

THE EXPLOSIVE POWER OF SELECTED GRAIN  
DUST IN A 20-LITER SPHERICAL EXPLOSION CHAMBER

by

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## CHAPTER 1

### INTRODUCTION

#### I. Background

Dust explosions are a real hazard in the grain industry. Whenever grain is handled, grain breakage occurs and combustible dust is generated. Thus with oxygen always present in an elevator, a dust explosion may occur whenever an ignition source of sufficient energy and duration exists.

A dust explosion is the result of an energy release in a short time in an enclosed or partially enclosed space. The energy release causes the expansion of gases, leading to a rapid rise in pressure in the space. The rapid pressure increase is a major cause of the damage in a dust explosion. An example of the disastrous effect of a dust explosion is depicted in the scenario that follows:

An ignition source ignites a dust cloud in the bucket elevator of a grain elevator, causing a dust explosion. The pressure rise ruptures the bucket elevator and then the pressure wave from the explosion dislodges dust in other parts of the elevator. Flames from the ruptured bucket elevator ignite the dust cloud generated and a secondary explosion occurs. The secondary explosion proceeds throughout the elevator causing major damage.

Grain dust explosions have been occurring frequently in the United States causing extensive property damage, injuries, and fatalities. The United States Department of Agriculture compiled a list of dust explosions in grain elevators and feed mills in the United States from 1958 through 1978 from several sources (Grain Elevators and Feed Mills, 1980). Even though the list may not be complete due to lack of an accurate and comprehensive recording system, 250 explosions were recorded, which caused 605 injuries and 164 deaths. And as recently as 1981, 8 explosions between January and May caused 11 deaths and 45 injuries (Shellenbarger, 1981).

Dust explosions may be controlled by either protective or preventive measures. Protective measures only reduce the dangerous and hazardous effects of an explosion; whereas, preventive measures attempt to prevent an explosion from occurring. Some of the protective measures are containment, unit separation, explosion suppression, and explosion relief venting (Cooks, 1979; Palmer, 1978 and 1973; Bartknecht, 1981). In the explosion containment, vessels are constructed to withstand the maximum explosion pressure without rupturing. The unit separation is when units are separated by enough distance to prevent an explosion in one unit from causing an explosion in another unit. The explosion suppression requires the detection of the flame in its early stages; an extinguishing agent can be used to extinguish the flame, thus, preventing pressure development. The explosion relief venting prevents high explosion pressure from occurring in a vessel by opening a relief area and releasing the pressure. Some of the preventive measures include minimizing dust accumulation, controlling explosive conditions, practicing good housekeeping, eliminating ignition sources, and monitoring operating changes (Cooks, 1979). By minimizing dust accumulation and practicing good housekeeping the mass available for generation of a dust cloud is minimized; ideally, thus, a dust explosion is rendered impossible. If the ignition sources are totally eliminated and the explosive conditions are not present, then no dust explosion can ever occur. If operating changes are monitored, then conditions giving rise to dust explosions may be detected and, consequently, dust explosions prevented.

## II. Objectives

Protective measures require knowledge of the maximum rate of pressure rise and the maximum pressure of a dust explosion. During an experimental dust explosion test the rapid rise in pressure can be measured with respect

to time. From this measurement the highest pressure obtained during the dust explosion, the maximum pressure, and the greatest change in pressure with respect to time obtained during the dust explosion, the maximum rate, are determined. These experimental dust explosion tests are conducted at different dust concentrations. Then the greatest maximum pressure is determined and recorded as the peak maximum pressure and the greatest maximum rate is determined and recorded as the peak maximum rate.

The explosion parameters were determined for corn, milo, oats, soybean, wheat, and combination dust samples. Each dust sample was characterized by its standard heat of combustion, specific surface area, average particle size, and ash and moisture content. Statistical correlations were developed relating the standard heat of combustion to the ash and moisture content, the peak maximum rate to the dust characteristics and the quantity of dust present in the dust cloud, and the peak maximum pressure to the dust characteristics and the quantity of dust present in the dust cloud.

## REFERENCES

- Bartknecht, W. 1981. Explosions: Course Prevention Protection, Springer-Verlag, Berlin Heidelberg, New York. Translated from German by H. Burg and T. Almond.
- Cooks, Richard E. 1979. Dust Explosions: Prevention and Control. Chemical Engineering 94-100. Nov. 5.
- Grain Elevators and Feed Mills. 1980. Project officer's review draft. November.
- Palmer, K. N. 1973. Dust explosions and fires. Chapman and Hall, Ltd., London, England.
- \_\_\_\_\_ 1978. Technical survey of grain dust explosions. Reprints of International Symposium on Grain Elevator Explosions. National Academy of Sciences, Washington, D. C.
- Shellenbarger, Sue. 1981. Grain-elevator explosions continue to threaten workers and property. Wall St. Journal. July 21.



## CHAPTER 2

## LITERATURE SURVEY

In designing and developing protective and preventive measures for grain elevators, the maximum rate of pressure rise and the maximum pressure for different grain dust are needed. Since it is unfeasible to determine the values in an actual dust explosion in a grain elevator, these values are measured in laboratory explosion chambers. Mechanistic mathematical models that can be used to predict the explosibility parameters, the maximum rate and maximum pressure, have not been developed. The value of the maximum rate obtained in laboratory explosion chambers can be scaled to obtain the value expected in chambers having different volumes. The scaling law and a few of the laboratory explosion chambers are discussed in this chapter. In explosion relief venting, a protective measure, a relief venting area opens during the dust explosion and releases pressure. Included in this chapter is a section in which the method used in determining the required relief venting area is discussed. In the final section several pressure development models are discussed.

## I. Scaling Law

Bartknecht (1978; 1981) developed the empirical cubic law used for scaling. The cubic law relationship is

$$\left(\frac{dP}{dt}\right)_{\text{MAX}} \cdot V^{1/3} = K_{\text{ST}}$$

where

$$\left(\frac{dP}{dt}\right)_{\text{MAX}} = \text{maximum rate of pressure rise [=] bar/sec}$$

$$V = \text{enclosed volume of the explosion chamber [=] m}^3$$

$$K_{\text{ST}} = \text{dust constant [=] bar}\cdot\text{m/sec}$$

Use of the cubic law relationship is restricted to explosion chambers with volumes of at least 16 liters. Bartknecht determined the validity of the cubic law for chambers with volumes greater than or equal to 16 liters in a comprehensive series of tests in which the explosion chambers ranged from 20 liters to 60 m<sup>3</sup>. In principle, the explosion chamber should be spherical or cubical with the ignition source positioned in the geometric center. Using the cubic law relationship, the  $K_{ST}$ -value can be determined from laboratory experiments and then used to calculate the maximum rate of pressure rise in larger enclosed volumes.

Dusts are classified into dust explosion hazard classes by their  $K_{ST}$ -values. The dust explosion hazard classes are defined in Table 2.1 (Bartknecht, 1981). Protective measures are developed and designed for the different hazard classes.

## II. Explosion Chambers

One of the first laboratory explosion chambers used was the Hartmann apparatus developed at the United States Bureau of Mines (Dorsett, 1960). The schematic of the apparatus is shown in Figure 2.1 (Palmer, 1973). The vertical explosion tube is steel and is 30.5 cm long with an inside diameter of 6.4 cm resulting in an enclosed volume of approximately 1.25 liters. A weighed dust sample is placed in the dispersion cup at the base of the explosion tube, dispersed by a release of compressed air, and then ignited by either an electric spark or wire coil. A pressure transducer mounted on the top of the tube measures the pressure. The drawback in the use of this apparatus is that the enclosed volume is below the minimum limit required for scaling. If the  $K_{ST}$  values are calculated from the laboratory experiments and then used to predict the maximum rates of pressure rise for larger volumes, the predicted maximum rates will be inaccurate.

Table 2.1. Definition of Dust Explosion Hazard Classes.

| Dust explosion class | $K_{ST}$<br>$\frac{\text{bar} \cdot \text{m}}{\text{sec}}$ |
|----------------------|------------------------------------------------------------|
| ST 0                 | 0                                                          |
| ST 1                 | > 0 - 200                                                  |
| ST 2                 | 201 - 300                                                  |
| ST 3                 | > 300                                                      |

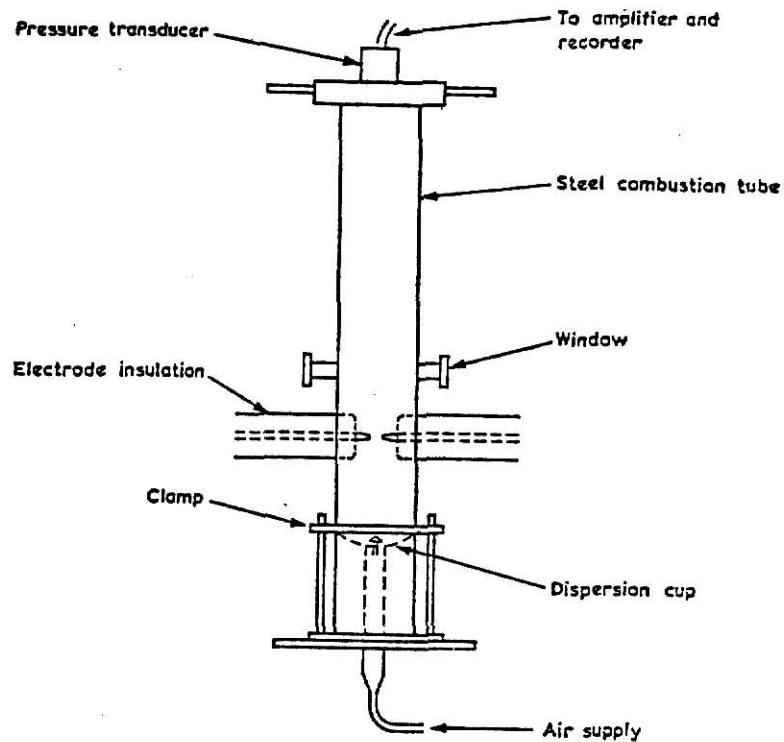


Figure 2.1. Hartman Explosion Test Apparatus (Palmer, 1973).

The United States Bureau of Mines has also developed an 8 liter apparatus (Hertzberg et al., 1979). The 8-liter apparatus is a modified Hartmann apparatus with a larger volume. In the 8-liter apparatus the lower half of the chamber has an inverted cone shape as shown in Figure 2.2 (Hertzberg et al., 1979). The cone shape provides a smooth contour from the dispersion cup to the side walls. As with the Hartmann apparatus, the enclosed volume is below the minimum limit required for scaling.

A 20-liter spherical explosion chamber has been manufactured by Adolf Kühner AG Apparatabau, Basel, Switzerland. The schematic is shown in Figure 2.3 (Kühner, 1979). A weighed dust sample is placed in the dust pre-chamber and pressurized. Upon the opening of the exit valve, the dust is dispersed by passing through a set of stainless steel horns containing two-millimeter-diameter holes into the chamber which is under vacuum. The dust can be ignited by pyrotechnic igniters, hot wire, condenser discharge, or continuous spark gap. Since the volume of the sphere is greater than the minimum volume of 16 liters, the  $K_{ST}$  values calculated can be used to predict the maximum rate of pressure rise expected from a dust explosion in a larger volume.

Another 20-liter spherical explosion chamber has been developed by Procter and Gamble of the United States. The schematic is shown in Figure 2.4 (Cocks, 1980). A weighed sample is placed in a sample chamber and dispersed by compressed air. About one third of the total air volume from the air reservoir enters with the dust from the top of the sphere. The remaining air volume enters simultaneously from the bottom of the sphere. The dust is ignited by two electric matches. Dow Chemical and Fenwal of the United States have also developed 20-liter explosion spheres. Both use a whipping hose to disperse the dust (ASTM Subcommittee E27.05, 1981).

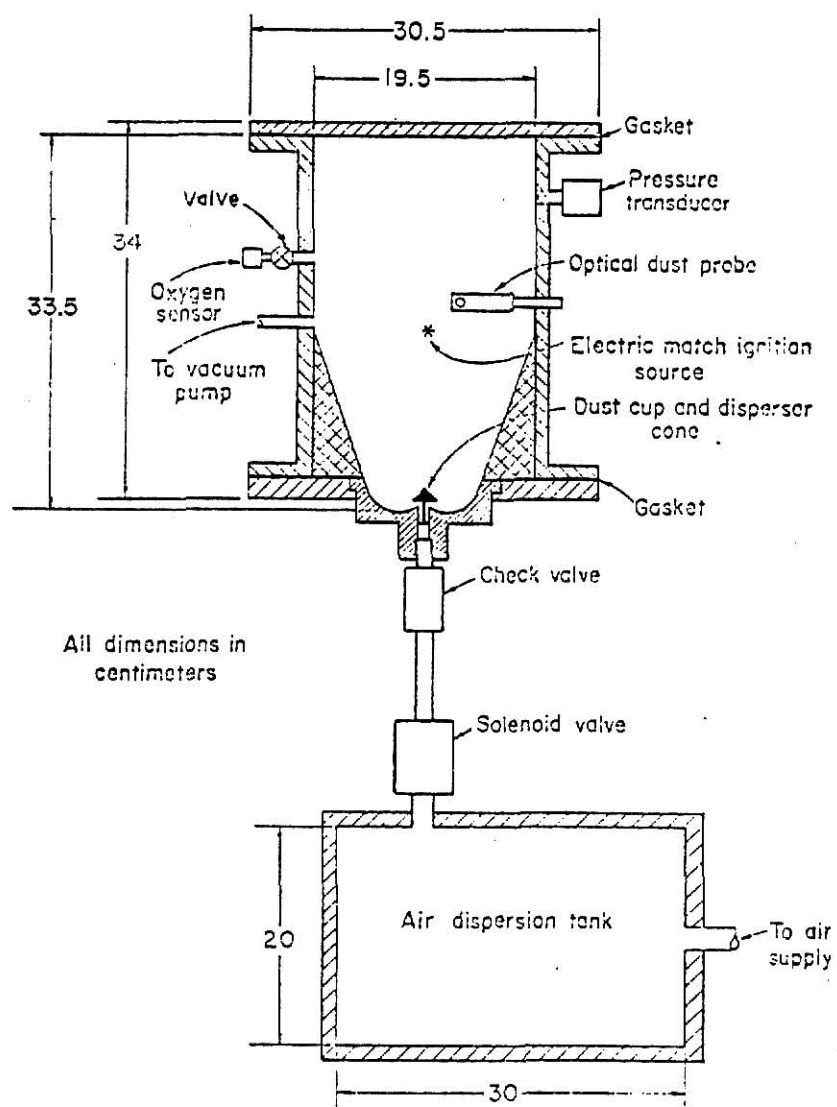


Figure 2.2. 8-Liter Explosion Test Apparatus  
(Hertzberg et al., 1979).

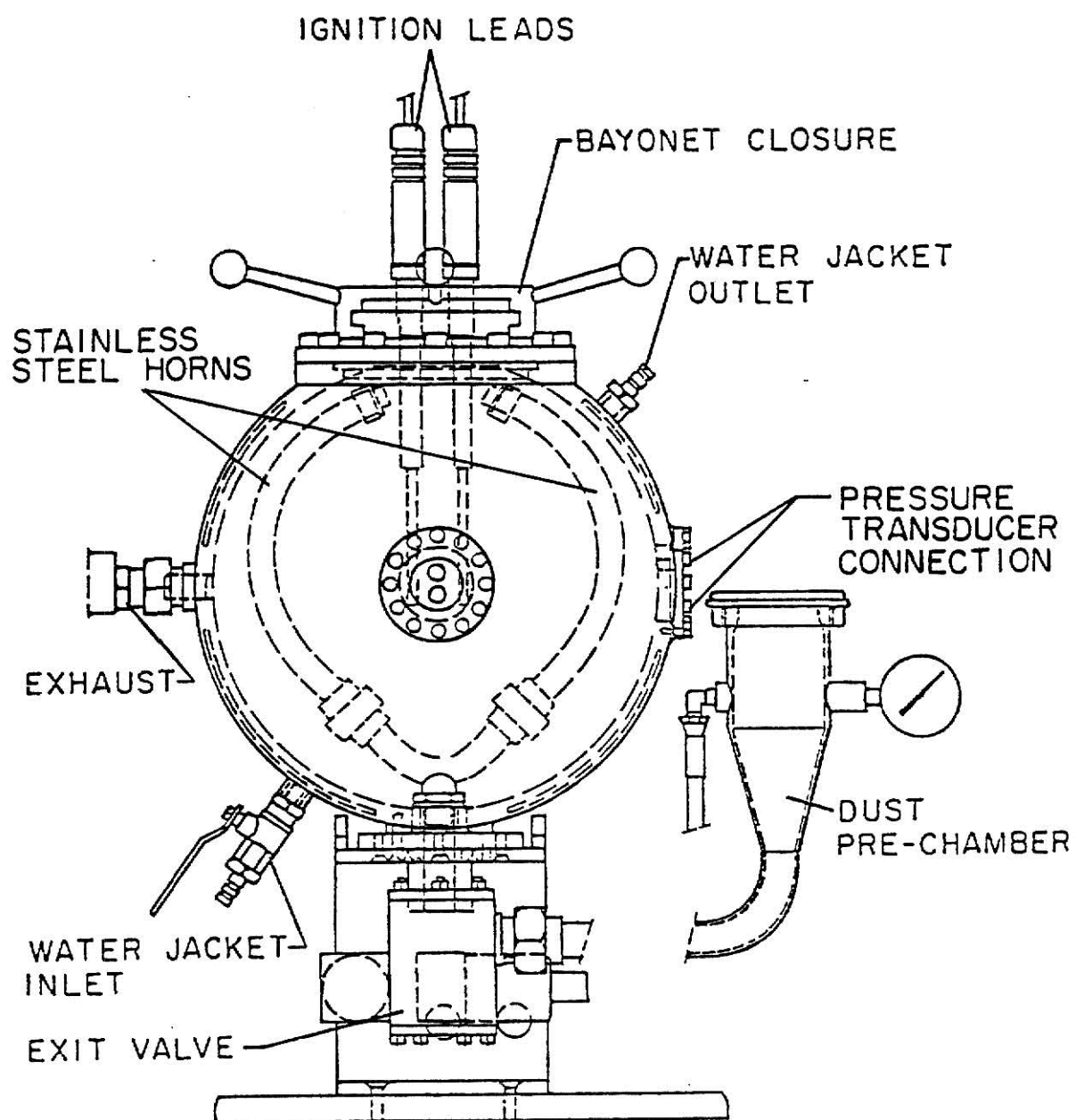


Figure 2.3. Kühner 20-Liter Explosion Sphere (Kühner, 1979).

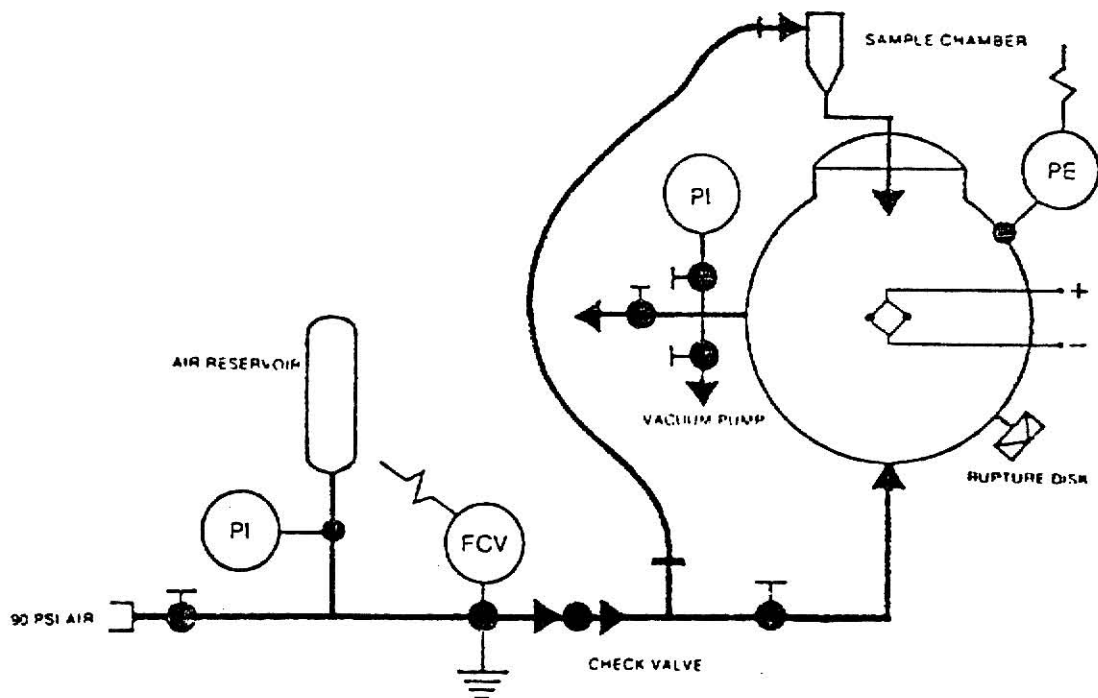


Figure 2.4. Procter and Gamble 20-Liter Explosion Chamber.  
(Cocks, 1980).

Larger chambers have been developed for studying dust explosions. In France dust explosions have been conducted in the Hartmann apparatus and 1, 10 and 100 m<sup>3</sup> chambers (Pineau et al., 1974, 1976, 1978; Giltairé et al., 1978). The Dutch have studied dust explosions in the Hartmann apparatus and a 1 m<sup>3</sup> chamber (Gooijer et al., 1975; Groothuizen, 1979). Bartknecht (1978, 1981) conducted dust explosions in chambers ranging from 20 liters to 60 m<sup>3</sup>, and Fenwal conducted tests in a 190 liter chamber (ASTM Subcommittee E27.05, 1981).

### III. Venting

Explosion relief venting is a protective measure that prevents high explosion pressure within a vessel by opening a relief area and releasing the pressure. Nomograms, such as in Figure 2.5 (Bartknecht, 1981), have been experimentally developed to determine the pressure relief venting areas for vessels. The relief area is a function of volume  $V$ , reduced explosion pressure  $P_{red}$ , and static activation pressure  $P_{stat}$ . The volume is the volume of the apparatus to be protected. Reduced explosion pressure is the highest pressure which will occur in the vented vessel and should be less than the mechanical strength of the structure. Static activation pressure is the pressure required to active the relief device.

The dashed lines on the nomograms in Figure 2.5 illustrate how the relief area is determined. First, on the nomogram with the correct  $P_{stat}$  value draw a vertical line upward from the enclosure volume to be protected to the correct  $P_{red}$  isobar. Second, from the intersection of the vertical line and the  $P_{red}$  isobar draw a horizontal line until it intersects the correct  $K_{ST}$  line. Finally, draw a vertical line downward from the intersection point on the  $K_{ST}$  line to the abscissa. The required vent area is the value at the intersection of the vertical line and the abscissa.



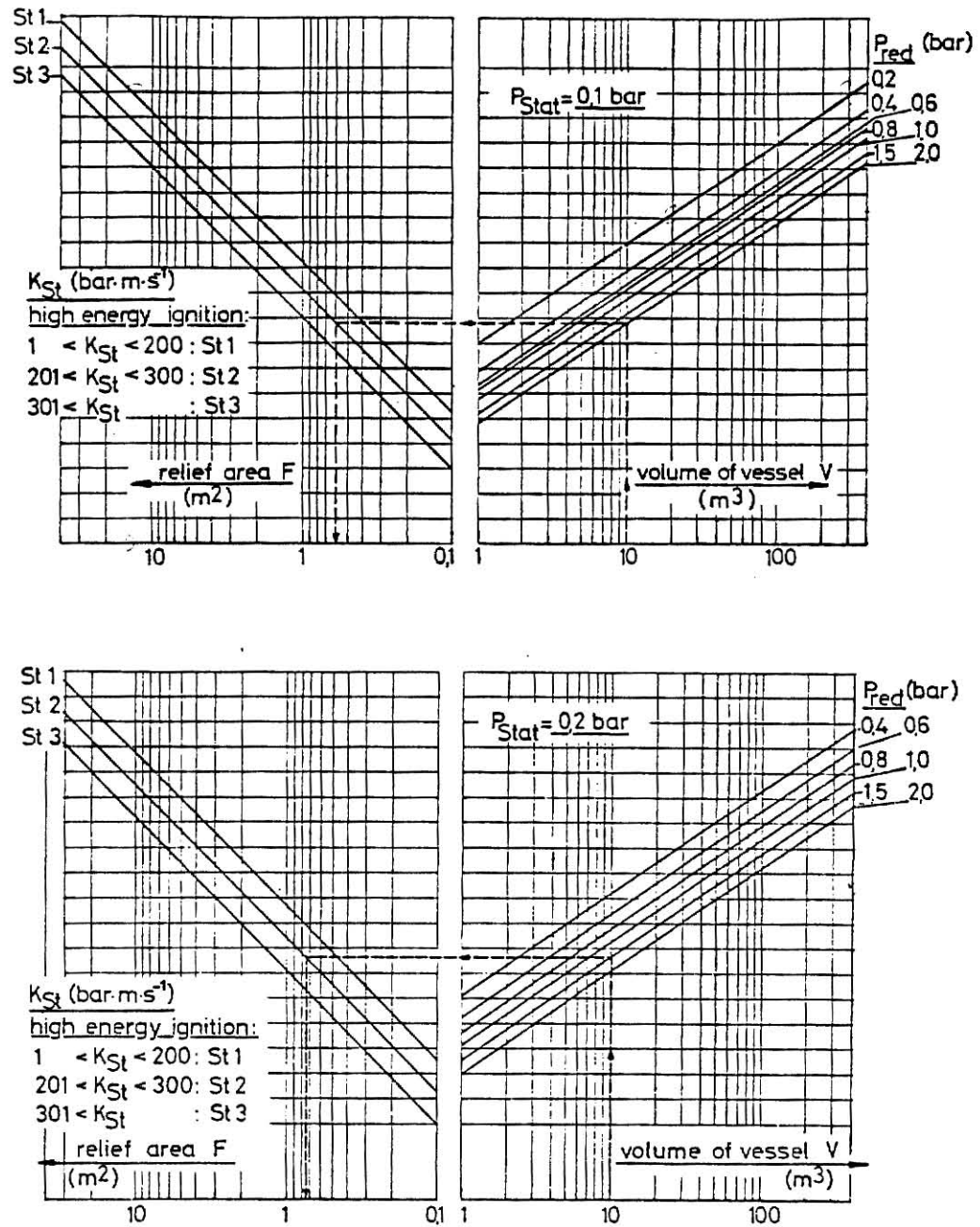


Figure 2.5. Nomograms Used in Determining the Explosion Relief Venting Area (Bartknecht, 1981).

Use of these nomograms is restricted to vessels which are approximately cubical in shape with a volume less than or equal to  $1000 \text{ m}^3$ . Due to the restrictions, the nomograms cannot be used for venting elongated structures such as silos. In such structures the maximum relief area is the cross sectional area, therefore, the roof is used for venting; however, the total area required for venting is still being investigated (Eckhoff, 1978).

#### IV. Pressure Development Models

Nagey et al., (1969) and Bradley and Mitcheson (1976) modeled mathematically the pressure development of an explosion in a closed spherical vessel. Both authors made the same simplifying assumptions; which were laminar combustion, stagnant uniform combustion mixture, central ignition, ideal gas behavior, uniform pressure, and negligible heat loss at the vessel walls. In both cases the flame front was assumed to be a thin spherical front which separated the unburnt and burnt gas and which moved radially outward as illustrated in Figure 2.6 (Nagey et al., 1969). Nagey et al. assumed that the heat capacity and volume of the solids present in the explosion were negligible; thus, their model represented a gaseous explosion. Bradley and Mitcheson's model was driven for a gaseous explosion.

The development by Nagey et al. (1969) included an empirical expression for the rate of the gaseous reaction which is a function of a reaction rate constant, surface area of the flame front, pressure and temperature of the unburnt zone. From the empirical rate expression and the assumptions, Nagey et al. derived an equation for the rate of pressure rise in an isothermal model and an equation for the rate of pressure rise in an adiabatic model. Bradley and Mitcheson (1976) developed two models. In one model they assumed the fractional pressure rise was proportional to the fractional mass burnt and the burning velocity was constant throughout the explosion.

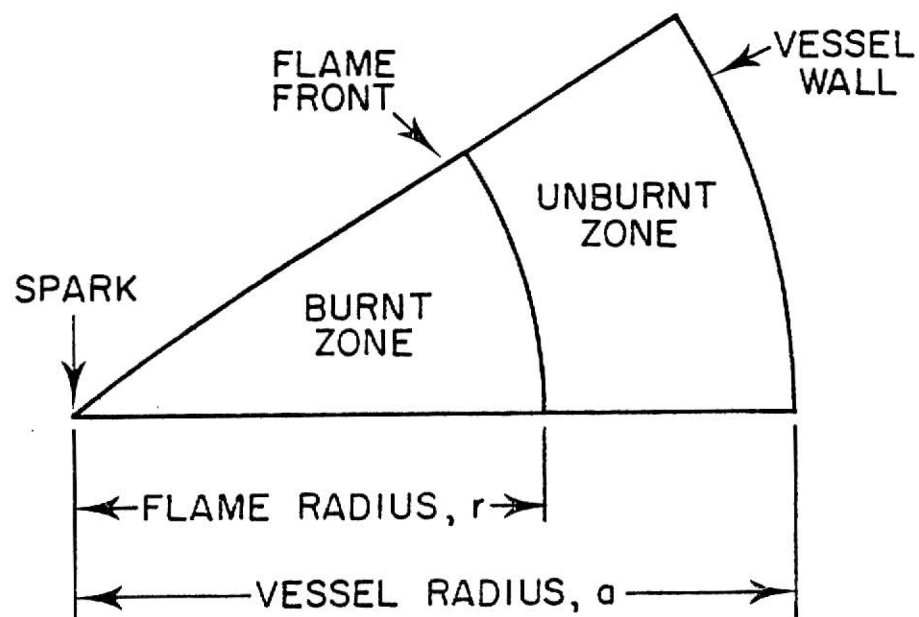


Figure 2.6. Model of Flame Front (Bradley and Mitcheson, 1976).

In the other model neither of the above assumptions were made. The models were solved numerically.

The experimental and theoretical agreement for the Nagey et al. (1969) and Bradley and Mitcheson (1976) models was reasonably good except near the end of the explosion where heat losses to the vessel walls become important. The adiabatic model developed by Nagey et al. agreed with the experimental data better than their isothermal model. The model developed by Bradley and Mitcheson which allows changes in the burning velocity agreed with the experimental data better than their model which assumed the burning velocity was constant. Even though Nagey et al. and Bradley and Mitcheson modeled a gaseous explosion, an extension of their work would be a reasonable approach for modeling a dust explosion. However, the differences between gaseous and dust explosions would have to be considered. One such difference is that the flame front in a dust explosion is not as thin as the flame front in a gaseous explosion.

Nomura and Tanaka (1980) studied theoretically the pressure development due to a dust explosion in a closed spherical vessel. The simplifying assumptions of a stagnant combustible mixture, ideal gas behavior, and central ignition made by Nomura and Tanaka were also made by Nagey et al. (1969) and Bradley and Mitcheson (1976). The additional assumptions made by Nomura and Tanaka were single sized spherical dust particles uniformly dispersed on a spherical surface as illustrated in Figure 2.7 (Nomura et al., 1980), adiabatic behavior, the maximum pressure and maximum rate of pressure rise occurred at the same time, and the rate of combustion was controlled by diffusion of oxygen through the ash layer. Even though Nomura and Tanaka assumed the rate of combustion was controlled by diffusion through the ash layer, they used a rate expression in which the chemical reaction was the controlling mechanism. Their assumptions that the maximum pressure and the

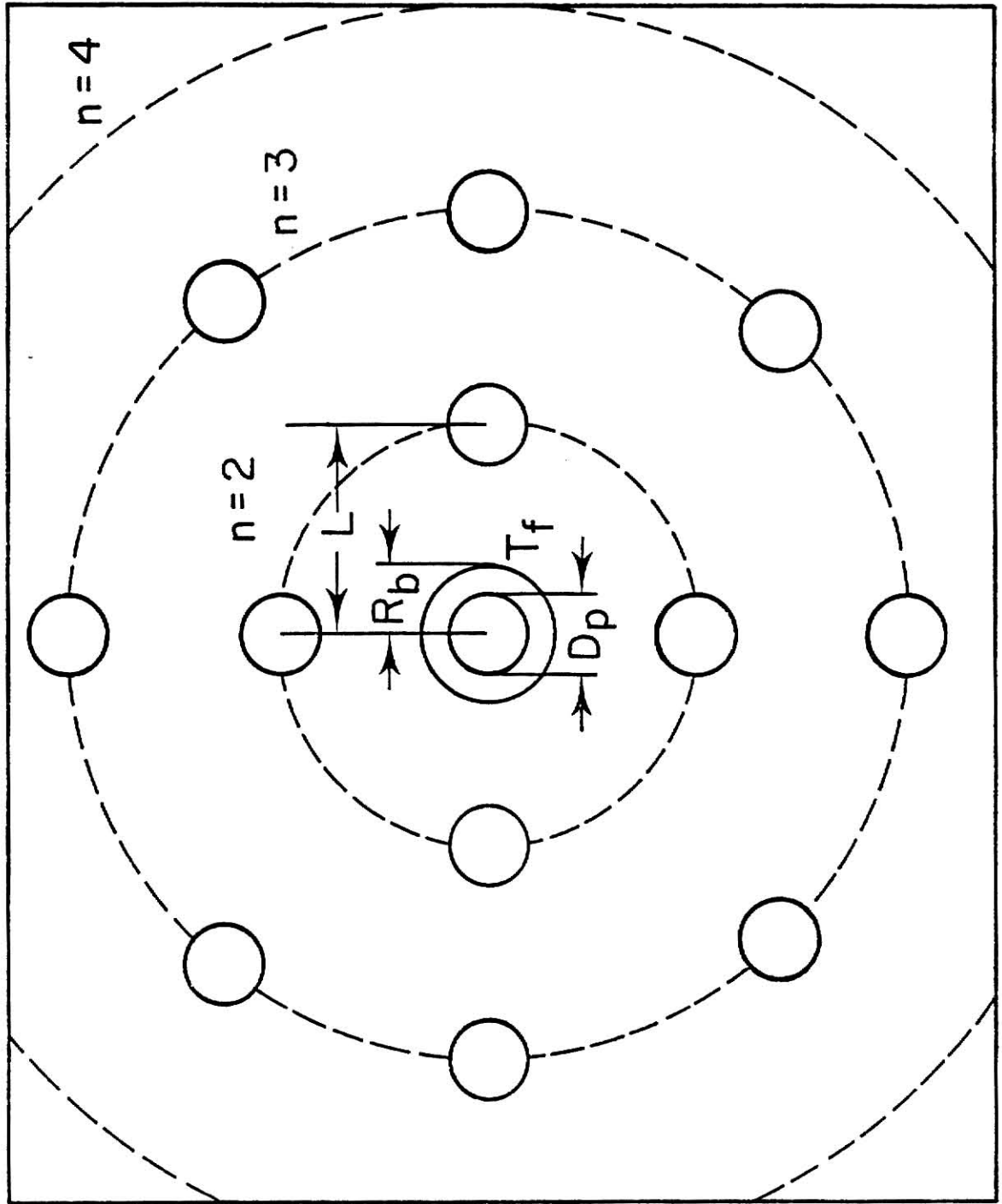


Figure 2.7. Model of Dust Particles (Nomura and Tanaka, 1980).

the maximum rate of pressure rise occurred at the same time and that the dust particles were single sized spherical particles uniformly dispersed are inaccurate. An additional problem in their development is their neglect of the expansion of the unburnt gas during the explosion. These errors are the reason the theoretical results are an order of magnitude different from the experimental data.

## REFERENCES

- ASTM Subcommittee E27.05-Dusts Minutes. 1981. Phoenix, Arizona. May.
- Bartknecht, W. 1978. Gas, vapor and dust explosions. Reprints of International Symposium on Grain Elevator Explosions. National Academy of Sciences, Washington, D.C. Translated from German by H. Burg.
- \_\_\_\_\_ 1981. Explosions: Course Prevention Protection, Springer-Verlag, Berlin Heidelberg, New York. Translated from German by H. Burg and T. Almond.
- Bradley, D., and Mitcheson, A. 1976. Mathematical solutions for explosions in spherical vessels. Combustion and Flame 26:201-217.
- Cocks, R. E. and Meyer, R. C. 1980. Fabrication and use of a 20 litre spherical dust testing apparatus. 88-th National AIChE Meeting. Philadelphia, Pa.
- Dorsett, H. G., Jr., Jacobson, M., Nagey, J., and Williams, R. P. 1960. Laboratory equipment and test procedures for evaluating explosibility of dusts. U.S. Department of the Interior, Bureau of Mines, Report of Investigations, RI-5624.
- Eckhoff, R. K. 1978. Necessary vent areas for grain and feedstuffs dust explosions in large storage bins. Cereal Foods World 23(11): 650-656.
- Giltaire, M., and Dangreux, J. 1978. Les poussières explosibles. [Explosive dusts.] Annales des Mines. Janvier-Fevrier, pp. 85-96.

- Gooijer, H., Groothuizen, Th. M., and Reinders, M. E. 1975. Literature investigation into the dust explosion danger in industries storing and processing cereals and flour. The Dutch Commodity Board for Cereals, Seeds and Podware. October.
- Groothuizen, Th. M. 1979. Onderzoek naar stofexplosive-eigenschappen van een aantal stoffen dat voorkomt in bedrijven die bloem, mengvoeders, zetmeel en zuivelprodukten verwerken en opslaan. The Dutch Commodity Board for Cereals, Seeds and Podware. August.
- Hertzberg, M., Cashdollar, K. L., and Opferman, J. J. 1979. The flammability of coal dust-air mixtures: lean limits, flame temperatures, ignition energies, and particle size effects. U.S. Department of the Interior, Bureau of Mines, Report of Investigations, RI-8360.
- Kühner, Adolf. 1979. Users guide for the 20-liter laboratory explosion testing apparatus. Translated from German by P. Pomeranz.
- Nagey, J., Conn, John W., and Verakis, H. C. 1969. Explosion development in a spherical vessel. U.S. Department of the Interior, Bureau of Mines, Report of Investigations, RI-7279.
- Nomura, S., and Tanaka, T. 1980. Prediction of maximum rate of pressure rise due to dust explosion in closed spherical and nonspherical vessels. Industrial and Engineering Chemistry, Process Development and Design 19:451-459.
- Palmer, K. N. 1973. Dust explosions and fires. Chapman and Hall Ltd., London, England.



Pineau, MM. J., Giltairé, M., and Dangreux, J. 1974. Efficacité des événements d'explosion: étude d'explosions de poussières en récipients de 1, 10 et 100 m<sup>3</sup>. Cahiers de Notes Documentaires No 74, 1er, Trimestre.

————— Giltairé, M., and Dangreux, J. 1976. Efficacité des événements étude d'explosions de poussières en récipients de 1, 10 et 100 m<sup>3</sup>: influence de la nature de la poussière et de la présence d'une canalisation prolongeant l'événement. Cahiers de Notes Documentaires No 83, 1er, Trimestre.

————— Giltairé, M., and Dangreux, J. 1978. Efficacité des événements dans le cas d'explosions de poussières: choix des surfaces d'événement et de leurs dispositifs d'obturation. Cahiers de Notes Documentaires No 90, 1er, Trimestre.

## CHAPTER 3

## MATERIALS AND METHODS

The 28 grain dust samples used in the experimental explosion tests were collected from grain elevators in the states of Kansas, Missouri, Iowa, and Texas. After collection, each dust sample was sieved and mixed before characterization and the dust explosion tests. Aspects of the dust collection, dust preparation, dust characterization, and dust explosion tests are detailed in this chapter. Besides the 28 grain dust samples, the experimental explosion tests were also performed on a cornstarch sample and a wheat flour sample.

## I. Dust Collection

A major problem in collecting grain dust is obtaining a dust sample composed of one type of dust. In many grain elevators two or more types of grain may be received simultaneously or sequentially before any cleanup operation, and therefore, any dust collected has a high probability of being a mixture. In an effort to obtain pure dust samples the grain dust was collected, whenever possible, from grain elevators which stored grain for feed mills. A feed mill manufactures feed for animals and normally receives one type of grain.

Elevators are classified as country, inland terminal, and export terminal elevators. The country elevators receive grain directly from farms and send it to the terminal elevators or grain processors. Inland terminal elevators receive grain from country elevators and farms for direct export or delivery to export terminal elevators or grain processors (Grain Elevator and Feed Mills, 1980). Export terminal elevators receive grain from inland terminal and country elevators and farms. Inland terminal and export terminal elevators receive grain that has been previously handled;

thus, they handle grain which produces finer dust. Dust was collected from one export terminal elevator. All remaining dust was collected from country and inland terminal elevators.

Some locations within a grain elevator have a high probability of being the site of a dust explosion. Three locations are in or near the bucket elevator, conveyor belt, and dust collection systems. At each elevator an attempt was made to collect dust in each of these vicinities. Table 3.1 lists the sources for all grain dust samples. Fugitive dust is generated during grain handling and settles out of the air onto a surface. Generally, the fugitive dust collected around the boot of the bucket elevator and around the conveyor belt was piled on the floor or on surfaces nearby. Dust collection system dust was tailing discharge from a baghouse or cyclone. One sample was collected from around a milo dryer, even though it was not one of the collection locations. The combination dust is a mixture of different dust types.

## II. Dust Preparation

Each dust sample was stored in an airtight container in a freezer maintained at 0°C. Storage in this cold environment suppressed insect activity. No attempt was made to equalize the moisture content of all dust samples, since maintaining the moisture content would have been extremely difficult.

Each dust sample was shaken for five minutes on a Fisher-Wheeler sieve shaker containing a one millimeter U.S.A. standard testing sieve. Dust that passed through the sieve was used in the explosion tests, while dust remaining on the sieve was considered trash and discarded. The sieve removed effectively the majority of trash present in each dust sample. However, with some soybean, milo and oats dust samples the sieving changed the nature of the dust slightly by creating balls of dust.

Table 3.1 Source of Grain Dust.

| Code  | Elevator | Geographical |       | Dust type   | Location in elevator                                         |
|-------|----------|--------------|-------|-------------|--------------------------------------------------------------|
|       |          | location     | state |             |                                                              |
| CB12  | A        | Texas        |       | combination | Fugitive dust falling from break in enclosed conveyor belt.  |
| CB12c | A        | Texas        |       | combination | Fugitive dust around enclosed conveyor belt.                 |
| CB13  | A        | Texas        |       | combination | Tailing discharge from dust bin.                             |
| CN21  | B        | Missouri     |       | corn        | Fugitive dust around boot of bucket elevator.                |
| CN22b | B        | Missouri     |       | corn        | Fugitive dust around open conveyor belt in basement.         |
| CN23  | B        | Missouri     |       | corn        | Tailing discharge from baghouse.                             |
| MO11  | C        | Kansas       |       | milo        | Fugitive dust around boot of bucket elevator.                |
| MO12  | C        | Kansas       |       | milo        | Fugitive dust on top floor.                                  |
| MO13  | C        | Kansas       |       | milo        | Fugitive dust around receiving operation.                    |
| MO20  | D        | Kansas       |       | milo        | Fugitive dust around operating grain dryer.                  |
| MO32b | B        | Missouri     |       | milo        | Fugitive dust around open conveyor belt in basement.         |
| MO32c | B        | Missouri     |       | milo        | Fugitive dust in room beside open conveyor belt in basement. |
| OT12  | E        | Iowa         |       | oats        | Fugitive dust falling from break in enclosed conveyor belt.  |
| OT12c | E        | Iowa         |       | oats        | Bridge belt - supplied by elevator staff.                    |
| OT13  | E        | Iowa         |       | oats        | Dust collector - supplied by elevator staff.                 |
| SB11  | F        | Kansas       |       | soybean     | Dust collection system on bucket elevator.                   |
| SB12a | F        | Kansas       |       | soybean     | Fugitive dust around end of open conveyor belt in a gallery. |
| SB13  | F        | Kansas       |       | soybean     | Tailing discharge from cyclone.                              |
| SB21  | G        | Missouri     |       | soybean     | Fugitive dust around top of bucket elevator.                 |
| SB22a | G        | Missouri     |       | soybean     | Fugitive dust around end of open conveyor belt in gallery.   |
| SB22b | G        | Missouri     |       | soybean     | Fugitive dust around end of open conveyor belt in basement.  |
| SB23  | G        | Missouri     |       | soybean     | Tailing discharge from baghouse.                             |
| WT11  | H        | Missouri     |       | wheat       | Fugitive dust around top of bucket elevator.                 |
| WT12a | H        | Missouri     |       | wheat       | Fugitive dust around end of open conveyor belt in gallery.   |
| WT12b | H        | Missouri     |       | wheat       | Fugitive dust around end of open conveyor belt in basement.  |
| WT21  | I        | Kansas       |       | wheat       | Fugitive dust around boot of bucket elevator.                |
| WT22a | I        | Kansas       |       | wheat       | Fugitive dust around end of open conveyor belt in gallery.   |
| WT23  | I        | Kansas       |       | wheat       | Tailing discharge from cyclone.                              |

All dust that passed through the one millimeter sieve from a dust sample was mixed in a MacLellan Batch mixer for fifteen minutes to obtain a homogeneous dust sample. Mixing also caused agglomeration in some soybean, milo, and oats dust samples.

### III. Dust Characterization

The average particle size of each sample was measured with a High Accuracy Particle Counter (Hiac) sensor (High Accuracy Products Corp, 1972) after being dispersed in a modified Hartmann pressure apparatus. The dispersion cup of the standard Hartmann pressure apparatus was modified to allow an airstream to pull dust laden air through it and past the sensor. In Figure 3.1, schematic A illustrates the standard Hartmann dispersion cup (Dorsett, 1960) and schematic B illustrates the modified Hartmann dispersion cup. When the dust is dispersed in the modified Hartmann apparatus a dust suspension is formed. In a dust suspension the particles may agglomerate or become unagglomerated; therefore, the particle size distribution for a suspended dust and unsuspended dust may be different. Since the dust explosion occurs in a dust cloud or dust suspension, the particle size distribution was determined using the modified Hartmann apparatus. Two average particle sizes were obtained for each dust sample. One was for the prepared dust and the other was for dust which had been collected inside the 20 liter explosion sphere after being dispersed.

The standard heat of combustion at 25°C was measured in a PARR adiabatic bomb calorimeter. It was assumed the prepared dust consisted of cellulose and the combustion products were gaseous carbon dioxide and liquid water.

Surface area measurements were performed on dust which had been collected inside the 20 liter explosion sphere after being dispersed. All

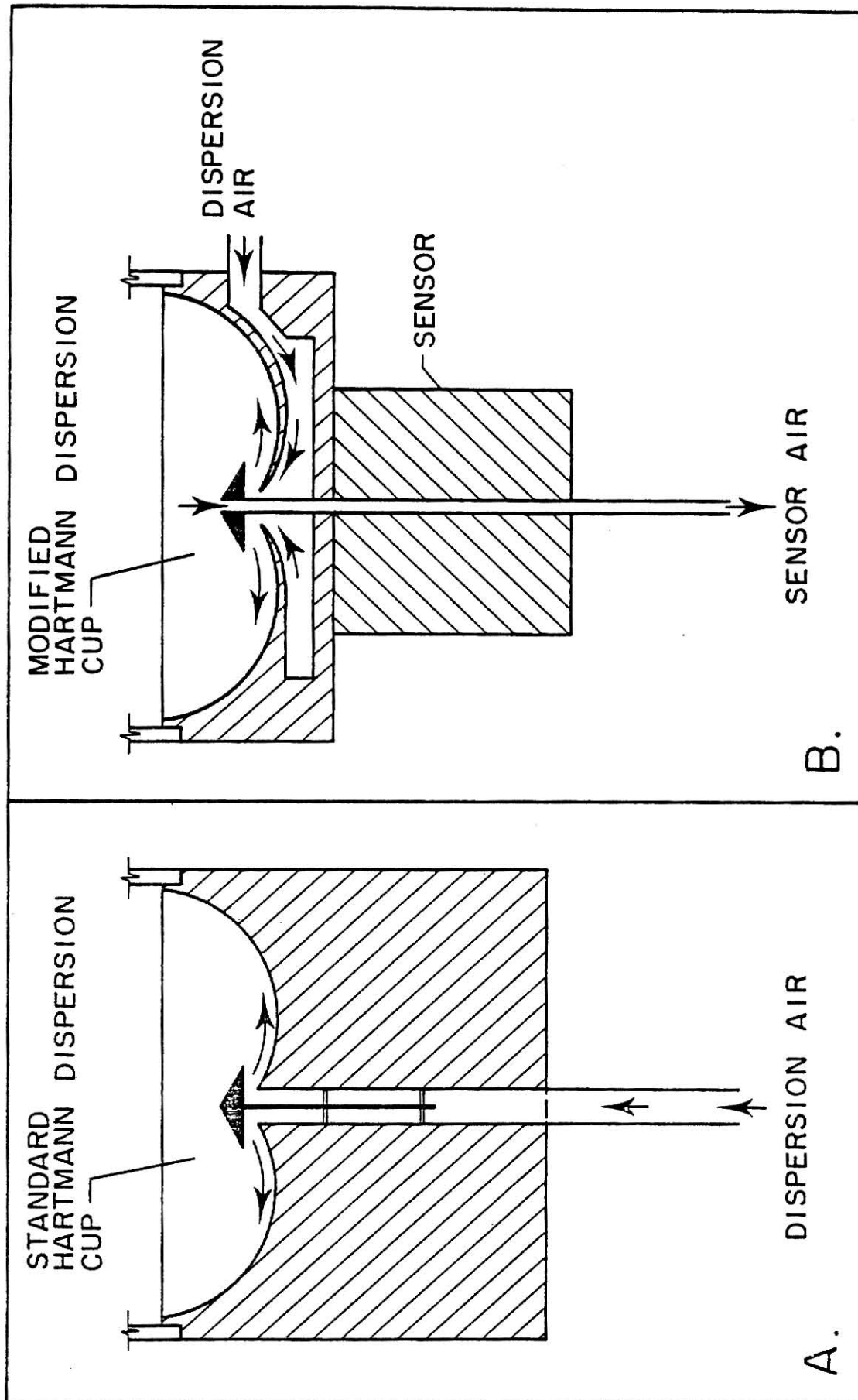


Figure 3.1. Comparison of the Standard and Modified Dispersion Cups.

samples were conditioned by maintaining them at 100°C overnight while purging them with helium gas and then analyzed using the 3-point Brunauer, Emmett, and Teller (BET) technique (Young et al., 1962). The specific surface area was calculated by the BET equation after determining the amount of nitrogen absorbed by a dust sample at three different partial pressures.

Ash content, in terms of weight percent, of each prepared dust sample was determined according to AACC Method 08-01 (AACC, 1976) at the U.S. Grain Marketing Research Laboratory.

Moisture content, in terms of weight percent, was determined according to AACC Method 44-01 (AACC, 1976). Small amounts of prepared dust were collected to determine the moisture content of the dust sample before, after, and sometimes during the experimental explosion test.

#### IV. Dust Explosion

All explosion tests were performed in a 20-liter explosion sphere manufactured by Adolf Kühner AG Apparatbau, Basel, Switzerland. The hollow stainless steel sphere is closed by a bayonet closure ring as shown in the schematics in Figures 2.2 and 3.2 (Kühner, 1979). A dust pre-chamber is connected to the sphere through an exit valve. Dust is loaded into the dust pre-chamber and pressurized before it exists through the exit valve and enters the sphere. Upon entering the sphere the dust is dispersed through a set of stainless steel horns, dispersion horns, containing two-millimeter-diameter holes.

Timing of the exit valve, operation, and ignition are controlled by a control unit called KSEP 210. Timing is important in the explosion tests since the time of ignition defines the turbulence and concentration at ignition. The active or effective ignition delay time,  $t_v$ , is defined as the time span between the opening of the exit valve and activation of

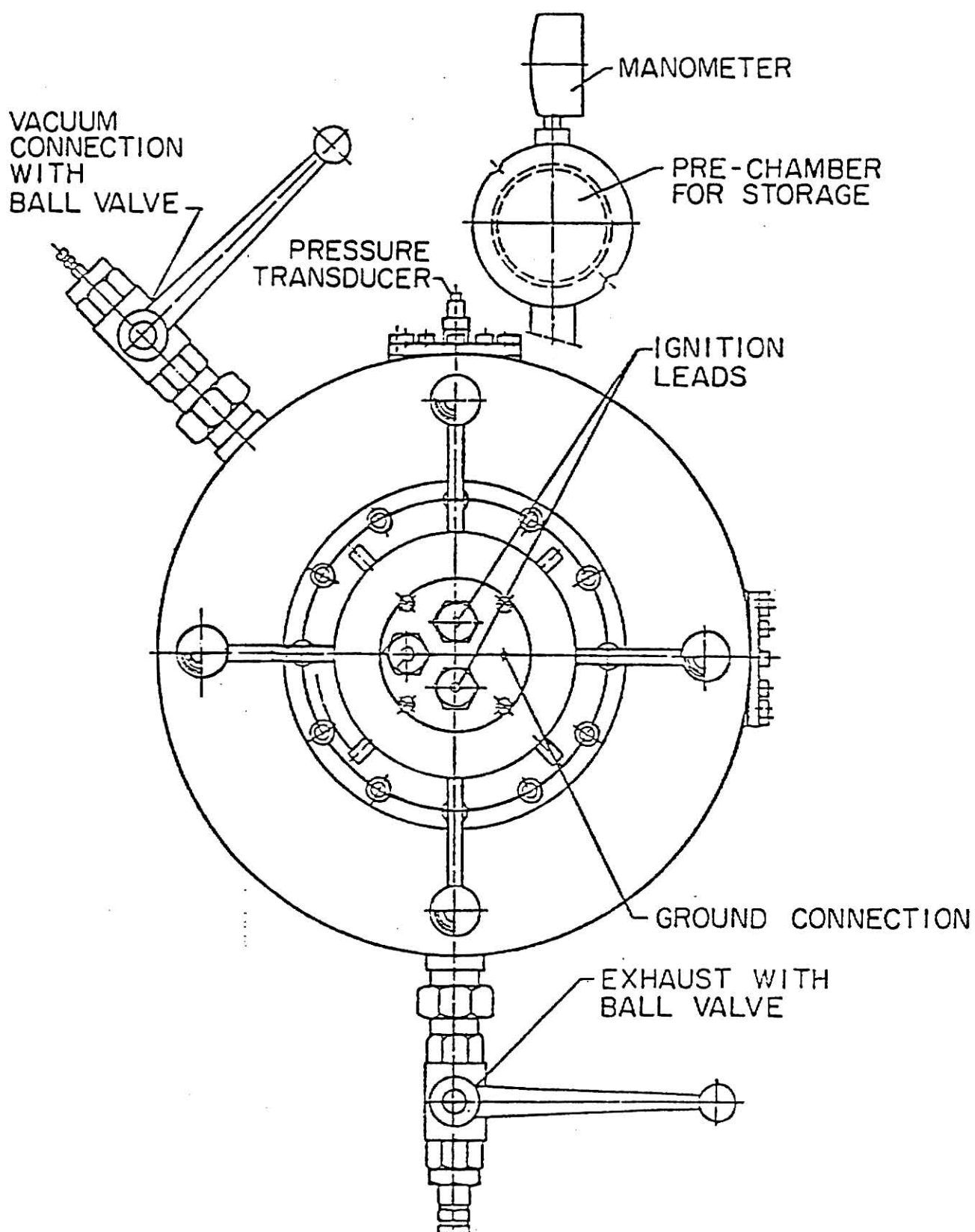


Figure 3.2. Schematic of 20-Liter Spherical Explosion Chamber (Kühner, 1979).



the ignition source (Kühner, 1979). The electric ignition delay time, TZV, setting located on the front panel of KSEP 210 determines  $t_v$ . If TZV equals 100 ms, then  $t_v$  equals 60 ms as shown in Figure 3.3 (Kühner, 1979). Mechanical operation of the exit valve accounts for the 40 ms difference.

A schematic of a high-energy chemical igniter is shown in Figure 3.4. An Atlas M103 electric match available from ICI Americas Inc. is used to ignite 1.2 grams FFF black powder contained in a gelatine capsule. Two igniters of this type were used in the explosion tests, releasing approximately 10 KJ of energy. Dust can also be ignited by a permanent spark gap or condenser discharge in the 20 liter explosion sphere. These two ignition sources release approximately 0.01 KJ and 0.1 KJ, respectively. Since these three ignition sources release different amounts of energy, the maximum explosion pressure and maximum rate of pressure determined using these types of ignition sources may differ.

The pressure was measured by two strain-gauge pressure transducers from Bell & Howell. One had a range of 0-500 psig and the other had a range of 0-200 psig. Duplicate pressure values were necessary to detect malfunctioning of a pressure transducer and to detect when recalibration of a pressure transducer was necessary. Both pressure transducers were recalibrated each day before performing any explosion tests. When operating properly the duplicate pressure values did not differ by more than  $\pm 0.3$  bar.

The explosion measurement method involved two steps. First, the optimum loading had to be determined. Typically, explosion tests were made at loadings of 10, 15, 20, 25, 30, and 35 grams. Loading was increased until both the maximum rate of pressure rise and maximum pressure decreased with an increase in loading. Loadings as high as 50 grams were required

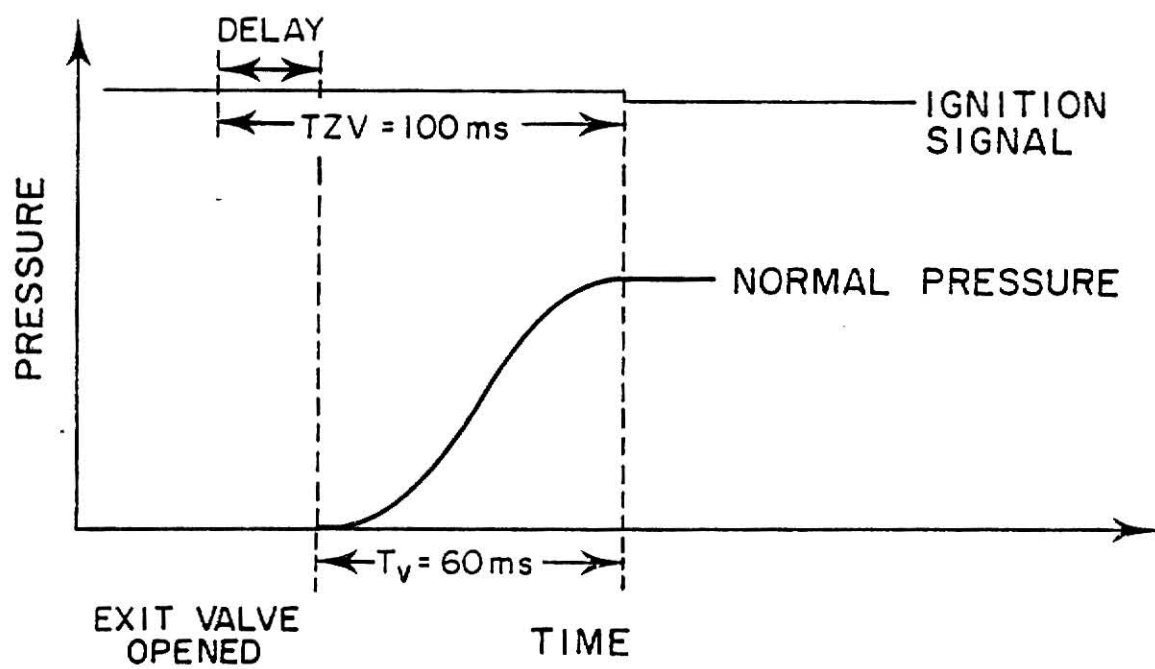


Figure 3.3. Timing Sequence of 20-Liter Spherical Explosion Chamber (Kuhner, 1979).

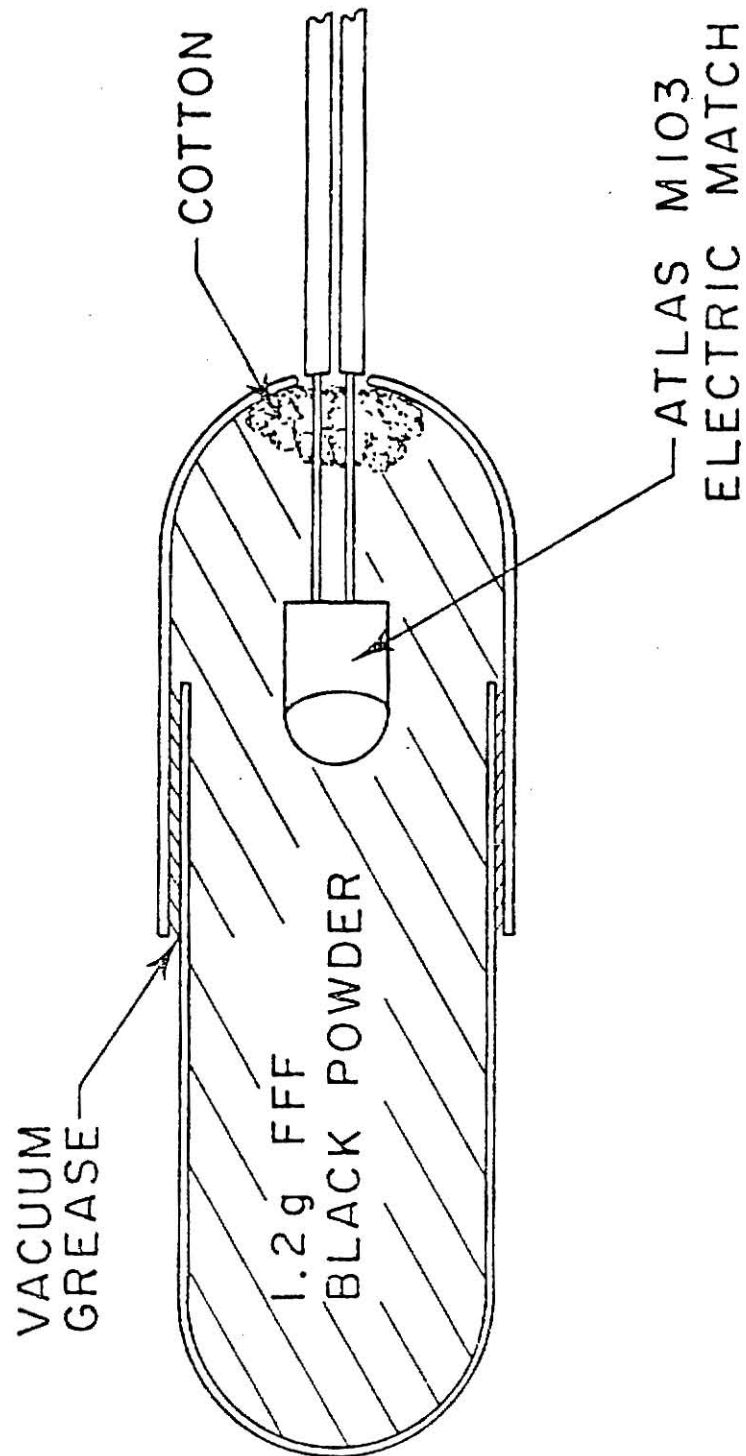


Figure 3.4. High-Energy Chemical Igniter.

for a few dust samples. For each loading at least three explosion tests were performed. All tests were run at a TZV setting of 60 ms.

A typical millivolt versus time trace obtained from an explosion test is illustrated in Figure 3.5. The positive and negative portions represent pressure transducer one and pressure transducer two, respectively. The linear calibration curves used to convert mv values of both pressure transducers to psi values had a correlation coefficient of at least 0.999. Values of the maximum rate and maximum pressure were calculated for each pressure transducer by the method shown in Figure 3.6 and 3.7. All maximum rate values at the same loading were averaged and all maximum pressure values at the same loading were also averaged. The optimum loading was the loading at which the averaged maximum rate value peaked as shown in Figure 3.8.

Next, the optimum TZV was determined by varying the TZV setting at the optimum loading. Initially only two explosion tests were made for each different TZV setting. For example, if the optimum loading at TZV equals 60 ms was 20 grams, then the TZV setting would be reset at 50 ms, and two explosion tests would be run at 50 ms and 20 grams. All maximum rates and maximum pressures at the same loading and TZV setting were averaged. If the averaged value of the maximum rate at 50 ms was less than the value at 60 ms, then the TZV setting would be changed to 70 ms and two explosion tests run. This procedure was continued until the optimum TZV setting was determined. The optimum TZV setting was the TZV setting at which the value of the averaged maximum rate peaked. At the optimum TZV setting and loading, four explosion tests were made and the results averaged and recorded as the value of the maximum rate for the dust sample, the peak maximum rate. A TZV setting of 100 ms is recommended by the manufacturers of the 20 liter explosion sphere (Kühner, 1979).

