GE-MTSD-R-062

# PYROTECHNIC HAZARDS CLASSIFICATION AND EVALUATION PROGRAM
# FINAL REPORT
# RUN-UP REACTION TESTING IN PYROTECHNIC DUST SUSPENSION

APRIL 19, 1971

CONTRACT NAS8-23524

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MISSISSIPPI TEST FACILITY

(NASA-CR-123039) PYROTECHNIC HAZARDS CLASSIFICATION AND EVALUATION PROGRAM. RUN-UP REACTION TESTING IN PYROTECHNIC DUST SUSPENSIONS Final Report (General Electric Co.) 19 Apr. 1971 66 p CSCL 19A G3/33

N72-18964

Unclas
20005

GENERAL ELECTRIC

N72 - 18964
GE-MTSD-R-062

# PYROTECHNIC HAZARDS CLASSIFICATION

# AND

# EVALUATION PROGRAM

## FINAL REPORT

## RUN-UP REACTION TESTING IN PYROTECHNIC DUST SUSPENSIONS

APRIL 19, 1971

CONTRACT NAS8-23524

Anthony H. Lasseigne
A. H. LASSEIGNE, PROJECT ENGINEER
PYROTECHNIC HAZARD CLASSIFICATION
AND EVALUATION (KEMOPS) PROGRAM
MTSD-GENERAL ELECTRIC COMPANY

Paul V. King
PAUL V. KING, MANAGER
MATERIEL TESTING AND RESEARCH
MTSD-GENERAL ELECTRIC COMPANY

# FOREWORD

The studies, tests, calculations, and analysis contained in the following report were prepared by the General Electric Company, Management and Technical Services Department (GE-MTSD), Bay Saint Louis, Mississippi, under National Aeronautics and Space Administration (NASA) Contract NAS8-23524 for the Engineering Test and Evaluation Section, Process Technology Branch, Chemical Process Laboratory, Weapons Development and Engineering Laboratory, Edgewood Arsenal, Maryland.

The work described herein was performed in accordance with the contract workscope with technical direction and assistance from W. P. Henderson, Chief, Engineering Test and Evaluation Section.

# ACKNOWLEDGEMENTS

Special acknowledgement is made of the following Edgewood Arsenal technical personnel who contributed significantly to the success of this program:

- B. Berger, Deputy, Weapons Development and Engineering Laboratory
- W. P. Junkin, Chief, Chemical Process Laboratory
- J. K. Bartell, Chief, Process Technology Branch
- A. E. Becher, Chief, Safety
- J. Vogelein, Safety Engineer

The following General Electric Materiel Testing and Research Project Engineers were responsible for the successful completion of their respective tasks:

- Data Acquisition - S. Russell
- Technical Support - T. Small and P. Fassnacht

All of the projects were under the technical direction of P. V. King, Sr., Manager of the Materiel Testing and Research Group, and D. M. Koger, KEMOPS Program Manager. Special mention must be made of the competence and efficiency of the entire test team, led by Mr. F. L. McIntyre, Test Supervisor, and S. Fuentes, Lead Technician and Ordnance Specialist, who worked diligently in the face of many obstacles to provide the valid, meaningful data in the minimum time.

# ABSTRACT

As a result of a systematic analysis of the findings from operational surveys, plant tours, and inspections conducted at Pine Bluff Arsenal, four manufacturing operations have been identified as areas of primary concern. These operations have been evaluated under Phase II, Segment 2, Operational Survey. However, another relatively important but potentially more serious accident mechanism, namely run-up reactions, has been identified as an area worthy of investigation. This report represents a preliminary investigation of the parameters included in the run-up dust reactions.

Two types of tests were conducted:

- Ignition criteria of large bulk pyrotechnic dusts
- Optimal run-up conditions of large bulk pyrotechnic dusts

These tests were used to evaluate the order of magnitude and gross scale requirements needed to induce run-up reactions in pyrotechnic dusts; in particular, to simulate at reduced scale an accident that occurred in a manufacturing installation.

Results of testing showed propagation of pyrotechnic dust clouds resulted in a fireball of relatively long duration and large size. In addition, a plane wave front was observed to travel down the length of the gallery.

# TABLE of CONTENTS

# TABLE of CONTENTS (cont'd)

## LIST of ILLUSTRATIONS



## LIST OF TABLES

# SECTION 1
# INTRODUCTION AND SUMMARY

## 1.1 GENERAL

In accordance with the requirements of Contract NAS8-23524, Amendment 8, General Electric, Management and Technical Services Department (GE-MTSD) has conducted the program described below with appropriate testing to determine the characteristics of a reaction propagating through a large scale pyrotechnic dust suspension.

## 1.2 RATIONALE

The concept of run-up and the sequence of events involved in dust reactions are as follows:

- Incident occurs during manufacturing operation whereby mechanical or electrical energy is dissipated in a small localized region or "hot spot" within bulk pyrotechnic mix.
- With ignition induced below the surface of the mix, the material above supplies a significant pressure head which allows a transient pressure buildup caused by the temporary confinement of reaction by-products.
- As a result of the above, extensive blow-out of the mix occurs with formation of a burning dust cloud. (Refer to Investigation of Hazards Associated with Pyrotechnic Manufacturing Processes, Phase II, Segments 4-7 Report, GE-MTSD-R-058.)
- If the above flame front is afforded a predetonation run, the end result is a larger or more extensive volume of material reacting with an increase in burn rate.
- As a result of a predetonation run of the flame front, it may undergo transition from subsonic to supersonic velocities (i.e., transition from the type of burning induced by heat transfer across the combustion wave to the type induced by heat generated by shock compression). During the run, a rarefaction wave propagates backward into the unburned dust suspension, and a jet of unburned dust develops which penetrates deeply into the burned gas. The shear between burned and unburned dust in this flow configuration produces extreme turbulence so that a sudden large increase of the burning occurs. The end result is an unstable detonation occurring at some distance from the ignition source. Additionally, previous investigations have revealed that the terminal velocity of the reaction front in dust suspensions may be subsonic for a given dust density, but, if a density gradient exists, the communication properties may be affected, opening the possibility of run-up to supersonic velocities.

As a result of a systematic analysis of the findings from operational surveys, plant tours, and inspections conducted at Pine Bluff Arsenal, dust/vapor atmospheres have been identified as areas of basic concern. Additionally, secondary hazards were evidenced in areas where settled dust and vapor accumulations could conceivably result in propagation to large concentrations of the bulk pyrotechnics with its ultimate detonation.

Data is required to furnish a basis for discrete safety assessments and design recommendations of manufacturing operations since small quantities of dust are always present and in the event of a minor accident much more may be generated.

The importance of this type of simulation is borne out by experience. A number of accidents that have occurred in manufacturing installations are suspected of resulting from run-up reactions propagating through dust cloud formations. This type of accident frequently results in severe damage to facilities and equipment and extensive injuries to personnel.

To establish the kinematics (location as a function of time) of the reaction front based on available information (heat of combustion, burn rate, density, etc.) would be too ambitious a task and well beyond the scope of this program.

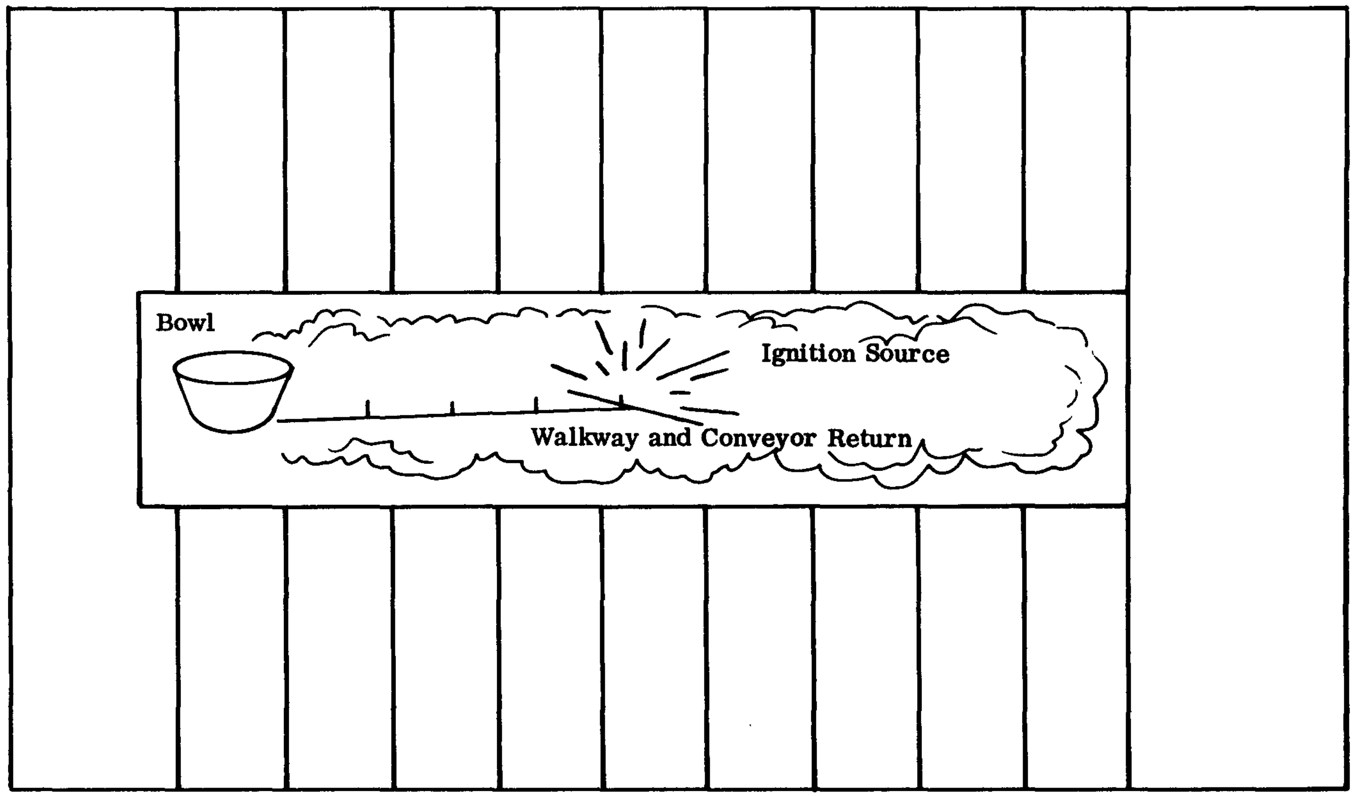
This program has:

- Investigated in a very limited way the order of magnitude and gross scale requirements needed to induce run-up reactions.
- Studied various initiation processes.
- Developed criteria for more definitive tests.
- Determined restraints that can be imposed on manufacturing operations which will prevent run-up type reactions.

In order to accomplish the above objectives, this test program (see Run-up Test 1, paragraph 2.2.3) simulated at reduced scale a possible accident on the mixing line for large bulk pyrotechnics at Pine Bluff Arsenal. (See Figure 1-1.) It is assumed that a pyrotechnic dust cloud can be simultaneously ignited and confined in the 8 x 12 x 32 foot passageway between the mixing bays of Building 31620. It is postulated that the passageway contains two 175 quart mixing vessels each filled with 125 pounds of a pyrotechnic mix.

The worst cast conditions which could possibly arise occur when the contents of one vessel is dispersed as a dust suspension in a cloud either through accidental spillage or dust being formed in conjunction with the sifter operation at the end of Building 31620. Furthermore, it is assumed that the dust suspension forms a cloud which decreases in density geometrically down the length of the passageway (varying in that direction only) with a final density of 0.1 oz/ft$^3$ (the minimum concentration range for ignition) at the far end. It is also assumed that an unspilled vessel is

TYPICAL - APPROXIMATE - NOT TO SCALE




BUILDING ASSIGNMENT

Building 33-530 Yellow Smoke Grenade
Building 33-630 CS Canister
Building 33-530 XM126 Thermate Bomblets

Figure 1-1. Conceptual Sketch of Simulated Accident Involving Mixing Bowls located at the high concentration end of the room and ignition of the dust cloud occurs at the low concentration end.

Based on the results of the above test, an additional test (run-up test 2) was designed to help establish the optimal conditions which lead to run-up reactions in dusts.

## 1.3 APPROACH

The overall program of dust investigation (see Figure 1-2) for studying ICT (ignition, communication, and transition) criteria encompasses two phases:

- Laboratory evaluation of the explosive characteristics of pyrotechnic dusts and parameters that affect their explosibility were conducted using procedures as specified by the Bureau of Mines for the Hartmann Apparatus. Data obtained in this manner gives minimum density and energy for ignition of pyrotechnic mixes.
- Investigations in partly open chambers or galleries ranging from 75 $in^3$ 512 $ft^3$.

### 1.3.1 INITIATION EVALUATION OF DUSTS

In any hazard appraisal, it is important that the ignition sensitivity of the pyrotechnic materials (suspended in the air) to the potential stimuli available be explored in detail. Specifically if one particular ignition source (e.g., open flame, glowing particle, electric arc, static discharge, frictional spark) is more effective than another.

To satisfy the above requirements, laboratory evaluation of the explosive characteristics of pyrotechnic dusts and parameters that affect their explosibility have been conducted using procedures as specified by the Bureau of Mines for the Hartmann Apparatus. Data obtained in this manner gives the minimum density and energy for ignition of pyrotechnics.

### 1.3.2 COMMUNICATION AND TRANSITION EVALUATION

The purpose of communication and transition testing is to study in a dust suspension the characteristics of a system interacting with its environment which affect the run-up potential of the critical system from ignition to detonation. Specifically, the tests are designed to determine the potential of the reacting material for communication (by shock wave, fragmentation, pyrotechnic spray, etc.) to adjacent material inducing ignition of the entire system. The nature of the reaction of pyrotechnic dust suspensions may be such that certain dust densities or variations in density may run up to transition within the confines of a room, thus providing a more severe and somewhat different hazard potential. The end result is a much larger critical mass than the initiating mass; consequently, the incident is much more severe and the damage to equipment and personnel is much more extensive.

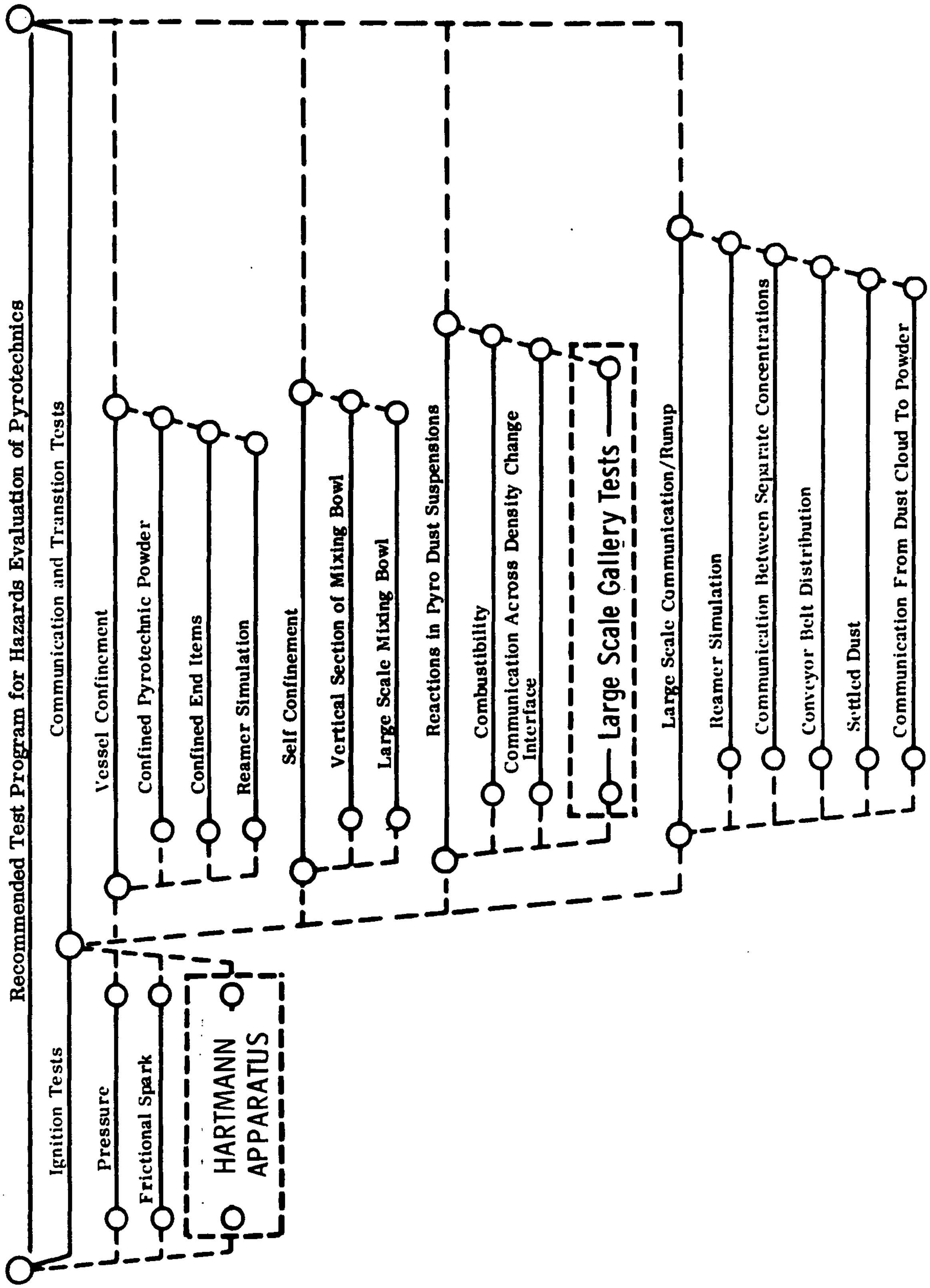



Figure 1-2. Flow Chart of Recommended Test Program

Because dust suspensions behave as a gas, they can occupy large volumes of a room, as such they can interface with any exposed material to provide a means of communication to other components. When the detonation or near detonation reaction front propagates to an interface with pyrotechnic powder, slurry, or end items, it encounters a significantly different environment. Whether it will continue to propagate, run up, run down, or fail to penetrate will depend on the nature of the incident reaction front and on the condition of the target material.

