1.081814

XMAX	SXMAX	CHAVE
0.030	0.034	1.979689

QNET	X	PLVOL
-9.784	0.000	-0.000
-9.275	0.001	0.208
-8.769	0.003	0.410
-8.267	0.004	0.607
-7.767	0.006	0.800
-7.269	0.007	0.988
-6.774	0.009	1.171
-6.281	0.010	1.350
-5.790	0.012	1.526
-5.302	0.013	1.699
-4.816	0.015	1.869
-4.332	0.016	2.036
-3.851	0.018	2.203
-3.375	0.019	2.368
-2.899	0.021	2.534
-2.427	0.022	2.700
-1.959	0.024	2.869
-1.494	0.026	3.042
-1.033	0.027	3.219
-0.574	0.029	3.404
0.000	0.030	3.827

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.151205

M	H	CM	DCM/DX
1	0.104091	1.424876	0.926731
2	0.050091	1.374670	6.996254
3	0.045532	1.339086	8.806861
4	0.042047	1.308395	24.752837
5	0.040024	1.278540	9.682547
6	0.037547	1.254562	16.373663
7	0.036273	1.233696	19.751951
8	0.035388	1.216208	11.571364
9	0.034077	1.201046	12.066038
10	0.032967	1.187631	7.529371
11	0.031376	1.179672	5.400693
12	0.029400	1.164998	10.037197
13	0.028441	1.155378	53.300846
14	0.026956	1.076189	-4.901639
15	0.025038	1.084824	-0.680737
16	0.022902	1.086278	0.309771
17	0.019445	1.085207	0.272106
18	0.013512	1.083595	0.000000

B	VEL	PM	S	X	R	CM
1.00	1.0000	1.000000	0.000	0.000	0.000	1.083593
1.30	0.7589	1.018649	0.001	0.001	0.000	1.083593
1.60	0.6107	1.030391	0.003	0.003	0.001	1.083593
1.90	0.5098	1.038475	0.005	0.005	0.001	1.083593
2.21	0.4365	1.044382	0.007	0.006	0.002	1.083593
2.82	0.3362	1.052423	0.010	0.010	0.003	1.083593
3.45	0.2700	1.057654	0.014	0.013	0.005	1.083593
4.11	0.2224	1.061335	0.018	0.016	0.006	1.084495
4.80	0.1854	1.064193	0.021	0.020	0.007	1.085422
5.56	0.1548	1.066524	0.025	0.023	0.009	1.085931
5.96	0.1414	1.067479	0.027	0.025	0.010	1.084831
6.38	0.1296	1.068248	0.028	0.026	0.011	1.077670
6.68	0.1236	1.068308	0.030	0.028	0.012	1.143308
8.89	0.0725	1.072669	0.032	0.029	0.013	1.166459
9.61	0.0639	1.075460	0.034	0.029	0.014	1.167420
7.85	0.0990	1.078336	0.036	0.028	0.015	1.156187
7.57	0.1106	1.079797	0.037	0.026	0.016	1.076265
7.85	0.1067	1.079810	0.039	0.025	0.017	1.083494
8.00	0.1067	1.080145	0.041	0.023	0.018	1.085721
8.21	0.1051	1.080330	0.043	0.022	0.019	1.086028
8.62	0.1020	1.080656	0.046	0.018	0.020	1.085037
9.05	0.0988	1.080907	0.050	0.015	0.022	1.084139
9.49	0.0955	1.081090	0.054	0.012	0.023	1.083593
9.95	0.0923	1.081238	0.057	0.008	0.025	1.083593
10.39	0.0896	1.081377	0.061	0.005	0.026	1.083593
10.82	0.0872	1.081504	0.065	0.002	0.027	1.083593
11.25	0.0850	1.081615	0.068	-0.001	0.028	1.083593

BOUNDARY VALUES

11.10	0.0898	1.081576	1.000	0.000	0.179	1.081576

XMAX	SXMAX	CMAVE
0.029	0.033	1.961313

QNET	X	PLVOL
-9.578	0.000	-0.000
-9.030	0.001	0.196
-8.586	0.002	0.387
-8.094	0.004	0.573
-7.604	0.005	0.754
-7.117	0.007	0.931
-6.632	0.008	1.104
-6.150	0.010	1.272
-5.670	0.011	1.438
-5.191	0.013	1.600
-4.716	0.014	1.760
-4.242	0.016	1.916
-3.772	0.017	2.075
-3.304	0.019	2.231
-2.839	0.020	2.387
-2.377	0.022	2.544
-1.919	0.023	2.703
-1.465	0.025	2.866
-1.013	0.026	3.033
-0.564	0.028	3.209
0.000	0.029	3.611

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.224520

N	H	CM	DCM/DX
1	0.132003	1.424876	0.608641
2	0.049542	1.374870	6.995504
3	0.044729	1.339096	9.937250
4	0.039269	1.278540	9.724347
5	0.028767	1.164999	10.041447
6	0.018919	1.085193	0.301154
7	0.013089	1.083438	0.000000