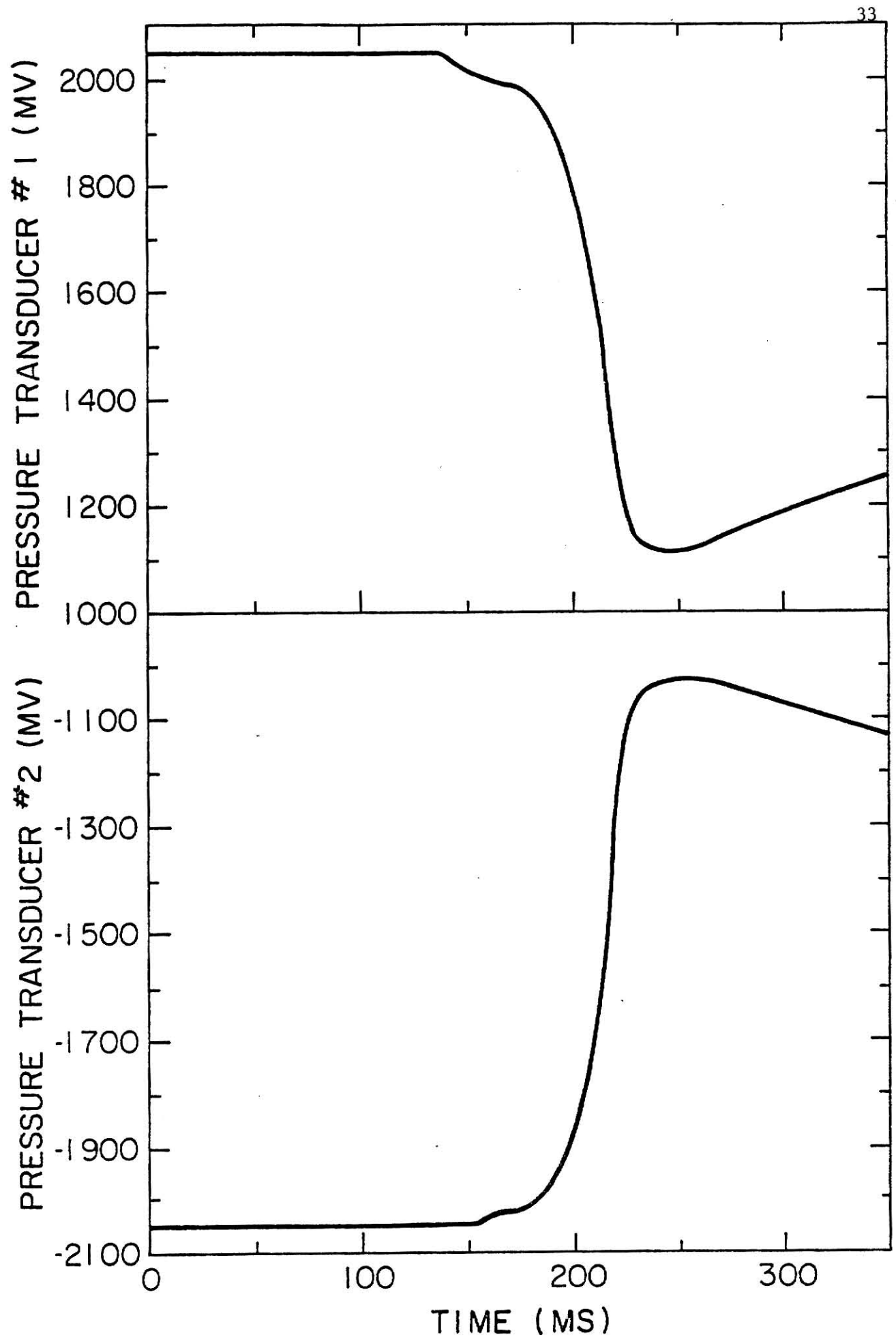
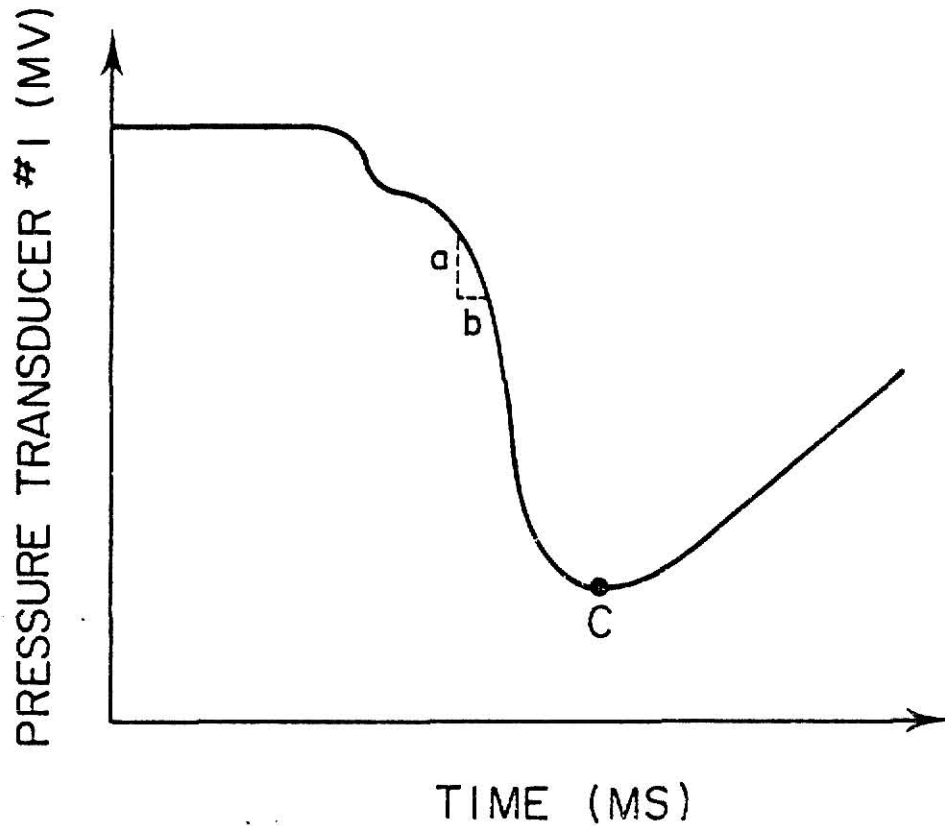
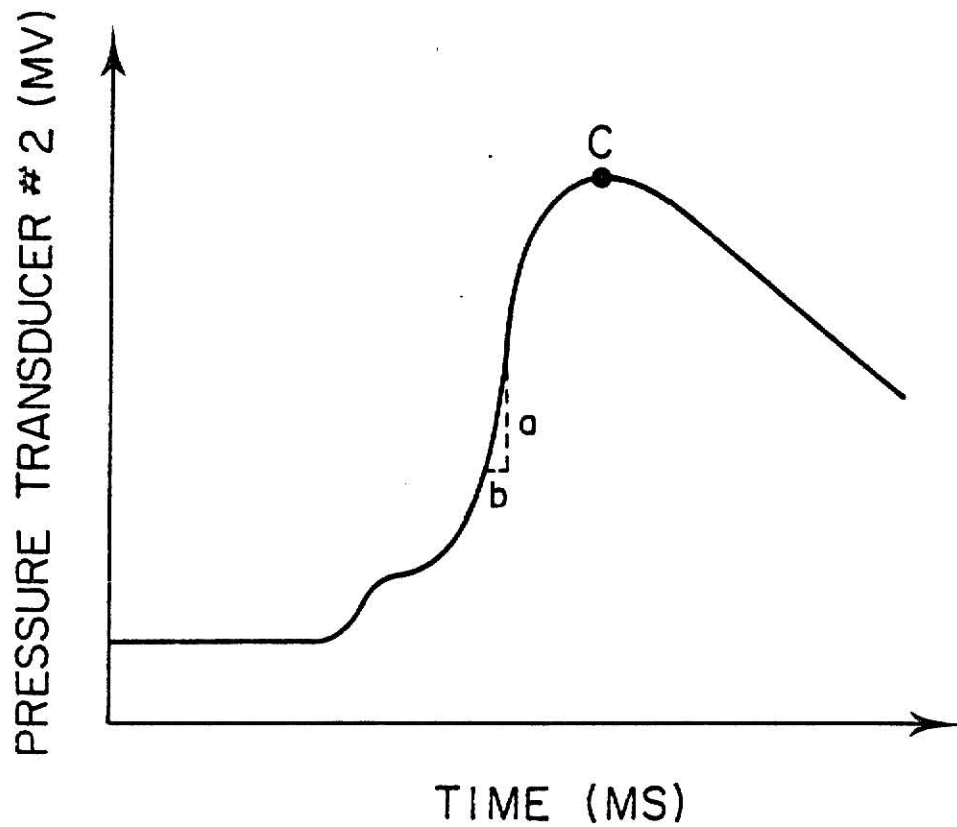


Figure 3.5. Experimental Explosion Test Result.



Maximum Rate of Pressure Rise = Maximum  $\left(\frac{a}{b}\right)$   
 Maximum Pressure = Minimum mv = C

Figure 3.6. Determination of the Experimental Maximum Rate of Pressure Rise and Maximum Pressure for Pressure Transducer #1.



Maximum Rate of Pressure Rise = Maximum  $\left(\frac{a}{b}\right)$

Maximum Pressure = Minimum mv = C

Figure 3.7. Determination of the Experimental Maximum Rate of Pressure Rise and Maximum Pressure for Pressure Transducer #2.

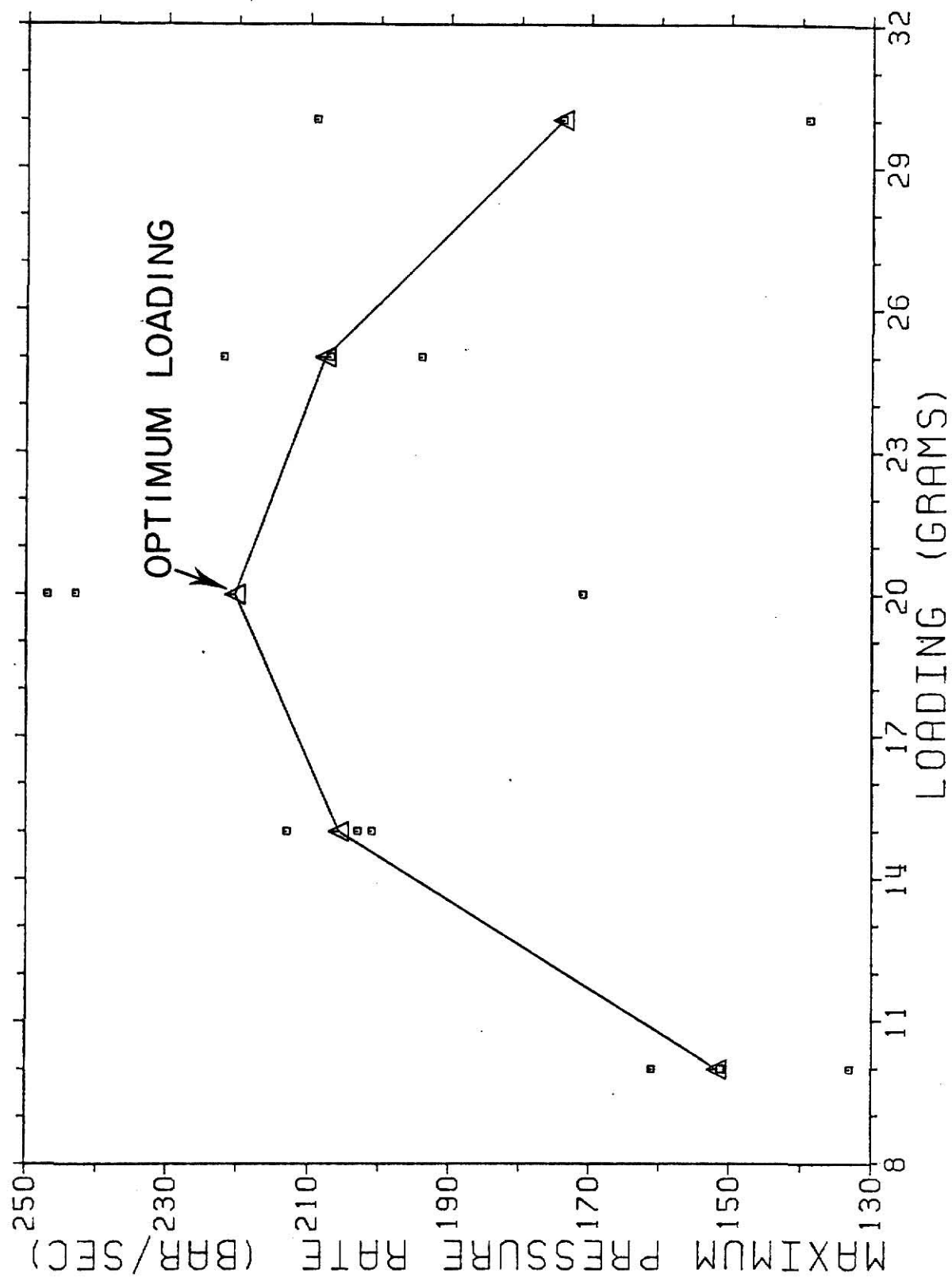


Figure 3.8. Determination of the Optimum Loading for the Maximum Rate of Pressure Rise.

□ = observed value      Δ = mean value



Hence, at the optimum loading of each dust sample two explosion tests were made with a TZV of 100 ms, even though this setting never gave the peak maximum rate.

The optimum loading with respect to the maximum pressure was determined by the same method as the optimum loading with respect to the maximum rate. The optimum loadings were not necessarily equal for all dust samples. The maximum pressure changed negligibly with different TZV settings at its optimum loading; consequently, to reduce the number of explosion tests, the optimum TZV setting was determined with respect to the maximum rate. The value of the maximum pressure, peak maximum pressure, recorded for each dust sample was the highest averaged maximum pressure value obtained in the explosion tests. For some dust samples the TZV setting at the peak maximum pressure equaled 100 ms.

Conducting the explosion tests involved a number of operations which had to be carefully performed to ensure consistent and accurate data. First, the dispersion horns were positioned inside the sphere, two igniters were positioned on the bayonet closure ring, weighed dust was loaded into the dust pre-chamber, and the pre-chamber closed. Second, the bayonet closure ring was tightened on top of the sphere and the sphere evacuated to a reduced pressure of 0.4 bar absolute. Third, the dust pre-chamber was pressurized to 21 bar absolute. Sphere evacuation and pre-chamber pressurization permitted the pressure inside the sphere at ignition to be approximately 1.0 bar absolute. Fourth, the exit valve between the sphere and dust pre-chamber opened and dust was forced through the dispersion horns and dispersed. Finally, the igniters were ignited while the dust was in suspension. The TZV setting on the KSEP 210 control unit controlled the time between the opening of the exit valve and ignition of the

igniters. Two pressure transducers recorded the explosion on a Nicolet Model 216 digital oscilloscope. After each explosion the dispersion horns were removed and cleaned, and the inside of the sphere was cleaned.

## REFERENCES

- American Association of Cereal Chemists. 1976. Approved Method of the AACC. Methods 08-01, approved April 1961, 44-01, approved Oct. 1975. The Association: St. Paul, Mn.
- Bartknecht, W. 1981. Explosions: Course Prevention Protection, Srpinger-Verlag, Berlin Heidelberg, New York. Translated from German by H. Burg and T. Almond.
- Dorsett, H. G., Jr., Jacobson, M., Nagy, J., and Williams, R. P. 1960. Laboratory equipment and test procedures for evaluating explosibility of dusts. U.S. Department of the Interior, Bureau of Mines, Report of Investigations, RI-5624.
- Grain Elevators and Feed Mills. 1980. Project officer's review draft. November.
- High Accuracy Products Corporation. 1972. Operation and Service Manual for HIAC Model SSTA.
- Kühner, Adolf. 1979. Users guide for the 20-liter laboratory explosion testing apparatus. Translated from German by P. Pomeranz.
- Martin, C. R. 1982. Personal communication.
- Young, D. M., and Crowell, A. D. 1962. Physical adsorption of gases. Butterworth and Co. Ltd. London, England.

## CHAPTER 4

## RESULTS AND DISCUSSION

In this chapter the experimental results are presented and analyzed. The results include the dust characteristics, the values of the maximum rates of pressure rise and the maximum pressures, the  $K_{ST}$ -values, and the total and external specific surface area. The effect of the dispersion method on the grain dust is discussed and, eventually, the statistical correlations are derived and compared to the experimental data. Furthermore, the experimental values of the peak maximum rate and peak maximum pressure and the  $K_{ST}$ -values are compared to the results obtained by other researchers.

## I. Dust Characteristics

The characteristics of dust samples are presented in Tables 4.1 through 4.6 by dust type. The dust sample codes used in these tables are explained in Table 3.1. These characteristics are parameters that may be used in predicting the explosibility parameters, i.e., the maximum rate of pressure rise and maximum pressure. Corn dust samples have the lowest ash content with an average value of 3.2% (Table 4.2) and soybean dust samples have the highest ash content with an average value of 40.7% (Table 4.5). The combination, milo, oats, and wheat dust samples have average values of 12.6, 16.4, 9.3, and 12.0%, respectively. A large deviation exists in the ash contents among the samples of each dust type. Cornstarch, 0.05%, and wheat flour, 0.41%, have the lowest ash contents, as expected, since they are processed dusts. The ash content is a measure of the portion of a dust sample that will not burn. Thus, the explosibility parameters may decrease as the ash content increases.

Table 4.1. Characteristics of Combination Dust.

| Dust Sample | Percent ash | Percent moisture | $-\Delta H_c$<br>$\frac{\text{cal}}{\text{gram}}$ | Specific surface area<br>$\frac{\text{m}^2}{\text{gram}}$ | Average particle size, $d$ ,<br>$\mu$ |
|-------------|-------------|------------------|---------------------------------------------------|-----------------------------------------------------------|---------------------------------------|
| CB12        | 25.31       | 9.1              | 3119                                              | 0.76                                                      | 20.3                                  |
| CB12c       | 5.55        | 15.0             | 3663                                              | 0.58                                                      | 18.4                                  |
| CB13        | 6.97        | 12.1             | 2412                                              | 1.26                                                      | 16.2                                  |

Table 4.2. Characteristics of Corn Dust.

| Dust Sample | Percent ash | Percent moisture | $-\Delta H_c$<br>$\frac{\text{cal}}{\text{gram}}$ | Specific surface area<br>$\frac{\text{m}^2}{\text{gram}}$ | Average particle size, $d$ ,<br>$\mu$ |
|-------------|-------------|------------------|---------------------------------------------------|-----------------------------------------------------------|---------------------------------------|
| CN21        | 2.33        | 12.0             | 3752                                              | 0.60                                                      | 21.4                                  |
| CN22b       | 3.55        | 11.9             | 3791                                              | 0.60                                                      | 18.4                                  |
| CN23        | 6.69        | 11.9             | 3888                                              | 0.68                                                      | 20.4                                  |
| Cornstarch  | 0.05        | 12.4             | 3624                                              | 0.61                                                      | 18.4                                  |

Table 4.3. Characteristics of Milo Dust.

| Dust Sample | Percent ash | Percent moisture | $\frac{-\Delta H_c}{\text{cal}} \frac{\text{gram}}{\text{gram}}$ | Specific surface area $\frac{\text{m}^2}{\text{gram}}$ | Average particle size, d, $\mu$ |
|-------------|-------------|------------------|------------------------------------------------------------------|--------------------------------------------------------|---------------------------------|
| M011        | 21.55       | 9.2              | 3477                                                             | 1.24                                                   | 19.7                            |
| M012        | 16.81       | 10.9             | 3658                                                             | 1.18                                                   | 24.5                            |
| M013        | 18.27       | 11.4             | 3446                                                             | 0.92                                                   | 21.9                            |
| M020        | 17.13       | 8.0              | 3756                                                             | 1.32                                                   | 23.6                            |
| M032b       | 17.70       | 10.1             | 3543                                                             | 0.73                                                   | 20.6                            |
| M032c       | 7.02        | 7.5              | 4435                                                             | 0.65                                                   | 18.1                            |

Table 4.4. Characteristics of Oats Dust.

| Dust Sample | Percent ash | Percent moisture | $\frac{-\Delta H_c}{\text{cal}} \frac{\text{gram}}{\text{gram}}$ | Specific surface area $\frac{\text{m}^2}{\text{gram}}$ | Average particle size, d, $\mu$ |
|-------------|-------------|------------------|------------------------------------------------------------------|--------------------------------------------------------|---------------------------------|
| OT12        | 3.08        | 8.9              | 4185                                                             | 0.85                                                   | 29.3                            |
| OT12c       | 18.50       | 9.9              | 3683                                                             | -----                                                  | 15.5                            |
| OT13        | 6.35        | 9.9              | 3791                                                             | 1.40                                                   | 14.2                            |

Table 4.5. Characteristics of Soybean Dust.

| Dust<br>Sample | Percent<br>ash | Percent<br>moisture | $-\Delta H_c$<br>$\frac{\text{cal}}{\text{gram}}$ | Specific<br>surface area<br>$\frac{\text{m}^2}{\text{gram}}$ | Average particle<br>size, $d$ ,<br>$\mu$ |
|----------------|----------------|---------------------|---------------------------------------------------|--------------------------------------------------------------|------------------------------------------|
| SB11           | 47.18          | 6.9                 | 2295                                              | 16.71                                                        | 16.1                                     |
| SB12a          | 44.55          | 7.0                 | 2419                                              | 13.35                                                        | 23.3                                     |
| SB13           | 14.06          | 6.7                 | 5006                                              | 1.24                                                         | 24.0                                     |
| SB21           | 41.29          | 7.1                 | 2606                                              | 1.14                                                         | 20.2                                     |
| SB22a          | 59.07          | 5.5                 | 1787                                              | 7.78                                                         | 19.4                                     |
| SB22b          | 43.50          | 6.9                 | 2647                                              | 0.53                                                         | 21.7                                     |
| SB23           | 35.42          | 8.7                 | 2867                                              | 11.84                                                        | 16.3                                     |

Table 4.6. Characteristics of Wheat Dust.

| Dust Sample | Percent ash | Percent moisture | $-\Delta H_c$<br>$\frac{\text{cal}}{\text{gram}}$ | Specific surface area<br>$\frac{\text{m}^2}{\text{gram}}$ | Average particle size, $d$ ,<br>$\mu$ |
|-------------|-------------|------------------|---------------------------------------------------|-----------------------------------------------------------|---------------------------------------|
| WT11        | 18.30       | 8.7              | 3481                                              | 1.03                                                      | 36.9                                  |
| WT12a       | 13.47       | 7.9              | 3433                                              | 1.00                                                      | 24.6                                  |
| WT12b       | 11.07       | 9.7              | 3714                                              | 0.86                                                      | 22.4                                  |
| WT21        | 11.75       | 10.3             | 3747                                              | 1.53                                                      | 24.5                                  |
| WT22a       | 20.56       | 13.6             | 3323                                              | 0.56                                                      | 35.3                                  |
| WT23        | 8.31        | 9.9              | 3936                                              | 0.92                                                      | 30.0                                  |
| Wheat Flour | 0.41        | 12.1             | 3868                                              | 0.52                                                      | 24.5                                  |



The moisture content of the dust samples does not vary as much as the ash content. The average moisture content of combination, corn, milo, oats, soybean, and wheat dust samples are 12.1, 12.1, 9.5, 9.6, 7.0, and 10.3%, respectively. Corn dust is one of the dust types with the highest moisture content. Soybean dust has the lowest moisture content. This is in contrast to the relationship between the ash content of corn dust and that of soybean dust. Consequently, the ash and moisture contents of a dust sample may be inversely related. The higher the moisture content of a sample the greater the quantity of the sample that can not burn; therefore, the explosibility parameters may decrease as the moisture content increases.

The values of the standard heat of combustion range from -1787 cal/g for SB22a to -5006 cal/g for SB13. The average absolute values for the dust types are 2804, 3064, 3643, 3719, 3764, and 3886 cal/g for soybean, combination, wheat, milo, corn, and oats dust, respectively. Soybean dust has the lowest value and corn dust has one of the highest values. These two dust types are also the types with the extreme moisture and ash content.

The order of the seven soybean dust samples ranked according to the decreasing value of their ash content is SB22a, SB11, SB12a, SB22b, SB21, SB23, and SB13. The order of the soybean dust samples ranked according to the increasing absolute value of the heat of combustion is SB22a, SB11, SB12a, SB21, SB22b, SB23, and SB13. Except for the fourth and fifth positions, the dust samples are in the same order in both rankings. Hence, the heat of combustion and the ash and moisture content may be related. Since the heat of combustion denotes the quantity of energy released during the oxidation or burning process, the explosibility parameters should tend to increase with an increase in the absolute value of the heat of combustion.

Excluding four soybean dust samples, the specific surface areas for the other dust samples are between 0.52 and 1.53 m<sup>2</sup>/g. The average values for the different dust types are 0.62, 0.87, 0.92, 0.97, 1.01, and 1.13 m<sup>2</sup>/g for corn, combination, wheat, soybean, milo, and oats, respectively. Corn dust has the lowest average value and oats dust has the highest average value. SB11, SB12a, SB22a, and SB23 have values of 16.1, 13.35, 7.78, and 11.84 m<sup>2</sup>/g, respectively. No trend in the characteristic data accounts for these large values. The specific surface area is an indication of the surface area available for formation of a fluid-solid reaction zone during the combustion reaction. Hence, the larger the surface area the faster the reaction may proceed, resulting in increased magnitudes of the explosibility parameters.

The average particle sizes in Tables 4.1 through 4.6 are the values obtained for dispersed dust. Dispersed dust is the dust that is collected inside the 20-liter explosion sphere after the loaded dust is dispersed and is the dust that creates the dust cloud. The range of the average particle sizes is from 14.2 - 36.9  $\mu$  for all the dust samples. The average diameters for combination, corn, milo, oats, soybean, and wheat dust samples are 18.3, 19.6, 21.4, 19.7, 20.1, and 28.3, respectively. The average particle size can be used to calculate the external specific surface area as shown in Appendix 3. The smaller the average diameter the greater the external surface area available for a reaction; therefore, the explosibility parameters should tend to increase with a decrease in the particle size.

## II. Maximum Rate of Pressure Rise and Maximum Pressure

All the plots of the maximum rate of pressure rise versus the dust loading can be divided into four categories by the number of peaks that

are on the plots. Loaded dust is the dust that is loaded into the dust pre-chamber of the 20-liter explosion sphere. These categories are no peak, one peak, two peaks, and the onset of a possible succeeding peak. Figures 4.1 through 4.4 illustrate, respectively, these shapes. On each plot the observed experimental values of the maximum rate at each loading, the average value of the maximum rate at each loading, and the peak maximum rate which occurred at the optimum TZV setting and optimum loading, are plotted. On the plots the average maximum rates are joined by a straight line. For all the dust samples except SB12a, the observed experimental values and the average values are obtained at a TZV setting equal to 60 ms. For SB12a the TZV setting equaled 90 ms.

OT13 is the only dust sample in category one. The explosion tests were discontinued before a peak was observed for OT13 because the supply of the dust sample was consumed. The dust samples in category two are CB12, CB12c, CN21, CN22b, cornstarch, MO12, MO32b, OT12, SB11, SB12a, SB21, SB22a, SB22b, WT12b, WT21, WT22a, and what flour. The dust samples in the third category are CB13, MO11, MO20, OT12c, SB23, WT12a, and WT23. CN23, MO13, MO32c, SB13, and WT11 are the dust samples in the fourth category. A complete list of the observed maximum rate values of the experimental explosion tests is in Appendix 1. In Appendix 2 the plots of the maximum rate versus the amount of loaded dust are presented for each dust sample.

The plots of the maximum pressure against the dust loading can be divided into five categories by the number of peaks on the plots. These categories are no peak, one peak, two peaks, one peak and the onset of a possible succeeding peak, and more than two peaks. Figures 4.5 through 4.9 illustrate, respectively, these shapes. The plots are similar to the type of plots in Figures 4.1 through 4.5, except that the

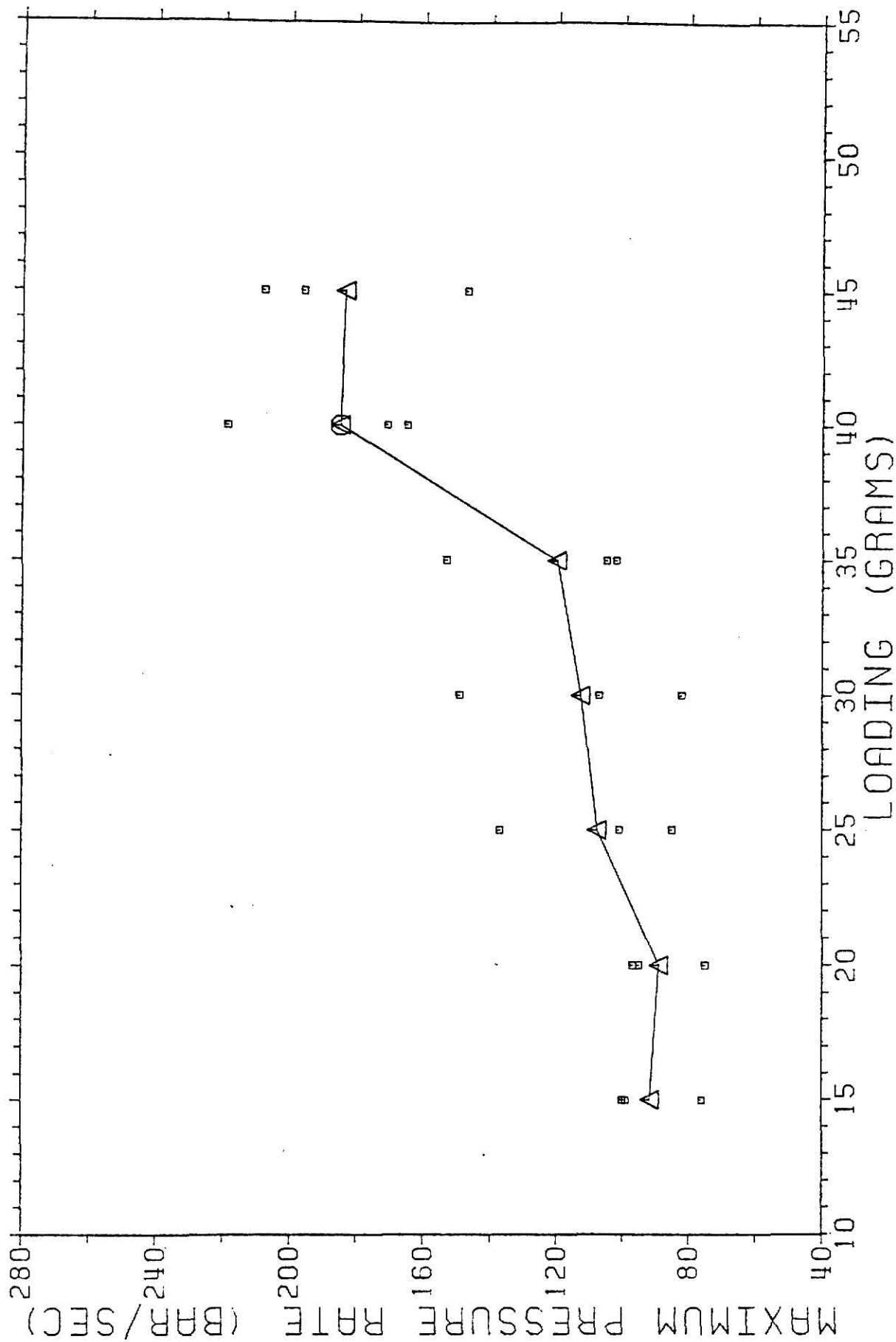


Figure 4.1. Effect of Dust Loading on Maximum Rate of Pressure Rise for OT13 (oats dust).  
 □ = observed value    Δ = mean value    ○ = peak value (average)

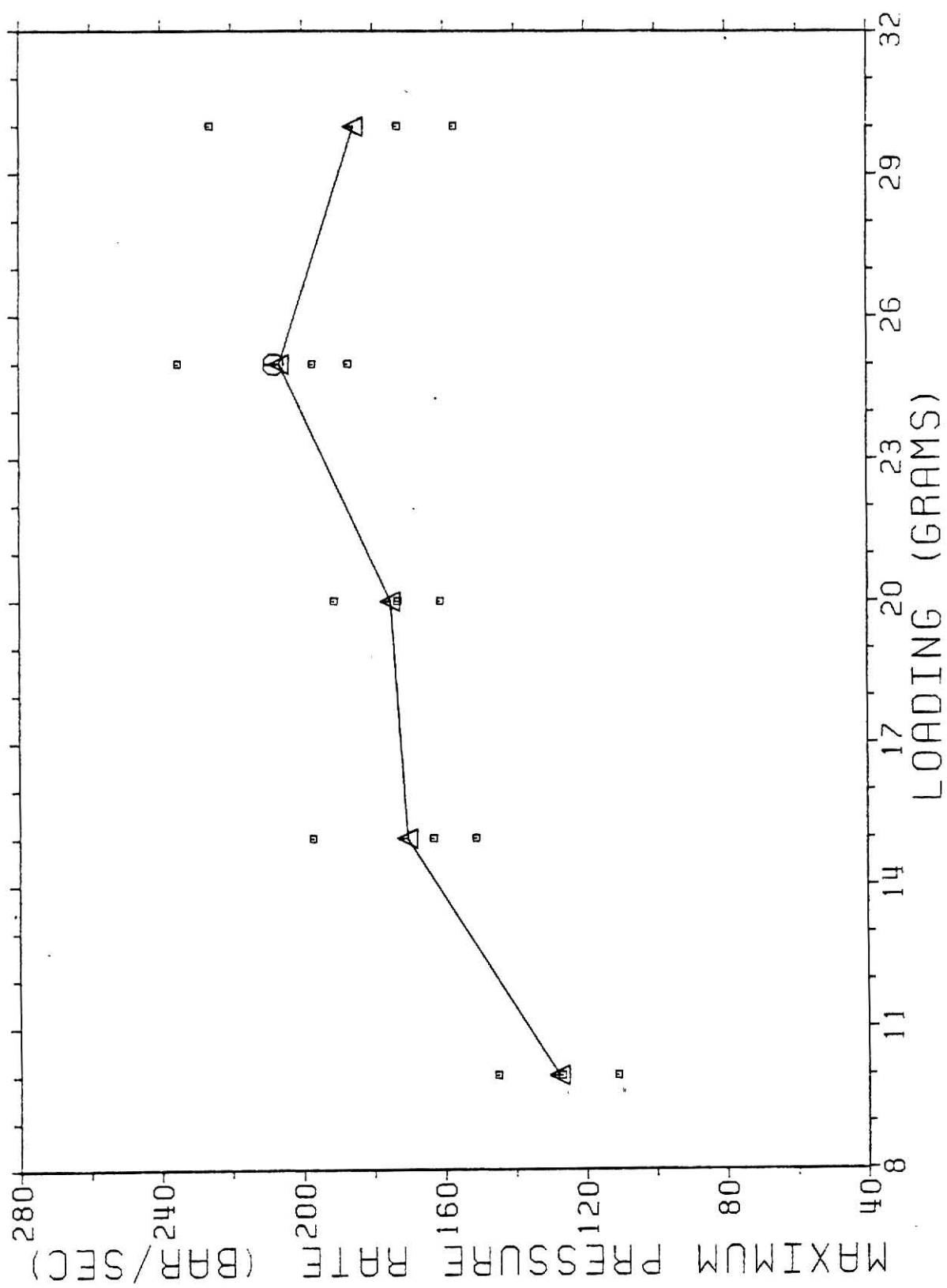


Figure 4.2. Effect of Dust Loading on Maximum Rate of Pressure Rise for Wheat Flour.  
 $\square$  = observed value     $\Delta$  = mean value     $\bigcirc$  = peak value (average)

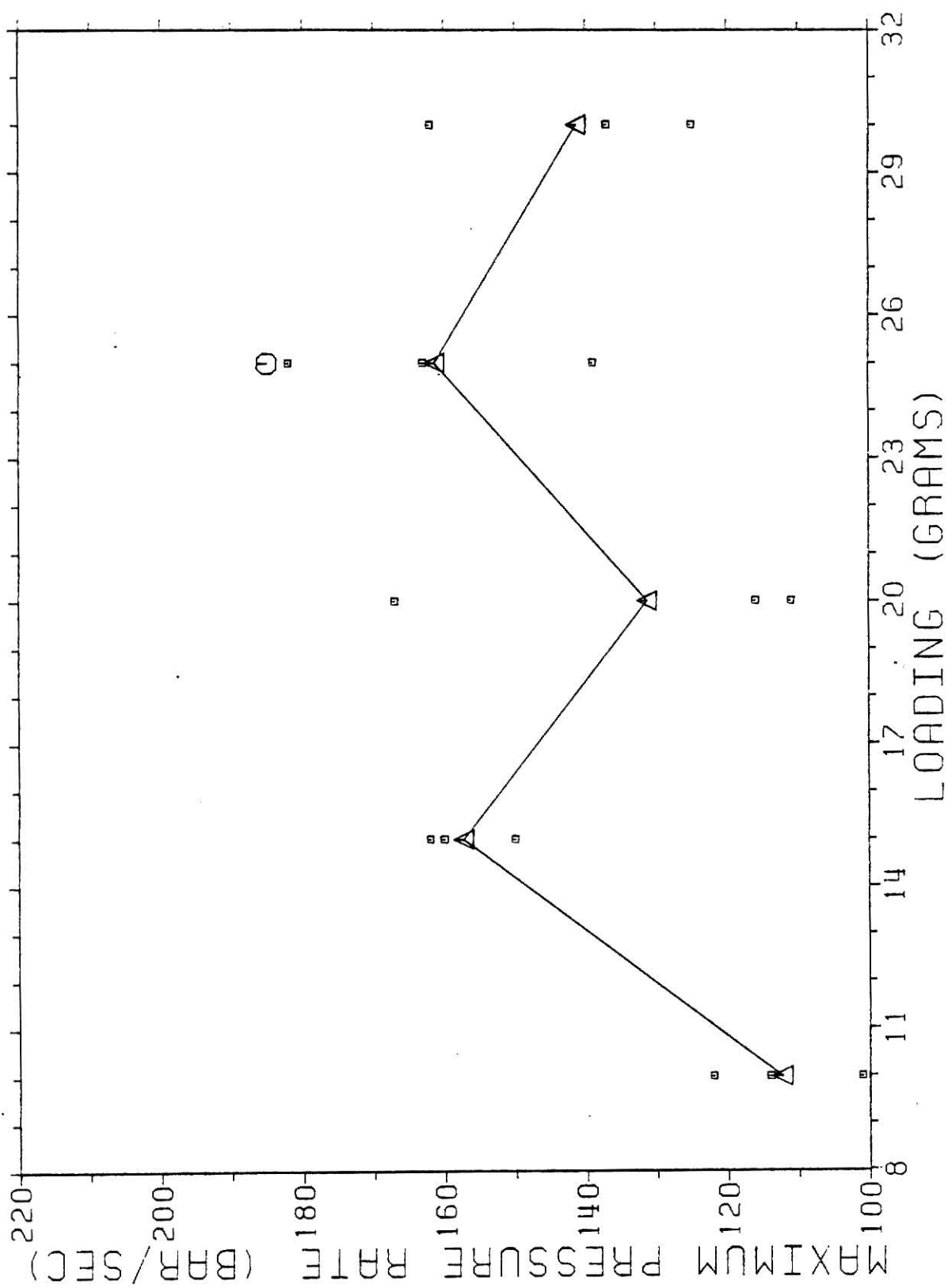


Figure 4.3. Effect of Dust Loading on Maximum Rate of Pressure Rise for M020 (milo dust).  
 □ = observed value    Δ = mean value    ○ = peak value (average)

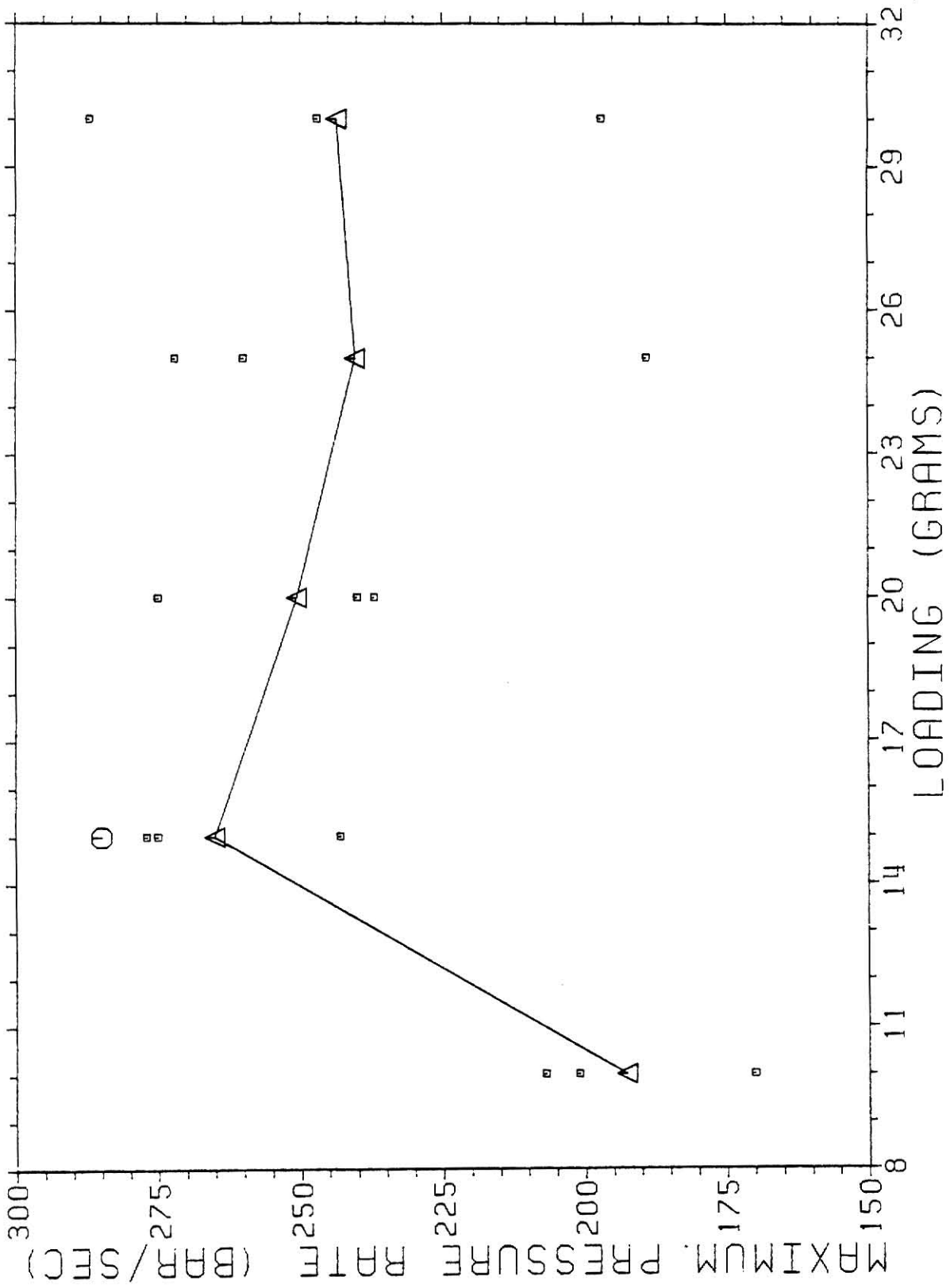


Figure 4.4. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB13 (soybean dust).  
 □ = observed value    △ = mean value    ○ = peak value (average)

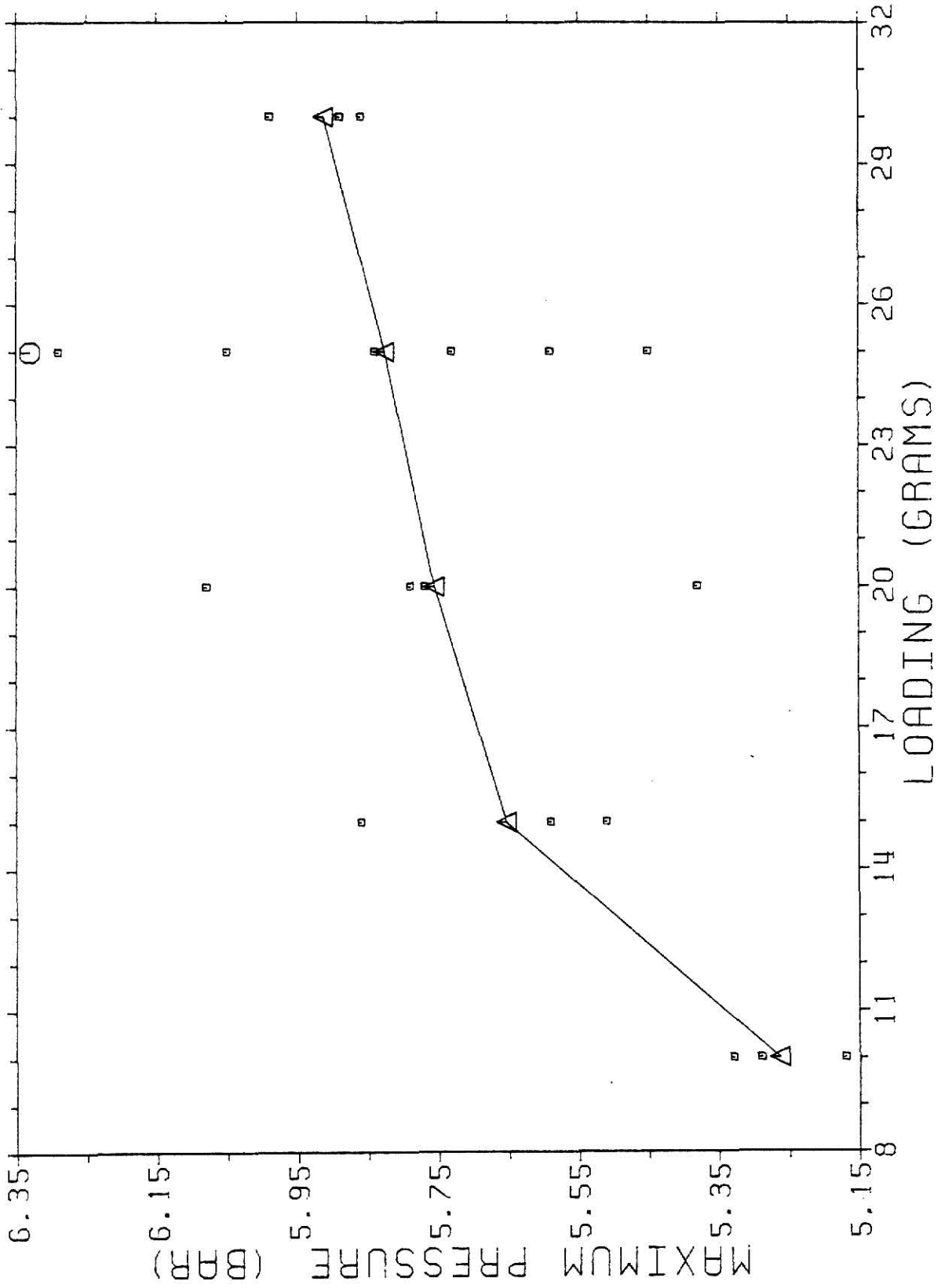


Figure 4.5. Effect of Dust Loading on Maximum Pressure for CBL3 (combination dust).  
 $\square$  = observed value     $\triangle$  = mean value     $\bigcirc$  = peak value (average)



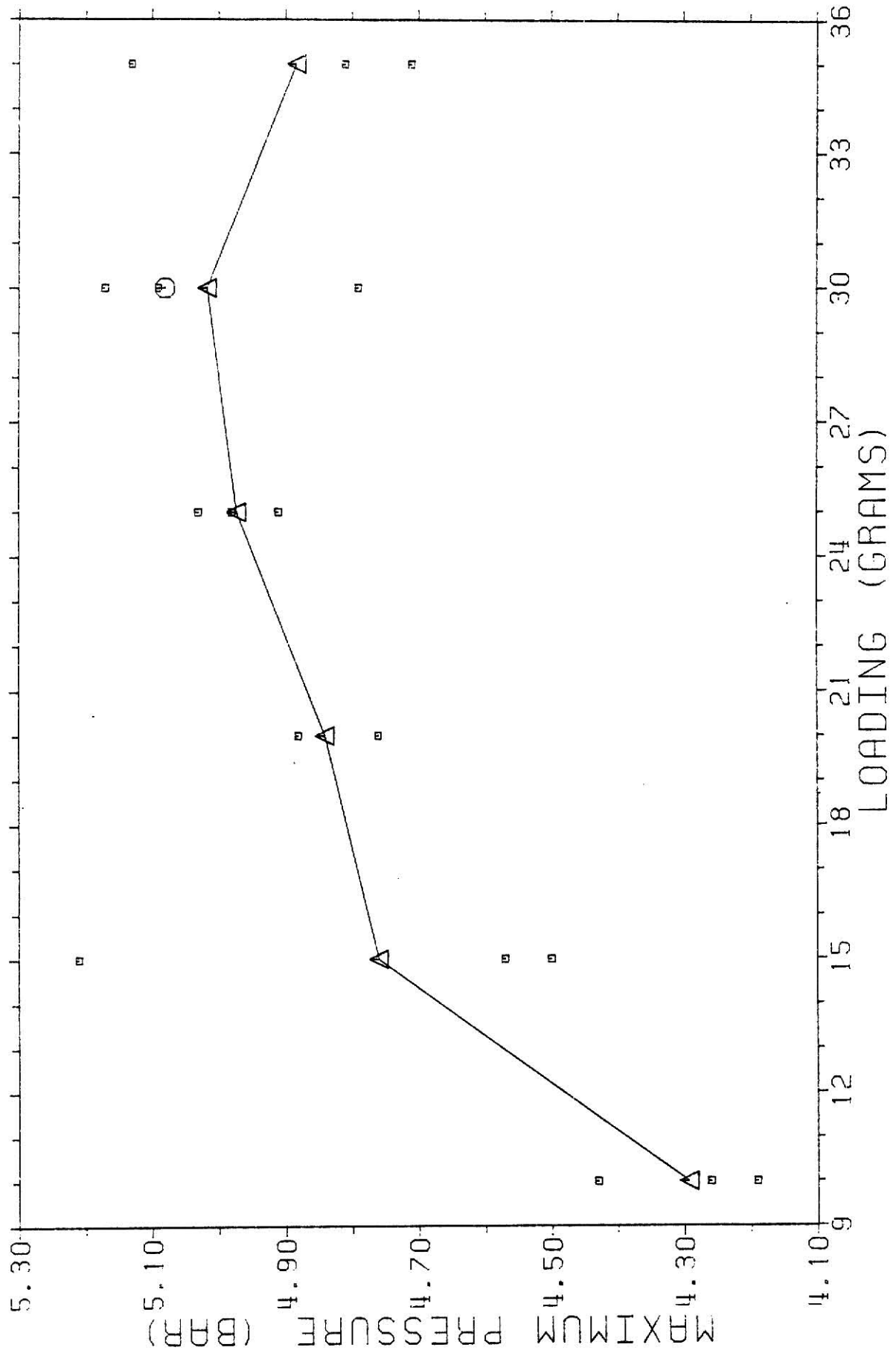


Figure 4.6. Effect of Dust Loading on Maximum Pressure for SB22b (soybean dust).  
 □ = observed value    △ = mean value    ○ = peak value (average)

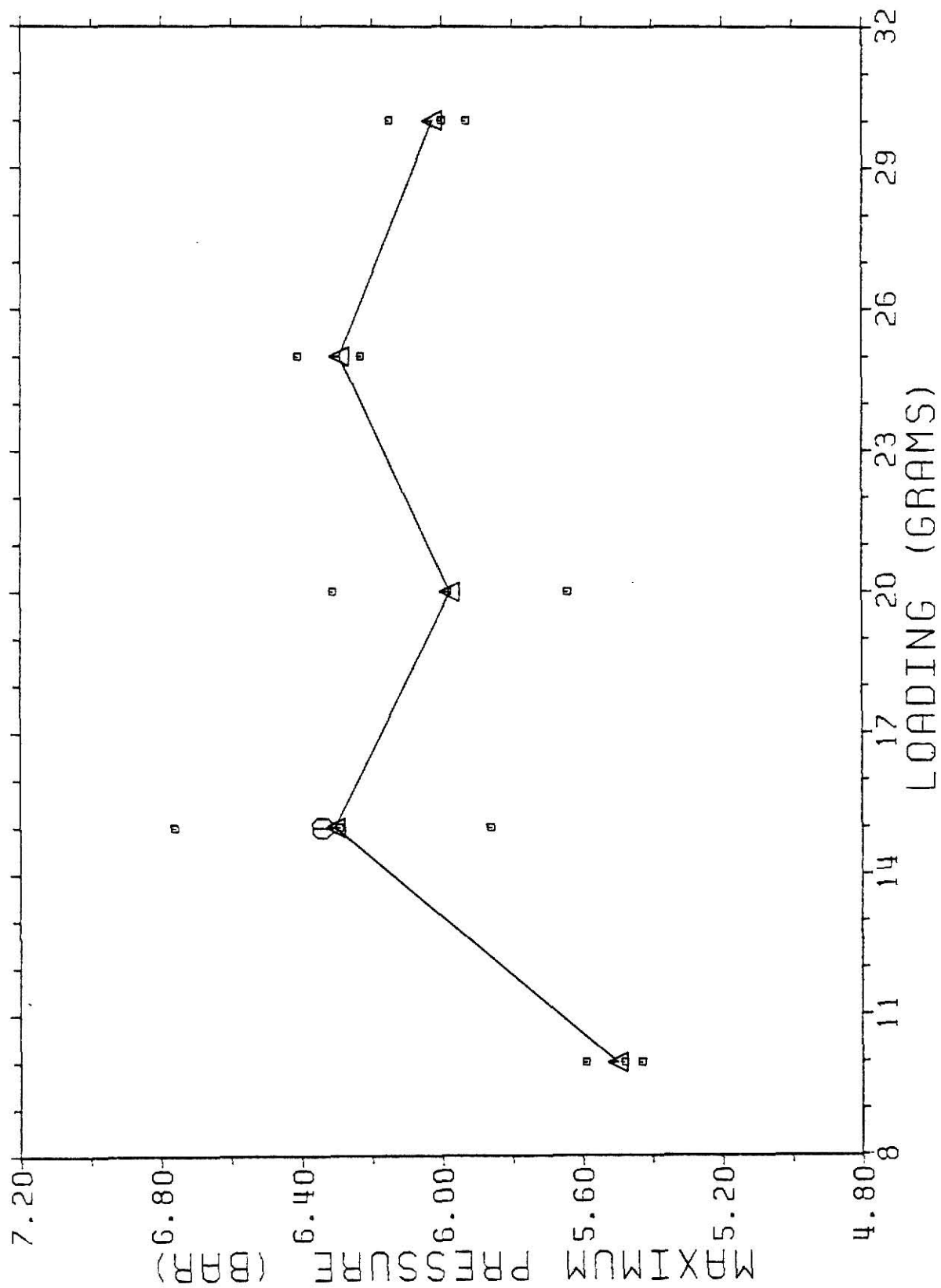


Figure 4.7. Effect of Dust Loading on Maximum Pressure for CB12c (combination dust).  
 □ = observed value    Δ = mean value    ○ = peak value (average)

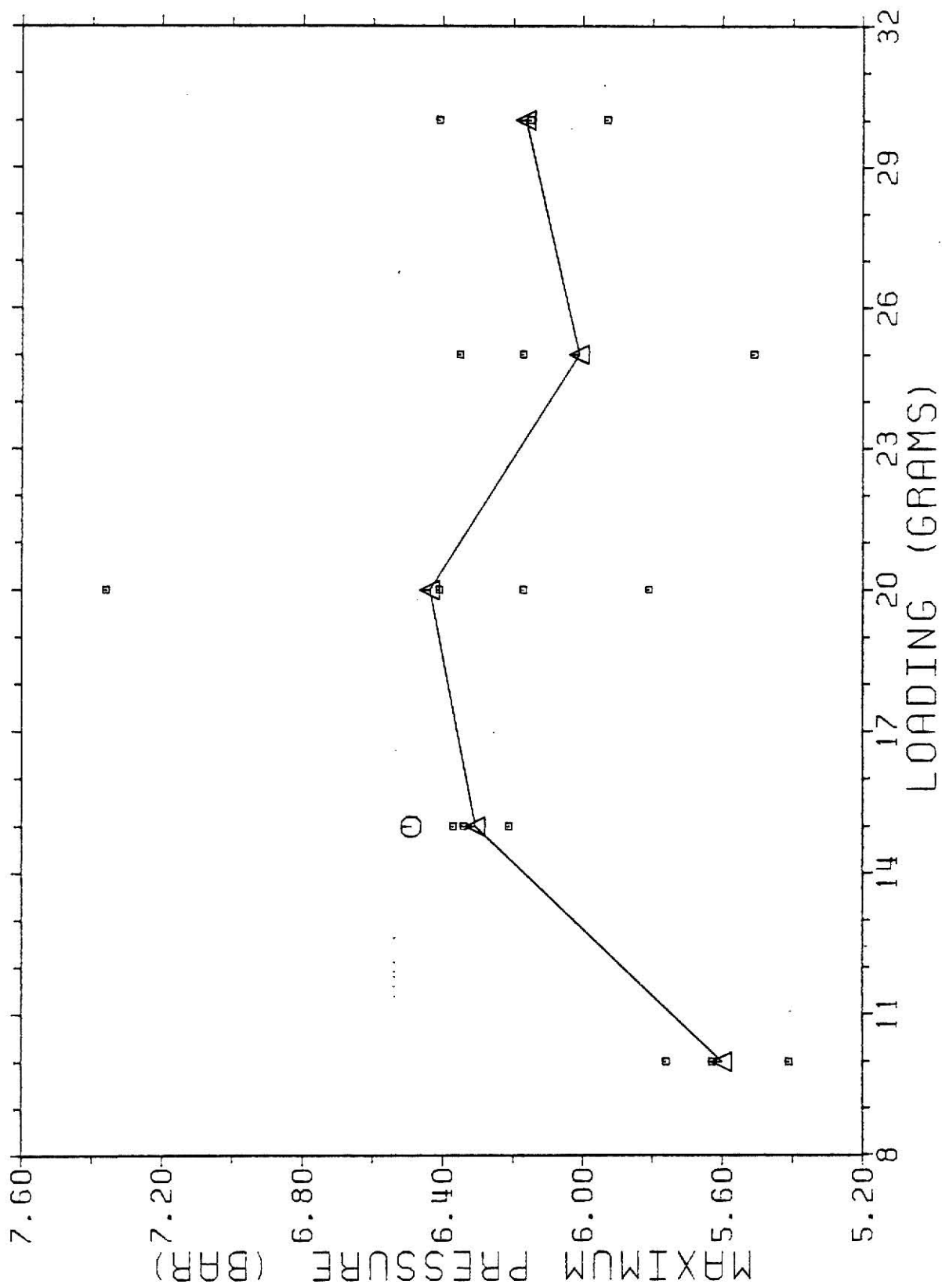


Figure 4.8. Effect of Dust Loading on Maximum Pressure for CN22b (corn dust).  
 □ = observed value    △ = mean value    ○ = peak value (average)

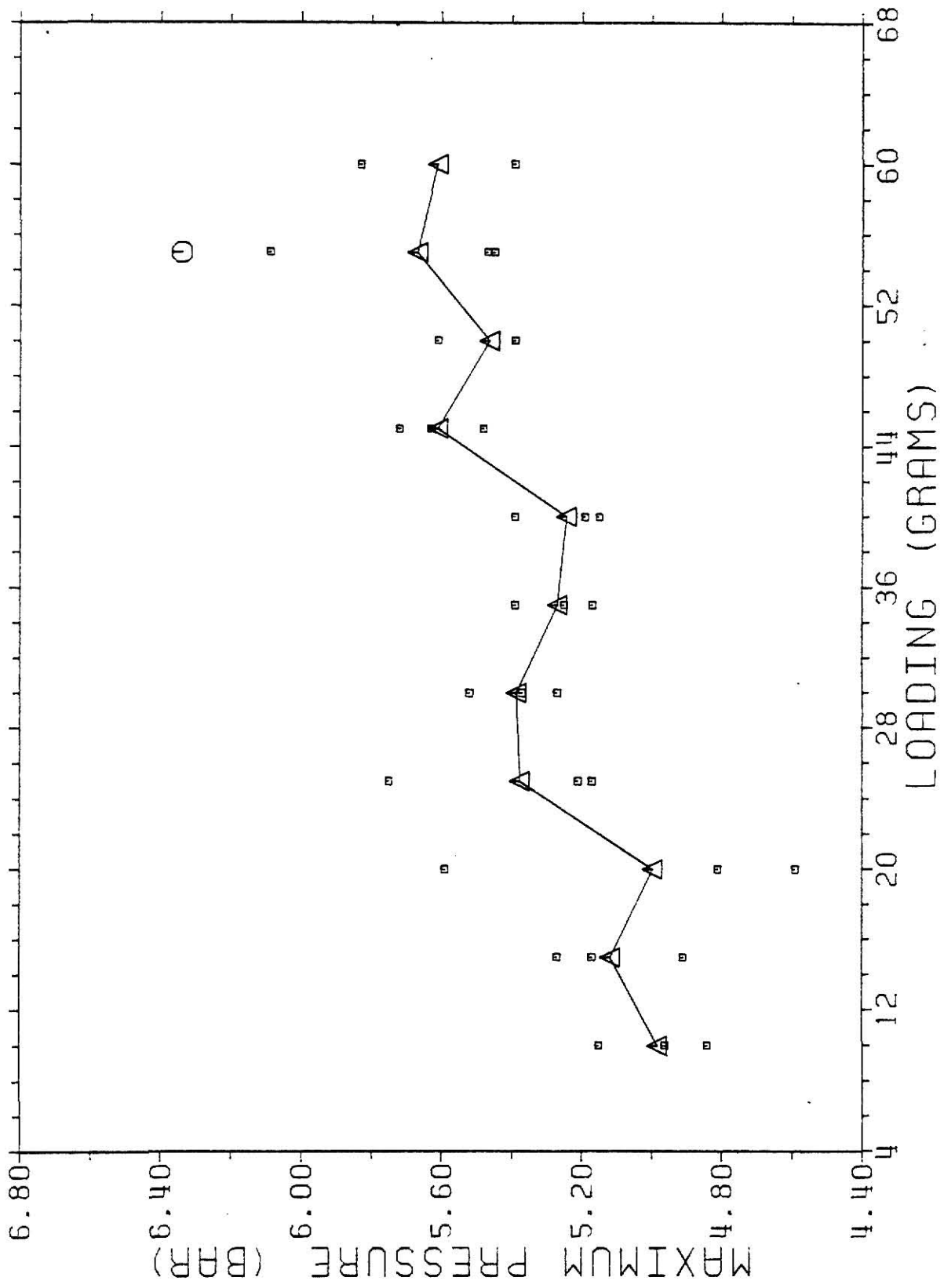


Figure 4.9. Effect of Dust Loading on Maximum Pressure for CB12 (combination dust).  
 □ = observed value    Δ = mean value    ○ = peak value (average)

maximum pressure replaces the maximum rate. In category one the shape of the line graph is the same shape as the line graph in category one of the maximum rate plots. Category two of the maximum pressure plots and the maximum rate plots have the same shape line graph. The same is true of categories three and four of the maximum pressure plots and the maximum rate plots. However, the corresponding categories do not contain the same dust samples.

CB13, OT12c, and OT13 are the only dust samples in category one. The experimental explosion tests were discontinued before a peak was observed because the supply of each dust sample was consumed. The dust samples in the second category are CN21, MO12, MO13, MO32b, SB11, SB12a, SB13, SB21, SB22a, SB22b, WT11, WT12a, and WT12b. CB12c, MO20, MO32c, OT12, and WT22a are the dust samples in the third category. The fourth category includes CN22b, CN23, cornstarch, MO11, SB23, WT21, WT23, and wheat flour. CB12 is the only dust sample in the fifth category. The observed maximum pressure values and maximum pressure plots are in Appendices 1 and 2.

A major problem encountered in studying grain dust explosions is the scatter of the experimental explosibility values as illustrated in Figures 4.1 through 4.9. Even though the experimental conditions, such as the loading and the TZV setting, are the same, the values obtained may be as much as 100 bar/sec different for the maximum rate and 1.0 bar different for the maximum pressure. This scatter makes analyzing the experimental results difficult.

Figures 4.10 through 4.15 present the maximum rate of pressure rise plotted against the dust loading by dust type. The plots allow all the samples of a dust type to be compared. On the plots the average maximum rates are joined by a straight line. For all the dust

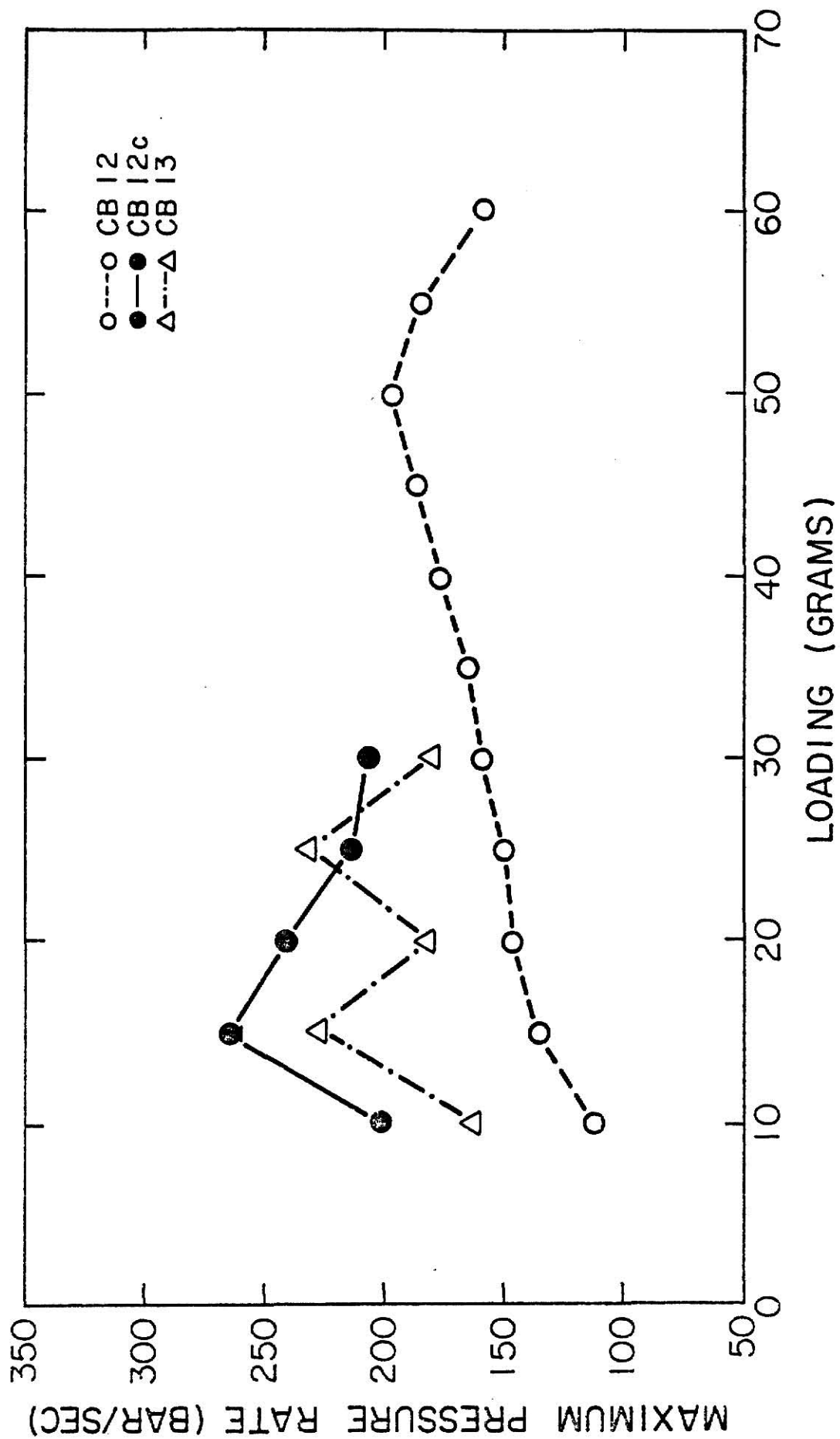


Figure 4.10. Effect of Dust Loading on Maximum Rate of Pressure Rise for Combination Dust Samples.

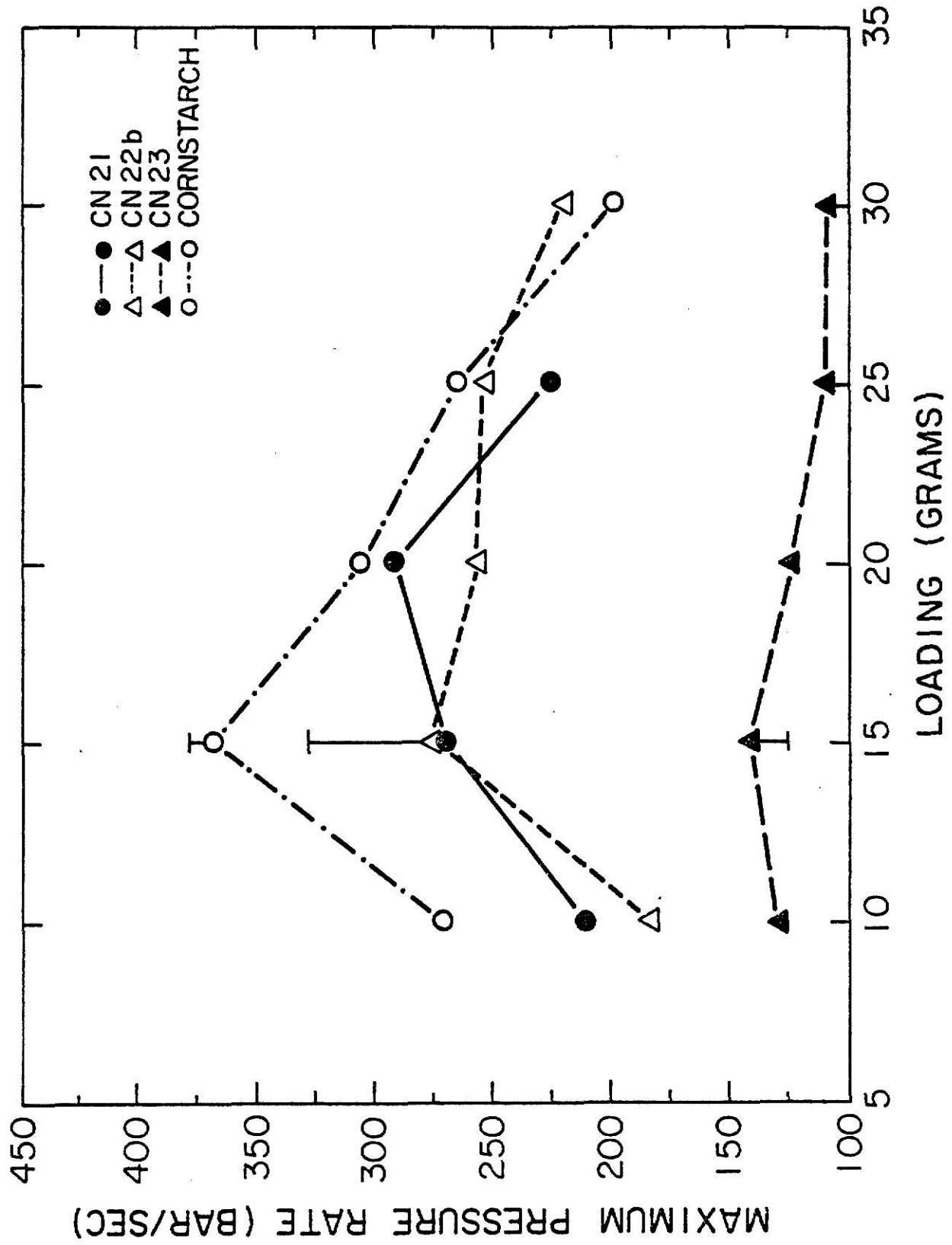


Figure 4.11. Effect of Dust Loading on Maximum Rate of Pressure Rise for Corn Dust Samples.