Two types of dust dispersal occur:

- Prior to the Passage of the Reaction Front by External Means

  Loose pyrotechnic powder is present in almost all manufacturing operations, and as a result, dust clouds may be emitted as a by-product or dispersed as a result of a spill.

- Coincident with the Reaction Front

  Turbulence or shock of the reaction front impinges upon open vessels or piles of pyrotechnic powder or where dust has settled on surfaces (particularly horizontal surfaces).

To be considered in the investigation of pyrotechnic dusts is that, unlike single base fuel/reactants, pyrotechnics are tertiary base reactants. For single base fuel suspensions, the air surrounding the particulate provides the required oxygen (a maximum run-up resulted when a stoichiometric ratio of fuel/oxygen was maintained. In the case of pyrotechnics, sufficient oxidizer to react with the fuel is already included in the material, but excess oxidization as supplied by the air may possibly increase the reaction rate by including the other components of the mix in the reaction and changing the energy output of the net reaction.

Dust suspensions of the final pyrotechnic mixtures are not the only materials of interest, for the component materials or incomplete mixtures encountered during manufacture may have similar or even more severe run-up characteristics. Organic liquids with large vapor pressures, including heptone and acetone, are used in various manufacturing operations. The existence of their vapors in the air-dust mixture may affect reaction rates for a particular dust density, particularly since the presence of vapor increases the fuel-oxidizer ratio.

# SECTION 2
# TECHNICAL APPROACH

## 2.1 GENERAL

From a functional point of view, the primary requirement of a dust suspension investigation is to establish the acceleration of the reaction front as a function of its velocity and the dust density, material, and particle size. The availability of this information and the properties of a given dust cloud are sufficient to fully establish the kinematics (location as a function of time) of the reaction front and, hence, the distance and time to detonation. Unfortunately, such an ambitious task is well beyond the scope of this program.

Instead, three programs are proposed which will determine:

- Ability of a dust suspension of certain densities to support combustion.
- Ability of a dust suspension to communicate to a powder.
- The propagation characteristics in a large scale experiment with a variety of dust densities and density gradients.

## 2.2 TEST PROGRAM DESCRIPTION

### 2.2.1 LABORATORY SCALE TESTS USING THE HARTMANN APPARATUS - 75 CUBIC INCHES

In order to evaluate pyrotechnic dust hazard characteristics, experimental work on explosibility of pyrotechnic dusts was performed in a special laboratory scale apparatus (Figures 2-1 and 2-2) developed by the Bureau of Mines.

Tests were designed to evaluate the ignition threshold of pyrotechnic dust atmosphere by determining:

- Minimum electrical energy of ignition as a function of dust particle density, humidity, and stoichiometric ratio.
- Maximum reaction induced pressure and rate of pressure rise as a function of chemical imbalance of stoichiometric ratio.

Basically, the chamber is a 2-3/4 inch diameter steel tube, 12 inches long, that is vertically mounted on a support stand. The interior of the support stand consists of the following:

- Dispersion cup (where weighed sample is placed).
- Adjustable compressed air deflector (in order to deflect compressed air onto sample).

Dust dispersal was accomplished by compressed air (80 psi - 100 psi) being released on command by an electrically operated full-pot solenoid valve. After dust dispersal, ignition is ordinarily

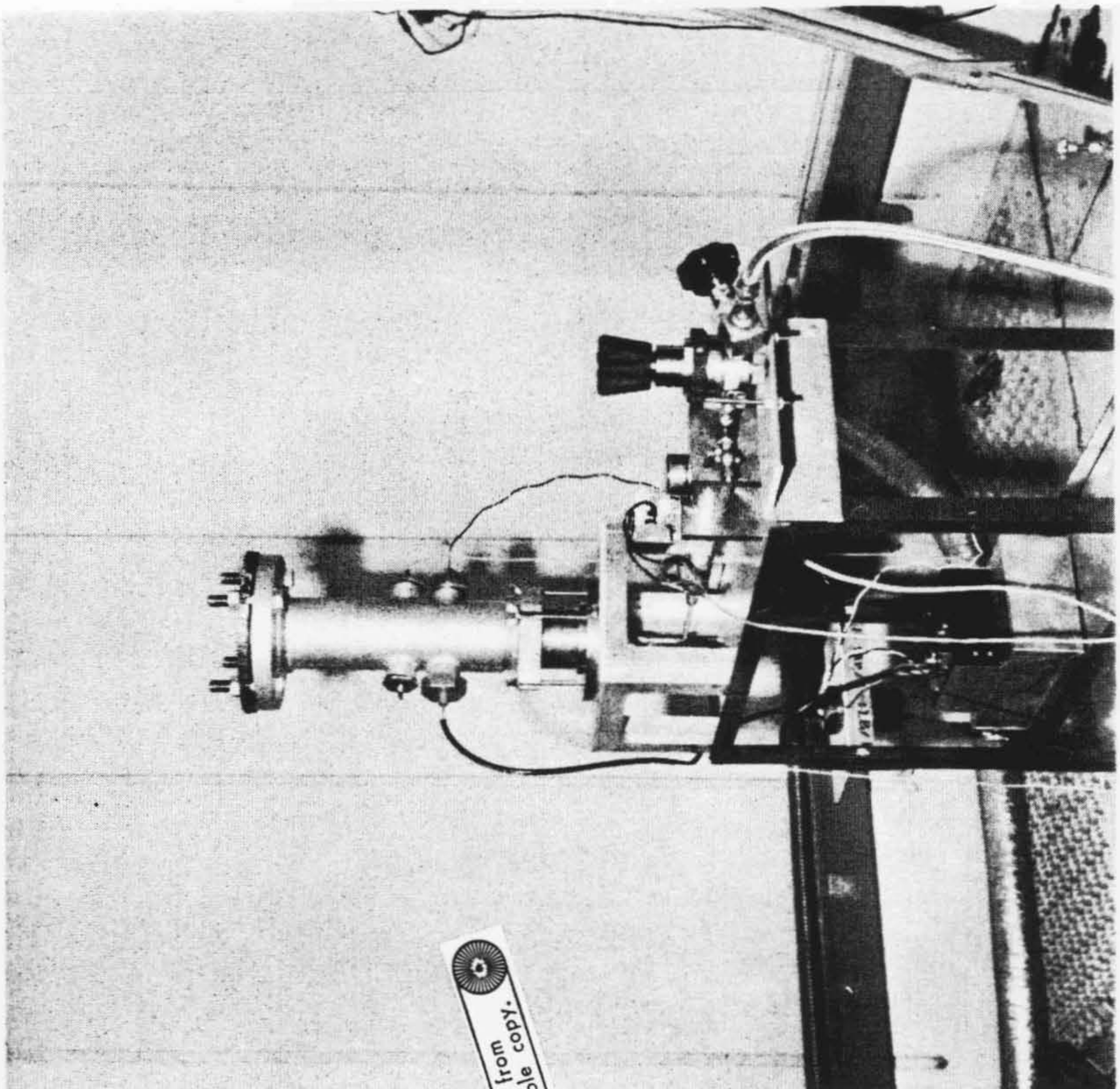


Figure 2-1. The Bureau of Mines' Hartmann Apparatus

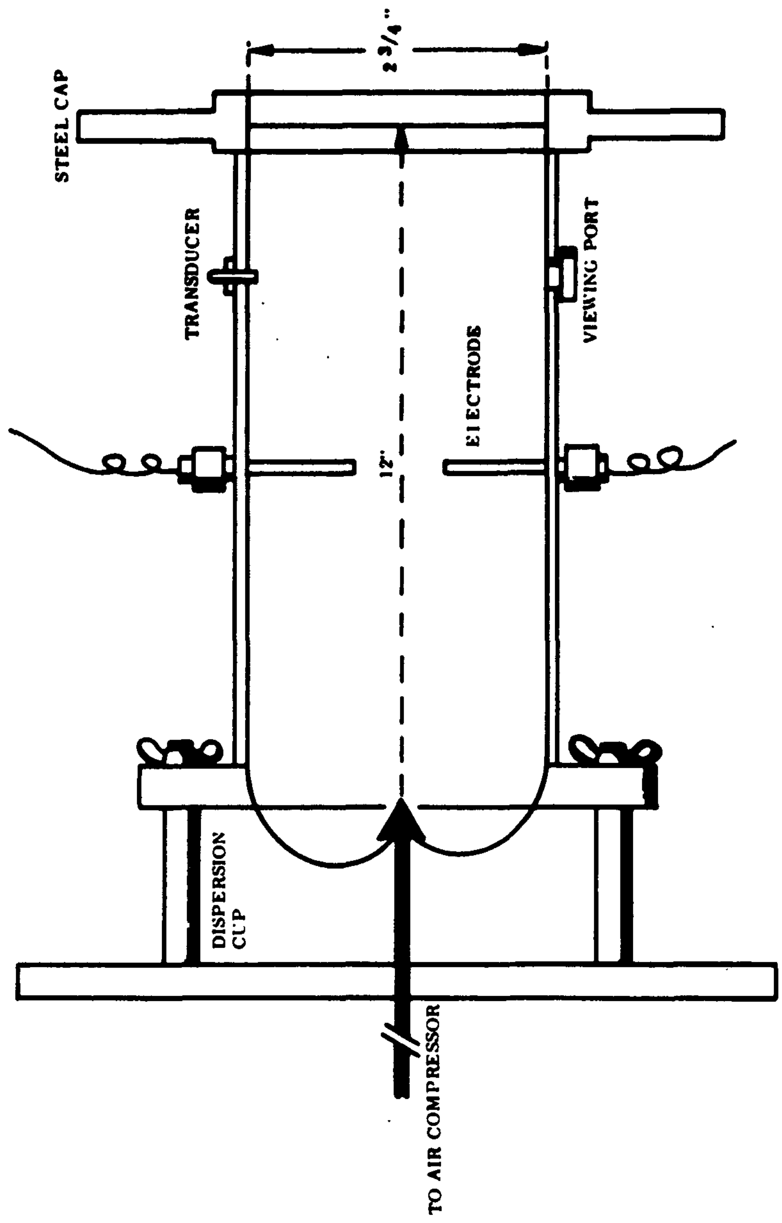



Figure 2-2. Cutaway of Hartmann Chamber

accomplished by connecting to the electrodes any one of the following electrical power supplies (listed in order of decreasing energy):

- Single spark discharge (50 Joules capacity) - using a Fluke 410 high voltage power supply (10,000 volt output) and a compatible capacitance bridge with a range of 10 picofarads to 1 microfarad.
- Hot wire - a 120 watt DC power supply was connected to a helical coil (1/2 inch in diameter and 3/4 inch long) made from a 15-inch length of No. 18 Nichrome V wire.
- 24-watt continuous induction spark - which consists of a capacitance discharge circuit of 1 microfarad being pulsed at 550 Hz through a high voltage transformer.

The following visual observation criteria have been established by the Bureau of Mines in their dust cloud ignition tests using the Hartmann Apparatus:

- Filter paper rupture - a single disc or sheet of No. 4 Whatman filter paper was held in place on top of chamber by a locking ring. Rupture of this disc provided evidence of ignition of the dust cloud.
- Flame propagation four inches or longer inside the tube (as observed through viewing ports inside of chamber).

### 2.2.2 32-CUBIC FOOT GALLERY (4 x 2 x 4 Ft.)

The purpose of testing this intermediate size gallery is to:

- Apply results obtained from the 75-cubic inch chamber to the full-size 32-foot length gallery (see Section 2.2.3) with minimum testing of the latter.
- Conduct series of trial testing to determine optimum size, duration, and intensity for ignition of large bulk pyrotechnic dusts.
- Feasibility of dispersing large bulk pyrotechnic dusts using various dispersion systems (e.g., pneumatic or detonating).

As shown in Figure 2-3, the 32-cubic foot gallery consisted of centrally mounted electrode holders, transparent Lucite viewing panel, and, when required, a pneumatic dust dispersion trough.

As previously mentioned, dust dispersal was accomplished by either of two techniques:

- Compressed air (400 psi - 800 psi) being released on command by a solenoid valve (the resulting turbulence generating dust dispersal).
- Number 8 blasting cap wired to the outside of an ordinary paper bag suspended from the ceiling of the gallery - method suggested and used by the Bureau of Mines for dust dispersal.


Figure 2-3. 32-Cubic Foot Test Gallery Setup Consisting of Pneumatic Dust Dispersion System and Power Supply for Single Spark Ignition Source

Various ignition sources were connected to the centrally mounted electrode holders:

- Single spark discharge of 50 Joules - using a Fluke 410 high voltage power supply (10,000 volt output) and a high voltage capacitor of 1 microfarad.
- Hot wire - a 120-volt AC power supply was connected to a heater coil 35 inches long.
- Booster igniter - consisting of a Number 8 blasting cap placed inside an ordinary paper bag containing 100 gm (S + $KClO_3$, 1:1).

High-speed motion picture was used to verify/identify ignition of dust dispersion and chronology of events; e.g., ignition delay time, propagation, size of fireball, etc.).

2.2.3 LARGE-SCALE GALLERY (32 x 4 x 4 Ft.)

It has been established that simulation of large-scale dust cloud reactions must be performed with large-scale equipment. Bureau of Mines' research has established that boundary influences of confining walls are significant. Since the walls affect reaction front velocities, wall separations should be as close to full scale as practical to properly access the run-up potential.

The gallery was bolted to a concrete pad for secure foundation with transparent Lucite front walls and black plywood back walls for motion picture measurement of flame front velocities. The ends and ceiling sections were sealed with mylar sheeting to contain the dust powder after dispersion. For purposes of velocity measurements, reference scales, graduated in feet, were placed both inside and outside the gallery.

The simulated gallery configuration has side walls and ceiling-floor separations of 4 feet each to minimize boundary conditions and a length of 32 feet to be consistent with typical maximum dimensions (see Paragraph 1.2).

Previously, having established the lower explosive limit with the Hartmann Apparatus and the most effective method of bulk powder dispersal with the intermediate scale gallery, three classes of experiments were performed with the large-scale gallery:

- Run-up test 1 - A constant dust density in order to establish the run-up to detonation potential versus dust concentration. It is quite possible that the terminal velocity of the reaction front will be subsonic under these conditions.
- Run-up test 2 - By varying the density as a function of distance from ignition point, the reaction front may be induced to run up to supersonic velocities. Therefore, while the former class of experiments is designed to establish the reaction properties of pyrotechnic dust suspension, the latter is designed to establish optimal conditions which lead to run-up reactions in dust.

- In conjunction with the above tests, another class of experiments was the investigation of the communication characteristics of a dust cloud reaction with undispersed pyrotechnics, whereby the high velocity reaction front generated in the gallery impinged upon a target situated at the downstream end of the gallery.

2.2.3.1 Run-up Test 1

The gallery is subdivided into four 8-foot sections, each of which had the same concentration of dust (see Figures 2-4 and 2-5). The volume of the gallery corresponds to one-sixth of that of the passageway in Building 31620,and in order to maintain the same mass to volume ratio, only one-sixth of the total amount of powder in the large 125-pound capacity mixing bowl was dispersed in the gallery.

2.2.3.1.1 Dust Distribution

In accordance with the requirement to establish the reaction properties of pyrotechnic dust suspensions, a homogenous dust distribution was accomplished by placing in each 8-foot section the following amounts of material (see Table 2-1):

- Four 1-lb bags of loose sulfur green powder were suspended from the ceiling in each of the eight-foot sections.
- A Number 8 blasting cap was wired to the outside of each of the paper bags.
- As shown in Figure 2-6, the first eight 1-lb bags were fired simultaneously followed by the second eight 1-lb bags plus two additional 100-gm bags of booster (see next section).

