VOLUME II

GRAIN DUST LEVELS CAUSED BY TENT CONTROL OF SHIP LOADING EMISSIONS COMPARED TO MINIMUM EXPLOSIVE LEVELS

Final Report

GCA/TECHNOLOGY DIVISION

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ABSTRACT

Explosions in grain handling facilities late in 1977 and early in 1978 generated considerable concern with respect to any operation where grain dust is generated and contained. As a result of this concern, the use of tents to control particulate emissions from ship loading at the Bunge and Louis Dreyfus terminal grain elevators in Portland, Oregon was temporarily halted. This has resulted in an increase in the suspendable particulate emission factor for ship loading at these facilities from about 6-10 g/1000 kg (0.012 - 0.020 lb/ton) of grain loaded to about 40 g/1000 kg (0.08 lb/ton). The purpose of this study was to determine whether the use of tents at the Bunge and Dreyfus ship loading facilities would, in fact, pose an explosion hazard. Measurements of dust concentration were made in the holds of ships at the United Grain terminal at Tacoma, Washington, at Bunge, and at Dreyfus during tent controlled loading and during uncontrolled loading. Both loading and weather conditions during these tests were typical of the Bunge and Dreyfus facilities. A total of 67 samples were taken over 5-20 min intervals. Average dust concentration was 0.40 g/m^3 with a maximum value of 1.1 g/m^3, well below the minimum explosive limit of 40 g/m^3.

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SECTION 1

SUMMARY AND CONCLUSIONS

Explosions in grain elevators in late 1977 and early 1978 caused considerable concern with respect to any operation where dust, particularly grain dust, is generated and contained.

Ship loading at terminal grain elevators results in the aerosolization of dust formed by abrasion of the grain in numerous transfer operations. The dust becomes aerosolized when the grain is dropped down long chutes (15 to 25 m, or 50 to 80 ft) into the ship holds. Preventing the emission of this dust requires proper control equipment design because of variations in ship and hold sizes, and because deck height will vary not only with tide or river level but with ship trim as well.

One method of controlling dust emissions during ship loading involves covering of the hold opening with tents, and aspiration of dust laden air under the tents to a fabric filtration system. At most terminals using tents, the tents are used only during general filling of bulk carriers, since they may interfere with loading operations if used during topping off or during tween-decker loading and are not needed for tanker loadings. Bulk carriers carry some 90 percent of the grain shipped in the United States, and 75 to 85 percent of the grain loaded to a bulk carrier is loaded in a general filling mode. Use of tents to control emissions from bulk carrier loading reduces the suspendable particulate emission factor (including topping off) from 40 g/metric ton (0.08 lb/ton) loaded to 6-10 g/t (0.012 - 0.02 lb/ton).[1]

Before early 1978, tents were used to control emissions from ship loading at the Bunge Corporation and the Louis Dreyfus Corporation terminals in Portland, Oregon. Tents were and are used at other grain loading facilities in the U.S. as relatively inexpensive method to reduce particulate emissions. In early 1978, the use of tents generated concern among Portland area stevedores, as they suggested that an explosion hazard could be caused by the dust concentrations in tent controlled ship holds. The tents are not presently used by the stevedores in Portland although they are still made available by the elevator operators and they are used in Tacoma, Washington.

This report describes tests by GCA/Technology Division for the U.S. Environmental Protection Agency, Oregon Operations Office, to determine whether or not the use of tents to control particulate emissions during ship loading represents an explosion hazard. Initial tests were conducted at the United Grain terminal in Tacoma, Washington during November 1978. In March 1979, additional tests were conducted at the Bunge and Dreyfus terminals.

Background data in the technical literature[2] indicates that the lower explosive limit for grain dust is 40 g/m^3. If this concentration is reached, an explosion is still only possible if an ignition source with enough energy is present. Suggested ignition sources include static electricity or tramp metal in the grain although documentation showing the presence of these sources is lacking. Data on dust concentration in ship holds were collected in this study and showed that dust levels are well below the minimum explosive limit.

A total of 67 measurements were conducted at United Grain (Tacoma, Washington) and Bunge and Dreyfus (Portland, Oregon). Average dust concentration over the 5-20 min sampling intervals was 0.40 g/m^3 with a maximum value of 1.1 g/m^3.

Based on the change in filter resistance as a function of time during each sample run, estimates of 1 minute concentrations were made. As expected, these indicated a slightly wider range of values. However, the maximum estimated concentration was 2.3 g/m^3 which occurred only once in 600 1-min intervals.

Graphical plots on log-probability paper of the distributions of measured and estimated dust concentrations indicated an insignificant (less than 1 chance in 10,000) chance of exceeding about 5 g/m^3 as either a 1-min or 10-min average.

SECTION 2

BACKGROUND INFORMATION: CONDITIONS REQUIRED FOR DUST EXPLOSIONS

A dust explosion is a reaction in a mixture of finely divided particles and a gas (generally air) which is initiated by a local heat source. For an explosion to occur, the simultaneous presence of an "explosible" dust cloud and an ignition source of sufficient magnitude is required. The explosibility of a dust cloud in air is determined by a number of factors, including type of dust; its concentration; the moisture content of the air and the dust; the flow dynamics and dimensions of the dust cloud; and the extent to which it is contained (see Appendix A for a more detailed discussion).

Dust concentration has a profound effect on explosibility. In fact, for a given dust, there is a minimum concentration below which an explosion cannot occur. It should be understood that at dust concentrations below this level it is essentially impossible to initiate an explosion even if an active flame exists within the dust cloud. In this case, only those particles which come in contact with the flame will burn, as there is insufficient heat transfer to ignite neighboring particles.

The precise minimum concentration at which an explosion can be initiated cannot be specified with complete certainty because of the many other factors that influence explosibility. Based on laboratory investigations by several researchers, however, it appears that one can infer a consensus on the minimum explosible concentration for a given dust. Table 1 summarizes values obtained from several sources for the minimum explosive concentration of wheat dust:

TABLE 1. MINIMUM MASS CONCENTRATIONS REQUIRED FOR WHEAT DUST EXPLOSIONS[2]

Mass concentration (g/m^3)	20 - 50	40	10.3	50 - 100	23	70
Literature source (reference)	3	4	5	6	7	8

The low value of 10.3 g/m^3 from Reference 3 probably resulted from the experimental method used for that determination which frequently yields underestimates of the minimum explosive concentrations. It thus appears that the average minimum concentration for the other sources is about 40 g/m^3 with a low limit of about 20 g/m^3. Table 2 lists minimum explosive concentrations measured for other agricultural dusts. This tends to confirm the 40 g/m^3 level which we have selected as the minimum explosive concentration for wheat dust.

TABLE 2. MINIMUM EXPLOSIBLE DUST CONCENTRATION OF AGRICULTURAL GRAINS[9]

Type of dust	Minimum explosible concentration (g/m^3)
Alfalfa	100
Coconut shell	35
Coffee	85
Coffee, instant	280
Corn cob	45
Cornstarch	40
Cottonseed meal	55
Malt barley	55
Rice	50
Soya flour	60
Soya protein	50
Sugar	45
Wheat flour	50
Wheat starch	45
Yeast	50

As would be expected, moisture tends to reduce the explosibility of dust, and the effect is shown by increases in the minimum explosible mass concentration and minimum ignition energy. Typically, the minimum dust concentration for explosibility increases by about a factor of 10 for admixed moisture concentrations of the order of 100 g/m^3, with respect to explosible dust concentrations at zero moisture levels.[9] Similarly, it has been determined that grain dust explosions are inhibited for dust moisture content in excess of about 20 percent.[3] It can thus be stated that small amounts of water adsorbed onto the dust particles drastically reduce the danger of explosibility given that the dust concentration is sufficiently high for such a danger to exist.

Particle size also has an effect on the explosibility of a dust cloud. The minimum explosive concentration tends to increase with increasing particle size for two reasons. First, for a given mass concentration, the number of particles increases with decreasing average diameter causing a decrease in the distance between the particles. This facilitates heat transfer between neighboring particles. Second, for a given mass concentration, the total surface area increases with decreasing size, and reaction rates between solids and gases are generally strongly dependent on the contact surface. Figure 1 shows the effect of average particle size on the minimum explosive limit of cornstarch.[10] The limit is constant up to about 100 μm, and increases drastically between 100 μm and 150 μm. Particles smaller than 75 μm are generally used in Bureau of Mines investigations of explosibility of dust clouds.[8] It should be noted that, in practice, the size distribution of dust generated by various means is not extremely variable as particles larger than 100 μm tend to settle out rapidly, leaving only smaller particles.

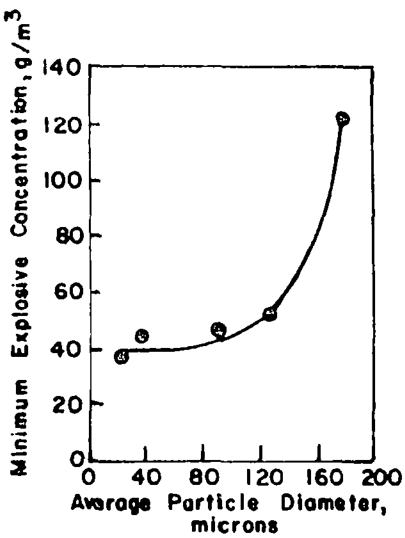

Figure 1. Effect of particle size on the minimum explosive concentration of cornstarch.

SECTION 3

MEASUREMENTS - PROCEDURES AND RESULTS

In order to determine whether the use of tents to control ship-loading emissions poses an explosion hazard, one must determine first whether the tents cause an appreciable change in the character of the atmosphere inside the hold, and second whether the resulting atmosphere is an explosible one. Background material on the conditions necessary for dust explosions indicates that the parameters which are most important in determining the explosibility of a dust cloud are (1) dust concentration, (2) dust size distribution, and (3) moisture content. Measurements of dust concentration and relative humidity were made at various locations in the holds during both uncontrolled loading and controlled loading with various aspirations rates. Based on background data on dust explosions (see Figure 1) and on the fact that the Bureau of Mines measures lower explosive limits using particles less than about 75 μm, it was decided that the concentration of only the dust smaller than about 100 μm should be measured. The aspiration which was varied by removing suction hoses from the hold was also measured. Particle size distributions were measured for both tent controlled and uncontrolled loading.

PROCEDURES AND EQUIPMENT

Dust Concentration and Humidity Measurements

Dust concentrations (smaller than about 100 μm or 0.0039 in.) and humidities were measured by a probe consisting of a remote humidity and temperature sensor and a dust collector designed and built by GCA. The probe can be suspended in a hold by an 18 m (60-foot) umbilical cord which contains shielded cable for the humidity sensor and air and pressure tap lines for the dust sampling device.

Dust Concentration--

The specially designed dust sampling probe is illustrated in Figure 2. Air is drawn through the probe at a predetermined rate by a remote pump. The rate is maintained using a dry gas meter and an orifice flow meter. A gravitational preseparator at the inlet of the probe allows only those particles with aerodynamic diameters smaller than about 100 μm to be drawn into the probe. Larger particles have settling velocities greater than the velocity of air in the preseparator, and are, thus, not collected. After passing through the preseparator, the air, with particles smaller than about 100 μm, passes through a filter holder. In the filter holder preweighed glass fiber filters are used to remove the remaining dust from the air. There are pressure taps to the airstream on either side of the filter holder which allow the measurement of the pressure drop across the filter at any instant. A schematic of the sampling system is presented in Figure 3.