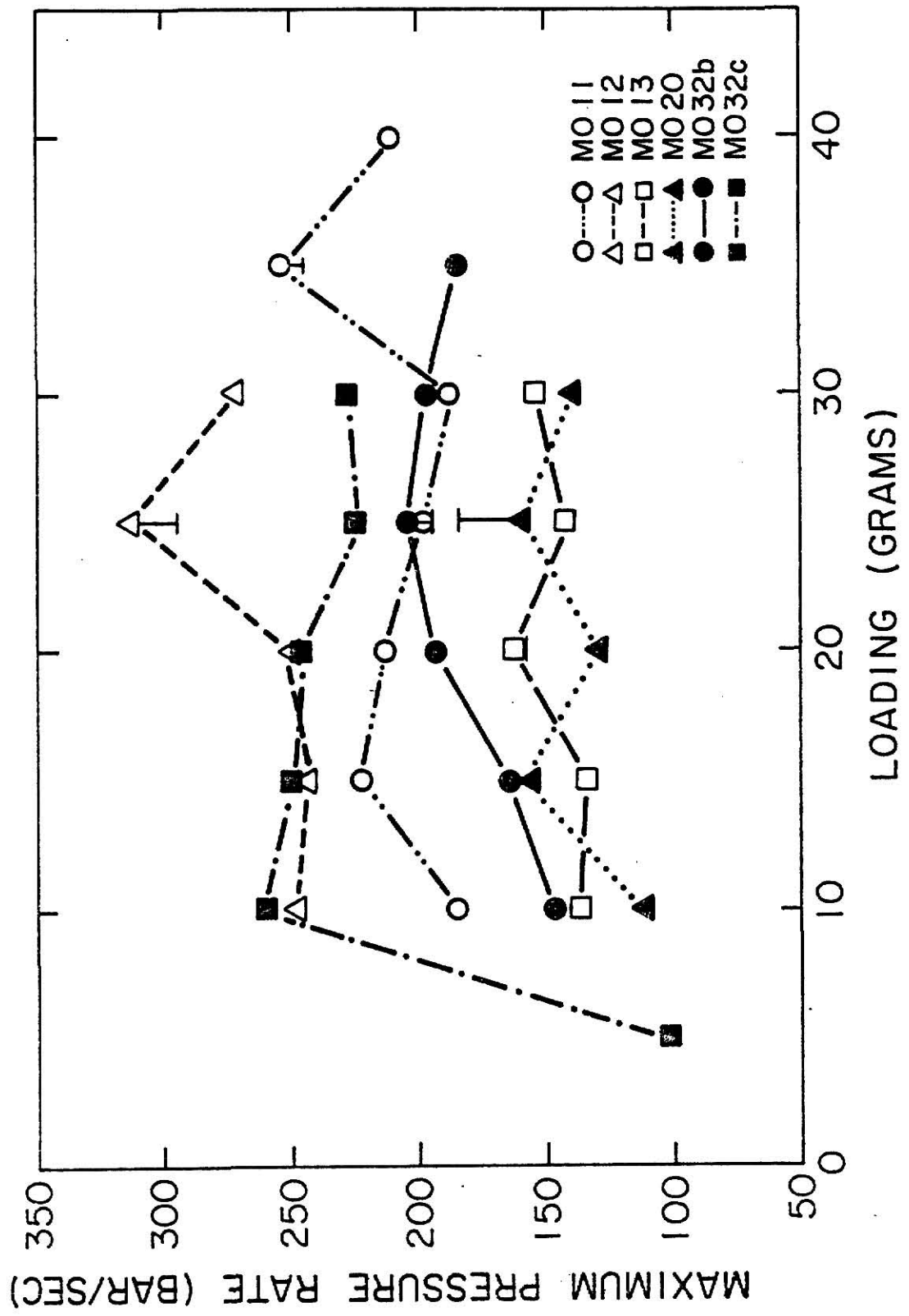


Figure 4.12. Effect of Dust Loading on Maximum Rate of Pressure Rise for Milo Dust Samples.



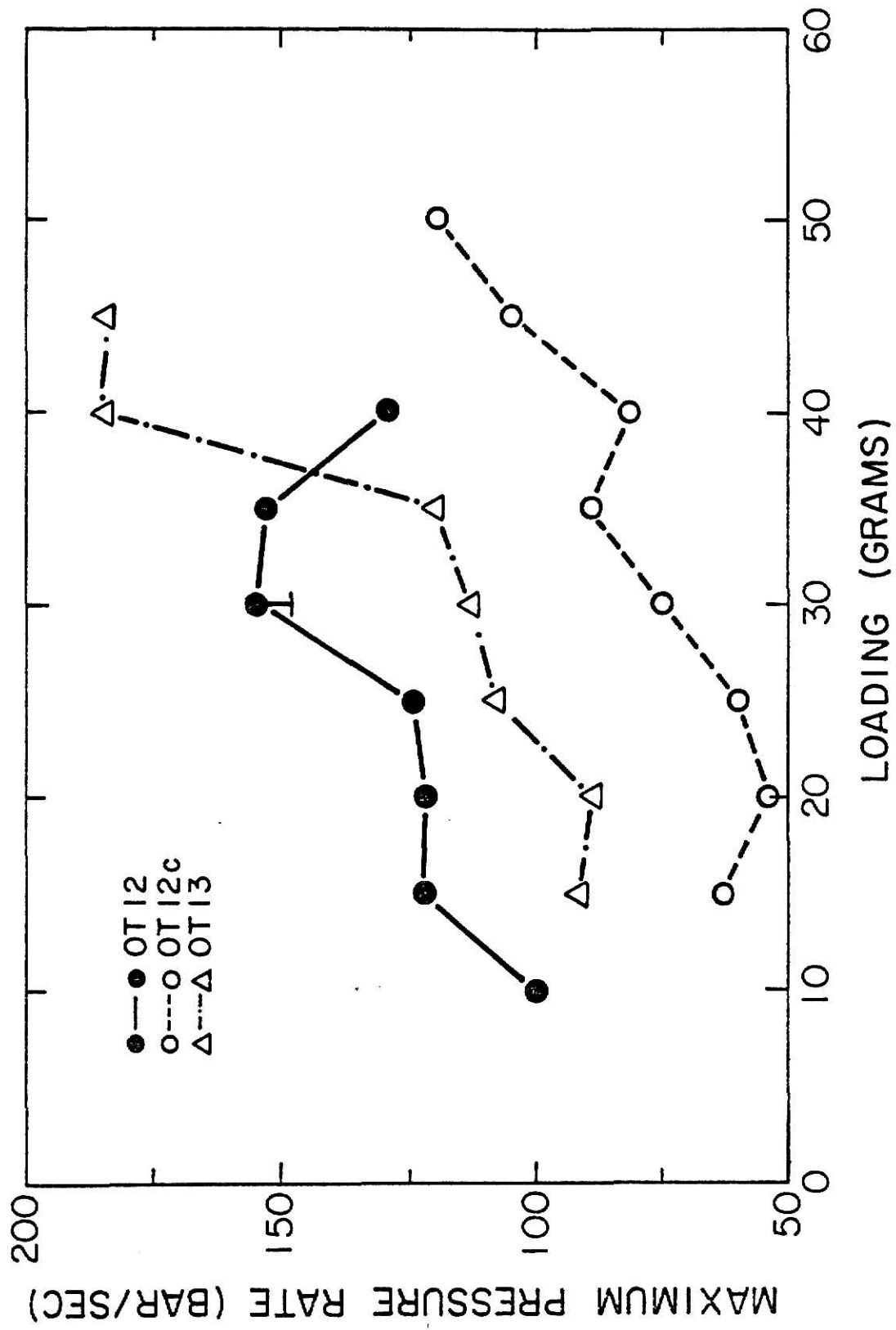


Figure 4.13. Effect of Dust Loading on Maximum Rate of Pressure Rise for Oats Dust Samples.

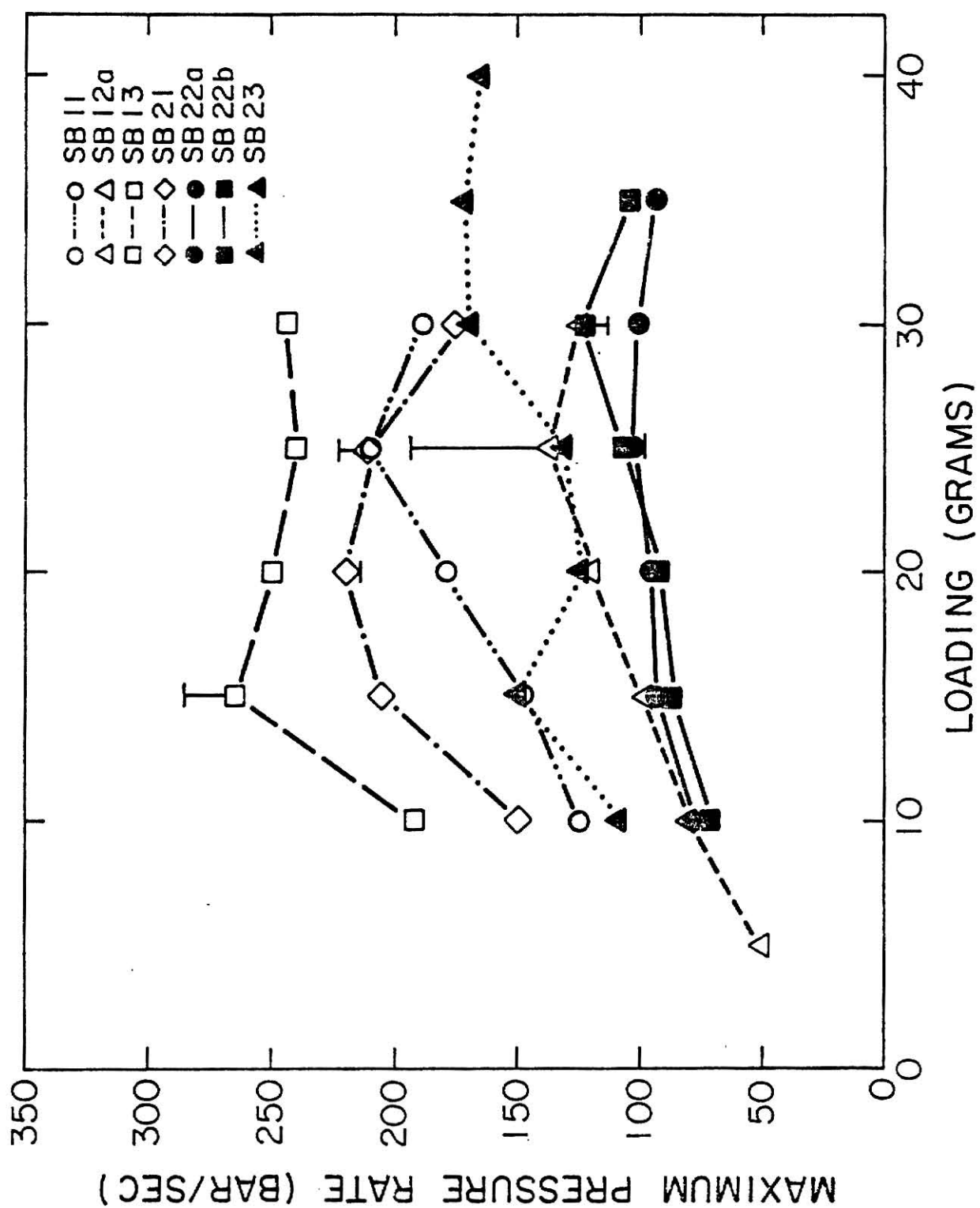


Figure 4.14. Effect of Dust Loading on Maximum Rate of Pressure Rise for Soybean Dust Samples.

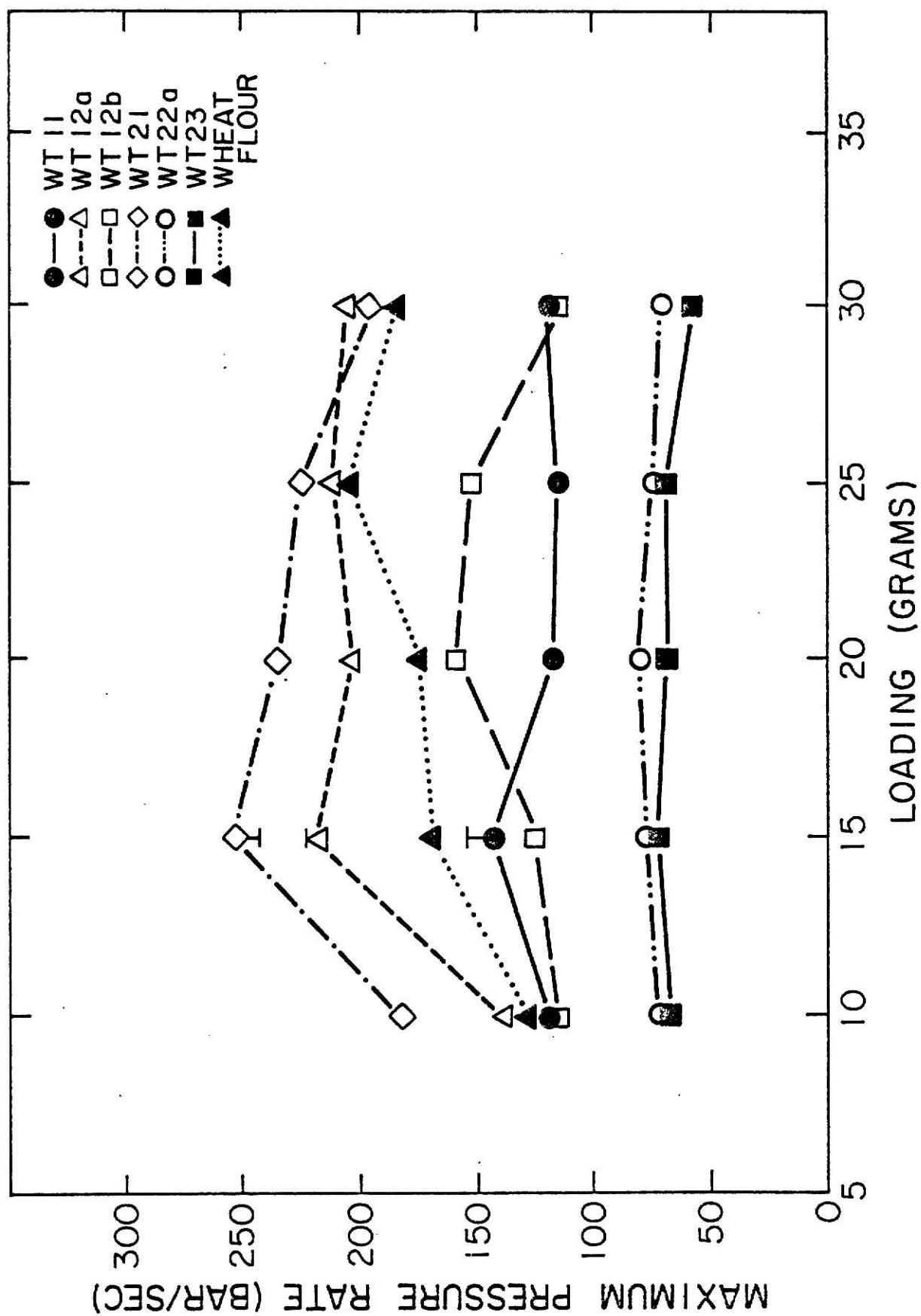


Figure 4.15. Effect of Dust Loading on Maximum Rate of Pressure Rise for Wheat Dust Samples.

samples except SB12a, the values of the average maximum rate were obtained at a TZV setting equal to 60 ms. For SB12a the TZV setting equaled 90 ms. If the peak maximum rate of a dust samples does not coincide with an average value, a line is drawn from the average value at the correct loading to the peak value. The individual plots are presented in Appendix 2.

For the combination dust samples presented in Figure 4.10, CB12c has the highest rates and CB12 has the lowest rates. CB12c has the lowest ash content and highest moisture content and CB12 has the highest ash content and lowest moisture content of all combination dust samples. The peak maximum rate of CB12 occurred at a loading of 50 grams; however, this is not an accurate indication of the quantity of dust in the dust cloud. At the heavy loadings of CB12 more than 75% of the length of the dispersion horns was packed with dust after the dispersion and explosion was completed.

In Figure 4.11, cornstarch has the highest rate of all the corn dust samples and CN23 has the lowest rate. The characteristics of corn dust presented in Table 4.2 show that cornstarch has the lowest ash content and absolute heat of combustion value and CN23 has the highest ash content and absolute heat of combustion value.

Of all the milo dust samples in Figure 4.12, M012 has the highest rate. Both M013 and M020 have the lowest rates, since they alternate increasing and decreasing between 100 and 175 bar/sec.

In Figure 4.13 OT12c has the lowest rate of the three dust samples. OT12 has the highest rate at loading less than 40 grams, but at 40 grams and greater, OT13 has the highest rate. The characteristics for oats dust presented in Table 4.4 show that OT12 has the lowest ash and moisture content and the highest absolute heat of combustion value and

OT12c has the highest ash and moisture content and the lowest absolute heat of combustion value. The experimental explosion tests were discontinued before a peak maximum rate was obtained for OT12c or OT13, since in each case the supply of dust was consumed. These dust samples were hard to disperse, making it impossible to get a large quantity of dust into the explosion chamber since most of the loaded dust became packed in the dispersion horns.

SB13 has the highest rate of all the soybean dust samples presented in Figure 4.14 and SB22a has the lowest rate. From Table 4.6, SB13 has the lowest ash content and the highest absolute heat of combustion value of all the soybean dust samples and SB22a has the highest ash content and the lowest absolute heat of combustion.

Figure 4.15 shows that WT21 has the highest rate and WT23 has the lowest rate of all the wheat dust samples. The two dust samples do not have opposite extreme values for any characteristics.

The combination, corn, oats, and soybean dust samples with the highest and lowest rates also have the highest and lowest values of either the ash content, moisture content, or heat of combustion. Thus, the heat of combustion, ash content, and moisture content appear to be characteristics important in determining the maximum rates. The average maximum rates range from 50 - 380 bar/sec for all dust samples. Oats dust samples have the lowest rates with a range of 50 - 190 bar/sec. Corn dust samples have the highest rates with a range of 100 - 380 bar/sec. The range of the oats dust samples includes the values for the two samples that were difficult to disperse. Since two out of three oats samples did not peak, this range may not be the range expected for all oats dust.

Figures 4.16 through 4.21 present the maximum pressure plotted against the dust loading for each dust type. With these plots all the

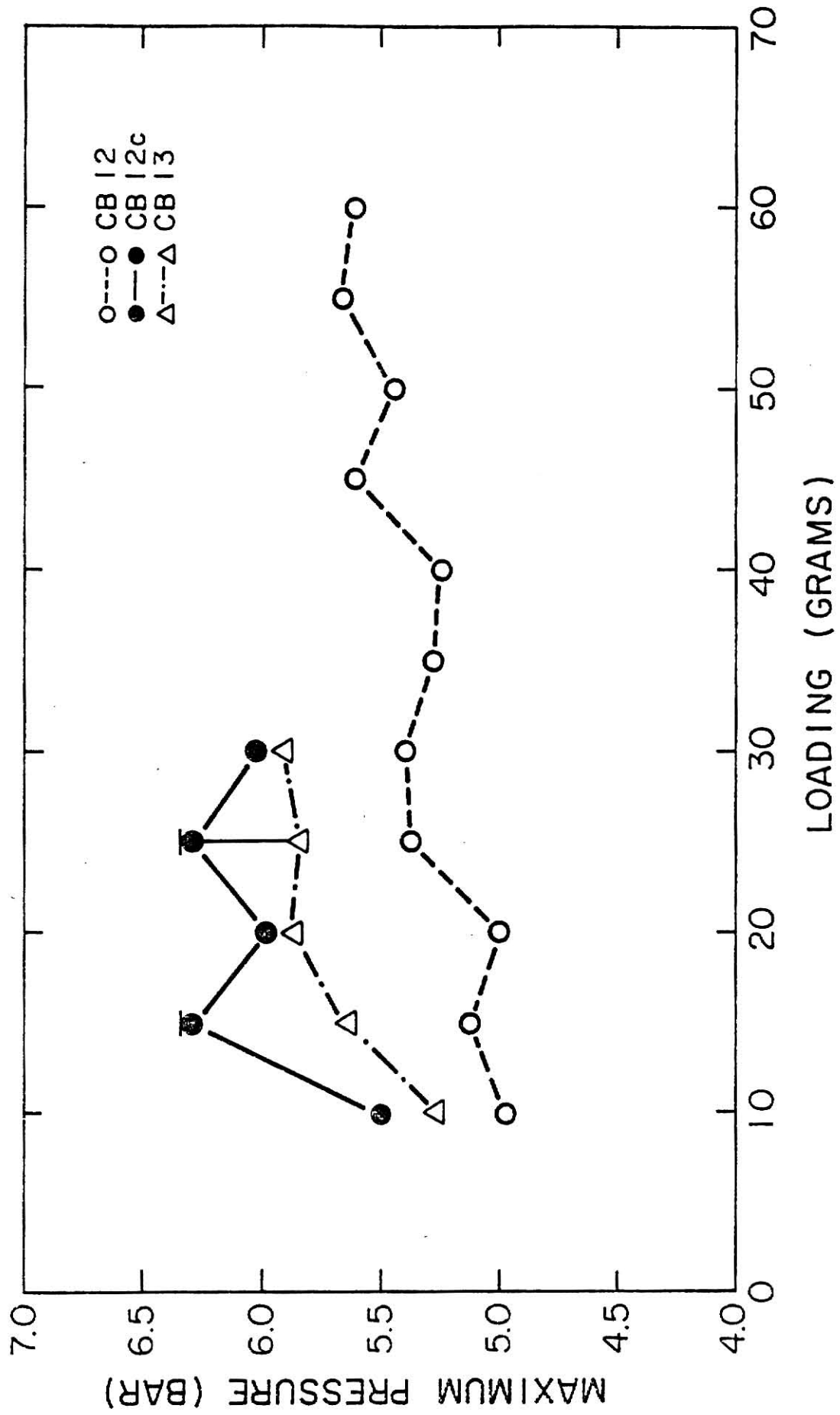


Figure 4.16. Effect of Dust Loading on Maximum Pressure for Combination Dust Samples.

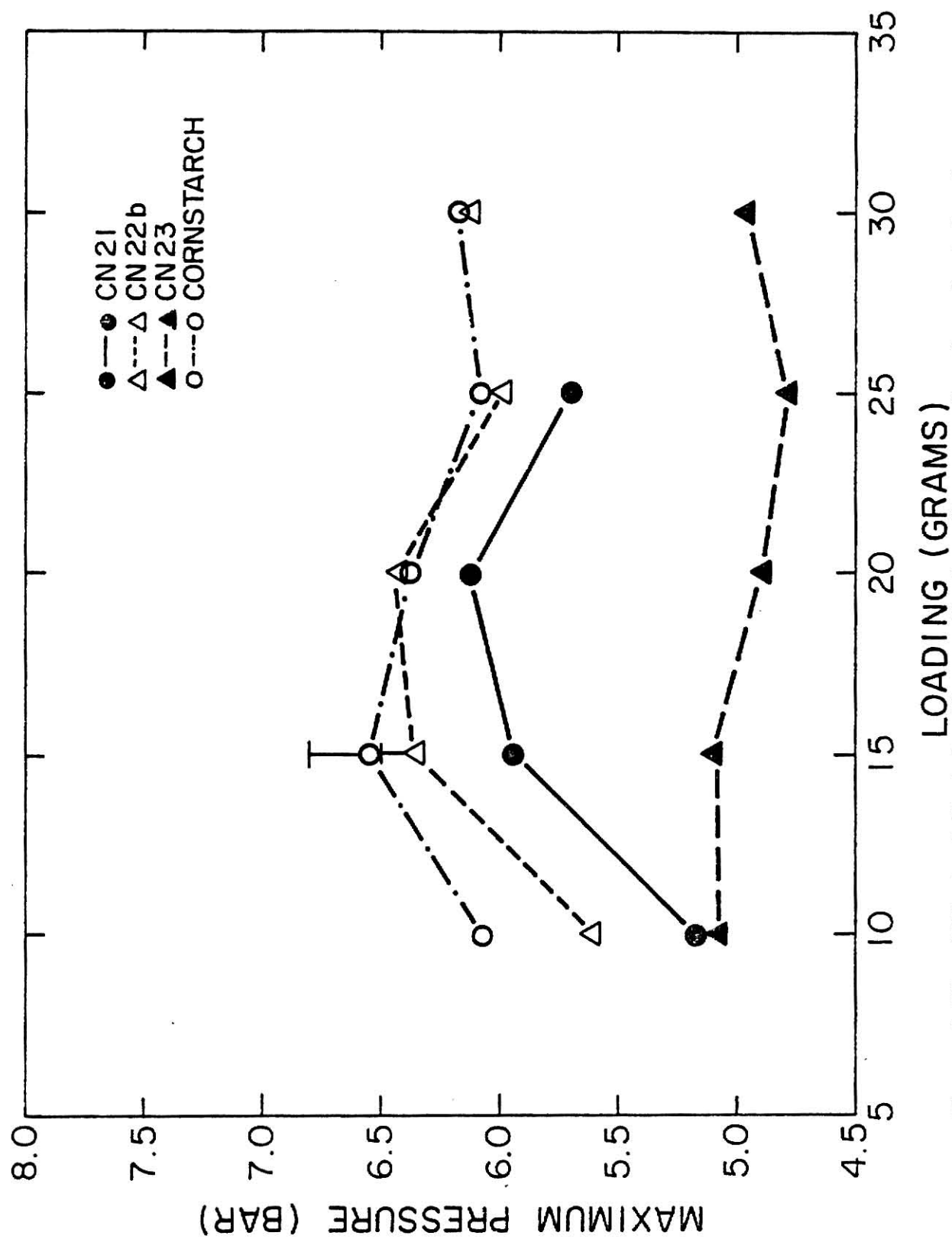


Figure 4.17. Effect of Dust Loading on Maximum Pressure for Corn Dust Samples.

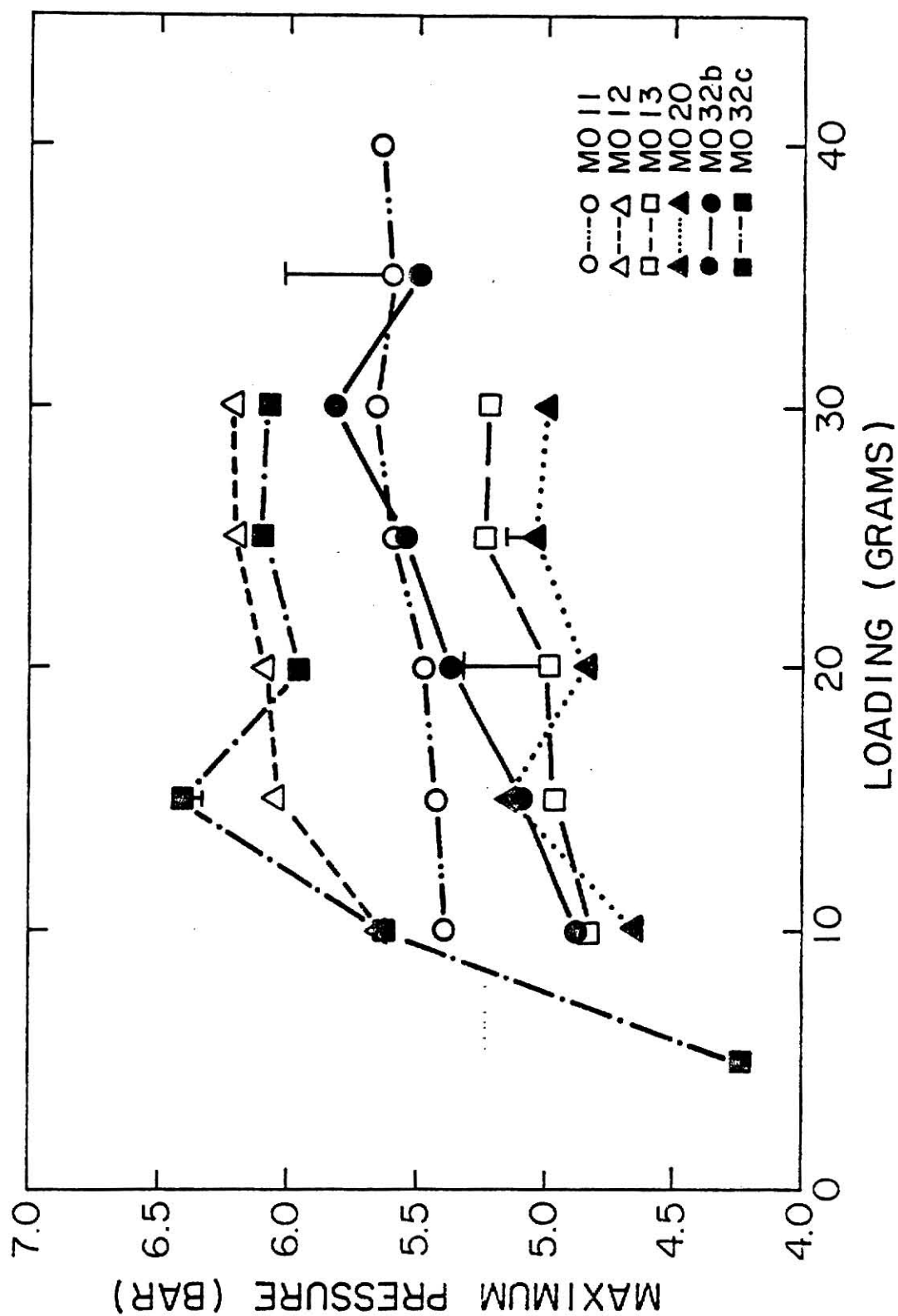


Figure 4.18. Effect of Dust Loading on Maximum Pressure for Milo Dust Samples.



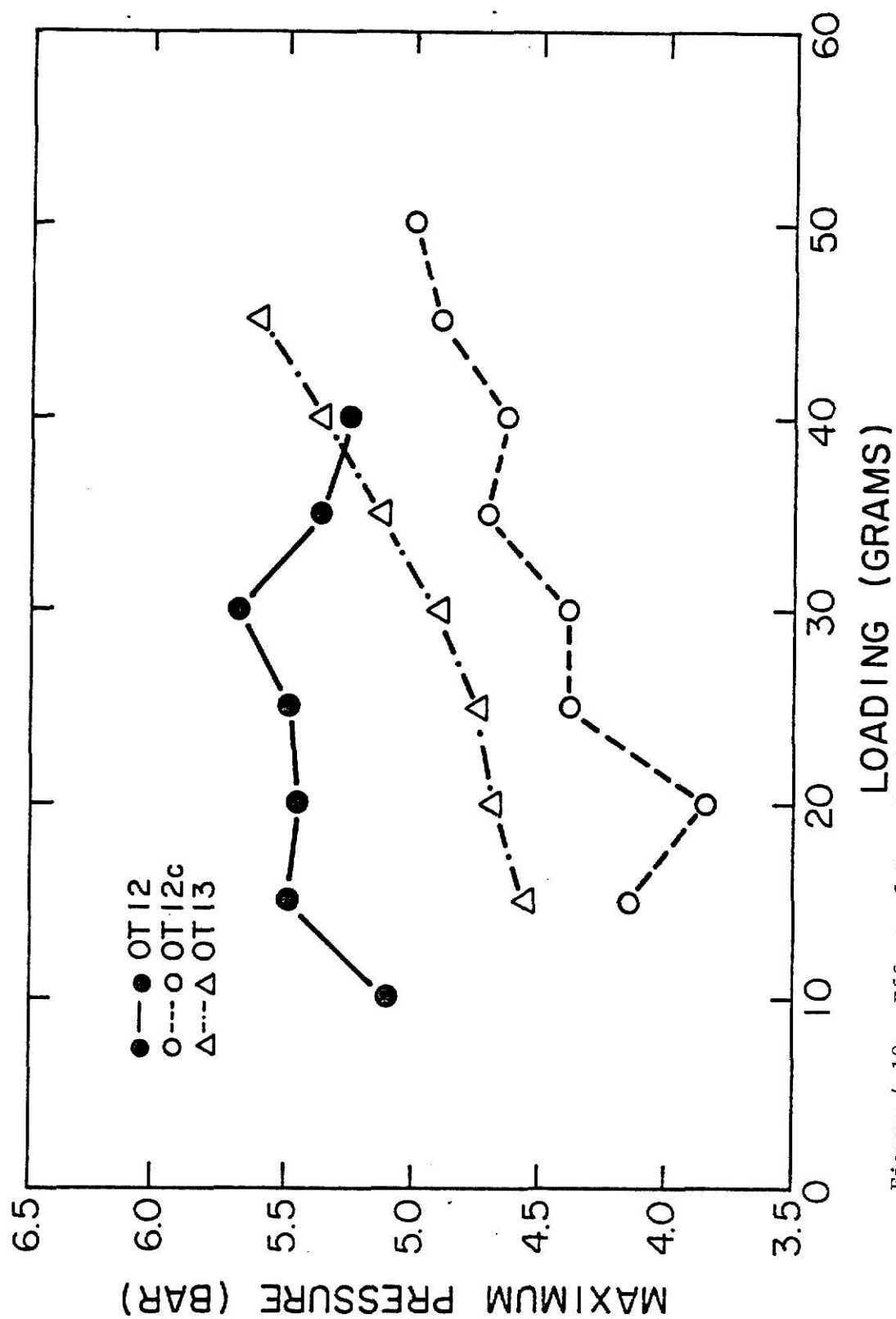


Figure 4.19. Effect of Dust Loading on Maximum Pressure for Oats Dust Samples.

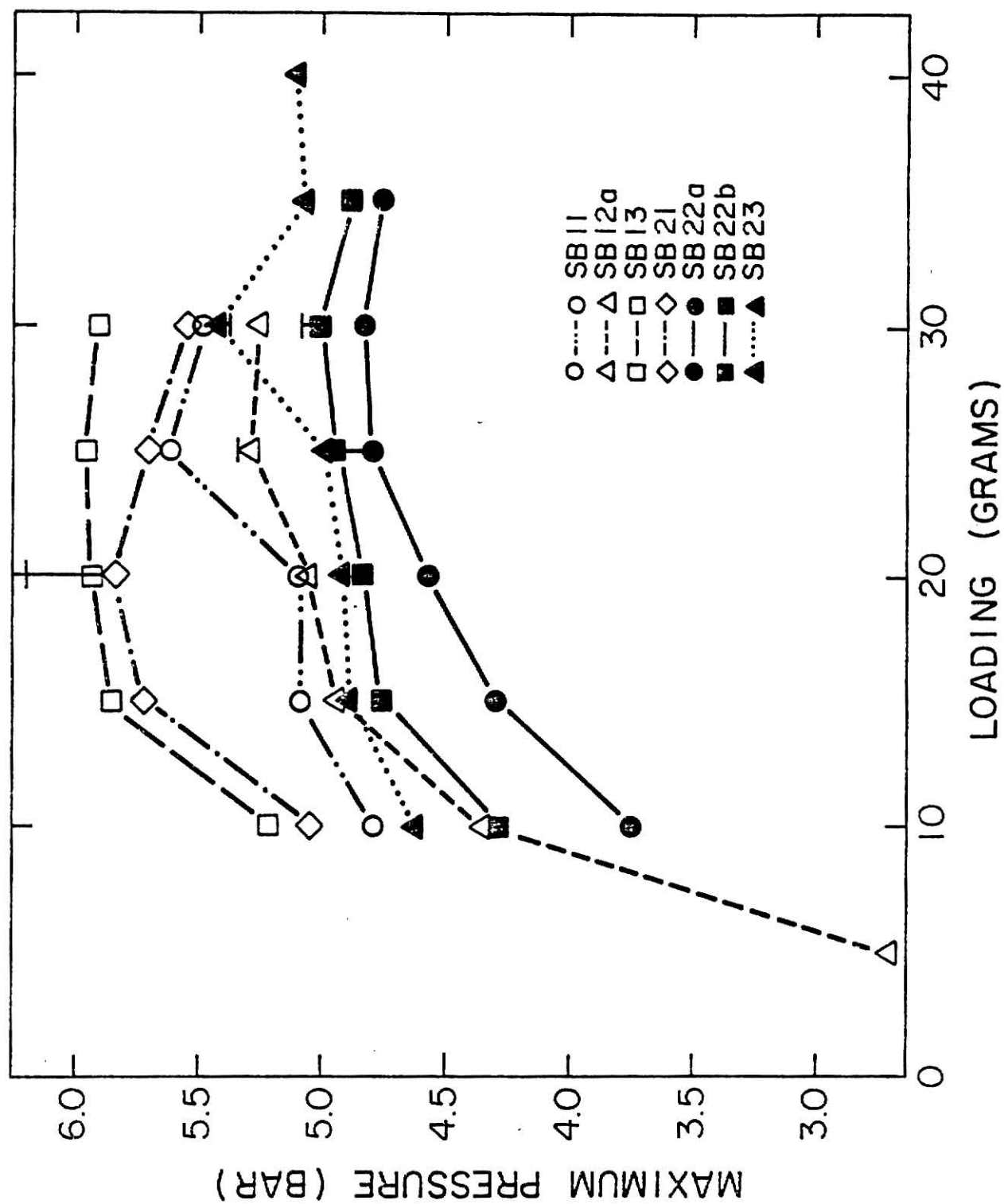


Figure 4.20. Effect of Dust Loading on Maximum Pressure for Soybean Dust Samples.

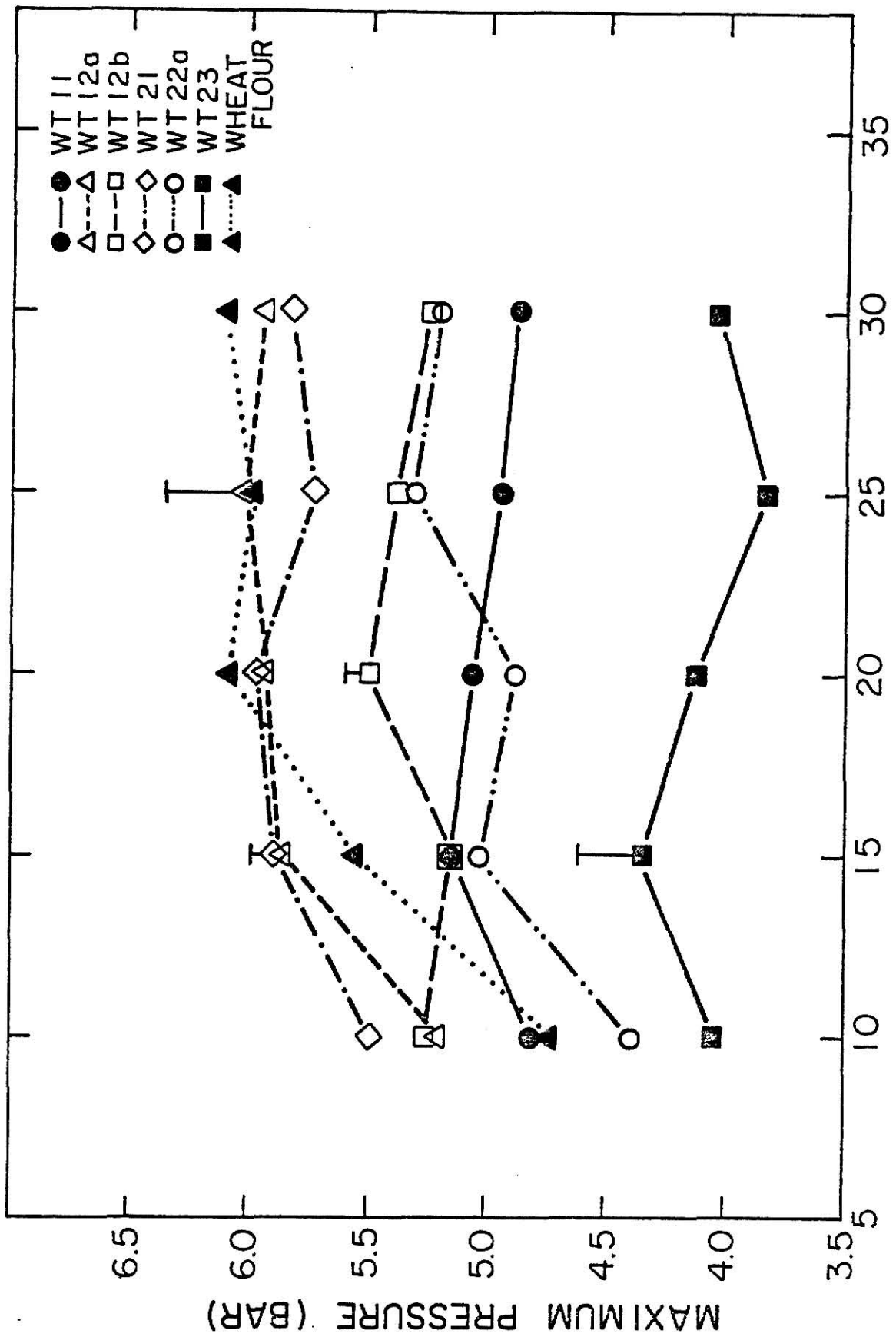


Figure 4.21. Effect of Dust Loading on Maximum Pressure for Wheat Dust Samples.

samples of a dust type can be compared. The plots are similar to the maximum rate plots in Figures 4.10 through 4.15, except the maximum pressure replaces the maximum rate. An individual plot for each dust sample is presented in Appendix 2.

Within a dust type, the dust samples which have the highest and lowest rates are also the dust samples which have the highest and lowest pressures or are one of the dust samples which have the highest and lowest pressures. If the dust samples in each dust type are ranked according to the decreasing value of the maximum pressure and according to the descending values of the maximum rate, they would tend to be in the same order. Sometimes it is difficult to distinguish the correct order since the line graphs overlap for some dust samples. The average peak pressures for all the dust samples range from 3.7 - 6.8 bar. The value of SB12a at 5 grams is not included in the range. Corn dust samples have the highest pressures with a range of 4.7 - 6.8 bar and oats dust has the lowest pressures with a range of 3.8 - 5.7 bar. The same dust types also have the highest and lowest rates.

The peak maximum rates of pressure rise and the peak maximum pressures for all the dust samples are presented in Table 4.7 through 4.12 by dust type. In each table the TZV setting and loading at the peak value, number of tests, average value, and range of values are listed for the peak maximum rate and peak maximum pressure. The dust sample with the highest (or lowest) peak maximum rate in each dust type may not be the dust sample with the highest (or lowest) peak maximum pressure.

CB12c in Table 4.7 has the highest peak maximum rate and peak maximum pressure of the combination dust samples with 261 bar/sec and 6.34 bar, respectively, and CB12 has the lowest values with 197 bar/sec and 5.67 bar, respectively. Of the corn dust samples in Table 4.8, cornstarch

Table 4.7. Maximum Rate of Pressure Rise and Maximum Pressure for Combination Dust.

| Dust sample | Maximum rate of pressure rise |      |              |     | Maximum pressure |     |              |                |
|-------------|-------------------------------|------|--------------|-----|------------------|-----|--------------|----------------|
|             | TZV                           |      | No. of tests |     | Average          |     | No. of tests |                |
|             | ms                            | gram | bar          | sec | bar              | sec | bar          | Range bar      |
| CB12        | 60                            | 50   | 3            | 197 | 180-209          | 60  | 55           | 5.67 5.45-6.09 |
| CB12c       | 60                            | 15   | 4            | 261 | 221-333          | 60  | 15           | 6.34 5.86-6.76 |
| CB13        | 60                            | 25   | 6            | 233 | 162-296          | 100 | 25           | 6.33 6.26-6.41 |

Table 4.8. Maximum Rate of Pressure Rise and Maximum Pressure for Corn Dust.

| Dust sample | Maximum rate of pressure rise |      |              |     | Maximum pressure |     |              |                |
|-------------|-------------------------------|------|--------------|-----|------------------|-----|--------------|----------------|
|             | TZV                           |      | No. of tests |     | Average          |     | No. of tests |                |
|             | ms                            | gram | bar          | sec | bar              | sec | bar          | Range bar      |
| CN21        | 60                            | 20   | 4            | 289 | 269-311          | 60  | 20           | 6.14 5.83-6.34 |
| CN22b       | 50                            | 15   | 4            | 323 | 313-335          | 50  | 15           | 6.49 6.43-6.60 |
| CN23        | 60                            | 15   | 4            | 127 | 87-157           | 60  | 10           | 5.07 4.71-5.43 |
| Corn-starch | 50                            | 15   | 4            | 380 | 345-489          | 100 | 15           | 6.82 7.25-7.25 |

Table 4.9. Maximum Rate of Pressure Rise and Maximum Pressure for Milo Dust.

| Dust sample | Maximum rate of pressure rise |      |       |                       |         | Maximum pressure |      |              |           |
|-------------|-------------------------------|------|-------|-----------------------|---------|------------------|------|--------------|-----------|
|             | Maximum rate of pressure rise |      | Range |                       | TZV     | Maximum pressure |      | No. of tests | Range     |
|             | ms                            | gram | tests | Average<br>bar<br>sec |         | ms               | gram |              |           |
| M011        | 60                            | 35   | 4     | 245                   | 203-283 | 100              | 35   | 2            | 5.93-6.11 |
| M012        | 60                            | 25   | 4     | 296                   | 243-327 | 60               | 30   | 3            | 6.01-6.50 |
| M013        | 60                            | 20   | 4     | 157                   | 139-195 | 100              | 20   | 2            | 5.15-5.50 |
| M020        | 50                            | 25   | 3     | 185                   | 145-229 | 50               | 25   | 3            | 5.07-5.31 |
| M032b       | 60                            | 25   | 4     | 196                   | 171-206 | 60               | 30   | 3            | 5.75-5.89 |
| M032c       | 50                            | 10   | 4     | 262                   | 238-319 | 60               | 15   | 4            | 6.03-7.09 |

Table 4.10. Maximum Rate of Pressure Rise and Maximum Pressure for Oats Dust.

| Dust sample | Maximum rate of pressure rise |      |       |                       |         | Maximum pressure |      |              |           |
|-------------|-------------------------------|------|-------|-----------------------|---------|------------------|------|--------------|-----------|
|             | Maximum rate of pressure rise |      | Range |                       | TZV     | Maximum pressure |      | No. of tests | Range     |
|             | ms                            | gram | tests | Average<br>bar<br>sec |         | ms               | gram |              |           |
| OT12        | 50                            | 30   | 4     | 149                   | 104-175 | 60               | 30   | 3            | 5.62-5.77 |
| OT12c       | 60                            | 50   | 2     | 120                   | 107-133 | 60               | 50   | 2            | 4.98-5.03 |
| OT13        | 60                            | 40   | 3     | 185                   | 165-219 | 60               | 45   | 3            | 5.43-5.74 |

Table 4.11. Maximum Rate of Pressure Rise and Maximum Pressure for Soybean Dust.

| Dust<br>sample | Maximum rate of pressure rise |      |                 |         |         | Maximum pressure    |           |                 |                 |                        |              |
|----------------|-------------------------------|------|-----------------|---------|---------|---------------------|-----------|-----------------|-----------------|------------------------|--------------|
|                | TZV                           |      | No. of<br>tests | Average |         | Range<br>bar<br>sec | TZV<br>ms | Loading<br>gram | No. of<br>tests | Average<br>bar         | Range<br>bar |
|                | ms                            | gram |                 | bar     | sec     |                     |           |                 |                 |                        |              |
| SB11           | 50                            | 25   | 4               | 222     | 213-242 | 60<br>100           | 25<br>25  | 3<br>2          | 5.62<br>5.62    | 5.35-5.89<br>5.50-5.74 |              |
| SB12a          | 60                            | 25   | 4               | 193     | 177-213 | 60                  | 25        | 4               | 5.34            | 5.14-5.59              |              |
| SB13           | 60                            | 15   | 4               | 285     | 243-343 | 60                  | 25        | 3               | 5.95            | 5.91-6.03              |              |
| SB21           | 60                            | 20   | 4               | 216     | 171-247 | 70                  | 20        | 2               | 6.18            | 6.11-6.25              |              |
| SB22a          | 70                            | 25   | 4               | 99      | 87-127  | 80<br>100           | 25<br>25  | 2<br>2          | 4.97<br>4.97    | 4.72-5.23<br>4.95-5.00 |              |
| SB22b          | 60                            | 30   | 4               | 113     | 71-145  | 100                 | 30        | 2               | 5.08            | 5.03-5.12              |              |
| SB23           | 60                            | 30   | 4               | 172     | 165-180 | 60                  | 30        | 4               | 5.39            | 5.25-5.62              |              |

Table 4.12. Maximum Rate of Pressure Rise and Maximum Pressure for Wheat Dust.

| Dust sample | Maximum rate of pressure rise |         |              |            |            | Maximum pressure |         |              |                   |
|-------------|-------------------------------|---------|--------------|------------|------------|------------------|---------|--------------|-------------------|
|             | TZV                           | Loading | No. of tests | Average    | Range      | TZV              | Loading | No. of tests | Range             |
|             | ms                            | gram    |              | bar<br>sec | bar<br>sec | ms               | gram    |              | bar               |
| WT11        | 50                            | 15      | 4            | 154        | 137-168    | 50               | 15      | 4            | 5.15<br>4.87-5.47 |
| WT12a       | 50                            | 15      | 4            | 222        | 185-239    | 60               | 25      | 3            | 6.01<br>5.77-6.24 |
| WT12b       | 50                            | 20      | 4            | 161        | 131-225    | 100              | 20      | 2            | 5.60<br>5.53-5.67 |
| WT21        | 60                            | 15      | 4            | 244        | 217-265    | 50               | 15      | 2            | 5.98<br>5.74-6.22 |
| WT22a       | 60                            | 20      | 4            | 77         | 63-96      | 60               | 25      | 3            | 5.31<br>5.26-5.35 |
| WT23        | 60                            | 15      | 4            | 75         | 65-89      | 100              | 15      | 2            | 4.62<br>4.53-4.71 |
| Wheat flour | 60                            | 25      | 4            | 208        | 187-235    | 100              | 25      | 2            | 6.35<br>6.21-6.50 |



has the highest rate and pressure with 380 bar/sec and 6.82 bar, respectively, and CN23 has the lowest values with 127 bar/sec and 5.07 bar, respectively. In Table 4.9, M012 has the highest rate of the milo dust samples with 296 bar/sec and M032c has the highest pressure with 6.33 bar. M013 has the lowest rate with 157 bar/sec and M020 has the lowest pressure with 5.16 bar. The oats dust sample from Table 4.10 with the lowest rate and pressure is OT12c with 120 bar/sec and 5.01 bar, respectively. OT13 has the highest rate with 185 bar/sec and OT12 has the highest pressure with 5.69 bar. In Table 4.11, SB22a is the soybean dust sample with the lowest rate and pressure with 99 bar/sec and 4.97 bar, respectively. SB13 has the highest rate with 285 bar/sec and SB21 has the highest pressure with 6.18 bar. WT23 in Table 4.12 is the wheat dust sample with the lowest rate and pressure with 75 bar/sec and 4.62 bar, respectively. WT21 has the highest rate with 244 bar/sec and wheat flour has the highest pressure with 6.35 bar.

Cornstarch has the highest peak maximum rate and peak maximum pressure of all the dust samples. This is not unexpected since cornstarch is a processed starch dust containing only a small quantity of non-combustible material. WT23 is the dust sample with the lowest values. A factor in the result may be that WT23 has the second largest average particle size, 30.0  $\mu$ , of all the dust samples. If the peak maximum rates of all dust samples of the same dust type are averaged, the values for corn, combination, milo, soybean, wheat, and oats dust are, respectively, 280, 230, 223, 186, 163, and 151 bar/sec. The average peak maximum pressure values for corn, combination, milo, wheat, soybean, and oats are, respectively, 6.13, 6.11, 5.82, 5.57, 5.50, and 5.44 bar. The results show the peak maximum rate is more dependent on the type of

dust than the peak maximum rate since the rates vary considerably more than the pressure.

The TZV settings and loadings recorded for the maximum rate of pressure rise in Tables 4.7 through 4.12 are the optimum values. Twenty of the thirty dust samples have an optimum TZV setting of 60 ms. Nine samples have an optimum TZV setting of 50 ms and one sample has a value of 70 ms. However, the optimum loading values vary considerably more than the optimum TZV settings. The loading values range from 10 to 50 grams with one dust sample having a value of 10 grams, nine a value of 15 grams, five a value of 20 grams, eight a value of 25 grams, three a value of 30 grams, and four a value greater than 30 grams. The loading values do not equal the quantities of dust in the dust cloud since not all of the loaded dust enters the inside of the 20-liter explosion sphere. Dust remains inside the dispersion horns, dust pre-chamber, and exit valve.

### III. $K_{ST}$ -Value

The calculated  $K_{ST}$ -values for dust samples are listed in Table 4.13. In the table, the number of tests, average values, and ranges of the values are presented. The average  $K_{ST}$ -values range from 20 - 103 bar·m/sec with cornstarch having the highest value and WT23 having the lowest value. The former is the dust sample that has the highest peak maximum rate of pressure rise and the latter the lowest, since  $K_{ST}$  is the product of the peak maximum rate times the cubic root of the explosion chamber volume.

### IV. Dispersion Method

As has been discussed, the quantity of loaded dust placed inside the dust pre-chamber does not equal the quantity of dust that creates the dust cloud inside the 20-liter explosion sphere. To investigate the effects of the dispersion method, the actual mass of dust dispersed, dust collected

Table 4.13.  $K_{ST}$ -Values for Dust-High Ignition  
Energy Source.

| Dust<br>sample | Number<br>of<br>tests | Average<br>$\frac{\text{bar} \cdot \text{m}}{\text{sec}}$ | Range<br>$\frac{\text{bar} \cdot \text{m}}{\text{sec}}$ |
|----------------|-----------------------|-----------------------------------------------------------|---------------------------------------------------------|
| CB12           | 3                     | 53                                                        | 49-57                                                   |
| CB12c          | 4                     | 71                                                        | 60-90                                                   |
| CB13           | 6                     | 62                                                        | 44-80                                                   |
| CN21           | 4                     | 78                                                        | 73-84                                                   |
| CN22b          | 4                     | 88                                                        | 85-91                                                   |
| CN23           | 4                     | 34                                                        | 24-43                                                   |
| Cornstarch     | 4                     | 103                                                       | 78-133                                                  |
| MO11           | 4                     | 67                                                        | 55-77                                                   |
| MO12           | 4                     | 80                                                        | 66-89                                                   |
| MO13           | 4                     | 43                                                        | 38-53                                                   |
| MO20           | 3                     | 50                                                        | 39-62                                                   |
| MO32b          | 4                     | 53                                                        | 46-56                                                   |
| MO32c          | 4                     | 71                                                        | 65-87                                                   |
| OT12           | 4                     | 40                                                        | 28-48                                                   |
| OT12c          | 2                     | 33                                                        | 29-36                                                   |
| OT13           | 3                     | 50                                                        | 45-59                                                   |
| SB11           | 4                     | 60                                                        | 58-66                                                   |
| SB12a          | 4                     | 52                                                        | 48-58                                                   |
| SB13           | 4                     | 77                                                        | 66-93                                                   |
| SB21           | 4                     | 59                                                        | 46-67                                                   |
| SB22a          | 4                     | 27                                                        | 24-34                                                   |
| SB22b          | 4                     | 31                                                        | 19-39                                                   |
| SB23           | 4                     | 47                                                        | 45-49                                                   |
| WT11           | 4                     | 42                                                        | 37-46                                                   |
| WR12a          | 4                     | 60                                                        | 50-65                                                   |
| WT12b          | 4                     | 44                                                        | 36-61                                                   |
| WT21           | 4                     | 66                                                        | 59-72                                                   |
| WT22a          | 4                     | 21                                                        | 17-26                                                   |
| WT23           | 4                     | 20                                                        | 18-24                                                   |
| Wheat flour    | 4                     | 56                                                        | 51-64                                                   |

inside the sphere after dispersion, for a given loading and TZV setting was measured. The results are presented in Table 4.14 and include the TZV setting, loading value, number of tests, average and range of the mass of dust dispersed, and average and range of the percentage of loaded dust that is dispersed. The TZV settings and loading values are the optimum values for the peak maximum rate, excluding M020, OT12c, and OT13. For these dust samples, the TZV setting equals the optimum setting but the loading value equals the quantity of dust available. Only 8 dust samples, CB12c, CN22, SB13, CN21, M020, cornstarch, SB21, and WT22a, have a percentage of loading value greater than or equal to 50%. Three dust samples, CB12, OT13, and OT12c, have values less than 20%. OT12c has the lowest value with a value of 11%. For the 3 dust samples with values less than 20%, the supply of dust was exhausted before peak values were measured for the maximum rate and maximum pressure. In each sample, loading as high as 40 grams were reached corresponding to less than 8 grams of dispersed dust. The majority of the dust that is not dispersed is packed inside the dispersion horns. Smaller quantities remain inside the exit valve and the dust pre-chamber. The quantity of loaded dust never equals the quantity of dispersed dust, but the difference increases as the loading increases.

The average diameter listed for each dust sample in Tables 4.1 through 4.7 is that of the dispersed dust. In Figure 4.22, the average diameter of the loaded dust is plotted against the average diameter of the dispersed dust with the difference between them as the parameter. Excluding OT12, the diameter of the dispersed dust is smaller than the diameter of the loaded dust. The difference is scattered around 5  $\mu$ . In passing through the holes in the dispersion horns, the dust size is slightly reduced.

Table 4.14. Actual Mass of Dust Dispersed for a Given Loading and TZV in the 20-Liter Spherical Explosion Chamber.

| Dust sample | TZV ms | Loading gram | Number of tests | Average gram | Range gram | % of loading |            |
|-------------|--------|--------------|-----------------|--------------|------------|--------------|------------|
|             |        |              |                 |              |            | Mean gram    | Range gram |
| CB12        | 60     | 50           | 1               | 9.0          | ----       | 18           | ---        |
| CB12c       | 60     | 15           | 3               | 8.8          | 8.6- 9.1   | 59           | 57-61      |
| CB13        | 60     | 25           | 4               | 10.2         | 8.1-14.9   | 41           | 32-60      |
| CN21        | 60     | 20           | 3               | 10.6         | 10.3-10.9  | 53           | 51-55      |
| CN22b       | 50     | 15           | 3               | 8.1          | 7.7- 8.4   | 54           | 51-56      |
| CN23        | 60     | 15           | 3               | 5.7          | 5.4- 5.8   | 38           | 36-39      |
| Cornstarch  | 50     | 15           | 3               | 7.8          | 7.1- 8.4   | 52           | 47-56      |
| MO11        | 60     | 35           | 3               | 9.8          | 7.8-12.3   | 28           | 22-35      |
| MO12        | 60     | 25           | 3               | 7.0          | 6.8- 7.1   | 28           | 27-28      |
| MO13        | 60     | 20           | 3               | 6.2          | 5.4- 6.9   | 31           | 27-35      |
| MO20        | 50     | 8.95         | 1               | 4.7          | ----       | 52           | ---        |
| MO32b       | 60     | 25           | 3               | 9.5          | 9.3- 9.5   | 38           | 37-38      |
| MO32c       | 50     | 10           | 4               | 4.2          | 2.9- 5.4   | 42           | 29-54      |
| OT12        | 50     | 30           | 4               | 6.9          | 5.0- 8.4   | 23           | 17-28      |
| OT12c       | 60     | 38.8         | 1               | 4.3          | ----       | 11           | ---        |
| OT13        | 60     | 28.5         | 1               | 4.6          | ----       | 16           | ---        |
| SB11        | 50     | 25           | 3               | 8.5          | 8.1- 8.7   | 34           | 32-35      |
| SB12a       | 60     | 25           | 3               | 8.5          | 7.4-10.3   | 34           | 30-41      |
| SB13        | 60     | 15           | 3               | 7.9          | 7.4- 8.3   | 53           | 49-55      |
| SB21        | 60     | 20           | 3               | 10.2         | 8.7-11.2   | 51           | 43-56      |
| SB22a       | 70     | 25           | 4               | 11.7         | 10.9-12.4  | 47           | 44-50      |
| SB22b       | 60     | 30           | 4               | 8.7          | 7.3- 9.4   | 29           | 24-31      |
| SB23        | 60     | 30           | 3               | 7.5          | 7.2- 7.6   | 25           | 24-25      |
| WT11        | 50     | 15           | 4               | 4.2          | 2.8- 4.8   | 28           | 19-32      |
| WT12a       | 50     | 15           | 3               | 7.5          | 7.3- 7.8   | 50           | 49-52      |
| WT12b       | 50     | 20           | 3               | 6.8          | 6.4- 7.1   | 34           | 32-35      |
| WT21        | 60     | 15           | 3               | 6.7          | 6.4- 7.1   | 45           | 43-47      |
| WT22a       | 60     | 20           | 3               | 6.6          | 5.5- 7.4   | 33           | 27-37      |
| WT23        | 60     | 15           | 4               | 3.0          | 2.8- 3.1   | 20           | 19-21      |
| Wheat Flour | 60     | 25           | 3               | 9.3          | 8.5- 9.9   | 37           | 34-40      |

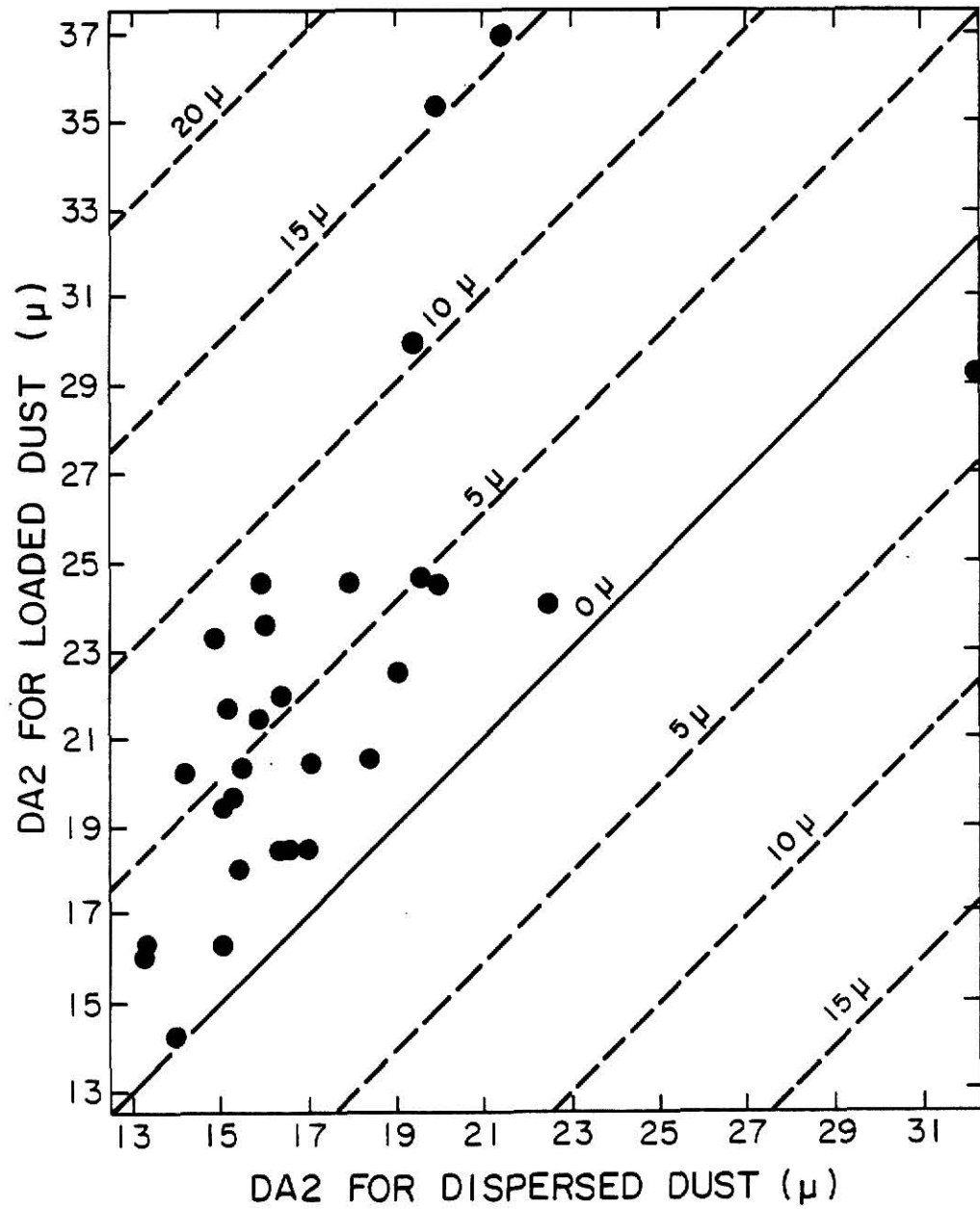


Figure 4.22. Comparison of the Average Particle Size for Loaded and Dispersed Dust with the Difference Between Them as the Parameter.

Figures 4.23 through 4.25 are representative shadowed optical micrographs of cornstarch, SB11, and WT23, respectively. The cornstarch dust particles are roughly spherical in shape, but they tend to agglomerate. The soybean and wheat dust particles have various shapes and sizes and a tendency to agglomerate. Cornstarch dust particles are more uniform in shape and size than either SB11 or WT23. Agglomeration and nonspherical shapes cause an error in the average diameter measurement and make it harder to disperse the dust. In measuring the diameter, it is assumed that the particles are single particles of spherical shape. When the dust is dispersed it has to pass through circular holes in the horns. Long, slender particles make this difficult. They have to be properly oriented in order to pass through circular holes.

#### V. Specific Surface Area

In Table 4.15 and Figure 4.26 the external specific surface area and the specific surface area measurement from the 3-point BET analysis are compared. Dust samples SB11, SB12a, SB22a, and SB23 are not included in Figure 4.26. The external specific surface area is calculated from the average particle size and the density by the method shown in Appendix 3. The BET value can be considered a total specific surface area measurement since its value includes the internal surface area of pores. The differences between the total and external specific surface areas are due to the area of the pores. If SB11, SB12a, SB22a, and SB23 are excluded, these differences range from  $0.32 - 1.32 \text{ m}^2/\text{gram}$ . The four soybean dust samples are excluded because they have abnormally large total specific surface area values as compared to the other dust samples. These large total values may indicate that the four soybean dust samples are extremely porous as compared to the other dust samples.