2.2.3.1.2 Ignition Source

Rather than use a minimal energy spark as used in the Hartmann Apparatus, ignition was by a positive means that would not allow ignition sensitivity to be a factor. As a result of a selected number of tests with the intermediate size gallery, the 100-gm booster igniter was found to be a more positive ignition source (i.e., more representative of the stimuli expected from a small incident - fire). This type of igniter provides a volume type ignition source rather than a point type ignition source, with the latter being sensitive to the dust distribution in a localized region/ immediate vicinity of the electrodes.

Based on testing in the intermediate size gallery, the booster ignition source consisted of two 1-lb bags, each containing 100 gms of $S + KClO_3$ (1:1). The reasoning behind a two-bag ignition source was to lessen the chance of a misfire, thereby having one bag as a contingency ignition source should the primary ignition bag fail.

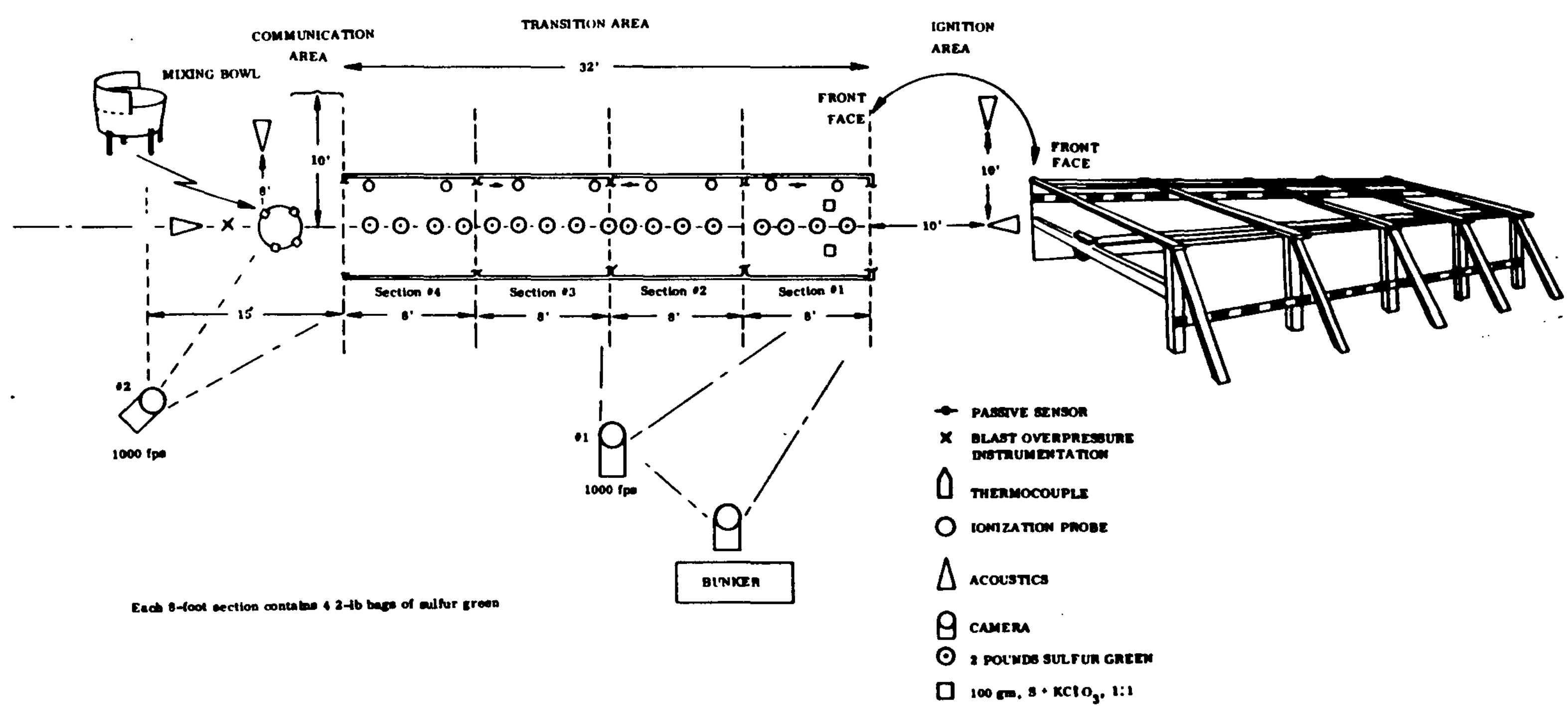



Figure 2-4. Test Setup for Run-up Test 1

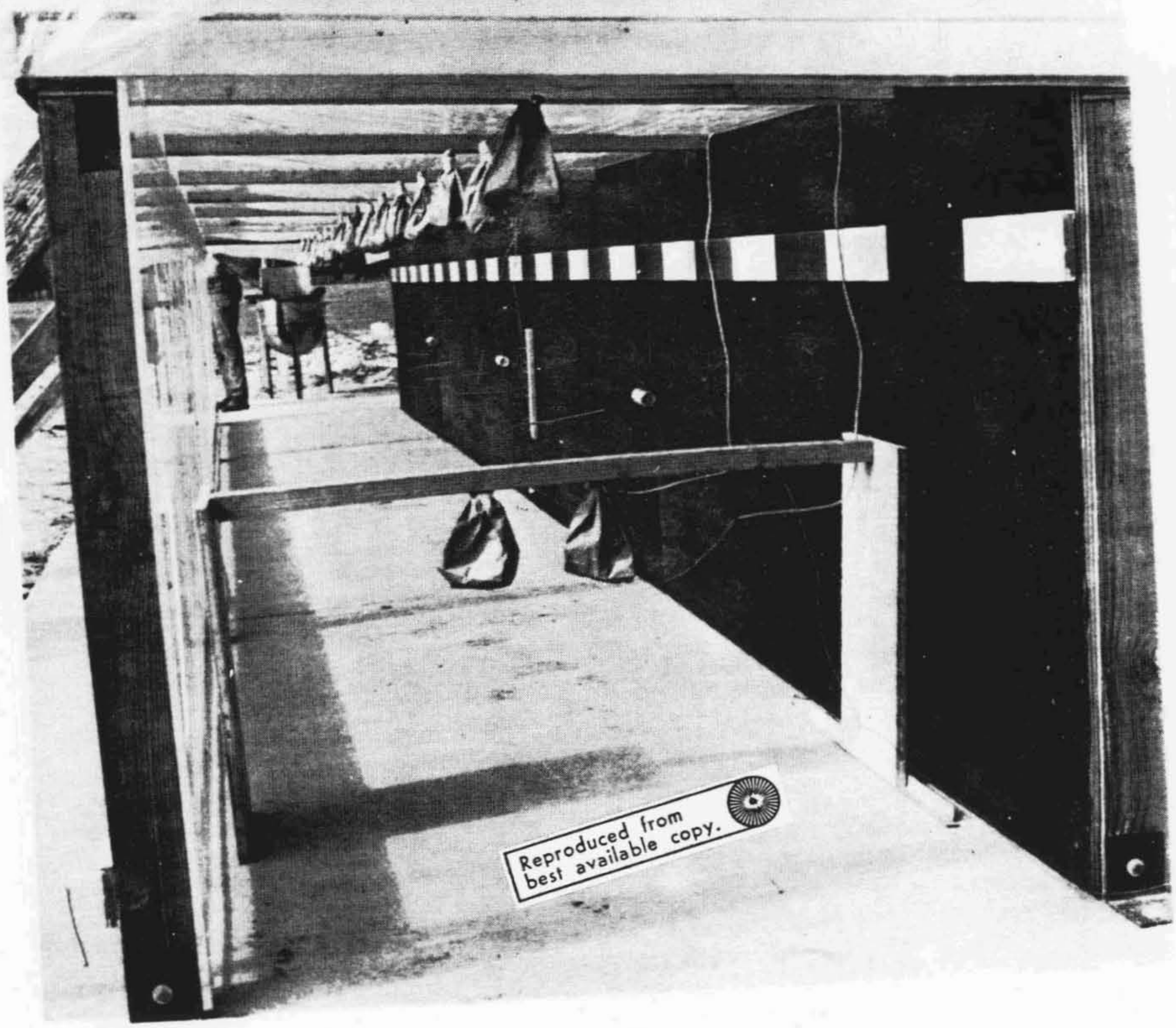



Figure 2-5. Run-up Reaction Test 1

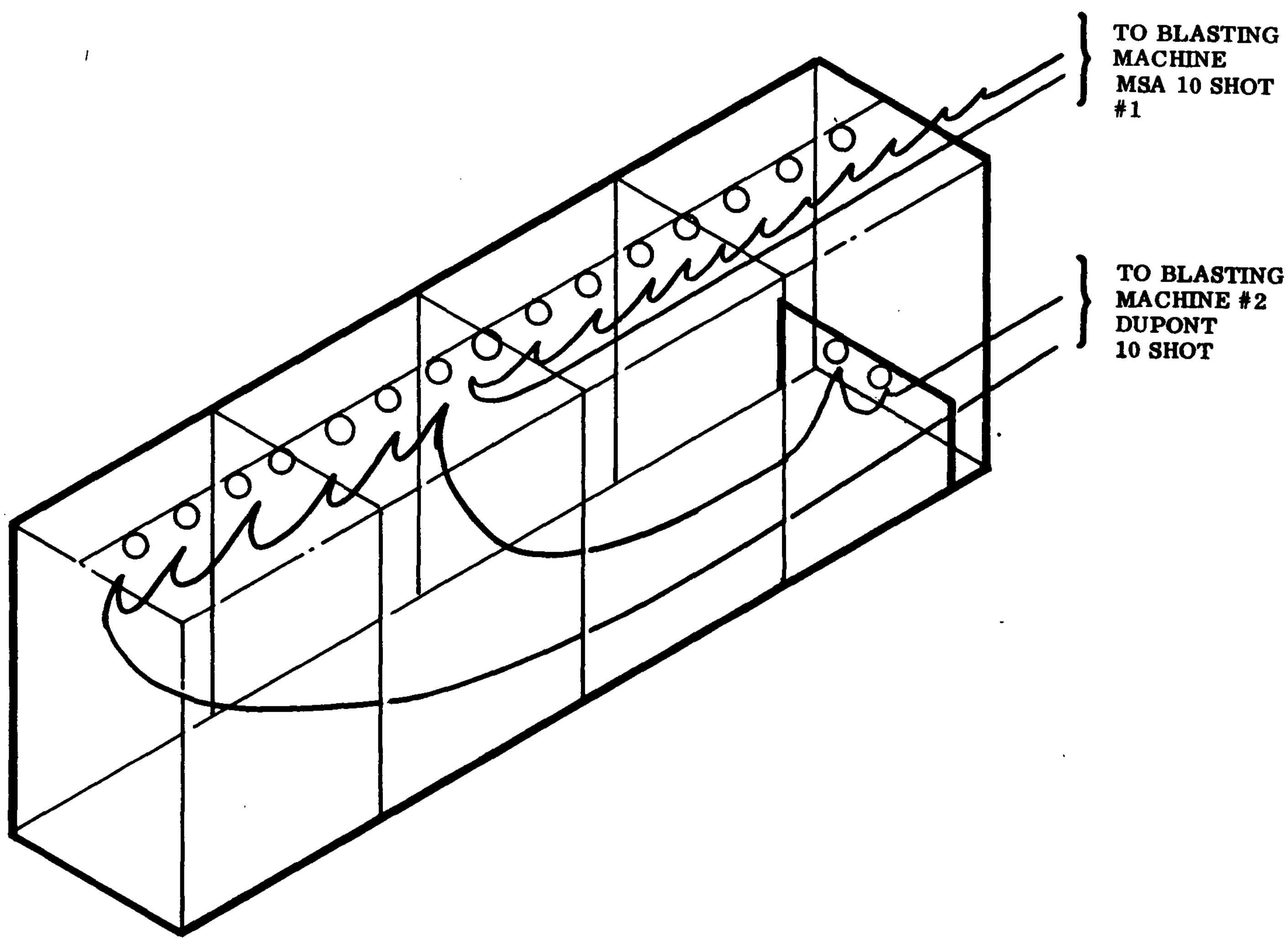



Figure 2-6. Wiring Schematic of Firing Circuit for Run-up Test 1

Table 2-1. Dust Distribution for Run-up Test 1

| SECTION | WEIGHT (LBS.) | MATERIAL | MESH |
|---|---|---|---|
| 1 | 4 | Sulfur Green | As received per Mil-Spec |
| 2 | 4 | Sulfur Green | As received per Mil-Spec |
| 3 | 4 | Sulfur Green | As received per Mil-Spec |
| 4 | 4 | Sulfur Green | As received per Mil-Spec |

So as to not exceed the capacity of the two single-shot blasting machines (each rated at 10-shot capacity), the following ignition sequence was used to fire a total of 18 blasting caps without biasing test results:

- As a result of firing the first eight 1-lb sulfur green bags simultaneously, the first sixteen feet of the gallery becomes filled with the sulfur green dust.
- Followed by a momentary delay of less than one second, after which the second eight sulfur green and two 100-gm booster bags were simultaneously fired, the net result is to ignite the booster in the first sixteen feet of the gallery where the dust cloud has had sufficient time to be distributed. The delay allows time for the dispersed dust to fill the interior of the gallery in the last sixteen feet before the arrival of the combustion/reaction front.

2.2.3.1.3 Communication Area

As shown in Figure 2-7, located at the end of the dust gallery was a communication area containing a scaled 80-qt mixing bowl of 20.8 pounds of smoke mix, thus permitting evaluation of the probability and characteristics of dust cloud communication to large bulk powders.

2.2.3.2 Run-up Test 2

The optimal conditions by which the reaction front may be induced to run up to supersonic velocities are as follows:

- Increasing the percent concentration of combustible material
- Using fineness particle size that is prescribed in the Pyrotechnic Mix Formulary
- Varying the dust density as a function of distance from ignition point

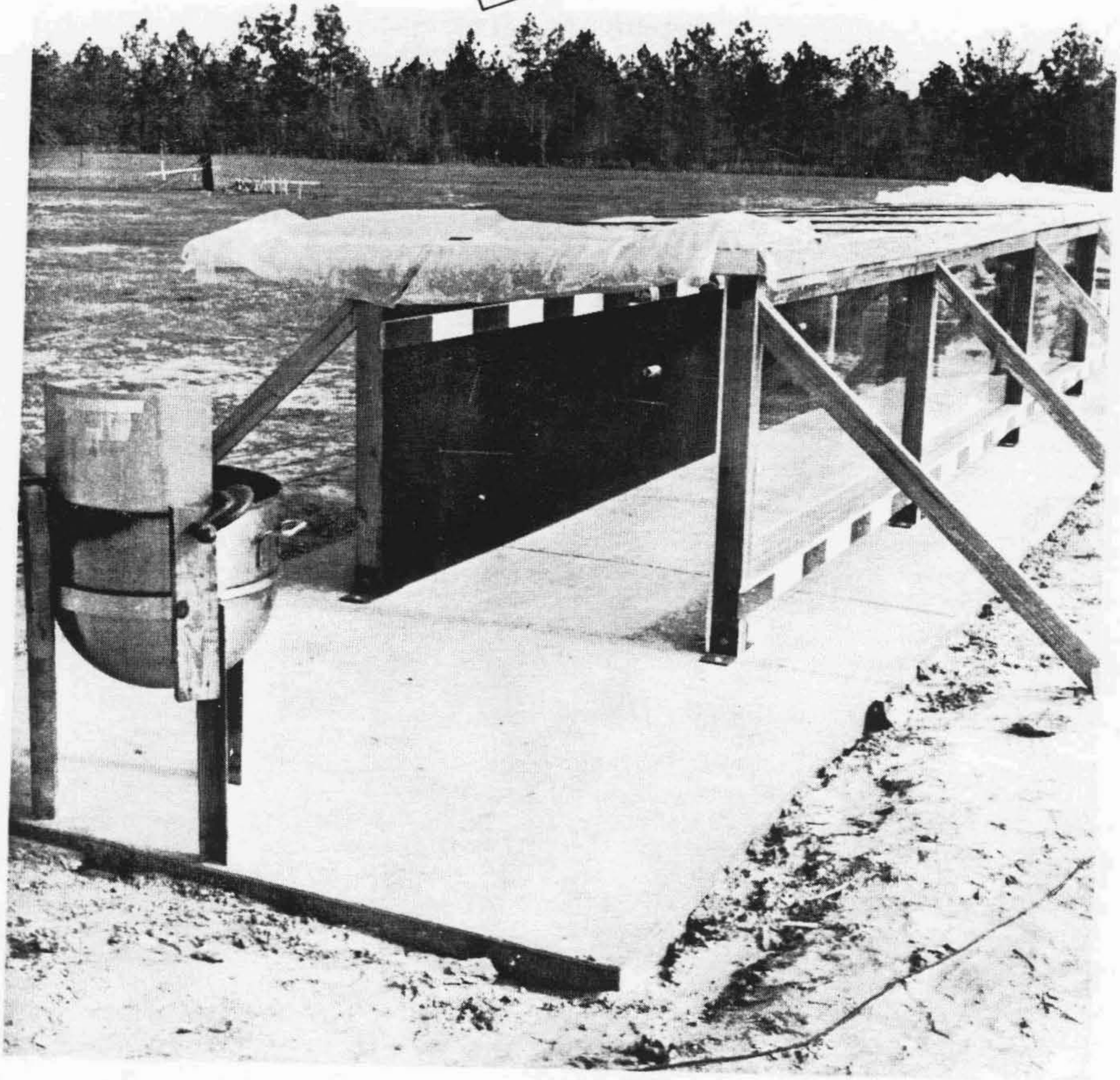


Figure 2-7. Communication Area for Run-up Test 1

2.2.3.2.1 Dust Distribution

As shown in Table 2-2 and Figures 2-8 and 2-9, the 32-foot gallery had a varying density of dust (increasing with distance from the ignition source). Each 8-foot section contained the following amounts of materials:

- Four 1-, 2-, and 3-lb bags of loose sulfur red powder (see description below) were suspended from the ceiling in each of the 8-foot sections.
- Afterwards, a Number 8 blasting cap was wired to the outside of each of the paper bags.
- All 16 of the bags (wired in parallel to a constant current type power supply) were fired simultaneously followed by a momentary delay, after which the 200-gm booster was fired (see Figure 2-10).