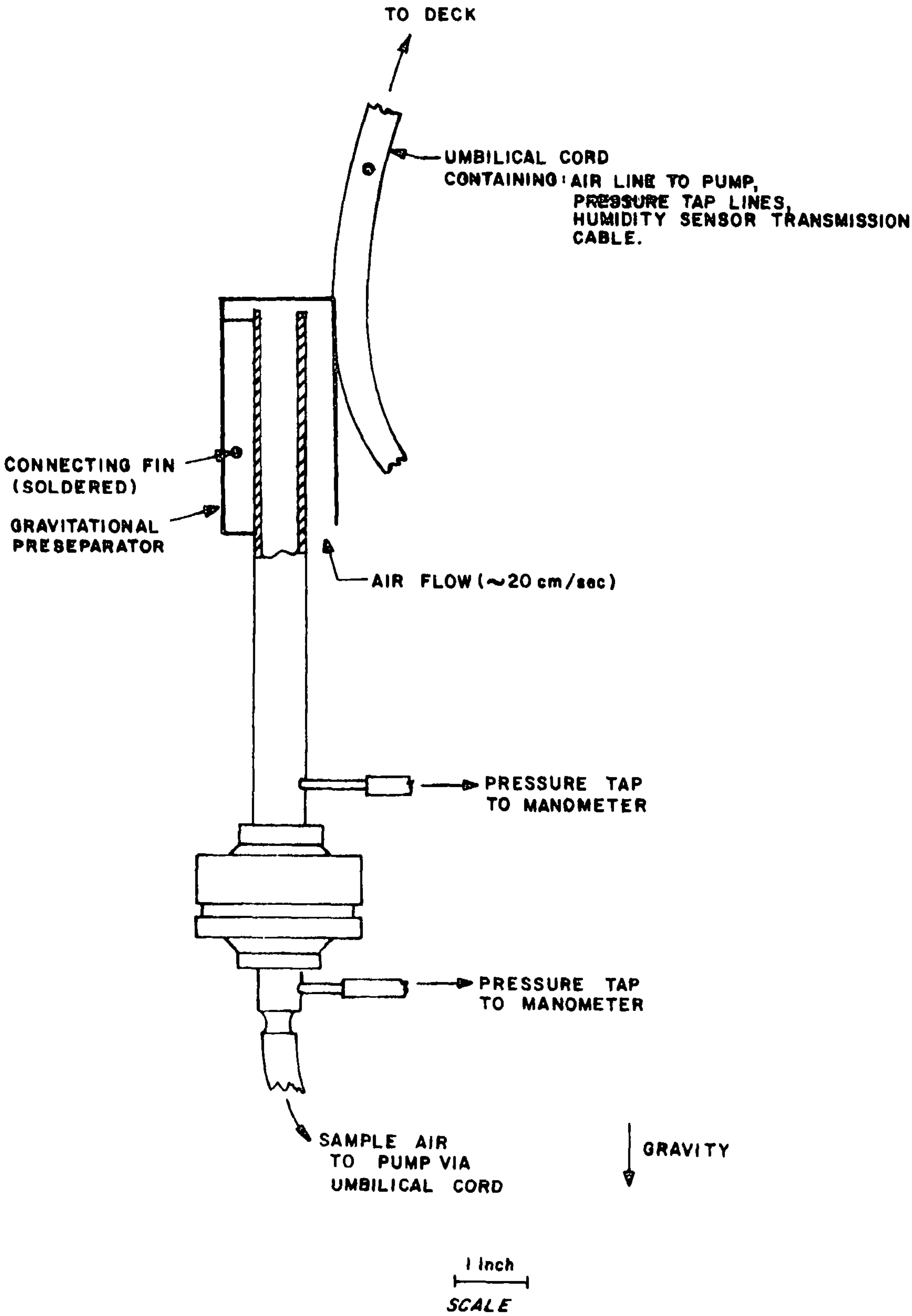

Figure 2. Sampling device used to measure grain dust concentrations in ship holds.

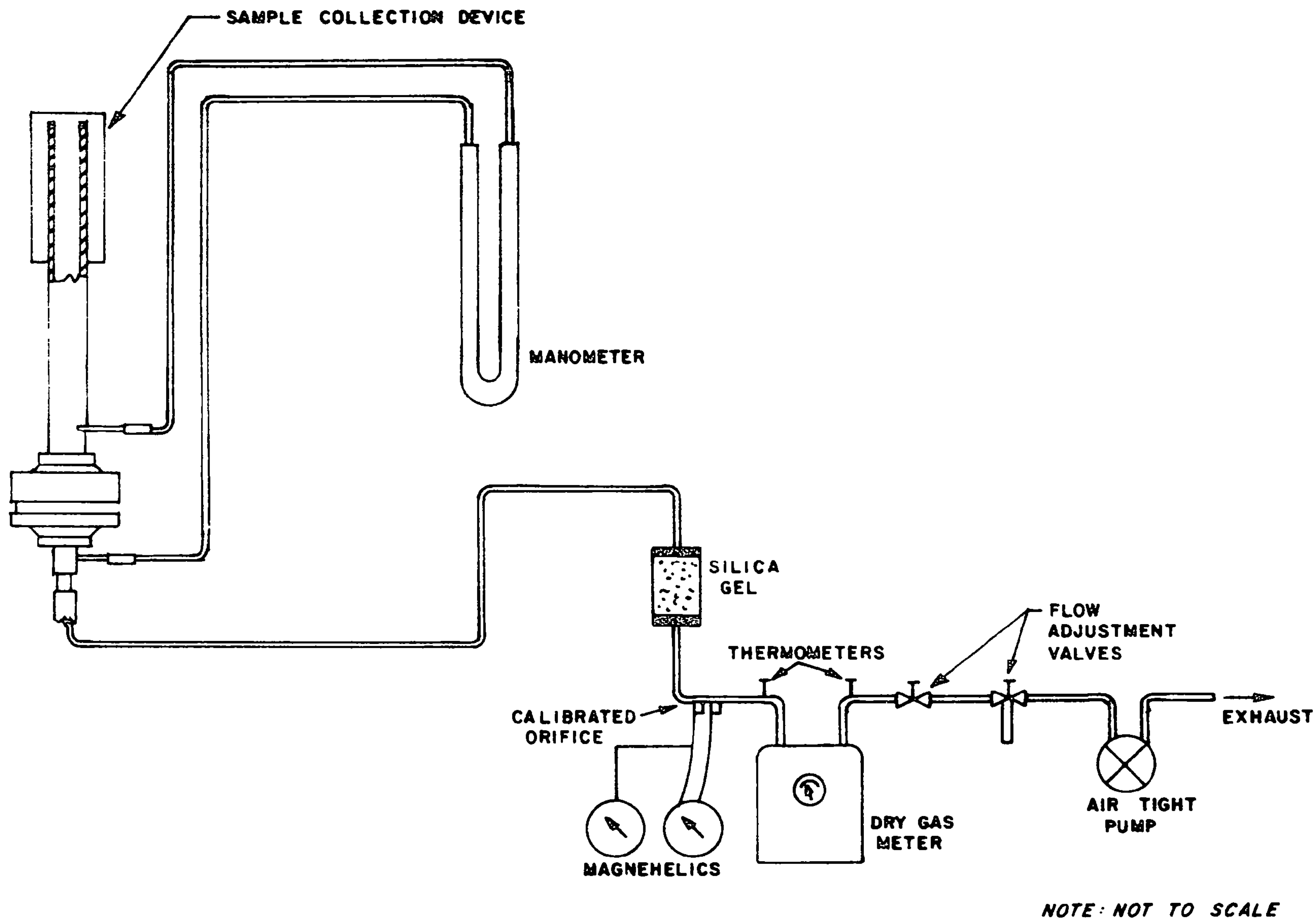

Figure 3. Schematic of dust sampling system.

The dust filter was changed every 5 to 20 min (typically 10 min) during the tests, and each filter change constituted a run. During each run the pressure drop across the filter was recorded once a minute for the duration of the run. The total number of runs made under various conditions was 67.

From the total volume of air drawn through the filter during a given run, and the dry weight of the filter before and after the run, one can determine the average concentration of particulates less than about 100 μm diameter in the sampled air.

From readings of the pressure drop across the filter at different times during the run, it is possible to estimate dust concentrations for shorter time intervals. It has been found that the relationship between the dust cake thickness on a fabric filter control device and the pressure drop across the fabric takes the general form of curve (a) in Figure 4.

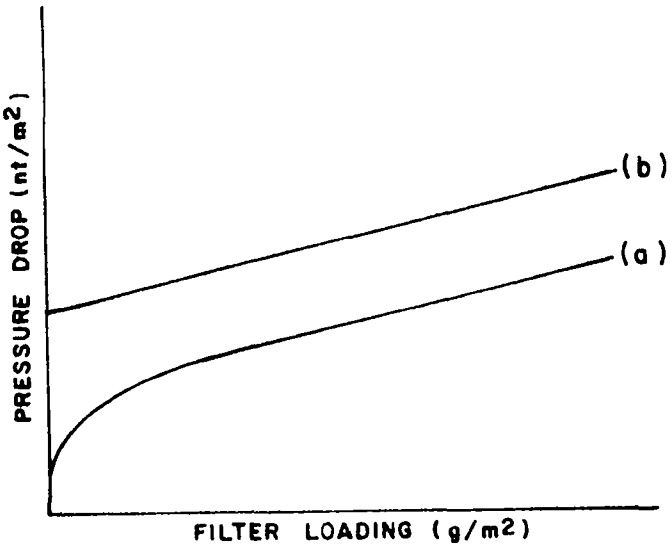

Figure 4. Pressure drop across particulate filters.

For the thick glass fiber filbers used in these experiments, the relationship between dust cake thickness and pressure drop across the filter approximates the straight line (b). Thus, one can expect a linear relationship between the rate of increase of the pressure drop across the filter and the rate of dust deposition on the filter. Since the flow rate of air through the filter is maintained at a constant value, the rate of dust deposition is directly proportional to the concentration of particulate matter in the air. To obtain the average dust concentration for a given minute of a given run, then, one need only multiply the average dust concentration over the entire run by the ratio of instantaneous pressure drop increase for a given minute to the average rate of pressure drop increase over the entire run.

Relative Humidity--

The remote humidity sensor was obtained from Phys-Chemical Research. The device contains two integrated circuits whose impedance is directly related to the temperature and humidity of the air around them. The circuits in the probe are connected by shielded cable to an indicator box built by GCA, and from which the temperature and humidity can be read. The temperature can be obtained directly from the impedance of one of the circuits, while the impedance of the other, when corrected for temperature, can be used to obtain the relative humidity. In the range of 60 to 90 percent relative humidity, the sensor is accurate to within 2 percent relative humidity.

Relative humidity measurements were made inside and outside the hold for 16 of the dust concentration runs.