B	VEL	PM	S	X	R	CM
1.00	1.0000	1.000000	0.000	0.000	0.000	1.083438
1.41	0.6942	1.023699	0.002	0.002	0.000	1.083438
1.93	0.5300	1.036780	0.004	0.004	0.001	1.083438
2.25	0.4265	1.045087	0.007	0.007	0.002	1.083438
2.68	0.3545	1.050832	0.009	0.009	0.003	1.083438
3.56	0.2610	1.059248	0.014	0.013	0.005	1.083711
4.49	0.2006	1.062860	0.019	0.018	0.007	1.085097
5.51	0.1562	1.066163	0.024	0.023	0.009	1.119424
6.43	0.1228	1.069632	0.027	0.025	0.010	1.137244
8.17	0.0803	1.073295	0.029	0.027	0.012	1.153097
9.17	0.0666	1.076694	0.032	0.027	0.014	1.155965
7.36	0.1088	1.080523	0.034	0.025	0.016	1.140866
6.96	0.1325	1.093841	0.037	0.023	0.017	1.122661
6.84	0.1498	1.088133	0.042	0.018	0.019	1.085170
7.71	0.1316	1.087824	0.047	0.014	0.020	1.063737
8.57	0.1176	1.087440	0.052	0.009	0.021	1.083438
9.40	0.1069	1.087097	0.057	0.004	0.023	1.083438
10.22	0.0981	1.086808	0.062	-0.000	0.025	1.083438

BOUNDARY VALUES

9.97	0.1028	1.086819	1.000	0.000	0.179	1.086818

XMAX	SXMAX	CMAVE
0.027	0.031	1.943612

QNET	X	PLVOL
-9.233	0.000	0.000
-8.761	0.001	0.147
-8.291	0.002	0.290
-7.821	0.004	0.427
-7.354	0.005	0.558
-6.887	0.006	0.684
-6.422	0.008	0.407
-5.957	0.009	0.924
-5.493	0.011	1.038
-5.031	0.012	1.149
-4.569	0.013	1.257

-4.106	0.015	1.359
-3.645	0.016	1.461
-3.188	0.018	1.563
-2.734	0.019	1.664
-2.283	0.020	1.766
-1.940	0.022	1.876
-1.407	0.023	1.991
-0.957	0.025	2.122
-0.565	0.026	2.297
0.000	0.027	2.690

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.320240

M	H	CM	DCM/DX
1	0.169263	1.424876	0.805145
2	0.101155	1.374870	11.433214
3	0.098025	1.339086	18.934700
4	0.094828	1.278540	20.740541
5	0.089353	1.164998	583.259470
6	0.089217	1.085193	9.904531
7	0.089039	1.083438	-16.979372
8	0.088847	1.086712	0.001877
9	0.035423	1.083652	3.280492
10	0.034567	1.081174	1.965192
11	0.033473	1.078827	1.481420
12	0.031855	1.076430	1.210240
13	0.029694	1.073815	0.944078
14	0.026713	1.071001	0.503745
15	0.022368	1.068825	1.175826
16	0.015355	1.060579	0.000000

B	VEL	PM	S	X	R	CM
1.00	1.0000	1.000000	0.000	0.000	0.000	1.060579
1.43	0.6907	1.017743	0.002	0.002	0.000	1.060579
1.86	0.5262	1.027308	0.005	0.004	0.001	1.060579
2.29	0.4234	1.033288	0.007	0.007	0.002	1.060579
2.73	0.3527	1.037386	0.010	0.009	0.003	1.060579
3.62	0.2610	1.042539	0.015	0.014	0.005	1.060579
4.55	0.2025	1.045843	0.020	0.019	0.007	1.065363
5.64	0.1556	1.049171	0.026	0.024	0.009	1.069735
7.01	0.1152	1.051932	0.031	0.028	0.012	1.072976
7.92	0.0954	1.053127	0.033	0.031	0.013	1.075398
9.19	0.0745	1.054245	0.036	0.033	0.015	1.078154
11.01	0.0541	1.055262	0.039	0.034	0.017	1.080905
11.42	0.0521	1.056185	0.041	0.034	0.019	1.080916
10.21	0.0677	1.057074	0.044	0.032	0.021	1.078120
9.55	0.0808	1.057890	0.046	0.030	0.023	1.075317
9.27	0.0897	1.058593	0.049	0.028	0.024	1.072869
9.19	0.0954	1.059182	0.052	0.026	0.025	1.070825
9.33	0.1012	1.060083	0.057	0.021	0.027	1.067887
9.85	0.0993	1.060493	0.062	0.016	0.029	1.062151
10.64	0.0922	1.060538	0.067	0.011	0.031	1.060579
11.39	0.0868	1.060597	0.072	0.006	0.033	1.060579
12.09	0.0827	1.060670	0.078	0.001	0.035	1.060579
12.87	0.0781	1.060695	0.083	-0.002	0.036	1.060579