Table 2-2. Dust Distribution for Run-up Test 2

| SECTION | WEIGHT OF PYRO (LBS) | MATERIAL | MESH |
|---|---|---|---|
| 1 | 4 | SR III | 200 |
| 2 | 4 | Spec. Red Smoke | As received per Mil-Spec |
| 3 | 8 | Spec. Red Smoke | As received per Mil-Spec |
| 4 | 12 | Spec. Red Smoke | As received per Mil-Spec |
| Total | 28 | | |

2.2.3.2.2 Particle Fineness and Composition

Bureau of Mines' research indicates that the ignition sensitivity and reaction rate increases to a limiting value with fineness of particle size and percent concentration of combustible material. Therefore, in order to optimize the run-up potential to supersonic reaction front velocities, the

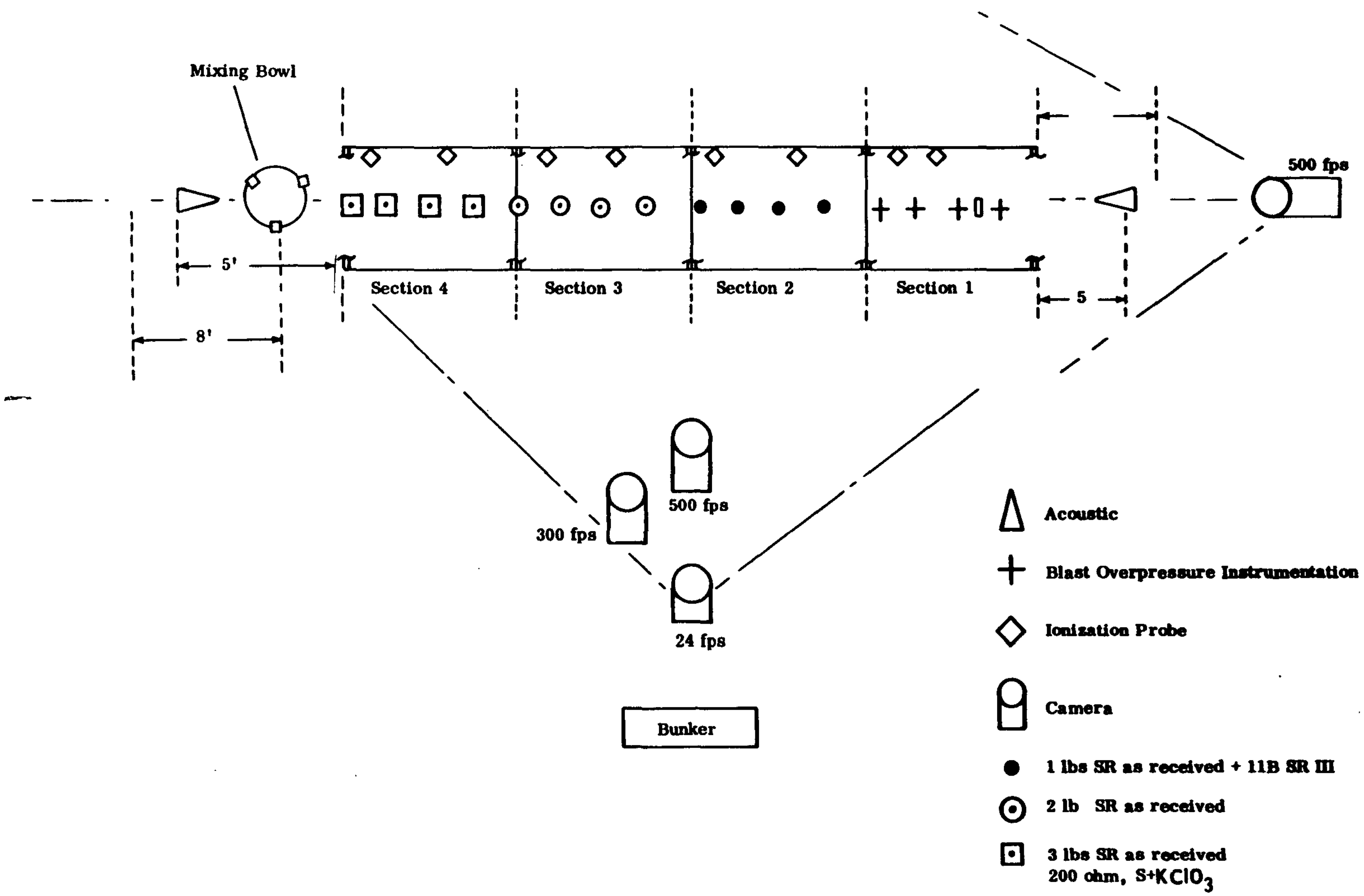



Figure 2-8. Test Setup for Run-up Test 2

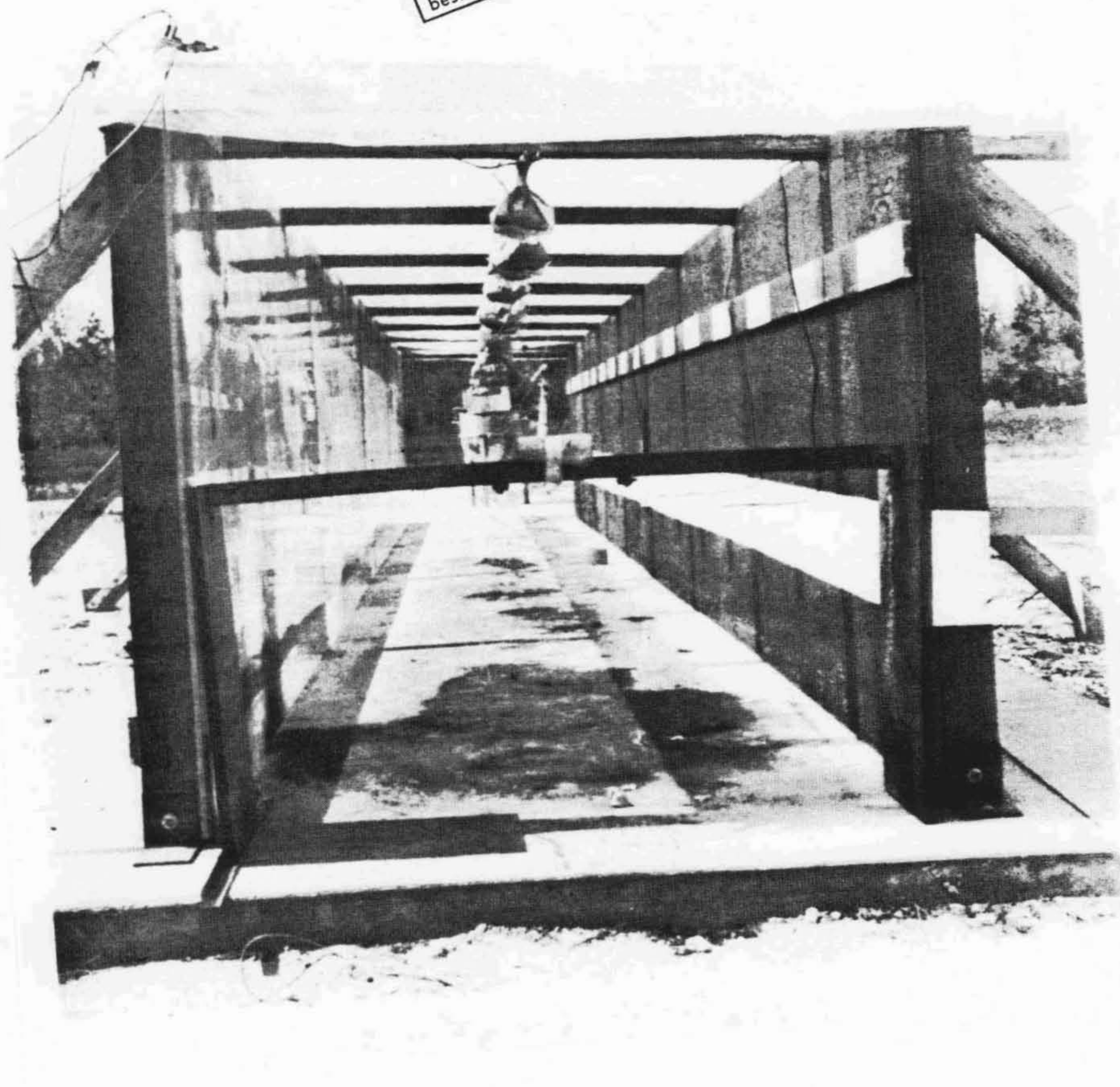


Figure 2-9. Run-up Test 2

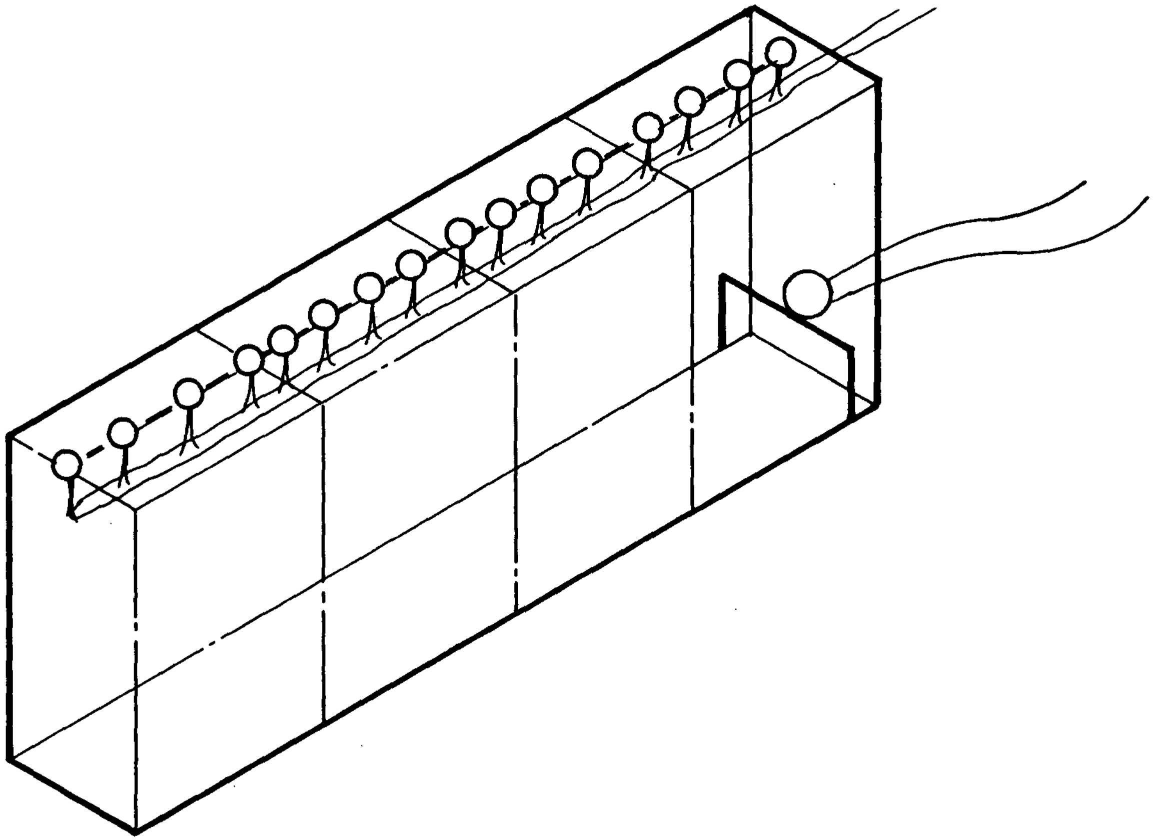



Figure 2-10. Wiring Schematic of Firing Circuit for Run-up Test 2

following modifications in the dust distribution were implemented:

- A specially blended formulation of sulfur red, which consisted of the maximum allowable percentage of fuel-oxidizer with the minimum allowable inhibitors and dyes*, was used as the dust medium (see Table 2-3).
- As shown in Table 2-2, the first section of the gallery contained four pounds of SR III. SR III refers to the same composition as sulfur red; however, the components of SR III have been individually screened through 200 mesh and prior to test stored in an oven operating at 75°C.

2.2.3.2.3 Ignition Source

The same type of ignition sources as described in 2.2.3.1 was used for Run-up Test 2 with the exception of using one 200-gm bag of booster, instead of two 100-gm bags of booster. The latter configuration was adopted as a result of reviewing films of Run-up Test 1 (see Paragraph 3.3.1) which showed the inability of both booster bags to fire simultaneously.

As discussed previously, all 16 of the sulfur red bags were fired simultaneously, allowing the entire length of the gallery to become filled with the sulfur red dust. After a delay of not more than half of a second, the booster igniter was fired. The purpose of the delay firing of the booster igniter was to allow time for the dispersed dust to completely fill the interior of the gallery.

2.2.3.2.4 Communication Area

A communication area containing a scaled mixing bowl of 15 pounds of sulfur red mix was located at the end of the dust gallery, thus permitting evaluation of the probability and characteristics of dust cloud communication to large bulk powders.

2.2.4 MATERIALS

2.2.4.1 <u>Laboratory Scale Tests Using Hartmann Apparatus</u>

To ensure the accuracy of the data, the following Bureau of Mines procedures were implemented:

- Dust was sieved through No. 200 (U. S. Standard series screens) to minimize particle size variance in each batch (and therefore variation in test data from batch to batch).

---

* Red Smoke III - In accordance with Pyrotechnic Mix Formulary Table 2-3 and End Item Information, December 1969, Weapons Dev. and Engr. Laboratories, Chemical Process Laboratory, Edgewood Arsenal, Maryland.

Table 2-3. Pyrotechnic Formulary

| TEST | MATERIALS | COMPOSITION (%) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sodium Bicarbonate | Potassium Chlorate | Sulfur | Red Dye | Yellow Dye | Benzathrone | Violet Dye | Lactose | Green Dye | Mag. Carbonate | Hexachorethane | Zinc Oxide | Aluminum Powder | Sugar | Pure C/S | TOTAL |
| Run-up test 2 | Sulfur Red | 23.0 | 28.0 | 10.0 | 39.0 | | | | | | | | | | | | 100 |
| Hartman Ap. | Sulfur Yellow | 31.0 | 23.5 | 8.5 | | 13.5 | 23.5 | | | | | | | | | | 100 |
| Run-up test 1 and Hartmann Ap. | Sulfur Green | 20.6 | 31.0 | 10.4 | | 3.5 | 7.5 | | | 27.0 | | | | | | | 100 |
| Hartmann Ap. | Lactose Yellow | | 32.0 | | | 16.0 | 29.0 | | 14.0 | | 9.0 | | | | | | 100 |
| Hartmann Ap. | Lactose Green | | 35.0 | | | 4.2 | 8.9 | | 18.0 | 31.9 | 2.0 | | | | | | 100 |
| Hartmann Ap. | C/S Fuel Mix (FM) | | 46.0 | | | | | | | | 26.0 | | | | 28.0 | | 100 |

NOTE: SR III (used in Run-up test 2) refers to the same composition as sulfur red; however, the components of SR III have been individually screened through 200 mesh and prior to test stored in oven operating at 75$^{o}$C.

- Sample materials were individually weighed on a triple beam balance accurate to $\pm 5 \times 10^{-4}$gm.
- All materials were dried in an overn at 75$^{\circ}$C for 24 hours.
- The entire Hartmann Apparatus was enclosed in an air tent containing heaters to further reduce the relative humidity in and around the chamber.

2.2.4.2 Material Formulation

The various formulations used in the reported tests are shown in Table 2-3.