Aspiration Rates

For each loading spout at the United Grain terminal there is one aspiration pipe attached to the spout and two flexible aspiration hoses which can be inserted under the tents at the edge of the hold. During loading, the two hoses and the pipe for the loading leg in use are always pulling air to the fabric filtration system. Generally, hoses for other legs are pulling air as well. The aspiration rate was adjusted during the course of the measurements by putting different numbers of hoses into the hold being loaded, or by turning off the suction system entirely. Aspiration rates for individual tubes were measured by GCA using a pitot tube. The tube was used to find air velocites at various distances from the center of the tube, and the total flow rates were found using these velocities and tube areas. Similar measurements of aspiration rates were made during the tests at Bunge and Dreyfus.

Particle Size Measurements

An Andersen particle fractioning sampler ("Andersen impactor") was used to obtain typical particle size distributions during tent controlled loading and also during uncontrolled loading (topping off).

Air is drawn through an Anderson impactor at a predetermined rate by a remote pump. The sampling rate is maintained constant by a dry gas meter and an orifice flow meter. The impactor itself contains eight plates mounted in series, each having a pattern of precision-drilled orifices. The orifices are smaller for successive stages. Generally, a cyclonic preseparator and a backup filter are mounted at the inlet and outlet of the impactor, respectively. Large particles are removed from the sample air stream by the cyclonic precollector Smaller particles are inertially impacted onto eight preweighed glass fiber substrates which are mounted below the precision-drilled plates. The aerodynamic size ranges of the particles deposited in the precollector and on the eight substrates can be calculated using the exact flow rate of air through the impactor and constants which are determined by the precollector dimensions and the diameters of the precision-drilled orifices. Particles which pass through the precollector and the impactor are trapped on the backup filter. Thus, dust entering the impactor-precollector-filter system is fractioned into ten size ranges. There are effectively nine size ranges, however, since the cutoff diameter for the precollector is lower than that for the first impaction plate. From the dry weight of the dust trapped in the precollector, and the dry weights of the eight substrates and the backup filter before and after a run, one can determine the total average dust concentration in the sampled air; and the size distribution of the dust.

An Andersen impactor is generally used to sample gas flowing out of a stack. When this is done, the inlet nozzle for the precollector is chosen so that, when the impactor is run at the desired flow rate, the gas velocity through the nozzle will be the same as the gas velocity in the stack. Since there is no constant airflow velocity or direction in the hold of a ship, this procedure could not be used. Instead, the nozzle size was chosen to minimize the airflow velocity through the nozzle and, thus, keep the collection efficiency for different size particles relatively constant. The impactor was held in such a way that the nozzle was mounted horizontally. It is estimated that particles up to about 150 μm (0.0059 in.) are collected using this technique, with collection efficiency becoming smaller as particle size increases.

RESULTS

Size Distribution

The results of Andersen impactor measurements of particle size distributions at the United Grain terminal are presented in Table 3 and Figure 5. Two runs were made, one during tent-controlled loading with an aspiration rate of about 225 m^3/min (8000 acfm) (run A1), and one during uncontrolled loading (run A2). In each case, the impactor was located in a moderately dusty section of the hold, somewhat removed from the grain impaction site. Figure 5 shows that the size distributions found in the two runs are essentially the same. The mass median diameter of the suspended particles was about 11 μm (4.33×10^{-4} in.) while the geometric standard deviation was about 3.2. Particles larger than 100 μm made up an insignificant fraction of the particles collected by the impactor.

Aspiration Rates

Aspiration rates for open hoses and tubes were measured during the loading of one hold at United Grain. There was one aspiration tube attached to the loading spout, and two tubes which could reach the hold being loaded. These three tubes must be on or off in unison. The tube attached to the spout was found to pull air at a rate of 160 m^3/min (5700 acfm), while each flexible hose maintained a flow of 70 m^3/min (2500 acfm). Three flexible tubes which would not reach the hold being loaded were valved open, but were placed end to the ground so there was no significant flow through them. The measured total amount of air being drawn through the fabric filtration system was about 300 m^3/min (10,700 acfm).

Aspiration rates were also measured during the tests at Bunge and Dreyfus. In both cases, the flow rate is a function of the number of hoses inserted into the hold, the number of hoses left open, and the location of the hoses in the manifold system. During the first series of tests at Bunge, one hose with an aspiration rate of 127 m^3/min (4500 acfm) was in use. Tenting and therefore aspiration was not used during the second series of tents at Bunge. At Dreyfus during the first series of tests, two hoses with a combined aspiration rate of 158 m^3/min (5600 acfm) were used. During the second series of

TABLE 3. PARTICLE SIZE DISTRIBUTION MEASURED WITH ANDERSEN IMPACTOR AT UNITED GRAIN

Run no.	Time (min)	Air sampled (m^3)	Total particulate concentration (g/m^3)	Weight percent less than stated size*							
				Cyclone	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
A1	7	0.0254	0.29	70.5 (19.6)	57.2 (16.4)	39.0 (11.2)	34.5 (7.63)	24.5 (4.75)	17.0 (2.10)	8.70 (1.44)	1.74 (0.883)
A2	7	0.0286	0.18	68.3 (18.4)	62.6 (15.4)	44.7 (10.5)	28.2 (10.5)	19.1 (7.16)	9.72 (4.46)	5.64 (1.35)	0 (0.825)

* Numbers in parenthesis are sizes in micrometers. Top numbers are percentage less than the stated sizes.

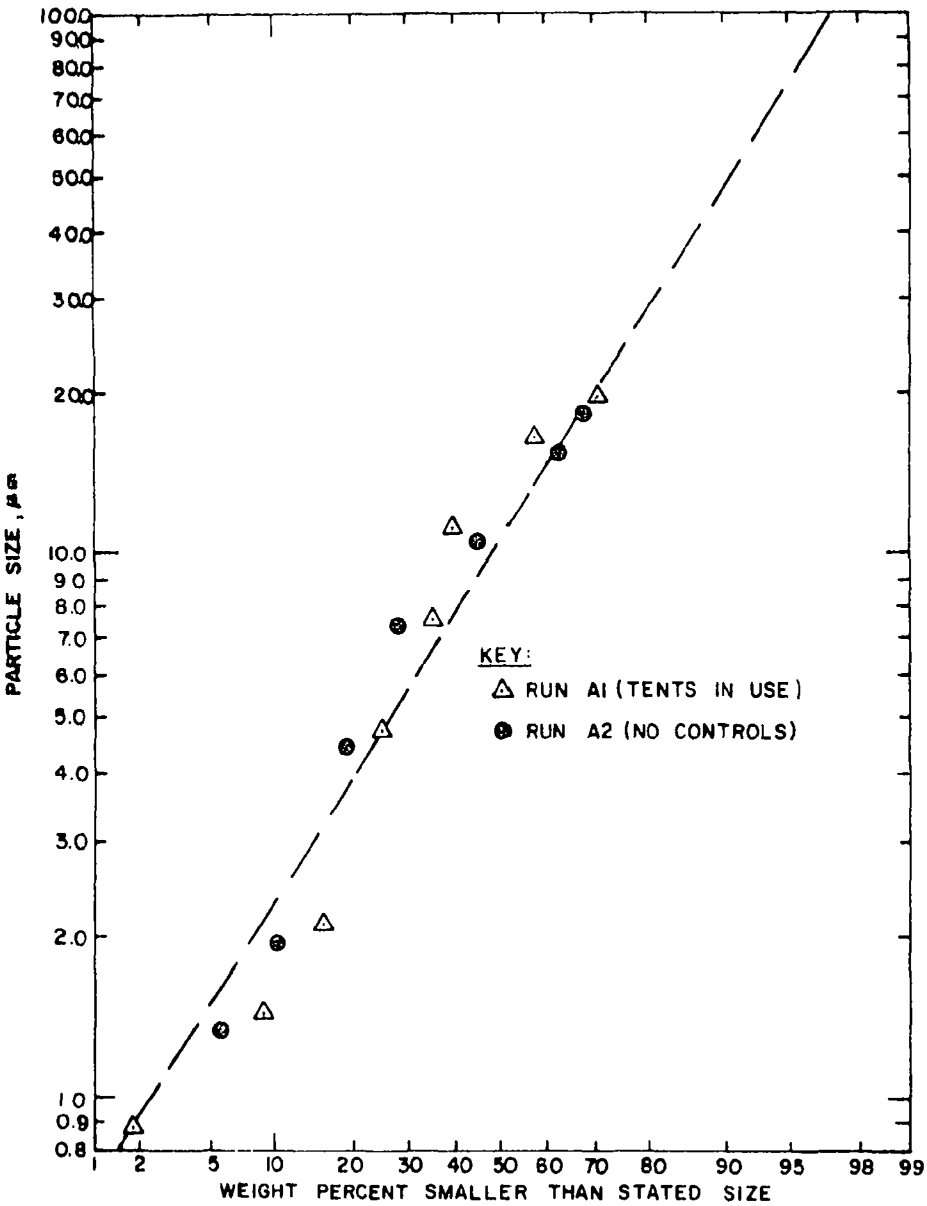

Figure 5. Particle size distribution measured with Andersen impactor at United Grain.

tests at Dreyfus, a single hose with an aspiration rate of 122 m^3/min (4300 acfm) was used. The higher flow rate through a single hose occurred because the hose entered the manifold system near the fabric filter and fewer hoses were left open.

Relative Humidity

The results of relative humidity measurements at United Grain are presented in Table 4. The table also indicates the general conditions under which the measurements were taken. Aspiration rates were estimated by considering which tubes were in use and the aspiration rates measured for such tubes. It is assumed that the aspiration rate for flexible hoses and the tube above the loading spouts are the same regardless of which loading spout is in use.

There does not appear to be a significant dependence of the humidity in the hold with whether or not tents are in use. There is some dependence of the difference between inside and outside humidity on outside humidity. For outside humidities of 72 percent and less, the humidity inside the hold was, on the average, only about 1 percent less than that outside. For outside humidities of 80 percent and above, the humidity inside the hold was on the average 7 percent below the outside humidity. This was true even when no test was used. In any case, the humidity inside the hold is not appreciably lower than the outside the hold.

Particulate Concentrations

As was previously mentioned, 67 measurements of dust concentrations were made during topping-off, during tent controlled loading with different aspiration rates at various locations in the holds and during uncontrolled loading. Because nearly all of the particulate matter collected in the two Andersen impactor runs were smaller than 80 to 100 μm (see Figure 5), the total dust concentrations measured in these runs can also be considered in any determinations of average suspended dust concentrations.

Results of the measurements at United Grain are presented in Table 5 and the location of the measuring points is shown in Figure 6. The time weighted average concentration was 0.34 g/m^3 and the highest measured concentration was a 12-min average of 1.1 g/m^3.

Results of the measurements at Bunge and Dreyfus are presented in Table 6. The location of the measuring points are shown in Figures 7, 8, 9 and 10. At Bunge the time weighted average concentration was 0.51 g/m^3 while the highest measured concentration was 0.85 g/m^3 as a 10-min average. Results at Dreyfus show a time weighted average of 0.32 g/m^3 and a highest value of 0.74 representing a 10-min average.

After a brief examination of the above data, one could reasonably conclude that the chances of measuring dust concentration greater than 40 g/m^3 is practically nil. Further information is provided by the distribution of the results on log-probability paper as shown in Figure 11. Data that have a log-normal distribution, plot as a straight line in this type of graph paper.