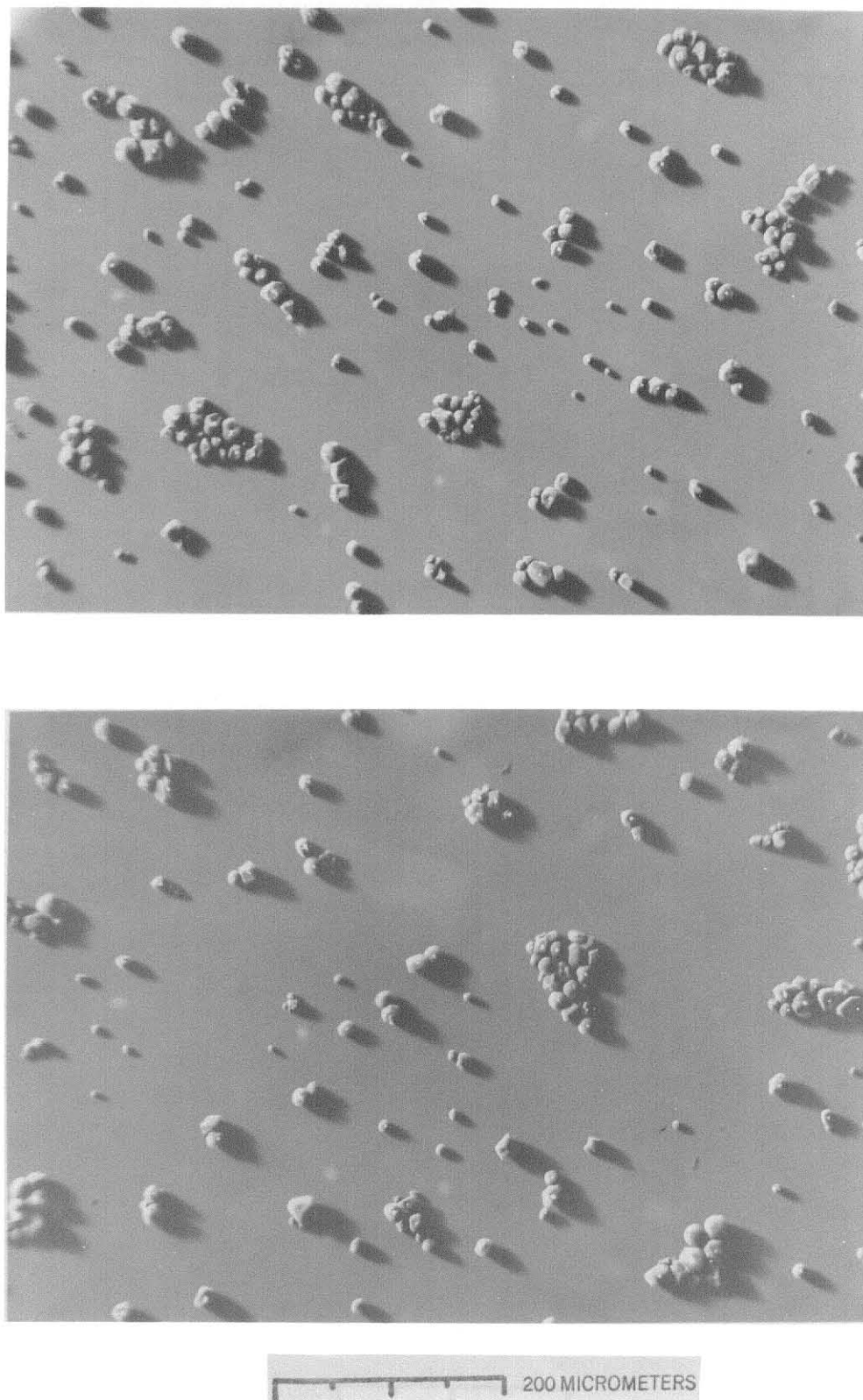
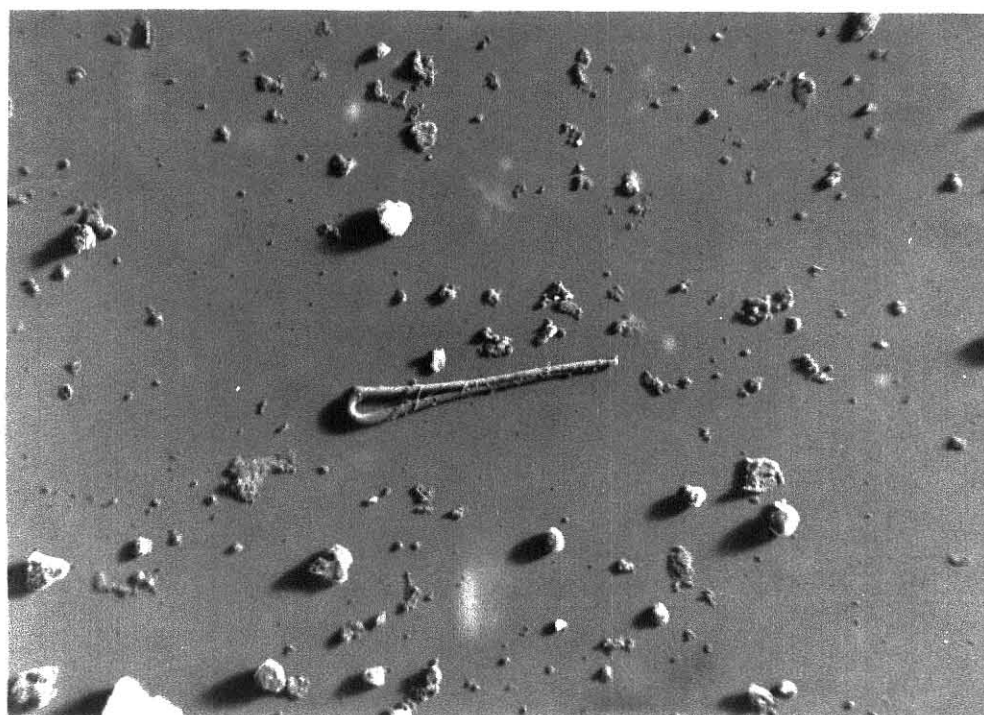
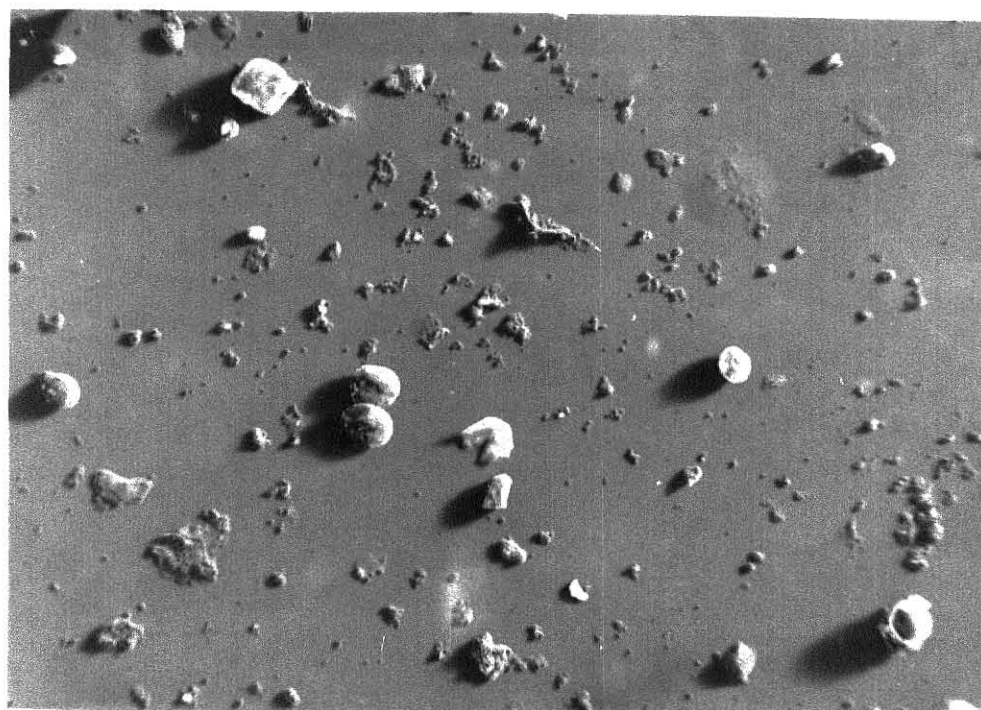


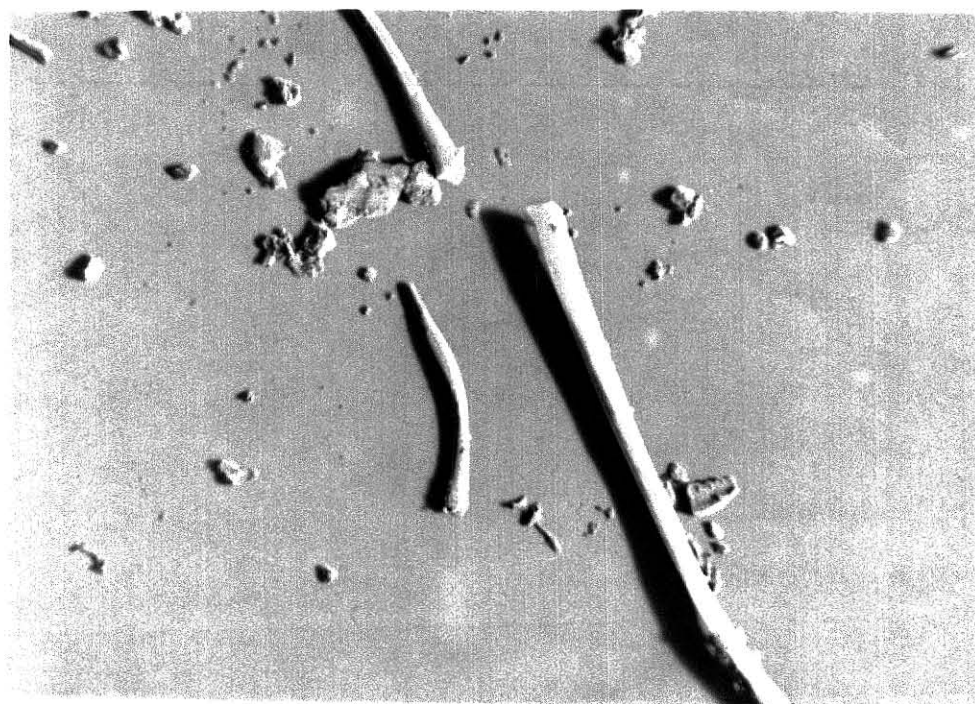
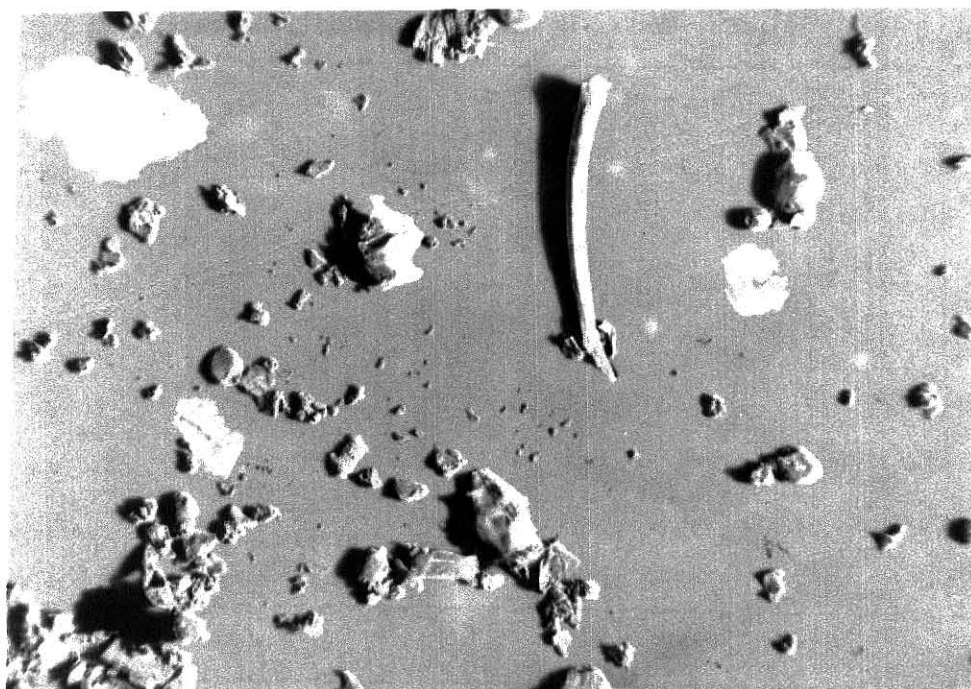
Figure 4.23. Representative Particle Size Distribution for Cornstarch.





200 MICROMETERS

Figure 4.24. Representative Particle Size Distribution for SB11.



200 MICROMETERS

Figure 4.25. Representative Particle Size Distribution for WT23.

Table 4.15. Surface Area Comparison.

| Dust Sample | Specific surface area                     |                                        |                                             |
|-------------|-------------------------------------------|----------------------------------------|---------------------------------------------|
|             | External<br>$\frac{\text{m}^2}{\text{g}}$ | Total<br>$\frac{\text{m}^2}{\text{g}}$ | Difference<br>$\frac{\text{m}^2}{\text{g}}$ |
| CB12        | 0.23                                      | 0.76                                   | 0.53                                        |
| CB12c       | 0.24                                      | 0.58                                   | 0.34                                        |
| CB13        | 0.26                                      | 1.26                                   | 1.00                                        |
| CN21        | 0.25                                      | 0.60                                   | 0.35                                        |
| CN22b       | 0.23                                      | 0.60                                   | 0.37                                        |
| CN23        | 0.23                                      | 0.68                                   | 0.45                                        |
| Cornstarch  | 0.24                                      | 0.61                                   | 0.37                                        |
| MO11        | 0.24                                      | 1.24                                   | 1.00                                        |
| MO12b       | 0.23                                      | 1.18                                   | 0.95                                        |
| MO13        | 0.22                                      | 0.92                                   | 0.70                                        |
| MO20        | 0.23                                      | 1.32                                   | 1.09                                        |
| MO32b       | 0.20                                      | 0.73                                   | 0.53                                        |
| MO32c       | 0.25                                      | 0.65                                   | 0.40                                        |
| OT12        | 0.12                                      | 0.85                                   | 0.73                                        |
| OT13        | 0.28                                      | 1.40                                   | 1.12                                        |
| SB11        | 0.24                                      | 16.71                                  | 16.47                                       |
| SB12a       | 0.22                                      | 13.35                                  | 13.13                                       |
| SB13        | 0.17                                      | 1.24                                   | 1.07                                        |
| SB21        | 0.23                                      | 1.14                                   | 0.91                                        |
| SB22a       | 0.20                                      | 7.78                                   | 7.58                                        |
| SB22b       | 0.21                                      | 0.53                                   | 0.32                                        |
| SB23        | 0.25                                      | 11.84                                  | 11.59                                       |
| WT11        | 0.17                                      | 1.03                                   | 0.86                                        |
| WT12a       | 0.19                                      | 1.00                                   | 0.81                                        |
| WT12b       | 0.20                                      | 0.86                                   | 0.66                                        |
| WT21        | 0.21                                      | 1.53                                   | 1.32                                        |
| WT22a       | 0.18                                      | 0.56                                   | 0.38                                        |
| WT23        | 0.20                                      | 0.92                                   | 0.72                                        |
| Wheat Flour | 0.20                                      | 0.52                                   | 0.32                                        |

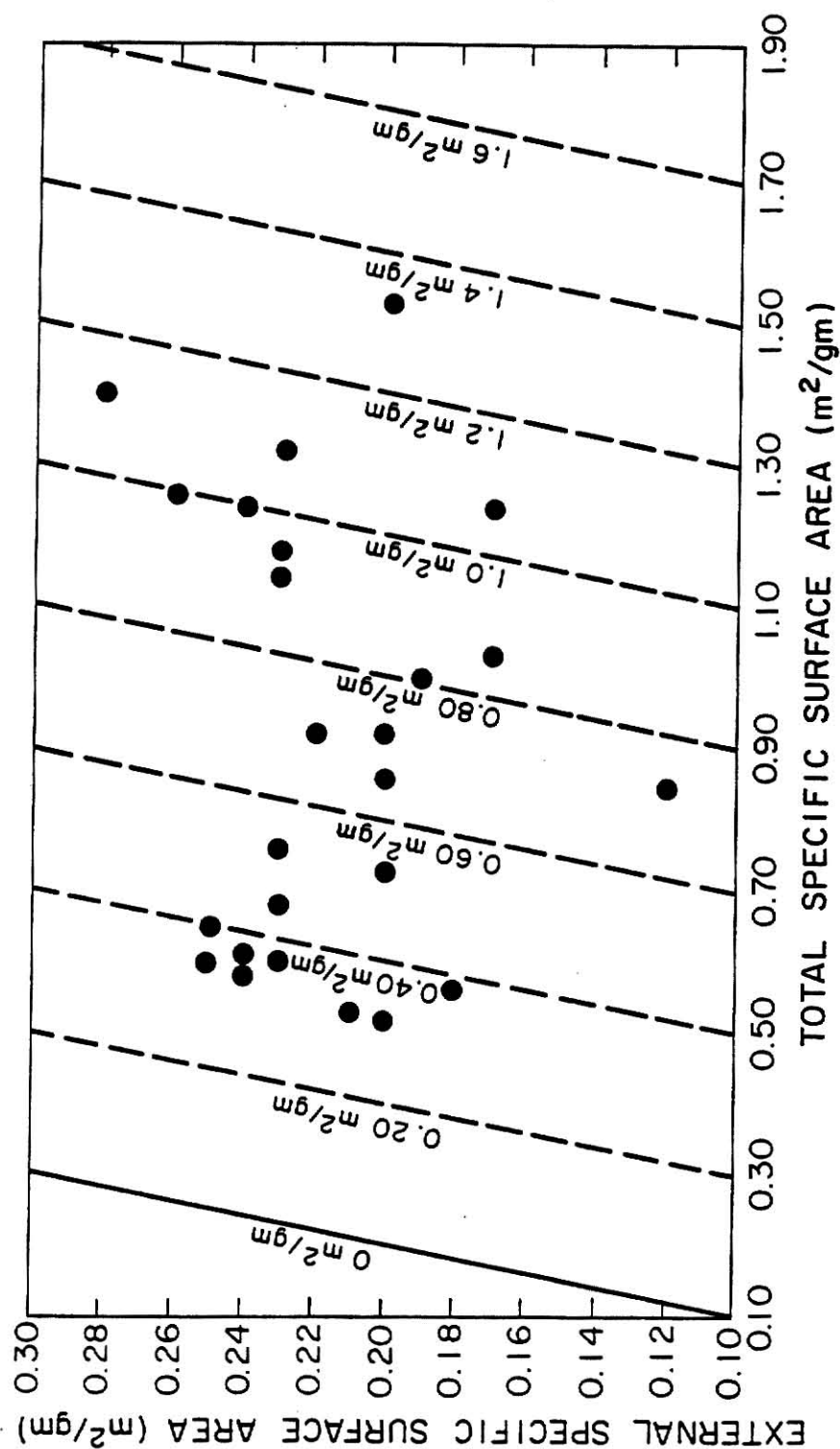


Figure 4.26. Comparison of the External Specific Surface Area and the Total Specific Surface Area with the Difference between Them as the Parameter.

## VI. Statistical Correlations

The characteristic data for the dust samples suggest the standard heat of combustion, ash content, and moisture content are related. Also, the assumption used to measure the standard heat of combustion imply the standard heat of combustion is a function of the ash content and moisture content. This relationship is shown by obtaining a corrected standard heat of combustion. In the corrected value the ash content and moisture content are divided out of the measured value of the standard heat of combustion resulting in a standard heat of combustion based upon an ash and moisture free basis. The corrected standard heat of combustion is calculated from

$$(-\Delta H_c') = \frac{(-\Delta H_c^*)}{(1.0 - \text{ash}/100 - \text{moist}/100)} \quad (4.1)$$

where

$\Delta H_c'$  = corrected standard heat of combustion based upon an ash free and moisture free basis [=] cal/gram

$\Delta H_c^*$  = measured standard heat of combustion from the PARR adiabatic bomb calorimeter [=] cal/gram

ash = percent ash content

moist = percent moisture content

The values of  $(-\Delta H_c')$  are shown in Appendix 4.

The values of  $(-\Delta H_c')$  can be considered repeated measurements of the standard heat of combustion of cellulose; therefore, the mean and standard deviation of the  $(-\Delta H_c')$  values were determined and are 4820 cal/gram and 519 cal/gram, respectively. The  $(-\Delta H_c')$  values for dust samples CB13 and SB13 are extremely low and high, respectively, as shown in Figure 4.27. The probability of these values actually occurring is approximately zero as shown in Appendix 4. Differences in the  $(-\Delta H_c')$  values are due to the dust samples containing other materials beside

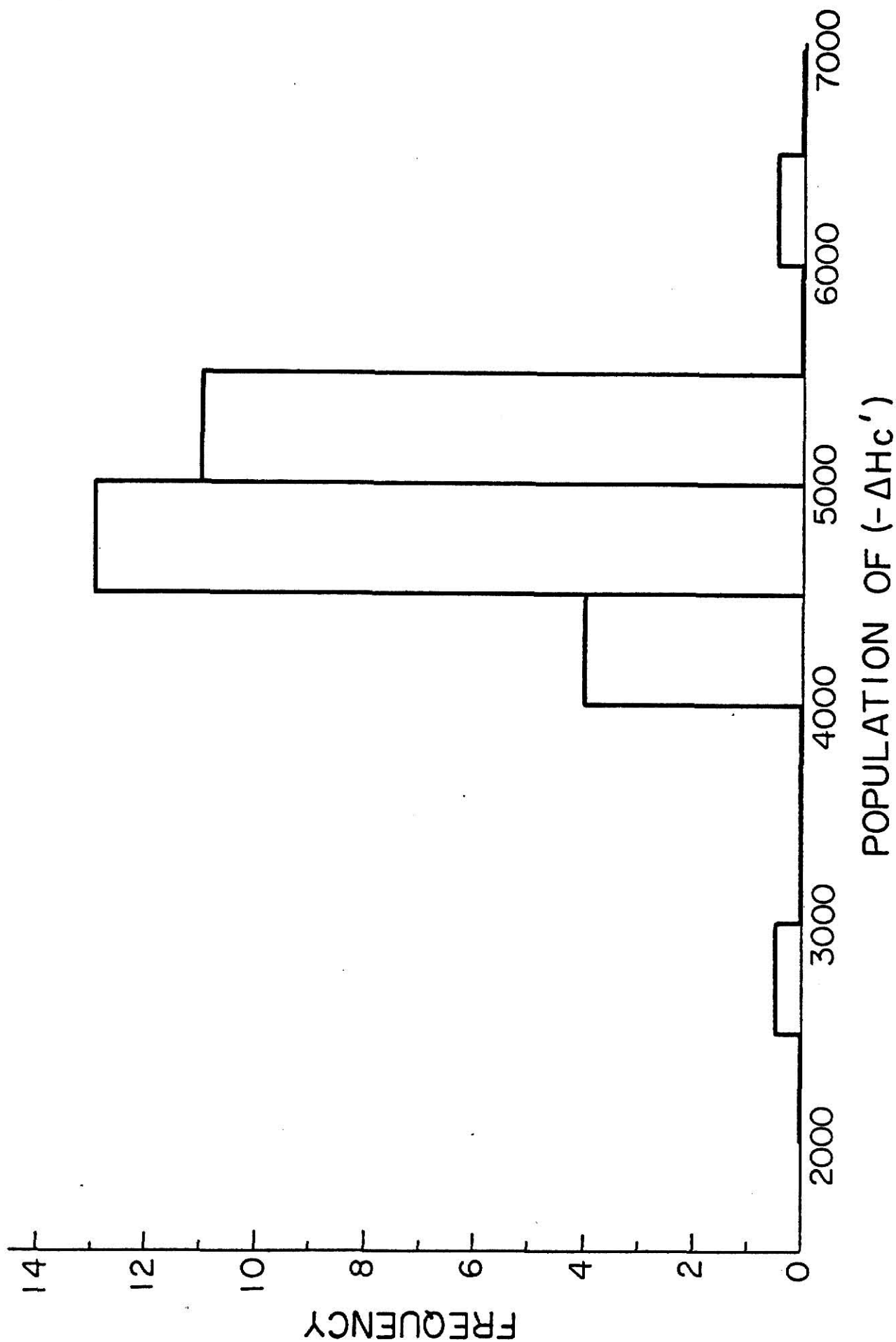


Figure 4.27. Frequency Distribution of the Absolute Values of the Heat of Combustion Based Upon An Ash and Moisture Free Basis.

cellulose, such as protein, fat, and fiber, and experimental error. The large difference between the mean value of  $(-\Delta H_c')$  and the values for CB13 and SB13 is probably due to experimental error, since the other combination and soybean dust samples have values within one standard deviation of the mean  $(-\Delta H_c')$  value.

The all possible regression statistical method (Draper et al., 1981) was used to determine the linear correlation between the standard heat of combustion,  $\Delta H_c^*$ , and the ash and moisture contents. Dust samples CB13 and SB13 were not included as data in the model building. The following statistical correlation represents the data with a correlation coefficient,  $R^2$ , value of 0.91.

$$(-\Delta H_c^*) = 4808 - 41.8 (\text{ash}) - 61.6 (\text{moist}) \quad (4.2)$$

Rearranging equation 4.1 and 4.2 gives, respectively,

$$(-\Delta H_c^*) = (-\Delta H_c') \left[ 1 - \frac{\text{ash}}{100} - \frac{\text{moist}}{100} \right] \quad (4.3)$$

$$(-\Delta H_c^*) = 4808 - 4180 \left( \frac{\text{ash}}{100} \right) - 6160 \left( \frac{\text{moist}}{100} \right) \quad (4.4)$$

The statistical correlation, equation 4.4, has the same form as equation 4.3. The difference between them is that in equation 4.3 the value of  $(-\Delta H_c')$  is the value of the intercept and the constant by which the ash and moisture is multiplied, but in equation 4.4, the three values are not equal. However, the value of the intercept in equation 4.4, 4808, is approximately equal to the mean value of  $(-\Delta H_c')$ , 4820.

The experimental and estimated values of  $(-\Delta H_c^*)$  are compared in Figures 4.28, 4.29, and 4.30. In Figure 4.28 the experimental and estimated values of  $(-\Delta H_c^*)$  are plotted against the percent ash content and in Figure 4.29 the experimental and estimated values are plotted against

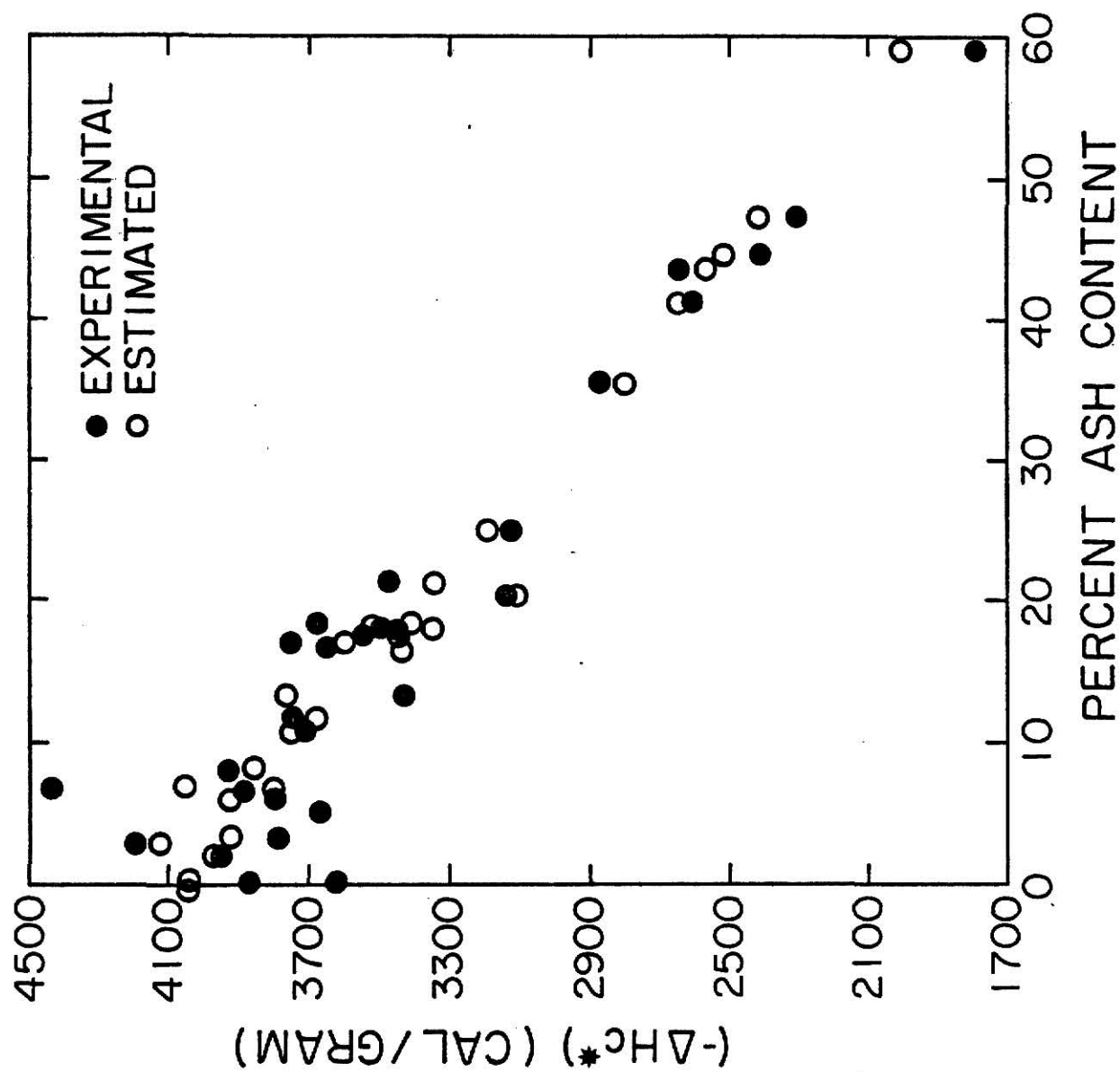


Figure 4.28. Comparison of the Experimental and Estimated Absolute Values of the Standard Heat of Combustion as a Function of Ash Content.



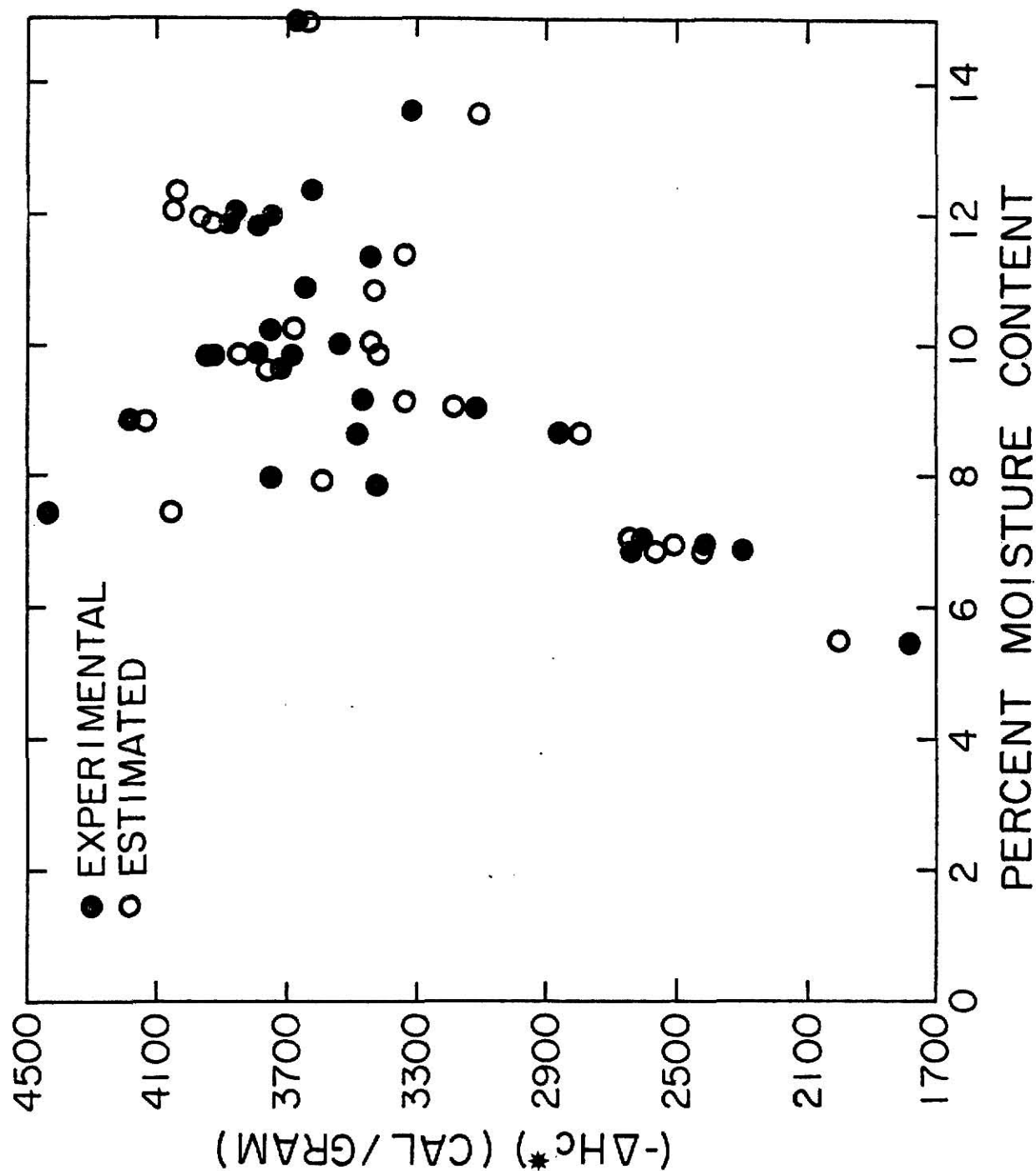


Figure 4.29. Comparison of the Experimental and Estimated Absolute Values of the Standard Heat of Combustion as a Function of Moisture Content.

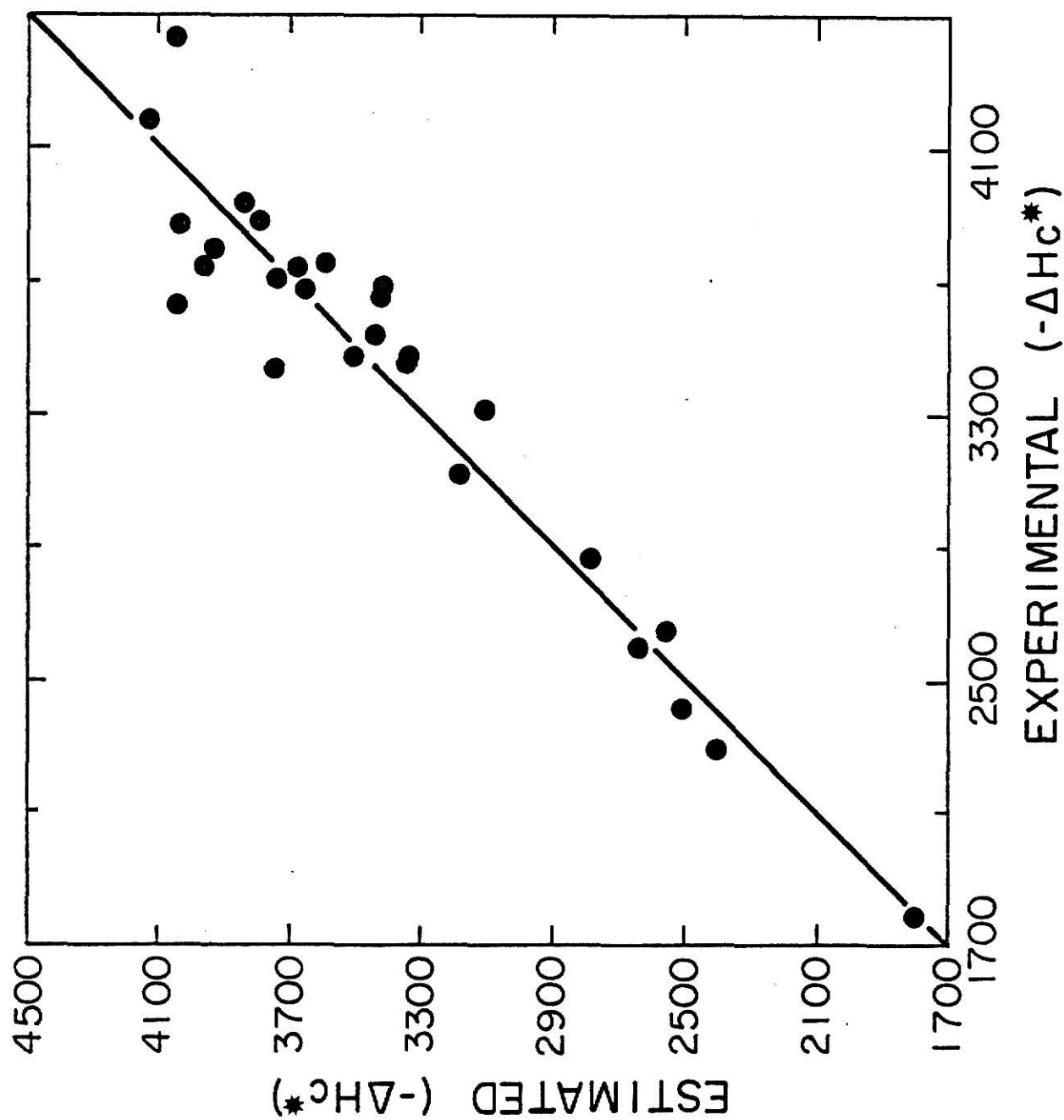


Figure 4.30. Comparison of the Experimental and Estimated Absolute Values of the Standard Heat of Combustion.

the percent moisture content. The estimated values are plotted against the experimental values in Figure 4.30. The three figures show the agreement between the experimental and estimated values is quite good. Only 3 dust samples have a difference greater than 300 cal/gram. In Appendix 4 the estimated values are presented. The statistical correlation has been developed for dust samples having a moisture content between 5.5 and 15.0 percent and an ash content between 0 and 60 percent; it should not be used outside these ranges.

The characteristics of the dust samples and the corrected loading at the peak maximum rate were used in deriving the statistical correlation for the peak maximum rate. These variables, presented in Table 4.16, were evaluated by the stepwise regression statistical method (Draper et al., 1981). Since the standard heat of combustion,  $\Delta H_c^*$ , is a function of the ash and moisture contents, it was used in the modeling but not the ash and moisture contents. The external specific surface area, ESA, was calculated from the average particle size, as shown in Appendix 3, and used in the modeling instead of the average particle size. By using the external specific surface area the differences in the density of the dust samples were taken into consideration. The corrected loading, LRC, was calculated from the product of the loading at the peak maximum rate and the percentage of loaded dust which was dispersed as shown in Appendix 5. The corrected loading was used rather than the loading because it gave a better estimate of the quantity of dust present in the dust cloud. Dust samples CB13 and SB13 were not included in the modeling because their heat of combustion values were inconsistent with the heat of combustion values of the other dust samples. Dust samples CB12, MO20, OT12c, and OT13 were not included in the modeling because, in all cases, there was an insufficient quantity of dust to complete the experimental explosion tests.

Table 4.16. Variables Evaluated in the Peak  
Maximum Rate Statistical Correlation.

| Variables                      | Symbols |
|--------------------------------|---------|
| -(Heat of Combustion)          | Heat    |
| Specific Surface Area          | SA      |
| Corrected Loading              | LRC     |
| External Specific Surface Area | ESA     |
| (Heat) <sup>2</sup>            | H2      |
| (Heat) <sup>3</sup>            | H3      |
| (SA) <sup>2</sup>              | SA2     |
| (SA) <sup>3</sup>              | SA3     |
| (LRC) <sup>2</sup>             | LRC2    |
| (LRC) <sup>3</sup>             | LRC3    |
| (ESA) <sup>2</sup>             | ESA2    |
| (ESA) <sup>3</sup>             | ESA3    |
| Heat*SA                        | HSA     |
| Heat*LRC                       | HLRC    |
| Heat*ESA                       | HESA    |
| SA*LRC                         | SALRC   |
| ESA*LRC                        | ESLRC   |
| SA*ESA                         | SAESA   |
| Heat*SA*LRC                    | HSALRC  |
| Heat*ESA*LRC                   | HESLRC  |
| Heat*SA*ESA                    | HSAES   |
| LRC*SA*ESA                     | LRCSAE  |
| Heat*SA*LRC*ESA                | ALLRC   |

The following statistical correlation represents the data with a  $R^2$  value of 0.93

$$\left(\frac{dP}{dt}\right)_{MAX} = 0.0363(-\Delta H_c^*)(ESA)(LRC) = 0.0363(X) \quad (4.5)$$

where

$\left(\frac{dP}{dt}\right)_{MAX}$  = peak maximum rate of pressure rise [=] bar/sec

$\Delta H_c^*$  = standard heat of combustion [=] cal/gram

ESA = external specific surface area [=]  $m^2$ /gram

LRC = corrected loading at the peak maximum rate [=] gram

$X = (-\Delta H_c^*)(ESA)(LRC)$  [=]  $cal \cdot m^2$ /gram

The intercept is forced to equal zero because in the correlation which included an intercept the  $R^2$  value equaled 0.46 and the intercept estimate had a significance level of 0.38. This large significance level implies the value of the intercept should equal zero. The value of zero for the intercept can be physically explained. If there is no dust present ( $LRC = 0$ ) or energy released ( $\Delta H_c^* = 0$ ), then a dust explosion can not occur and, thus, the peak maximum rate should equal zero.

The statistical correlation in equation 4.5 supports the physical observations determined by analyzing the dust characteristics and the experimental data. Three of these observations are that the value of the explosibility parameters should tend to increase with an increase in the absolute value of the heat of combustion, an increase in the specific surface area and a decrease in the average particle size. Additional observations are that the explosibility parameters should tend to decrease as the ash and moisture content increases. In the correlation the value of the peak maximum rate does increase with an increase in the value of the  $(-\Delta H_c^*)$  and the external specific surface area. Since the value of

$(-\Delta H_c^*)$  in equation 4.5 can be replaced with equation 4.2, the value of the peak maximum rate does decrease as the ash and moisture contents increase. The external specific surface area calculated from the average particle size increases as the particle size decreases (see Appendix 3). Thus, the value of the peak maximum rate does increase as the value of the average particle size decreases. In the correlation the value of the peak maximum rate also increases as the corrected loading increases.

The external specific surface area is a variable in the correlation in equation 4.5 but not the total specific surface area determined from the 3-point BET analysis. A difference exists in the two specific surface area values because the total value includes the internal surface area of pores, whereas, the external value does not. The total specific surface area may not be significant because the explosion proceeds so fast that there is insufficient time for diffusion through the pores to take place. The entire dust explosion is completed in less than 100 ms.

The experimental and estimated values of the peak maximum rate are compared in Figure 4.31. The agreement between the two values is reasonable considering the scatter in the experimental values of the maximum rates used in determining the peak maximum rates. Figure 4.1 through 4.4 and Tables 4.7 through 4.12 illustrate this scatter. The correlation line shows the trend of the values of the peak maximum rate. In Appendix 6 the values estimated from the correlation are presented. The correlation has been developed for values of the peak maximum rate between 75 and 380 bar/sec; it should not be used outside this range.

If the external specific surface area of the loaded dust is used in equation 4.5 instead of the surface area of the dispersed dust, the value of the peak maximum rate calculated will change. The average particle

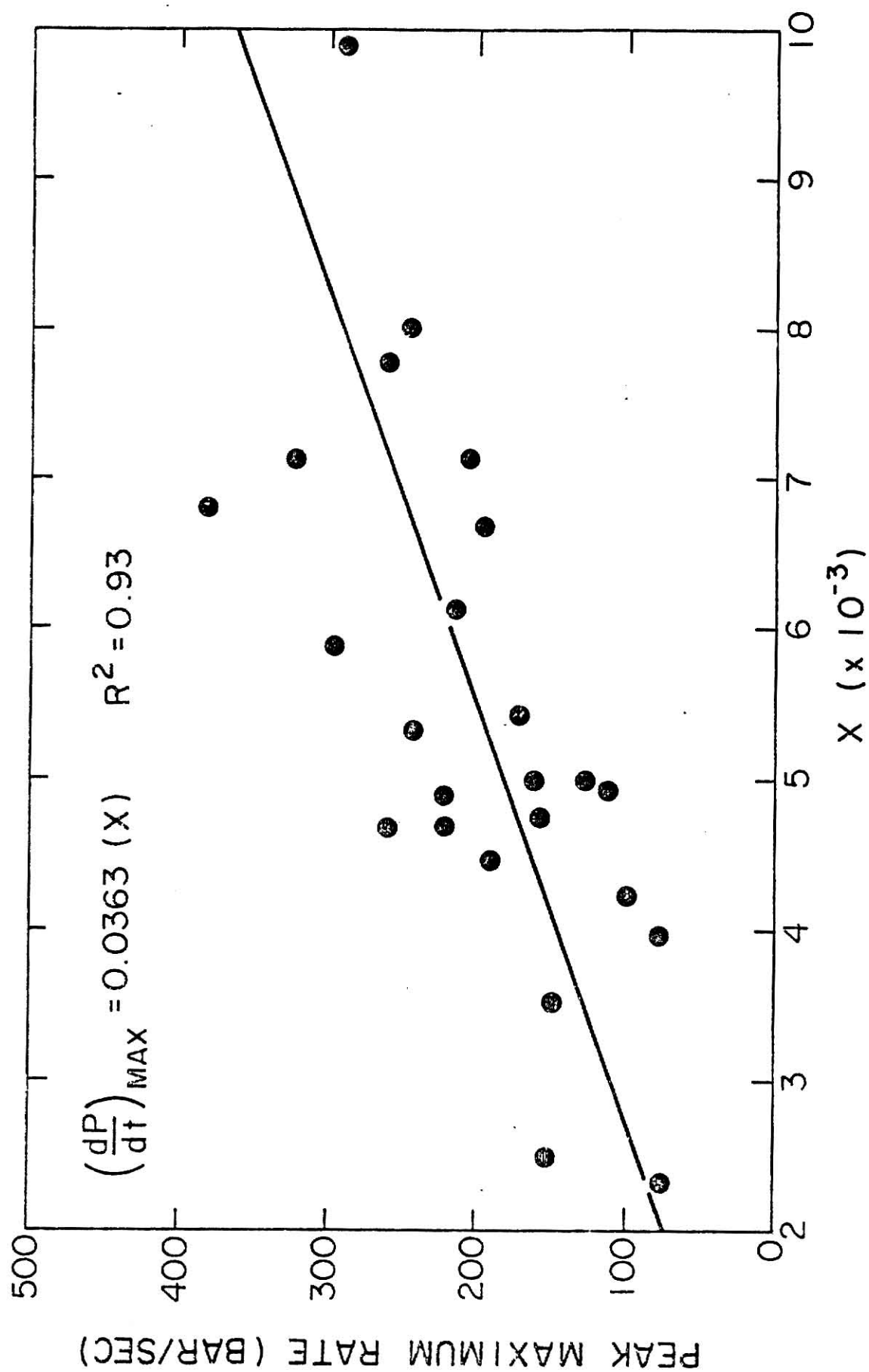


Figure 4.31. Comparison of the Experimental and Estimated Values of the Peak Maximum Rate of Pressure Rise.

size of the dispersed dust is smaller than the average particle size of the loaded dust, thus, the external specific surface area of the dispersed dust has the larger value. Consequently, the value of the peak maximum rate calculated for the dispersed dust will be greater than the value calculated for the loaded dust. In Figure 4.32 the percent change in the peak maximum rate is plotted against  $X$  or  $(-\Delta H_c^*)(ESA)(LRC)$ . The percent change is calculated by subtracting the value of the peak maximum rate of the loaded dust from the value of the dispersed dust and dividing the result by the value of the dispersed dust. Figure 4.32 demonstrates that the value of the peak maximum rate for the dispersed dust may be as much as 45% greater than the value for the loaded dust. Even though the peak maximum rates measured in the 20-liter explosion chamber are not the correct values for the loaded dust, for safety considerations, it is better that the value is overestimated instead of underestimated.

The characteristics of the dust samples and the corrected loading at the peak maximum pressure were used in deriving the statistical correlation for the peak maximum pressure. These variables, presented in Table 4.17, were evaluated by the stepwise regression statistical method (Draper et al., 1981). The corrected loadings were calculated by the same method, but for several dust samples the loading at the peak maximum pressure did not equal the loading at the peak maximum rate. The dust samples not included in the modeling of the peak maximum rate are also not included in the modeling of the peak maximum rate.

The following statistical correlation represents the data with a  $R^2$  value of 0.60

$$\begin{aligned} P_{MAX} &= 4.44 + 0.000225(-\Delta H_c^*)(ESA)(LPC) \\ &= 4.44 + 0.000225(Y) \end{aligned} \quad (4.6)$$



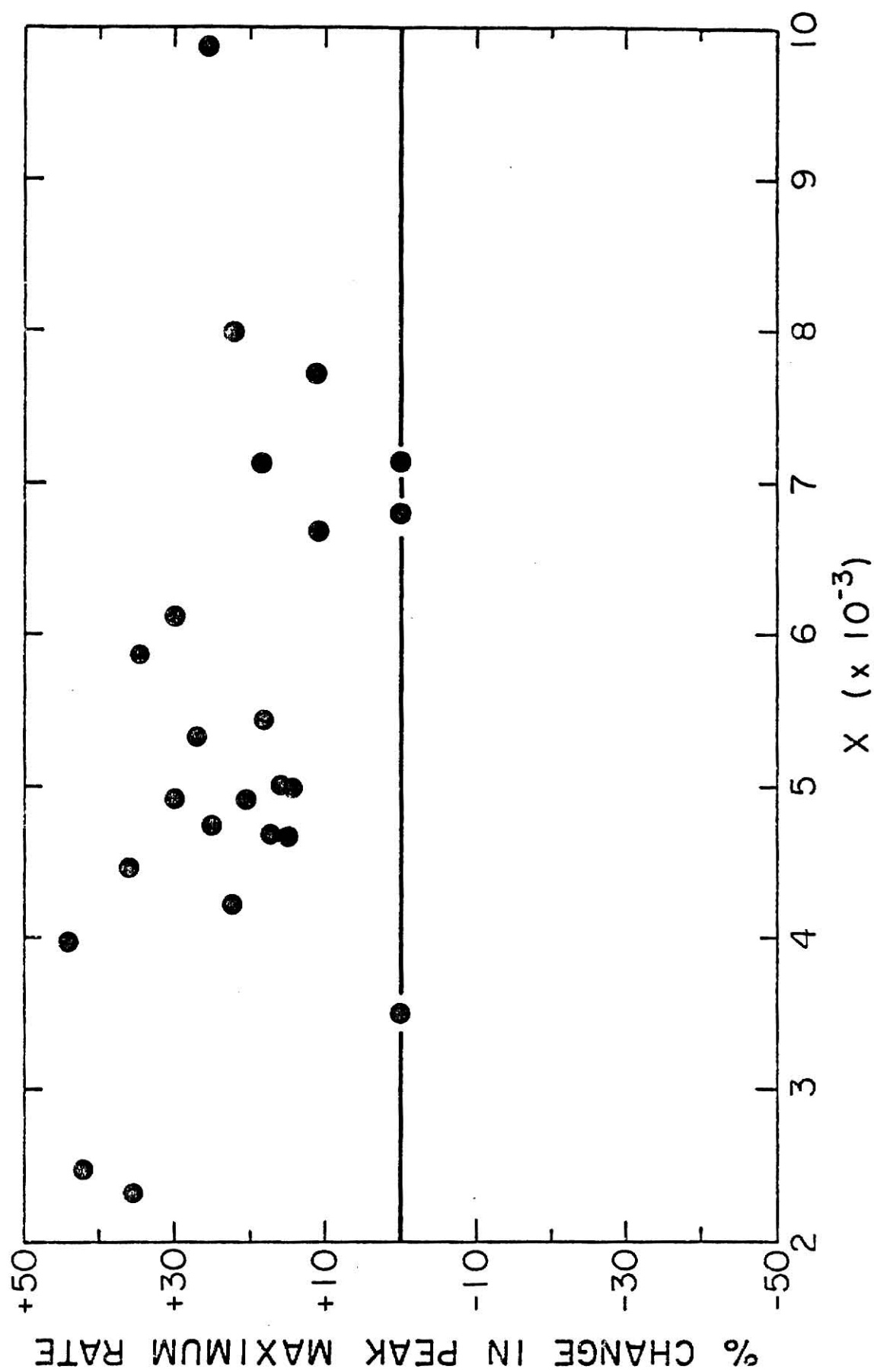


Figure 4.32. Effect of Using Loaded Dust versus Dispersed Dust Values in Calculating the Peak Maximum Rate of Pressure Rise.

Table 4.17. Variables Evaluated in the Peak Maximum  
Pressure Statistical Correlation.

| Variables                      | Symbols |
|--------------------------------|---------|
| -(Heat of Combustion)          | Heat    |
| Specific Surface Area          | SA      |
| Corrected Loading              | LPC     |
| External Specific Surface Area | ESA     |
| (Heat) <sup>2</sup>            | H2      |
| (Heat) <sup>3</sup>            | H3      |
| (SA) <sup>2</sup>              | SA2     |
| (SA) <sup>3</sup>              | SA3     |
| (LPC) <sup>2</sup>             | LPC2    |
| (LPC) <sup>3</sup>             | LPC3    |
| (ESA) <sup>2</sup>             | ESA2    |
| (ESA) <sup>3</sup>             | ESA3    |
| Heat*SA                        | HSA     |
| Heat*LPC                       | HLPC    |
| Heat*ESA                       | HESA    |
| SA*LPC                         | SALPC   |
| ESA*LPC                        | ESLPC   |
| SA*ESA                         | SAESA   |
| Heat*SA*LPC                    | HSALPC  |
| Heat*ESA*LPC                   | HESLPC  |
| Heat*SA*ESA                    | HSAES   |
| LPC*SA*ESA                     | LPCSAE  |
| Heat*SA*LPC*ESA                | ALLPC   |

where

$P_{MAX}$  = peak maximum pressure [=] bar

$\Delta H_c^*$  = standard heat of combustion [=] cal/gram

ESA = external specific surface area [=]  $m^2/\text{gram}$

LPC = corrected loading at the peak maximum pressure [=] gram

$Y = (-\Delta H_c^*)(ESA)(LPC)$  [=]  $\text{cal} \cdot m^2/\text{gram}$

The variables in equation 4.6 are the same variables that are in the statistical correlation for the peak maximum rate, equation 4.5. Hence, the statistical correlation for the peak maximum pressure supports the observations that the statistical correlation for the peak maximum rate supports.

The experimental and estimated values of the peak maximum pressure are compared in Figure 4.33. The agreement is reasonable considering the scatter in the experimental values of the maximum pressures used in determining the peak maximum pressure. Figures 4.5 through 4.9 and Tables 4.7 through 4.12 illustrate this scatter. In an attempt to improve the agreement a polynomial regression model was investigated. The result is

$$P_{MAX} = 3.48 + 0.000593(Y) - 3.14 \times 10^{-8}(Y)^2 \quad (4.7)$$

with a  $R^2$  value of 0.65. As shown in Figure 4.33, the agreement between the experimental and predicted values was improved slightly by using equation 4.7.

When a dust explosion occurs energy is released, which results in an increase in the pressure. Hence, the peak maximum pressure may be considered a function of the energy released during a dust explosion. This energy release is a product of the standard heat of combustion and the corrected loading. The statistical correlation for this functionality has a  $R^2$  value of 0.49; it is

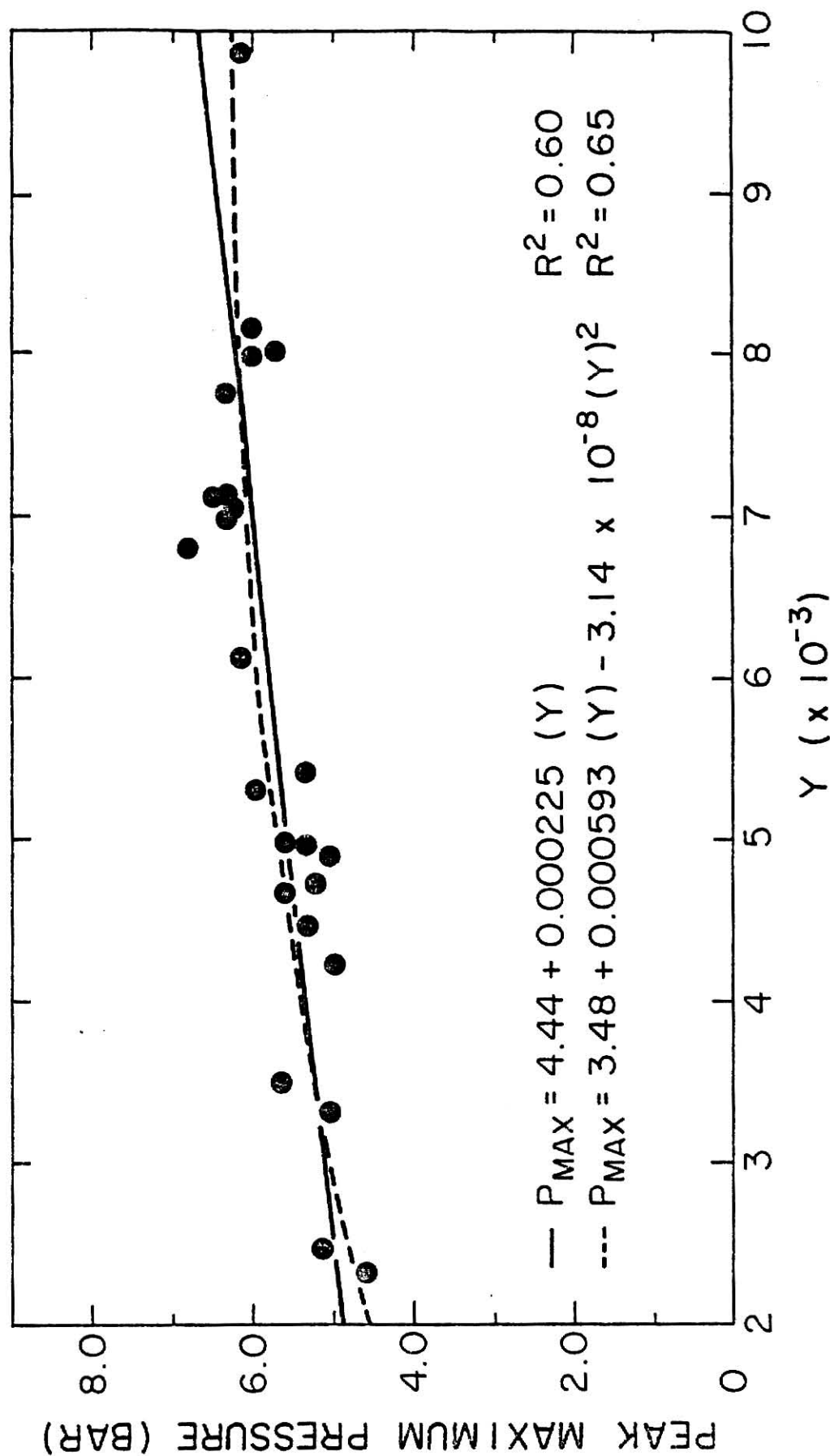


Figure 4.33. Comparison of the Experimental and Estimated Values of the Peak Maximum Pressure as a Function of  $Y$ .

$$\begin{aligned}
 P_{\text{MAX}} &= 4.44 + 0.0000484(-\Delta H_c^*)(\text{LPC}) \\
 &= 4.44 + 0.0000484(Z)
 \end{aligned}
 \tag{4.8}$$

where  $Z = (-\Delta H_c^*)(\text{LPC})$

In Figure 4.34 the estimated values from equation 4.8 and the experimental values of the peak maximum pressure are compared. The agreement is reasonable considering the scatter involved in the experimental results. In an attempt to improve the agreement a polynomial regression model was investigated. The result is

$$P_{\text{MAX}} = 2.63 + 0.000192(Z) - 2.62 \times 10^{-9}(Z)^2 \tag{4.9}$$

with a  $R^2$  value of 0.62. The polynomial correlation did improve the agreement as shown in Figure 4.34. The value of  $R^2$  also gives an indication of the agreement between the predicted and experimental values since the larger the  $R^2$  value the better the agreement. By using the polynomial correlation the agreement improved or the  $R^2$  value increased by 0.13. The  $R^2$  value for equation 4.9 is approximately the same as the  $R^2$  values for equations 4.6 and 4.7; thus, the agreement between the predicted and experimental values of the peak maximum pressure are approximately the same. In Appendix 6 the predicted values of the peak maximum pressure obtained from equations 4.6 through 4.9 are presented. All of the peak maximum pressure equations were developed for values of the peak maximum pressure between 4.6 and 6.9 bar and should not be used outside this range.

## VII. Comparison of Results

The values of the peak maximum rate and peak maximum pressure and the  $K_{\text{ST}}$ -values of wheat flour and cornstarch are compared to the results obtained by other researchers in Table 4.18. The explosion chambers are not the same size, but the peak maximum rate values can be compared by using the  $K_{\text{ST}}$ -values. For the cornstarch results the values of the

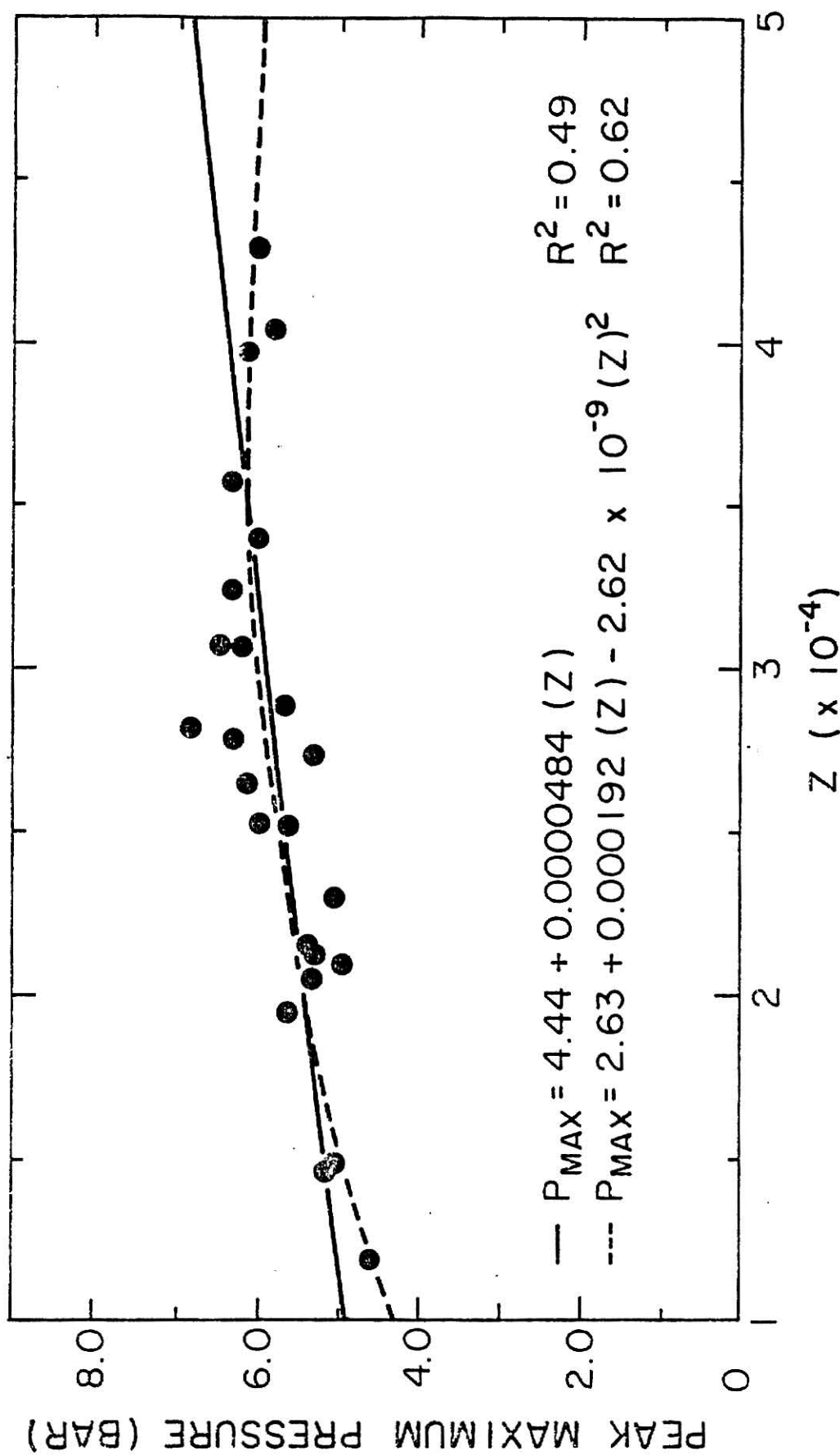


Figure 4.34. Comparison of the Experimental and Estimated Values of the peak maximum pressure as a function of  $Z$ .

Figure 4.18. Comparison of the Experimental Results for Cornstarch and Wheat Flour to the Results Obtained by Other Researchers.

| Dust                                                   | Volume of<br>Explosion Chamber<br>$\text{m}^3$ | $P_{\max}$<br>bar | $\left(\frac{dP}{dt}\right)_{\max}$<br>$\frac{\text{bar}}{\text{sec}}$ | $K_{ST}$<br>$\frac{\text{m} \cdot \text{bar}}{\text{sec}}$ |
|--------------------------------------------------------|------------------------------------------------|-------------------|------------------------------------------------------------------------|------------------------------------------------------------|
| Grain Marketing Cornstarch<br>(Lewis, 1982)            | 0.02                                           | 6.82              | 380                                                                    | 103                                                        |
| Procter & Gamble Cornstarch<br>(Cocks et al., 1980)    | 0.02                                           | 6.2               | 320                                                                    | 87                                                         |
| Bureau of Mines Cornstarch<br>(Jacobson et al., 1961)  | 0.0013                                         | 7.92              | 621                                                                    | 68                                                         |
| Grain Marketing Cornstarch<br>(Garrett, 1981)          | 0.0013                                         | 5.60              | 355                                                                    | 39                                                         |
| Grain Marketing Wheat Flour<br>(Lewis, 1982)           | 0.02                                           | 6.35              | 208                                                                    | 57                                                         |
| French Wheat Flour<br>(Giltaire et al., 1978)          | 1.0                                            | 6.6               | 95                                                                     | 95                                                         |
| French Wheat Flour<br>(Giltaire et al., 1978)          | 0.0013                                         | 3.6               | 71.5                                                                   | 8                                                          |
| Bureau of Mines Wheat Flour<br>(Jacobson et al., 1961) | 0.0013                                         | 6.55              | 255                                                                    | 28                                                         |

maximum pressure are approximately the same. The  $K_{ST}$ -values obtained by the Bureau of Mines (Jacobson et al., 1961) and Grain Marketing (Garrett, 1981) in the  $0.0013 \text{ m}^3$  chamber, the Hartmann apparatus, are lower than the  $K_{ST}$ -values obtained by Grain Marketing and Procter & Gamble (Cocks et al., 1980) in 20-liter chambers.

All the values of the maximum pressure obtained for wheat flour are approximately the same, except, for the results obtained by Giltair et al. (1978) in the Hartmann apparatus. This value is much lower than the other pressure values. All the  $K_{ST}$ -values should be approximately 95 bar·m/sec since this is the value obtained in a  $1.0 \text{ m}^3$  chamber (Giltair et al., 1978). However, the  $K_{ST}$ -values obtained in the Hartmann apparatus by Giltair et al. and by the Bureau of Mines (Jacobson et al., 1961) are considerably lower than 95 bar·m/sec. The value obtained at Grain Marketing in the 20-liter chamber is only slightly lower.