2.2.5 INSTRUMENTATION

The basic instrumentation requirements include the ability to determine the reaction front velocity as a function of distance (or time), communication of the dust reaction with undispersed powder, and determination of the order of reaction in the pyrotechnic powder. In order to accomplish the objectives, the instrumentation system included:

- Time of Flight - two 500-fps Mitchell cameras with coded digital print-out of time on frames, one FASTAX camera and eight ionization probes with magnetic tape recorder.
- Transverse/Side-on Pressure - transducers located in reaction front in order to determine wave shape and amplitude (see Appendix B).
- Passive Sensors (Refer to Document 120) - the passive sensor study was added to the run-up tests as a supplement to investigate whether passive sensors can be effectively used to determine pyrotechnic safety criteria. The passive sensors consisted of thin aluminum foil cylinders placed inside gallery to indicate ranges of pressure.
- Acoustic - microphones placed 5 feet and 10 feet from each end.

# SECTION 3
# TEST RESULTS

## 3.1 HARTMANN APPARATUS

### 3.1.1 MATERIALS

#### 3.1.1.1 Pyrotechnics

In order to obtain the maximum amount of information with the minimum number of tests, the following representative materials were tested:

- C/S Fuel Mix
- Sulfur Yellow
- Lactose Yellow
- Sulfur Green
- Lactose Green

In previous TB 700-2, TNT equivalency, DTA and Parr bomb tests, these materials proved to exhibit sensitivity and energy release value representative of the lactose, sulfur base, and fuel mix smoke compositions.

#### 3.1.1.2 Fuels

The following five basic fuels used in pyrotechnic munitions were tested individually:

- Coal
- Sugar
- Sulfur
- Aluminum
- Lactose

### 3.1.2 DETERMINATION OF THE MINIMUM DENSITY REQUIRED FOR IGNITION

The lowest weight at which flame propagates or the minimum density required for ignition was determined as follows:

- A weighed sample was placed in the dust dispersion cup. Initially, the amount of weighted sample was determined to be at a level where a 50 percent response (see paragraph 2.2.1) is expected.
- The concentration level was moved up one step after each non-response, and down one step after each response.

- The next series of tests consisted in either moving the concentration up or down 50 percent of the previous level. This was continued until at the 5 mg concentration level, an increase in the quantity of materials fails to propagate a flame in any of four successive trails.

Results of testing using the hot-wire ignition source in conjunction with 80-psi continuous air flow are given in Appendix A. Shown in Table 3-1 are the minimum concentration of fuels determined by the Bureau of Mines using single spark discharge ignition source.

## 3.2 INTERMEDIATE SIZE GALLERY

Results of the nine tests using the intermediate size gallery are given in Table 3-2.

## 3.3 LARGE SCALE GALLERY TESTS

### 3.3.1 CALIBRATION TEST FIRING

In view of the success of test 9, it was decided to use the same type of igniter (200 gm of sulfur/potassium chlorate) for the 32-foot gallery. Therefore, for purposes of comparison, a calibration test was conducted to determine the size of the fireball, growth rate, etc., in open air; consequently, by comparing this data with the run-up tests to this calibration test any appreciable difference can be attributed to reaction of dust suspension.

#### 3.3.1.1 Chronology of Events

The test consisted of a calibration firing of a paper bag containing 200 gm of S + $KCLO_3$ (1.1) with a No. 8 blasting cap. The chronology of events, as recorded by a 500 fps Mitchell camera, was as follows:

| EVENT | TIME (sec) |
|---|---|
| Dispersion of booster | 0.0 |
| Fireball 2-1/2 feet in diameter | 0.016 |
| Fireball 3-1/2 feet in diameter (maximum fireball size) | 0.020 |

### 3.3.2 RUN-UP TEST 1

#### 3.3.2.1 Velocity Measurements

The velocity of the compression plane wave was determined by the following techniques:

- Pictorial - As recorded by two 1000 fps FASTAX cameras, the distance of travel of wave was timed by counting elapsed frames:

$$\text{Distance of wave front} \Big/ \left[1000\ \frac{\text{frames}}{\text{sec}}\right] \times \left[\text{Elapsed frames}\right]$$

Table 3-1. Summary of Results on Minimum Dust Concentration Tests (Using Hot Wire Igniter with 80 PSI Continuous Air Flow)

| Material | 1 Minimum Mass Required for Ignition (mg) | 1 Minimum Mass Required for Ignition ($x\ 10^{-5}$ oz) | 2 Minimum Concentration ($oz/ft^3$) | 3 Bureau of Mines* Minimum Concentration ($oz/ft^3$) |
|---|---|---|---|---|
| I Pyrotechnic Formulations | | | | |
| Fuel Mix | 2.0 | 7.05 | .002 | |
| Lactose Green | 9.0 | 31.7 | .007 | |
| Lactose Yellow | 9.0 | 31.7 | .007 | |
| Sulfur Yellow | 10.0 | 35.2 | .008 | |
| Sulfur Green | 31.0 | 109 | .025 | |
| II Fuels | | | | |
| Aluminum | 15 | (52.9) | .013 | .020 |
| Sugar | 32 | (112) | .027 | .045 |
| Sulfur | 131 | (461) | .107 | .035 |
| Coal - Illinois | 500 | (1750) | .407 | |
| Lactose | No Ignition | | | |
| Pittsburg Coal | | | | .035 |

*Note: Determined using a single spark discharge ignition source.

Table 3-2. Results of Intermediate Size Gallery Tests

| TEST NUMBER | IGNITION SOURCE | TIME DELAY OF IGNITION SOURCE (sec) | MATERIAL | AMOUNT (lb) | METHOD OF DISPERSION/ EVALUATION | REACTION PRIMARY | REACTION SECONDARY |
|---|---|---|---|---|---|---|---|
| 1 | Single spark (50J) | -- | Sulfur Green | .2 | Compressed air at 400 psi - Unsatisfactory | None | None |
| 2 | Single spark (50J) | -- | Sulfur Green | 3.2 | Compressed air at 400 psi - Unsatisfactory | None | None |
| 3 | Single spark (50J) | -- | Sulfur Green | 3.2 | Compressed air at 800 psi - Unsatisfactory | None | None |
| 4 | -- | -- | Sulfur Green | 1.0 | #8 Cap -Satisfactory | None | None |
| 5 | Hot wire coil | -- | Sulfur Green | 1.0 | #8 Cap - Satisfactory | None | Mild sparking on floor |
| 6 | Hot wire coil | -- | Sulfur Green | 1.0 | #8 Cap - Satisfactory | None | Flames on floor |
| 7 | S-94 | 2 | Sulfur Green | 1.0 | #8 Cap - Satisfactory | None | Mild burning on floor |
| 8 | Hot wire coil | -- | Sulfur Green | 1.0 | #8 Cap - Satisfactory | Ignition of bag by No. 8 Cap | Mild burning on floor |
| 9 | #8 Cap plus 100 gm | 1 - 2 | Sulfur Green | 1.0 | #8 Cap | Large fire-ball of long duration | All powder blown out of gallery |

NOTE:

Primary - pertains to immediate ignition of dust atmosphere
Secondary - pertains to several seconds after dust dispersion

- Ionization Probes - Coincident with the passage of the plane wave front, five ionization probes were triggered. It was not possible to determine which locations were triggered. Therefore, the calculated velocity was determined by using an average distance for the spacing of the probes. Distance between the ionization pulses on a strip chart recorder was measured to determine time.
- Acoustic Monitors - The velocity of the wave was determined by measuring the total distance between the microphones at each end of the gallery and the elapsed time for the wave signal to reach each pickup.

Results of the above technique are shown in Figure 3-1 and as shown below:

| Velocity Measurements | Average Velocity |
|---|---|
| Pictorial | 890 ft/sec |
| Ionization Probes | 1300 ft/sec |
| Acoustic | 1700 ft/sec |

3.3.2.2 Chronology of Events

As recorded by two FASTAX cameras and acoustic instrumentation, the following chronology of events was observed:

| Event | Time (sec) | | |
|---|---|---|---|
| | Camera #1 | Camera #2 | Acoustic |
| Dispersion of Dust by First Eight Bags | 0 | 0 | 0 |
| Booster* Ignition | .85 | -- | -- |
| Fireball Three Feet in Diameter | 1.05 | -- | -- |
| Six Foot of Gallery Filled with Fireball | 1.35 | | |
| Plane Wave Front | 1.42 | 1.56 | 1.2 |
| Eight Foot Section of Gallery Filled with Fireball | 1.50 | -- | -- |
| Dispersion of Dust by Second Eight Bags | 3.09 | 3.37 | 2.5 |

* 200 gm of S + $KClO_3$

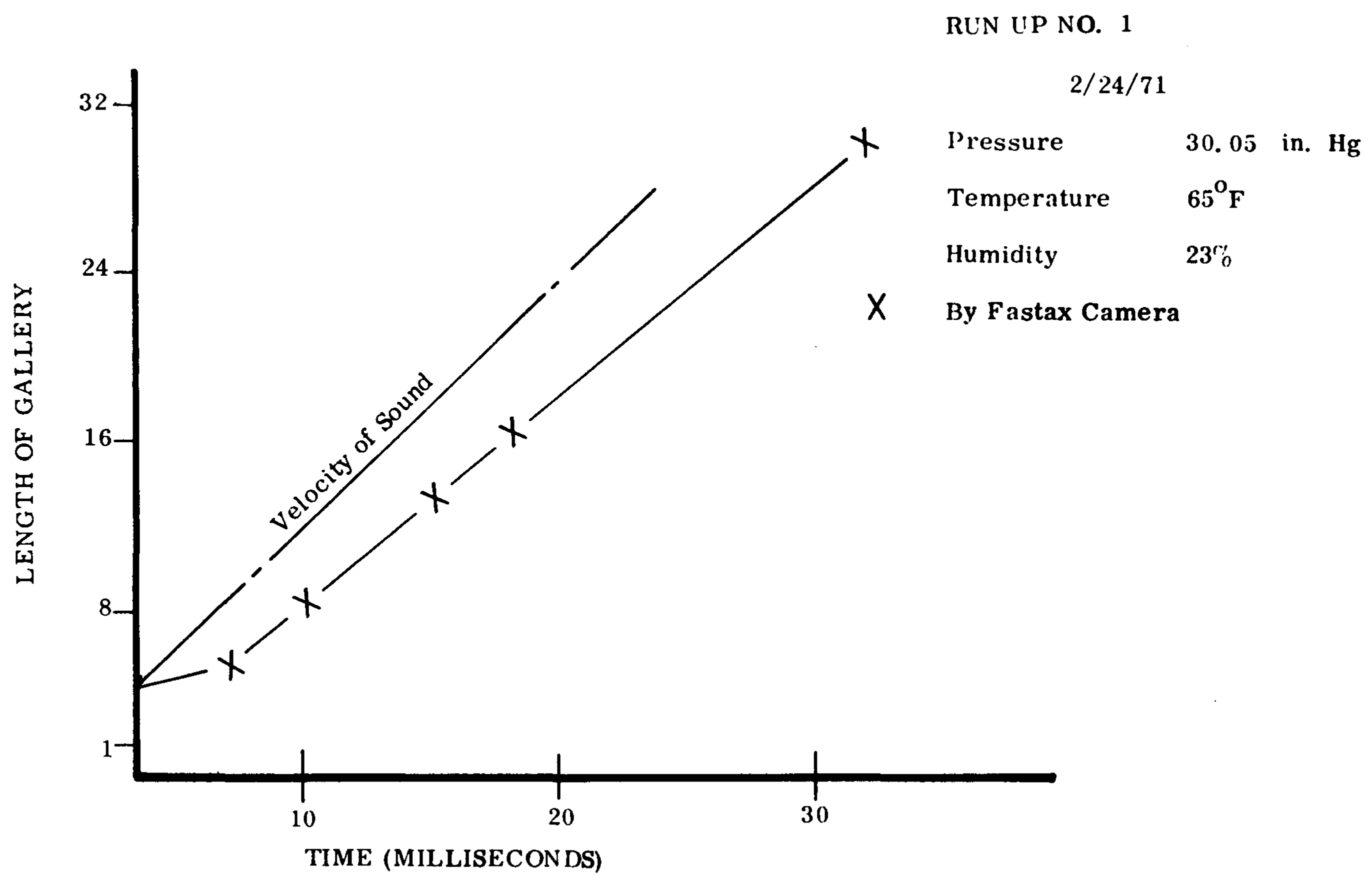



Figure 3-1. Travel of Plane Wave/Elapsed Time

## 3.3.3 RUN-UP TEST 2

### 3.3.3.1 Velocity Measurements

The velocity of the compression plane wave was determined as follows:

- Pictorial - As recorded by a 500 fps Mitchell camera with binary coded digital printout of time directly on film; therefore, the distance of travel of the wave was directly timed to ± 0.5 percent accuracy (as opposed to the previous methods, this technique does not rely on filming speed accuracy).
- Ionization Probes - Plane wave did not trigger ionization circuitry.
- Acoustic Monitors - Procedure for velocity determination is same as given in paragraph 3.3.2, Acoustic Monitors.

Results of the above technique are shown in Figure 3-2 and as shown below:

| Velocity Measurements | Average Velocity |
|---|---|
| Pictorial | |
| Mitchell | 1675 ft/sec |
| FASTAX | 1164 ft/sec |
| Acoustic | 1230 ft/sec |

### 3.3.3.2 Chronology of Events

As recorded by one Mitchell camera, the following chronology of events was observed:

| Event | Time (sec) Camera |
|---|---|
| Dispersion of Dust by all Sixteen Bags | 0 |
| Booster Ignition and Plane Wave Front | .55 |
| Fireball 3 feet in Diameter | .58 |
| Six feet of Gallery Filled with Fireball | .66 |
| Maximum Size of Fireball | .75 |

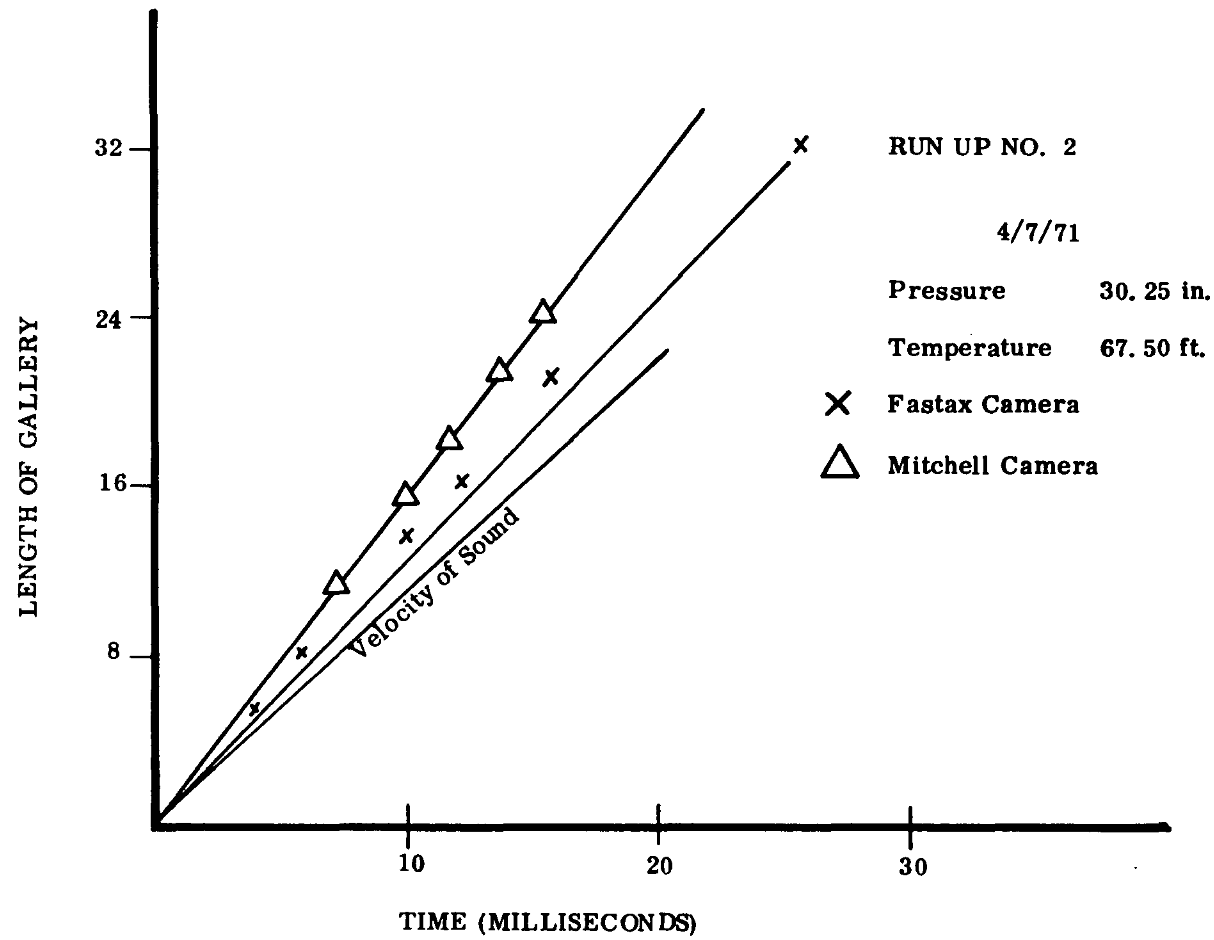



Figure 3-2. Travel of Plane Wave/Elapsed Time

# SECTION 4
# TEST CONCLUSIONS AND RECOMMENDATIONS

## 4.1 TEST CONCLUSIONS

### 4.1.1 HARTMANN TESTING

The pyrotechnic formulations and fuels are ranked (Table 3-1) according to the minimum mass required for ignition. Fuel mix containing no additives (dyes or inhibitors) is rated the highest pyrotechnic formulation followed by Lactose Green, Lactose Yellow, Sulfur Yellow, and Sulfur Green. Aluminum is the hottest fuel followed by sugar, sulfur, and coal. Lactose did not ignite; therefore, on the basis of this test, it would represent only a fire hazard as compared to a dust explosion hazard.