TABLE 4. RELATIVE HUMIDITY RESULTS AT UNITED GRAIN

Run code	Relative humidity (percent)		Difference	Conditions	
	Outside hold	Inside hold		Tent in use? (X)	Aspiration rate (m^3/min)
1	60	63	+3	X	225
2	63	61	-2	X	225
3	63	59	-4	X	225
4	63	58	-5	X	225
5	63	58	-5	X	160
11	62	63	+1	X	0
12	62	62	0	X	0
13	62	59	-3	X	160
15	68	70	+2	X	160
16	68	70	+2	X	160
20	82	82	0		-
21	82	73	-9		-
22	82	73	-9		-
23	82	73	-9		-
24	80	70	-10		-
25	70	72	+2	X	0

TABLE 5. RESULTS OF DUST CONCENTRATION MEASUREMENTS AT UNITED GRAIN, TACOMA, WASHINGTON

Run	Date	Time	Sampling Duration (min)	Visual observation of probe area*	Tents in use yes (X) or no (-)	Aspiration rate (m^3/min)	Hoses in use†	Dust concentration (g/m^3)
1	10/27	11:35	15	D	X	225	A, B	0.02
2		13:30	7	D	X	225	A, B	0.34
3		14:45	15	D	X	225	A, B	0.11
4		14:26	15	D	X	225	A, B	0.07
5		14:48	20	T	X	160	A	0.08
7		15:55	12	T	X	160	A	0.45
8		16:15	15	T	X	160	A	0.18
9	10/28	08:50	6	T	-	-	-	0.18
10		09:30	10	T	X	0	-	0.83
11		09:45	10	T	X	0	-	0.82
12		10:00	10	T	X	0	-	0.75
13		10:15	17	T	X	160	A	0.66
14		10:35	13	T	X	160	A	0.30
15		11:10	15	D	X	160	A	0.38
16		11:40	10	T	X	160	A	0.18
17		13:24	2	T	X	160	A	0.61
A1		14:30	7	T	X	225	A, B	0.29
18		15:00	12	T	X	225	A, B	0.87
19		15:13	10	D	-	-	-	0.75
A2	10/30	08:15	7	D	-	-	-	0.18
20		08:44	10	T	-	-	-	0.04
21		09:05	15	T	-	-	-	0.17
22		09:20	15	T	-	-	-	0.01
23		09:40	6	T	-	-	-	0.02
24		09:52	1.83	T	-	-	-	0.02
25		10:30	7	D	X	0	-	1.1

* D = Dustier than the rest of the hold
T = Typical

† A = Pipe attached to grain spout
B = One flexible hose

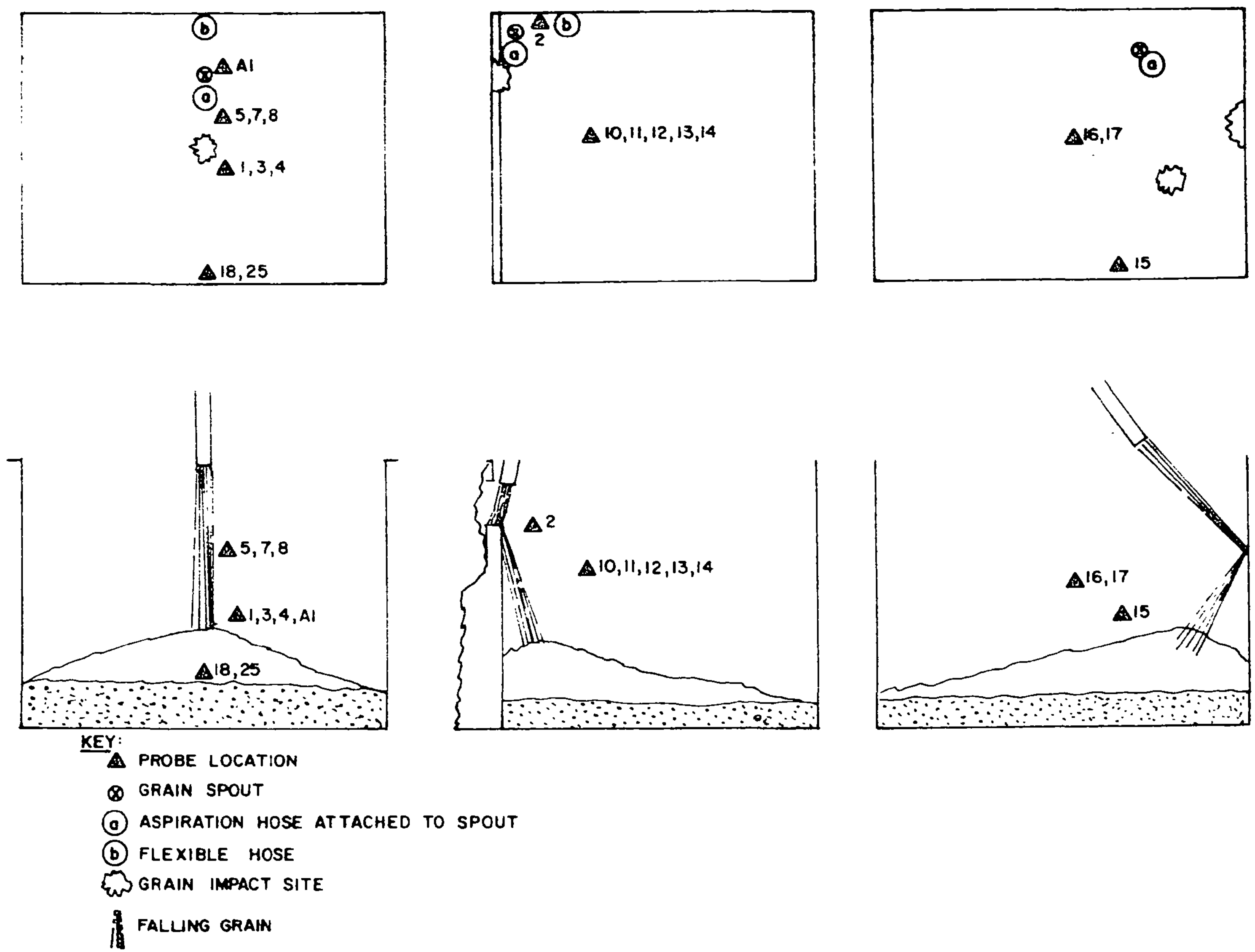

Figure 6. Measuring probe locations at United Grain.

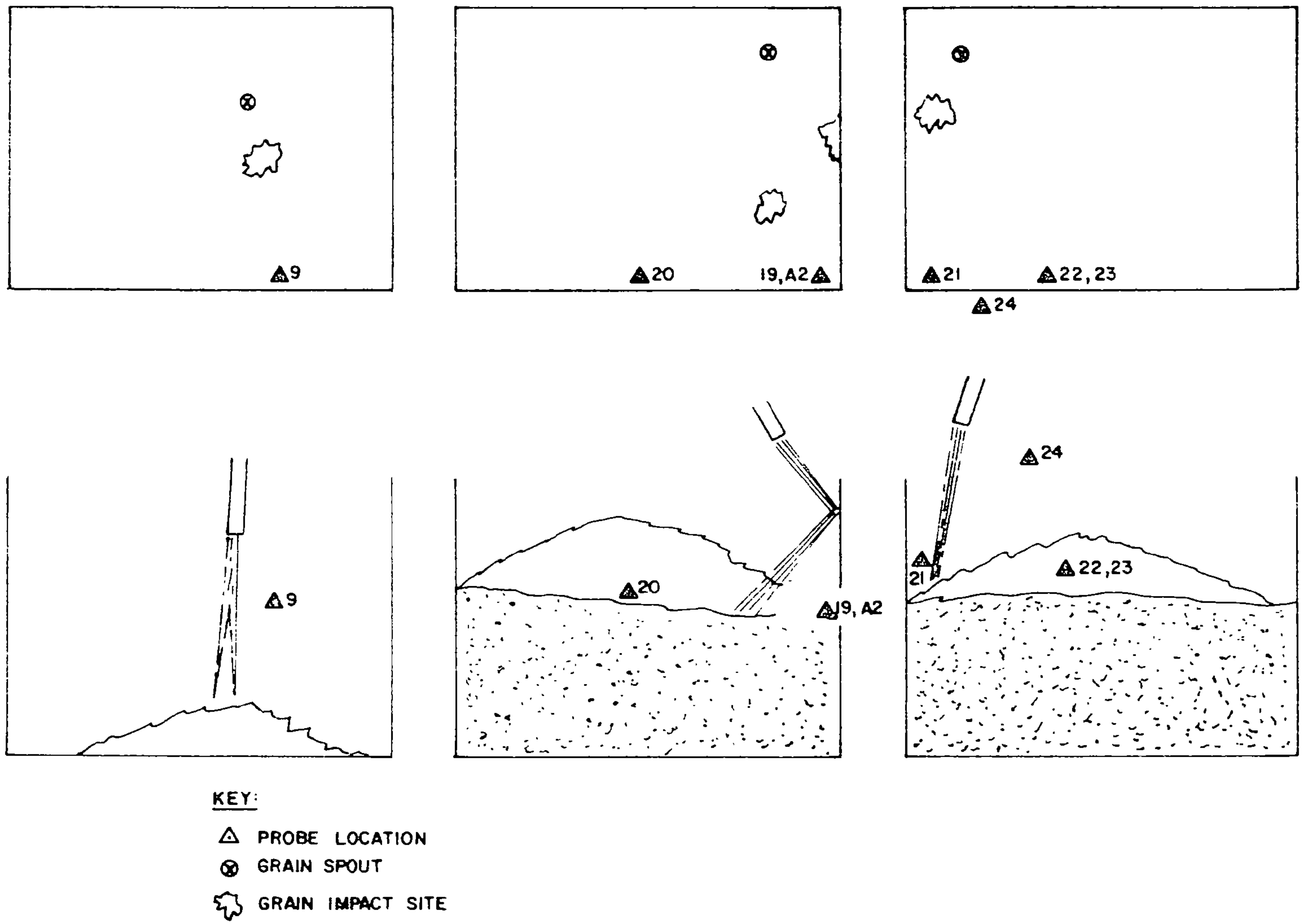

Figure 6 (continued).