## REFERENCES

- Cocks, R. E. and Meyer, R. C. 1980. Fabrication and use of a 20 litre spherical dust testing apparatus. 88-th National AIChE Meeting. Philadelphia, Pa.
- Draper, Norman and Smith, Harry. 1981. Applied regression analysis. John Wiley & Sons, Inc. New York.
- Garrett, D. W. 1981. Study of mechanisms of grain dust explosions as affected by particle size and composition. Master's Thesis. Kansas State University.
- Giltaire, M., and Dangreux, J. 1978. Les poussières explosibles. [Explosive ducts]. Annales des Mines. Janvier-Février, pp. 85-96.
- Jacobson, M., Nagy, J., Cooper, A. R., and Ball, F. J. 1961. Explosibility of agricultural dusts. U.S. Department of the Interior, Bureau of Mines, Report of Investigation, RI-5753.

## CHAPTER 5

## CONCLUSIONS AND RECOMMENDATIONS

## I. Conclusion

Peak maximum rates of pressure rise and peak maximum pressures were measured for 30 dust samples in a 20-liter spherical explosion chamber. The values of the peak maximum rates ranged from 197 to 261 bar/sec for combination dust samples, 127 to 380 bar/sec for corn dust samples, 157 to 296 bar/sec for milo dust samples, 120 to 185 bar/sec for oats dust samples, 99 to 285 bar/sec for soybean dust samples and 75 to 244 bar/sec for wheat dust samples. The values of the peak maximum pressures ranged from 5.67 to 6.34 bar for combination dust samples, 5.07 to 6.82 bar for corn dust samples, 5.16 to 6.33 bar for milo dust samples, 5.01 to 5.69 bar for oats dust samples, 4.97 to 6.18 bar for soybean dust samples and 4.02 to 6.35 bar for wheat dust samples. These ranges show the wide range of values obtained within a dust type.

Each dust sample was characterized by its standard heat of combustion, specific surface area, average particle size, and ash and moisture content. This data was used in deriving statistical correlations for the explosibility parameters and the standard heat of combustion. Several statistical correlations have been developed showing that the peak maximum rate and peak maximum pressure are functions of the standard heat of combustion, external specific surface area, and quantity of dust present in the dust cloud. An additional correlation has been developed showing the standard heat of combustion is a function of the ash and moisture content. The heat of combustion correlation should only be used when the ash content is between 0 and 60 percent and the moisture content is between 5.5 and 15.0 percent. The explosibility parameter correlations should only be used

## II. Recommendations

The dispersion problem should be investigated. It may be possible to modify the dispersion horns or design a completely new method to disperse the dust. An aerodynamic study of the dusts and possible dispersion methods will be necessary. A possible method may be the injection of dust and air into the chamber from the top of the chamber.

Another area that should be investigated is controlled dust explosion tests in which the ash content, moisture content, and average particle size are varied. The results from these tests may provide a better understanding of dust explosions.

when the peak maximum rates are between 75 and 380 bar/sec and the peak maximum pressures are between 4.6 and 6.9 bar.

The values of the peak maximum rates and peak maximum pressures and the  $K_{ST}$ -values of cornstarch and wheat flour were compared to the results obtained by other researchers. These values agreed fairly well with the results obtained by other researchers in 20-liter and 1.0 m<sup>3</sup> chambers; however, the values did not agree with the results obtained in the Hartmann apparatus.

The values of the peak maximum rates were scaled by the cubic law to obtain  $K_{ST}$ -values. These  $K_{ST}$ -values and the values of the peak maximum pressures obtained provide the engineering data needed to design protective and preventive measures. For example, in explosion relief venting, a protective measure, the relief venting area required to release pressure can be determined from the  $K_{ST}$ -value.

The experimental explosion tests have demonstrated that the method for dispersing the dust is a limitation of the 20-liter spherical explosion chamber. First, the dispersion system, the dispersion horns, does not disperse all the dust. Much of the dust that enters the dispersion horns remains in them and is not dispersed into the chamber. Second, the average particle size of the dust is reduced by passing through the dispersion horns. The horns act like a separator by letting the smaller particles pass through but not the larger particles. This problem is enhanced by the spherical holes in the dispersion horns. Many of the dust particles are nonspherical and, thus, have to be properly oriented to pass through the spherical holes. Since the dust being tested is changed when it is dispersed, the value of the peak maximum rate and peak maximum pressure measured are not the correct values for the as received dust.

## APPENDIX 1

### OBSERVED VALUES OF THE EXPERIMENTAL DUST EXPLOSION TESTS

Table A1 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| CB12        | 60     | 60           | 155                                   | 5.83                 |
| CB12c       | 60     | 10           | 206                                   | 5.43                 |
| CB12c       | 60     | 10           | 194                                   | 5.59                 |
| CB12c       | 60     | 10           | 203                                   | 5.48                 |
| CB12c       | 60     | 15           | 221                                   | 5.86                 |
| CB12c       | 60     | 15           | 237                                   | 6.29                 |
| CB12c       | 60     | 15           | 333                                   | 6.76                 |
| CB12c       | 60     | 15           | 253                                   | 6.45                 |
| CB12c       | 60     | 20           | 218                                   | 6.31                 |
| CB12c       | 60     | 20           | 283                                   | 5.98                 |
| CB12c       | 60     | 20           | 226                                   | 5.64                 |
| CB12c       | 60     | 25           | 273                                   | 6.41                 |
| CB12c       | 60     | 25           | 149                                   | 6.23                 |
| CB12c       | 60     | 25           | 219                                   | 6.23                 |
| CB12c       | 60     | 30           | 241                                   | 5.93                 |
| CB12c       | 60     | 30           | 187                                   | 6.00                 |
| CB12c       | 60     | 30           | 197                                   | 6.15                 |
| CB12c       | 50     | 15           | 285                                   | 6.45                 |
| CB12c       | 50     | 15           | 209                                   | 5.98                 |
| CB12c       | 50     | 15           | 221                                   | 6.27                 |
| CB12c       | 70     | 15           | 206                                   | 5.87                 |
| CB12c       | 70     | 15           | 225                                   | 5.93                 |
| CB12c       | 100    | 15           | 146                                   | 6.00                 |
| CB13        | 100    | 15           | 136                                   | 5.81                 |
| CB13        | 60     | 10           | 166                                   | 5.29                 |
| CB13        | 60     | 10           | 172                                   | 5.33                 |
| CB13        | 60     | 10           | 157                                   | 5.17                 |
| CB13        | 60     | 15           | 278                                   | 5.86                 |
| CB13        | 60     | 15           | 225                                   | 5.51                 |
| CB13        | 60     | 15           | 184                                   | 5.59                 |
| CB13        | 60     | 20           | 230                                   | 5.77                 |
| CB13        | 60     | 20           | 219                                   | 6.08                 |

Table A1. Explosion Test Results for Combination Dust

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| CB12        | 60     | 10           | 131                                   | 5.15                 |
| CB12        | 60     | 10           | 99                                    | 4.84                 |
| CB12        | 60     | 10           | 105                                   | 4.96                 |
| CB12        | 60     | 15           | 103                                   | 4.91                 |
| CB12        | 60     | 15           | 136                                   | 5.17                 |
| CB12        | 60     | 15           | 165                                   | 5.27                 |
| CB12        | 60     | 20           | 167                                   | 5.59                 |
| CB12        | 60     | 20           | 136                                   | 4.81                 |
| CB12        | 60     | 20           | 136                                   | 4.59                 |
| CB12        | 60     | 25           | 170                                   | 5.75                 |
| CB12        | 60     | 25           | 123                                   | 5.17                 |
| CB12        | 60     | 25           | 158                                   | 5.21                 |
| CB12        | 60     | 30           | 155                                   | 5.52                 |
| CB12        | 60     | 30           | 163                                   | 5.37                 |
| CB12        | 60     | 30           | 160                                   | 5.27                 |
| CB12        | 60     | 35           | 194                                   | 5.39                 |
| CB12        | 60     | 35           | 159                                   | 5.17                 |
| CB12        | 60     | 35           | 165                                   | 5.25                 |
| CB12        | 60     | 40           | 176                                   | 5.15                 |
| CB12        | 60     | 40           | 182                                   | 5.19                 |
| CB12        | 60     | 40           | 173                                   | 5.39                 |
| CB12        | 60     | 45           | 197                                   | 5.72                 |
| CB12        | 60     | 45           | 213                                   | 5.63                 |
| CB12        | 60     | 45           | 151                                   | 5.48                 |
| CB12        | 60     | 50           | 201                                   | 5.61                 |
| CB12        | 60     | 50           | 180                                   | 5.39                 |
| CB12        | 60     | 50           | 209                                   | 5.39                 |
| CB12        | 60     | 55           | 194                                   | 6.09                 |
| CB12        | 60     | 55           | 139                                   | 5.47                 |
| CB12        | 60     | 55           | 223                                   | 5.45                 |
| CB12        | 60     | 60           | 161                                   | 5.39                 |

Table A1 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| CB13        | 60     | 20           | 122                                   | 5.38                 |
| CB13        | 60     | 20           | 159                                   | 5.79                 |
| CB13        | 60     | 25           | 241                                   | 5.45                 |
| CB13        | 60     | 25           | 259                                   | 5.84                 |
| CB13        | 60     | 25           | 243                                   | 5.59                 |
| CB13        | 60     | 25           | 162                                   | 5.73                 |
| CB13        | 60     | 25           | 296                                   | 6.29                 |
| CB13        | 60     | 25           | 195                                   | 6.05                 |
| CB13        | 60     | 30           | 189                                   | 5.99                 |
| CB13        | 60     | 30           | 132                                   | 5.86                 |
| CB13        | 60     | 30           | 223                                   | 5.89                 |
| CB13        | 50     | 25           | 153                                   | 6.01                 |
| CB13        | 50     | 25           | 141                                   | 5.71                 |
| CB13        | 70     | 25           | 181                                   | 6.05                 |
| CB13        | 70     | 25           | 162                                   | 5.94                 |
| CB13        | 100    | 25           | 198                                   | 6.41                 |
| CB13        | 100    | 25           | 213                                   | 6.26                 |

Table A2. Explosion Test Results for Corn Dust

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| CN21        | 60     | 10           | 199                                   | 5.22                 |
| CN21        | 60     | 10           | 156                                   | 4.89                 |
| CN21        | 60     | 10           | 249                                   | 5.39                 |
| CN21        | 60     | 15           | 260                                   | 5.86                 |
| CN21        | 60     | 15           | 294                                   | 5.86                 |
| CN21        | 60     | 15           | 252                                   | 6.10                 |
| CN21        | 60     | 20           | 311                                   | 6.21                 |
| CN21        | 60     | 20           | 269                                   | 5.83                 |
| CN21        | 60     | 20           | 293                                   | 6.34                 |
| CN21        | 60     | 20           | 285                                   | 6.19                 |
| CN21        | 60     | 25           | 193                                   | 5.99                 |
| CN21        | 60     | 25           | 231                                   | 5.59                 |
| CN21        | 60     | 25           | 241                                   | 5.53                 |
| CN21        | 50     | 20           | 278                                   | 5.79                 |
| CN21        | 50     | 20           | 285                                   | 5.75                 |
| CN21        | 70     | 20           | 193                                   | 5.84                 |
| CN21        | 70     | 20           | 279                                   | 5.95                 |
| CN21        | 100    | 20           | 201                                   | 6.17                 |
| CN21        | 100    | 20           | 153                                   | 5.89                 |
| CN22b       | 60     | 10           | 211                                   | 5.41                 |
| CN22b       | 60     | 10           | 167                                   | 5.63                 |
| CN22b       | 60     | 10           | 174                                   | 5.76                 |
| CN22b       | 60     | 15           | 177                                   | 6.21                 |
| CN22b       | 60     | 15           | 345                                   | 6.34                 |
| CN22b       | 60     | 15           | 297                                   | 6.37                 |
| CN22b       | 60     | 15           | 285                                   | 6.55                 |
| CN22b       | 60     | 20           | 222                                   | 6.17                 |
| CN22b       | 60     | 20           | 319                                   | 6.41                 |
| CN22b       | 60     | 20           | 209                                   | 5.81                 |
| CN22b       | 60     | 20           | 279                                   | 7.36                 |
| CN22b       | 60     | 25           | 246                                   | 6.17                 |

Table A2 (continued)

| Dust Sample | T2V ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| CN22b       | 60     | 25           | 253                                   | 5.51                 |
| CN22b       | 60     | 25           | 263                                   | 6.35                 |
| CN22b       | 60     | 30           | 222                                   | 6.41                 |
| CN22b       | 60     | 30           | 218                                   | 5.93                 |
| CN22b       | 60     | 30           | 221                                   | 6.15                 |
| CN22b       | 50     | 15           | 329                                   | 6.50                 |
| CN22b       | 50     | 15           | 316                                   | 6.43                 |
| CN22b       | 50     | 15           | 313                                   | 6.60                 |
| CN22b       | 50     | 15           | 335                                   | 6.45                 |
| CN22b       | 40     | 15           | 339                                   | 6.43                 |
| CN22b       | 40     | 15           | 213                                   | 6.01                 |
| CN22b       | 100    | 15           | 143                                   | 5.88                 |
| CN22b       | 100    | 15           | 169                                   | 6.15                 |
| CN23        | 60     | 10           | 145                                   | 5.07                 |
| CN23        | 60     | 10           | 136                                   | 5.43                 |
| CN23        | 60     | 10           | 105                                   | 4.71                 |
| CN23        | 60     | 15           | 147                                   | 5.23                 |
| CN23        | 60     | 15           | 157                                   | 5.27                 |
| CN23        | 60     | 15           | 119                                   | 4.79                 |
| CN23        | 60     | 15           | 87                                    | 4.59                 |
| CN23        | 60     | 20           | 127                                   | 5.11                 |
| CN23        | 60     | 20           | 114                                   | 4.79                 |
| CN23        | 60     | 20           | 125                                   | 4.79                 |
| CN23        | 60     | 25           | 123                                   | 4.93                 |
| CN23        | 60     | 25           | 99                                    | 4.69                 |
| CN23        | 60     | 25           | 102                                   | 4.77                 |
| CN23        | 60     | 30           | 117                                   | 5.01                 |
| CN23        | 60     | 30           | 97                                    | 4.88                 |
| CN23        | 60     | 30           | 114                                   | 5.03                 |
| CN23        | 50     | 15           | 115                                   | 5.11                 |
| CN23        | 50     | 15           | 102                                   | 4.69                 |
| CN23        | 70     | 15           | 104                                   | 4.85                 |

Table A2 (continued)

| Dust Sample | T2V ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| CN23        | 70     | 15           | 130                                   | 5.01                 |
| CN23        | 100    | 15           | 83                                    | 4.85                 |
| CN23        | 100    | 15           | 85                                    | 4.99                 |
| Cornstarch  | 60     | 10           | 297                                   | 6.23                 |
| Cornstarch  | 60     | 10           | 253                                   | 5.91                 |
| Cornstarch  | 60     | 10           | 262                                   | 6.07                 |
| Cornstarch  | 60     | 15           | 337                                   | 6.48                 |
| Cornstarch  | 60     | 15           | 306                                   | 6.49                 |
| Cornstarch  | 60     | 15           | 457                                   | 6.67                 |
| Cornstarch  | 60     | 20           | 333                                   | 6.31                 |
| Cornstarch  | 60     | 20           | 263                                   | 6.45                 |
| Cornstarch  | 60     | 20           | 321                                   | 6.39                 |
| Cornstarch  | 60     | 25           | 269                                   | 5.95                 |
| Cornstarch  | 60     | 25           | 335                                   | 6.31                 |
| Cornstarch  | 60     | 25           | 191                                   | 5.99                 |
| Cornstarch  | 60     | 30           | 191                                   | 6.03                 |
| Cornstarch  | 60     | 30           | 215                                   | 6.11                 |
| Cornstarch  | 60     | 30           | 189                                   | 6.41                 |
| Cornstarch  | 50     | 15           | 421                                   | 7.99                 |
| Cornstarch  | 50     | 15           | 489                                   | 7.03                 |
| Cornstarch  | 50     | 15           | 369                                   | 7.09                 |
| Cornstarch  | 50     | 15           | 345                                   | 6.73                 |
| Cornstarch  | 50     | 15           | 433                                   | 6.45                 |
| Cornstarch  | 50     | 15           | 366                                   | 6.53                 |
| Cornstarch  | 50     | 15           | 287                                   | 6.32                 |
| Cornstarch  | 50     | 15           | 327                                   | 6.38                 |
| Cornstarch  | 40     | 15           | 331                                   | 7.07                 |
| Cornstarch  | 40     | 15           | 303                                   | 6.97                 |
| Cornstarch  | 100    | 15           | 367                                   | 7.25                 |
| Cornstarch  | 100    | 15           | 339                                   | 7.25                 |



Table A3. Explosion Test Results for Milo Dust

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| M011        | 60     | 10           | 181                                   | 5.15                 |
| M011        | 60     | 10           | 194                                   | 5.57                 |
| M011        | 60     | 10           | 181                                   | 5.45                 |
| M011        | 60     | 15           | 231                                   | 5.51                 |
| M011        | 60     | 15           | 231                                   | 5.43                 |
| M011        | 60     | 15           | 203                                   | 5.35                 |
| M011        | 60     | 20           | 175                                   | 5.23                 |
| M011        | 60     | 20           | 238                                   | 5.65                 |
| M011        | 60     | 20           | 225                                   | 5.57                 |
| M011        | 60     | 25           | 207                                   | 5.43                 |
| M011        | 60     | 25           | 145                                   | 5.48                 |
| M011        | 60     | 25           | 244                                   | 5.88                 |
| M011        | 60     | 30           | 200                                   | 5.85                 |
| M011        | 60     | 30           | 177                                   | 5.55                 |
| M011        | 60     | 30           | 187                                   | 5.58                 |
| M011        | 60     | 35           | 283                                   | 5.69                 |
| M011        | 60     | 35           | 203                                   | 5.36                 |
| M011        | 60     | 35           | 273                                   | 5.77                 |
| M011        | 60     | 35           | 219                                   | 5.72                 |
| M011        | 60     | 40           | 225                                   | 5.75                 |
| M011        | 60     | 40           | 228                                   | 5.59                 |
| M011        | 60     | 40           | 181                                   | 5.60                 |
| M011        | 50     | 35           | 203                                   | 6.10                 |
| M011        | 50     | 35           | 267                                   | 5.53                 |
| M011        | 70     | 35           | 231                                   | 5.76                 |
| M011        | 70     | 35           | 177                                   | 5.72                 |
| M011        | 100    | 35           | 190                                   | 6.11                 |
| M011        | 100    | 35           | 152                                   | 5.93                 |
| M012        | 60     | 10           | 274                                   | 5.65                 |
| M012        | 60     | 10           | 225                                   | 5.61                 |

Table A3 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| M012        | 60     | 10           | 249                                   | 5.62                 |
| M012        | 60     | 15           | 283                                   | 6.00                 |
| M012        | 60     | 15           | 237                                   | 5.93                 |
| M012        | 60     | 15           | 218                                   | 6.21                 |
| M012        | 60     | 20           | 148                                   | 5.72                 |
| M012        | 60     | 20           | 321                                   | 6.21                 |
| M012        | 60     | 20           | 286                                   | 6.38                 |
| M012        | 60     | 25           | 308                                   | 6.47                 |
| M012        | 60     | 25           | 306                                   | 6.31                 |
| M012        | 60     | 25           | 327                                   | 6.43                 |
| M012        | 60     | 25           | 243                                   | 5.57                 |
| M012        | 60     | 30           | 247                                   | 6.13                 |
| M012        | 60     | 30           | 286                                   | 6.50                 |
| M012        | 60     | 30           | 283                                   | 6.01                 |
| M012        | 50     | 25           | 296                                   | 6.05                 |
| M012        | 50     | 25           | 243                                   | 5.87                 |
| M012        | 70     | 25           | 204                                   | 5.93                 |
| M012        | 70     | 25           | 201                                   | 5.83                 |
| M012        | 100    | 25           | 176                                   | 6.23                 |
| M012        | 100    | 25           | 182                                   | 6.01                 |
| M013        | 60     | 10           | 123                                   | 4.81                 |
| M013        | 60     | 10           | 130                                   | 4.67                 |
| M013        | 60     | 10           | 157                                   | 5.01                 |
| M013        | 60     | 15           | 141                                   | 4.96                 |
| M013        | 60     | 15           | 109                                   | 4.71                 |
| M013        | 60     | 15           | 153                                   | 5.25                 |
| M013        | 60     | 20           | 139                                   | 4.77                 |
| M013        | 60     | 20           | 155                                   | 5.12                 |
| M013        | 60     | 20           | 195                                   | 5.12                 |
| M013        | 60     | 20           | 139                                   | 4.95                 |
| M013        | 60     | 25           | 139                                   | 5.49                 |
| M013        | 60     | 25           | 120                                   | 4.93                 |

Table A3 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| M032b       | 60     | 15           | 149                                   | 4.74                 |
| M032b       | 60     | 15           | 203                                   | 5.34                 |
| M032b       | 60     | 15           | 165                                   | 5.19                 |
| M032b       | 60     | 15           | 145                                   | 5.13                 |
| M032b       | 60     | 20           | 168                                   | 5.17                 |
| M032b       | 60     | 20           | 180                                   | 5.48                 |
| M032b       | 60     | 20           | 234                                   | 5.47                 |
| M032b       | 60     | 25           | 203                                   | 5.74                 |
| M032b       | 60     | 25           | 206                                   | 5.62                 |
| M032b       | 60     | 25           | 203                                   | 5.33                 |
| M032b       | 60     | 25           | 171                                   | 5.69                 |
| M032b       | 60     | 30           | 200                                   | 5.75                 |
| M032b       | 60     | 30           | 203                                   | 5.89                 |
| M032b       | 60     | 30           | 187                                   | 5.83                 |
| M032b       | 60     | 35           | 231                                   | 5.69                 |
| M032b       | 60     | 35           | 190                                   | 5.52                 |
| M032b       | 60     | 35           | 134                                   | 5.29                 |
| M032b       | 50     | 25           | 161                                   | 5.26                 |
| M032b       | 50     | 25           | 168                                   | 5.14                 |
| M032b       | 70     | 25           | 133                                   | 5.24                 |
| M032b       | 70     | 25           | 136                                   | 5.35                 |
| M032b       | 100    | 25           | 134                                   | 5.65                 |
| M032b       | 100    | 25           | 91                                    | 5.25                 |
| M032c       | 60     | 5            | 87                                    | 4.15                 |
| M032c       | 60     | 5            | 101                                   | 4.17                 |
| M032c       | 60     | 5            | 117                                   | 4.38                 |
| M032c       | 60     | 10           | 281                                   | 5.79                 |
| M032c       | 60     | 10           | 275                                   | 5.55                 |
| M032c       | 60     | 10           | 229                                   | 5.55                 |
| M032c       | 60     | 15           | 249                                   | 6.03                 |
| M032c       | 60     | 15           | 250                                   | 7.09                 |
| M032c       | 60     | 15           | 247                                   | 6.13                 |

Table A3 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| M013        | 60     | 25           | 171                                   | 5.29                 |
| M013        | 60     | 30           | 183                                   | 5.50                 |
| M013        | 60     | 30           | 153                                   | 5.19                 |
| M013        | 60     | 30           | 129                                   | 5.00                 |
| M013        | 50     | 20           | 196                                   | 5.33                 |
| M013        | 50     | 20           | 114                                   | 4.79                 |
| M013        | 70     | 20           | 175                                   | 5.51                 |
| M013        | 70     | 20           | 117                                   | 4.98                 |
| M013        | 100    | 20           | 111                                   | 5.50                 |
| M013        | 100    | 20           | 102                                   | 5.15                 |
| M020        | 60     | 10           | 114                                   | 4.60                 |
| M020        | 60     | 10           | 101                                   | 4.61                 |
| M020        | 60     | 10           | 122                                   | 4.77                 |
| M020        | 60     | 15           | 150                                   | 5.27                 |
| M020        | 60     | 15           | 160                                   | 5.17                 |
| M020        | 60     | 15           | 162                                   | 4.97                 |
| M020        | 60     | 20           | 116                                   | 4.83                 |
| M020        | 60     | 20           | 111                                   | 4.52                 |
| M020        | 60     | 20           | 167                                   | 5.21                 |
| M020        | 60     | 25           | 182                                   | 4.81                 |
| M020        | 60     | 25           | 163                                   | 5.12                 |
| M020        | 60     | 25           | 139                                   | 5.19                 |
| M020        | 60     | 30           | 125                                   | 4.93                 |
| M020        | 60     | 30           | 162                                   | 5.13                 |
| M020        | 60     | 30           | 137                                   | 4.91                 |
| M020        | 50     | 25           | 229                                   | 5.07                 |
| M020        | 50     | 25           | 182                                   | 5.11                 |
| M020        | 50     | 25           | 145                                   | 5.31                 |
| M032b       | 60     | 10           | 153                                   | 4.79                 |
| M032b       | 60     | 10           | 149                                   | 4.98                 |
| M032b       | 60     | 10           | 149                                   | 4.87                 |
| M032b       | 60     | 10           | 137                                   | 4.88                 |

Table A3 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| M032c       | 60     | 15           | 261                                   | 6.09                 |
| M032c       | 60     | 20           | 221                                   | 5.86                 |
| M032c       | 60     | 20           | 263                                   | 5.74                 |
| M032c       | 60     | 20           | 257                                   | 6.33                 |
| M032c       | 60     | 25           | 209                                   | 5.96                 |
| M032c       | 60     | 25           | 247                                   | 6.19                 |
| M032c       | 60     | 25           | 216                                   | 6.15                 |
| M032c       | 60     | 30           | 237                                   | 6.13                 |
| M032c       | 60     | 30           | 167                                   | 5.95                 |
| M032c       | 60     | 30           | 281                                   | 6.15                 |
| M032c       | 50     | 10           | 243                                   | 5.19                 |
| M032c       | 50     | 10           | 319                                   | 5.79                 |
| M032c       | 50     | 10           | 238                                   | 5.31                 |
| M032c       | 50     | 10           | 247                                   | 5.50                 |
| M032c       | 40     | 10           | 157                                   | 4.93                 |
| M032c       | 40     | 10           | 275                                   | 5.36                 |
| M032c       | 100    | 10           | 143                                   | 5.36                 |
| M032c       | 100    | 10           | 127                                   | 4.99                 |

Table A4. Explosion Test Results for Oats Dust

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| OT12        | 60     | 10           | 89                                    | 5.19                 |
| OT12        | 60     | 10           | 105                                   | 5.07                 |
| OT12        | 60     | 10           | 107                                   | 5.03                 |
| OT12        | 60     | 15           | 120                                   | 5.47                 |
| OT12        | 60     | 15           | 114                                   | 5.19                 |
| OT12        | 60     | 15           | 132                                   | 5.81                 |
| OT12        | 60     | 20           | 130                                   | 5.39                 |
| OT12        | 60     | 20           | 117                                   | 5.29                 |
| OT12        | 60     | 20           | 120                                   | 5.69                 |
| OT12        | 60     | 25           | 93                                    | 5.09                 |
| OT12        | 60     | 25           | 136                                   | 5.57                 |
| OT12        | 60     | 25           | 143                                   | 5.79                 |
| OT12        | 60     | 30           | 153                                   | 5.69                 |
| OT12        | 60     | 30           | 143                                   | 5.77                 |
| OT12        | 60     | 30           | 168                                   | 5.62                 |
| OT12        | 60     | 35           | 155                                   | 5.50                 |
| OT12        | 60     | 35           | 136                                   | 5.05                 |
| OT12        | 60     | 35           | 168                                   | 5.57                 |
| OT12        | 60     | 40           | 114                                   | 5.07                 |
| OT12        | 60     | 40           | 136                                   | 5.45                 |
| OT12        | 60     | 40           | 136                                   | 5.23                 |
| OT12        | 50     | 30           | 145                                   | 5.33                 |
| OT12        | 50     | 30           | 171                                   | 5.27                 |
| OT12        | 50     | 30           | 175                                   | 5.50                 |
| OT12        | 50     | 30           | 104                                   | 5.26                 |
| OT12        | 40     | 30           | 114                                   | 5.21                 |
| OT12        | 40     | 30           | 79                                    | 5.17                 |
| OT12        | 100    | 30           | 76                                    | 4.61                 |
| OT12        | 100    | 30           | 75                                    | 4.72                 |
| OT12c       | 60     | 15           | 63                                    | 4.15                 |

Table A4 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| OT12c       | 60     | 20           | 54                                    | 3.85                 |
| OT12c       | 60     | 25           | 51                                    | 4.41                 |
| OT12c       | 60     | 25           | 63                                    | 4.37                 |
| OT12c       | 60     | 25           | 66                                    | 4.36                 |
| OT12c       | 60     | 30           | 81                                    | 4.43                 |
| OT12c       | 60     | 30           | 83                                    | 4.38                 |
| OT12c       | 60     | 30           | 65                                    | 4.37                 |
| OT12c       | 60     | 35           | 96                                    | 4.75                 |
| OT12c       | 60     | 35           | 97                                    | 4.81                 |
| OT12c       | 60     | 35           | 73                                    | 4.55                 |
| OT12c       | 60     | 40           | 95                                    | 4.47                 |
| OT12c       | 60     | 40           | 53                                    | 4.60                 |
| OT12c       | 60     | 40           | 97                                    | 4.83                 |
| OT12c       | 60     | 45           | 115                                   | 5.07                 |
| OT12c       | 60     | 45           | 87                                    | 4.83                 |
| OT12c       | 60     | 45           | 113                                   | 4.79                 |
| OT12c       | 60     | 50           | 107                                   | 4.98                 |
| OT12c       | 60     | 50           | 133                                   | 5.03                 |
| OT13        | 60     | 15           | 99                                    | 4.48                 |
| OT13        | 60     | 15           | 100                                   | 4.77                 |
| OT13        | 60     | 15           | 76                                    | 4.45                 |
| OT13        | 60     | 20           | 97                                    | 4.77                 |
| OT13        | 60     | 20           | 95                                    | 4.65                 |
| OT13        | 60     | 20           | 75                                    | 4.62                 |
| OT13        | 60     | 25           | 137                                   | 4.88                 |
| OT13        | 60     | 25           | 101                                   | 4.69                 |
| OT13        | 60     | 25           | 85                                    | 4.69                 |
| OT13        | 60     | 30           | 82                                    | 4.69                 |
| OT13        | 60     | 30           | 149                                   | 4.98                 |
| OT13        | 60     | 30           | 107                                   | 5.07                 |
| OT13        | 60     | 35           | 105                                   | 5.17                 |
| OT13        | 60     | 35           | 102                                   | 5.19                 |

Table A4 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| OT13        | 60     | 35           | 153                                   | 5.03                 |
| OT13        | 60     | 40           | 219                                   | 5.83                 |
| OT13        | 60     | 40           | 165                                   | 5.00                 |
| OT13        | 60     | 40           | 171                                   | 5.29                 |
| OT13        | 60     | 45           | 196                                   | 5.65                 |
| OT13        | 60     | 45           | 208                                   | 5.74                 |
| OT13        | 60     | 45           | 147                                   | 5.43                 |

Table A5 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| SB12a       | 90     | 15           | 105                                   | 4.86                 |
| SB12a       | 90     | 15           | 99                                    | 5.07                 |
| SB12a       | 90     | 15           | 120                                   | 5.17                 |
| SB12a       | 90     | 20           | 137                                   | 5.17                 |
| SB12a       | 90     | 20           | 99                                    | 4.97                 |
| SB12a       | 90     | 20           | 131                                   | 5.09                 |
| SB12a       | 90     | 25           | 143                                   | 5.51                 |
| SB12a       | 90     | 25           | 108                                   | 5.03                 |
| SB12a       | 90     | 25           | 159                                   | 5.35                 |
| SB12a       | 90     | 25           | 152                                   | 5.48                 |
| SB12a       | 90     | 25           | 123                                   | 5.15                 |
| SB12a       | 90     | 30           | 123                                   | 5.43                 |
| SB12a       | 90     | 30           | 131                                   | 5.34                 |
| SB12a       | 90     | 30           | 127                                   | 5.00                 |
| SB12a       | 50     | 25           | 165                                   | 5.29                 |
| SB12a       | 50     | 25           | 108                                   | 4.95                 |
| SB12a       | 60     | 25           | 177                                   | 5.14                 |
| SB12a       | 60     | 25           | 213                                   | 5.59                 |
| SB12a       | 60     | 25           | 193                                   | 5.45                 |
| SB12a       | 60     | 25           | 187                                   | 5.19                 |
| SB12a       | 70     | 25           | 197                                   | 5.21                 |
| SB12a       | 70     | 25           | 158                                   | 5.12                 |
| SB12a       | 80     | 25           | 145                                   | 5.01                 |
| SB12a       | 80     | 25           | 180                                   | 5.33                 |
| SB12a       | 100    | 25           | 105                                   | 5.17                 |
| SB12a       | 100    | 25           | 111                                   | 5.27                 |
| SB12a       | 100    | 25           | 135                                   | 5.19                 |
| SB12a       | 100    | 25           | 149                                   | 5.59                 |
| SB12a       | 100    | 25           | 155                                   | 5.48                 |
| SB12a       | 100    | 25           | 133                                   | 5.27                 |
| SB12a       | 100    | 25           | 124                                   | 5.36                 |
| SB12a       | 100    | 25           | 121                                   | 5.29                 |

Table A5. Explosion Test Results for Soybean Dust

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| SB11        | 60     | 10           | 111                                   | 4.85                 |
| SB11        | 60     | 10           | 137                                   | 4.71                 |
| SB11        | 60     | 10           | 131                                   | 4.85                 |
| SB11        | 60     | 15           | 164                                   | 5.11                 |
| SB11        | 60     | 15           | 136                                   | 5.07                 |
| SB11        | 60     | 15           | 145                                   | 5.09                 |
| SB11        | 60     | 20           | 170                                   | 4.74                 |
| SB11        | 60     | 20           | 185                                   | 5.24                 |
| SB11        | 60     | 20           | 182                                   | 5.29                 |
| SB11        | 60     | 25           | 216                                   | 5.35                 |
| SB11        | 60     | 25           | 207                                   | 5.89                 |
| SB11        | 60     | 25           | 209                                   | 5.61                 |
| SB11        | 60     | 30           | 253                                   | 5.74                 |
| SB11        | 60     | 30           | 139                                   | 5.36                 |
| SB11        | 60     | 30           | 171                                   | 5.34                 |
| SB11        | 50     | 25           | 219                                   | 5.47                 |
| SB11        | 50     | 25           | 213                                   | 5.55                 |
| SB11        | 50     | 25           | 213                                   | 5.31                 |
| SB11        | 50     | 25           | 242                                   | 5.63                 |
| SB11        | 40     | 25           | 169                                   | 5.17                 |
| SB11        | 40     | 25           | 194                                   | 5.45                 |
| SB11        | 100    | 25           | 157                                   | 5.50                 |
| SB11        | 100    | 25           | 139                                   | 5.74                 |
| SB12a       | 90     | 5            | 49                                    | 2.86                 |
| SB12a       | 90     | 5            | 48                                    | 2.38                 |
| SB12a       | 90     | 5            | 57                                    | 2.86                 |
| SB12a       | 90     | 10           | 79                                    | 4.29                 |
| SB12a       | 90     | 10           | 70                                    | 4.26                 |
| SB12a       | 90     | 10           | 92                                    | 4.53                 |
| SB12a       | 90     | 15           | 73                                    | 4.61                 |

Table A5 (continued)

| Dust Sample | TZV<br>ms | Loading<br>gram | Maximum rate of<br>pressure rise<br>bar/sec | Maximum pressure<br>bar |
|-------------|-----------|-----------------|---------------------------------------------|-------------------------|
| SB12a       | 100       | 25              | 139                                         | 5.37                    |
| SB13        | 60        | 10              | 207                                         | 5.31                    |
| SB13        | 60        | 10              | 201                                         | 5.27                    |
| SB13        | 60        | 10              | 170                                         | 5.07                    |
| SB13        | 60        | 15              | 277                                         | 5.63                    |
| SB13        | 60        | 15              | 275                                         | 6.19                    |
| SB13        | 60        | 15              | 243                                         | 5.72                    |
| SB13        | 60        | 15              | 343                                         | 5.96                    |
| SB13        | 60        | 20              | 275                                         | 6.03                    |
| SB13        | 60        | 20              | 240                                         | 5.69                    |
| SB13        | 60        | 20              | 237                                         | 6.07                    |
| SB13        | 60        | 25              | 260                                         | 5.91                    |
| SB13        | 60        | 25              | 272                                         | 5.91                    |
| SB13        | 60        | 25              | 189                                         | 6.03                    |
| SB13        | 60        | 30              | 247                                         | 5.77                    |
| SB13        | 60        | 30              | 287                                         | 5.98                    |
| SB13        | 60        | 30              | 197                                         | 5.97                    |
| SB13        | 50        | 15              | 284                                         | 6.09                    |
| SB13        | 50        | 15              | 151                                         | 5.58                    |
| SB13        | 70        | 15              | 191                                         | 5.59                    |
| SB13        | 70        | 15              | 240                                         | 5.91                    |
| SB13        | 100       | 15              | 112                                         | 5.31                    |
| SB13        | 100       | 15              | 102                                         | 5.19                    |
| SB21        | 60        | 10              | 133                                         | 4.97                    |
| SB21        | 60        | 10              | 161                                         | 5.05                    |
| SB21        | 60        | 10              | 161                                         | 5.14                    |
| SB21        | 60        | 15              | 203                                         | 5.62                    |
| SB21        | 60        | 15              | 213                                         | 5.74                    |
| SB21        | 60        | 15              | 201                                         | 5.81                    |
| SB21        | 60        | 20              | 171                                         | 5.64                    |
| SB21        | 60        | 20              | 247                                         | 5.71                    |

Table A5 (continued)

| Dust Sample | TZV<br>ms | Loading<br>gram | Maximum rate of<br>pressure rise<br>bar/sec | Maximum pressure<br>bar |
|-------------|-----------|-----------------|---------------------------------------------|-------------------------|
| SB21        | 60        | 20              | 243                                         | 6.17                    |
| SB21        | 60        | 20              | 203                                         | 5.79                    |
| SB21        | 60        | 25              | 222                                         | 5.87                    |
| SB21        | 60        | 25              | 194                                         | 5.53                    |
| SB21        | 60        | 25              | 207                                         | 5.73                    |
| SB21        | 60        | 30              | 209                                         | 5.49                    |
| SB21        | 60        | 30              | 139                                         | 5.45                    |
| SB21        | 60        | 30              | 174                                         | 5.69                    |
| SB21        | 50        | 20              | 209                                         | 5.77                    |
| SB21        | 50        | 20              | 213                                         | 5.65                    |
| SB21        | 70        | 20              | 217                                         | 6.25                    |
| SB21        | 70        | 20              | 187                                         | 6.11                    |
| SB21        | 100       | 20              | 183                                         | 6.03                    |
| SB21        | 100       | 20              | 149                                         | 5.97                    |
| SB22a       | 60        | 10              | 80                                          | 3.69                    |
| SB22a       | 60        | 10              | 77                                          | 3.65                    |
| SB22a       | 60        | 10              | 80                                          | 3.89                    |
| SB22a       | 60        | 15              | 109                                         | 4.39                    |
| SB22a       | 60        | 15              | 91                                          | 4.27                    |
| SB22a       | 60        | 15              | 83                                          | 4.25                    |
| SB22a       | 60        | 20              | 111                                         | 4.61                    |
| SB22a       | 60        | 20              | 87                                          | 4.43                    |
| SB22a       | 60        | 20              | 89                                          | 4.69                    |
| SB22a       | 60        | 25              | 111                                         | 4.67                    |
| SB22a       | 60        | 25              | 124                                         | 4.81                    |
| SB22a       | 60        | 25              | 75                                          | 4.95                    |
| SB22a       | 60        | 30              | 105                                         | 4.71                    |
| SB22a       | 60        | 30              | 99                                          | 4.76                    |
| SB22a       | 60        | 30              | 99                                          | 5.01                    |
| SB22a       | 60        | 35              | 75                                          | 4.95                    |
| SB22a       | 60        | 35              | 115                                         | 4.91                    |
| SB22a       | 60        | 35              | 93                                          | 4.45                    |

Table A5 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| SB22a       | 70     | 25           | 127                                   | 4.93                 |
| SB22a       | 70     | 25           | 89                                    | 5.00                 |
| SB22a       | 70     | 25           | 87                                    | 5.01                 |
| SB22a       | 70     | 25           | 95                                    | 4.86                 |
| SB22a       | 80     | 25           | 79                                    | 4.72                 |
| SB22a       | 80     | 25           | 116                                   | 5.23                 |
| SB22a       | 50     | 25           | 61                                    | 4.61                 |
| SB22a       | 50     | 25           | 53                                    | 4.50                 |
| SB22a       | 100    | 25           | 70                                    | 5.00                 |
| SB22a       | 100    | 25           | 83                                    | 4.95                 |
| SB22b       | 60     | 10           | 76                                    | 4.43                 |
| SB22b       | 60     | 10           | 75                                    | 4.19                 |
| SB22b       | 60     | 10           | 64                                    | 4.26                 |
| SB22b       | 60     | 15           | 88                                    | 5.21                 |
| SB22b       | 60     | 15           | 99                                    | 4.57                 |
| SB22b       | 60     | 15           | 77                                    | 4.50                 |
| SB22b       | 60     | 20           | 92                                    | 4.88                 |
| SB22b       | 60     | 20           | 76                                    | 4.76                 |
| SB22b       | 60     | 20           | 114                                   | 4.88                 |
| SB22b       | 60     | 25           | 113                                   | 4.98                 |
| SB22b       | 60     | 25           | 125                                   | 5.03                 |
| SB22b       | 60     | 25           | 88                                    | 4.91                 |
| SB22b       | 60     | 30           | 115                                   | 5.09                 |
| SB22b       | 60     | 30           | 119                                   | 5.17                 |
| SB22b       | 60     | 30           | 145                                   | 4.79                 |
| SB22b       | 60     | 30           | 71                                    | 4.65                 |
| SB22b       | 60     | 35           | 99                                    | 4.81                 |
| SB22b       | 60     | 35           | 101                                   | 5.13                 |
| SB22b       | 60     | 35           | 119                                   | 4.71                 |
| SB22b       | 50     | 30           | 109                                   | 4.61                 |
| SB22b       | 50     | 30           | 67                                    | 4.74                 |
| SB22b       | 70     | 30           | 108                                   | 4.75                 |

Table A5 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure rise bar/sec | Maximum pressure bar |
|-------------|--------|--------------|---------------------------------------|----------------------|
| SB22b       | 70     | 30           | 99                                    | 5.15                 |
| SB22b       | 100    | 30           | 80                                    | 5.15                 |
| SB22b       | 100    | 30           | 97                                    | 5.03                 |
| SB23        | 60     | 10           | 99                                    | 4.69                 |
| SB23        | 60     | 10           | 115                                   | 4.48                 |
| SB23        | 60     | 10           | 117                                   | 4.71                 |
| SB23        | 60     | 15           | 136                                   | 4.89                 |
| SB23        | 60     | 15           | 181                                   | 5.00                 |
| SB23        | 60     | 15           | 135                                   | 4.86                 |
| SB23        | 60     | 20           | 114                                   | 5.00                 |
| SB23        | 60     | 20           | 93                                    | 5.00                 |
| SB23        | 60     | 20           | 167                                   | 4.93                 |
| SB23        | 60     | 20           | 127                                   | 4.79                 |
| SB23        | 60     | 25           | 125                                   | 5.14                 |
| SB23        | 60     | 25           | 156                                   | 5.05                 |
| SB23        | 60     | 25           | 120                                   | 4.81                 |
| SB23        | 60     | 25           | 132                                   | 4.98                 |
| SB23        | 60     | 30           | 175                                   | 5.62                 |
| SB23        | 60     | 30           | 180                                   | 5.25                 |
| SB23        | 60     | 30           | 165                                   | 5.43                 |
| SB23        | 60     | 30           | 169                                   | 5.26                 |
| SB23        | 60     | 35           | 181                                   | 5.00                 |
| SB23        | 60     | 35           | 155                                   | 5.05                 |
| SB23        | 60     | 35           | 180                                   | 5.19                 |
| SB23        | 60     | 40           | 213                                   | 5.23                 |
| SB23        | 60     | 40           | 122                                   | 5.01                 |
| SB23        | 50     | 30           | 162                                   | 5.47                 |
| SB23        | 50     | 30           | 135                                   | 5.24                 |
| SB23        | 70     | 30           | 120                                   | 5.08                 |
| SB23        | 70     | 30           | 159                                   | 5.40                 |
| SB23        | 100    | 30           | 135                                   | 5.07                 |
| SB23        | 100    | 30           | 129                                   | 4.98                 |

Table A6 (continued)

| Dust Sample | TZV ms | Loading gram | Maximum rise of pressure bar/sec | Maximum pressure bar |
|-------------|--------|--------------|----------------------------------|----------------------|
| WT12a       | 60     | 20           | 201                              | 5.89                 |
| WT12a       | 60     | 20           | 213                              | 6.10                 |
| WT12a       | 60     | 20           | 198                              | 5.86                 |
| WT12a       | 60     | 25           | 194                              | 6.24                 |
| WT12a       | 60     | 25           | 238                              | 6.01                 |
| WT12a       | 60     | 25           | 204                              | 5.77                 |
| WT12a       | 60     | 30           | 256                              | 6.00                 |
| WT12a       | 60     | 30           | 207                              | 5.86                 |
| WT12a       | 60     | 30           | 155                              | 5.88                 |
| WT12a       | 50     | 15           | 229                              | 6.09                 |
| WT12a       | 50     | 15           | 231                              | 5.69                 |
| WT12a       | 50     | 15           | 239                              | 5.79                 |
| WT12a       | 50     | 15           | 185                              | 5.45                 |
| WT12a       | 40     | 15           | 219                              | 5.83                 |
| WT12a       | 40     | 15           | 228                              | 5.54                 |
| WT12a       | 100    | 15           | 114                              | 5.65                 |
| WT12a       | 100    | 15           | 117                              | 5.55                 |
| WT12b       | 60     | 10           | 91                               | 5.15                 |
| WT12b       | 60     | 10           | 136                              | 5.26                 |
| WT12b       | 60     | 10           | 123                              | 5.29                 |
| WT12b       | 60     | 15           | 101                              | 5.19                 |
| WT12b       | 60     | 15           | 175                              | 5.38                 |
| WT12b       | 60     | 15           | 97                               | 4.87                 |
| WT12b       | 60     | 20           | 133                              | 5.49                 |
| WT12b       | 60     | 20           | 199                              | 5.73                 |
| WT12b       | 60     | 20           | 145                              | 5.31                 |
| WT12b       | 60     | 25           | 143                              | 5.33                 |
| WT12b       | 60     | 25           | 167                              | 5.25                 |
| WT12b       | 60     | 25           | 149                              | 5.60                 |
| WT12b       | 60     | 30           | 111                              | 5.17                 |
| WT12b       | 60     | 30           | 105                              | 5.13                 |
| WT12b       | 60     | 30           | 133                              | 5.39                 |

Table A6. Explosion Test Results for Wheat Dust

| Dust Sample | TZV ms | Loading gram | Maximum rate of pressure bar/sec | Maximum pressure bar |
|-------------|--------|--------------|----------------------------------|----------------------|
| WT11        | 60     | 10           | 149                              | 5.07                 |
| WT11        | 60     | 10           | 85                               | 4.53                 |
| WT11        | 60     | 10           | 121                              | 4.83                 |
| WT11        | 60     | 15           | 152                              | 5.24                 |
| WT11        | 60     | 15           | 171                              | 5.24                 |
| WT11        | 60     | 15           | 107                              | 4.93                 |
| WT11        | 60     | 15           | 108                              | 4.79                 |
| WT11        | 60     | 20           | 98                               | 4.83                 |
| WT11        | 60     | 20           | 149                              | 5.31                 |
| WT11        | 60     | 20           | 105                              | 5.05                 |
| WT11        | 60     | 25           | 136                              | 5.07                 |
| WT11        | 60     | 25           | 89                               | 4.86                 |
| WT11        | 60     | 25           | 121                              | 4.93                 |
| WT11        | 60     | 30           | 123                              | 5.03                 |
| WT11        | 60     | 30           | 121                              | 4.77                 |
| WT11        | 60     | 30           | 117                              | 4.81                 |
| WT11        | 50     | 15           | 159                              | 4.87                 |
| WT11        | 50     | 15           | 168                              | 5.24                 |
| WT11        | 50     | 15           | 151                              | 5.03                 |
| WT11        | 50     | 15           | 137                              | 5.47                 |
| WT11        | 40     | 15           | 114                              | 4.71                 |
| WT11        | 40     | 15           | 123                              | 4.86                 |
| WT11        | 100    | 15           | 76                               | 4.87                 |
| WT11        | 100    | 15           | 79                               | 4.79                 |
| WT12a       | 60     | 10           | 124                              | 5.36                 |
| WT12a       | 60     | 10           | 143                              | 5.05                 |
| WT12a       | 60     | 10           | 151                              | 5.24                 |
| WT12a       | 60     | 15           | 197                              | 5.81                 |
| WT12a       | 60     | 15           | 235                              | 5.87                 |
| WT12a       | 60     | 15           | 226                              | 5.93                 |



Table A6 (continued)

| Dust Sample | TZV<br>ms | Loading<br>gram | Maximum rate of<br>pressure rise<br>bar/sec | Maximum pressure<br>bar |
|-------------|-----------|-----------------|---------------------------------------------|-------------------------|
| WT12b       | 50        | 20              | 225                                         | 5.74                    |
| WT12b       | 50        | 20              | 147                                         | 5.48                    |
| WT12b       | 50        | 20              | 142                                         | 5.45                    |
| WT21        | 50        | 20              | 131                                         | 5.29                    |
| WT21        | 40        | 20              | 109                                         | 5.57                    |
| WT21        | 40        | 20              | 87                                          | 5.41                    |
| WT21        | 100       | 20              | 112                                         | 5.67                    |
| WT21        | 100       | 20              | 89                                          | 5.53                    |
| WT21        | 60        | 10              | 156                                         | 5.36                    |
| WT21        | 60        | 10              | 231                                         | 5.70                    |
| WT21        | 60        | 10              | 161                                         | 5.39                    |
| WT21        | 60        | 15              | 237                                         | 5.75                    |
| WT21        | 60        | 15              | 265                                         | 5.93                    |
| WT21        | 60        | 15              | 258                                         | 5.96                    |
| WT21        | 60        | 15              | 217                                         | 5.74                    |
| WT21        | 60        | 20              | 248                                         | 6.03                    |
| WT21        | 60        | 20              | 231                                         | 5.88                    |
| WT21        | 60        | 20              | 224                                         | 5.99                    |
| WT21        | 60        | 25              | 218                                         | 5.81                    |
| WT21        | 60        | 25              | 220                                         | 5.61                    |
| WT21        | 60        | 25              | 255                                         | 5.76                    |
| WT21        | 60        | 30              | 167                                         | 5.69                    |
| WT21        | 60        | 30              | 209                                         | 5.93                    |
| WT21        | 60        | 30              | 213                                         | 5.87                    |
| WT21        | 50        | 15              | 205                                         | 6.22                    |
| WT21        | 50        | 15              | 184                                         | 5.74                    |
| WT21        | 70        | 15              | 191                                         | 5.71                    |
| WT21        | 70        | 15              | 171                                         | 5.74                    |
| WT21        | 100       | 15              | 123                                         | 5.49                    |
| WT21        | 100       | 15              | 117                                         | 5.22                    |
| WT22a       | 60        | 10              | 66                                          | 4.07                    |
| WT22a       | 60        | 10              | 70                                          | 4.27                    |

Table A6 (continued)

| Dust Sample | TZV<br>ms | Loading<br>gram | Maximum rate of<br>pressure rise<br>bar/sec | Maximum pressure<br>bar |
|-------------|-----------|-----------------|---------------------------------------------|-------------------------|
| WT22a       | 60        | 10              | 75                                          | 4.83                    |
| WT22a       | 60        | 15              | 67                                          | 4.95                    |
| WT22a       | 60        | 15              | 82                                          | 5.03                    |
| WT22a       | 60        | 15              | 79                                          | 5.12                    |
| WT22a       | 60        | 20              | 73                                          | 4.85                    |
| WT22a       | 60        | 20              | 75                                          | 4.83                    |
| WT22a       | 60        | 20              | 96                                          | 5.00                    |
| WT22a       | 60        | 20              | 63                                          | 4.95                    |
| WT22a       | 60        | 25              | 67                                          | 5.35                    |
| WT22a       | 60        | 25              | 79                                          | 5.26                    |
| WT22a       | 60        | 25              | 76                                          | 5.31                    |
| WT22a       | 60        | 30              | 63                                          | 4.89                    |
| WT22a       | 60        | 30              | 73                                          | 5.35                    |
| WT22a       | 60        | 30              | 73                                          | 5.35                    |
| WT22a       | 50        | 20              | 92                                          | 4.89                    |
| WT22a       | 50        | 20              | 76                                          | 4.93                    |
| WT22a       | 50        | 20              | 63                                          | 4.67                    |
| WT22a       | 40        | 20              | 57                                          | —                       |
| WT22a       | 40        | 20              | 73                                          | 4.88                    |
| WT22a       | 70        | 20              | 63                                          | 4.79                    |
| WT22a       | 70        | 20              | 63                                          | 4.81                    |
| WT22a       | 100       | 20              | 72                                          | —                       |
| WT22a       | 100       | 20              | 61                                          | 5.03                    |
| WT23        | 60        | 10              | 65                                          | 3.79                    |
| WT23        | 60        | 10              | 71                                          | 4.39                    |
| WT23        | 60        | 10              | 67                                          | 3.99                    |
| WT23        | 60        | 15              | 65                                          | 4.19                    |
| WT23        | 60        | 15              | 67                                          | 4.25                    |
| WT23        | 60        | 15              | 89                                          | 4.61                    |
| WT23        | 60        | 15              | 79                                          | 4.62                    |
| WT23        | 60        | 20              | 64                                          | 4.27                    |
| WT23        | 60        | 20              | 81                                          | 4.07                    |

Table A6 (continued)

| Dust Sample | TZV<br>ms | Loading<br>gram | Maximum rate of<br>pressure rise<br>bar/sec | Maximum pressure<br>bar |
|-------------|-----------|-----------------|---------------------------------------------|-------------------------|
| WT23        | 60        | 20              | 60                                          | 4.05                    |
| WT23        | 60        | 25              | 57                                          | 3.72                    |
| WT23        | 60        | 25              | 78                                          | 3.90                    |
| WT23        | 60        | 25              | 73                                          | 3.89                    |
| WT23        | 60        | 30              | 51                                          | 4.24                    |
| WT23        | 60        | 30              | 51                                          | 4.01                    |
| WT23        | 60        | 30              | 71                                          | 3.86                    |
| WT23        | 50        | 15              | 63                                          | 4.43                    |
| WT23        | 50        | 15              | 69                                          | 4.47                    |
| WT23        | 70        | 15              | 63                                          | 4.19                    |
| WT23        | 70        | 15              | 71                                          | 4.41                    |
| WT23        | 100       | 15              | 60                                          | 4.71                    |
| WT23        | 100       | 15              | 53                                          | 4.53                    |
| Wheat Flour | 60        | 10              | 145                                         | 4.89                    |
| Wheat Flour | 60        | 10              | 111                                         | 4.79                    |
| Wheat Flour | 60        | 10              | 127                                         | 4.47                    |
| Wheat Flour | 60        | 15              | 197                                         | 5.93                    |
| Wheat Flour | 60        | 15              | 151                                         | 5.13                    |
| Wheat Flour | 60        | 15              | 163                                         | 5.63                    |
| Wheat Flour | 60        | 20              | 161                                         | 5.93                    |
| Wheat Flour | 60        | 20              | 173                                         | 6.01                    |
| Wheat Flour | 60        | 20              | 191                                         | 6.31                    |
| Wheat Flour | 60        | 25              | 187                                         | 6.15                    |
| Wheat Flour | 60        | 25              | 235                                         | 6.05                    |
| Wheat Flour | 60        | 25              | 197                                         | 5.81                    |
| Wheat Flour | 60        | 25              | 213                                         | 6.33                    |
| Wheat Flour | 60        | 30              | 173                                         | 6.05                    |
| Wheat Flour | 60        | 30              | 157                                         | 5.69                    |
| Wheat Flour | 60        | 30              | 226                                         | 6.53                    |
| Wheat Flour | 50        | 25              | 207                                         | 6.13                    |
| Wheat Flour | 50        | 25              | 197                                         | 6.05                    |
| Wheat Flour | 70        | 25              | 204                                         | 6.53                    |

Table A6 (continued)

| Dust Sample | TZV<br>ms | Loading<br>gram | Maximum rate of<br>pressure rise<br>bar/sec | Maximum pressure<br>bar |
|-------------|-----------|-----------------|---------------------------------------------|-------------------------|
| Wheat Flour | 70        | 25              | 207                                         | 5.89                    |
| Wheat Flour | 100       | 25              | 170                                         | 6.50                    |
| Wheat Flour | 100       | 25              | 145                                         | 6.21                    |

## APPENDIX 2

PLOTS OF THE MAXIMUM RATE OF  
PRESSURE RISE VERSUS THE AMOUNT  
OF LOADED DUST AND PLOTS OF  
THE MAXIMUM PRESSURE VERSUS  
THE AMOUNT OF LOADED DUST FOR  
EACH DUST SAMPLE

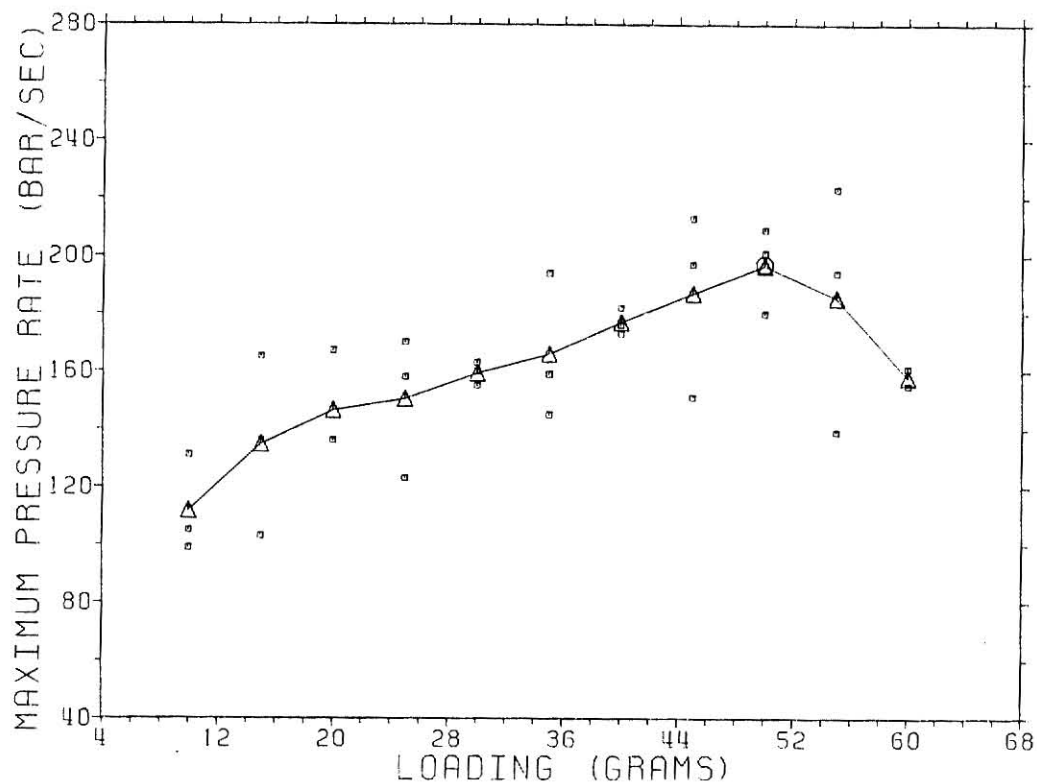


Figure A1. Effect of Dust Loading on Maximum Rate of Pressure Rise for CB12.  
 □ = observed value    △ = mean value    ○ = peak value (average)

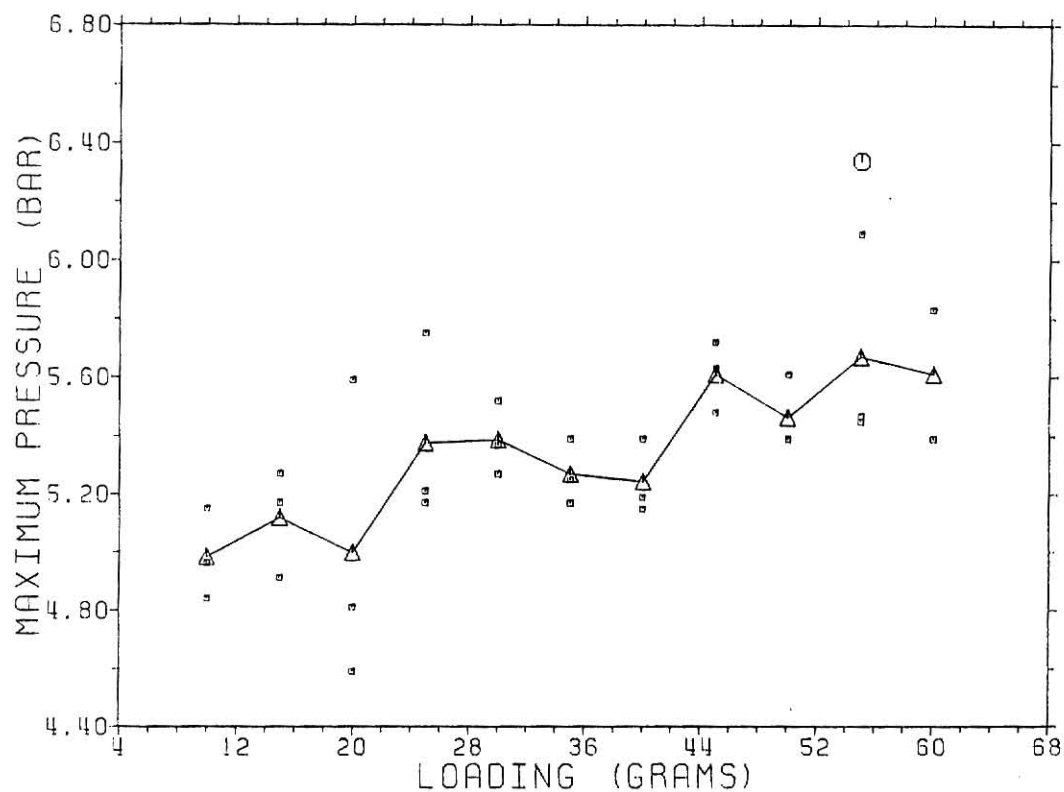


Figure A2. Effect of Dust Loading on Maximum Pressure for CB12.  
 □ = observed value    △ = mean value    ○ = peak value (average)

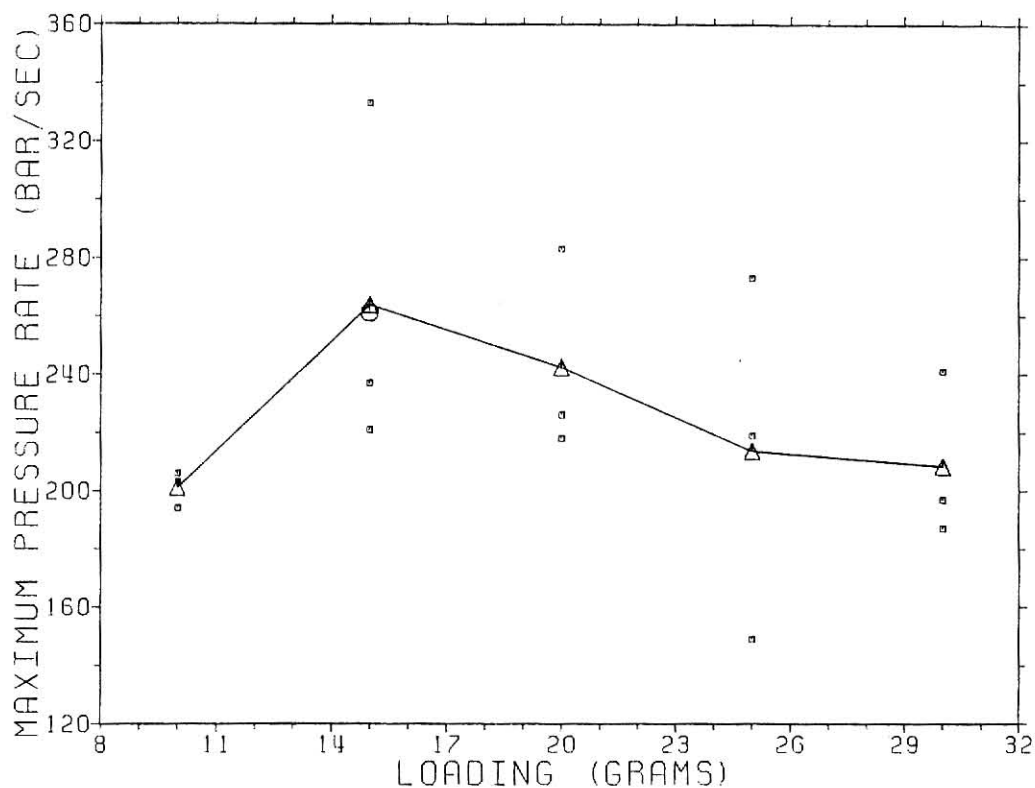


Figure A3. Effect of Dust Loading on Maximum Rate of Pressure Rise for CB12c.  
 □ = observed value    △ = mean value    ○ = peak value (average)

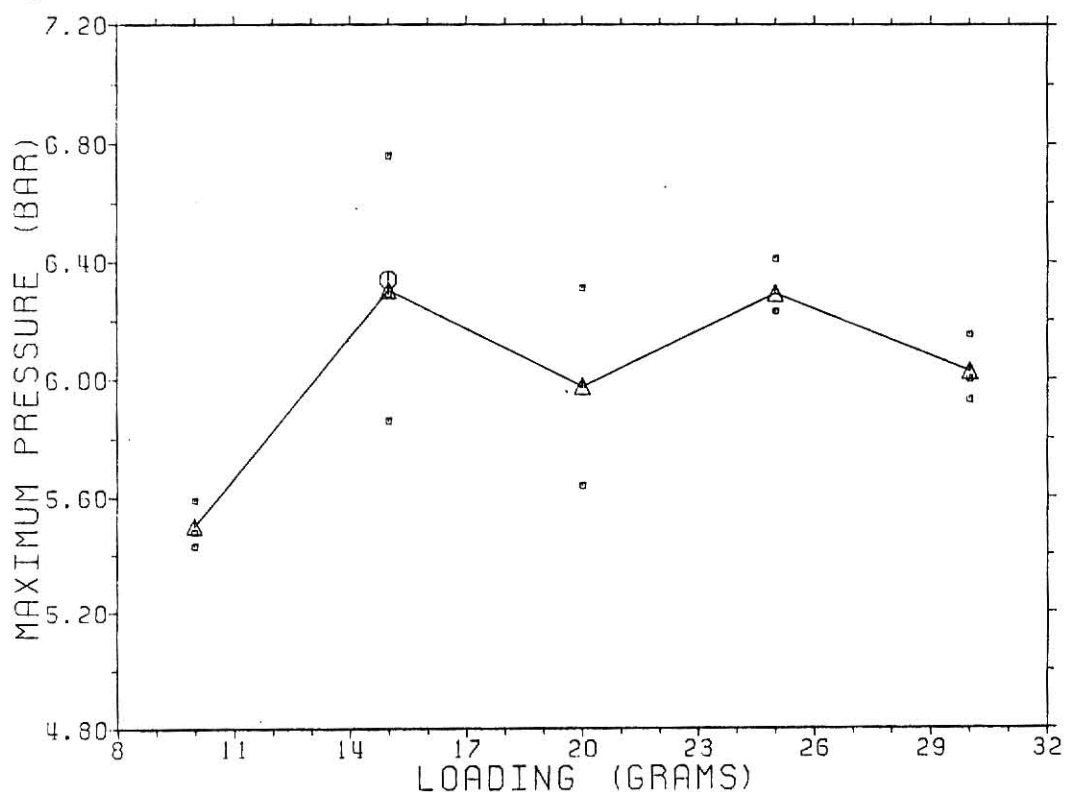


Figure A4. Effect of Dust Loading on Maximum Pressure for CB12c.  
 □ = observed value    △ = mean value    ○ = peak value (average)