Greater reproducibility in test results was obtained using a continuous air flow in conjunction with the hot wire igniter as compared to the recommended Bureau of Mines technique consisting of a single blast of air. Deviation from recommended testing procedures was justified since it was observed that the continuous air flow operation generates greater turbulence (therefore, greater dust dispersion than the single blast technique).

The following additional information was derived from the Hartmann Testing:

- Comparison of both single and continuous spark ignition sources with the hot wire source showed that the physical dimensions of the ignition sources greatly affect the ignition threshold or minimum amount of material required for ignition. Since it was observed that dust cloud dispersion was non-uniform, it can be concluded that the probability of ignition increases greatly with size of the ignition source. Therefore, the success of the hot wire ignition source over the spark techniques is explained in view of the large physical dimensions of the hot wire source as compared to the other spark modes. It is concluded that radiating heated surfaces (i. e., broken light bulb) can represent a more hazardous ignition source in a dust environment than spark discharge (i. e. , motor brushing or frayed grounding strap).
- The Hartmann Apparatus is useful for conducting small scale tests because the dust chamber represents, at reduced scale, an operational situation with all data directly relatable to a full scale accident.
- For over 15 years, the Hartmann Apparatus has been the standard method used to determine dust ignition criteria. Data obtained under the present testing program can be directly compared to Bureau of Mines data (with appropriate modification) for the same material.

- It was observed that there was a delay of 3 - 5 seconds associated with the ignition of pyrotechnic mixes in contrast to the fuels, which ignited immediately. In view of the fact that typical pyrotechnic formulations contain 20 to 30 percent combustible fuel, a longer time is required before criteria for ignition of dusts are satisfied.
- Comparison of the minimum concentrations as obtained by the Bureau of Mines with those obtained herein show good agreement in view of the fact that different types of igniter sources were used (hot wire for data obtained herein and single spark discharge for Bureau of Mines investigations).

### 4.1.2 THE INTERMEDIATE SIZE GALLERY

As reported in Table 3-2, the most positive results occurred in test number 9 in which all of the dust propagated. The fact that all of the powder propagated resulted in a much larger fireball of longer duration than was observed for the open air calibration firing.

As a result of dust propagation, the mylar curtain was heavily charred (Figure 4-1). It was also observed that all of the powder was either consumed or blown out of the gallery.

### 4.1.3 RUN-UP TEST 1

During the functioning of the first eight blasting caps, the powder in the second bag from the right (in the immediate vicinity of the booster) ignited and fell onto the booster causing its premature ignition (see Figure 4-2). As a result, dispersion of dust by the second eight bags did not occur as planned.

Between 1.2 seconds and 1.42 seconds after dispersion of the dust by the first eight bags, a well defined plane front traveled down what appears to be the first sixteen feet of the gallery. Unfortunately, the wave front was no longer detectable in the last sixteen feet of the gallery. The result of velocity determination indicates the wave front to be in the sonic range (Figure 3-1).

It was observed that a large amount of powder propagated resulting in a larger fireball of longer duration than was observed in open air test (See Figure 4-3).

### 4.1.4 RUN-UP TEST 2

In conjunction with firing the booster, a plane wave front traveled down the entire length of the gallery. As shown in Figure 3-2, pictorial determination of the velocity of the wave indicates it to be traveling in the sonic range.

## 4.2 COMPARISON OF TESTS (TEST 9 (RUN-UP TESTS 1 AND 2)

Comparison of run-up tests 1 and 2 with open air calibration tests (all used a 200 gm booster igniter) clearly shows the fireball in the run-up tests to be of longer duration and larger size than in the calibration tests. This is attributed to the excessive amount of unburned pyrotechnic dust which apparently propagated as a result of the booster fireball.

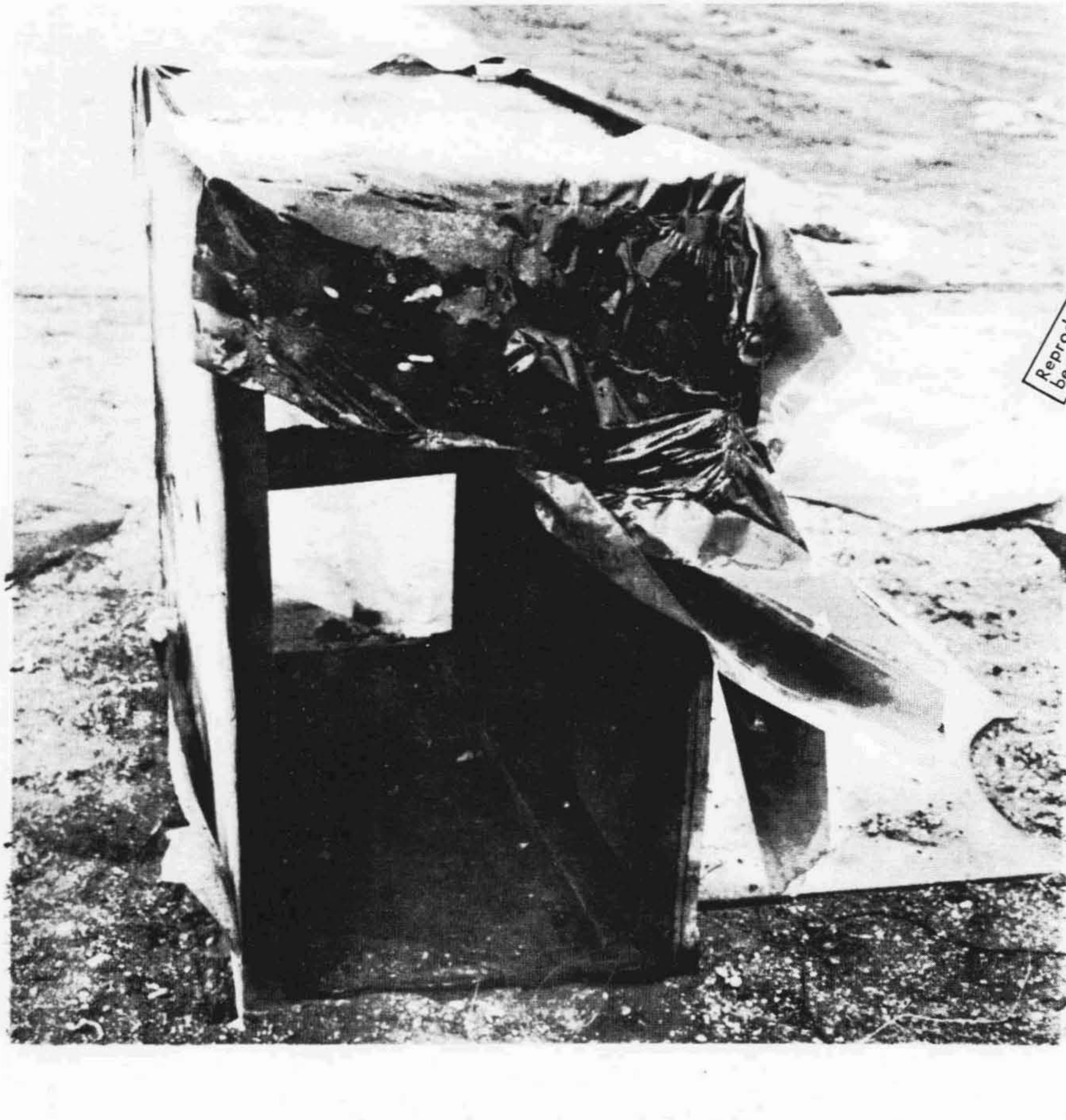




Figure 4-1. Results of Dust Ignition Inside 32 Cu. Ft. Gallery



Figure 4-2. Results of Run-Up Test 1

Figure 4-3. Results of Run-Up Test 2

## 4.3 RECOMMENDATIONS

Based upon results observed during the Hartmann Tests, the following recommendations are made:

- Need exists for future work using the Hartmann Apparatus to determine maximum explosive pressure developed by semi-vented and completely closed chambers so as to obtain the explosive severity and run-up potential of dust reactions.
- A need exists to determine ignition criteria for dust/vapor atmosphere.
- Future work is planned that provides (cost effective) validation/replication of information required for operational shielding, suppressive construction for run-up and operational shielding applications. This will be obtained by modification of Hartmann chamber by addition of a second chamber into which suppressive/quenching materials can be inserted.
- Results of findings that dust explosions in general, during their initial phase, are relatively slow, suggest that it would be highly advantageous to achieve control of an explosion during the incipient stage. Designing tests to evaluate quenching techniques and relief vents in likely ignition areas would help to greatly control pressure buildup; and consequently, abort the tendency for flame front to undergo transition from subsonic to supersonic velocity.
- Need exists for future work using other materials (such as C/S fuel mix) to determine maximum explosive pressure developed and their run-up potential in order to fully understand the hazards involved in the manufacture of pyrotechnics.

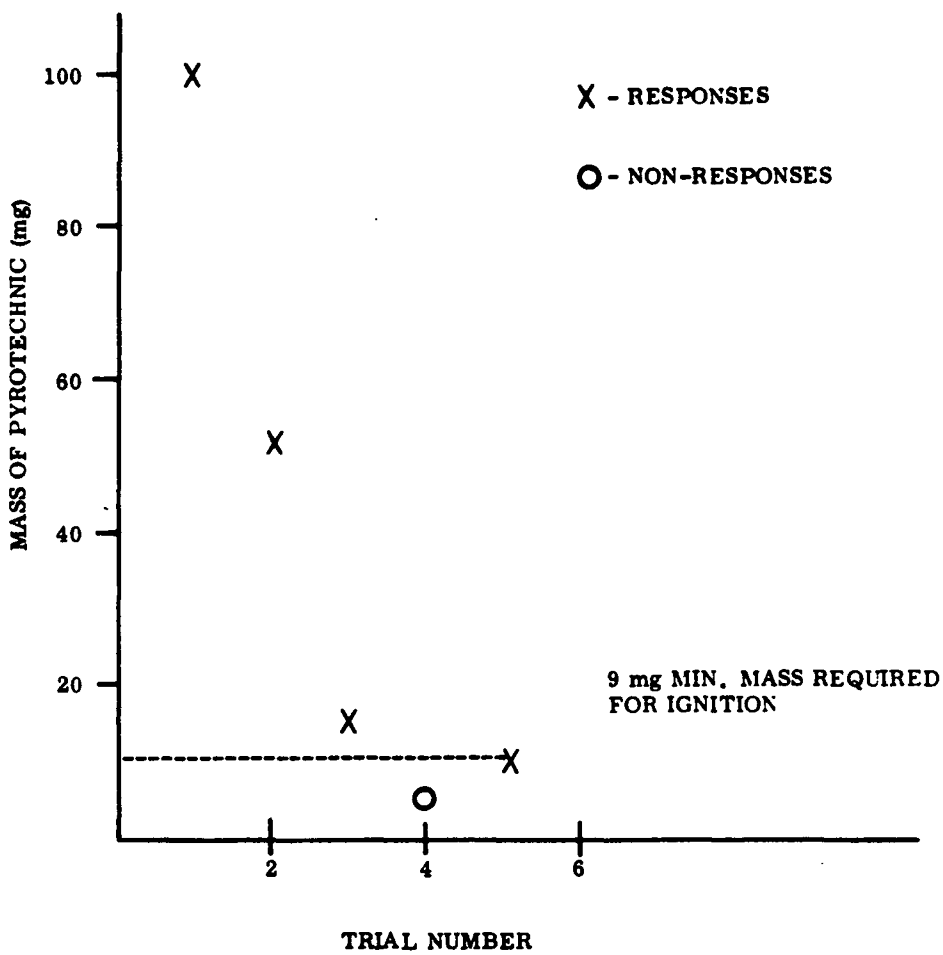



Figure A-1. Minimum Ignition Concentration Tests versus Trial Number for Lactose Yellow

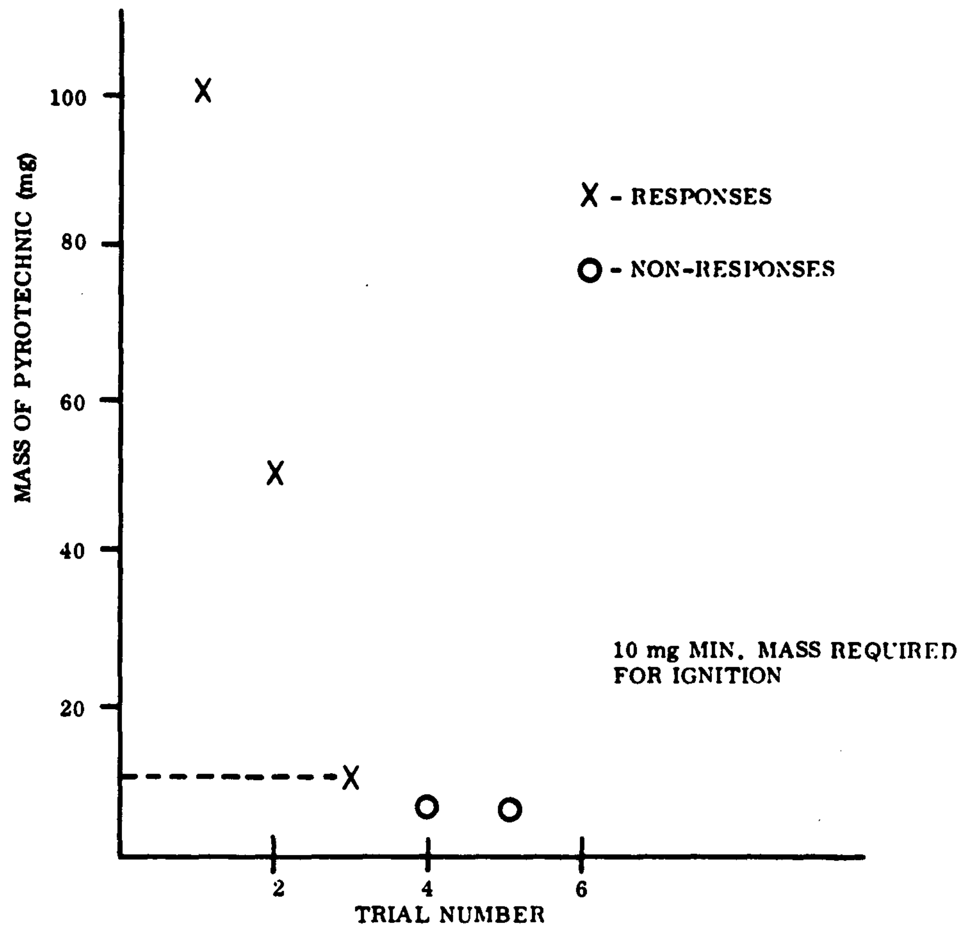



Figure A-2. Minimum Ignition Concentration Tests versus Trial Number for Sulfur Yellow