TABLE 6. SUMMARY OF GRAIN DUST CONCENTRATIONS MEASURED IN SHIP HOLDS AT PORTLAND TERMINALS

Run No.	Location	Date	Time	Sampling Duration (min)	Grain type*	Tent in use yes (X) or no (-)	Aspiration flow rate (m^3/min)	Sample concentration[†] (g/m^3)
1	B[‡]	3/26	10:30 a.m.	15	WW	X	127	0.324
2	B		10:57 a.m.	10	WW	X	127	0.467
3	B			15	WW	X	127	0.536
4	B		1:21 p.m.	10	WW	X	-	0.236
5	B		1:45 p.m.	10	WW	X	-	0.414
6	B		1:59 p.m.	10	WW	X	-	0.670
7	B		2:10 p.m.	10	WW	X	127	0.609
8	B		2:27 p.m.	10	WW	X	127	0.417
9	B		3:00 p.m.	10	WW	X	127	0.847
10	D[§]		9:05 p.m.	15	WW	X	79	0.135
11	D		9:25 p.m.	15	WW	X	79	0.167
12	D		11:10 p.m.	15	WW	X	79	0.695
13	D		11:30 p.m.	10	WW	X	79	0.740
14	D		11:45 p.m.	10	WW	X	79	0.632
15	D	3/28	12:55 a.m.	15	WW	X	158	0.149
16	D		1:25 a.m.	6	HRW	X	158	0.121
17	D		1:36 a.m.	20	HRW	X	158	0.143
18	D		2:00 a.m.	20	HRW	X	158	0.127
19	B		1:59 p.m.	10	NS	-	-	0.326
20	B		2:14 p.m.	10	NS	-	-	0.429
21	B		2:26 p.m.	10	NS	-	-	0.751
22	B		2:40 p.m.	10	NS	-	-	0.527
23	B		2:58 p.m.	10	NS	-	-	0.647
24	B		3:09 p.m.	10	NS	-	-	0.776
25	B		3:25 p.m.	10	NS	-	-	0.561
26	B		3:38 p.m.	10	NS	-	-	0.449
27	B		3:55 p.m.	5	NS	-	-	0.099
28	D	3/29	9:25 a.m.	10	DNS	X	-	0.713
29	D		9:42 a.m.	10	DNS	X	-	0.341
30	D		9:45 a.m.	10	DNS	X	-	0.318
31	D		10:07 a.m.	10	DNS	X	122	0.226
32	D		10:22 a.m.	10	DNS	X	122	0.468
33	D		10:40 a.m.	10	DNS	X	-	0.475
34	D		10:52 a.m.	10	DNS	X	122	0.399
35	D		11:05 a.m.	10	DNS	X	122	0.463
36	D		1:15 p.m.	10	DNS	X	122	0.201
37	D		1:25 p.m.	10	DNS	X	122	-[#]
38	D		1:40 p.m.	10	DNS	X	122	-[#]
39	D		1:51 p.m.	10	DNS	X	122	0.337
40	D		2:09 p.m.	10	DNS	X	122	-[#]
41	D		2:20 p.m.	10	DNS	X	122	-[#]
42	D		2:32 p.m.	10	DNS	X	122	0.320

* WW indicates Western White, HRW indicates Hard Red Winter, NS indicates Northern Spring and DNS indicates Dark Northern Spring.

† Corrected to standard conditions.

‡ B indicates Bunge Corporation.

§ D indicates Louis Dreyfus Corporation.

\# Sample mishandled - dust was lost.

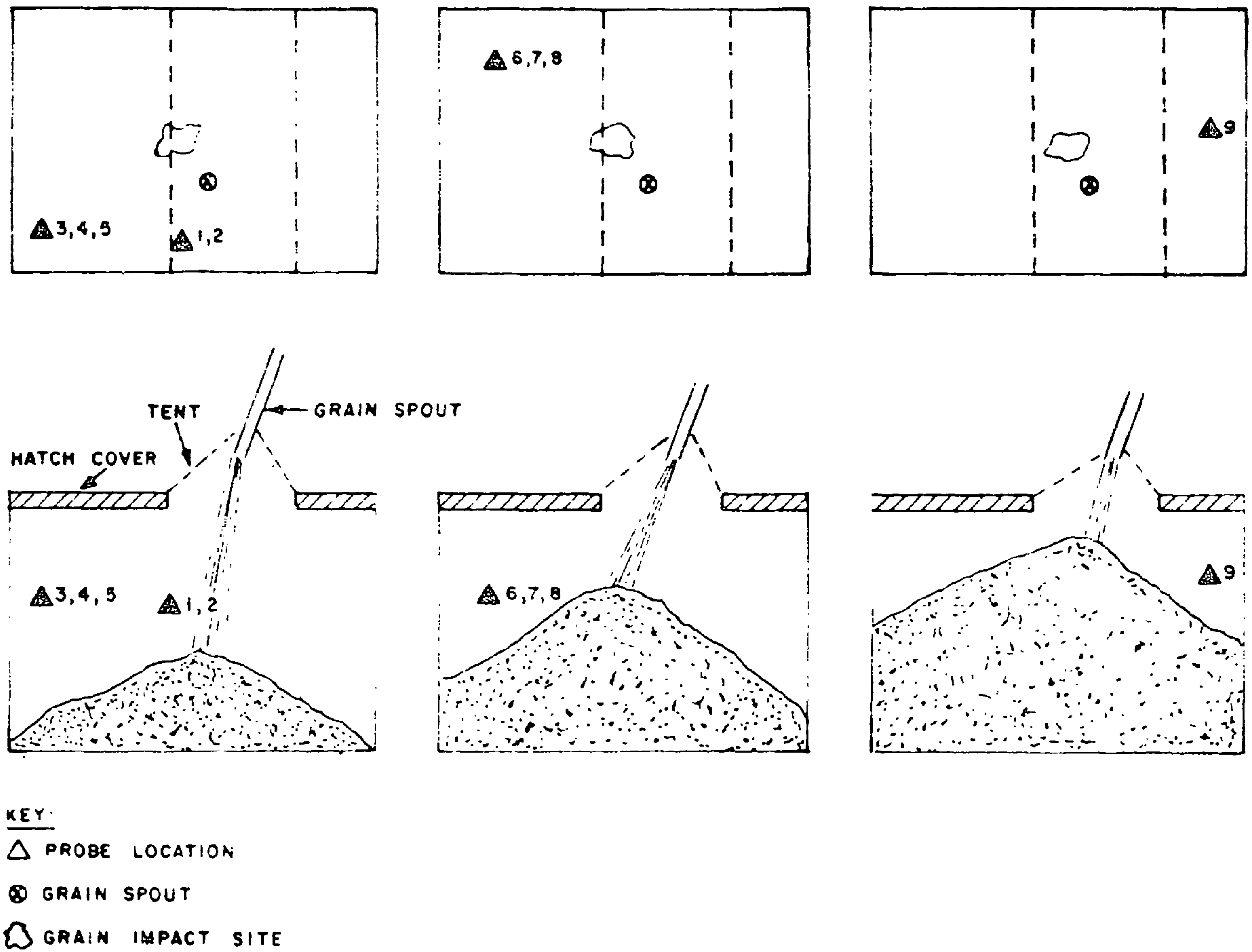

Figure 7. Sample positions at Bunge Corporation, March 26, 1979.

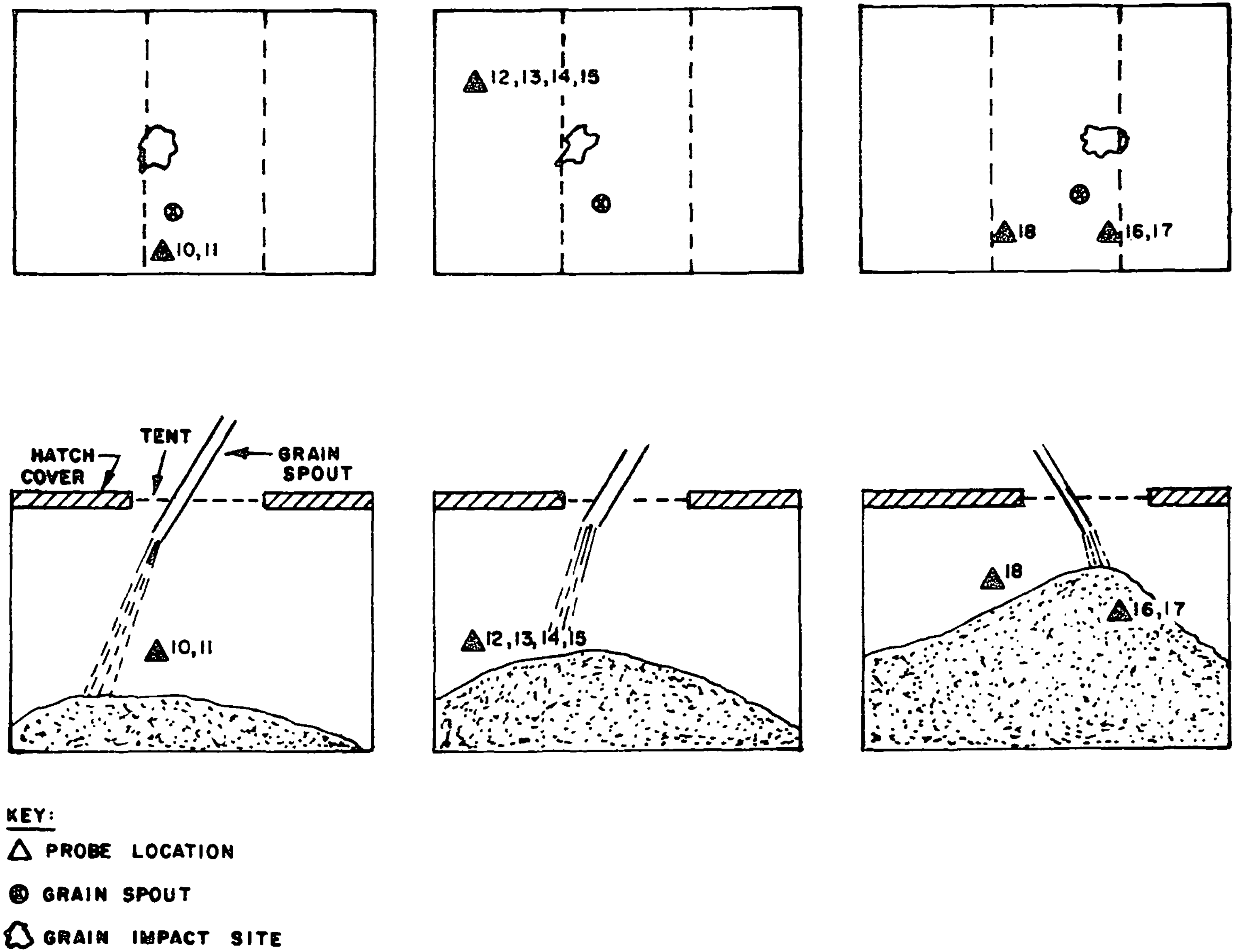

Figure 8. Sample positions at Louis Dreyfus Corporation, March 27, 1979.