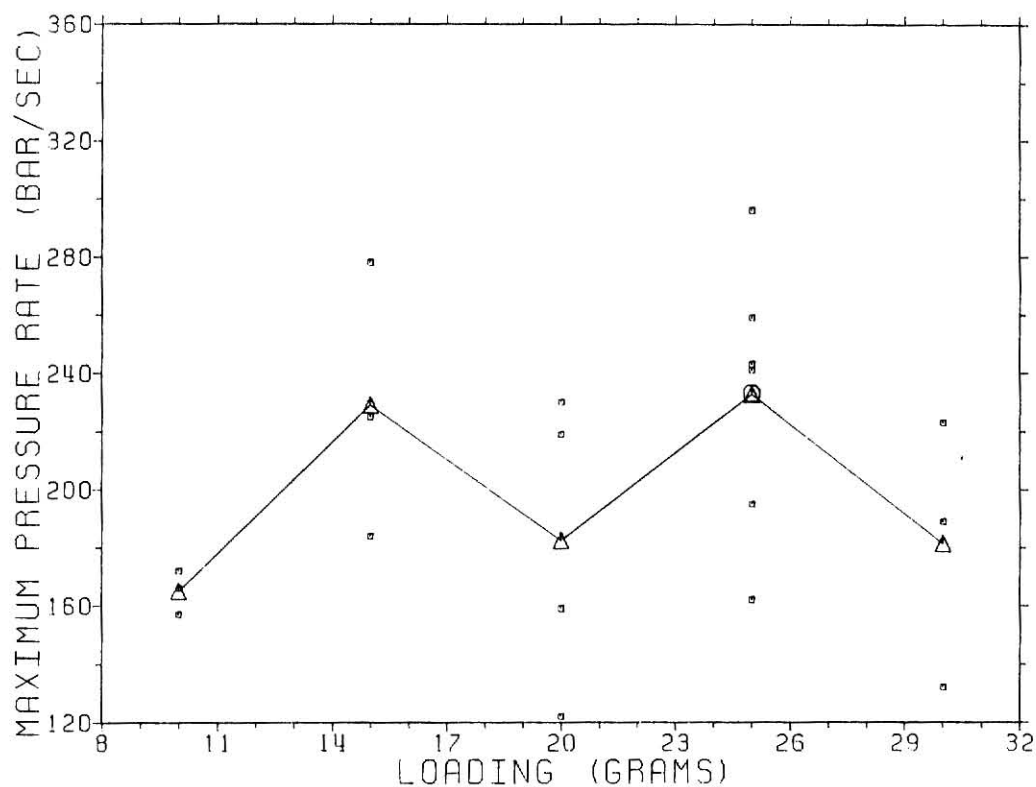


Figure A5. Effect of Dust Loading on Maximum Rate of Pressure Rise for CB13.  
 □ = observed value    △ = mean value    ○ = peak value (average)

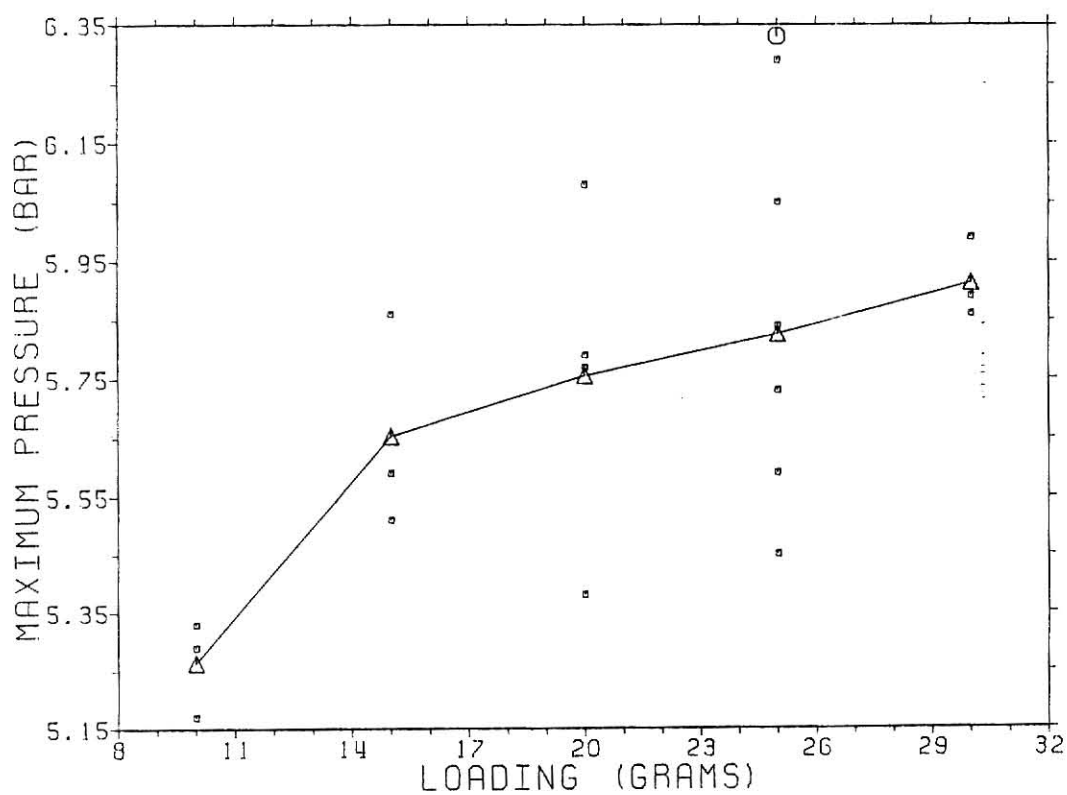


Figure A6. Effect of Dust Loading on Maximum Pressure for CB13.  
 □ = observed value    △ = mean value    ○ = peak value (average)

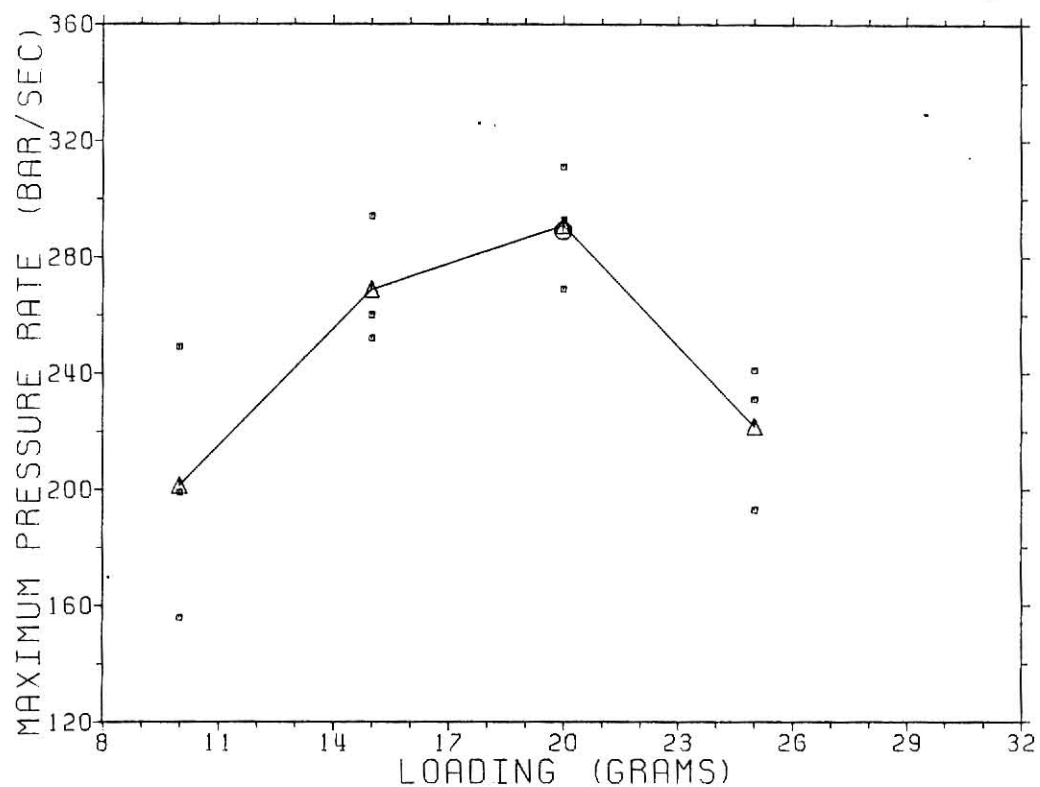


Figure A7. Effect of Dust Loading on Maximum Rate of Pressure Rise for CN21.  
 □ = observed value    △ = mean value    ○ = peak value (average)

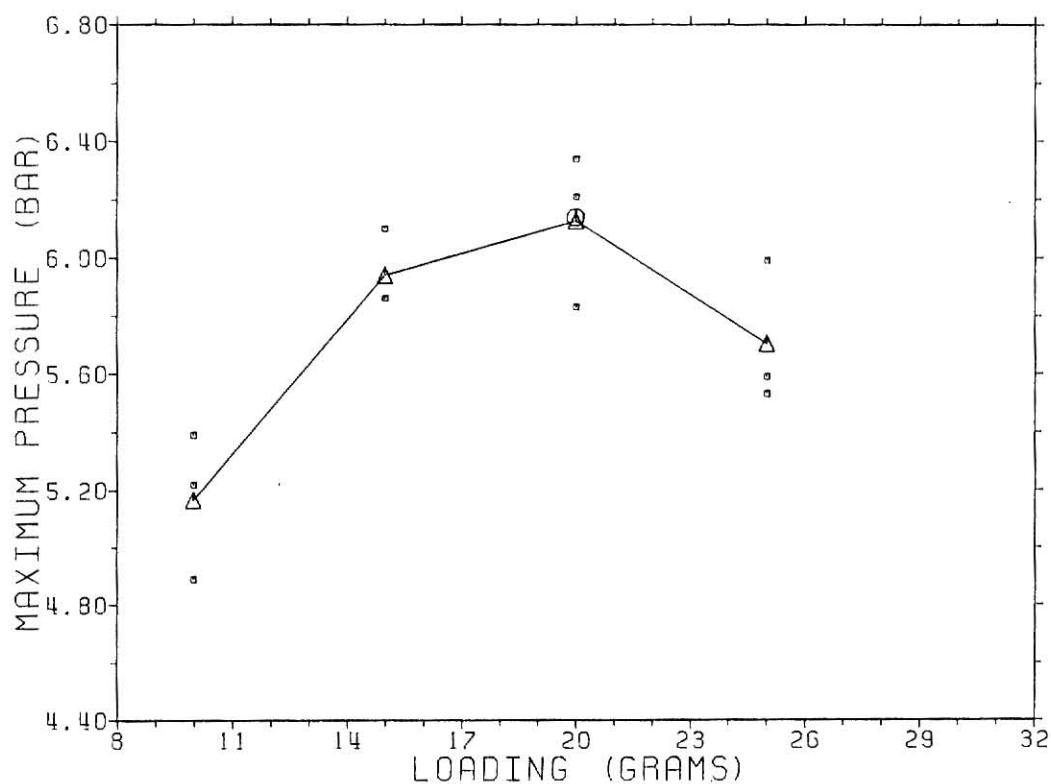


Figure A8. Effect of Dust Loading on Maximum Pressure for CN21.  
 □ = observed value    △ = mean value    ○ = peak value (average)

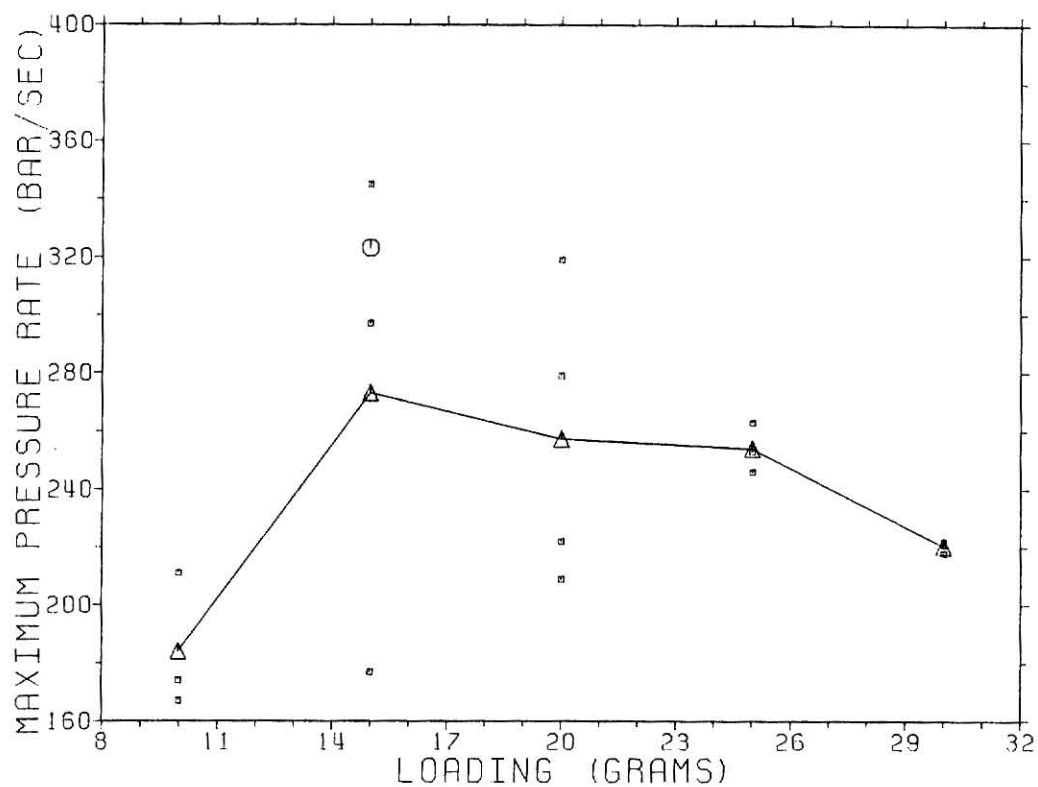


Figure A9. Effect of Dust Loading on Maximum Rate of Pressure Rise for CN22b.  
 □ = observed value    △ = mean value    ○ = peak value (average)

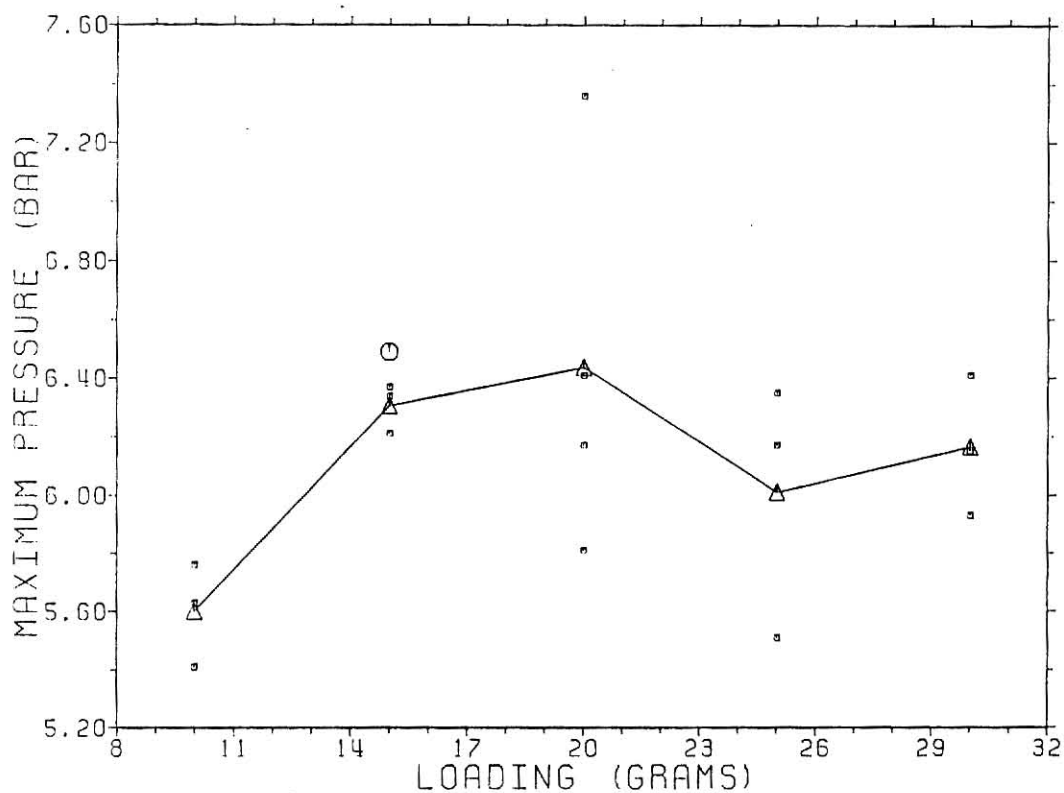


Figure A10. Effect of Dust Loading on Maximum Pressure for CN22b.  
 □ = observed value    △ = mean value    ○ = peak value (average)



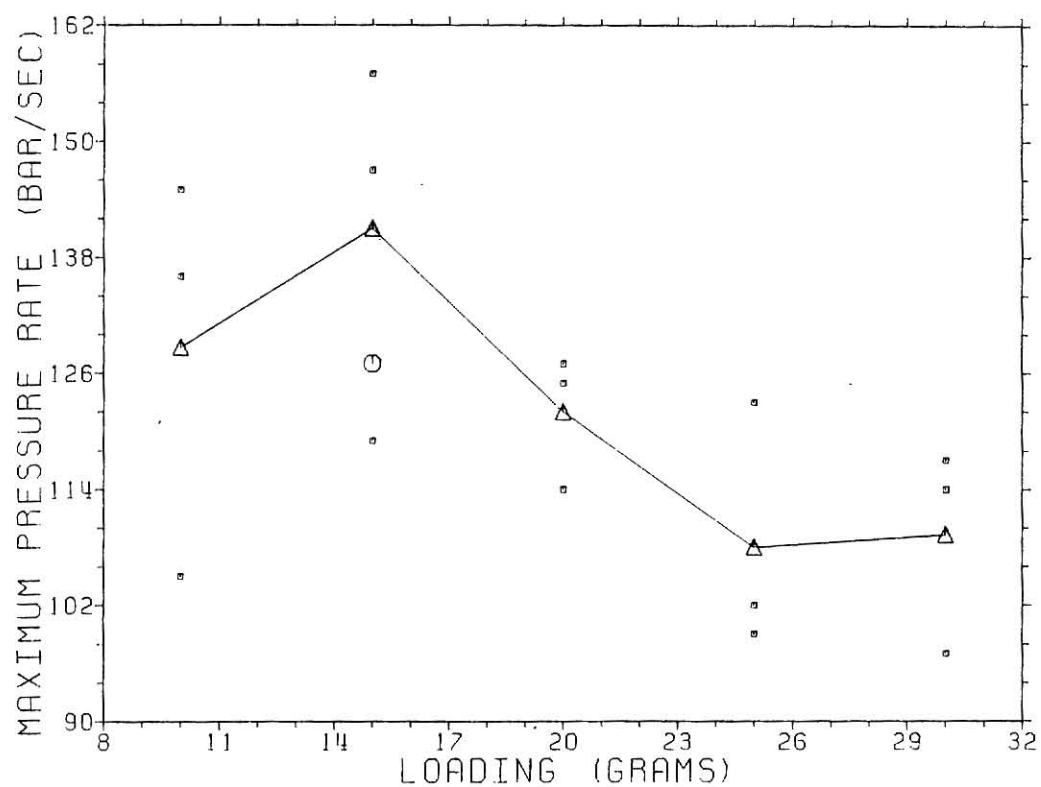


Figure A11. Effect of Dust Loading on Maximum Rate of Pressure Rise for CN23.  
 □ = observed value    △ = mean value    ○ = peak value (average)

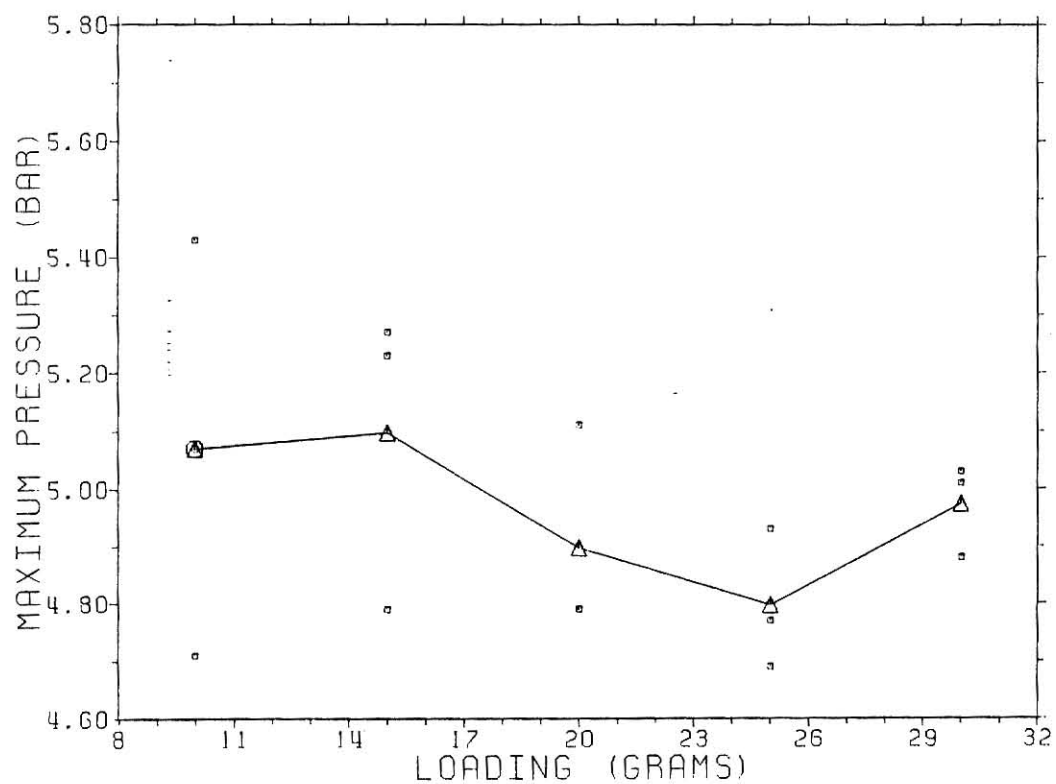


Figure A12. Effect of Dust Loading on Maximum Pressure for CN23.  
 □ = observed value    △ = mean value    ○ = peak value (average)

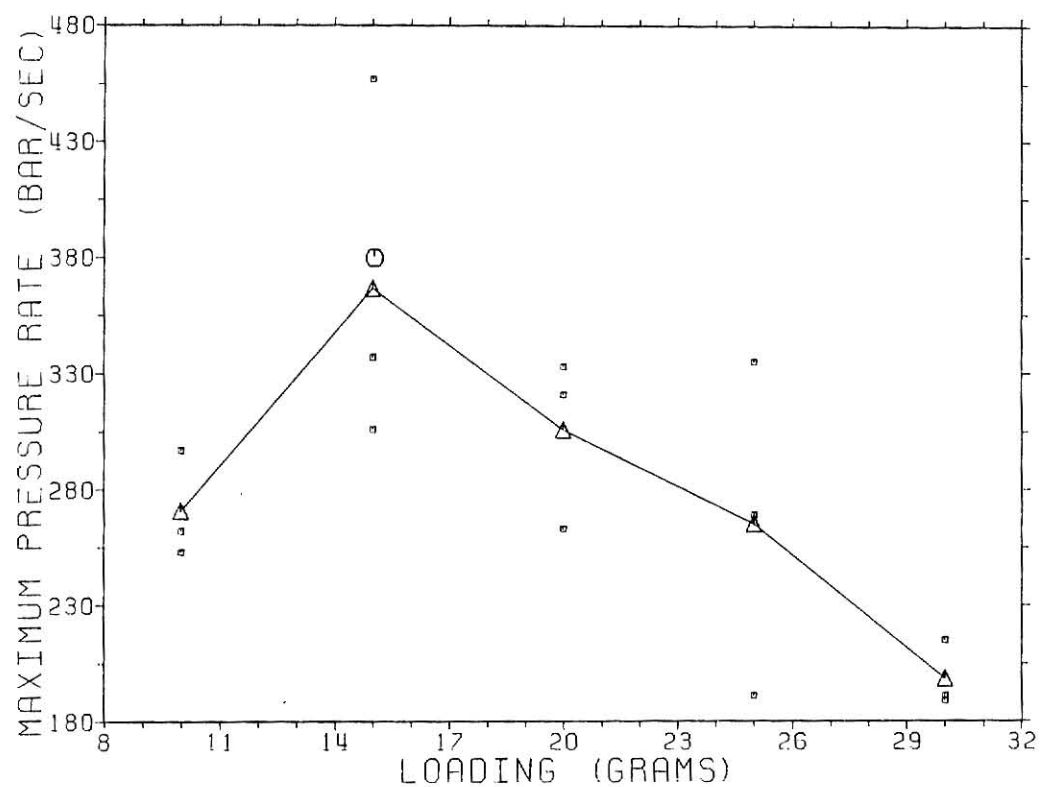


Figure A13. Effect of Dust Loading on Maximum Rate of Pressure Rise for Cornstarch.  
 □ = observed value    △ = mean value    ○ = peak value (average)

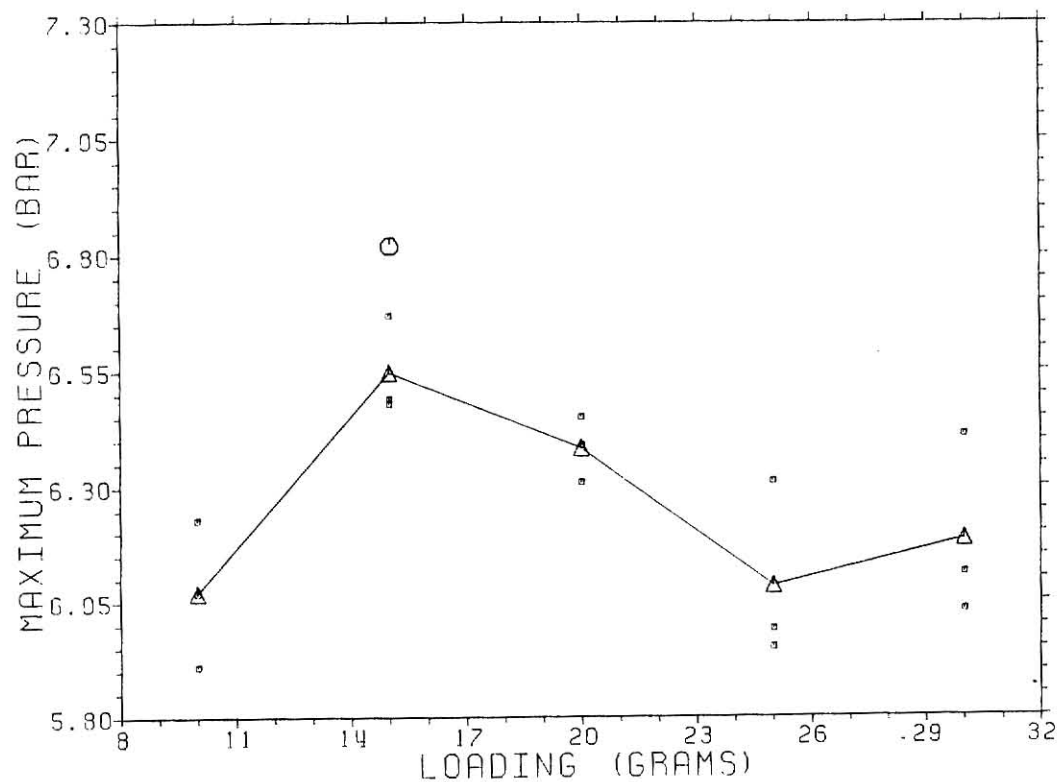


Figure A14. Effect of Dust Loading on Maximum Pressure for Cornstarch.  
 □ = observed value    △ = mean value    ○ = peak value (average)

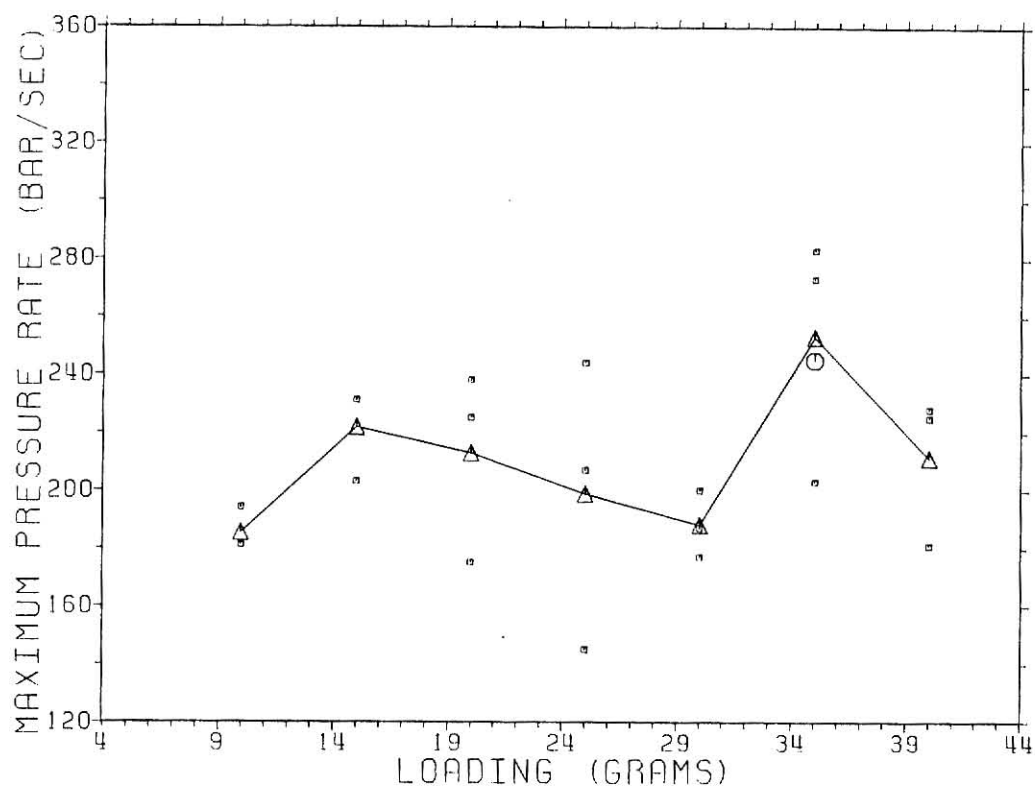


Figure A15. Effect of Dust Loading on Maximum Rate of Pressure Rise for M011.  
 □ = observed value    △ = mean value    ○ = peak value (average)

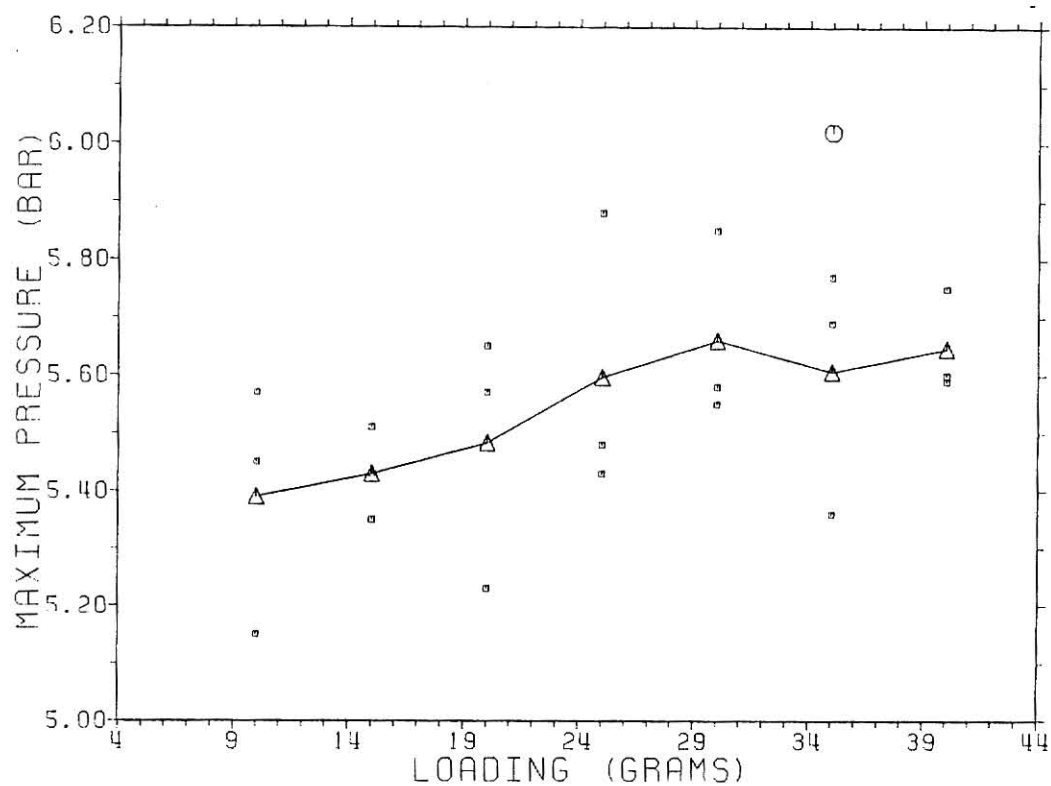


Figure A16. Effect of Dust Loading on Maximum Pressure for M011.  
 □ = observed value    △ = mean value    ○ = peak value (average)

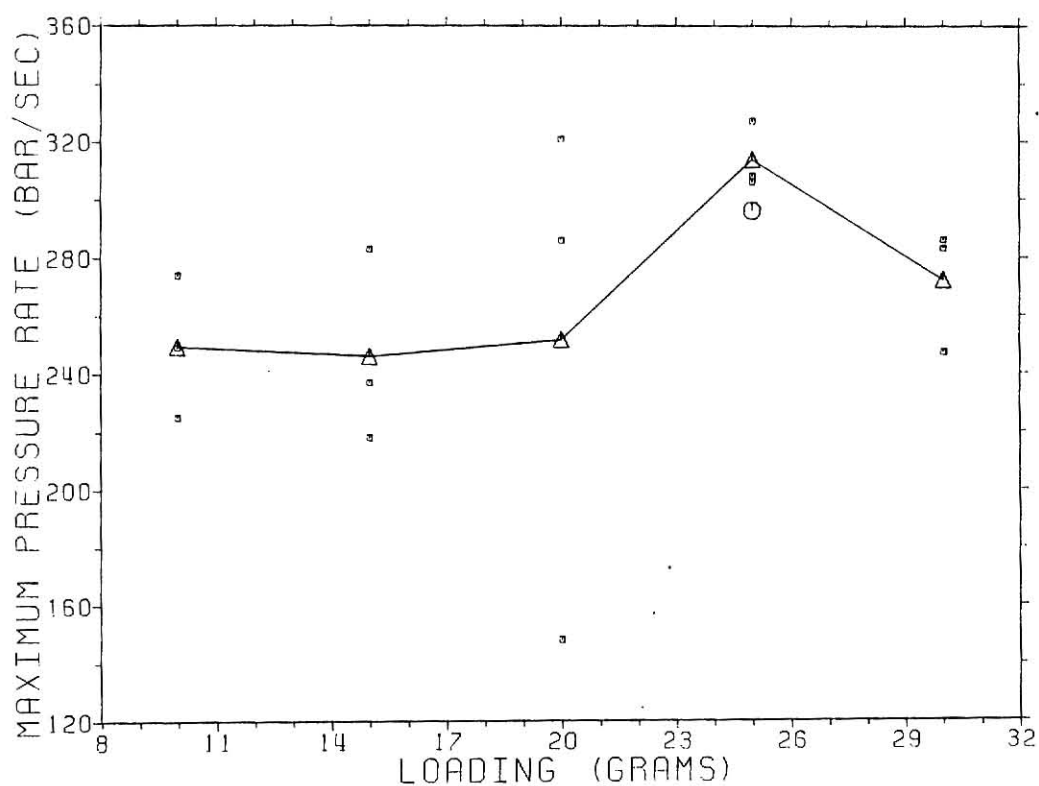


Figure A17. Effect of Dust Loading on Maximum Rate of Pressure Rise for M012.  
 □ = observed value    △ = mean value    ○ = peak value (average)

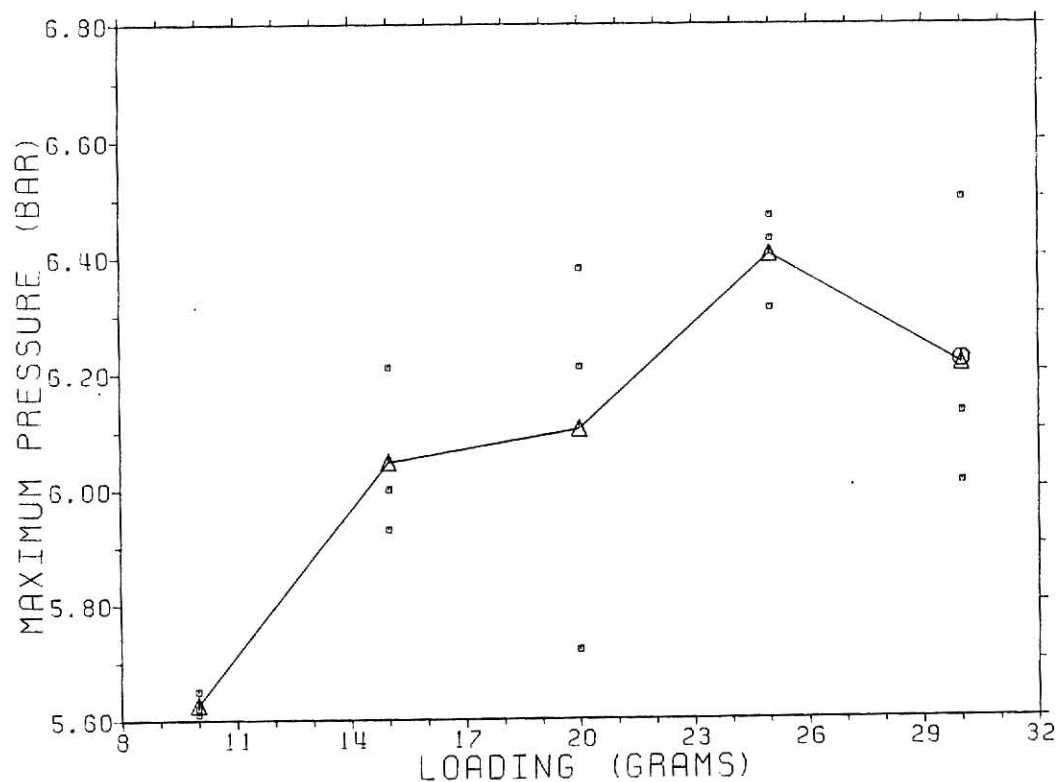


Figure A18. Effect of Dust Loading on Maximum Pressure for M012.  
 □ = observed value    △ = mean value    ○ = peak value (average)

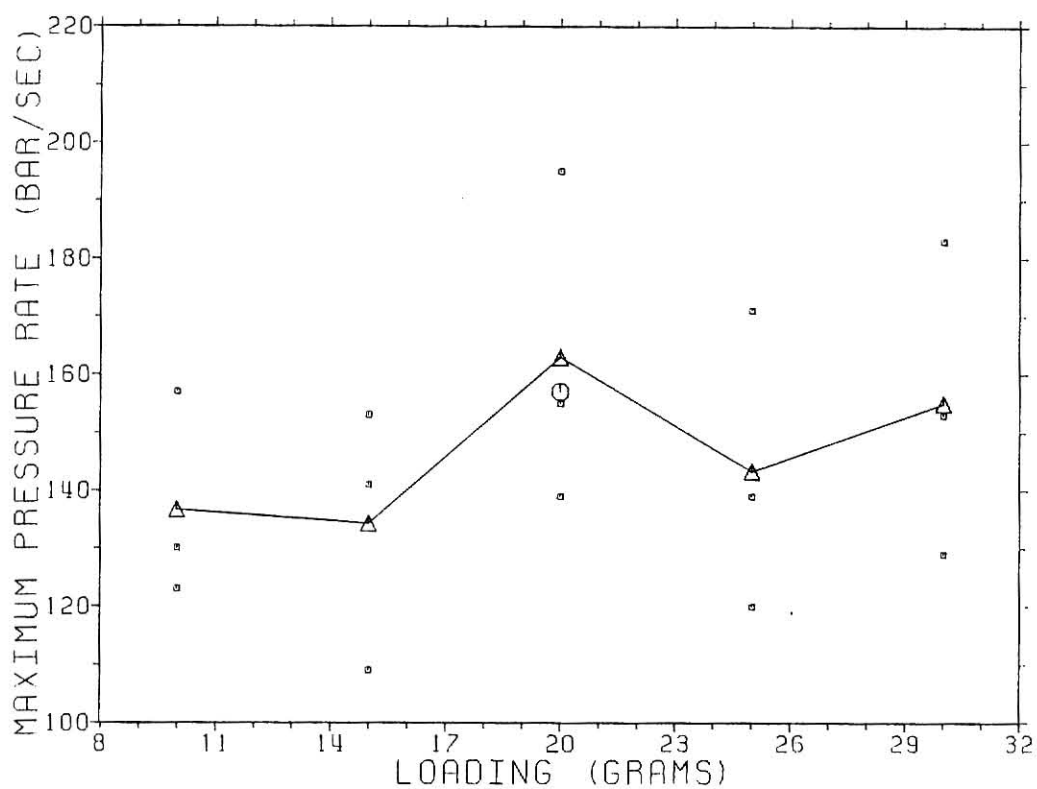


Figure A19. Effect of Dust Loading on Maximum Rate of Pressure Rise for M013.  
 □ = observed value    △ = mean value    ○ = peak value (average)

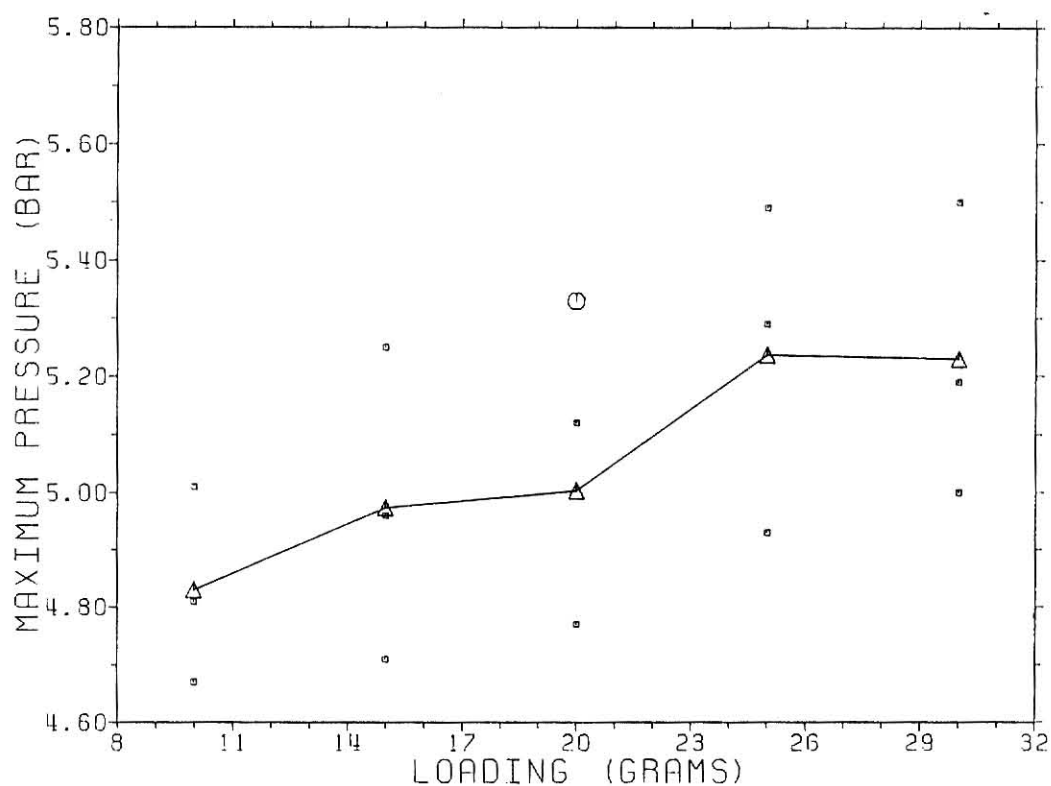


Figure A20. Effect of Dust Loading on Maximum Pressure for M013.  
 □ = observed value    △ = mean value    ○ = peak value (average)

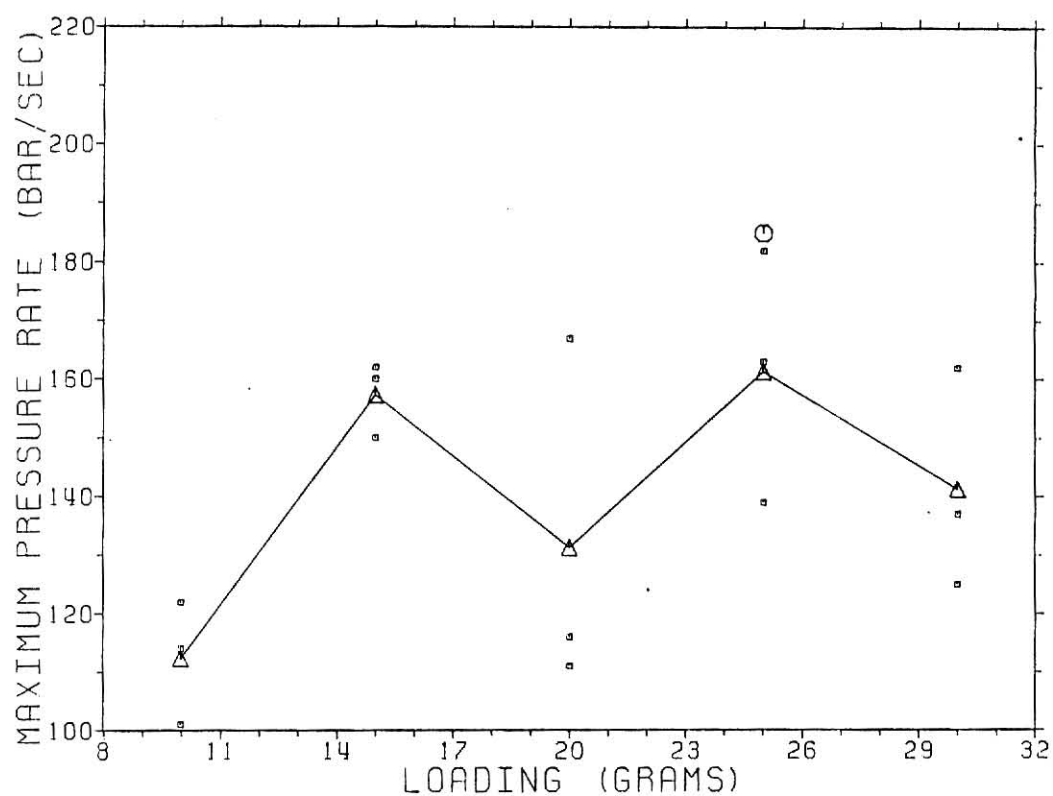


Figure A21. Effect of Dust Loading on Maximum Rate of Pressure Rise for M020.  
 □ = observed value    △ = mean value    ○ = peak value (average)

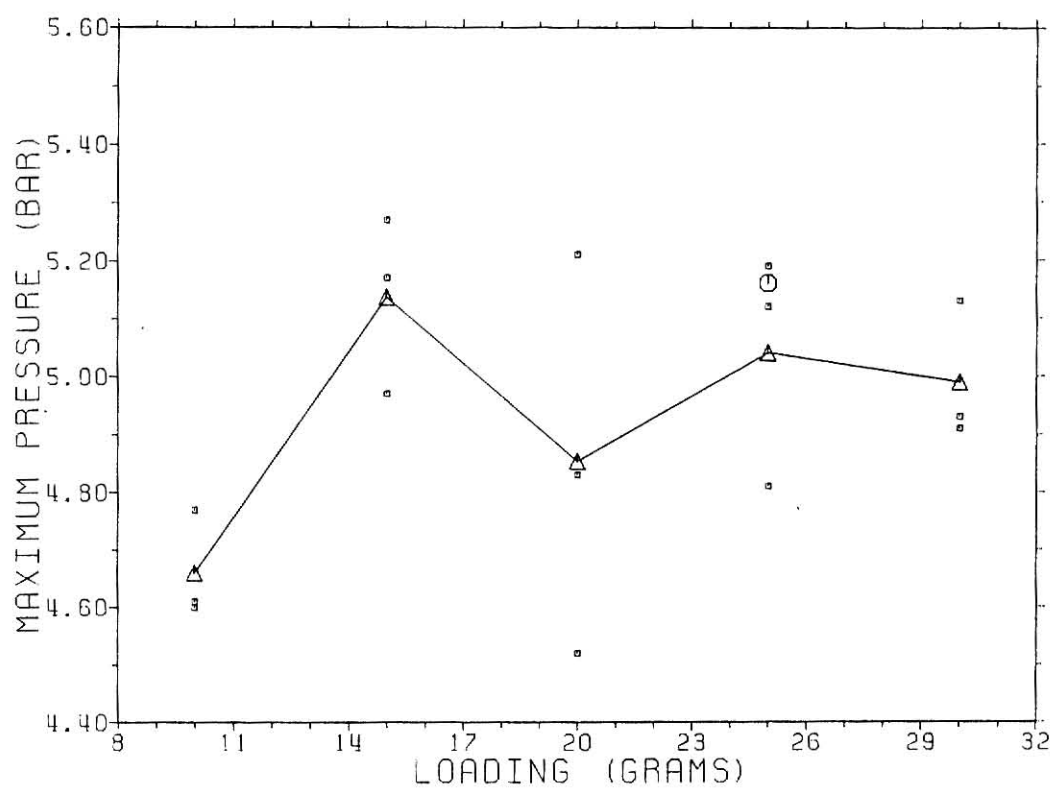


Figure A22. Effect of Dust Loading on Maximum Pressure for M020.  
 □ = observed value    △ = mean value    ○ = peak value (average)

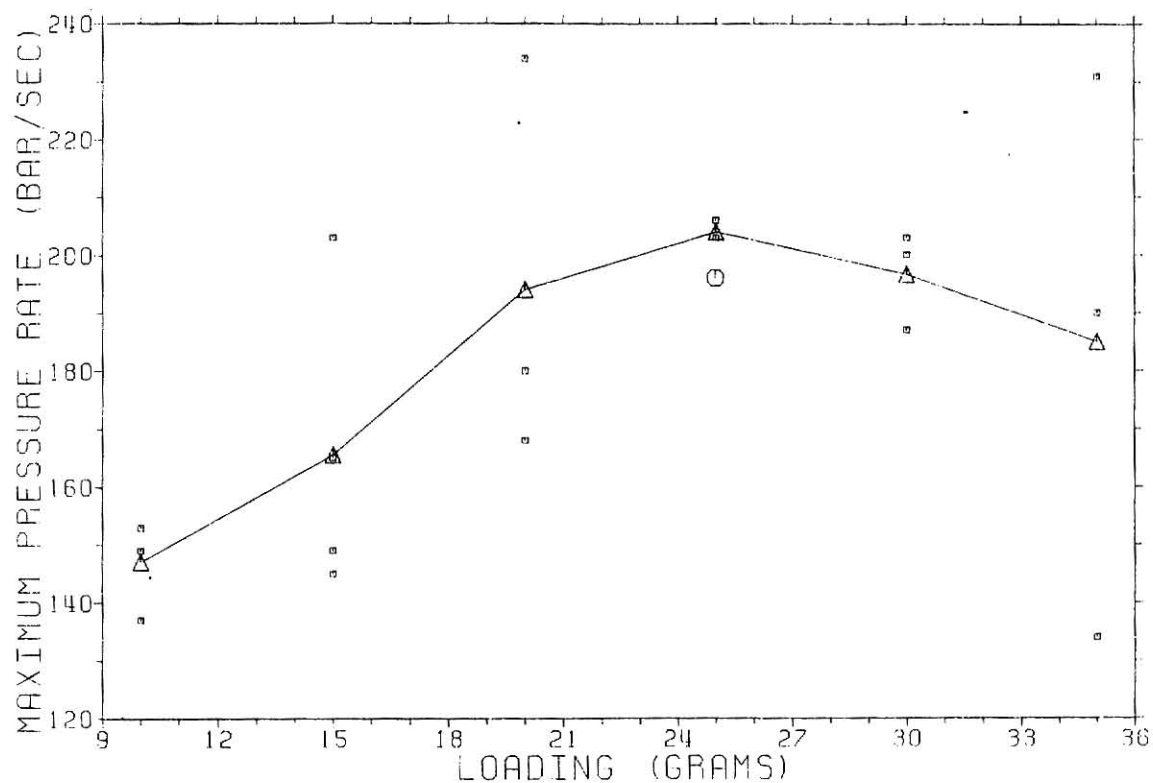


Figure A23. Effect of Dust Loading on Maximum Rate of Pressure Rise for M032b.  
 □ = observed value    △ = mean value    ○ = peak value (average)

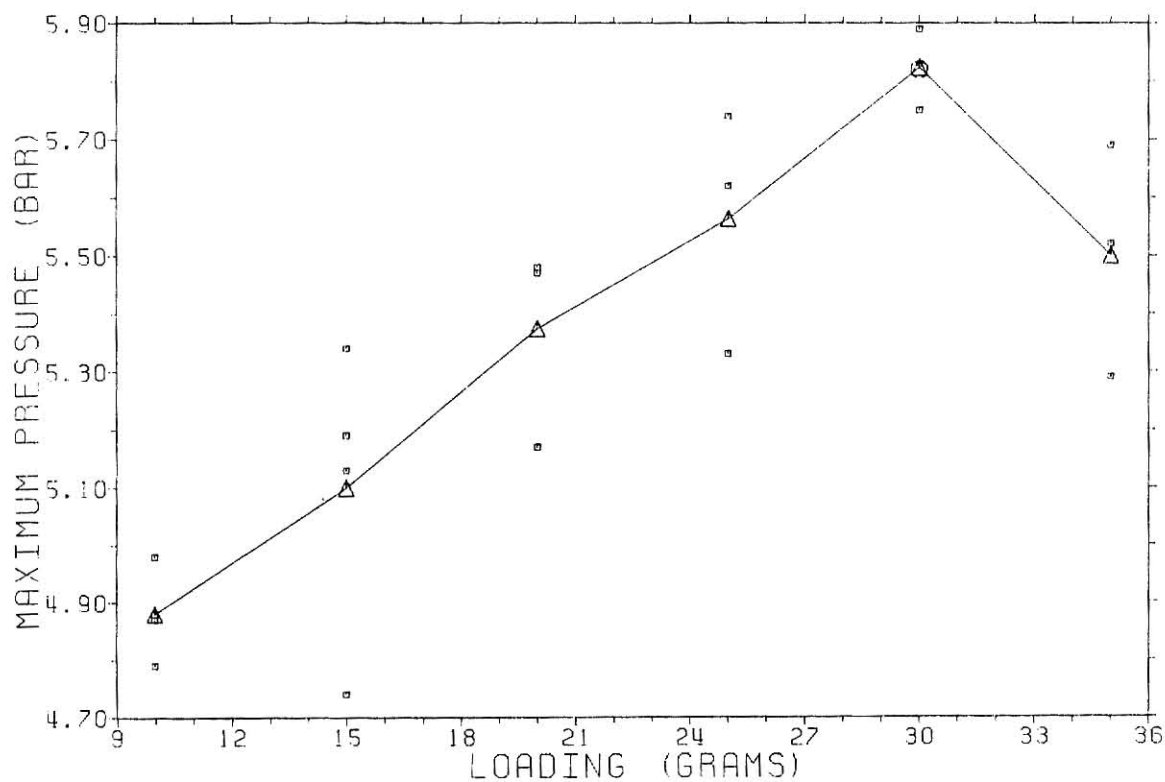


Figure A24. Effect of Dust Loading on Maximum Pressure for M032b.  
 □ = observed value    △ = mean value    ○ = peak value (average)

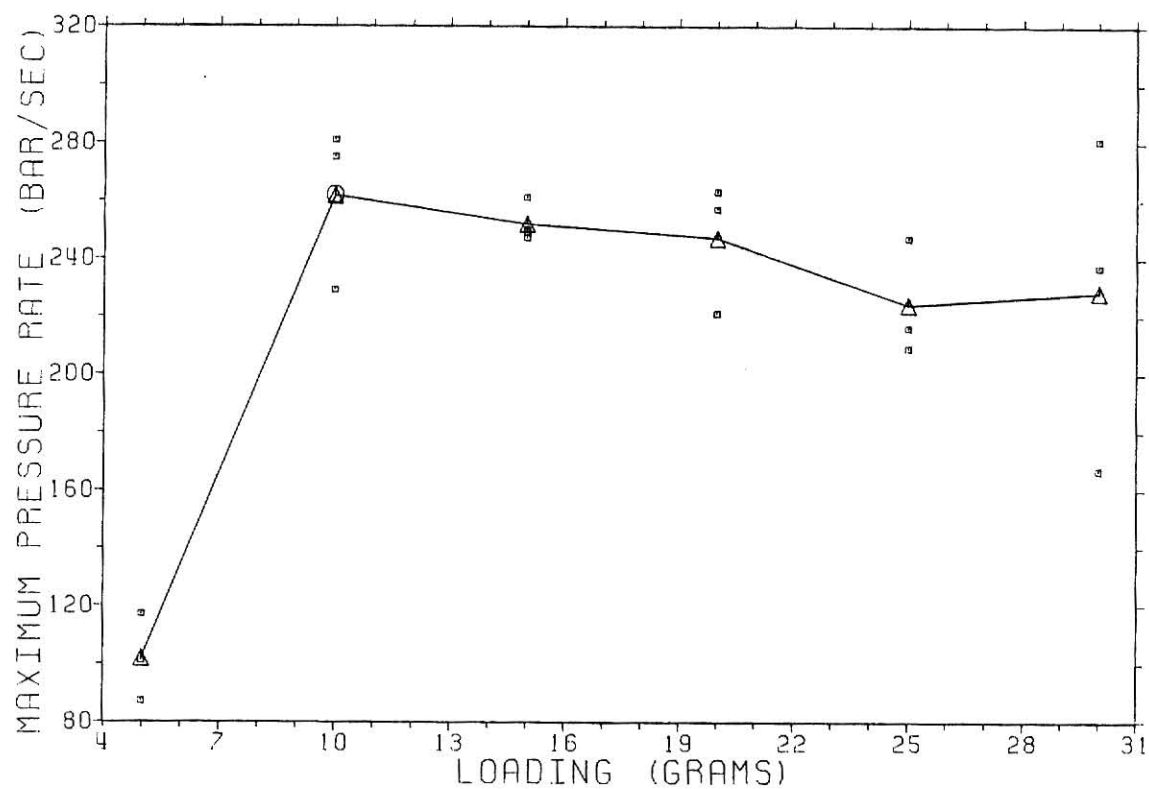


Figure A25. Effect of Dust Loading on Maximum Rate of Pressure Rise for M032c.  
 □ = observed value    △ = mean value    ○ = peak value (average)

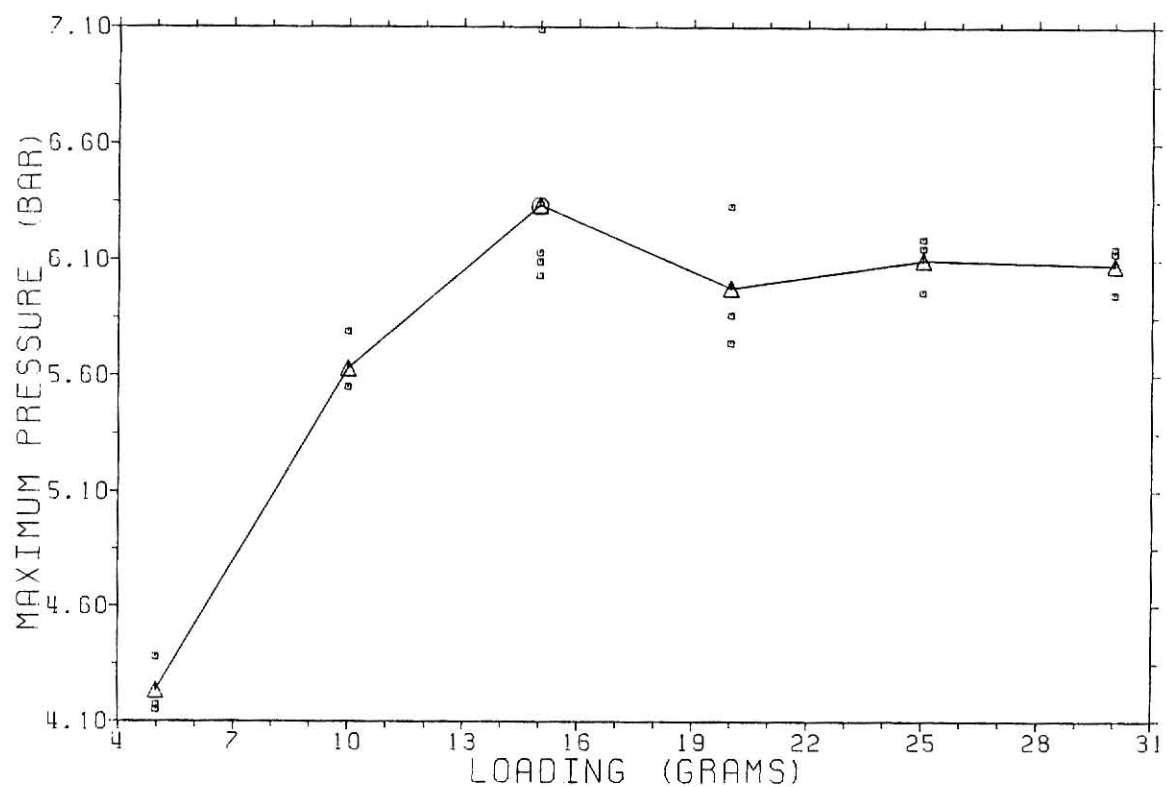


Figure A26. Effect of Dust Loading on Maximum Pressure for M032c.  
 □ = observed value    △ = mean value    ○ = peak value (average)



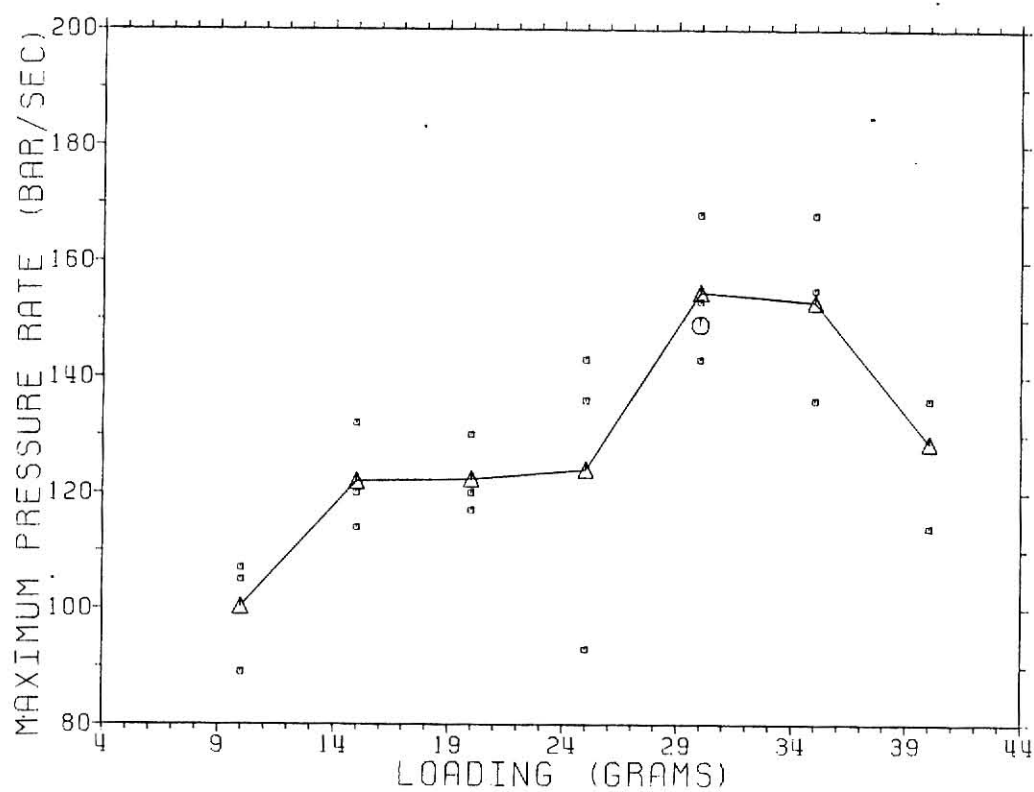


Figure A27. Effect of Dust Loading on Maximum Rate of Pressure Rise for OT12.  
 □ = observed value    △ = mean value    ○ = peak value (average)

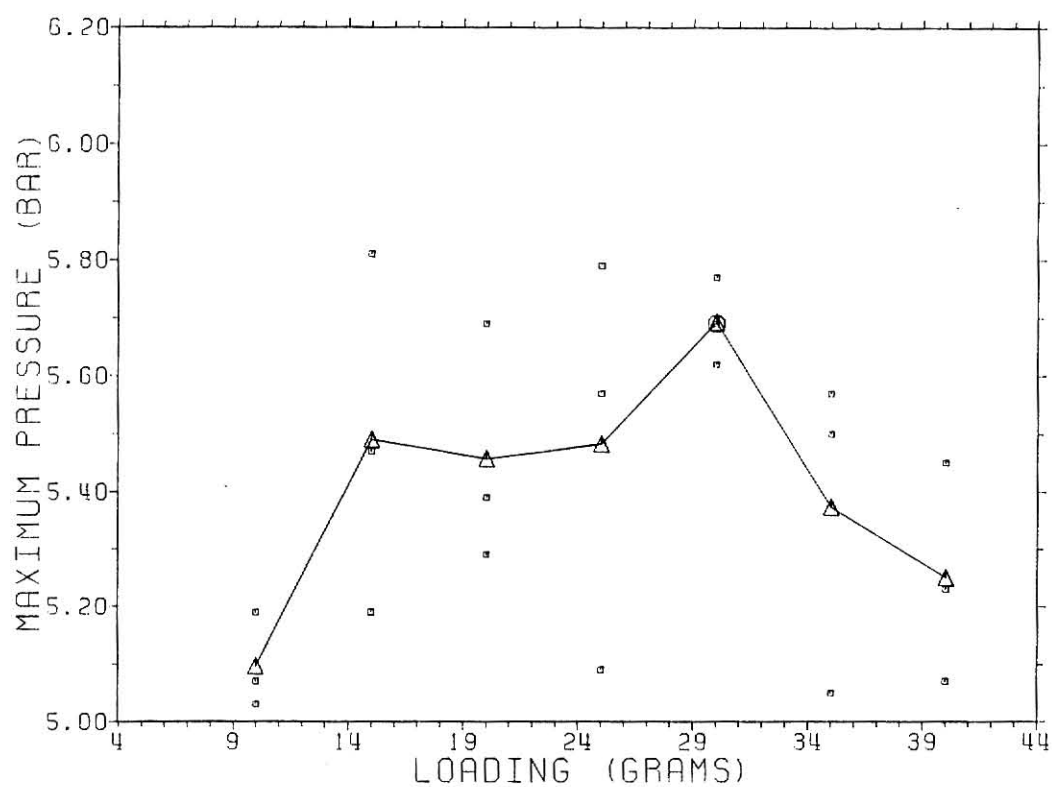


Figure A28. Effect of Dust Loading on Maximum Pressure for OT12.  
 □ = observed value    △ = mean value    ○ = peak value (average)