BOUNDARY VALUES

12.39	0.0809	1.060685	1.000	0.000	0.179	1.060685

XMAX	SXMAX	CMAVE
0.034	0.040	1.920107

QNET	X	PLVOL
-11.439	0.000	-0.000
-10.850	0.001	0.280
-10.264	0.003	0.550
-9.681	0.005	0.811
-9.099	0.006	1.064
-8.520	0.008	1.309
-7.942	0.010	1.546
-7.366	0.012	1.775
-6.790	0.013	1.994
-6.218	0.015	2.210
-5.647	0.017	2.420
-5.079	0.019	2.626
-4.517	0.020	2.837
-3.961	0.022	3.048
-3.411	0.024	3.264
-2.870	0.026	3.497
-2.338	0.027	3.740
-1.816	0.029	4.004
-1.305	0.031	4.306
-0.782	0.032	4.694
0.000	0.034	5.612

BUOYANT PLUME IN A SPHERICAL CAVITY

TIME = 0.430208

M	H	CM	DCM/DX
1	0.191015	1.424876	0.964026
2	0.139743	1.374870	14.675915
3	0.137305	1.339086	24.535068
4	0.134837	1.278540	27.249069
5	0.130070	1.164998	773.548809
6	0.130567	1.085193	13.143069
7	0.130434	1.083438	-22.546005
8	0.130289	1.086712	0.001040
9	0.034422	1.083652	3.237609
10	0.033056	1.081174	1.964980
11	0.032462	1.078827	1.496315
12	0.030860	1.076430	1.226022
13	0.028727	1.073815	0.959318
14	0.025793	1.071001	0.510732
15	0.021533	1.068825	1.221709
16	0.014096	1.060472	0.000000

B	VEL	PM	S	X	R	CM
1.00	1.0000	1.000000	0.000	0.000	0.000	1.060472
1.41	0.6965	1.017362	0.002	0.002	0.000	1.060472
1.83	0.5329	1.026842	0.005	0.004	0.001	1.060472
2.26	0.4300	1.032812	0.007	0.007	0.002	1.060472
2.68	0.3588	1.036923	0.010	0.009	0.003	1.060472
3.55	0.2661	1.042121	0.015	0.014	0.005	1.060472
4.46	0.2067	1.045471	0.020	0.018	0.007	1.065589
5.52	0.1588	1.048883	0.025	0.023	0.009	1.069835
6.85	0.1177	1.051666	0.030	0.028	0.011	1.073119
7.74	0.0975	1.052878	0.032	0.030	0.013	1.075543
8.98	0.0762	1.054009	0.035	0.032	0.014	1.078277
10.74	0.0554	1.055037	0.037	0.033	0.016	1.080994
11.17	0.0532	1.055968	0.040	0.033	0.019	1.081040
10.00	0.0689	1.056864	0.043	0.032	0.021	1.078295
9.34	0.0823	1.057690	0.045	0.030	0.022	1.075511
9.06	0.0915	1.058406	0.048	0.027	0.024	1.073054
8.98	0.0975	1.059008	0.050	0.025	0.025	1.070938
9.11	0.1036	1.059930	0.055	0.021	0.027	1.068192
9.59	0.1020	1.060374	0.060	0.016	0.029	1.062397
10.35	0.0950	1.060432	0.065	0.011	0.030	1.060472
11.08	0.0893	1.060487	0.070	0.006	0.032	1.060472
11.77	0.0850	1.060559	0.075	0.001	0.034	1.060472
12.53	0.0802	1.060585	0.081	-0.002	0.035	1.060472

BOUNDARY VALUES

12.07	0.0831	1.060575	1.000	0.000	0.179	1.060575

XMAX	SXMAX	CMAVE
0.033	0.039	1.895978

QNET	X	PLVOL
-11.126	0.000	-0.000
-10.553	0.001	0.258
-9.983	0.003	0.508
-9.415	0.005	0.749
-8.850	0.006	0.982
-8.286	0.008	1.207
-7.724	0.010	1.426
-7.163	0.011	1.637
-6.603	0.013	1.839
-6.046	0.015	2.039
-5.491	0.016	2.233
-4.939	0.018	2.424
-4.393	0.020	2.618
-3.852	0.021	2.814
-3.318	0.023	3.015
-2.792	0.025	3.231
-2.275	0.027	3.457
-1.768	0.028	3.703
-1.270	0.030	3.985
-0.762	0.032	4.345
0.000	0.033	5.200

APPENDIX 5

PHYSICAL PROPERTIES OF OXYGEN AND METHANE

P = 1 atm

Gas	T °F	$\gamma = C_p/C_v$	ρ lbm/cu ft	$\mu \times 10^5$ lbm/ft sec	$\nu \times 10^3$ sq ft/sec	R ft lbf/lbm°R
Oxygen*	100	1.4	0.0785	1.420	0.181	48
	200	1.4	0.0666	1.610	0.241	48
Methane**	68	1.32	0.0371	0.726	0.196	96
	212	1.32	0.0334	0.895	0.268	96

* F. Kreith, "Principles of Heat Transfer", International Textbook Co., Scranton, Pa. (1958).

** R. C. Reid and T. K. Sherwood, "The Properties of Gases and Liquids", McGraw-Hill Book Co., Inc., New York (1959).