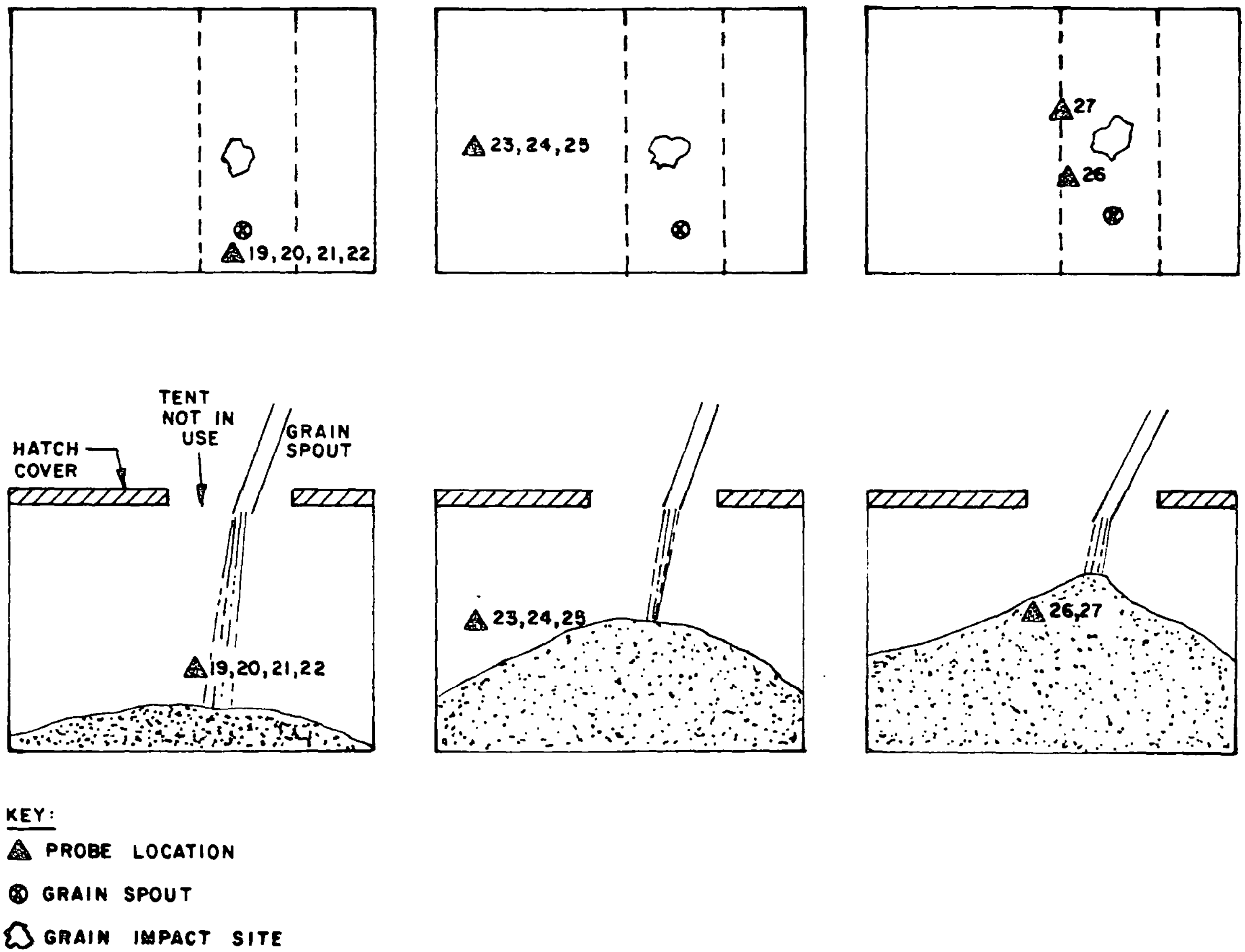

Figure 9. Sample positions at Bunge Corporation, March 28, 1979.

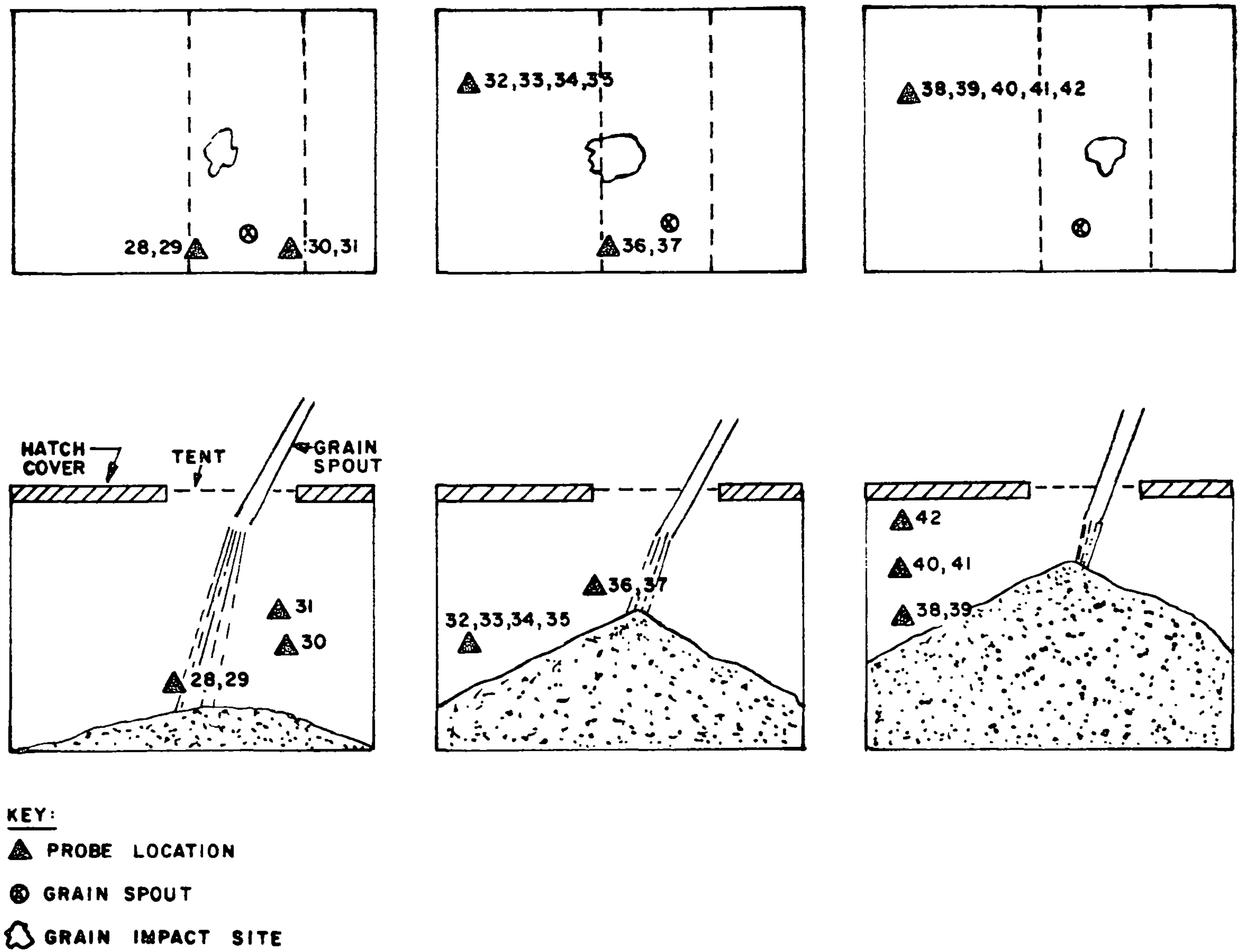

Figure 10. Sample positions at Louis Dreyfus Corporation, March 29, 1979.

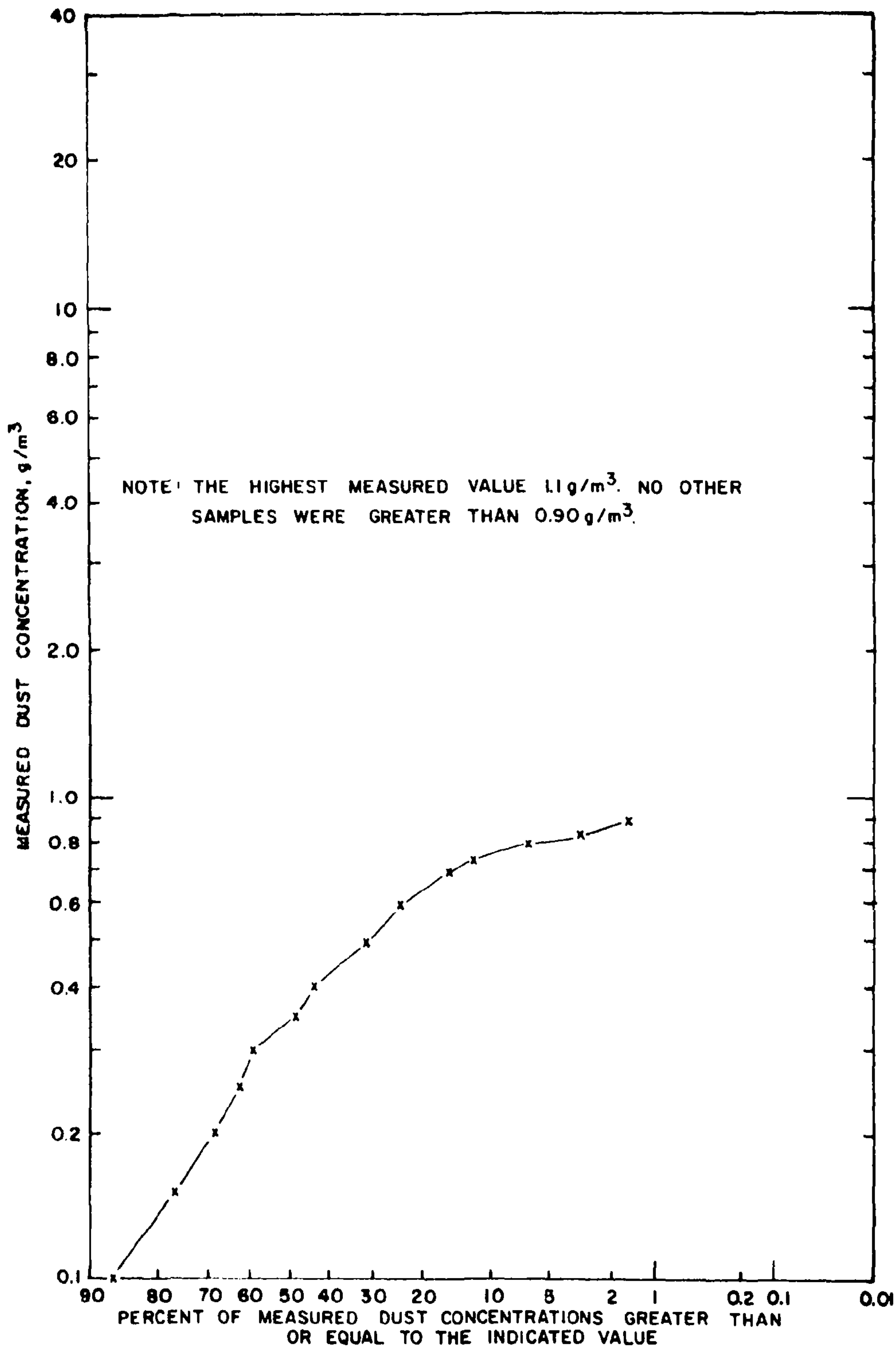

Figure 11. Log-probability plot of measured dust concentrations.

The data in Figure 11 show that there is less than a 2 percent chance of measuring a concentration, over the typical 10-min interval, of greater than 0.9 g/m^3. The curve can be graphically extrapolated in either of two extreme ways - ignoring the lower half or the upper half of the curve. Extrapolation of the upper half indicates only one chance in 10,000 of exceeding about 1.5 g/m^3 while extrapolation of the lower half indicates one chance in 10,000 of exceeding about 5-6 g/m^3. In either case, one must conclude that there is no significant chance of exceeding 40 g/m^3 as a 10-min average.