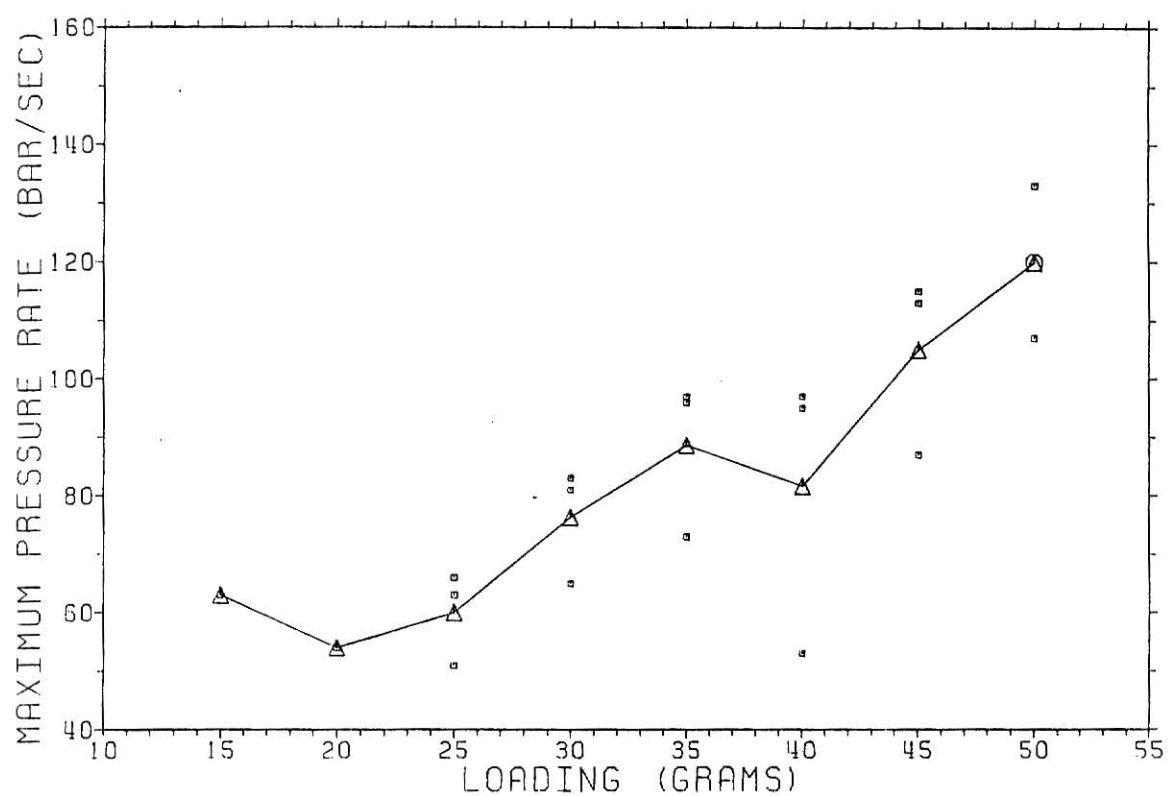


Figure A29. Effect of Dust Loading on Maximum Rate of Pressure Rise for OT12c.  
 □ = observed value    △ = mean value    ○ = peak value (average)

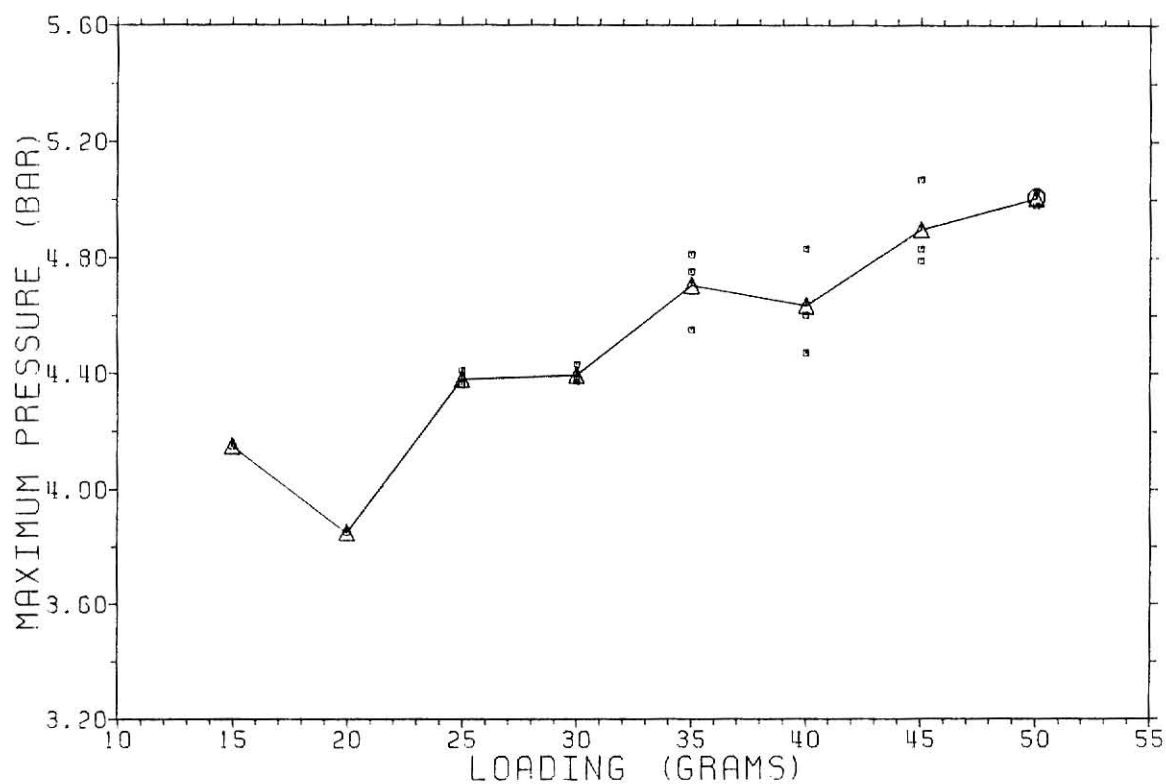


Figure A30. Effect of Dust Loading on Maximum Pressure for OT12c.  
 □ = observed value    △ = mean value    ○ = peak value (average)

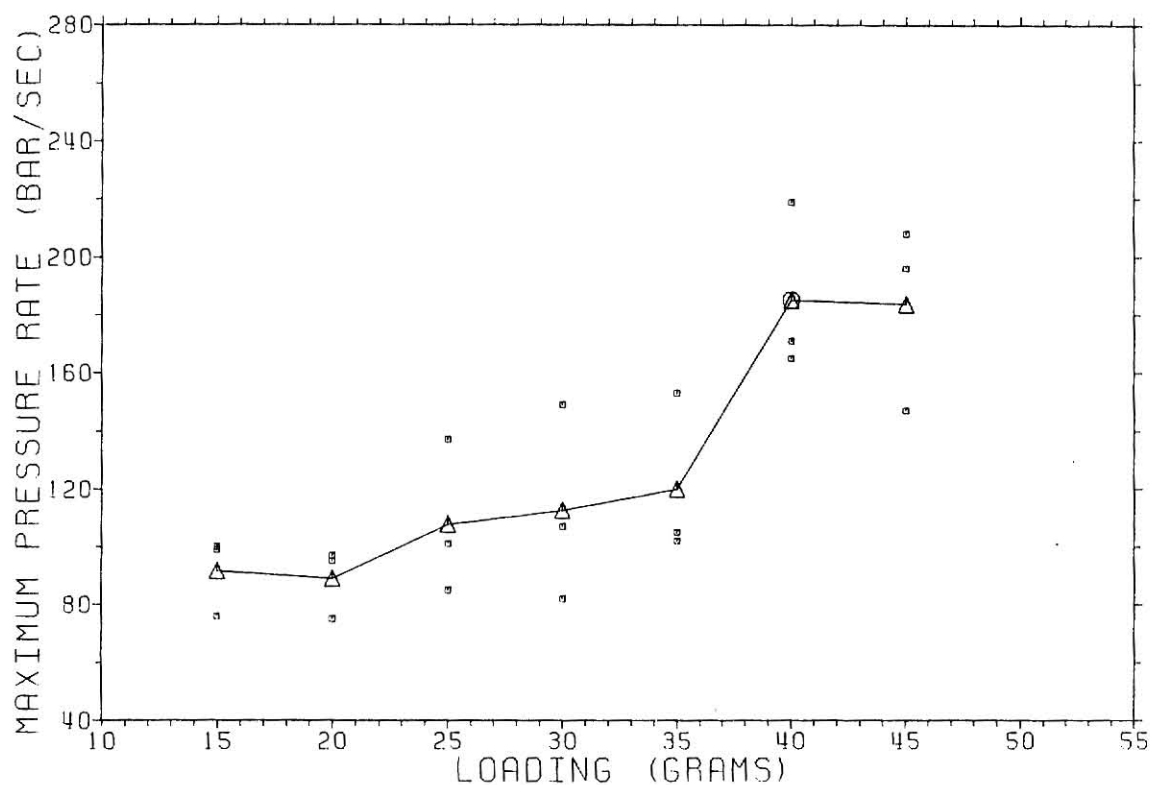


Figure A31. Effect of Dust Loading on Maximum Rate of Pressure Rise for OT13.  
 □ = observed value    △ = mean value    ○ = peak value (average)

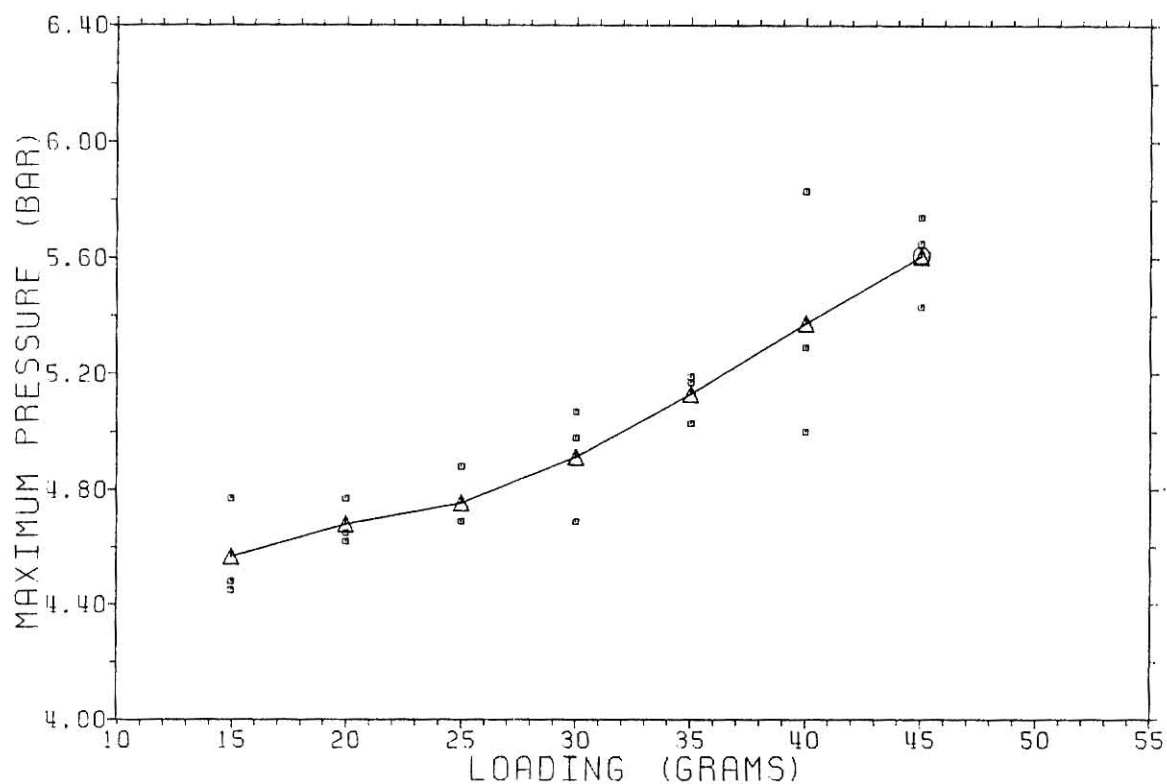


Figure A32. Effect of Dust Loading on Maximum Pressure for OT13.  
 □ = observed value    △ = mean value    ○ = peak value (average)

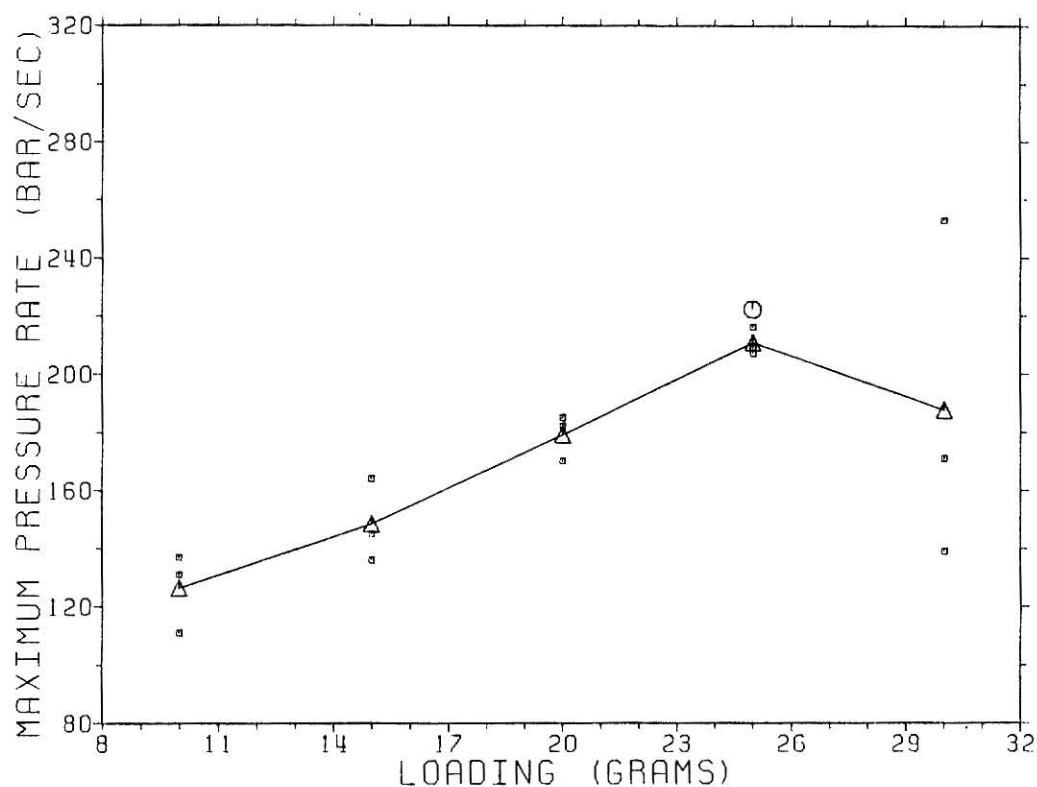


Figure A33. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB11.  
 □ = observed value    △ = mean value    ○ = peak value (average)

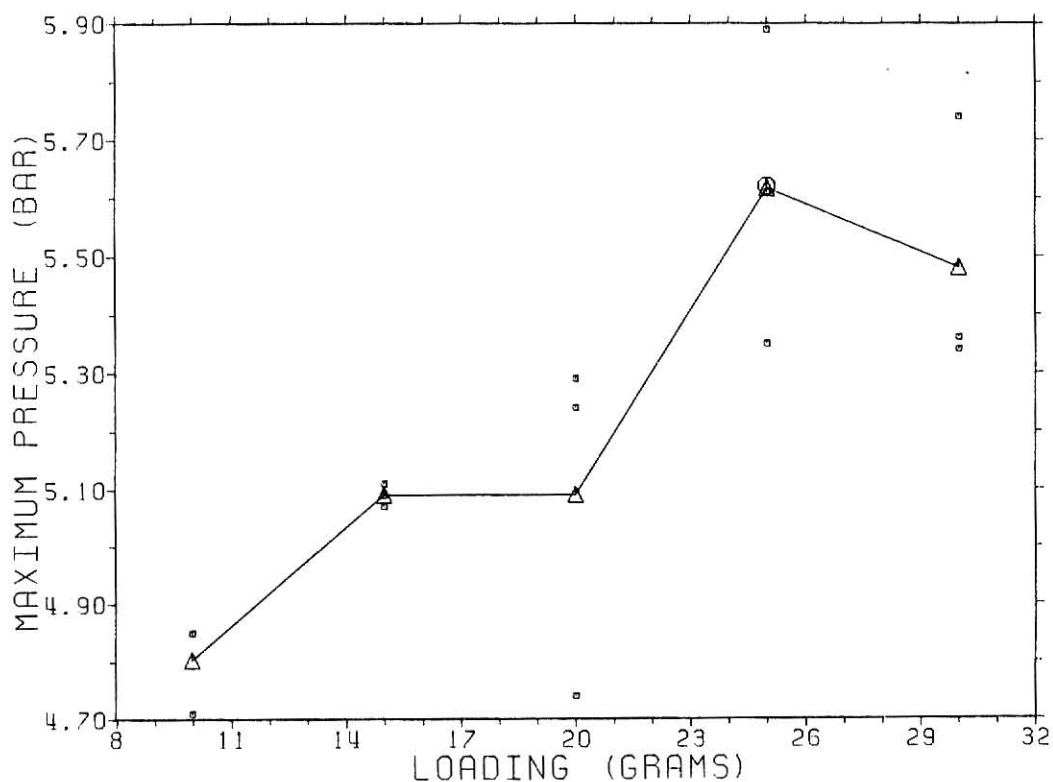


Figure A34. Effect of Dust Loading on Maximum Pressure for SB11.  
 □ = observed value    △ = mean value    ○ = peak value (average)

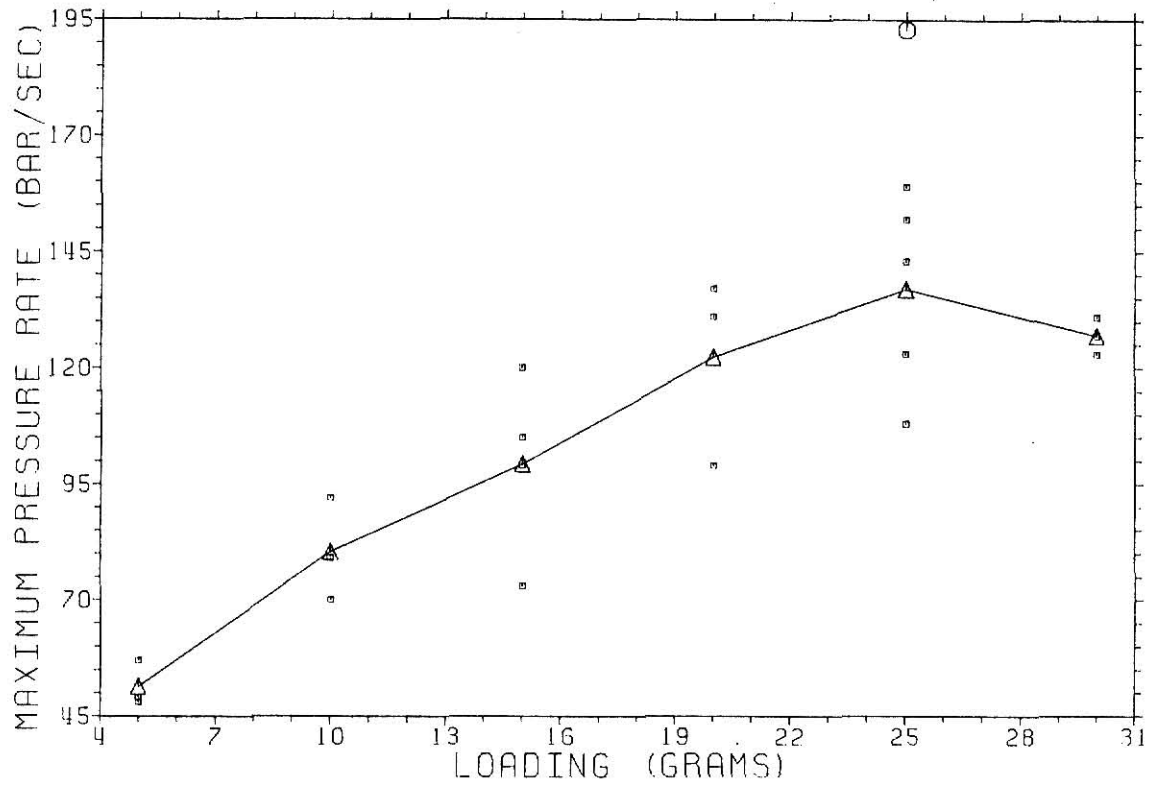


Figure A35. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB12a.  
 □ = observed value    △ = mean value    ○ = peak value (average)

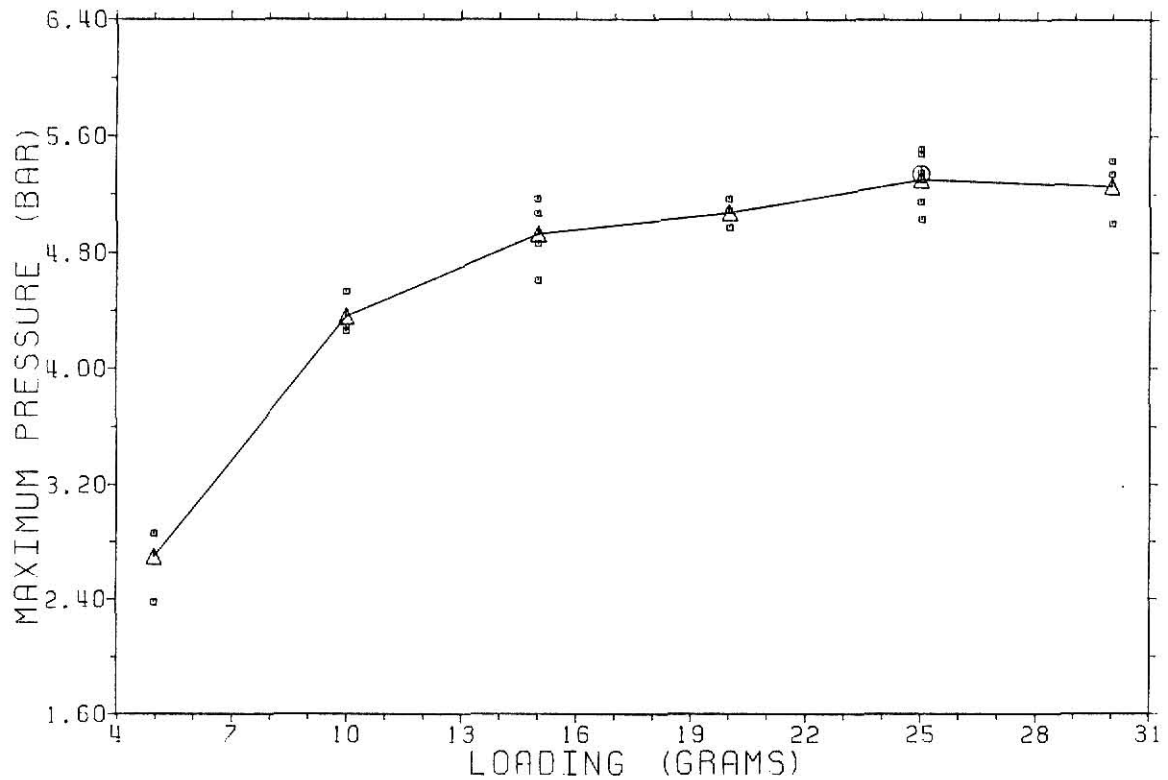


Figure A36. Effect of Dust Loading on Maximum Pressure for SB12a.  
 □ = observed value    △ = mean value    ○ = peak value (average)

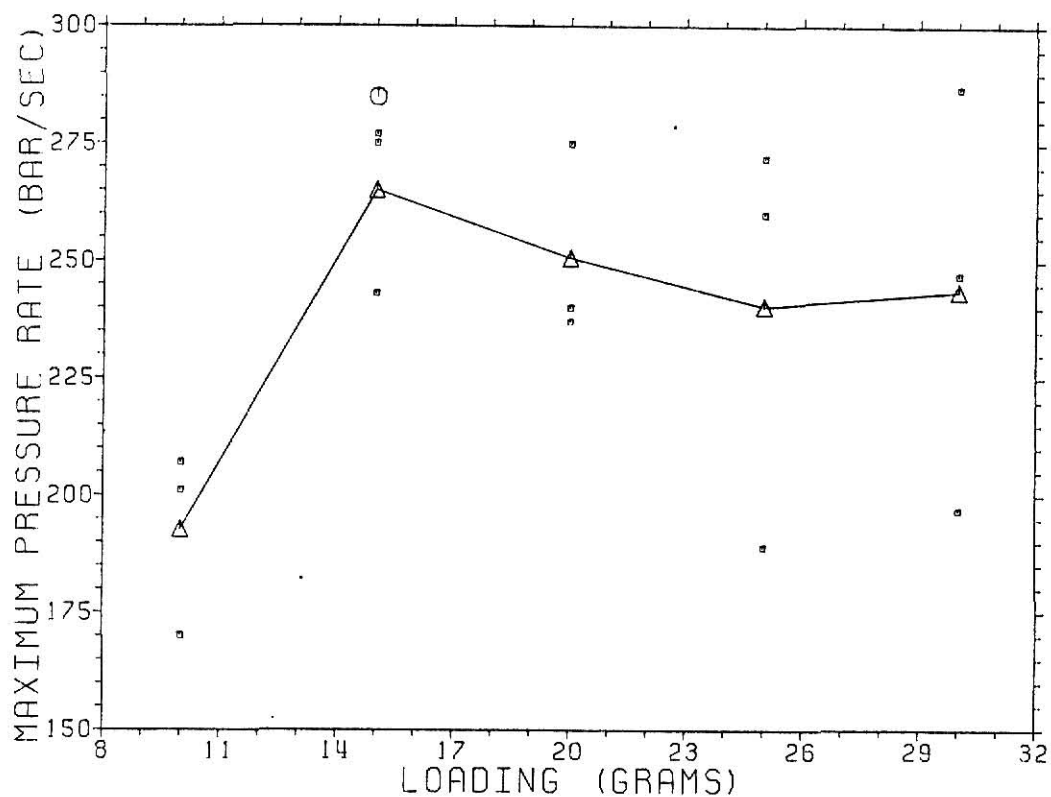


Figure A37. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB13.  
 □ = observed value    △ = mean value    ○ = peak value (average)

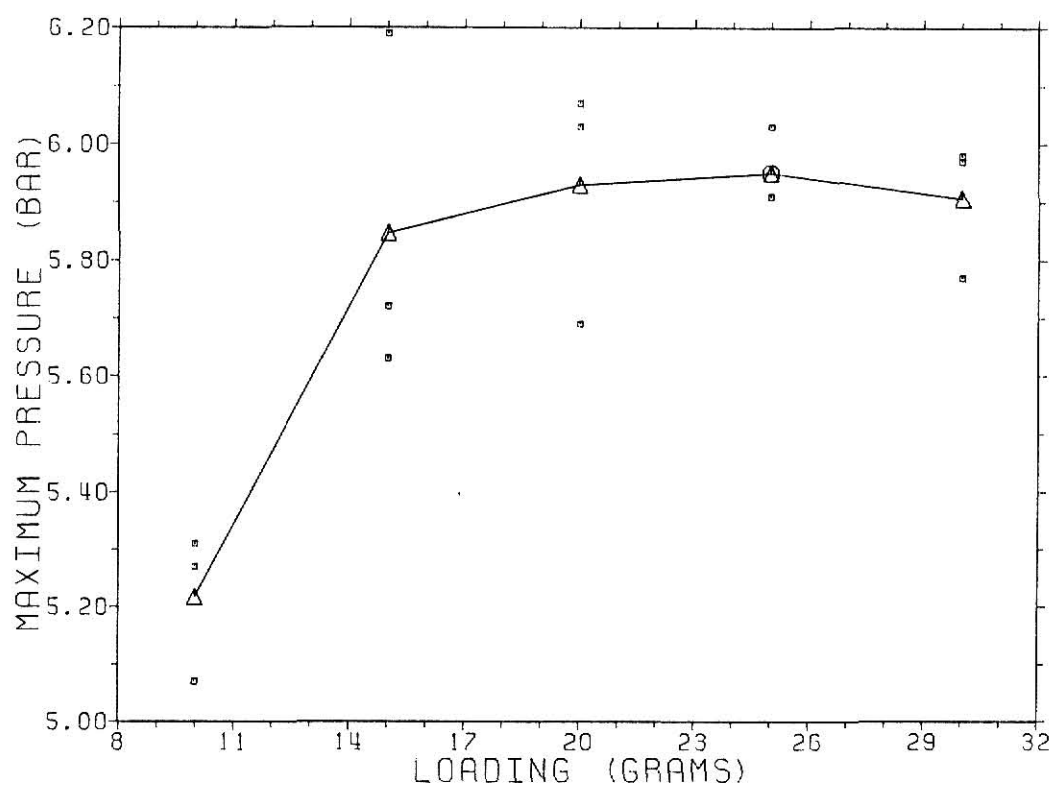


Figure A38. Effect of Dust Loading on Maximum Pressure for SB13.  
 □ = observed value    △ = mean value    ○ = peak value (average)

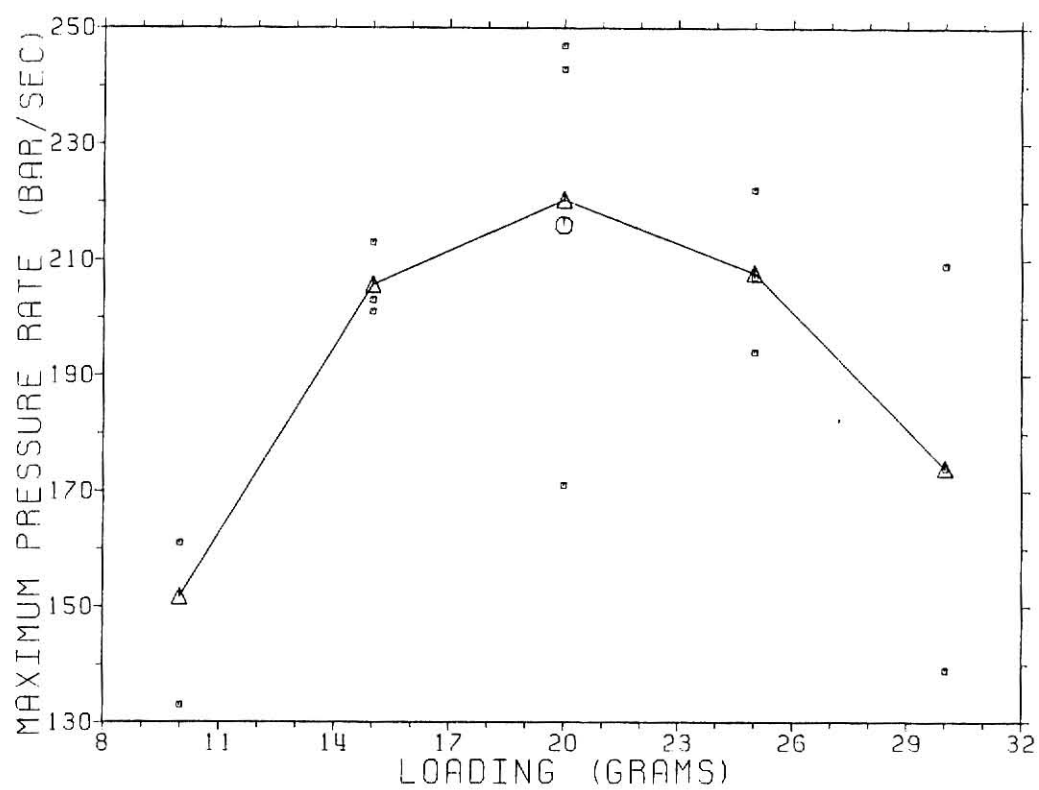


Figure A39. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB21.  
 □ = observed value    △ = mean value    ○ = peak value (average)

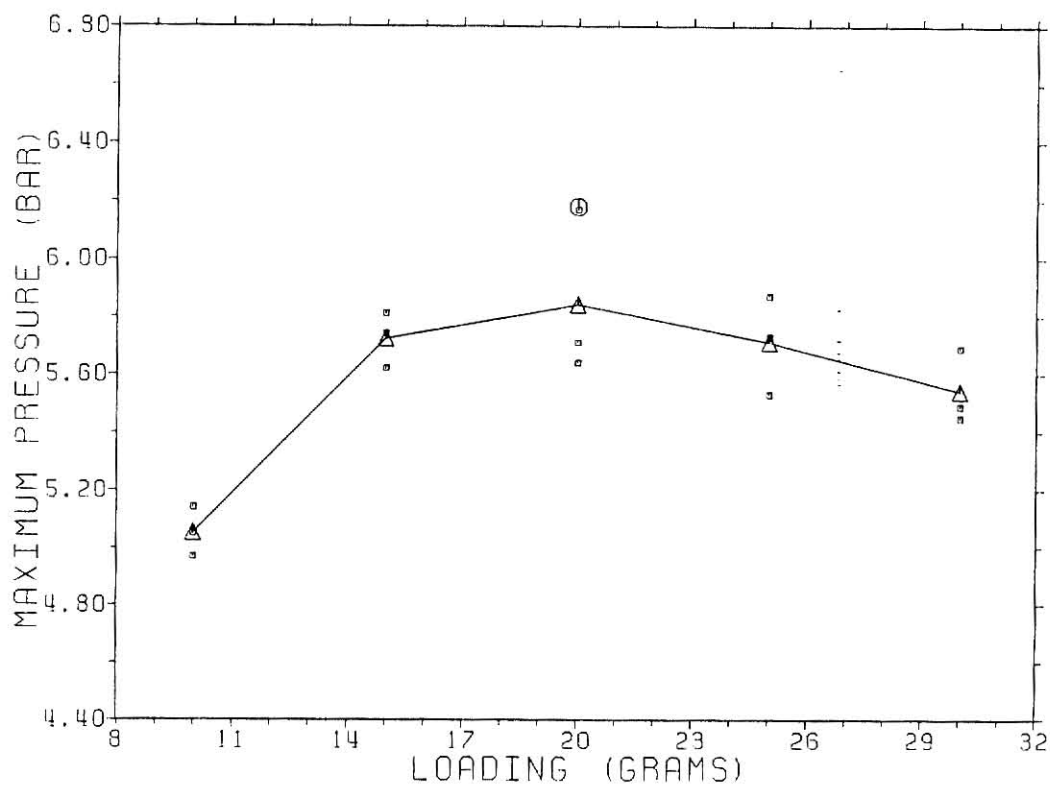


Figure A40. Effect of Dust Loading on Maximum Pressure for SB21.  
 □ = observed value    △ = mean value    ○ = peak value (average)

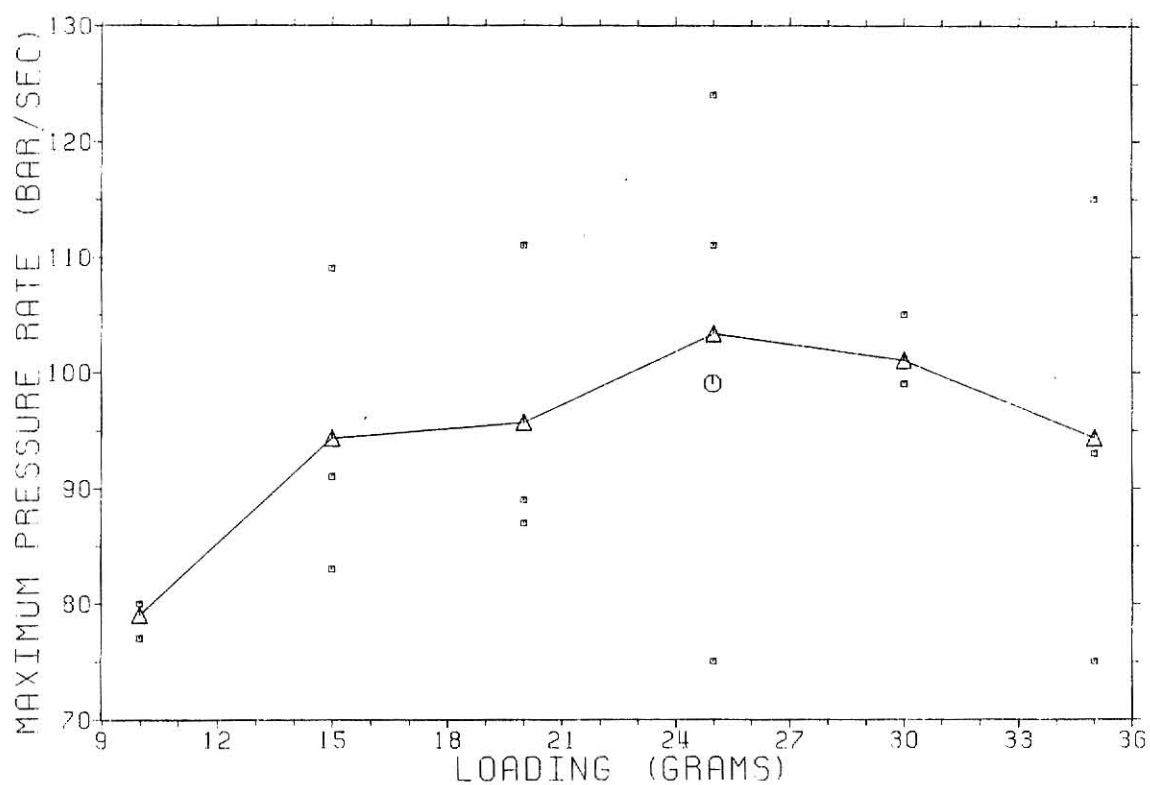


Figure A41. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB22a.  
 □ = observed value    △ = mean value    ○ = peak value (average)

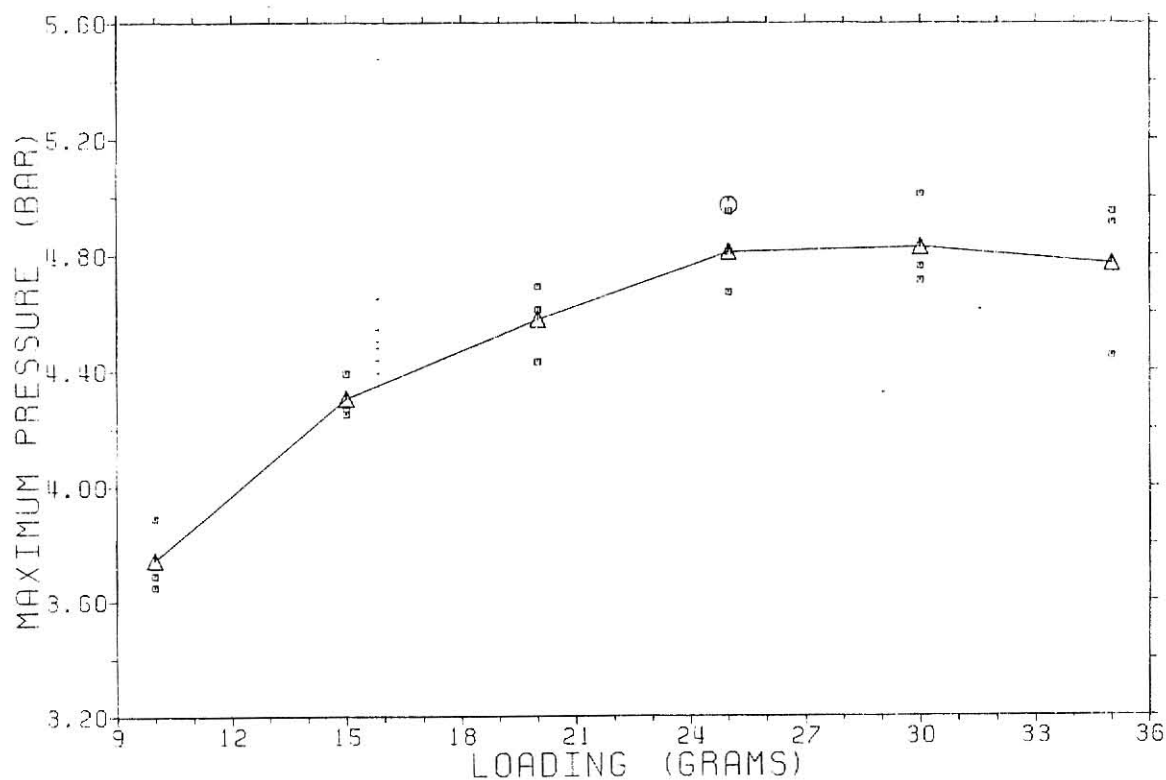


Figure A42. Effect of Dust Loading on Maximum Pressure for SB22a.  
 □ = observed value    △ = mean value    ○ = peak value (average)



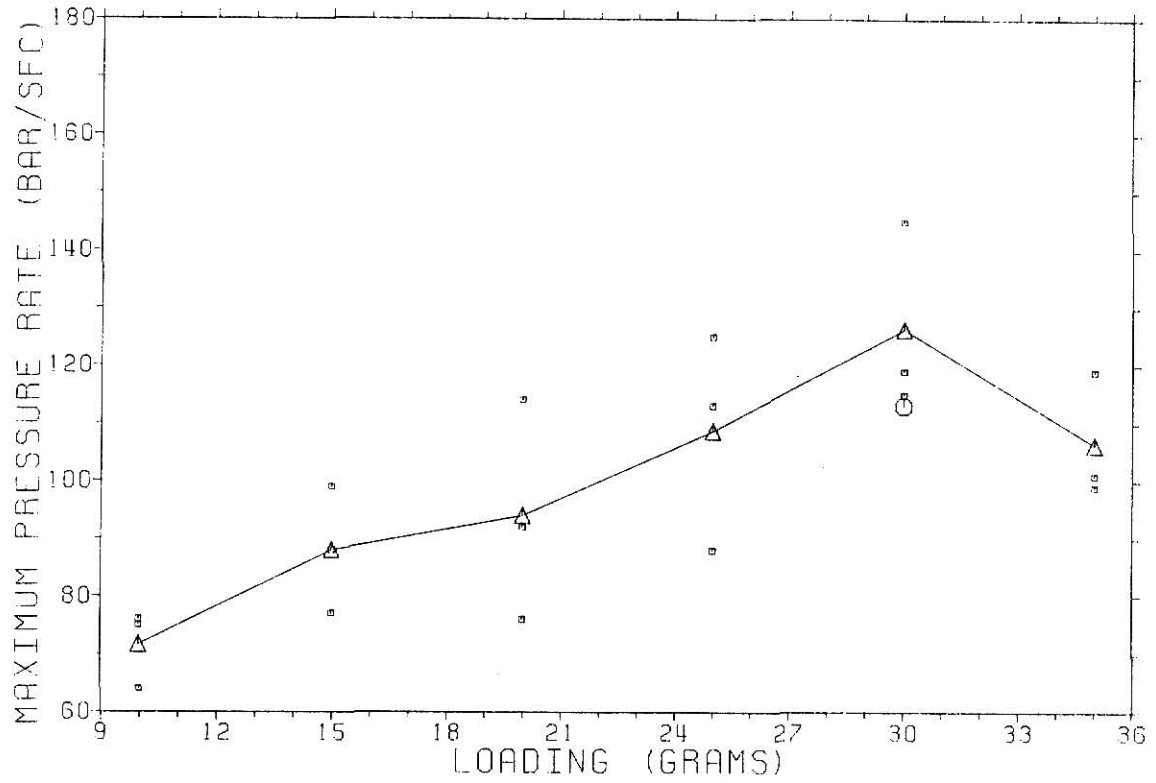


Figure A43. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB22b.  
 □ = observed value    △ = mean value    ○ = peak value (average)

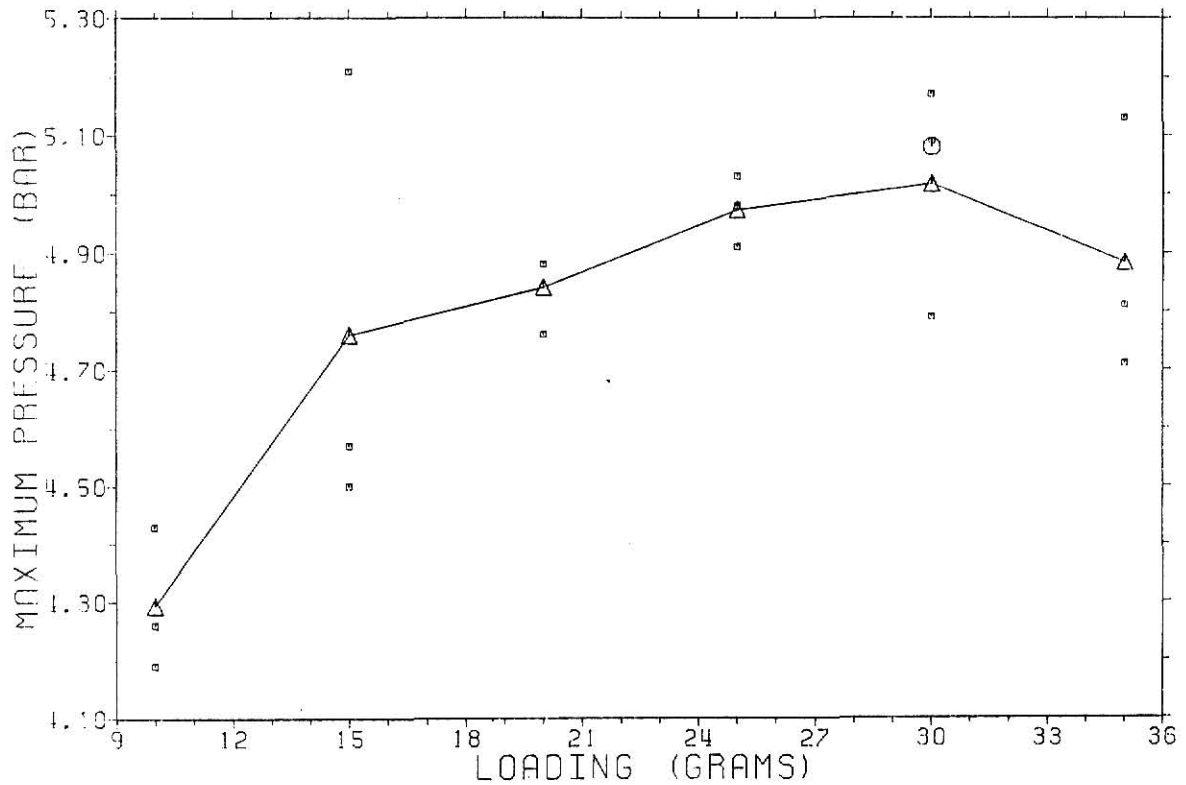


Figure A44. Effect of Dust Loading on Maximum Pressure for SB22b.  
 □ = observed value    △ = mean value    ○ = peak value (average)

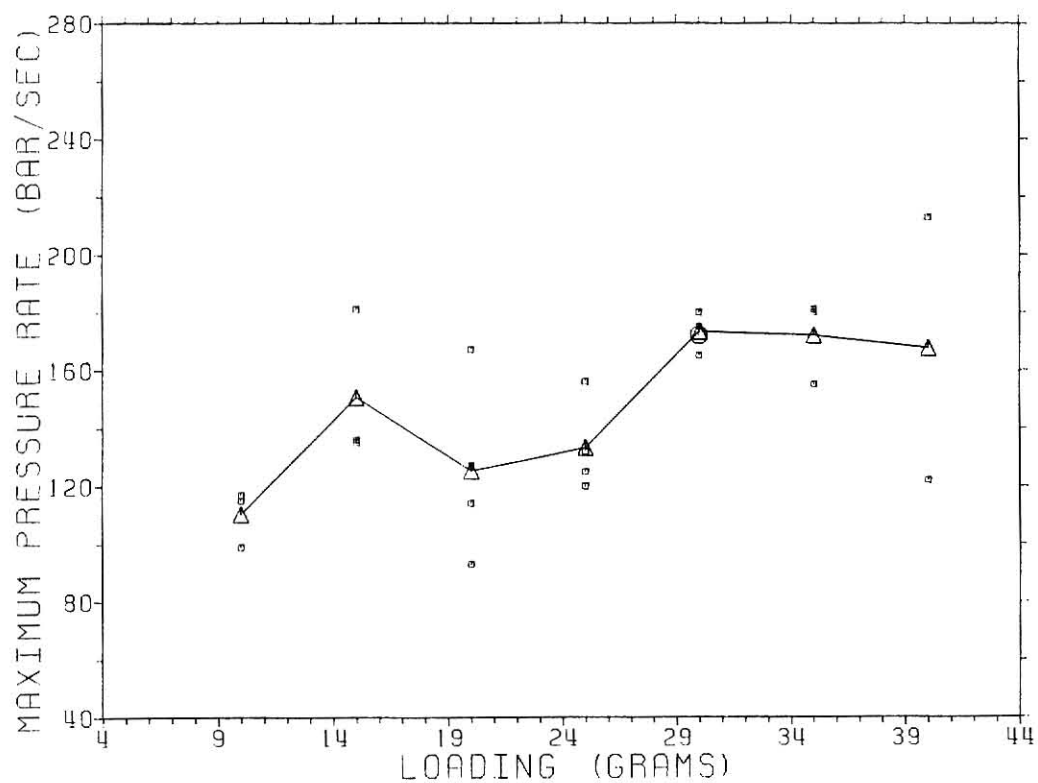


Figure A45. Effect of Dust Loading on Maximum Rate of Pressure Rise for SB23.  
 □ = observed value    △ = mean value    ○ = peak value (average)

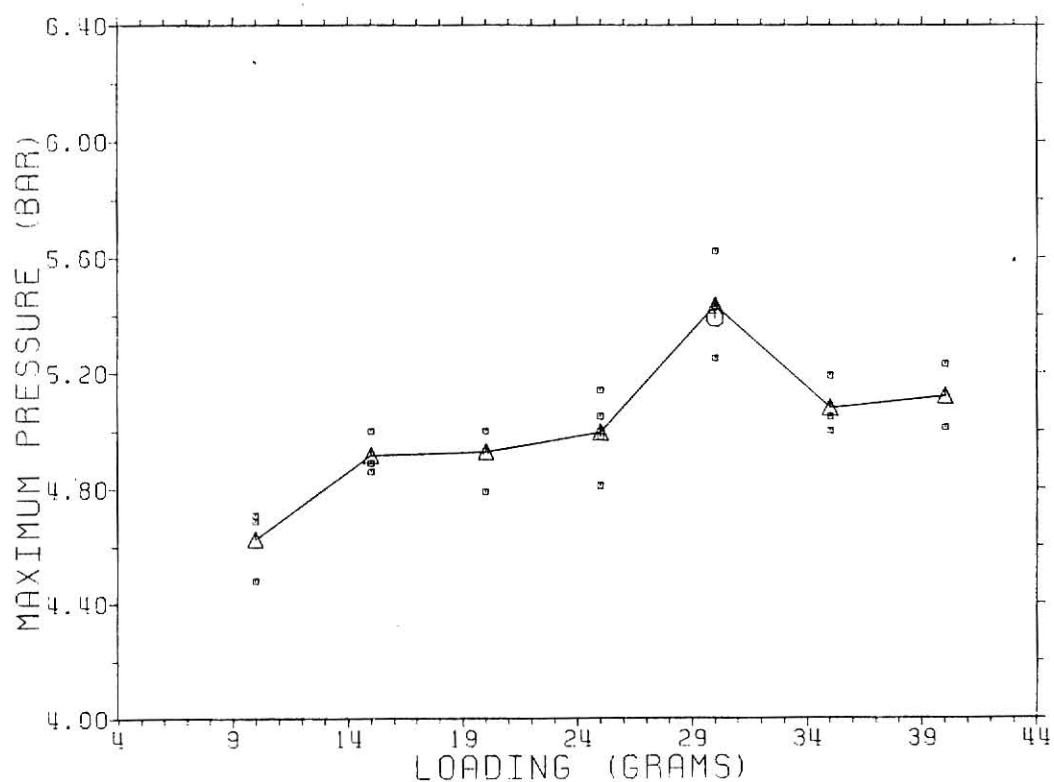


Figure A46. Effect of Dust Loading on Maximum Pressure for SB23.  
 □ = observed value    △ = mean value    ○ = peak value (average)

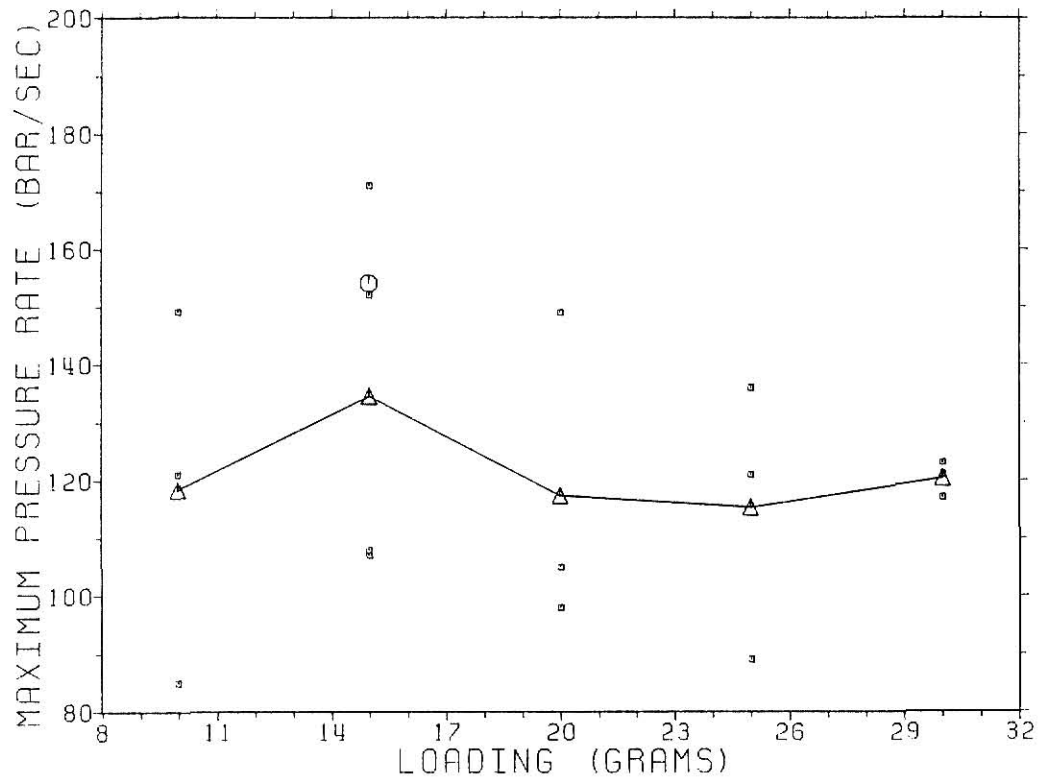


Figure A47. Effect of Dust Loading on Maximum Rate of Pressure Rise for WT11.  
 □ = observed value    △ = mean value    ○ = peak value (average)

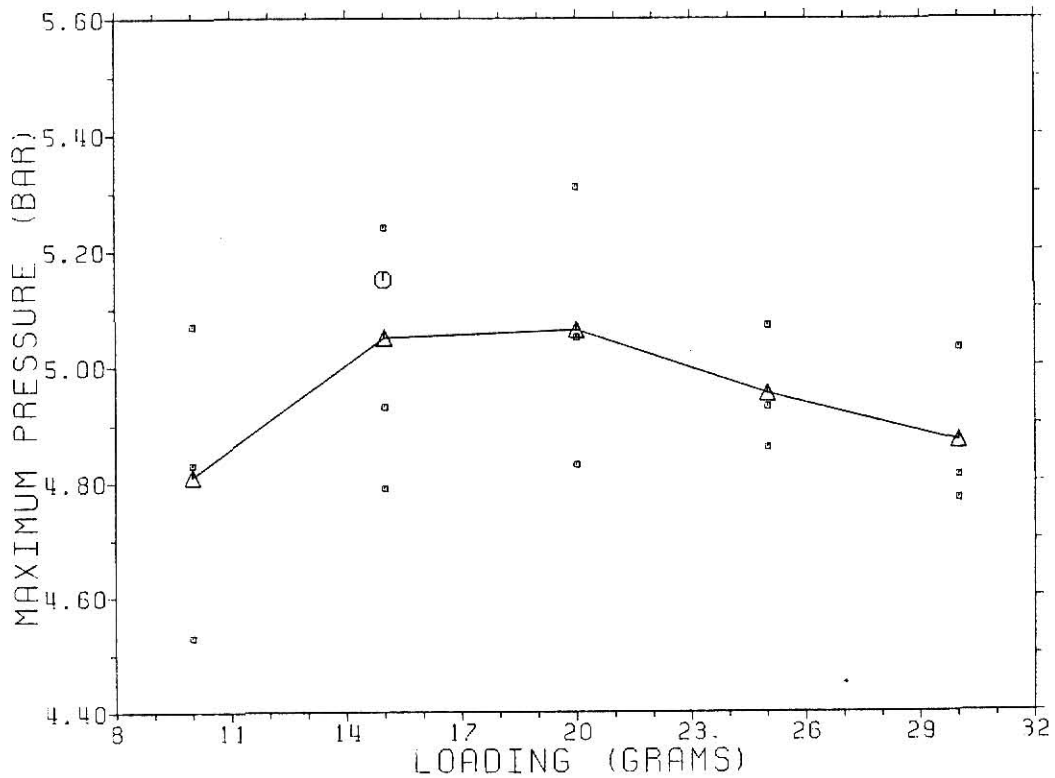


Figure A48. Effect of Dust Loading on Maximum Pressure for WT11.  
 □ = observed value    △ = mean value    ○ = peak value (average)

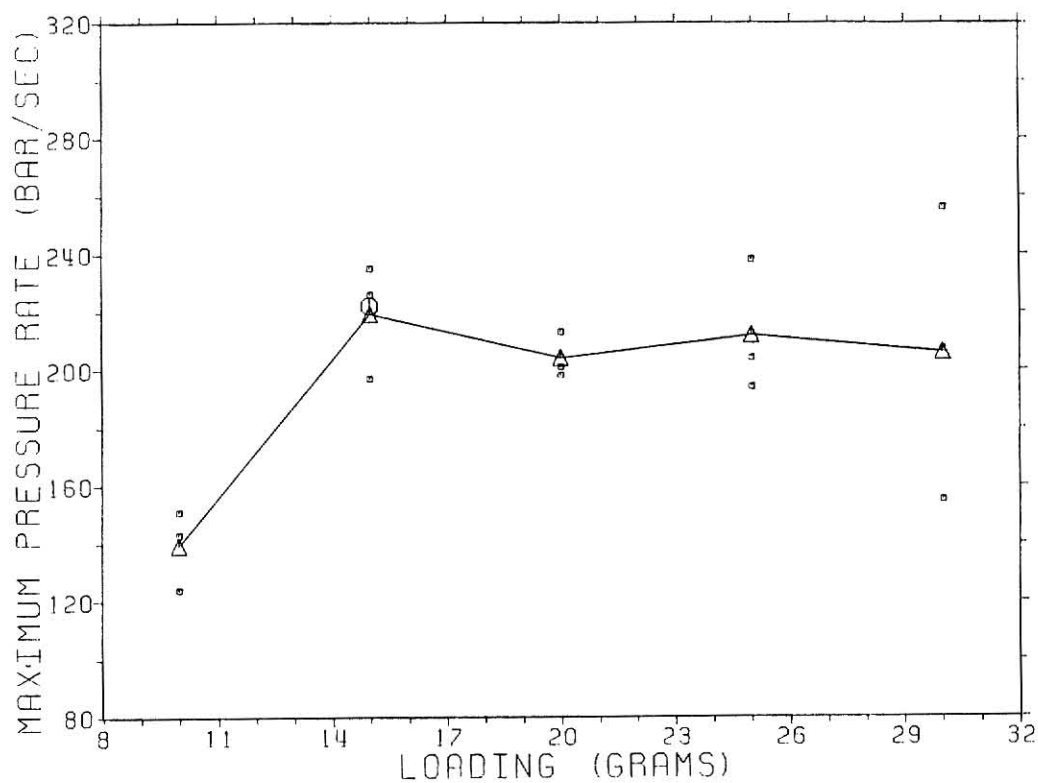


Figure A49. Effect of Dust Loading on Maximum Rate of Pressure Rise for WT12a.  
 □ = observed value    △ = mean value    ○ = peak value (average)

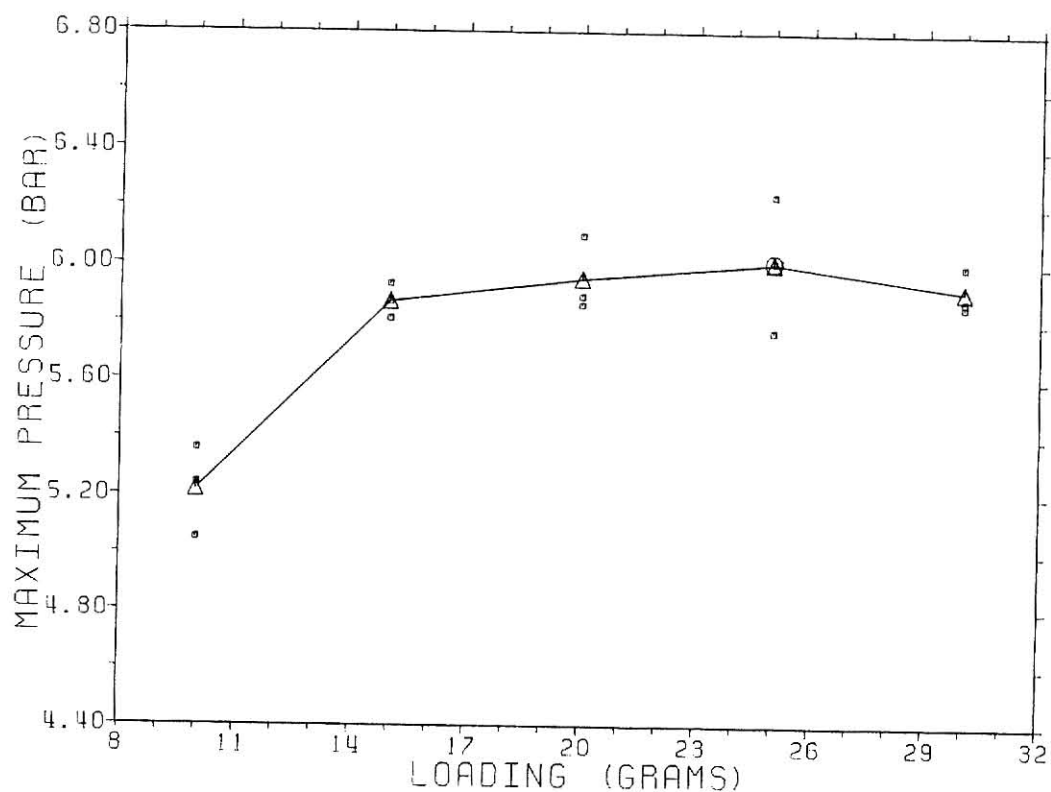


Figure A50. Effect of Dust Loading on Maximum Pressure for WT12a.  
 □ = observed value    △ = mean value    ○ = peak value (average)

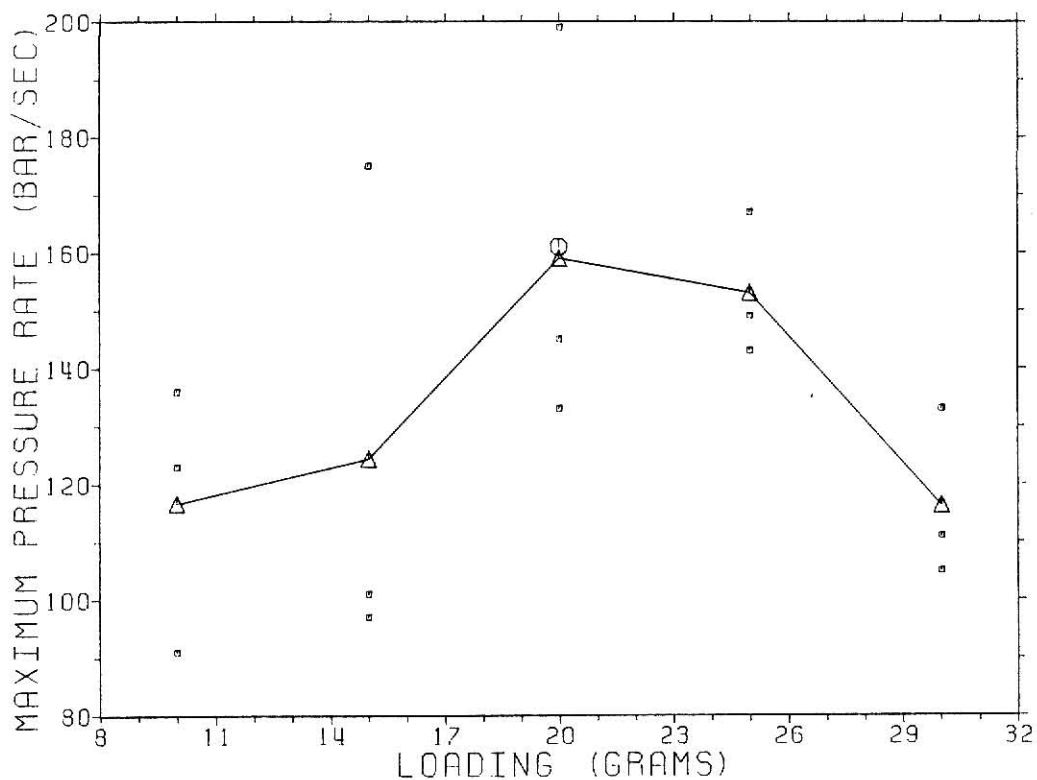


Figure A51. Effect of Dust Loading on Maximum Rate of Pressure Rise for WT12b.  
 □ = observed value    △ = mean value    ○ = peak value (average)

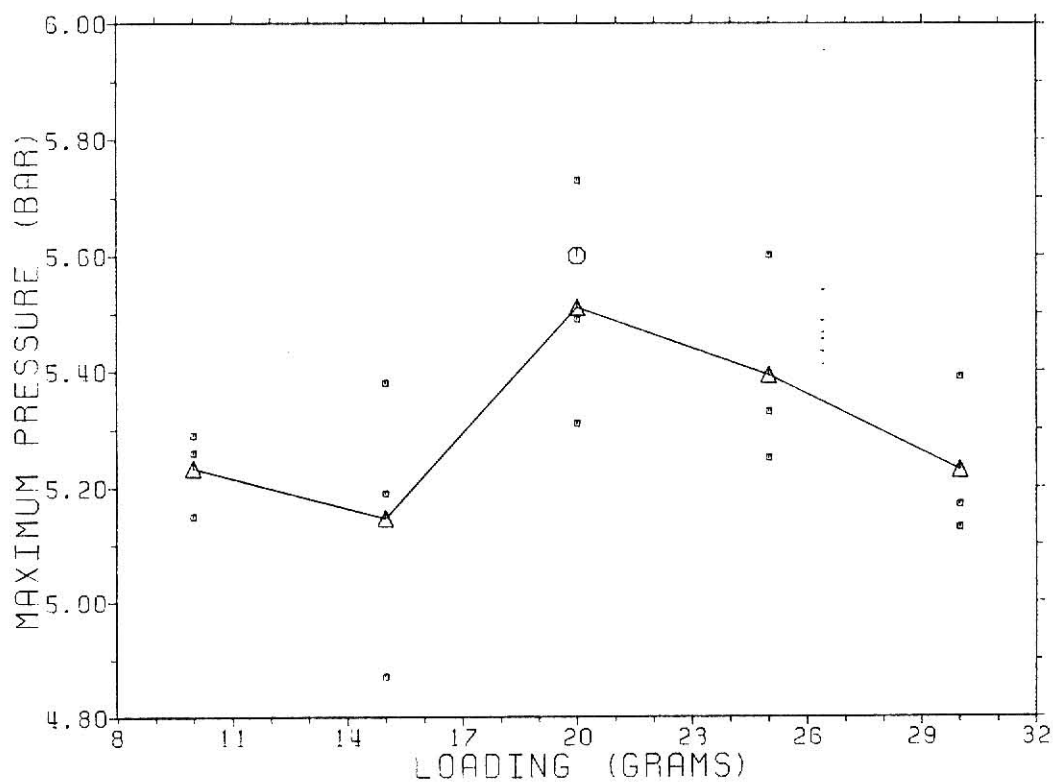


Figure A52. Effect of Dust Loading on Maximum Pressure for WT12b.  
 □ = observed value    △ = mean value    ○ = peak value (average)