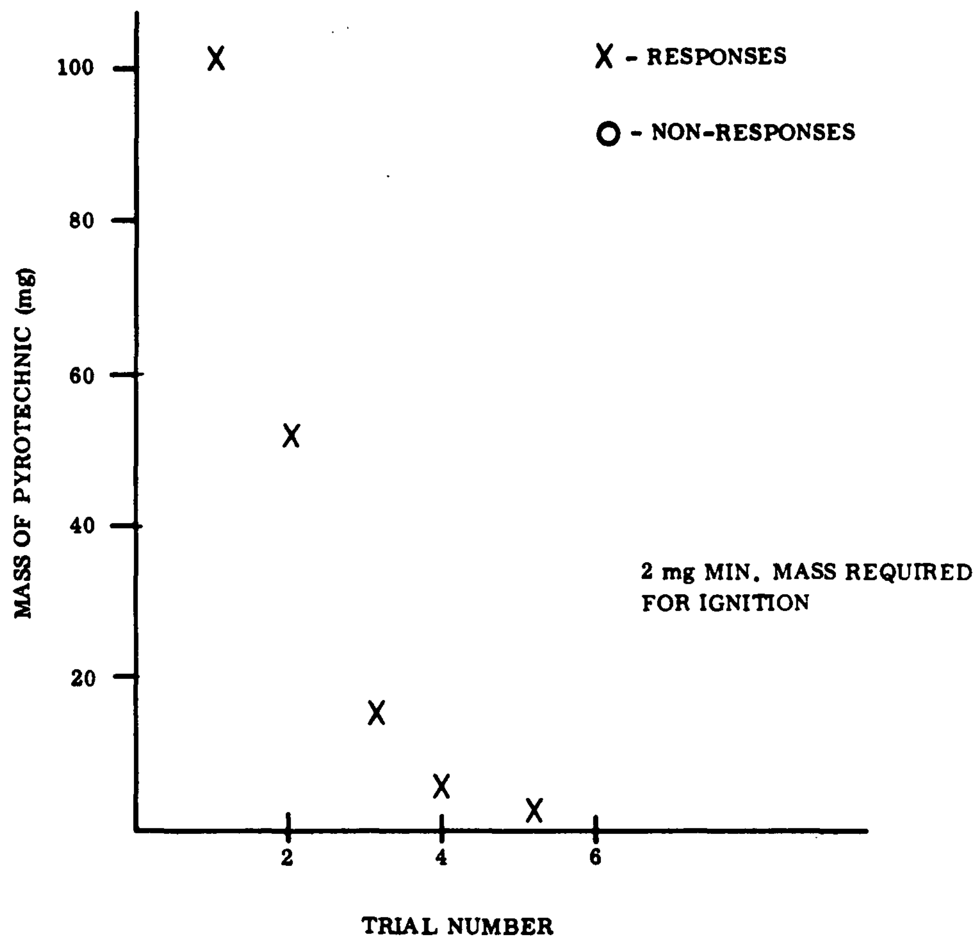
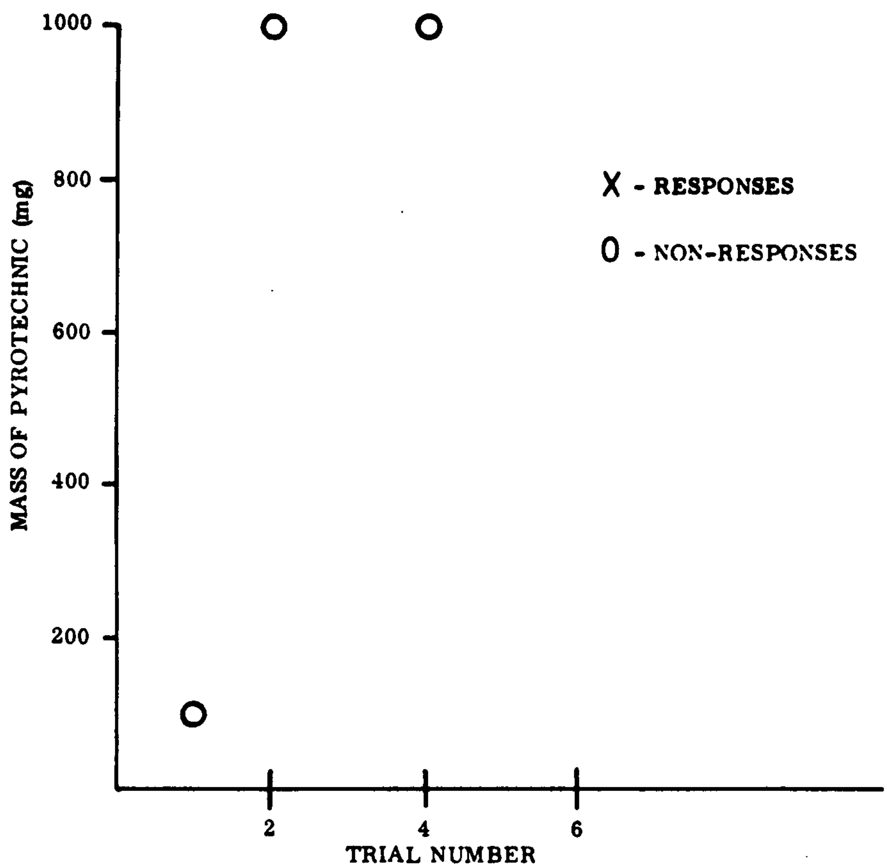



Figure A-3. Minimum Ignition Concentration Tests versus Trial Number for Fuel Mix IV




NOTE: IT IS CONCLUDED THAT LACTOSE PRESENTS NO EXPLOSION HAZARD.

Figure A-4. Minimum Ignition Concentration Tests versus Trial Number for Lactose

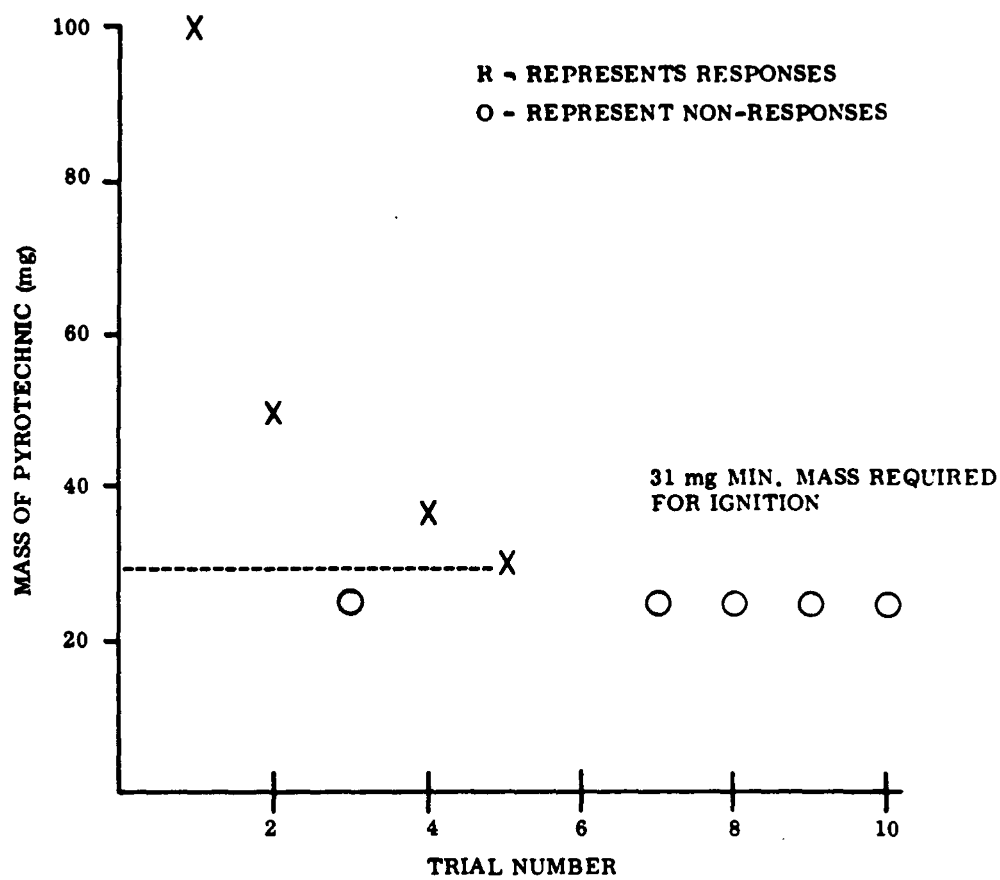



Figure A-5. Minimum Ignition Concentration Tests versus Trial Number for Sulfur Green

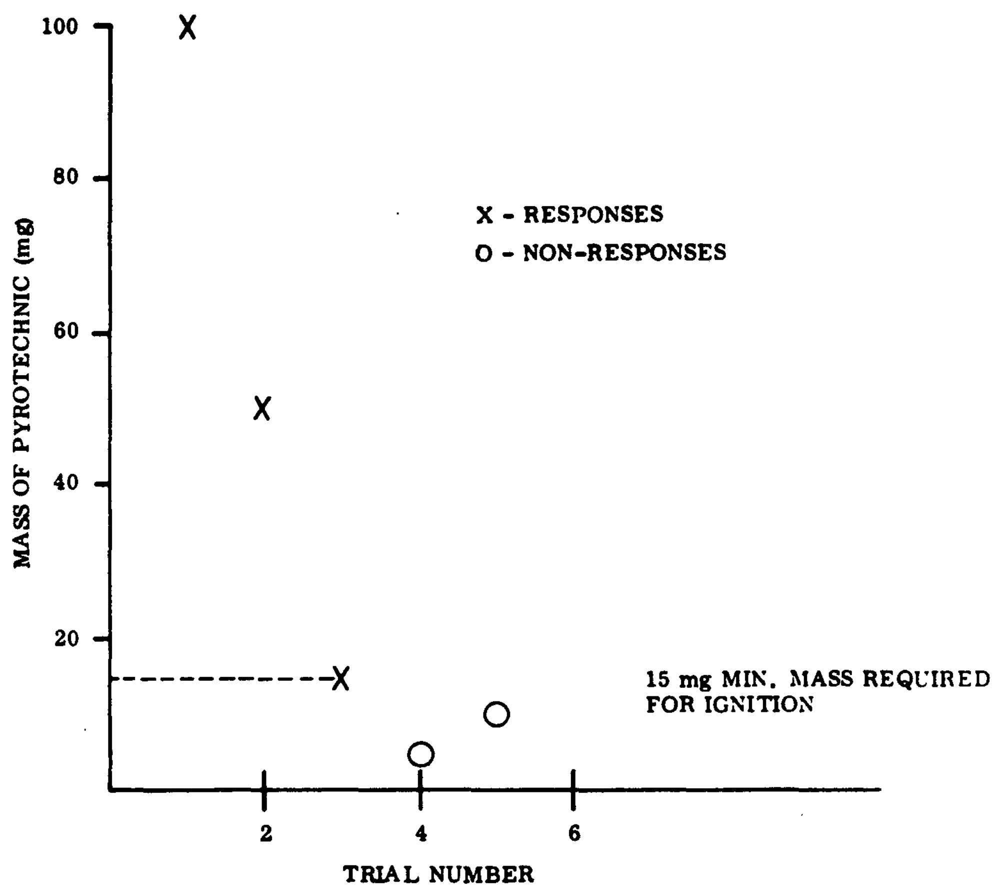



Figure A-6. Minimum Ignition Concentration Tests versus Trial Number for Aluminum