It should be further noted that the measurements were deliberately biased to measure high concentrations by taking samples in the dustiest portions of the holds. Also, the chances of explosion are further reduced by the fact that two events must occur at the same time - an ignition source and a dust concentration over 40 g/m^3 must both be present.

As previously discussed, it is possible to estimate 1-min dust concentrations from the rate of change in pressure drop across the filter. For example, assume that an average concentration of 1 g/m^3 was measured during a 10-min sample and the pressure drop across the filter rose by 2.49 kPa (10 in H_2O). Then, if over a selected 1 min interval the pressure drop increased by 0.249 kPa (1 in H_2O), the estimated concentration for that interval would be 1 g/m^3. Similarly, if the pressure drop increased by 0.5 kPa (2 in H_2O) in 1 min the estimated concentration would be 2 g/m^3. These calculations were performed for all sample runs yielding about 600 1-min concentration values. The distribution of these values is presented in Figure 12.

The results for the estimated 1-min concentrations are similar to the longer term averages. This is not surprising because the rate of pressure drop increase did not exhibit extremely large variations. The 1-min concentrations do, however, show a few values outside the range of the longer term averages. The highest estimated 1-min concentration was 2.3 g/m^3 and the second highest was 1.7 g/m^3. Extrapolation of the curve in Figure 12 indicates that there is one chance in 10,000 of finding a 1-min concentration greater than 2-5 g/m^3. Again the implication is that the chances of an explosion are insignificant.

The small differences in measured values between tent controlled loading with and without aspiration and between tent controlled and uncontrolled loading combined with the scarcity of measurements under some of these conditions and other variables such as the type of wheat make the evaluation of other data groupings rather tenuous.

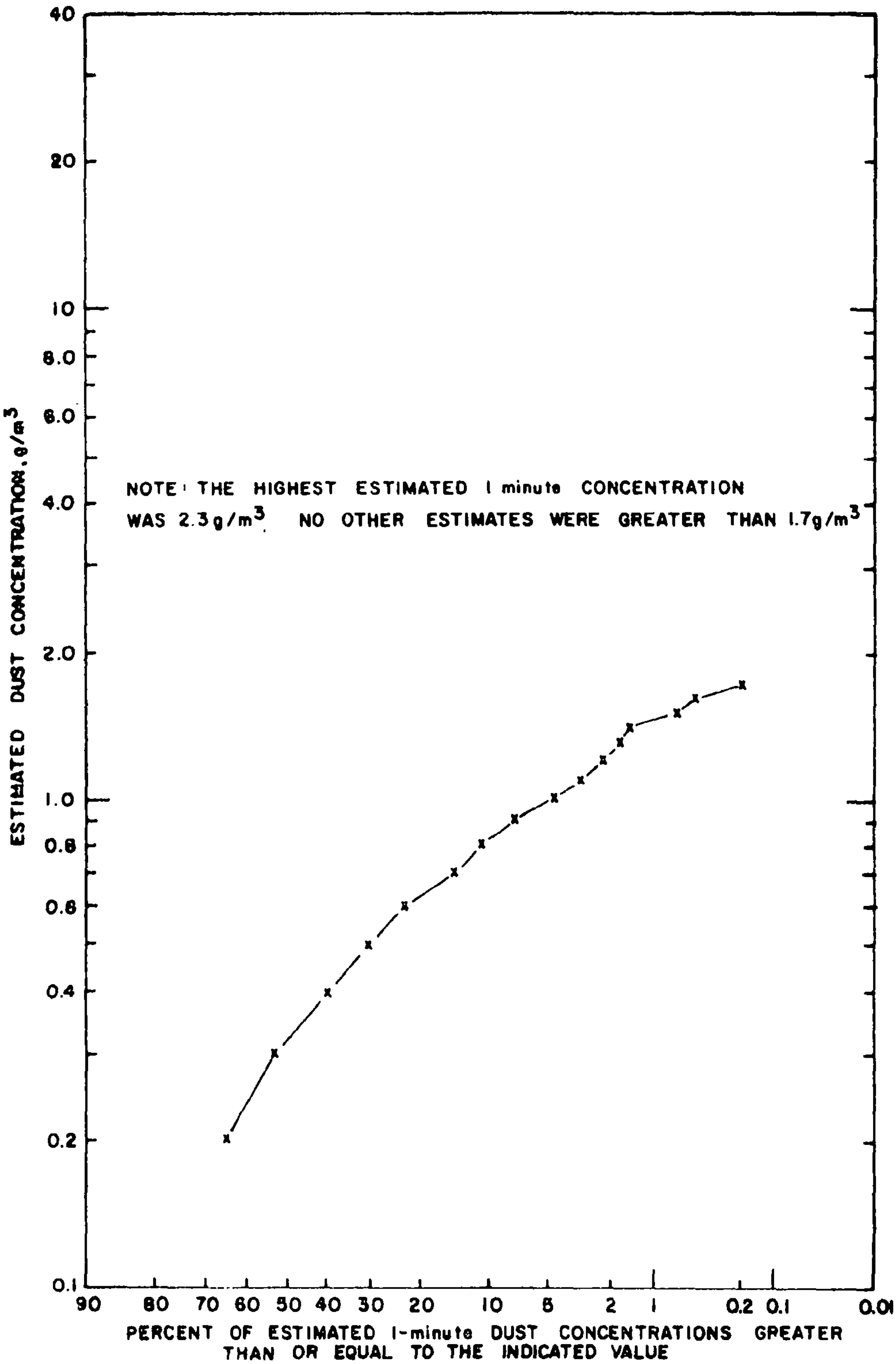

Figure 12. Log-probability plot of estimated 1-min dust concentrations.

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APPENDIX A

REPRINT OF

"SPECIAL REPORT ON DUST EXPLOSIBILITY"

GCA-TR-78-17-G

FEASIBILITY OF CONTROL OF PARTICULATE EMISSIONS FROM GRAIN TERMINALS

Contract No. 68-01-4143
Technical Service Area 1
Task No. 24

EPA Project Officer

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SPECIAL REPORT ON DUST EXPLOSIBILITY

by

Pedro Lilienfeld

GCA CORPORATION
GCA/TECHNOLOGY DIVISION
Bedford, Massachusetts

27 March 1978

U.S. ENVIRONMENTAL PROTECTION AGENCY
Division of Stationary Source Enforcement
Washington, D.C. 20460

DISCLAIMER

SECTION 1

INTRODUCTION

The recent explosions in grain elevators and the resultant loss of lives has generated considerable concern with respect to any operation where grain dust is generated and, in particular, contained.

Grain loading of ships is accompanied by the aerosolization of the dust mixed with the grain. This aerosolization results from the free fall of the grain from the chute opening and the impact of this stream on the deposited grain within the ship hold.

In order to prevent and/or reduce the fugitive emission of this airborne dust from the face of the hold during grain loading various measures have been taken, among which is the method of covering the face of the hold by means of a tent or tarpaulin. This method is usually combined with a high-flow rate suction system whereby a hose is inserted into the hold and air is pulled into a fabric-filter baghouse. Dilution air thus flows from the outside, under the tent into the hold in order to provide this aspiration flow. This system usually prevents any visible emissions from being detected above the hold during loading.

The containment of grain dust by means of tents has generated an acute concern as to the possibility of explosions under such enclosed loading conditions, and as a result OSHA has recommended that this method be discontinued until the safety from dust explosions has been determined.

The purpose of this report is to provide information from which a preliminary determination of the safety of tent-controlled ship grain loading operations can be made. Furthermore, this document will summarize additional information required to arrive at a more definitive conclusion of this question.

SECTION 2

HISTORICAL BACKGROUND

Agricultural dust explosions have been a problem for many years. They are not unique to our times although reliable records of such accidents are restricted to the last 200 years. Probably the first recognized explosion of this type occurred in Italy on December 14, 1785 involving flour dust.[1] Increasing industrialization thereafter is correlated with an increasing number of such explosions both in Europe and the U.S.[2] From about 1860 on, grain dust explosions become considerably more frequent. In the U.S. about 100 violent conflagrations associated with flour and grain dust were reported between 1870 and 1922,[2] and 59 explosions in industries storing and processing cereals and flour, between 1949 and 1973.[3] It is noteworthy to indicate that none of the reviewed grain dust explosions occurred on ships as a result of grain loading operations. As a matter of fact, no grain dust explosions on ships are mentioned at all.

The primary causes for grain dust explosions had remained largely unknown until recently, when improved surveillance and reporting methodology have been applied. Thus for 535 grain dust explosions between 1860 and 1973, 46 percent of them were of unknown origin, whereas for the period 1949 to 1973, of 128 such accidents, 26 percent were unexplained. This number drops to only 9 percent during that latter interval for grain dust explosions in the Netherlands.[3] For conflagration in grain elevators alone 62 percent of these had unknown causes for the period 1958 to 1975 in the U.S.[4] Primary causatory factors for grain dust explosions identified by various authors are: welding, handlamps, open fires or flames, frictional heat, mechanical sparks, electrical sparks, sparks from foreign materials, etc. In addition, less frequent causes are: lightning, spontaneous combustion, etc.

SECTION 3

EXPLOSION MECHANISMS AND REQUIRED CONDITIONS

PROPERTIES AND CHARACTERISTICS

A dust explosion is a reaction in a mixture of finely divided solid substance and a gas, mostly air, which is initiated by local heat supply; the reaction then proceeds quickly through the entire mixture. Initially, the reaction is restricted to a fraction of the dust cloud. This reacting part forms the flame. The heat released in the flame is transferred to nonreacting particles at the flame front. As a result of this heat transport, the flame front advances. The speed at which this flame front moves is called the propagation velocity or flame velocity. The propagation velocity is the resultant of the burning velocity and the expansion velocity of the hot gaseous products. Under nonchanging conditions (temperature and pressure) the burning velocity is constant. This velocity is called linear burning velocity. In case of a "point" ignition the flame spreads like a sphere.

If the expanding gas develops turbulence, the flame front area will expand considerably and the mass-conversion rate increases. The heat transfer of the reacting dust particles to those that have not yet reacted plays an important part in the propagation of the explosion. The heat transport takes place by conduction, convection and radiation. It is assumed that radiation in particular makes an important contribution.

Furthermore, the rate at which the substance decomposes under the influence of high temperature-yielding combustible gases (pyrolysis), and the rate at which the oxygen required for the reaction is supplied by diffusion, are important factors determining the development of the explosion. The violence or intensity of the explosion depends on how finely the airborne material is divided (i.e., particle size), since the reaction velocity between the solid substance and the gas is strongly dependent on the dimensions of the contact surface. Thus, rigorously it is not the mass concentration of the dust particles, but the specific surface concentration what determines the reaction velocity. For practical reasons, however, mostly the mass concentration is used in this context and the particle size stated when known.

Since optical aerosol measurement methods (i.e., light scattering and extinction) are more closely related to particle area than to particle volume, these methods should be considered uniquely compatible with dust cloud characterizations from the point of view of explosiveness.

The energy released at the combustion of a dust particle will have to bring an adjacent particle to such a temperature that this particle itself starts reacting with the oxygen in the ambient air, and, as a result, starts functioning as a new heat source. Thus, the distance between particles must be below a certain value. This means that a minimum number concentration of particles must exit for an explosive condition. This minimum concentration is the lower explosion limit. If the dust concentration is raised gradually, the upper explosion limit will be reached above which no explosion occurs any longer. This condition is reached as a result of the cooling action of the excess of dust. Between the two limits there is the explosive region.