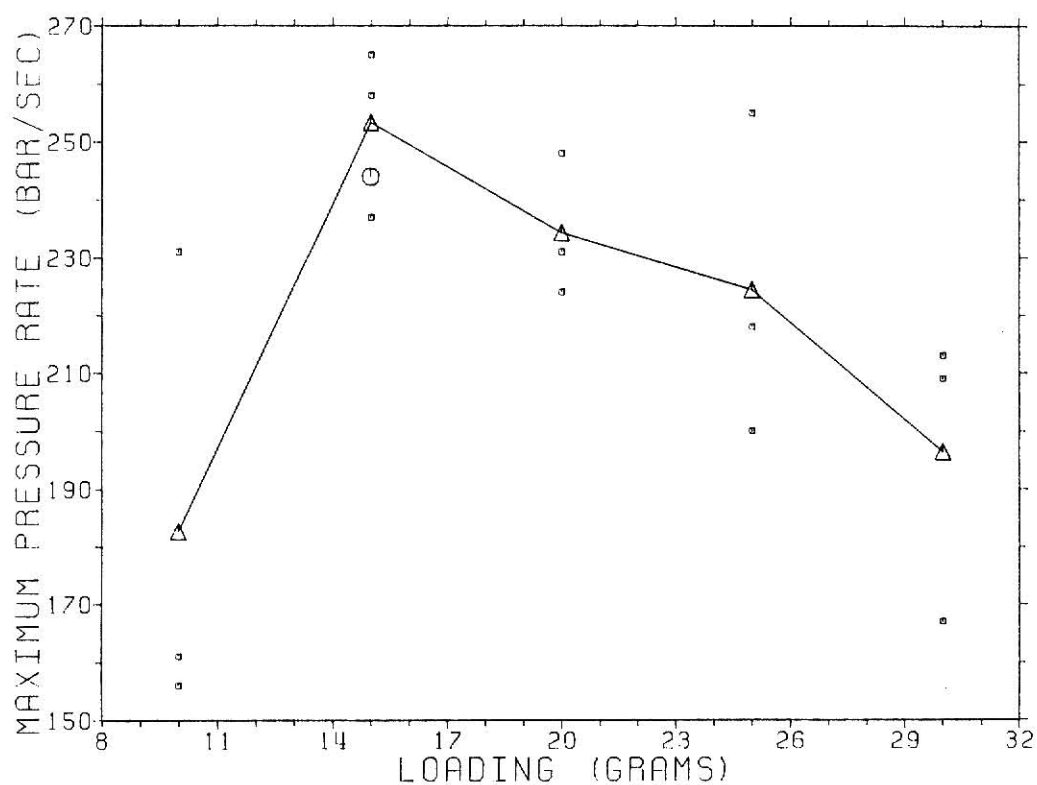


Figure A53. Effect of Dust Loading on Maximum Rate of Pressure Rise for WI21.  
 □ = observed value    △ = mean value    ○ = peak value (average)

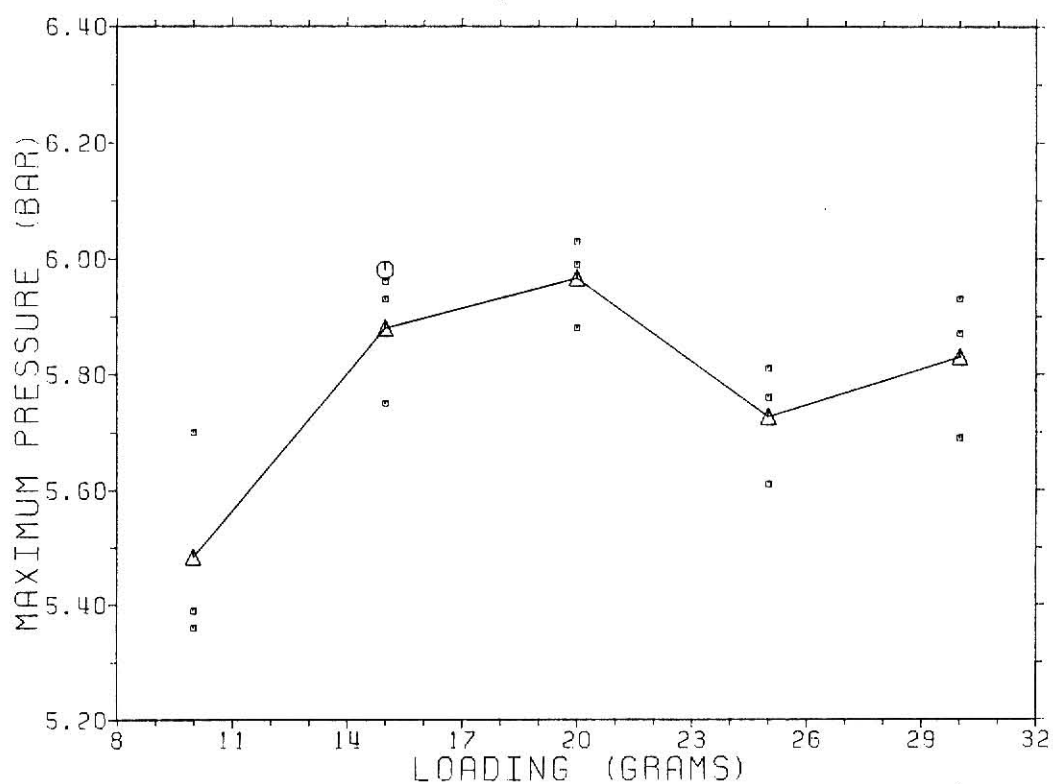


Figure A54. Effect of Dust Loading on Maximum Pressure for WI21.  
 □ = observed value    △ = mean value    ○ = peak value (average)

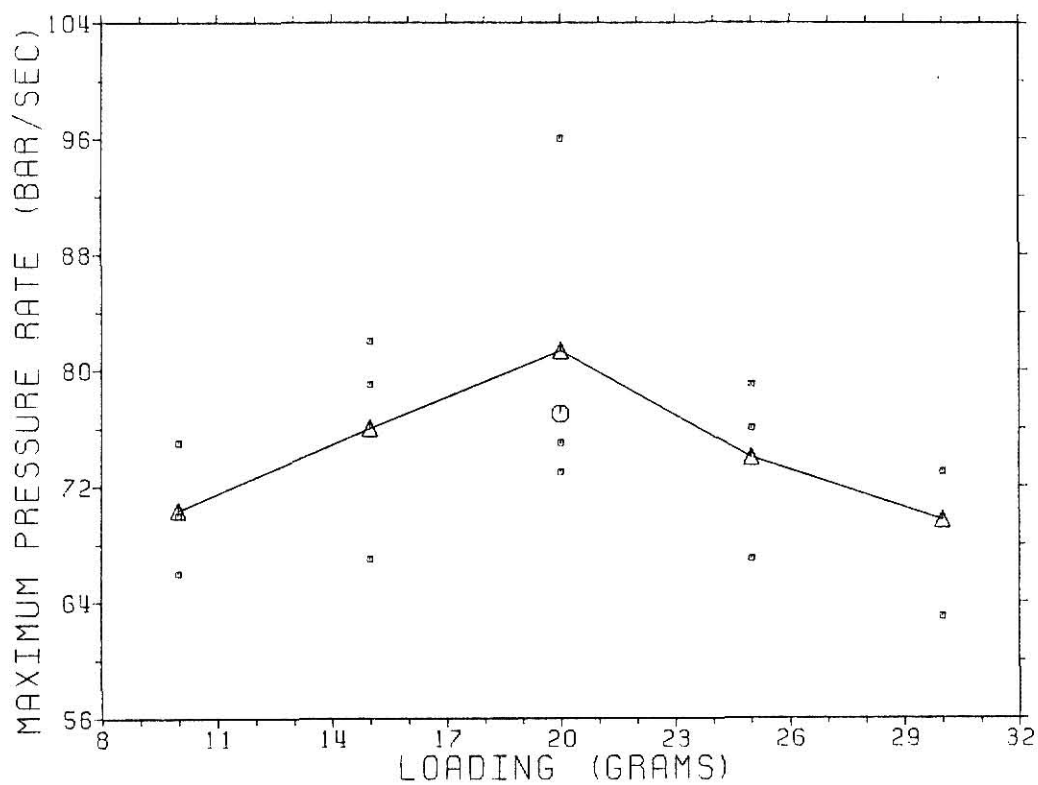


Figure A55. Effect of Dust Loading on Maximum Rate of Pressure Rise for WT22a.  
 □ = observed value    △ = mean value    ○ = peak value (average)

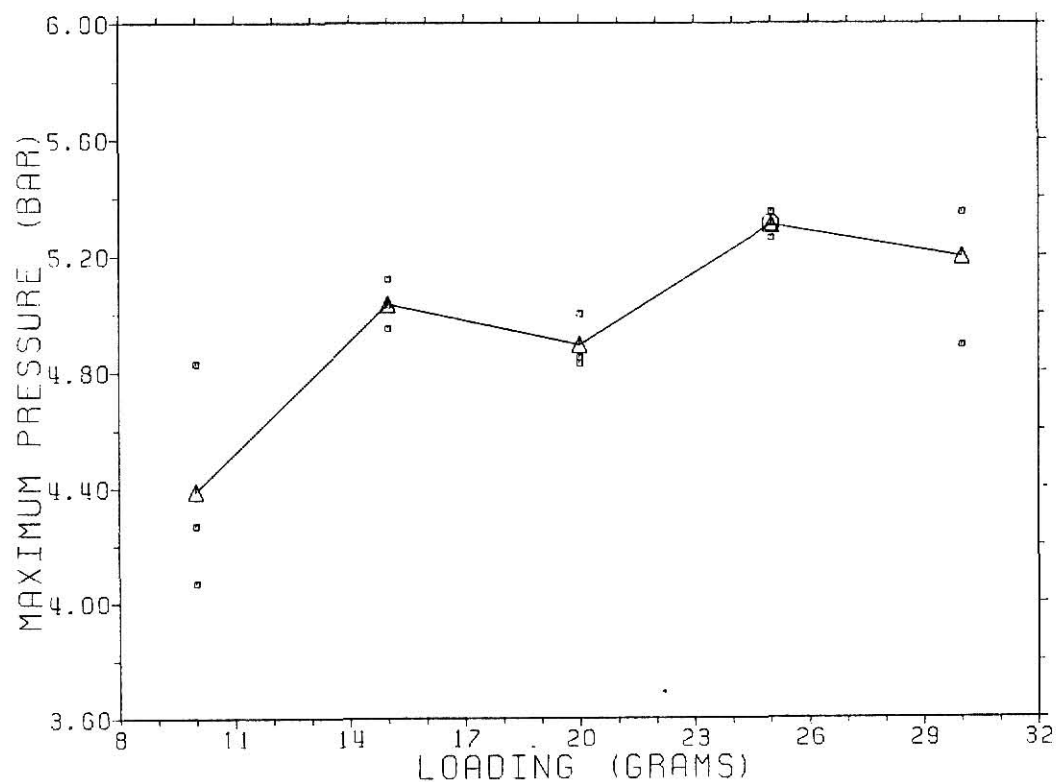


Figure A56. Effect of Dust Loading on Maximum Pressure for WT22a.  
 □ = observed value    △ = mean value    ○ = peak value (average)

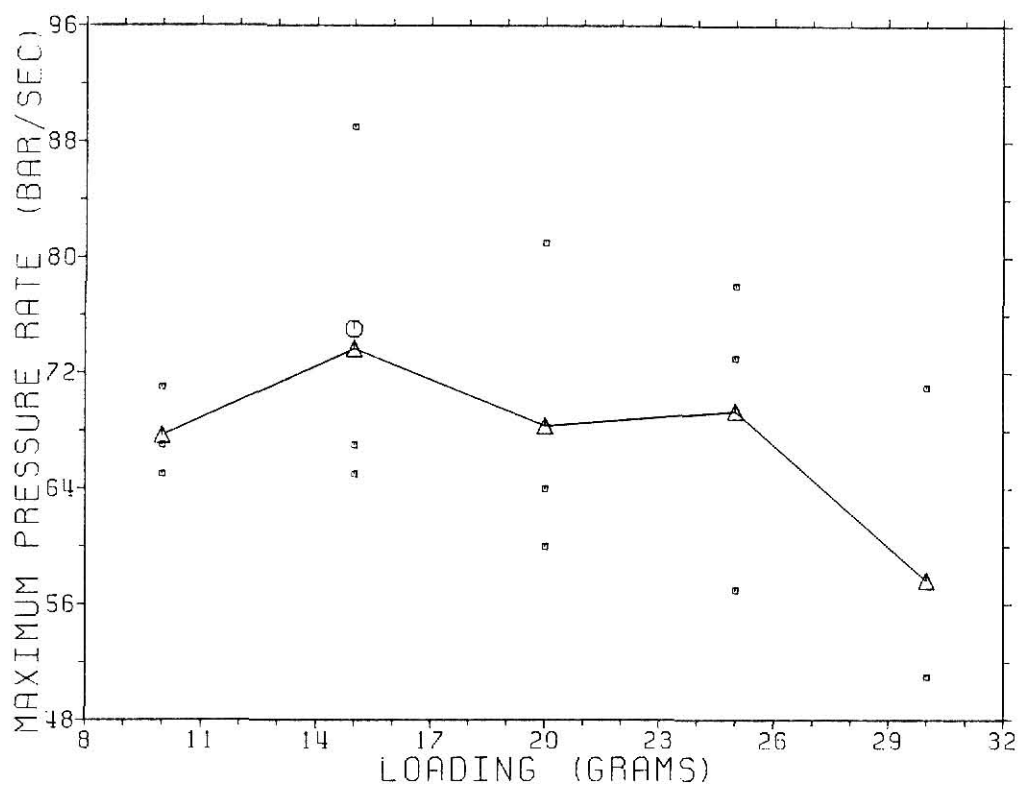


Figure A57. Effect of Dust Loading on Maximum Rate of Pressure Rise for WT23.  
 □ = observed value    △ = mean value    ○ = peak value (average)

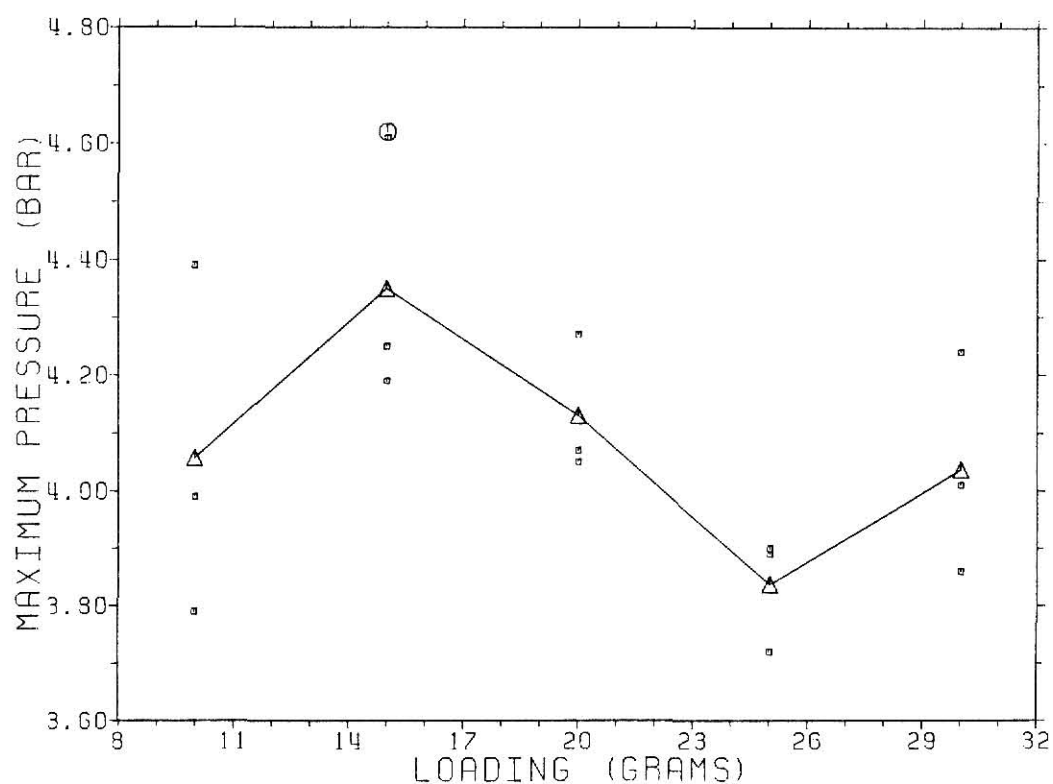


Figure A58. Effect of Dust Loading on Maximum Pressure for WT23.  
 □ = observed value    △ = mean value    ○ = peak value (average)



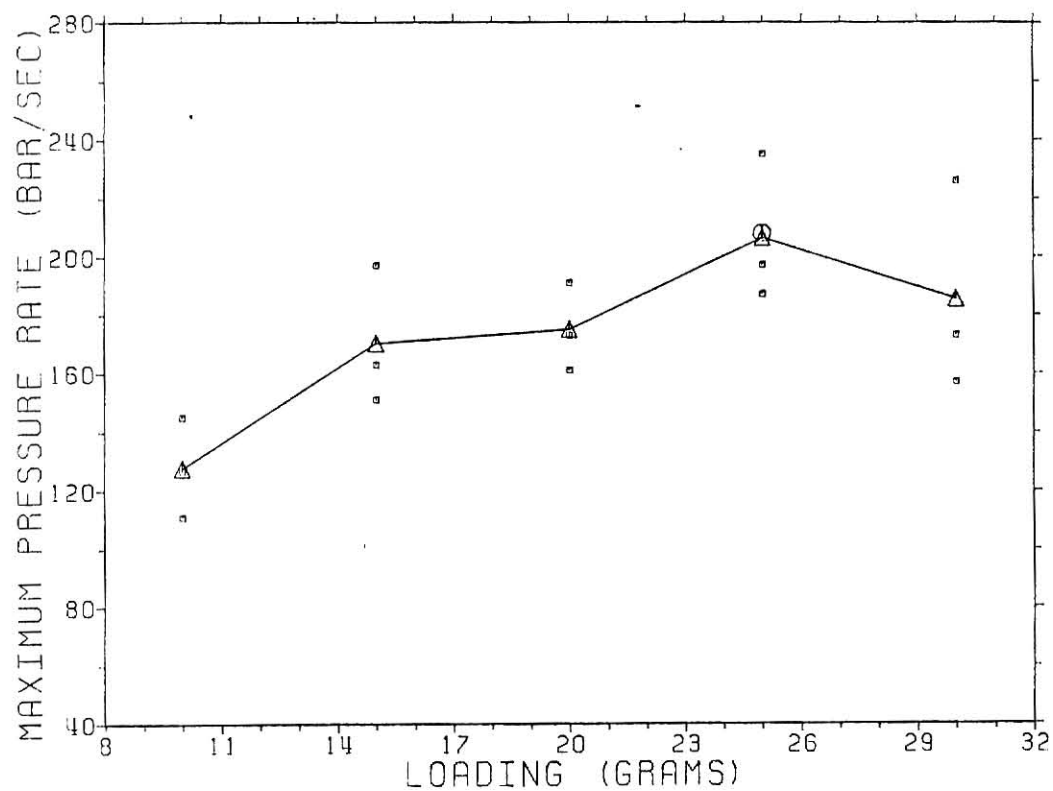


Figure A59. Effect of Dust Loading on Maximum Rate of Pressure Rise for Wheat Flour.  
 □ = observed value    △ = mean value    ○ = peak value (average)

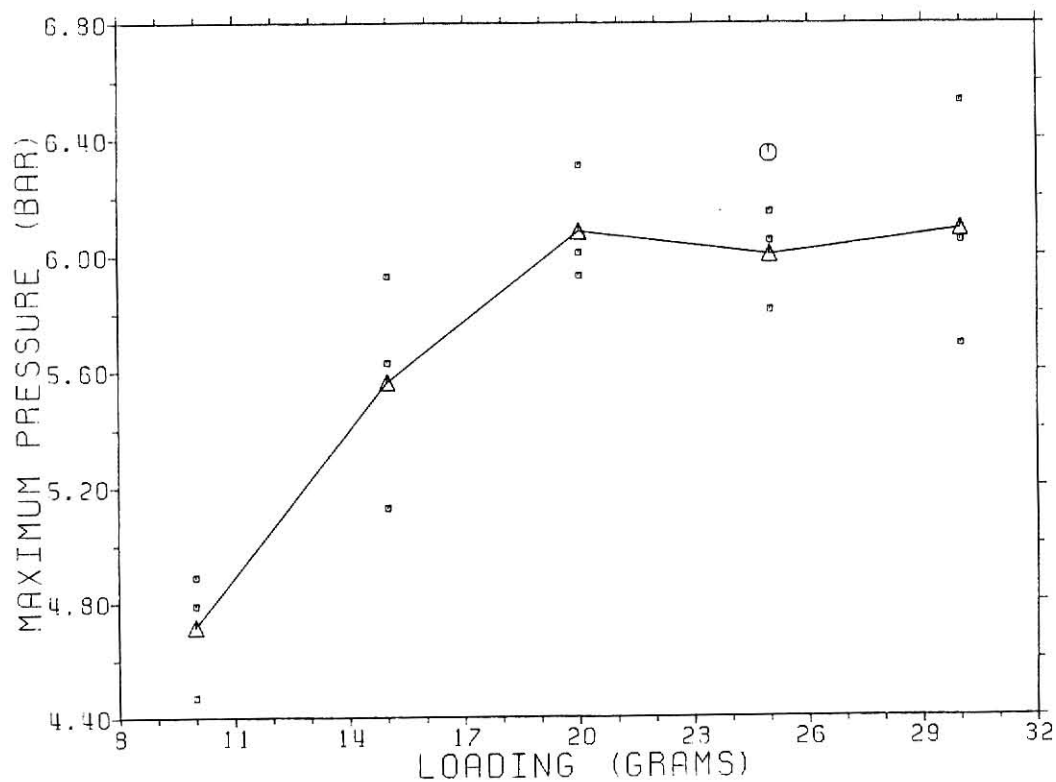


Figure A60. Effect of Dust Loading on Maximum Pressure for Wheat Flour.  
 □ = observed value    △ = mean value    ○ = peak value (average)

## APPENDIX 3

### DETERMINATION OF THE CALCULATED EXTERNAL SPECIFIC SURFACE AREA

The calculated external specific surface area is calculated from

$$SSA = \frac{6.0}{D\rho}$$

where

SSA = calculated external specific surface area [=]  $\text{m}^2/\text{gram}$

D = average arithmetic second moment diameter, average particle size of dust sample [=]  $\mu$

$\rho$  = density of dust sample [=]  $\text{gram}/\text{cm}^3$

The density is calculated from

$$\rho = 1.5[1.0 + 0.53(\text{ash}/100)]$$

where

ash = percent ash content

## APPENDIX 4

DETERMINATION OF THE STANDARD  
HEAT OF COMBUSTION ON AN ASH AND  
MOISTURE FREE BASIS AND THE  
ESTIMATED VALUES OF THE STANDARD  
HEAT OF COMBUSTION FROM THE  
STATISTICAL CORRELATION

calculated from

$$(-\Delta H_c') = \frac{(-\Delta H_c^*)}{[1.0 - \text{ash}/100 - \text{moist}/100]}$$

where

$\Delta H_c'$  = standard heat of combustion for a dust sample based on the mass of combustible dust in the dust sample (ash free and moisture free basis) [=] cal/gram

$\Delta H_c^*$  = standard heat of combustion for a dust sample from the PARR adiabatic bomb calorimeter [=] cal/gram

ash = percent ash content

moist = percent moisture content

The following results were obtained for the dust samples:

| Dust sample | $-\Delta H_c'$<br>cal/gram | $-\Delta H_c^*$<br>cal/gram |
|-------------|----------------------------|-----------------------------|
| CB12        | 4755                       | 3119                        |
| CB12c       | 4610                       | 3663                        |
| CB13        | 2980                       | 2412                        |
| CN21        | 4380                       | 3752                        |
| CN22b       | 4657                       | 3791                        |
| CN23        | 4776                       | 3888                        |
| Cornstarch  | 4139                       | 3624                        |
| MO11        | 5021                       | 3477                        |
| MO12b       | 5060                       | 3658                        |
| MO13        | 4900                       | 3446                        |
| MO20        | 5017                       | 3756                        |
| MO32b       | 4907                       | 3543                        |
| MO32c       | 5188                       | 4435                        |
| OT12        | 4755                       | 4185                        |
| OT12c       | 5144                       | 3683                        |
| OT13        | 4527                       | 3791                        |
| SB11        | 5000                       | 2295                        |
| SB12a       | 4992                       | 2419                        |
| SB13        | 6318                       | 5006                        |
| SB21        | 5049                       | 2606                        |
| SB22a       | 5043                       | 1787                        |
| SB22b       | 5336                       | 2647                        |
| SB23        | 5131                       | 2867                        |
| WT11        | 4768                       | 3481                        |
| WT12a       | 4366                       | 3433                        |
| WT12b       | 4688                       | 3714                        |
| WT21        | 4807                       | 3747                        |
| WT22a       | 5047                       | 3323                        |
| WT23        | 4812                       | 3936                        |
| Wheat Flour | 4421                       | 3868                        |

The sample mean and sample standard deviation are calculated from

$$\bar{X} = \frac{\sum_{i=1}^n X_i}{n} = 4819.8$$

$$\hat{\sigma} = \left[ \frac{\sum_{i=1}^n X_i^2 - \left( \sum_{i=1}^n X_i \right)^2 / n}{n - 1} \right]^{\frac{1}{2}} = 518.9$$

where

$\bar{X}$  = sample mean

$\hat{\sigma}$  = sample standard deviation

$X = -\Delta H_c'$

$n$  = number of values of  $-\Delta H_c' = 30$

The probability of 2980 occurring for CB13 and 6318 occurring for SB13 is calculated below:

$$\text{CB13} \quad Z = \frac{X - \bar{X}}{\hat{\sigma}} = \frac{2980 - 4819.8}{518.9} = -3.55$$

$$P(X \leq 2980) = P(Z \leq -3.55) = 0.000$$

$$\text{SB13} \quad Z = \frac{6318 - 4819.8}{518.9} = 2.89$$

$$P(X \geq 6318) = P(Z \geq 2.89) = 0.002 \approx 0.0$$

where

$Z$  = standard score for a standard normal distribution

## DEP VARIABLE: HEAT

| SOURCE   | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PROB>F |
|----------|----|----------------|-------------|---------|--------|
| MODEL    | 2  | 8959739        | 4479869     | 126.972 | 0.0001 |
| ERROR    | 25 | 882662         | 35282.478   |         |        |
| C TOTAL  | 27 | 9841801        |             |         |        |
| ROOT MSE |    | 187.836        | R-SQUARE    | 0.9104  |        |
| DLP MEAN |    | 3426.214       | ADJ R-SQ    | 0.9032  |        |
| C.V.     |    | 5.482328       |             |         |        |

| VARIABLE | DF | PARAMETER ESTIMATE | STANDARD ERROR | T FOR H0: PARAMETER=0 | PROB >  T |
|----------|----|--------------------|----------------|-----------------------|-----------|
| INTERCEP | 1  | 4808.343           | 267.530        | 17.973                | 0.0001    |
| ASH      | 1  | -41.793056         | 3.200352       | -13.059               | 0.0001    |
| MCIST    | 1  | -61.555979         | 22.556788      | -2.725                | 0.0115    |

| OBS                      | ACTUAL | PREDICT VALUE | STD ERR PREDICT | LOWER95% MEAN | UPPER95% MEAN | LOWER95% PREDICT | UPPER95% PREDICT | STD ERR RESIDUAL | STUDENT RESIDUAL | -2-1-0 1 2 | CLOCK'S D |
|--------------------------|--------|---------------|-----------------|---------------|---------------|------------------|------------------|------------------|------------------|------------|-----------|
| 1                        | 3119   | 3190          | 38.507          | 3111          | 3270          | 2796             | 3585             | -71.401          | 133.847          |            | 0.002     |
| 2                        | 3663   | 3653          | 100.515         | 3446          | 3860          | 3214             | 4092             | 5.949            | 158.680          |            | 0.001     |
| 3                        | 3624   | 4043          | 58.200          | 3923          | 4163          | 3638             | 4448             | -418.959         | 178.592          | ****       | 0.155     |
| 4                        | 3752   | 53.382        | 3862            | 3570          | 4082          | 3570             | 4374             | -220.293         | 180.091          | **         | 0.044     |
| 5                        | 3791   | 3927          | 51.627          | 3821          | 4034          | 3526             | 4329             | -136.461         | 180.602          |            | 0.016     |
| 6                        | 3880   | 3796          | 49.931          | 3694          | 3899          | 3396             | 4196             | 91.769           | 181.106          |            | 0.006     |
| 7                        | 3756   | 3600          | 55.593          | 3485          | 3714          | 2947             | 4003             | 156.020          | 179.421          |            | 0.024     |
| 8                        | 3477   | 3341          | 36.456          | 3266          | 3417          | 2947             | 3735             | 135.613          | 184.257          |            | 0.007     |
| 9                        | 3658   | 3435          | 42.026          | 3348          | 3521          | 3038             | 3931             | 223.159          | 183.075          | ***        | 0.026     |
| 10                       | 3446   | 3343          | 51.025          | 3238          | 3448          | 2942             | 3744             | 102.955          | 180.773          |            | 0.009     |
| 11                       | 3543   | 3447          | 36.083          | 3373          | 3521          | 3053             | 3841             | 96.110           | 184.338          |            | 0.003     |
| 12                       | 4435   | 4053          | 88.619          | 3871          | 4236          | 3626             | 4491             | 381.715          | 165.618          | ***        | 0.507     |
| 13                       | 3683   | 3426          | 35.657          | 3352          | 3459          | 3032             | 3820             | 257.233          | 184.421          | ***        | 0.024     |
| 14                       | 3791   | 3934          | 51.299          | 3828          | 4039          | 3523             | 4335             | -142.592         | 180.696          |            | 0.017     |
| 15                       | 4185   | 4132          | 73.774          | 3980          | 4284          | 3716             | 4547             | 53.228           | 172.742          |            | 0.006     |
| 16                       | 2295   | 2412          | 73.667          | 2260          | 2564          | 1956             | 2927             | -116.810         | 172.788          |            | 0.024     |
| 17                       | 2419   | 2516          | 68.576          | 2374          | 2657          | 2104             | 2927             | -96.570          | 174.871          |            | 0.016     |
| 18                       | 2606   | 2646          | 62.852          | 2516          | 2775          | 2238             | 3054             | -39.660          | 177.009          |            | 0.002     |
| 19                       | 1787   | 2001          | 98.277          | 1799          | 2203          | 1564             | 2438             | -214.069         | 160.075          | **         | 0.225     |
| 20                       | 2647   | 2566          | 66.942          | 2428          | 2703          | 2155             | 2976             | 81.372           | 175.503          |            | 0.010     |
| 21                       | 2867   | 2792          | 53.864          | 2682          | 2903          | 2390             | 3155             | 74.505           | 179.948          |            | 0.005     |
| 22                       | 3481   | 3508          | 42.973          | 3419          | 3596          | 3111             | 3905             | -26.993          | 182.855          |            | 0.000     |
| 23                       | 3433   | 3759          | 65.017          | 3625          | 3893          | 3350             | 4168             | -326.098         | 176.225          | ***        | 0.155     |
| 24                       | 3714   | 3749          | 43.424          | 3659          | 3838          | 3352             | 4166             | -34.600          | 182.748          |            | 0.001     |
| 25                       | 3747   | 3683          | 39.991          | 3603          | 3764          | 3288             | 4078             | 64.752           | 183.745          |            | 0.002     |
| 26                       | 3323   | 3112          | 98.165          | 2910          | 3314          | 2675             | 3548             | 211.084          | 160.144          | ***        | 0.218     |
| 27                       | 3936   | 3852          | 46.585          | 3755          | 3948          | 3453             | 4250             | 84.362           | 181.865          |            | 0.005     |
| 28                       | 3468   | 4046          | 56.023          | 3931          | 4162          | 3643             | 4450             | -178.390         | 179.287          |            | 0.032     |
| SUM OF RESIDUALS         |        |               | 3.33102E-11     |               |               |                  |                  |                  |                  |            |           |
| SUM OF SQUARED RESIDUALS |        |               | 882661.9        |               |               |                  |                  |                  |                  |            |           |

## APPENDIX 4

DETERMINATION OF THE STANDARD  
HEAT OF COMBUSTION ON AN ASH AND  
MOISTURE FREE BASIS AND THE  
ESTIMATED VALUES OF THE STANDARD  
HEAT OF COMBUSTION FROM THE  
STATISTICAL CORRELATION



The loading at the peak maximum pressure and the loading at the peak maximum rate of pressure rise are corrected by the following method

$$\text{LRC} = \text{LR}(\text{PERCENT}/100)$$

$$\text{LPC} = \text{LP}(\text{PERCENT}/100)$$

where

LRC = corrected loading at the peak maximum rate [=] gram

LPC = corrected loading at the peak maximum pressure [=] gram

LR = loading at the peak maximum rate [=] gram

LP = loading at the peak maximum pressure [=] gram

PERCENT = percentage of the loaded dust that is dispersed

The following results were obtained for the dust samples:

| Dust<br>sample | LRC<br>gram | LPC<br>gram |
|----------------|-------------|-------------|
| CB12           | 9.0         | 9.9         |
| CB12c          | 8.8         | 8.8         |
| CB13           | 10.2        | 10.3        |
| CN21           | 10.6        | 10.6        |
| CN22b          | 8.1         | 8.1         |
| CN23           | 5.7         | 3.8         |
| Cornstarch     | 7.8         | 7.8         |
| MO11           | 9.8         | 9.8         |
| MO12b          | 7.0         | 8.4         |
| MO13           | 6.2         | 6.2         |
| MO20           | 13.0        | 13.0        |
| MO32b          | 9.5         | 11.4        |
| MO32c          | 4.2         | 6.3         |
| OT12           | 6.9         | 6.9         |
| OT12c          | 5.5         | 5.5         |
| OT13           | 6.4         | 7.2         |
| SB11           | 8.5         | 8.5         |
| SB12a          | 8.5         | 8.5         |
| SB13           | 7.9         | 13.3        |
| SB21           | 10.2        | 10.2        |
| SB22a          | 11.7        | 11.7        |
| SB22b          | 8.7         | 8.7         |
| SB23           | 7.5         | 7.5         |
| WT11           | 4.2         | 4.2         |
| WT12a          | 7.5         | 12.5        |
| WT12b          | 6.8         | 6.8         |
| WT21           | 6.7         | 6.7         |
| WT22a          | 6.6         | 8.3         |
| WT23           | 3.0         | 3.0         |
| Wheat Flour    | 9.3         | 9.3         |

## APPENDIX 6

ESTIMATED VALUES OF THE PEAK  
MAXIMUM RATE OF PRESSURE RISE  
AND THE PEAK MAXIMUM PRESSURE  
FROM STATISTICAL CORRELATIONS

## DEP VARIABLE: RATE

| SOURCE   | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PROB>F |
|----------|----|----------------|-------------|---------|--------|
| MODEL    | 1  | 1038482        | 1038482     | 305.487 | 0.0001 |
| ERROR    | 23 | 78186.841      | 3399.428    |         |        |
| TOTAL    | 24 | 1116669        |             |         |        |
| ROOT MSE |    | 58.304613      | R-SQUARE    | 0.9300  |        |
| DEP MEAN |    | 201.708        | ADJ R-SQ    | 0.9300  |        |
| C.V.     |    | 28.90541       |             |         |        |

NOTE: NO INTERCEPT TERM IS USED. R-SQUARE IS REDEFINED.

| VARIABLE | CF | PARAMETER ESTIMATE | STANDARD ERROR | T FOR H0: PARAMETER=C | PROB >  T |
|----------|----|--------------------|----------------|-----------------------|-----------|
| HESLRC   | 1  | 0.036325           | 0.002078285    | 17.478                | 0.0001    |

| GBS | ACTUAL  | PREDICT VALUE | STD ERR PREDICT | UPPER95% MEAN | LOWER95% MEAN | UPPER95% PREDICT | LOWER95% PREDICT | STD RESIDUAL | STD ERR RESIDUAL | STUDENT RESIDUAL | -2-1-0 1 2 | COCK'S D |
|-----|---------|---------------|-----------------|---------------|---------------|------------------|------------------|--------------|------------------|------------------|------------|----------|
| 1   | 261.000 | 280.714       | 16.061          | 247.490       | 313.938       | 155.610          | 405.817          | -19.714      | 56.049           | -0.352           |            | 0.010    |
| 2   | 380.000 | 247.355       | 14.152          | 218.080       | 276.631       | 123.242          | 371.469          | 132.645      | 56.561           | 2.345            | ***        | 0.344    |
| 3   | 289.000 | 355.007       | 20.540          | 316.517       | 401.498       | 231.130          | 486.884          | -70.007      | 54.567           | -1.283           | **         | 0.233    |
| 4   | 323.000 | 259.130       | 14.826          | 228.461       | 289.800       | 134.681          | 383.580          | 63.870       | 56.388           | 1.133            | **         | 0.089    |
| 5   | 127.000 | 131.859       | 10.405          | 160.335       | 203.383       | 59.342           | 304.376          | -54.859      | 57.369           | -0.956           | *          | 0.030    |
| 6   | 245.000 | 290.424       | 16.616          | 256.050       | 324.797       | 165.010          | 415.837          | -45.424      | 55.887           | -0.813           | *          | 0.058    |
| 7   | 296.000 | 213.510       | 12.216          | 188.240       | 238.780       | 90.280           | 336.740          | 82.490       | 57.011           | 1.447            | **         | 0.056    |
| 8   | 157.000 | 172.578       | 9.874           | 152.152       | 193.003       | 50.249           | 294.906          | -15.578      | 57.662           | -0.271           |            | 0.002    |
| 9   | 196.000 | 242.995       | 13.903          | 214.235       | 271.754       | 119.002          | 366.587          | -46.995      | 56.623           | -0.830           | *          | 0.042    |
| 10  | 262.000 | 165.441       | 9.694           | 149.387       | 189.495       | 47.174           | 291.708          | 92.559       | 57.493           | 1.610            | ***        | 0.074    |
| 11  | 149.000 | 128.207       | 7.335           | 113.035       | 143.383       | 6.647            | 249.771          | 20.791       | 57.841           | 0.359            |            | 0.002    |
| 12  | 222.000 | 170.484       | 9.754           | 150.306       | 190.661       | 48.196           | 292.771          | 51.516       | 57.483           | 0.896            | *          | 0.023    |
| 13  | 193.000 | 162.208       | 9.281           | 143.009       | 181.406       | 40.078           | 284.337          | 30.792       | 57.561           | 0.535            | *          | 0.007    |
| 14  | 216.000 | 223.153       | 12.767          | 196.741       | 249.564       | 99.684           | 346.622          | -7.153       | 56.890           | -0.126           |            | 0.001    |
| 15  | 99.000  | 153.872       | 8.804           | 135.660       | 172.043       | 31.893           | 275.850          | -54.872      | 57.636           | -0.952           | *          | 0.021    |
| 16  | 113.000 | 178.892       | 10.235          | 157.720       | 200.065       | 56.427           | 301.368          | -65.892      | 57.399           | -1.148           | **         | 0.042    |
| 17  | 172.000 | 157.780       | 11.316          | 174.372       | 221.189       | 74.918           | 320.642          | -25.780      | 57.196           | -0.451           |            | 0.008    |
| 18  | 156.000 | 90.490        | 5.177           | 79.780        | 101.200       | -30.596          | 211.575          | 63.510       | 58.074           | 1.094            | **         | 0.010    |
| 19  | 222.000 | 178.153       | 10.193          | 157.067       | 199.238       | 55.712           | 300.593          | 43.847       | 57.407           | 0.764            | *          | 0.013    |
| 20  | 161.000 | 181.476       | 10.383          | 159.997       | 202.954       | 58.957           | 303.984          | -20.476      | 57.373           | -0.357           |            | 0.004    |
| 21  | 244.000 | 193.268       | 11.058          | 170.393       | 216.142       | 70.506           | 316.029          | 50.732       | 57.246           | 0.886            | *          | 0.029    |
| 22  | 77.000  | 144.399       | 8.262           | 127.309       | 161.489       | 22.583           | 266.215          | -67.399      | 57.716           | -1.168           | **         | 0.028    |
| 23  | 75.000  | 84.707        | 4.846           | 74.681        | 94.732        | -36.320          | 205.734          | -9.707       | 58.103           | -0.167           |            | 0.003    |
| 24  | 208.000 | 255.368       | 14.840          | 228.671       | 290.066       | 134.912          | 383.325          | -51.368      | 56.385           | -0.911           | *          | 0.057    |

SUM OF RESIDUALS

77.5297

SUM OF SQUARED RESIDUALS

78186.84

## DEP VARIABLE: PRESS

| SOURCE   | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PROB>F |
|----------|----|----------------|-------------|---------|--------|
| MODEL    | 1  | 4.408335       | 4.408335    | 32.855  | 0.0001 |
| ERROR    | 22 | 2.951461       | 0.134157    |         |        |
| C TOTAL  | 23 | 7.359796       |             |         |        |
| ROOT MSE |    | 0.366275       |             |         |        |
| DEP MEAN |    | 5.744583       | R-SQUARE    | 0.5990  |        |
| C.V.     |    | 6.376005       | ADJ R-SQ    | 0.5807  |        |

| VARIABLE  | DF | PARAMETER ESTIMATE | STANDARD ERROR | T FOR HO: PARAMETER=0 | PROB >  T |
|-----------|----|--------------------|----------------|-----------------------|-----------|
| INTERCEPT | 1  | 4.442689           | 0.239105       | 18.581                | 0.0001    |
| HESLPC    | 1  | 0.0002254747       | 0.0003933397   | 5.732                 | 0.0001    |

| OBS | ACTUAL | PREDICT VALUE | STD ERR PREDICT | UPPER95% MEAN | LOWER95% MEAN | PREDICT | UPPER95% PREDICT | STUDENT RESIDUAL | STU ERR RESIDUAL | -2-1-0 1 2 | CHECKS |
|-----|--------|---------------|-----------------|---------------|---------------|---------|------------------|------------------|------------------|------------|--------|
| 1   | 6.340  | 6.185         | 0.107222        | 5.963         | 6.407         | 5.394   | 6.977            | 0.154862         | 0.350230         |            | 0.005  |
| 2   | 6.820  | 5.978         | 0.085141        | 5.802         | 6.155         | 5.198   | 6.758            | 0.841925         | 0.356242         | ***        | 0.160  |
| 3   | 6.140  | 6.671         | 0.178088        | 6.302         | 7.040         | 5.826   | 7.516            | -0.531120        | 0.320065         | ***        | 0.426  |
| 4   | 6.490  | 6.051         | 0.091926        | 5.861         | 6.242         | 5.258   | 6.834            | 0.438835         | 0.354552         | **         | 0.051  |
| 5   | 5.070  | 5.195         | 0.121547        | 4.943         | 5.447         | 4.395   | 5.996            | -0.125246        | 0.345519         |            | 0.003  |
| 6   | 6.020  | 6.245         | 0.114992        | 6.007         | 6.484         | 5.469   | 7.042            | -0.225409        | 0.347756         | *          | 0.023  |
| 7   | 6.220  | 6.033         | 0.090124        | 5.846         | 6.220         | 5.251   | 6.815            | 0.186949         | 0.355014         | *          | 0.009  |
| 8   | 5.330  | 5.514         | 0.034907        | 5.338         | 5.690         | 4.734   | 6.294            | -0.183915        | 0.356298         | *          | 0.008  |
| 9   | 5.820  | 6.253         | 0.115958        | 6.012         | 6.493         | 5.456   | 7.049            | -0.432671        | 0.347435         | **         | 0.089  |
| 10  | 6.330  | 6.020         | 0.088903        | 5.836         | 6.205         | 5.239   | 6.802            | 0.309677         | 0.355322         |            | 0.024  |
| 11  | 5.690  | 5.239         | 0.115689        | 4.999         | 5.478         | 4.442   | 6.035            | 0.451492         | 0.357524         | **         | 0.094  |
| 12  | 5.620  | 5.501         | 0.086005        | 5.323         | 5.679         | 4.721   | 6.281            | 0.119083         | 0.356034         |            | 0.004  |
| 13  | 5.340  | 5.450         | 0.090769        | 5.261         | 5.638         | 4.667   | 6.232            | -0.109545        | 0.354850         |            | 0.003  |
| 14  | 6.180  | 5.828         | 0.076163        | 5.670         | 5.986         | 5.052   | 6.604            | -0.352156        | 0.358269         | *          | 0.022  |
| 15  | 4.970  | 5.398         | 0.096175        | 5.198         | 5.597         | 4.612   | 6.183            | -0.427803        | 0.353423         | **         | 0.054  |
| 16  | 5.080  | 5.553         | 0.081888        | 5.383         | 5.723         | 4.775   | 6.331            | -0.473111        | 0.357004         | **         | 0.049  |
| 17  | 5.390  | 5.670         | 0.075879        | 5.513         | 5.828         | 4.895   | 6.446            | -0.280351        | 0.358329         | *          | 0.019  |
| 18  | 5.150  | 5.004         | 0.149212        | 4.695         | 5.314         | 4.184   | 5.825            | 0.145624         | 0.334504         |            | 0.019  |
| 19  | 6.010  | 6.295         | 0.120425        | 6.036         | 6.535         | 5.486   | 7.085            | -0.275741        | 0.345912         | *          | 0.039  |
| 20  | 5.600  | 5.569         | 0.080787        | 5.402         | 5.737         | 4.791   | 6.347            | 0.030855         | 0.357254         |            | 0.000  |
| 21  | 5.980  | 5.642         | 0.076864        | 5.483         | 5.802         | 4.866   | 6.418            | 0.337659         | 0.358114         |            | 0.020  |
| 22  | 5.310  | 5.563         | 0.081194        | 5.395         | 5.731         | 4.785   | 6.341            | -0.253081        | 0.357162         | *          | 0.013  |
| 23  | 4.620  | 4.968         | 0.154663        | 4.648         | 5.289         | 4.144   | 5.793            | -0.346431        | 0.332019         | **         | 0.120  |
| 24  | 6.350  | 6.053         | 0.092076        | 5.862         | 6.244         | 5.269   | 6.836            | 0.297357         | 0.354513         | *          | 0.024  |

SUM OF RESIDUALS 1.08802E-14  
 SUM OF SQUARED RESIDUALS 2.951461

DEP VARIABLE: PPESS X = HESLPC X2 = HESLPC\*HESLPC

| SOURCE   | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PROB>F |
|----------|----|----------------|-------------|---------|--------|
| MODEL    | 2  | 4.314576       | 2.407288    | 19.842  | 0.0001 |
| ERROR    | 21 | 2.545219       | 0.121201    |         |        |
| C. TOTAL | 23 | 7.359796       |             |         |        |

ROOT MSE 0.343139 R-SQUARE 0.6542  
 DEP MEAN 5.744583 ADJ R-SQ 0.6212  
 C.V. 6.060304

| VARIABLE | DF | PARAMETER ESTIMATE | STANDARD ERROR | T FOR HO: PARAMETER=0 | PROB >  T |
|----------|----|--------------------|----------------|-----------------------|-----------|
| INTERCEP | 1  | 3.434037           | 0.570819       | 6.104                 | 0.0001    |
| X        | 1  | 0.0005927748       | 0.002040773    | 2.905                 | 0.0085    |
| X2       | 1  | -3.144995-08       | 1.71783E-04    | -1.831                | 0.0814    |

| ORS | ACTUAL | PREDICT | STD ERR  | LOWER95% | UPPER95% | PREDICT | RESIDUAL | STD ERR   | STUDENT  | RESIDUAL | -2-1-0 1 2 | CCOK'S |
|-----|--------|---------|----------|----------|----------|---------|----------|-----------|----------|----------|------------|--------|
| 1   | 6.340  | 6.187   | 0.101917 | 5.975    | 6.355    | 5.432   | 6.941    | 0.153259  | 0.332887 | 0.460    |            | 0.007  |
| 2   | 6.820  | 6.062   | 0.093072 | 5.869    | 6.256    | 5.313   | 6.812    | 0.757761  | 0.335468 | 2.259    | ***        | 0.131  |
| 3   | 6.140  | 6.271   | 0.276611 | 5.695    | 6.846    | 5.346   | 7.195    | -1.30595  | 0.211394 | -0.618   | *          | 0.218  |
| 4   | 5.490  | 6.112   | 0.093527 | 5.918    | 6.307    | 5.363   | 6.862    | 0.377756  | 0.335341 | 1.126    | **         | 0.033  |
| 5   | 5.070  | 5.112   | 0.124121 | 4.854    | 5.370    | 4.344   | 5.881    | -0.42166  | 0.325261 | -0.130   |            | 0.001  |
| 6   | 6.020  | 6.213   | 0.110722 | 5.983    | 6.443    | 5.453   | 6.973    | -1.193013 | 0.330063 | -0.585   | *          | 0.013  |
| 7   | 6.220  | 6.100   | 0.093241 | 5.907    | 6.294    | 5.351   | 6.850    | 0.119533  | 0.335421 | 0.356    |            | 0.003  |
| 8   | 5.330  | 5.590   | 0.090379 | 5.401    | 5.779    | 4.842   | 6.339    | -2.60418  | 0.336068 | -0.775   | *          | 0.015  |
| 9   | 5.820  | 6.216   | 0.112034 | 5.932    | 6.449    | 5.455   | 6.976    | -3.55875  | 0.329620 | -1.201   | **         | 0.056  |
| 10  | 6.330  | 6.092   | 0.093119 | 5.898    | 6.286    | 5.343   | 6.841    | 0.238050  | 0.335455 | 0.710    | *          | 0.013  |
| 11  | 5.690  | 5.184   | 0.113855 | 4.948    | 5.421    | 4.423   | 5.946    | 0.505537  | 0.328995 | 1.537    | ***        | 0.094  |
| 12  | 5.620  | 5.573   | 0.090821 | 5.334    | 5.762    | 4.825   | 6.322    | 0.046632  | 0.336084 | 0.139    |            | 0.000  |
| 13  | 5.340  | 5.504   | 0.091247 | 5.314    | 5.694    | 4.755   | 6.252    | -1.63939  | 0.335969 | -0.488   |            | 0.006  |
| 14  | 6.180  | 5.939   | 0.094278 | 5.742    | 6.135    | 5.189   | 6.689    | 0.241296  | 0.335102 | 0.720    | *          | 0.014  |
| 15  | 4.970  | 5.431   | 0.094163 | 5.237    | 5.624    | 4.681   | 6.180    | -4.60708  | 0.335442 | -1.373   | **         | 0.049  |
| 16  | 5.080  | 5.641   | 0.094323 | 5.451    | 5.930    | 4.892   | 6.289    | -5.60565  | 0.325948 | -1.669   | ***        | 0.069  |
| 17  | 5.390  | 5.779   | 0.094474 | 5.595    | 5.974    | 5.030   | 6.529    | -3.82216  | 0.335356 | -1.161   | **         | 0.035  |
| 18  | 5.150  | 4.766   | 0.192695 | 4.365    | 5.166    | 3.939   | 5.593    | 0.384452  | 0.289948 | 1.326    |            | 0.259  |
| 19  | 6.010  | 6.223   | 0.118716 | 5.981    | 6.475    | 5.463   | 6.993    | -2.18084  | 0.327273 | -0.666   | *          | 0.019  |
| 20  | 5.600  | 5.451   | 0.091585 | 5.470    | 5.891    | 4.912   | 6.409    | -0.60521  | 0.335877 | -0.180   |            | 0.001  |
| 21  | 5.980  | 5.748   | 0.092380 | 5.453    | 5.941    | 4.958   | 6.497    | 0.222363  | 0.335493 | 0.693    | *          | 0.012  |
| 22  | 5.210  | 5.653   | 0.091482 | 5.463    | 5.843    | 4.904   | 6.402    | -3.43017  | 0.335905 | -1.021   | **         | 0.026  |
| 23  | 4.620  | 4.695   | 0.204554 | 4.260    | 5.131    | 3.850   | 5.540    | -0.75327  | 0.279383 | -0.271   |            | 0.014  |
| 24  | 6.350  | 6.113   | 0.093556 | 5.919    | 6.308    | 5.364   | 6.863    | 0.236813  | 0.335333 | 0.706    | *          | 0.013  |

SUM OF RESIDUALS -1.37668E-14  
 SUM OF SQUARED RESIDUALS 0.545219

## DEP VARIABLE: PRESS

| SOURCE   | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PROB>F |
|----------|----|----------------|-------------|---------|--------|
| MODEL    | 1  | 3.603839       | 3.603839    | 21.109  | 0.0001 |
| ERROR    | 22 | 3.75557        | 0.170725    |         |        |
| C TOTAL  | 23 | 7.359496       |             |         |        |
| RCCT MSE |    | 0.413189       | R-SQUARE    | 0.4897  |        |
| DEP MEAN |    | 5.744583       | ADJ R-SQ    | 0.4665  |        |
| C.V.     |    | 7.192675       |             |         |        |

| VARIABLE | DF | PARAMETER ESTIMATE | STANDARD ERROR | T FOR H0: PARAMETER=0 | PROB >  T |
|----------|----|--------------------|----------------|-----------------------|-----------|
| INTERCEP | 1  | 4.443856           | 0.295405       | 15.043                | 0.0001    |
| HLP      | 1  | .00004843126       | .00001054125   | 4.594                 | 0.0001    |

| OBS | ACTUAL | PREDICT VALUE | STD ERR PREDICT | LOWER95% MEAN | UPPER95% MEAN | LOWER95% PREDICT | UPPER95% PREDICT | RESIDUAL | STD ERR RESIDUAL | STUDENT RESIDUAL | -2-1-0 1 2 | CHECK'S D |
|-----|--------|---------------|-----------------|---------------|---------------|------------------|------------------|----------|------------------|------------------|------------|-----------|
| 1   | 6.340  | 6.014         | 0.102709        | 5.801         | 6.227         | 5.131            | 6.897            | 0.326121 | 0.400220         | 0.815            | *          | 0.022     |
| 2   | 6.820  | 5.813         | 0.085642        | 5.635         | 5.990         | 4.938            | 6.688            | 1.007    | 0.404216         | 2.492            | ***        | 0.139     |
| 3   | 6.140  | 6.370         | 0.160140        | 6.038         | 6.702         | 5.451            | 7.289            | -.230025 | 0.380894         | -0.604           | *          | 0.032     |
| 4   | 6.490  | 5.931         | 0.093598        | 5.737         | 6.125         | 5.052            | 6.810            | 0.558960 | 0.402448         | 1.389            | **         | 0.052     |
| 5   | 5.070  | 5.159         | 0.152761        | 4.843         | 5.476         | 4.246            | 6.073            | -.089399 | 0.383913         | -0.233           |            | 0.004     |
| 6   | 6.020  | 6.094         | 0.113586        | 5.859         | 6.230         | 5.205            | 6.983            | -.074132 | 0.397270         | -0.187           |            | 0.001     |
| 7   | 6.220  | 5.932         | 0.093690        | 5.738         | 6.126         | 5.053            | 6.811            | 0.287987 | 0.402427         | 0.716            | *          | 0.014     |
| 8   | 5.330  | 5.479         | 0.102299        | 5.266         | 5.691         | 4.596            | 6.361            | -.148600 | 0.400325         | -0.371           |            | 0.004     |
| 9   | 5.820  | 6.400         | 0.165723        | 6.056         | 6.744         | 5.477            | 7.323            | -.580004 | 0.378499         | -1.532           | ***        | 0.225     |
| 10  | 6.330  | 5.797         | 0.085111        | 5.621         | 5.974         | 4.922            | 6.672            | 0.532950 | 0.404328         | 1.318            | **         | 0.038     |
| 11  | 5.690  | 5.842         | 0.086987        | 5.662         | 6.023         | 4.967            | 6.718            | -.152381 | 0.403929         | -0.377           |            | 0.003     |
| 12  | 5.620  | 5.389         | 0.114525        | 5.151         | 5.626         | 4.499            | 6.278            | 0.231371 | 0.397001         | 0.583            | *          | 0.014     |
| 13  | 5.340  | 5.440         | 0.107321        | 5.217         | 5.662         | 4.554            | 6.325            | -.099675 | 0.399008         | -0.250           |            | 0.002     |
| 14  | 6.180  | 5.731         | 0.084392        | 5.556         | 5.906         | 4.857            | 6.606            | 0.448783 | 0.404479         | 1.110            | **         | 0.027     |
| 15  | 4.970  | 5.461         | 0.104543        | 5.244         | 5.678         | 4.577            | 6.345            | -.450779 | 0.399745         | -1.228           | **         | 0.052     |
| 16  | 5.080  | 5.559         | 0.093499        | 5.365         | 5.753         | 4.681            | 6.438            | -.479175 | 0.402471         | -1.191           | **         | 0.038     |
| 17  | 5.390  | 5.485         | 0.101487        | 5.275         | 5.696         | 4.603            | 6.368            | -.095249 | 0.400532         | -0.238           |            | 0.002     |
| 18  | 5.150  | 5.152         | 0.154119        | 4.832         | 5.472         | 4.237            | 6.066            | -.001931 | 0.383370         | -0.005           |            | 0.000     |
| 19  | 6.010  | 6.522         | 0.189055        | 6.130         | 6.914         | 5.580            | 7.465            | -.512163 | 0.367381         | -1.394           | **         | 0.257     |
| 20  | 5.600  | 5.667         | 0.086016        | 5.489         | 5.845         | 4.752            | 6.542            | -.066997 | 0.404137         | -0.166           |            | 0.001     |
| 21  | 5.980  | 5.669         | 0.085940        | 5.491         | 5.847         | 4.794            | 6.544            | 0.311208 | 0.404153         | 0.770            | *          | 0.013     |
| 22  | 5.310  | 5.772         | 0.084546        | 5.596         | 5.947         | 4.897            | 6.646            | -.461587 | 0.404447         | -1.141           | **         | 0.028     |
| 23  | 4.620  | 5.016         | 0.179664        | 4.643         | 5.388         | 4.081            | 5.950            | -.395732 | 0.372083         | -1.064           | **         | 0.132     |
| 24  | 6.350  | 6.177         | 0.126327        | 5.915         | 6.439         | 5.281            | 7.073            | 0.173322 | 0.393404         | 0.441            |            | 0.010     |

SUM OF RESIDUALS 3.55271E-14  
 SUM OF SQUARED RESIDUALS 3.755957

DEP VARIABLE: PRESS X = HLPC X2 = HLPC \* HLPC

| SOURCE   | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE  | PROB>F |
|----------|----|----------------|-------------|----------|--------|
| MODEL    | 2  | 4.564799       | 2.282400    | 17.149   | 0.0001 |
| ERROR    | 21 | 2.794596       | 0.133095    |          |        |
| C TOTAL  | 23 | 7.359396       |             |          |        |
| R-SQ     |    |                | R-SQUARE    | 0.6202   |        |
| DEP MEAN |    |                | ADJ R-SQ    | 0.5841   |        |
| C.V.     |    |                |             | 0.350712 |        |

PARAMETER ESTIMATE STANDARD ERROR T FOR H0: PARAMETER=0 PROB > |T|

|           |   |              |              |        |        |
|-----------|---|--------------|--------------|--------|--------|
| INTERCEPT | 1 | 2.624940     | 0.721965     | 3.650  | 0.0015 |
| X         | 1 | 0.000192347  | 0.0005436217 | 3.538  | 0.0020 |
| X2        | 1 | -2.61834E-09 | 9.74440E-10  | -2.687 | 0.0138 |

| OPS | ACTUAL | PREDICT | STD ERR  | LOWER95 | UPPER95 | LOWER95 | PREDICT | UPPER95   | STD ERR  | STUDENT | -2-1-0 1 2 | CHECK'S |
|-----|--------|---------|----------|---------|---------|---------|---------|-----------|----------|---------|------------|---------|
| 1   | 6.340  | 6.119   | 0.098727 | 5.913   | 6.324   | 5.333   | 6.905   | 0.221254  | 0.351209 | 0.630   | *          | 0.010   |
| 2   | 6.820  | 5.980   | 0.097887 | 5.776   | 6.183   | 5.194   | 6.765   | 0.840097  | 0.351444 | 2.390   | ***        | 0.148   |
| 3   | 6.140  | 6.143   | 0.164667 | 5.801   | 6.486   | 5.311   | 6.976   | -0.03249  | 0.325545 | -0.010  |            | 0.000   |
| 4   | 6.490  | 6.072   | 0.097976 | 5.869   | 6.276   | 5.287   | 6.858   | 0.417547  | 0.351420 | 1.188   | **         | 0.037   |
| 5   | 5.070  | 4.905   | 0.164746 | 4.563   | 5.248   | 4.073   | 5.738   | 0.164788  | 0.325505 | 0.506   | *          | 0.022   |
| 6   | 6.020  | 6.149   | 0.102346 | 5.936   | 6.362   | 5.361   | 6.937   | -0.128984 | 0.350172 | -0.368  |            | 0.004   |
| 7   | 6.220  | 6.073   | 0.097977 | 5.869   | 6.277   | 5.288   | 6.859   | 0.146914  | 0.351419 | 0.418   |            | 0.005   |
| 8   | 5.330  | 5.549   | 0.094075 | 5.354   | 5.745   | 4.766   | 6.333   | -0.219271 | 0.352484 | -0.622  | *          | 0.009   |
| 9   | 5.320  | 6.132   | 0.177002 | 5.764   | 6.500   | 5.299   | 6.976   | -0.312389 | 0.319307 | -0.579  | *          | 0.098   |
| 10  | 6.330  | 5.965   | 0.097779 | 5.762   | 6.168   | 5.180   | 6.751   | 0.364856  | 0.351474 | 1.038   | **         | 0.028   |
| 11  | 5.690  | 6.006   | 0.097999 | 5.802   | 6.210   | 5.220   | 6.792   | -0.315935 | 0.351413 | -0.899  | *          | 0.021   |
| 12  | 5.620  | 5.291   | 0.101122 | 5.180   | 5.601   | 4.603   | 6.178   | 0.229243  | 0.350527 | 0.654   | *          | 0.012   |
| 13  | 5.340  | 5.483   | 0.096115 | 5.283   | 5.683   | 4.698   | 6.267   | -0.142911 | 0.351933 | -0.406  |            | 0.004   |
| 14  | 6.190  | 5.838   | 0.096916 | 5.696   | 6.099   | 5.113   | 6.683   | 0.282264  | 0.351714 | 0.803   | *          | 0.016   |
| 15  | 4.970  | 5.519   | 0.094841 | 5.322   | 5.717   | 4.735   | 6.303   | -0.549310 | 0.352279 | -1.559  | ***        | 0.059   |
| 16  | 5.080  | 5.676   | 0.093285 | 5.482   | 5.970   | 4.893   | 6.459   | -0.595892 | 0.352694 | -1.690  | ***        | 0.067   |
| 17  | 5.320  | 5.560   | 0.093956 | 5.365   | 5.755   | 4.777   | 6.344   | -0.170270 | 0.352542 | -0.483  |            | 0.006   |
| 18  | 5.150  | 4.887   | 0.167952 | 4.538   | 5.237   | 4.052   | 5.723   | 0.262580  | 0.323363 | 0.811   | *          | 0.059   |
| 19  | 6.010  | 6.067   | 0.237739 | 5.573   | 6.562   | 5.162   | 6.973   | -0.057394 | 0.276723 | -0.207  |            | 0.011   |
| 20  | 5.600  | 5.823   | 0.095519 | 5.624   | 6.021   | 5.038   | 6.607   | -0.222656 | 0.352096 | -0.632  | *          | 0.010   |
| 21  | 5.980  | 5.825   | 0.095562 | 5.626   | 6.024   | 5.041   | 6.609   | 0.153121  | 0.352084 | 0.441   |            | 0.005   |
| 22  | 5.310  | 5.940   | 0.097525 | 5.737   | 6.143   | 5.155   | 6.726   | -0.620219 | 0.351545 | -1.793  | ***        | 0.082   |
| 23  | 4.620  | 4.541   | 0.237414 | 4.047   | 5.035   | 3.636   | 5.446   | 0.078500  | 0.277001 | 0.235   |            | 0.020   |
| 24  | 6.350  | 6.165   | 0.111622 | 5.933   | 6.397   | 5.372   | 6.958   | 0.184916  | 0.347326 | 0.532   | *          | 0.010   |

SUM OF RESIDUALS 4.26326E-14  
SUM OF SQUARED RESIDUALS 2.794996

THE EXPLOSIVE POWER OF SELECTED GRAIN  
DUST IN A 20-LITER SPHERICAL EXPLOSION CHAMBER

by

BRENDA LORIE LEWIS

B. CHE., Georgia Institute of Technology, 1980

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY  
Manhattan, Kansas

1982



## ABSTRACT

Grain dust explosions have been occurring frequently in the United States causing injuries, fatalities, and extensive property damage. To combat dust explosions, protective and preventive measures are used that require knowledge of the peak maximum rate of pressure rise and peak maximum pressure occurring during an explosion.

Peak maximum rates and peak maximum pressures were measured for corn, milo, oats, soybean, wheat, and mixed dust samples in a 20-liter spherical explosion chamber. These dust samples were collected from around the bucket elevator, conveyor belt, and dust collection system in several grain elevators. The peak maximum rates and peak maximum pressures were also measured for a cornstarch sample and a wheat flour sample. Each dust sample was characterized by its standard heat of combustion, specific surface area, average particle size, and ash and moisture content.

The peak maximum rates and peak maximum pressures for dust samples within a dust type had wide ranges of values. These ranges were as large as 253 bar/sec and 1.75 bar, respectively, for one dust type, corn dust. If all the dust samples are considered, the values ranged from 75 to 380 bar/sec and from 4.62 to 6.82 bar, respectively. A wheat dust sample had the lowest values of peak maximum rate and peak maximum pressure, and cornstarch had the highest values.

Several statistical correlations have been developed showing that the peak maximum rate and peak maximum pressure are functions of the standard heat of combustion, external specific surface area, and quantity of dust present in the dust cloud. An additional correlation has been developed showing that the standard heat of combustion is a function of the ash and moisture contents.

The experimental explosion tests have demonstrated that the method for dispersing the dust is a limitation of the 20-liter spherical explosion chamber. The dispersion system does not disperse all the dust, and in dispersing the dust the average particle size is reduced. The dust being tested is changed when the average particle size is reduced; therefore, the value of the peak maximum rate and peak maximum pressure measured are not the correct values for the tested dust.

The values of the peak maximum rate can be scaled to obtain results expected in larger chambers. These scaled values and the values of the peak maximum pressure provide the engineering data needed in designing protective and preventive measures.