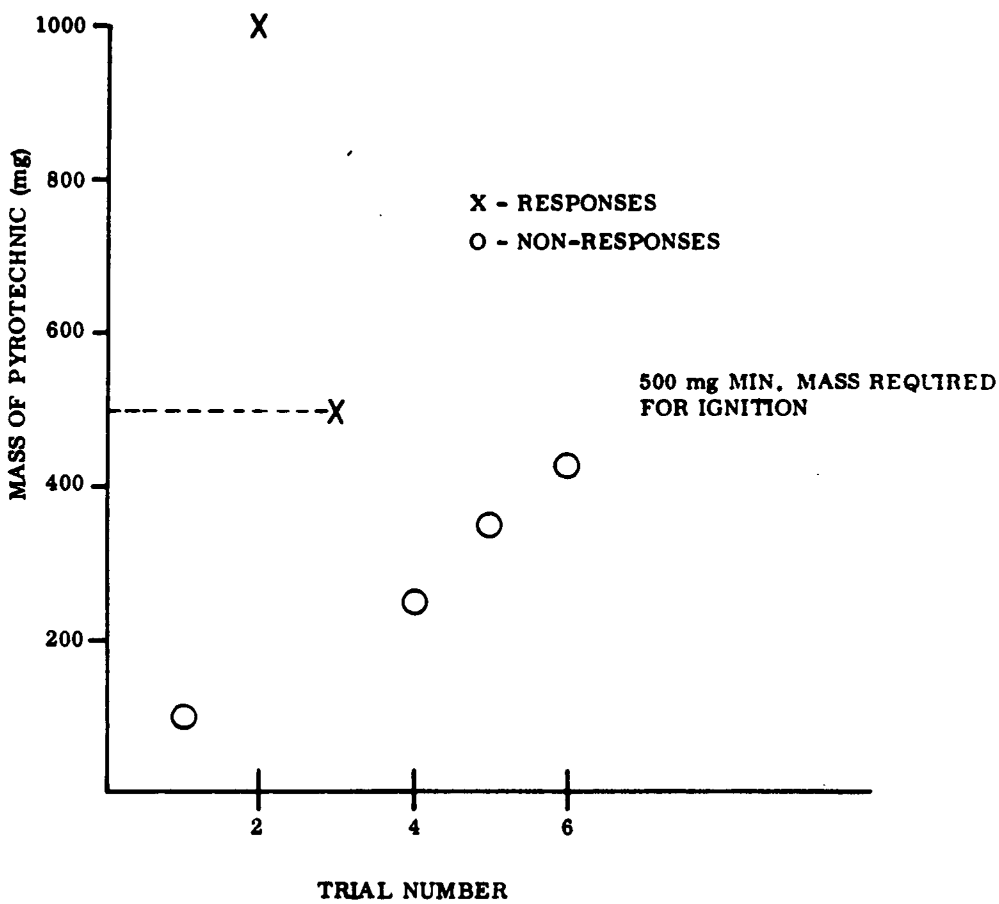



Figure A-7. Minimum Ignition Concentration Tests versus Trial Number for Coal #1

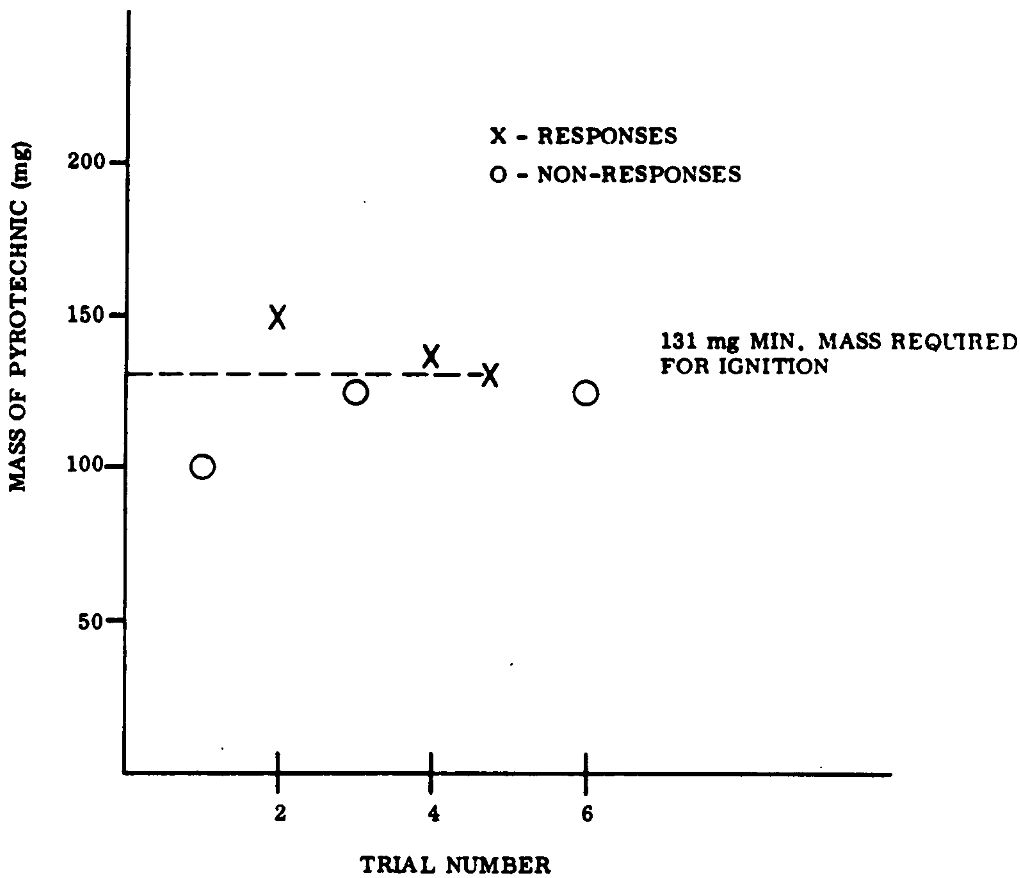



Figure A-8. Minimum Ignition Concentration Tests versus Trial Number for Sulfur

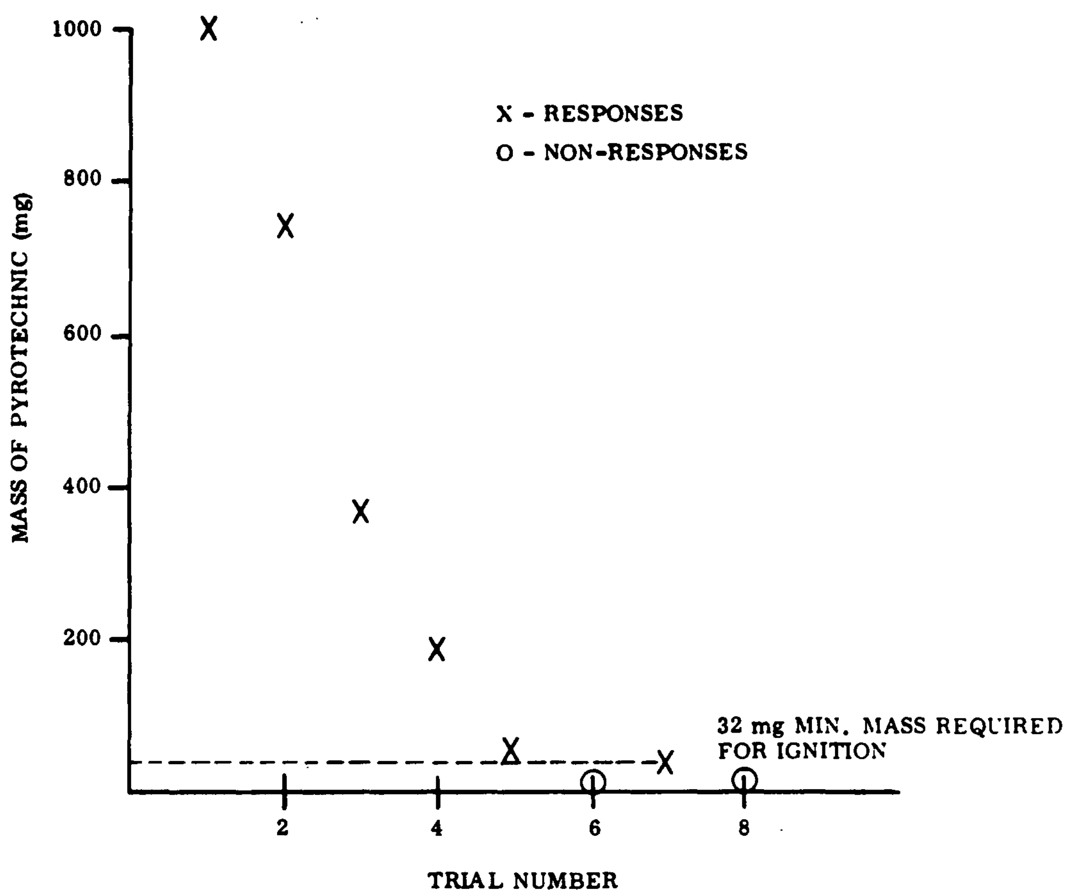



Figure A-9. Minimum Ignition Concentration Tests versus Trial Number for Sugar

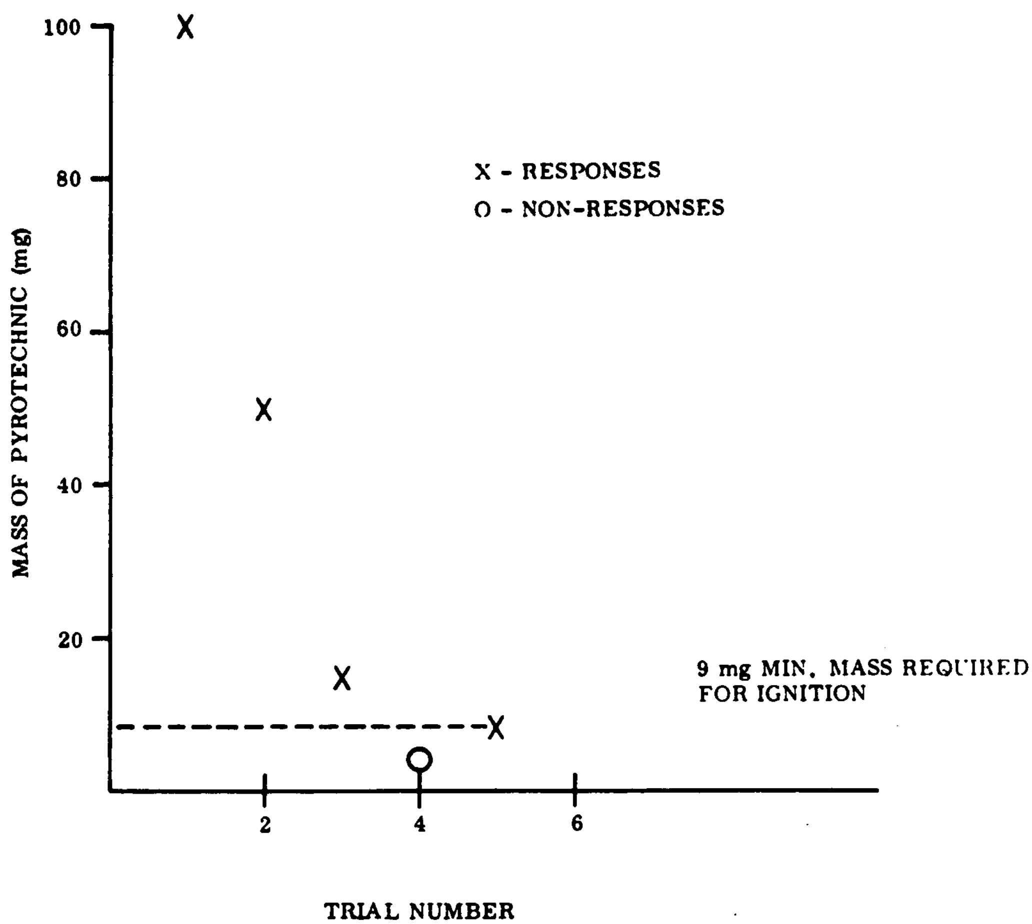



Figure A-10. Minimum Ignition Concentration Tests versus Trial Number for Lactose Green

# APPENDIX B
# BLAST OVERPRESSURE INSTRUMENTATION

The blast instrumentation system used in this program is shown in Figure B-1 and consisted of the following:

- Piezoelectric Transducer - which emits a signal that is a function of the magnitude of the overpressure. Since it is a dynamic instrument, it requires no external overpressure excitation potential.
- Source Follower - an integrated circuit that is directly coupled to the piezoelectric transducer and converts the charge signal from the transducer to voltage signals suitable for memory of the biomation transient recorders.
- Charge Amplifier - a solid-state unit which converts charge signals from the piezoelectric transducer to voltage signals suitable for display on oscilloscopes.
- Peak Meter - which indicates the voltage signal encountered from the blast overpressure signal.
- Transient Recorders - which utilize a very high speed six-bit analog to digital converter with a maximum word conversion rate of 10 mHz combined with a 6 bit x 128 word MOS shift register memory to capture and hold the digital equivalent of the analog signal from the transducer. This signal is then displayed on an X-Y plotter to be converted into engineering units for data reduction of a blast overpressure and impulse readings.
- Oscilloscope - which is set for a single sweep external trigger and is triggered by the blasting machine on the positive rise of the firing pulse. The oscilloscope records blast overpressure utilizing the Polaroid camera pack.
- Electronic Counter - which is triggered by a break wire to record time of arrival of the shock front of the blast overpressure at each transducer.
- X-Y Plotter - an analog device that graphically displays the blast overpressure held in memory by the transient recorder. The graphic display is then converted into engineering units for further data reduction.

The equipment utilized for the GE blast overpressure instrumentation system consists of the following:

- Susquehanna Instrument Company Model ST-7, Piezoelectric Transducer
- PCB Piezotronics Inc., Model 401A11 ICP, Source Follower

- Kistler Model 504A, Charge Amplifier
- Kistler Model 538A, Peak Meter Indicator
- Type 502A, Dual-beam Oscilloscope with Camera Pack
- Hewlett-Packard Model 2501C, Digital Voltmeter
- Hewlett-Packard 5233L, Electronic Counter
- DuPont Model CD-12, Blasting Machine or equivalent
- Firing Circuit Voltage Divider (as-built).
- X-Y Plotter

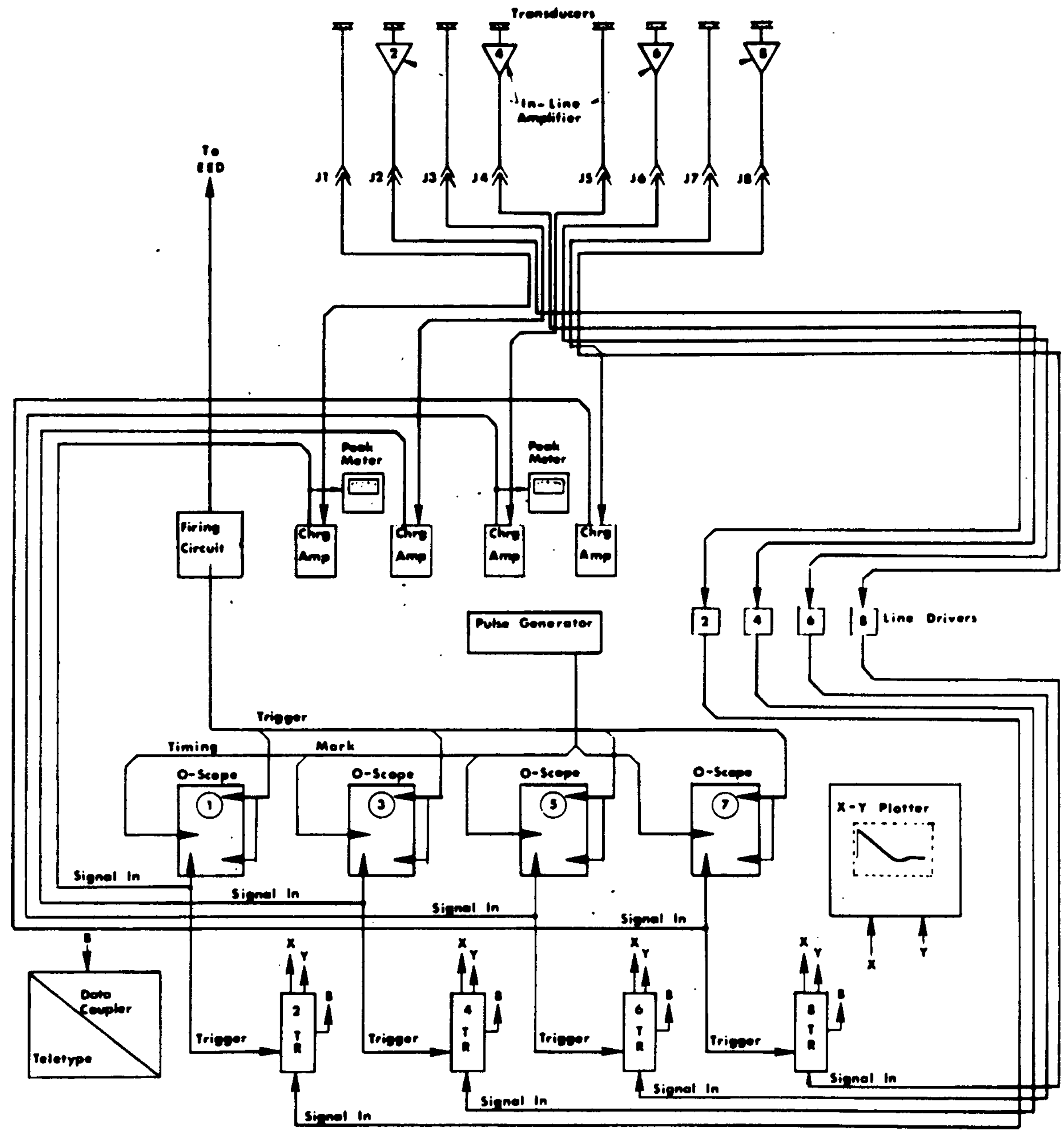



Figure B-1. Blast Instrumentation System

# APPENDIX C
# BIBLIOGRAPHY


Doc. 5 Ellern, Dr. Herbert. Military and Civilian Pyrotechnics. Chemical Publishing Company, New York. 1968.

Doc. 14 The Theory of Detonation, the Combustion Mechanism, and the Properties of Explosives. ATD Report 64-88. Aerospace Technology Division, Library of Congress. 11 August 1964.

Doc. 26 McLain, Joseph H. and McClure, Michael D. Effect of Phase Change in Solid-Solid Reactions. AD 831 733. Department of the Army, Edgewood Arsenal Research Laboratories, Chemical Research Laboratory, Edgewood Arsenal, Maryland. Prepared by Department of Chemistry, Washington College. Chestertown, Maryland.

Doc. 38 Engineering Design Handbook, Explosive Series, Explosive Trains. Headquarters, U. S. Army Material Command. AMC 706-179. March 1965.

Doc. 47 Liddiard, T. P., Jr. Low Amplitude Shock Initiation of Burning in High Explosives. AD 827 739. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland. 1 November 1967.

Doc. 61 Cohen, E. and Dobbs, N. Supporting Studies to Establish Safety Design Criteria for Storage and Processing of Explosive Materials. AD 617 614. Ammann and Whitney, New York, New York. (Contract Da-28-017-AMC-42 (A) for Picatinny Arsenal, Dover, New Jersey.) June 1965.

Doc. 63 Investigation of Hazards in the Processing of Pyrotechnic Mixtures for Chemical Agent Munitions. Final Technical Report, 1 July 1964 through 1 December 1964. AD 474 401. Edgewood Arsenal, Maryland. March 1965.

Doc. 80 Explosives Accident/Incident: Abstracts - July 1967 through 1968. AD 673 013. Armed Services Explosives Safety Board. July 1968.

Doc. 101 Potassium Chlorate, Technical. MIL-P-150B. 19 July 1956.

Doc. 120 Schuman, William J., Jr. The Response of Cylindrical Shells to External Blast Loading. Memorandum Report No. 1461. Ballistic Research Laboratories, Aberdeen Proving Grounds, Maryland. March 1963.

Doc. 123 Nagy, John, Cooper, Austin R. and Dorsett, Henry G., Jr. Explosibility of Miscellaneous Dusts. Report of Investigation 7208. United States Department of the Interior, Bureau of Mines. December 1968

Doc. 124 Zabetakis, Michael G. Flammability Characteristics of Combustible Gases and Vapors. Bulletin 627. United States Department of the Interior, Bureau of Mines. 1965.

Doc. 125 Shear, R. E. and Day, B. D. Tables of the Thermodynamic and Shock Front Parameters for Air. Memorandum Report No. 1206. Ballistic Research Laboratories, Aberdeen Proving Grounds, Maryland. May 1959.

Doc. 158 Watson, Richard W. Gauge for Determining Shock Pressures. Explosives Research Center, Bureau of Mines, U. S. Department of the Interior, Pittsburg, Pennsylvania. 20 January 1967.

Doc. 201 Wilhold, G. A., Jones, J., and Guest, S. Environmental Hazards of Acoustics Energy. Aerospace Medical Research Laboratories (AMD), Wright-Patterson Air Force Base, Ohio.

Doc. 210 Physics of Explosives and Propellants. TM 9-1300-214/TO 11A-1-34.

Doc. 261 Dust Explosibility of Chemicals, Drugs, Dyes, and Pesticides. Bureau of Mines. RI 7132. May 1968.

Doc. 266 Irani, Riyad R., and Callis, Clayton F. Particle Size: Measurement and Interpretation and Application. 541.345 IR1. John Wiley and Sons, Inc., New York. 1963

Doc. 267 Penner, S. S. and Mullins, B. P. Explosions, Detonations, Flammability, and Ignition. 541.36 P38. Pergamon Press, New York. 1959.

Doc. 268 Williams, Forman A. Combustion Theory. 541.36 W6T. Addison-Wesley Publishing Co., Inc. 1965.

Doc. 278 Transmittal of Explosives Accident Reports. Armed Services Explosives Safety Board. 1 August 1969.

Doc. 293 Hazards Tests and Studies, MTF. P. V. King, Mgr., Safety, MTSD. General Electric. September 1967.

Doc. 308 Burger, Joseph P. and Rost, D. L. Preliminary Report of the Initiation of Various Types of Electroexplosives by Induced Lighting. AD 827 746.

Doc. 313 BRL Publications. Ballistic Research Laboratories, Aberdeen Proving Grounds, Maryland. 1956-1960.

Doc. 320 Pyrotechnic Mix Formulary and End Item Information. Weapons Development and Engineering Laboratories, Chemical Process Laboratory, Edgewood Arsenal, Maryland. December 1969.

Doc. 323 Cohen, Edward, Consulting Editor. Prevention of and Protection Against Accidental Explosion of Munitions, Fuels, and Other Hazardous Mixtures. Annals of the New York Academy of Sciences. 152, 1-913.

Doc. 332 Hartmann, Irving, and Nagy, John. Vending Dust Explosions. Industrial and Engineering Chemistry. 49, 1734 (October 1957).

Doc. 334 Hartmann, Irving. Recent Findings on Dust Explosions. Chemical Engineering Progress. 53, 107-M (March 1957).

Doc. 335 Kerker, Milton, Cox, Lucile A., and Shoenberg, Melvin D. Maximum Particle Sizes in Polydispersed Aerosols. Journal of Colloid Science. 10, 413 (1955).

Doc. 336 Hartmann, Irving. Recent Research on the Explosibility of Dust Dispersions. Industrial Engineering Chemistry. 40, 752 (1948).