An important parameter is the energy required for the ignition of an explosive dust/air mixture (ignition energy). This energy depends on the composition of the explosive mixture and the particle size (i.e., specific surface). As the particle size decreases, the ignition energy decreases and the combustion rate increases.

The effect of a dust explosion on the environment is determined by the velocity at which the combustion reaction progresses (propagation velocity or flame velocity), by the heat of reaction and by the gas volume formed by the reaction. In Figure 1 are shown the values characteristic for the effect; i.e., the maximum overpressure, the maximum rate of pressure rise and the average rate of pressure rise.

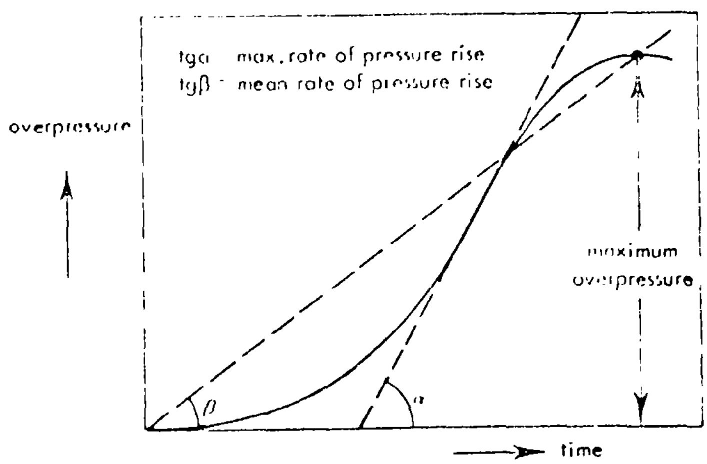

Figure 1. Pressure versus time of a dust explosion in a closed vessel.

The effect of an explosion depends on:

1. the nature, shape and dimensions of the substance;
2. the amount of oxygen available;
3. shape and size of the volume in which the explosion takes place;
4. turbulence.

The burning velocity in a dust cloud is many times greater than at an ordinary combustion process (for example a massive solid substance).

The maximum overpressures that may occur at dust explosions are between 5 and 10 atmospheres. The average maximum overpressure amounts to 7 to 8 atmospheres, if the initial pressure is 1 atmosphere. Most customary building constructions cannot resist a higher internal explosion overpressure than about 0.3 to 0.5 atmosphere. The pressure-rise process takes place in a very short time (0.01 to 1 second), the surrounding gas being heated to some thousands of degrees centigrade.

EXPLOSIVITY CONDITIONS

Several dust cloud parameters determine the explosive potential. The most important are: dust concentration, particle size, and moisture.

Dust Concentration

The precise minimum dust concentration level at which a grain dust explosion can occur cannot be specified with complete certainty because particle size, particle size distribution, type of grain, moisture content, dimensions of the contained volume, flow dynamics, etc., all influence the onset of an explosion of this type. In practice, however, and based on laboratory investigations by several researchers, it appears that a general consensus can be inferred. Table 1 summarizes this values as obtained from several representative sources:

TABLE 1. MINIMUM MASS CONCENTRATIONS REQUIRED FOR GRAIN DUST EXPLOSIONS

Mass concentration (g/m^3)	20 to 50	40	10.3	50 - 100	23
Literature source (reference)	3	4	2	5	6

The low value of 10.3 g/m^3 from Reference 2 probably resulted from the experimental method used for that determination which frequently yields underestimates of the minimum explosive concentrations.[3] It thus appears that the average minimum concentration for the other sources is about 40 g/m^3 with a low limit of about 20 g/m^3.

Concentrations of airborne dust of these values are extremely high. Dust clouds with concentrations of the order of 0.5 g/m^3 usually produce nearly 100 percent opacity over path lenghts of the order of 10 meters, and may be easily misjudged as potentially explosive. It should be understood that for dust concentrations below the explosive minimum it is essentially impossible to initiate an explosion even it an active flame exists within the cloud, in which case only those particles that come in direct contact with this flame undergo combustion but without propagation to neighboring particles. Table 2 lists specific types of agricultural grains and their minimum explosive concentrations.[7]

TABLE 2. MINIMUM EXPLOSIBLE DUST CONCENTRATION OF AGRICULTURAL GRAINS[7]

Type of dust	Minimum explosible concentration (g/m^3)
Alfalfa	100
Coconut shell	35
Coffee	85
Coffee, instant	280
Corn cob	45
Cornstarch	40
Corn flock	50
Cottonseed meal	55
Malt barley	55
Rice	50
Soya flour	60
Soya protein	50
Sugar	45
Wheat, flour	50
Wheat starch	45
Yeast	50

Table 2 again confirms the general range of minimum explosivity concentrations above 40 g/m^3 for these types of dust. The explosibility of agricultural grain dusts may be somewhat enhanced by the concomitant presence of insecticides as recently reported. The contribution of these chemicals, however, will probably be restricted to reducing the minimum ignition energy at the minimum mass concentration of dust.

Moisture

As would be expected, moisture tends to reduce the explosibility of dust, and the effect is shown by increases in the minimum explosible mass concentration and minimum ignition energy. Typically, the minimum dust concentration for explosibility increases by about a factor of 10 for admixed moisture concentrations of the order of 100 g/m^3, with respect to explosible dust concentrations at zero moisture levels.[7] Similarly, it has been determined that grain dust explosions are inhibited for dust moisture content in excess of about 20 percent.[3] It can thus be stated that small amounts of water adsorbed onto the dust particles drastically reduces the danger of explosibility given that the dust concentration is sufficiently high for such a danger to exist.

Particle Size

In general, as mentioned previously, for a given mass concentration of airborne dust the explosibility increases with decreasing particle size because the ratio of particle area to volume is inversely proportional to size, and at the same time the average distance between particles is proportional to size. It must be considered, however, that in practice, the size distribution of grain dust generated by various means is probably not too variable since the large particles tend to settle out rapidly leaving only a population of those smaller than about 100 μm in diameter which are also the more important contributors to a potential explosion.

PREVENTIVE MEASURES

Grain dust explosions can be prevented or their effect drastically reduced by several means which will now be discussed in the context of loading ship holds.

The most obvious preventive method is centered around the reduction of the concentration of airborne dust well below the explosibility levels mentioned previously. The containment technique using a tent or tarpaulin over the hold in itself would tend to increase this concentration, but in combination with aspiration the concentration can be reduced below the level that would exist in the hold without tenting. The equation for the average mass concentration as a function of time within the hold can be calculated from:

$$C(t) = \frac{\dot{m}}{Q_a} \left(1 - e^{-tQ_a/V_h}\right)$$

where $C(t)$ is the concentration as a function of time (g/m^3)

$\dot{m}$ is the rate of dust generation (g/sec)

Q_a is the aspiration flow rate (m^3/sec)

V_h is the hold volume (m^3).

This equation assumes that the aspiration flow rate exceeds the airflow entrained through the chute by the inflowing grain; i.e., that the pressure inside the tent-covered hold is negative with respect to the surrounding atmosphere. The gradual decrease of the actual hold volume V_h as the grain fills it has no practical effect on the above analysis since it occurs slowly with respect to other time-dependent variables.

The in-flow of dilution air from the outside of the hold has another important effect in the case of grain loading operations into slip holds. For obvious reasons, the air surrounding a ship usually has a high moisture content and if this air is drawn into the hold by the aspiration suction, the relative humidity of the air under the tent is raised considerably. As mentioned before, this will tend to drastically reduce any degree of explosibility as the airborne dust will adsorb water vapor.

Further measures that should be considered in order to prevent any danger of explosion are: proper attention to grounding all metallic elements that come into contact with the grain flow and the airborne dust, such as chute ducts, aspiration hoses, machinery, etc. Proper electrical grounding is required to prevent build-up of static charge, and should be checked on a regular basis since salt spray-produced oxidation or corrosion contamination of interfaces by dust and oils, etc., will tend to rapidly degrade electrical grounding contacts.

The tent itself represents an effective means of pressure relief in the extremely unlikely case of a conflagration within the hold. Since the overpressures thus generated are of the order of 5 to 10 atmospheres, the upward force on a tent of 10 x 10 meters (1000 sq. feet) would be of the order of 10^8 newtons ($\sim 10^7$ lbs) and nearly instantaneous relief would thus result.

SECTION 4

PRELIMINARY CONCLUSIONS BASED ON RECENT MEASUREMENTS BY GCA

The dust measurement program recently performed by GCA/Technology Division personnel in Portland, Oregon[8] was aimed at assessing the amount of fugitive particulate emissions resulting from the grain loading operations within the port of that city. Although that program was not directed at obtaining information concerning explosibility problems within ship holds during grain loading procedures, however, some of the determinations and measurements provide preliminary indications of the concentration levels to be expected within ship holds when using tents as a means of dust control in combination with aspiration flow. Two ship loading operations with tents were monitored within that program, Bunge and Dreyfus.[8] Fugitive emissions directly adjacent to the latter were measured at 200 mg/m^3; it should be noted that at Dreyfus no aspiration flow from the hold was used. At Bunge no visible emissions were detected from the tent-covered hold with a reduced aspiration flow of only 5000 cfm. During this same period, however, measurements taken with the GCA model RDM-101 respirable mass monitor with its inlet placed within a 1-foot high and 6-foot long opening on the side of the tent indicated respirable (i.e., less than about 3.5 μm diameter unit density spherical particles) mass concentrations ranging from 1.7 to 5.5 mg/m^3 with an average of about 3.6 mg/m^3. These values, in combination with the particle size distribution of the dust without the tent cover (see Figure 1, curve (1), Reference 8) during topping off indicate that the concentration within the tent-covered and aspirated hold did not exceed, but probably was less than, the total concentration of 89 mg/m^3 observed without the tent. This conclusion is qualitatively supported by the Dreyfus measurements without aspiration, mentioned above.

If indeed the mass concentration of airborne grain dust within aspirated tent-covered holds is of the order of 100 to 200 mg/m^3 (0.1 to 0.2 g/m^3) the concentration safety margin is of the order of 100 to 200 within respect to a most conservative (or pessimistic) explosibility level of 20 g/m^3. It should be considered that even if highly localized (e.g., near the stream of grain falling from the chute) areas may exhibit higher concentrations, any significant propagation of an explosion requires a distributed high concentration which appears extremely unlikely based on these preliminary determinations. The in-flow of moist dilution air into the hold should further contribute to the safety of the operation.

SECTION 5

PROPOSED ADDITIONAL EFFORT

In order to develop further substantiating and supporting evidence to the preliminary assessment presented within this report, additional measurements should be performed aimed specifically at determining the mass concentration and its spatial distribution in the interior of tent-covered holds during grain loading operations. Since most of the measurements cited in this report were performed above or near the edge of the holds, the proposed additional determinations should be performed preferentially well within the hold volume, just above the grain level and towards the central regions of the hold. In addition it would be desirable to determine the relative humidity of the air at those same locations. A monitoring program of this type, whose objective is to solidify the initial safety contention of these operations, will be proposed in more detail in a separate document.

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